Flavour Physics

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FÉDÉRALE DE LAUSANNE

Contents

- Pre-B Factory Era
- B Factory Era
- Post-B Factory Era
- Currently Interesting Indications
- Very brief look for future
- Reflection

Apology: I will touch a little for top and virtually nothing for the QCD aspect of flavour, which is a very very active field, + many more.

Pre B factory Era

-established the flavour structure of the Standard Model-

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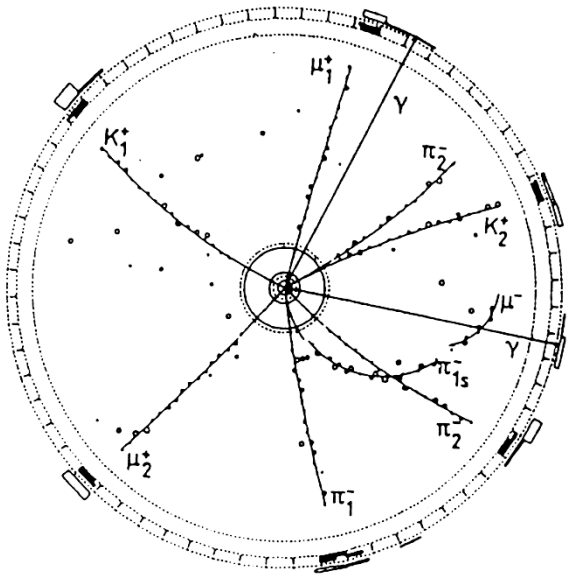
- families, GIM mechanism and mass hierarchy
  $m_t >>>> m_b >>> m_c >> m_s > m_u \approx m_d$
  discovery of kaons, hyperons, J/ψ, ϒ and top-quark

Pre B factory Era



ARGUS 1987

$\Upsilon(4S) \rightarrow B_d^0 \overline{B}_d^0$

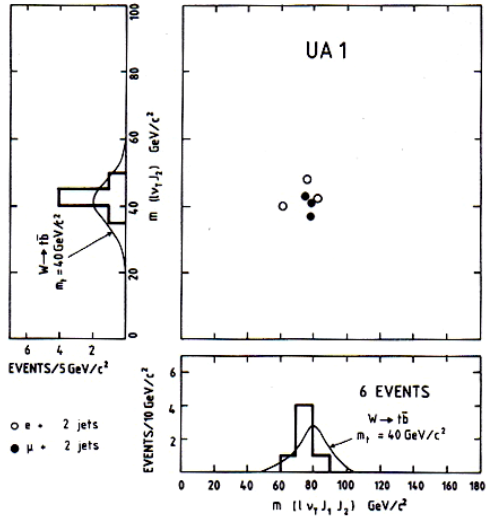
$\rightarrow B_d^0 B_d^0$ or $\overline{B}_d^0 \overline{B}_d^0$

$\rightarrow \ell^+\ell^+$ or $\ell^-\ell^-$

$24.8 \pm 7.6 \pm 3.8$

$\Delta m(B_d) \sim 100 \times \Delta m(K^0)$

$m_t > 50$ GeV/c^2



cf. $m_t \approx 40$ GeV/c^2

UA1 1984

Pre B factory Era

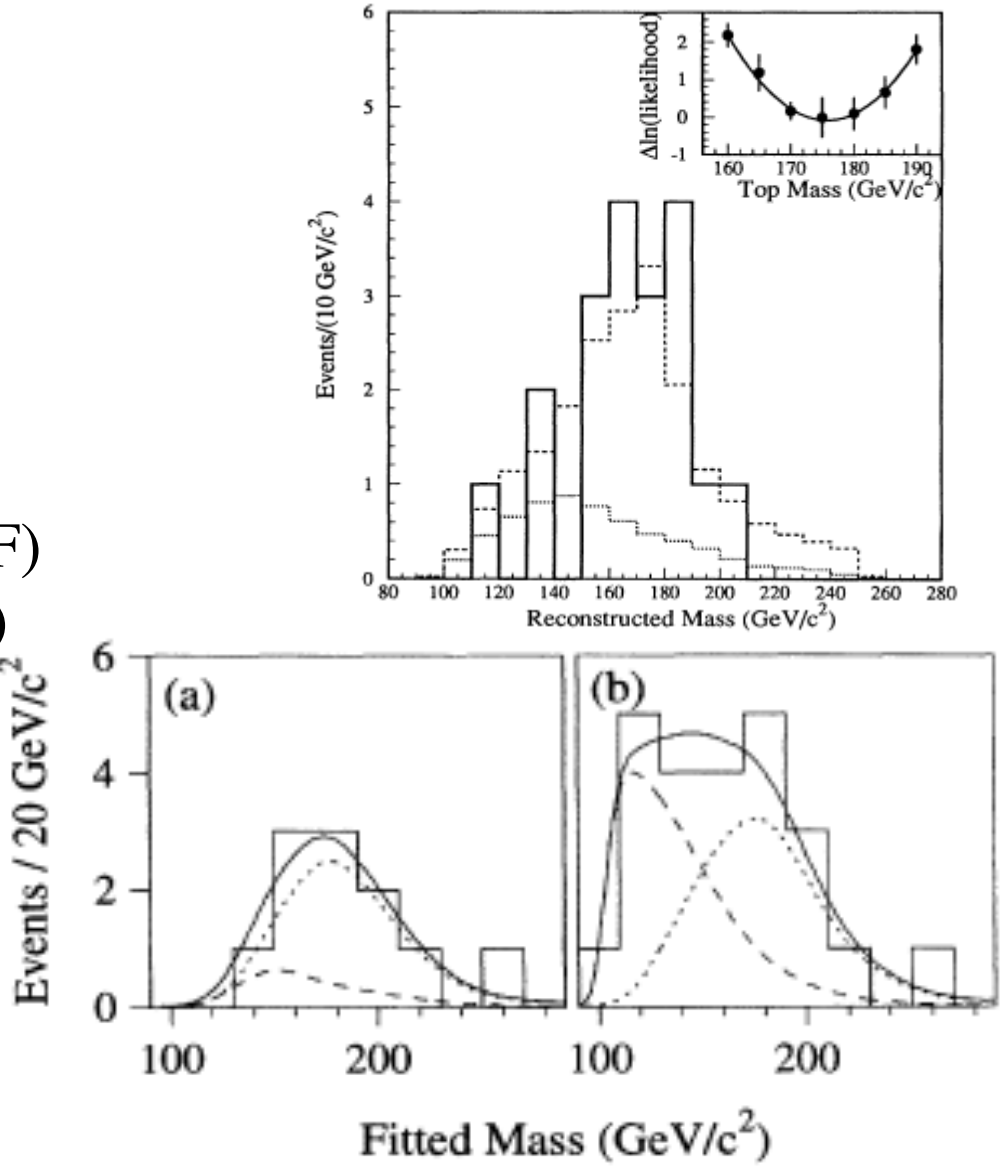
- Top discovery by CDF and D0 1995

$t\bar{t} \rightarrow WbW\bar{b}$

$m_t =$

$176 \pm 8 \pm 10$ GeV/c^2 (CDF)

$199\ ^{+19}_{-21} \pm 22$ GeV/c^2 (D0)



Pre B factory Era

-established the flavour structure of the Standard Model-

- families, GIM mechanism and mass hierarchy
  $m_t >>>> m_b >>> m_c >> m_s > m_u \approx m_d$
  discovery of kaons, hyperons, J/ψ, ϒ and top-quark
- no tree level flavour changing neutral current
  e.g. very small $Br(K_L \to \mu^+\mu^-) = (6.84 \pm 0.11) \times 10^{-9}$
- Structure of the charged current coupling constants
  $\Gamma(b \to u) \approx \Gamma(t \to d) < \Gamma(b \to c) \approx \Gamma(t \to s) < \Gamma(s \to u) \approx \Gamma(c \to d)$
  $< \Gamma(t \to b) \approx \Gamma(c \to s) \approx \Gamma(u \to d)$
  direct (tree) and indirect (loop) processes
  $B \to X l\nu$, $B \to D^{(*)} l\nu$, $B \to \rho l\nu$, …
  Δm_K, Δm_B, $H_b \to X_s \gamma$

Pre B factory Era

- lepton momentum
  CLEO 1990

Observation of b → u$l\nu$ decay

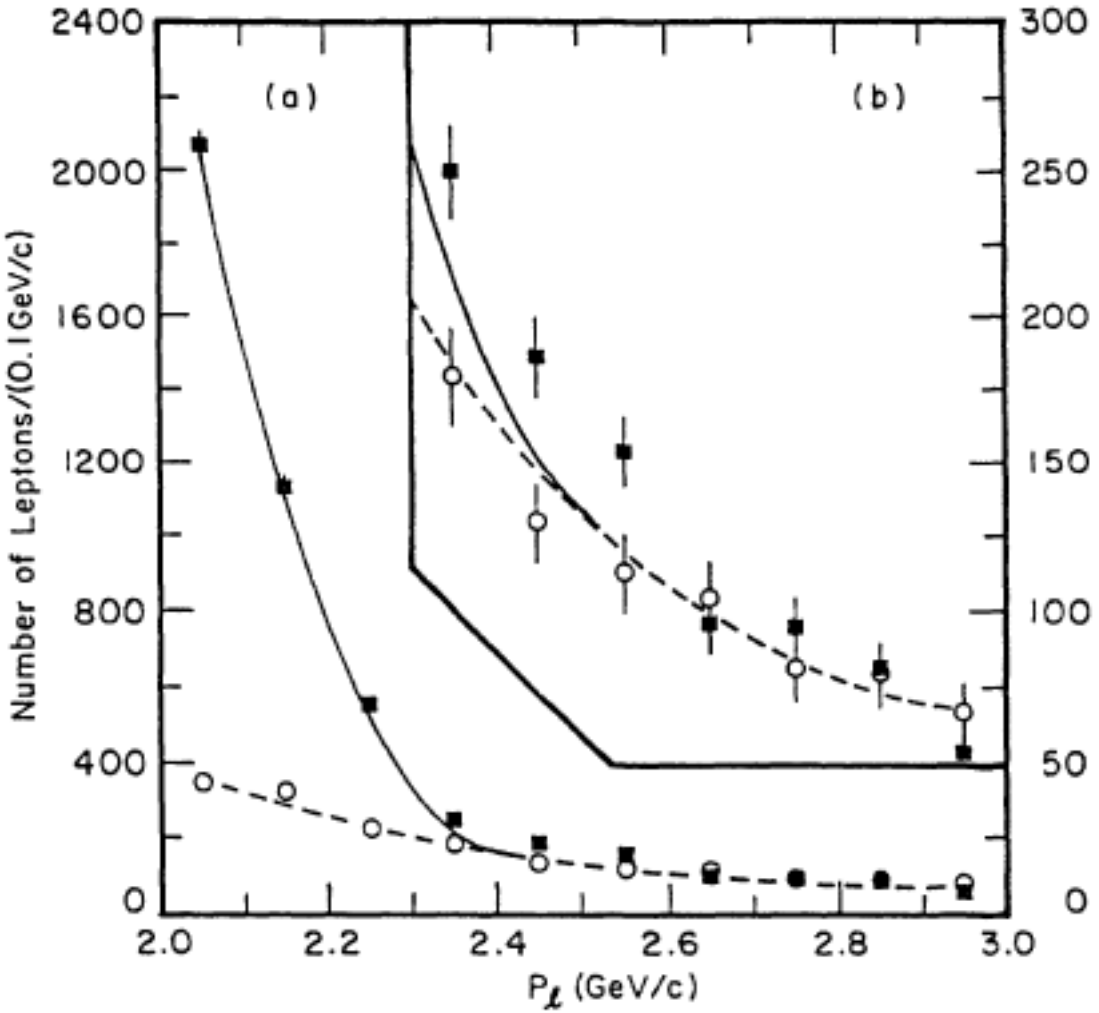
$|V_{ub}| \neq 0$

$|\boldsymbol{p}_l| = 2.4 - 2.6$ GeV/c
in the B rest frame

$= 76 \pm 18 \pm 8$

a similar observation
by ARGUS 1990

but $|V_{ub}|$ is very small
≈ 0.005



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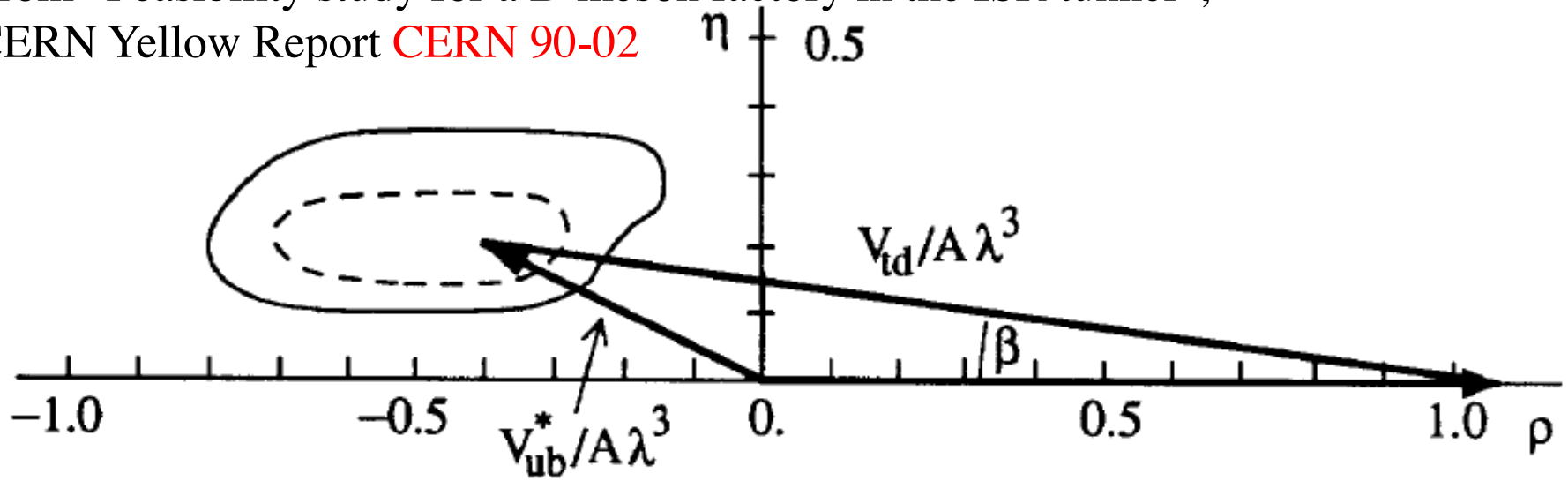
  Δm_K, Δm_B, $H_b \to X_s\gamma$
  (CKM triangle looked somewhat different than now)

Pre B factory Era

- Unitarity Triangle
  Solution was in the second quadrant,
  this is largely due to the theoretical estimate on f_B, which was ~120MeV, much smaller than now, needing longer $|V_{td}|$.

