Flavour Theory (EPS 2009)

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Cracow, July 22nd, 2009

Good Afternoon !!

Overture

(A Novel Look at Short Distance Scales)

Frontiers of Elementary Particle Physics → **Search for Physics Laws at very short distance scales**

Heisenberg Principle : **To test 10^{-18} m we need E ≅ 200 GeV**

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LHC E ≈ 4 TeV → **Tests at $5 \cdot 10^{-20}$ m possible**

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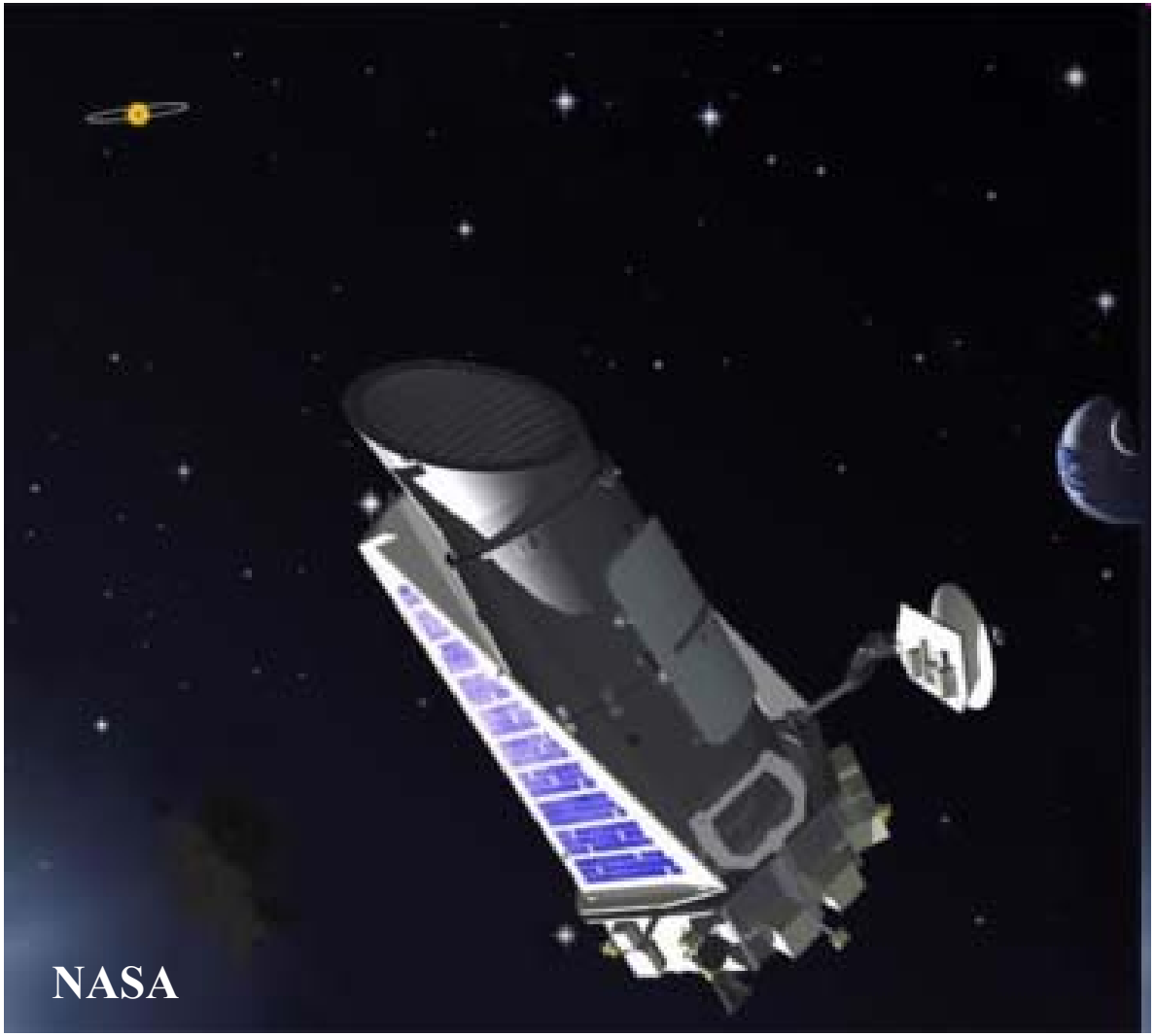
Flavour Physics governed by Quantum Fluctuations is sensitive to E ≈ 200 TeV and even higher energy scales → **Tests at 10^{-21} m and shorter scales possible** → **Frontiers in testing very very short distance scales belong to Flavour Physics**

but **Very high precision required !!**

Usual Picture of the Month

(CERN Courier)

Kepler Searching for new Planetary Systems and New Lifes

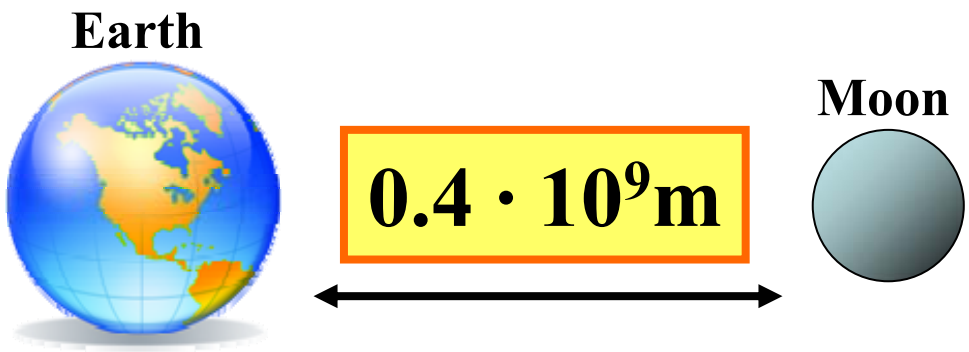


March 2009

Dual Picture of Short Distances

10^9m

3 light seconds



Dual Picture of Short Distances

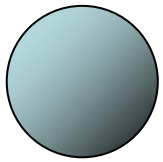
10^9m

3 light seconds

Earth

$0.4 \cdot 10^9$m

Moon



10^{18}m

105 light years

Dual Picture of Short Distances

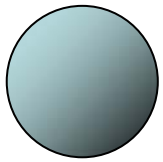
10^9m

3 light seconds

Earth

$0.4 \cdot 10^9$m

Moon



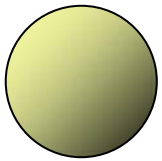
10^{18}m

105 light years

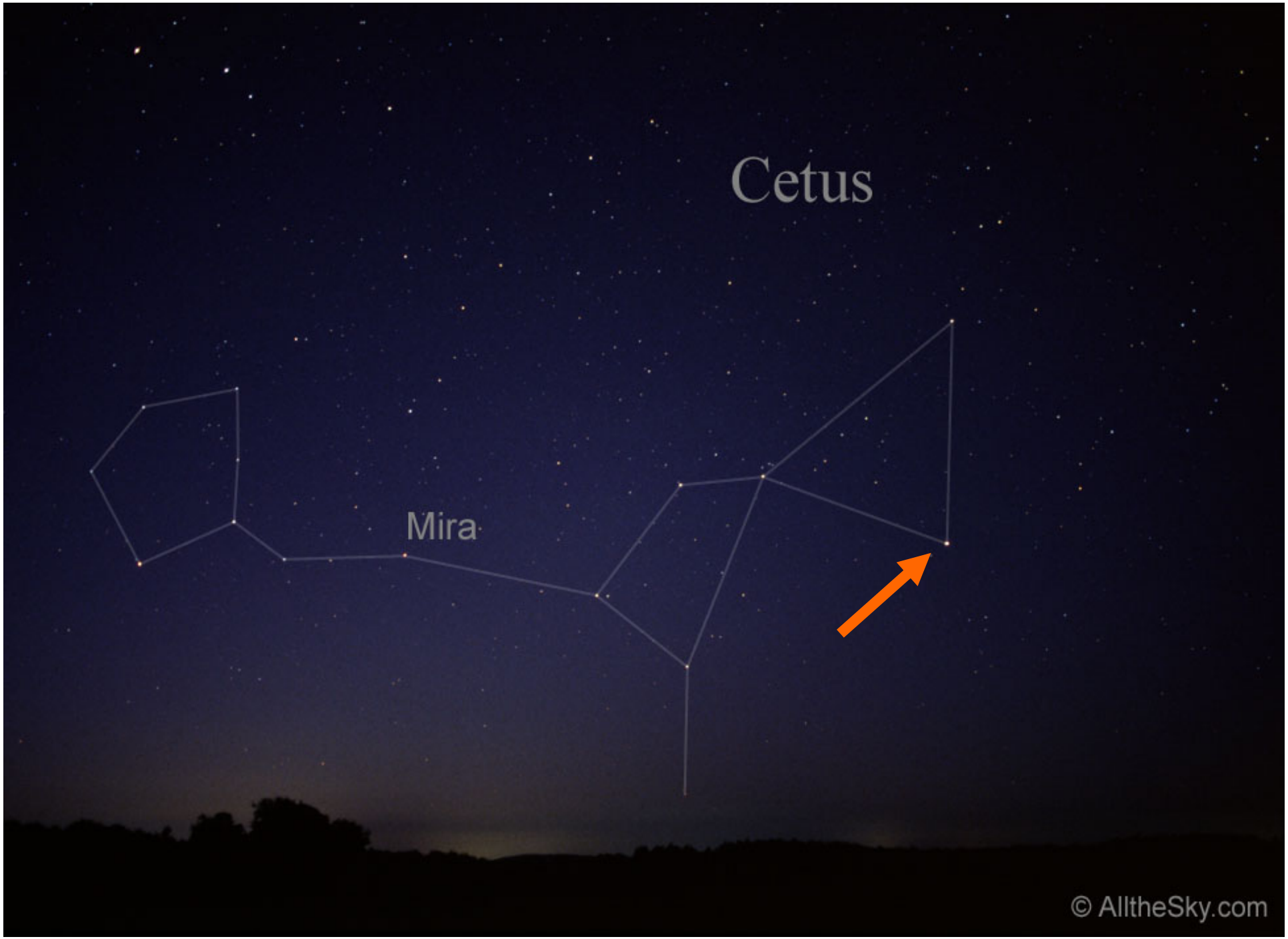
Earth

92 light years

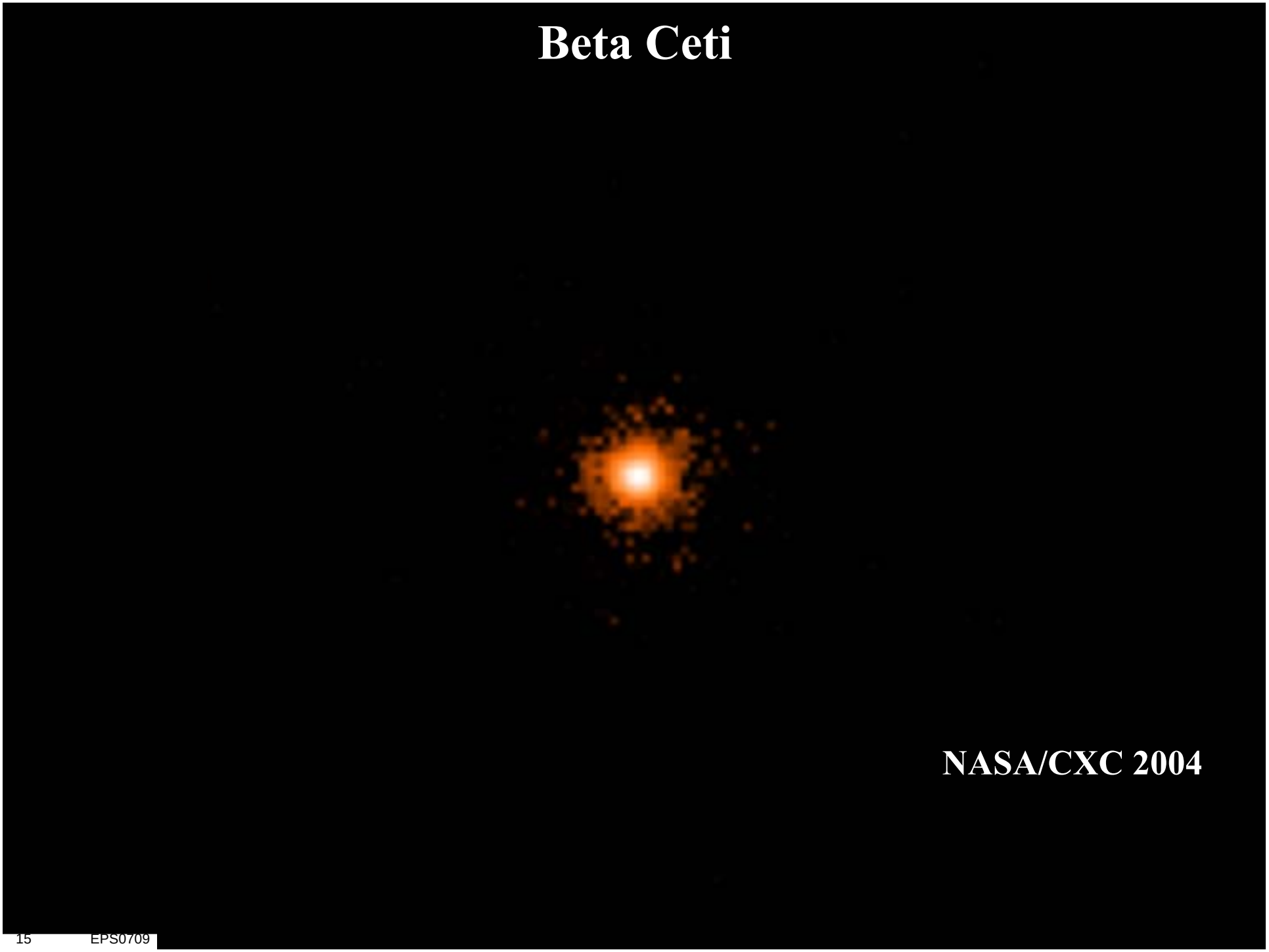
Beta Ceti

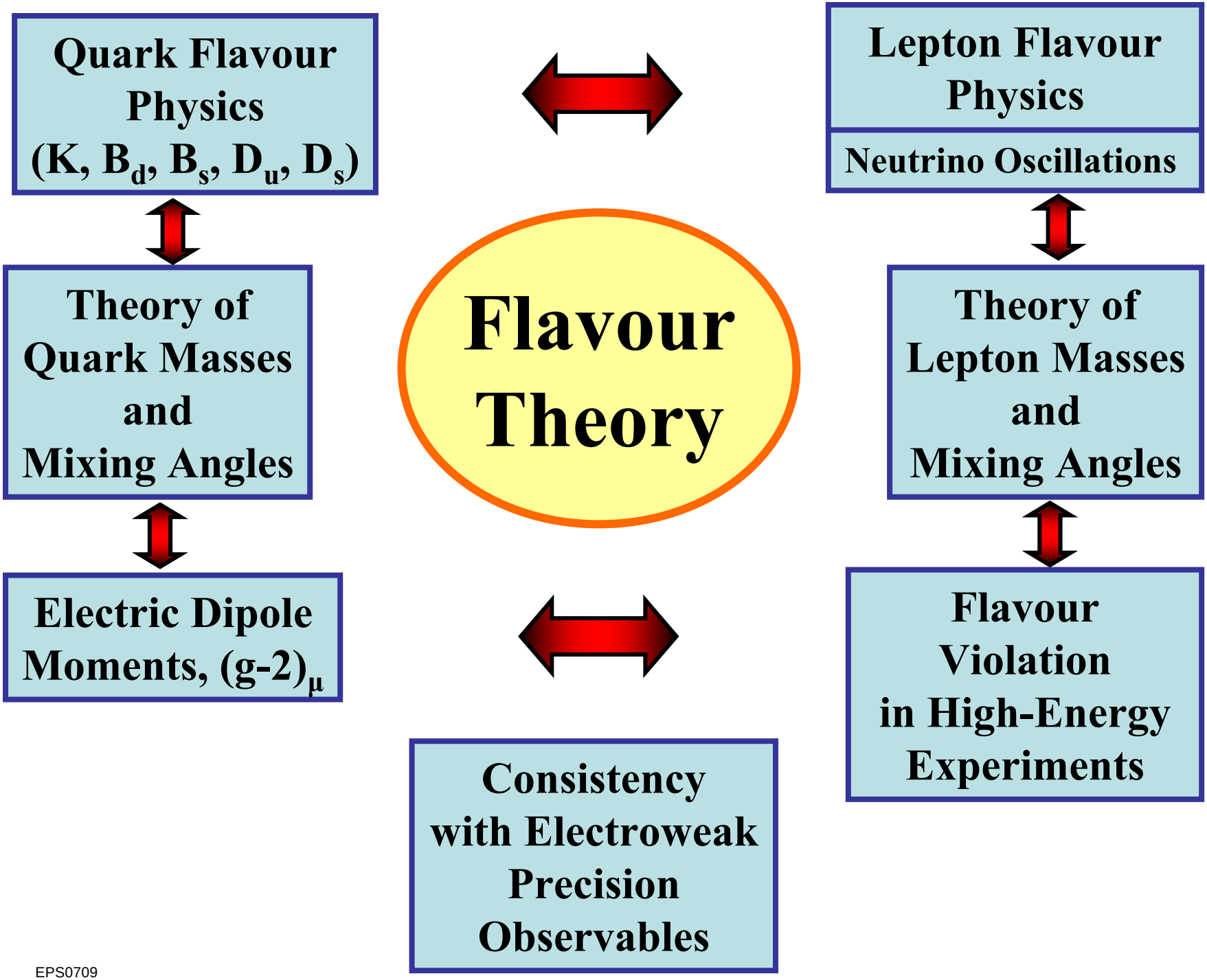


(in the constellation Cetus)


Cetus
Mira
© AlltheSky.com

Beta Ceti




Quark Flavour Physics
(K, B_d, B_s, D_u, D_s)
Theory of Quark Masses and Mixing Angles
Electric Dipole Moments, $(g-2)_\mu$
Lepton Flavour Physics
Neutrino Oscillations
Theory of Lepton Masses and Mixing Angles
Flavour Violation in High-Energy Experiments
Flavour Theory
Consistency with Electroweak Precision Observables

Impressive Success of the CKM Picture of Flavour Changing Interactions

(GIM)

Yet

1. Several tensions between the flavour data and the SM exist.

2. Hierarchies in Fermion Masses and Mixing Angles have to be understood with the help of some New Physics (NP).

3. There is still a lot of room for NP contributions, in particular in rare decays of mesons and leptons, in $\not{CP}$ flavour violating transitions and EDM´s.

Are 1. - 3. somehow related ?
Will we see any footprints of this NP in 2010´s ?

Strategy for the Next 36 Min ± Possible Tensions

1. **Theoretical Framework (~ 9 min)**

2. **20 Goals in Flavour Physics for the Next Decade (~ 5 min)**

3. **Waiting for Signals of New Physics in FCNC Processes (~ 20 min)**

4. **Final Messages (~ 2 min)**

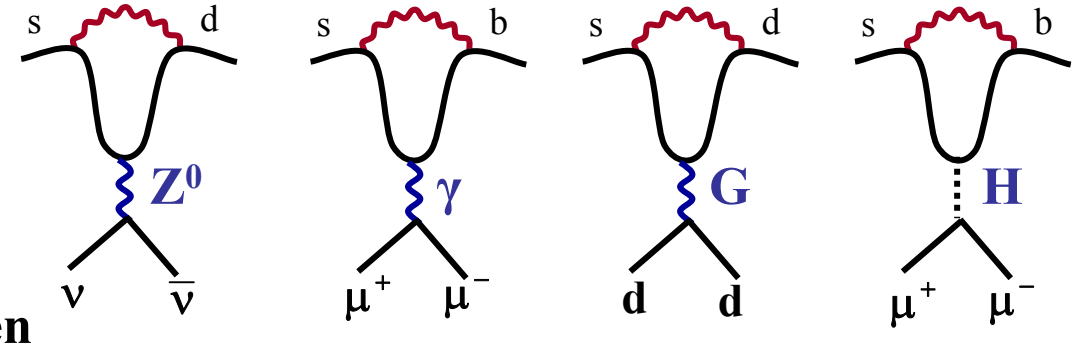
See also talks by G. Punzi, A. Bevian and A. Golutvin and parallel session talks

1.

