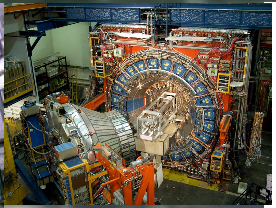
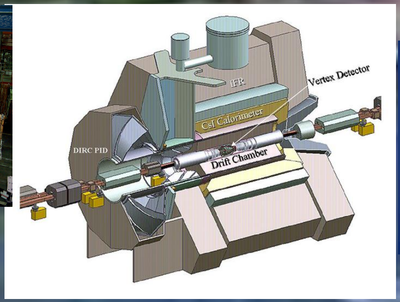
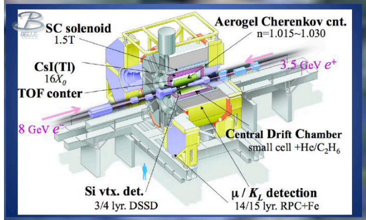
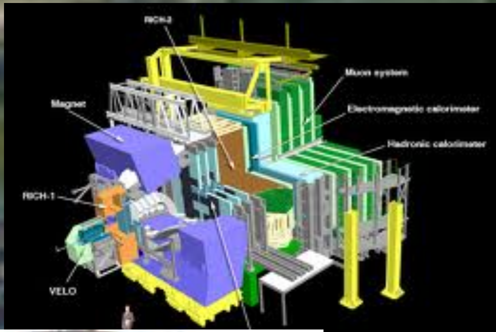
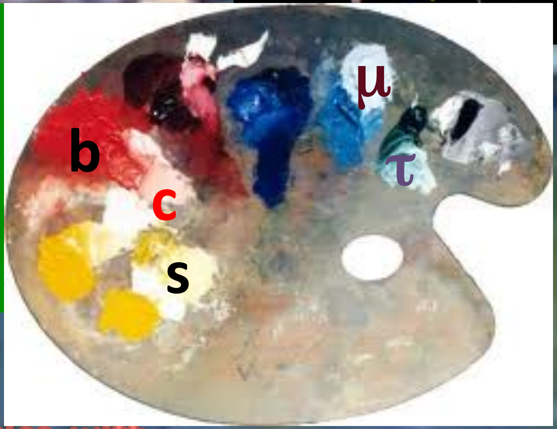








Physics using

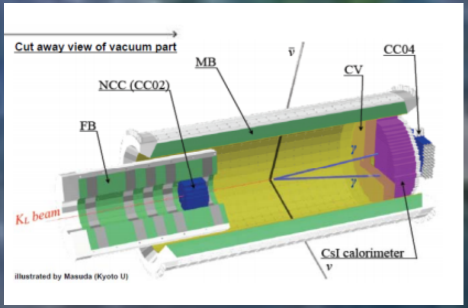


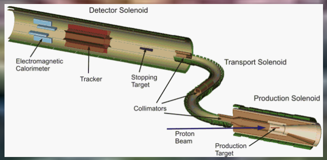
Marina Artuso
Syracuse University

an impressionist look at the wonderful world of flavor physics with apologies to the people who worked hard on several intriguing topics that I am not able to cover….

so much beautiful physics so little time!

Please refer to the contributions in the parallel sessions for more information and details





The ingredients of the Standard Model relevant to flavor physics

- In the Standard Model, mass arises as a dynamical coupling to the Higgs boson (Yukawa Lagrangian)
- The fields in the Yukawa Lagrangian are not mass eigenstates

⇒ Charged current couples the "up-type quarks" with a linear combination of "down-type" quarks

- QCD "clouds" experimental observables

$$\text{observable} = \sum_i \underbrace{C_i(\mu)}_{\text{UV}} \underbrace{\text{ME}_i(\mu)}_{\text{IR}} + \underbrace{\mathcal{O}\left(\frac{\Lambda_{\text{QCD}}}{\Lambda_{\text{EW}}}\right)^2}_{< 0.01\%}$$

non-perturbative QCD
⇒importance of lattice QCD

Puzzles that motivate new physics

- dark matter
- dark energy

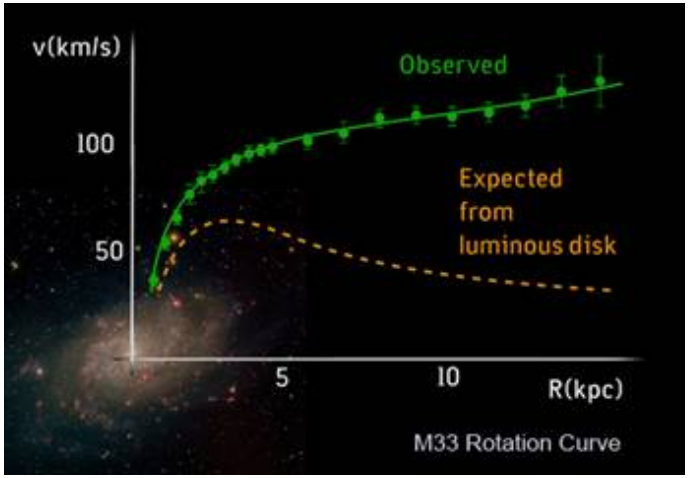
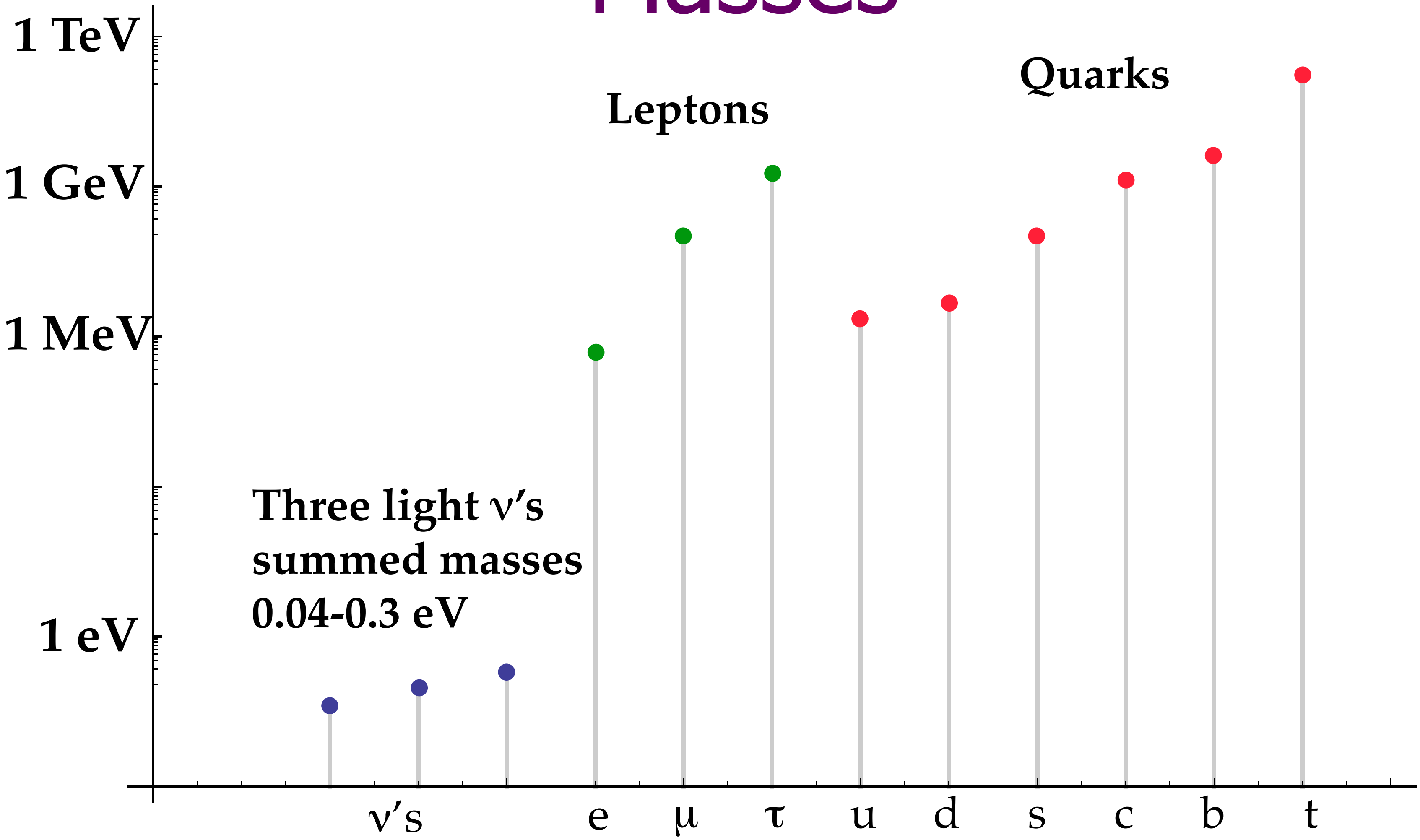


image of bullet cluster galaxy

- Hierarchy Problem: We don't understand how we get from the Planck scale of Energy ~10^{19} GeV to the Electroweak Scale ~100 GeV without "fine tuning" quantum corrections
- Baryon asymmetry of the universe

Masses



12 orders of magnitude differences not explained; t quark as heavy as Tungsten (so heavy that it deserves a talk of its own!)

Quark Mixing & CKM Matrix

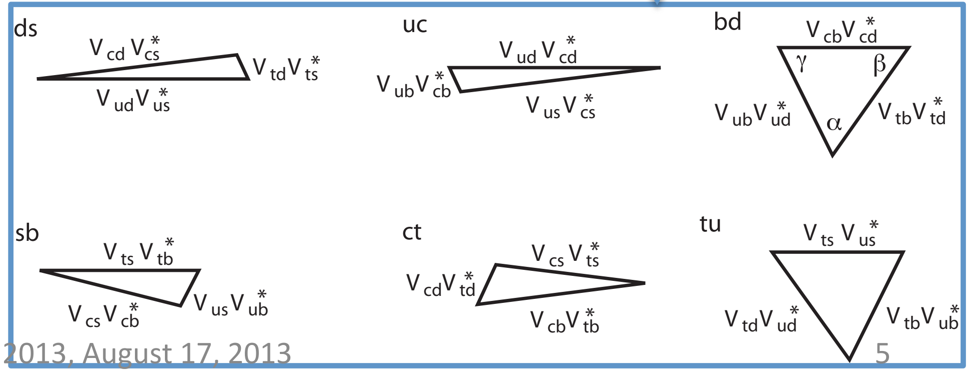
- In SM charge -1/3 quarks (d, s, b) are mixed
- Described by CKM matrix (also ν are mixed)

$$V_{\left(\frac{2}{3},-\frac{1}{3}\right)} = \left.\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}\right\}$$

$$= \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3\left(\rho-i\eta\right) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3\left(1-\rho-i\eta\right) & -A\lambda^2 & 1 \end{pmatrix} + O\left(\lambda^4\right)$$

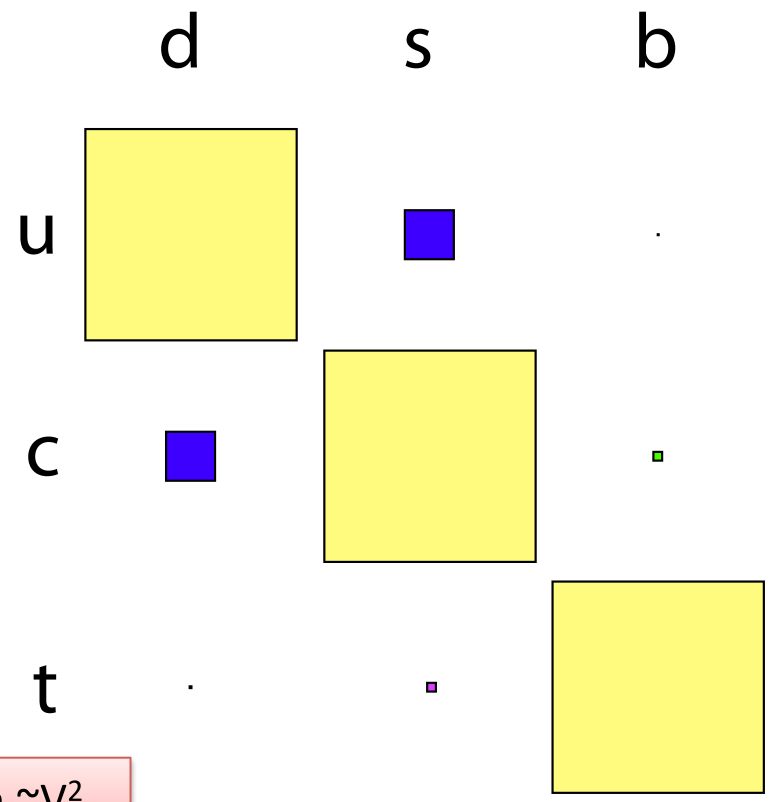
Unitary matrix described by 4 independent parameters, unitarity conditions commonly visualized by unitarity triangles

λ=0.225, A=0.8, constraints on ρ & η will be discussed, these are fundamental constants in SM



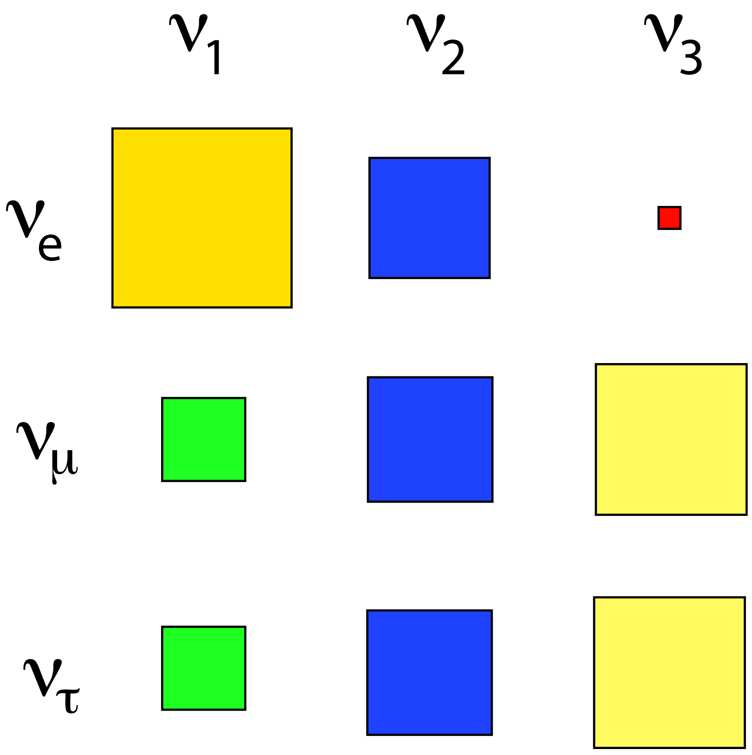
CKM vs. PMNS

CKM



Area ~V^2

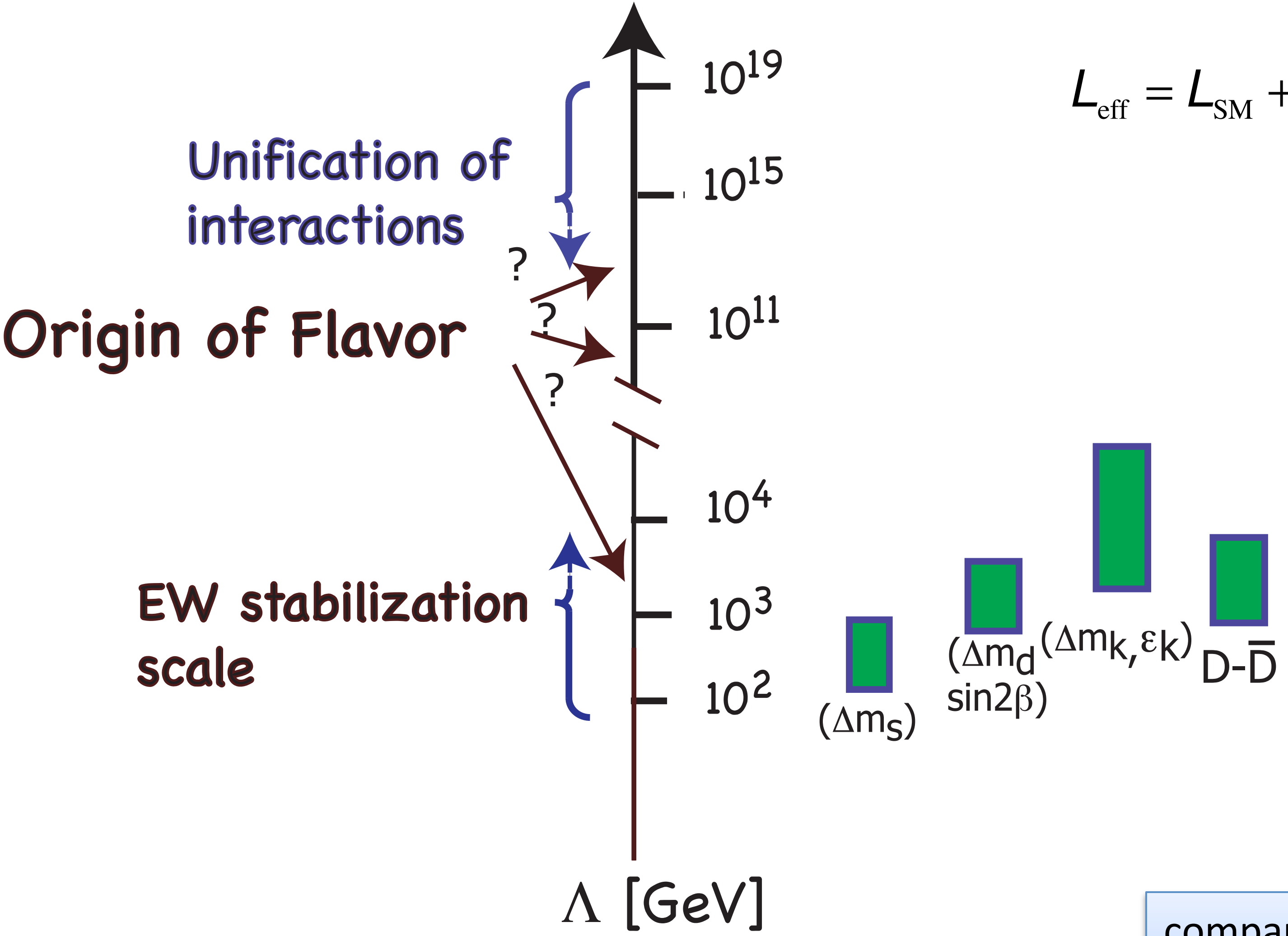
PMNS



Why these values? Are the two related? Are they related to masses?

