Rencontres de Moriond

ELECTROWEAK INTERACTIONS and UNIFIED THEORIES

La Thuile, Valle d'Aosta, March 2-9, 2013

GIM mechanism: origin, predictions and recent uses

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CERN and Roma "La Sapienza"

1. LATE NINETEEN-SIXTIES...

...hopes of a basic theory for strong, e.m. and weak interactions

- well established results:
  - -Gell-Mann-Zweig quarks in 3 flavours (baryons=qqq, etc.)
  - -Cabibbo theory of semileptonic decays, ΔS=0,1:

$$q = \begin{bmatrix} u \\ d \\ s \end{bmatrix}$$

$$\mathcal{L}_F = \frac{G_F}{\sqrt{2}} J^\lambda J_\lambda^+$$

$$J^\lambda = \bar{\nu}_e \gamma^\lambda (1-\gamma_5) e + \bar{\nu}_\mu \gamma^\lambda (1-\gamma_5)\mu + \bar{u}\gamma^\lambda (1-\gamma_5) d_C$$

$$d_C = \cos\theta d + \sin\theta s$$

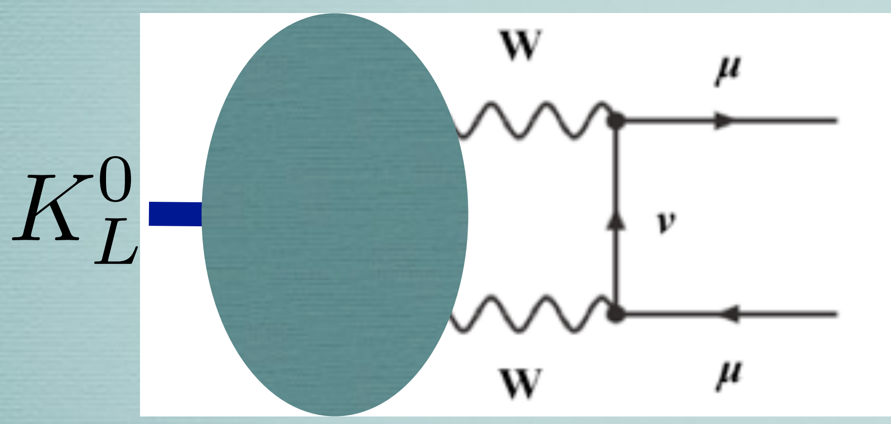
only one weak doublet:

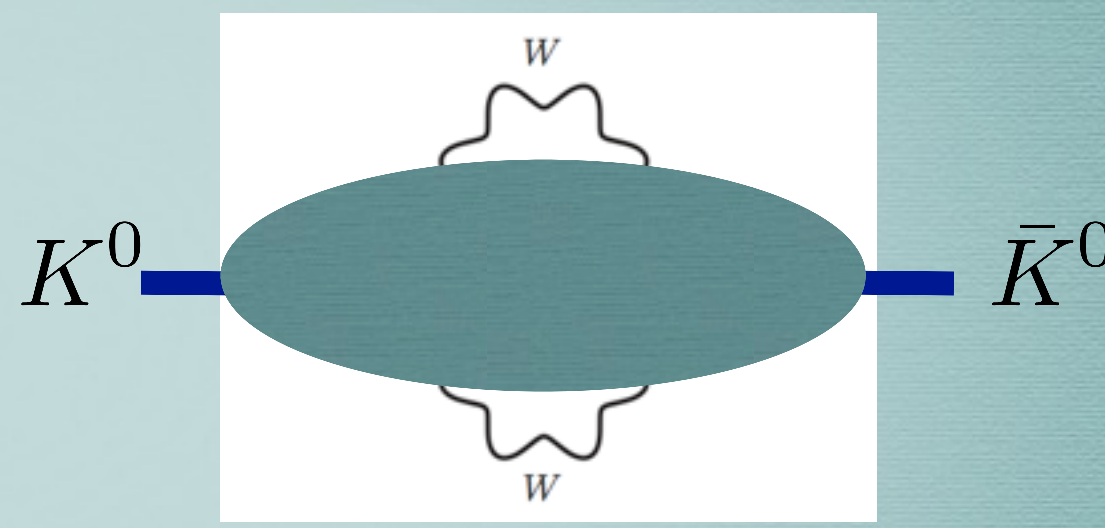
$$\begin{pmatrix} u \\ d_C \end{pmatrix}_L ; (s_C)_L ; d_R ; u_R ; s_R$$

- clouds:
  - -do quark clash with Fermi-Dirac statistics? first ideas about color (Han-Nambu)
  - -basic strong interactions: are they gluon (abelian) mediated? or string-like ?
  - -Fermi theory not renormalizable. W boson? strong interaction form factors?
- Schwinger ideas about EW unification+Yang-Mills
  - - Glashow's SU(2)⊗U(1) (1961)
  - - Brout-Englert-Higgs Mechanism (1965) -> Weinberg-Salam (1967)
- embedding Cabibbo theory in SU(2) ⊗ U(1) led to unobserved Flavor Changing Neutral Currents: Unification worked for leptons only.

THE GΛ² PUZZLE, 1968

- The discussion on higher order weak interactions was opened in 1968 by a calculation by Boris Ioffe and Evgeny Shabalin, indicating that $\Delta S = \pm 1$ neutral currents and $\Delta S=2$ amplitudes would result from higher order weak interactions, ***even in a theory with only the charged W***





- the amplitudes were found to be divergent, of order $G(G\Lambda^2)$, and in disagreement with experiments, unless limited by an ultraviolet cut-off $\Lambda \approx$ 3-4 GeV (from Δm_K);
- result based on current algebra commutators, shows hadron form factors are irrelevant: ***current commutators imply hard constituents***;
- Similar results were found by R. Marshak and coll. and by F. Low.

