Beyond the SM in B physics

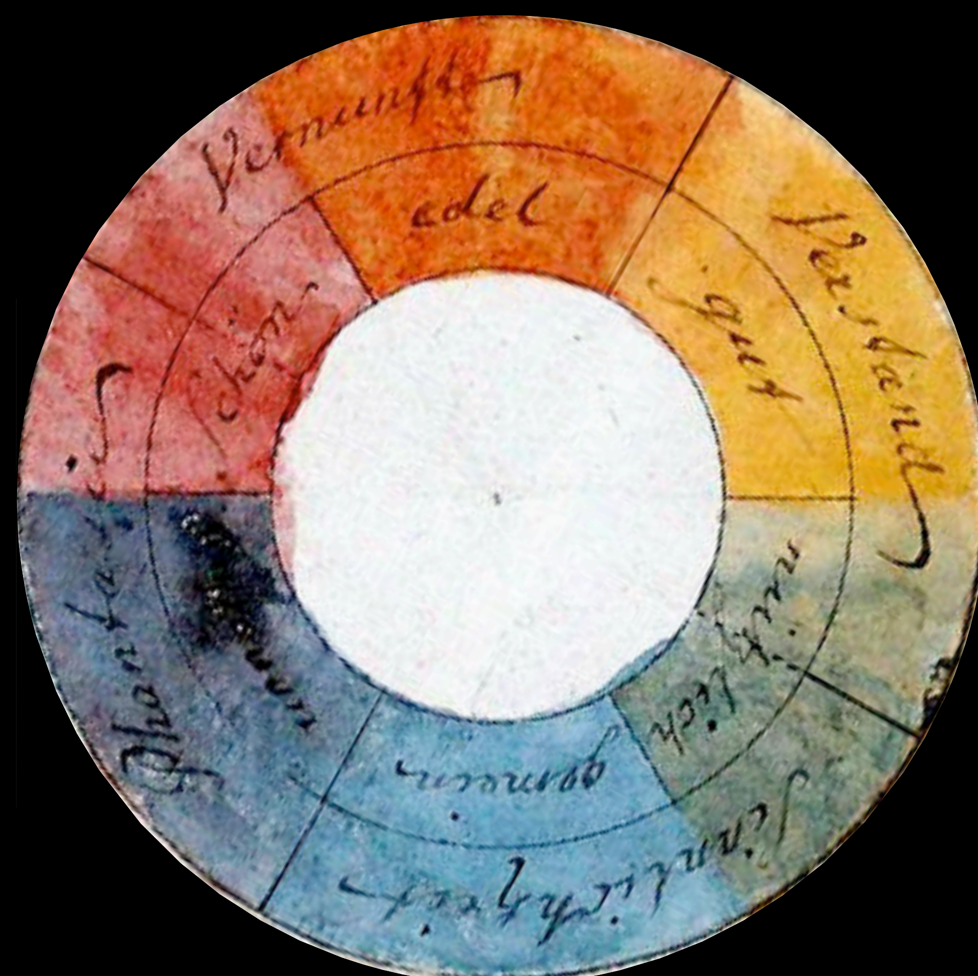
Sebastian Jaeger

University of Sussex

Lattice meets phenomenology

IPPP, Durham, September 15-17, 2010

Particle physics deals with a wide range of length/mass scales



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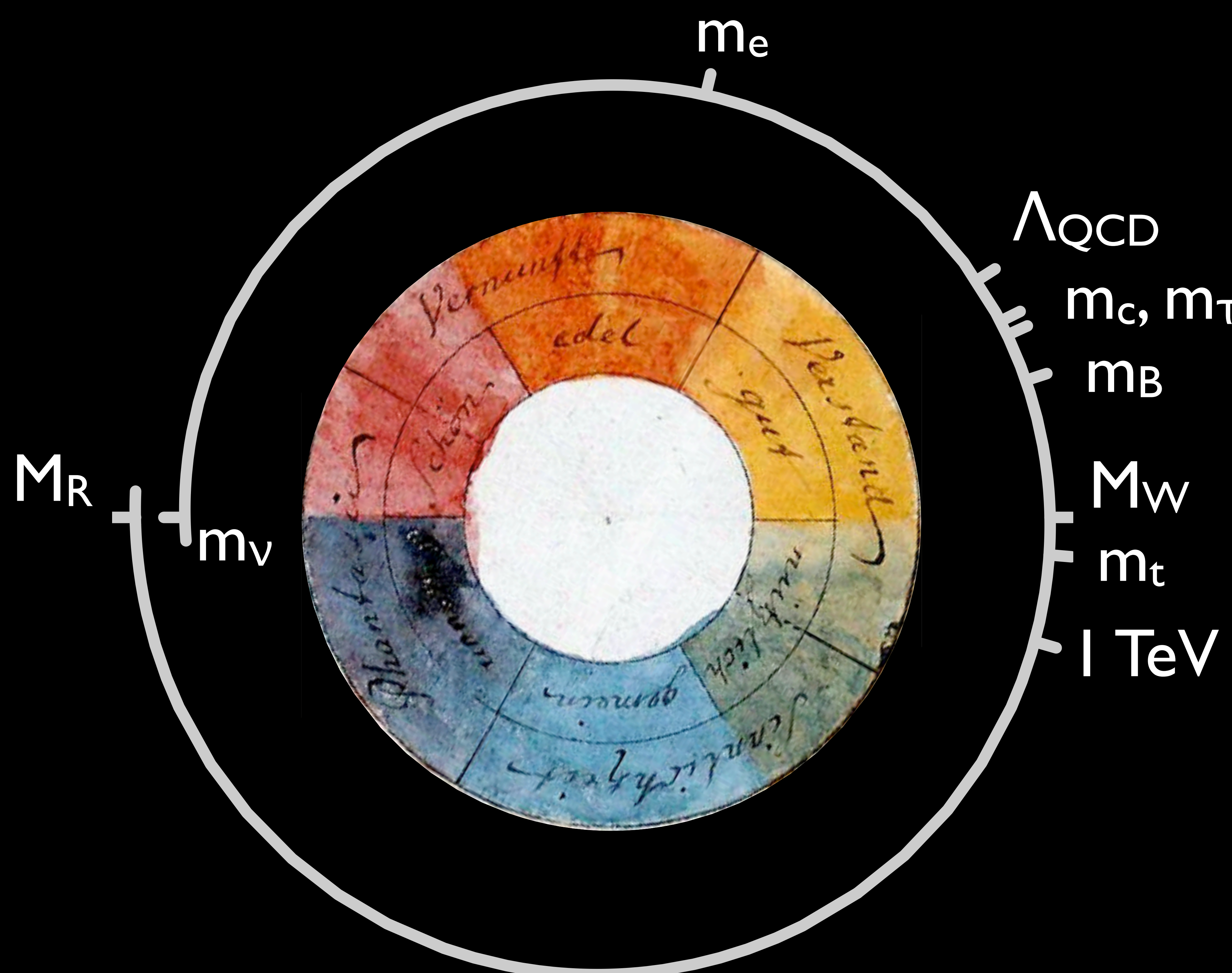

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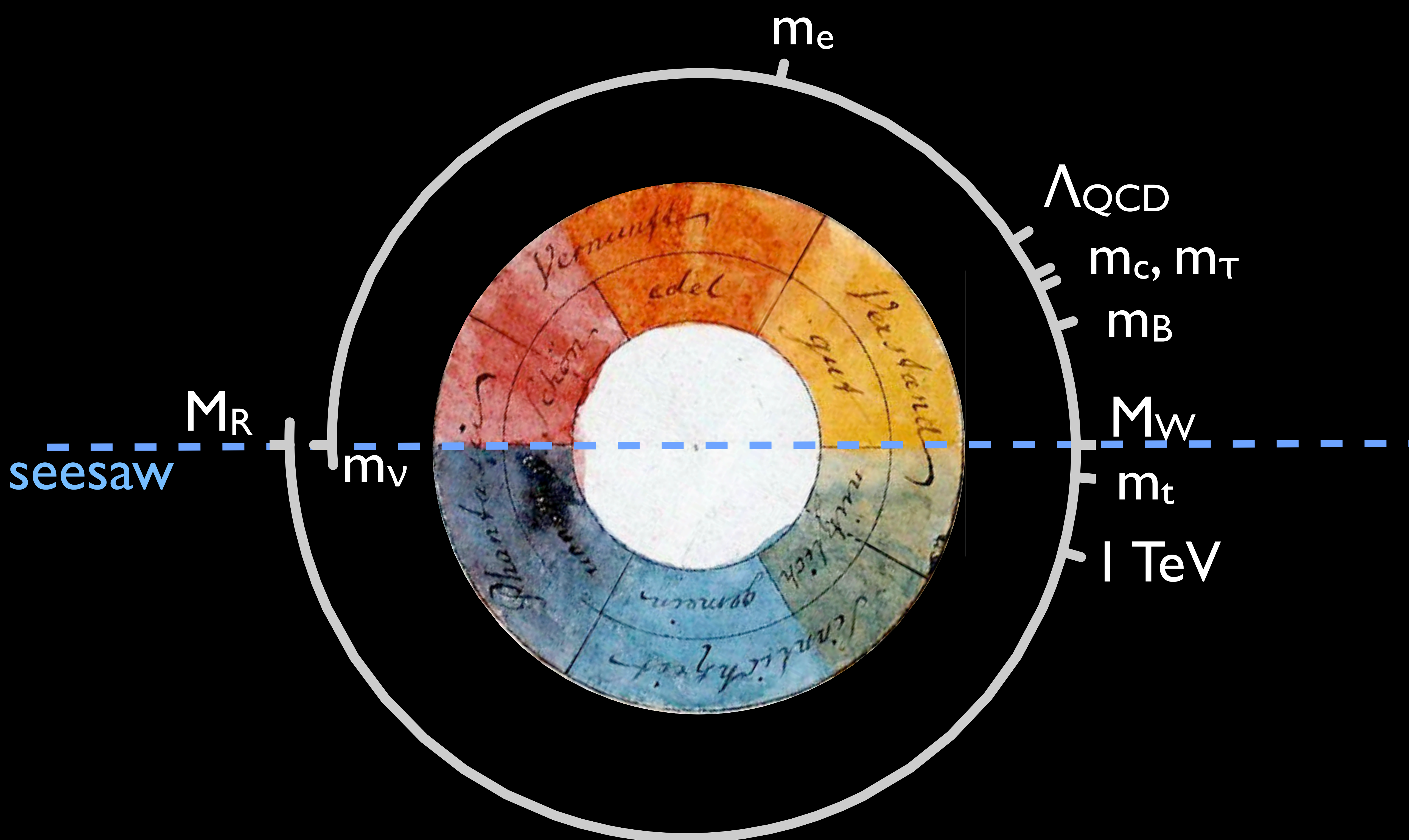

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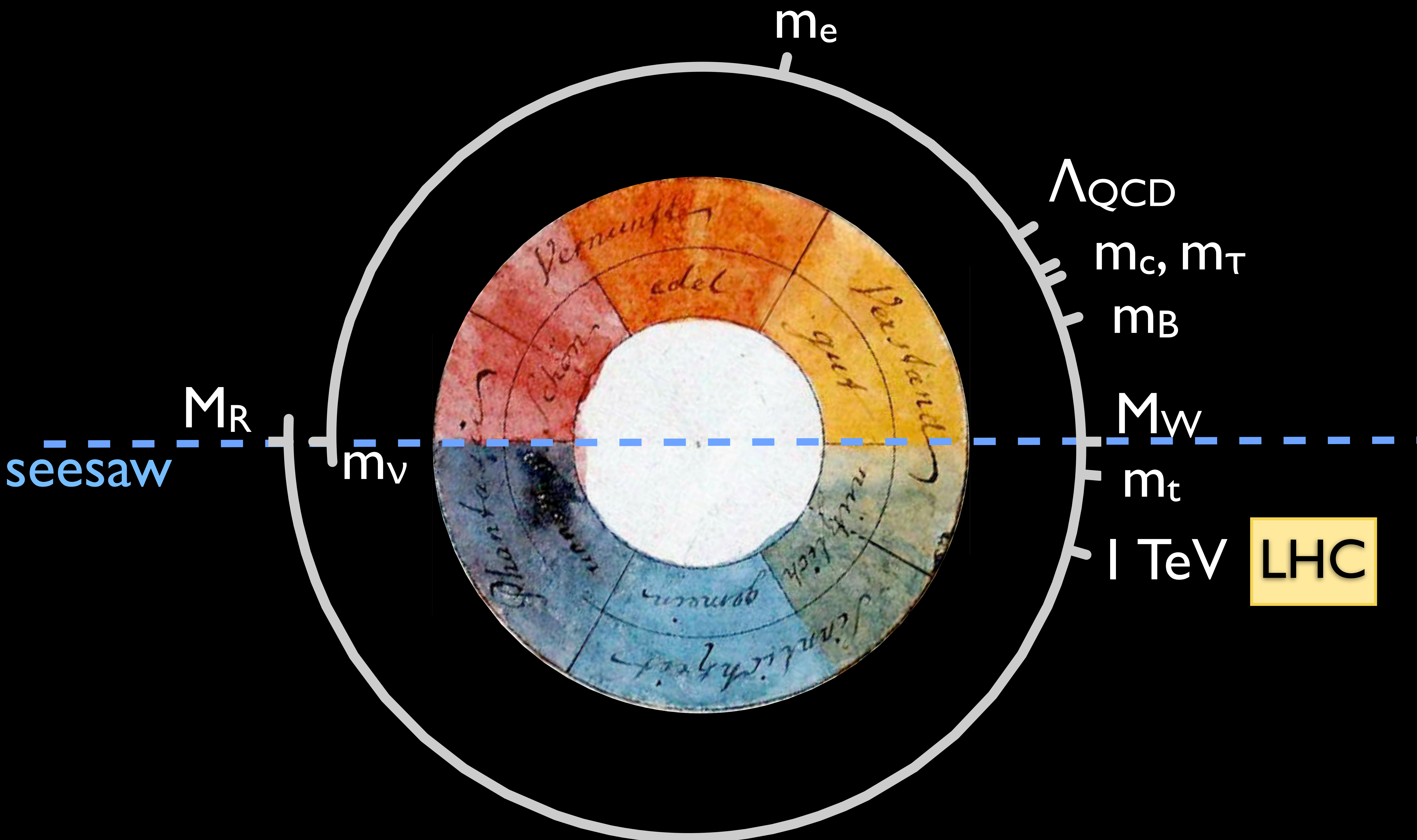

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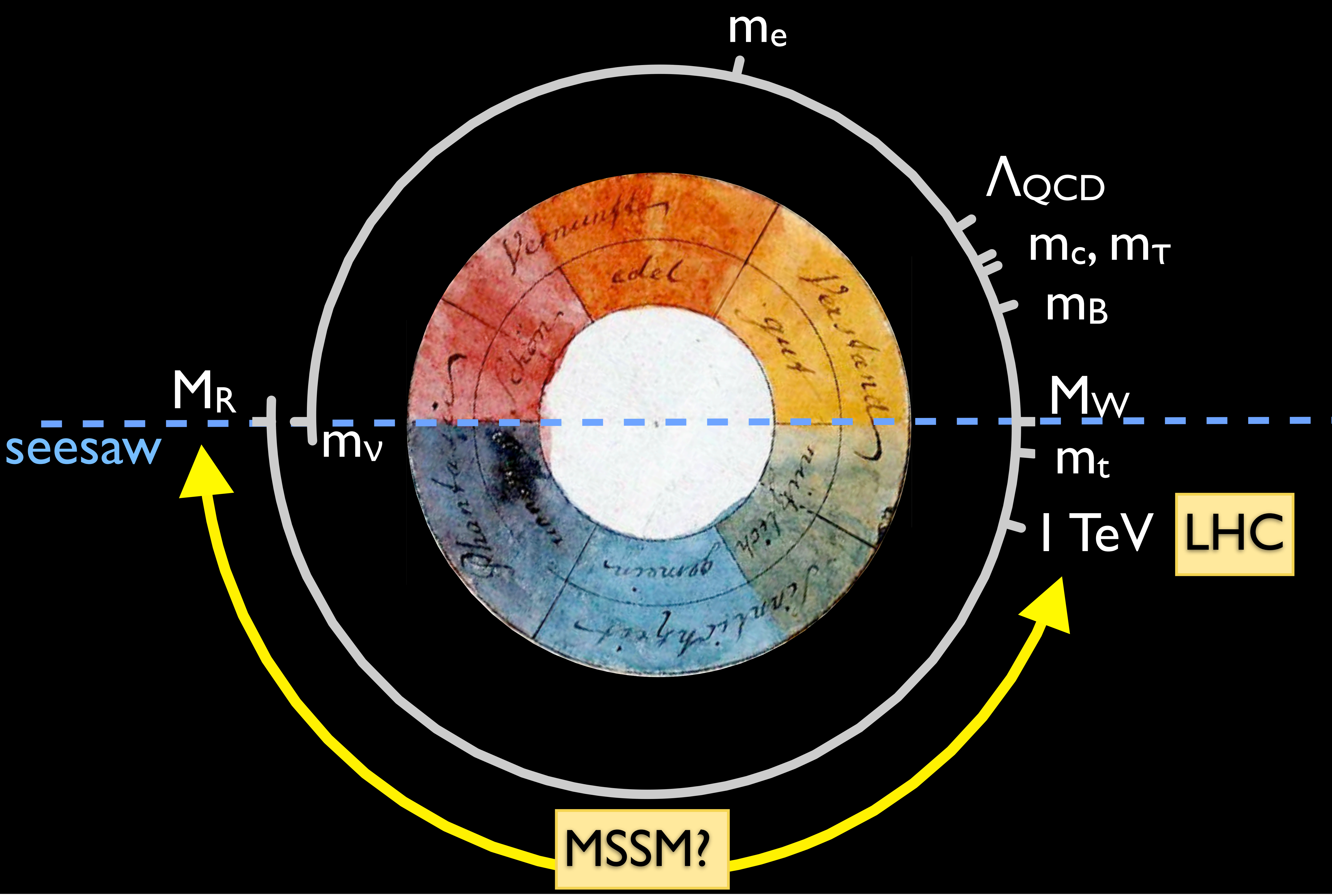

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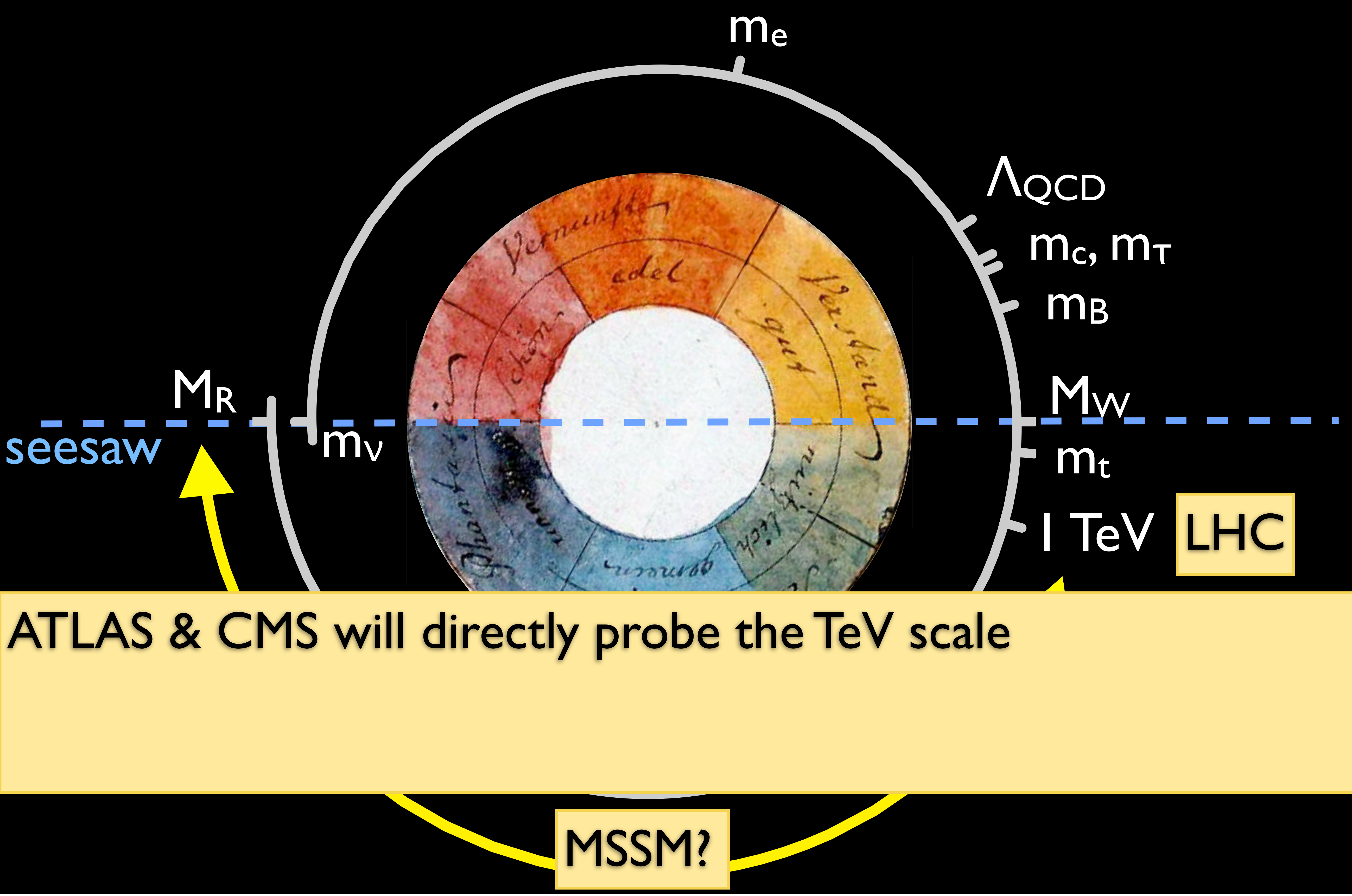