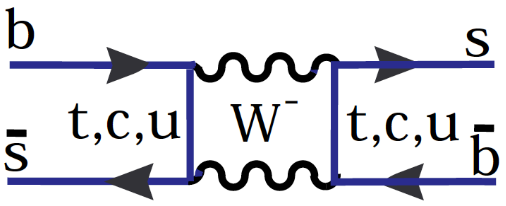
New physics mass scale and quark observables

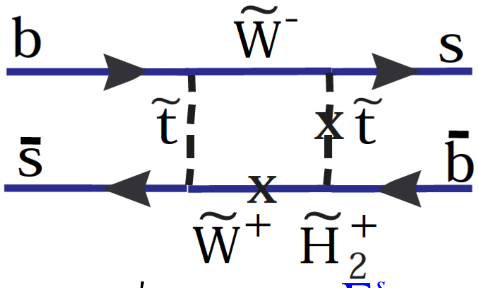
$$L_{\text{eff}} = L_{\text{SM}} + \frac{c_i}{\Lambda_i^2} O_i$$



comparable range from CLFV limits

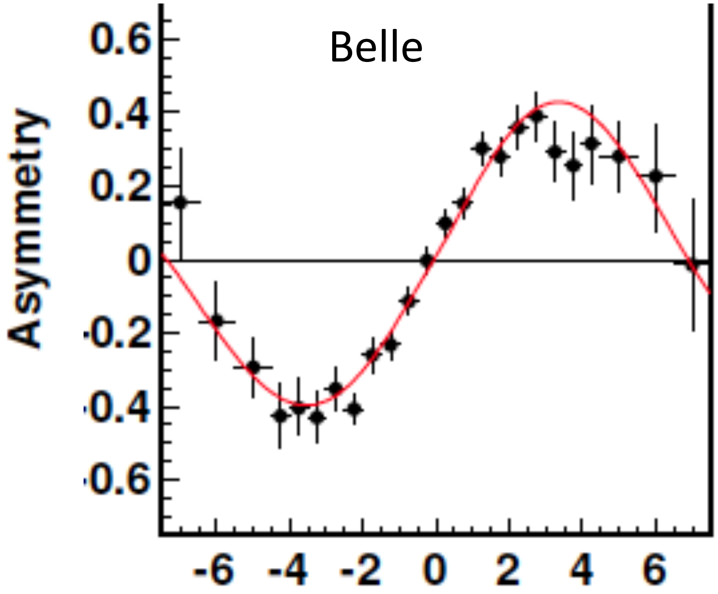
B mixing and CP violation





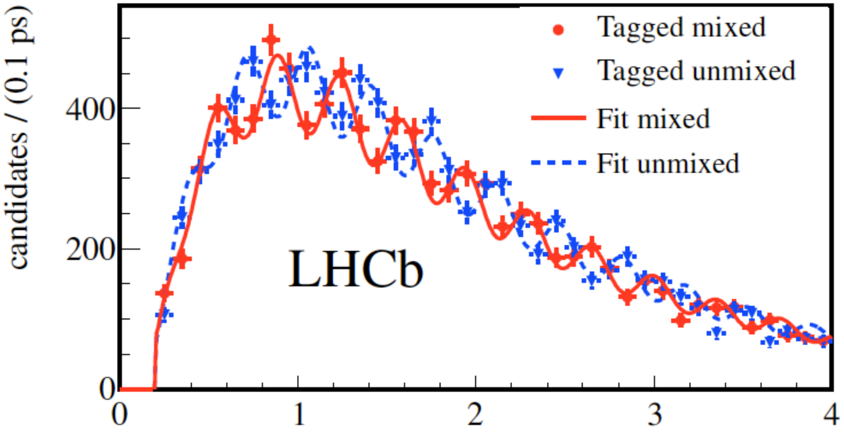
Time evolution of Flavor Eigenstates

$$i\frac{d}{dt}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} = \begin{pmatrix} M_{11}^s - i\frac{\Gamma_{11}^s}{2} & M_{12}^s - i\frac{\Gamma_{12}^s}{2} \\ M_{12}^{s*} - i\frac{\Gamma_{12}^{s*}}{2} & M_{22}^s - i\frac{\Gamma_{22}^s}{2} \end{pmatrix}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix}$$



PDG 2012

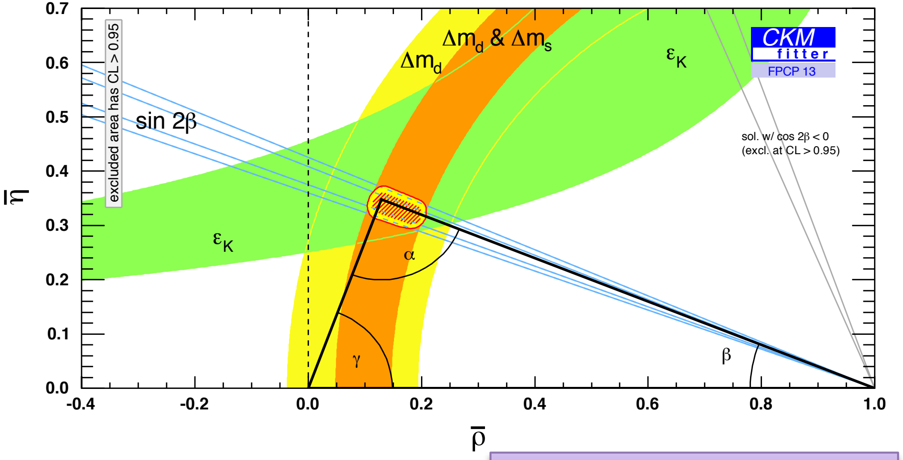
$$\Delta m_d = 0.507 \pm 0.004 \ \ \mathrm{ps}^{-1}$$



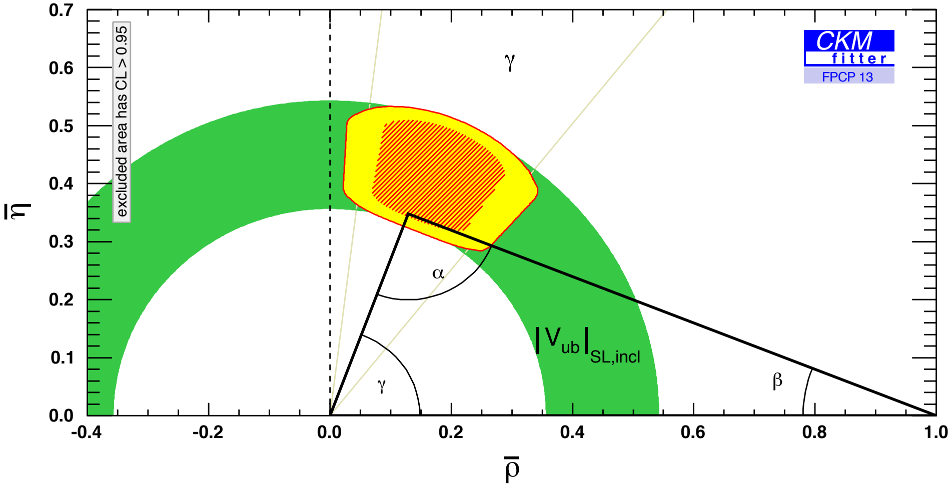
$$\Delta m_s = 17.768 \pm 0.023 \ \mathrm{(stat)} \pm 0.006 \ \mathrm{(syst)} \ \mathrm{ps}^{-1}$$

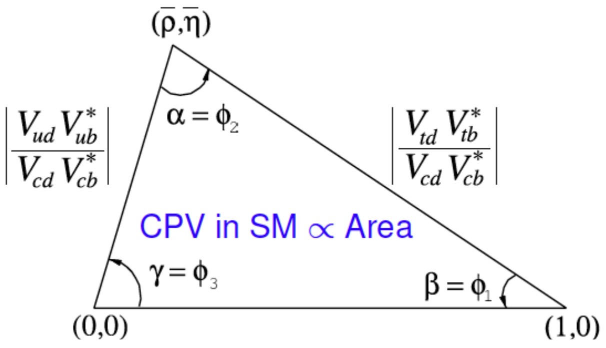
The αβγ triangle: triumph of the CKM picture?

Loop variables



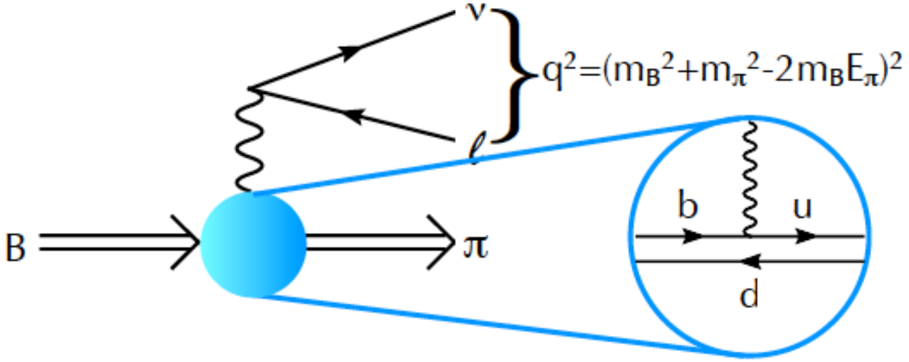
Tree variables



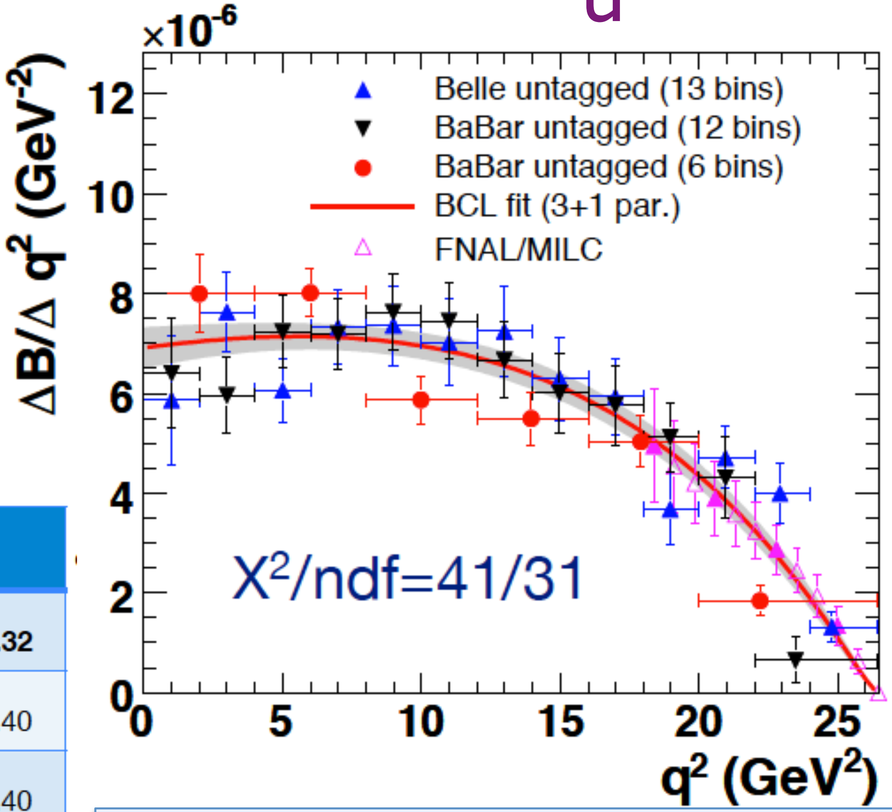


- Each colored shape represents an experimental constraint
- A comparison of CKM parameters extracted from "loop" variables and "tree" variables shows slight tension
- V_{ub} inclusive used to construct triangle from tree variables

$|V_{ub}|$ from exclusive $B \longrightarrow X_u \ell \nu$

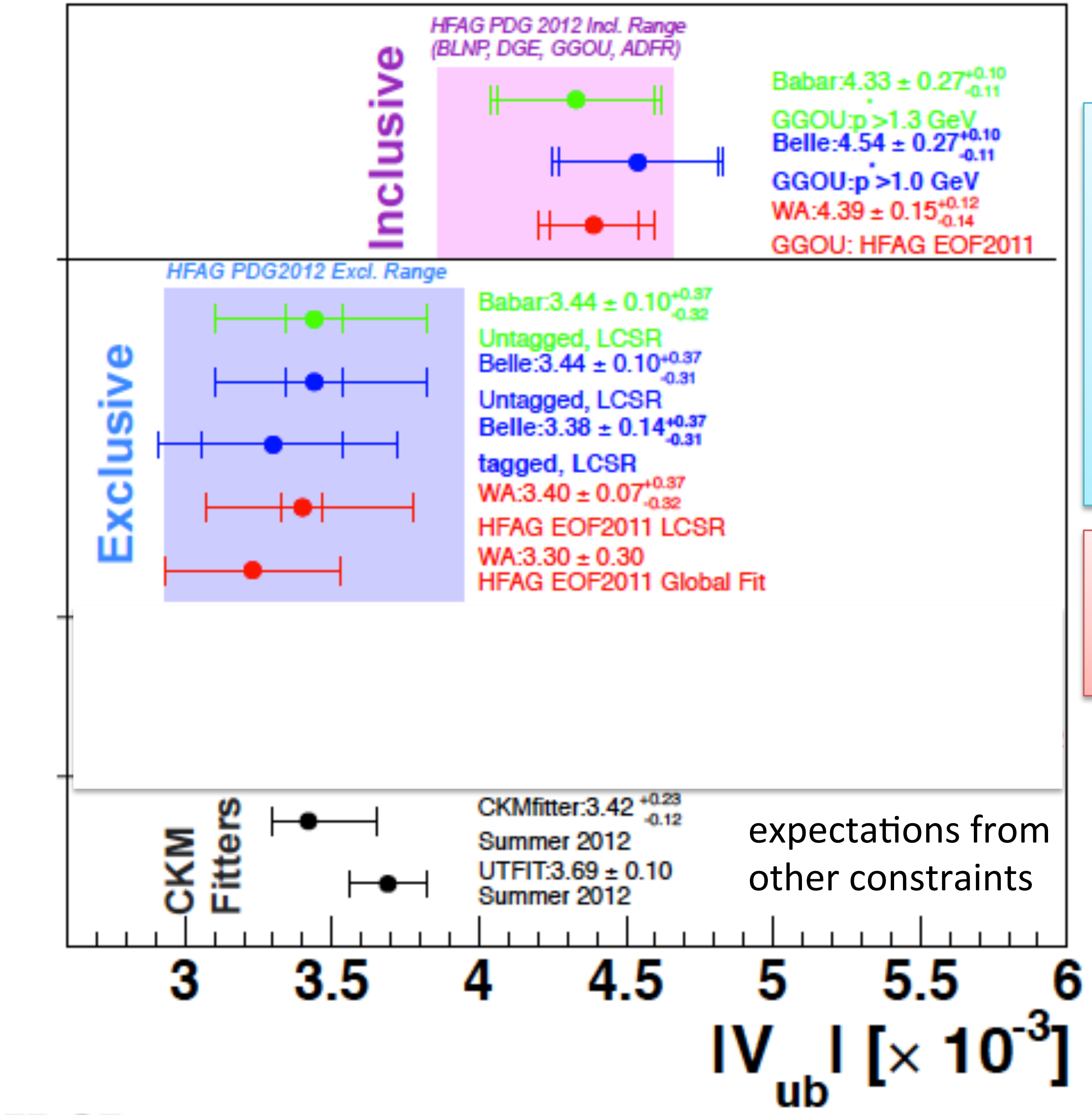


HFAG PDG 2013	q^2 (GeV/c)^2	$\lvert V_{ub}\rvert 10^3$
LCSR Siegen	**<12**	**$3.42\pm0.06^{+0.37}_{-0.32}$**
LCSR Ball/Zwicky	<16	$3.58\pm0.06^{+0.59}_{-0.40}$
LQCD HPQCD	>16	$3.49\pm0.09^{+0.60}_{-0.40}$
LQCD FNAL/MILC	>16	$3.33\pm0.08^{+0.37}_{-0.31}$
Global Fit (FNAL)	**All**	**3.26±0.29**
Global Fit (LCSR)	All	3.26±0.19



inclusive method uses lepton energy, M_u recoiling against $\ell\nu$ pair..

⇒challenge to suppress the $B \longrightarrow X_c \ell \nu$ background without cutting away too much of the phase space to control theory errors



expectations from other constraints

$|V_{ub}|$ inclusive

⇕

$|V_{ub}|$ exclusive

$(B\to\pi l\nu)$

tension ~3 σ

after decades of experimental and theoretical efforts

Tne saga of the V_{ub} tension

- Failure of LQCD & Sum rules to predicted exclusive form-factors?
- Failure of the HQE to evaluate correctly the hadronic matrix element?
  - General framework: non-quantified uncertainties such as assumption of quark-hadron duality
  - Analysis specific: effects of phase space cuts introduced to suppress Cabibbo favored semileptonic decay background
- New physics?