FIRST ATTEMPTS

- Attempts were made during 1968-69 to make the amplitude more convergent:
  - introducing more than one Intermediate Vector Boson (Gell-Mann, Low, Kroll, Ruderman) (too many were needed);
  - introducing negative metrics (ghost) states (T.D.Lee and G.C. Wick), of mass ≃ Λ!
- another line was to cancel the quadratic divergence, in correspondence to a specific value of the angle, i.e. “computing” the Cabibbo angle (Gatto, Sartori, Tonin; Cabibbo, Maiani);
- it was realised that quadratic divergent amplitudes at order $G\Lambda^2$ would also arise, in the IVB theory, with potential violations of strong interaction symmetries (parity, isospin, SU(3) and strangeness).
- C. Bouchiat, J. Iliopoulos and J. Prentki observed that, with chiral SU(3) ⊗ SU(3) breaking described by a (3,3bar) representation, the leading divergences give only diagonal contributions (no parity and strangeness violations).
- ...but the small cutoff in the $G(G\Lambda^2)$ terms still called for an explanation.

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Weak Interactions with Lepton-Hadron Symmetry*

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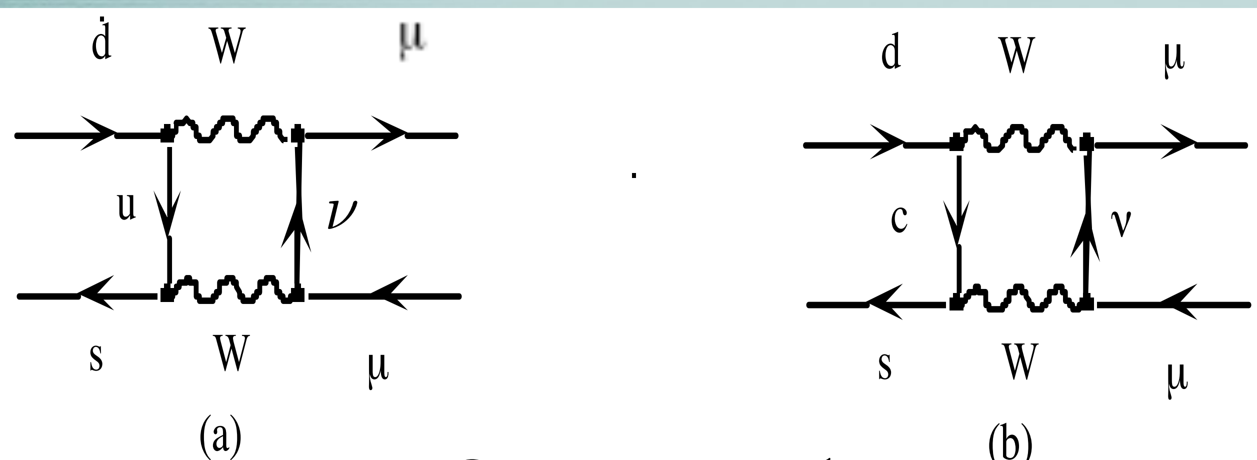
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Mills theory is discussed.



GIM proposal

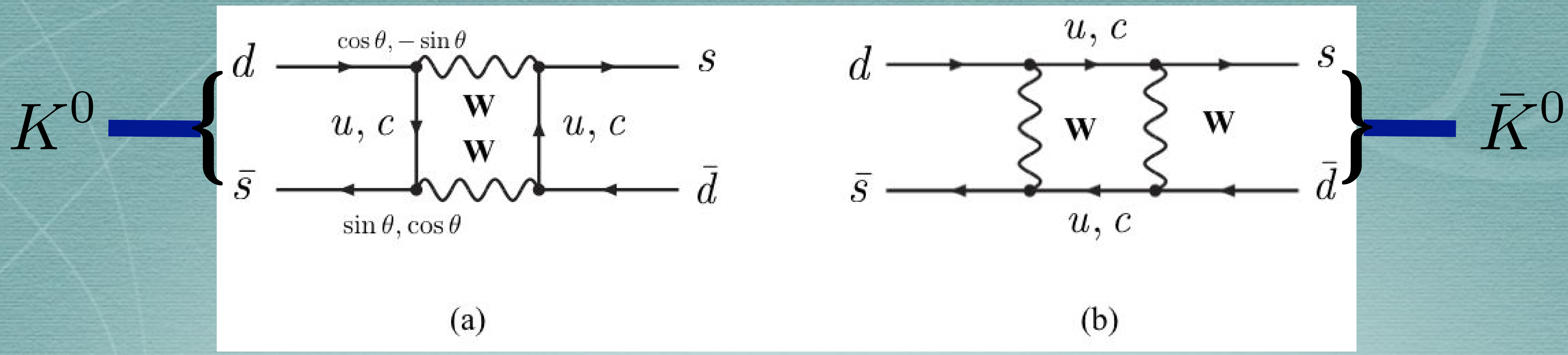
$$\begin{pmatrix} u \\ d_C \end{pmatrix}_L ; \begin{pmatrix} c \\ s_C \end{pmatrix}_L ; (d_C)_R; (s_C)_R; u_R; c_R$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L ; \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L ; e_R; \mu_R$$

$$J^W_\mu(quark) = \bar{q} C \gamma_\mu q_L$$

$$C = \begin{pmatrix} 0 & 0 & \cos\theta & \sin\theta \\ 0 & 0 & -\sin\theta & \cos\theta \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$ =quark ***mixing matrix***

divergent amplitude:
$\propto G(G\Lambda^2)[C,C^\dagger]$
= flavor diagonal!



- each quark line, which leads to ΔF≠ 0, carries a factor

$$\sum_{i=u,c} U^*_{si} S(k, m_i) U_{di} = \sin\theta\cos\theta\,[S(k,m_u) - S(k,m_c)]$$

quark propagator

since

$$\sum_{i=u,c} U^*_{si} U_{di} = 0$$

- the subtraction makes the integral convergent
- The result has to vanish for $m_c=m_u$
- the upshot is that one finds an amplitude of order $G[G(m^2_c-m^2_u)]$, i.e. Ioffe&Shabalin's result with:

$$\Lambda^2 \to m_c^2 - m_u^2 \approx (3-4\ \mathrm{GeV})^2$$

Ioffe&Shabalin's result has turned into a prediction of the charm quark mass, m_c=1.5-2 GeV !!