From "Feasibility study for a B-meson factory in the ISR tunnel",
CERN Yellow Report CERN 90-02



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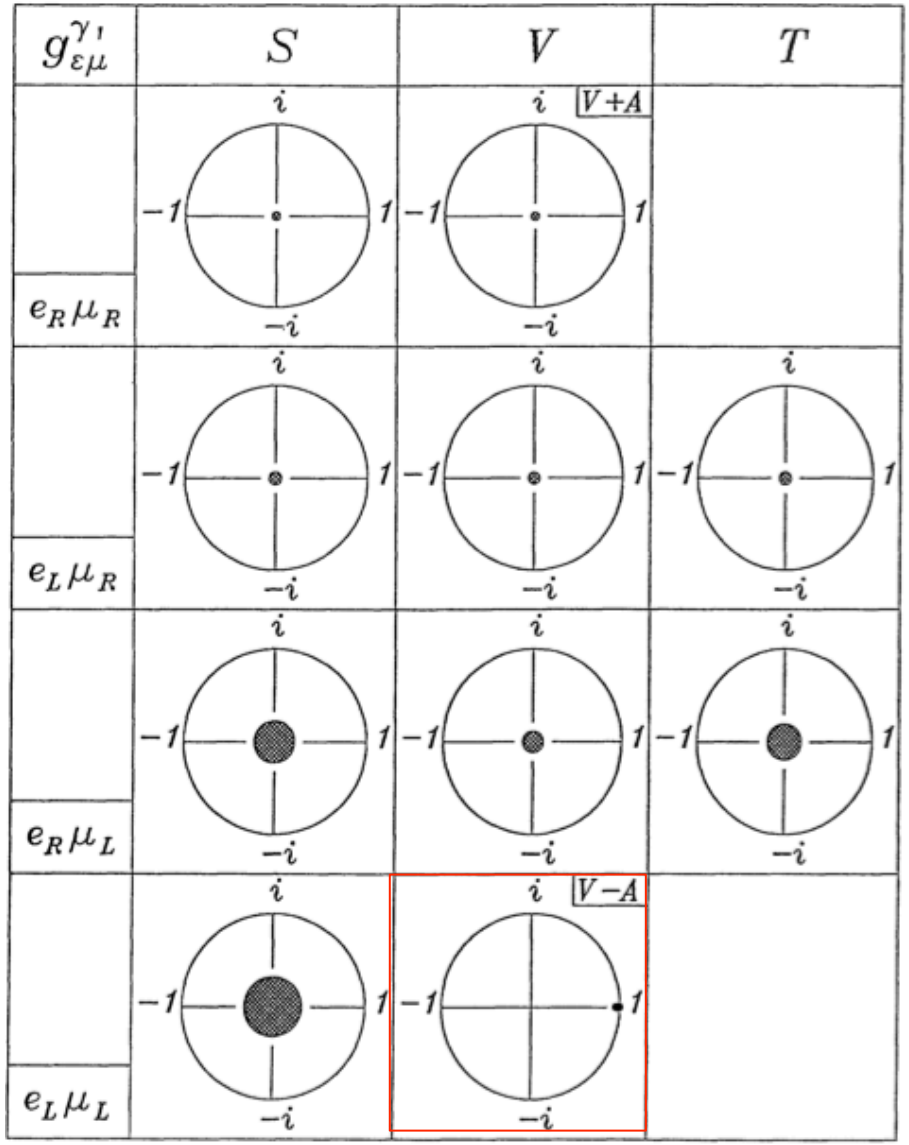
  direct (tree) and indirect (loop) processes
  $B \to X l \nu$, $B \to D^{(*)} l \nu$, $B \to \rho l \nu$, …
  Δm_K, Δm_B, $H_b \to X_s \gamma$
  (CKM triangle looked somewhat different than now)
- Charged lepton structure as in the SM

Pre B factory Era

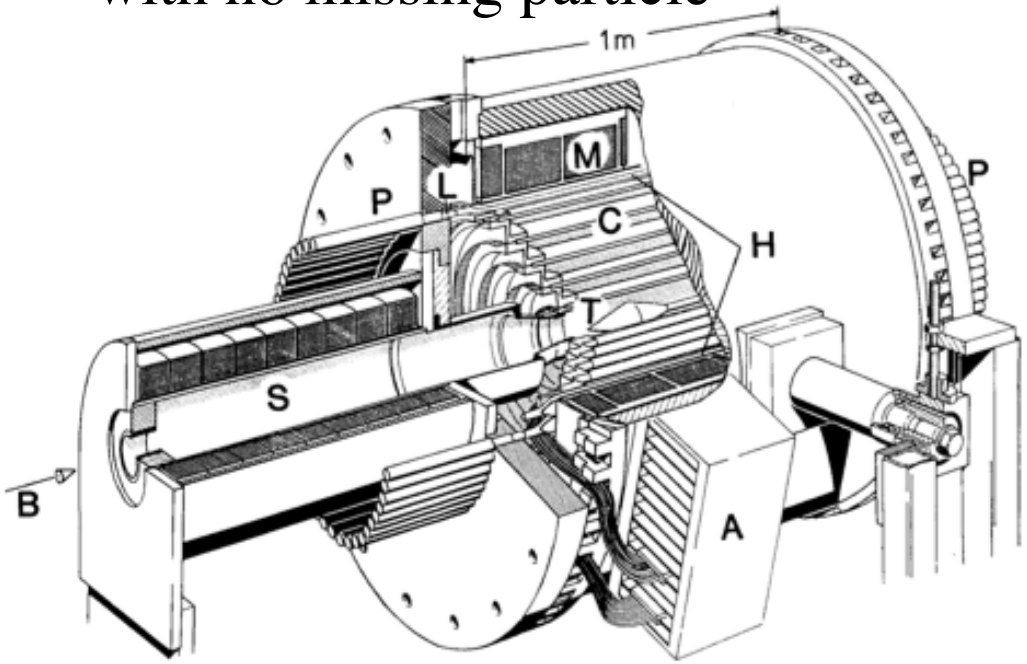
- Muon decay
  Lorentz structure
  (Fetscher, Gerber 1886)

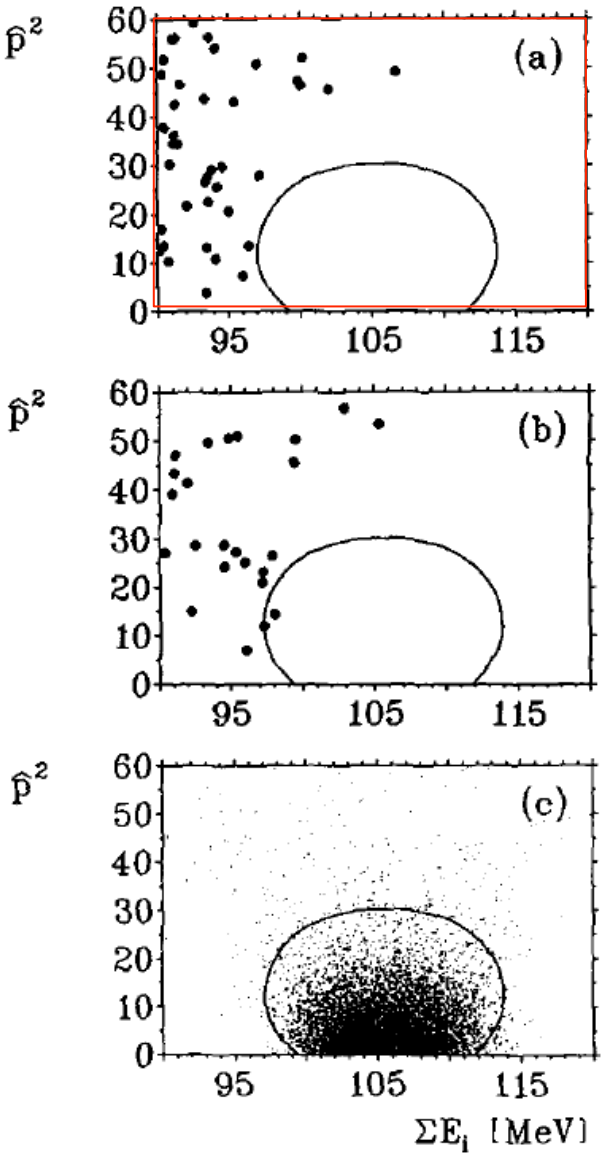
90% confidence area
validation of $V - A$



Pre B factory Era

- Search for μ→3e
  (SINDRUM 1886)
  Muon decay at rest to 3 charges particles, with no missing particle





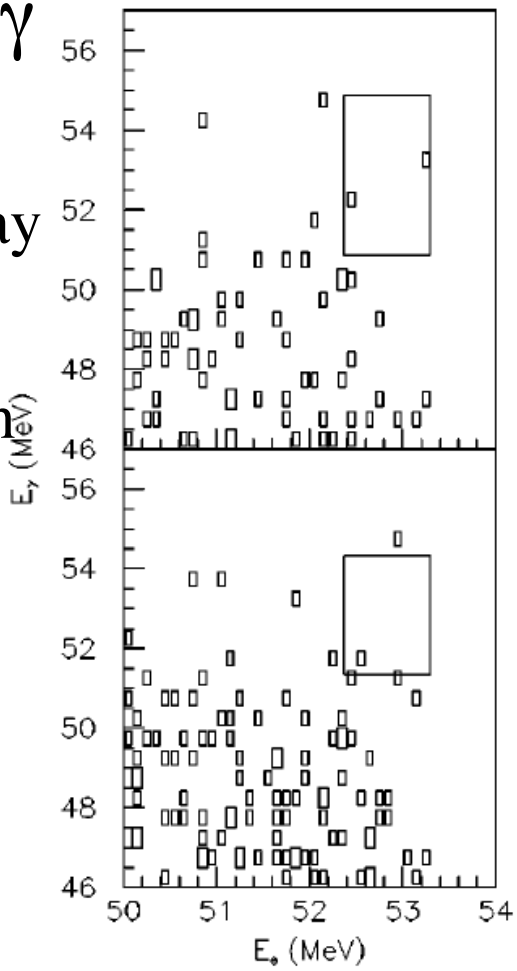
$$\frac{Br(\mu\rightarrow 3e)}{Br(\mu\rightarrow e2\nu)} < 1.0\times10^{-12}$$

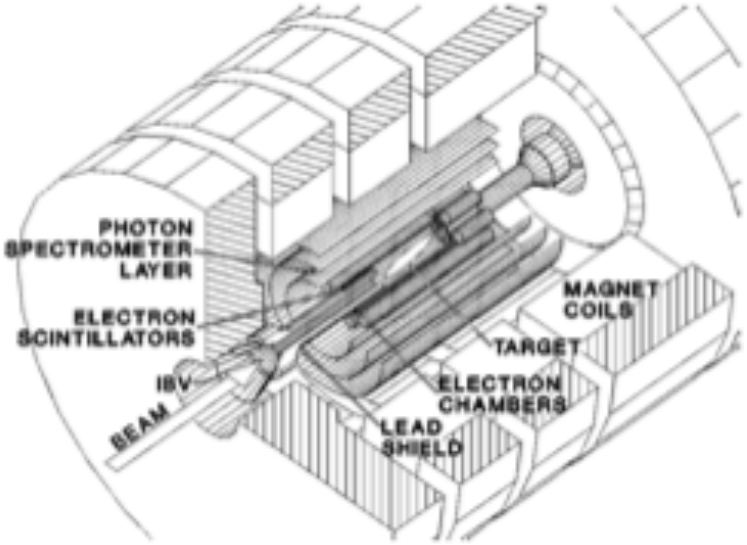
Pre B factory Era

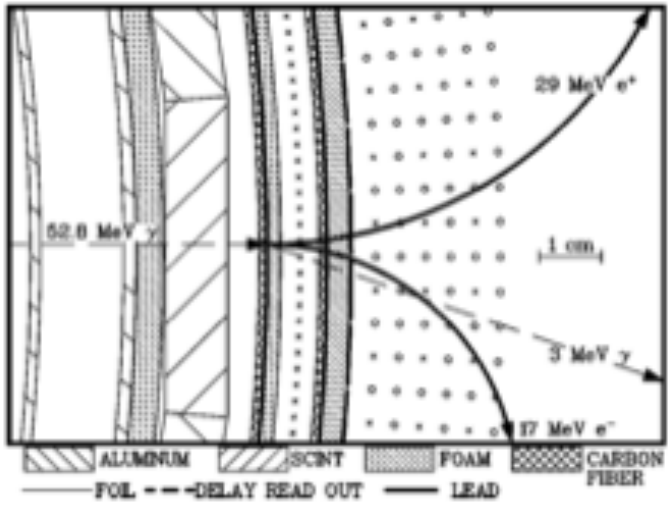
- Search for $\mu \rightarrow e\gamma$ (MEGA 1999)

  Two body muon decay at rest

  Photon detection with two converters







$$\frac{\Gamma(\mu \rightarrow e\gamma)}{\Gamma(\mu \rightarrow e2\nu)} < 1.2 \times 10^{-12}$$

B Factory Era

Consolidation and start to explore new physics

B Factory Era

Consolidation and start to explore new physics

- $CPV(K_L \to \pi^+\pi^-) \neq CPV(K_L \to \pi^0\pi^0)$
  death of the Superweak model