Λ_b lifetime & HQE

- ☐ V_{ub} inclusive relies upon HQE expansion

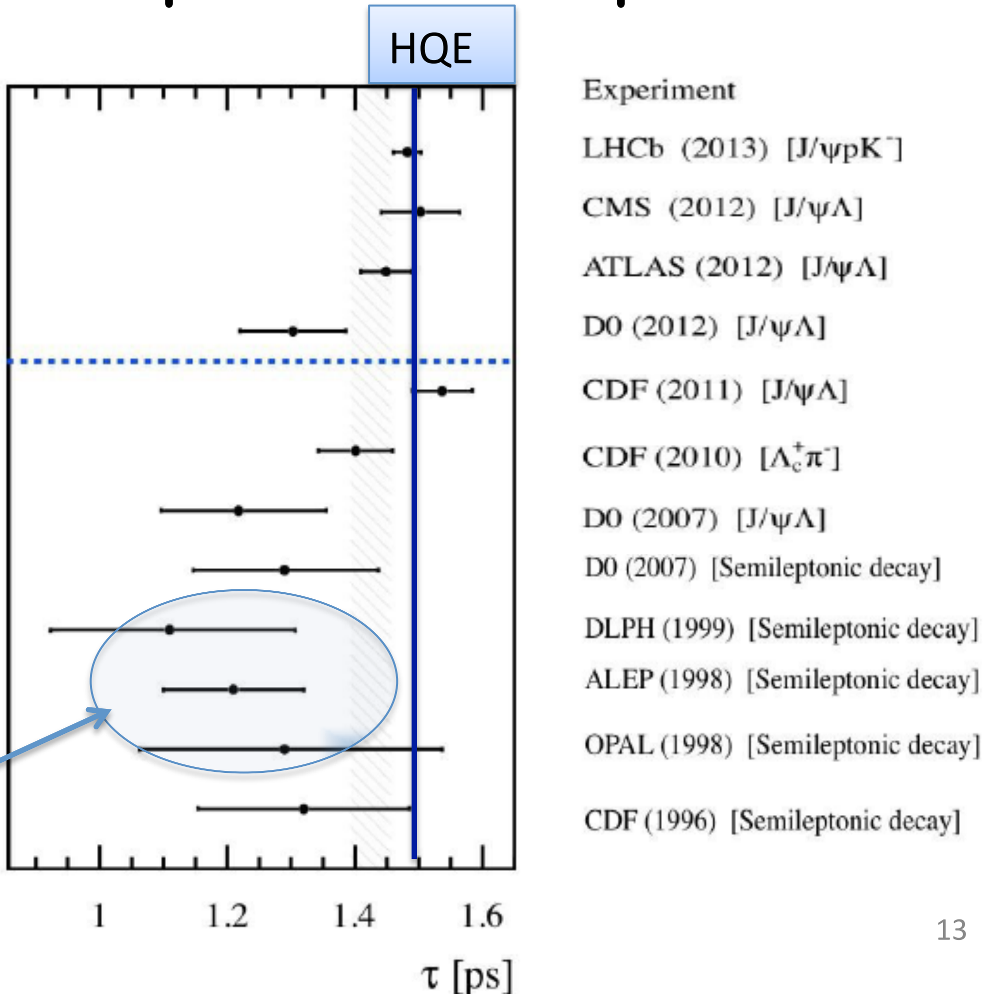
HQE predictions for b-hadron lifetimes

$$\frac{\tau(B^-)}{\tau(B_d)} = 1 + O(1/m_b^3)\,,$$

$$\frac{\tau(B_s)}{\tau(B_d)} = (1.00 \pm 0.01) + O(1/m_b^3)\,,$$

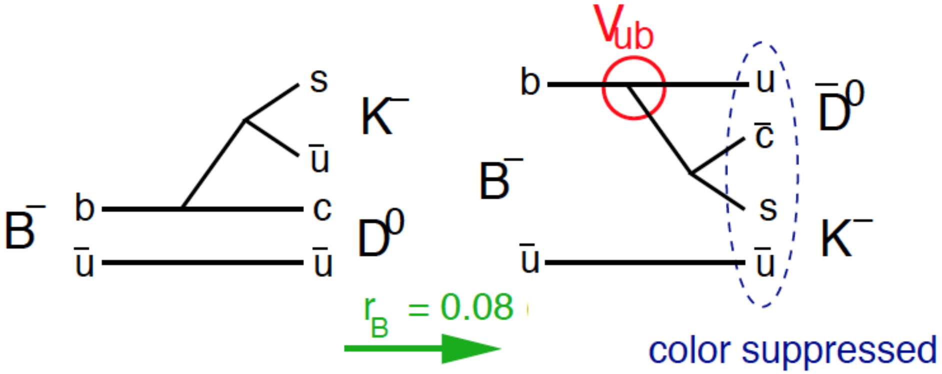
$$\frac{\tau(\Lambda_b)}{\tau(B_d)} = 0.98 + O(1/m_b^3)\,.$$

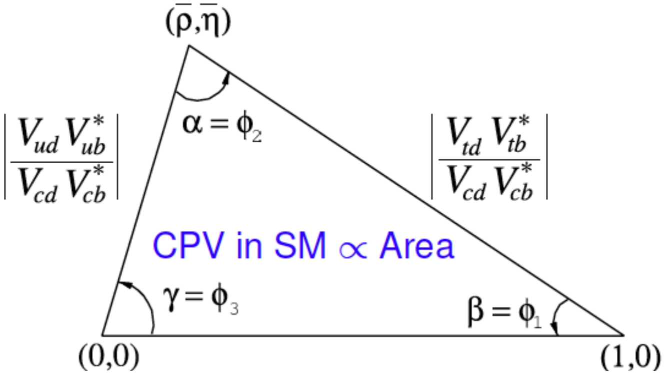
Neubert, Sachrajda
NPB 483,339(1997)



The LEP challenge to HQE

The angle γ





D/D are studied in final states accessible to both to achieve interference:

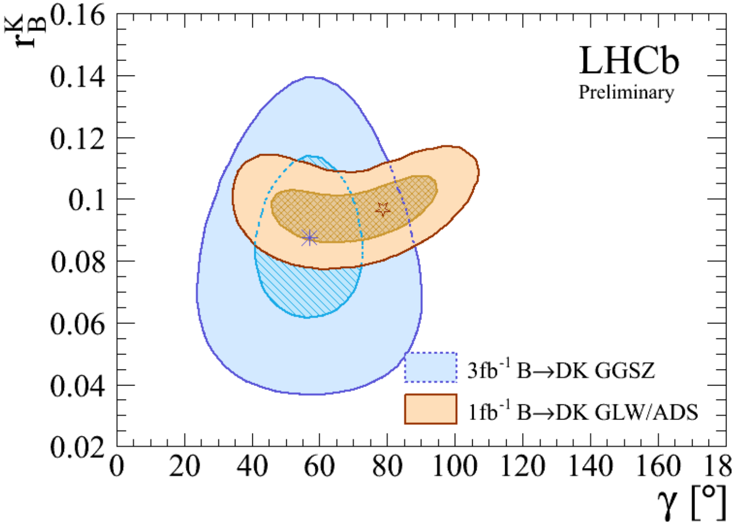
- ☐ GLW: CP eigenstates, e.g. K^+K^-,$\pi^+\pi^-$
- ☐ ADS: common flavor state (e.g $K^+\pi^-$)
- ☐ GGSZ: "Dalitz self-conjugate 3 body final state (e.g. $K_s$hh)

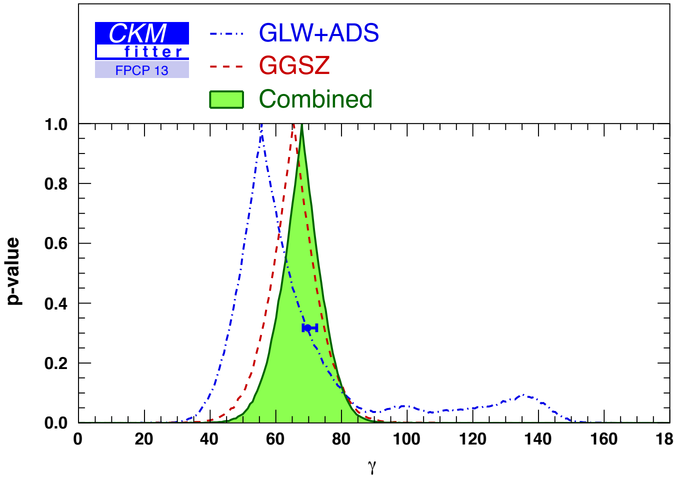
LHCb-CONF-2013-006, arXiv:1305:2050 subm PLB

☐ tree level interference of b→c$\bar{u}$s ($B^-\to D^0K^-$) and b→u$\bar{c}$s ($B^-\to D^0K^-$) ⇨ extremely clean theoretically

Angle γ: what we know so far

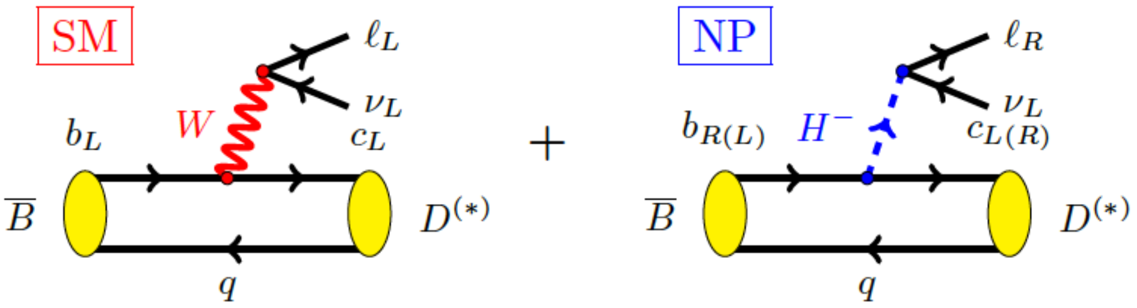
EXPERIMENT	**γ(◦)**
BaBar	68^{+15}_{-14}
LHCb	67±12
BELLE	69^{+17}_{-16}
UTFit	**68.6±3.6**
CKMFitter	$\mathbf{68.0^{+4.1}_{-4.6}}$





B→D$^{(*)}$τν

Window to new physics through tree level processes

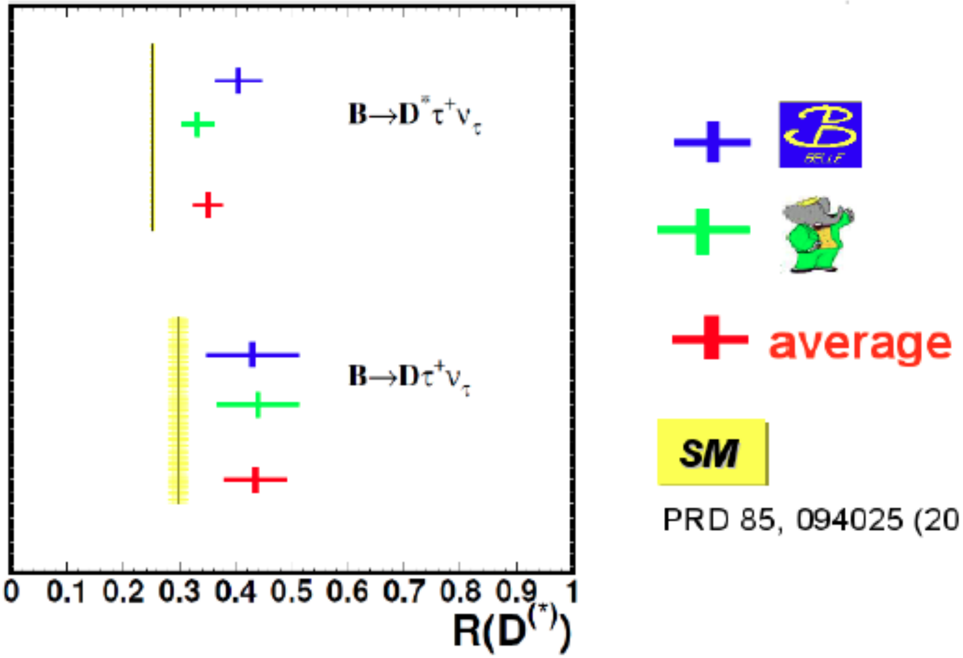


- B-decays with τ in the final state offer possibilities to study NP effects not present in processes with light leptons.
- Popular NP test via

$$R(D) = \frac{\mathcal{B}(B \to D\tau\overline{\nu}_\tau)}{\mathcal{B}(B \to D\ell\overline{\nu}_\ell)}, \quad R(D^*) = \frac{\mathcal{B}(B \to D^*\tau\overline{\nu}_\tau)}{\mathcal{B}(B \to D^*\ell\overline{\nu}_\ell)} \quad (\ell = e, \mu)$$

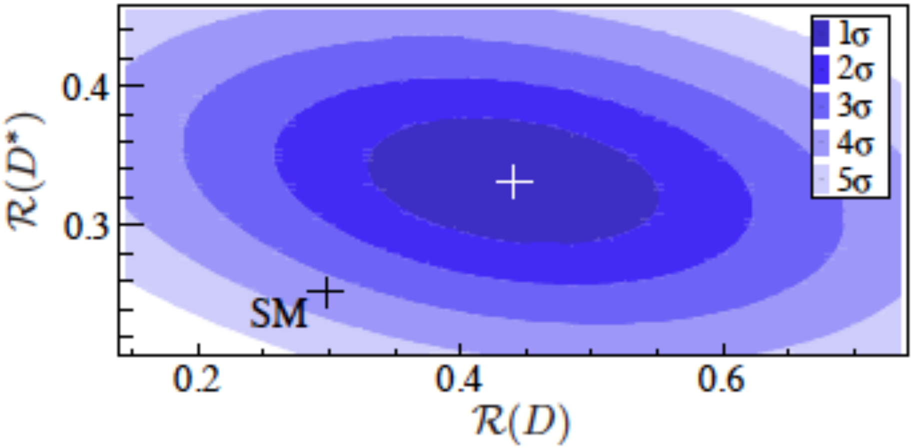
in order to cancel/reduce theoretical uncertainties in V_{cb}/FF.

Current status



PRD 85, 094025 (2012)

arXiV:1303.0571



Belle deviations from SM:

- Unofficial averages of prior Belle results:
  - (See A. Bozek, FPCP)
- R(D): 3.0 σ
- R(D^*): 1.4 σ
- Combined D/D^*: 3.3 σ

BaBar deviations from SM:

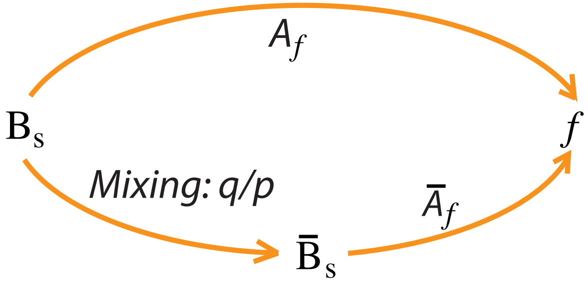
- R(D): 2.0 σ
- R(D^*): 2.7 σ
- Combined D/D^*: 3.4 σ

Combined for Belle / BaBar: 4.8 σ

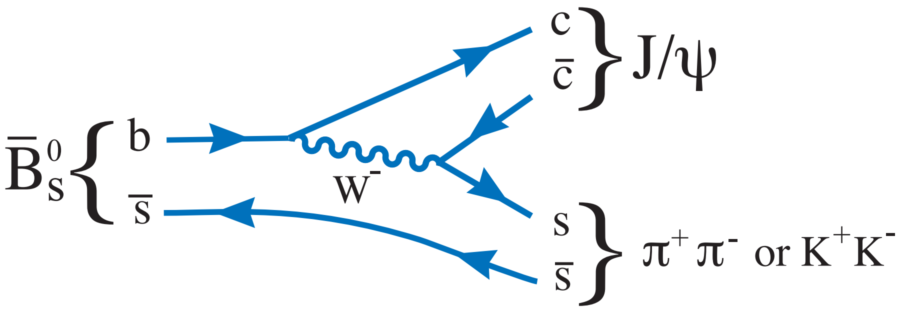
- ❑ still waiting for Belle final analysis
- ❑ Future: full angular analysis offer opportunity to search for new physics in a competitive way to the "loop strategy" Becirevic EPS 2013

CPV in $B_s \rightarrow J/\psi$ X

- CP violation means, for example, that a B will have a different decay rate than a B
- Can occur via interference between mixing & decay



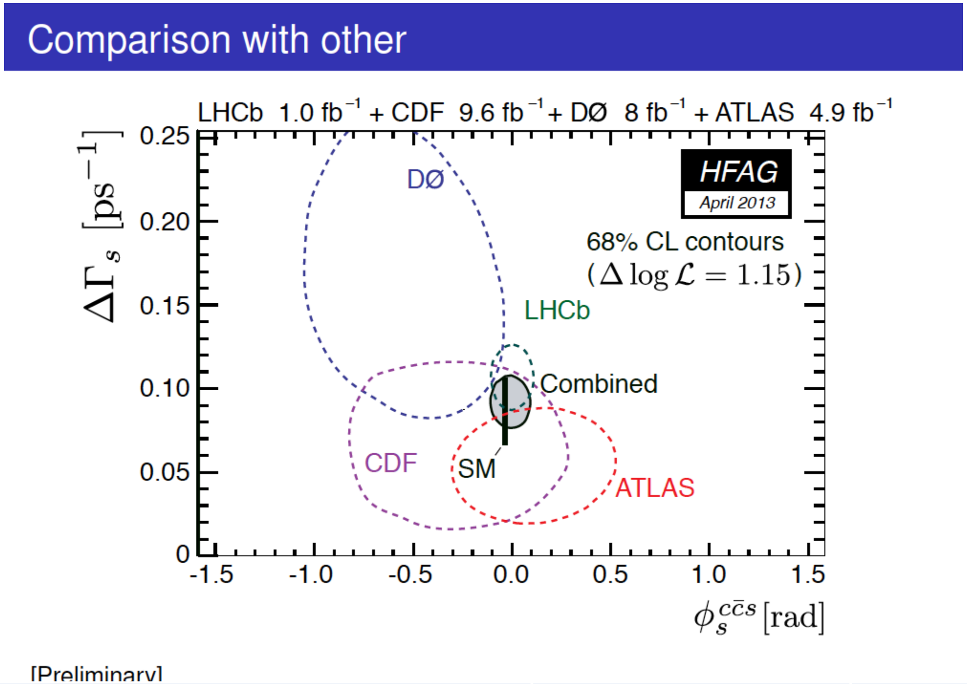
- For *f* =$J/\psi\ \phi$ (higher $\mathcal{B}$, but CP odd/even mixture need to be disentangled)
  or $J/\psi f_0$ smaller yields, but purely CP odd
- S-wave under Φ (mass window ±12MeV) ≈(4±2)°



- Small CPV expected, good place for NP to appear

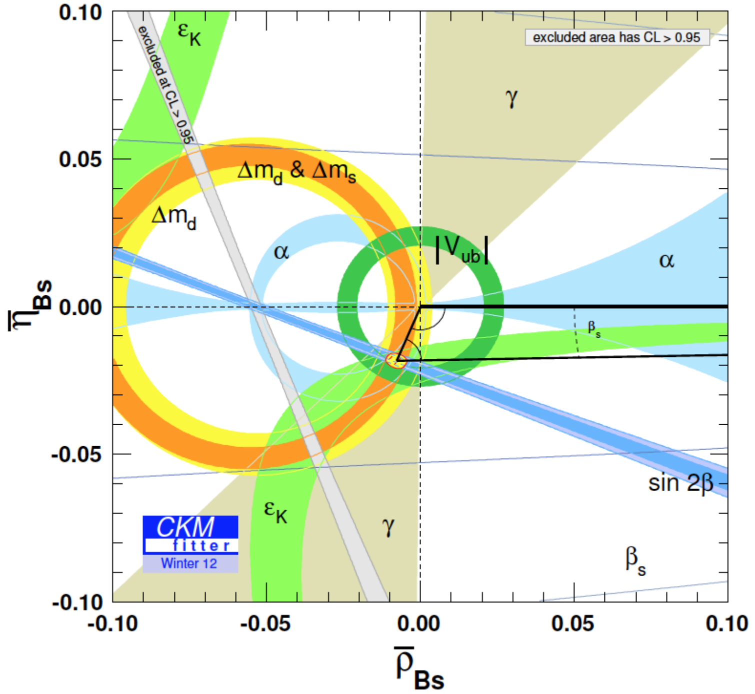
$$\varphi_s^{SM} \equiv -2\beta_s = -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -2^\circ$$