2. UNIFIED THEORY FOR QUARKS

•The matrices: $\mathcal{C},\ \mathcal{C}^\dagger,\ [\mathcal{C},\ \mathcal{C}^\dagger] = 2\mathcal{C}_3,$ and Q

$$\mathcal{C}_3 = \begin{pmatrix} 1/2 & 0 & 0 & 0 \\ 0 & 1/2 & 0 & 0 \\ 0 & 0 & -1/2 & 0 \\ 0 & 0 & 0 & -1/2 \end{pmatrix};\ Q = \begin{pmatrix} 2/3 & 0 & 0 & 0 \\ 0 & 2/3 & 0 & 0 \\ 0 & 0 & -1/3 & 0 \\ 0 & 0 & 0 & -1/3 \end{pmatrix}$$

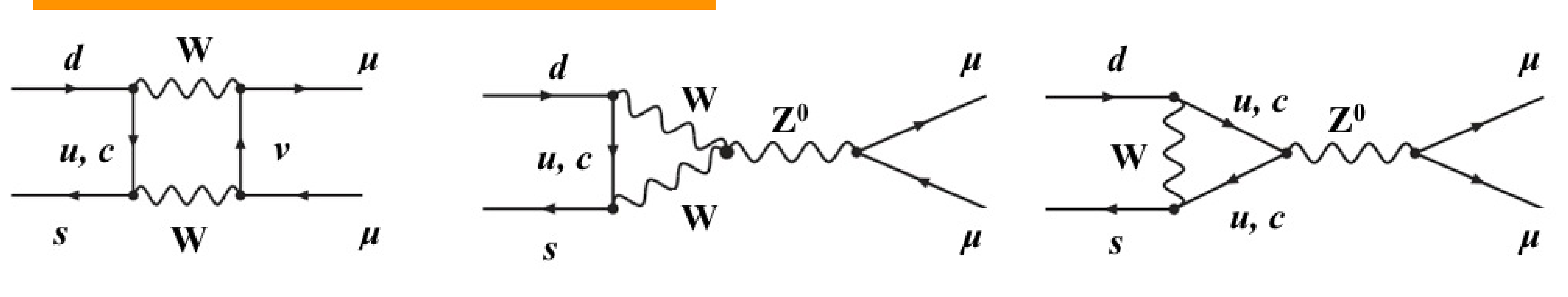
make an SU(2) ⊗ U(1) algebra without Flavor Changing Neutral Currents (FCNC) and can be taken as the generators of the unified Glashow-Weinberg-Salam theory of the Electroweak Interactions

•GIM: FCNC processes arise to order G^2

•UV divergences are cut-offed by heavy quark exchange; if there are no additional, long distance, contributions, amplitudes may be reliably computed, due to asymptotic freedom

heavy quarks in FCNC provide a tool to search for new physics at high energy

M. K. Gaillard, B. W. Lee, 1974



but there is a long-distance contribution from: $K_L \to \gamma\gamma \to \mu^+\mu^-$

FACTS AND PREDICTIONS FOLLOWING GIM

- Neutrino neutral current processes must exist

  -Flavour conserving, neutral current processes are indeed predicted, in W boson theory, or in Yang-Mills theory, to order G $[C,C^{\dagger}]$ = flavor diagonal;

  -in the unified theory, they appear in lowest order, mediated by Z^0

- In 1973, the Gargamelle bubble chamber collaboration at CERN observed muonless or electronless neutrino events soon recognised to be neutrino processes of the type $\nu(\bar{\nu}) + \mathrm{Nucleous} \rightarrow \nu(\bar{\nu}) + \mathrm{hadrons}$

  -strange particles (and, at higher energy, charmed particles) are pair produced, indicating flavour conservation in these abundant neutral current reactions.

- Quark-lepton symmetry.

  -Restoring quark-lepton symmetry was one of the basic motivations of the GIM paper and is at the basis of the partial cancellation of FCNC amplitudes.

  -quark-lepton symmetry is ***mandatory*** in the unified electroweak theory for the cancellation of the Adler-Bell-Jackiw anomalies, the last obstacle towards a renormalizable theory, as shown by C. Bouchiat, J. Iliopoulos and P. Meyer (fractionally charged and $SU(3)_{color}$ triplet quarks).

- CP violation ?

  -with 4 quarks in 2 doublets the weak coupling matrix U can be made real

  - already worried by the charm quark, GIM did not ask what would happen with even more quarks and failed to discover a simple theory of CP violation.