ATLAS & CMS will directly probe the TeV scale

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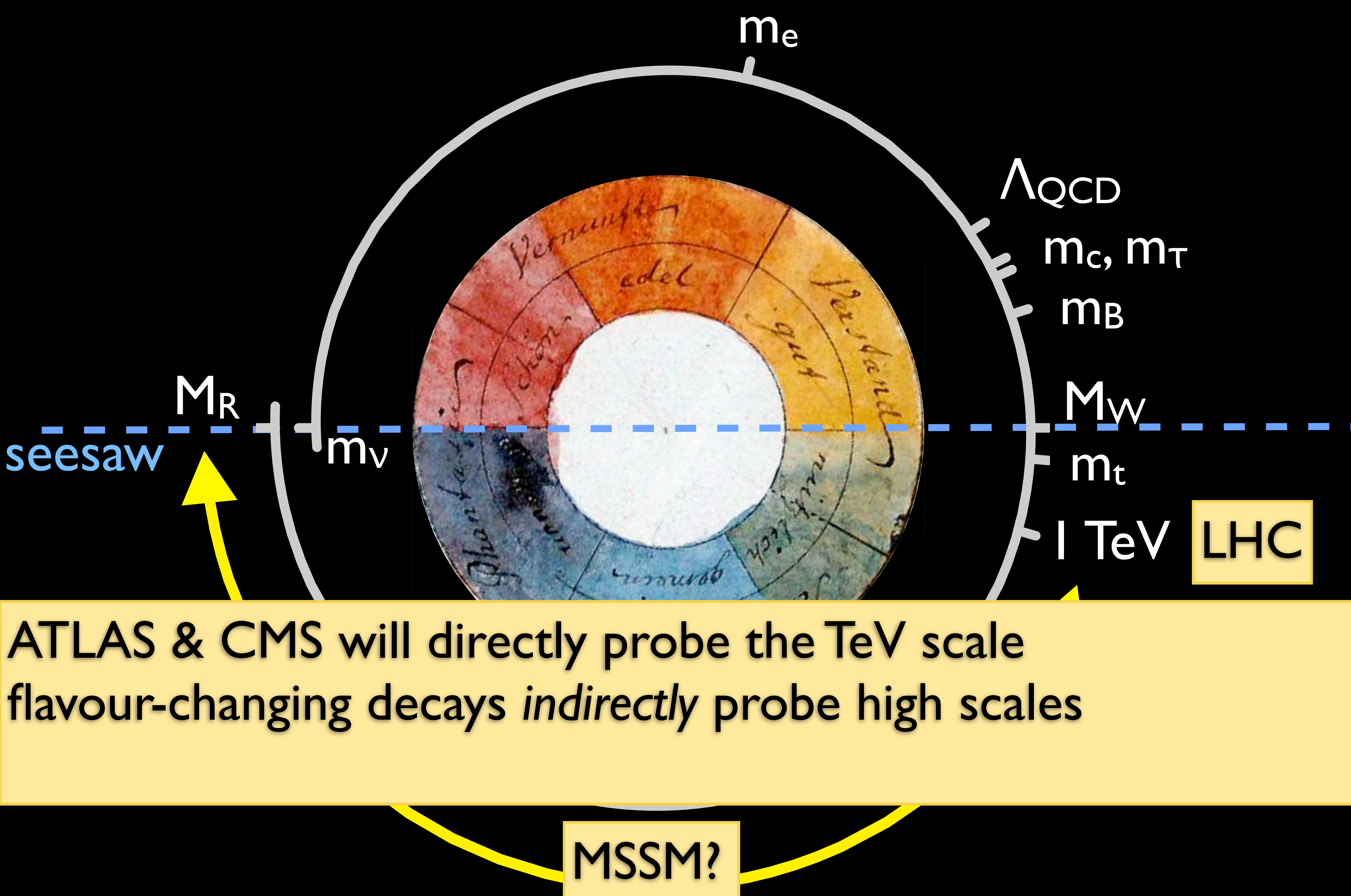

ATLAS & CMS will directly probe the TeV scale
flavour-changing decays *indirectly* probe high scales

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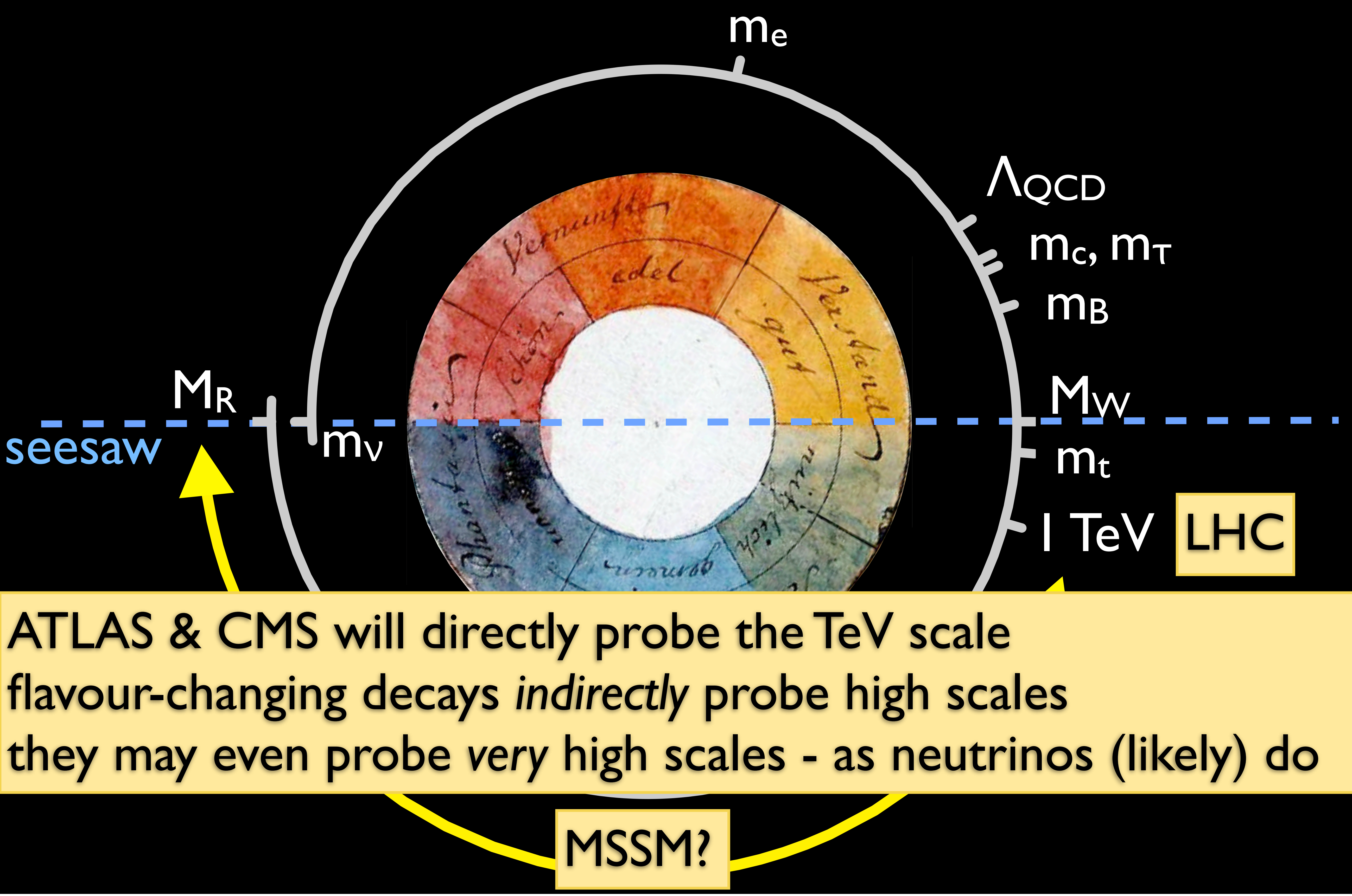

ATLAS & CMS will directly probe the TeV scale
flavour-changing decays *indirectly* probe high scales
they may even probe *very* high scales - as neutrinos (likely) do

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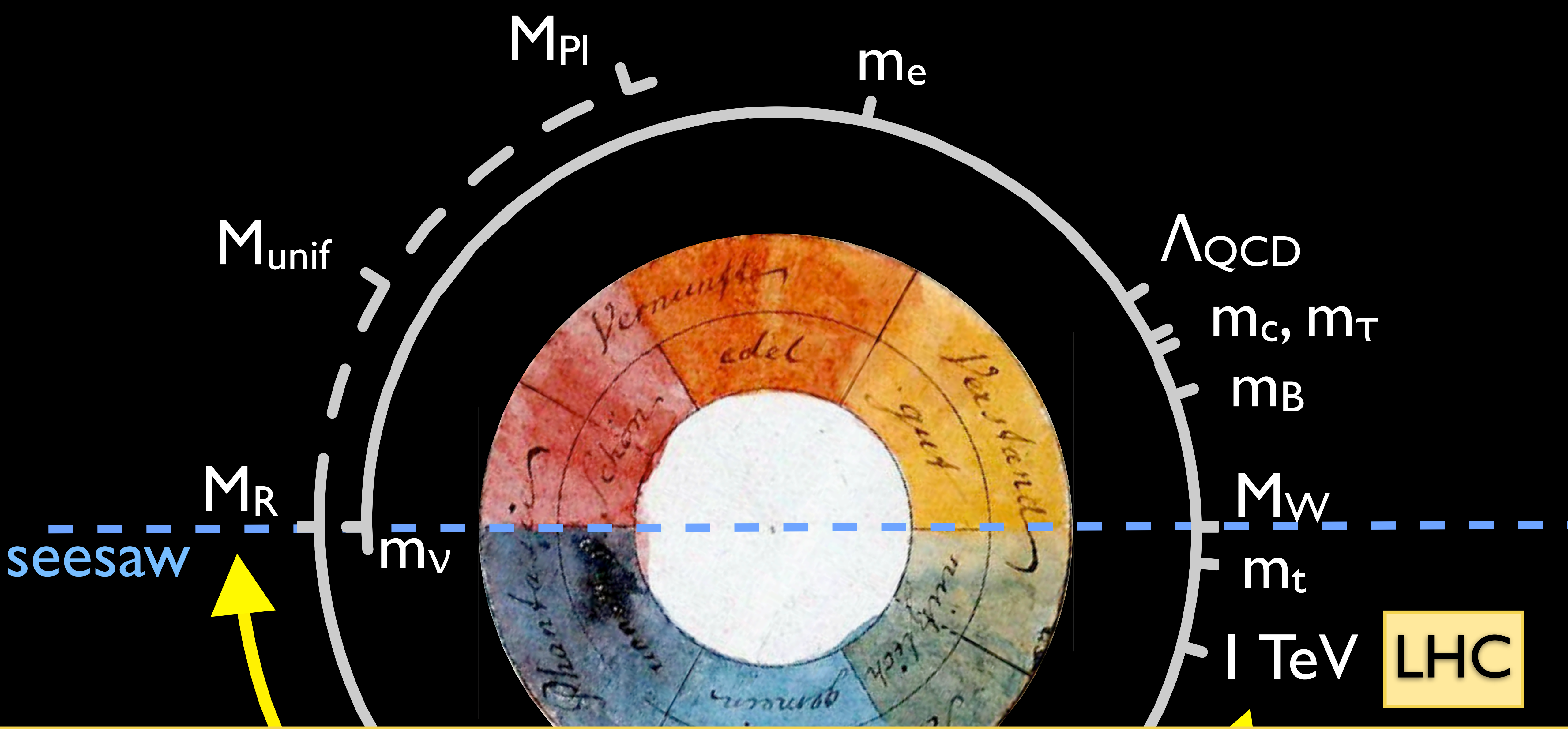

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MSSM?

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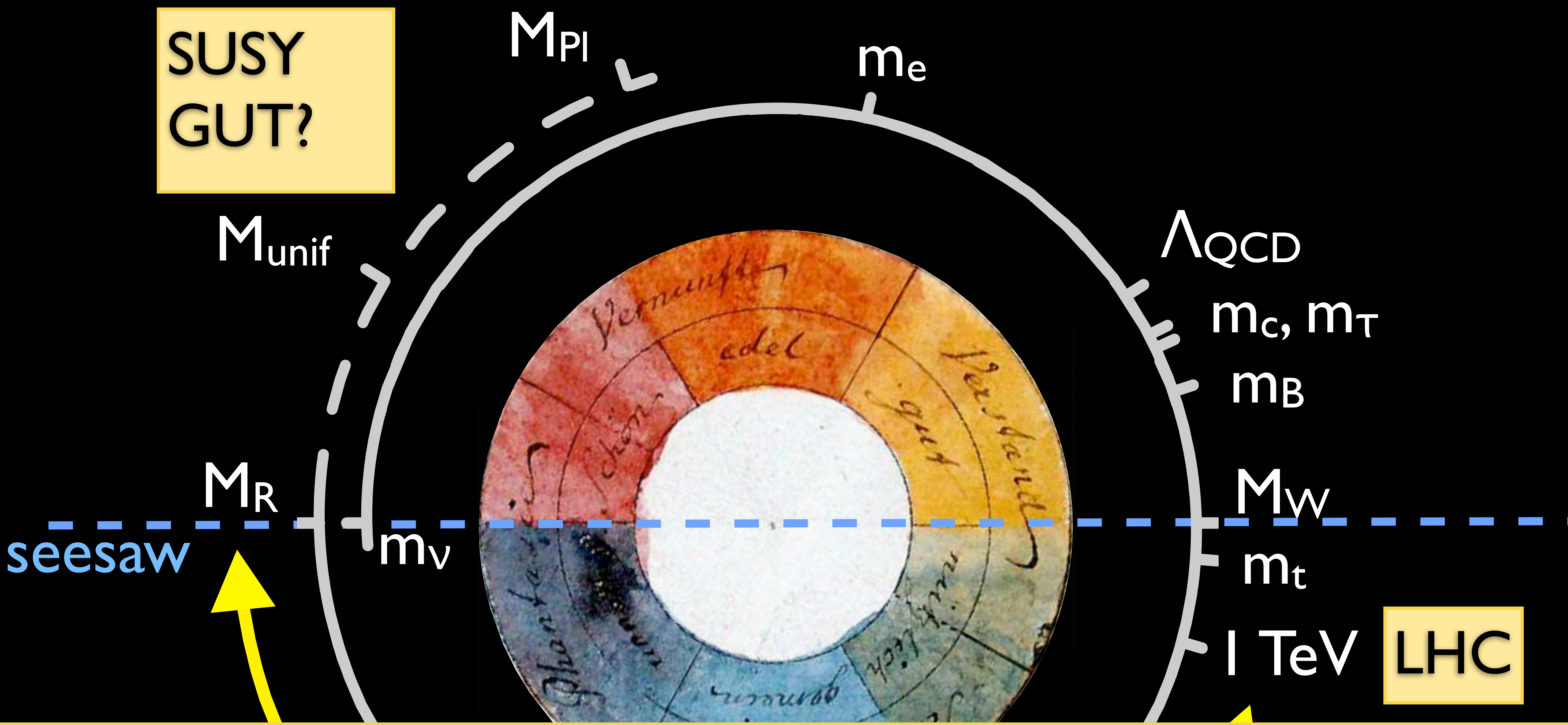

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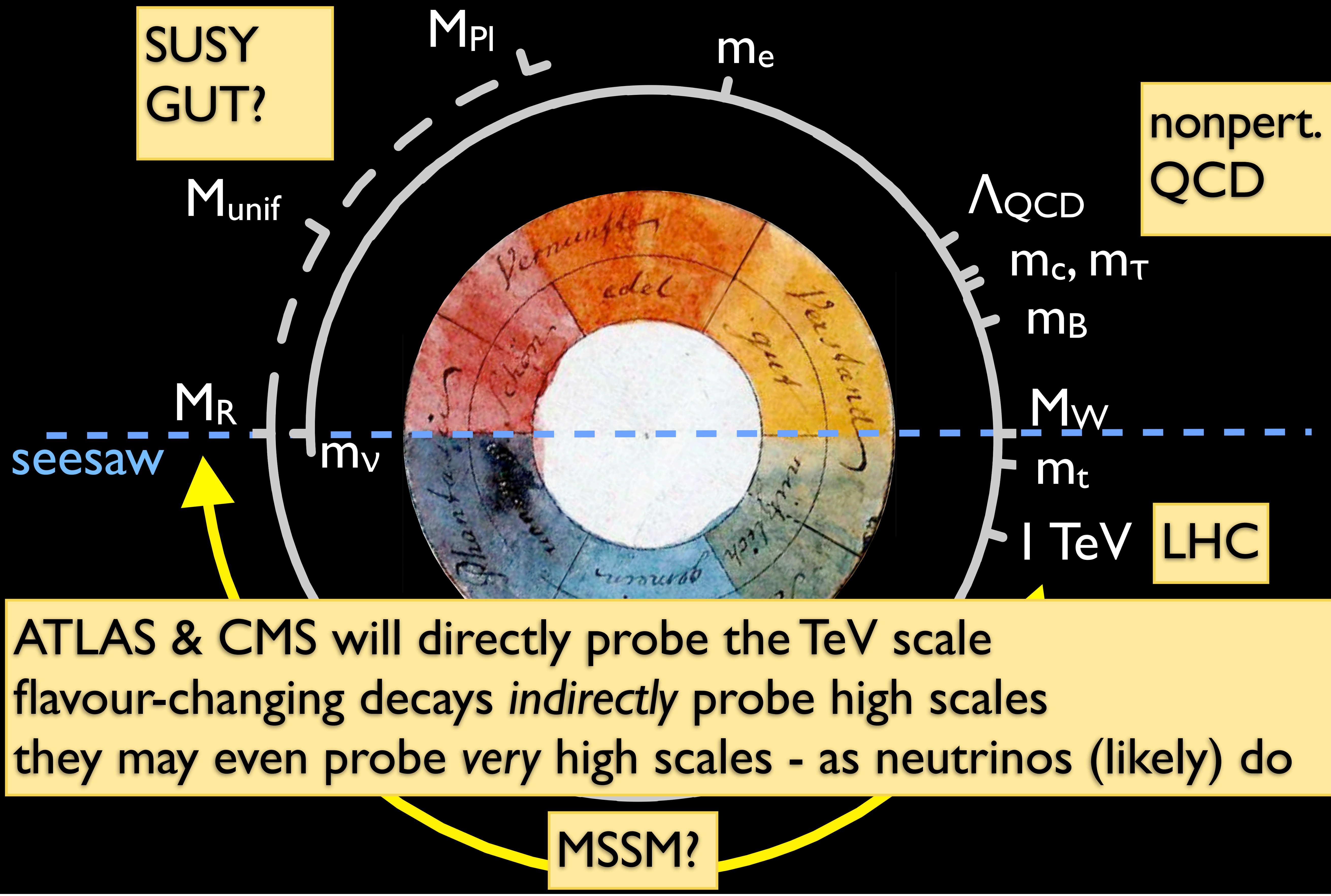

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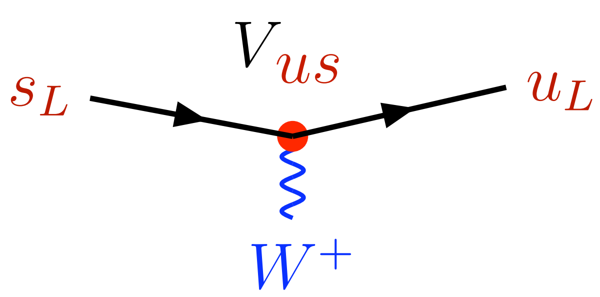
Contents

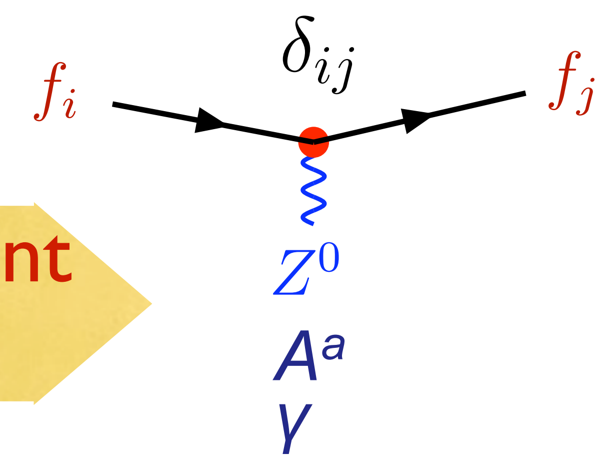
- Flavour in SM
- NP by model
- NP by mode
  - Leptonic decays
  - puzzles in charmless hadronic 2-body decays

SM flavour: CKM matrix



all flavour violation in charged current

(tree) neutral current conserves flavor



$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$\lambda \equiv \frac{|V_{us}|}{\sqrt{|V_{ud}|^2 + |V_{us}|^2}} = 0.2255 \pm 0.0029$$ nucl. beta decay, n lifetime

$$|V_{cb}| = A\lambda |V_{us}| = (41.2 \pm 1.1) \times 10^{-3}$$ excl. & incl. b->c decay

PDG08, no unitarity used

$$\bar\rho + i\bar\eta \equiv -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} = \rho + i\eta + \mathcal{O}(\lambda^2)$$

2 parameters to be determined
one complex - CP violating

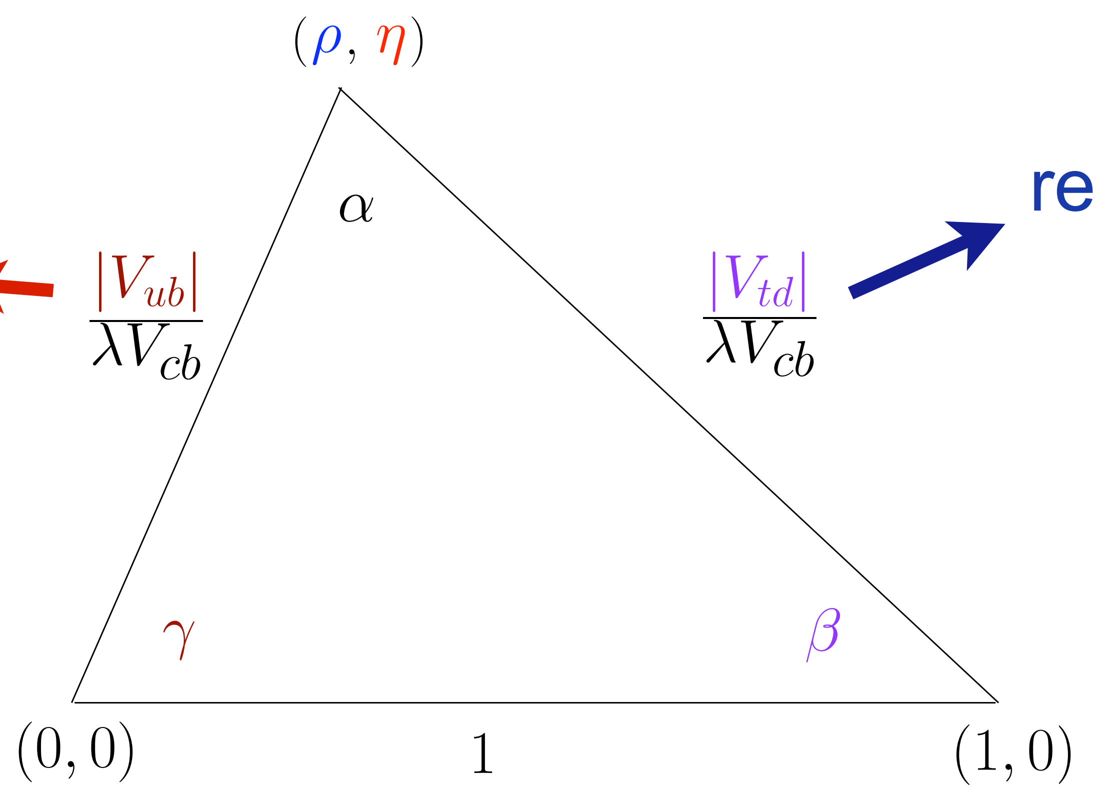
Unitarity triangle

Unitarity of $V \Rightarrow$

$$\begin{array}{ccccccccc} V_{ub}^* V_{ud} & + & V_{cb}^* V_{cd} & + & V_{tb}^* V_{td} & = & 0 \\ A\lambda^3(\rho + i\eta) & - & A\lambda^3 & + & A\lambda^3(1-\rho-i\eta) & = & 0 \end{array}$$

Graphically,

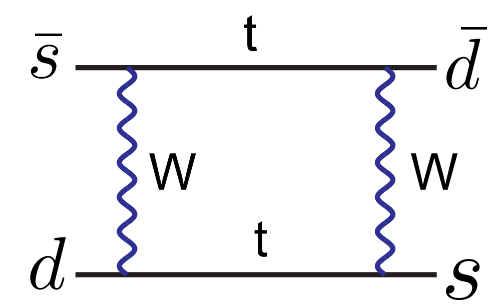
b →u l v
b →u q q
(tree-level
Weak int.)