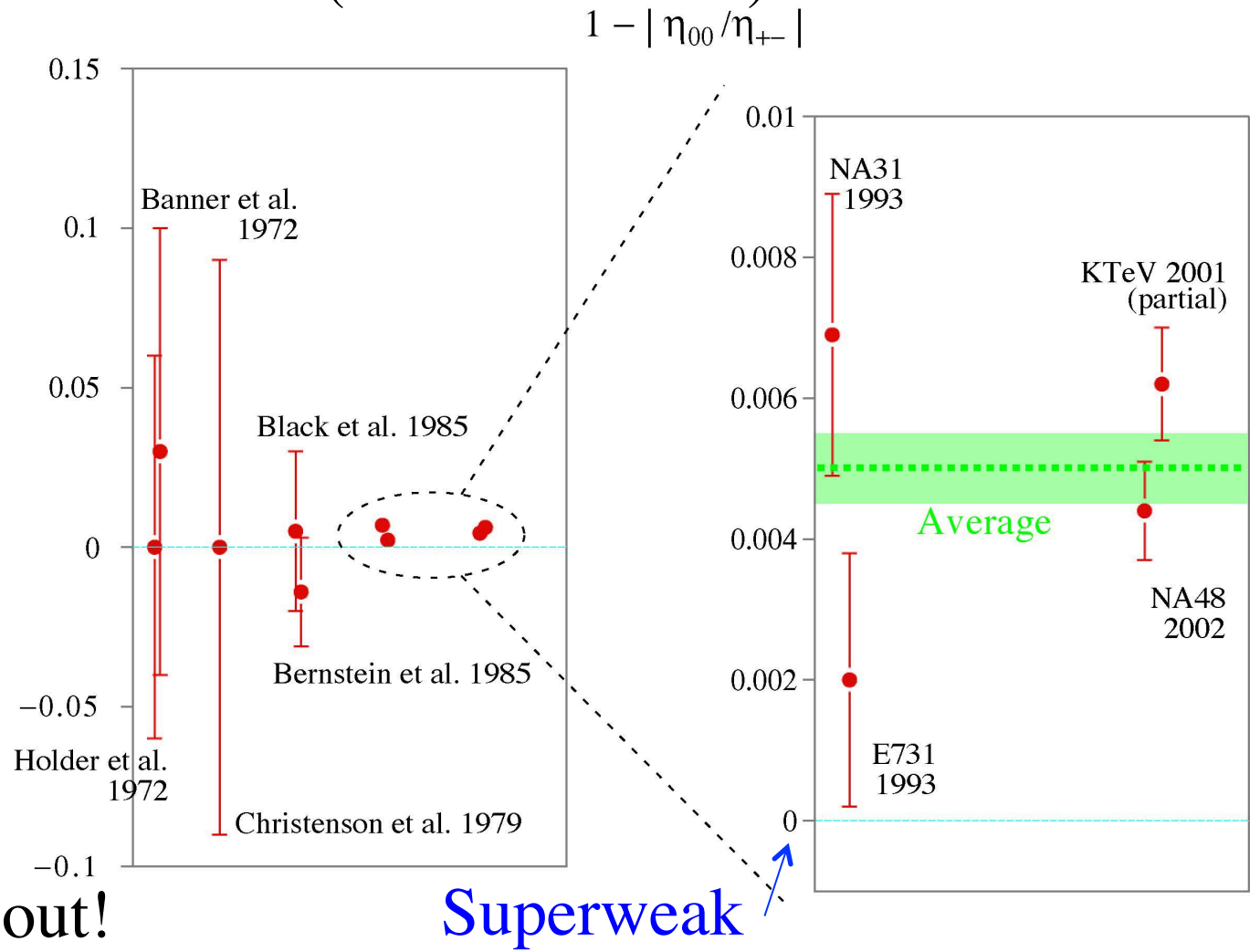
B Factory Era

- Re(ε´/ε) measurements (KTeV and NA48)

$$|\eta_{+-}|^2 = \frac{\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^+\pi^-)}$$

$$|\eta_{00}|^2 = \frac{\Gamma(K_S \to \pi^0\pi^0)}{\Gamma(K_L \to \pi^0\pi^0)}$$

compatible with SM predictions, superweak ruled out!



B Factory Era
Consolidation and start to explore new physics

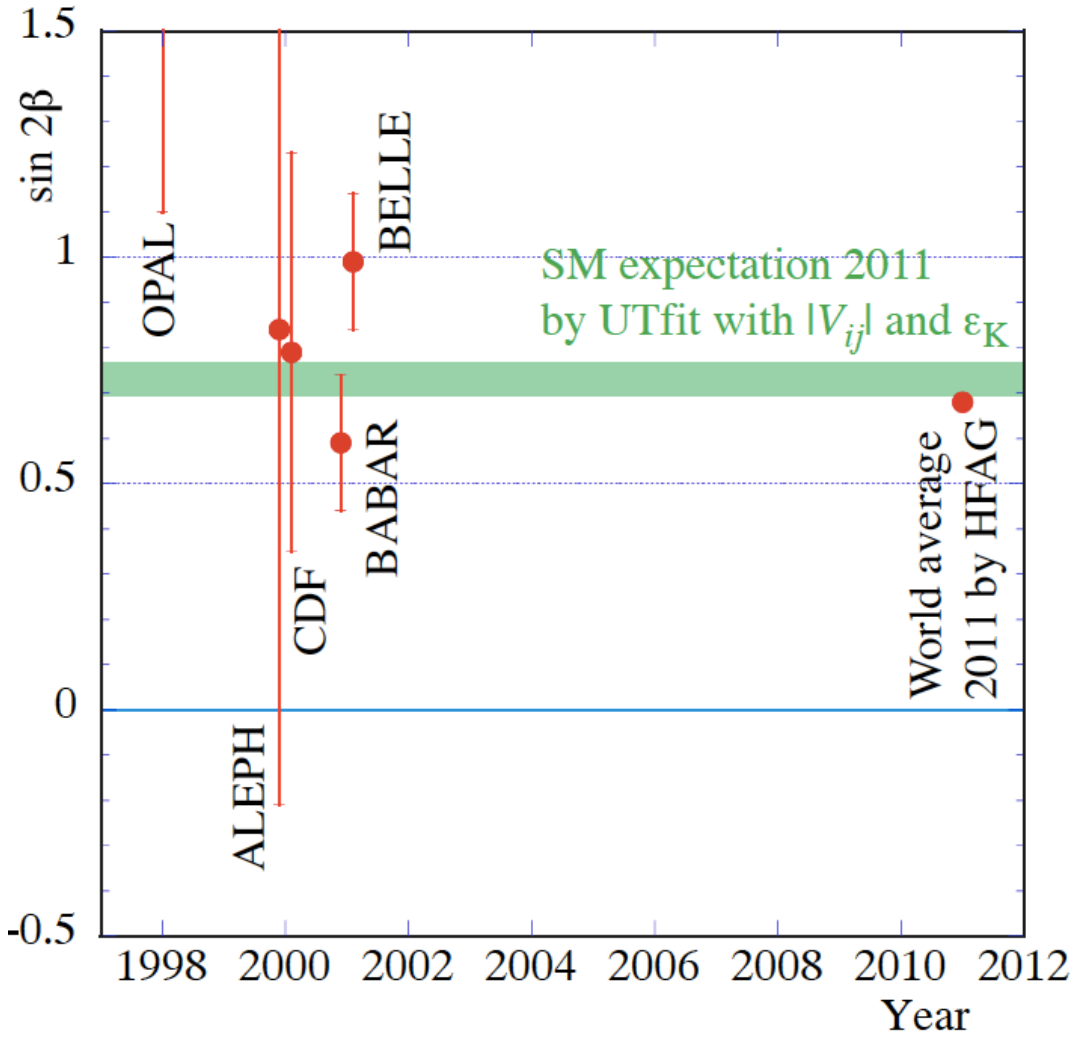
- CPV($K_L \to \pi^+\pi^-$) ≠ CPV($K_L \to \pi^0\pi^0$)
  death of the Superweak model
- CPV in $B_d \to J/\psi K_S$ ($\sin 2\beta$)
  first quantitative test of the Standard Model for CPV

B Factory Era

- sin2β measurements
  (BABAR and Belle)

$\beta = -\arg V_{td}$ in commonly used phase convention

NB: End of data taking
BABAR, 2008
Belle, 2010



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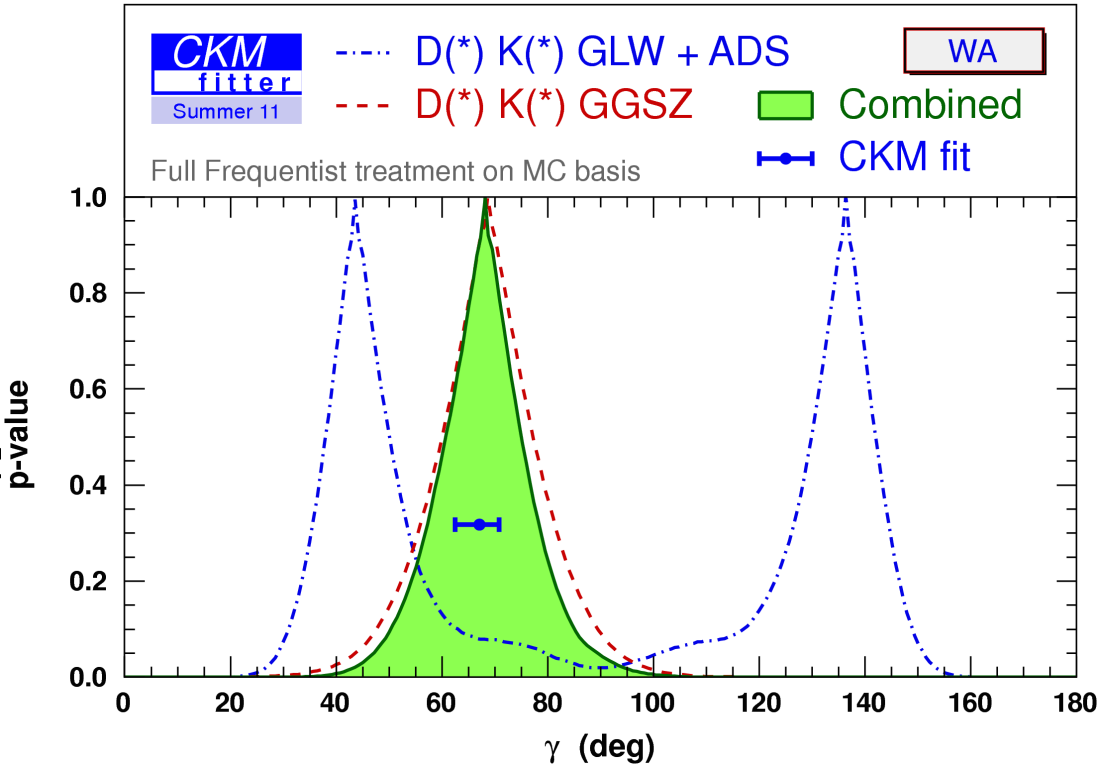
- Measurement of γ
  constraint test of the CKM picture with CPV

B Factory Era

- γ measurements
  (BABAR and Belle)

γ = arg V_{ub} in commonly used phase convention

Measured via interference between b→c and b→u in $B \to D^{(*)} K^{(*)}$ with a help of Cabibbo favoured and doubly Cabibbo suppressed decays using decay time integrated rates



Since only tree diagrams, no (very little) BSM contribution

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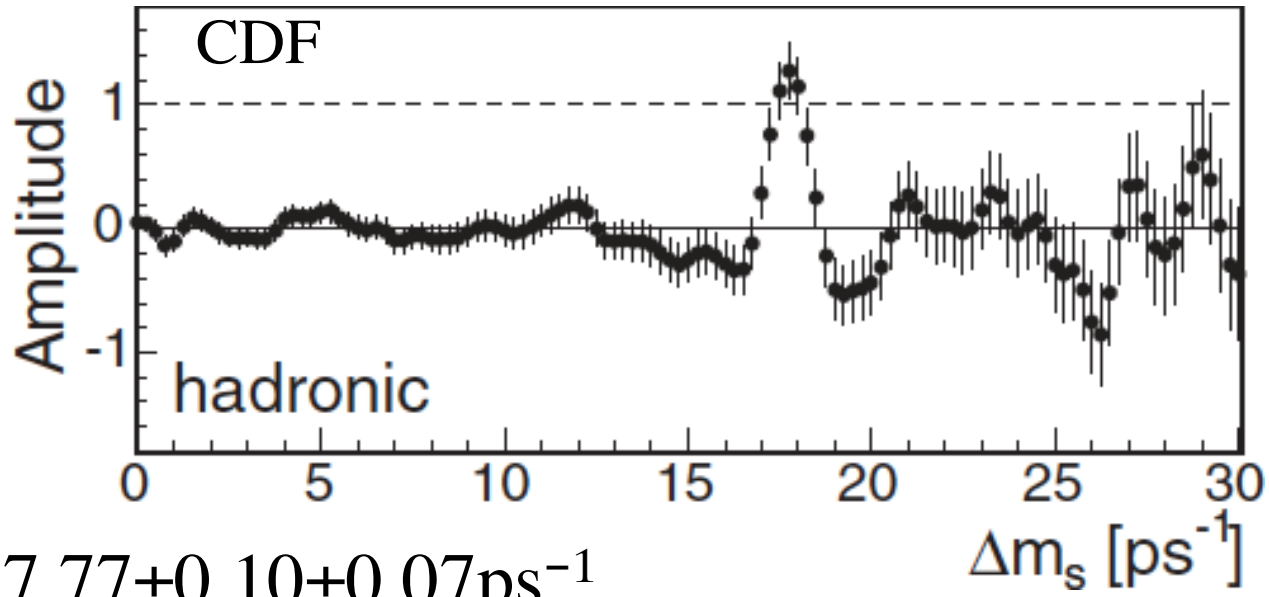
- B_s-$\overline{B}_s$ oscillation measurement (Δm_s)
  go beyond B_u and B_d system, demonstrating the strength of hadron machine

B Factory Era

- B_s-$\bar{B}_s$ oscillations (CDF and D0)