Current knowledge on Φ_s and the B_s triangle



Comparison with other

[Preliminary]



	CDF	D0	LHCb	ATLAS	CMS*)
$\int\mathcal{L}$ [fb^{-1}]	9.6	8.0	1.0	4.9	5.0
#$B_s \rightarrow J\psi KK(f_0)$	11K	5.6K	27.6K(7.4K)	22.7K	14.5K
εD^2 OS[%]	1.39±0.05	2.48±0.22	2.29±0.22	1.45±0.05	-
εD^2 SS[%]	3.5±1.4	-	0.89±0.18	-	-
σ_t[fs]	100	100	48	100	
ref	Prl 109(2012)171802	Prd 85(2012)032006	Prd87(2013)112010	Atlas-conf-2013.029	Cms-aps-bph-11-006

CP violation in mixing

- flavor specific asymmetry, typically accessed through semileptonic decays

$$a_{\rm sl}^{s} \equiv \frac{\Gamma(\overline{B}{}^0_s \to D_s^- \mu^+ \nu_\mu) - \Gamma(B^0_s \to D_s^+ \mu^- \overline{\nu}_\mu)}{\Gamma(\overline{B}{}^0_s \to D_s^- \mu^+ \nu_\mu) + \Gamma(B^0_s \to D_s^+ \mu^- \overline{\nu}_\mu)} = \frac{1-(1-a_s)^2}{1+(1-a_s)^2} \approx a_s$$

Most recent (and most precise) measurements

$$a_{\rm sl}^{s}[\mathrm{LHCb}] = (-0.06 \pm 0.50 \pm 0.36)\%$$

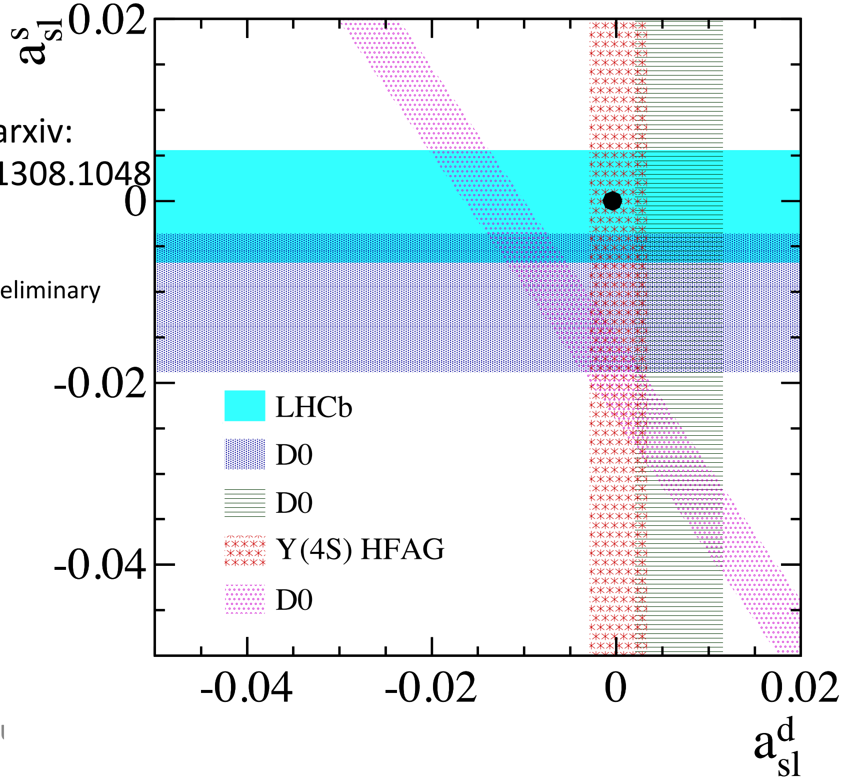
$$a_{\rm sl}^{d}[\mathrm{BaBar}] = (0.06 \pm 0.16^{+0.36}_{-0.32})\%$$

SM predictions

A.Lenz
arXiv:1205.1444

$$a_{sl}^{s} = (1.9 \pm 0.3) \times 10^{-5}$$

$$a_{sl}^{d} = (-4.1 \pm 0.6) \times 10^{-4}$$

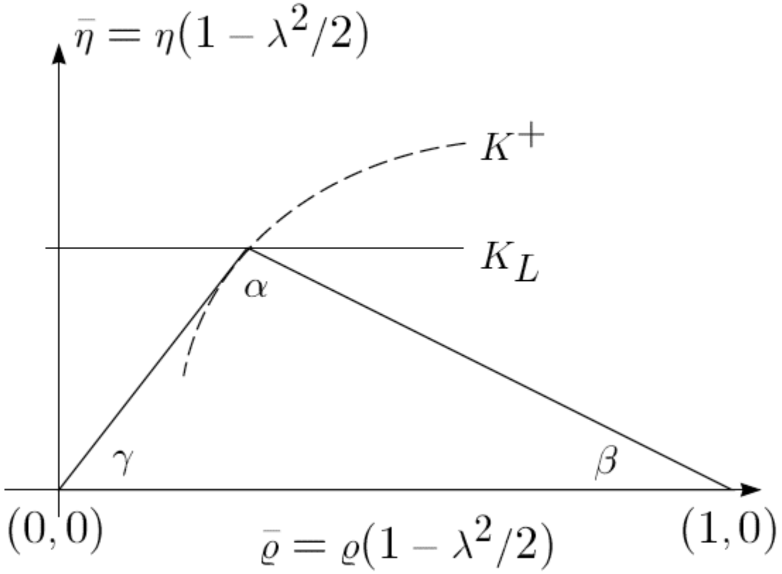


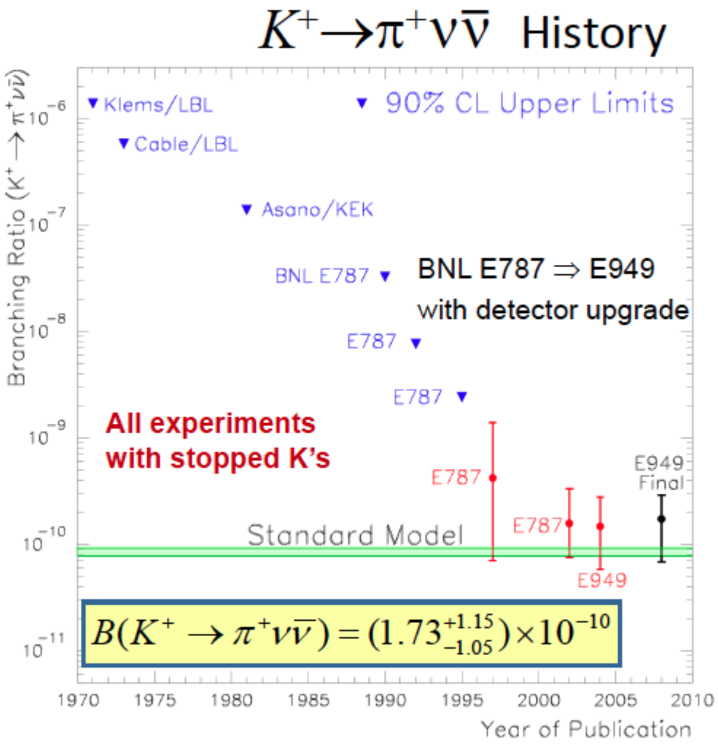
arxiv: 1308.1048

preliminary

The K unitarity triangle

Constraints from K→$\pi\nu\bar{\nu}$





BNL E787/949 observed a total of 7 signal events.

$$B(K^+ \to \pi^+\nu\bar{\nu})_{\mathrm{SM}} = (7.8 \pm 0.8)\times 10^{-11}$$

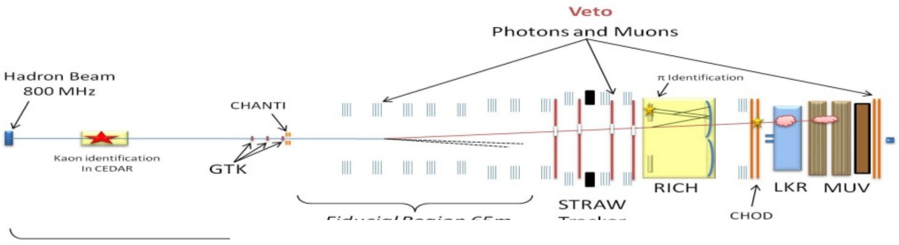
$$B(K_L^0 \to \pi^0\nu\bar{\nu})_{\mathrm{SM}} = (2.4 \pm 0.4)\times 10^{-11}$$

Brod, Gorbahn, and Stamou, PR D **83**, 034030(2011)

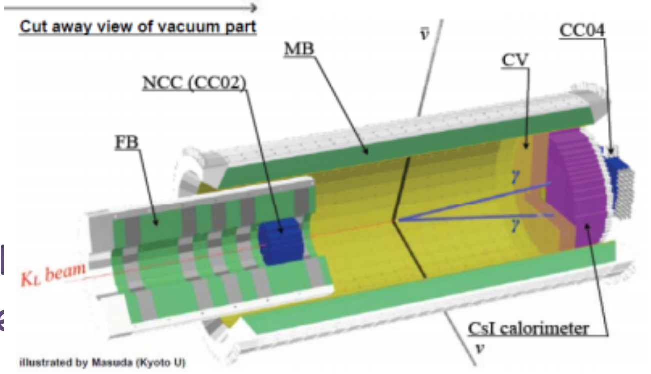
largest uncertainties CKM factors ➪precision will improve by a factor of ~ 2

Future prospects

- CERN NA-62 ($K^+ \longrightarrow \pi \nu \bar{\nu}$)
  - Decay-in-flight experiment
    - Complementary technique to ORKA
  - Expect 10% measurement of BR
    - ~55 events per year (SM)
    - ~7 bg events per year
    - ~100 total events



- J-PARC E14 "KOTO" ($K^0 \longrightarrow \pi \nu \bar{\nu}$)
  - Pencil beam decay-in-flight experiment
  - Improved J-PARC beam line
  - 2nd generation detector building on E391 at KE
  - Re-using KTeV CsI crystals to improve calorime
  - Expect ~3 signal events (SM rate)

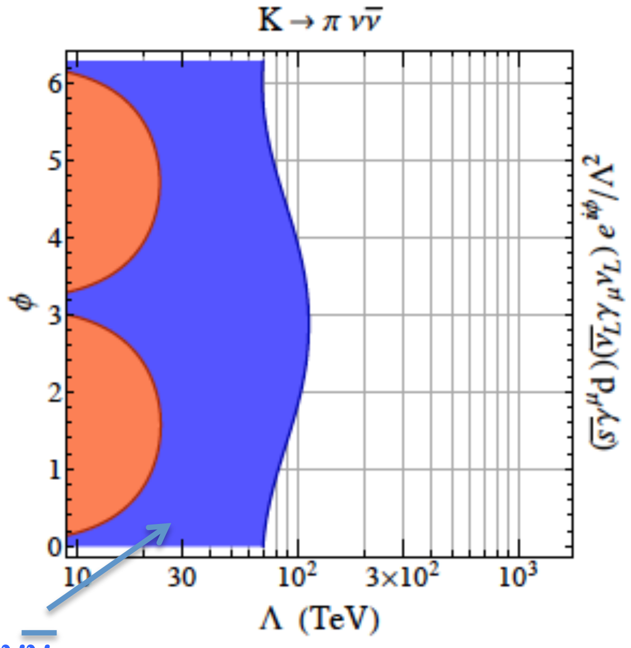


- ORKA:precision measurement of $\mathcal{B}(K^+ \rightarrow \pi^+ \nu\nu)$ with ~**1000 events** using the FNAL Main Injector, expected BR uncertainty matches Standard Model uncertainty

$K\longrightarrow\pi\nu\nu$ and the NP scale

Altmannshofer, ANL IF workshop

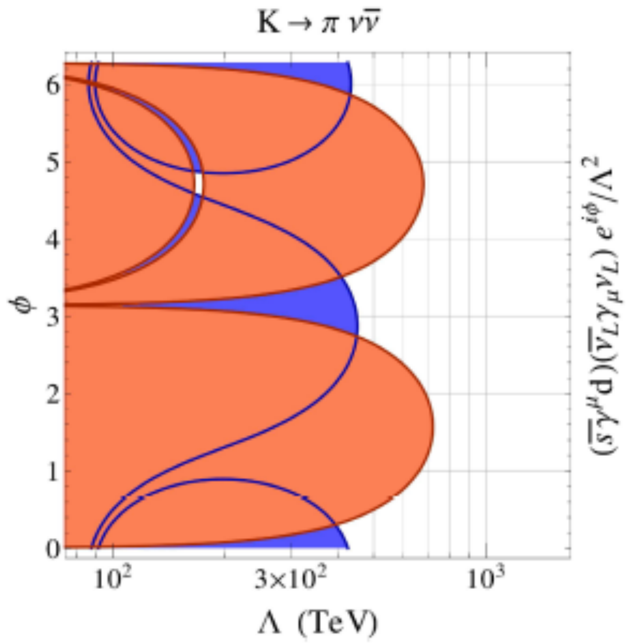
current situation



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

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

assuming 5% measurements of both modes



Scale of 100 TeV already probed by $K^+\longrightarrow\pi^+\nu\bar{\nu}$

Charm Mixing

- Various experiments have seen evidence for D^o-$\overline{D}^o$ mixing, but none with significance $>5\sigma$.
- $D^{*+}\rightarrow\pi^+D^o$ provides an initial flavor tag
- "Wrong-sign" (WS) D^o can appear via mixing or doubly-Cabbibo suppressed decay (DCS).
- DCS follows ~$\exp(-t/\tau_{D^o})$.
  Define R_D=DCS/(Cabibbo favored). Mixing is parameterized as x' & y', functions of Δm & $\Delta\Gamma$.
- Measure Wrong-sign/Right-sign, R(t)= (WS/RS)

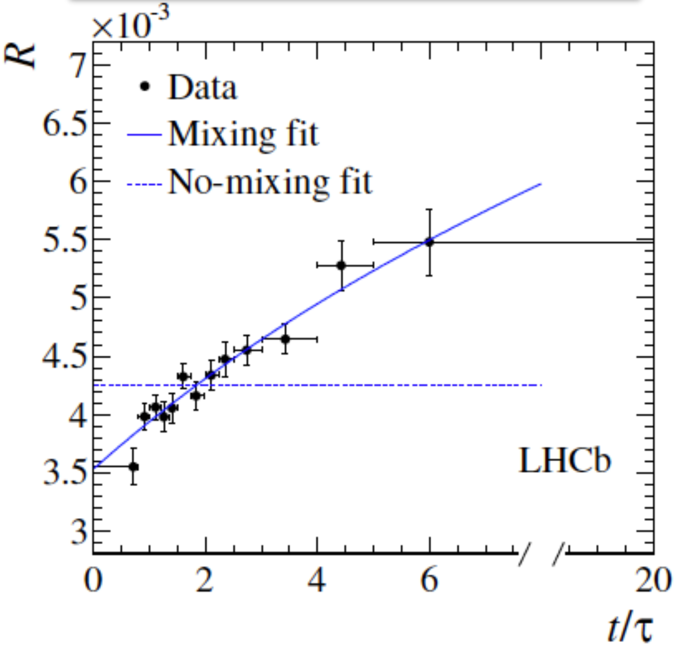
$$R(t) \approx R_D + \sqrt{R_D}\, y' \,\frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2$$

