Flavour Physics at e+e- colliders

Including a brief look back

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B'ham PPAP meeting 2012

Queen Mary University of London

Overview

- Past:
  - BaBar: Still publishing well: UK involvement more or less down to review level work and finalising the physics of the B factories book.
  - At least 50 interesting papers left to write on the data.
  - Fitting given that SLAC is now 50 years young.
- Running:
  - BES III / KLOE
- Under construction:
  - Belle II / SuperB
- Other:
  - Novosibirsk Super τ-charm

What BaBar did for us

- Found:
  - CPV in B decays
  - Direct CPV in B decays
  - A bunch of new particles
  - Charm mixing
  - T-violation
- Produced:
  - Over 500 papers in PRL and PRD
  - a large number of high quality theses: CERN formally thanked SLAC a few years ago for their PhD students contributions to the LHC.
- Confirmed the SM: CKM matrix and the KM mechanism.
- Killed the 2HDM – type II (to name but one model), found evidence for NP ... and much more!
- Still to come:
  - Physics of the B Factories book [thanks to funding from Canada, France, and the US]
  - Many more papers...

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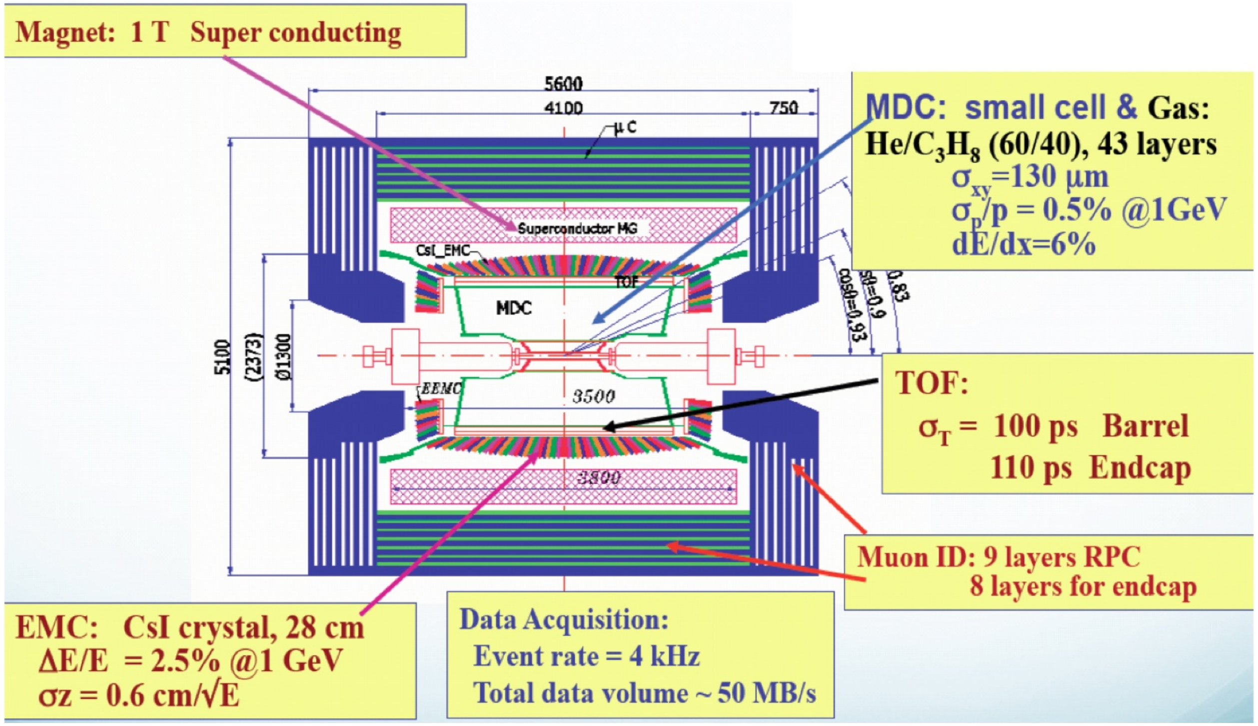
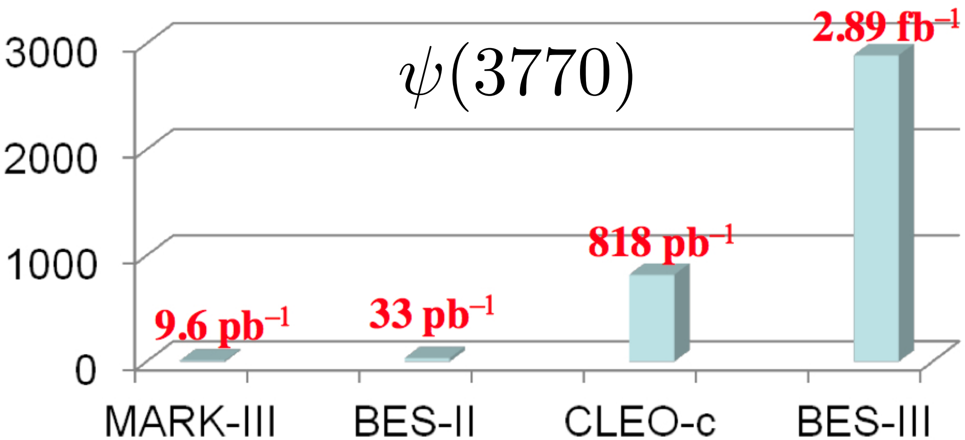
The B factories

- BaBar had more talks this year (about 150 in 2012) than last year
- Performed the most precise tests of the Unitarity Triangle
- Verified CKM matrix and KM mechanism as the leading order description of quark flavour changing & CPV in B_u and B_d decay.
- Not yet to be surpassed in these areas.

Institute of High Energy Physics
Chinese Academy of Sciences



BES III aim: $10 fb^{-1}$ at charm threshold



SuperB: $1000 fb^{-1}$ At charm threshold

- BES III now producing precision charm results:
  - Some measurements will play an important role in controlling systematic uncertainties for LHCb: charm mixing and γ (and later on for Belle II as well).
  - Charmonium result programme continues to be strong.

BESIII Preliminary

$$N(D^+ \to \mu^+ \nu) = 377.3 \pm 20.6$$

$$\mathcal{B}(D^+ \to \mu^+ \nu) = (0.0374 \pm 0.0021 \pm 0.0006)\%$$

$$f_{D^+} = (203.9 \pm 5.7 \pm 2.0) \text{ MeV}$$

BESIII Preliminary

$$\mathcal{B}(D^0 \to K^+ e\nu) = (3.542 \pm 0.030 \pm 0.067)\%$$

$$\mathcal{B}(D^0 \to \pi^+ e\nu) = (0.288 \pm 0.008 \pm 0.005)\%$$

$$\frac{\Delta\Gamma}{\Delta q^2} \text{ distributions } \to \text{ FF fits, parameters}$$

  - Very relevant for the UK flavour programme, though no direct interest in participating at this time.
  - Expect a lot of interesting results over the coming years.

Belle II / SuperB overview

- Physics case:
  - globally acknowledged as sound for a number of years
    - 4S: (50-75/ab)
      - Rare decay searches to constrain NP models
      - Precision SM tests: *CKM, T-violation etc.*
      - τ physics [*CPV, LFV, g-2, EDM, ...*]
    - 5S: (few /ab)
      - Rare decays (states with neutrals and neutrinos)
    - and some data at the other ϒ resonances.
  - Unique to SuperB:
    - ψ(3770) (1/ab)
      - Rare charm decays, Precision measurements, TDCPV, etc.
    - Polarisation
      - $\sin^2\theta_W$ at a Q^2 that is theoretically clean (i.e. for the one measurement that is off: $e^+e^- \rightarrow bb$).