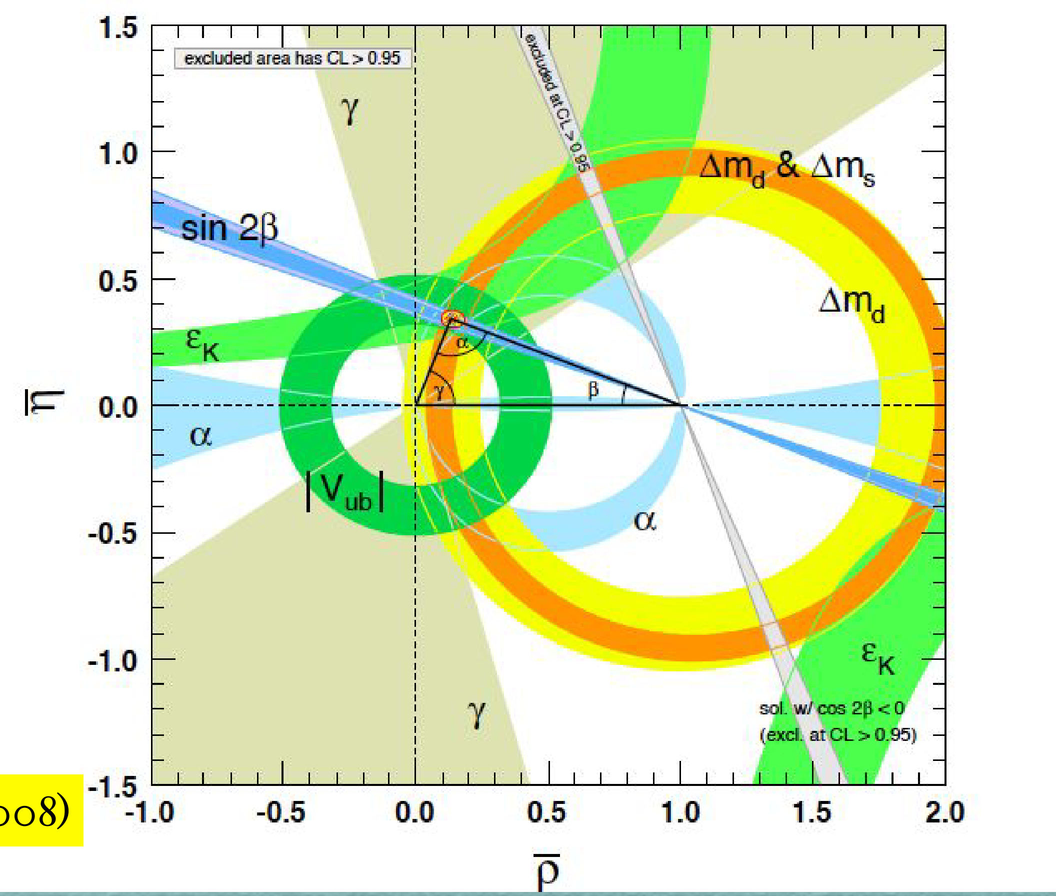
CP VIOLATION, IN BRIEF

- 1973, Kobayashi and Maskawa: three left-handed quark doublets allow for one CP violating phase in the quark mixing matrix, since known as the Cabibbo-Kobayashi-Maskawa matrix;
- the phase could agree with the observed CP violation in K decays and led to neutron electric dipole vanishing at one loop (Pakvasa & Sugawara, Maiani, 1976);
- 1986, I. Bigi and A. Sanda predict direct CP violation in B decay;
- 2001, Belle and BaBar discover CP violating mixing effects in B-decays.

Wolfenstein's parametrization

$$U_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3[1-(\rho+i\eta)] & -A\lambda^2 & 1 \end{pmatrix}$$

U_{CKM} is in an extraordinary agreement with data



C.-Amsler *et al.* [Particle Data Group Collaboration], Phys. Lett. B**667**, (2008)

CAN GIM MECHANISM SURVIVE IN THE PRESENCE OF STRONG INTERACTIONS ?

- One may suspect that strong interactions will spoil the cancellations at the basis of GIM;
- Preparata & Weisberger: the universality relations of weak interactions are preserved by strong interactions mediated by a neutral gluon
- ... but at that time people believed that strong interactions had to be described by dual models (introduced by G. Veneziano in 1968), there was room for suspicion.
- what seemed a simple curiosity (the PW theorem for the abelian gluon) became reality after the discovery of $SU(3)_{color}$ commuting with the EW group (eight gluons, all electrically neutral, anyway) and asymptotic freedom
- strong interactions, in leading order, renormalize quark EW parameters, i.e. masses and gauge couplings, and the strenght of non leptonic processes (but wait for A. Soni's talk) in a calculable way.

3. CHARM PRECURSORS

- Elementary particles in the Sakata model:

$$\begin{pmatrix} & p & \\ n & & \Lambda \end{pmatrix} \begin{pmatrix} & \nu & \\ e & & \mu \end{pmatrix}$$

- In 1962, after the discovery of the two neutrinos, Sakata et al. (Nagoya) and Katayama et al. (Tokyo) proposed to extend the model to a fourth baryon, called V^+:

$$\begin{pmatrix} p & V^+ \\ n & \Lambda \end{pmatrix} \quad \begin{pmatrix} \nu_1 & \nu_2 \\ e & \mu \end{pmatrix}$$

a possible mixing among ν_e and ν_μ was paralleled by n-Λ mixing a-la Cabibbo, giving rise to weak couplings of p and V^+ similar to the ones we have assumed for u and c.

- In 1964, Glashow and Bjorken proposed a 4th quark and invented the name "charm". The motivation was again lepton-quark symmetry and, in addition, they speculated that the charm quark was related to the meson φ(1020) and that it could give rise to hadrons below 1 GeV; weak couplings: u -> d_C and c -> s_C were assumed.

4. THE DISCOVERY OF CHARMED PARTICLES

•In 1970 there was no experimental evidence of weakly decaying hadrons beyond the lowest lying strange baryons and mesons.

•GIM's explanation: *...Suppose they are all relatively heavy, say 2 GeV.*

-*..will decay rapidly (10^{-13} sec) by weak interactions....into a very wide variety of uncharmed final states*