First both side bounds by D0 (06)

Δm_s measurement by CDF (06)



CDF: $\Delta m_s = 17.77 \pm 0.10 \pm 0.07 \text{ps}^{-1}$

5600 signal, $\varepsilon_{\text{eff-tag}}^{\text{OS}} = 1.8 \pm 0.1$, $\sigma_\tau = 87$ fs

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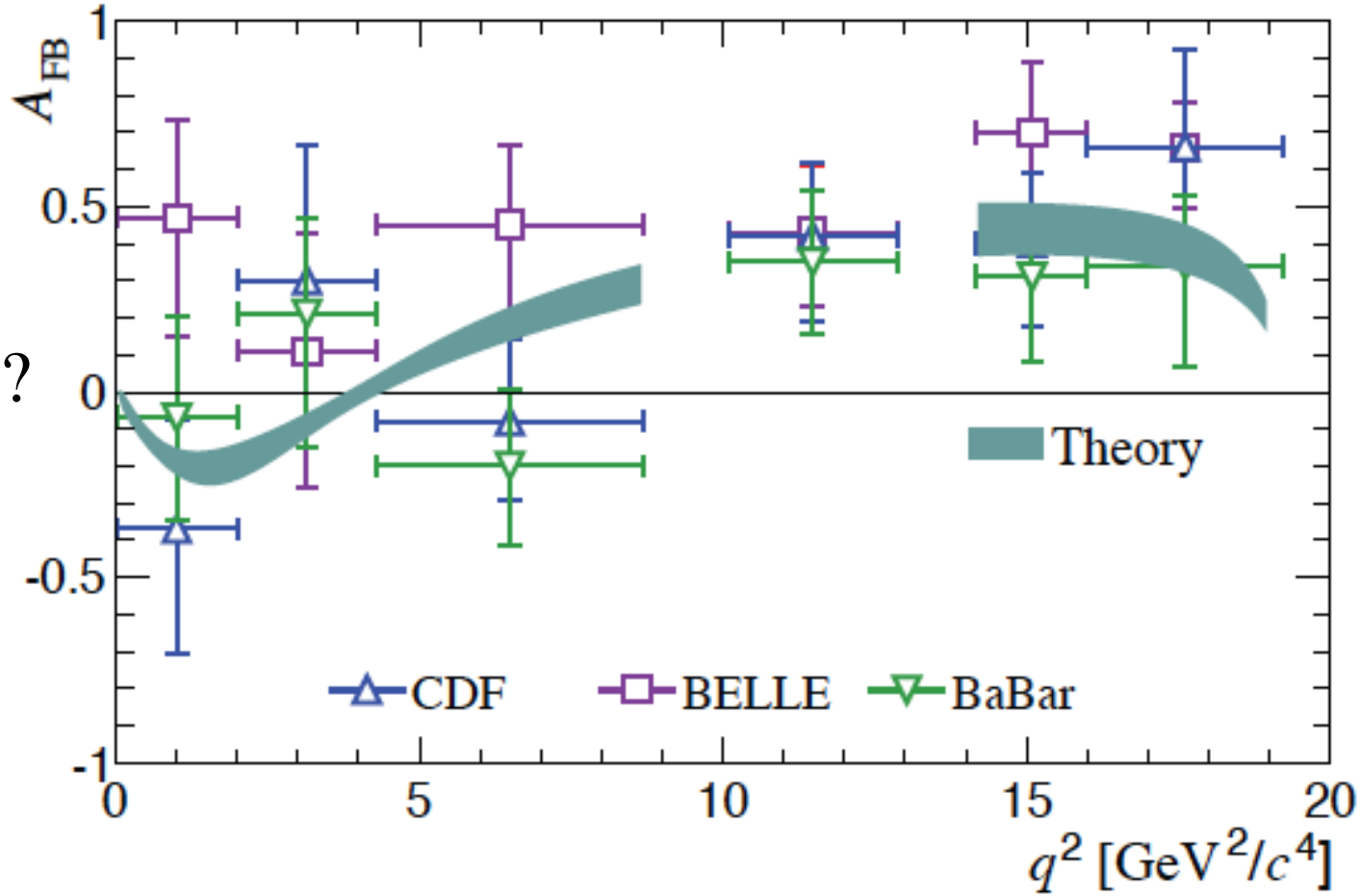
- A_{FB} for $B \to K^{*0}\mu^+\mu^-$ (W-box and electroweak penguins)
  the Lorentz structure in the hadrnoic weak decay

B Factory Era

- Muon forward and backward asymmetry in $B \to K^{*0}\mu^+\mu^-$ decays BABAR(09), Belle(09) and CDF(11)

In agreement
or disagreement?



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  go beyond B_u and B_d system, demonstrating the strength of hadron machine
- A_{FB} for $B \to K^{*0}\mu^+\mu^-$ (W-box and electroweak penguins)
  the Lorentz structure in the hadrnoic weak decay
- Observation of D-$\bar{D}$ mixing

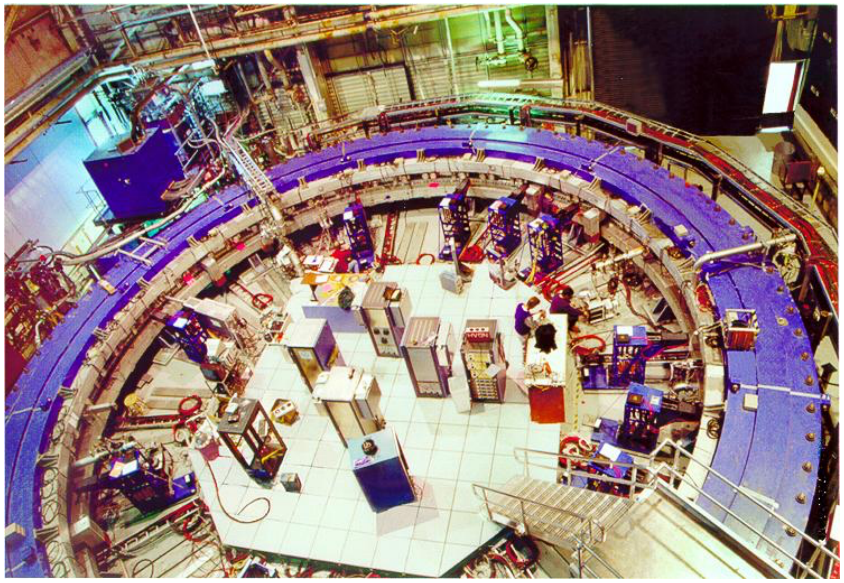
B Factory Era

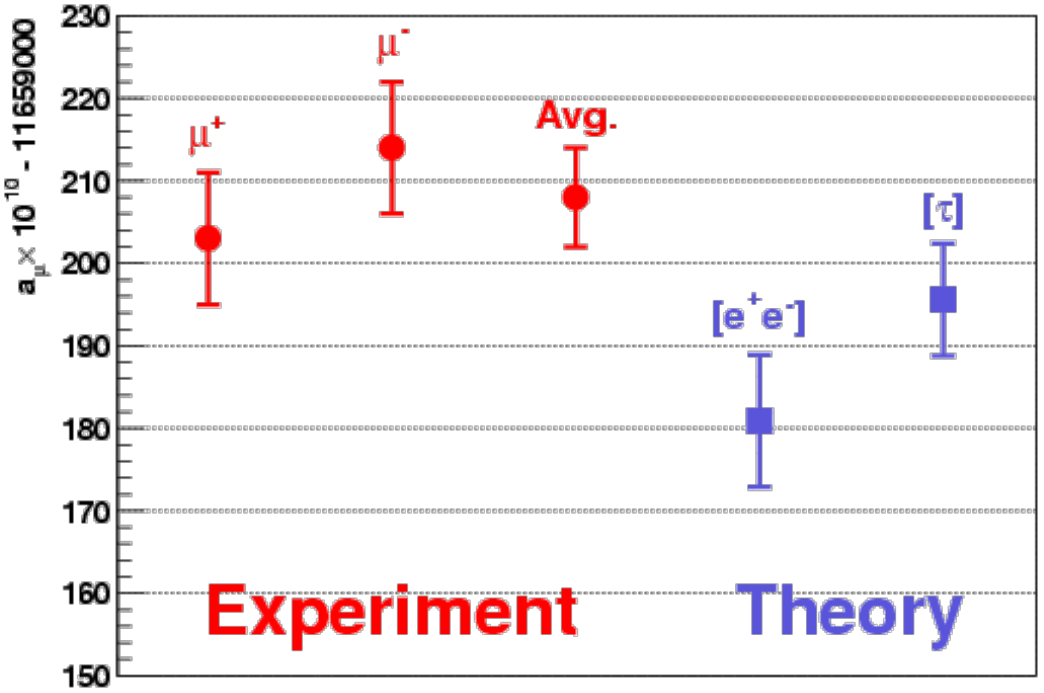
Consolidation and start to explore new physics

- Measurement of μ(g−2) with 0.5 ppm(!) error, compatible with the SM or a sign of deviation? Depending on the estimation for the hadronic contribution to g−2.

B Factory Era

- Measurement of μ(g-2)
  (E821 2004)





$$\frac{\Delta_{g-2}(\text{measurements} - \text{SM})}{\sigma_{\text{total}}} = 2.7\ (e^+e^-\ \text{data})\ \text{or}\ 1.4\ (\tau\ \text{data})$$

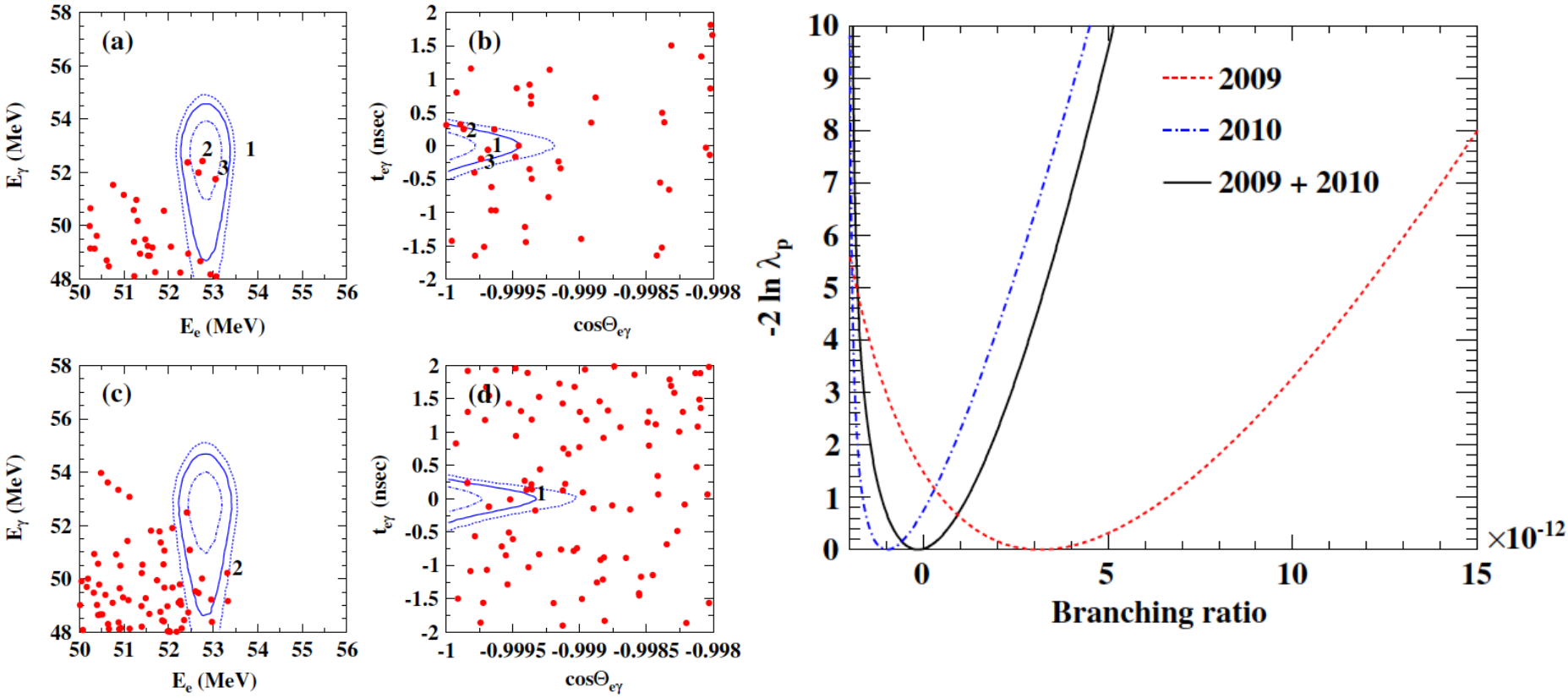
for the hadronic contribution

B Factory Era
Consolidation and start to explore new physics

- Measurement of μ(g−2) with 0.5 ppm(!) error, compatible with the SM or a sign of deviation? Depending on the estimation for the hadronic contribution to g−2.
- Search for $\mu \rightarrow e\gamma$ down to ~10^{-12}(!), start to constrain the parameter space for new physics scenarios

B Factory Era

- Search for $\mu \rightarrow e\gamma$ (MEG 2011)



$$\frac{\Gamma(\mu \rightarrow e\gamma)}{\Gamma(\mu \rightarrow e2\nu)} < 2.4 \times 10^{-12} \text{ with 90\% CL}$$

Post-B Factory Era
Search for new physics through flavour

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- Many new results from the LHC Run-1 data mainly from LHCb, some from ATLAS/CMS
  - Discovery of $B_s \to \mu^+\mu^-$: sensitivity down to 10^{-9}!
    in good agreement with the SM.
    CPV in $B_s \to J/\psi\phi$
    in good agreement with the SM
    where ATLAS, CMS and LHCb are contributing

