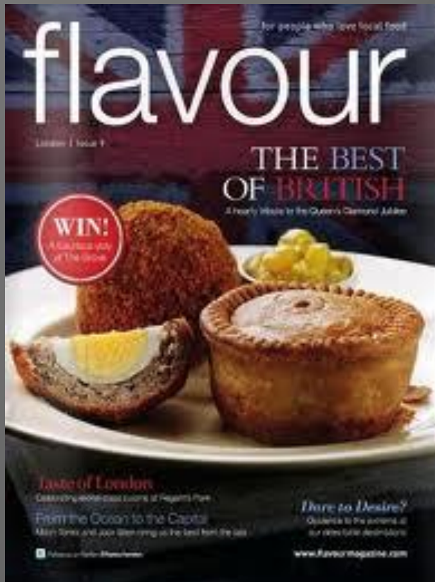


Augusto Ceccucci/CERN

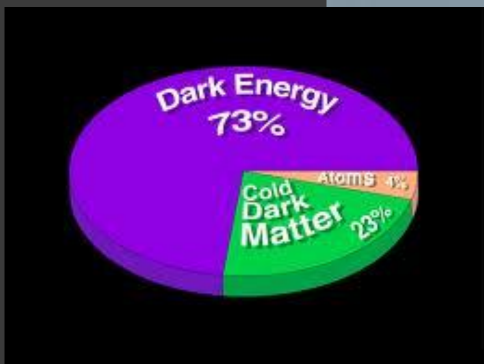
FLAVOUR PHYSICS
LECTURE 1

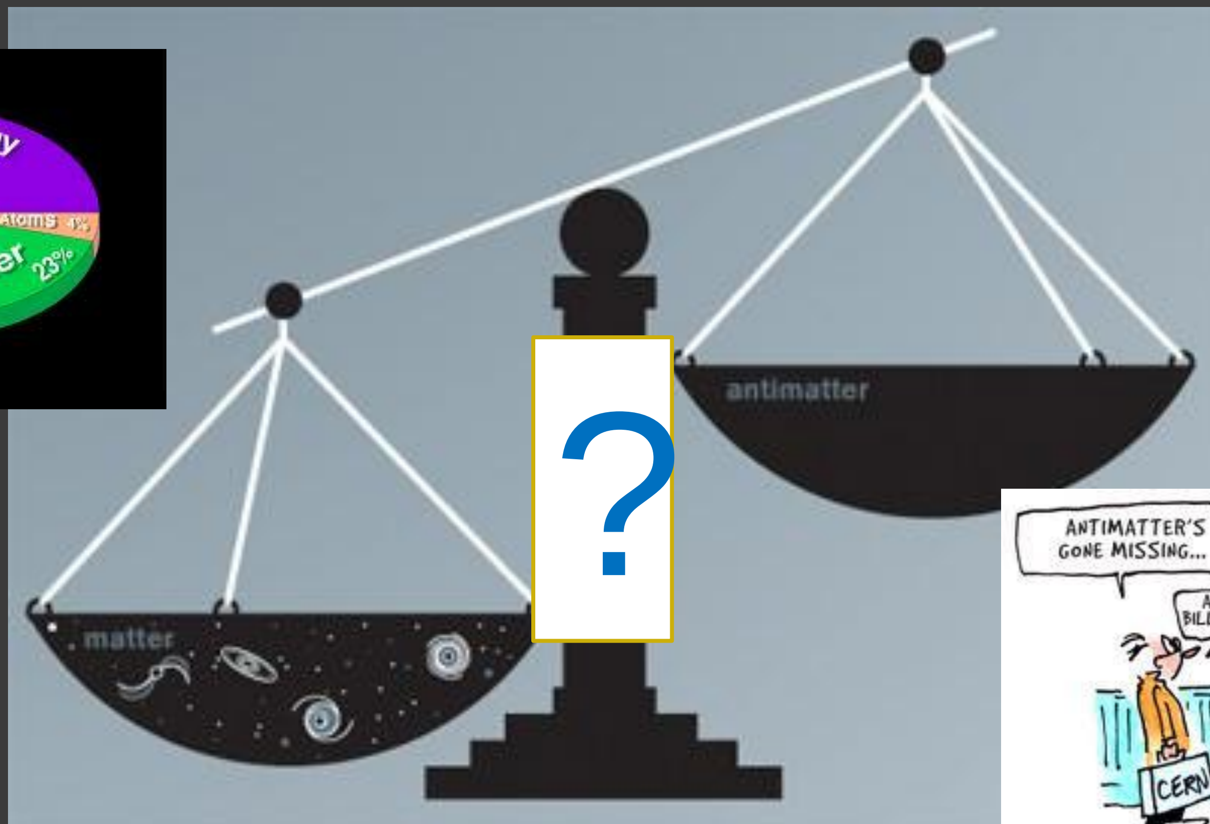
Primorsko, Bulgaria, June 14, 2012

Contents of Lecture 1

- Why Flavour Physics and CP-Violation are important
- CP-Violation in the “Standard Model”, quark mixing and decay
- CKM matrix
- Experimental State of the Art
  - K, D & B mesons
- Current trends & Outlook

Baryon Asymmetry of the Universe (BAU)





$n_{quark}-n_{antiquark}/n_{quark}$ (Proto Universe) ~n_{baryon}/n_{photon} (Today)~**5×10^{-10}**

Sakharov Conditions for BAU

Andrei Sakharov (1967)

To allow the development of an asymmetry between matter and anti-matter

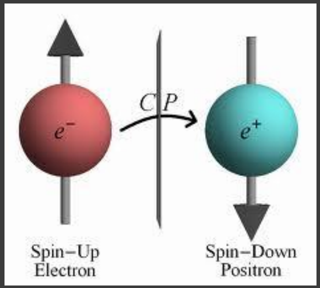
1. Violation of Baryonic Number

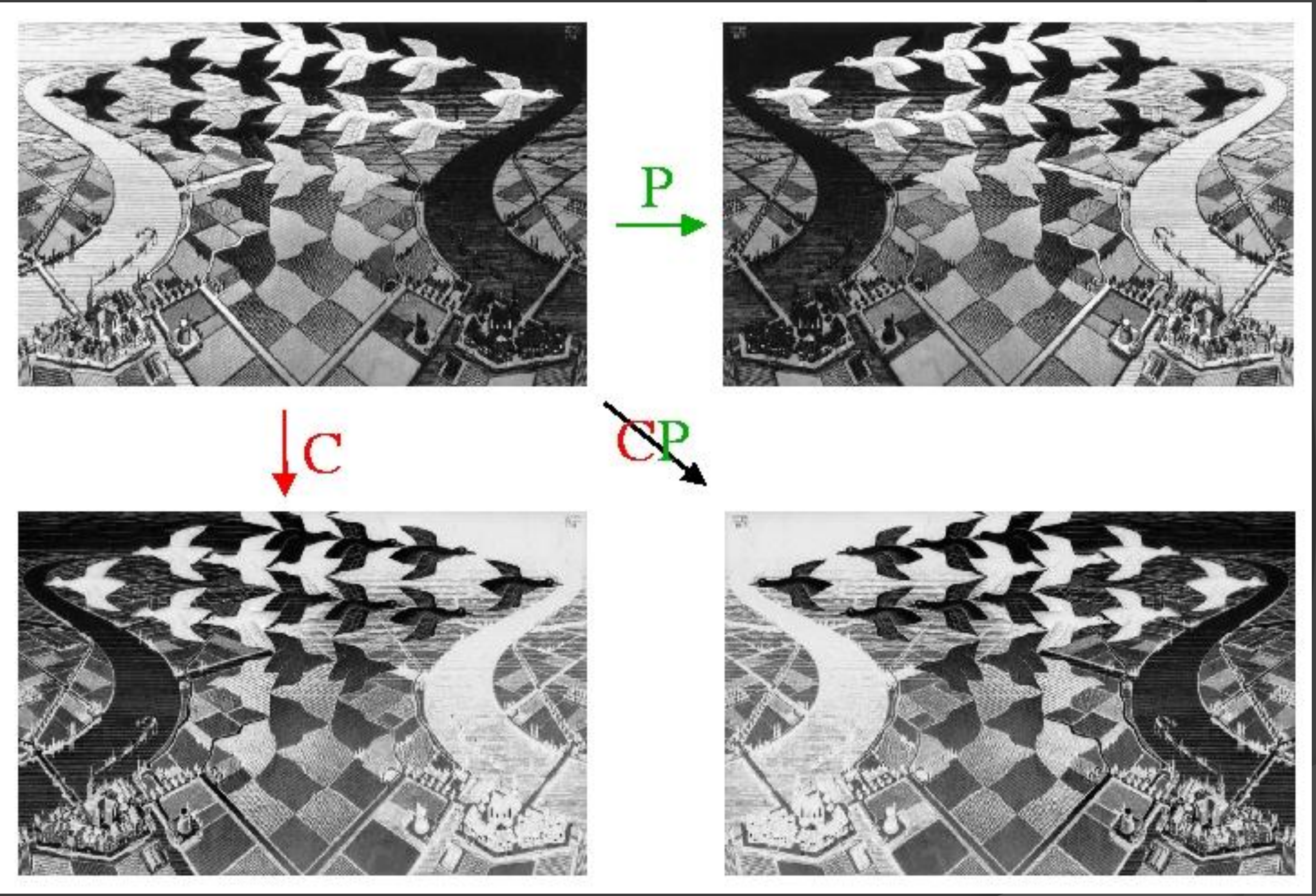
2. Thermodynamic Non-equilibrium

3. Violation of C & CP

Origin of BAU: Baryogenesis or Leptogenesis?

CP-Violation





Da Gino Isidori: http://scienzapertutti.lnf.infn.it/P1/schedaCP.html

CP-Violation and Flavour Physics in the Era of the LHC

- Many open questions are associated with flavour and CP-Violation:
- Why are there three generations (if they are three)?
- What determines the hierarchy of the quark masses?
- What determines the pattern of the quark mixing?
- What determines the non-zero neutrino mass and mixing?

- **Flavour Problem:**
  - **Many reasons to expect New Physics (NP) at $\Lambda \sim 1$ TeV**
  - **Naïve Flavour bounds $\Lambda > 10^4$ TeV**

  → the full theory must have a non-trivial flavour structure

Types of CP-Violation

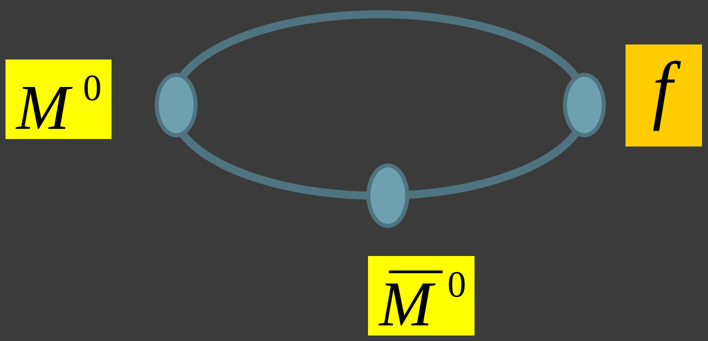
$$|M_L\rangle \propto p|M^0\rangle + q|\overline{M}^0\rangle$$
$$|M_H\rangle \propto p|M^0\rangle - q|\overline{M}^0\rangle$$

ΔF = 2

$$\mathrm{A_f} = \langle \mathrm{f}|\mathrm{H}|\mathrm{M}\rangle, \quad \overline{\mathrm{A}}_\mathrm{f} = \langle \mathrm{f}|\mathrm{H}|\overline{\mathrm{M}}\rangle$$
$$\mathrm{A_{\bar f}} = \langle \bar{\mathrm{f}}|\mathrm{H}|\mathrm{M}\rangle, \quad \overline{\mathrm{A}}_\mathrm{\bar f} = \langle \bar{\mathrm{f}}|\mathrm{H}|\overline{\mathrm{M}}\rangle$$

ΔF = 1

1. CP Violation in mixing $|q/p| \neq 1$ (indirect)
2. CP Violation in decays $|\overline{A}_{\bar f}/A_f| \neq 1$ (direct)
3. CP Violation in the interference



$$\mathrm{Im}\,\lambda_f \neq 0$$

$$\lambda_f \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

Quark masses and mixing

- The masses and mixings of quarks have a common origin in the standard model (SM): they arise from the Yukawa interactions with the Higgs condensate

$$\mathcal{L}_Y = -Y^d_{ij}\,\overline{Q^I_{Li}}\,\phi\, d^I_{Rj} - Y^u_{ij}\,\overline{Q^I_{Li}}\,\epsilon\,\phi^* u^I_{Rj} + \text{h.c.}$$

- When ϕ acquires a VEV we get the masses of the quarks
- The diagonalization yields the physical states. As a result the charged currents couples to the physical quarks as:

$$\frac{-g}{\sqrt{2}}\left(\overline{u_L}, \overline{c_L}, \overline{t_L}\right)\gamma^\mu W^+_\mu V_{\text{CKM}}\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.},$$

- V_{CKM} is a 3 x 3 complex matrix know as the Cabibbo, Kobayashi, Maskawa matrix

Cabibbo-Kobayashi-Maskawa (CKM) Quark Mixing

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

With 3 generations CP violation is naturally introduced by an irreducible complex phase in the quark mixing matrix (Komayashi & Maskawa, 1973)

$\lvert V_{ud}\rvert = 0.97425 \pm 0.00022$	$0^+ \rightarrow 0^+$ super-allowed nuclear β decays
$\lvert V_{us}\rvert = 0.2252 \pm 0.0009$	Kaon semi-leptonic and leptonic decays
$\lvert V_{cd}\rvert = 0.230 \pm 0.011$	$2\mu/1\mu$ ratio in neutrino/antineutrino interactions
$\lvert V_{cs}\rvert = 1.006 \pm 0.023$	Average of semi-leptonic D and leptonic D_s decays
$\lvert V_{cb}\rvert = (40.9 \pm 1.1) \times 10^{-3}$	Combination of exclusive and inclusive B decays
$\lvert V_{ub}\rvert = (4.15 \pm 0.49) \times 10^{-3}$	Comb. of exclusive and inclusive charmless B decays*
$\lvert V_{tb}\rvert = 0.89 \pm 0.07$	Single top-quark production cross-section

V_{td} & V_{ts} accessible from FCNC processes (loops)

*But tension inclusive and exclusive determinations (see later)

Hierarchical Structure

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Wolfenstein parameterization

From Global fit (PDG review, 2010):

Imposing SM constraint (3 generation unitarity):

λ**= 0.2253 ± 0.0007** **A = 0.808** $^{+0.022}_{-0.015}$

ρ **= 0.132** $^{+0.022}_{-0.014}$ η **= 0.341 ± 0.013**

V_{us} and universality

$$\frac{g}{\sqrt{2}} W^+_\alpha \left(\overline{\mathbf{U}}_L \mathbf{V}_{\rm CKM} \gamma^\alpha \mathbf{D}_L + \overline{e}_L \gamma^\alpha \nu_{e\,L} + \overline{\mu}_L \gamma^\alpha \nu_{\mu\,L} + \overline{\tau}_L \gamma^\alpha \nu_{\tau\,L} \right) \quad + \quad \text{h.c.}$$

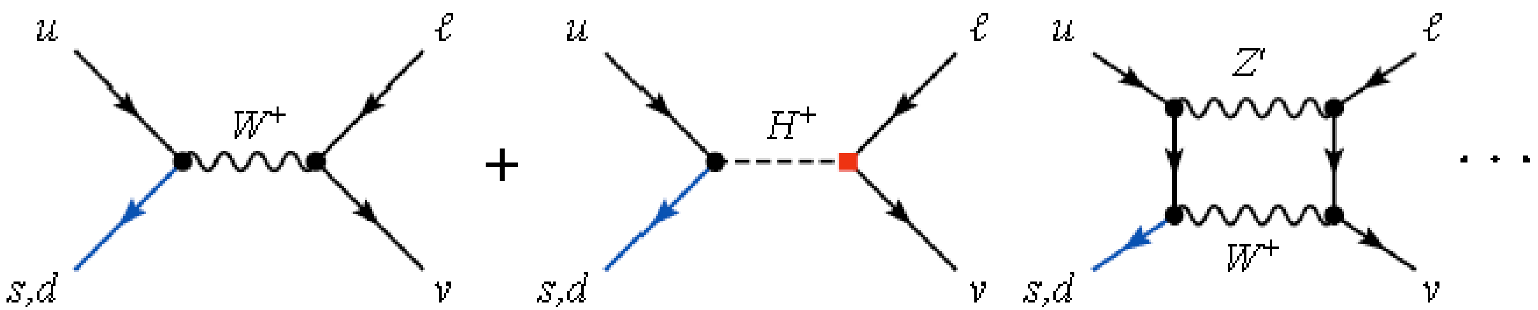
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

Standard-model coupling of quarks and leptons to W

Universality: Is G_F from μ decay equal to G_F from π, K, nuclear β decay?

$$G_\mu^2 = (g_\mu g_e)^2 / M_W^4 \quad \stackrel{?}{=} \quad G_{\rm CKM}^2 = (g_q g_\ell)^2 \left(|V_{ud}|^2 + |V_{us}|^2\right) / M_W^4$$

Physics beyond the Standard Model can break gauge universality:



V_{us} from semileptonic decays

$$\Gamma(K_{\ell 3(\gamma)}) = \frac{C_K^2 G_F^2 m_K^5}{192\pi^3} S_{\mathrm{EW}} |V_{us}|^2 |f_+^{K^0\pi^-}(0)|^2 \times I_{K\ell}(\lambda_{K\ell}) \left(1 + 2\Delta_K^{SU(2)} + 2\Delta_{K\ell}^{\mathrm{EM}}\right)$$

with $K \in \{K^+, K^0\}$; $\ell \in \{e, \mu\}$, and:

C_K^2 1/2 for K^+, 1 for K^0

S_{EW} Universal SD EW correction (1.0232)

Inputs from experiment:

$\Gamma(K_{\ell 3(\gamma)})$ Rates with well-determined treatment of radiative decays:

- Branching ratios
- Kaon lifetimes

$I_{K\ell}(\{\lambda\}_{K\ell})$ Integral of form factor over phase space: λs parameterize evolution in t

- K_{e3}: Only λ_+ (or λ_+', λ_+'')
- $K_{\mu 3}$: Need λ_+ and λ_0

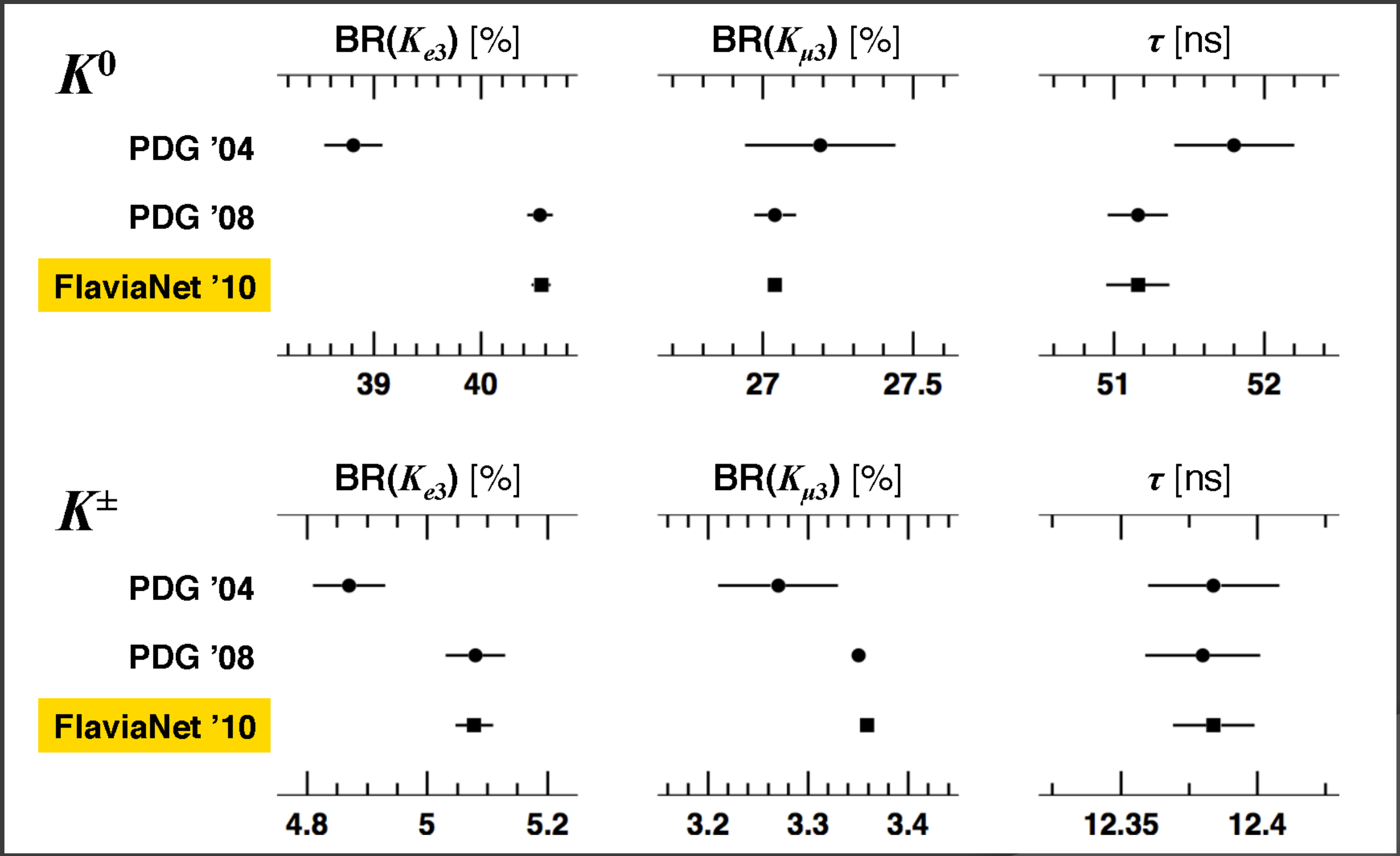
Inputs from theory:

$f_+^{K^0\pi^-}(0)$ Hadronic matrix element (form factor) at zero momentum transfer ($t = 0$)

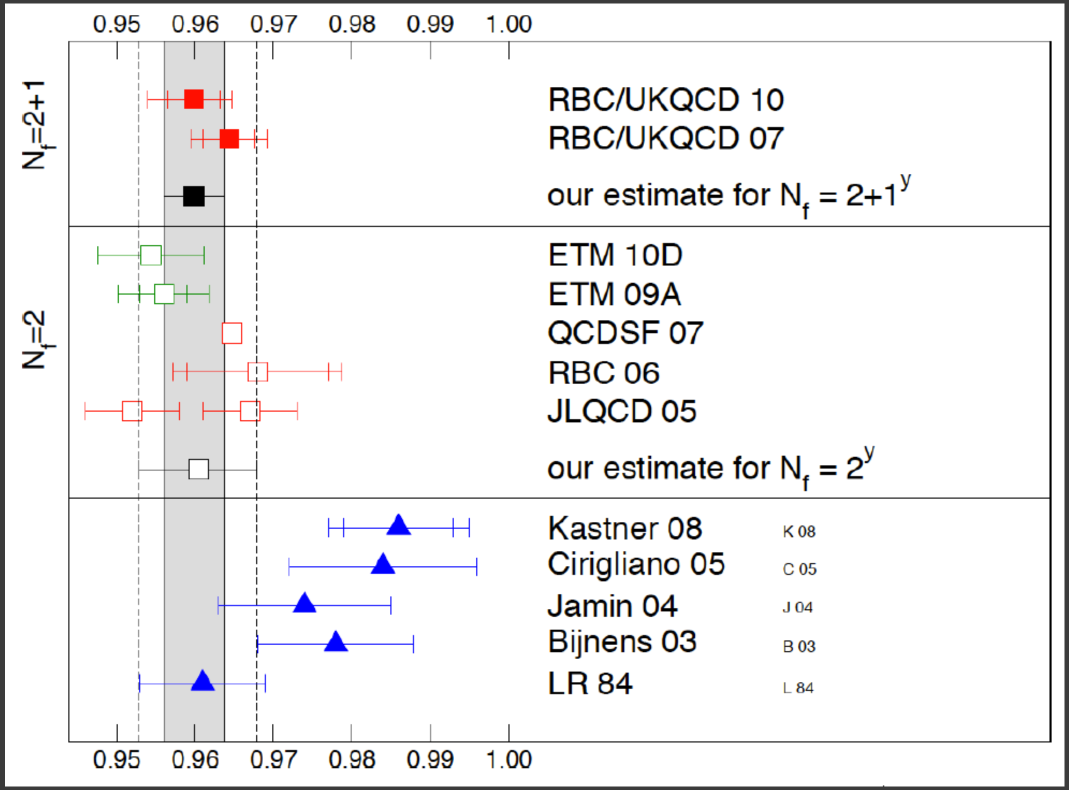
$\Delta_K^{SU(2)}$ Form-factor correction for $SU(2)$ breaking

$\Delta_{K\ell}^{\mathrm{EM}}$ Form-factor correction for long-distance EM effects

Evolution of Experimal Input…



...and of the theoretical one $f_+(0)$



The **Cabibbo** angle can be precisely determined (~0.4%)!