Theoretical Framework

Basic Diagrams in FCNC Processes

Penguin Family :

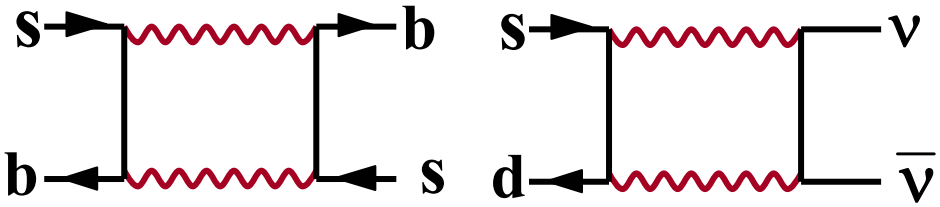


New Physics enters here

Similar diagrams in LFV and EDM´s

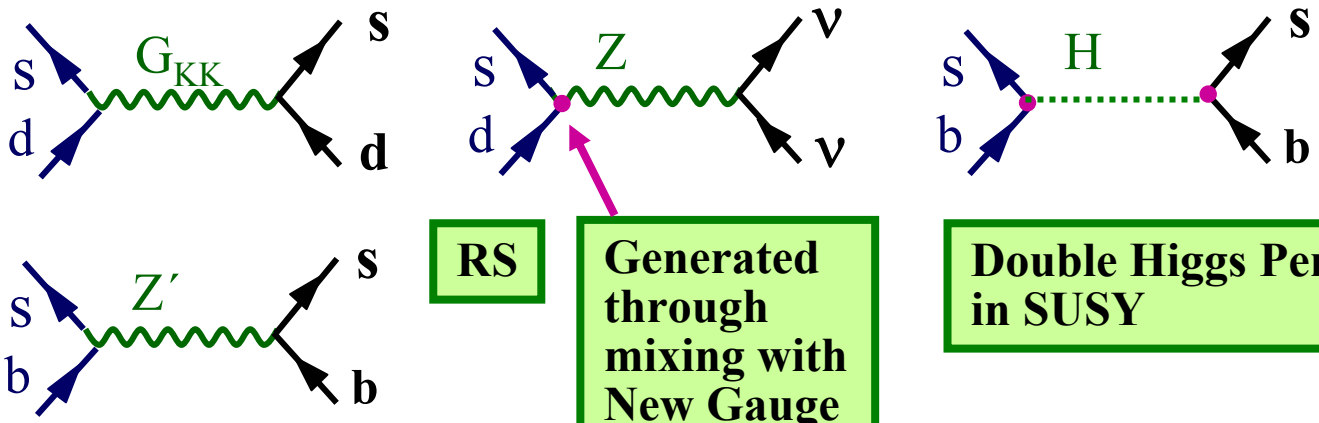
(GIM broken at one loop)

Box Diagrams



+ **other box diagrams**

Tree Diagrams



(GIM broken at tree level)

RS

Generated through mixing with New Gauge Bosons

Double Higgs Penguin in SUSY

Master Formula for FCNC Amplitudes

Long Distance (Non-perturbative Lattice)

Flavour and CPV in SM and MFV enters only here

Short Distance Functions (Perturbation TH)

(real for MFV)

$$A(\mathrm{FCNC}) = \sum_i B_i \eta_i^{QCD} V_i^{CKM} F_i(m_t, NP)$$

Renormalization Group (QCD) LD ↔ SD

Only Loops if GIM works

NP can add new B_i´s absent in SM

(New Operators with new Dirac Structures)

Q_{LR} (right-handed currents, S, P)

NP can add new loops and trees with new flavour parameters and CPV phases

non-MFV

Most popular BSM Directions

CMFV

(constrained MFV)

MFV

(NMFV)
(GMFV)

LHT

(Littlest Higgs
with T-parity)

SUSY

(flavour models)

Z′

(Langacker…)

RS

(Randall-Sundrum)
(Warped Extra Dimensions)

4th G

(Hou…, Soni…, Lenz…)

Vector-Like Quarks

(Branco…,
del Aguila)

Non-Decoupling

New gauge bosons, fermions, scalars in loops and even trees with often non-CKM interactions.

Little Hierarchy Problem

Electroweak Precision Tests

+

Agreement of the CKM Picture of Flavour and CP Violation with existing Data (FCNC)

$\Lambda_{NP} \approx 1000$ TeV (generic)

(generic)

$\Lambda_{NP} \approx 5$ TeV

Very strong Constraints on Physics beyond SM with scales O (1 TeV)

Necessary to solve the hierarchy problem

$(M_{PLANCK} >> \Lambda_{EW})$

Message 1 : **New Physics at TeV-Scale must have a non-Generic Flavour Structure**

Message 2 : **Protection Mechanisms to suppress FCNCs generated by TeV-Scale New Physics required**

★

Ciuchini et al
Isidori et al
Agashe et al
+50

MFV **GIM** **RS-GIM** **T-Parity** **R-Parity**

Alignment **Degeneracy** **Flavour Symmetries**

(abelian, non-abelian)

Custodial Symmetries

(continuous, discrete)

Minimal Flavour Violation (MFV)

MFV

SM Yukawa Couplings are the only breaking sources of the $SU(3)^5$ flavour symmetry of the low-energy effective theory

(Y_t, Y_b)

D´Ambrosio, Guidice, Isidori, Strumia (02) Chivukula, Georgi (87)

CKM the only source of Flavour Violation but for $Y_t \approx Y_b$ new operators could enter

~~CP~~ SM-like

CMFV

Operator structure of SM remains

VERY STRONG RELATIONS BETWEEN K and B Physics and generally $\Delta F=2$ and $\Delta F=1$ FCNC Processes

AJB, Gambino, Gorbahn, Jäger, Silvestrini (00)
Ali, London

Related Studies : Ratz et al (08)
Smith et al (08)
Zupan et al (09)

Spurion Technology

Nir et al.
AGIS
Feldmann, Mannel

also beyond MFV

Dominant New Flavour and CP Violating Interactions at $0(\mu_{NP})$

SUSY:

GIM

a) Misalignment of quark- and squark mass matrices, similarly for lepton sector

b) Effects enhanced at large $\tan\beta$: δ_{ij}^{AB}

Typical scales(200-1000 GeV)

LHT:

New flavour and CP violating mixing matrices in the interactions of SM fermions with mirror fermions mediated by W_H, Z_H, A_H

Typical scales (500-1000 GeV)

RS:

RS-GIM

New Heavy Gauge Bosons (KK)

New Heavy Vector-like Fermions (KK)

Tree Level FCNC´s mediated by KK Gluon ($\Delta F=2$) and Z($\Delta F=1$)

(Typical scales $M_{KK} \approx 2\text{-}3$ TeV)

Related to the explanation of hierarchies in masses and mixings

Battle in the Bulk to save RS with $M_{KK} \sim$ 2-3 TeV

"Warped Flavour"

Some fine tuning required

Blanke et al

Custodial Symmetries, Flavour Symmetries, etc.

(some related to EWPT, some related to FCNC´s)

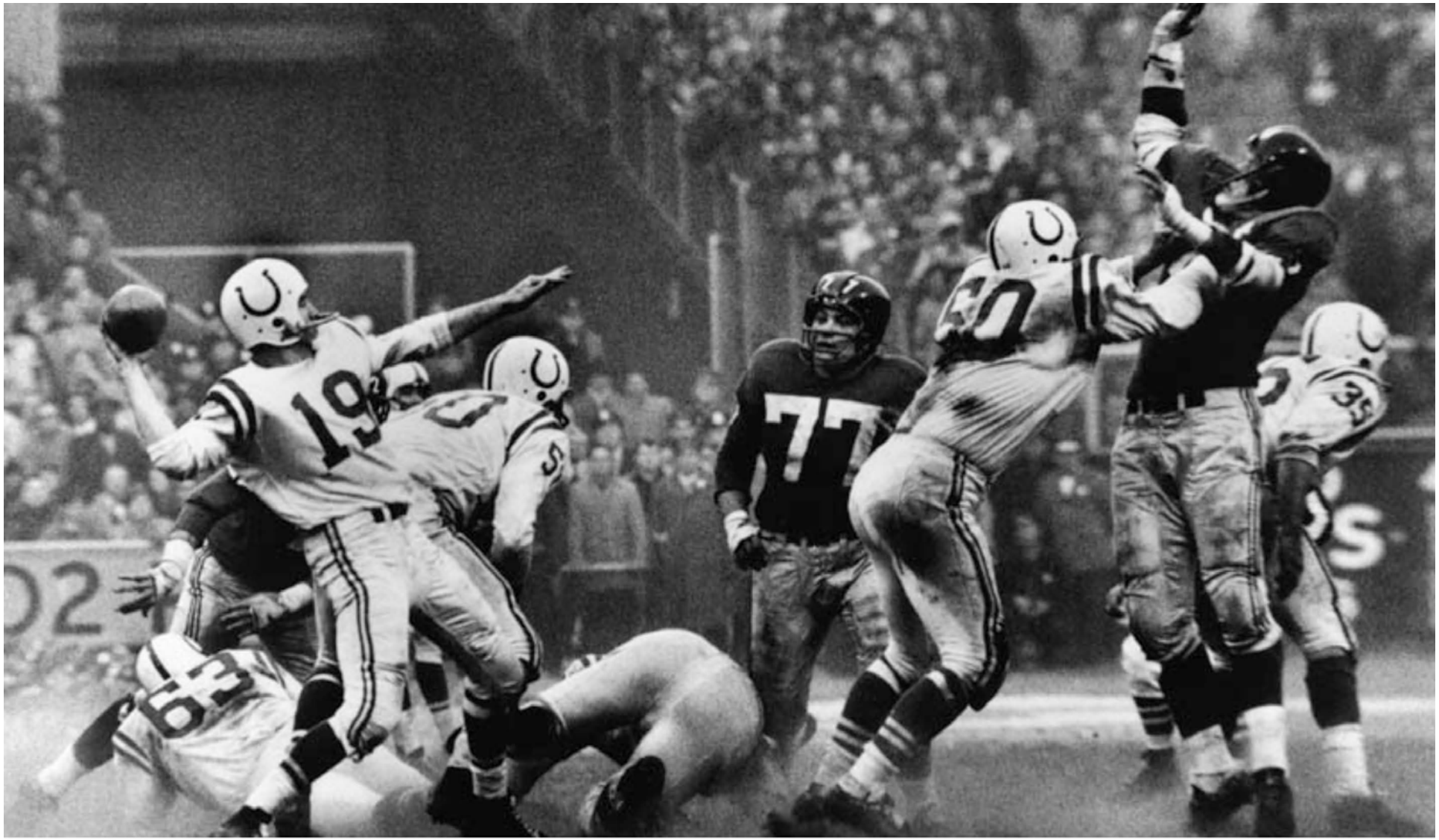
Ghergetta, Pomarol; Huber, Shafi (03)
Agashe, Delgado, May, Sundrum (03)
Csaki, Grojean, Pilo, Terning (03)
Agashe, Contino, Da Rold, Pomarol (06)
Agashe, Perez, Soni (06)
Cacciapaglia, Csaki, Weiler et al. (07)
Csaki, Falkowski, Weiler (08)
Fitzpatrick, Perez, Randall (07)
Santiago (08)
Casagrande, Goertz, Haisch, Neubert (08)
Blanke, AJB, Duling, Gori, Weiler (08)
Albrecht, Blanke, AJB, Duling, Gemmler (09)
AJB, Duling, Gori (09)
Csaki, Grossman, Perez, Surujon, Weiler (09)

Agashe, Azatov, Zhu (08)
Azatov, Toharia, Zhu (09)
Agashe, Contino (09)
Gedalia, Isidori, Perez (09)
Csaki, Curtin (09)

Q_{LR} and dipole operators most problematic

ε_K, $B \to X_s\gamma$, $\mu \to e\gamma$, d_n

ε'/ε



Quark flavor in RS: Overtime

Ulrich Haisch

2 x 2 Flavour Matrix of Basic NP Scenarios

(AJB, hep-ph/0101336, Erice)

	SM Operators	+ Additional Operators
CKM	**A** CMFV (Y_t) SM, 2 HDM at low tanβ LH without T-parity Universal flat ED	**B** MFV (Y_t,Y_b) MSSM with MFV 2 HDM at large tanβ
New Flavour (CP) Violating Interactions	**C** beyond CMFV LH with T-parity Some Z´-models 4th generation	**D** beyond MFV MSSM with $(\delta_{ij})_{AB}\neq 0$ RS, Other Z´models, LR Models, NMFV

2.

20 Goals in Flavour Physics for the Next Decade

1.

Determination of $|V_{us}|$, $|V_{cb}|$, $|V_{ub}|$ and γ from Tree Level Decays

2.

Improved Lattice Calculations of $F_{B_{s,d}}$, B_i -parameters

3.

Is ε_K (1964) consistent with $S_{\psi K_S} = \sin 2\beta$ (2001) within the SM?

4.

Is $S_{\psi\varphi}$ much larger than $\left(S_{\psi\varphi}\right)_{SM} \approx 0.035$?

($\not{C}\not{P}$ in $B_s \to \psi\varphi$) $\left(A^s_{SL}\right)$

5.

Clarification of few puzzles in Non-Leptonic Decays $\left(S_{\varphi K_S}, S_{\pi^o K_S}, \pi K, \ldots\right)$

(Fleischer,..Buchalla, Gronau, London, …)

6.

Discovery of $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$

7.

Improved TH+EXP

$B \to X_{s,d}\gamma$

$B \to K^*(\rho)\gamma$

$A_{CP}^{dir}(B \to X_s\gamma)$

(Misiak,…)

8.

$B \to X_s l^+ l^-$

$B \to K^* l^+ l^-$

in particular various angular observables (sensitive to NP)

(Hurth; Straub)

9.

$B^+ \to \tau^+ \nu$

$B^+ \to D^0 \tau^+ \nu$

$H^\pm$ effects in Tree Level Decays

(Hou…,Recksiegel,.. Isidori, …Westhoff,…)

10.

Rare K Decays

$K^+ \to \pi^+ \nu\bar{\nu}$

$K^0 \to \pi^o \nu\bar{\nu}$

$K_L \to \pi^o \mu^+ \mu^-$

$K_L \to \pi^o e^+ e^-$

(TH very clean, sensitive to NP)

11.

Rare B Decays

$B \to X_s \nu\bar{\nu}$

$B \to K^* \nu\bar{\nu}$

$B \to K \nu\bar{\nu}$

(Straub) (sensitive to right-handed currents)

12.

Lattice Calculations of Penguin hadronic matrix elements for ε'/ε (NA31, NA48, KTeV)

(Very sensitive to NP in the EW-Penguins)

13.

$\not{CP}$ in Charm Decays and

$D^+ \to l^+\nu$, $D_s^+ \to l^+\nu$

$D^0 \to \mu^+\mu^-$

(Bigi; Grossman,..Golowich.. Kronfeld)

14.

Search for $\not{CP}$ in the Lepton Sector and θ_{13}

(Feruglio,…Antusch,… Branco,…Hagedorn)

15.

Tests of μ-e, μ-τ universalities in $K^+ \to l^+\nu$, $B^+ \to l^+\nu$

(Isidori,…Paradisi, …)

16.

Lepton Flavour Violation

$\mu \to e\gamma$, $\tau \to \mu\gamma$, $\tau \to e\gamma$

$\mu \to 3e$, $\tau \to 3e$

$\tau \to 3\mu$

(Hisano,…Raidal,…)

17.

Electric Dipole Moments of neutron, leptons (d_n, d_e)

(Nagai, …Paradisi,…)

18.

Clarification of $(g-2)_\mu$ Anomaly

(Passera,…Jegerlehner, Czarnecki,…de Rafael)

19.

Tests of Flavour Violation in High Energy Processes

(Hiller, Nir,…)

19.

Tests of Flavour Violation in High Energy Processes

(Hiller, Nir,…)

20.

Construction of a New SM

19.

Tests of Flavour Violation in High Energy Processes

(Hiller, Nir,…)

20.

Construction of a New SM

21.

22.

23.

24.

3.

Waiting for Signals of New Physics in FCNC Processes

3.

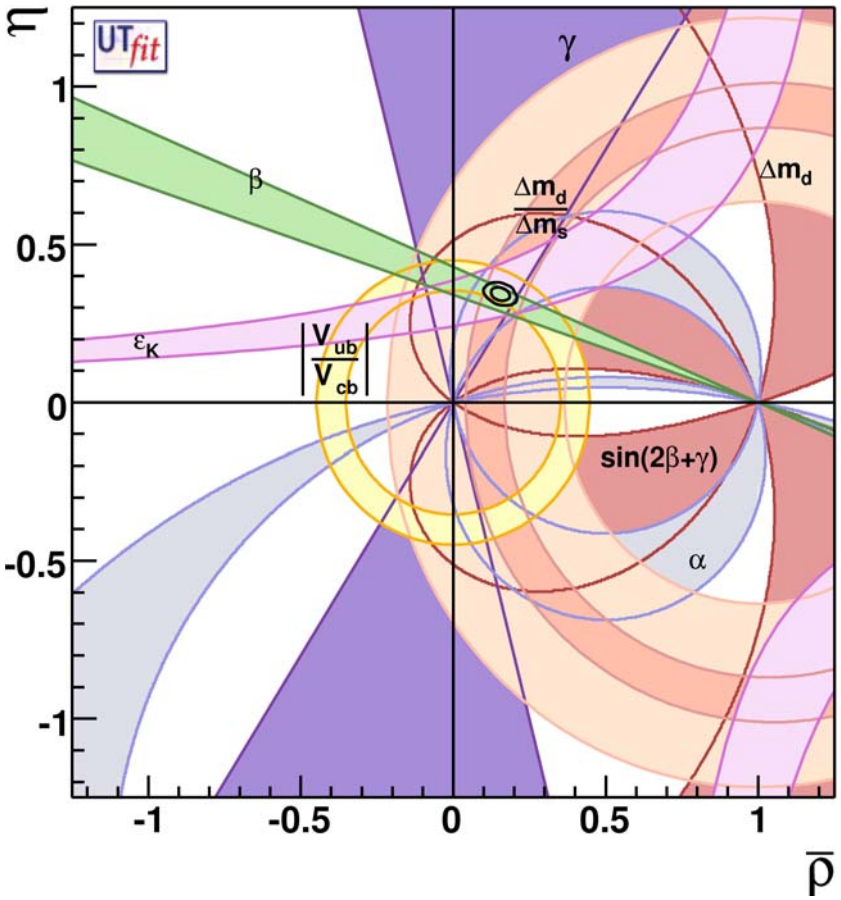
Waiting for Signals of New Physics in FCNC Processes

Many Thanks for inviting me to give this Talk !!