UK detector/ physics interest from: Queen Mary University of London & Particle Physics Rutherford Appleton Laboratory

UK machine interest from: JAI John Adams Institute for Accelerator Science

Belle II / SuperB overview

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Japan and Italy want UK involvement

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Japan and Italy want UK involvement

& UK scientists want to be involved

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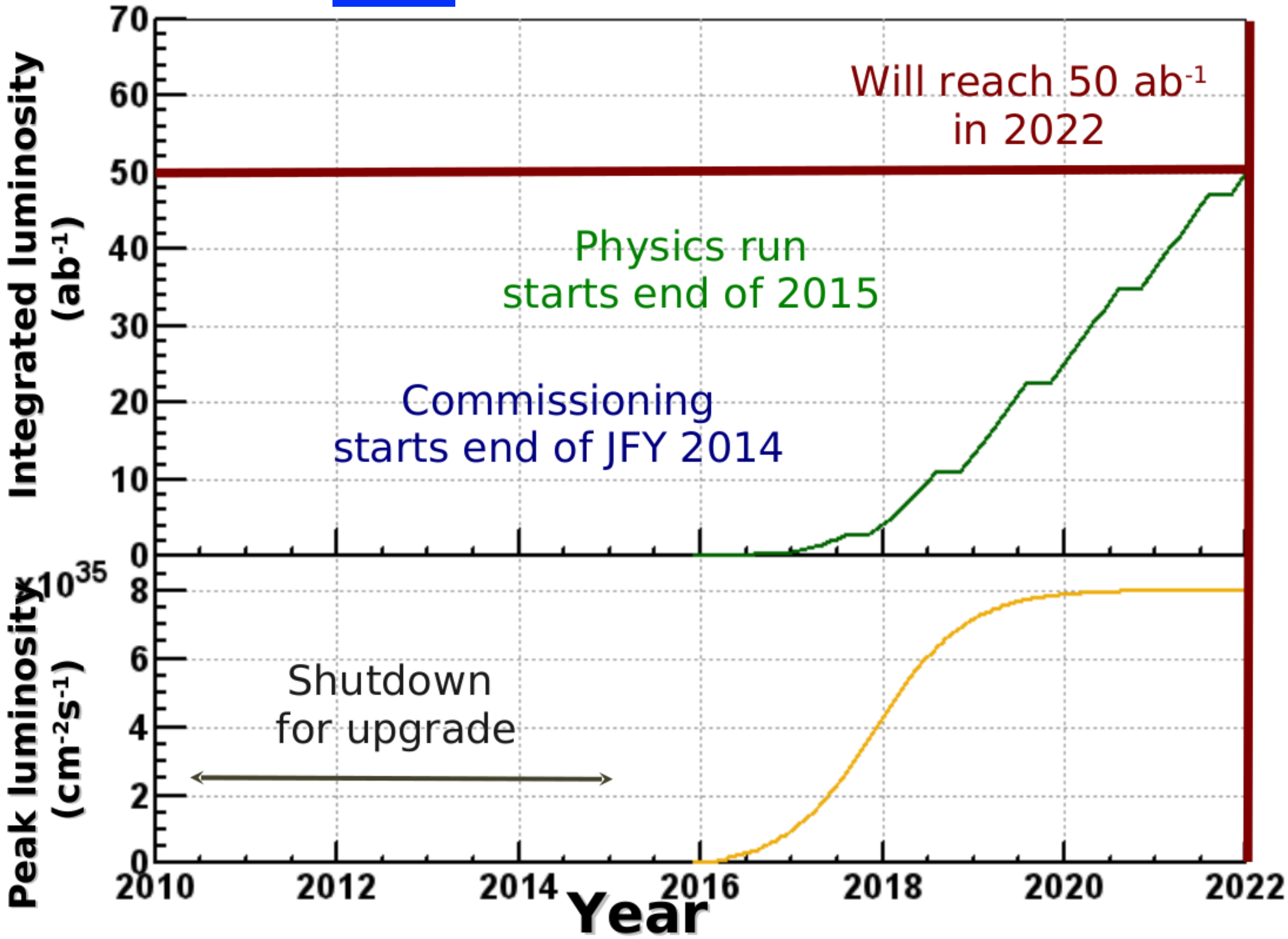
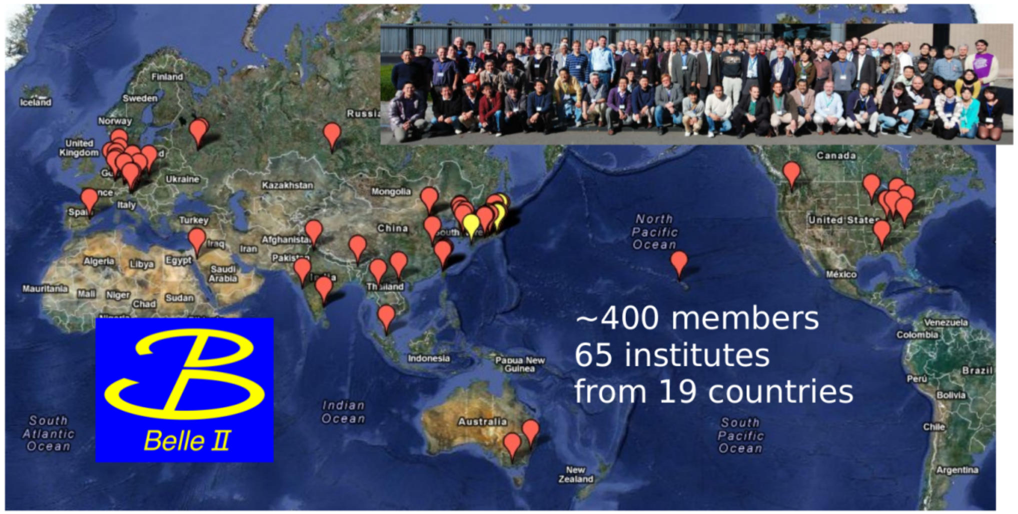
Schedule



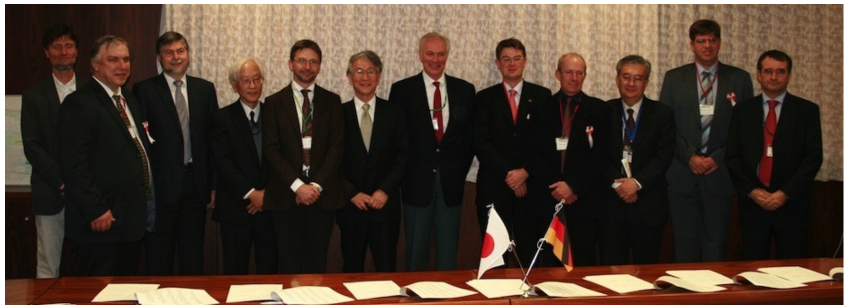
Integrated luminosity (ab-1)
70
60
50
40
30
20
10
0
Will reach 50 ab-1 in 2022
Physics run starts end of 2015
Commissioning starts end of JFY 2014
Peak luminosity (cm-2s-1)
x10^35
8
6
4
2
0
Shutdown for upgrade
2010
2012
2014
2016
2018
2020
2022
Year