CP-Violation in Kaons

- Neutral Kaon Mixing ($\pi\pi$, semi-leptonic)

$$|\varepsilon| = \frac{G_F^2 f_K^2 m_K m_W^2}{12\sqrt{2}\pi^2 \Delta m_K} \hat{B}_K \{\eta_1 S(x_c)\,\mathrm{Im}(V_{cs}V_{cd}^*)^2 + \eta_2 S(x_t)\,\mathrm{Im}(V_{ts}V_{td}^*)^2 + 2\eta_3 S(x_c, x_t)\,\mathrm{Im}(V_{cs}V_{cd}^* V_{ts}V_{td}^*)\}$$

$$|\varepsilon| = (2.233 \pm 0.015) \times 10^{-3}$$

- Neutral Kaon Decays into $\pi\pi$

PDG Average

$$\mathrm{Re}\frac{\varepsilon'}{\varepsilon} \propto \mathrm{Im}(V_{td}V_{ts}^*)$$

$$\mathrm{Re}\frac{\varepsilon'}{\varepsilon} = (1.67 \pm 0.23) \times 10^{-3}$$

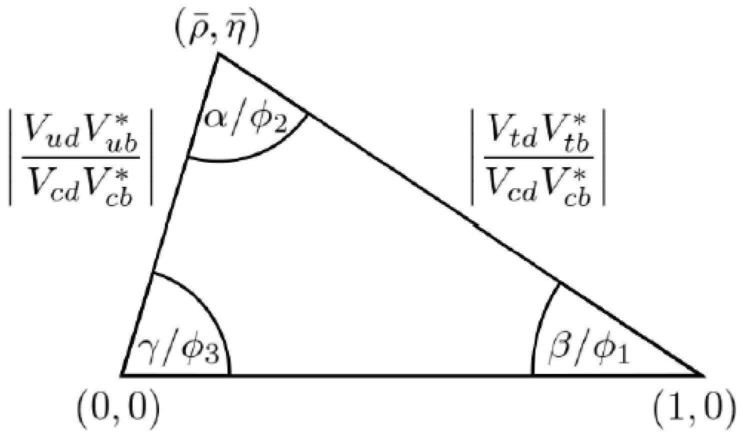
$$\Gamma(K^0 \to \pi^+\pi^-) \neq \Gamma(\bar{K}^0 \to \pi^+\pi^-)$$

Direct CP-Violation

Decisive Experiments: NA48 & KTeV

One (of the six) Unitarity Relations

$$V_{td}V_{tb}^{*} + V_{cd}V_{cb}^{*} + V_{ud}V_{ub}^{*} = 0$$



$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

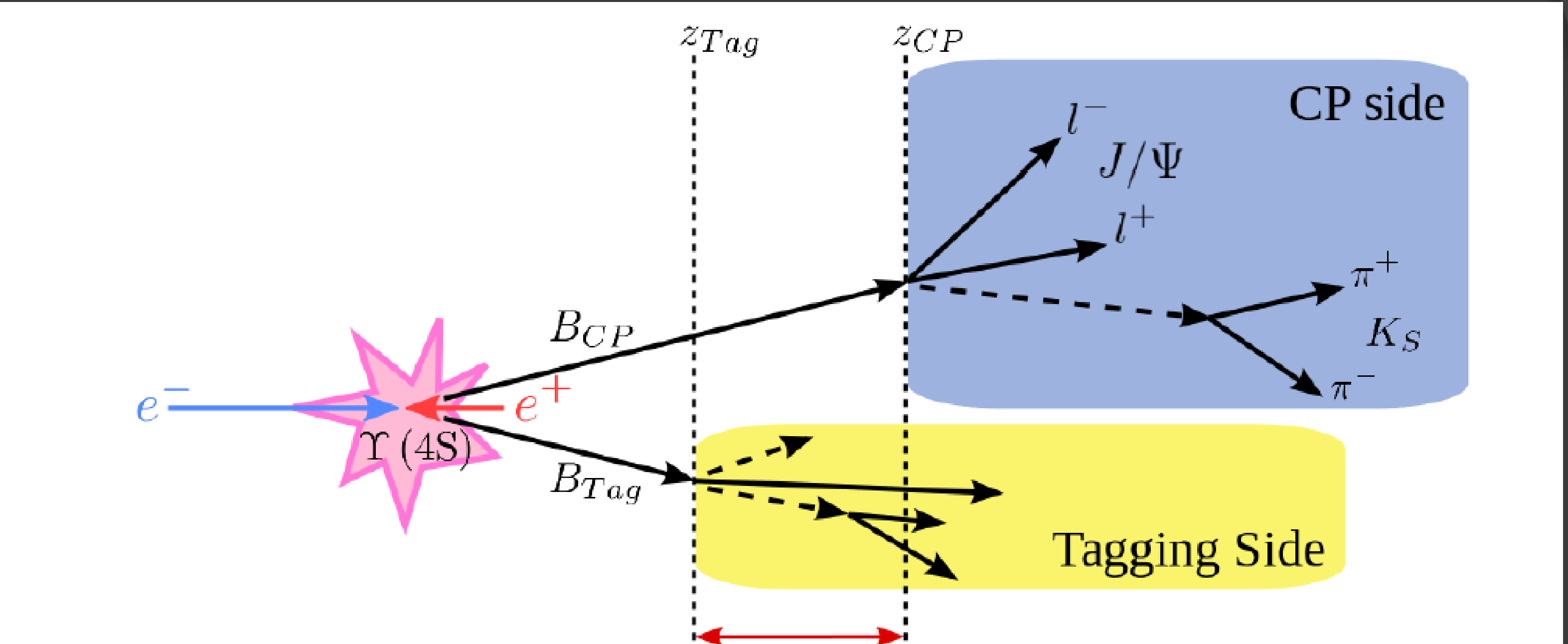
$$\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

Constraints (examples)

Process	CKM and other factors	Constraint
$b \to u$ / $b \to c$	$\|V_{ub}\|^2 / \|V_{cb}\|^2$	$\rho^2 + \eta^2$
Δm_{Bd}	$\|V_{td}\|^2 \ (f_{Bd} B_{Bd})^2$	$(1-\rho)^2 + \eta^2$
$\Delta m_{Bd} / \Delta m_{Bs}$	$\|V_{td} / V_{ts}\|^2 \ (f_{Bd} B_{Bd} / f_{Bs} B_{Bs})^2$	$(1-\rho)^2 + \eta^2$
ε_K	(see before)	$\eta(1-\rho)$
$B(K^0_L \to \pi^0 \nu \nu)$	$\|Im(V_{td} V^*_{ts})\|^2$	η^2

B mesons: Time dependent CP-Asymmetry



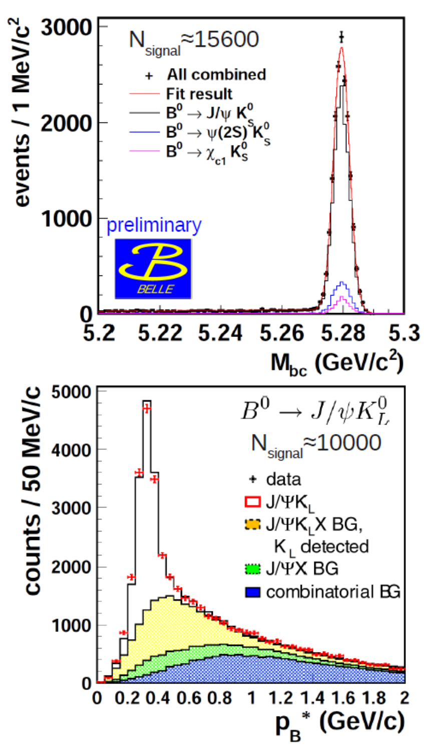
Courtesy by Markus Roehrken $\Delta z = \beta\gamma c \Delta t, \quad \langle|\Delta z|\rangle \approx 200\,\mu m$

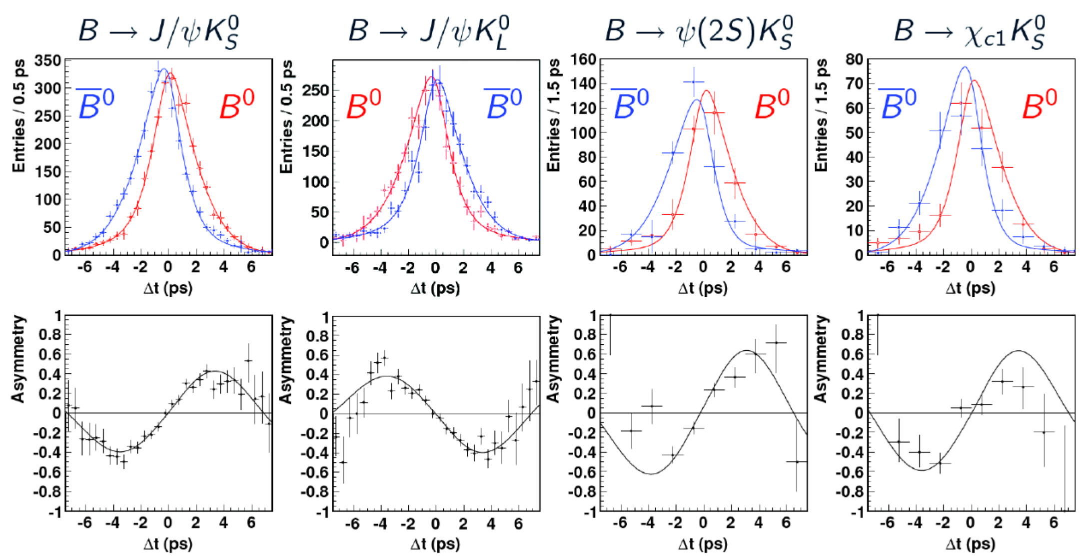
$$A_{CP} = \frac{\Gamma(\overline{M}^0 \to f) - \Gamma(M^0 \to f)}{\Gamma(\overline{M}^0 \to f) + \Gamma(M^0 \to f)} = \sin(2\Psi)\sin(\Delta m t)$$

For $f = \bar{f}$

Most recent determination of $\sin(2\phi_1)=\sin(2\beta)$: Belle

Belle's update on full dataset (preliminary):





Belle with 772×10^6 BB:

$$\mathcal{A} = 0.007 \pm 0.016\,(\mathrm{stat}) \pm 0.013\,(\mathrm{syst})$$

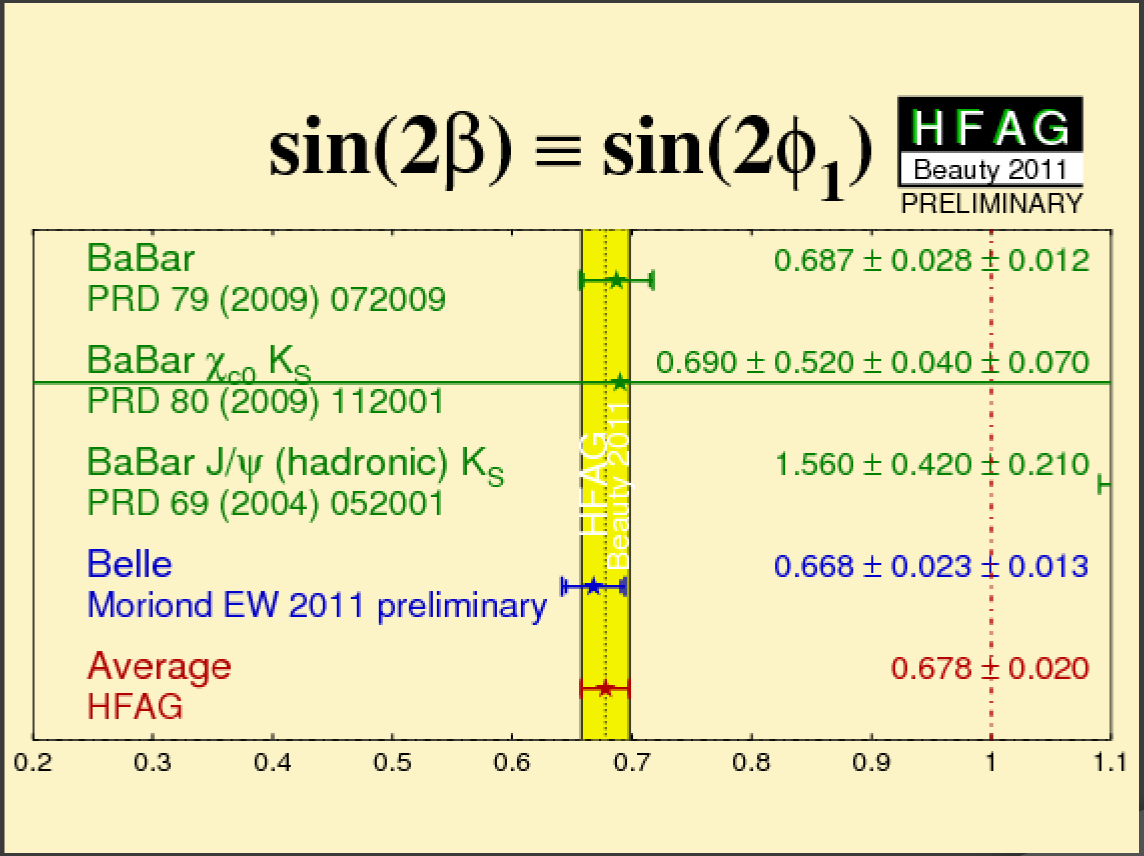
$$\sin(2\phi_1) = 0.668 \pm 0.023 \qquad \pm 0.013$$

preliminary

Current world's most precise measurement of Φ_1

Courtesy by Markus Roehrken, Beauty 2011

Time-Dependent CP-Asymmetry in b→c c s

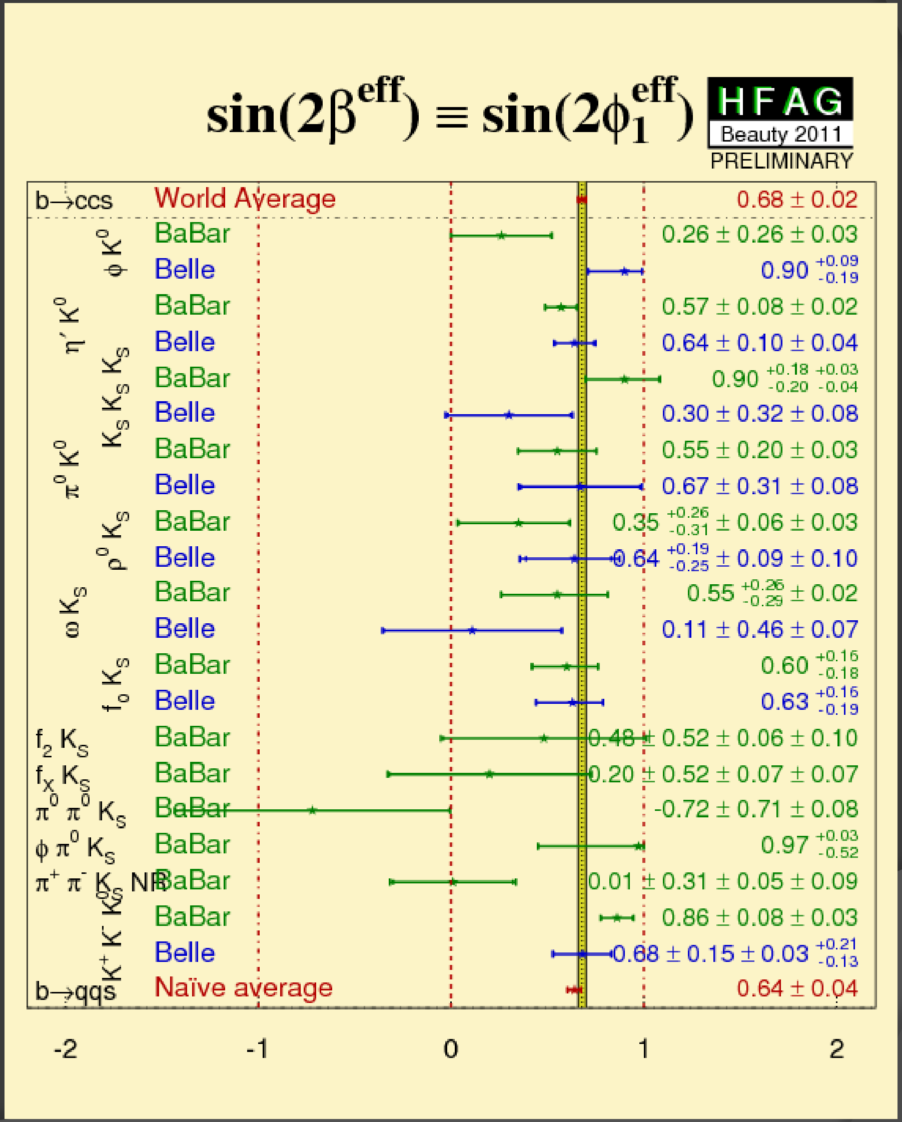


$\text{Sin}2\beta^{eff}$ from "Penguins"

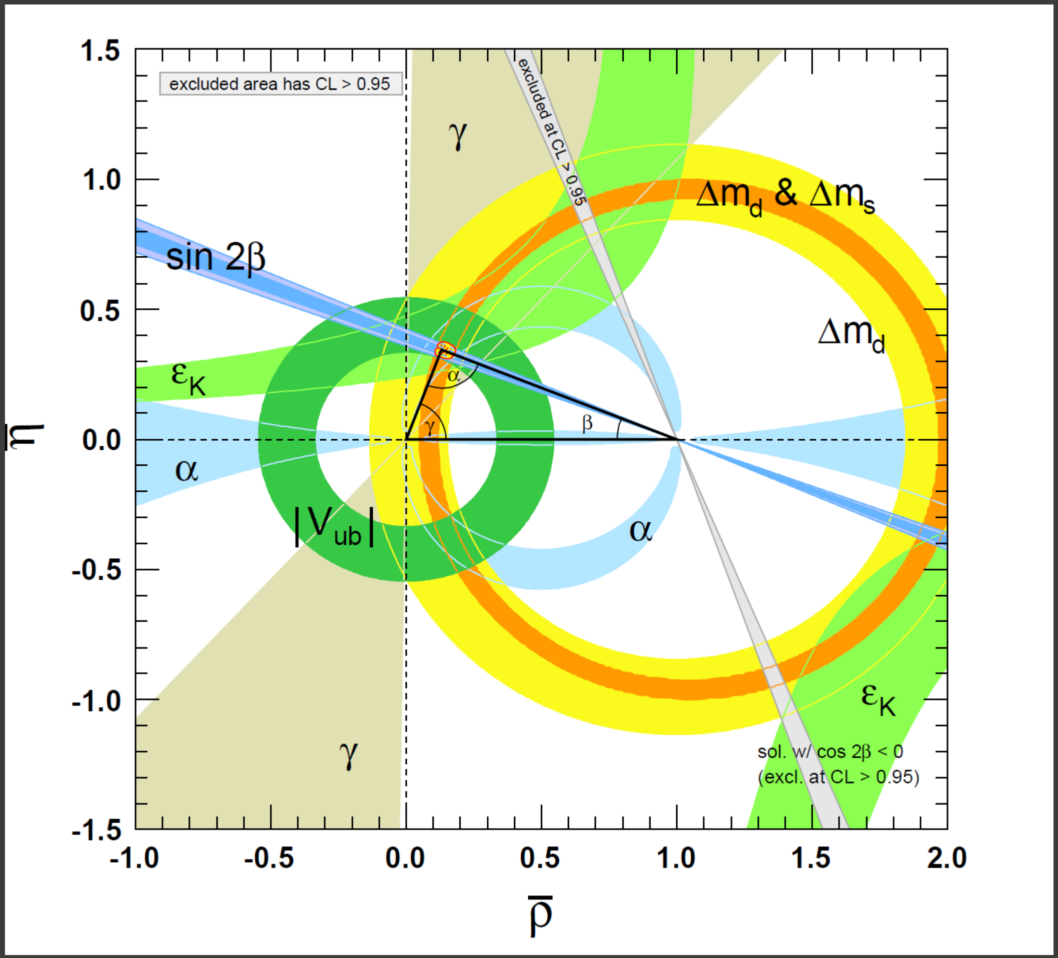
Determinations of sin2β from modes other than charmonium can be affected by New Physics Contributions via Penguin (loop) diagrams

Naïve average (use with extreme caution!) consistent to the b→ cc s determination

Δ = 0.04 ± 0.04



Constraints on the rho eta plane



PDG 2012

The unique measure of CP-Violation in the SM is the area of the Unitarity Triangle (Jarlskog invariant J)

$$J = (2.96^{+0.20}_{-0.16}) \times 10^{-5}$$

Masiero's glass: New Physics generically entails new Sources of CP-violation

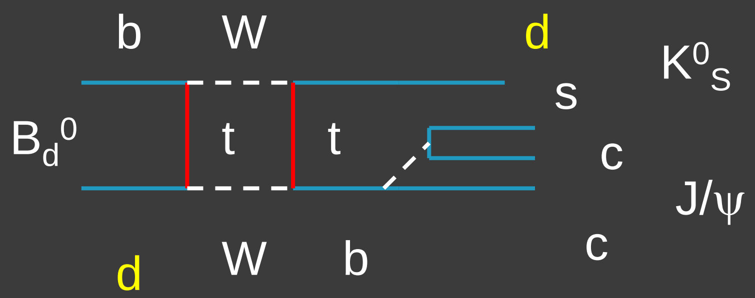
- The stringent limits from FCNC are a threat to New Physics Searches

- Departure from the SM predictions → Possible hints of New Physics

Half Empty Glass… **….Half Full !**

Are there any "hints" of deviation from the CKM description of quark mixing?

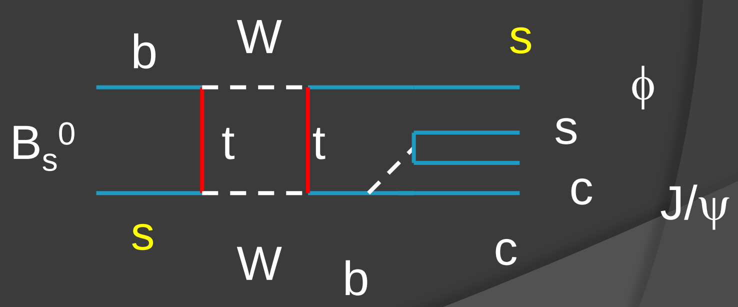
Time dependent CP-Asymmetries in B_s



$V_{td}V^*_{td} \sim e^{i2\beta}$

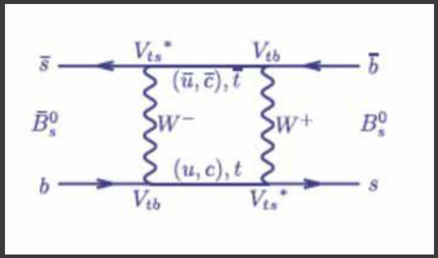
Large CP asymmetry in SM ($\beta=\phi_1$)