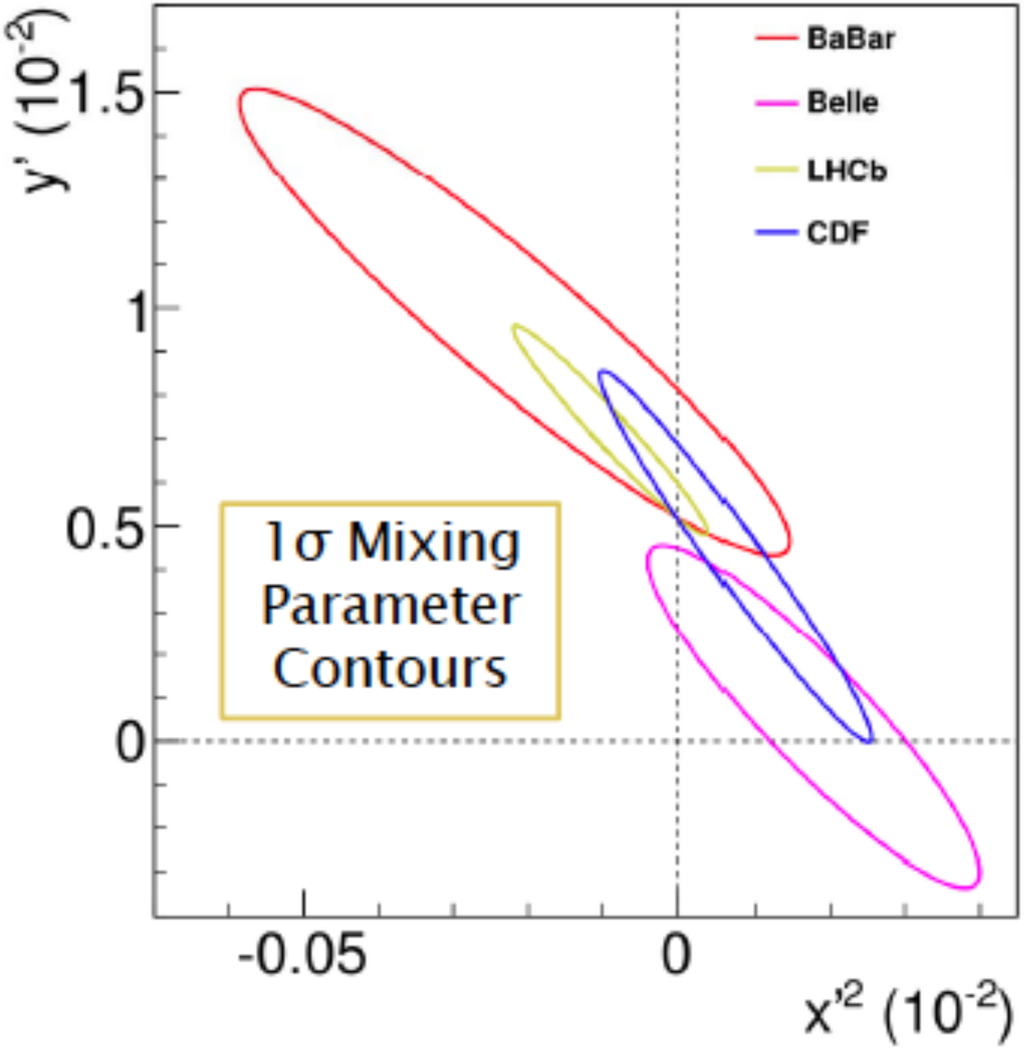
Charm mixing

LHCb: no mixing excluded at 9.1 σ, systematic errors are included

$y' = (0.72 \pm 0.24)\%$

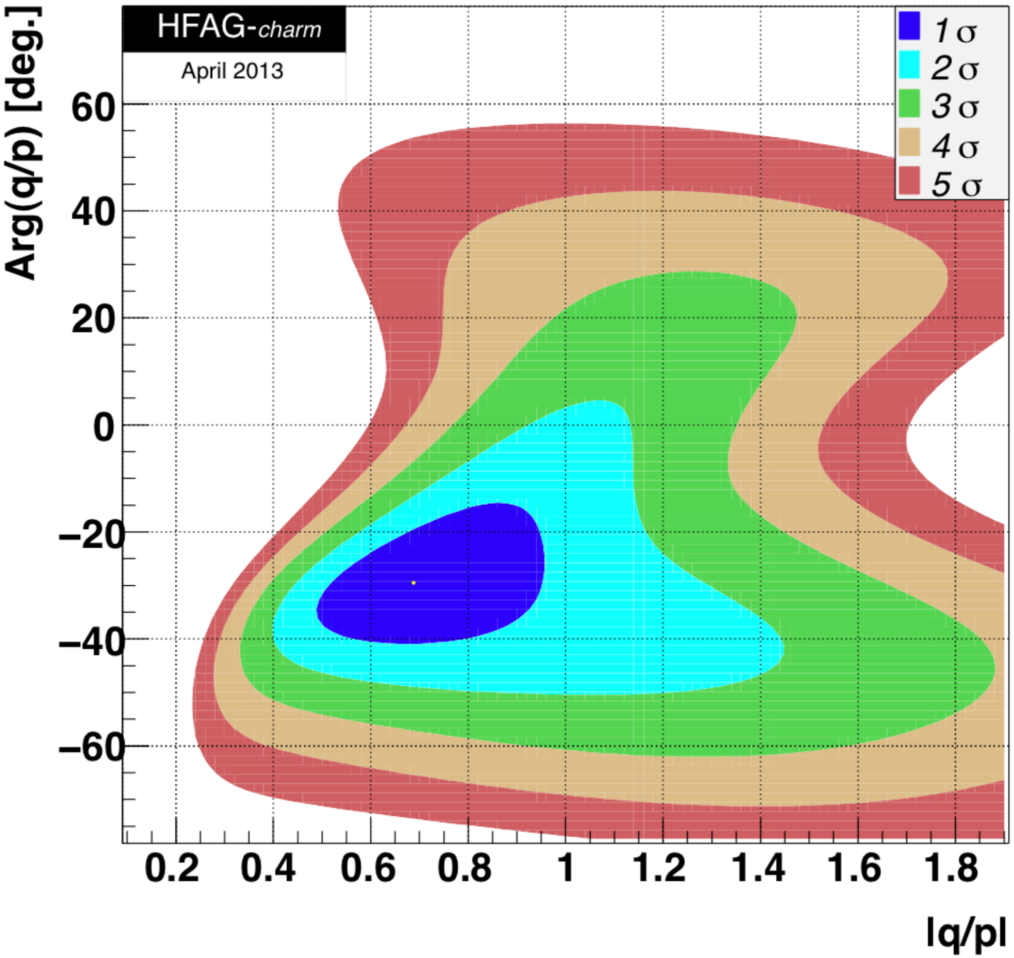
$x'^2 = (-0.9 \pm 1.3) \times 10^{-4}$





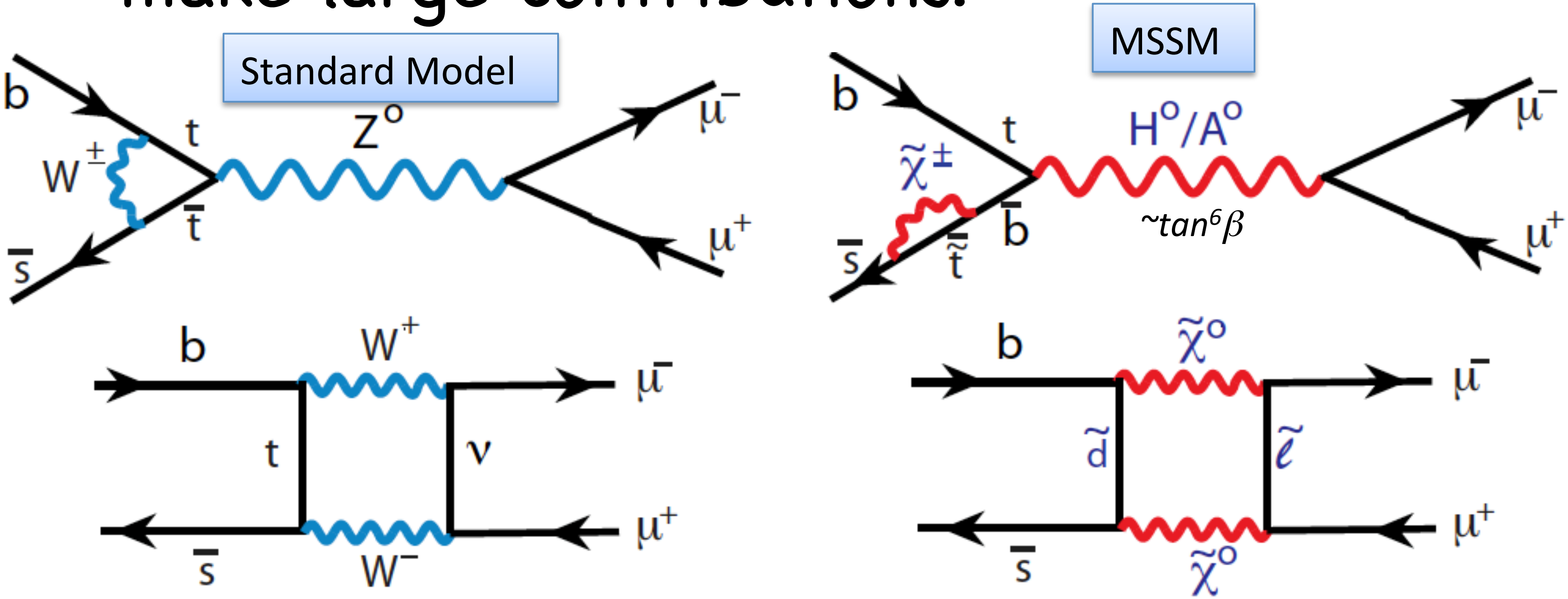
CPV in D-$\bar{D}$ mixing?

- ❑ Only meson mixing generated by down-type quarks (in SUSY up-type squarks in the loop!)
- ❑ Possible connection to FCNC in top decays
- ❑ Uncertainty of |q/p| ~0.2⇒lots of room for new physics!



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

- SM "experimental" branching ratio is $(3.6\pm0.2)\times10^{-9}$ [Buras arXiv:1012.1447], NP can make large contributions.

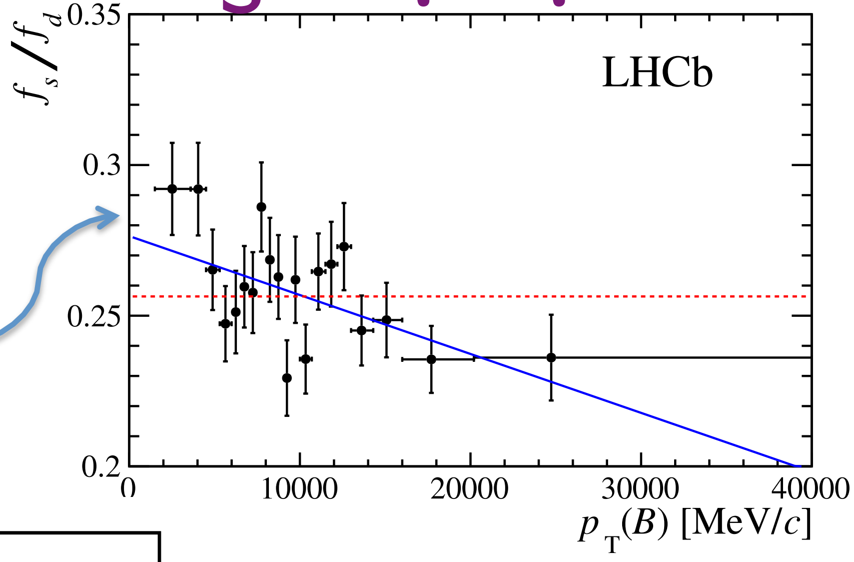


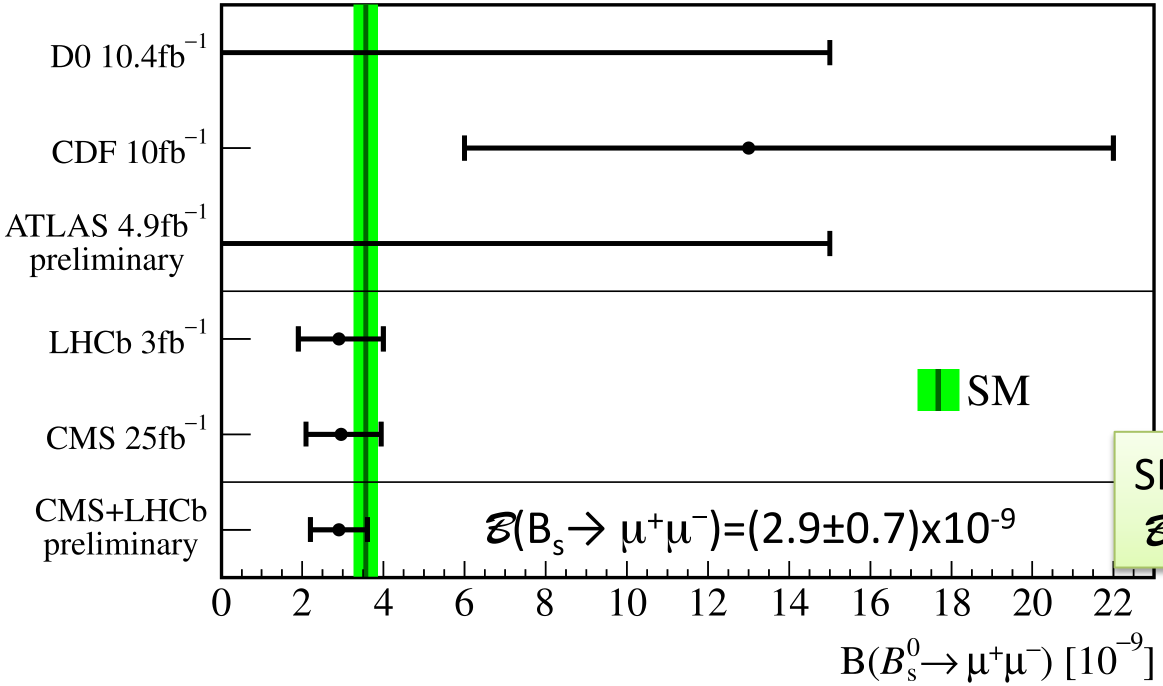
- Many NP models possible, not just Supersymmetry

Observation of $B_s \to \mu^+\mu^-$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \frac{N[B_s^0 \to \mu^+\mu^-]}{N[B_s^0]}$$

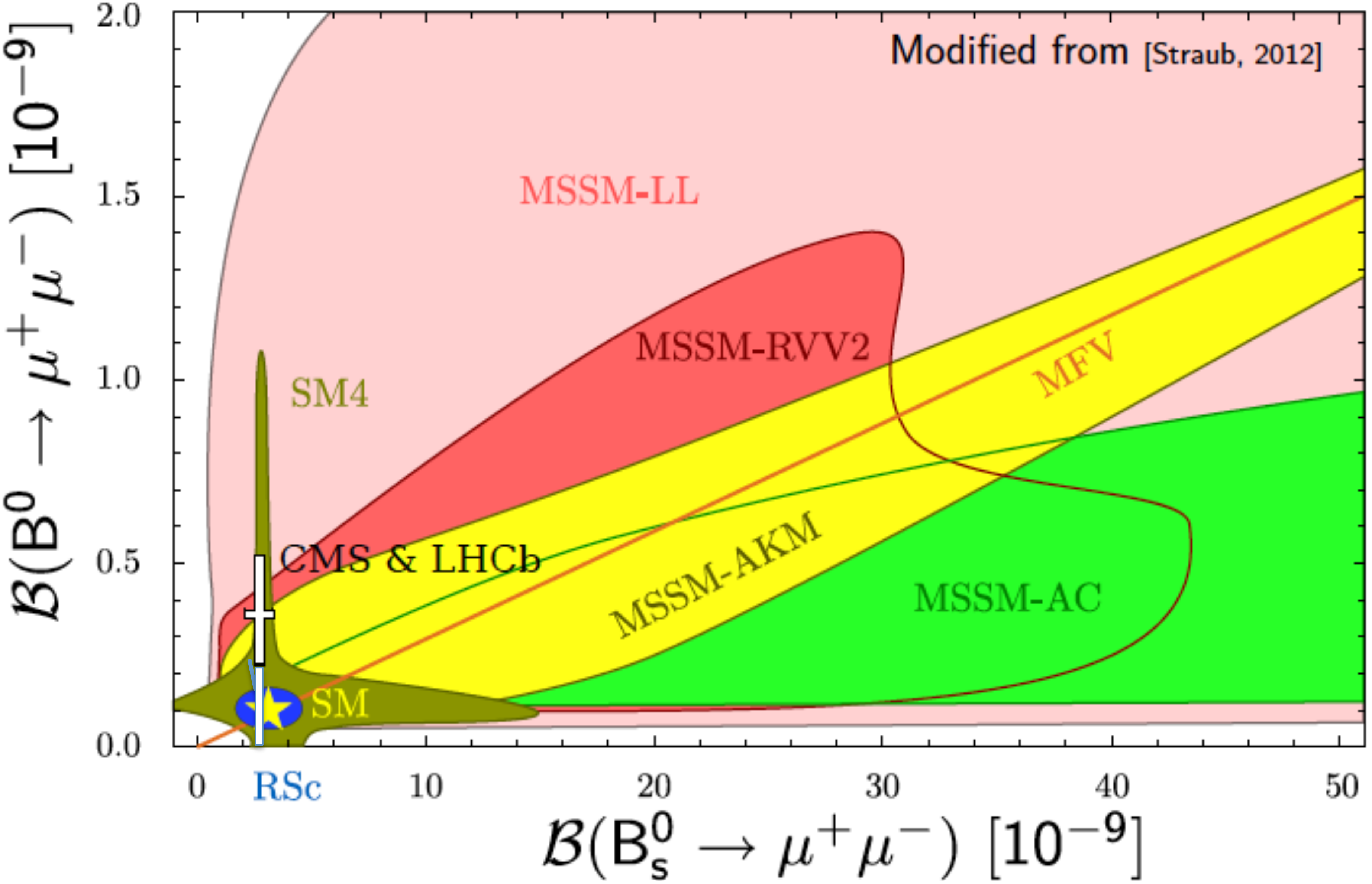
need normalization mode:
LHCb uses $B^0 \to K^+\pi^-$ and $B^+ \to J/\psi K^+$
& measures the $B_s/B_{d,u}$ production ratio $f_s/f_{d,u}$
CMS uses $f_s/f_{d,u}$ from LHCb





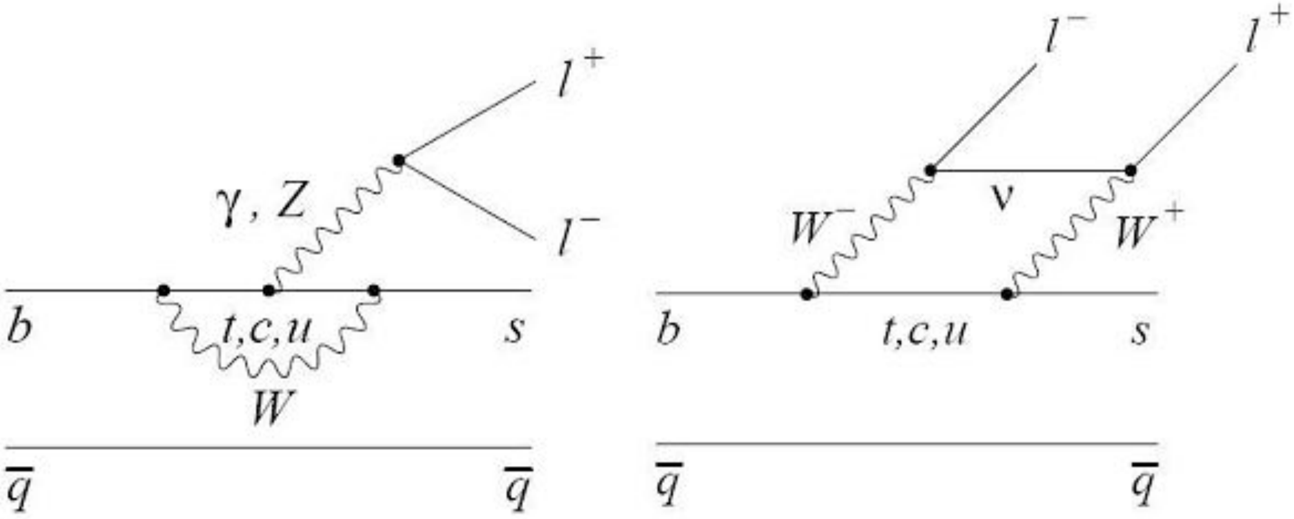
$\mathcal{B}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$

SM predictions:
$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.56 \pm 0.17) \times 10^{-9}$

Modified from [Straub, 2012]
MSSM-LL
MSSM-RVV2
SM4
MFV
CMS & LHCb
MSSM-AKM
MSSM-AC
SM
RSc
2.0
1.5
1.0
0.5
0.0
0
10
20
30
40
50
$\mathcal{B}(B^0 \to \mu^+\mu^-)$ $[10^{-9}]$
$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ $[10^{-9}]$

$B \to K^{(*)}\ell^+\ell^-$

- Similar to $K^*\gamma$, but more decay paths



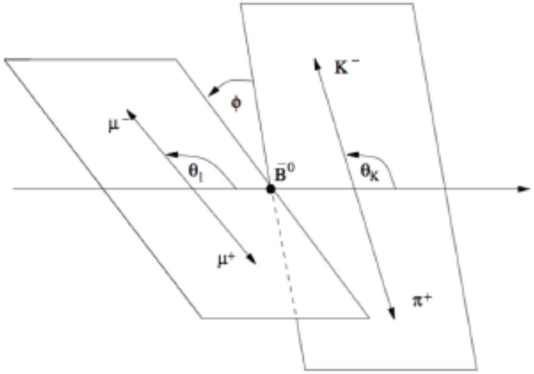
+ new particles in loops

- Several variables can be examined, e.g. muon forward-backward asymmetry, A_{FB} is well predicted in SM
- Not all the variables are equal! The never ending struggle to tame strong interaction effects!