International Collaboration

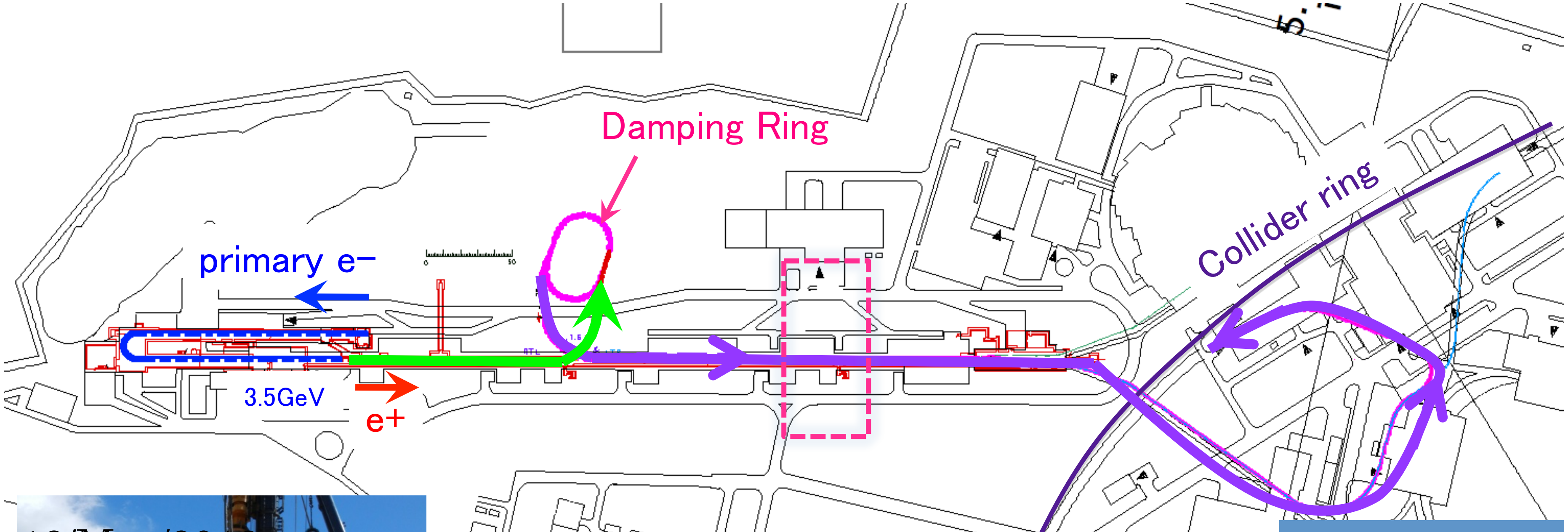


Ground breaking ceremony, November 2011

MoU with German funding agencies



Progress


Damping Ring
primary e−
3.5GeV
e+
Collider ring

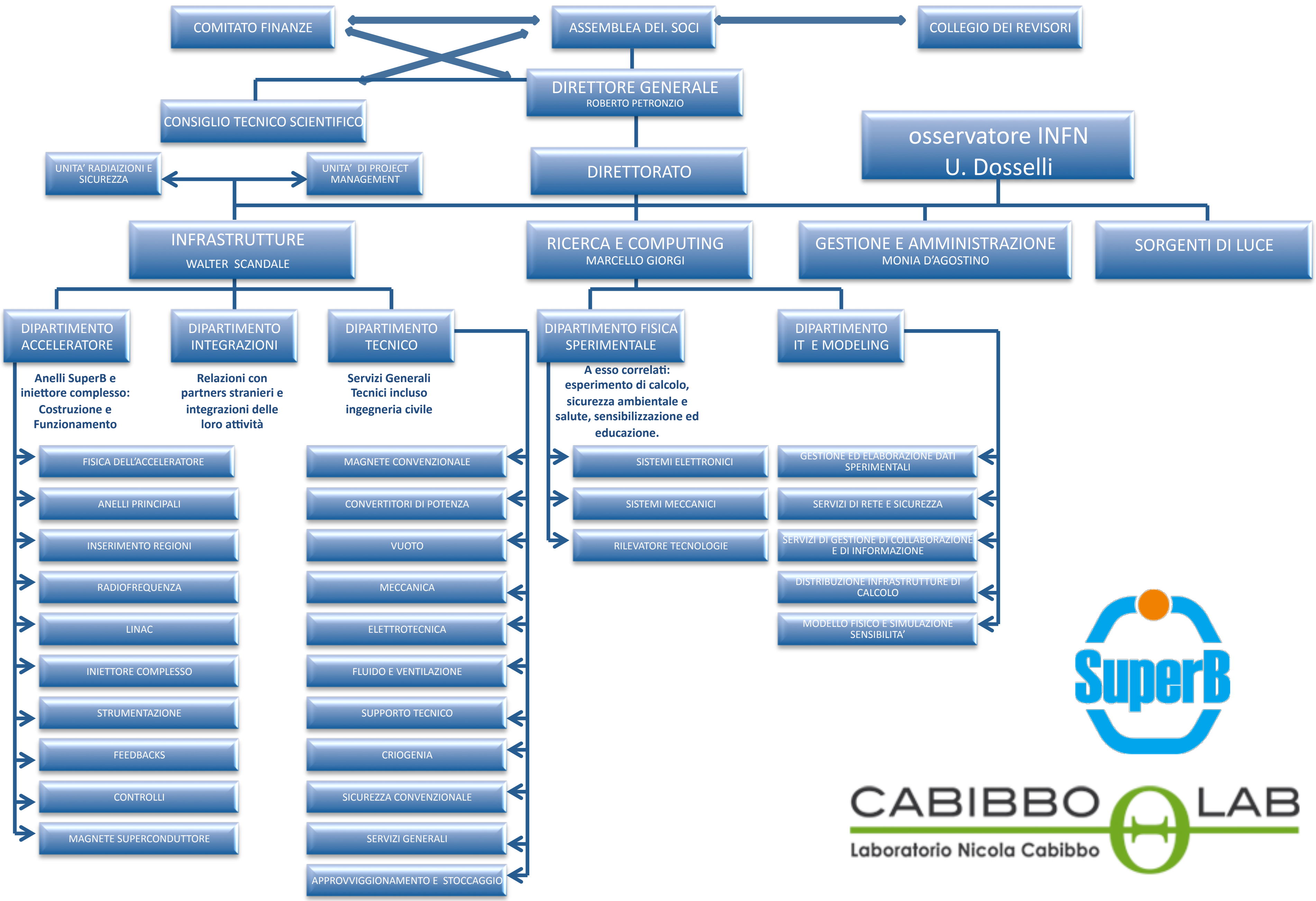

13/May/2012
LINAC


First Dipole


Quadrapole

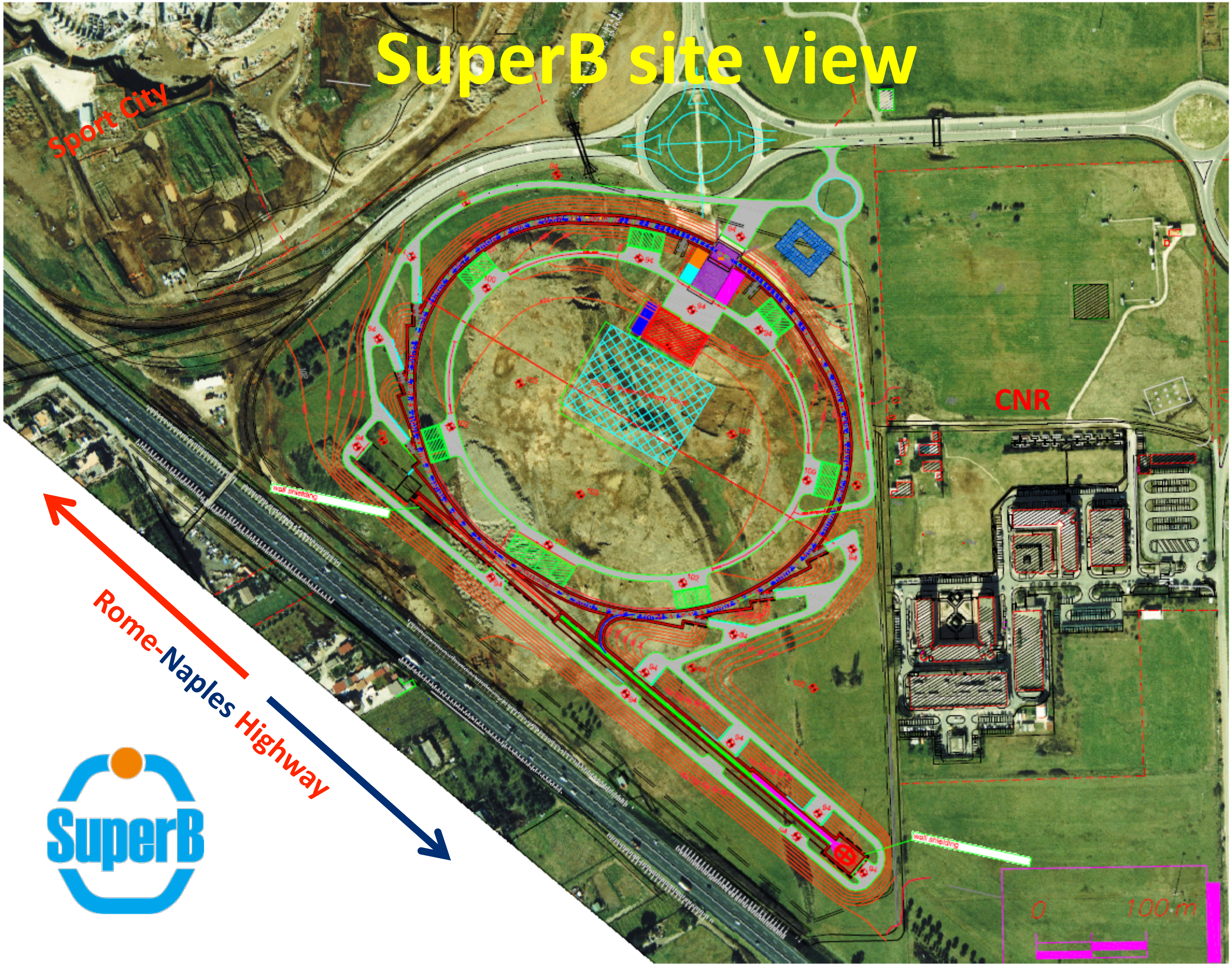
- Director general: Roberto Petronzio
  - Sub-level of area directors and responsible in place.
  - 18 engineers have been recruited at the lab.
- Several agreements already in place:
  - MOU with Novosibirsk: a strong group of machine physicists from Novosibirsk (60-80 people) to start immediately to work to Lattice engineering.
  - INFN's involvement has been approved by the board.
- Recent meeting between Cabibbo, LNF and JAI regarding planning.
  - JAI to contribute to the final focus, among other things.