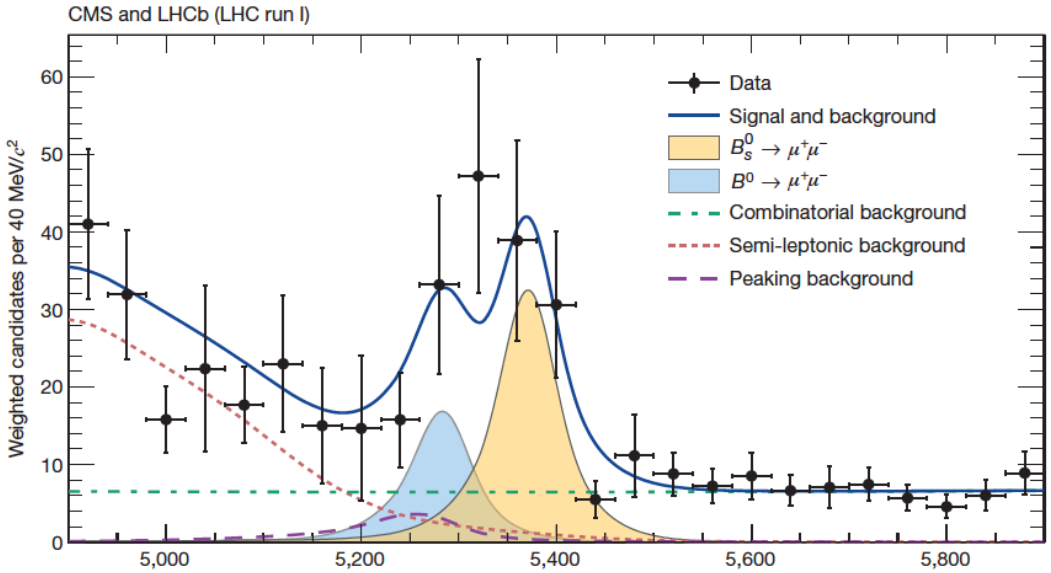
Post-B Factory Era

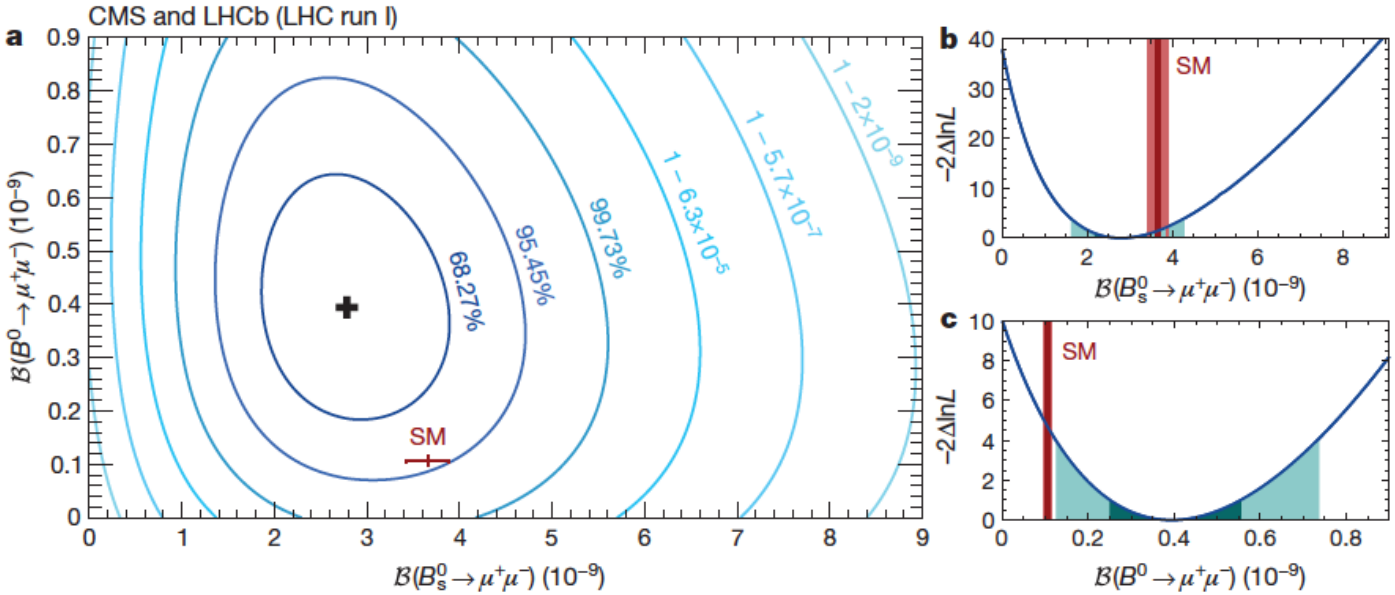
- $B \rightarrow \mu^+\mu^-$
  (CMS+LHCb 2015)

Branching fractions

$(3.9^{+1.6}_{-1.4}) \times 10^{-10}$ (B_d) 3.2σ

$(2.8^{+0.7}_{-0.6}) \times 10^{-9}$ (B_s) 6.2σ

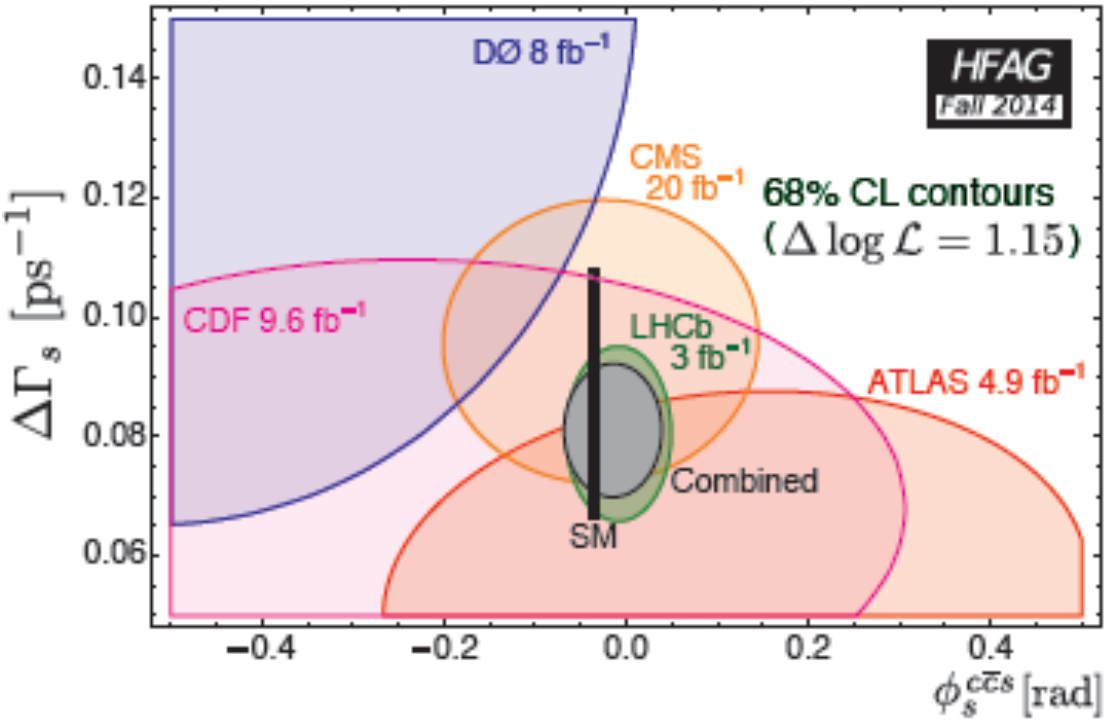




Post-B Factory Era

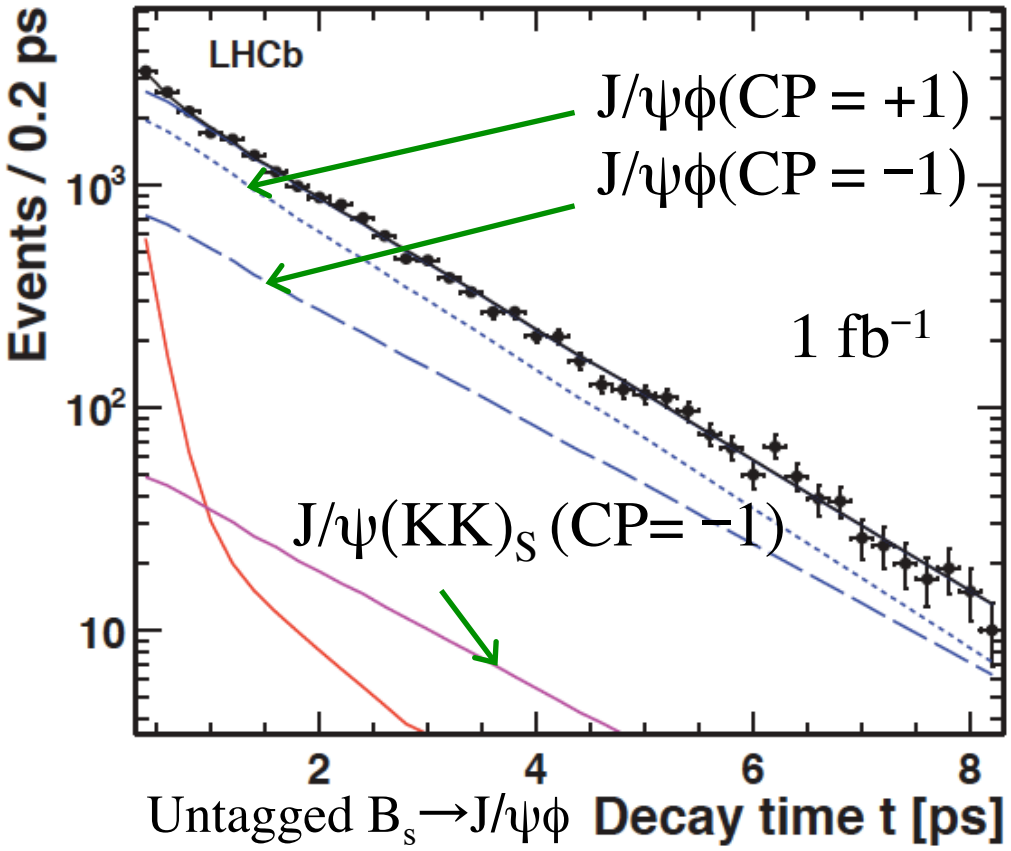
- CPV in $B_s \rightarrow J/\psi\phi$

Summary compiled by Heavy Flavour Averaging Group



an interesting observation…

- Power to have multi-body decay final stats!



+
the strong phase difference between K-K P-wave and S-wave, $\delta_P - \delta_S$

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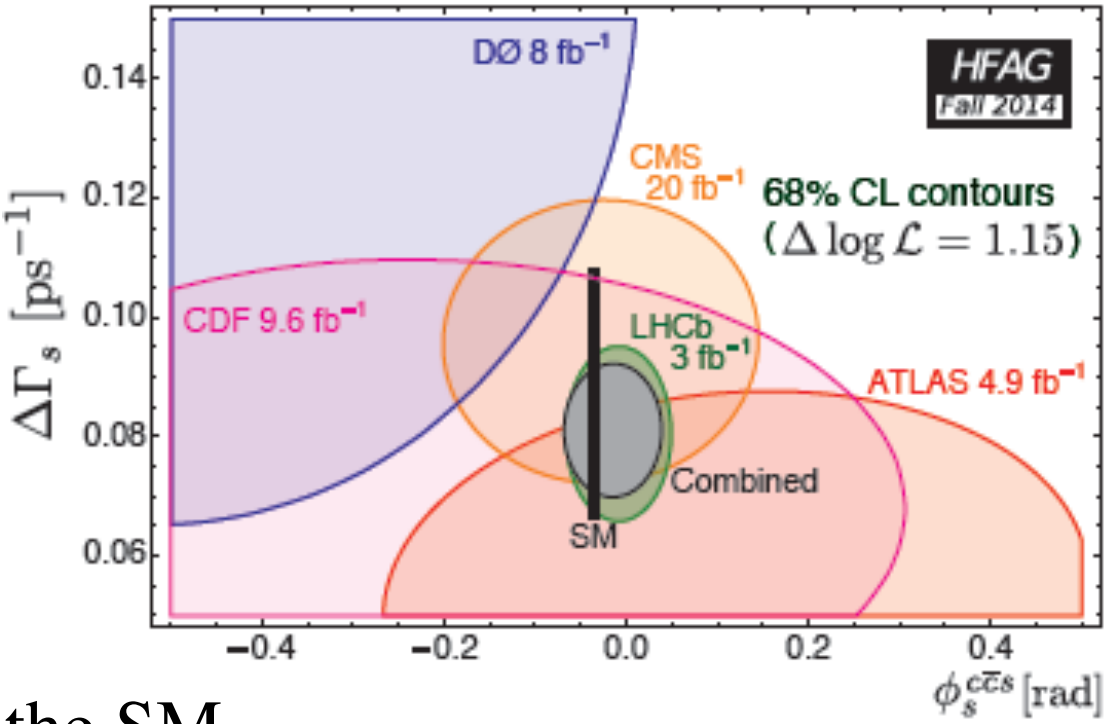

In good agreement with the SM.