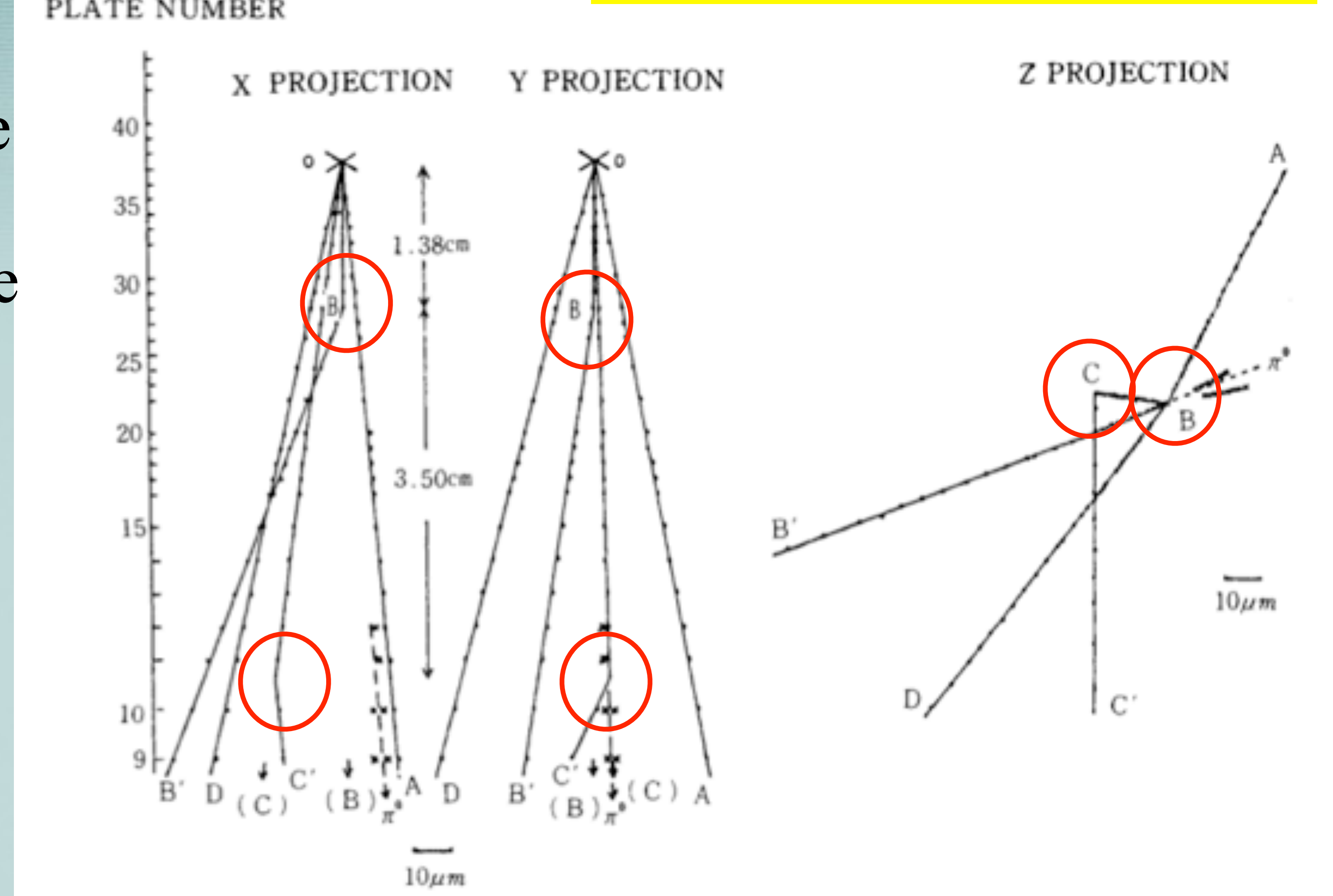
-*.....are copiously produced only in associated production, such events will necessarily be of very complex topology*

-*...Charmed particles could easily have escaped notice.*

CHARMED PARTICLES OBSERVATION

K.Niu, Proc. Japan Acad. B 84 (2008) 1

- In 1971, K. Niu and collaborators observed ***kinks*** in cosmic ray emulsion events, indicating unstable particles with lifetimes of order of 10^{-12} to 10^{-13} sec. These lifetimes are in the right ballpark for charmed particles and indeed they were identified as such in Japan.
- But cosmic rays events were paid not much attention in western countries.



The November Revolution

$$J/\Psi = c\bar{c} \text{ (3097 MeV)}$$

is discovered in 1974 by C. C. Ting and coll. (Brookhaven) and by B. Richter and coll. (SLAC); immediately after, was observed in Frascati.

$$D^0 = c\bar{u} \text{ (1865 MeV)}$$

the lightest weakly decaying charmed meson, D^0, is discovered by the Mark I detector (SLAC) in 1976.

The same year, Lederman and coll. discover the Υ=(b b-bar), the first evidence of the 3rd family

5. FCNC PROCESSES TODAY: STANDARD THEORY

$$M_{12}(\bar{K}^0 \to K^0) = < K^0| - \mathcal{L}_{eff}|\bar{K}^0 > = \frac{(G_F M_W^2)(G_F f_K^2)}{12\pi^2} \times \sum_{i,j=c,t} C_i C_j E(x_i, x_j) \times m_K$$

Loop factors, x=$(m_q/M_W)^2$ (Inami & Lim)

CKM factors-squared

•in ΔF=2 transitions for K and B, quark loops with d ➞ s, b transitions are dominated by c and t quarks,

•leading QCD corrections are calculable multiplicative renormalizations to loop amplitudes, and are reliable for t-quark-dominated loops

$$M_{12}(\bar{K}^0 \to K^0)|_{corr} = \frac{(G_F M_W^2)(G_F f_K^2)}{12\pi^2} \times$$
$$\times [\eta_1 C_c^2 E(x_c, x_c) + \eta_2 C_t^2 E(x_t, x_t) + 2\eta_3 C_c C_t E(x_c, x_t)] \times m_K \times B_K$$