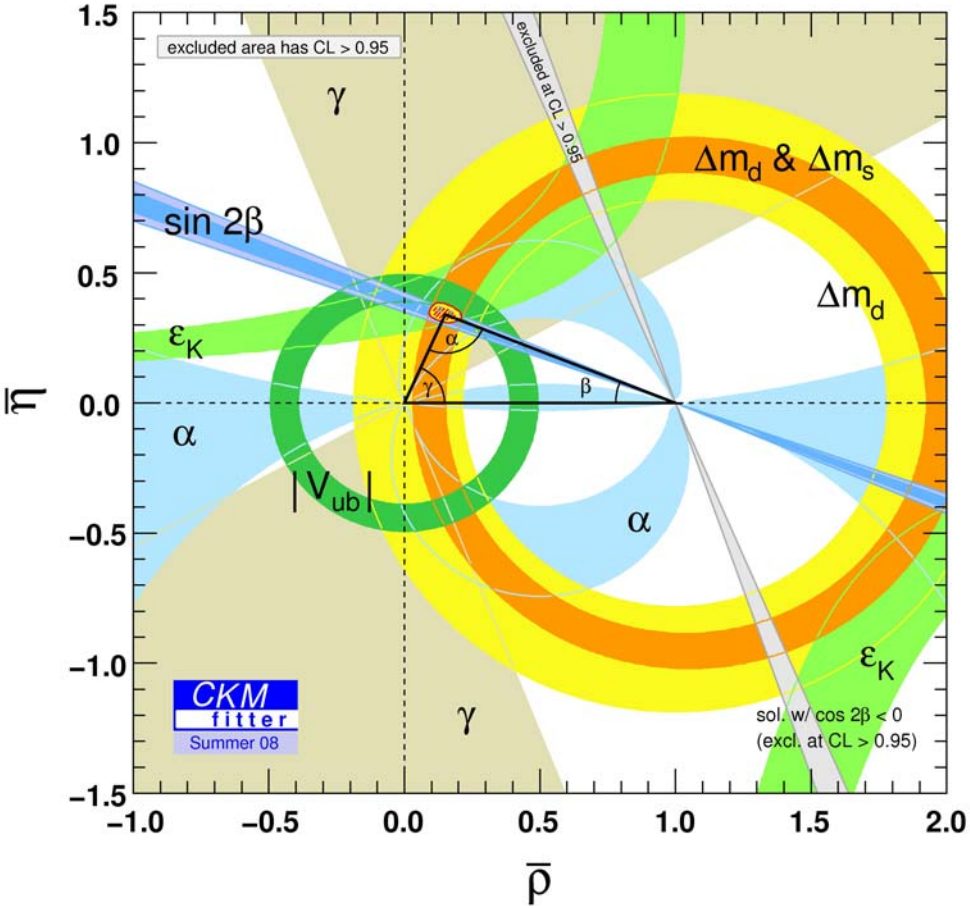
Unitarity Triangle Fits

(Icons of Flavour Physics)

UT fit



CKM fitter



Unitarity Triangle

(R_b, γ)
Reference UT
(Goto et al)

(coming decade)

$\alpha \overset{?}{=} 90°$

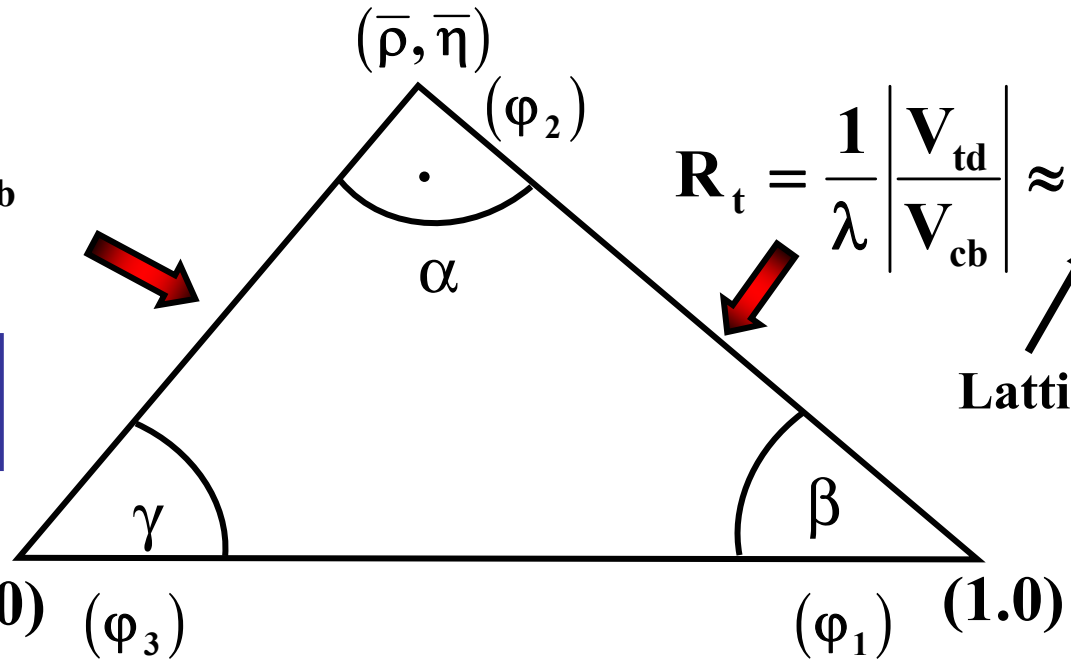
(this decade)

R_t, β
Universal UT
of CMFV
(BGGJS, BBGT)

$(\varphi_{NP}=0,\ r_{NP}=1)$

$$\frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right| \cong R_b$$

$$R_t = \frac{1}{\lambda}\left|\frac{V_{td}}{V_{cb}}\right| \approx \xi\sqrt{\frac{\Delta M_d}{\Delta M_s}}\, r_{NP}$$



Tree Level Determination
(NP free)

Lattice

$\xi = 1.21 \pm 0.04$

Loop Determination
(Not NP free)

Flavour Matrix

$\varphi_{NP} = 0$, $r_{NP} = 1$	$\varphi_{NP} = 0$, $r_{NP} \neq 1$
$\varphi_{NP} \neq 0$, $r_{NP} \neq 1$	$\varphi_{NP} \neq 0$, $r_{NP} \neq 1$

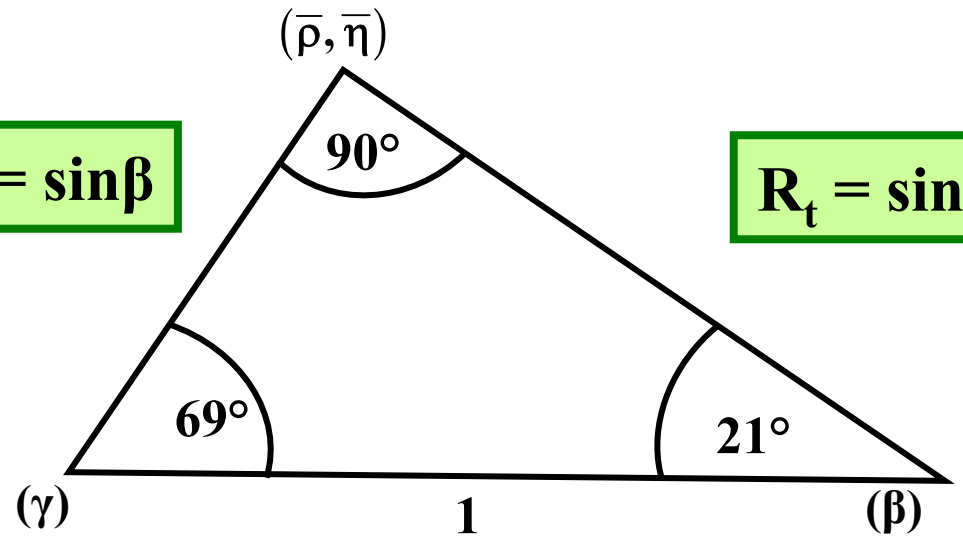
$$S_{\psi K_s} = \sin(2\beta + 2\varphi_{NP})$$

Unitarity Triangle in LO Approximation

$\alpha = 90°$ $\sin 2\beta = 2/3$

$R_b = \sin\beta$

$R_t = \sin(\alpha+\beta)$



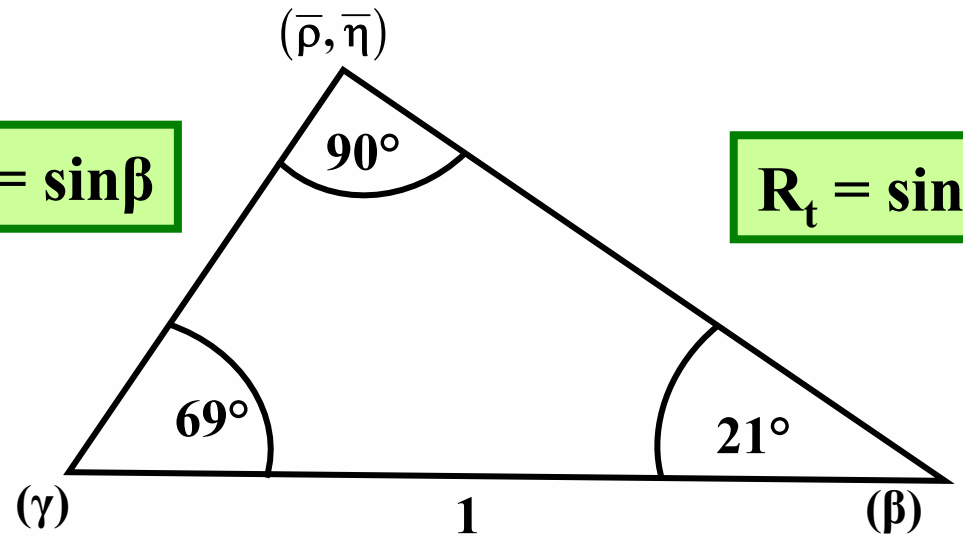
$\bar{\rho} = \sin\beta\cos\gamma$ $\bar{\eta} = \sin\beta\sin\gamma$

Unitarity Triangle in LO Approximation

$\alpha = 90°$ $\sin 2\beta = 2/3$

$R_b = \sin\beta$

$R_t = \sin(\alpha+\beta)$

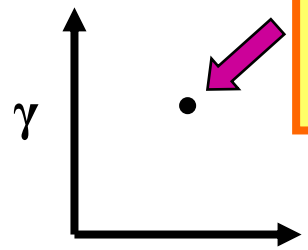


$\bar{\rho} = \sin\beta\cos\gamma$ $\bar{\eta} = \sin\beta\sin\gamma$

Search for New Physics in 2010´s

★ To study transparently possible tensions between ε_K, $\sin 2\beta$, V_{ub}, γ, $\Delta M_d / \Delta M_s$

Leave $(\bar{\rho}, \bar{\eta})$ plane → Go to



Tree level (NP free) Determination possible

$$R_b \sim \left|\frac{V_{ub}}{V_{cb}}\right|$$

★ To search for NP in rare K, B, B_s, D decays, $\not{C}\not{P}$ in B_s, D decays, Lepton Flavour Violations

Go to → **Specific Plots** (Correlations)

$Br(K_L \to \pi^0 \nu\bar{\nu})$ vs $Br(K^+ \to \pi^+ \nu\bar{\nu})$

$Br(B_s \to \mu^+\mu^-)$ vs $S_{\psi\varphi}$

$Br(B_s \to \mu^+\mu^-)$ vs $Br(B_d \to \mu^+\mu^-)$

$Br(K^+ \to \pi^+ \nu\bar{\nu})$ vs $S_{\psi\varphi}$

d_n vs $S_{\varphi K_s}$

$A_{CP}(B \to X_S \gamma)$ vs $S_{\varphi K_s}$

$Br(\tau \to \mu\gamma)$ vs $\Delta(g-2)_\mu$

$Br(\tau \to \mu\mu\mu)$ vs $Br(\tau \to \mu\gamma)$

$Br(\mu \to 3e)$ vs $Br(\mu \to e\gamma)$

★ Correlations will be crucial to distinguish various NP scenarios

Can SM describe simultaneously $\not{C}\not{P}$ in K and B_d Systems?

$$|\varepsilon_K|^{SM} \sim \kappa_\varepsilon \hat{B}_K |V_{cb}|^2 \left(\frac{1}{2} |V_{cb}|^2 R_t^2 \sin 2\beta \underbrace{\eta_{tt}^{QCD}}_{\text{BJW (90)}} S_0(x_t) + F\left(\underbrace{\eta_{ct}^{QCD}, \eta_{cc}^{QCD}}_{\text{HN (94)}}, m_c, .. \right) \right)$$

(NLO) (NLO)

2009 News

★ $\hat{B}_K \cong 0.72 \pm 0.03$ (precise and lower by ~ 10% vs 2007)

★ $\kappa_\varepsilon \cong 0.92 \pm 0.02$ (correction neglected in the past)

RBC-UKQCD
Aubin et al.
ETMC

AJB + Guadagnoli (08)
(Nierste; Vysotsky)

Large N
$\hat{B}_K = 0.75$
BBG (87)

★ NNLO QCD calculation of η_{cc}, η_{ct} Brod + Gorbahn (09)

(BG) $|\varepsilon_K^{SM}| = (1.80 \pm 0.22) \cdot 10^{-3}$ $|\varepsilon_{exp}| = (2.223 \pm 0.012) \cdot 10^{-3}$

(BaBar Belle) using $(\sin 2\beta)_{\psi K_s} = 0.672 \pm 0.023$ (NA48, KLOE, KTeV)

Possible Solutions to ε_K - Anomaly

$$|\varepsilon_K|^{SM} \sim \kappa_\varepsilon \hat{B}_K |V_{cb}|^2 \left(\frac{1}{2} |V_{cb}|^2 R_t^2 \sin 2\beta \eta_{tt}^{QCD} S_0(x_t) + F\left(\eta_{ct}^{QCD}, \eta_{cc}^{QCD}, m_c, ..\right) \right)$$

1. Add New Physics to ε_K

CMFV $S_0(x_t) \to S_0(x_t) + \Delta S_0^{NP}$ or simply $\Delta\varepsilon_k$ (Non-MFV)

AJB
Guadagnoli

2. Increase $\sin 2\beta \cong 0.67 \Rightarrow 0.85$

$S_{\psi K_s} = \sin(2\beta + 2\varphi_{NP})$

(Utfit; BBGT; Ball, Fleischer; Branco et al)

$\varphi_{NP} \cong -8.1^o$

Large $|V_{ub}|$ ⟷ Super-B

Lunghi
Soni

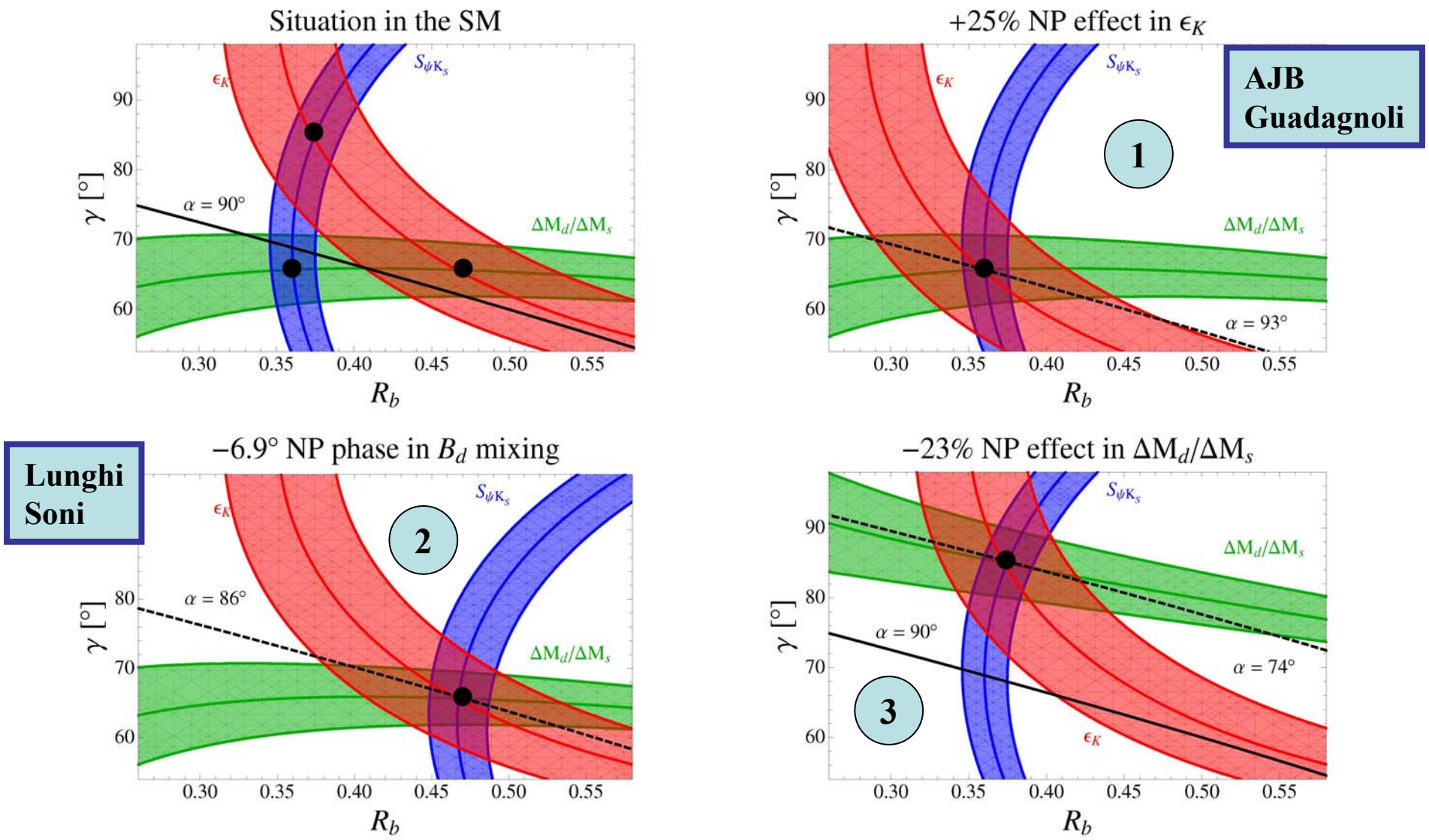
3. Increase R_t ➡ $\gamma = \delta_{CKM} \approx 67^o \Rightarrow 82^o$ ⟷ LHC

4. Increase $|V_{cb}| \approx (41.2 \cdot 10^{-3}) \Rightarrow (43.5 \cdot 10^{-3})$ ⟷ Super-B

AJB, Parodi, Stocchi (2002)
Altmannshofer, AJB, Guadagnoli (2007)

The R_b-γ Plane

Altmannshofer, AJB, Gori, Paradisi, Straub (2009)



$K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ (Z°-penguins)

(TH cleanest FCNC decays in Quark Sector)

Extensive TH efforts over 20 years :

Buchalla, AJB; Misiak, Urban (NLO QCD)
AJB, Gorbahn, Haisch, Nierste (NNLO QCD)
Brod, Gorbahn (QED, EW two loop)
Isidori, Mescia, Smith (several LD analyses)
Buchalla, Isidori (LD in $K_L \to \pi^0 \nu\bar{\nu}$)

$$\frac{Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)}{Br\left(K_L \to \pi^0 \nu\bar{\nu}\right)} = 3.2 \pm 0.2$$

SM :

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(8.4 \pm 0.7\right) \cdot 10^{-11}$$

$$Br\left(K_L \to \pi^0 \nu\bar{\nu}\right) = \left(2.6 \pm 0.4\right) \cdot 10^{-11}$$

Exp :

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(17^{+11}_{-10}\right) \cdot 10^{-11}$$

(E787, E949 Brookhaven)

$$Br\left(K_L \to \pi^0 \nu\bar{\nu}\right) \leq 6.8 \cdot 10^{-8}$$

(E391a, KEK)

Future :

NA62
Project X (FNAL)

Both very sensitive to New Physics

J-PARC KOTO

CP-conserving
TH uncertainty 2-3%

CP-Violation in Decay
TH uncertainty 1-2%

Maximal Enhancements of $K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$

Model independent bound

$$Br\left(K_L \to \pi^0 \nu\bar{\nu}\right) \le 4.4\ Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)$$