Also it was shown by LHCb,
B-heavy mostly decays into J/ψhh (CP = −1) and decay slower
B-light mostly decays into J/ψhh (CP = +1) and decay faster
as the kaon system

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Search for new physics through flavour

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  - Discovery of $B_s \to \mu^+\mu^-$: sensitivity down to 10^{-9}!
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    CPV in $B_s \to J/\psi\phi$
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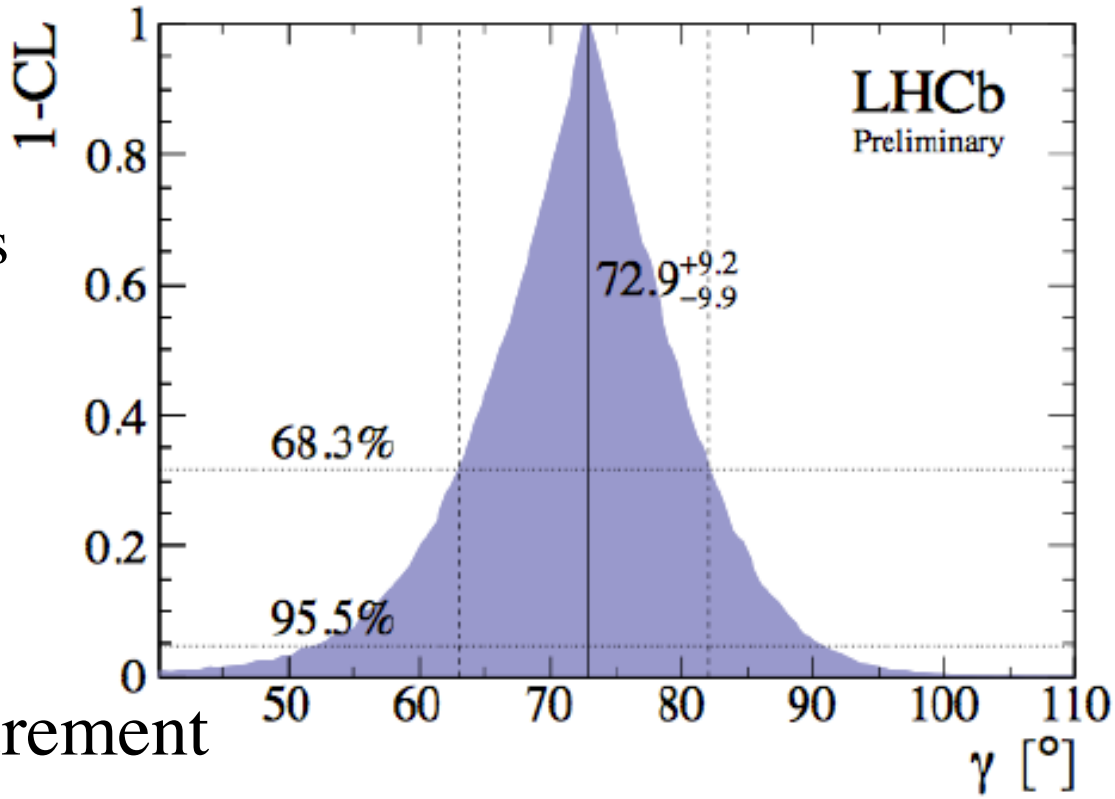
  - γ measurements by LHCb in $B \to DK$

Post-B Factory Era

- γ measurement by LHCb
  Combination of
  - $B \rightarrow DK^{(*)}$
    for different D decay modes
    decay time integrated rates
  - $B_s \rightarrow D_s K$
    decay time dependent rates

LHCb-CONF-2014-004



Already single best measurement

Belle $(68 \pm {}^{15}_{14})°$

BABAR $(69 \pm {}^{17}_{16})°$

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Very fast progress, which proved that broad B physics programme can be done at a hadron collider!

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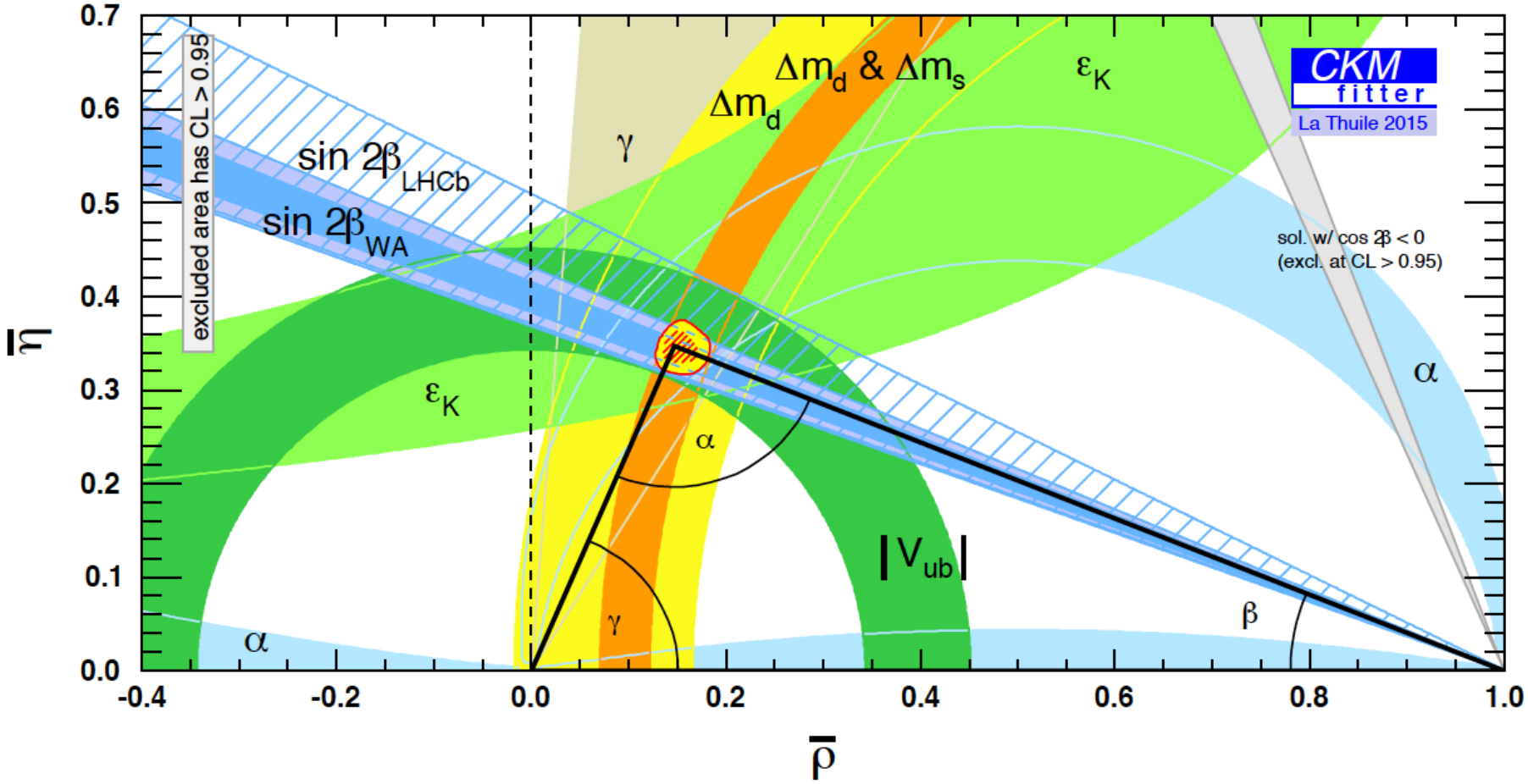
Very fast progress, which proved that broad B physics programme can be done at a hadron collider!

- $Br(\mu \to e\gamma) < 5.7\times10^{-13}$ (90% CL) MEG 2013

Post-B Factory Era

- Most recent unitarity triangle fit
  globally speaking, consistent with the SM picture

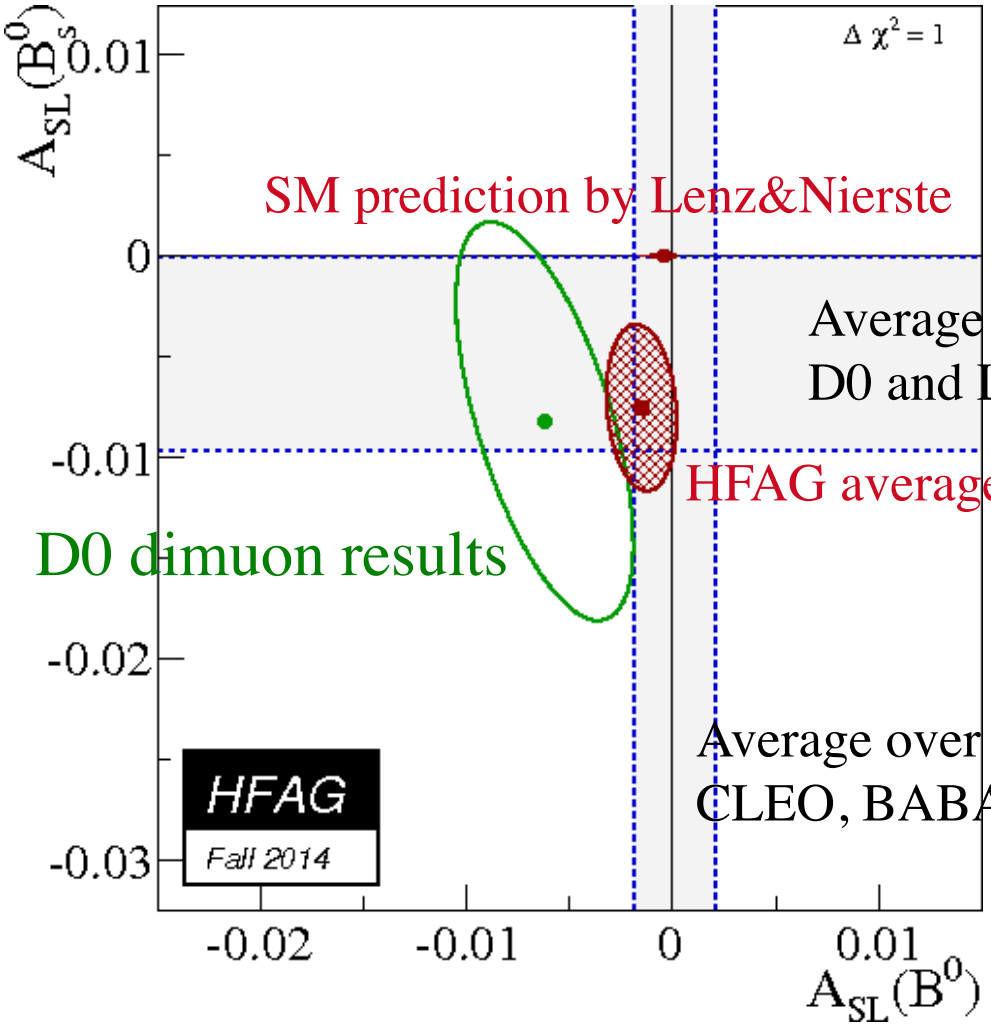


Currently Interesting Indications
any sign of new physics?

- Excess in like-sign dimuon charge asymmetry
- Enhanced $B_d \rightarrow \mu^+\mu^-$ rate
- Anomaly in $B \rightarrow K^*\mu^+\mu^-$ angular distributions

Currently Interesting Indications

- Excess in like-sign dimuon charge asymmetry



Corresponds to CPV in the oscillations.

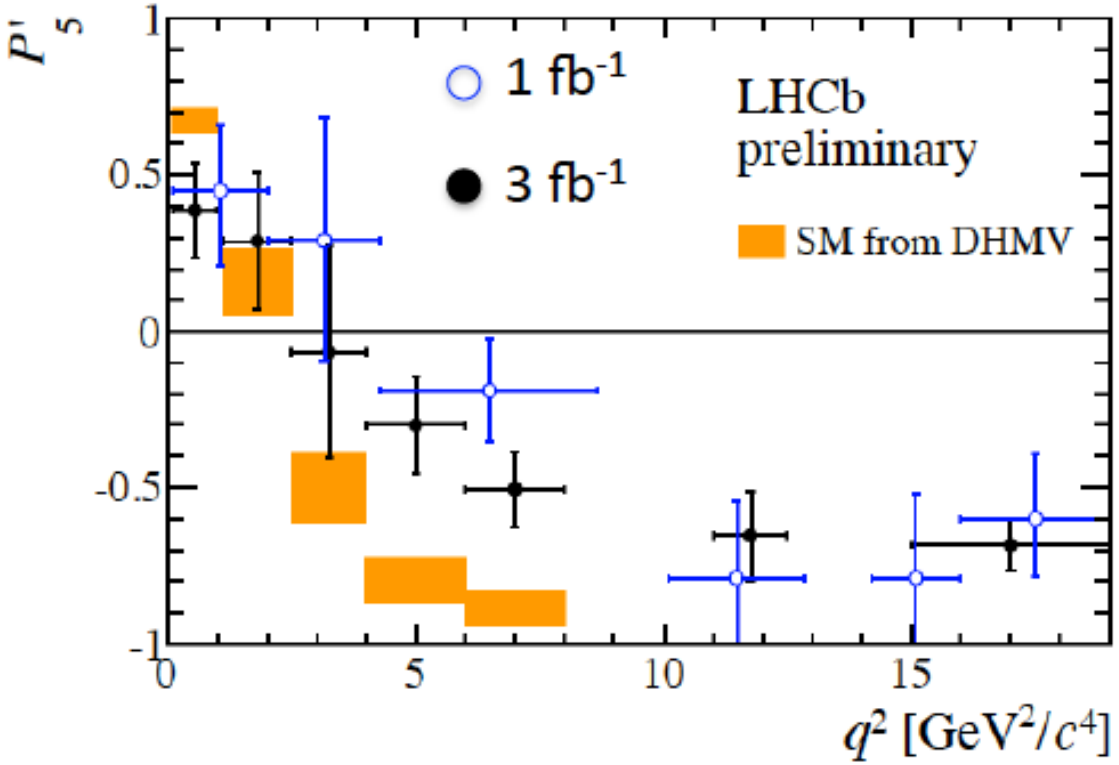
Average over
D0 and LHCb (semileptonic B_s decays)

Average over
CLEO, BABAR, Belle, D0 and LHCb

LHCb analysis with $3fb^{-1}$ data for B_s would be nice.

Currently Interesting Indications

- $B \to K^{*} \mu^{+} \mu^{-}$ ATLAS, CMS and LHCb results on the decay products angular distributions
  - all A_{FB}'s largely agree with the SM prediction
  - LHCb measures so called P_5'



1 fb^{-1} 2013 published
3 fb^{-1} 2015 conf note
DHMV:
JHEP 1412 (2014) 125

Currently Interesting Indications
any sign of new physics?