$V_{ts}\, V^*_{t\,s} \sim$ real

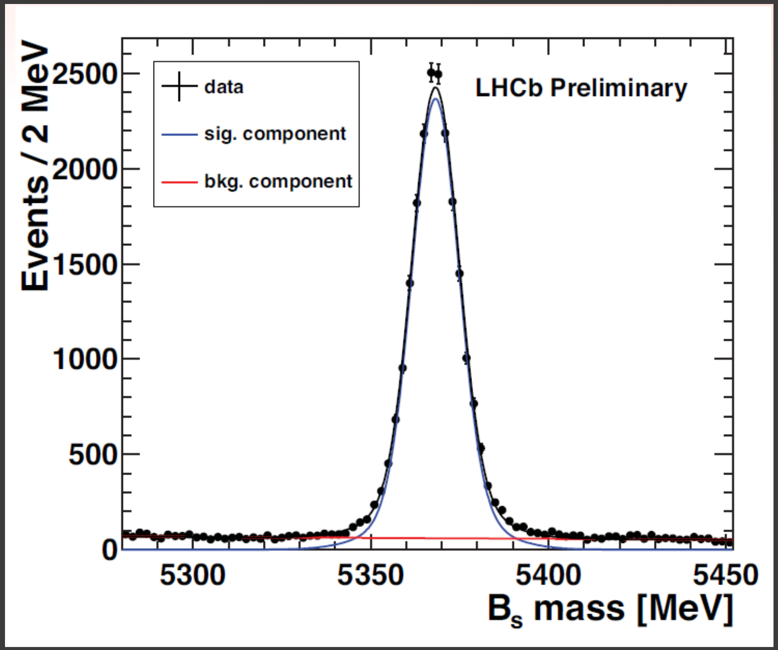


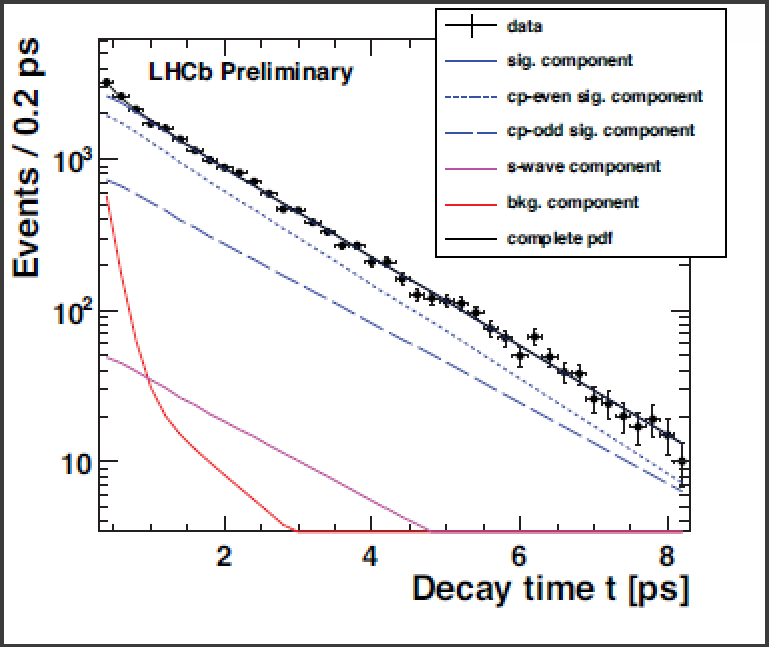
Very small CP asymmetry expected in SM

Important new input: LHCb@LHC



$B_s \to J/\psi\ \phi$

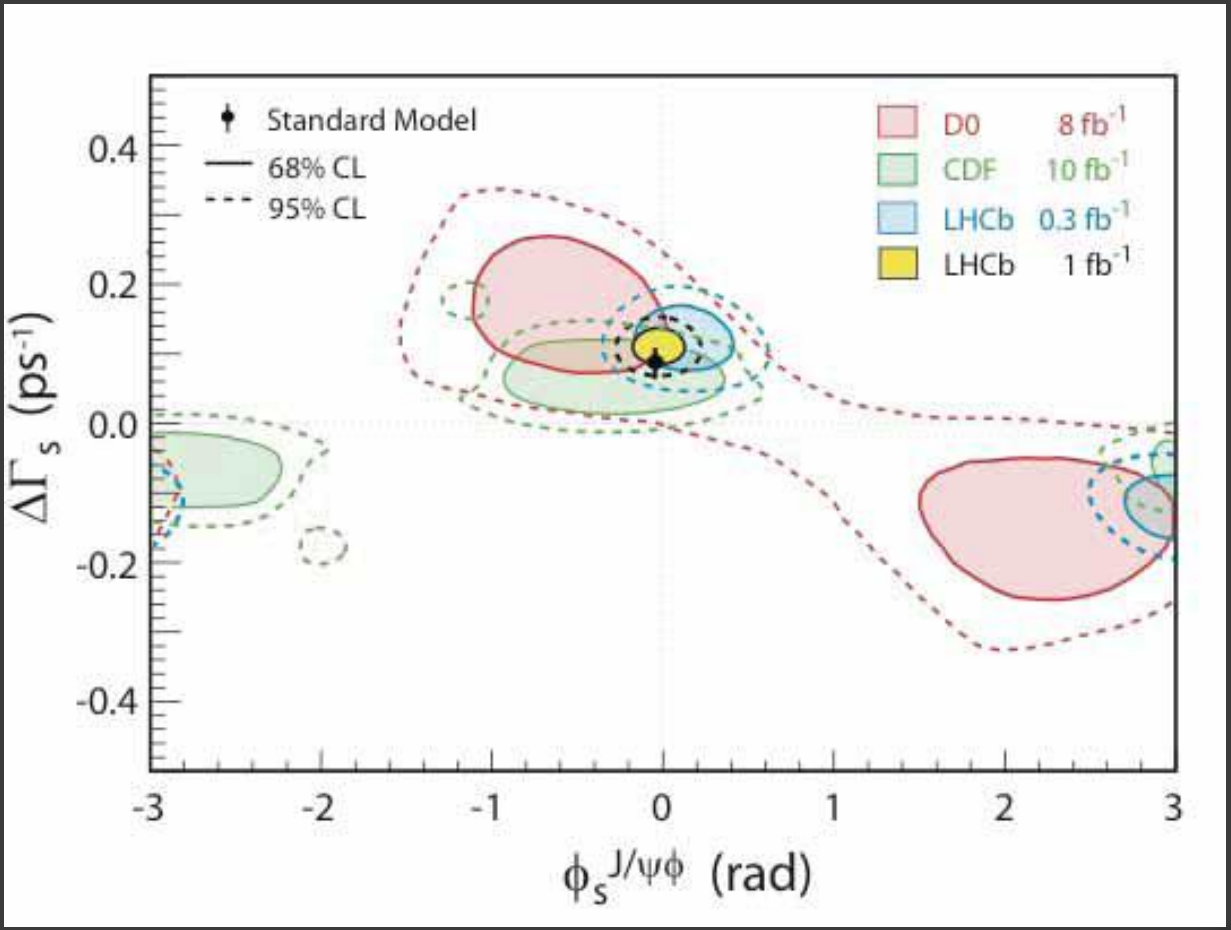




1 fb^{-1}

Peter Clark @ Moriond EW 2012

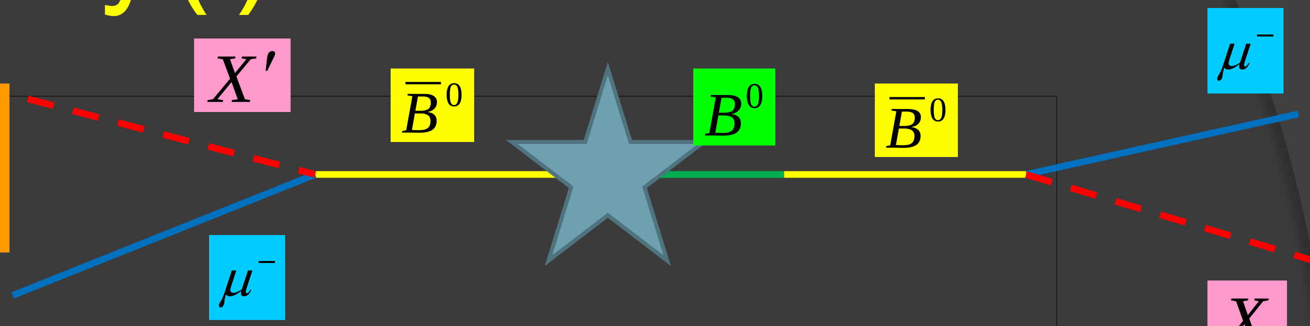
CP-Asymmetry in $B_s \rightarrow J/\psi\ \phi$



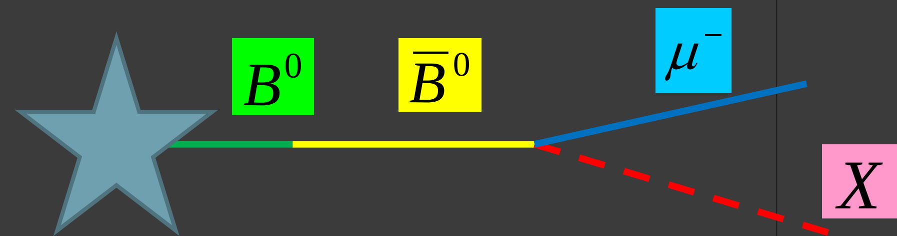
$\phi_s = -0.002 \pm 0.083(\text{stat.}) \pm 0.027(\text{syst.})$ rad

CP–Violating muon charge Asymmetry (I)

$$A_{sl}^{b} = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$



$$a_{sl}^{b} = \frac{n_b^{+} - n_b^{-}}{n_b^{+} + n_b^{-}}$$



$$a_{sl}^{b} \equiv \frac{\Gamma(\overline{B} \to B \to \mu^+ X) - \Gamma(B \to \overline{B} \to \mu^- X)}{\Gamma(\overline{B} \to B \to \mu^+ X) + \Gamma(B \to \overline{B} \to \mu^- X)} = A_{sl}^{b}$$

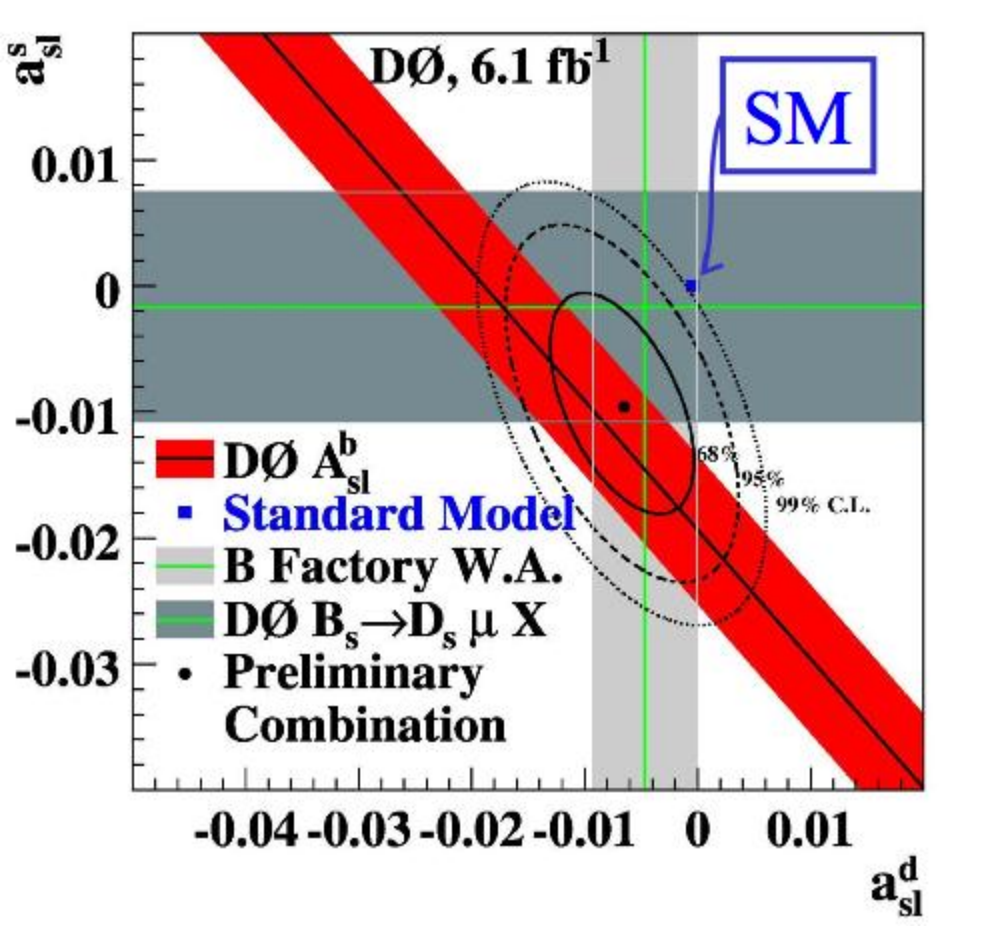
In SM ~0

$A^b{}_{sl}$ = [– 0.957 ± 0.251 (stat.) ± 0.146 (syst.)] %

Two independent methods
To measure the asymmetry

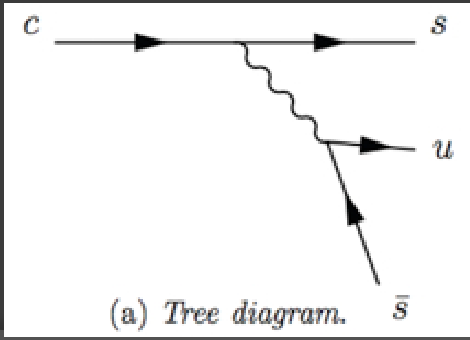
D0: PRL, 081801 (2010)

CP–Violating muon charge asymmetry (II)

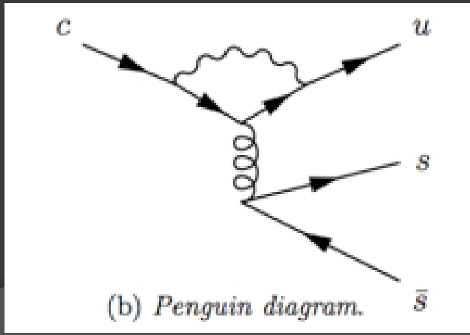


CP Violation in charm?

- CP violation contributions:
  - Direct contribution → in decay
  - Indirect contributions → in mixing and in interference
- In the SM CP violation is conserved to first approximation (dominance of 2generations)
- New Physics can enhance CP violating observables
- Cabibbo-favoured modes not interesting
  - Tree-level SM contribution swamps everything else
- Singly-Cabibbo-suppressed modes with gluonic penguin diagrams very promising
- Interference between Tree and Penguin can generate direct CP asymmetries
  - Several classes of NP can contribute
  - but also non-negligible SM contribution



(a) *Tree diagram.*



(b) *Penguin diagram.*

LHCb & CDF: Measurement of ΔA_{CP} ($D^0 \to K^- K^+$ - $D^0 \to \pi^- \pi^+$)

arXiv:1112:09838

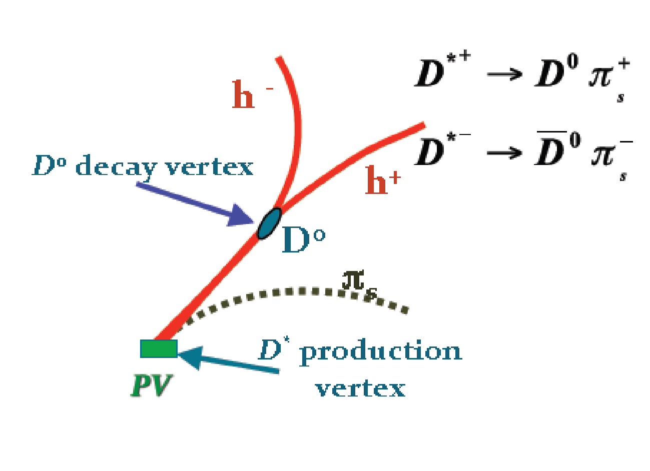
Time integrated asymmetry:

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$$

f is the finale state K^+K^- or $\pi^+\pi^-$

Both direct and indirect CPV contributions

The D^0 flavour is determined by the charge sign of the slow pion from the D* decay



CPV in charm

$$A_{RAW}(f)^* = \frac{N\left(D^{*+} \to D^0(f)\pi_s^+\right) - N\left(D^{*-} \to \bar{D}^0(\bar{f})\pi_s^-\right)}{N\left(D^{*+} \to D^0(f)\pi_s^+\right) + N\left(D^{*-} \to \bar{D}^0(\bar{f})\pi_s^-\right)}$$

$$A_{RAW}(f)^* = A_{CP}(f) + A_D(f) + A_D(\pi_s) + A_P(D^{*+})$$

Physics CP asymmetry

Detection asymmetry of D^0 and of slow pion

Production asymmetry

$$A_{RAW}(K^-K^+)^* - A_{RAW}(\pi^-\pi^+)^* = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) \equiv \Delta A_{CP}$$

HCP 2011: LHCb, 620 pb^{-1} : first evidence (3.5 σ) of CPV in charm:

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-0.82 \pm 0.21 \pm 0.11)\%$$

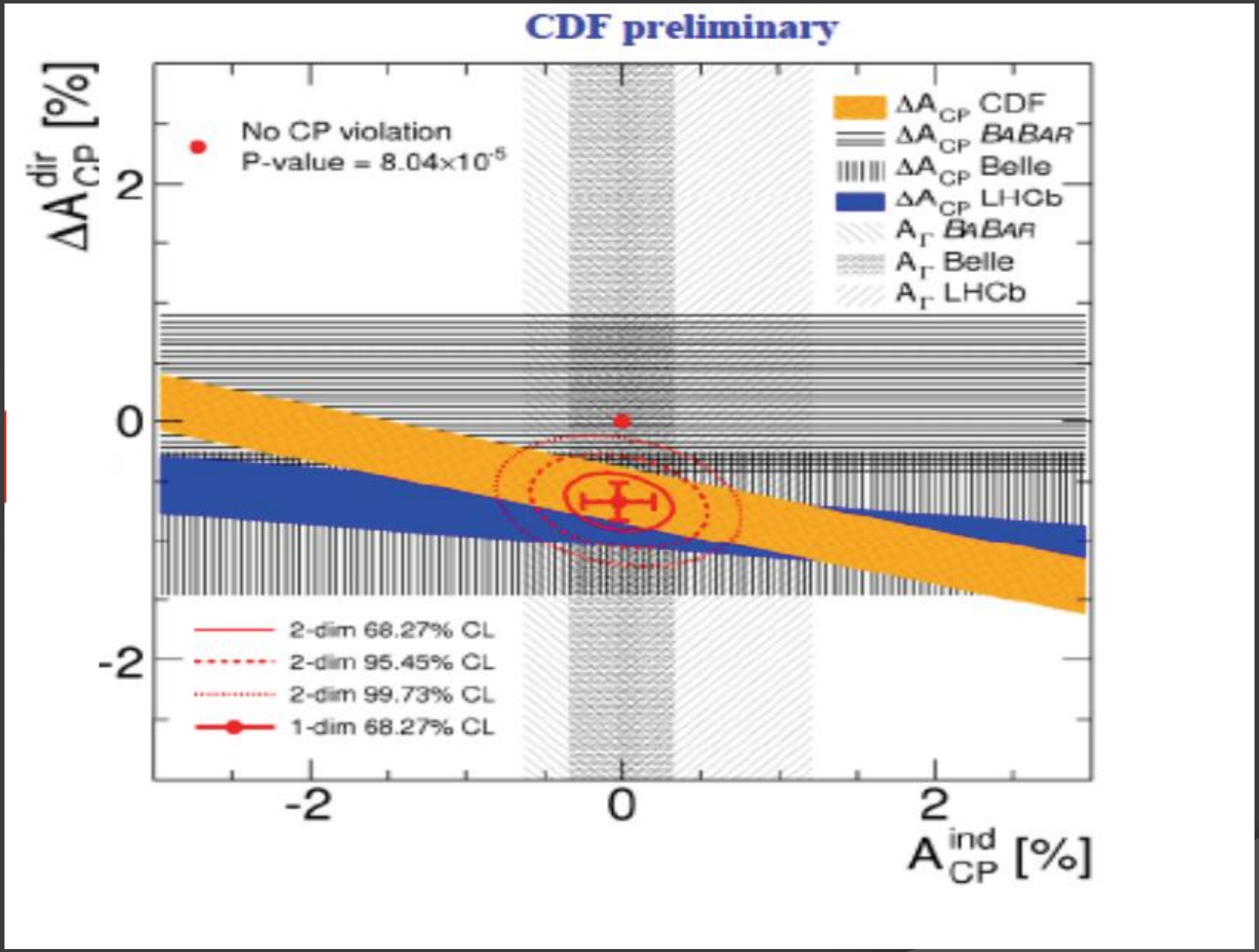
LHCb, PRL 108 (2012) 11602

Moriond 2012: CDF, 9.6 fb^{-1}, confirms this result

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = \mathbf{(-0.62 \pm 0.21 \pm 0.10)\ \%}$$

CDF, PRD 85 (2012) 012009

CPV in charm: state of the art



CPV in charm: SM or NP?

- Generically parametrically suppressed in SM
  - in mixing it enters as $\mathcal{O}(V_{cb}V_{ub}/V_{cs}V_{us}) \sim 10^{-3}$
  - direct CPV in SCS as $\mathcal{O}([V_{cb}V_{ub}/V_{cs}V_{us}]\alpha_s/\pi) \sim 10^{-4}$
- …could be enhanced by SM penguins and corrections
  - e.g. Brod, Grossman, Kagan, Zupan (arXiv:1203.6659)
- more channels to be studied (charm three body decays…)

V_{ub} "tension"

- Charmless b decays → first evidence of mixing between first and third generation (Argus & CLEO, 1990)
- As we saw, V_{ub} is an important constraint to the CKM fits
- In addition, it's value is needed to fix the SM expectation for $B(B^+ \to \tau^+ \nu)$ which, beyond SM, is sensitive to contributions coming from charged Higgs exchanges
- Big effort to bring theoretical errors under control
- Big experimental effort to reduce background (Full reconstruction methods etc.)
- There is a persisting tension between the exclusive and inclusive determinations

V_{ub} "tension"

As summarized by Guido Altarelli at FPCP 2011

V_{ub}incl = 4.35±0.18±0.23 Bernlocher

V_{ub}excl = 3.25±0.12±0.28

V_{ub}incl- V_{ub}excl = 1.10 ±0.42 2.6 σ

I think that this "tension" is due to the fact that over the last 30 years hundreds of theory papers have been devoted to the determination of Vub: each author claiming that his work led to a decrease of the theor. error

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

In the SM it measures the combination $f_b|V_{ub}|$

$$B(B \to \ell \nu) = \frac{G_F m_B}{8\pi} m_\ell^2 (1 - \frac{m_\ell^2}{m_B^2})^2 f_B^2 |V_{ub}|^2 \tau_B$$

Using V_{ub} as external input, the decay can be used to determine the B meson decay constant f_B and compare it to the lattice QCD value

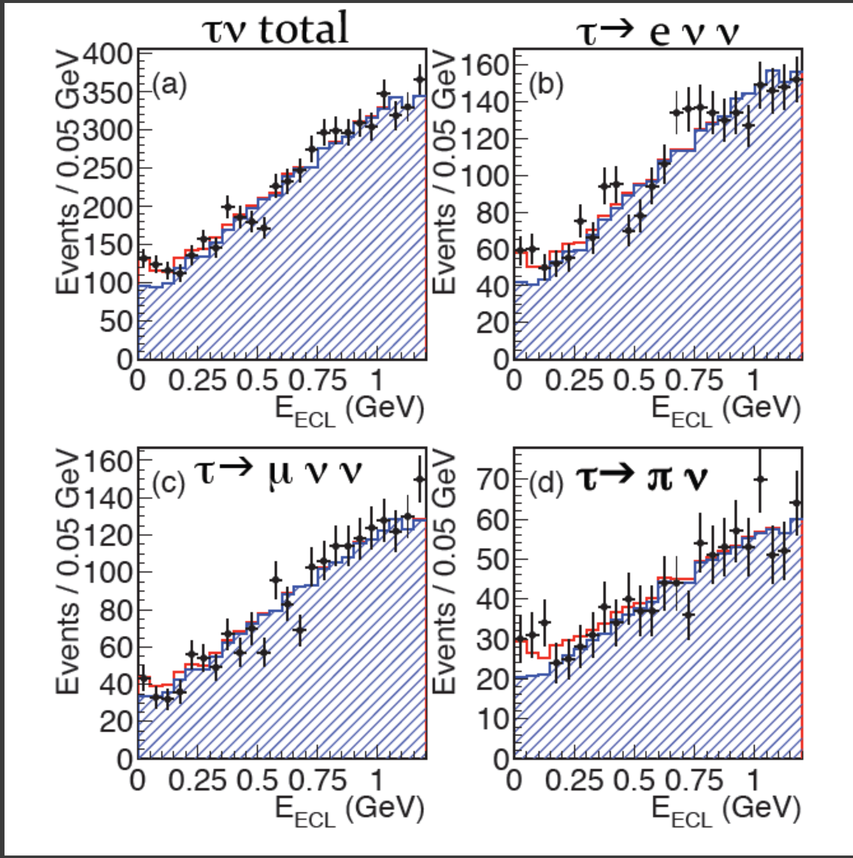
(e.g. f_B= 190 ±13MeV (HPQCD collaboration arXiv:0902.1815v2)

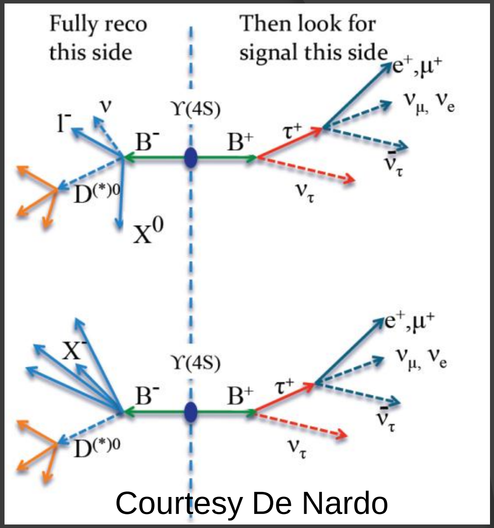
Helicity suppressed in the SM, sensitive to Charged Higgs mass in SM extensions

B Factories: $B^+ \rightarrow \tau^+ \nu$

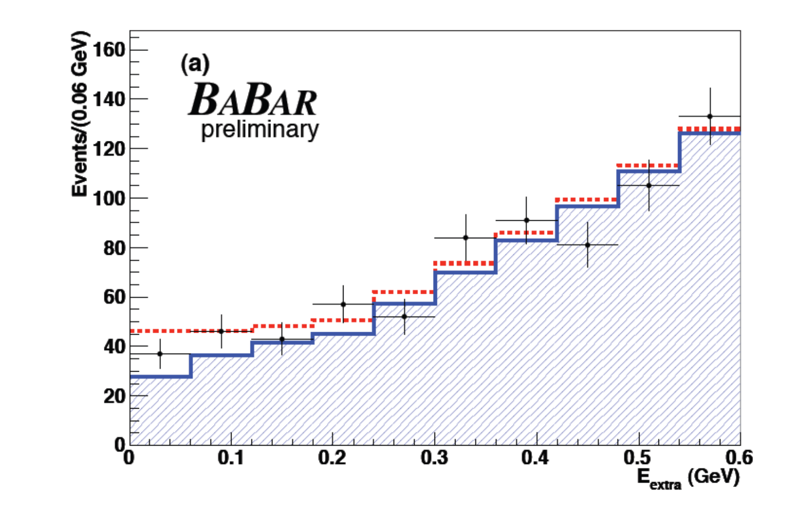
No kinematic constraints, **many neutrinos!**

Belle Semi Leptonic tags PRD 82 071101 R (2010)