Grossman Nir

Model	$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)$	$Br\left(K_L \to \pi^0 \nu\bar{\nu}\right)$	
CMFV	20%	20%	(Bobeth et al Haisch, Weiler Isidori et al)
MFV	30%	30%	
LHT	200%	300%	(Blanke et al)
RS	100%	200%	(Duling et al)
GMSSM	300%	500%	
AC	2%	2%	(ABGPS)
RVV	10%	10%	

SUSY with flavour symmetries

(abelian)

(non-abelian)

Large RH Currents

RC = RC with custodial protections

AC = Agashe, Carone

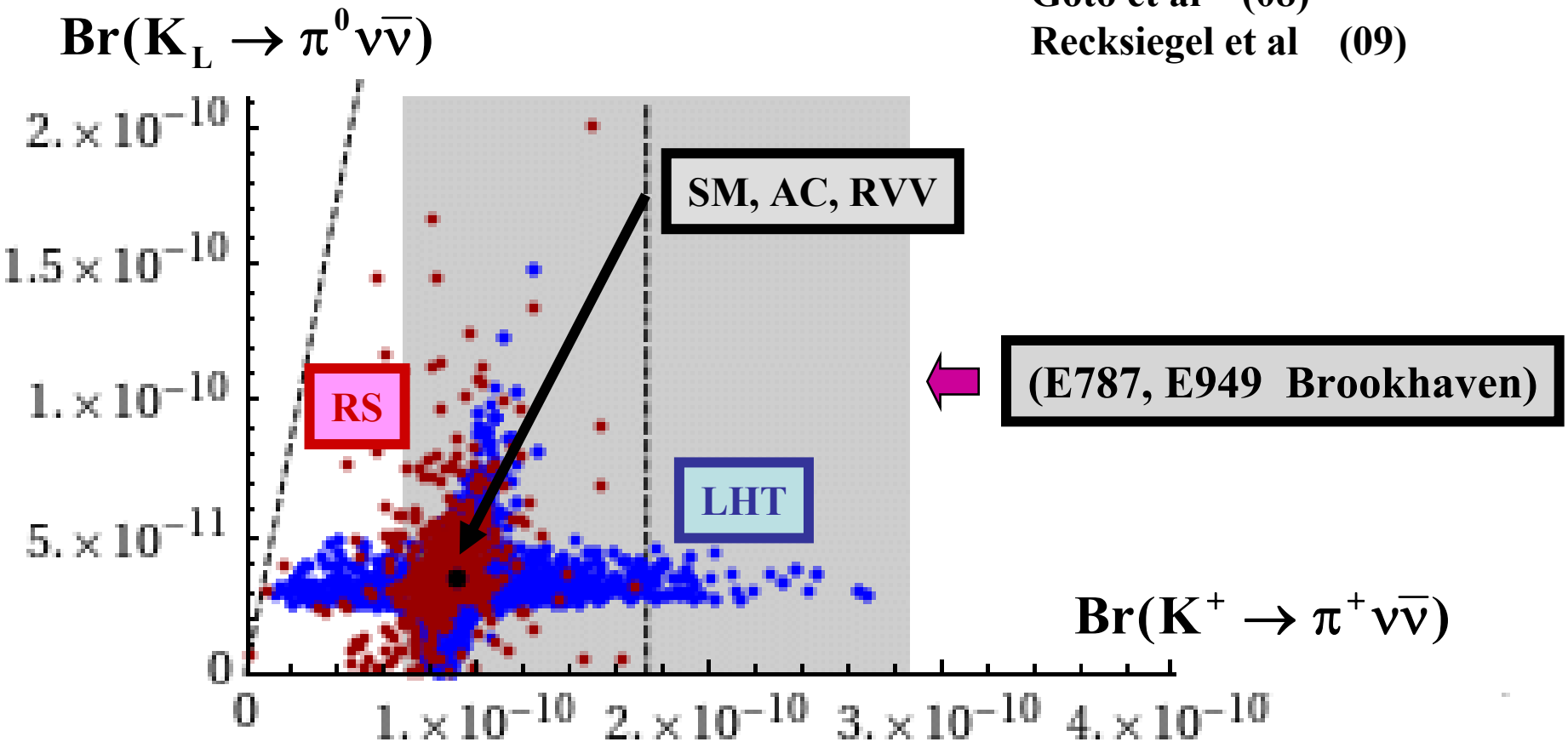
RVV = Ross, Velaso-Sevilla, Vives (04)

$U(1)_F$

$SU(3)_F$

$K_L \to \pi^0 \nu\bar{\nu}$ vs. $K^+ \to \pi^+ \nu\bar{\nu}$

Blanke et al (08)
Goto et al (08)
Recksiegel et al (09)



$B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$

Z-Penguin (SM + Boxes CMV)

SM

$$Br(B_s \to \mu^+\mu^-) = (3.6 \pm 0.4)\cdot 10^{-9}$$
$$Br(B_d \to \mu^+\mu^-) = (1.1 \pm 0.1)\cdot 10^{-10}$$

Error dominated by $\hat{B}_{d,s}$

AJB (03)

CMFV "Golden Relation"

$$\frac{Br(B_s \to \mu^+\mu^-)}{Br(B_d \to \mu^+\mu^-)} = \frac{\hat{B}_d}{\hat{B}_s}\frac{\tau(B_s)}{\tau(B_d)}\frac{\Delta M_s}{\Delta M_d}$$

$(\Delta B = 1)$ (1.00 ± 0.03) Lattice $(\Delta B = 2)$

Valid in all CMFV models

Can be strongly violated in SUSY, LHT, RS

95% CL

$$Br(B_s \to \mu^+\mu^-) \le \begin{cases} 3.3\cdot 10^{-8} & \text{(CDF)} \\ 5.3\cdot 10^{-8} & \text{(D0)} \end{cases}$$

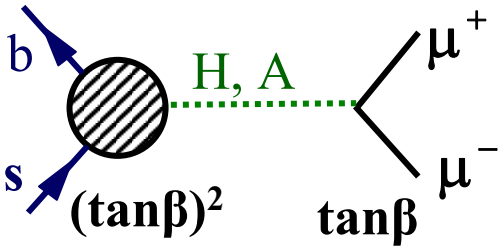
$$Br(B_d \to \mu^+\mu^-) \le 1\cdot 10^{-8} \text{ (CDF)}$$

LHC should be able to discover $B_s \to \mu^+\mu^-$ even at the SM level

$B_{s,d} \to \mu^+\mu^-$ in SUSY and Higgs Penguins

(Helicity suppression lifted)

Babu, Kolda (99),…+100



$$Br\left(B_{s,d} \to \mu^+\mu^-\right) \sim \frac{(\tan\beta)^6}{M_A^4}$$

Can reach CDF and DØ bounds

Very important for the distinction of SUSY from LHT and RS !!!

★

$$\frac{Br\left(B_{s,d} \to \mu^+\mu^-\right)_{LHT}}{Br\left(B_{s,d} \to \mu^+\mu^-\right)_{SM}} \leq 1.3$$

(Z-penguin)
(Blanke et al) (09)

$$\frac{Br\left(B_{s,d} \to \mu^+\mu^-\right)_{RS}}{Br\left(B_{s,d} \to \mu^+\mu^-\right)_{SM}} \leq 1.1$$

(Z-penguin + Z-tree with r.h. couplings)
(Custodial protection at work)
(Gori et al) (08)

Mixing Induced CP Asymmetry in $B_s \to \psi\varphi$ $\left(S_{\psi\varphi}\right)$

(TH very clean*); Analog of $S_{\psi K_s}$)

$$S_{\psi\varphi} = \sin\left(2|\beta_s| - 2\varphi_s^{new}\right) \overset{SM}{\cong} 0.035$$

$$V_{ts} = -|V_{ts}|e^{-\beta_s}$$
$$(\beta_s = -1°)$$

New Phase in $B_s^0 - \overline{B}_s^0$ mixing

$0.53^{+0.23}_{-0.21}$

★ CDF D0

$$0.20 \le \left(S_{\psi\varphi}\right)_{exp} \le 0.98$$

90% C.L. (HFAG)

If confirmed, clear signal of NP with non-MFV interactions and new sources of $\not{CP}$

See also Perez et al

Model Expectations

$S_{\psi\varphi} \le$

- 0.75 (AC) (abelian flavour, SUSY) (Higgs penguin) ABGPS
- 0.50 (RVV) (non-abelian flavour, SUSY) (Higgs penguin)
- 0.75 (RS) (Heavy KK Gauge Bosons) (Duling et al (08))
- 0.30 (LHT) (Mirror Fermions at work) (Tarantino et al (09))

*) See however Faller, Fleischer, Mannel (08)

Maximal Enhancements of $S_{\psi\varphi}$, $Br\left(B_s \to \mu^+\mu^-\right)$ and $K^+ \to \pi^+\nu\bar{\nu}$

(without taking correlation between them)

Model	Upper Bound on ($S_{\psi\varphi}$)	Enhancement of $Br\left(B_s \to \mu^+\mu^-\right)$	Enhancement of $Br\left(K^+ \to \pi^+\nu\bar{\nu}\right)$
CMFV	0.04	20%	20%
MFV	0.04	1000%	30%
LHT	0.30	30%	200%
RS	0.75	10%	100%
GMSSM	0.75	1000%	300%
AC	0.75	1000%	2%
RVV	0.50	1000%	10%

Correlations between $K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$, $S_{\psi\varphi}$, $B_s \to \mu^+\mu^-$

Impact of a future $S_{\psi\varphi} \approx 0.3$

LHT
RS

Sizable Enhancements in $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ excluded in RS and unlikely in LHT

$B_{s,d} \to \mu^+\mu^-$ SM-like

(Blanke et al)

(abelian)
AC
RVV
(non-abelian)

$Br(B_s \to \mu^+\mu^-)$ forced to be $3 \cdot Br(B_s \to \mu^+\mu^-)_{SM} \sim 10^{-8}$

SUSY Flavour Models

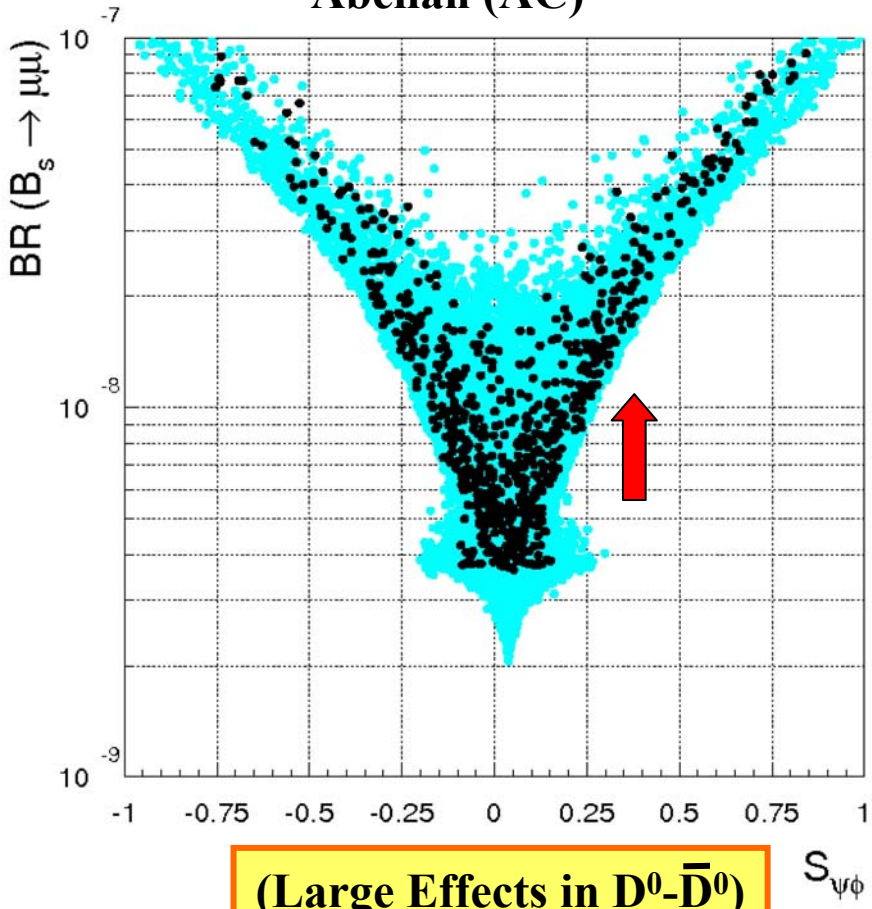
Altmannshofer, AJB, Gori, Paradisi, Straub (09) ABGPS

CDF, D0
LHCb

$Br(B_s \to \mu^+\mu^-)$ vs $S_{\psi\varphi}$

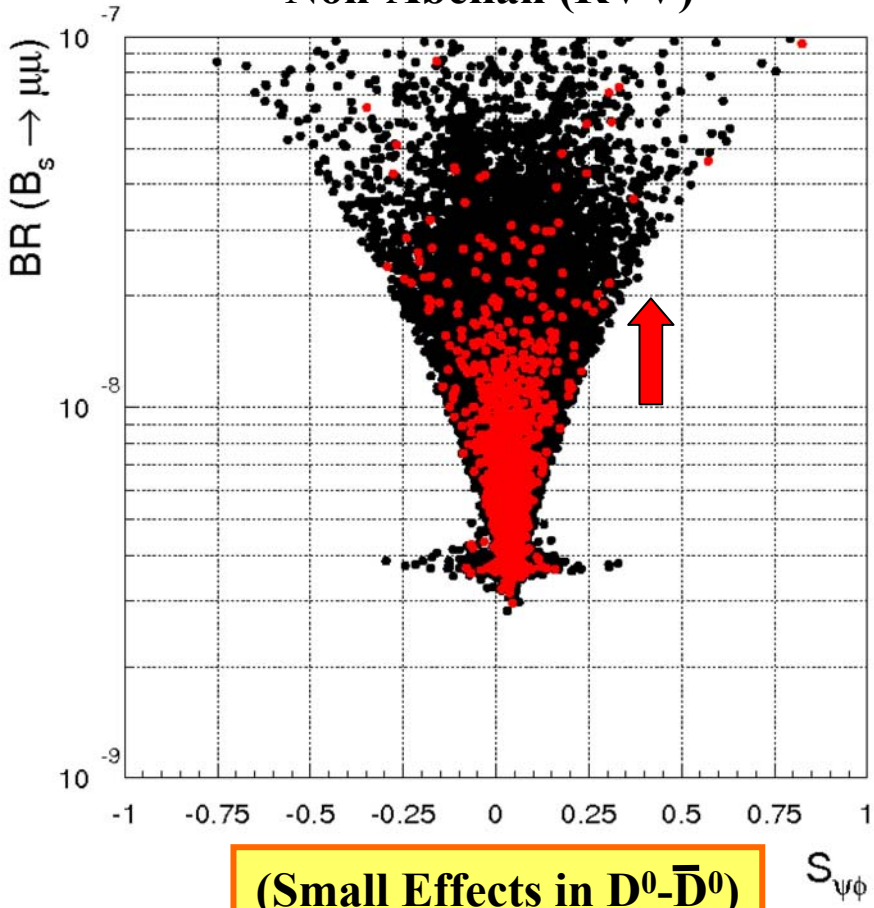
ABGPS

Solution 3 to ε_K-Anomaly
Abelian (AC)



(Large Effects in D^0-$\bar{D}^0$)

Solution 1 to ε_K-Anomaly
Non-Abelian (RVV)



(Small Effects in D^0-$\bar{D}^0$)

Lepton Flavour Violation, $\Delta(g-2)_\mu$ and EDM's

(MEGA) $Br(\mu \to e\gamma) < 1.2 \cdot 10^{-11}$ ➡ 10^{-13}(MEG) SM:10^{-54}

$(a_\mu)_{SM} < (a_\mu)_{exp}$ (3.6σ)

(Brookhaven) 1.9σ

$$a_\mu = \frac{1}{2}(g-2)_\mu$$

(Regan et al) $d_e < 1.6 \cdot 10^{-27}$ ➡ 10^{-31} $(d_e)_{SM} \approx 10^{-38}$

(Baker et al) $d_n < 2.9 \cdot 10^{-26}$ ➡ 10^{-28} $(d_n)_{SM} \approx 10^{-32}$

[e cm]

Clear Distinction between MSSM and LHT

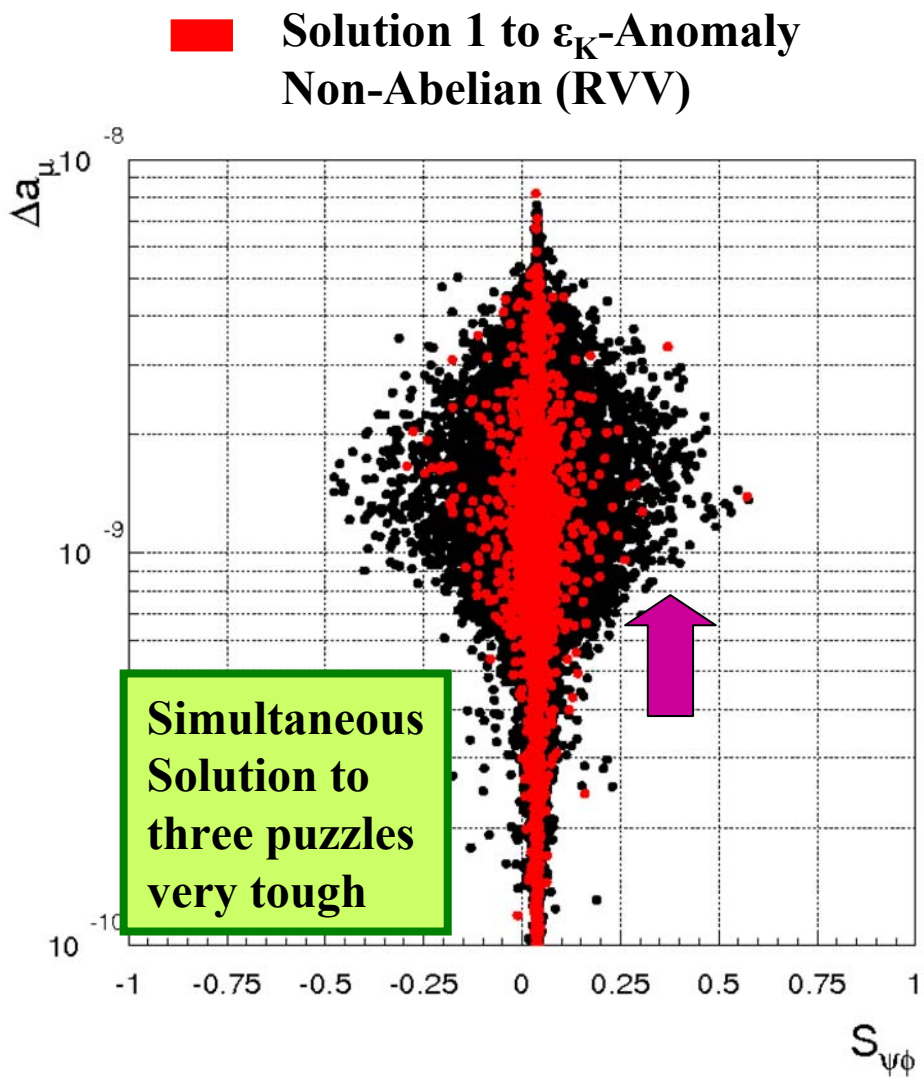
MSSM	LHT	Both can reach MEGA´s $\mu \to e\gamma$ bound
$\dfrac{Br(\mu^- \to e^- e^+ e^-)}{Br(\mu^- \to e^- \gamma)} \approx \dfrac{1}{161}$	0.02 – 1	
$\dfrac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau^- \to \mu^- \gamma)} \approx \dfrac{1}{435}$	0.04 – 0.4	