New observables in B→K$^{(*)}$l$^+$l$^-$

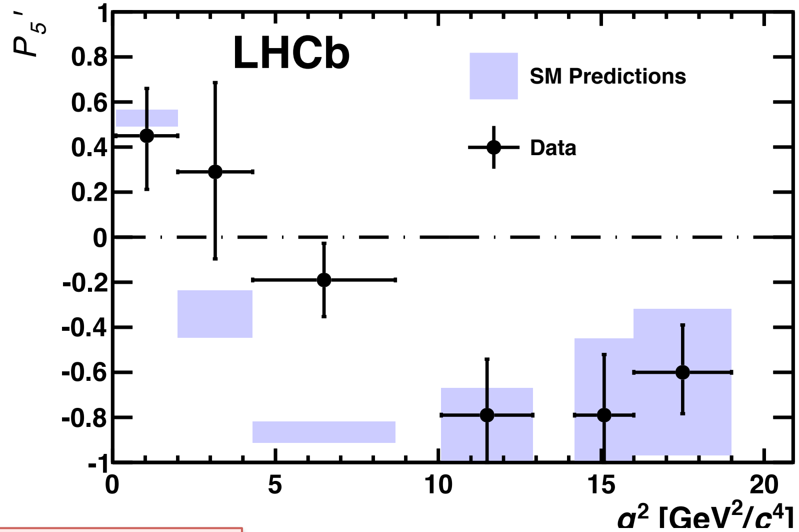
Goal: express differential decay rate in terms of parameters that are less sensitive to the hadronic matrix element uncertainty ⇔ prevent NP from hiding under strong interaction effects

$$\begin{aligned}\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[&\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell \\ &- F_L\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + \\ &\sqrt{F_L(1-F_L)}P_4'\sin 2\theta_K\sin 2\theta_\ell\cos\phi + \sqrt{F_L(1-F_L)}P_5'\sin 2\theta_K\sin\theta_\ell\cos\phi + \\ &(1-F_L)A_{Re}^T\sin^2\theta_K\cos\theta_\ell + \sqrt{F_L(1-F_L)}P_6'\sin 2\theta_K\sin\theta_\ell\sin\phi + \\ &\sqrt{F_L(1-F_L)}P_8'\sin 2\theta_K\sin 2\theta_\ell\sin\phi + (S/A)_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\ \Big]\end{aligned}$$



New from the press

- ☐ 3.7σ discrepancy with respect to the Standard Model in the region $4.3<q^2<8.68$ GeV^2
- ☐ 2.5σ discrepancy with respect to the Standard Model in the region $1.0<q^2<6.0$ GeV^2
- ☐ 0.5% probability (2.8σ) to observe such a deviation considering 24 independent measurements



Jaeger,Kamalich SM calculation

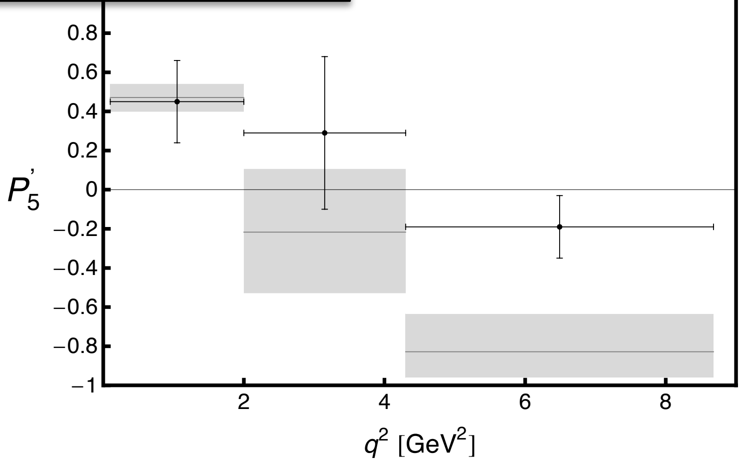
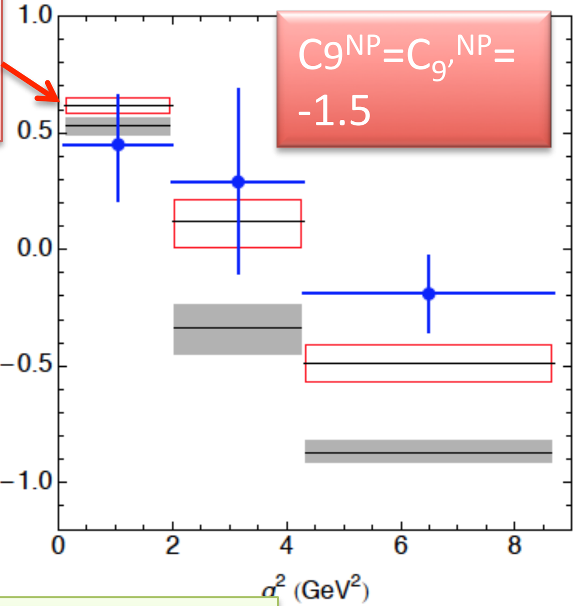
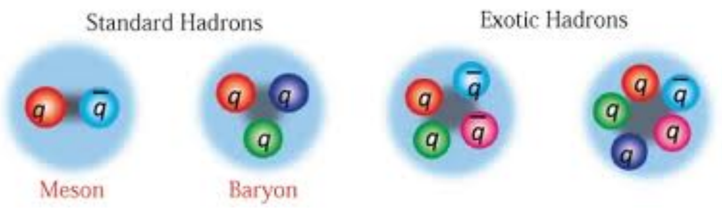


Illustration of possible NP interpretation: Descotes-Genon, Matias, Virto arXiv: 1307.5683



$C9^{NP}=C_{9'}{}^{NP}=-1.5$

To be continued!

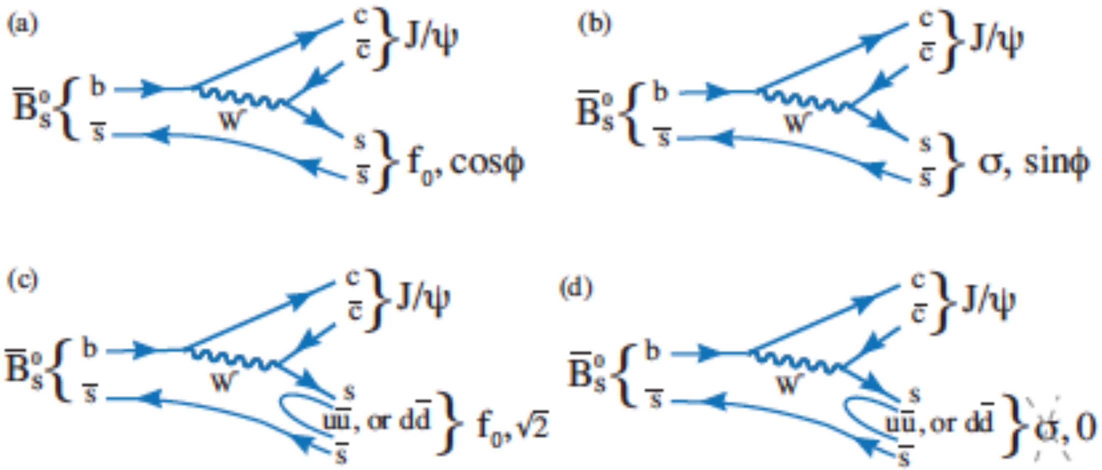


A QCD interlude

- theory perspective:
  - lattice QCD is poised to predict mass and decay properties of ordinary hadrons, but also exotica (glueballs, tetraquarks…)
  - "Multiquark correlations inside hadrons can have a significant and in some cases even striking impact on the hadron spectrum. We show how such correlations in general, and mesons with a dominant tetraquark content in particular, emerge holographically in the AdS/QCD framework." Forkel arXiv:1206.5745
- experimental perspective:
  - Nature of scalar nonet still a mystery
  - zoo of exotic X,Y,Z particles containing b and c quarks are being discovered

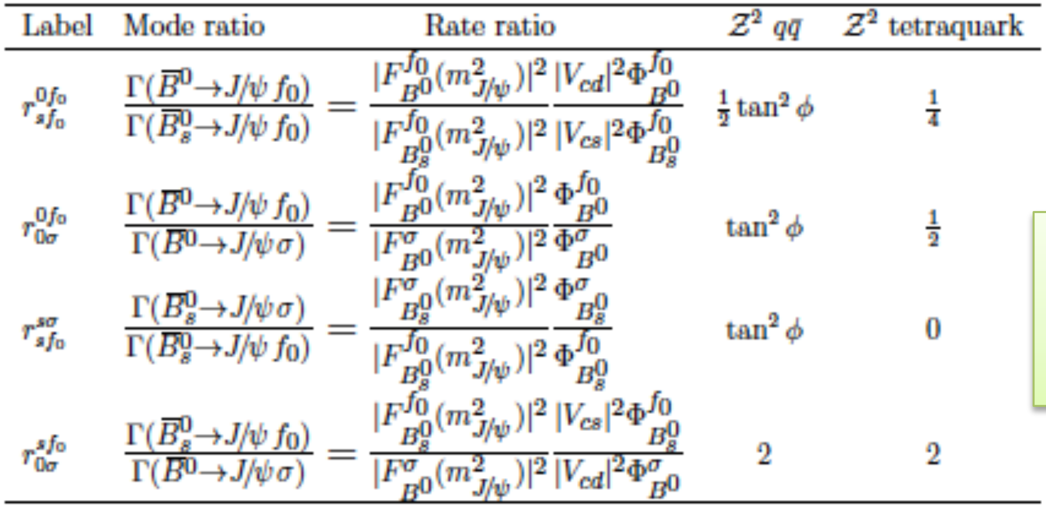
The nature of the σ scalar

Stone-Zhang
arXiV:1305.6554



$q\bar{q}$

tetraquark



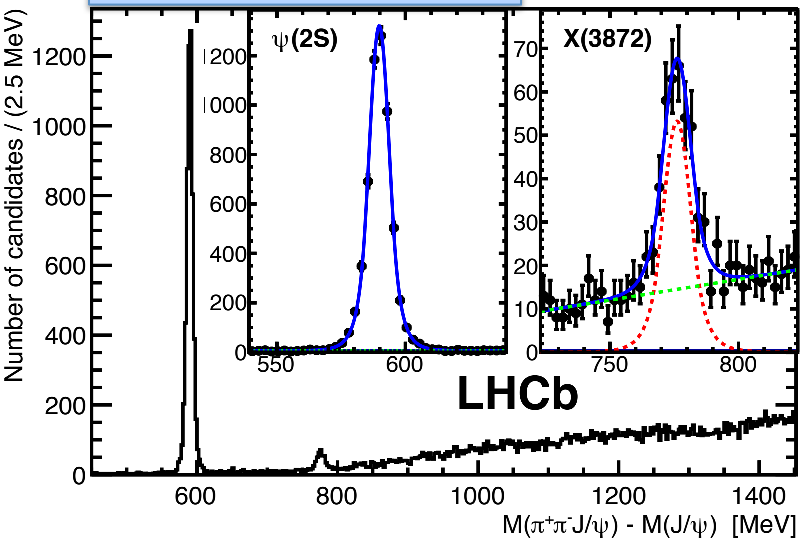
Label	Mode ratio	Rate ratio	$\mathcal{Z}^2$ $q\bar{q}$	$\mathcal{Z}^2$ tetraquark
$r^{0f_0}_{sf_0}$	$\frac{\Gamma(\overline{B}^0\to J/\psi\, f_0)}{\Gamma(\overline{B}^0_s\to J/\psi\, f_0)}$	$=\frac{\lvert F^{f_0}_{B^0}(m^2_{J/\psi})\rvert^2}{\lvert F^{f_0}_{B^0_s}(m^2_{J/\psi})\rvert^2}\frac{\lvert V_{cd}\rvert^2\Phi^{f_0}_{B^0}}{\lvert V_{cs}\rvert^2\Phi^{f_0}_{B^0_s}}$	$\frac{1}{2}\tan^2\phi$	$\frac{1}{4}$
$r^{0f_0}_{0\sigma}$	$\frac{\Gamma(\overline{B}^0\to J/\psi\, f_0)}{\Gamma(\overline{B}^0\to J/\psi\,\sigma)}$	$=\frac{\lvert F^{f_0}_{B^0}(m^2_{J/\psi})\rvert^2}{\lvert F^{\sigma}_{B^0}(m^2_{J/\psi})\rvert^2}\frac{\Phi^{f_0}_{B^0}}{\Phi^{\sigma}_{B^0}}$	$\tan^2\phi$	$\frac{1}{2}$
$r^{s\sigma}_{sf_0}$	$\frac{\Gamma(\overline{B}^0_s\to J/\psi\,\sigma)}{\Gamma(\overline{B}^0_s\to J/\psi\, f_0)}$	$=\frac{\lvert F^{\sigma}_{B^0_s}(m^2_{J/\psi})\rvert^2}{\lvert F^{f_0}_{B^0_s}(m^2_{J/\psi})\rvert^2}\frac{\Phi^{\sigma}_{B^0_s}}{\Phi^{f_0}_{B^0_s}}$	$\tan^2\phi$	0
$r^{sf_0}_{0\sigma}$	$\frac{\Gamma(\overline{B}^0_s\to J/\psi\, f_0)}{\Gamma(\overline{B}^0\to J/\psi\,\sigma)}$	$=\frac{\lvert F^{f_0}_{B^0_s}(m^2_{J/\psi})\rvert^2}{\lvert F^{\sigma}_{B^0}(m^2_{J/\psi})\rvert^2}\frac{\lvert V_{cs}\rvert^2\Phi^{f_0}_{B^0_s}}{\lvert V_{cd}\rvert^2\Phi^{\sigma}_{B^0}}$	2	2

σ not present in B_s decay if tetraquark

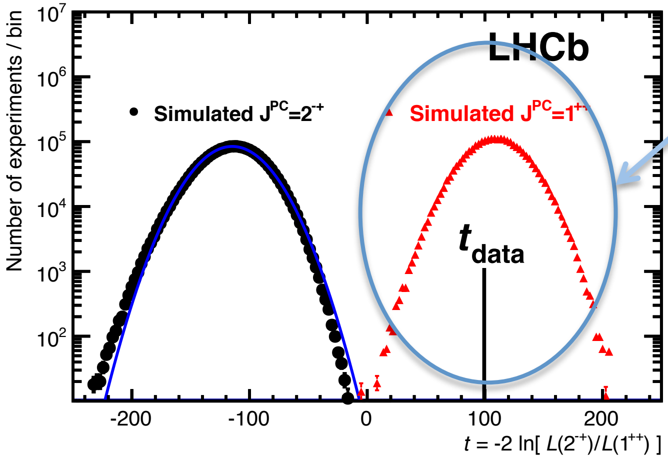
the "poster boy" for new heavy hadrons: X(3872)

E. Swanson, Phys.Rep. 429(2006)243

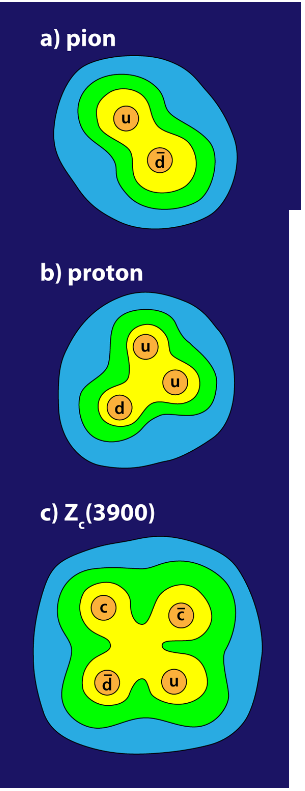
$B^+ \rightarrow X(3872)K^+$



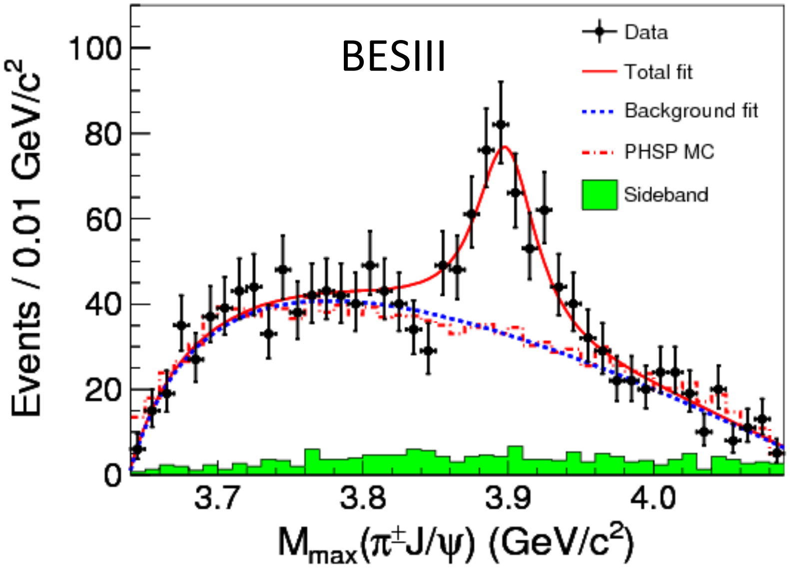
Experiment	Mass[X(3872)](MeV)
CDF2	3871.61±0.16±0.19
BaBar(B^+)	3871.4±0.6±0.1
BaBar(B^0)	3868.7±1.5±0.4
D0	3871.8±3.1±3.0
Belle	3871.84±0.27±0.19
LHcb	3871.95±0.48±0.12
Average	3871.68±0.17