Governance of the CABIBBO Lab

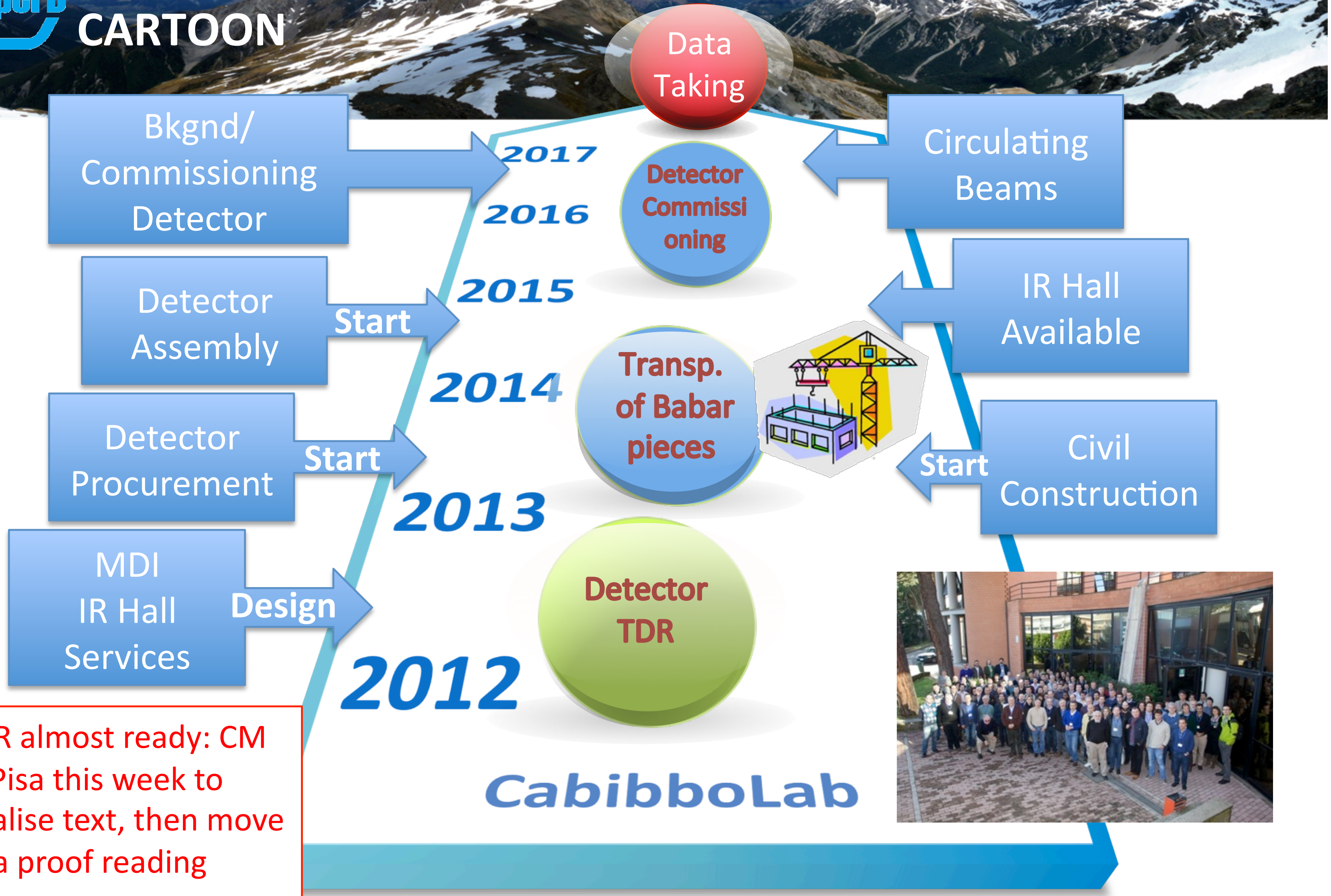


- Project was approved in December 2010.
  - The leading national flagship project.
  - 250M€ on the table, knowing the full amount was more like 550-650M€
  - This is new money to be injected into our field.
- In 2011
  - the site was chosen: Tor Vergata (May/June)
  - the collaboration was formed at QMUL (Sept)
- In 2012:
  - BINP officially signs MOU to work with Cabibbo lab.
  - TDR coming together: meeting next week (Pisa)
  - Fioni review: (to check the budget is sensible)
    - Costing finalized for Fioni committee
    - Project schedule to follow soon.

SuperB site view



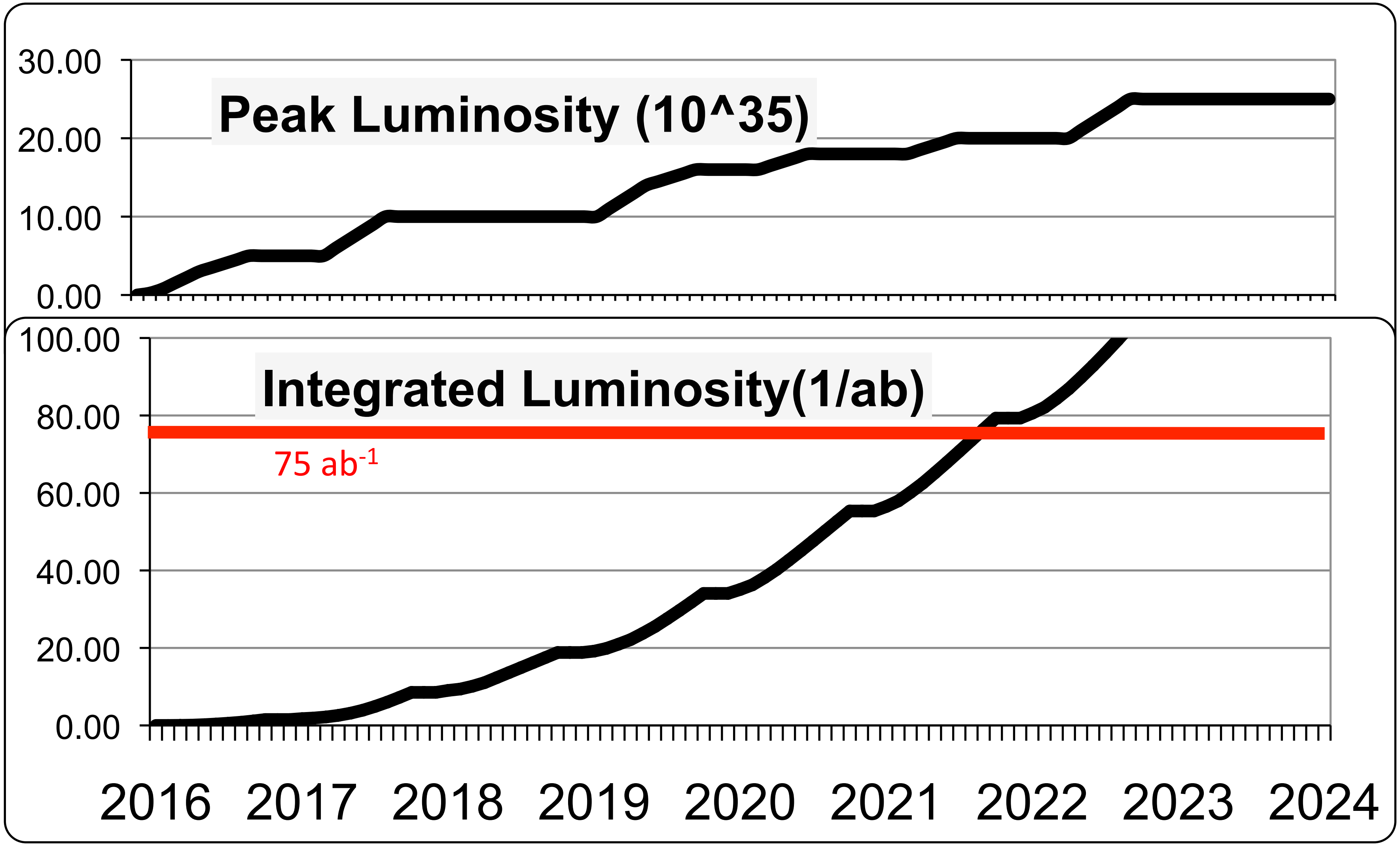
DETECTOR TIMELINE
CARTOON



TDR almost ready: CM in Pisa this week to finalise text, then move to a proof reading phase.