MSSM : (Ellis, Hisano, Raidal, Shimizu; Arganda, Herrero; Paradisi)
(Brignole, Rossi)

LHT : (Blanke, AJB, Duling, Poschenrieder, Tarantino) (2007)
del Aguila, Illana, Jenkins (2008), Goto, Okada, Yamamoto (2009)

ABGPS (09)

More Correlations in Flavour SUSY Models



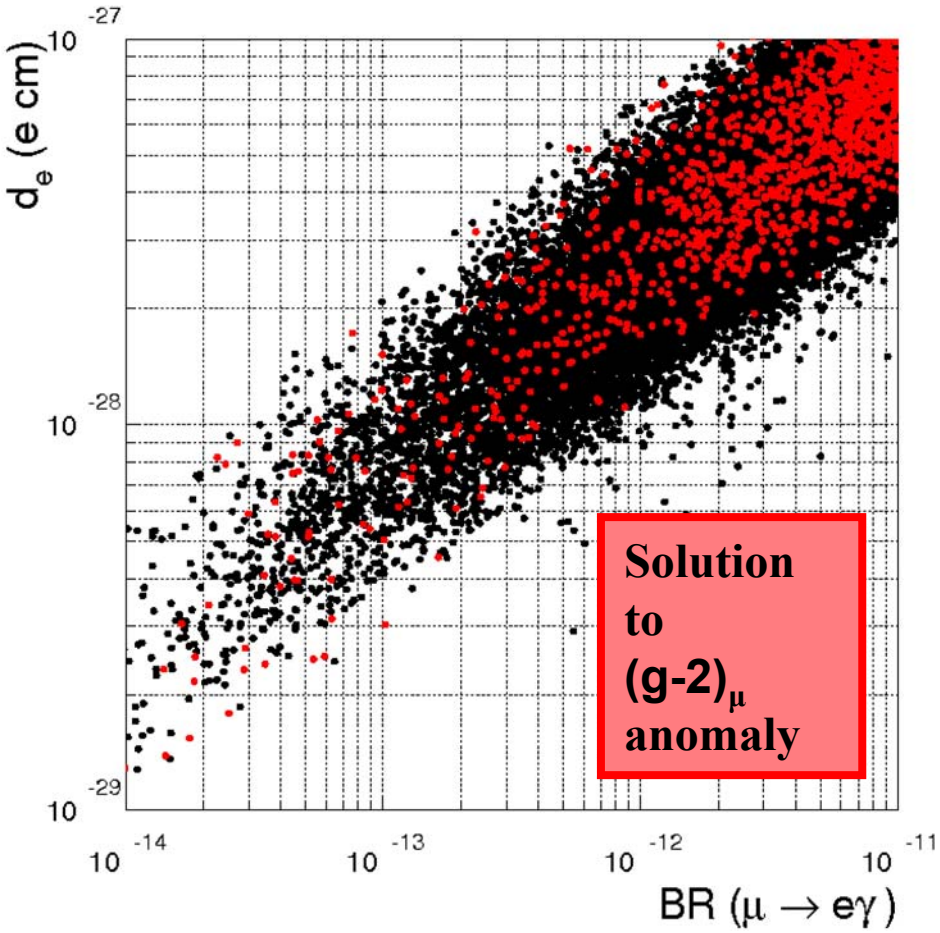
(See also Perez et al)

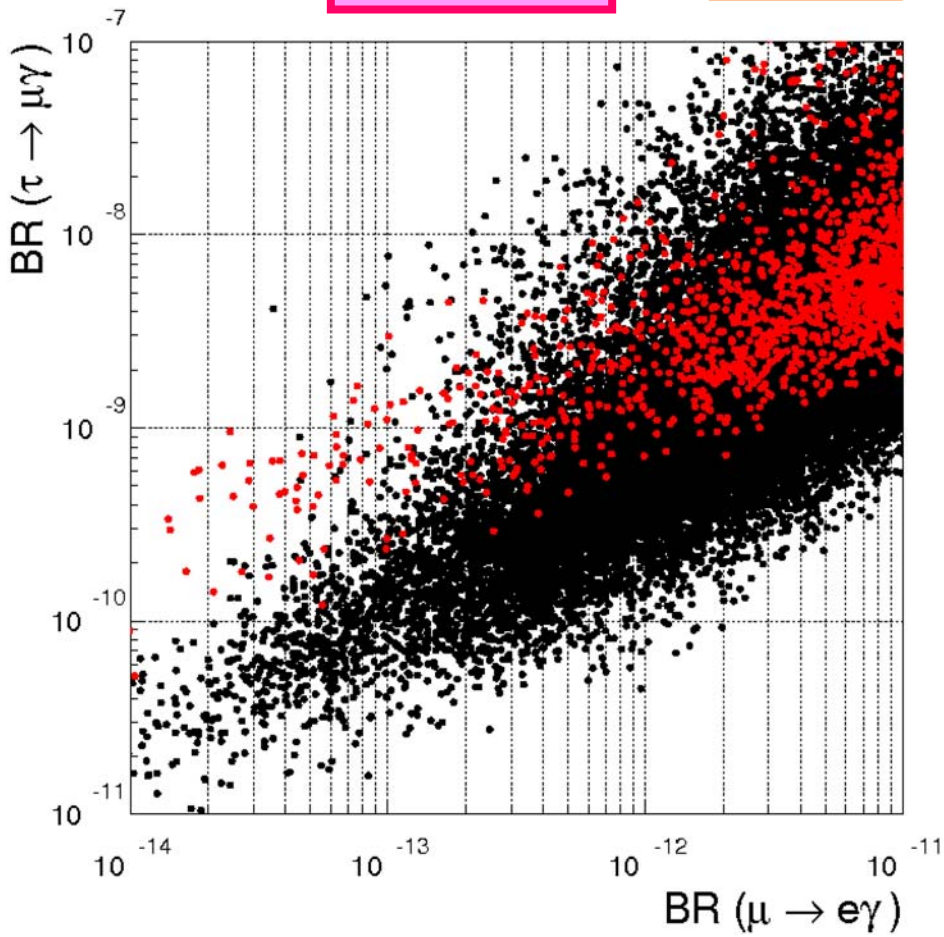
Testing SUSY through d_e, $(g-2)_\mu$, Br $(l_i \to l_j \gamma)$

Hisano, Nagai, Paradisi, Shimizu (09)
Isidori et al (08) ABGPS (09)

Dipole Transitions

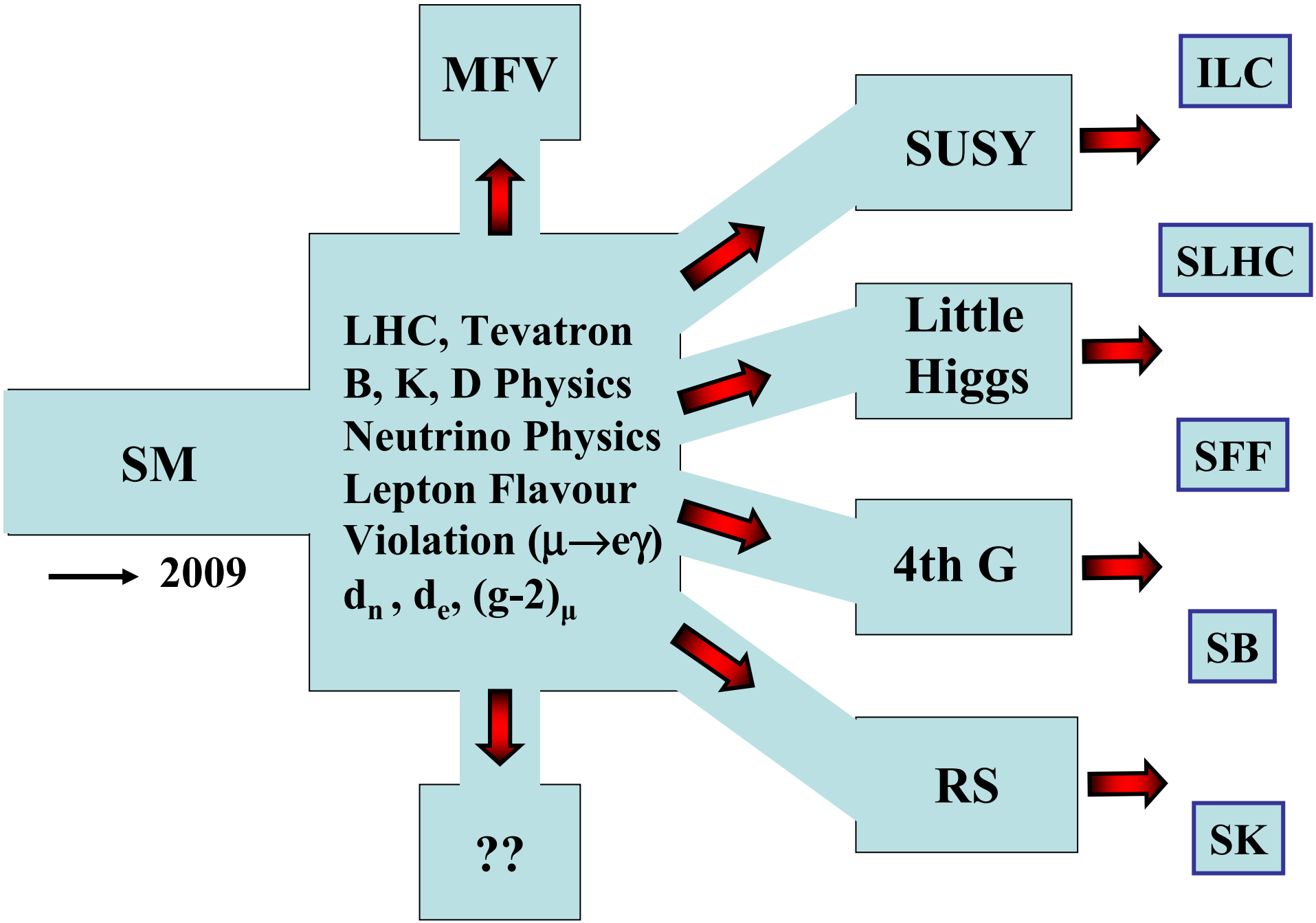
RVV





4.

Final Messages


MFV
SM
2009
LHC, Tevatron
B, K, D Physics
Neutrino Physics
Lepton Flavour
Violation (μ→eγ)
d_n , d_e, $(g-2)_\mu$
??
SUSY
Little
Higgs
4th G
RS
ILC
SLHC
SFF
SB
SK

Final Messages of this Talk

Flavour Physics (Quarks and Leptons) :

Many observables (decays) not measured yet or measured poorly. Flavour Physics only now enters the precision era.

↓

Spectacular deviations from SM still possible ⟷ **Interplay** ⟷ **Direct searches at Tevatron, LHC, ILC**

Final Messages of this Talk

Flavour Physics (Quarks and Leptons) :

Many observables (decays) not measured yet or measured poorly. Flavour Physics only now enters the precision era.

↓

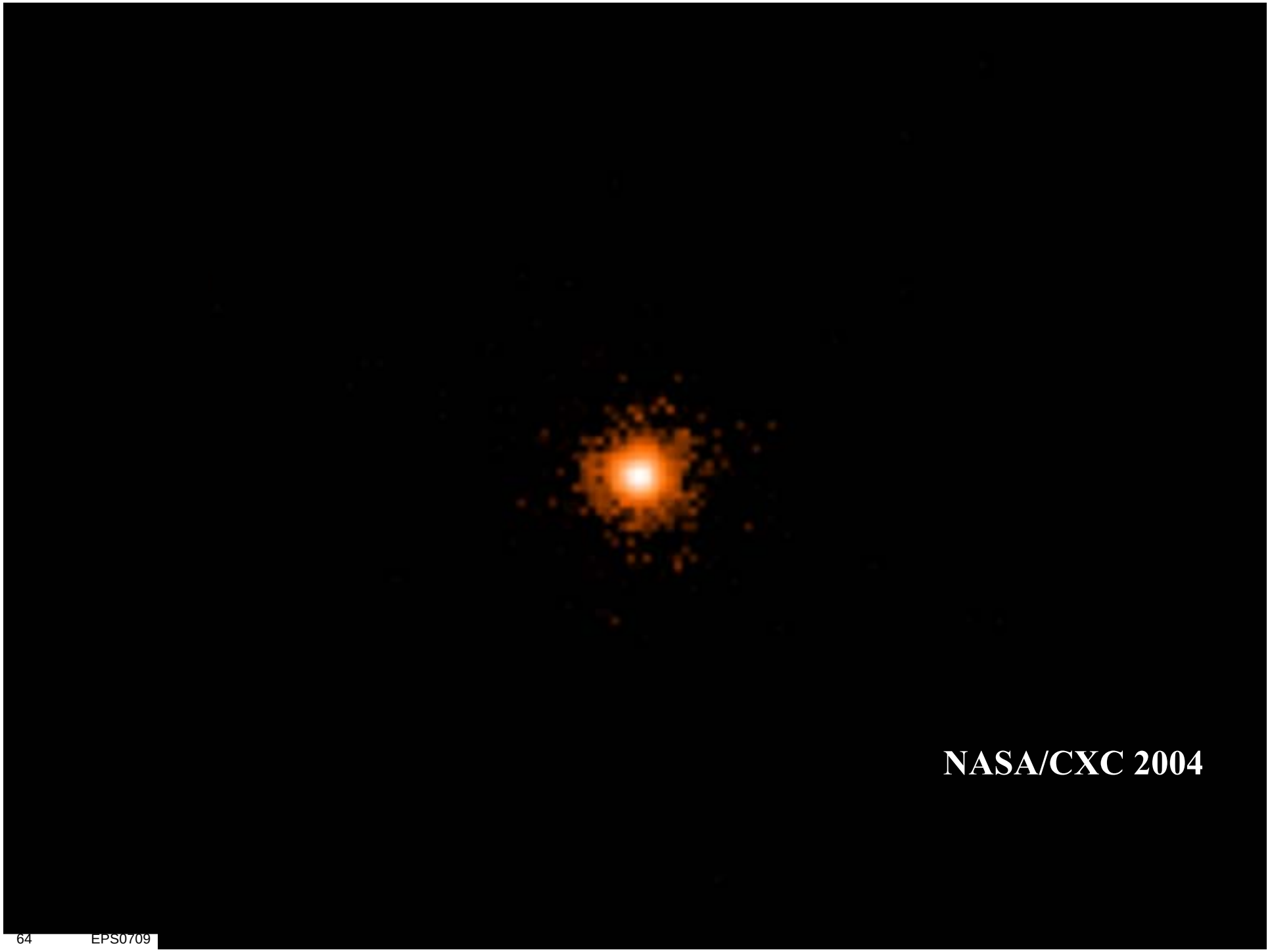
Spectacular deviations from SM still possible ⟷ **Direct searches at Tevatron, LHC, ILC**