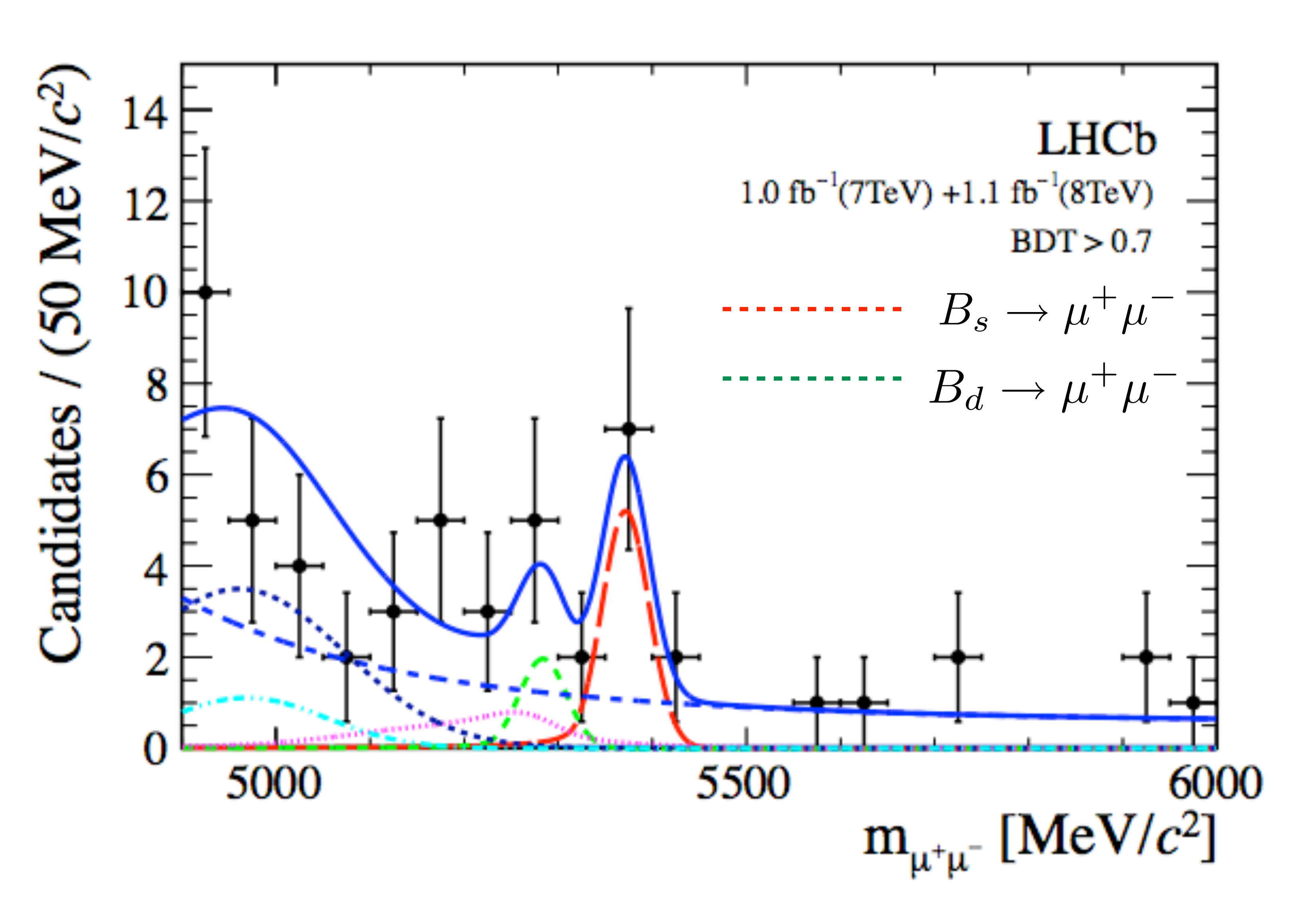
QCD corrections

•by comparison, ΔF=2 transitions for D-mesons are dominated by s and b quarks, but b is CKM suppressed much more than s and long-distance effects

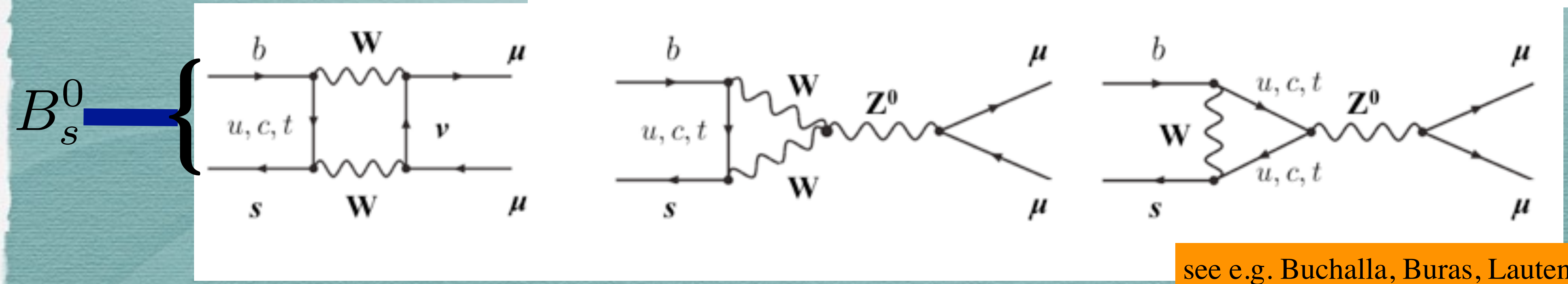
$$M_{12}(\bar{D}^0 \to D^0) = \frac{(G_F M_W^2)(G_F f_D^2)}{12\pi^2} \times \sum_{i,j=s,b} C_i C_j E(x_i, x_j) \times m_D$$

$$C_b \approx (\sin\theta_C)^5$$
$$C_s \approx (\sin\theta_C)$$

BREAKING NEWS FROM LHCB: $B_s \to \mu^+\mu^-$



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2\,^{+1.4}_{-1.2}(\text{stat})\,^{+0.5}_{-0.3}(\text{syst})) \times 10^{-9}$$



see e.g. Buchalla, Buras, Lautenbacher, 1995

COMPARISON OF ST WITH DATA

	$\lvert\epsilon_K\rvert$	Δm_K	$\lvert\Delta M(B_d^0)\rvert$	$\lvert\Delta M(B_s^0)\rvert$	$\lvert\Delta M(D^0)\rvert$	$Br(B_s \to \mu^+\mu^-)\rvert$
EW diagr.	$6.34\ 10^{-3}$	$3.12\ 10^{-12}$	$7.51\ 10^{-10}$	$294\ 10^{-10}$	$2.0\ 10^{-13} \cdot (\frac{m_s}{0.15GeV})^2$	$4.0\ 10^{-9}$
QCD corrcts	$2.65\ 10^{-3}$	$3.85\ 10^{-12}$	$4.13\ 10^{-10}$	$119\ 10^{-10}$	??	$(3.53 \pm 0.38)\ 10^{-9}$
expt	$2.228\ 10^{-3}$	$3.483\ 10^{-12}$	$3.34\ 10^{-10}$	$117.0\ 10^{-10}$	$(1.57 \pm 0.39)\ 10^{-11}$	$(3.2 \pm 1.4)\ 10^{-9}$