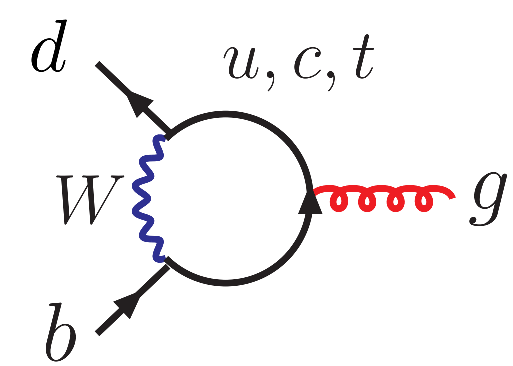


requires top loop

$V_{ub} = |V_{ub}|e^{-i\gamma}$

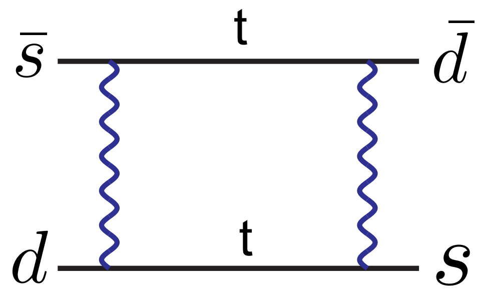
$V_{td} = |V_{td}|e^{-i\beta}$



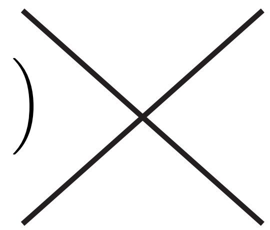


suppression of FCNC by loops and CKM hierarchy

Short vs long distance: $K^0 - \bar{K}^0$ mixing

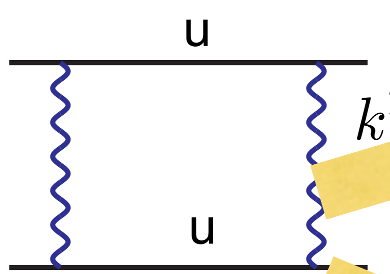


$\propto (V_{ts}V_{td}^*)^2 \frac{1}{16\pi^2}\frac{1}{M_W^2}\left(\frac{m_t^2}{M_W^2} + \ldots\right)$



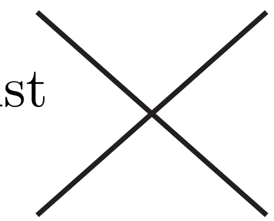
$\sim \frac{10^{-6}}{M_W^2}$

top quark loop
CKM-suppressed



$k^2 \sim M_W^2$

$\propto (V_{us}V_{ud}^*)^2 \frac{1}{16\pi^2}\frac{1}{M_W^2} \times \text{const}$

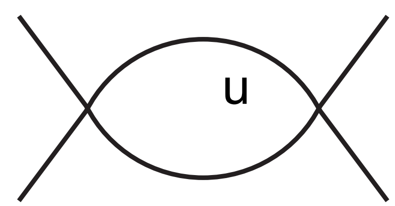


$\sim \frac{10^{-4}}{M_W^2}$

light quark loop
CKM-enhanced

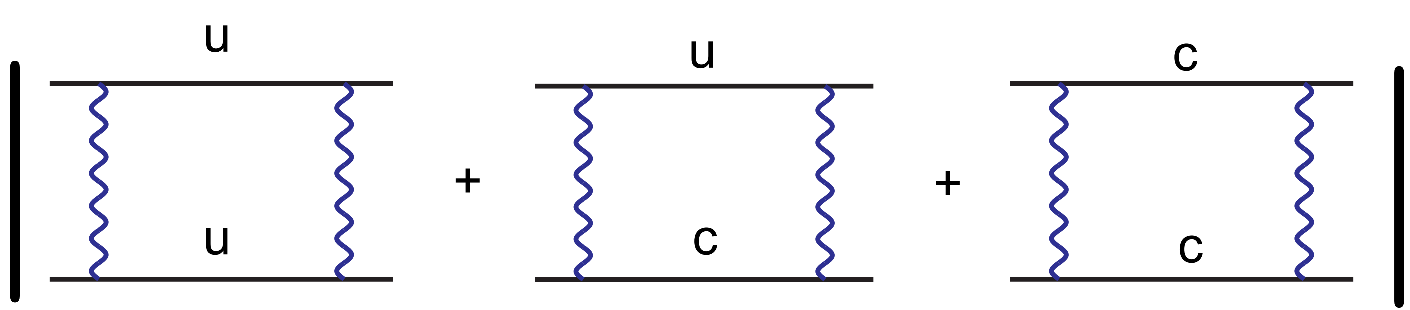
$k^2 \sim \Lambda_{QCD}^2$

$\propto (V_{us}V_{ud}^*)^2 \frac{1}{M_W^4}$



$\propto (V_{us}V_{ud}^*)^2 \frac{\Lambda_{QCD}^2}{M_W^4}$

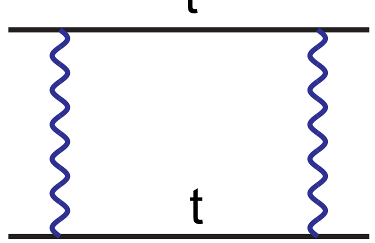
long-distance
power-suppressed
but CKM-enhanced



$= \mathcal{O}(\Delta m_K^{\text{exp}})$ if $m_c \lesssim \text{GeV}$

$(V_{us}V_{ud}^*)^2 + 2\,(V_{us}V_{ud}^*)(V_{cs}V_{cd}^*) + (V_{cs}V_{cd}^*)^2 = (V_{ts}V_{td}^*)^2$

unitarity / GIM
cancellation

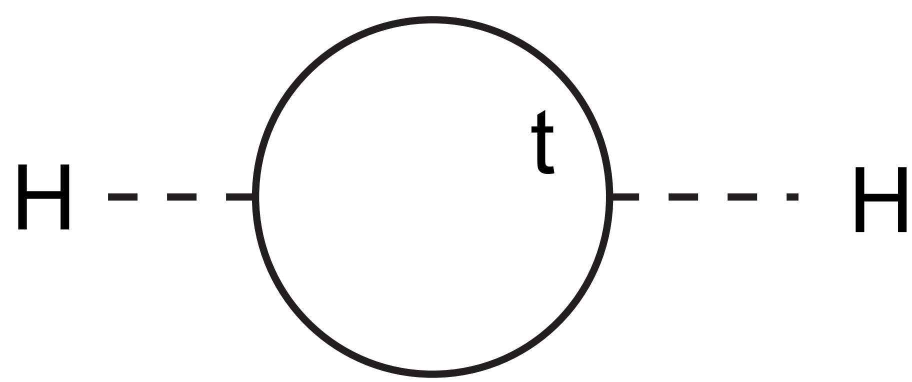
Im 

=> $\epsilon_K = \mathcal{O}(10^{-3})$ constraint on V_{td}

Flavour at the TeV scale

- Much of present theory activity (and experiment - LHC) are motivated by exploring the weak scale and by its sensitivity to radiative corrections

- This derives in part from



$$\propto y_t^2 \Lambda_{\mathrm{UV}}^2$$

hence physics that stabilizes weak scale should contain new flavoured particles. This is what happens in
  SUSY (stop),
  warped extra dimensions (KK modes),
  little Higgs (heavy T),
  technicolour,
  etc.

- Such particles will always contribute to FCNC

SUSY flavour

SuperCKM basis: Superfield basis that diagonalizes Yukawas

Squark mass matrices are still 6x6 with independent flavour structure:

3x3 flavour-violating

$$\mathcal{M}^2_{\tilde d} = \begin{pmatrix} \hat m^2_{\tilde Q} + m_d^2 + D_{dLL} & v_1 \hat T_D - \mu^* m_d \tan\beta \\ v_1 \hat T_D^\dagger - \mu m_d \tan\beta & \hat m^2_{\tilde d} + m_d^2 + D_{dRR} \end{pmatrix} \equiv \begin{pmatrix} (\mathcal{M}^2_{\tilde d})^{LL} & (\mathcal{M}^2_{\tilde d})^{LR} \\ (\mathcal{M}^2_{\tilde d})^{RL} & (\mathcal{M}^2_{\tilde d})^{RR} \end{pmatrix}$$

LR mass terms are $SU(2)_W$-breaking - related to trilinear scalar couplings

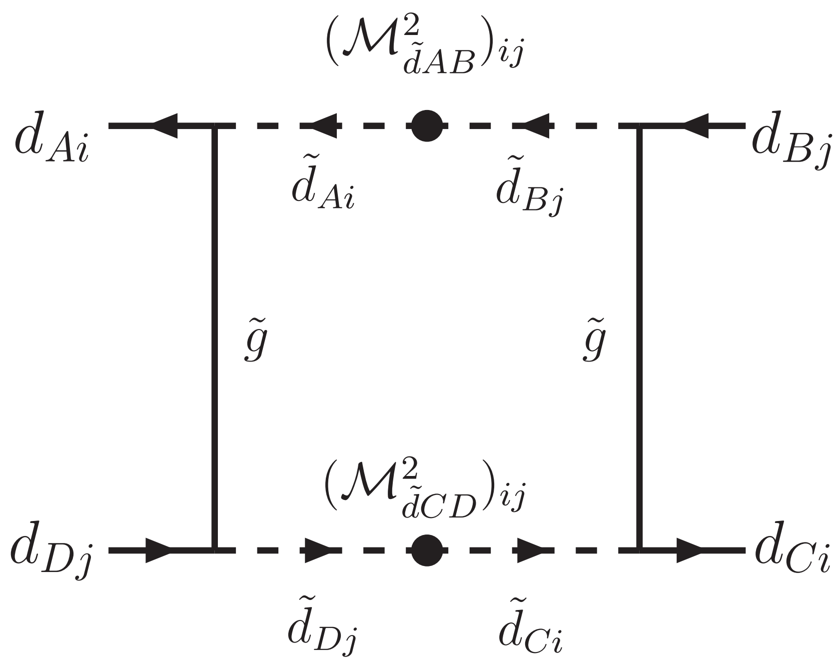
similar for up squarks, charged sleptons. 3x3 LL for sneutrinos

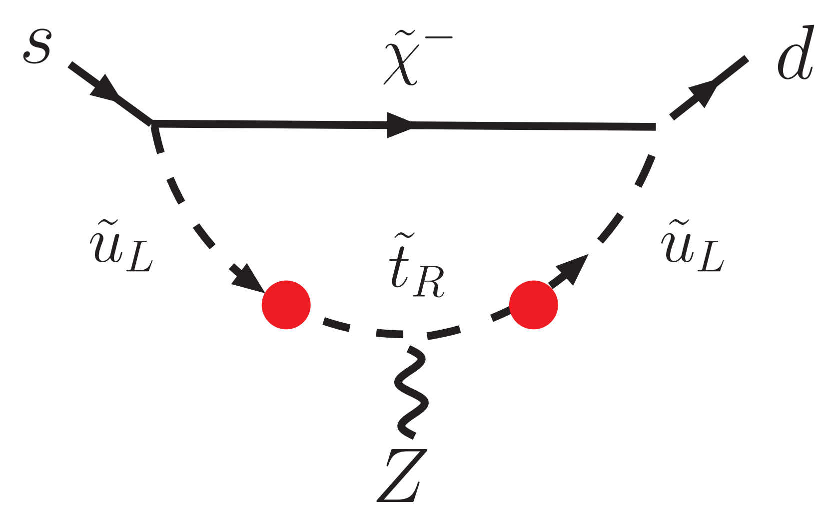
$$\left(\delta_{ij}^{u,d,e,\nu}\right)_{AB} \equiv \frac{\left(\mathcal{M}^2_{\tilde u,\tilde d,\tilde e,\tilde\nu}\right)_{ij}^{AB}}{m^2_{\tilde f}}$$

33 flavour-violating parameters

45 CPV (some flavour-conserving)

SUSY flavour (2)





K-$\overline{\text{K}}$, B_d-$\overline{B}_d$, B_s-$\overline{B}_s$ mixing

ΔF=1 decays

B ➔$K^*\mu^+\mu^-$
B ➔Kπ
$B_{s,d}$ ➔$\mu^+\mu^-$
K ➔πνν
...

SuperFlavour puzzle

$$\left(\delta_{ij}^{u,d,e,\nu}\right)_{AB} \equiv \frac{\left(\mathcal{M}^2_{\tilde{u},\tilde{d},\tilde{e},\tilde{\nu}}\right)_{ij}^{AB}}{m^2_{\tilde{f}}}$$

where are their effects?

Quantity	upper bound
$\sqrt{\lvert\mathrm{Re}(\delta^d_{ds})^2_{LL}\rvert}$	4.0×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{ds})^2_{RR}\rvert}$	4.0×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{ds})^2_{LR}\rvert}$	4.4×10^{-3}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{ds})_{LL}(\delta^d_{ds})_{RR}\rvert}$	2.8×10^{-3}
$\sqrt{\lvert\mathrm{Im}(\delta^d_{ds})^2_{LL}\rvert}$	3.2×10^{-3}
$\sqrt{\lvert\mathrm{Im}(\delta^d_{ds})^2_{RR}\rvert}$	3.2×10^{-3}
$\sqrt{\lvert\mathrm{Im}(\delta^d_{ds})^2_{LR}\rvert}$	3.5×10^{-4}
$\sqrt{\lvert\mathrm{Im}(\delta^d_{ds})_{LL}(\delta^d_{ds})_{RR}\rvert}$	2.2×10^{-4}

Quantity	upper bound
$\sqrt{\lvert\mathrm{Re}(\delta^d_{db})^2_{LL}\rvert}$	9.8×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{db})^2_{RR}\rvert}$	9.8×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{db})^2_{LR}\rvert}$	3.3×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{db})_{LL}(\delta^d_{db})_{RR}\rvert}$	1.8×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{sb})^2_{LL}\rvert}$	4.8×10^{-1}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{sb})^2_{RR}\rvert}$	4.8×10^{-1}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{sb})^2_{LR}\rvert}$	1.62×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{sb})_{LL}(\delta^d_{sb})_{RR}\rvert}$	8.9×10^{-2}

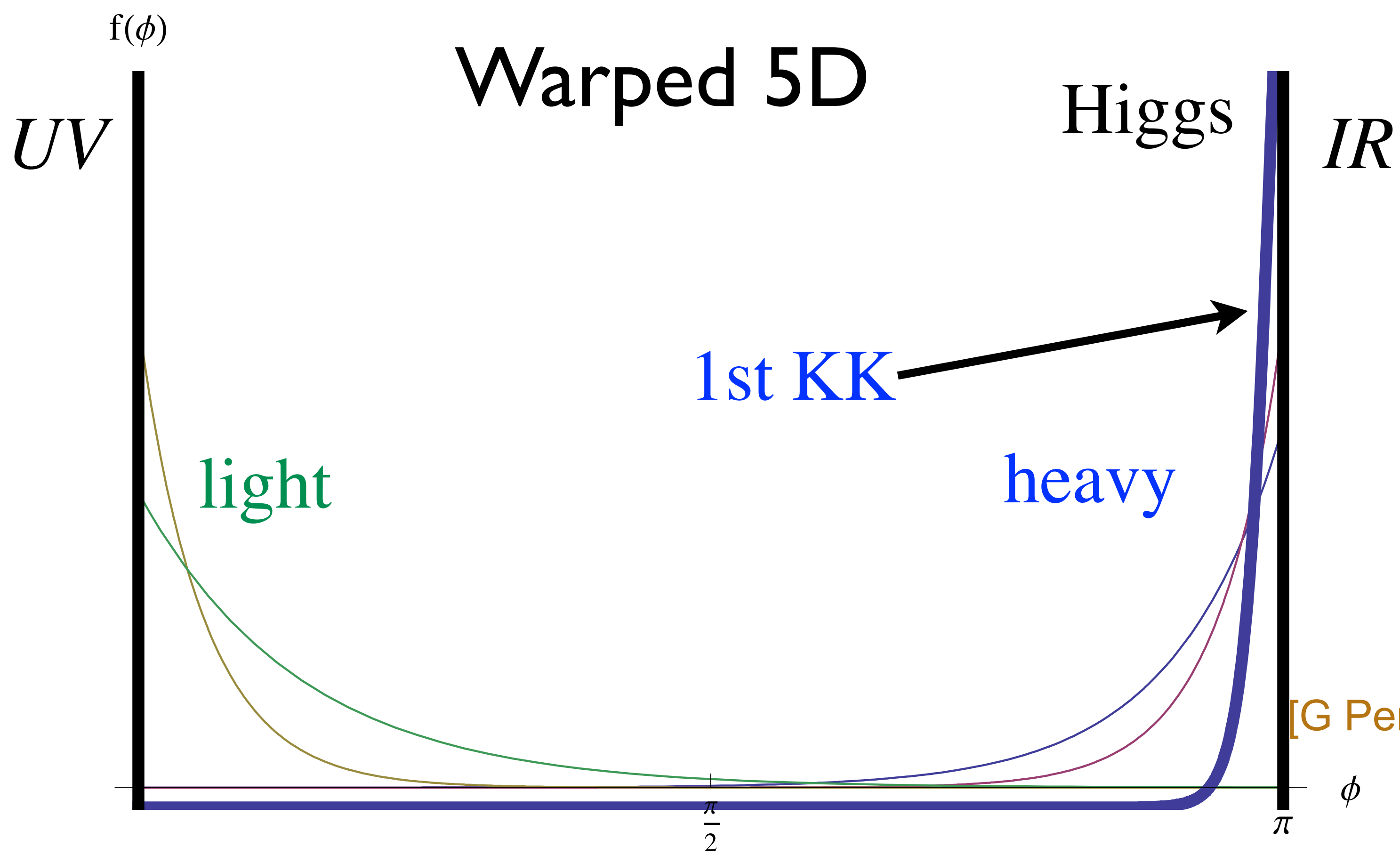
Quantity	upper bound
$\sqrt{\lvert\mathrm{Re}(\delta^{\bar{u}}_{uc})^2_{LL}\rvert}$	3.9×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^{\bar{u}}_{ud})^2_{RR}\rvert}$	3.9×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^{\bar{u}}_{uc})^2_{LR}\rvert}$	1.20×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^{\bar{u}}_{uc})_{LL}(\delta^{u}_{uc})_{RR}\rvert}$	6.6×10^{-3}

[Gabbiani et al 96; Misiak et al 97]
these numbers from [SJ, 0808.2044]

- elusiveness of deviations from SM in flavour physics seems to make MSSM look unnatural

- pragmatic point of view: flavour physics highly sensitive to many MSSM parameters

Flavour - warped ED

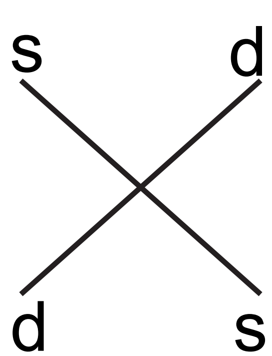


SM fermions are zero modes of fields present in the bulk (like DWF)

Higgs localized on IR brane

light (heavy) fermions localized near UV (IR) brane

hierarchical SM fermion masses

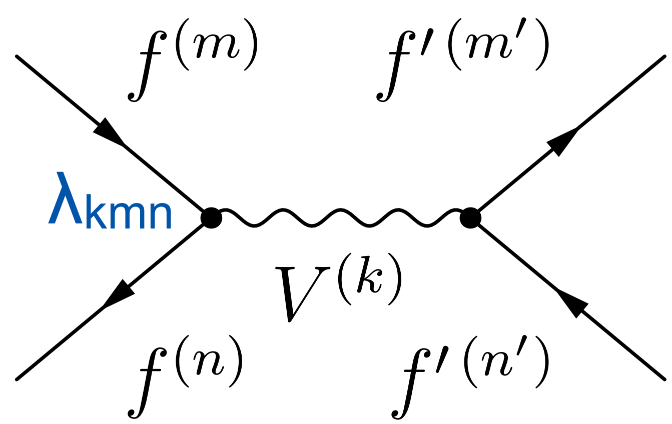


dangerous four-fermion operators with TeV suppression are “natural” on the IR brane

not so dangerous after taking into account localization of SM fermions (“RS-GIM”)

Flavour - warped ED (2)

- dominant contribution to FCNC usually not from brane contact terms but from tree-level KK boson exchange



$$\lambda_{kmn} = \int d\phi \, w(\phi) f^{(m)}(\phi) f^{(n)}(\phi) f_V^{(k)}(\phi)$$

$$Y_{mn} \propto f^{(m)}(\pi) f^{(n)}(\pi)$$

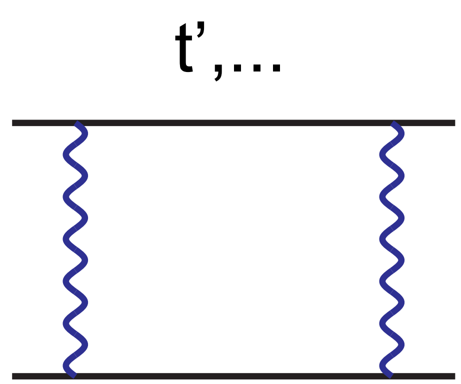
non-minimal flavour violation !

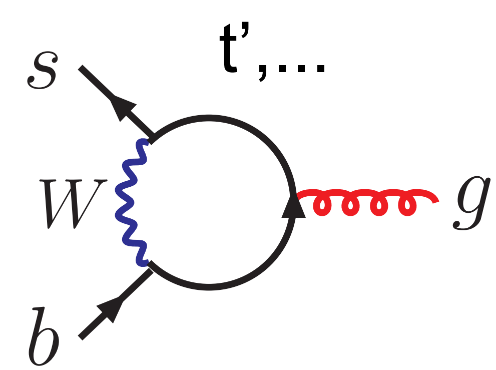
Other scenarios

- fourth SM generation
  CKM matrix becomes 4x4, giving new sources of flavour and CP violation

- little(st) higgs model with T parity
  (higgs light because a pseudo-goldstone boson)
  finite, calculable 1-loop contributions due to new heavy particles with new flavour violating couplings

- ...





non-minimal flavour violation !