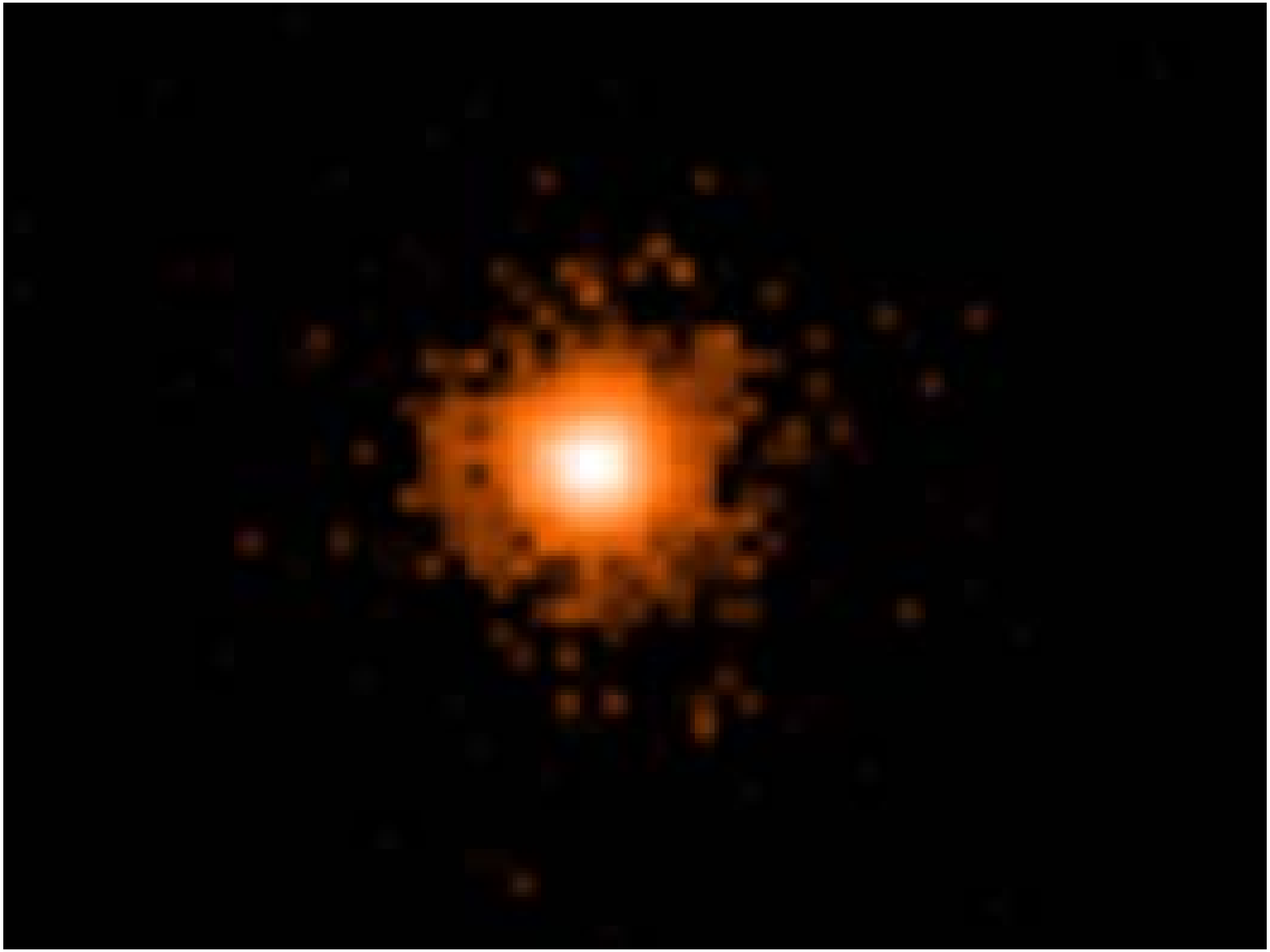
Interplay

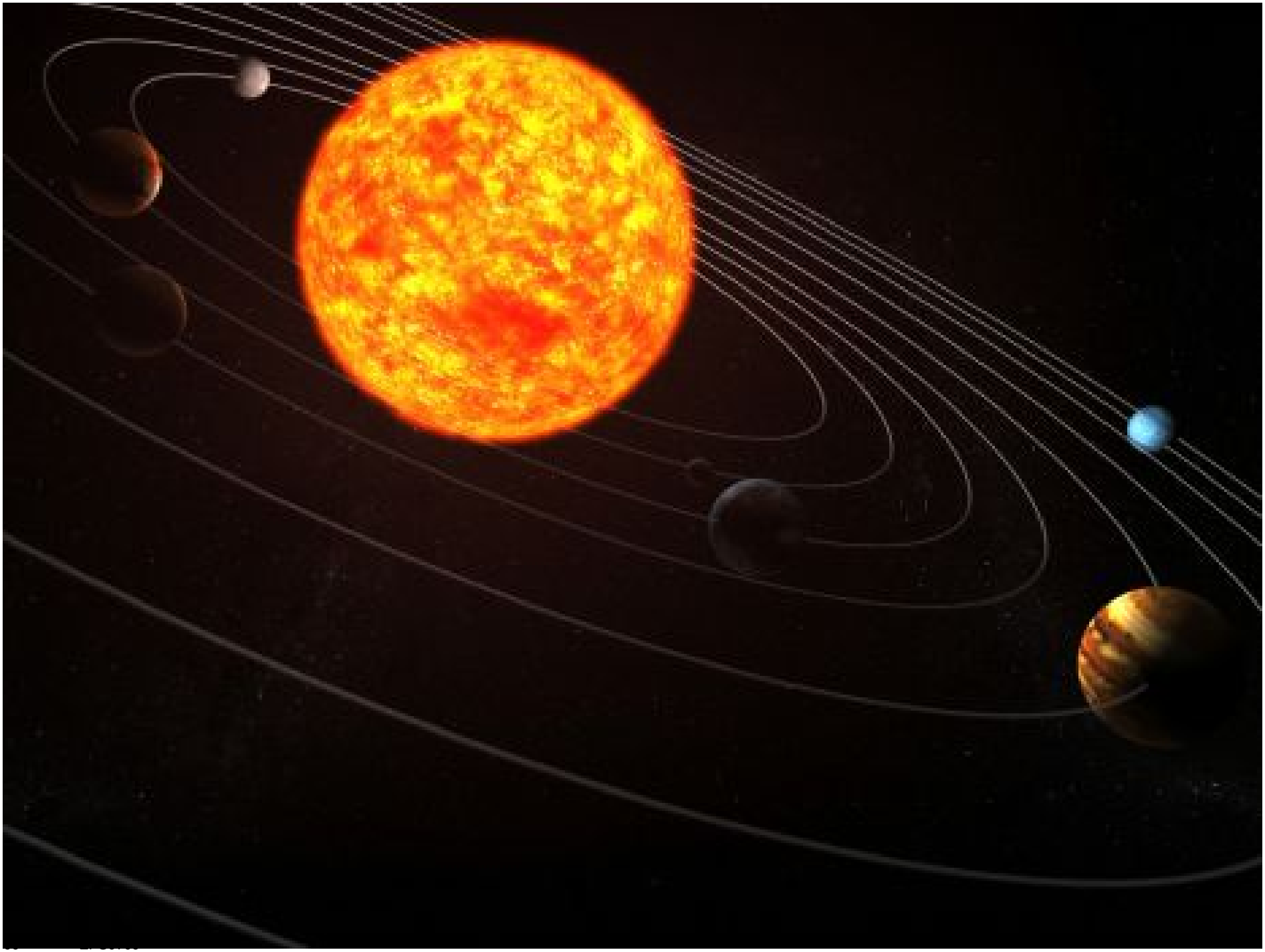
DNA Flavour Test of NP models

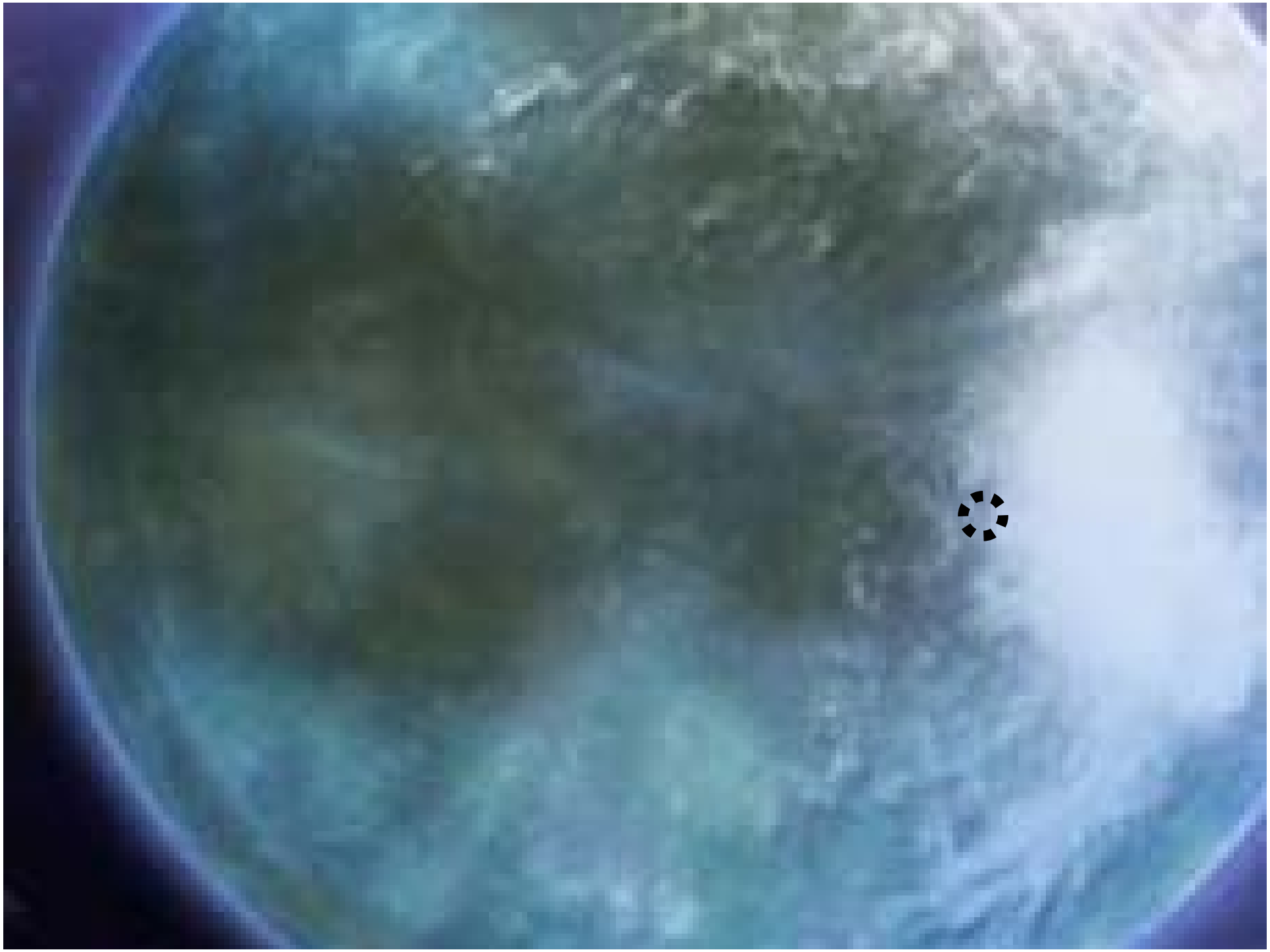
Correlations between various observables can distinguish NP scenarios easier than LHC ! ★

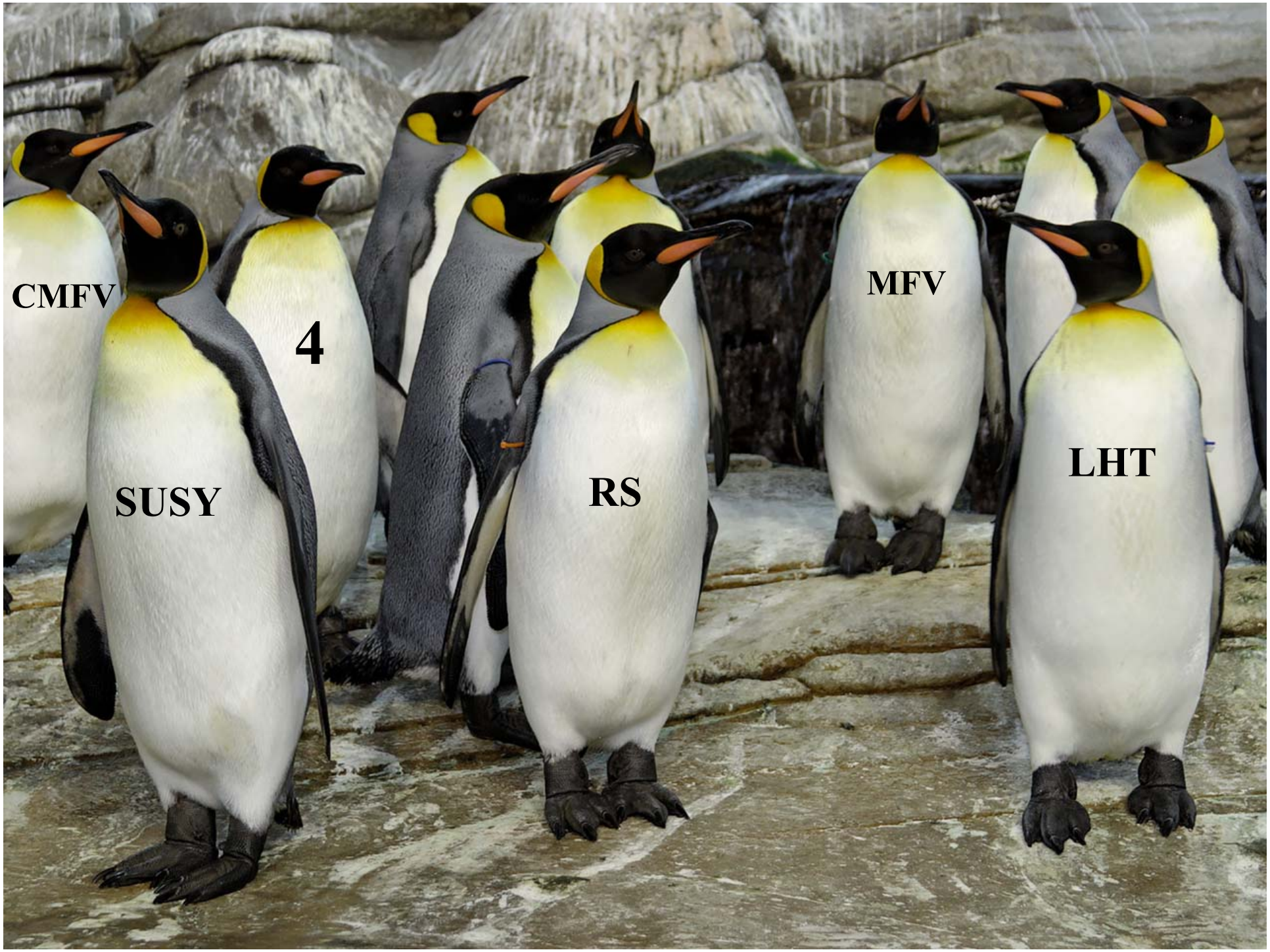
Great discoveries are just ahead of us !

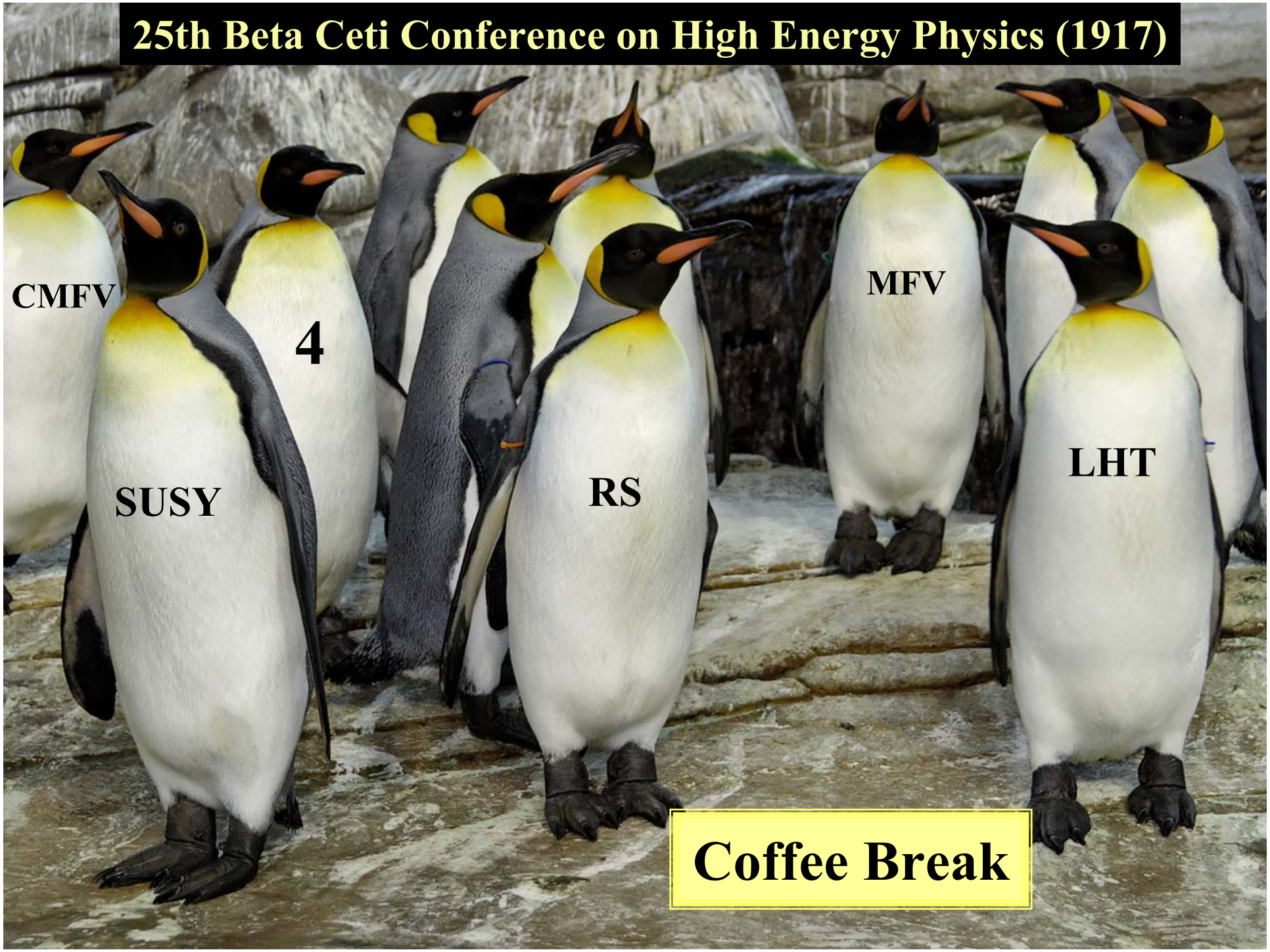

NASA/CXC 2004

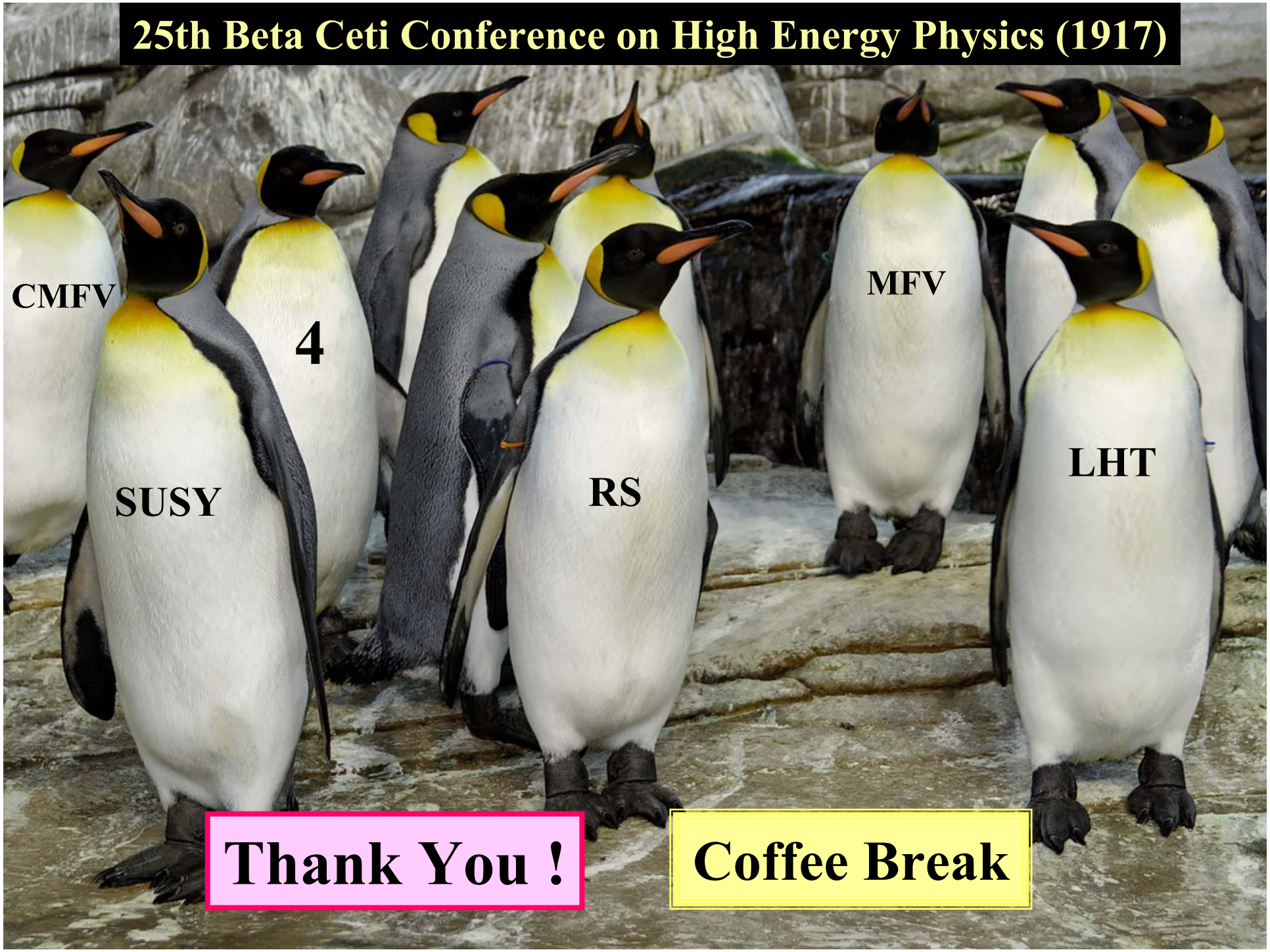







CMFV
SUSY
4
RS
MFV
LHT


25th Beta Ceti Conference on High Energy Physics (1917)
CMFV
SUSY
4
RS
MFV
LHT
Coffee Break


25th Beta Ceti Conference on High Energy Physics (1917)
CMFV
SUSY
4
RS
MFV
LHT
Thank You !
Coffee Break