The Inaugural SuperB collaboration meeting: was held at QMUL in September 2011

SuperB Luminosity model

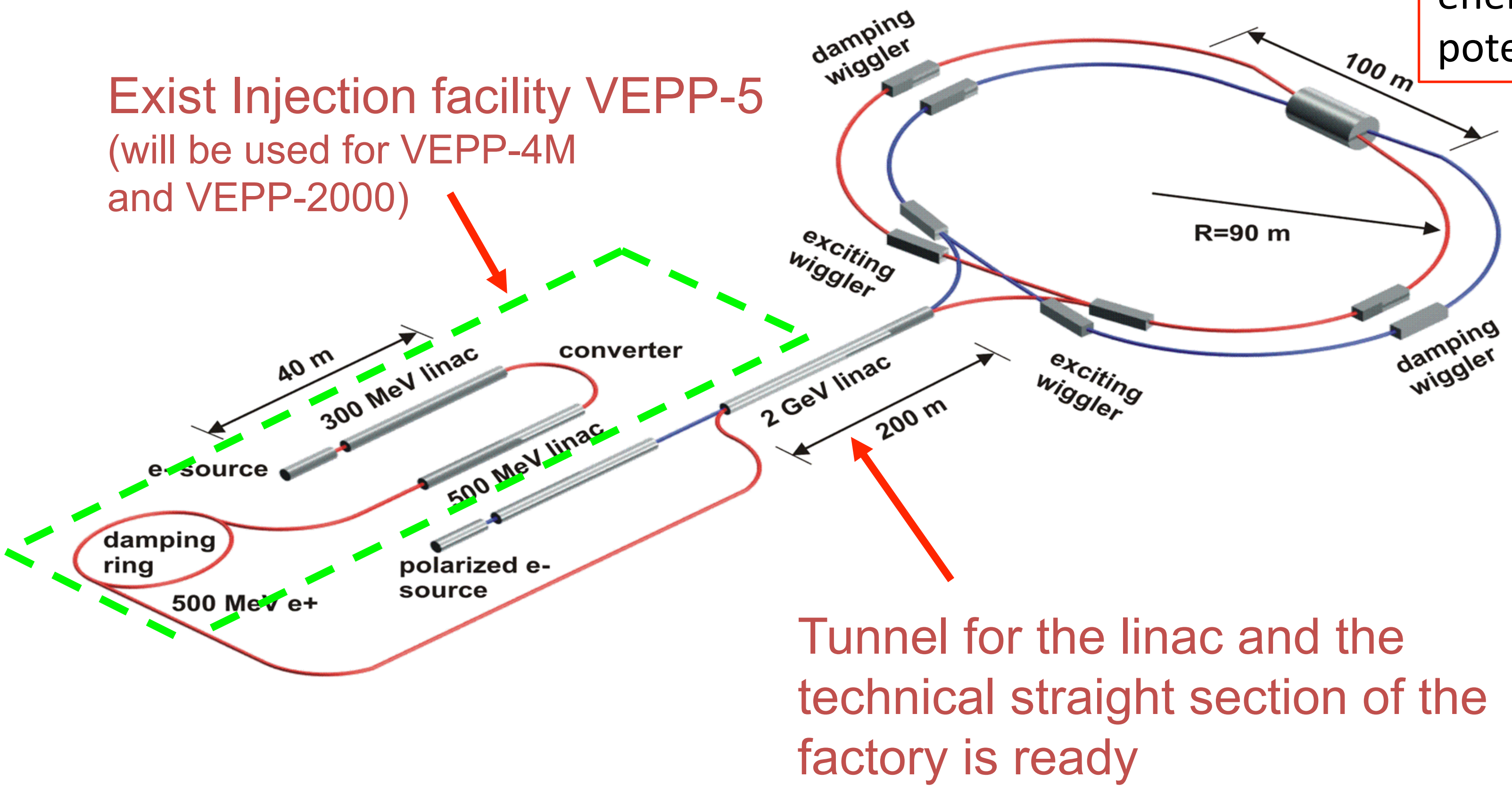


T_0 may need to shift to T_0+2.

Other future possibilities

- Proposal to build a super τ-charm factory at Novosibirsk is still on the table.

Symmetric beam energies: no TDCPV potential

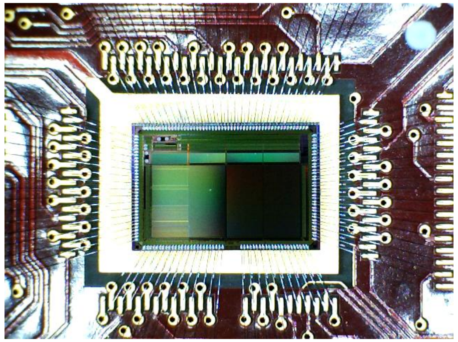


Project not yet approved, but nonetheless has an interesting potential.

Arachnid

Relevant Technology

- The UK is a world leader in CMOS sensor development for various applications.
  - Generic R&D sought after by ALICE, SuperB, ILC communities, KE opportunities, yet ***still*** no long term funding in the STFC model.



Low noise devices: reference pixels ~12e noise (RMS)
Low mass: epi layer is only 12um, ideal base for vertex detectors.
Versatile technology spanning several experiments in different areas of the STFC programme

- 180nm INMAPS CMOS technology pioneered by RAL.
- For use in vertexing, calorimetery, imaging, ...
- Working in collaboration with CERN, DESY and INFN.
- STFC and Science board should find a sensible way to maintain development of technologies like this!

Future prospects

"Minimalistic" list of the key (low-energy) quark flavor-violating observables:

✔	• γ from tree ($B \to DK$, …)	S-LHCb S-Bfactory
✔	• $\lvert V_{ub}\rvert$ from exclusive semi-leptonic B decays	S-Bfactory [SuperKEKB & SuperB]
	• $B_{s,d} \to l^+l^-$	S-LHCb + ATLAS & CMS
	• CPV in B_s mix. [ϕ_s]	S-LHCb + ATLAS & CMS
✔	• $B \to K^{(*)}\, l^+l^-$, $\nu\nu$	S-LHCb / S-Bfactory
✔	• $B \to \tau\nu$, $\mu\nu$ (+D)	S-Bfactory
	• $K \to \pi\nu\nu$	Kaon beams [NA62, KOTO, ORKA]
✔	• CPV in charm	S-LHCb / S-Bfactory

Future prospects

"Minimalistic" list of the key (low-energy) quark flavor-violating observables:

My interpretation:

Complementarity between hadron, e+e- and kaon experiments.

To cover all eventualities, we need all areas supported.

- ✔ γ fr…
- ✔ $|V_{ub}$… & SuperB]
- $B_{s,d}$…
- CPV…
- ✔ B →…
- ✔ B →…
- $K \to \pi\nu\nu$ Kaon beams [NA62, KOTO, ORKA]
- ✔ CPV in charm S-LHCb / S-Bfactory

Additional material

Top-10 list of key flavor-changing measurements [a (motivated) personal choice]

	Observable	Target
	• $B(\mu \to e\gamma)$	$SES < 10^{-13}$
	• $B(\mu N \to eN)$	$SES < 10^{-16}$
✔	• $B(\tau \to \mu\gamma)$	$SES < 10^{-9}$
	• $B(B_s \to \mu^+\mu^-)$	$\sigma_{rel} < 5\%$
	• ϕ_s	$\sigma < 0.01$
	• $B(K^+ \to \pi^+\nu\nu)$ or $B(K_L \to \pi^0\nu\nu)$	$\sigma_{rel} < 5\%$
✔	• $B(B^+ \to l^+\nu)$	$\sigma_{rel} < 5\%$
✔	• $a_{CP}(D \to \pi\pi\gamma)$	$\sigma < 0.005$
✔	• $\lvert V_{ub} \rvert$	$\sigma_{rel} < 5\%$
✔	• γ_{CKM}	$\sigma < 1^o$

N.B.: the observables are not listed in order of importance

Summary

- Strong global e^+e^- flavour community exists beyond BaBar and Belle data taking.
  - UK has a strong history with this area through BaBar and CLEO involvement.
  - Physics goals are different to those previous experiments: 100 times the data, broader programme.
  - The community was asked more than a decade ago to make a choice:
    - BaBar or LHCb – you can't have both.

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Summary

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  - The community was asked more than a decade ago to make a choice:
    - BaBar or LHCb – you can't have both.
    - In the recent past we have been asked a modern variant of this question.
  - The question is stupid and misses the point
    - We ***need*** both an involvement in an e+e- flavour experiment and LHCb upgrade: they are complimentary!

If we are *told* otherwise, then the UK is not serious about a future role in leading exploration of flavour physics

STOP

SuperB/Belle II Physics

See the following preprints for a more comprehensive overview:

Physics contribution to the ESG meeting form SuperB:
http://indico.cern.ch/contributionDisplay.py?contribId=68&confId=175067

arXiv:1109.5028 [Impact of SuperB]

arXiv:1008.1541 [SuperB Physics progress report]

arXiv:1002.5012 [Belle II Physics Programme]

+ a collection of older documents.

SuperB is finalising its detector TDR
(meeting starts tomorrow in Pisa to consolidate this).

This table concentrates on observables that SFFs can measure, with a few of the prime examples from hadron experiments to highlight that there are many things that need to be measured well.