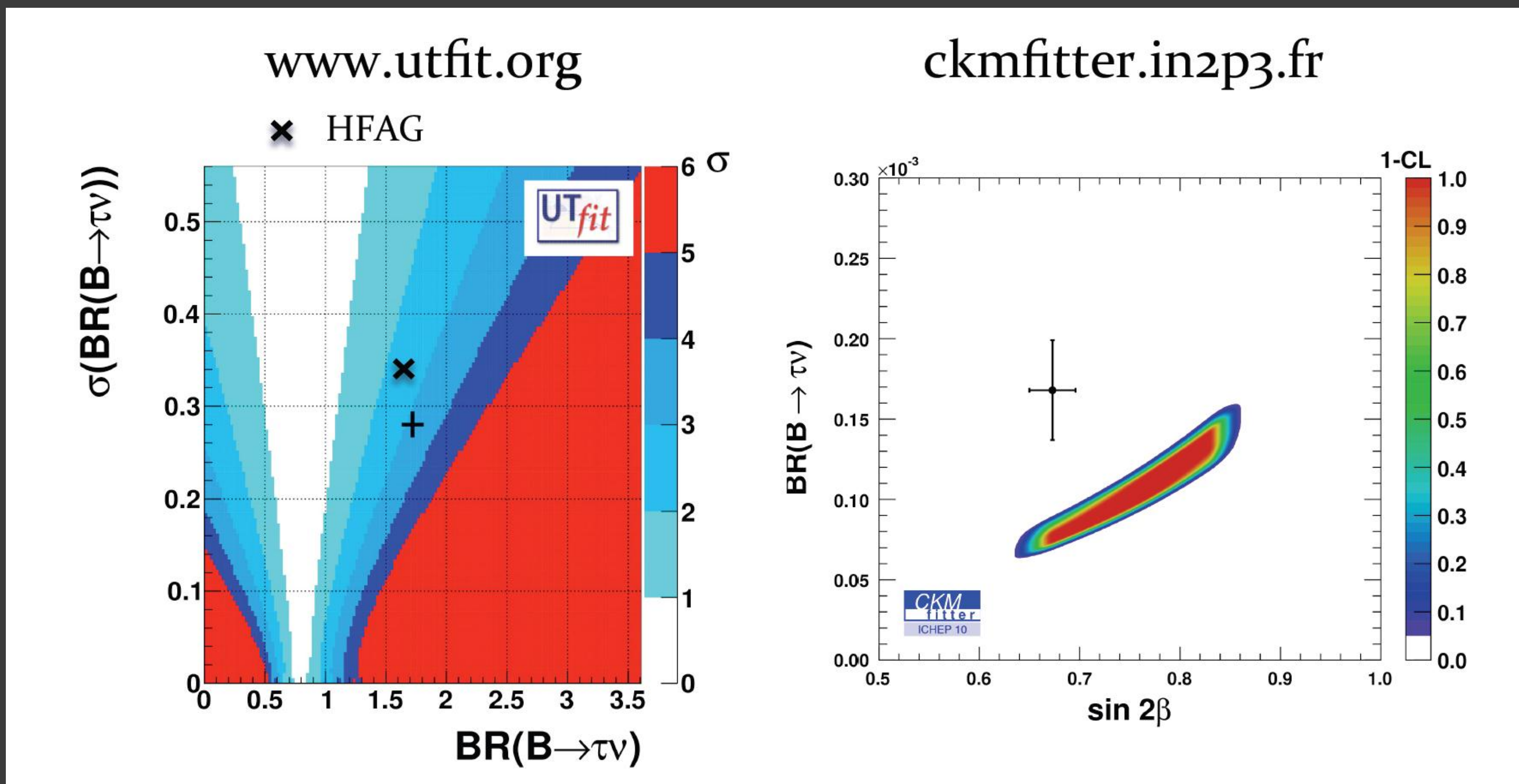


Babar Hadronic tags (arXiv:1008.0104 (2010)



HFAG Average: $B(B^+ \rightarrow \tau^+ \nu) = (1.64 \pm 0.34) \times 10^{-4}$

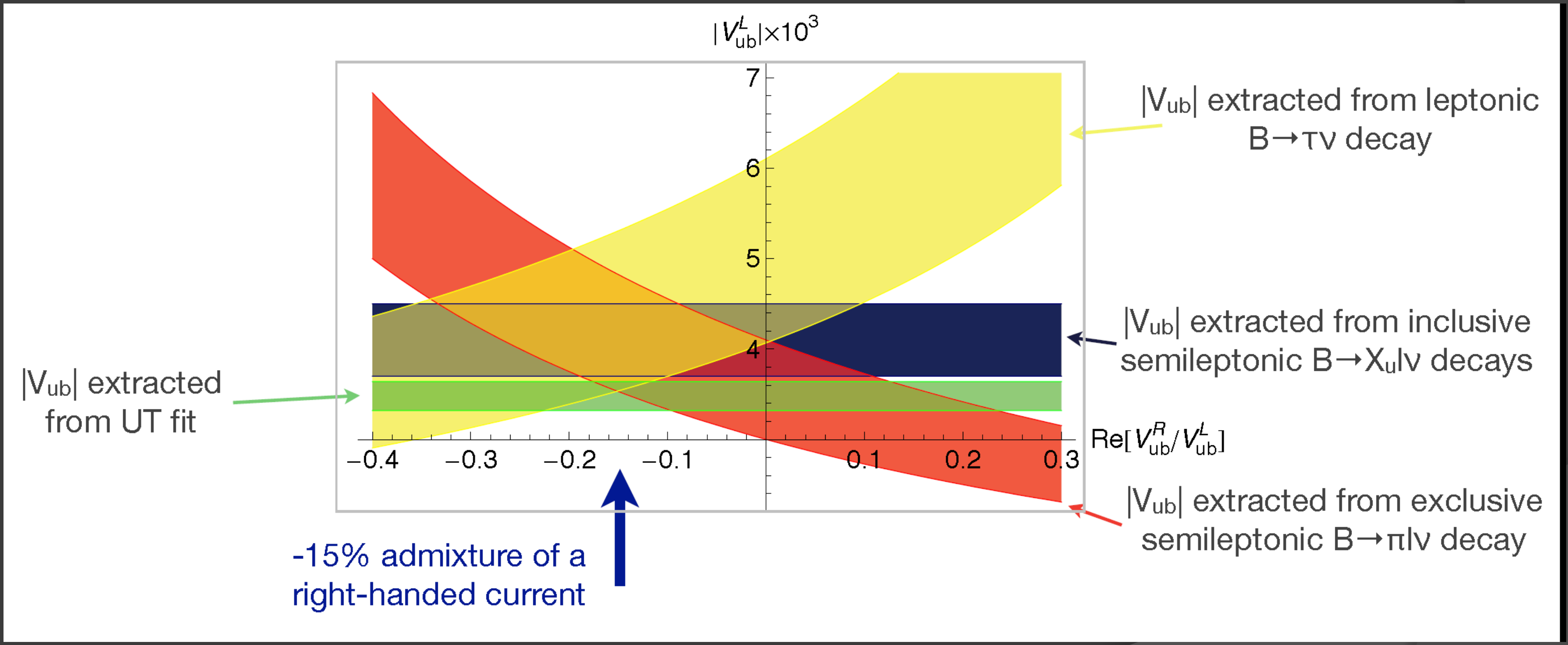
$B^+ \to \tau^+ \nu$ and CKM fits



As shown by G. De Nardo at FPCP 2011

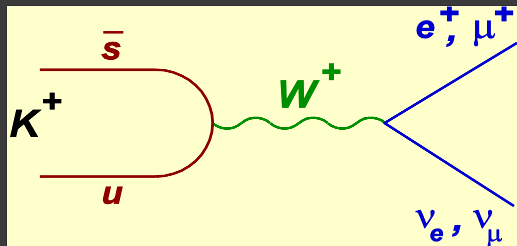
V_{ub} & RH currents?

Crivellin (2009);
see also: Buras, Gemmler (2011)



Similarly: $R_K = K_{e2}/K_{\mu 2}$

SM

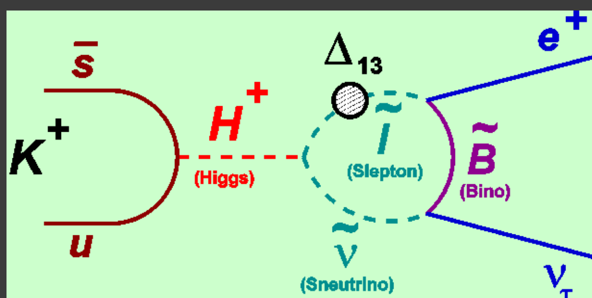


$$R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = \frac{m_e^2}{m_\mu^2} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \cdot (1 + \delta R_K^{rad.corr.})$$

$R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$

Cirigliano & Rosell PRL 99 (2007) 231801

BSM, LFV



e.g. Masiero, Paradisi Petronzio
PRD 74 (2006) 011701,
JHEP 0811 (2008) 042

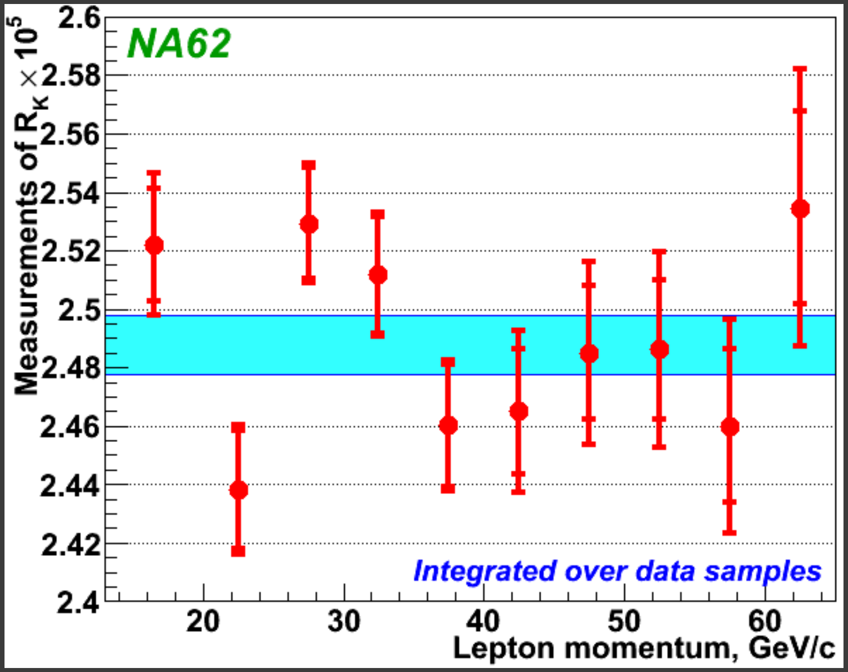
$$R_K^{LFV} \approx R_K^{SM} \left[1 + \left(\frac{m_K^4}{M_{H^\pm}^4}\right) \left(\frac{m_\tau^2}{M_e^2}\right) |\Delta_{13}|^2 \tan^6 \beta \right]$$

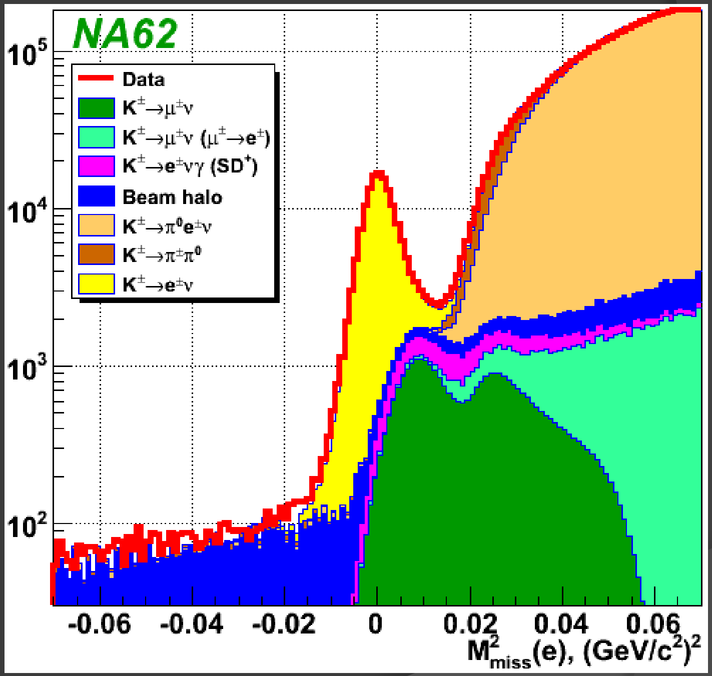
Example:
($\Delta_{13} = 5 \times 10^{-4}$, $\tan\beta = 40$, $M_H = 500$ GeV/c^2)
lead to $R_K^{MSSM} = R_K^{SM}(1+0.013)$.

NA62: R_K full data set

$R_K = (2.488 \pm 0.007_{stat} \pm 0.007_{syst}) \times 10^{-5}$
$R_K = (2.487 \pm 0.010) \times 10^{-5}$

Published (40% sample)
CERN-PH-EP-2011-004,
arXiv:1101.4805,
PLB B698 (2011) 105

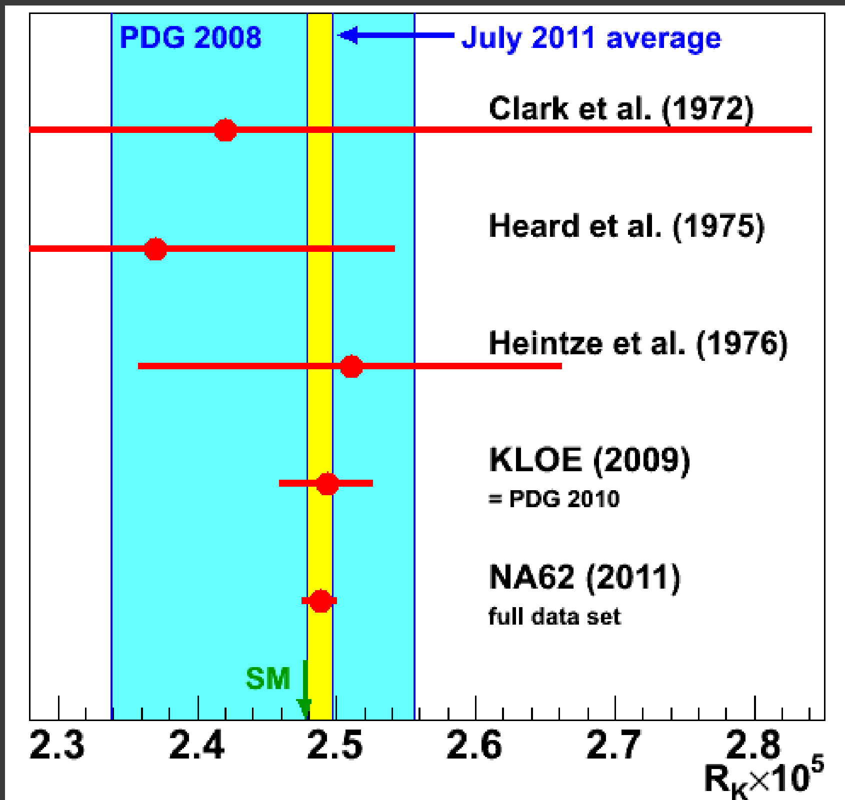


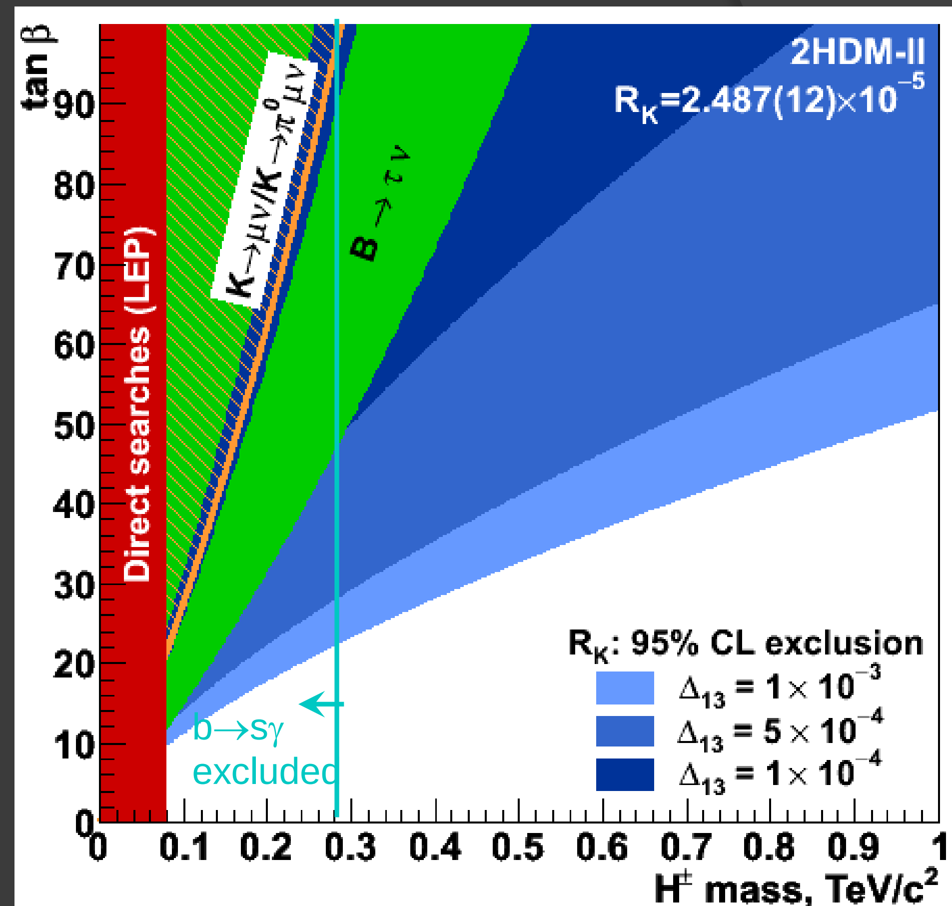


Errors in momentum bins are partially correlated

Angela Romano, La Thuile 2012

R_K world average





World average	$\delta R_K \times 10^5$	Precision
PDG 2008	2.447±0.109	4.5%
Today	2.488±0.009	0.4%

Other limits on 2HDM-II:
PRD 82 (2010) 073012
SM with 4 generations:
JHEP 1007 (2010) 006.

A. Buras list of Flavour Superstars

Superstars of 2011 – 2015 (Flavour Physics)

- $S_{\psi\varphi}$ — $\not{CP}$ in $B_s^0 - \bar{B}_s^0$ — $(B_s \to \varphi\varphi)$
- $B_s \to \mu^+\mu^-$ — $(B_d \to \mu^+\mu^-)$ — $(B^+ \to \tau^+\nu_\tau)$
- $K^+ \to \pi^+\nu\bar{\nu}$ — $(K_L \to \pi^0\nu\bar{\nu})$ — $(B_d \to K^*\mu^+\mu^-)$
- γ from Tree Level Decays
- $\mu \to e\gamma$, $\tau \to \mu\gamma$, $\tau \to e\gamma$, $\mu \to 3e$, $\tau \to$ 3 leptons
- ε'/ε *) (Lattice)
- EDM´s, $(g\text{-}2)_\mu$

*) Direct $\not{CP}$ in $K_L \to \pi\pi$

37 Amsterdam0411

Strategies for Indirect NP Searches

- Improve meaurement precision of CKM elements
  - Compare measurements of the same quantities which may or may not be sensitive to new physics
  - Extract all CKM angles and sides in many different ways → inconsistencies would signal NP
- Measure Flavour Changing Neutral Currents (FCNC) processes where the SM contributions are suppressed

—e.g. OPE expansion for b→s transitions:

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [\underbrace{C_i(\mu) O_i(\mu)}_{\text{left-handed part}} + \underbrace{C_i'(\mu) O_i'(\mu)}_{\text{right-handed part suppressed in SM}}]$$

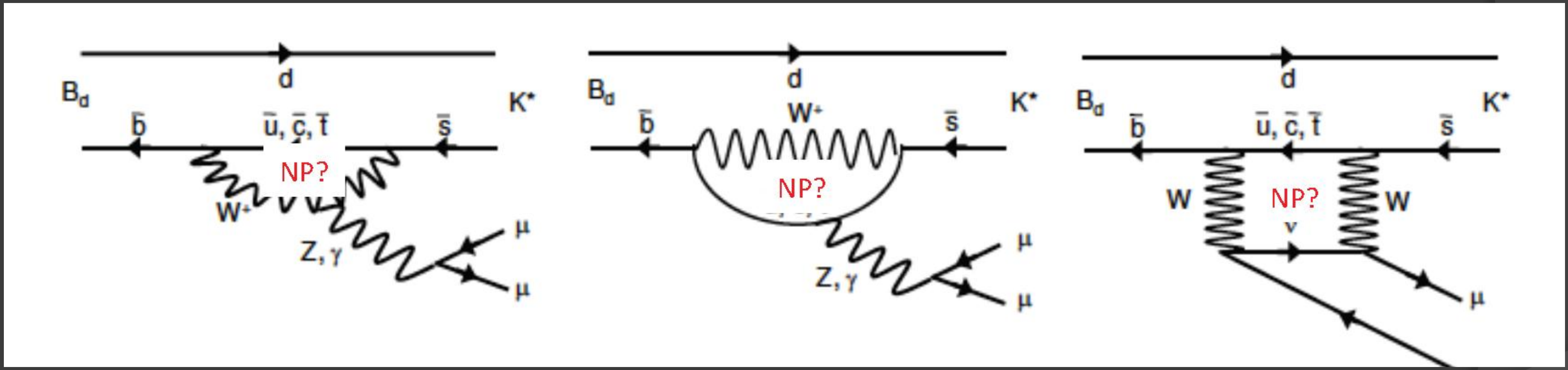
—New Physics may

- modify $C_i^{(')}$ short-distance Wilson coefficients
- add new long-distance operators $O_i^{(')}$

$i = 1,2$	Tree
$i = 3-6,8$	Gluon penguin
$i = 7$	Photon penguin
$i = 9,10$	Electroweak penguin
$i = S$	Higgs (scalar) penguin
$i = P$	Pseudoscalar penguin

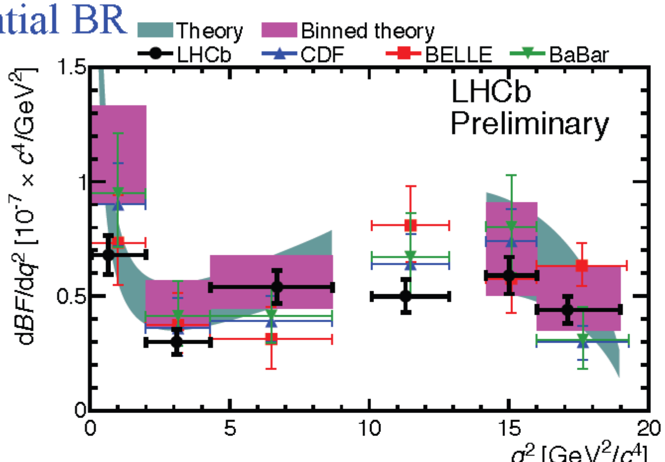
$B \to K^* \mu^+ \mu^-$

FCNC Forbidden at tree level
NP can modify the helicity structure (angular resolution)



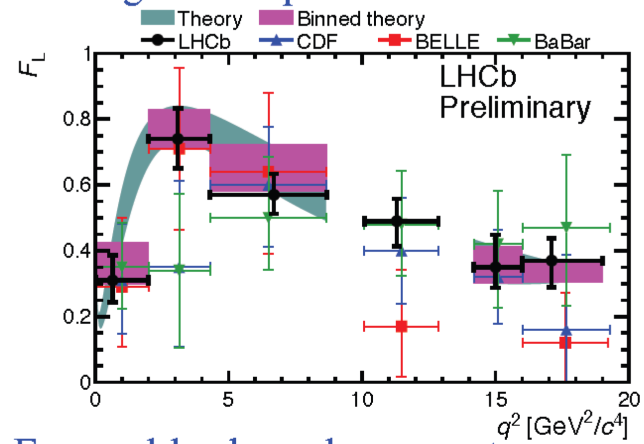
Partial BF and angular observables have been measured by Babar, Belle, CDF and LHCb: all show good agreement with SM predictions (within the uncertainties)

Differential BR



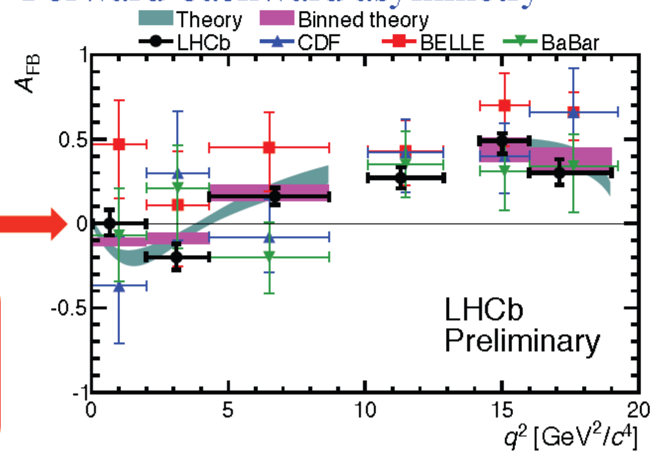
K* longitudinal polarization

q^2= invariant di-leptons mass



Babar: S. Akar, Lake Louise 2012
Belle: Phys. Rev. Lett. 103, 171801 (2009)
CDF: Phys. Rev. Lett. 108, 081807 (2012)
LHCb: LHCb-CONF-2012-008
Theory predictions:
C. Bobeth, G. Hiller, D. van Dyk, JHEP 07 067 (2011)