NP flavour puzzle

- Naturalness suggests

$$\mathcal{L}_{\rm eff} = \Lambda_{\rm UV}^2 H^2 + \mathcal{L}_{\rm gauge, Yukawa} + \frac{1}{\Lambda_{\rm UV}}(H^\dagger L)^2 + \frac{1}{\Lambda_{\rm UV}^2}\left[(\bar{s}\gamma_\mu d)^2 + \cdots\right]$$

v ~ 246 GeV => Λ < TeV

NP --->	MSSM	WED	generic
EW precision bound	weak	3 TeV	$10^{1\text{-}2}$ TeV
flavour bound	$10^{3\text{-}4}$ TeV	20 TeV	10^4 TeV

Ellis, Nanopoulos 82
Gabbiani et al 96

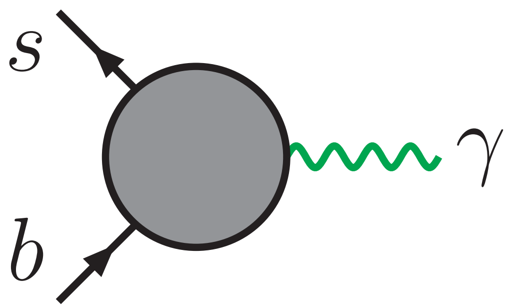
Agashe,Delgado,May,Sundrum 03
Csaki,Falkowski,Weiler 08

Bona et al (UTfit) 06

- flavour violation in SM "unnaturally" small: weak coupling, highly non-generic structure (CKM, GIM)

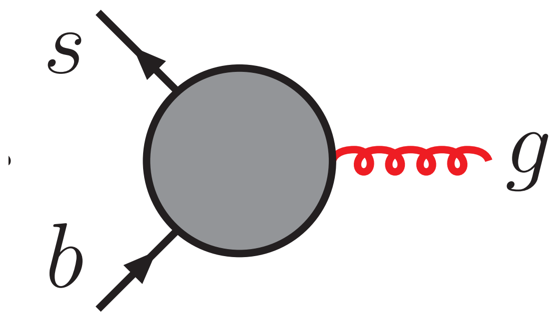
$\Delta M_K, \epsilon_K \sim \frac{1}{16\pi^2}(V_{td}V_{ts})^2$ (gives strong NP constraint)

ΔF=1 FCNC transitions



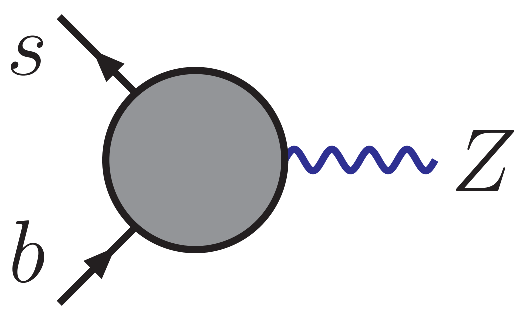
$\bar{s}_L b_R \gamma$ $\bar{s}_R b_L \gamma$ magnetic penguin

$\bar{s}_L b_L \gamma^*$ $\bar{s}_R b_R \gamma^*$ QED penguin

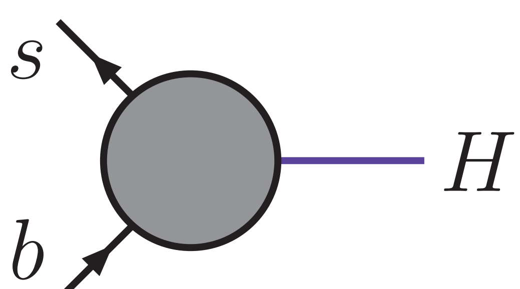


$\bar{s}_L b_R g$ $\bar{s}_R b_L g$ chromomagnetic penguin

$\bar{s}_L b_L g^*$ $\bar{s}_R b_R g^*$ QCD penguin

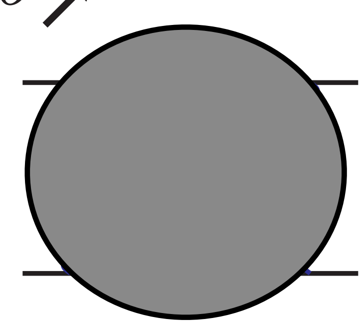


$\bar{s}_L b_L Z$ $\bar{s}_R b_R Z$ Z-penguin



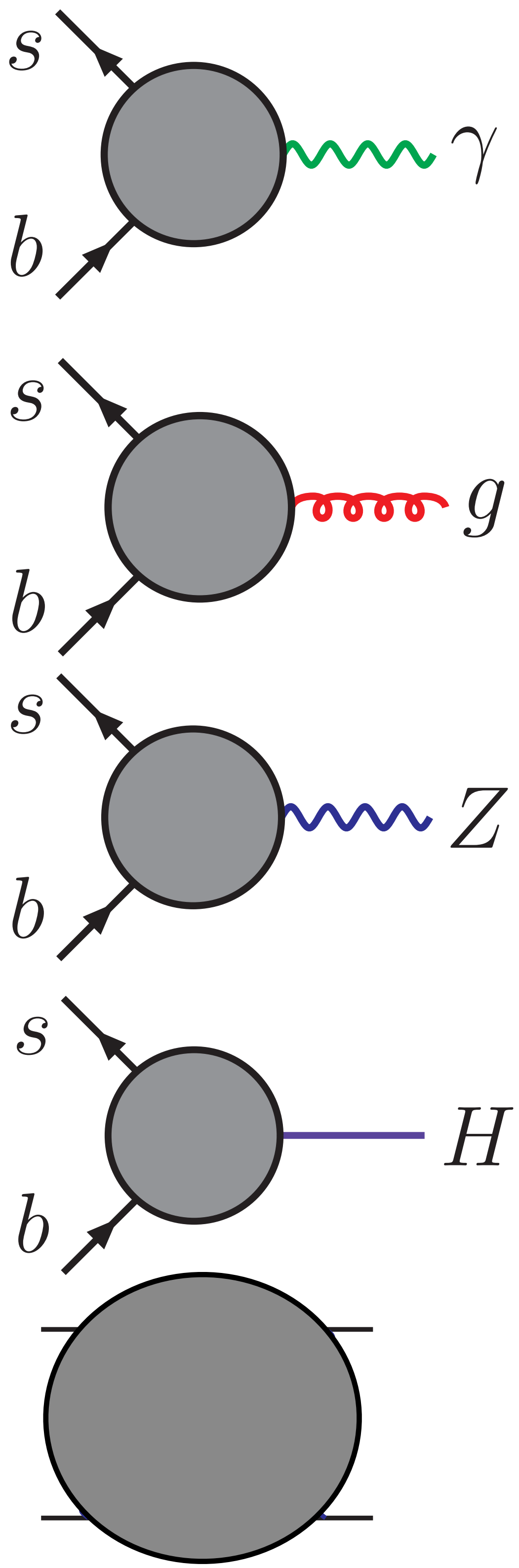
$\bar{s}_L b_R H$

$\bar{s}_R b_L H$



four-fermion vertices

ΔF=1 FCNC transitions



$\bar{s}_L b_R \gamma$	$\bar{s}_R b_L \gamma$	magnetic penguin
$\bar{s}_L b_L \gamma^*$	$\bar{s}_R b_R \gamma^*$	QED penguin
$\bar{s}_L b_R g$	$\bar{s}_R b_L g$	chromomagnetic penguin
$\bar{s}_L b_L g^*$	$\bar{s}_R b_R g^*$	QCD penguin
$\bar{s}_L b_L Z$	$\bar{s}_R b_R Z$	Z-penguin

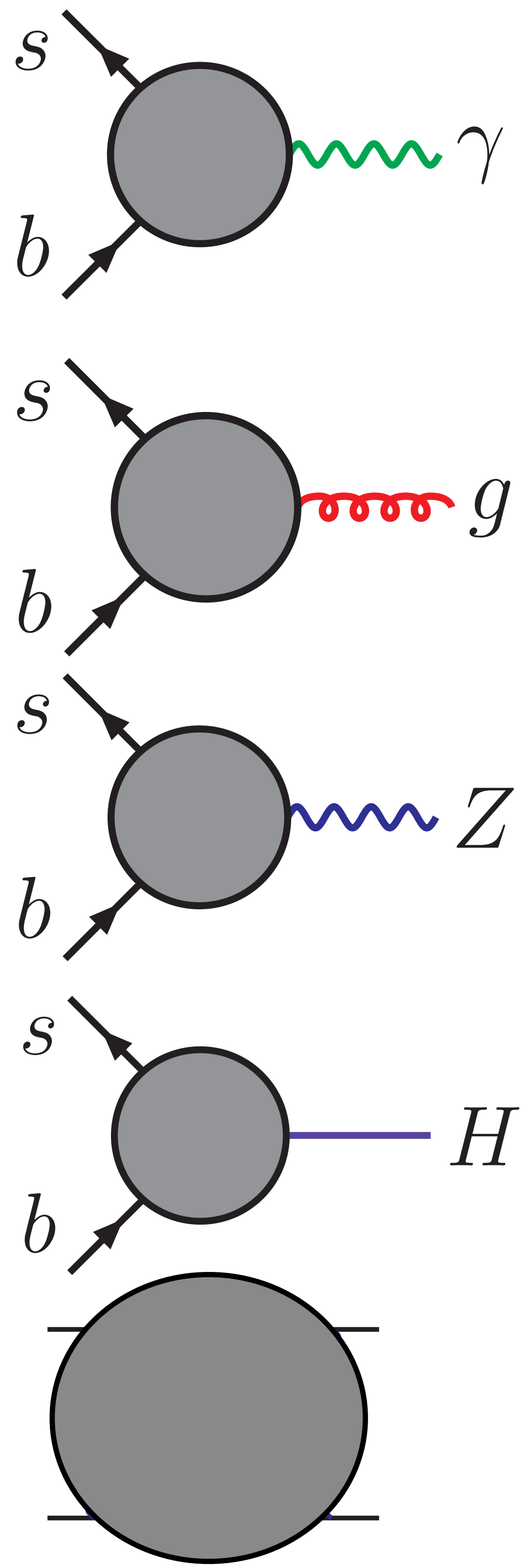
negligible in SM

$\bar{s}_L b_R H$

$\bar{s}_R b_L H$

four-fermion vertices

ΔF=1 FCNC transitions



require chirality flip

$\bar{s}_L b_R \gamma$	$\bar{s}_R b_L \gamma$	magnetic penguin
$\bar{s}_L b_L \gamma^*$	$\bar{s}_R b_R \gamma^*$	QED penguin
$\bar{s}_L b_R g$	$\bar{s}_R b_L g$	chromomagnetic penguin
$\bar{s}_L b_L g^*$	$\bar{s}_R b_R g^*$	QCD penguin
$\bar{s}_L b_L Z$	$\bar{s}_R b_R Z$	Z-penguin

SU(2)$_W$-breaking

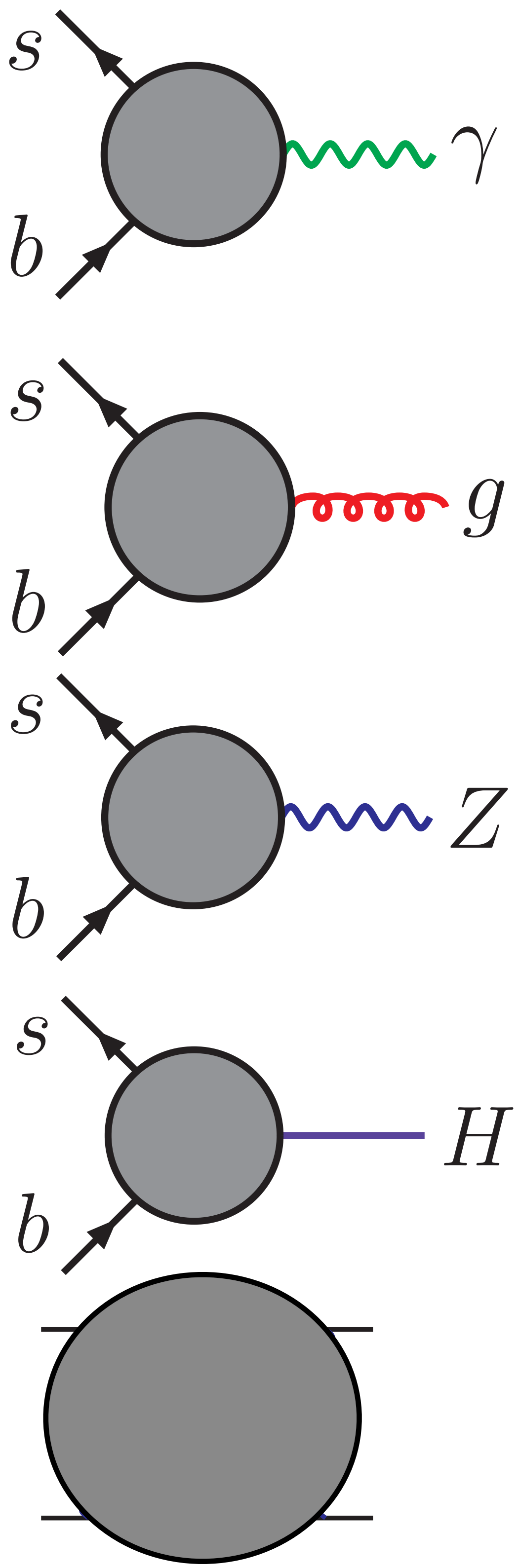
negligible in SM

$\bar{s}_L b_R H$

$\bar{s}_R b_L H$

four-fermion vertices

ΔF=1 FCNC transitions



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$\bar{s}_L b_L \gamma^*$	$\bar{s}_R b_R \gamma^*$	QED penguin
$\bar{s}_L b_R g$	$\bar{s}_R b_L g$	chromomagnetic penguin
$\bar{s}_L b_L g^*$	$\bar{s}_R b_R g^*$	QCD penguin
$\bar{s}_L b_L Z$	$\bar{s}_R b_R Z$	Z-penguin

SU(2)$_W$-breaking

negligible in SM

$\bar{s}_L b_R H$

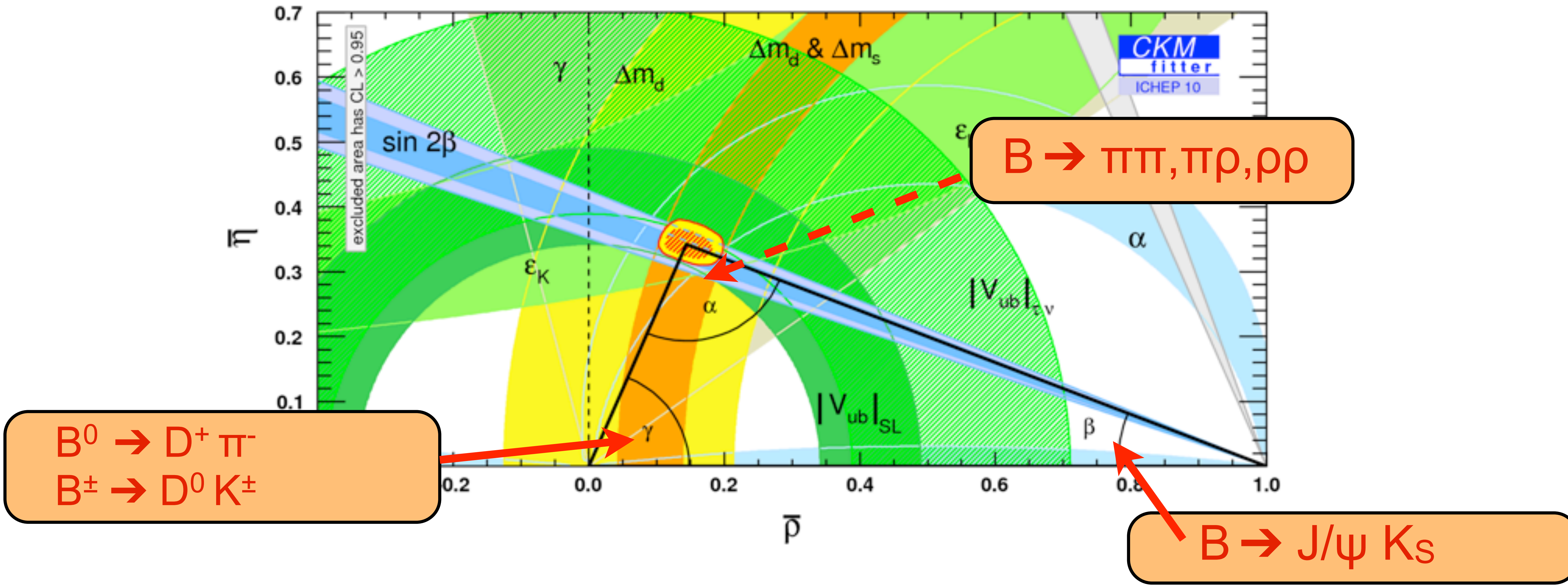
$\bar{s}_R b_L H$

important in 2HDM at large tan(β)

four-fermion vertices

UT 2010

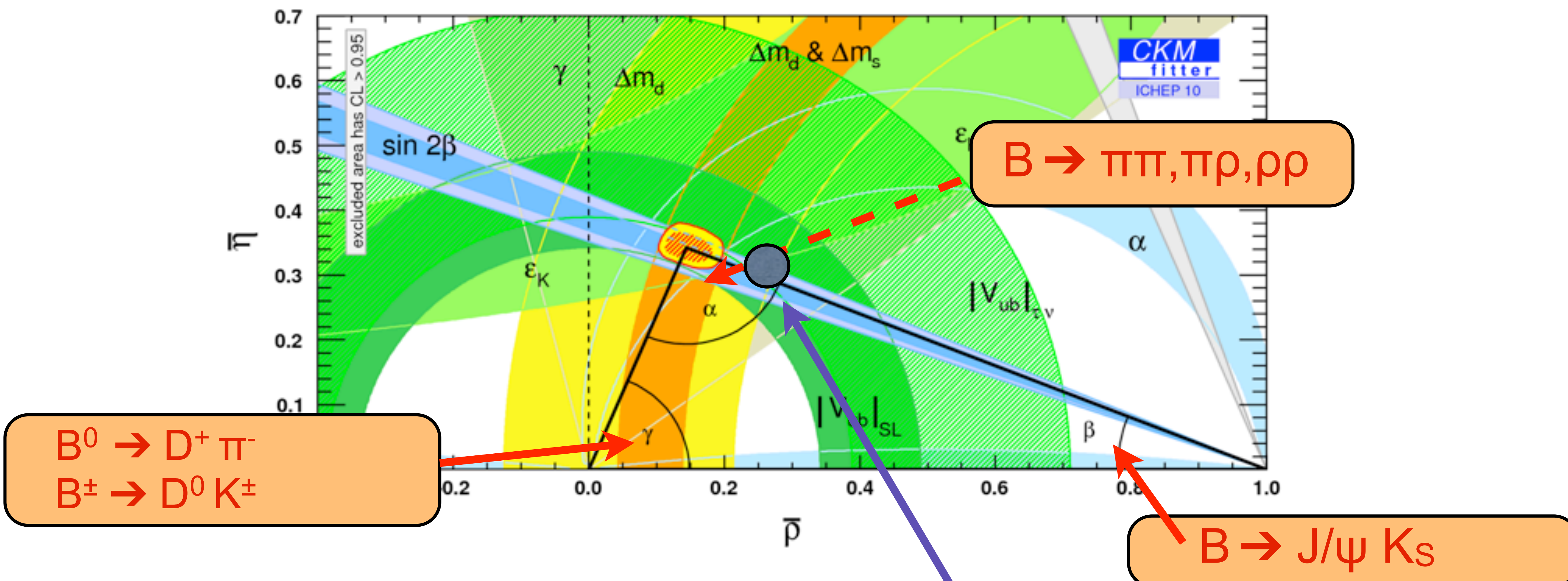
apologies to UTfit, who obtain consistent results



consistency of CKM picture established by B factories

UT 2010

apologies to UTfit, who obtain consistent results

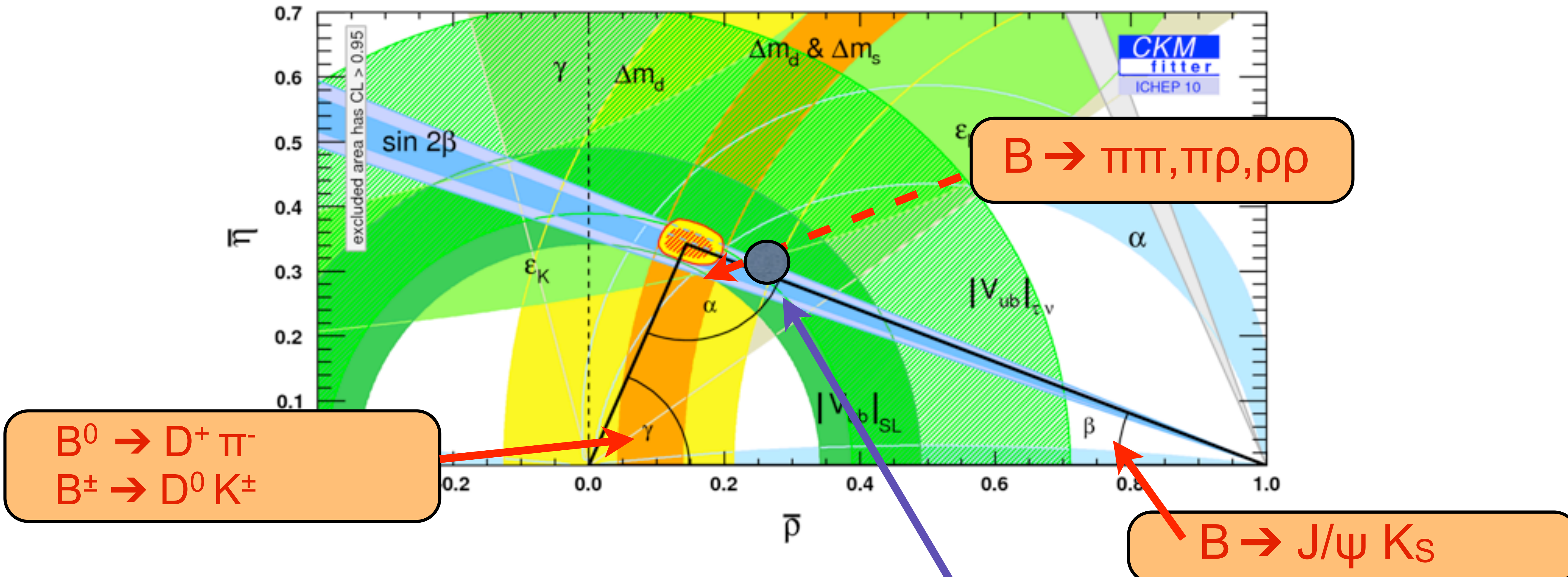


consistency of CKM picture established by B factories

But it is possible that the TRUE (ρ,η) lies here (for example)
as only the γ and V_{ub} determinations are robust against new physics
certainly there is room for O(10%) NP in b->d transitions

UT 2010

apologies to UTfit, who obtain consistent results

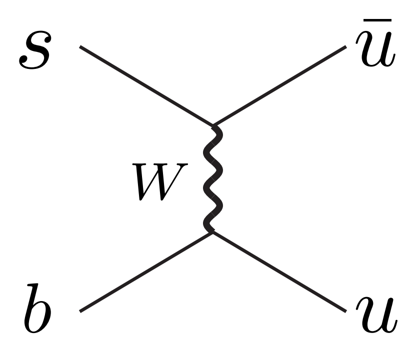


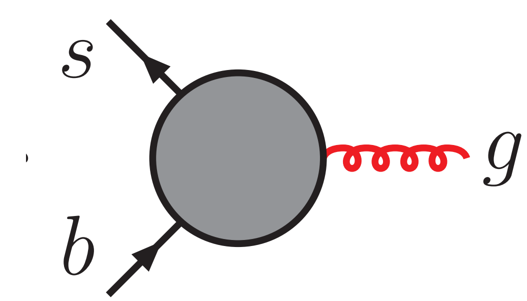
consistency of CKM picture established by B factories

But it is possible that the TRUE (ρ,η) lies here (for example)
as only the γ and V_{ub} determinations are robust against new physics
certainly there is room for O(10%) NP in b->d transitions

b→s transitions only weakly sensitive to (ρ,η)
but can be sensitive to BSM flavour

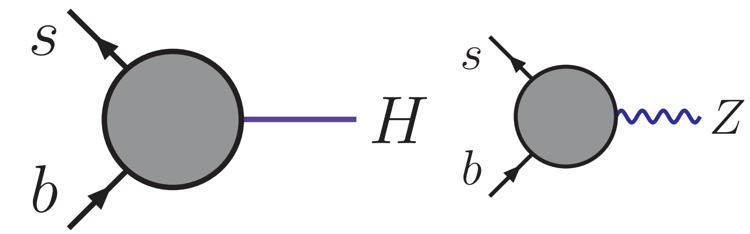
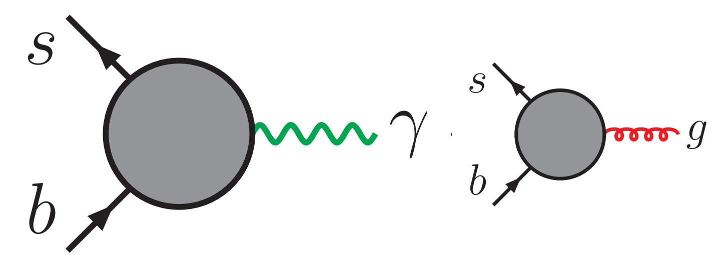
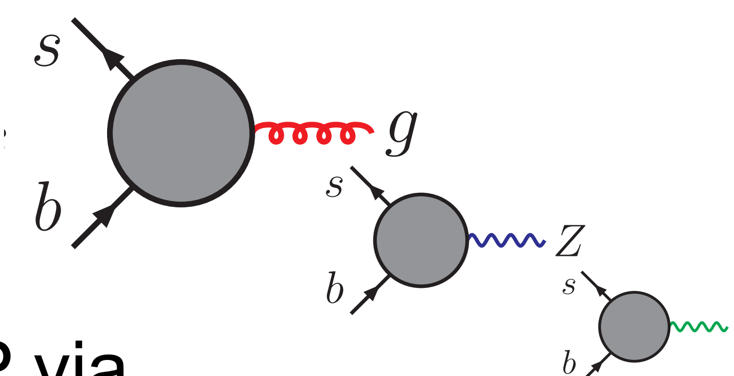
b→s transitions





- trees carry small CKM factor ~ λ^4, penguins ~ λ^2
  b➔s decays penguin-dominated in SM, sensitive to new physics

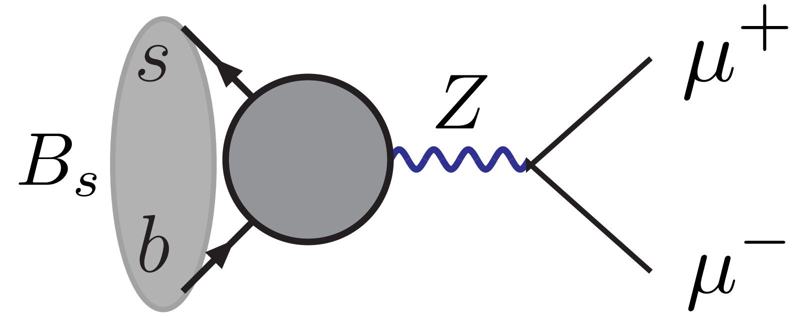
Classes of exclusive decays

final state	strong dynamics	#obs	NP enters through
Leptonic $B \to l\nu$, $B \to l^+ l^-$	decay constant $\langle 0 \vert j^\mu \vert B \rangle \propto f_B$	O(1)	
semileptonic, radiative $B \to K^* l^+ l^-$, $K^* \gamma$	form factors $\langle \pi \vert j^\mu \vert B \rangle \propto f^{B\pi}(q^2)$	O(10)	
charmless hadronic $B \to \pi\pi$, πK, $\rho\rho$, ...	matrix element $\langle \pi\pi \vert Q_i \vert B \rangle$	O(100)	

All non-radiative modes are also sensitive to NP via four-fermion operators

Decay constants and form factors are essential. Accessible by QCD sum rules and in some (-> all?) cases by lattice QCD!