Golden Measurements: General

Experiment:	No Result	Moderately precise	Precise	Very precise
Theory:		Moderately clean	Clean, needs Lattice	Clean

Observable/mode Luminosity	Current $\sim 1\,\text{ab}^{-1}$	LHCb (2017) $5\,\text{fb}^{-1}$	Super$B$ (2022) $75\,\text{ab}^{-1}$	LHCb upgrade $50\,\text{fb}^{-1}$	Theory	
τ Decays						
$\tau \to \mu\gamma$	[yellow]	[yellow]	[green]	[yellow]	[green]	Benefit from polarised e⁻ beam
$\tau \to e\gamma$	[yellow]	[yellow]	[green]	[yellow]	[green]	
$B_{u,d}$ Decays						
$B \to \tau\nu, \mu\nu$	[yellow]	[red]	[blue]	[red]	[blue]	very precise with improved detector
$B \to K^{(*)+}\nu\overline{\nu}$	[red]	[red]	[green]	[red]	[green]	Statistically limited: Angular analysis with >75ab^{-1}
S in $B \to K_S^0\pi^0\gamma$	[yellow]	[red]	[green]	[red]	[yellow]	Right handed currents
S (other penguin modes)	[yellow]	[yellow]	[green]	[blue]	[yellow]	SuperB measures many more modes
A_{CP} ($B \to X_s\gamma$)	[blue]	[yellow]	[green]	[yellow]	[green]	systematic error is main challenge
BR($B \to X_s\gamma$)	[blue]	[yellow]	[green]	[yellow]	[yellow]	control systematic error with data
BR($B \to X_s ll$)	[yellow]	[red]	[green]	[red]	[green]	
BR($B \to K^{(*)} ll$)	[yellow]	[blue]	[green]	[green]	[yellow]	SuperB measures e mode well, LHCb does μ
B_s Decays						
$B_s \to \mu\mu$	[red]	[blue]	[red]	[green]	[green]	
β_S from $B_s \to J/\psi\,\phi$	[red]	[blue]	[red]	[green]	[green]	
$B_s \to \gamma\gamma$	[red]	[red]	[blue]	[red]	[green]	
a_{sl}	[red]	[blue]	[green]	[green]	[green]	
D Decays						
Mixing parameters	[yellow]	[blue]	[green]	[green]	[green]	
CP Violation	[red]	[blue]	[green]	[green]	[green]	Clean NP search
Precision Electroweak						
$\sin^2\theta_W$ at $\Upsilon(4S)$	[red]	[red]	[green]	[red]	[green]	Theoretically clean
$\sin^2\theta_W$ at Z-Pole	[green]	[blue]	[red]	[green]	[yellow]	b fragmentation limits interpretation

This table concentrates on observables that SFFs can measure, with a few of the prime examples from hadron experiments to highlight that there are many things that need to be measured well.

Golden Measurements: CKM

- Comparison of relative benefits of SuperB (75ab^{-1}) vs. existing measurements and LHCb (5fb^{-1}) and the LHCb upgrade (50fb^{-1}).

Observable/mode Luminosity	Current $\sim 1\,\mathrm{fb}^{-1}$	LHCb (2017) $5\,\mathrm{fb}^{-1}$	Super$B$ (2022) $75\,\mathrm{ab}^{-1}$	LHCb upgrade $50\,\mathrm{fb}^{-1}$	Theory
α					
β from $b \to c\bar{c}s$					
$B_d \to J/\psi \pi^0$					
$B_s \to J/\psi K_S^0$					
γ					
$\lvert V_{ub}\rvert$ inclusive					
$\lvert V_{ub}\rvert$ exclusive					
$\lvert V_{cb}\rvert$ inclusive					
$\lvert V_{cb}\rvert$ exclusive					

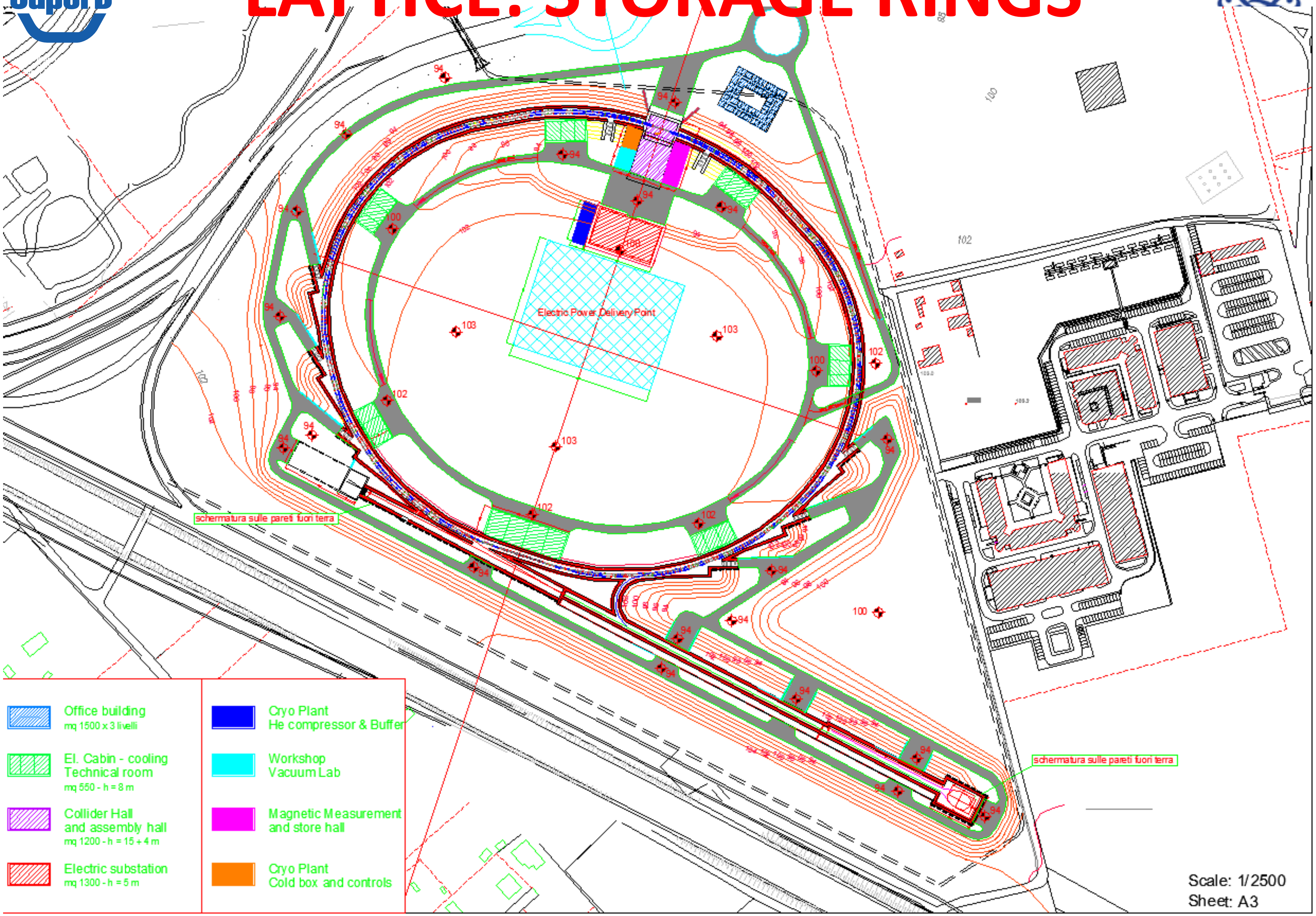
LHCb can only use ρπ

βtheory error B_d
βtheory error B_s

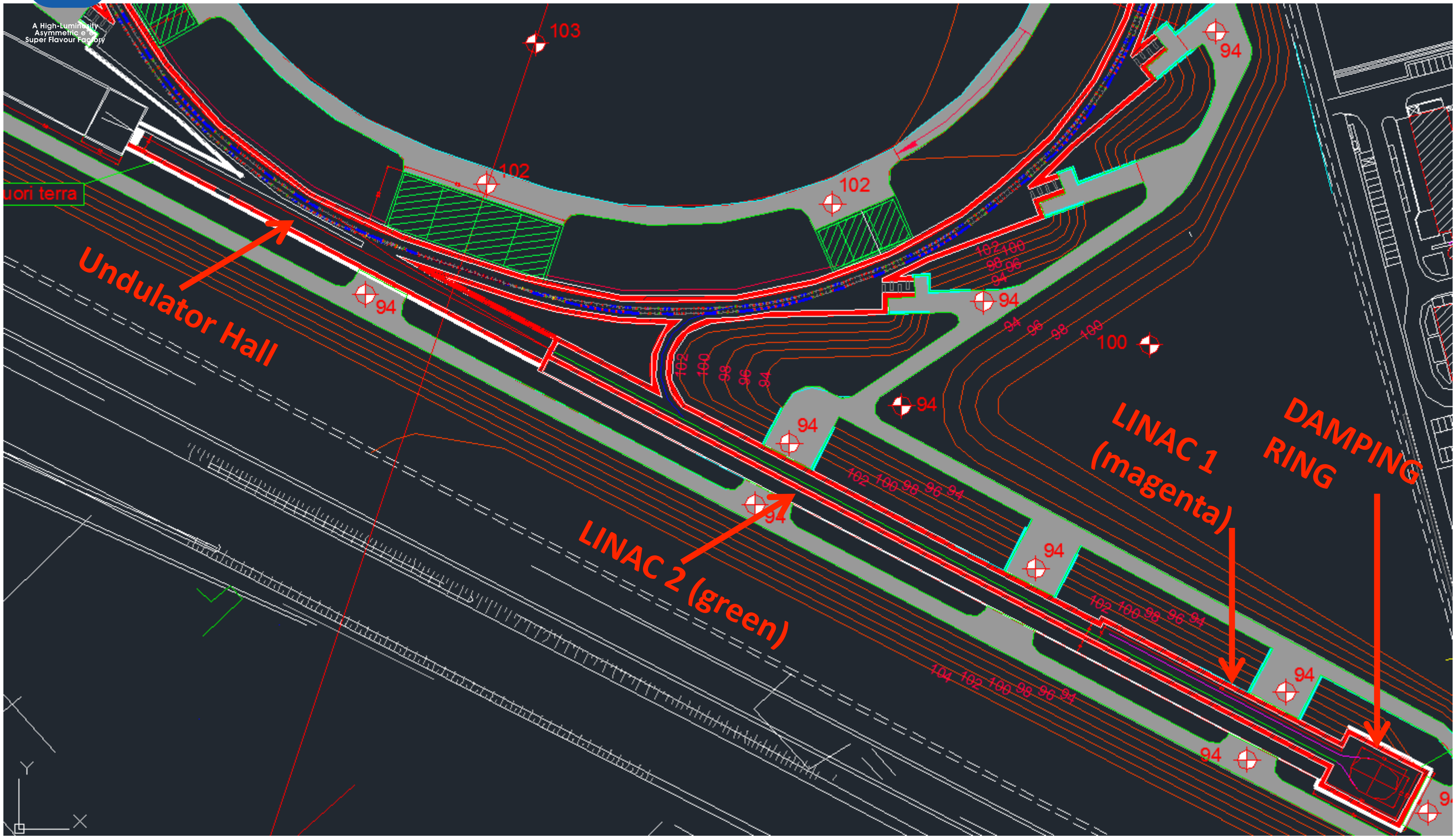
Need an e^+e^- environment to do a precision measurement using semi-leptonic B decays.