Forward-backward asymmetry



Tensions" seen by others in region $1 < q^2 < 6\ \mathrm{GeV}^2/c^4$ not confirmed by LHCb

33

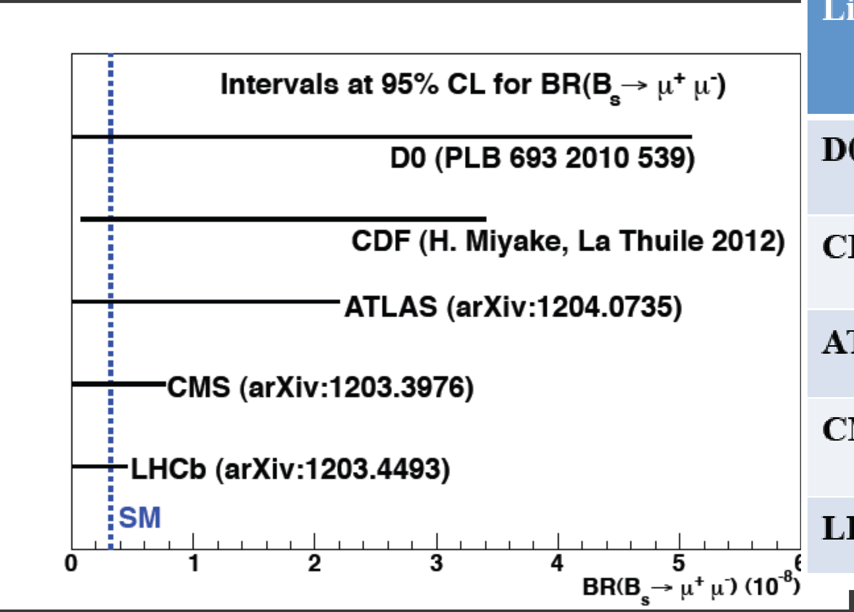
As presented by G. Lanfranchi (Blois 2012)
Detailed presentation M. Patel CERN seminar, May 8, 2012

$B_{d,s}^0 \to \mu^+\mu^-$

- Exploratory decay sensitive to non-standard Higgs(es)

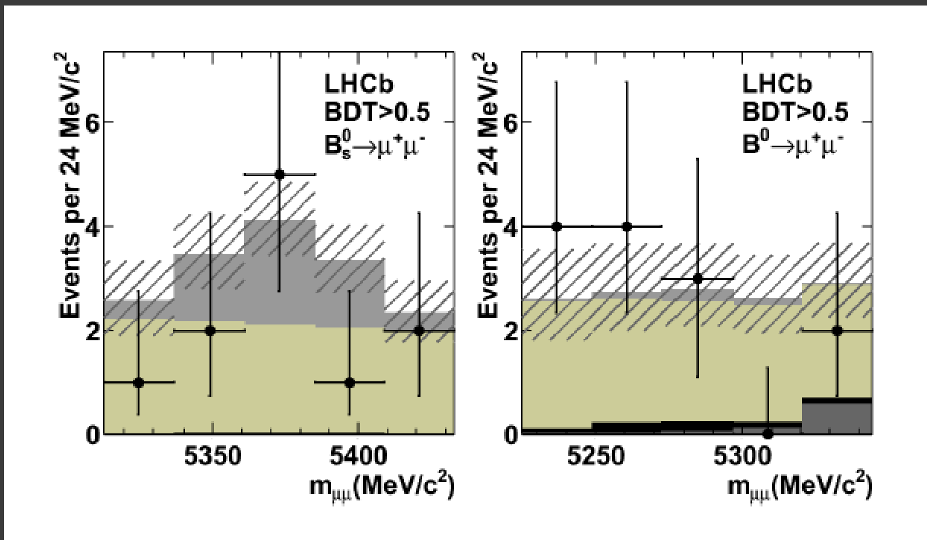
$$(c_{S,P}^{MSSM})^2 \propto \left(\frac{m_b m_\mu \tan^3\beta}{M_A^2}\right)^2$$

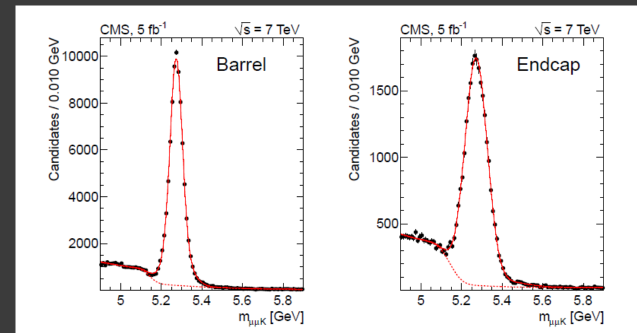
- Clean signature at hadronic colliders



Limit @95%CL	L [fb^{-1}]
D0: < 51×10^{-9}	6.1
CDF: $[0.8,34]\times10^{-9}$	10
ATLAS:< 22×10^{-9}	2.4
CMS: < 7.7×10^{-9}	4.9
LHCb: < 4.5×10^{-9}	1

LHCb & CMS: $B_{d,s}^0 \to \mu^+\mu^-$

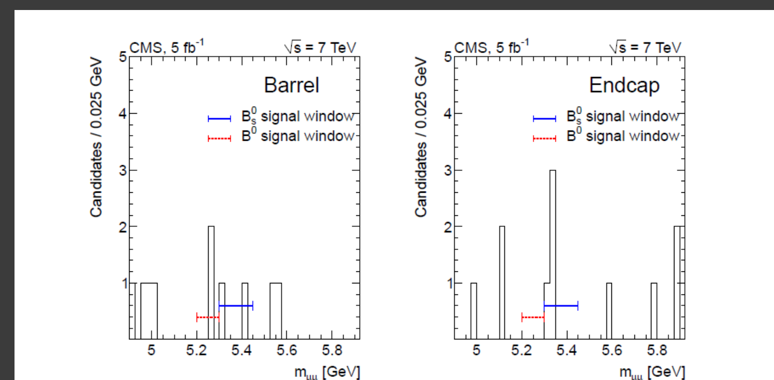




$B^+ \to J/\psi K^+$ invariant-mass

Mode	Limit	at 90 % CL	at 95 % CL
$B_s^0 \to \mu^+\mu^-$	Exp. bkg+SM	6.3×10^{-9}	7.2×10^{-9}
	Exp. bkg	2.8×10^{-9}	3.4×10^{-9}
	Observed	3.8×10^{-9}	4.5×10^{-9}
$B^0 \to \mu^+\mu^-$	Exp. bkg	0.91×10^{-9}	1.1×10^{-9}
	Observed	0.81×10^{-9}	1.0×10^{-9}

LHCb



$\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 7.7 \times 10^{-9}$ (6.4×10^{-9})

$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.8 \times 10^{-9}$ (1.4×10^{-9})

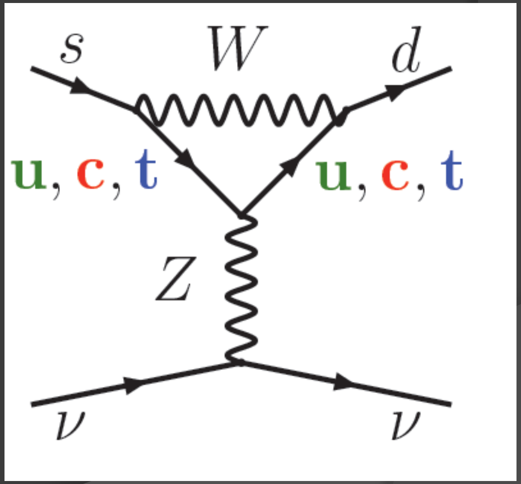
95% (90%) CL.

CMS

Ultra-rare K Decays

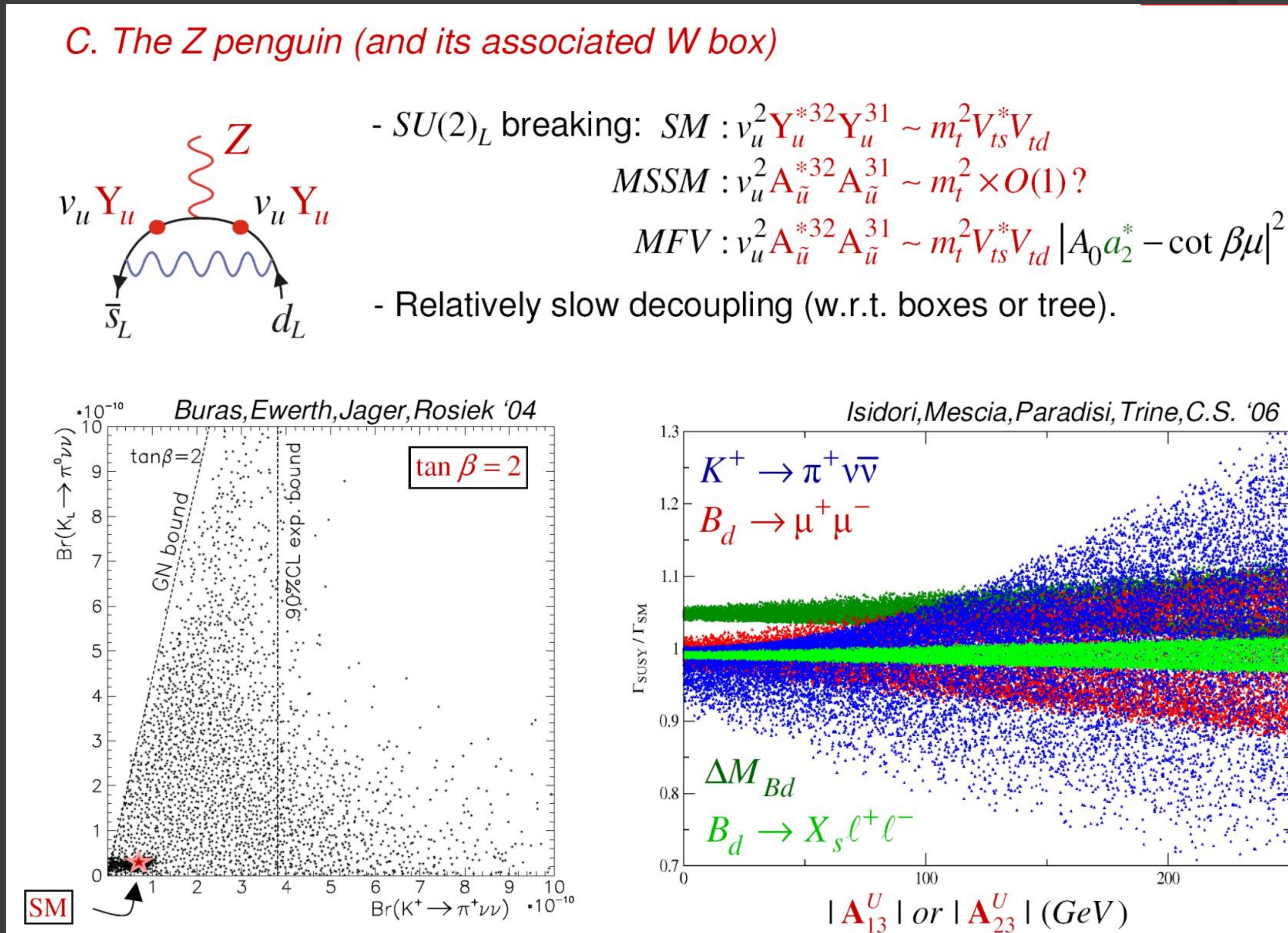
Decay	Branching Ratio ($\times 10^{10}$)	
	Theory (SM)	Experiment
$K^+ \to \pi^+ \nu\bar{\nu}(\gamma)$	0.85 ± 0.07[1]	$1.73^{+1.15}_{-1.05}$[2]
$K_L^0 \to \pi^0 \nu\bar{\nu}$	0.26 ± 0.04[3]	< 260 (90% CL)[4]

[1] J.Brod, M.Gorbahn, PRD78, arXiv:0805.4119
[2] AGS-E787/E949 PRL101, arXiv:0808.2459
[3] M. Gorbahn
[4] KEK-E391a arXiv:0911.4789v1



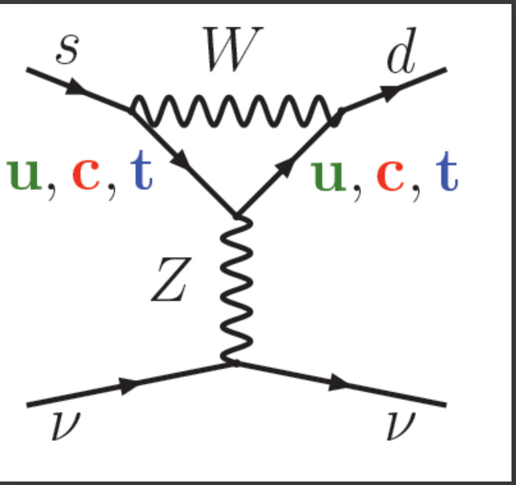
- New experiments under construction:
  - KOTO JPARC: $K^0_L \to \pi^0 \nu \nu$
  - NA62 CERN: $K^+ \to \pi^+ \nu \nu$

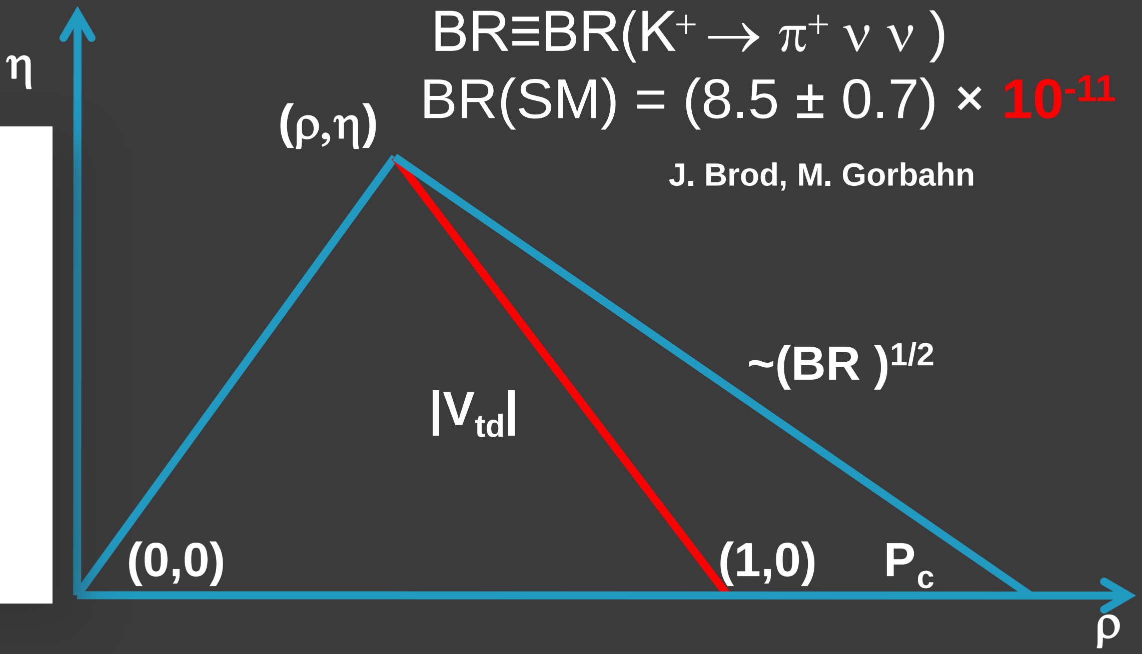
Kaon Rare Decays and NP



(courtesy by Christopher Smith)

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





$BR \equiv BR(K^+ \to \pi^+ \nu \bar{\nu})$

$BR(SM) = (8.5 \pm 0.7) \times 10^{-11}$

J. Brod, M. Gorbahn

$$\delta |V_{td}| / |V_{td}| \approx 0.4\, \delta P_c/P_c \oplus 0.7\, \delta BR/BR \oplus \delta |V_{cb}| / |V_{cb}|$$

~2 % (mostly δm_c) 62 % BNL 3 %

7% aim of NA62 (2y)

NA62 Sensitivity

Decay Mode	Events
Signal: $K^+ \to \pi^+ \nu \nu$ *[flux = 4.8×10^{12} decay/year]*	55 *evt/year*
$K^+ \to \pi^+ \pi^0$ $[\eta_{\pi 0} = 2 \times 10^{-8}$ (3.5×10^{-8})]	4.3% (7.5%)
$K^+ \to \mu^+ \nu$	2.2%
$K^+ \to e^+ \pi^+ \pi^- \nu$	≤3%
Other 3 – track decays	≤1.5%
$K^+ \to \pi^+ \pi^0 \gamma$	~2%
$K^+ \to \mu^+ \nu \gamma$	~0.7%
$K^+ \to e^+ (\mu^+)$ $\pi^0 \nu$, others	negligible
Expected background	≤13.5% (≤17%)

Future Projects

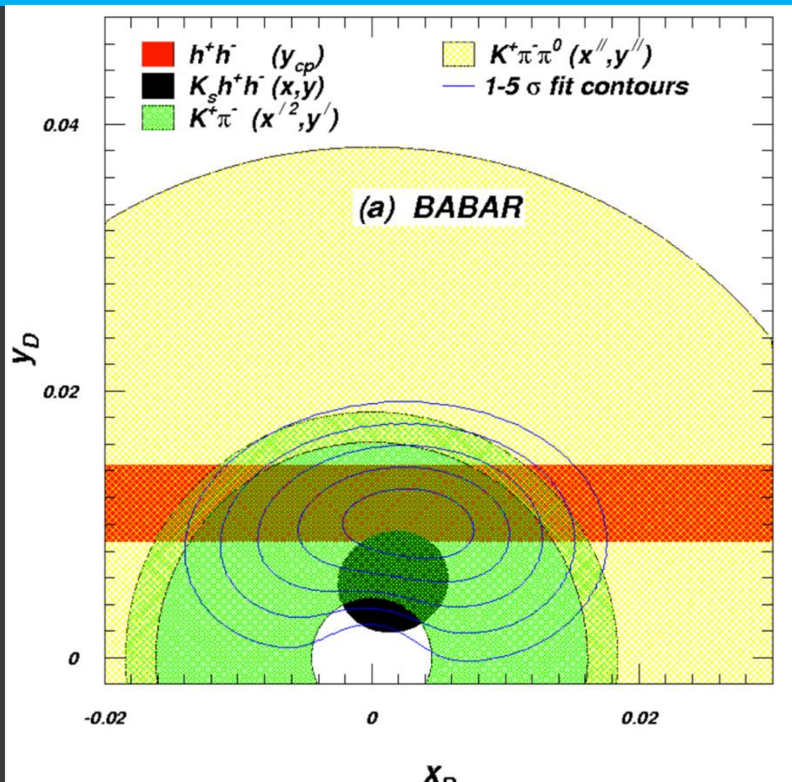
- e^+e^- Super-Flavour Factories
  - Italian SuperB
  - Japanese KEK/Belle II
- LHCb Upgrade
- Fermilab Project X

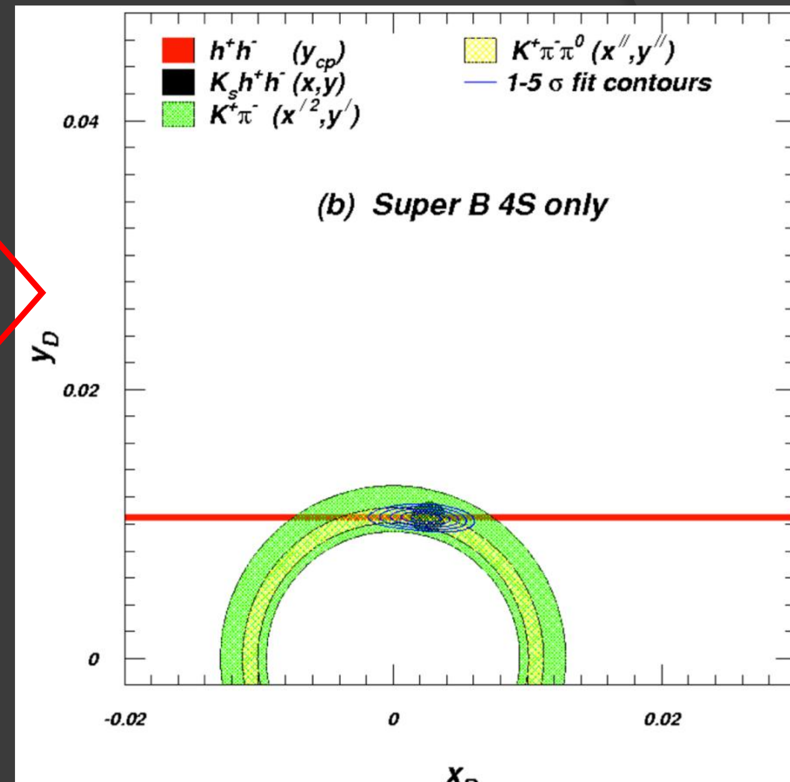
Summary of Lecture 1

- There has been significant progress during the past decade in flavour physics
- So far all manifestations of CP violation are consistent with "just" one complex phase in the CKM quark mixing matrix
- We are moving towards very quantitative SM tests
- Flavour is at the heart of particle physics. There is a strong programme to continue the search for CP-Violation and FCNC beyond the SM. A fully complementary approach to the searches for new phenomena performed at the energy frontier
- The next lecture will focus on some of the detector techniques required to advance the frontier of **very rare processes**

Spares

Sensitivity projections with 75 ab^{-1} at $\Upsilon(4S)$





Fit	$x \times 10^3$	$y \times 10^3$	$\delta^\circ_{K^+\pi^-}$	$\delta^\circ_{K^+\pi^-\pi^0}$
(a)	$3.01^{+3.12}_{-3.39}$	$10.10^{+1.69}_{-1.72}$	$41.3^{+22.0}_{-24.0}$	43.8 ± 26.4
Stat.	(2.76)	(1.36)	(18.8)	(22.4)

Fit	$x \times 10^3$	$y \times 10^3$	$\delta^\circ_{K^+\pi^-}$	$\delta^\circ_{K^+\pi^-\pi^0}$
(b)	$xxx^{+0.72}_{-0.75}$	$xxx \pm 0.19$	$xxx^{+3.7}_{-3.4}$	$xxx^{+4.6}_{-4.5}$
Stat.	(0.18)	(0.11)	(1.3)	(2.9)

Uncertainties shrink:
$x_D \rightarrow x_D/4$; $y_D \rightarrow y_D/10$
Precision in x_D is limited by Dalitz plot model.

KEKB/Belle status: official statement

„As is now well known, Japan suffered a terrible earthquake and tsunami on March 11, which has caused tremendous damage, especially in the Tohoku area. Fortunately, all KEK personnel and users are safe and accounted for.

The injection linac did suffer significant but manageable damage, and repairs are underway. The damage to the KEKB main rings appears to be less serious, though non-negligible. No serious damage has been reported so far at Belle. Further investigation is necessary.

We would like to convey our deep appreciation to everyone for your generous expressions of concern and encouragement.“

As reported by Peter Krizan at the SuperB workshop, May 2011

Other Kaon measurements

$K^+ \rightarrow \pi^0 \mu^+ \nu$ (Transverse Polarization -T violation)

$K^+ \rightarrow e^+ \nu \,/\, K^+ \rightarrow \mu^+ \nu$ (Universality, LFV, Pseudoscalars...)