- Excess in like-sign dimuon charge asymmetry
- Enhanced $B_d \rightarrow \mu^+\mu^-$ rate
- Anomaly in $B \rightarrow K^*\mu^+\mu^-$ angular distributions

$\Rightarrow$

Run-2 data at LHC by ATLAS, CMS and LHCb

Better theoretical understanding in hadronic effect for the angular distributions

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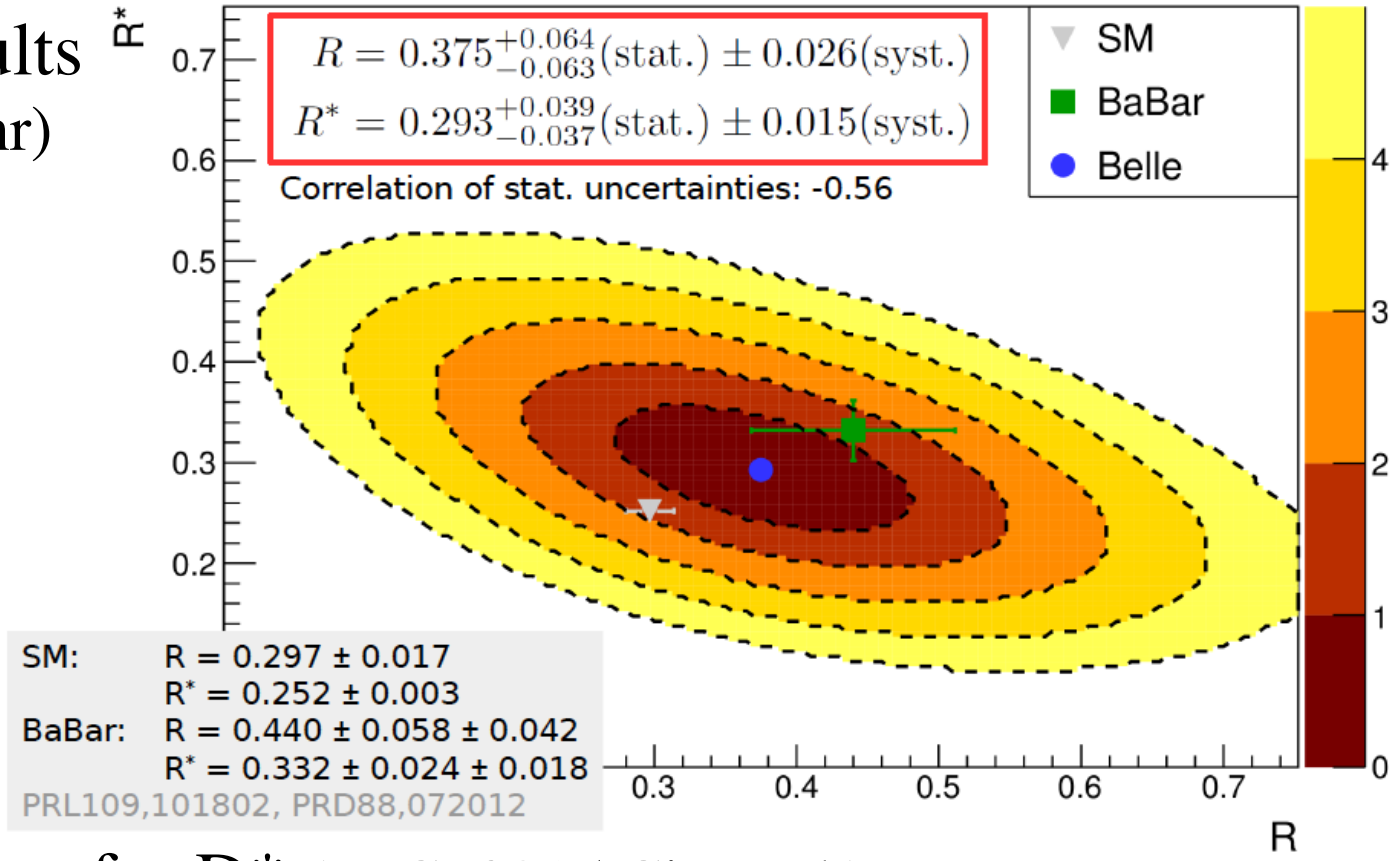
- Enhanced $B \rightarrow D^{(*)}\tau\nu$ rates
- Disagreement in inclusive and exclusive $|V_{ub}|$
- Disagreement in inclusive and exclusive $|V_{cb}|$
- Large CP violation in charm decay amplitudes

Currently Interesting Indications

- BABAR measurements on $Br(B \to D^{(*)}\tau\nu)/Br(B \to D^{(*)}\mu\nu)$ have been larger than the SM predictions (3.4σ).
- Belle new results (FPCP2015, Kuhr)



- LHCb also gives for D* (FPCP2015 Ciezarek)

$$R(D^*) = 0.336 \pm 0.027 \pm 0.030$$

Currently Interesting Indications

- $|V_{ub}|$ ($|V_{cb}|$) measured with inclusive final states have been larger than those measured with exclusive final states.
- LHCb measured $|V_{ub}|$ /$|V_{cb}|$ from the ratio of the exclusive final state $\Lambda_b \rightarrow p\mu\nu$ and $\Lambda_b \rightarrow \Lambda_c\mu\nu$.
  $|V_{ub}|$ = LHCb measurement $\oplus$ form factor ratios by lattice QCD(W. Detmold, C. Lehner, and S. Meinel) $\oplus$ existing exclusive $|V_{ub}|$
  $|V_{ub}| = (3.27 \pm 0.15 \pm 0.17 \pm 0.06) \times 10^{-3}$ (arXiv:1504.01568v1)
  theory error on $|V_{cb}|$

In agreement with $B \rightarrow \pi l\nu$ and $\rightarrow \rho l\nu$ measurements

$(3.28 \pm 0.29) \times 10^{-3}$ (PDG2014)

Currently Interesting Indications

- Situation with CPV in the charm sector is more complicated. Combined results are compatible with no CPV. Looking forward to see the 3 fb^{-1} analysis of LHCb with prompt $D^{(*)}$.

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Run-2 data at LHC mainly by LHCb (PID)

q^2 dependence would be nice…

Better theoretical understanding of hadronic effect

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Currently Interesting Indications

- $Br(B^+ \to K^+\mu^+\mu^-)/Br(B^+ \to K^+e^+e^-)$ must be very close to 1, only a small phase space correction: lepton universality
  LHCb measurement (2014)
  $0.745^{+0.090}_{-0.074} \pm 0.036 \quad 1 < q^2 < 6\ \mathrm{GeV}^2/c^4$
  c.f. BABAR (2012)
  $0.74\ ^{+0.40}_{-0.31} \pm 0.06 \qquad 1 < q^2 < 8.12\ \mathrm{GeV}^2/c^4$

  Only 2.6σ discrepancy with the SM, but difficult to understand, i.e. cannot be hadronic effect….

It is not an easy measurement for LHCb:e^+e^-

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⇒New experiment at FNAL in preparation + better theoretical understanding in the hadronic effect

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- (Signal for $H \to \tau\mu$) ⇒LHC Run-2 ATLAS/CMS

Very Brief Look for Future

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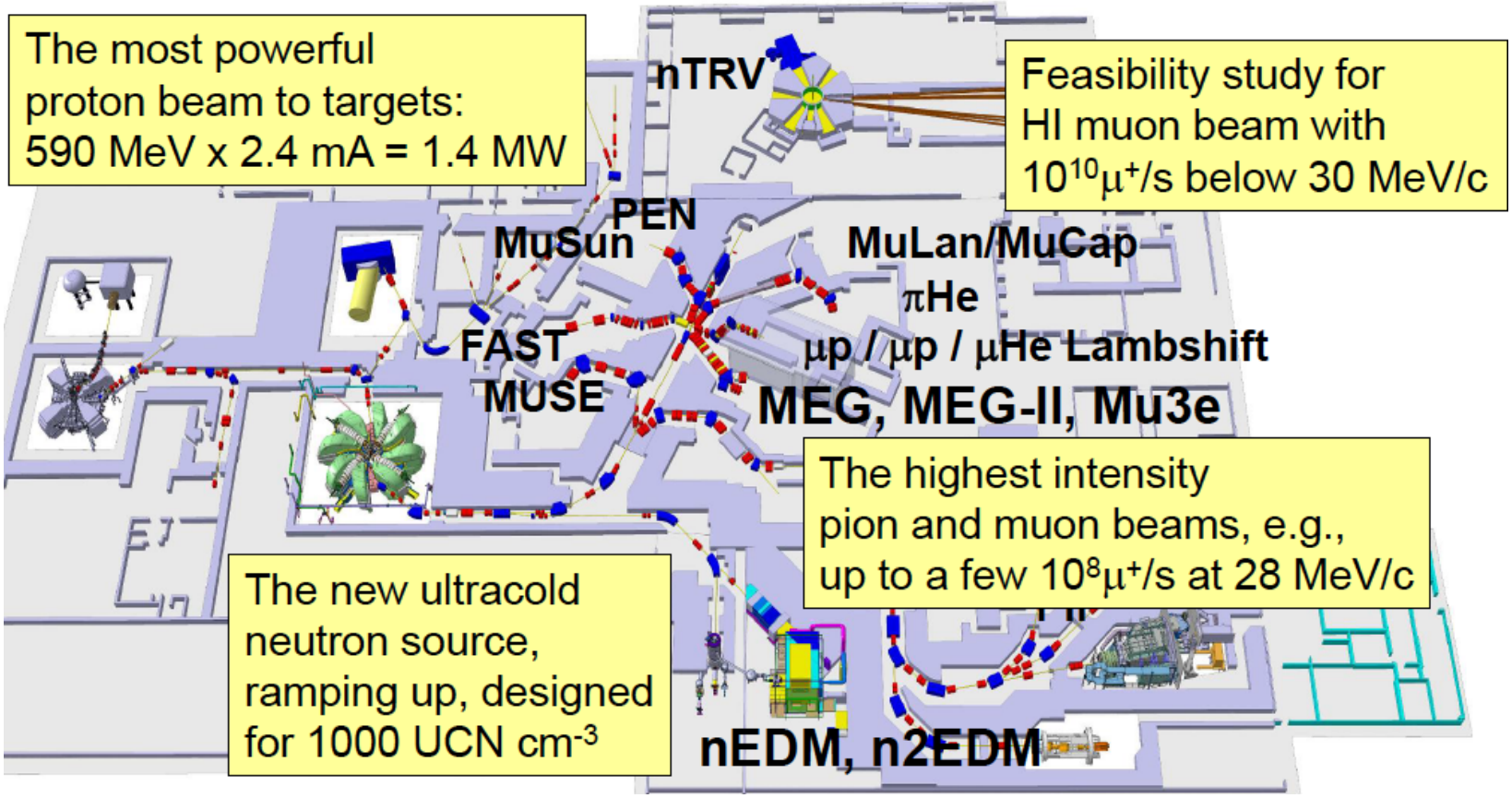
- Also EDM, $N\bar{N}$ oscillation, may be BEPC-Upgrade or even a bigger machine?
- And ATLAS and CMS at High Luminosity LHC

Very Brief Look for Future

- Important to realise that flavour physics can be done at "small" laboratories in "small" countries.

PSI in CH as an example (K. Kirch)



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- We are in the era where flavour physics, i.e. CP violation and rare and forbidden decays, has become a promising tool to search for new physics.
- However, this might be still a long journey: cf. How long did it take from theoretical ideas emerging and experimentally proven for Higgs and KM?

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Reflection

- Hadronic system, i.e. K, B and D have been the driving force for this effort with many experiments and facilities. This may be partly because those hadrons offer very wide physics programme.
- Studies with hadronic system may eventually hit a limit due to the uncertainties in the theoretical predictions due to (mainly) strong interactions.
- Some are better than others: m_t prediction from $\Delta m(B_d)$ was rather limited compared to that from Z^0 decay properties, although both relies on the loop.

Reflection continues

- Can progress in theory together with experimental inputs overcome this weakness? Or we should better look into leptons and gauge bosons? Is $\mu(g-2)$ borderline case?

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- By the way, is there CPV in strong interactions?

To conclude

- The Standard Model will remain as a theory hard to crack. Although we know that there is physics beyond the Standard Model, we have little idea what it is.

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- The Standard Model will remain as a theory hard to crack. Although we know that there is physics beyond the Standard Model, we have little idea what it is.
- Without this, there is no success guaranteed research programme (B factories and LHC had the Standard Model). We need to look for everywhere. But resources are limited and making choices are being asked.
- I personally believe studies of rare phenomena and precision measurements have a big potential, but on hadron, leptons, gauge boson, Higgs or all of them?

Finally

- For the next several years will be certainly very exciting with the new LHC data,

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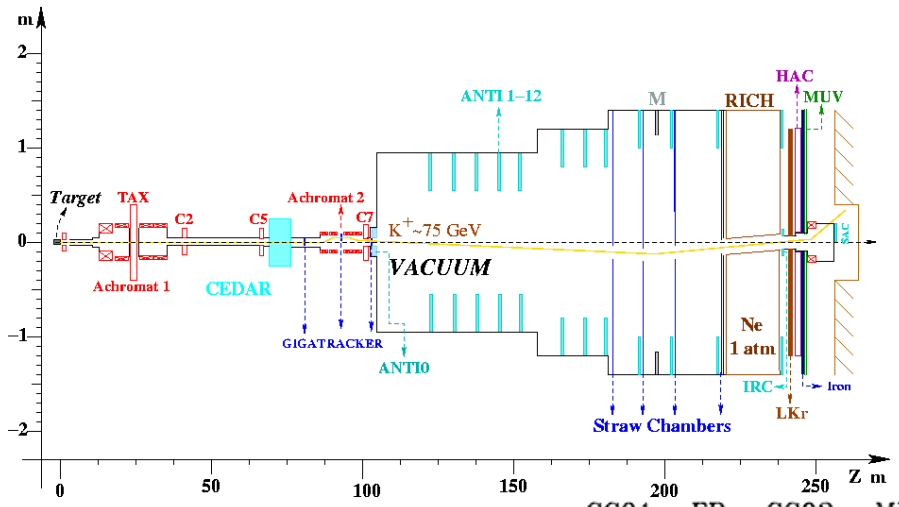
and thank you very much for listening!