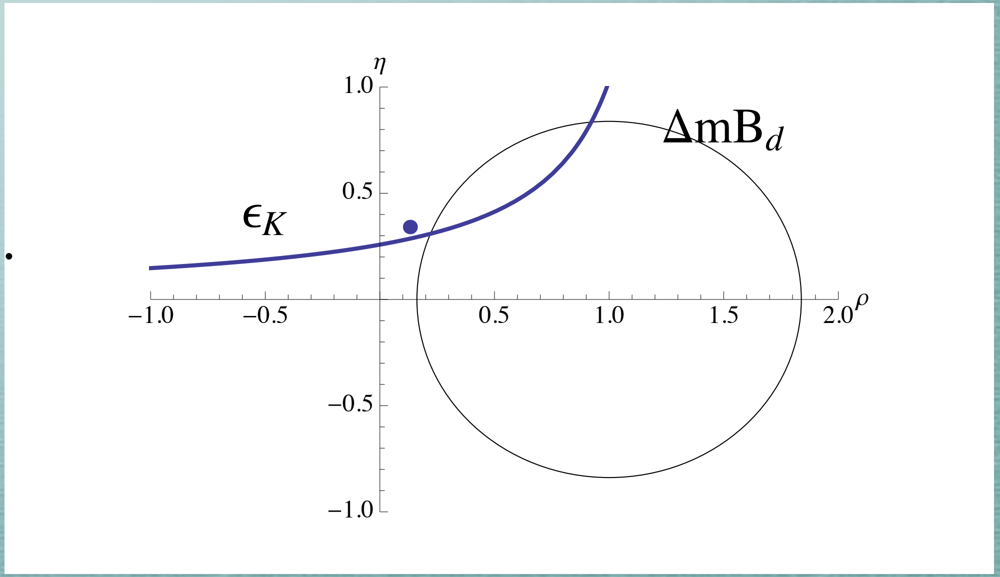
Table 1: Masses in MeV

dominated by the t-quark

dominated by the c-quark

Input data:
CKM coefficients (weak decays of s, c and b)
m_c=1.5, m_t=173, m_s=0.150, m_b=5.0

Simplified determination of the CKM coefficients ρ and η from the experimental values of $|\epsilon_K|$ and $|\Delta M(B_d^0)|$. The point corresponds to the values given in PDG



GIM MECH AND NEW PHYSICS AT TEV SCALE

•A light Brout-Englert-Higgs scalar boson in the ST calls for new physics (NP) at TeV scale: SUSY, Composite Higgs, etc.;

•the new particles most likely carry flavor and will potentially add new FCNC effects: this is the so-called *flavor problem*.

•let's write, for example,

$$\mathcal{L}_{eff}(d\bar{s} \to \bar{d}s) =$$

$$= -\frac{G_F^2 M_W^2}{16\pi^2} \times \sum_{i,j=c,t} (U_{id}^* U_{is})(U_{jd}^* U_{js}) E(x_i, x_j) \times \left(\bar{d}s\right)_{V-A} \left(\bar{d}s\right)_{V-A} +$$

← Standard Theory

$$+ \begin{pmatrix} +\frac{1}{\Lambda^2} \\ \\ +\frac{c_S}{\Lambda^2} \end{pmatrix} \left(\bar{d}s\right)_{S,P} \left(\bar{d}s\right)_{S,P}$$

← New Physics at larger scale ?

•|NP|<|ST| ➩ very large Λ

• or very small coefficient:

Operator	Bounds on Λ in TeV ($c_{NP} = 1$) Re	Bounds on Λ in TeV ($c_{NP} = 1$) Im	Bounds on c_{NP} ($\Lambda = 1$ TeV) Re	Bounds on c_{NP} ($\Lambda = 1$ TeV) Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $S_{\psi\phi}$
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	Δm_{B_s}; $S_{\psi\phi}$

Table 1.1: Bounds on representative dimension-six $\Delta F = 2$ operators, assuming an effective coupling c_{NP}/Λ^2.

•Isidori, 2012 CERN HEP Summer School, arXiv:1302.0661v1 [hep-ph]

GIM MECH AND NEW PHYSICS AT TEV SCALE

•NP cannot be couple to flavor generically; many insights and many interesting papers (see G. Isidori@CERN School 2012)

•Minimal Flavor Violation: *Yukawa couplings are the only source of flavor symmetry violation*

-Chivukula and Georgi, *Composite Technicolor Standard Model*, PL **B188** (1987)

-D'Ambrosio, Giudice, Isidori and Strumia, Minimal flavor violation: *An Effective field theory approach*, NP **B 645** (2002) 155 [hep-ph/0207036];

– applies to technicolor and/or SUSY

•Elementary fermions mixed with composite fermions:

-R. Contino, Y. Nomura, and A. Pomarol, Nucl.Phys. B671 (2003) 148, K. Agashe, R. Contino, and A. Pomarol, Nucl.Phys. B719 (2005) 165–187,

-see e.g. R. Barbieri et al. arXiv:1211.5085 [hep-ph]

•Are Yukawa couplings the VEVs of new fields? If so, Yukawa couplings can be determined by a variational principle, i.e. by the minimum of a new hidden potential

-an idea pioneered by Froggat & Nielsen, arXiv:hep-ph/9905445;

-recent applications to neutrino masses and mixing by B. Gavela and coll. (this Conference)

CMSSM, BOUNDS FROM $B_s \to \mu^+\mu^-$

Supersymmetric constraints from $B_s \to \mu^+\mu^-$ and $B \to K^*\mu^+\mu^-$ observables

F. Mahmoudi[1,2,*] S. Neshatpour[2,†] and J. Orloff[2,‡]

arXiv:1205.1845v1 [hep-ph]