$K^+ \rightarrow \mu^+ \nu_H$ (Heavy neutrinos)

$K_L^0 \rightarrow \pi^0 ee \,/\, \pi^0 \mu\mu$ (CP Violation)

$K_L^0, K^+ \rightarrow LFV$ e.g. $K_L^0 \rightarrow \mu e$

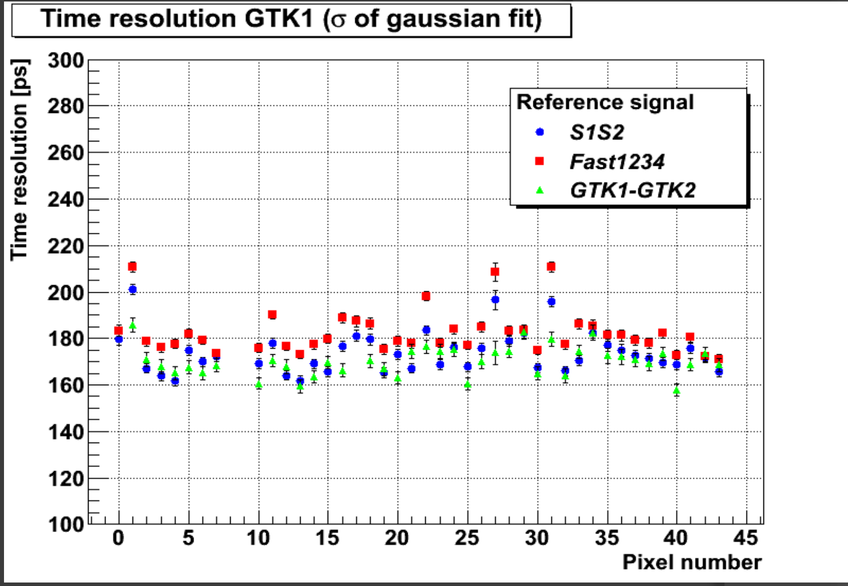
K^0 Interferometry (Plank scale physics)

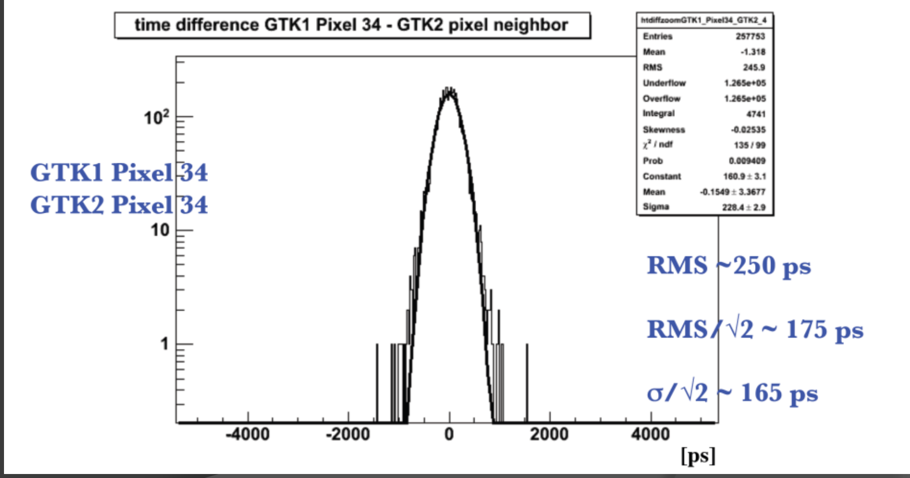
$K \rightarrow \pi l \nu$ ... (Universality, Chiral PT)

Enormous data sets + multipurpose detectors = lots of physics

NA62 Gigatracker: Test Beam Results

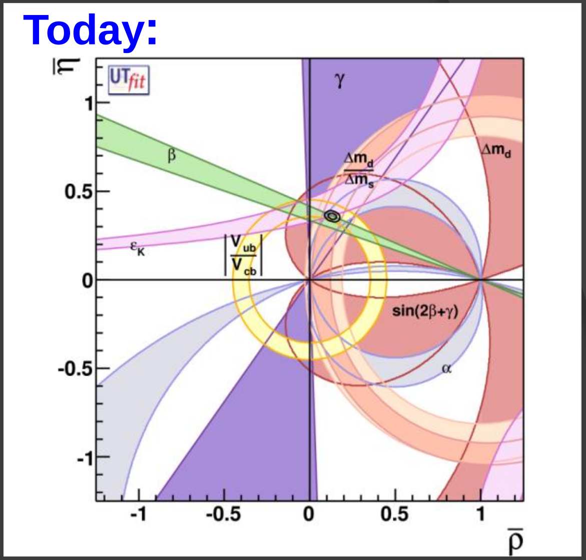
- Albeit only 6% of the incoming particles are kaons, all of them (~ 1 GHz) have to be tracked
- Material budget ~0.5% X_0 per station
- Time resolution < 200 ps / station
- Silicon micro-pixels with ultra-fast ASIC front end with DLL TDC
- Prototypes beam tested at CERN PS

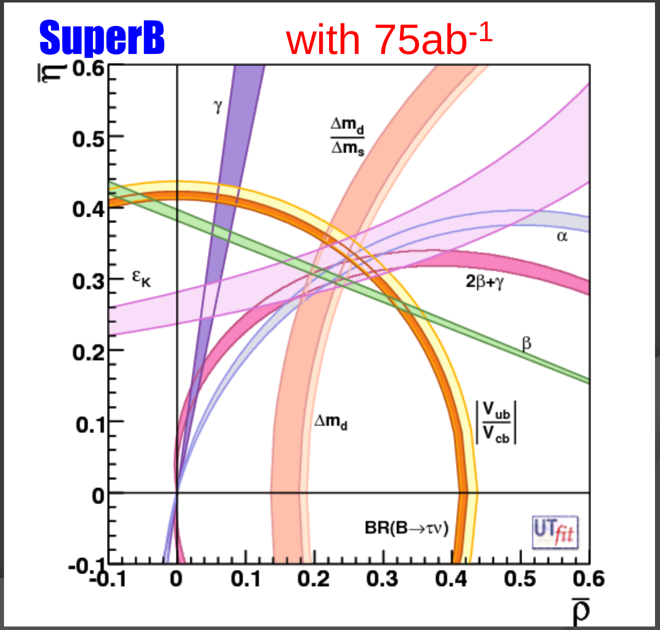




SuperB Motivation

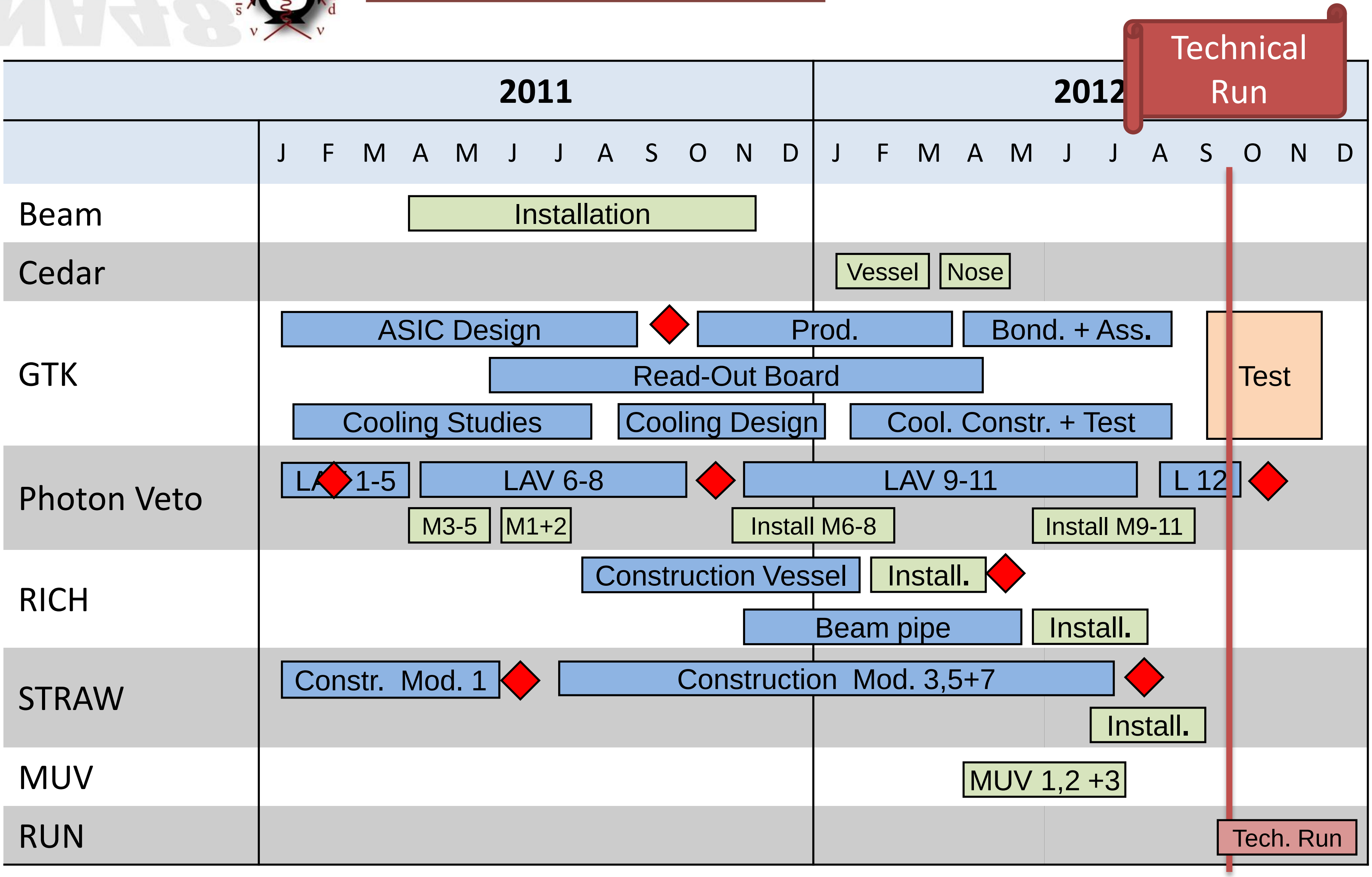
- SuperB measures the sides and angles of the Unitarity Triangle (UT)
- Many measurements constrain the sides and angles of the UT: the SM predicts that all measurements "intersect" at apex of the triangle
- When NP is present, the measurements do not yield a unique apex, but you need the high precision of a Super Flavour Factory.





Adapted from M. Giorgi

NA62 Schedule



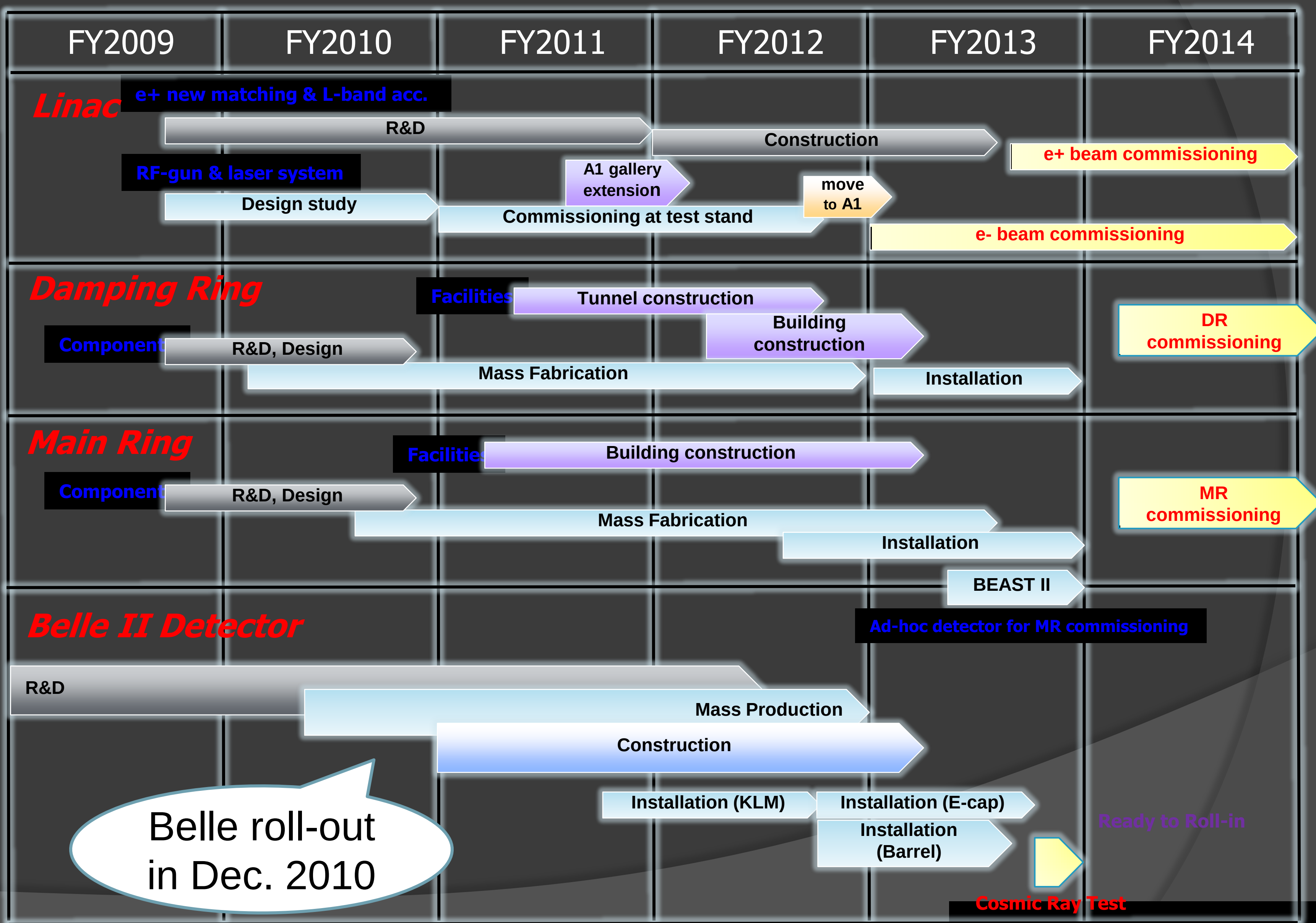
Construction

Installation

Milestones

Note: not all milestones are shown on this planning

SuperKEKB/Belle II



Neutral Meson Mixing

CP violation in decay is defined by

$|\bar{A}_{\bar{f}}/A_f| \neq 1$.

In charged meson decays, where mixing effects are absent, this is the only possible source of *CP asymmetries:*

A

f± ≡ *Γ(M− → f−) − Γ(M+ → f+)*

Γ(*M− → f−) + Γ(M+ → f+)*

=

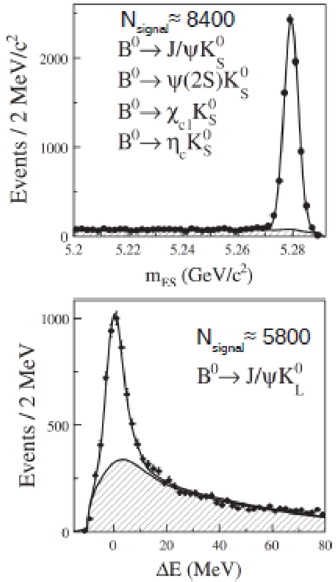
|Af−/Af+|2 − 1

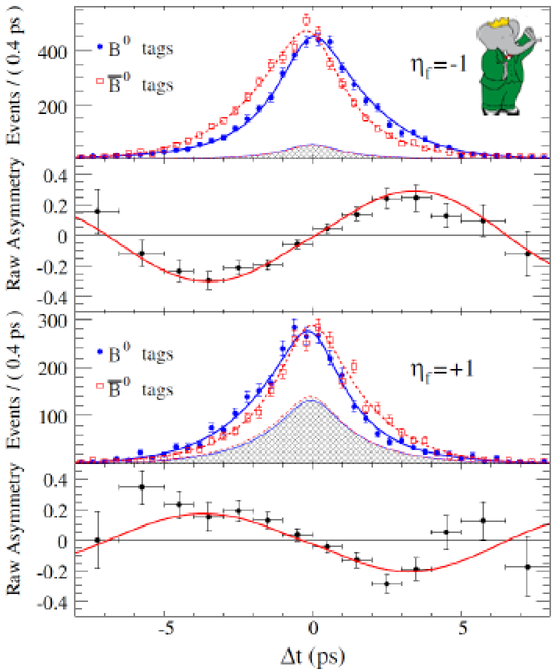
|Af−/Af+|2 + 1

.

Measurement of Φ_1/β

BaBar's last update on full dataset:





BaBar with 465×10⁶ BB:

PRD 79, 072009 (2009)

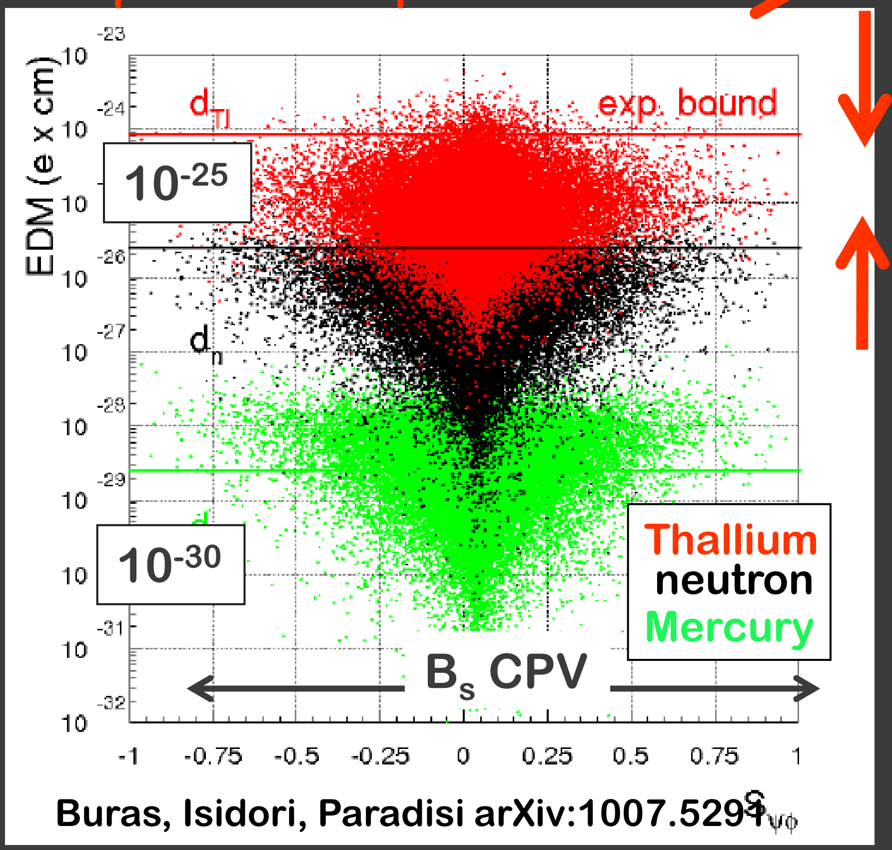
$$\mathcal{A} = -0.024 \pm 0.020\,(\mathrm{stat}) \pm 0.016\,(\mathrm{syst})$$

$$\sin(2\phi_1) = 0.687 \pm 0.028 \pm 0.012$$

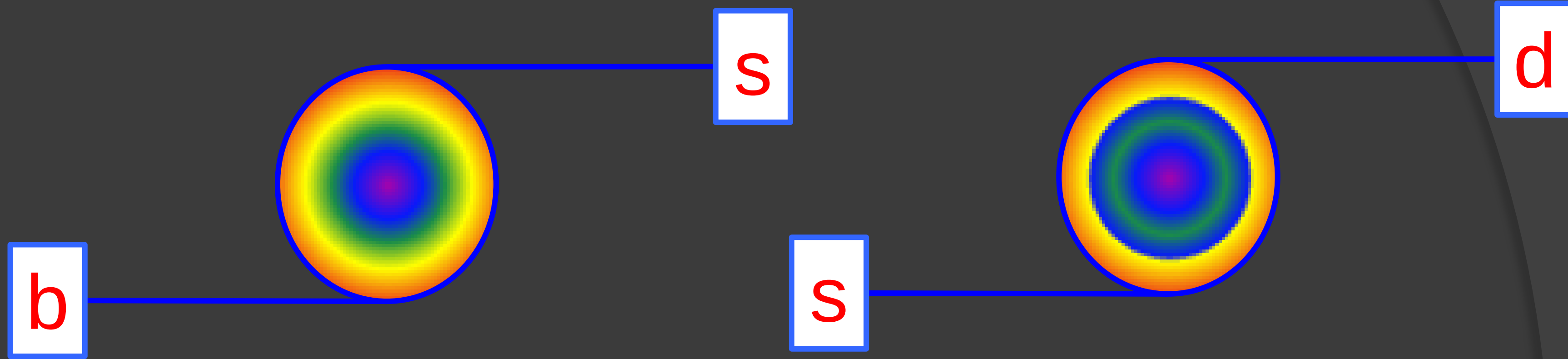
EDMs

MFV + 1 new phase + Bs CPV = EDM

Large B_s CPV shrinks available parameter space



Same motivation for FCNC B and K programs



Difference is the size of the SM ‘background’

B mesons: $V_{ts} \approx \lambda^2$ or $V_{td} \approx \lambda^3$ or $V_{ub} \approx \lambda^3$

Kaons: $V_{ts}^* V_{td} \approx \lambda^5$

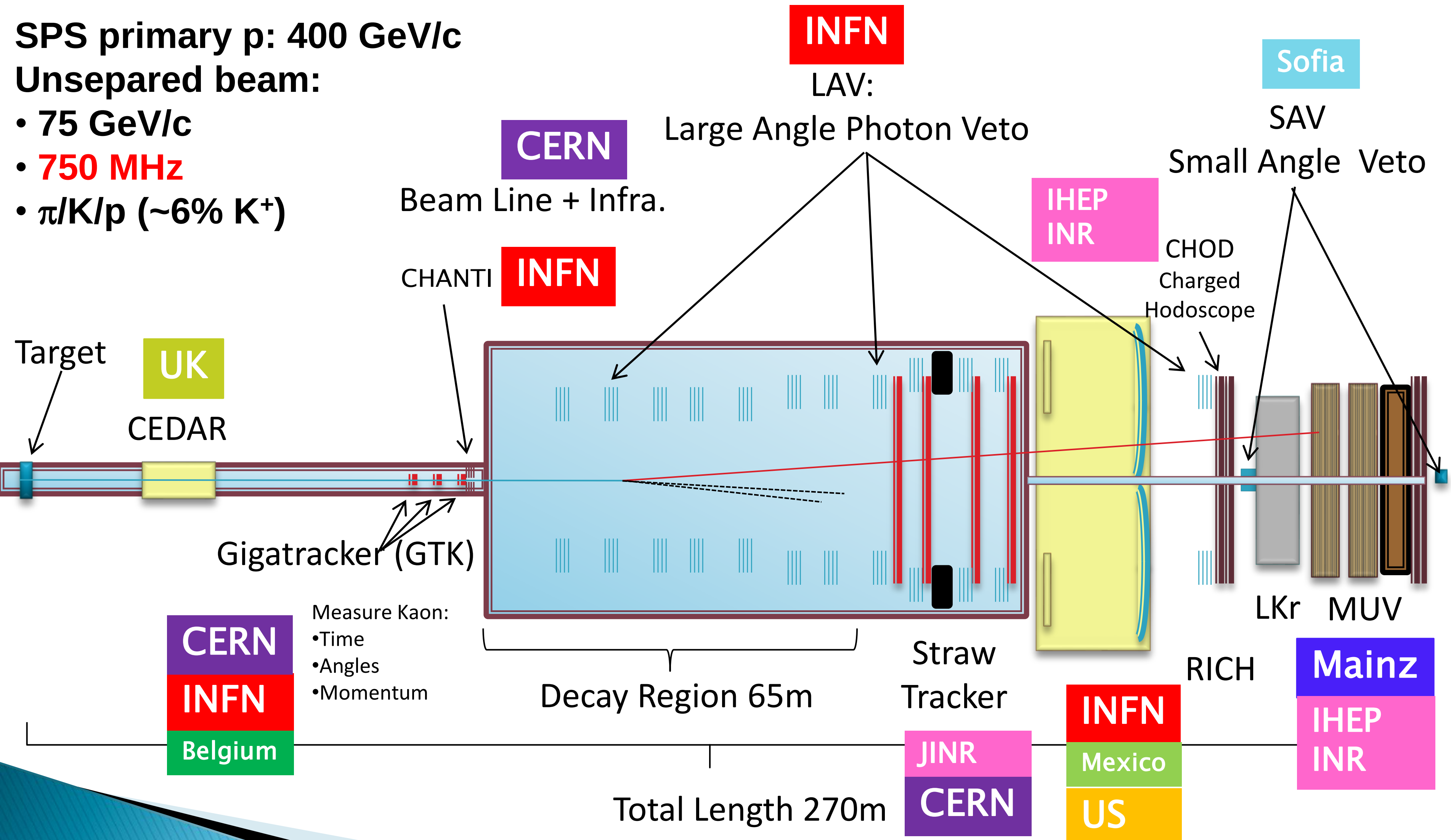
$b \to s\gamma : 3\times10^{-4}$ $\qquad$ $K^+ \to \pi^+ \nu\bar{\nu} : 7.8\times10^{-11}$

$B_s \to \mu\mu : 3\times10^{-9}$ $\qquad$ $K^0 \to \pi^0 \nu\bar{\nu} : 2.4\times10^{-11}$

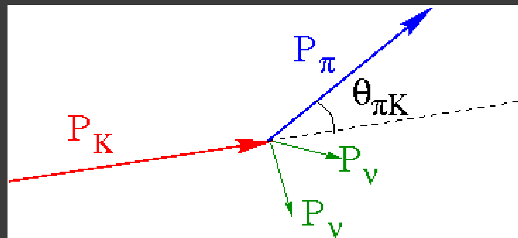
Generic couplings: Kaons win, flavor specific: need both

NA62 Beam & Detectors

SPS primary p: 400 GeV/c
Unseparated beam:
- **75 GeV/c**
- **750 MHz**
- **π/K/p (~6% K^+)**