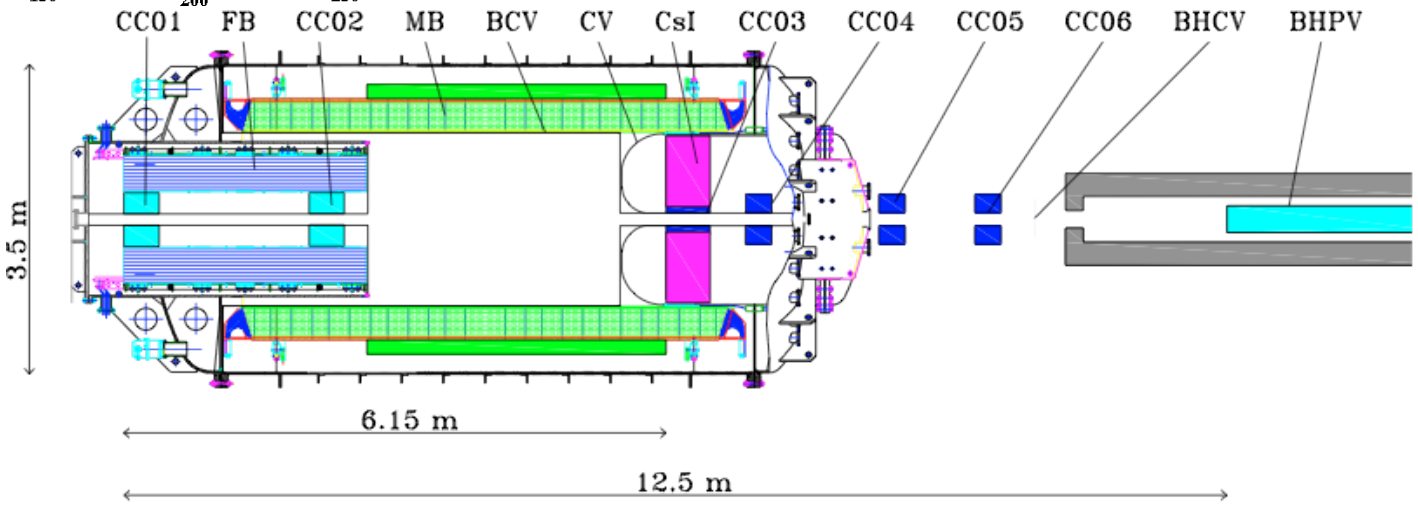
Some of the highlight

- Belle II & LHCb Upgrade

Some of the highlight

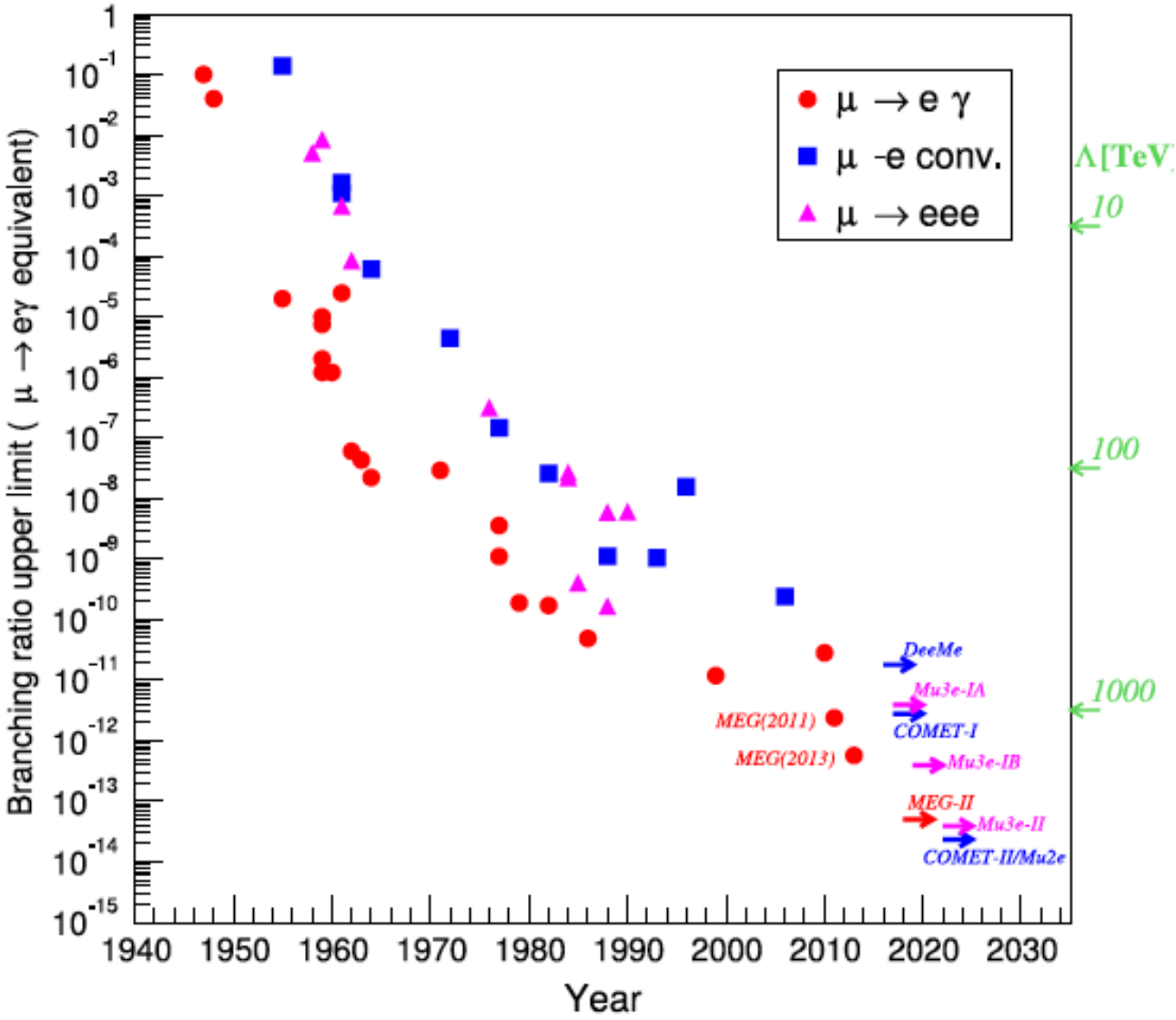
- NA





Some of the highlight

- A summary of Progress in the LFV muon decays
(Mori&Ootami 2014)



Some of the highlight

- Example of planned experiments:
  MEG II (PSI),

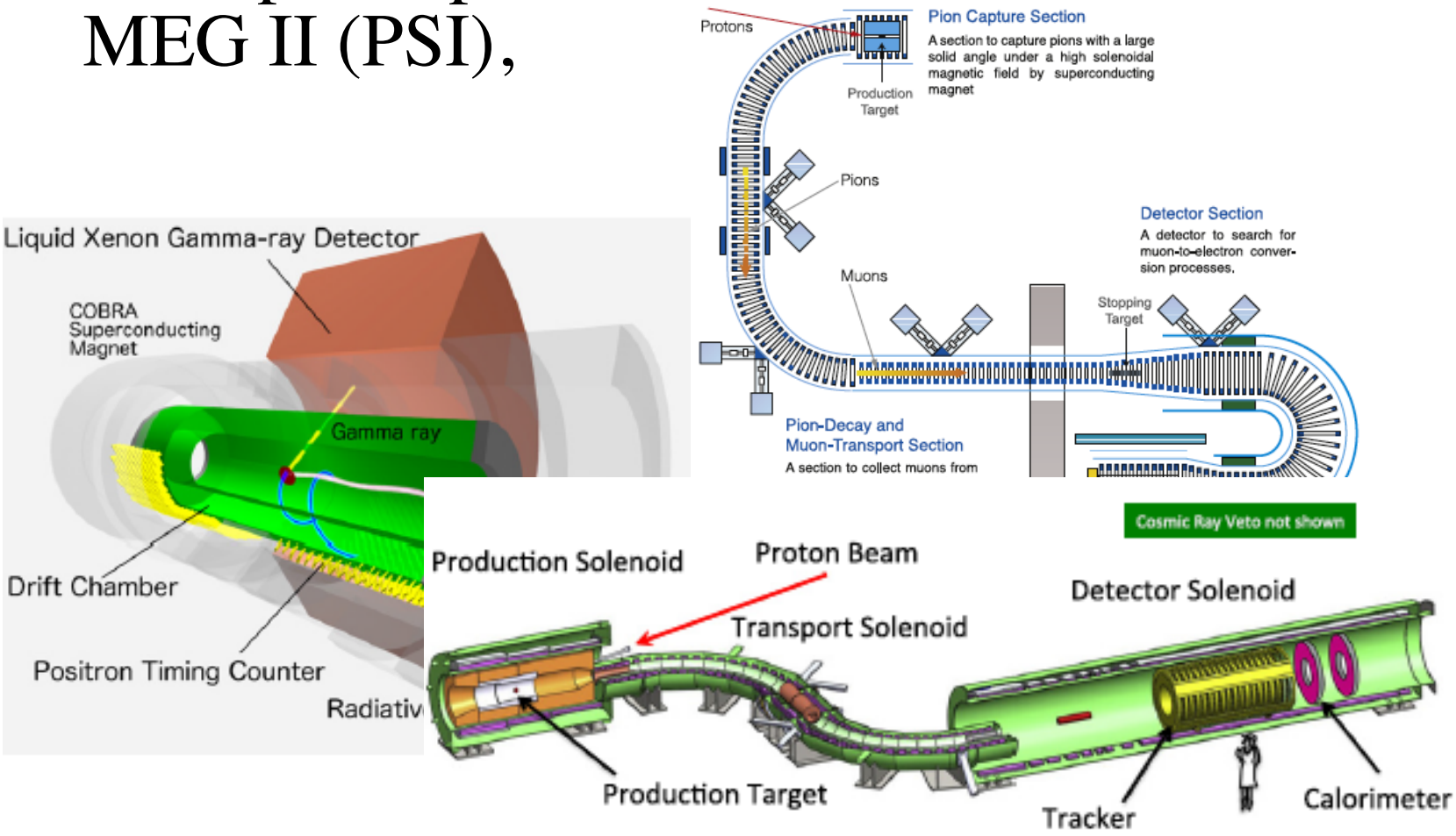
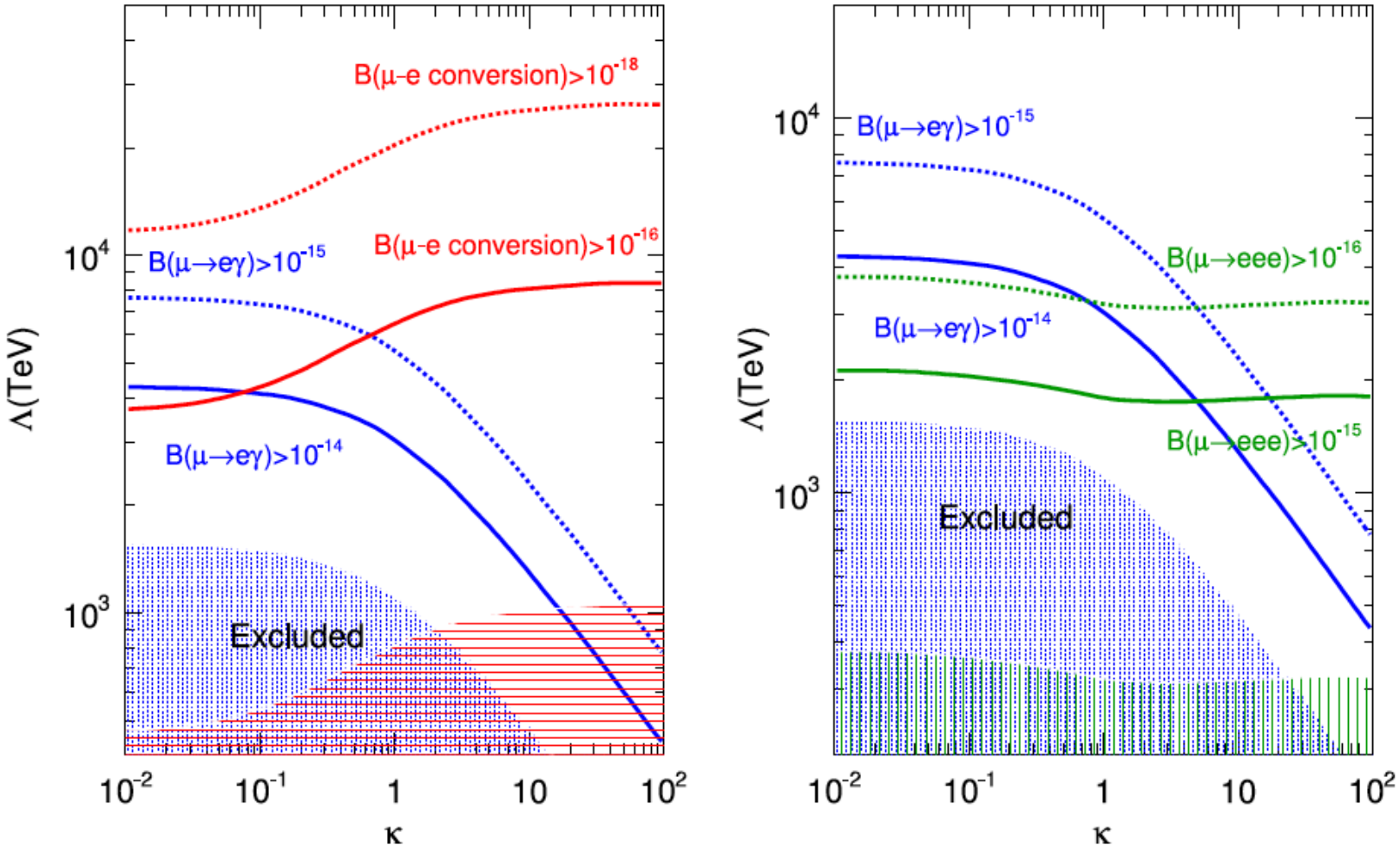


Fig. 33. Mu2e experimental setup.
Source: Provided by R. Ray.


B(μ-e conversion)>10^-18
B(μ→eγ)>10^-15
B(μ-e conversion)>10^-16
B(μ→eγ)>10^-14
Excluded
Λ(TeV)
10^4
10^3
10^-2
10^-1
1
10
10^2
κ
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