Experiment:	No Result	Moderately precise	Precise	Very precise
Theory:		Moderately clean	Clean, needs Lattice	Clean

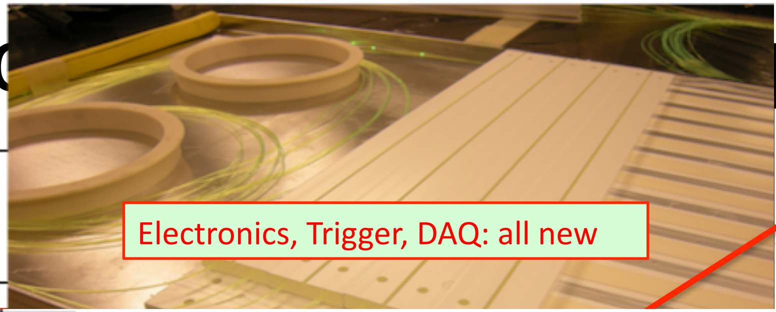
LATTICE: STORAGE RINGS



LINACs and Transfer Lines



Detec… ptions)



Electronics, Trigger, DAQ: all new

IFR: Replace LSST with scintillator + WLS Fibers + SiPM

Solenoid

PID: Focu
Reuse qu
New Ligh

EMC: Opti
Pb / Scinti

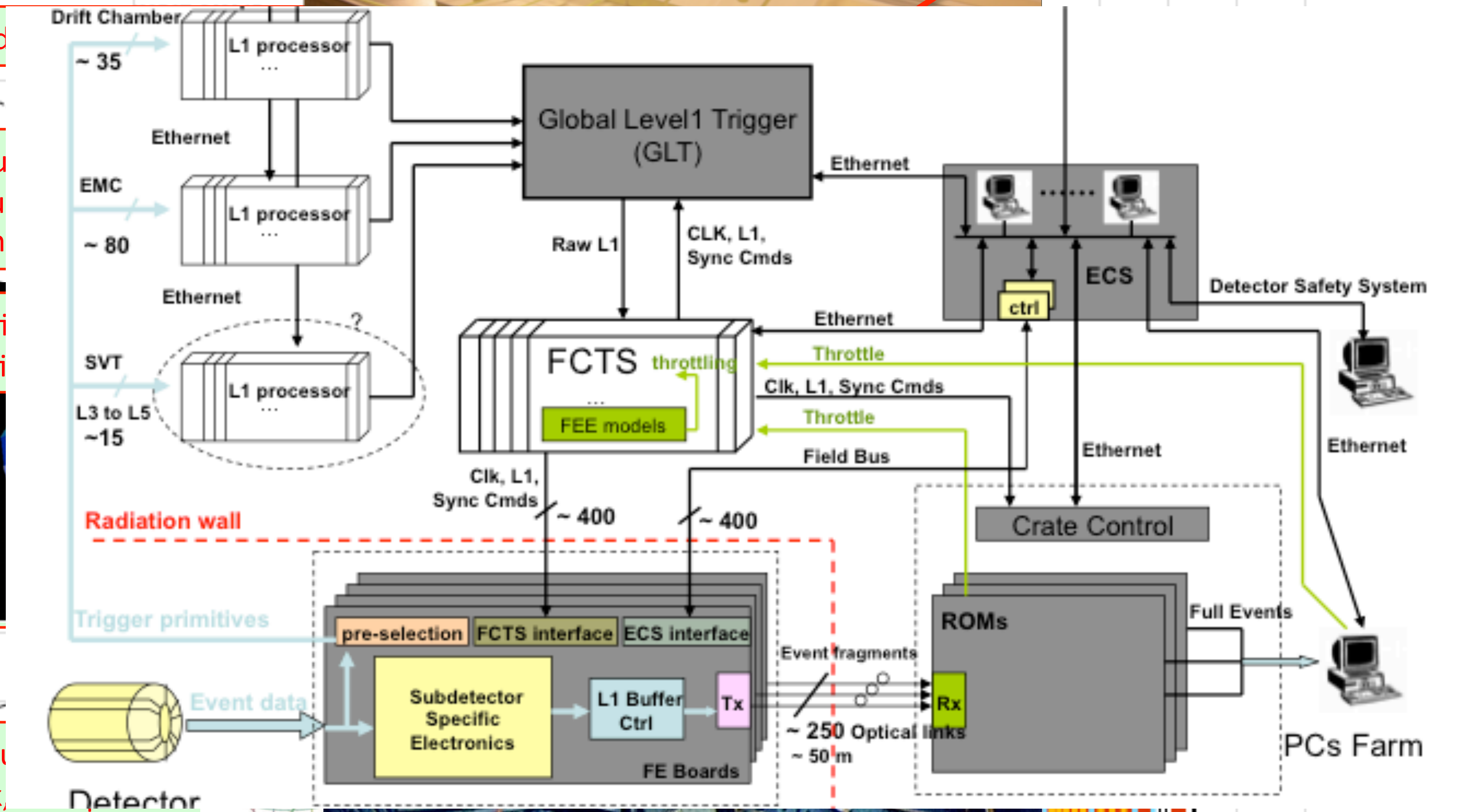
SVT: Fiv
strips +

Backgrou
Toushek,

)barrel with

d, faster

aster



THE FLAVOUR PROBLEMS

FERMION MASSES

What is the rationale hiding behind the spectrum of fermion masses and mixing angles (our “**Balmer lines**” problem)

→ **LACK OF A FLAVOUR “THEORY”**

(new flavour – horizontal symmetry, radiatively induced lighter fermion masses, dynamical or geometrical determination of the Yukawa couplings, …?)

FCNC

Flavour changing neutral current (FCNC) processes are suppressed.

In the SM two nice mechanisms are at work: the **GIM mechanism** and the structure of the **CKM mixing matrix.**

How to cope with such delicate suppression if the there is new physics at the electroweak scale?

From a closer look

UTfit

From the UTA (excluding its exp. constraint) → Prediction

	Prediction	Measurement	Pull
$\sin 2\beta$	0.81 ± 0.05	0.680 ± 0.023	2.4 ←
γ	$68° \pm 3°$	$76° \pm 11°$	<1
α	$88° \pm 4°$	$91° \pm 6°$	<1
$\|V_{cb}\| \cdot 10^3$	42.3 ± 0.9	41.0 ± 1.0	<1
$\|V_{ub}\| \cdot 10^3$	3.62 ± 0.14	3.82 ± 0.56	<1
$\varepsilon_K \cdot 10^3$	1.96 ± 0.20	2.23 ± 0.01	1.4 ←
$BR(B \to \tau \nu) \cdot 10^4$	0.82 ± 0.08	1.67 ± 0.30	-2.7 ←

TARANTINO 2012

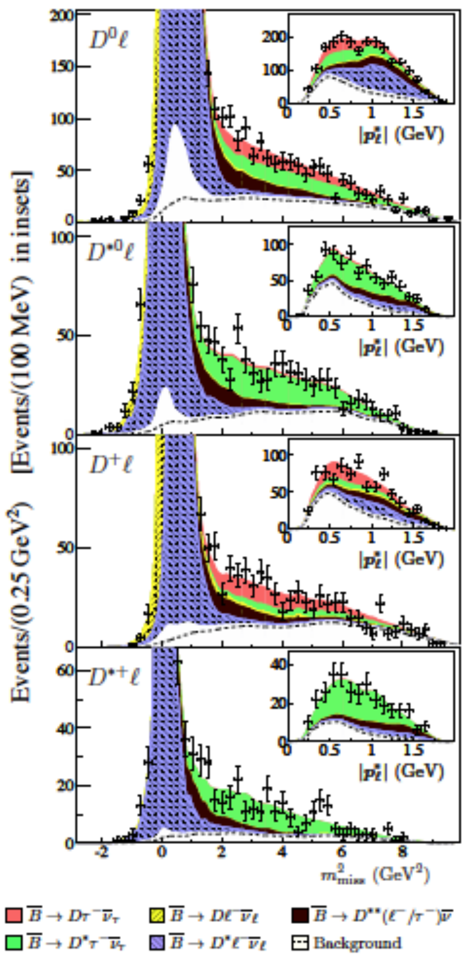
Which are the sources of flavor symmetry breaking accessible at low energies?