Leptonic decay, NP and LHC

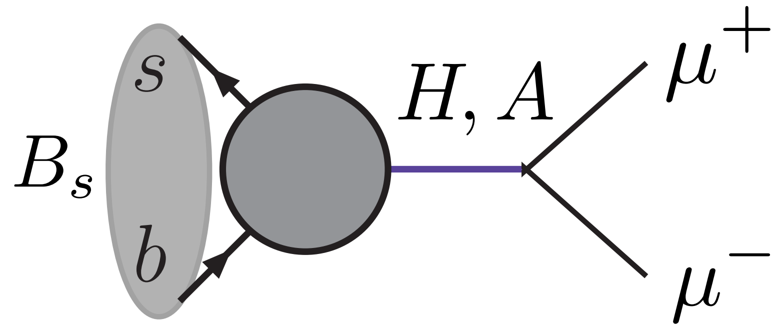


$\propto \frac{m_\mu^2}{M_W^2}$

loop and helicity suppressed in SM

$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$

Buras et al 2010

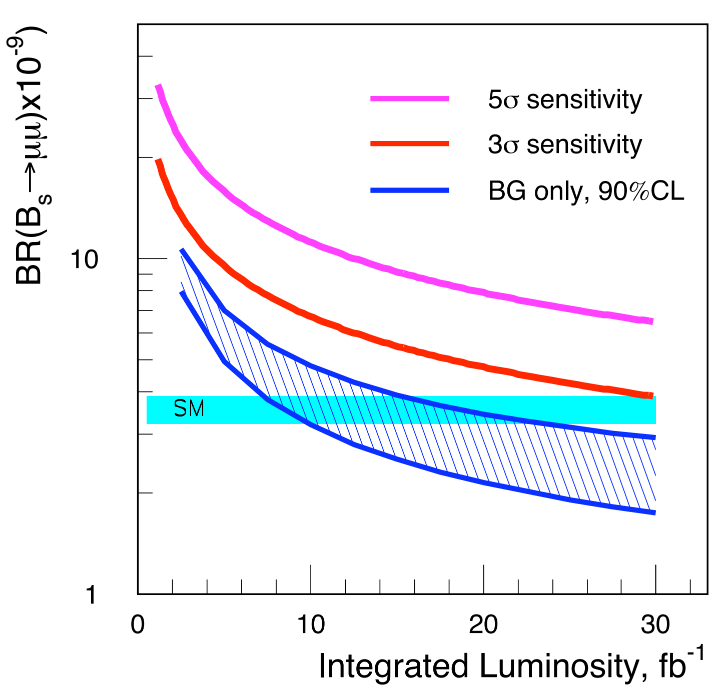


$\propto \frac{m_b^2 m_\mu^2}{M_W^4} \tan^6\beta$

Yukawa suppressed in SM

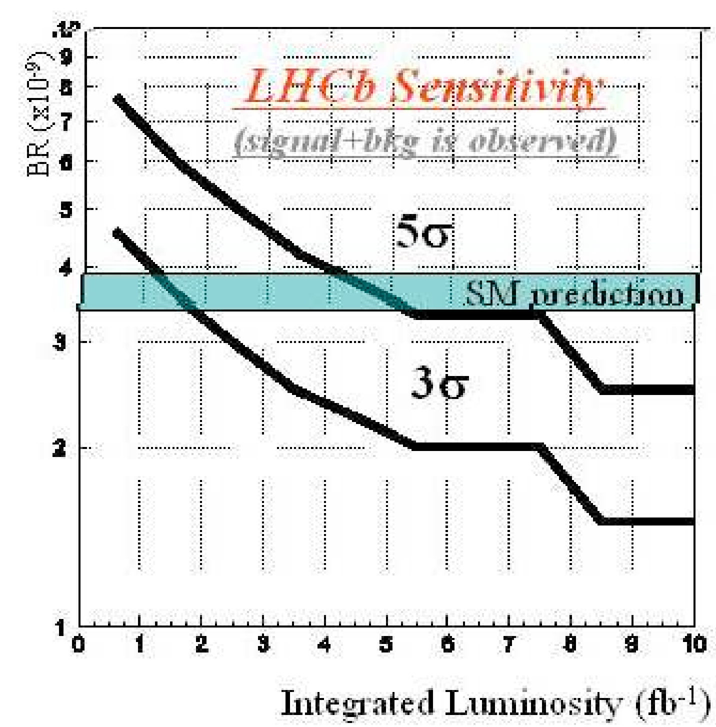
in 2HDM (or MSSM) Yukawas can be very large

Loop suppression and possible removal of helicity/Yukawa suppression imply strong sensitivity to new physics



ATLAS/CMS

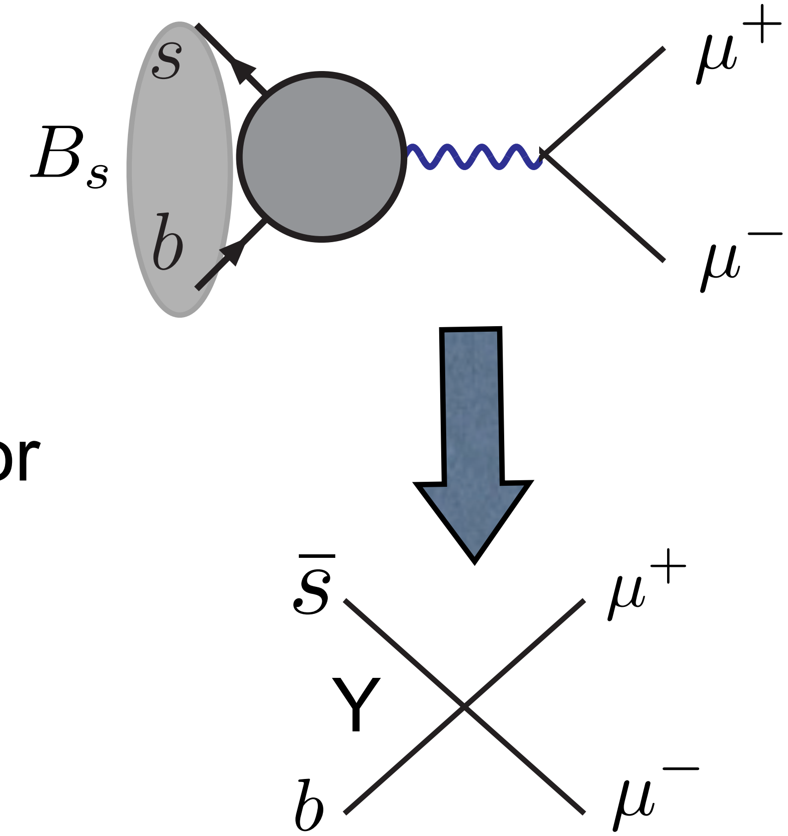
[Artuso et al 0801.1833]



LHCb

Standard Model

- Mediated by short-distance
  Z penguin and box - long distance
  strongly CKM / GIM suppressed



- including QCD corrections, matches onto single relevant effective operator

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{\pi \sin^2 \theta_W} V_{tb}^* V_{tq} Y Q_A$$

$$Q_A = \bar{b}_L \gamma^\mu q_L \, \bar{\ell} \gamma_\mu \gamma_5 \ell$$

$$Y\left(\bar{m}_t(m_t)\right) = 0.9636 \left[\frac{80.4 \text{ GeV}}{M_W} \frac{\bar{m}_t}{164 \text{ GeV}} \right]^{1.52}$$

(approximates NLO to <10^{-4})

[Buchalla&Buras 93,
Misiak&Urban 99;
Artuso et al 0801.1833]

higher orders negligible

- branching fraction

$$B(B_s \to l^+ l^-) = \tau(B_s) \frac{G_F^2}{\pi} \left(\frac{\alpha}{4\pi \sin^2 \Theta_W} \right)^2 F_{B_s}^2 m_l^2 m_{B_s} \sqrt{1 - 4\frac{m_l^2}{m_{B_s}^2}} |V_{tb}^* V_{ts}|^2 \, Y^2$$

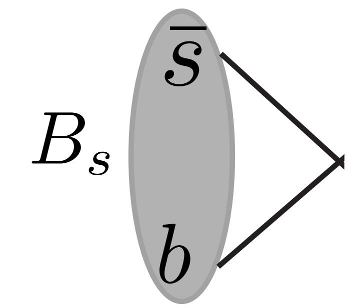
main uncertainties: decay constant, CKM
for D or K decays long-distance contributions are important

Standard Model

- F_{Bs} = (238.8 ± 9.5) MeV

  Lunghi, Laiho, van de Water 2009

  lattice QCD average



- error can be reduced by normalizing to $B_s - \bar{B}_s$ mixing

$$B(B_q \to \ell^+\ell^-) = C \frac{\tau_{B_q}}{\hat{B}_q} \frac{Y^2(\overline{m}_t^2/M_W^2)}{S(\overline{m}_t^2/M_W^2)} \Delta M_q$$

Buras 2003

  where S is the ΔF=2 box function and C a numerical const and in the bag factor $\hat{B}_{B_s} = 1.33 \pm 0.06$, some systematic uncertainties cancel. Then

$$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$$

Buras et al 2010

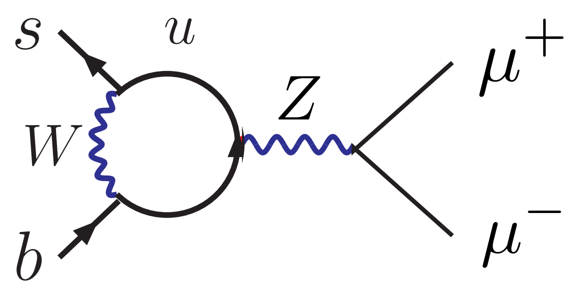
- Very precise test of SM from hadronic observables at LHC!

- same trick for $B_d \to \mu^+\mu^-$, $B_{s,d} \to e^+e^-$, $e^+\mu^-$, etc

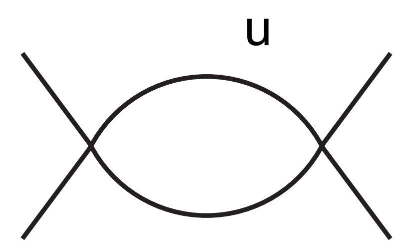
- not for $D \to \mu^+\mu^-$ or $K \to \mu^+\mu^-$ as mixing is not calculable

Long distance

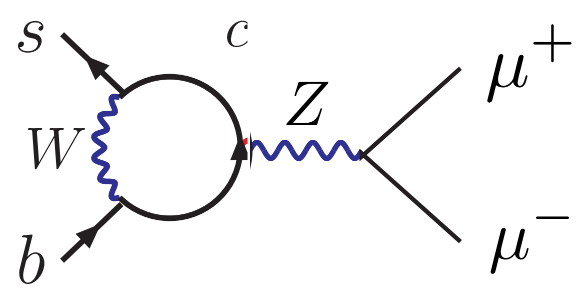
- For $B_{s,d} \rightarrow \mu^+\mu^-$ long distance effects are CKM & power suppressed



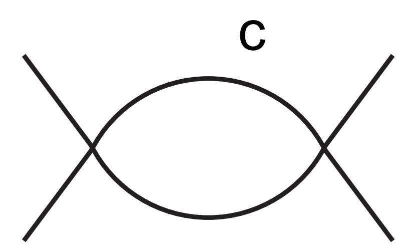
$k^2 \sim \Lambda^2_{\rm QCD}$



$$\propto V_{ub}V^*_{us}\frac{\Lambda^2_{\rm QCD}}{M_W^2\, M_Z^2}$$



$k^2 \sim m_c^2$



$$\propto V_{cb}V_{cs}\frac{m_c^2}{M_W^2\, M_Z^2}\frac{1}{16\pi^2}$$

"power-like" suppression, as opposed to eg $\ln(m_c/m_W)$ in eg photon penguin contributions, and CKM suppression

- "background" effects such as undetected soft photons are not included in uncertainties quoted before and are traditionally left to experimentalists... see arXiv:0801.1833 sect. 3.4.

Experiment

- present upper bounds

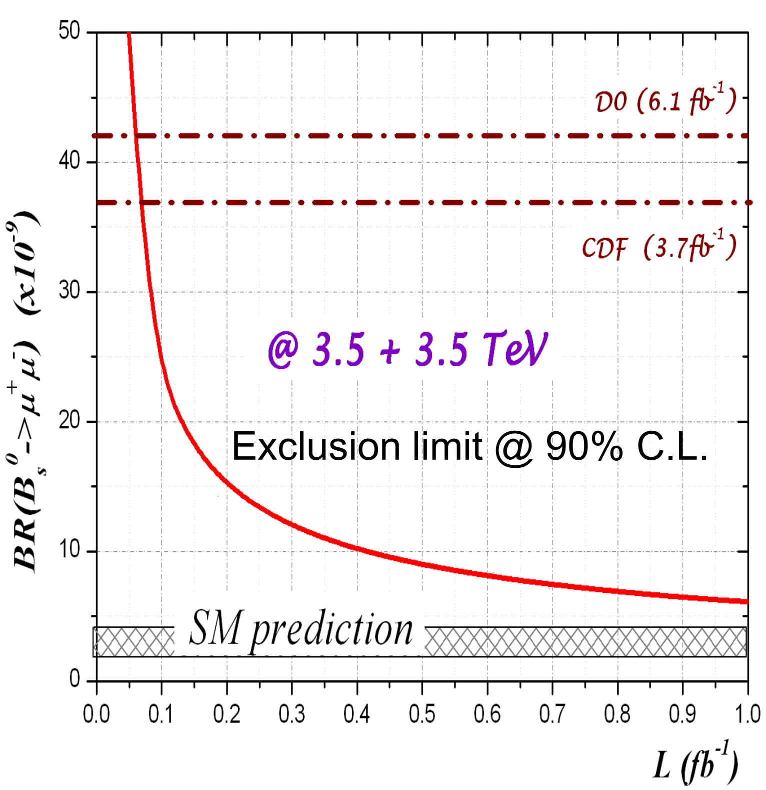
	CDF	D0	SM theory
$B_s \rightarrow \mu^+\mu^-$	$4.3\ 10^{-8}$ 95% CL	$5.2\ 10^{-8}$ 95% CL	$(3.2\pm0.2)\ 10^{-9}$
$B_d \rightarrow \mu^+\mu^-$	$7.6\ 10^{-9}$ 95% CL		$(1.0\pm0.1)\ 10^{-10}$
$D \rightarrow \mu^+\mu^-$	$3.0\ 10^{-7}$ 95% CL		$\sim 10^{-13}$

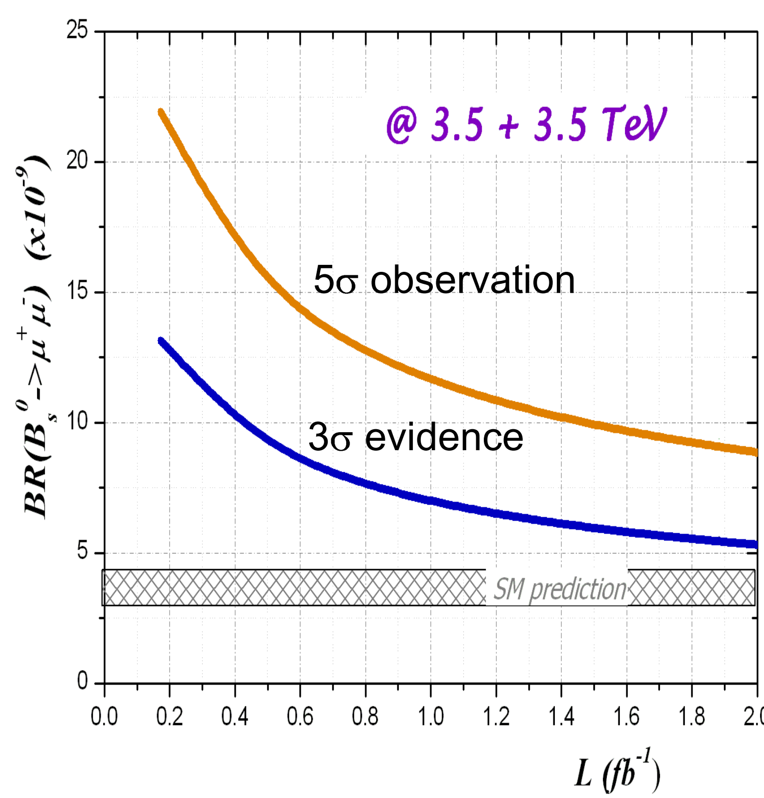
CDF public note 9892 D0 arXiv:1006.3469 D0 arXiv:1008.5077

Kreps arXiv:1008.0247 Buras et al arXiv:1007.1993

Burdman et al 2001

- early LHCb prospects

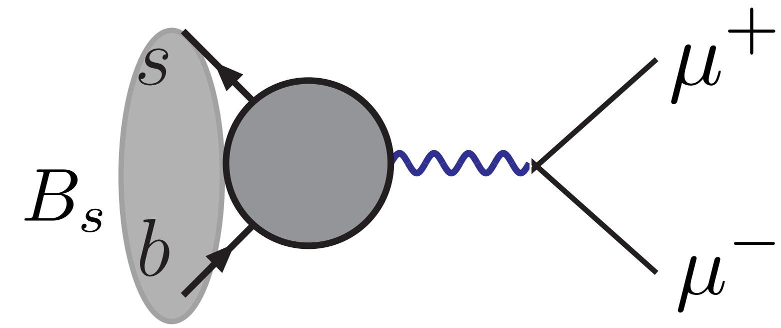




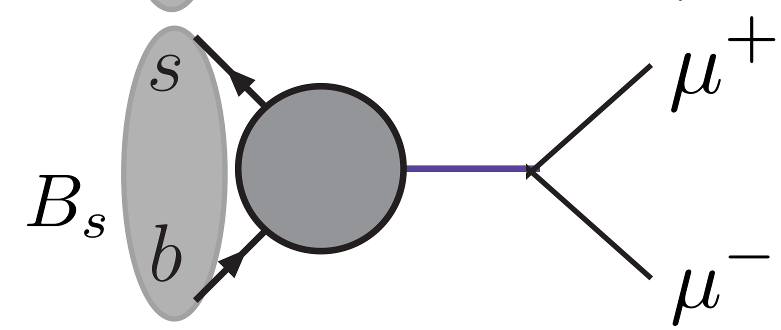
(Guy Wilkinson at CKM2010)

Beyond the SM

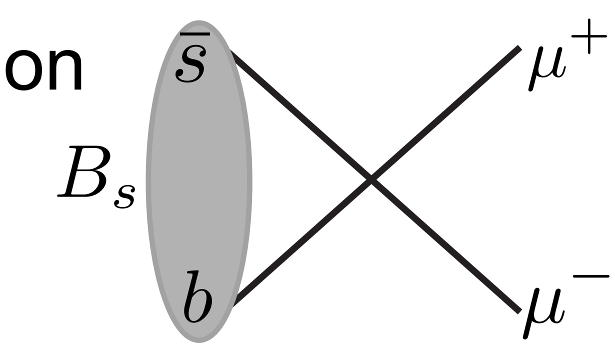
- New physics can modify the Z penguin ....



... induce a Higgs penguin ...



... or induce (or comprise) four-fermion contact interactions directly



could also violate lepton flavour

- most general effective hamiltonian

$$\frac{G_F}{\sqrt{2}} \frac{\alpha}{\pi \sin^2\theta_W} V_{tb}^* V_{tq} \left[C_S Q_S + C_P Q_P + C_A Q_A \right]$$ + parity reflections

$$B\left(B_q \to \ell^+\ell^-\right) = \frac{G_F^2\,\alpha^2}{64\,\pi^3 \sin^4\theta_W} \left|V_{tb}^* V_{tq}\right|^2 \tau_{B_q} M_{B_q}^3 f_{B_q}^2 \sqrt{1 - \frac{4m_\ell^2}{M_{B_q}^2}}$$
$$\times \left[\left(1 - \frac{4m_\ell^2}{M_{B_q}^2}\right) M_{B_q}^2\, C_S^2 + \left(M_{B_q} C_P - \frac{2m_\ell}{M_{B_q}} C_A\right)^2 \right]$$

could violate lepton flavour !