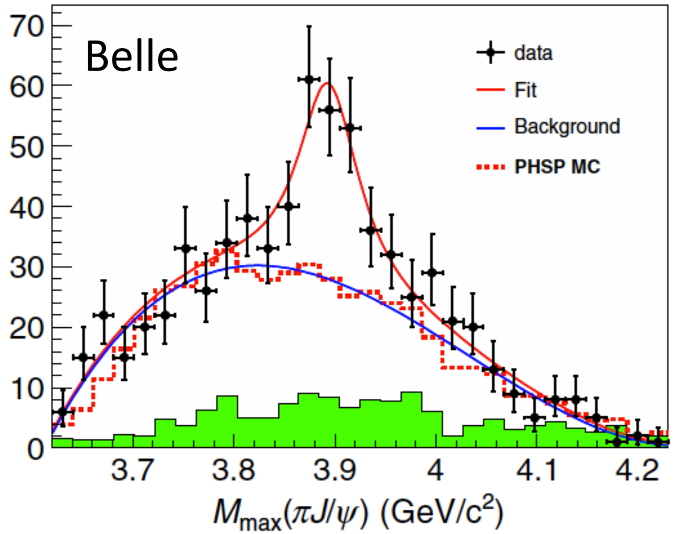


1^{++} spin-parity favor exotic interpretation



Z_c(3900)





Belle: 927 fb^{-1} of ISR data at Υ(nS) energy

Phys.Rev.Lett. 110 (2013) 252002

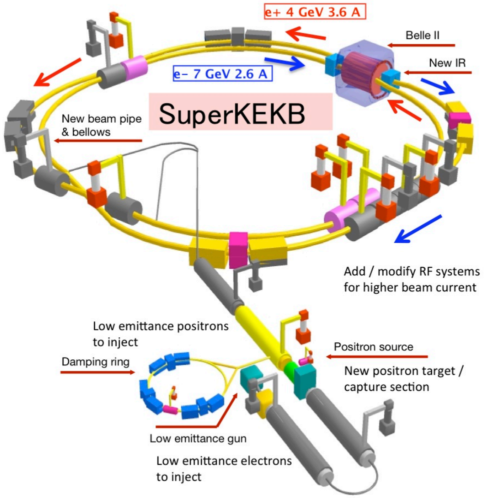
- Mass = (3894.5±6.6±4.5) MeV
- Width = (63±24±26) MeV
- Fraction = (29.0±8.9)% (stat. error only)

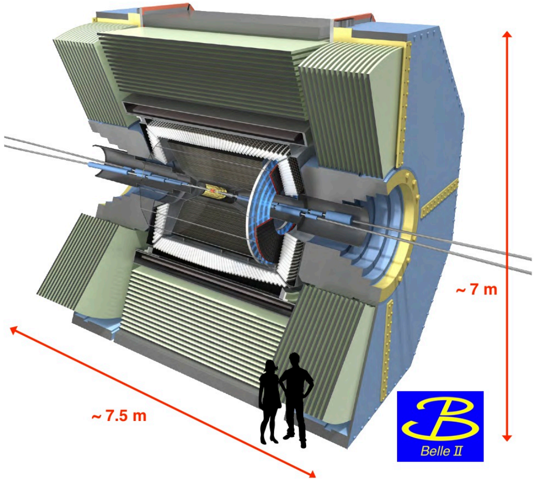
BES-III: 525 pb^{-1} @ Υ(4260) peak energy

Phys.Rev.Lett. 110 (2013) 252001

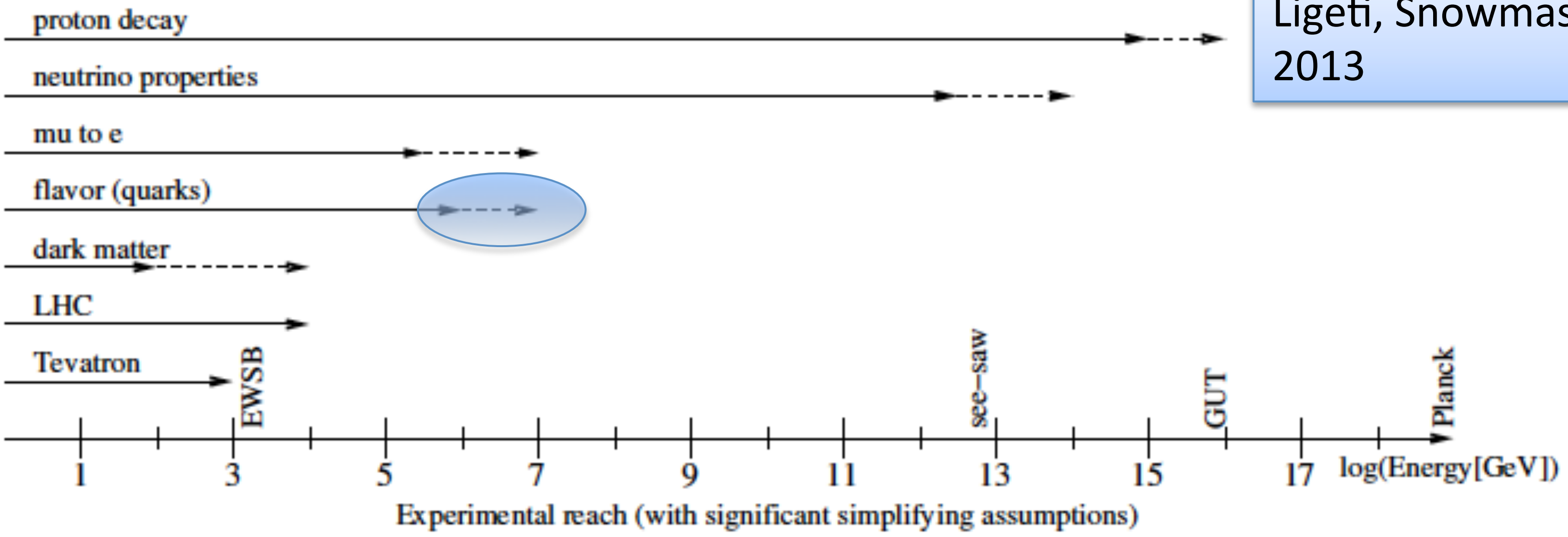
- Mass = (3899.0±3.6±4.9) MeV
- Width = (46±10±20) MeV
- Fraction = (21.5±3.3±7.5)%

Future prospects



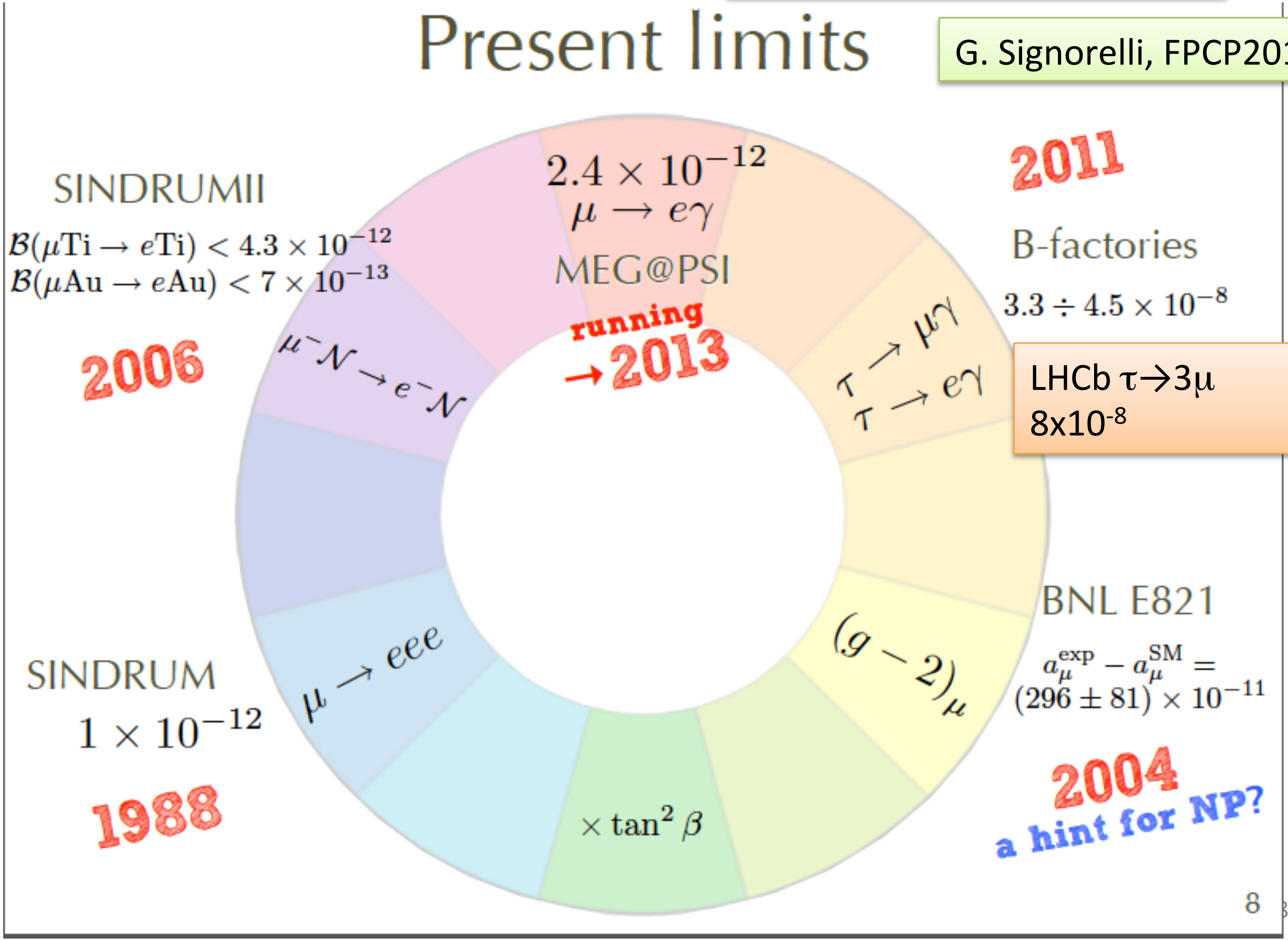


Ligeti, Snowmass 2013



the CLFV wheel

experiments described in detail in R. Bernstein plenary talk



Present limits

G. Signorelli, FPCP2013

SINDRUMII

$\mathcal{B}(\mu\mathrm{Ti} \rightarrow e\mathrm{Ti}) < 4.3 \times 10^{-12}$

$\mathcal{B}(\mu\mathrm{Au} \rightarrow e\mathrm{Au}) < 7 \times 10^{-13}$

2006

2.4×10^{-12}

$\mu \rightarrow e\gamma$

MEG@PSI

running

→2013

2011

B-factories

$3.3 \div 4.5 \times 10^{-8}$

$\tau \rightarrow \mu\gamma$

$\tau \rightarrow e\gamma$

LHCb τ→3μ $8\text{x}10^{-8}$

$\mu^- \mathcal{N} \rightarrow e^- \mathcal{N}$

$\mu \rightarrow eee$

SINDRUM

1×10^{-12}

1988

$\times \tan^2 \beta$

$(g-2)_\mu$

BNL E821

$a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} =$

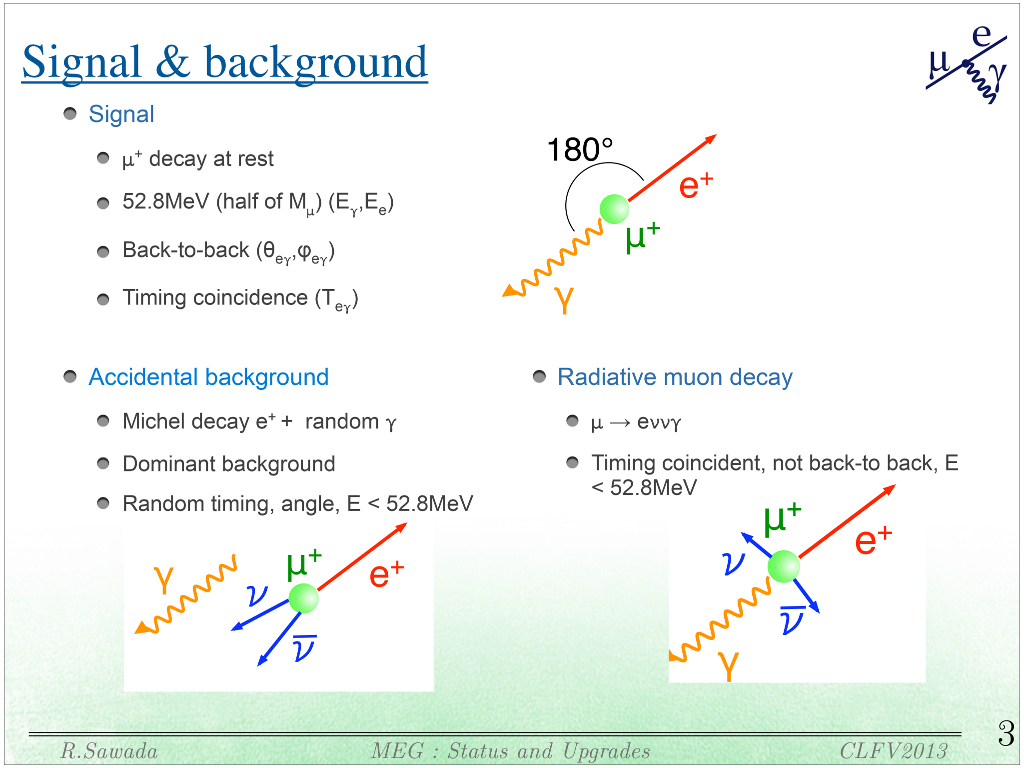
$(296 \pm 81) \times 10^{-11}$

2004

a hint for NP?

LFV in muon decays

Example: MEG experiment using stopped muons at PSI, current upper limit < 5.7×10^{-13} at 90% CL



Signal & background

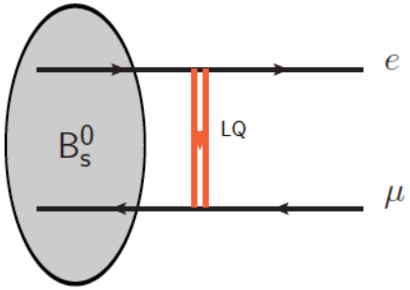
- Signal
  - μ^+ decay at rest
  - 52.8MeV (half of M_μ) (E_γ,E_e)
  - Back-to-back ($\theta_{e\gamma}$,$\varphi_{e\gamma}$)
  - Timing coincidence ($T_{e\gamma}$)
- Accidental background
  - Michel decay e^+ + random γ
  - Dominant background
  - Random timing, angle, E < 52.8MeV
- Radiative muon decay
  - $\mu \to e\nu\nu\gamma$
  - Timing coincident, not back-to back, E < 52.8MeV

R.Sawada MEG : Status and Upgrades CLFV2013 3

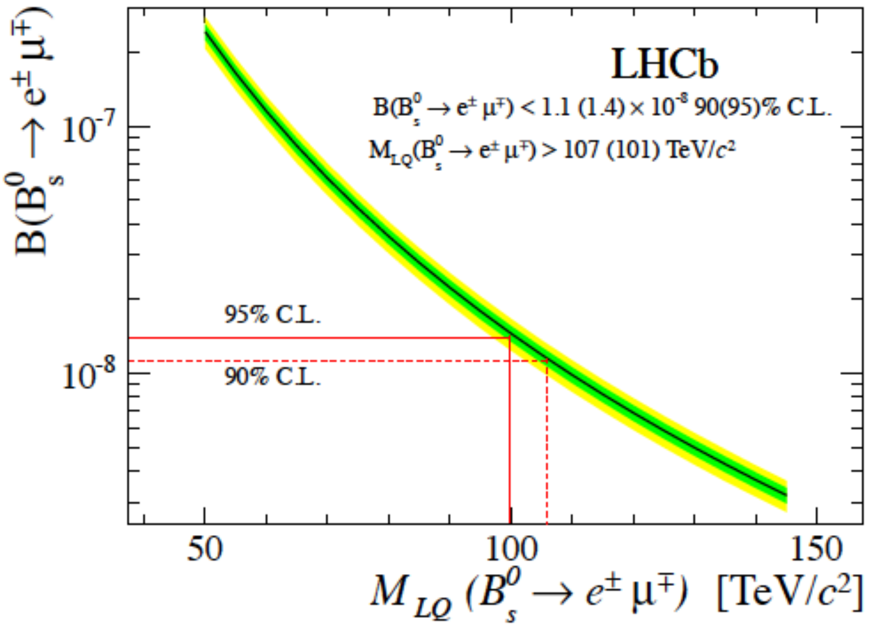
Future prospects

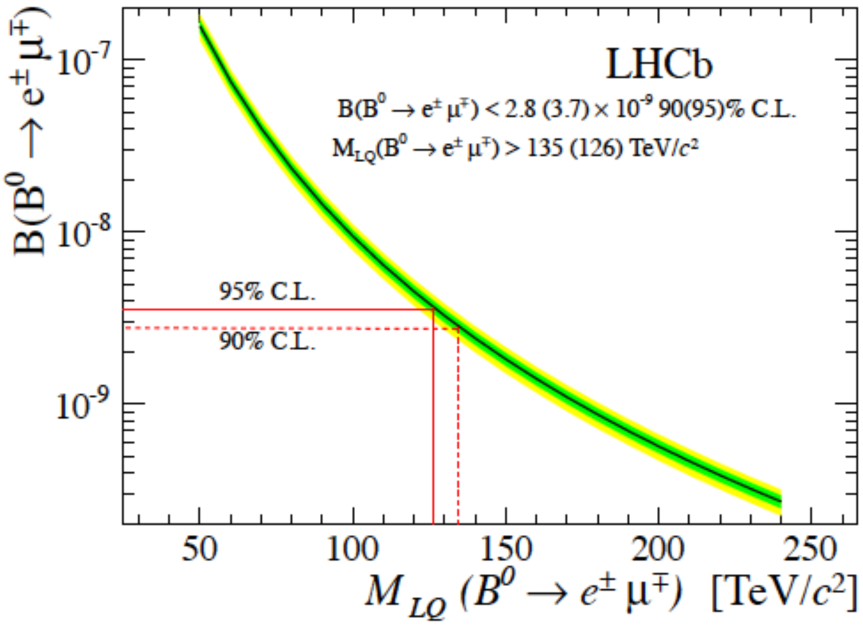
Experiment	**location**	**Channel**	**Sensitivity**
mu2e	FNAL	$\mu N \rightarrow eN$	$\sim 10^{-17}$
comet	j-park	$\mu N \rightarrow eN$	$\sim 10^{-15}$
mu3e	PSI	$\mu \rightarrow eee$	$\sim 10^{-16}$
MEG-UP	PSI	$\mu \rightarrow e\gamma$	$\sim 10^{-14}$
GM2	FNAL	Da_{μ}	$(xxx \pm 34) x 10^{-15}$
LHCb Upgrade	CERN	$\tau \rightarrow \mu\mu\mu$	$\sim 10^{-9}$
Belle II	KEK	$\tau \rightarrow \mu\gamma$	$\sim 10^{-9}$