Backup

SUSY


W. Altmannshofer


S. Gori


P. Paradisi


D. Straub

LHT


M. Blanke


B. Duling


S. Recksiegel


C. Tarantino

RS


M. Albrecht


M. Blanke


B. Duling


K. Gemmler


S. Gori


A. Weiler

U(2) Custodial Flavour Symmetry

SUSY


W. Altmannshofer

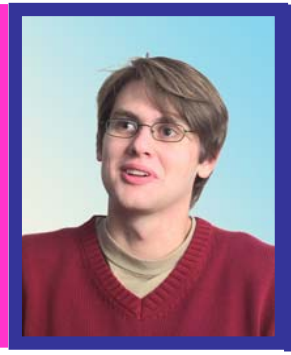

S. Gori


P. Paradisi


D. Straub

LHT


M. Blanke


B. Duling

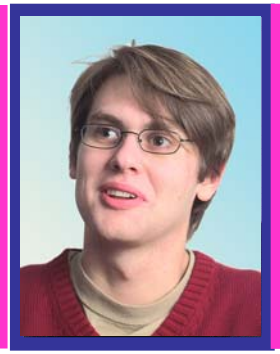

S. Recksiegel


C. Tarantino

RS


M. Albrecht

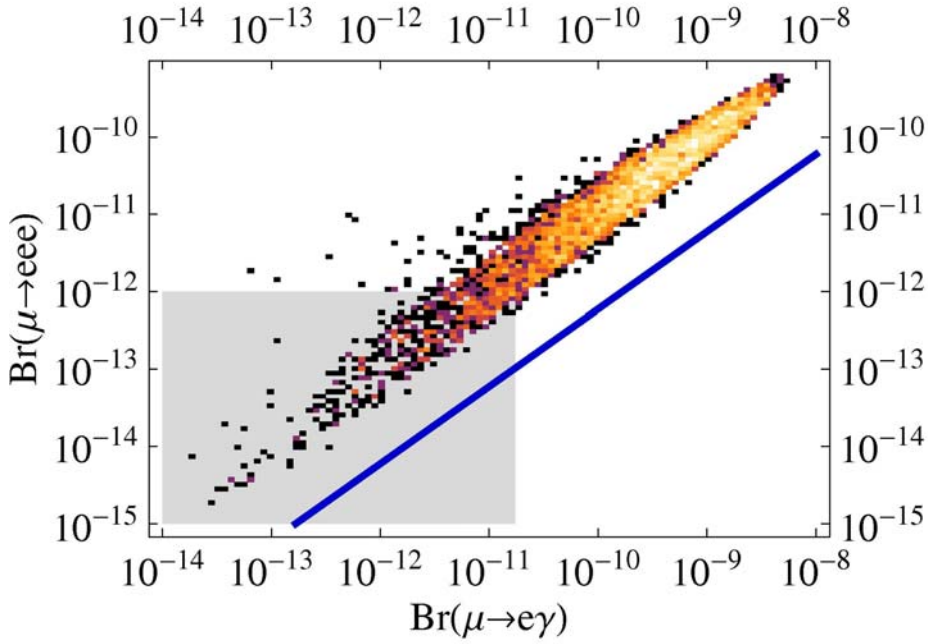

M. Blanke

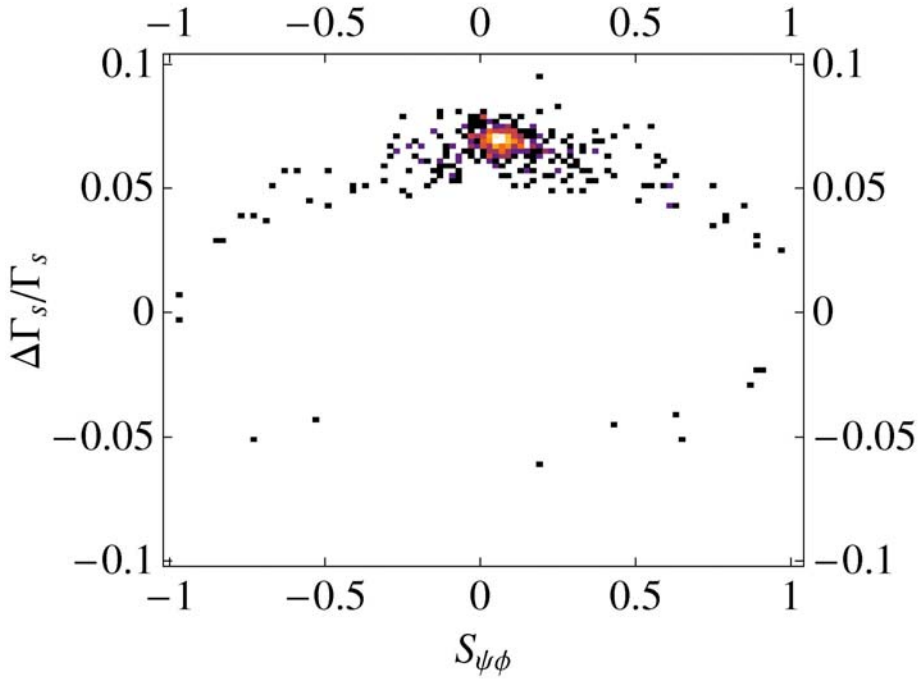

B. Duling

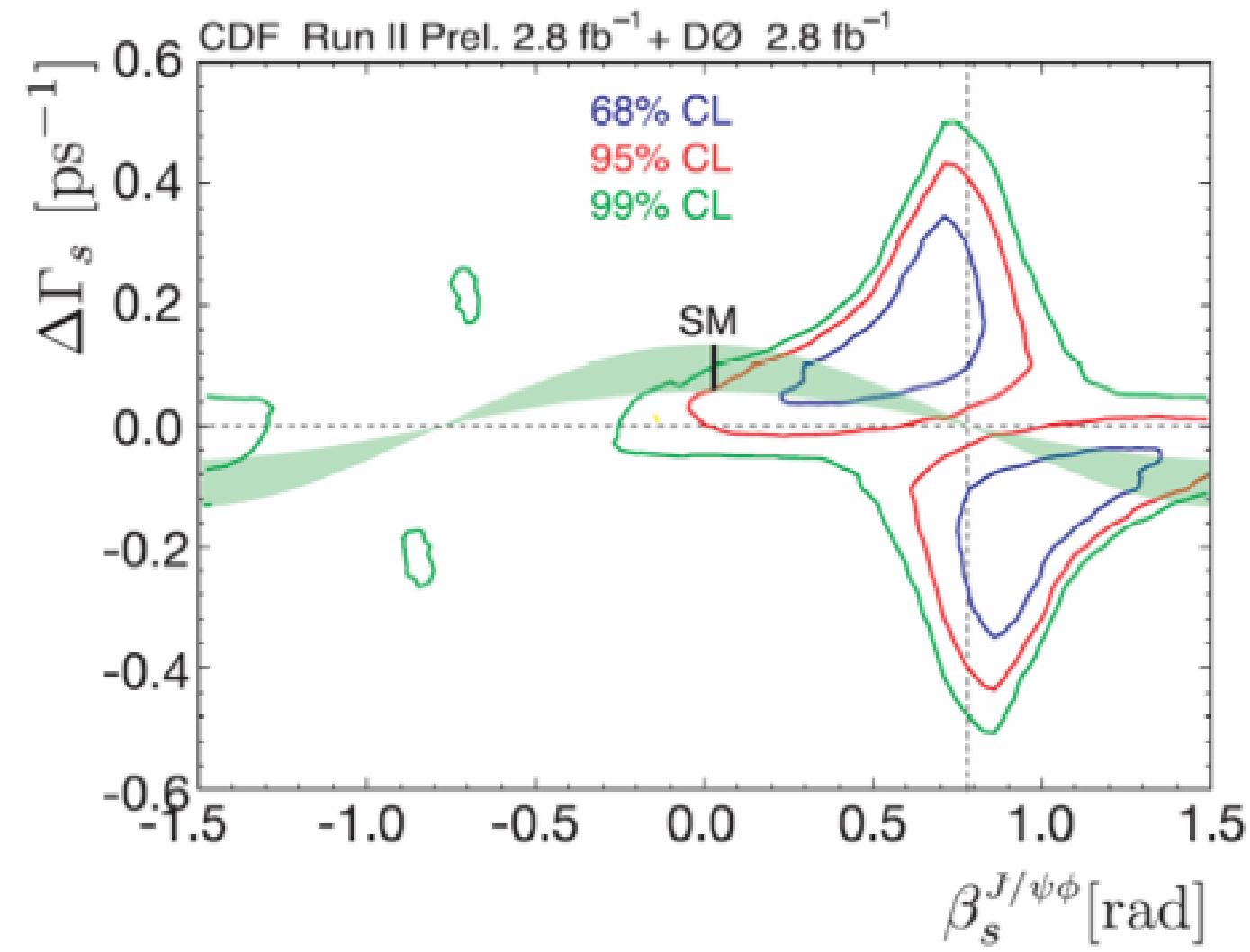

K. Gemmler


S. Gori


A. Weiler


Br(μ→eee)
Br(μ→eγ)


ΔΓs/Γs
Sψφ


CDF Run II Prel. 2.8 fb^{-1} + DØ 2.8 fb^{-1}
68% CL
95% CL
99% CL
SM
$\Delta\Gamma_s$ [ps^{-1}]
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
$\beta_s^{J/\psi\phi}$ [rad]

DNA Flavour Test of New Physics Models

	GMSSM	AC	RVV	δ_{LL} only	FBMSSM
$D^0 - \bar{D}^0$ mixing	★★★	★★★	★	★	★
ϵ_K	★★★	★	★★★	★	★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★
$S_{\phi K_S}$, $S_{\eta' K_S}$	★★★	★★★	★★	★★★	★★★
$A_{CP}^{bs\gamma}$	★★★	★	★	★★★	★★★
$\langle A_{7,8}\rangle(B \to K^* \mu^+ \mu^-)$	★★★	★	★★	★★★	★★★
$\langle A_9\rangle(B \to K^* \mu^+ \mu^-)$	★★★	★	★★	★	★
$B_s \to \mu^+ \mu^-$	★★★	★★★	★★★	★★★	★★★
$B \to K^{(*)} \nu\bar{\nu}$	★★	★	★	★	★
$K \to \pi\nu\bar{\nu}$	★★★	★	★★	★	★
d_e, d_n	★★★	★★★	★★	★★	★★★

★★★: large effects, ★★: medium effects, ★: small effects

Return of ε′/ε ?

Final Result (NA48, KTeV)

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (16.8 \pm 1.4)\cdot 10^{-4}$$

(2009)

$$\mathrm{Re}(\varepsilon'/\varepsilon)_{SM} \approx \left\{\begin{matrix}\text{QCD}\\ \text{Penguins}\end{matrix}\right\} - \left\{\begin{matrix}\text{Electroweak}\\ \text{Penguins}\end{matrix}\right\}$$

(B_6) (B_8)

Very sensitive to New Physics

Wilson Coefficients of Penguins known at NLO (1990´s)
Munich (92,93)
Rome (93)

Large N calculations of hadronic Matrix Elements

Bardeen, AJB, Gerard (85)
Pich et al
De Rafael et al.
Bijnens + Prades
} (1990´s)

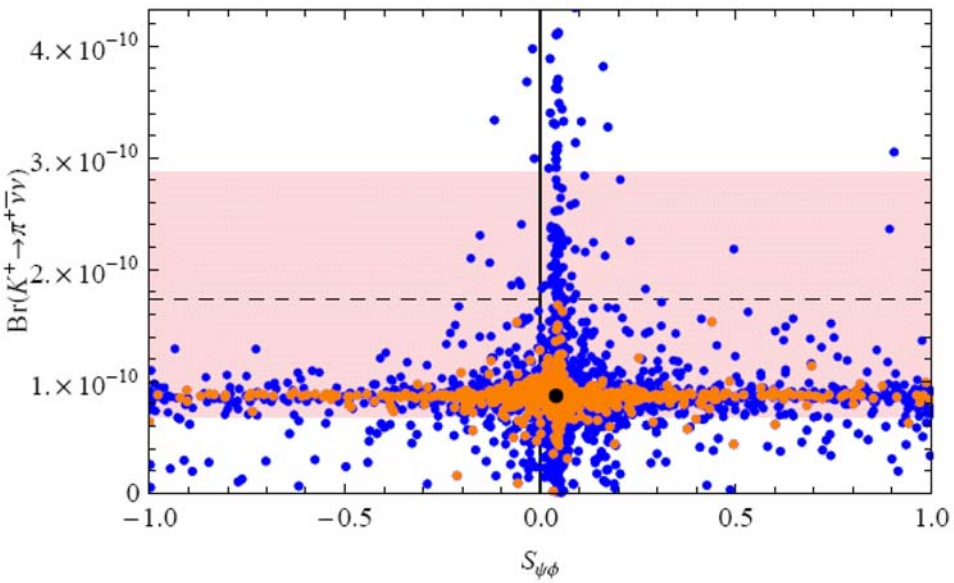
New Efforts on the Lattice

(Norman Christ et al.)

20015 ?

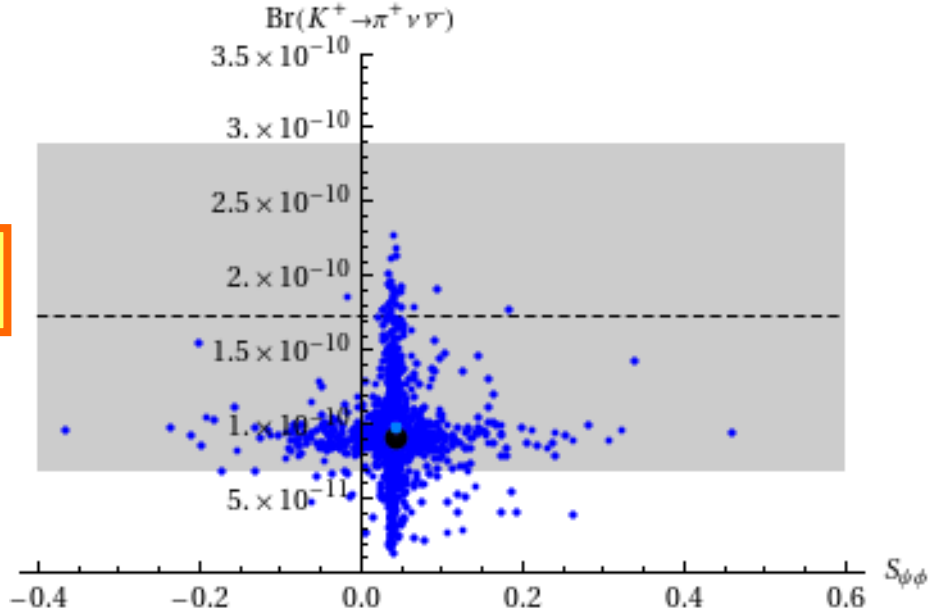
$K^+ \to \pi^+ \nu\bar{\nu}$ vs. $S_{\psi\varphi}$

(Simultaneous Large Enhancements unlikely)



RS

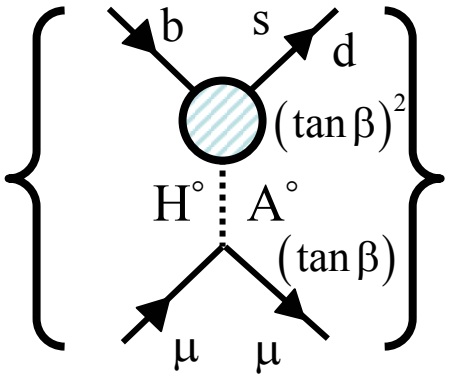
LHT



$B_{s,d} \to \mu^+\mu^-$ and MSSM with MFV at large tanβ

In MSSM at large tanβ
(CKM still the only source of Flavour and CP Violation)

Strong Enhancement



$$\mathrm{Br}\left(B_{s,d} \to \mu\bar{\mu}\right) \sim \left(\tan\beta\right)^6$$

$10^{-6}\left(10^{-7}\right)$ possible

SM ~ 10^{-9}

Babu, Kolda
Chankowski, Slawianowska
Bobeth, Ewerth, Krüger, Urban
Huang, Liao, Yan, Zhu
Isidori, Retico
Dedes, Dreiner, Nierste
Dedes, Pilaftis
Chankowski, Rosiek
Foster, Okumura, Roszkowski
Carena et al.
Isidori, Paradisi

$$\mathbf{Br}\left(\mathbf{B_s} \to \mu\bar{\mu}\right) < \mathbf{6 \cdot 10^{-8}}$$

95% C.L
(CDF, DØ)

$$\mathbf{Br}\left(\mathbf{B_d} \to \mu\bar{\mu}\right) < \mathbf{2 \cdot 10^{-8}}$$

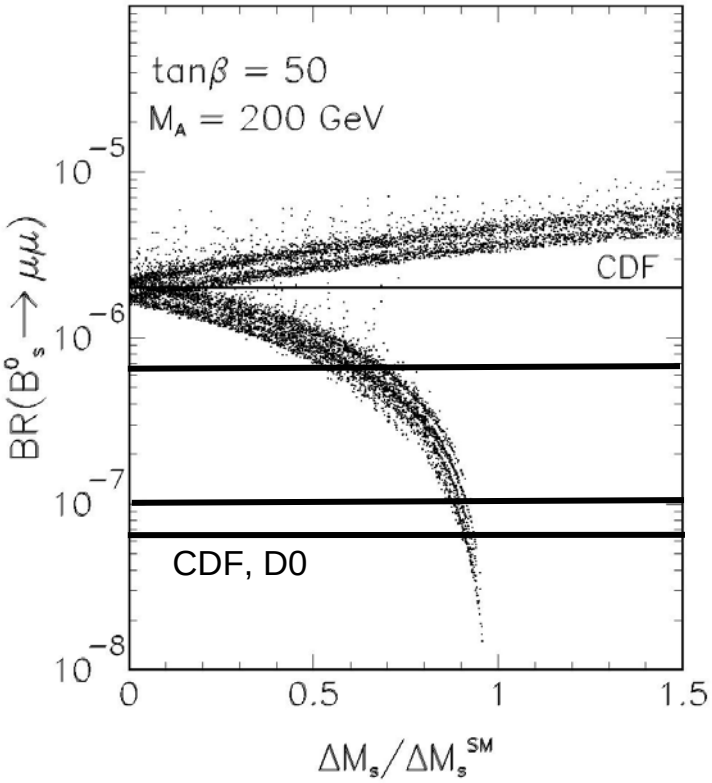
95% C.L.

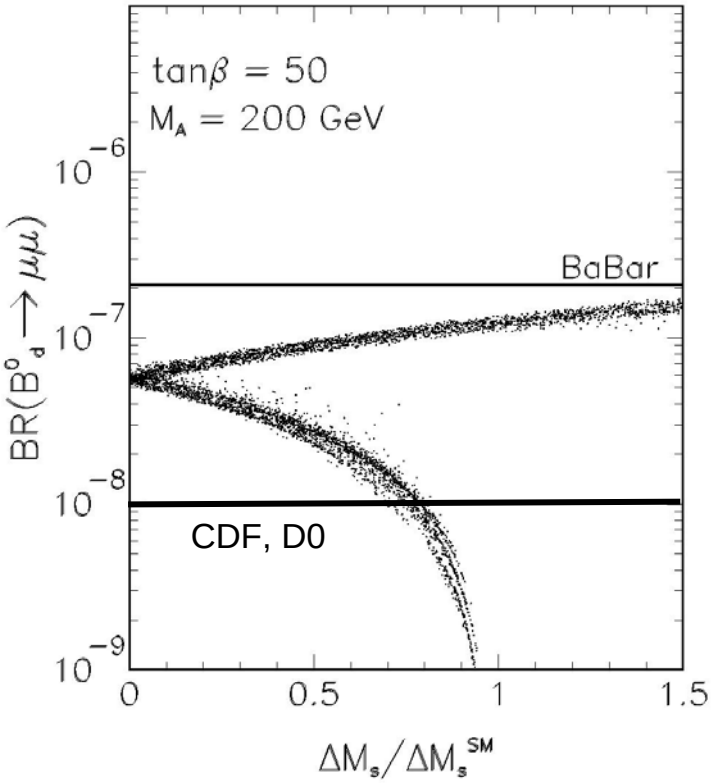
$Br\left(B_{s,d} \to \mu^+\mu^-\right)$ vs $\left(\Delta M_s\right)^{exp} / \left(\Delta M_s\right)^{SM}$ in SUSY at Large $\tan\beta$

AJB, Chankowski, Rosiek, Slawianowska (2002)
Gorbahn, Jäger, Nierste, Trine (2008)
Could be modified by Non-MFV (Chankowski; Dedes, Pilaftsis)

2002
2004

2007
2008





2002

2008

$B^+ \to \tau^+ \nu$ $(\mu^+ \nu)$

$$Br\left(B^+ \to \tau^+ \nu\right)_{exp} = \left(1.73 \pm 0.35\right) \cdot 10^{-4}$$

(Belle, BaBar)

$$Br\left(B^+ \to \tau \nu\right)_{SM} \approx G_F^2 F_B^2 \left|V_{ub}\right|^2 = \left(1.1 \pm 0.5\right) \cdot 10^{-4}$$

$$\frac{Br\left(B^+ \to \tau \nu\right)_{MSSM}}{Br\left(B^+ \to \tau \nu\right)_{SM}} = \left[1 - \left(\frac{m_B}{m_{H^\pm}}\right)^2 \frac{\tan^2 \beta}{1 + \varepsilon_0 \tan \beta}\right]^2$$

(Hou)
(Akeroyd, Recksiegel)
(Isidori, Paradisi)

Tree-Level H^+ exchange

This decay could be problematic for MSSM-MFV with large tanβ

Altmannshofer, AJB, Guadagnoli, Wick (07)

$$B^+ \to \tau^+\nu,\ K^+ \to l^+\nu$$

(LFV effects in B and K Physics)

Sensitivity to NP

A.

$$\frac{Br\left(B^+ \to \mu^+\nu\right)}{Br\left(B^+ \to \tau^+\nu\right)}$$

(test of $\mu \leftrightarrow \tau$ universitality)

Isidori - Paradisi (2006)

B.

$$\frac{\Gamma\left(K^+ \to \mu^+\nu\right)}{\Gamma\left(K^+ \to e^+\nu\right)}$$

(test of $\mu \leftrightarrow e$ universitality)

Masiero, Paradisi, Petronzio (2005)

Very accurate precision test

Tested soon at CERN to 0.5%

TH: ± 0.1%

$(g-2)_\mu$ and EDM´s

Flavour Conserving ★

A $(g-2)_\mu$: Flavour and CP conserving

Resolution of the $(g-2)_\mu$ problem

$$\left[(g-2)_\mu\right]_{SM} \neq \left[(g-2)_\mu\right]_{exp}$$

$$a_\mu^{exp} = 11659\ 2080\ \ (63)\ \ 10^{-11}$$

$$a_\mu^{SM} = 11659\ 1785\ \ (51)\ \ 10^{-11}$$

3.6 σ discrepancy

MSSM ~~LHT~~

But e^+e^- from BaBar → 0.9 σ

(?)