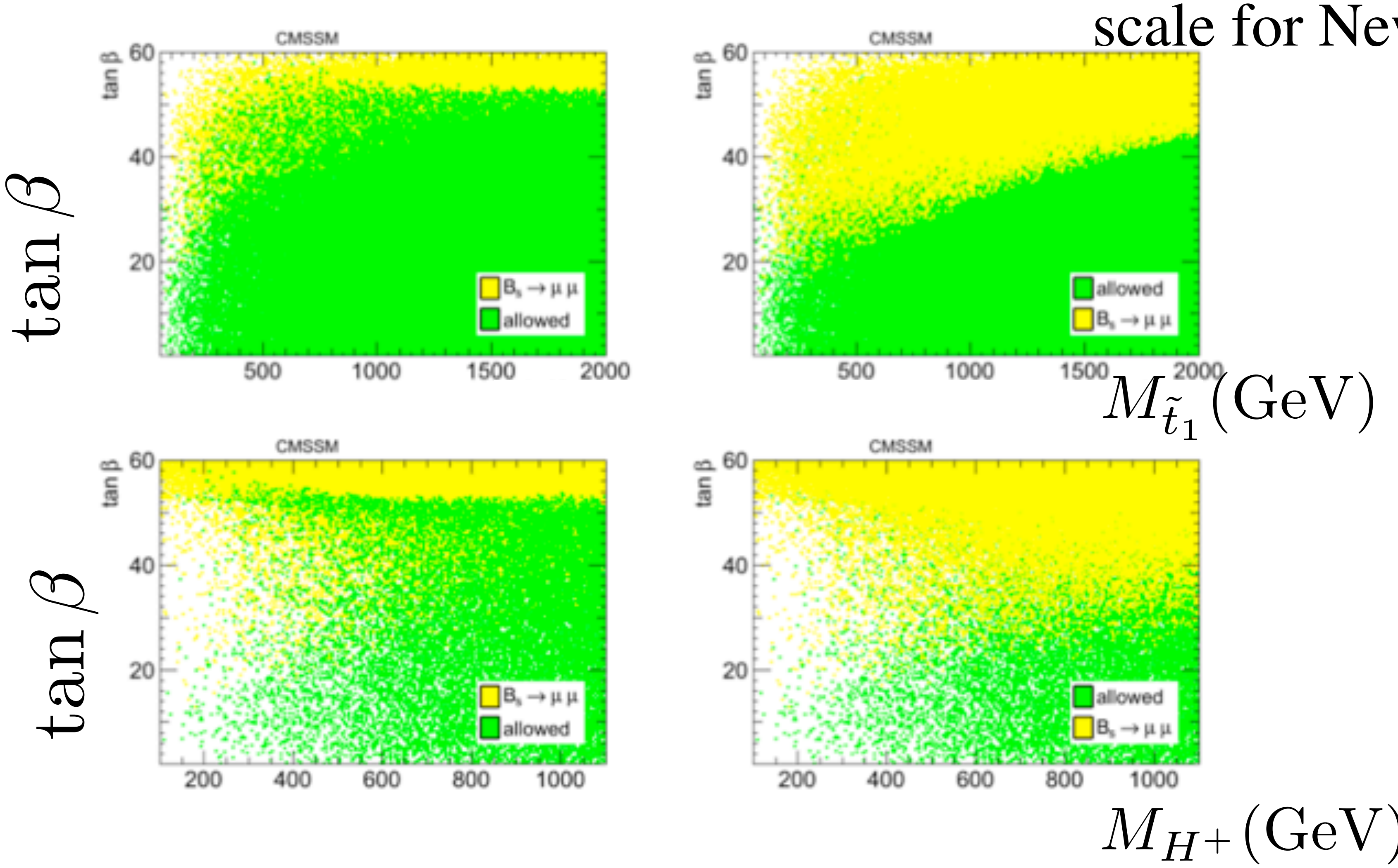


Figure 1: Constraint from BR($B_s \to \mu^+\mu^-$) in the CMSSM plane ($M_{\tilde{t}_1}$, $\tan\beta$) in the upper panel and ($M_{H^\pm}$, $\tan\beta$) in the lower panel, with the allowed points displayed in the foreground in the left and in the background in the right.

- The Constrained MSSM (CMSSM) is a SUSY model which satisfies the principles of Minimal Flavour Violation, thus the limits from FCNC are compatible with a relatively low energy scale for New Physics

A NEW VIEW OF YUKAWA COUPLINGS

- ST has a large global flavor group, commuting with the gauge group SU(3)xSU(2)xU(1)
- with 2 doublets of quark and leptons, Q_L, L_L, and 3 singlets, U_R, D_R, E_R, all in 3 generations, $\mathcal{G}$=U(3)^5
- MFV: Yukawa couplings are the sole source of $\mathcal{G}$ symmetry breaking, like quark masses in QCD....
- and preon masses in Tecnhicolor
  - -this was the idea of Georgi & Chivukula

$$\mathcal{L}_Y = \bar{Q}_L Y_D H D_R + \bar{Q}_L Y_U \tilde{H} U_R + \bar{L}_L Y_E H E_R \to$$
$$\to \mathcal{L}_{mass} = \left(\bar{D}_L M_D D_R + \bar{U}_L M_U U_R + \bar{E}_L M_E E_R\right)$$
$$M_D =< H_0 > Y_D, \text{ etc.}$$

One could speculate that Ys are VEVs... $Y_D = \frac{< \Phi_D >}{\Lambda}$ and the same for $Y_{U,E}$, etc.

and Φ couple to ST and NP particles in a way which is ***invariant under $\mathcal{G}$***.

Effects of NP at low energy which break flavor have to come with appropriate powers of <Φ> s, in line with Minimal Flavor Violation, and experiment, perhaps with small variations to be detected in precision experiments...

CONCLUSIONS

- Checking selection rules has been an effective way to guess new physics at higher energy;
- the suppression of $\Delta S=1,2$ neutral current processes led to the charm quark, CP violation to the third generation;
- several other processes, besides those considered here, may give useful information and are actively searched:

$$K^+ \to \pi^+ \nu\bar{\nu};\ K_L \to \pi^0 \nu\bar{\nu};\ B_d \to \mu^+\mu^-;\ b \to s\gamma;$$
$$\mu \to e\gamma;\ \mu + N \to e + \cdots$$

- the effectiveness of the GIM mechanism to describe the observed FCNC suppression gives already important restrictions on what may be the physics beyond ST;
- and gives insights on the nature of the Yukawa couplings and the breaking of the global flavor symmetry.