$B_{(s)} \rightarrow e\mu$

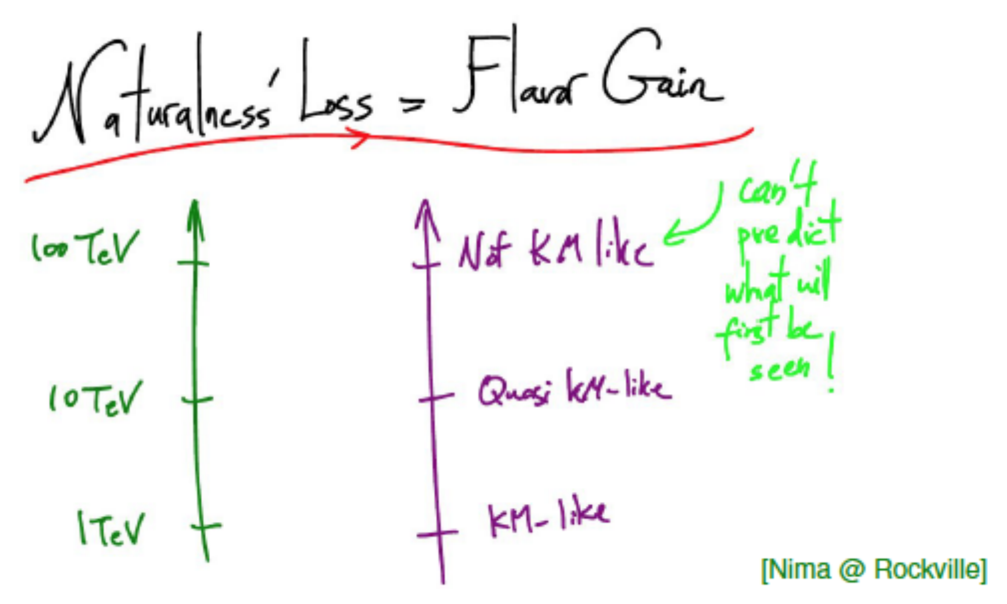


Cast stringent limits on Pati-Salam leptoquark mass (formalism by Valencia-Willenbrock PRD 50 (1994) 6843)



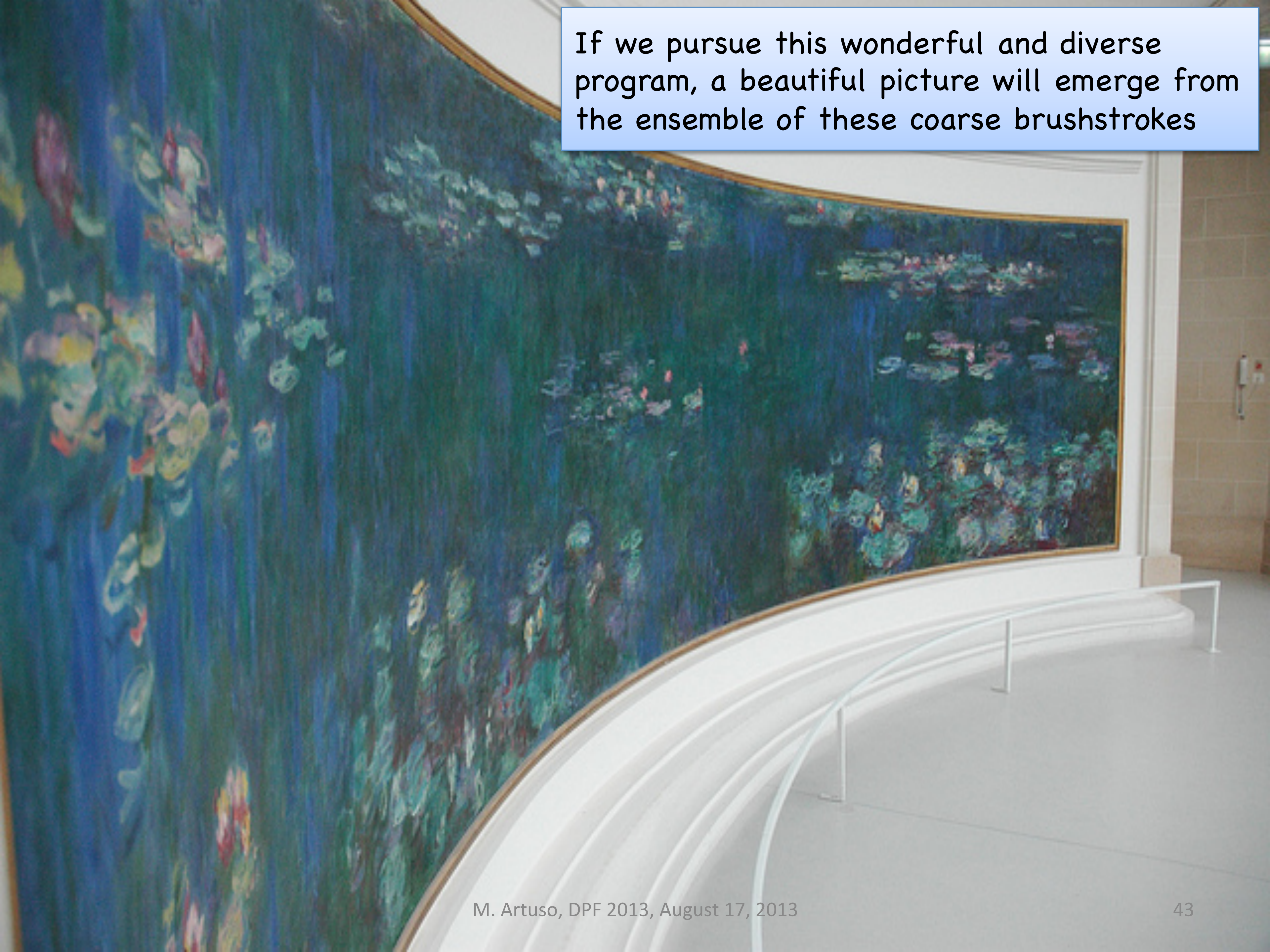


Conclusions



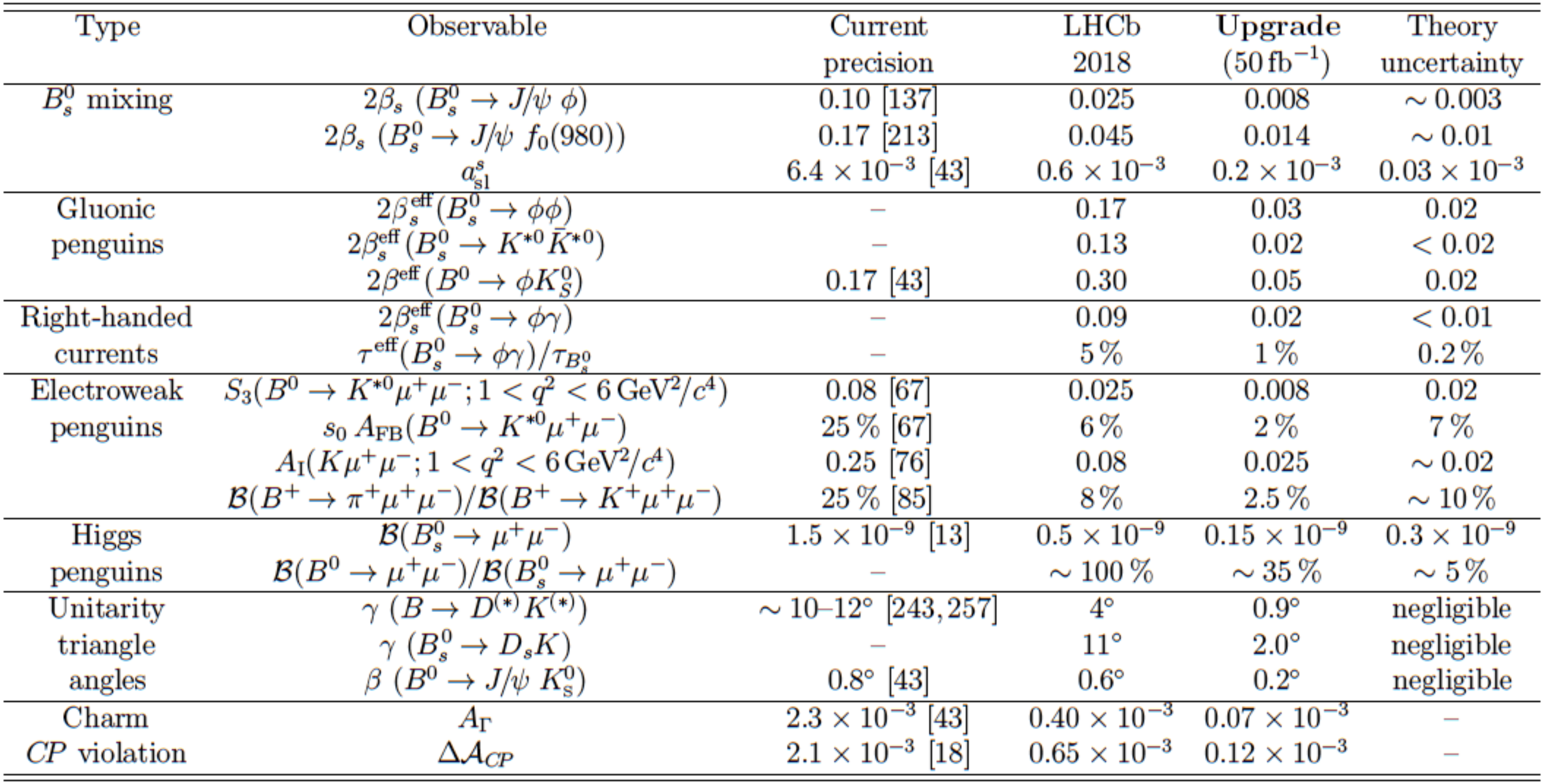
[Nima @ Rockville]

- ☐ As the new physics scale is pushed up, the flavor structure is less bound to conform to the MFV ansatz
- ☐ Flavor measurements can probe multi-TeV new physics with SM flavor structure and 100-1000 TeV new physics with generic flavor structure
- ☐ New physics is proving to be elusive: we need to cast a wide net!
- ☐ the LHCb upgrade and Belle II will cast a broad net to capture new physics in beauty and charm
- ☐ Rare K, μ decay experiments will provide complementary information



If we pursue this wonderful and diverse program, a beautiful picture will emerge from the ensemble of these coarse brushstrokes

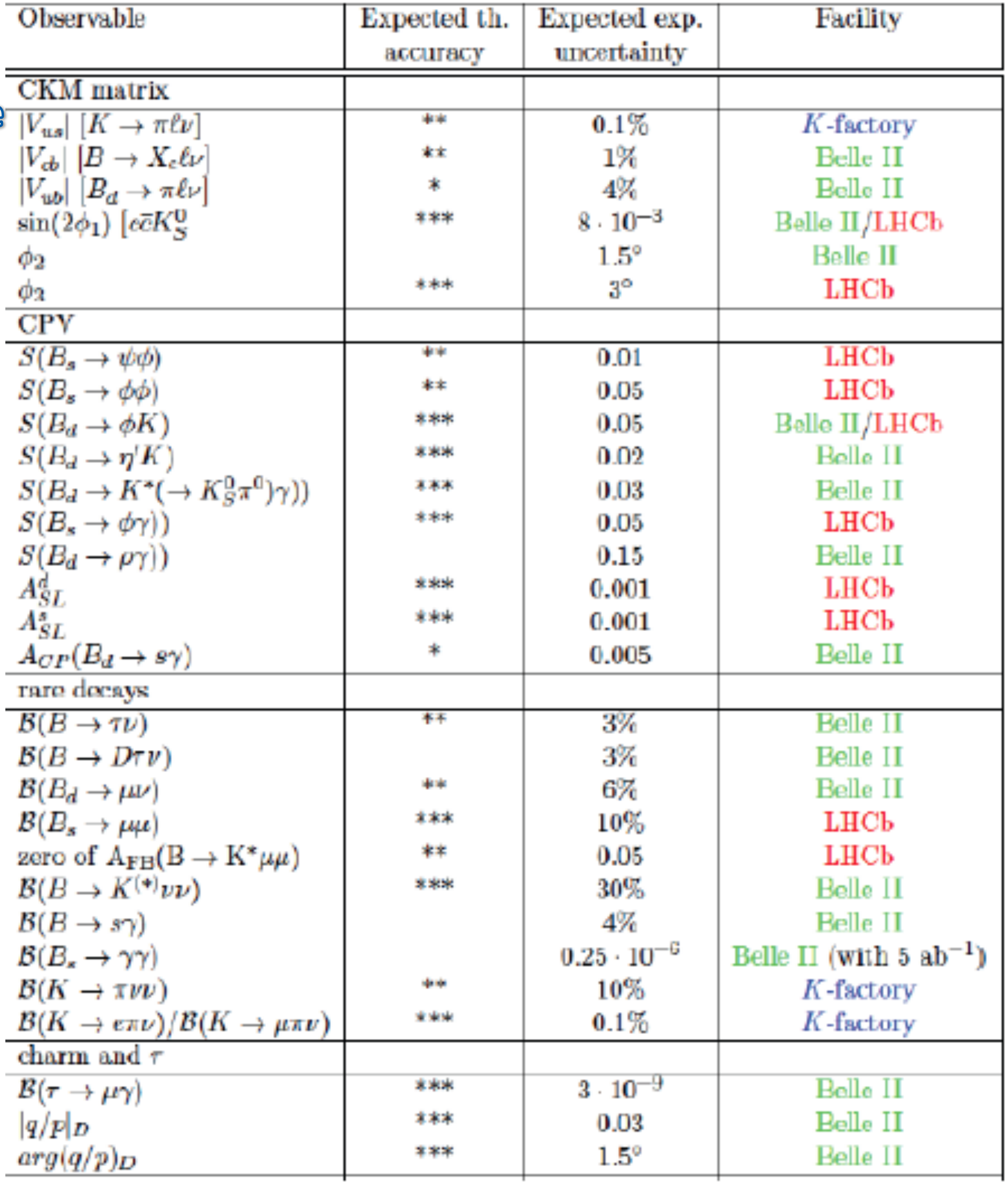
Sensitivity of the upgraded LHCb experiment to key observables



Type	Observable	Current precision	LHCb 2018	Upgrade ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [137]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [213]	0.045	0.014	~ 0.01
	a_{sl}^s	6.4×10^{-3} [43]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [43]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [67]	0.025	0.008	0.02
	$s_0\,A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [67]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [76]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [85]	8 %	2.5 %	$\sim 10\,\%$
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [13]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	$\sim 100\,\%$	$\sim 35\,\%$	$\sim 5\,\%$
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–12° [243, 257]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\ K_S^0)$	0.8° [43]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [43]	0.40×10^{-3}	0.07×10^{-3}	–
	$\Delta\mathcal{A}_{CP}$	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}	–

Implications of LHCb measurements and future prospects, LHCB-PAPER-2012-031

from Tom Browder
Slac summer institute



Observable	Expected th. accuracy	Expected exp. uncertainty	Facility
CKM matrix			
$\|V_{us}\|$ $[K \to \pi \ell \nu]$	**	0.1%	K-factory
$\|V_{cb}\|$ $[B \to X_c \ell \nu]$	**	1%	Belle II
$\|V_{ub}\|$ $[B_d \to \pi \ell \nu]$	*	4%	Belle II
$\sin(2\phi_1)$ $[c\bar{c}K^0_S$	***	$8 \cdot 10^{-3}$	Belle II/LHCb
ϕ_2		1.5°	Belle II
ϕ_3	***	3°	LHCb
CPV			
$S(B_s \to \psi\phi)$	**	0.01	LHCb
$S(B_s \to \phi\phi)$	**	0.05	LHCb
$S(B_d \to \phi K)$	***	0.05	Belle II/LHCb
$S(B_d \to \eta' K)$	***	0.02	Belle II
$S(B_d \to K^*(\to K^0_S \pi^0)\gamma))$	***	0.03	Belle II
$S(B_s \to \phi\gamma))$	***	0.05	LHCb
$S(B_d \to \rho\gamma))$		0.15	Belle II
A^d_{SL}	***	0.001	LHCb
A^s_{SL}	***	0.001	LHCb
$A_{CP}(B_d \to s\gamma)$	*	0.005	Belle II
rare decays			
$\mathcal{B}(B \to \tau\nu)$	**	3%	Belle II
$\mathcal{B}(B \to D\tau\nu)$		3%	Belle II
$\mathcal{B}(B_d \to \mu\nu)$	**	6%	Belle II
$\mathcal{B}(B_s \to \mu\mu)$	***	10%	LHCb
zero of $\mathrm{A_{FB}(B \to K^*\mu\mu)}$	**	0.05	LHCb
$\mathcal{B}(B \to K^{(*)}\nu\nu)$	***	30%	Belle II
$\mathcal{B}(B \to s\gamma)$		4%	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$		$0.25 \cdot 10^{-6}$	Belle II (with 5 ab^{-1})
$\mathcal{B}(K \to \pi\nu\nu)$	**	10%	K-factory
$\mathcal{B}(K \to e\pi\nu)/\mathcal{B}(K \to \mu\pi\nu)$	***	0.1%	K-factory
charm and τ			
$\mathcal{B}(\tau \to \mu\gamma)$	***	$3 \cdot 10^{-9}$	Belle II
$\|q/p\|_D$	***	0.03	Belle II
$arg(q/p)_D$	***	1.5°	Belle II