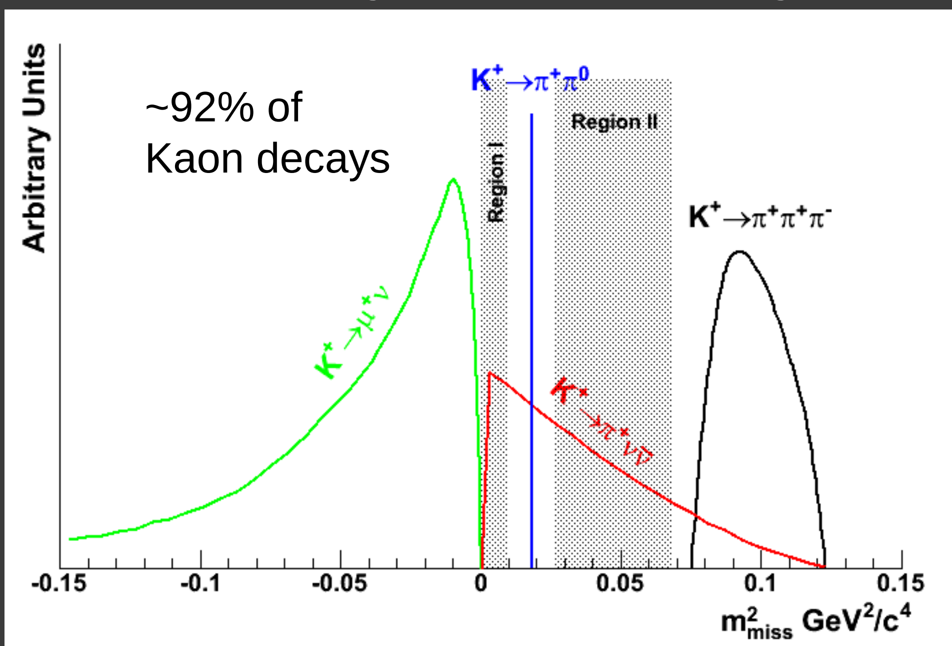


NA62 Technique: Decay in Flight

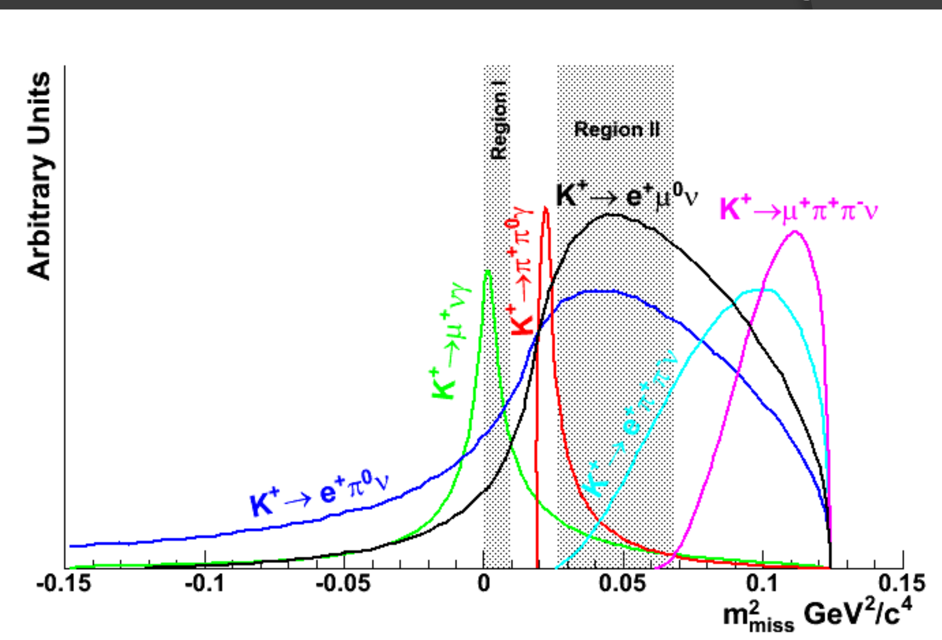


$$m^2_{miss} = (\tilde{p}_K - \tilde{p}_\pi)^2$$

Kinematically Constraint Decays



Unconstraint Decays



B physics @Υ(4S)

Variety of measurements for any observable

Observable	B Factories (2 ab^{-1})	Super$B$ (75 ab^{-1})
$\sin(2\beta)$ $(J/\psi K^0)$	0.018	0.005 (†)
$\cos(2\beta)$ $(J/\psi K^{*0})$	0.30	0.05
$\sin(2\beta)$ (Dh^0)	0.10	0.02
$\cos(2\beta)$ (Dh^0)	0.20	0.04
$S(J/\psi \pi^0)$	0.10	0.02
$S(D^+D^-)$	0.20	0.03
α $(B \to \pi\pi)$	$\sim 16°$	3°
α $(B \to \rho\rho)$	$\sim 7°$	1–2° (∗)
α $(B \to \rho\pi)$	$\sim 12°$	2°
α (combined)	$\sim 6°$	1–2° (∗)
γ $(B \to DK$, $D \to CP$ eigenstates)	$\sim 15°$	2.5°
γ $(B \to DK$, $D \to$ suppressed states)	$\sim 12°$	2.0°
γ $(B \to DK$, $D \to$ multibody states)	$\sim 9°$	1.5°
γ $(B \to DK$, combined)	$\sim 6°$	1–2°
$2\beta + \gamma$ $(D^{(*)\pm}\pi^\mp$, $D^\pm K^0_S\pi^\mp)$	20°	5°
$S(\phi K^0)$	0.13	0.02 (∗)
$S(\eta' K^0)$	0.05	0.01 (∗)
$S(K^0_S K^0_S K^0_S)$	0.15	0.02 (∗)
$S(K^0_S \pi^0)$	0.15	0.02 (∗)
$S(\omega K^0_S)$	0.17	0.03 (∗)
$S(f_0 K^0_S)$	0.12	0.02 (∗)
$\|V_{cb}\|$ (exclusive)	4% (∗)	1.0% (∗)
$\|V_{cb}\|$ (inclusive)	1% (∗)	0.5% (∗)
$\|V_{ub}\|$ (exclusive)	8% (∗)	3.0% (∗)
$\|V_{ub}\|$ (inclusive)	8% (∗)	2.0% (∗)

Observable	B Factories (2 ab^{-1})	Super$B$ (75 ab
$\mathcal{B}(B \to \tau\nu)$	20%	4% (†)
$\mathcal{B}(B \to \mu\nu)$	visible	5%
$\mathcal{B}(B \to D\tau\nu)$	10%	2%
$\mathcal{B}(B \to \rho\gamma)$	15%	3% (†)
$\mathcal{B}(B \to \omega\gamma)$	30%	5%
$A_{CP}(B \to K^*\gamma)$	0.007 (†)	0.004 († ∗)
$A_{CP}(B \to \rho\gamma)$	~ 0.20	0.05
$A_{CP}(b \to s\gamma)$	0.012 (†)	0.004 (†)
$A_{CP}(b \to (s+d)\gamma)$	0.03	0.006 (†)
$S(K^0_S\pi^0\gamma)$	0.15	0.02 (∗)
$S(\rho^0\gamma)$	possible	0.10
$A_{CP}(B \to K^*\ell\ell)$	7%	1%
$A^{FB}(B \to K^*\ell\ell)s_0$	25%	9%
$A^{FB}(B \to X_s\ell\ell)s_0$	35%	5%
$\mathcal{B}(B \to K\nu\bar{\nu})$	visible	20%
$\mathcal{B}(B \to \pi\nu\bar{\nu})$	–	possible

Possible also at LHCb

Similar precision at LHCb

Example of «SuperB specifics»

- inclusive in addition to exclusive analyses
- channels with π^0, γ's, ν, many Ks…

| physics (polarized beams)

Process	Sensitivity
$\mathcal{B}(\tau \to \mu\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to e\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to \mu\mu\mu)$	2×10^{-10}
$\mathcal{B}(\tau \to eee)$	2×10^{-10}
$\mathcal{B}(\tau \to \mu\eta)$	4×10^{-10}
$\mathcal{B}(\tau \to e\eta)$	6×10^{-10}
$\mathcal{B}(\tau \to \ell K_s^0)$	2×10^{-10}

Charm at Y(4S) and threshold

Mode	Observable	B Factories (2 ab^{-1})	Super$B$ (75 ab^{-1})
$D^0 \to K^+K^-$	y_{CP}	$2\text{–}3 \times 10^{-3}$	5×10^{-4}
$D^0 \to K^+\pi^-$	y'_D	$2\text{–}3 \times 10^{-3}$	7×10^{-4}
	x'^2_D	$1\text{–}2 \times 10^{-4}$	3×10^{-5}
$D^0 \to K_S^0\pi^+\pi^-$	y_D	$2\text{–}3 \times 10^{-3}$	5×10^{-4}
	x_D	$2\text{–}3 \times 10^{-3}$	5×10^{-4}
Average	y_D	$1\text{–}2 \times 10^{-3}$	3×10^{-4}
	x_D	$2\text{–}3 \times 10^{-3}$	5×10^{-4}
$D^0 \to K^+\pi^-$	x'^2	*To be evaluated at LHCb*	3×10^{-5}
	y'		7×10^{-4}
$D^0 \to K^+K^-$	y_{CP}		5×10^{-4}
$D^0 \to K_S^0\pi^+\pi^-$	x		4.9×10^{-4}
	y		3.5×10^{-4}
	$\lvert q/p \rvert$		3×10^{-2}
	ϕ		2°

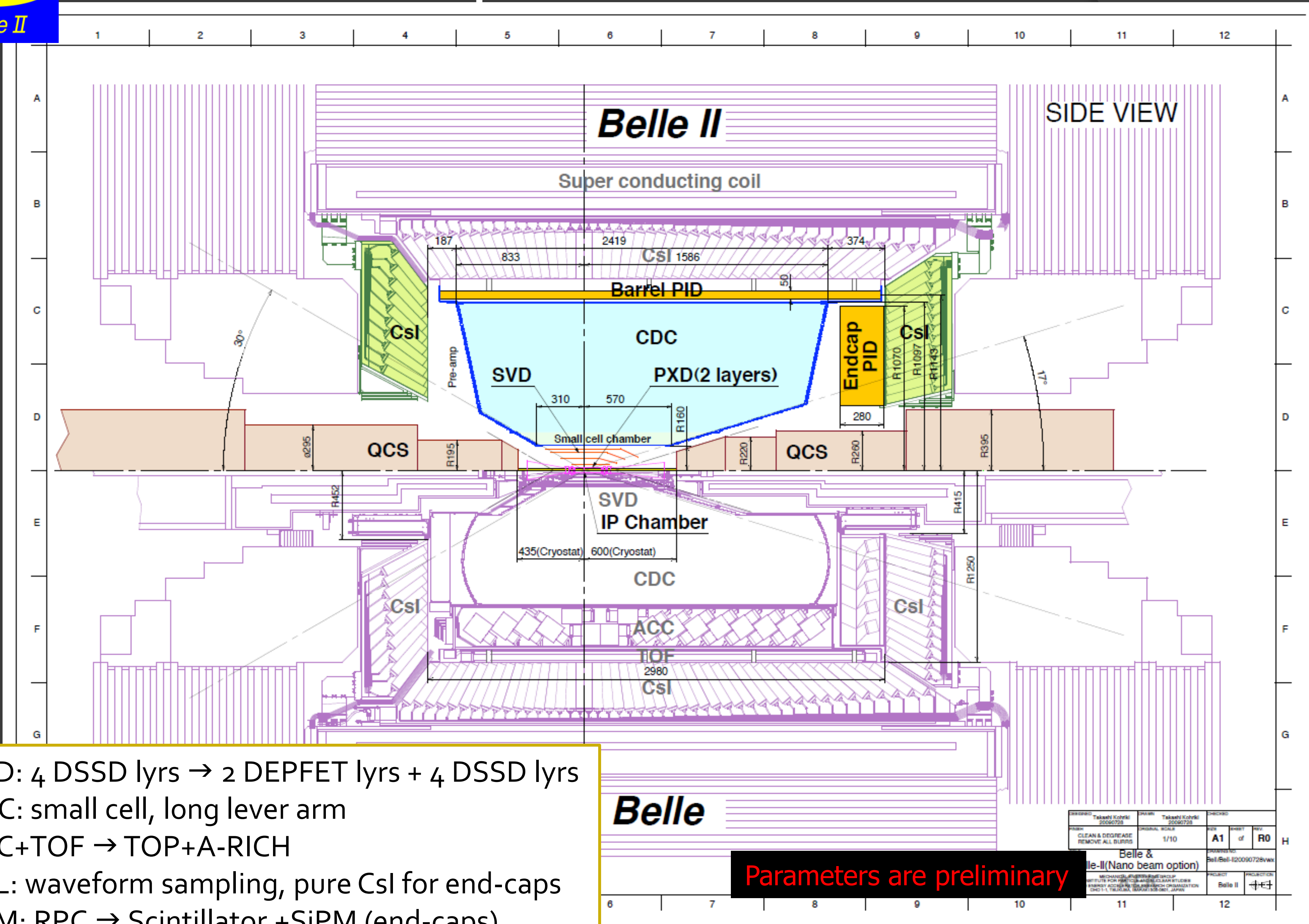
B_s at Y(5S)

Observable	Error with 1 ab^{-1}	Error with 30 ab^{-1}
$\Delta\Gamma$	0.16 ps^{-1}	0.03 ps^{-1}
Γ	0.07 ps^{-1}	0.01 ps^{-1}
β_s from angular analysis	20°	8°
A_{SL}^s	0.006	0.004
A_{CH}	0.004	0.004
$\mathcal{B}(B_s \to \mu^+\mu^-)$	-	$< 8 \times 10^{-9}$
$\lvert V_{td}/V_{ts} \rvert$	0.08	0.017
$\mathcal{B}(B_s \to \gamma\gamma)$	38%	7%
β_s from $J/\psi\phi$	16°	6°
β_s from $B_s \to K^0\bar{K}^0$	24°	11°

Bs : Definitively better at LHCb

Channel	Sensitivity
$D^0 \to e^+e^-$, $D^0 \to \mu^+\mu^-$	1×10^{-8}
$D^0 \to \pi^0e^+e^-$, $D^0 \to \pi^0\mu^+\mu^-$	2×10^{-8}
$D^0 \to \eta e^+e^-$, $D^0 \to \eta\mu^+\mu^-$	3×10^{-8}
$D^0 \to K_S^0e^+e^-$, $D^0 \to K_S^0\mu^+\mu^-$	3×10^{-8}
$D^+ \to \pi^+e^+e^-$, $D^+ \to \pi^+\mu^+\mu^-$	1×10^{-8}
$D^0 \to e^\pm\mu^\mp$	1×10^{-8}
$D^+ \to \pi^+e^\pm\mu^\mp$	1×10^{-8}
$D^0 \to \pi^0e^\pm\mu^\mp$	2×10^{-8}
$D^0 \to \eta e^\pm\mu^\mp$	3×10^{-8}
$D^0 \to K_S^0e^\pm\mu^\mp$	3×10^{-8}
$D^+ \to \pi^-e^+e^+$, $D^+ \to K^-e^+e^+$	1×10^{-8}
$D^+ \to \pi^-\mu^+\mu^+$, $D^+ \to K^-\mu^+\mu^+$	1×10^{-8}
$D^+ \to \pi^-e^\pm\mu^\mp$, $D^+ \to K^-e^\pm\mu^\mp$	1×10^{-8}

Belle II in comparison with Belle



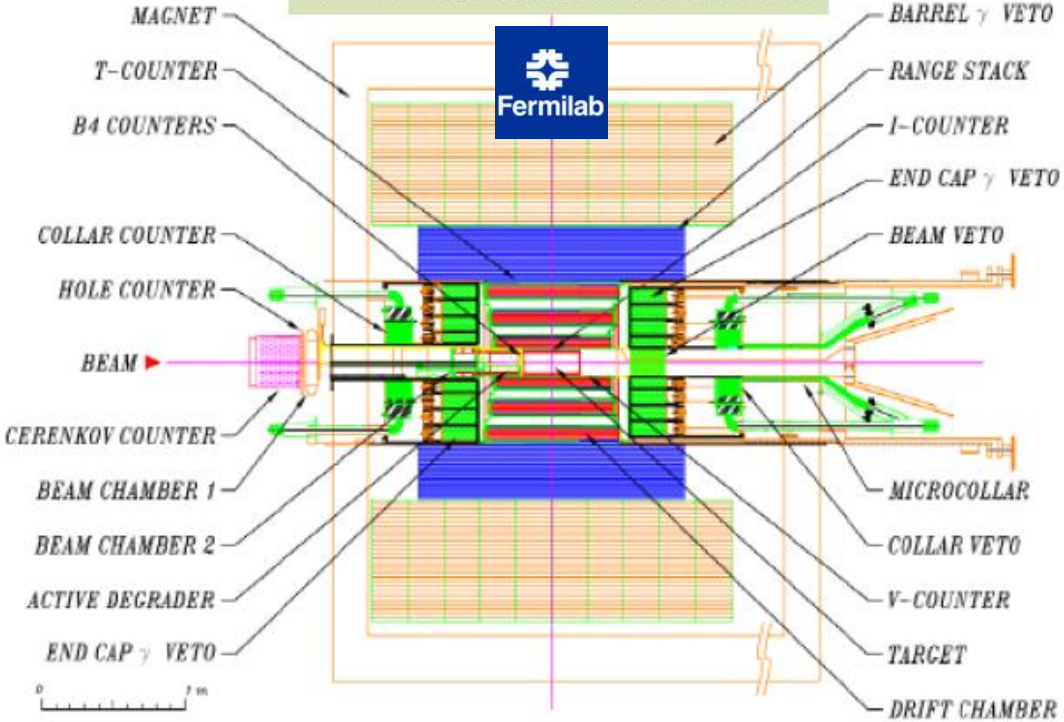
SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling, pure CsI for end-caps
KLM: RPC → Scintillator +SiPM (end-caps)

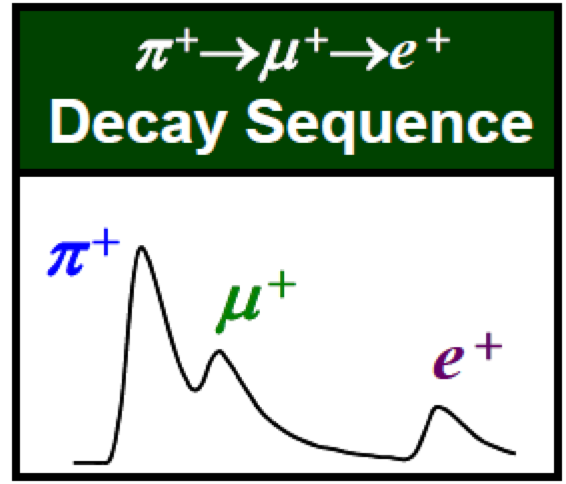
Parameters are preliminary

$K^+ \rightarrow \pi^+ \nu\nu$

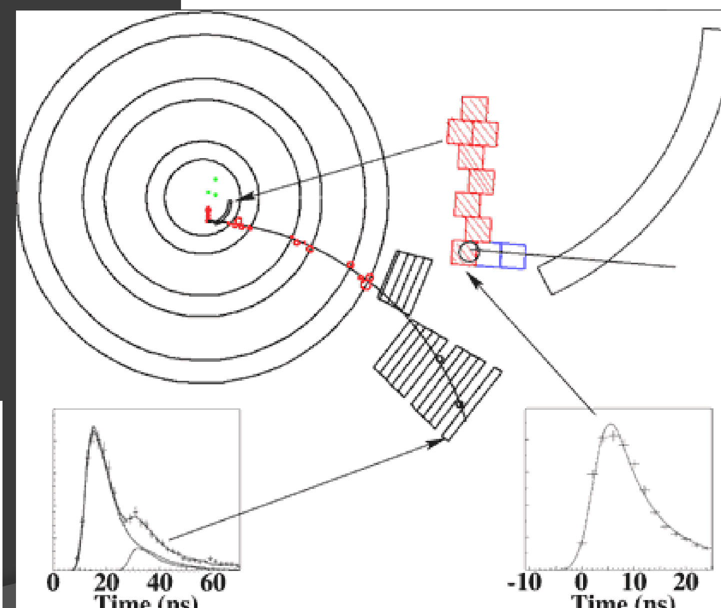
1st 2nd 3rd generation at BNL
= 7 event data sample

4th Generation Detector



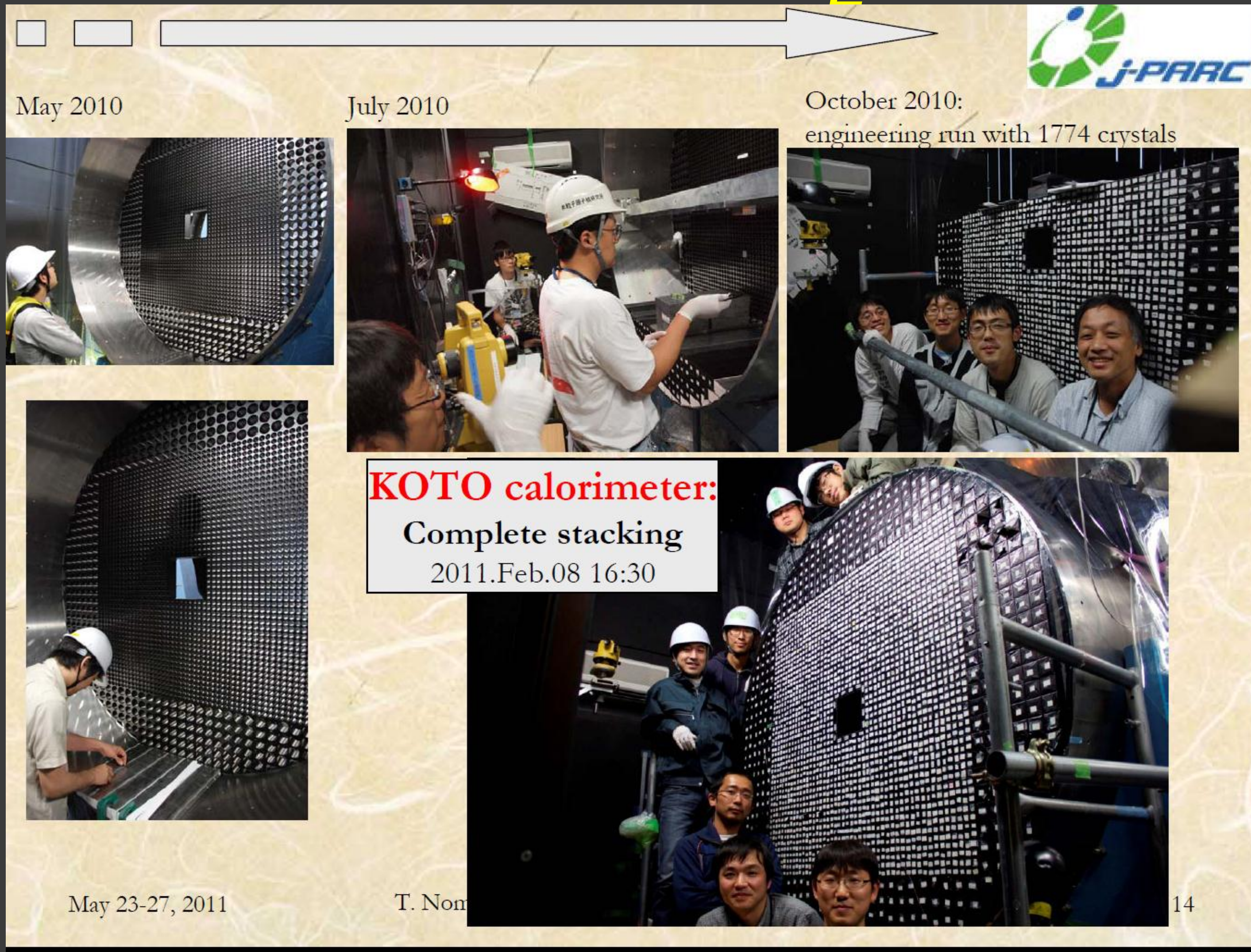


BNL E787 event display



Can get hundreds of evts per year starting with beam from Main Injector and continuing with Project X

KOTO Experiment $K^0_L \to \pi^0 \nu\nu$

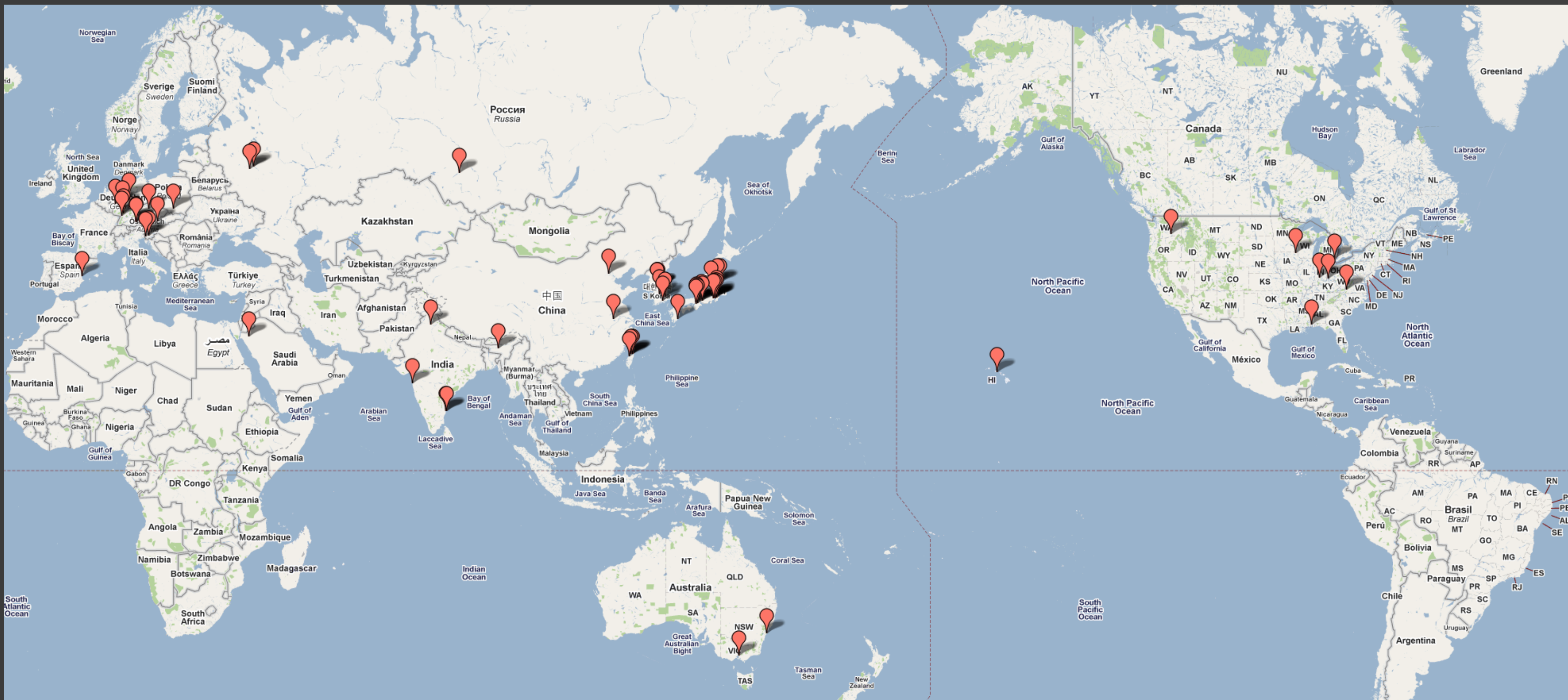


Courtesy of Tadashi Nomura (FPCP 2011)