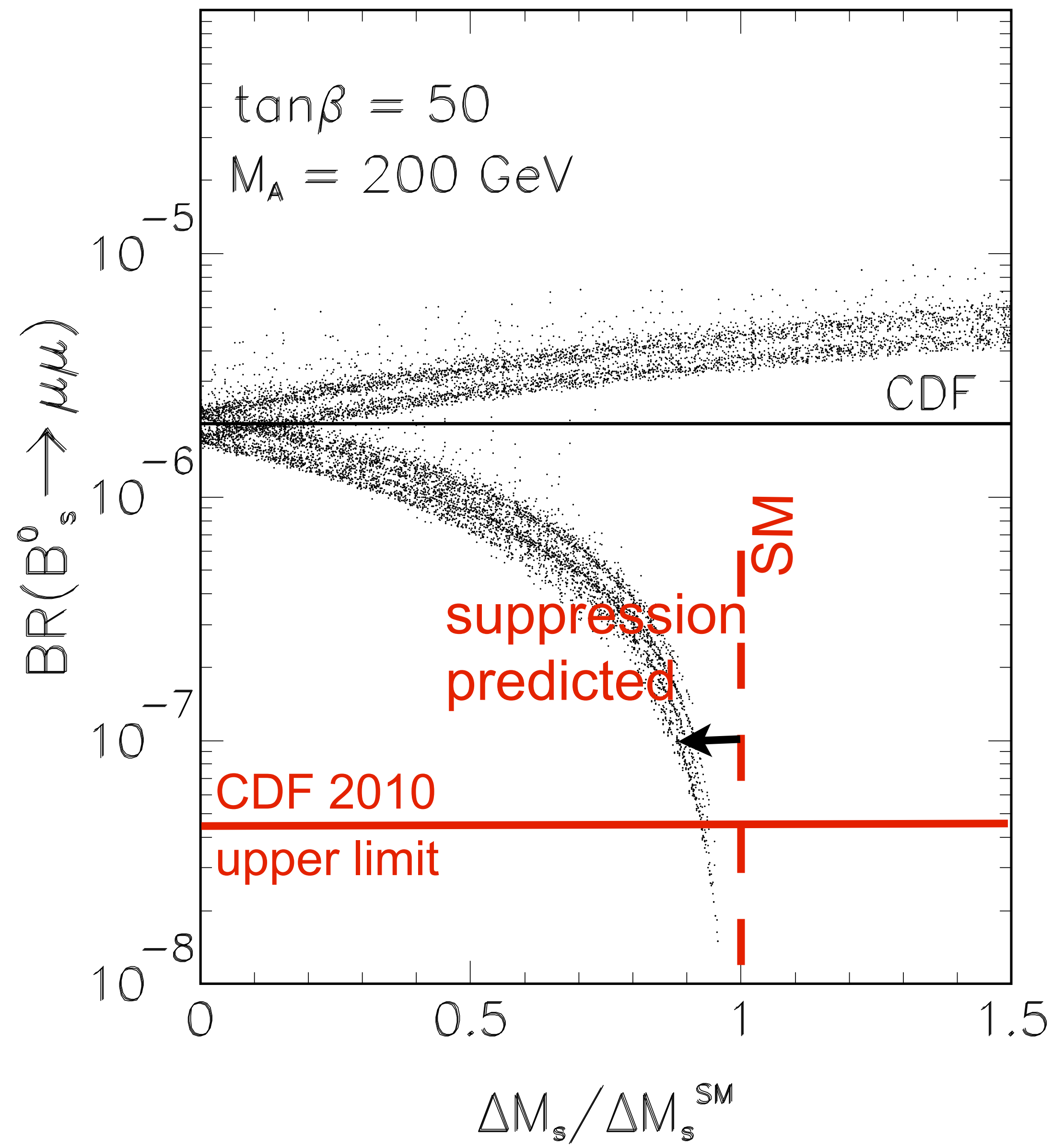
MSSM - large tan β - MFV

- huge rates possible, even for minimal flavour violation (MFV) (via heavy-Higgs penguin)

- correlation (for MFV) with ΔM_{B_s} [Buras et al 2002] [Gorbahn, SJ, Nierste, Trine 2009]

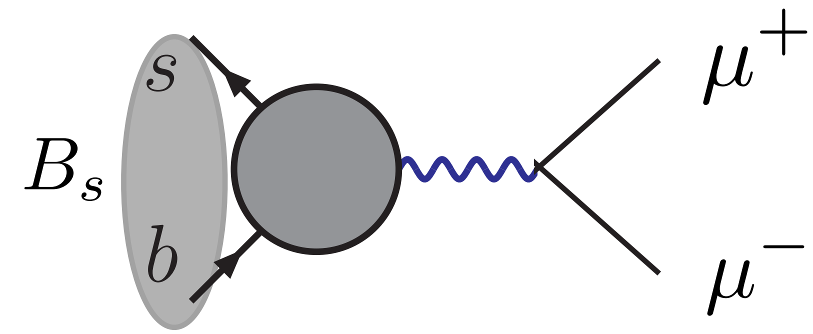
  bound on BR($B_s \rightarrow \mu^+\mu^-$) in these models implies closeness of ΔM_{B_s} to SM. In turn, ΔM_{B_s} at present does not constrain $B_s \rightarrow \mu^+\mu^-$

- beyond MFV, no correlations ! not necessarily suppression of $B_d \rightarrow \mu^+\mu^-$ with respect to $B_s \rightarrow \mu^+\mu$



MSSM - small tan β

- Z penguin contributions now relatively more important and interference effects possible

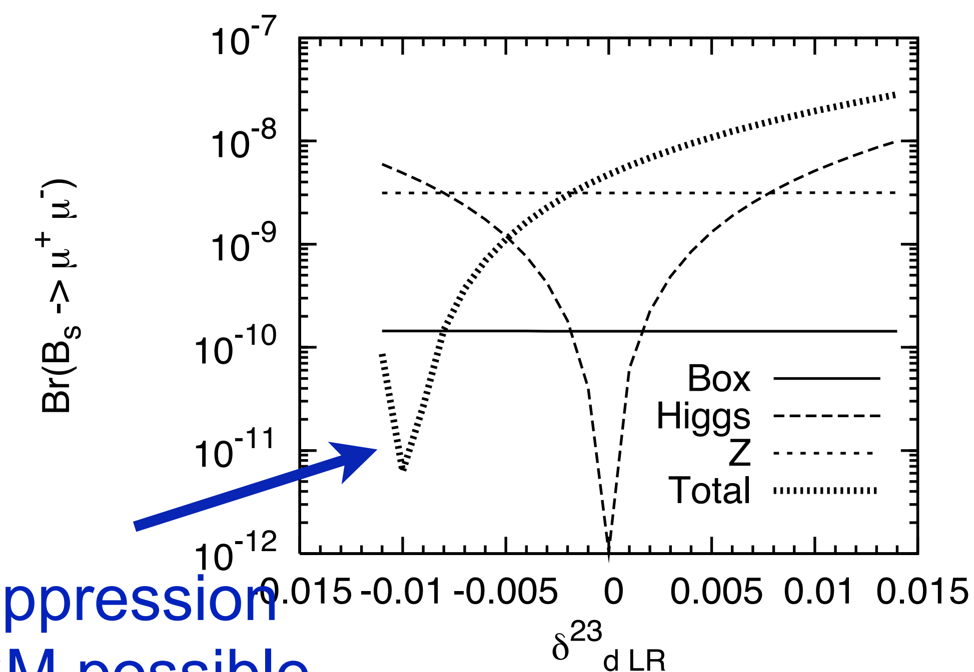


complete 1-loop calculation in general MSSM

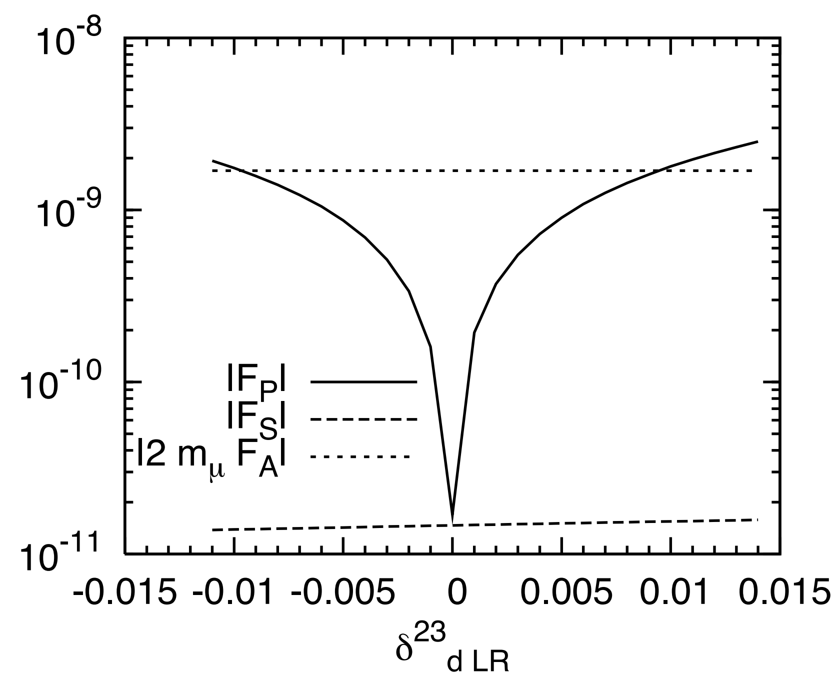
[Dedes, Rosiek, Tanedo 2008]

implemented in public computer program “SUSY_FLAVOR”

[Rosiek, Chankowski, Dedes, SJ, Tanedo 2010]

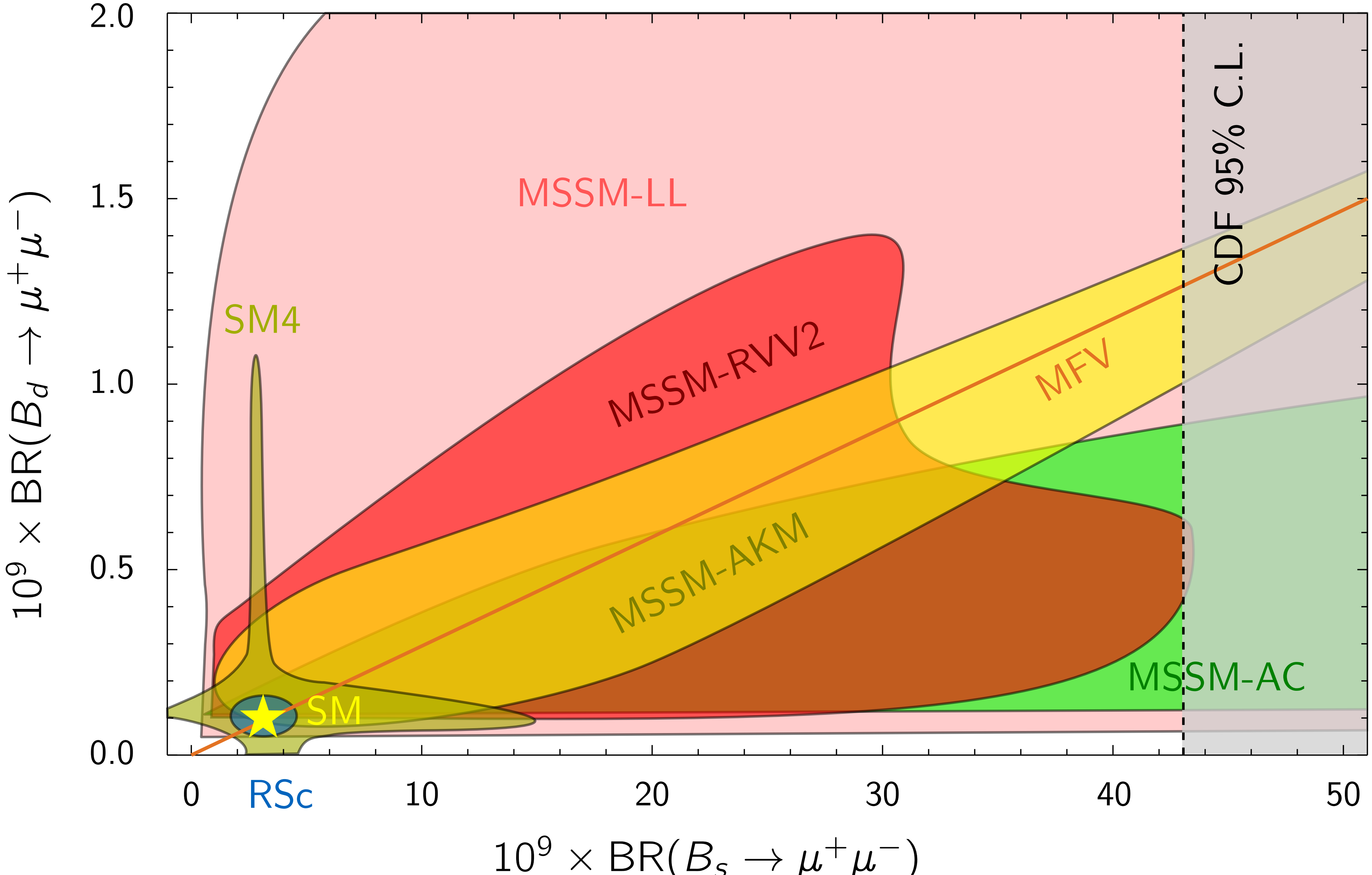


even suppression below SM possible



(in this plot the Z penguin does not receive large contributions, in general it can)

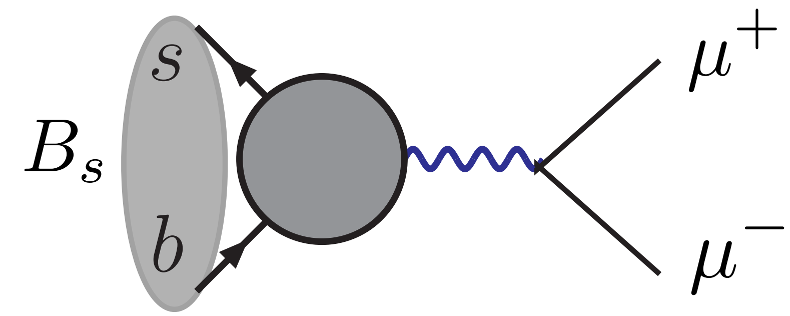
BSM model comparison



David Straub at CKM 2010

Leptonic summary

- Leptonic B decays measure the higgs penguin, Z penguin, and semileptonic four-quark operators



- Even if the higgs penguin is small (i.e. no 2HDM/MSSM with large tan(beta)) then this can be O(1) affected - easily

- To the extent these modes are correlated to others, they are so through the FCNC Z penguin vertex

Radiative/semileptonic

- many observables accessible at LHCb (FB asymmetry, time-dependent CP violation, ...)
- see Christoph Bobeth's talk

Hadronic decays

- Any SM 2-light-hadron amplitude can be written

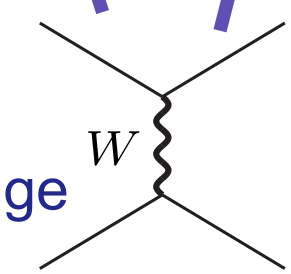
$$\mathcal{A}(\bar{B} \to M_1 M_2) = e^{-i\gamma} T_{M_1 M_2} + P_{M_1 M_2}$$

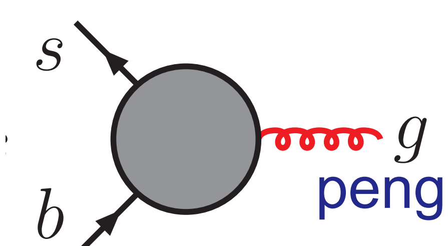
$$T_{M_1 M_2} = V_{uD} |V_{ub}| \Big[C_1 \langle Q_1^u \rangle + C_2 \langle Q_2^u \rangle + \sum_{i=3}^{12} C_i \langle Q_i \rangle \Big]$$ "tree"

$$P_{M_1 M_2} = V_{cD} |V_{cb}| \Big[C_1 \langle Q_1^c \rangle + C_2 \langle Q_2^c \rangle + \sum_{i=3}^{12} C_i \langle Q_i \rangle \Big]$$ "penguin"

CKM factor
(D=d or s)

tree W exchange



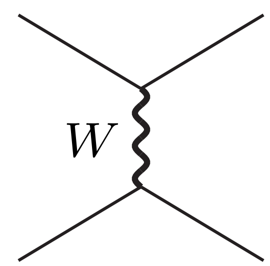


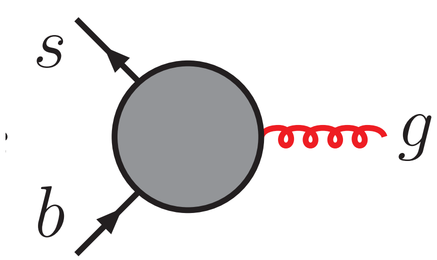
penguins (QCD, magnetic, EW)

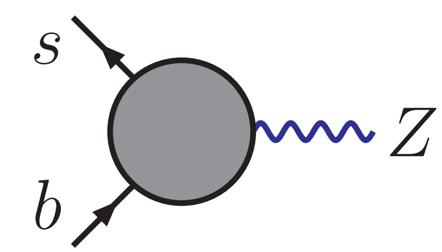
Q_i: operators in weak hamiltonian
C_i: QCD corrections from short distances (< hc/m_b) & new physics
$\langle Q_i \rangle = \langle M_1\ M_2 \mid Q_i \mid B \rangle$: QCD at distances > hc/$m_b$, strong phases

$B \to \pi K$ direct CP puzzle

$$A(B^0 \to \pi^- K^+) \;=\; T\,e^{i\gamma} \;+\; P \;+\; P^c_{EW}$$







$$-\,A(B^+ \to \pi^0 K^+) \;=\; (T+C)\,e^{i\gamma} \;+\; P \;+\; P_{EW} \;+\; P^c_{EW}$$

data: $A_{CP}(B^+ \to \pi^0 K^+) - A_{CP}(B^0 \to \pi^- K^+) = 0.14 \pm 0.03$ (expt)

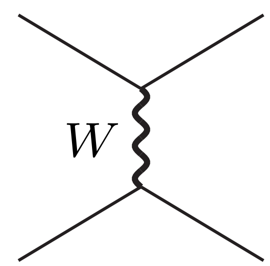
In general, only isospin relation [Gronau 2005; Gronau & Rosner 2006]

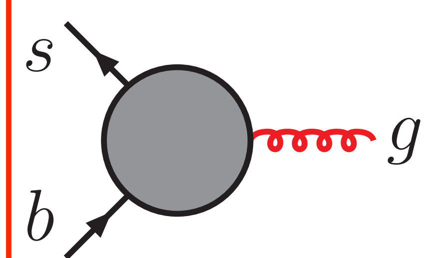
$$A_{CP}(B^+ \to \pi^0 K^+) + A_{CP}(B^0 \to \pi^0 K^0) \approx A_{CP}(B^0 \to \pi^- K^+) + A_{CP}(B^+ \to \pi^0 K^0)$$

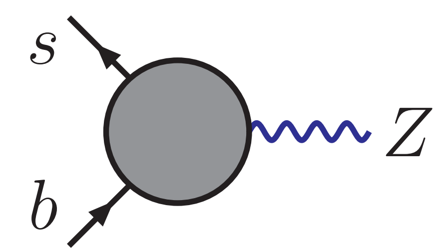
how small are the “small” amplitude ratios C/T and P_{EW}/T

B→πK direct CP puzzle

$A(B^0 \rightarrow \pi^- K^+) \quad = \quad T\, e^{i\gamma} \quad + \quad P \quad + \quad P^c_{EW}$







$- A(B^+ \rightarrow \pi^0 K^+) \quad = \quad (T+C)\, e^{i\gamma} \quad + \quad P \quad + \quad P_{EW} \quad + \quad P^c_{EW}$

(QCD) penguin amplitudes

data: $A_{CP}(B^+ \rightarrow \pi^0 K^+) - A_{CP}(B^0 \rightarrow \pi^- K^+) = 0.14 \pm 0.03$ (expt)

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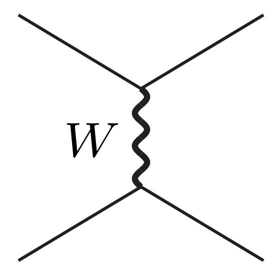
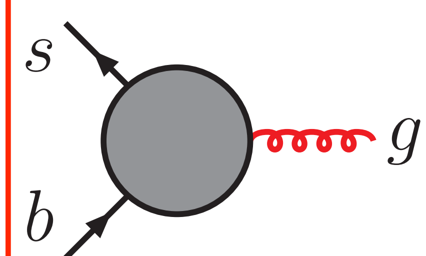
how small are the “small” amplitude ratios C/T and P_{EW}/T

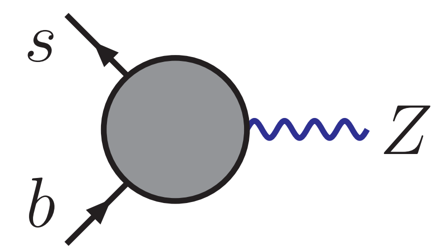
$B \to \pi K$ direct CP puzzle

$$A(B^0 \to \pi^- K^+) = T e^{i\gamma} + P + P^c_{EW}$$

tree amplitudes







$$-A(B^+ \to \pi^0 K^+) = (T+C) e^{i\gamma} + P + P_{EW} + P^c_{EW}$$

(QCD) penguin amplitudes

EW penguin amplitudes

data: $A_{CP}(B^+ \to \pi^0 K^+) - A_{CP}(B^0 \to \pi^- K^+) = 0.14 \pm 0.03$ (expt)

In general, only isospin relation [Gronau 2005; Gronau & Rosner 2006]

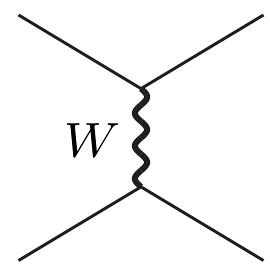
$$A_{CP}(B^+ \to \pi^0 K^+) + A_{CP}(B^0 \to \pi^0 K^0) \approx A_{CP}(B^0 \to \pi^- K^+) + A_{CP}(B^+ \to \pi^0 K^0)$$

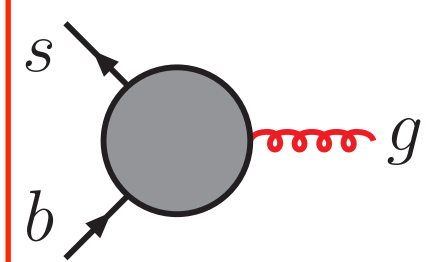
how small are the “small” amplitude ratios C/T and P_{EW}/T

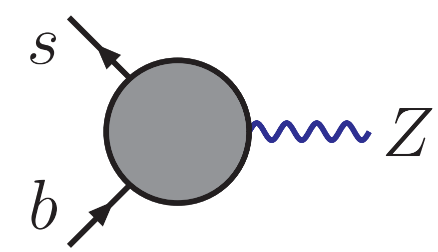
B→πK direct CP puzzle

$$A(B^0 \to \pi^- K^+) = T e^{i\gamma} + P + P^c_{EW}$$

tree amplitudes







$$-A(B^+ \to \pi^0 K^+) = (T+C)\, e^{i\gamma} + P + P_{EW} + P^c_{EW}$$

(QCD) penguin amplitudes

EW penguin amplitudes

data: $A_{CP}(B^+ \to \pi^0 K^+) - A_{CP}(B^0 \to \pi^- K^+) = 0.14 \pm 0.03$ (expt)

In general, only isospin relation [Gronau 2005; Gronau & Rosner 2006]

$$A_{CP}(B^+ \to \pi^0 K^+) + A_{CP}(B^0 \to \pi^0 K^0) \approx A_{CP}(B^0 \to \pi^- K^+) + A_{CP}(B^+ \to \pi^0 K^0)$$

how small are the “small” amplitude ratios C/T and P_{EW}/T

Theory of hadronic amplitudes

- 1/N expansion (only counting rules)
- expansion in Λ_{QCD}/m_B ~0.2 (QCDF/SCET; “pQCD”): reduce amplitudes to simpler objects (form factors etc)

	T/a_1	C/a_2	P	E/b_1	A/b_1
1/N	1	1/N	1/N	1/N	1 [?]
Λ/m_B	1	1	1	Λ/m_B	Λ/m_B

- QCD light-cone sum rules: partly complementary set of calculable amplitudes; constrain “inputs” to heavy-quark expansion
- SU(3) / U-spin relates $\Delta D=1$ and $\Delta S=1$ amplitudes
  $T(B\to\pi K) \approx T(B\to\pi\pi)$; $P(B\to\rho\rho) \approx P(B\to\rho K^*)$, etc.
  (corrections in m_s/Λ_{QCD} ~0.3 uncontrolled; annihilation amplitudes spoil simple relations)