B EDM´s Flavour conserving but ~~CP~~

MSSM, ~~LHT~~, WED

Putting S0(10)-SUSY-GUT of Dermisek-Raby into difficulties

M. Albrecht, W. Altmannshofer, AJB, D. Guadagnoli, D. Straub

1. The Model gives a nice description of quark and lepton masses, PMNS and most of CKM elements.

Also SUSY Spectrum

2. But fails to describe simultaneously the data on

$$B_{s,d} \to \mu^+\mu^-,\ B \to X_s\gamma,\ B \to X_s l^+ l^-,\ B_u \to \tau\nu$$

3. Gives $|V_{ub}| \approx 3.2 \cdot 10^{-3}$

$$< \underbrace{(4.2 \pm 0.3) \cdot 10^{-3}}_{\text{Exp.}}$$

Generally too low

Some recent solutions: Altmannshofer et al.

$K^+ \to \pi^+ \nu\bar{\nu},\ K_L \to \pi^0 \nu\bar{\nu},\ K_L \to \pi^0 l^+ l^-,\ B \to K(K^*)$ ★

Z^0 - Penguin dominated Decays

Decay	SM	Exp	TH
$K^+ \to \pi^+ \nu\bar{\nu}$	$(8.5 \pm 0.7) \cdot 10^{-11}$	$(17.3\,^{+11.5}_{-10.5}) \cdot 10^{-11}$ (BNL)	±2-3%
$K_L \to \pi^0 \nu\bar{\nu}$	$(2.6 \pm 0.3) \cdot 10^{-11}$	$< 6.7 \cdot 10^{-8}$ (KEK)	±1-2%
$K_L \to \pi^0 e^+ e^-$	$(3.5 \pm 1.0) \cdot 10^{-11}$	$< 28 \cdot 10^{-11}$ (KTeV)	±15%
$K_L \to \pi^0 \mu^+ \mu^-$	$(1.4 \pm 0.3) \cdot 10^{-11}$	$< 38 \cdot 10^{-11}$ (KTeV)	±15%
$B \to K^+ \nu\bar{\nu}$	$(4.5 \pm 0.7) \cdot 10^{-6}$	$< 14 \cdot 10^{-6}$ (Belle)	±15%
$B \to K^* \nu\bar{\nu}$	$(6.8 \pm 1.1) \cdot 10^{-6}$	$< 80 \cdot 10^{-6}$ (BABAR)	±15%
$B \to X_S \nu\bar{\nu}$	$(2.7 \pm 0.2) \cdot 10^{-5}$	$< 64 \cdot 10^{-5}$ (ALEPH)	±3%

Very strong Constraints on New Physics

$$\mathrm{Br}(B \to X_S \gamma)_{exp} = (3.52 \pm 0.24) \cdot 10^{-4}$$

$$\mathrm{Br}(B \to X_S \gamma)_{SM} = \begin{cases} (3.15 \pm 0.23) \cdot 10^{-4} & \text{(Misiak et al)} \\ (2.98 \pm 0.26) \cdot 10^{-4} & \text{(Becher, Neubert)} \end{cases}$$

$$\mathrm{Br}(B \to X_S l^+ l^-)_{exp} = \begin{cases} (1.6 \pm 0.5) \cdot 10^{-6} & (\text{low } q^2) \\ (4.4 \pm 1.3) \cdot 10^{-7} & (\text{high } q^2) \end{cases}$$

$$\mathrm{Br}(B \to X_S l^+ l^-)_{SM} = \begin{cases} (1.6 \pm 0.1) \cdot 10^{-6} & (\text{low } q^2) \\ (2.3 \pm 0.8) \cdot 10^{-6} & (\text{high } q^2) \end{cases}$$

Isidori et al. (incl.)
Gorbahn et al. (incl.)
Feldmann et al. (excl.)

Zero in A_{FB}

$$\hat{s}_0 = (3.50 \pm 0.12)\,\mathrm{GeV}^2$$

★

TH
very clean

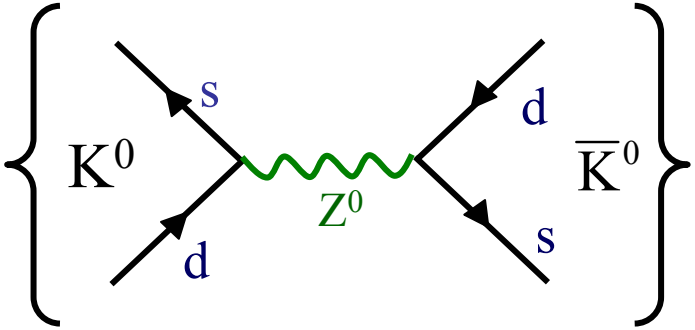
$$A_{CP}(B \to X_S \gamma)_{exp} = 0.004 \pm 0.036$$

$$A_{CP}(B \to X_S \gamma)_{SM} = 0.004 \pm 0.002$$

All this can be improved
at Super-B
Super-Belle

(Still factor 10 enhancement possible !)

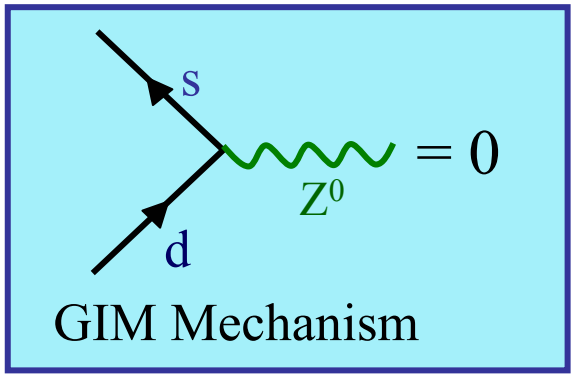
FCNCs at Tree Level and ΔM_K



$$\Delta M_K \cong 2 \cdot 10^{-7}\,\mathrm{GeV}$$

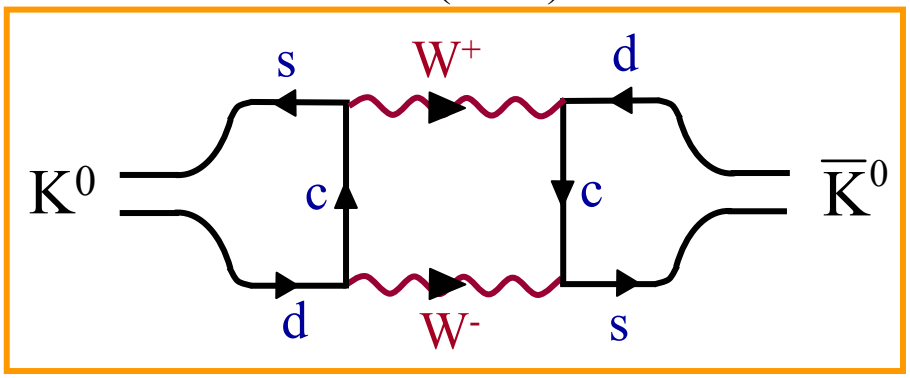
(ε_K even worse)

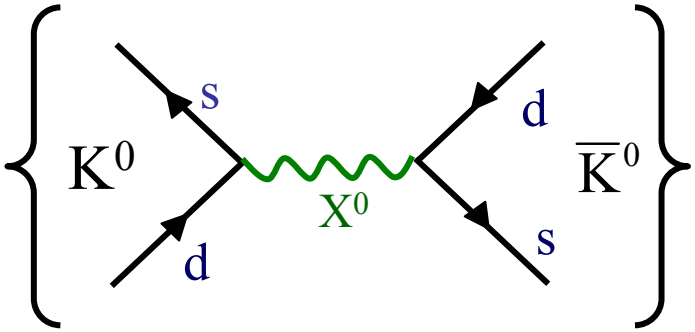
Disaster !!!
Missed by
8 orders of
magnitude !!!



(1971)

Gaillard + Lee (1974)





$$\Delta M_K \cong 2 \cdot 10^{-7} \left[\frac{M_Z^2}{M_X^2} \right] \mathrm{GeV} = 3.5 \cdot 10^{-15}\,\mathrm{GeV}$$

$$M_X \cong 10^6\,\mathrm{GeV}$$

Testing 10^{-22}m !

New very heavy neutral boson !

Tree Level FCNC mediated by KK gauge bosons and Z (breakdown of standard GIM mechanism)

RS

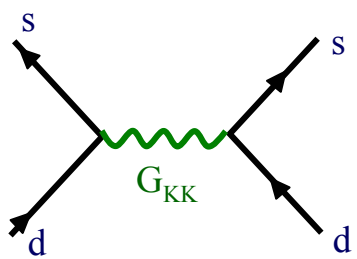
$$d \equiv \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

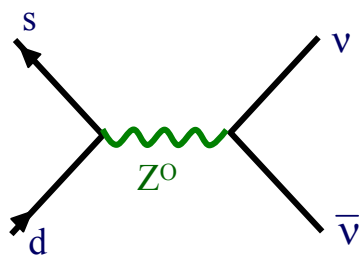
$$\bar{d} D_L^{+} \begin{pmatrix} a & & \\ & b & \\ & & c \end{pmatrix} D_L \gamma_\mu Z^\mu d \neq \bar{d} \gamma_\mu Z^\mu d$$

(non-universality in gauge interactions)

Related to the explanation of hierarchies in masses and mixings

$$0\left(\frac{v^2}{M_{KK}^2}\right)$$





$$0\left(\frac{v^2}{M_{KK}^2}\right)$$

But RS-GIM helps in avoiding disaster.

Gherghetta, Pomarol
Huber, Shafi
Agashe, Soni, Perez

Essential Ingredients in the Master Formula

1. Hadronic Matrix Elements $\left(\hat{B}_i\right)$

(Progress still has to be made) Recent progress: $\hat{B}_K$

2. QCD and QED RG-Effects for $\mu < m_t$ $\left(\eta_i^{QCD}\right)$

1990´s - era of NLO calculations
2000´s - era of NNLO calculations

- ★ $B \to X_s l^+ l^-$ (Greub et al; Isidori et al, Beneke et al
- ★ $B \to X_s \gamma$ (Misiak et al) Bobeth et al)
- ★ $K^+ \to \pi^+ \nu\bar{\nu}$ (AJB, Gorbahn, Haisch, Nierste)

★ Non-Leptonic (Buchalla; Beneke, Jäger,…)
+ Semi-Leptonic (Gorbahn, Haisch)
3 Loop $\hat{\gamma}_{anom}$

Selected Actors for the next 15 Minutes

$|V_{ub}|, |V_{cb}|, \gamma$ from tree decays

ε_K

$K^+ \to \pi^+ \nu\bar{\nu}$

$K_L \to \pi^0 \nu\bar{\nu}$

$B_{s,d} \to \mu^+\mu^-$

$S_{\psi\varphi}, \; A_{SL}^s$

$\mu \to e\gamma, \; \tau \to \mu\gamma$

$d_n, \; d_e$ (EDM´s)

$S_{\varphi K_s}, \; (S_{\varphi\varphi})$

$\Delta(g-2)_\mu$

$A_{CP} \; (b \to s\gamma)$

$B \to K^* l^+ l^-$

4th Generation

GIM at tree level
but strongly broken
at one loop
m_t, m_b, $>m_t>>m_c$

Still a possibility !!

New activities:

George Hou at al.

Soni, Alok, Giri, Mohanda, Nandi (08)
Bobrowski, Lenz, Riedl, Rohrwild (09)

This NP Scenario
is very different
from
SUSY, LHT, RS

:

Non-Decoupling Effects
of the 4th Generation
Fermions in Low Energy
Processes

However

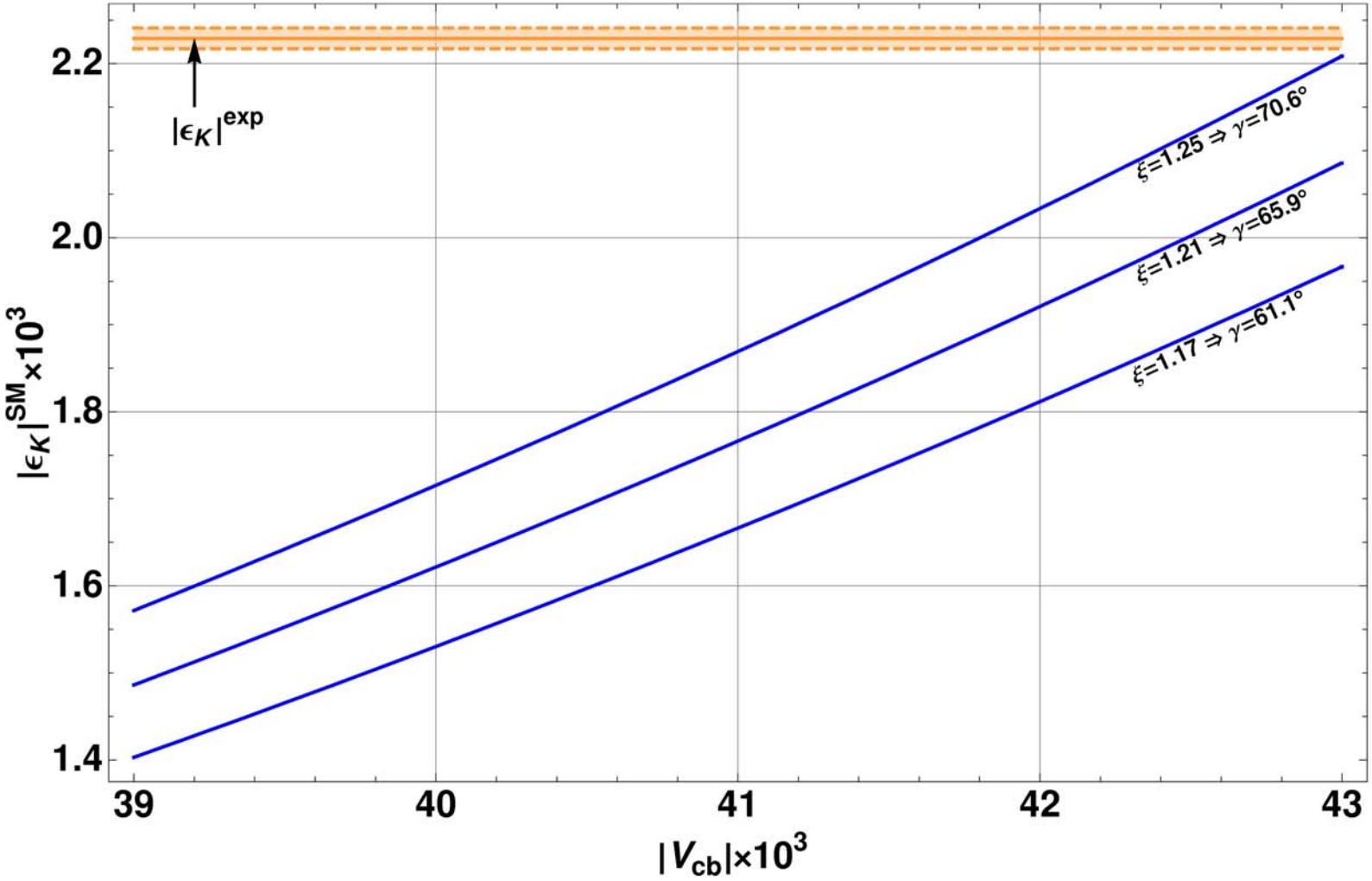
:

It does not address
the hierarchy problems

ε_K needs precise value of $|V_{cb}|$

AJB
Guadagnoli
(2009)

$$\varepsilon_K \sim |V_{cb}|^4$$



Number of new Flavour Parameters

(Quark Sector) (physical)

	Real	$\not{CP}$ Phases	
SUSY	36	27	(R-parity)
FBMSSM	6	1	
LHT	7	3	some sensitivity to UV
RS	18	9	
SM	9	1	

Where to Expect Large NP Effects

1. LFV ($\mu \to e\gamma$, $\mu \to 3e$, $\tau \to 3e$) ; EDM´s
2. $K_L \to \pi^o \nu\bar{\nu}$, $K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^o l^+ l^-$, (ε_K), ε'/ε
3. CP-Violation in B_s-Decays, in $B \to X_d \gamma$
4. $B_{s,d} \to \mu^+ \mu^-, (B_{s,d} \to \tau^+ \nu)$
5. CP-Violation in D-Decays
6. $B \to X_s \nu\bar{\nu}$, $B_{s,d} \to K^* l^+ l^-$
7. CP-Violation in B_d, $B^\pm$ Decays $(S_{\varphi K_s}, S_{\pi^o K_s}, \ldots)$

Other interesting Processes

- $\mu^- \to e^- e^+ e^-$: even more constrained than $\mu \to e\gamma$

$$Br(\mu^- \to e^- e^+ e^-)_{\exp} < 1.0 \cdot 10^{-12}$$

[SINDRUM Collaboration]

- $\tau \to \mu\gamma$ and $\tau \to e\gamma$: similar to $\mu \to e\gamma$

$$Br(\tau \to \mu\gamma)_{exp} < 1.6 \cdot 10^{-8}$$

[Belle, BaBar]

$$Br(\tau \to e\gamma)_{exp} < 9.4 \cdot 10^{-8}$$

[BaBar, Belle]

- $\tau \to \mu\pi$: semileptonic decay

$$Br(\tau \to \mu\pi)_{exp} < 5.8 \cdot 10^{-8}$$

[Belle, BaBar]

(Future: Super B)

- $\mu \to e$ conversion

$$R(\mu T_i \to e T_i) < 4.3 \cdot 10^{-12}$$

10^{-18} (J-Parc)

- $K_L \to \mu e$: flavour violating in both quark and lepton sectors

$$Br(K_L \to \mu e)_{\exp} < 4.7 \cdot 10^{-12}$$

[BNL E871 Collaboration]

ABGPS (09)

More Correlations in Flavour SUSY Models

Solution 3 to ε_K-Anomaly Abelian (AC)

Solution 1 to ε_K-Anomaly Non-Abelian (RVV)