LHCb Upgrade (Letter of Intent)

- CERN/LHCC 2011-001, March 2011
- LHCb expects to accumulate 5 fb^{-1} in the years up to 2017
- Then plans to upgrade to collet 5 fb^{-1} per year
- Not limited by LHC luminosity
- Main Motivations:
  - Precise measurement of the B_s oscillation phase
  - Analysis of $B \rightarrow V\ V$ decays
  - ~1 deg determination of gamma angle
  - Make precision measurement of $B_s \rightarrow \mu^+ \mu^-$ and extend to $B_d \rightarrow \mu^+ \mu^-$
  - Exploit the NP sensitivity of the full kinematic distribution in $B_d \rightarrow K^{0*} \mu^+ \mu^-$

Belle II Collaboration

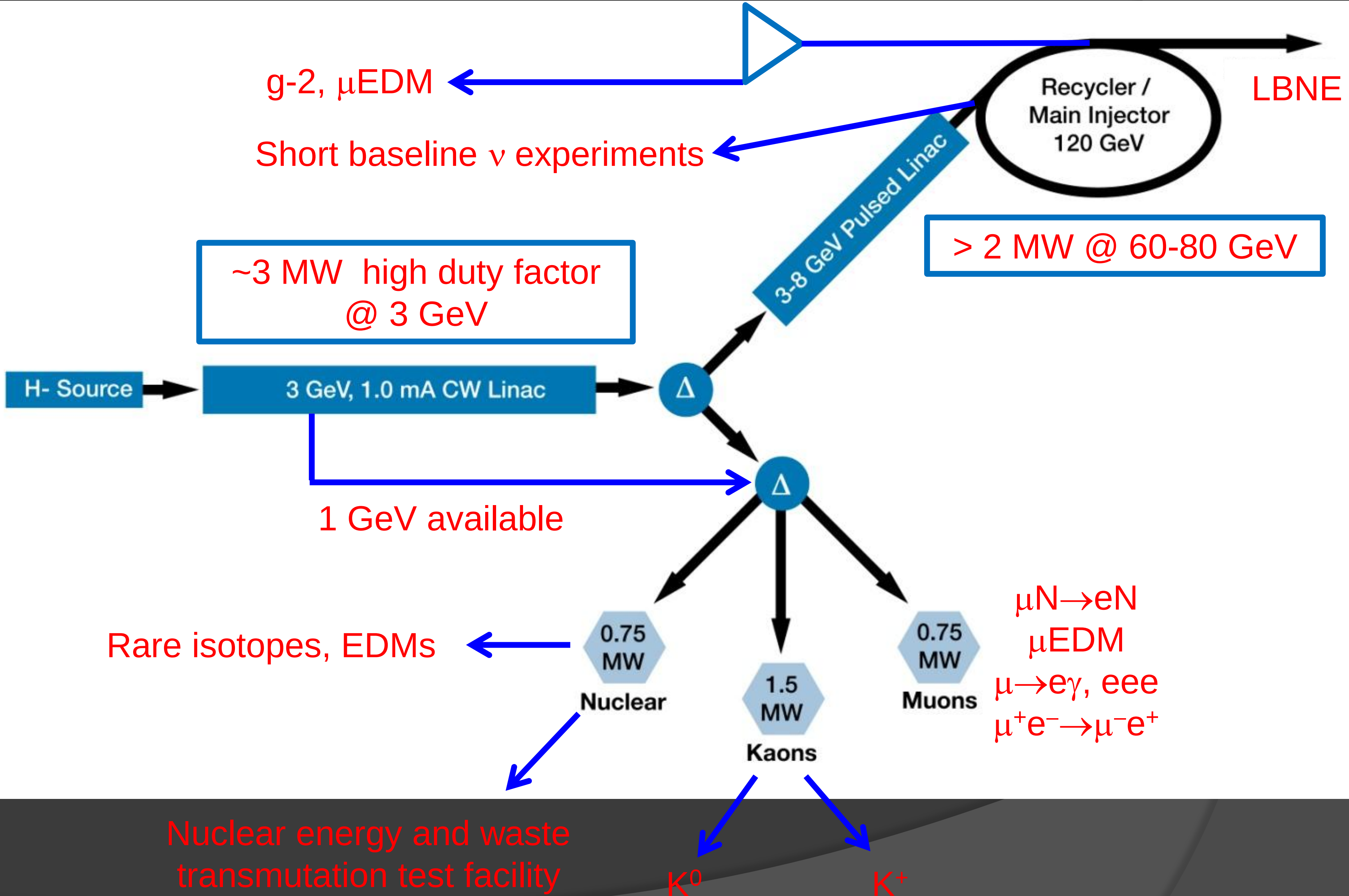


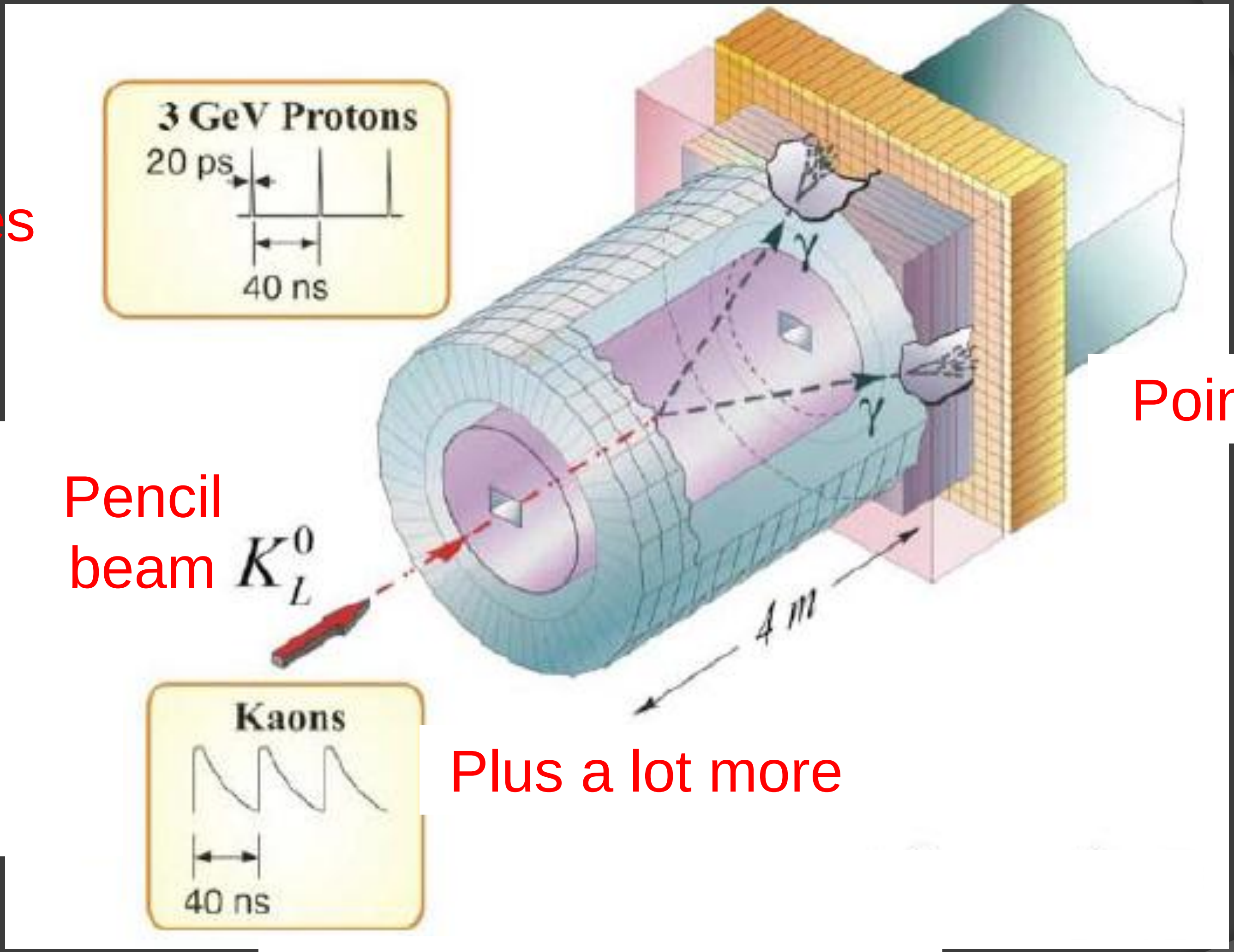
15 countries, ~60 institutions

~400 collaborators

Courtesy of Peter Križan

Fermilab Intensity Frontier: Project X





Pico-bunches

Pencil beam

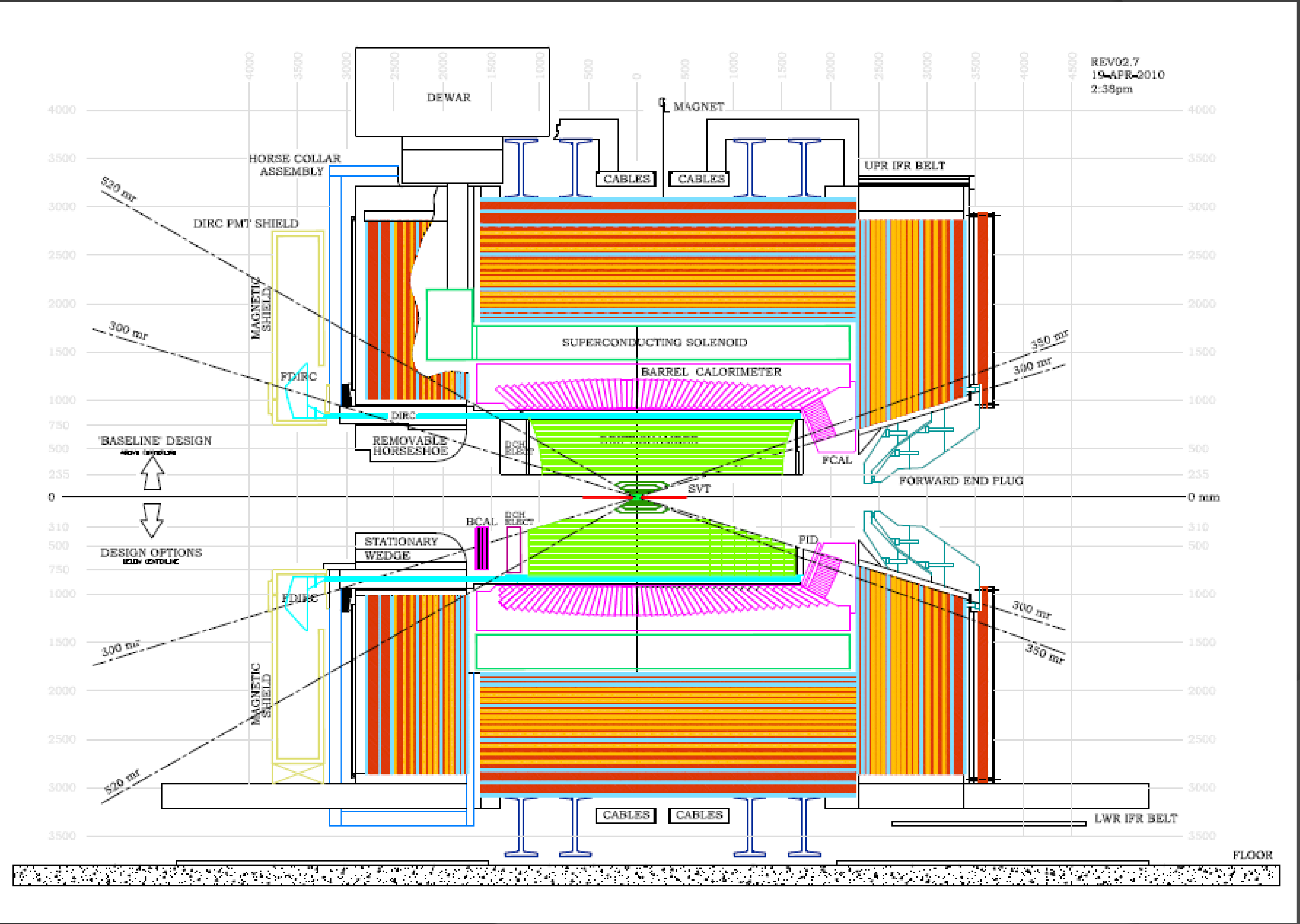
Pointing

Plus a lot more

200 evt/yr possible with Project X

$K^0 \rightarrow \pi^0 \nu \nu$

SuperB Detector (with options)



Future Super B Factories

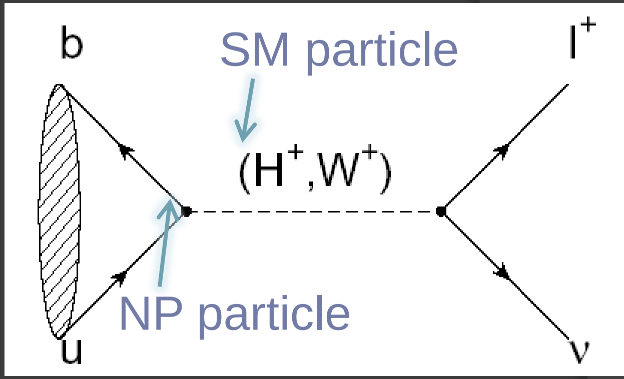
	SuperB	Super KEKB
Peak Luminosity	$>10^{36}$	0.8×10^{36}
Integrated Luminosity	75 ab^{-1}	50 ab^{-1}
Site	Green Field	KEKB Laboratory
Collisions	mid 2016	2015
Polarization	80% electron beam	No
Low energy running	10^{35} @ charm threshold	No
Approval status	Approved	Approved

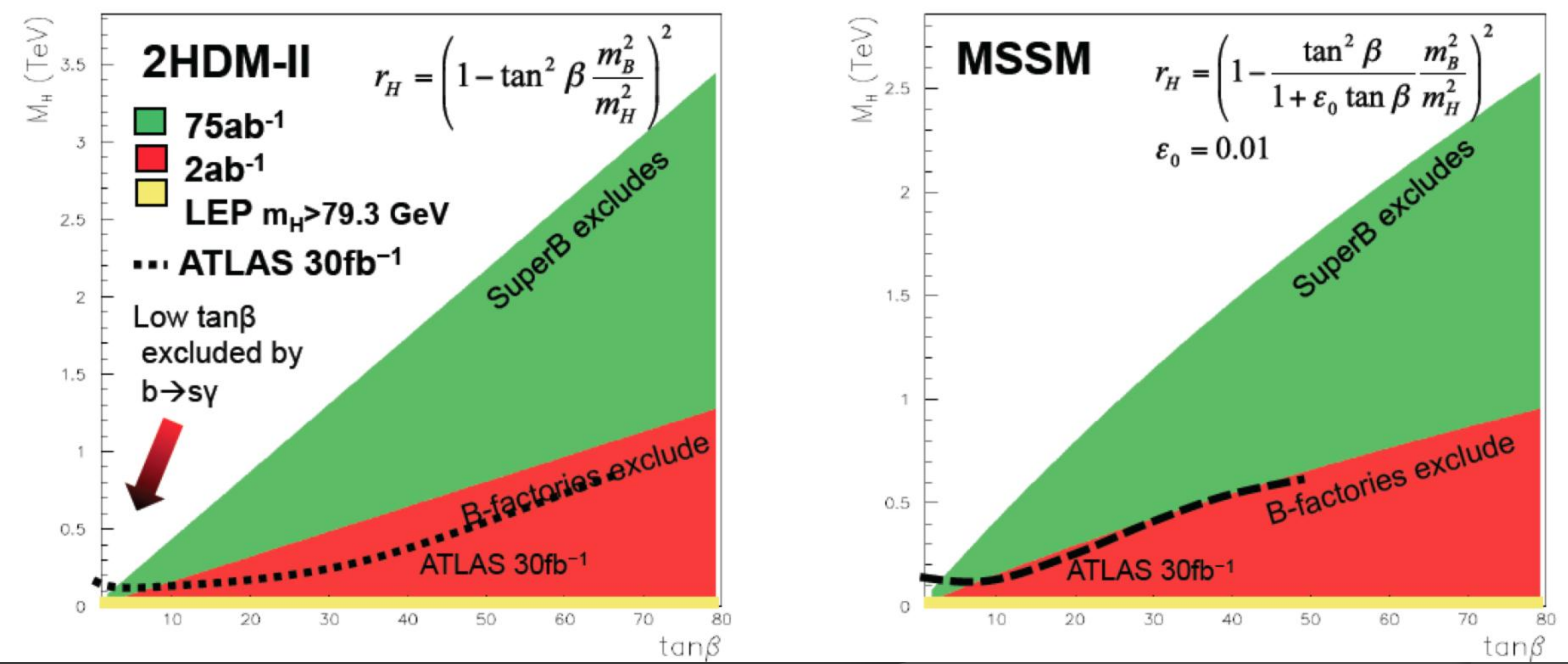
Courtesy of Marcello Giorgi

$B_{u,d}$ physics: Rare Decays

- Example: $B^{\pm} \to \tau^{\pm}\nu$
  - Rate modified by presence of H^+

$$r_H = \frac{\mathcal{B}_{SM+NP}}{\mathcal{B}_{SM}}$$





JPARC Flavour Programme

- $K^0_L \to \pi^0 \nu \nu$ (KOTO)

$$B(K_L \to \pi^0 \nu\nu) = \kappa_L \left(\frac{\mathrm{Im}(V_{ts}^* V_{td})}{\lambda^5} X_t \right)^2$$

$$= (2.43^{+0.40}_{-0.37} \pm 0.06) \times 10^{-11}$$

- T-Violation Search in $K^+ \to \pi^0 \mu^+ \nu$

  μ transverse polarization (TREK):

  aim to $\delta(P_T)$(stat)~10^{-4}, $\delta(P_T)$(syst)~10^{-4}

KOTO Sensitivity and timeline

Note: As is considered before the earthquake. Will be updated.

- Goal: ~3 SM events / 3 years
  with S/N ratio ~ 2

  *** assuming design MR power ~270kW

COMPLETED
- 2009 Beamline survey

PARTIALLLY
- 2010 Calorimeter engineering

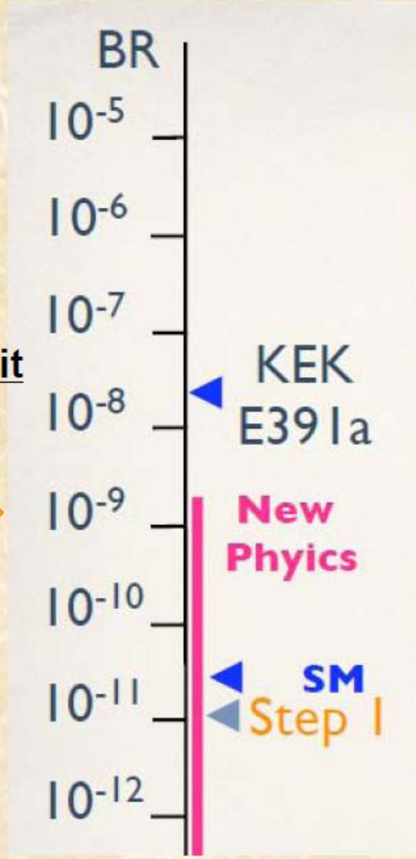
- 2011 Full engineering and
  Start physics run

  ➔ *1st milestone:*
  ***Grossman-Nir limit** by summer 2012*

~1YEAR DELAY ?
UNDER DISCUSSION

- Next step depends on scenario
  of accelerator's power upgrade.

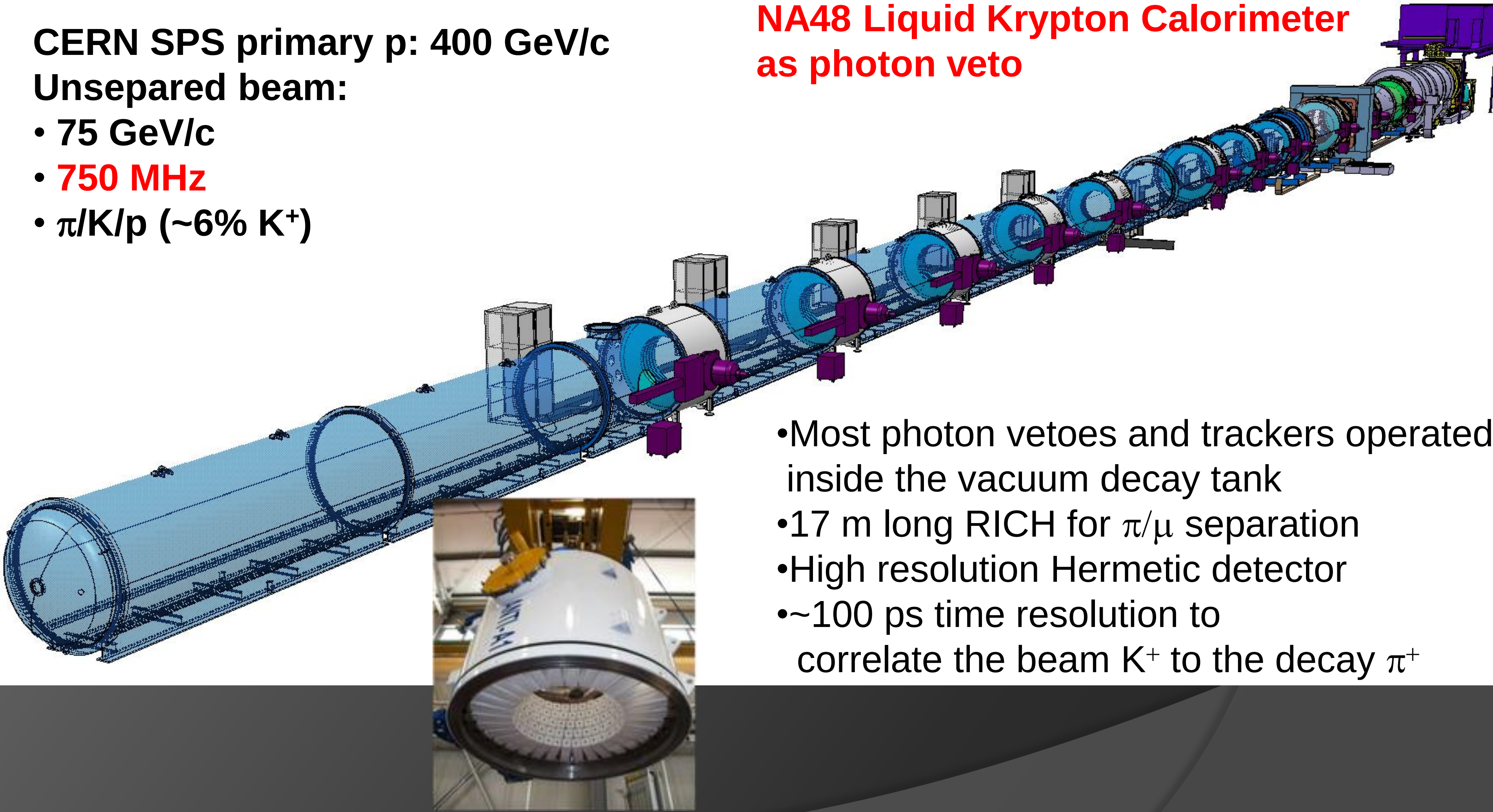
G-N limit
30kW x
1month



NA62 EXPERIMENT: $K^+ \to \pi^+ \nu\nu$
K^+ DECAYS IN FLIGHT

CERN SPS primary p: 400 GeV/c
Unsepared beam:
- **75 GeV/c**
- **750 MHz**
- **π/K/p (~6% K^+)**

NA48 Liquid Krypton Calorimeter as photon veto



- Most photon vetoes and trackers operated inside the vacuum decay tank
- 17 m long RICH for π/μ separation
- High resolution Hermetic detector
- ~100 ps time resolution to correlate the beam K^+ to the decay π^+