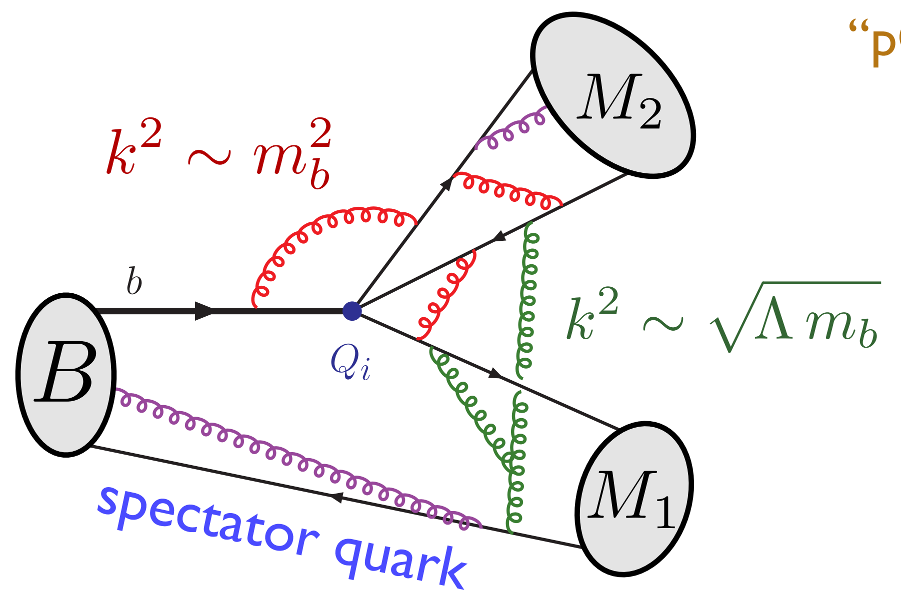
QCD factorization

Beneke, Buchalla, Neubert, Sachrajda 99-01
SCET: Bauer, Pirjol, Rothstein, Stewart 04

"pQCD": Keum, Li, Sanda 00

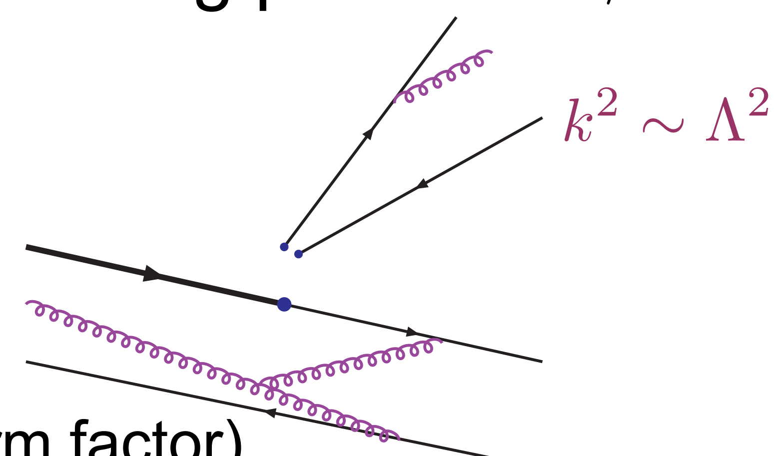
"nonfactorizable" gluons
are perturbative

$$\langle M_1 M_2 | Q_i | \bar{B} \rangle =$$



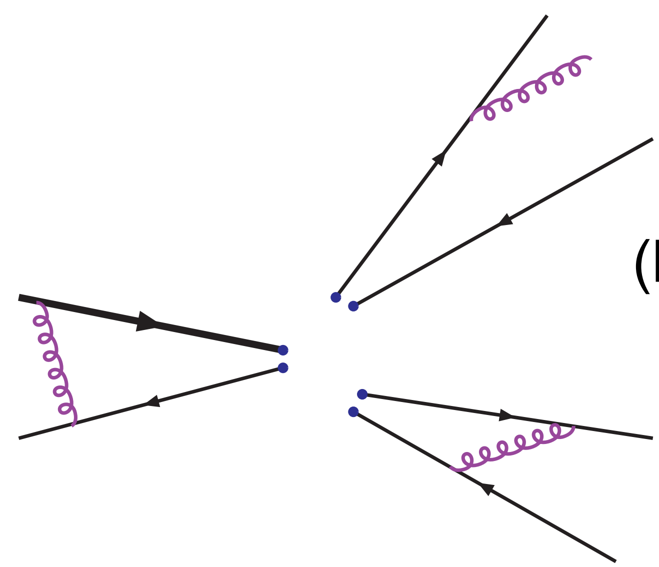
$$+ \ldots$$

To leading power in Λ/m_b *long-distance* interactions look like



soft overlap (form factor)

or



(hard) spectator scattering

model dependence enters (only) at subleading power
(factorization breaks at O(Λ/m) for some amplitudes)

$$\langle M_1 M_2 | Q_i | \bar{B} \rangle =$$

perturbative, includes strong phases

non-perturbative QCD

$$f_+^{BM_1}(0) f_{M_2} \int du\, T_i^{\mathrm{I}}(u) \phi_{M_2}(u) + f_B f_{M_1} f_{M_2} \int du\, dv\, d\omega\, T_i^{\mathrm{II}}(u, v, \omega)\, \phi_{B_+}(\omega) \phi_{M_1}(v) \phi_{M_2}(u)$$

soft overlap (form factor)

hard spectator scattering

$$T_i^{\mathrm{I}} \sim 1 \; + \; t_i\, \alpha_s \; + \; \mathcal{O}(\alpha_s^2)$$

“naive factorization”

BBNS 99-01

Bell 07, 09 (trees),
Beneke et al 09 (trees)

$$T_i^{\mathrm{II}} \sim H_i \star J$$

$$\sim \left(1 + h_i\, \alpha_s + \mathcal{O}(\alpha_s^2)\right) \left(j^{(0)} \alpha_s + j^{(1)} \alpha_s^2 + \mathcal{O}(\alpha_s^3)\right)$$

BBNS 99-01

BBNS 99-01

Hill, Becher, Lee, Neubert 2004; Beneke, Yang 2005; Kirilin 2005

Beneke, SJ 2005 (trees), 2006 (penguins); Kivel 2006; Pilipp 2007 (trees);
Jain, Rothstein, Stewart 2007 (penguins)

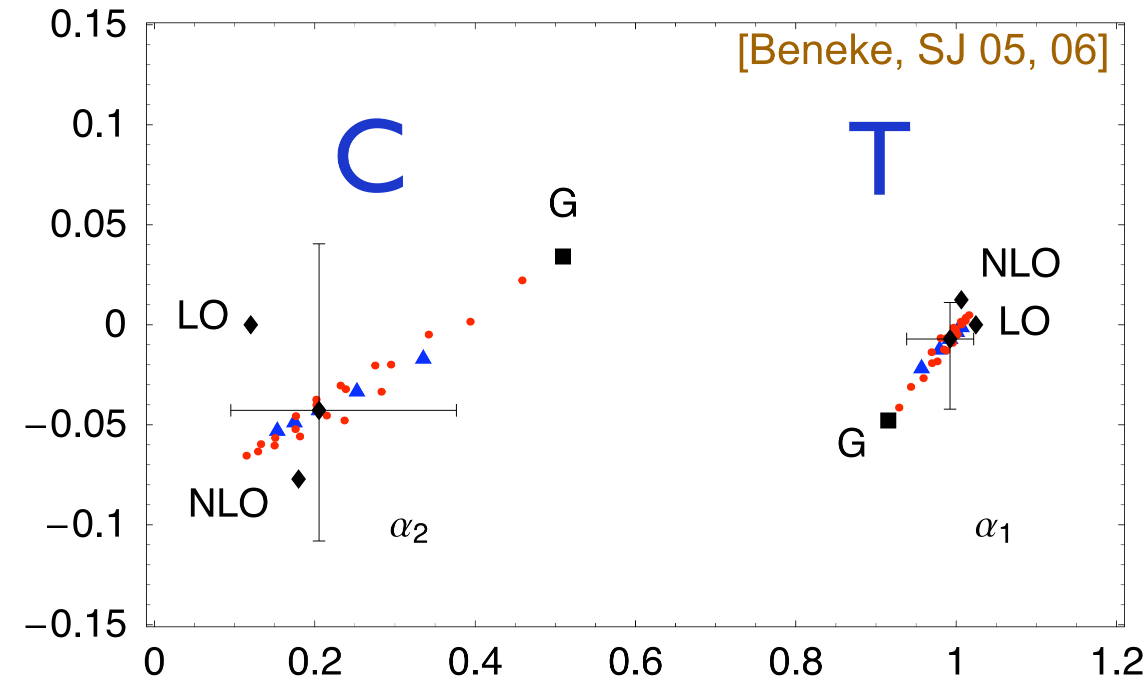
Implementations of factorization

	BBNS Beneke, Buchalla,Neubert, Sachrajda	BPRS/"SCET" Bauer, Pirjol, Rothstein, Stewart	pQCD Keum, Li, Sanda
hard scale (m_b)	perturbative; identical kernels [up to basis]		not separated, perturbative
hardcollinear scale ($\sqrt{m_b\Lambda}$)	perturbative	fit to data (possible for LO hard kernels)	
charm penguin	no special treatment (generally) small perturbative phase	introduce extra complex parameter (fit to data)	not (yet) calculated
most important theory inputs	QCD form factor, B & light meson LCDA	2 soft form factors, light meson LCDA	k_T dependent B wave function
power corrections	calculate or model potentially large ones	various treatments in the literature	computed

- charming penguin phenomenologically indistinguishable from penguin annihilation term (power correction)
- pQCD school claims soft overlap calculable, hence no form factors remain (but more complicated meson wave functions)

phenomenological summary

- Corrections to naive factorization small for T and P_{EW}, stable perturbation series ; small uncertainties



- Corrections O(1) for C (and P_{EW}^c), stable perturbation series large uncertainties (hadronic inputs; large incalculable power correction for final states with pseudoscalars)

parameter set “G” (fit hadronic parameters to B➔ππ BR’s):
C/T ~ 0.69 + 0.17 i
large magnitude, small phase

- (physical) penguin amplitudes moderately affected by incalculable penguin annihilation terms. Spoils precise predictions for direct CP asymmetries

- certain SU(3)-type relations satisfied in good approximation

$B \to \pi K$ direct CPV

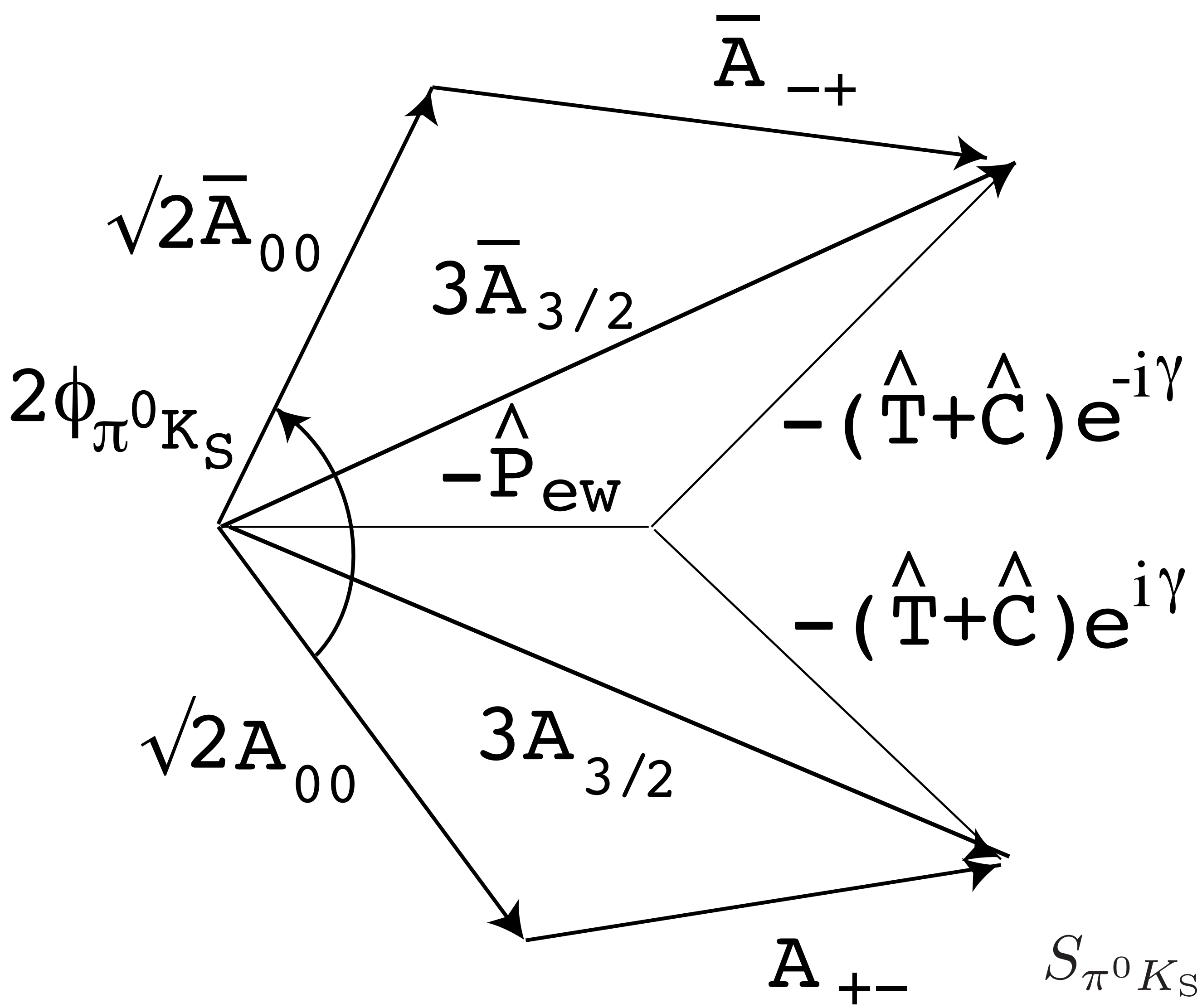
- QCDF, with usual estimate of uncertainties (in particular BBNS model of power corrections), cannot accomodate data:
  $A_{CP}(B^+ \to \pi^0 K^+) - A_{CP}(B^0 \to \pi^- K^+) = 0.14 \pm 0.03$ (expt)
  $= 0.03 \pm 0.03$ (QCDF) [Beneke 08]
  reason: small arg(C/T); if it were large, could accomodate data
  [eg Baek, Chiang, London 09]
- one possibility: new physics with the structure of an electroweak penguin amplitude (modified Zsb vertex, Z´boson etc)
  [Buras, Fleischer, Recksiegel, Schwab; Baek et al; Imbeault, Baek, London; Kim et al; Lunghi, Soni; Arnowitt et al; Khalil, Kou; Hou; Soni et al; Barger et al; Khalil, Masiero, Murayama; Ciuchini et al ...]
- $S_{\pi K}$ (time-dependent CP asymmetry): no significant deviation; direct CP asymmetry interpretation depends on a model of power corrections, which may (plausibly) underestimate C
- can we better use the data to reduce the theory uncertainty?

$B \to \pi K$ isospin analysis

Fleischer, SJ, Pirjol, Zupan 08

Gronau, Rosner 08

The two B^0 decay amplitudes add up to a pure $\Delta I=3/2$ amplitude.
(The two B^+ decay amplitudes add up to the *same amplitude.)*
The situation for the four CP-conjugate modes is analogous.



In the SM, $A_{3/2}$ stems solely from tree and electroweak penguin amplitudes (QCD penguins are $\Delta I=3/2$)

The ratio $P_{EW}/(T+C)$ is known in the SU(3) limit. Neubert, Rosner 98

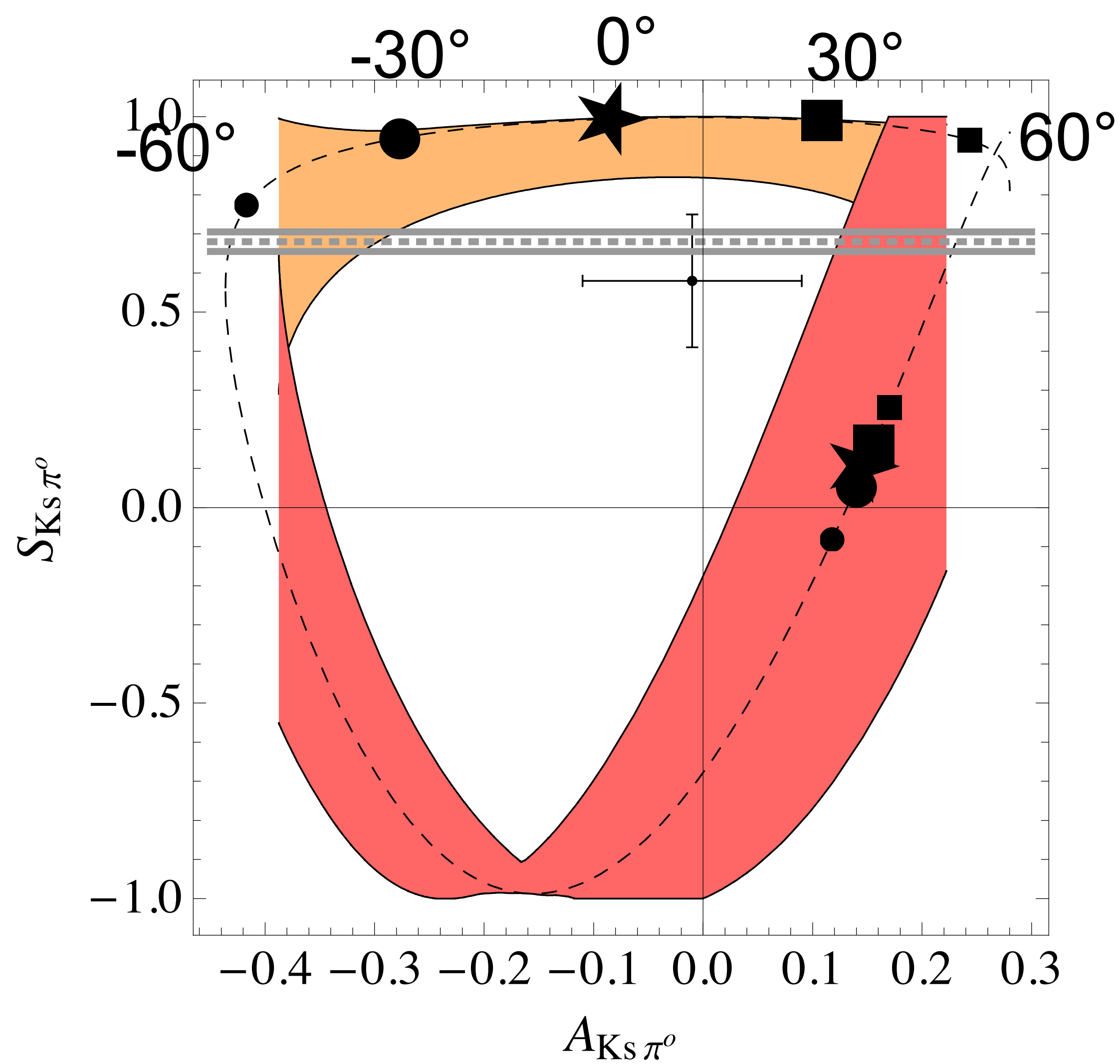
T+C is SU(3)-related to BR($B^0 \to \pi^0 \pi^0$)

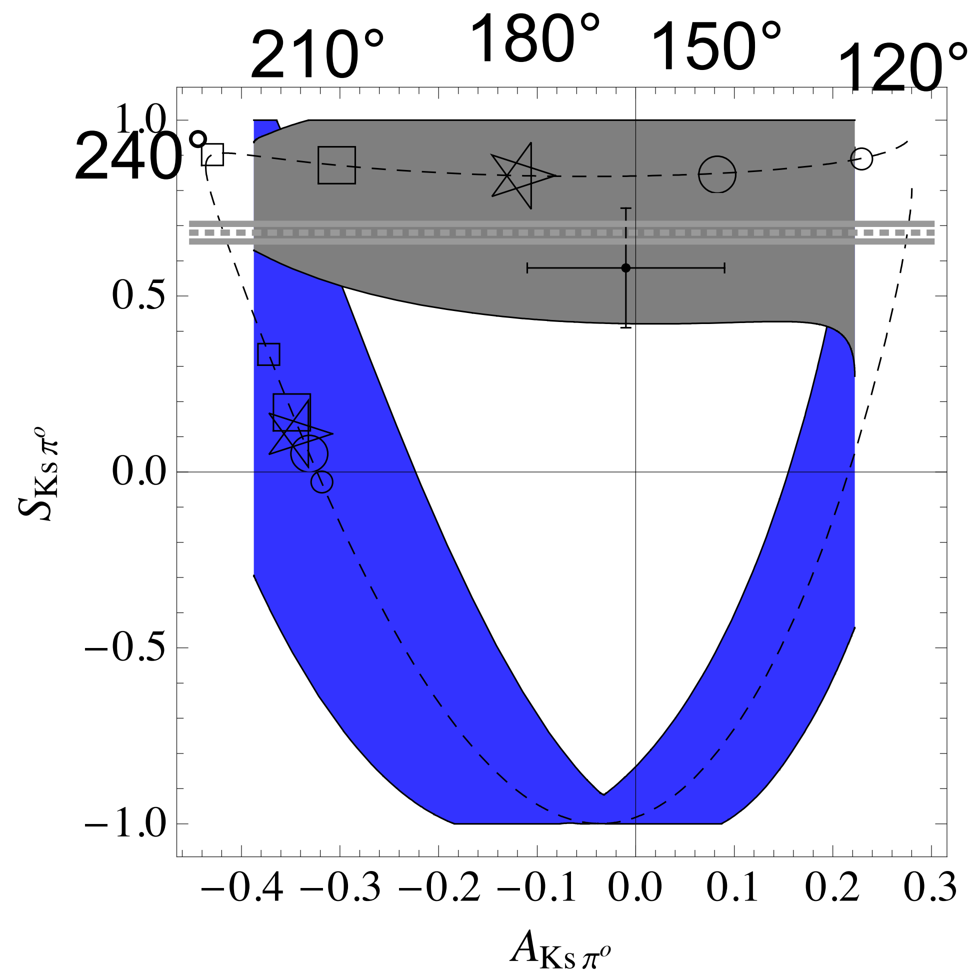
$$S_{\pi^0 K_S} = \frac{2|\bar{A}_{00} A_{00}|}{|\bar{A}_{00}|^2 + |A_{00}|^2} \sin(2\beta - 2\phi_{\pi^0 K_S})$$

One relation between 4 decay rates (all measured) and $S_{\pi K}$

Mode	BR $[10^{-6}]$	$A_{\rm CP}$
$\bar{B}^0 \to \pi^+ K^-$	19.4 ± 0.6	-0.098 ± 0.012
$\bar{B}^0 \to \pi^0 \bar{K}^0$	9.8 ± 0.6	-0.01 ± 0.10

four-fold ambiguity: resolve by considering strong phase of P/(T+C)





Fleischer, SJ, Pirjol, Zupan 08

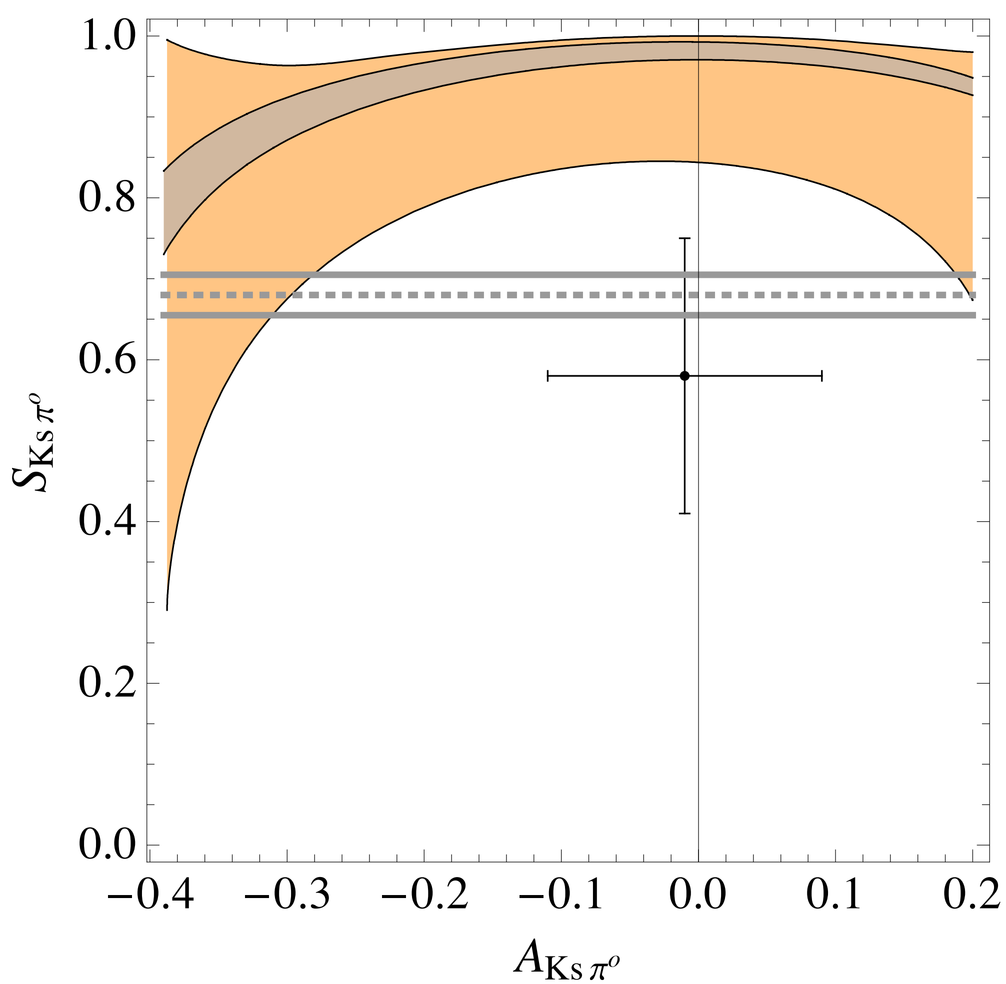
heavy-quark limit predicts ≈0°

SU(3) relation with B➔ππ gives ≈0°

both exclude the solution in the red band

- use QCD factorization only to estimate SU(3) breaking

$$S_{\pi^0 K_S} = 0.99^{+0.01}_{-0.08}\Big|_{\mathrm{exp.}}\,{}^{+0.000}_{-0.001}\Big|_{R_{T+C}}\,{}^{+0.00}_{-0.11}\Big|_{R_q}\,{}^{+0.00}_{-0.07}\Big|_{\gamma}$$



Fleischer, SJ, Pirjol, Zupan 08

error dominated by form-factor ratio

$F^{B\to K}(0)/F^{B\to\pi}(0)$

$$R_q = (1.02^{+0.27}_{-0.22})e^{i(0^{+1}_{-1})^\circ}$$

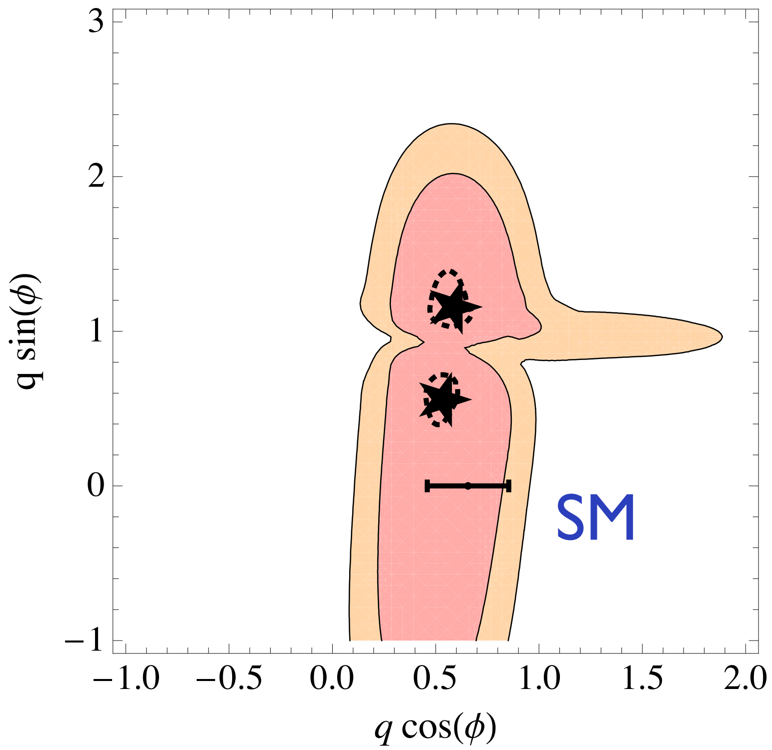
assuming 30% error on future lattice calculation of SU(3) breaking in $F^{B\to K}(0)/F^{B\to\pi}(0)$ would reduce error:

$$R_q = (0.908^{+0.052}_{-0.043})e^{i(0^{+1}_{-1})^\circ}$$

[arbitrary central value]

[assuming superB statistics]

- can be explained a modified electroweak penguin

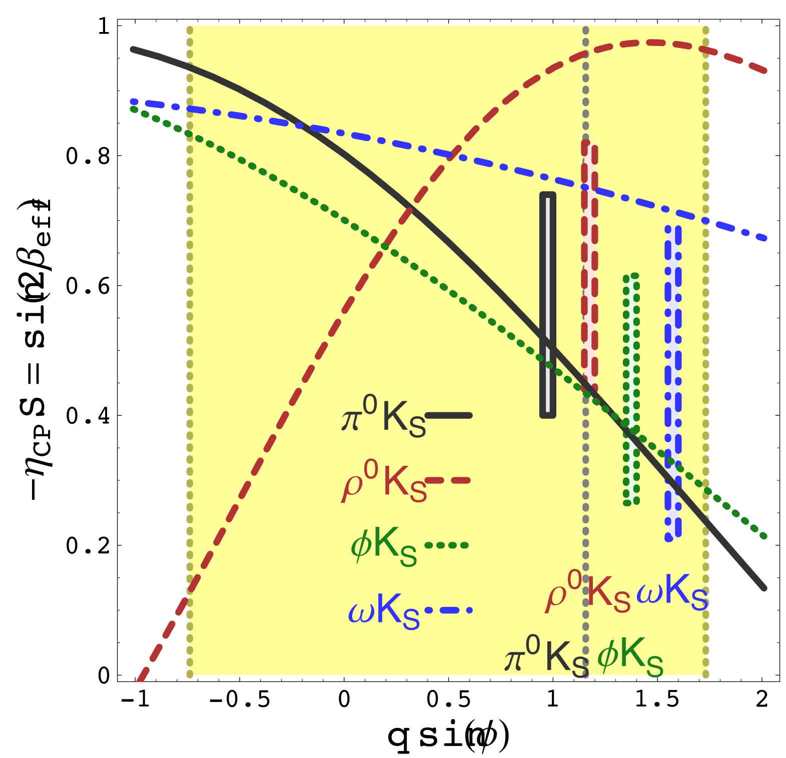


$$qe^{i\phi} = \frac{\hat{P}_{ew}}{0.66\,\hat{T}}$$

Fleischer, SJ, Pirjol, Zupan 08

Barger et al 09

- best fit works a bit better for (other) time-dependent CP asymmetries than SM - details depend on how EW Wilson coefficients are modified

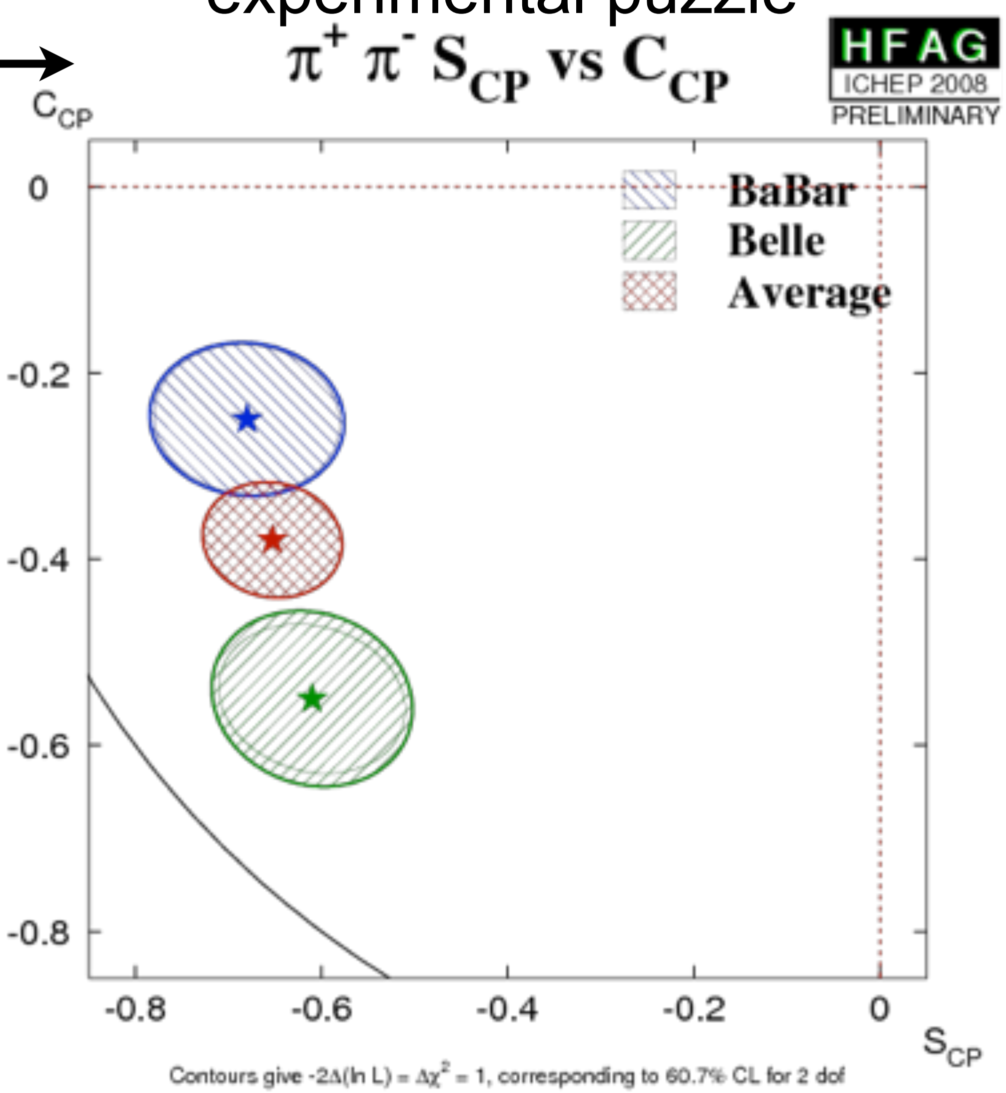


Impressive LHCb prospects

	Current knowledge	LHCb stat sensitivity with 200 pb^{-1}
$\mathcal{A}^{CP}_{K^+\pi^-}$	$-0.098^{+0.012}_{-0.011}$	0.008
$\mathcal{A}^{CP}_{\pi^+K^-}$	$0.39 \pm 0.15 \pm 0.08$	0.05
$\mathcal{A}^{CP}_{p\pi^-}$	$0.03 \pm 0.17 \pm 0.05$	0.05
$\mathcal{A}^{CP}_{pK^-}$	$0.37 \pm 0.17 \pm 0.03$	0.03
$\mathcal{A}^{dir}_{\pi^+\pi^-}$	0.38 ± 0.06	0.13
$\mathcal{A}^{mix}_{\pi^+\pi^-}$	-0.65 ± 0.07	0.13
$\mathrm{Corr}(\mathcal{A}^{dir}_{\pi^+\pi^-}, \mathcal{A}^{mix}_{\pi^+\pi^-})$	0.08	-0.03
$\mathcal{A}^{dir}_{K^+K^-}$	**Still unmeasured**	0.15
$\mathcal{A}^{mix}_{K^+K^-}$		0.11
$\mathrm{Corr}(\mathcal{A}^{dir}_{K^+K^-}, \mathcal{A}^{mix}_{K^+K^-})$		0.02
$\frac{\mathcal{BR}(B^0\to\pi^+\pi^-)}{\mathcal{BR}(B^0\to K^+\pi^-)}$	0.264 ± 0.011	0.006
$\frac{\mathcal{BR}(B^0\to K^+K^-)}{\mathcal{BR}(B^0\to K^+\pi^-)}$	$0.020 \pm 0.008 \pm 0.006$	0.005
$\frac{f_s\,\mathcal{BR}(B^0_s\to K^+K^-)}{f_d\,\mathcal{BR}(B^0\to K^+\pi^-)}$	$0.347 \pm 0.020 \pm 0.021$	0.006
$\frac{f_s\,\mathcal{BR}(B^0_s\to \pi^+K^-)}{f_d\,\mathcal{BR}(B^0\to K^+\pi^-)}$	$0.071 \pm 0.010 \pm 0.007$	0.004
$\frac{f_s\,\mathcal{BR}(B^0_s\to \pi^+\pi^-)}{f_d\,\mathcal{BR}(B^0\to K^+\pi^-)}$	$0.007 \pm 0.004 \pm 0.005$	0.002
$\frac{f_{\Lambda_b}\,\mathcal{BR}(\Lambda_b\to p\pi^-)}{f_d\,\mathcal{BR}(B^0\to K^+\pi^-)}$	$0.0415 \pm 0.0074 \pm 0.0058$	0.0016
$\frac{f_{\Lambda_b}\,\mathcal{BR}(\Lambda_b\to pK^-)}{f_d\,\mathcal{BR}(B^0\to K^+\pi^-)}$	$0.0663 \pm 0.0089 \pm 0.0084$	0.0018

Guy Wilkinson at CKM2010

should resolve long-standing experimental puzzle



perhaps shed some light on SU(3) / $1/m_b$ expansion

Hadronic summary

- Hadronic decays are short-distance sensitive, there are many modes, and many are accessible at LHCb
- They are sensitive to electroweak penguins which also enter leptonic and semileptonic decays
- The theoretical description relies on the heavy-quark limit and form factor inputs (and light-cone DA's), and/or SU(3) flavour symmetry
- There are certain puzzles in the data, it will be interesting to see what LHCb can say. New physics is very likely to affect these modes, and in some combinations of observables the effects may eventually become significant

Backup

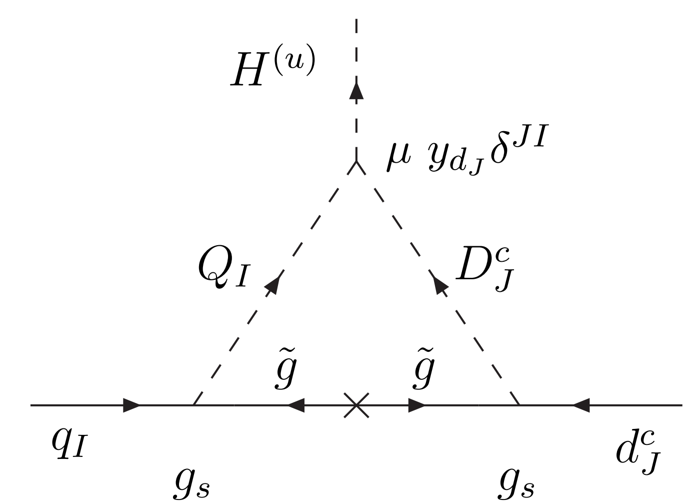
MSSM - large tan β

In SM, higgs couplings flavour diagonal
(proportional mass matrix) $$M^d_{ij} = v \; Y^d_{ij}$$

MSSM - large tan β

In SM, higgs couplings flavour diagonal
(proportional mass matrix)

$$M^d_{ij} = v_d Y^d_{ij} + v_u \Delta_{ij}$$



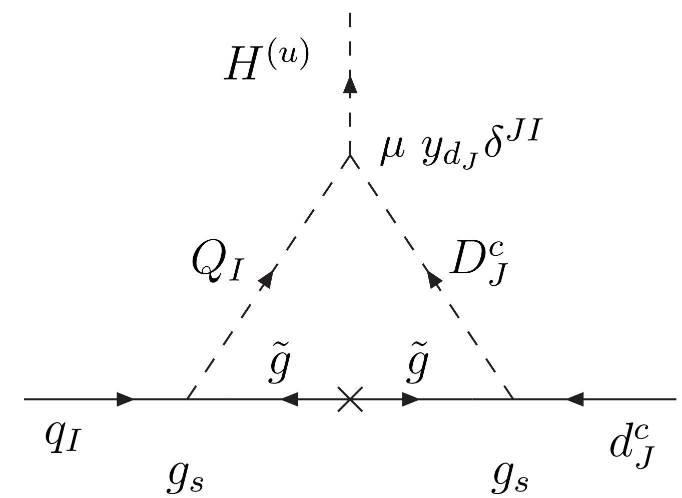
In MSSM, 3 neutral higgses, 2 vevs v_u, v_d

MSSM - large tan β

parametrically large if $v_u \gg v_d$

In SM, higgs couplings flavour diagonal (proportional mass matrix)

$$M^d_{ij} = v_d Y^d_{ij} + v_u \Delta_{ij}$$



In MSSM, 3 neutral higgses, 2 vevs v_u, v_d

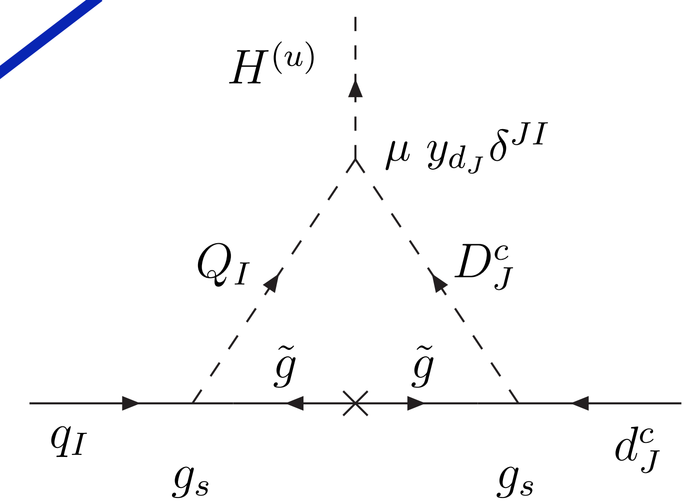
tan β=v_u/v_d

MSSM - large tan β

parametrically large if $v_u \gg v_d$

In SM, higgs couplings flavour diagonal
(proportional mass matrix)

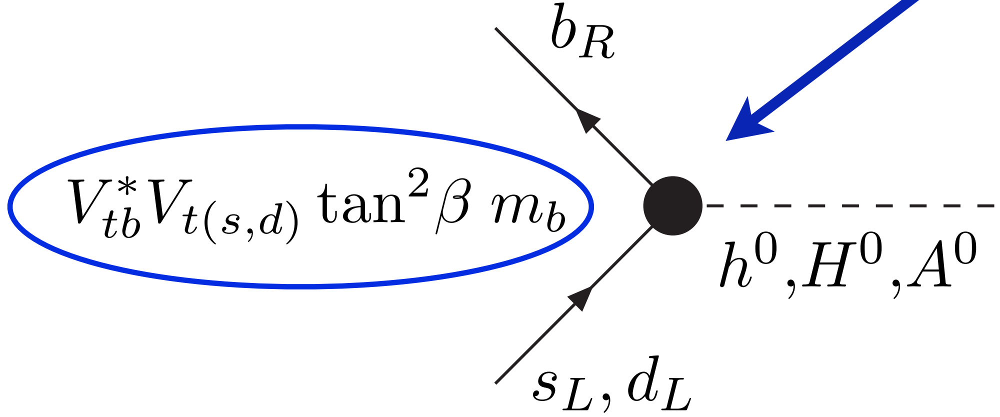
$$M^d_{ij} = v_d Y^d_{ij} + v_u \Delta_{ij}$$



In MSSM, 3 neutral higgses, 2 vevs v_u, v_d

tan $\beta = v_u/v_d$

Yukawa becomes flavour-violating



MSSM - large tan β

In SM, higgs couplings flavour diagonal
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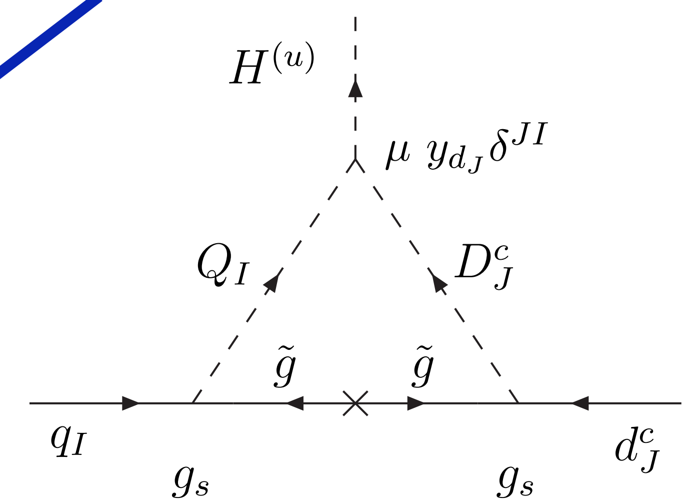


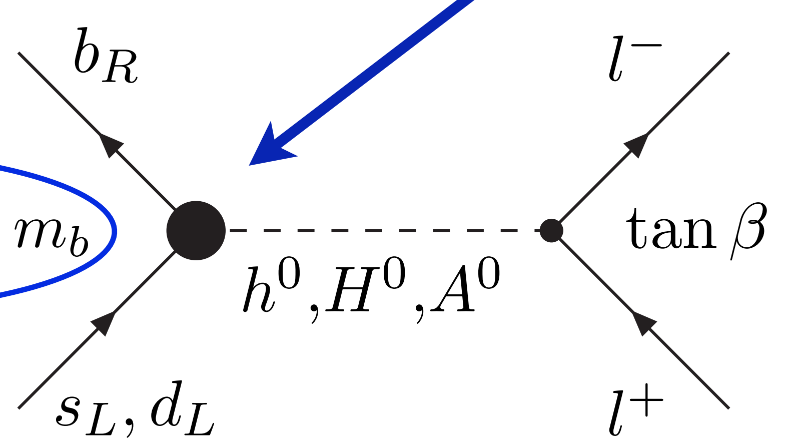
In MSSM, 3 neutral higgses, 2 vevs v_u, v_d

tan $\beta = v_u / v_d$

Yukawa becomes
flavour-violating

$V^*_{tb} V_{t(s,d)} \tan^2\beta\, m_b$

(for minimal
flavour violation)



$$BR(B_s \to \mu\mu) \propto \tan^6 \beta$$

[Choudhury&Gaur 99; Hamzaoui, Pospelov, Toharia 99; Babu, Kolda 99; Isidori, Retico; Buras et al 02; Foster et al 04-06,...]