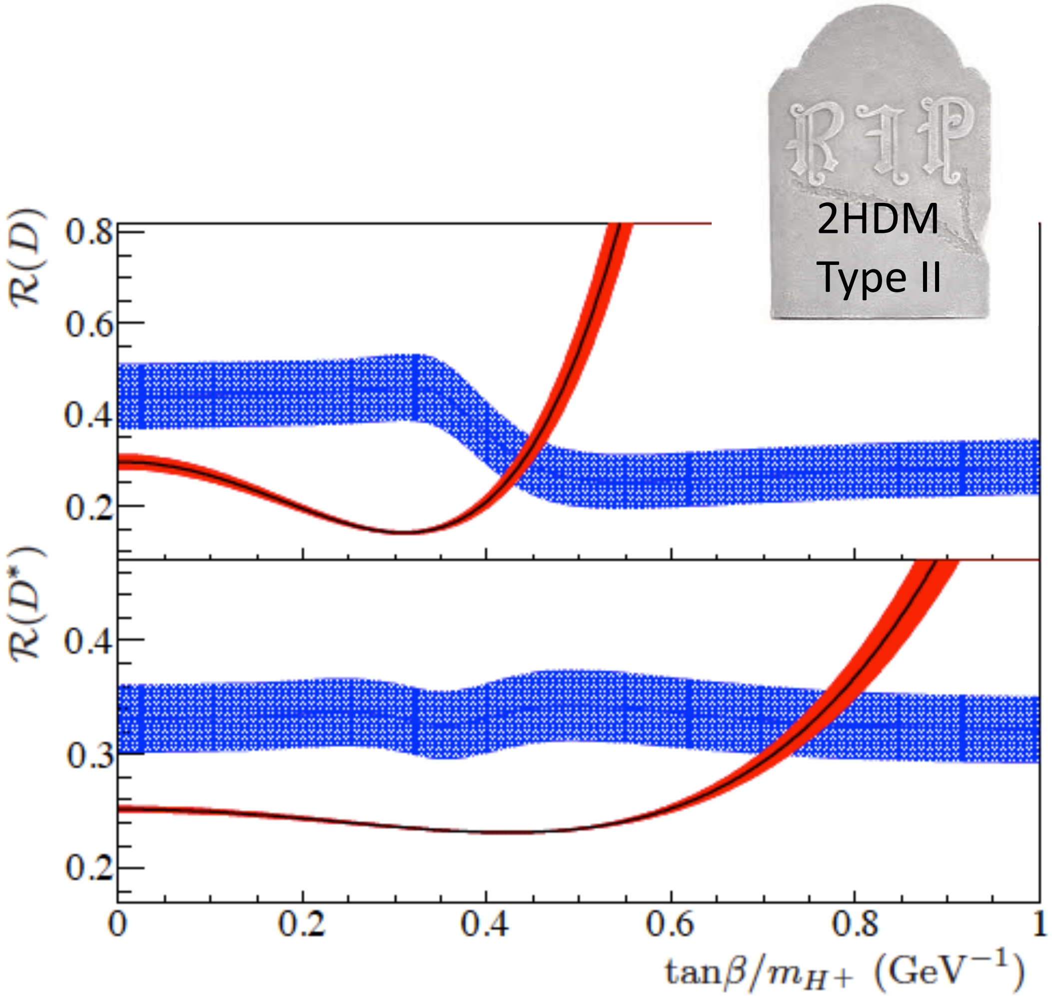
$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM+\nu} + \frac{c_{\rm NP}}{\Lambda^2} O_{ij}^{(6)}$$

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

New flavor-breaking sources at the TeV scale (if any) are highly tuned arXiv:1205.5442 (BaBar) B→D*τν

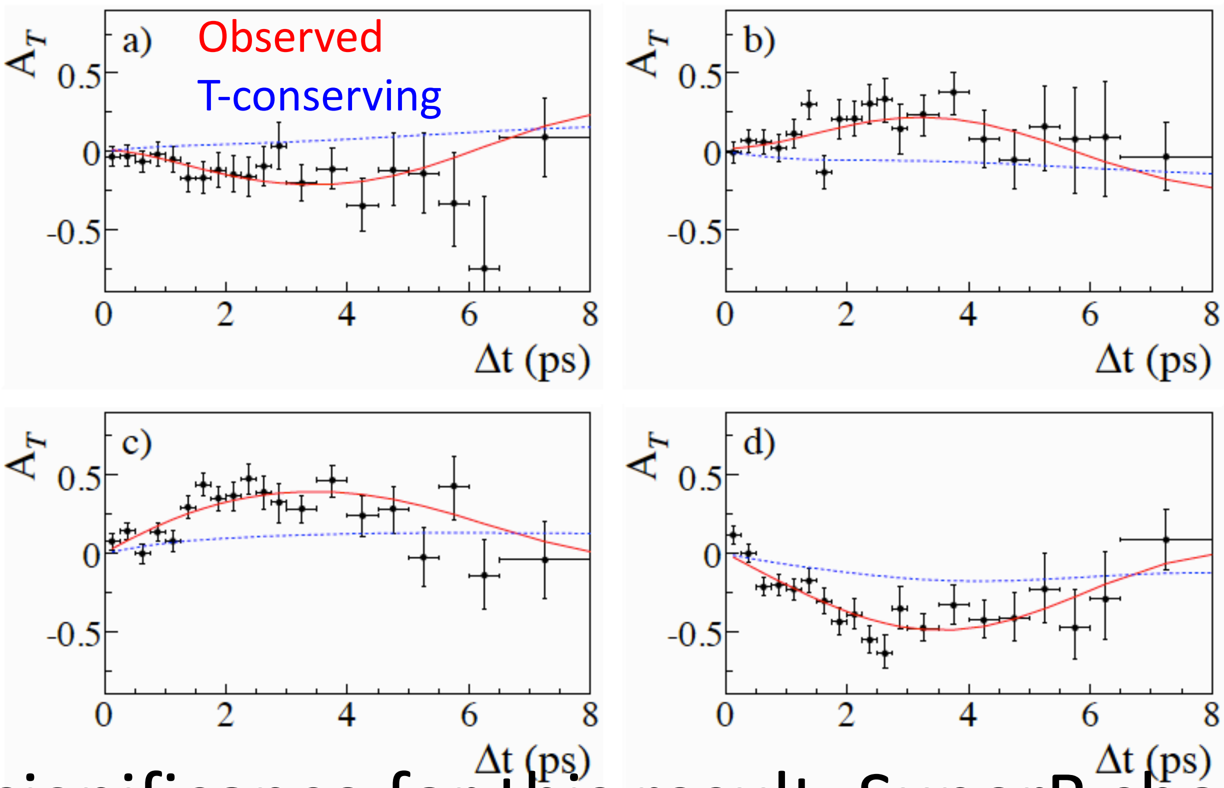
- Measure a ratio of modes to reduce theoretical dependence of constraint.
- 2D fit, using E_{extra} in an MVA that has a loose cut on it to minimise systematic impact on result.





T Violation

- BaBar showed results at FPCP



Compatible with sin2β results on CPV and with CPT

- 14σ significance for this result: SuperB should confirm this measurement with high precision.
  - Part of our symmetry testing programme.

DIRECT CPV IN $D^0 \to \pi^+\pi^-, K^+K^-$

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

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

2012: fom CDF, 9.6 fb^{-1}, + LHCb + BELLE

$$\Delta A_{CP} \equiv A_{CP}\left(K^+K^-\right) - A_{CP}\left(\pi^+\pi^-\right) = \left(-0.74 \pm 0.15\right)\%$$

This result demands an enhancement of the suppressed CKM amplitudes of the SM of a factor approx. 5 – 10 Isidori, Kamenik, Ligeti, Perez 2011

But the charm quark is ***TOO HEAVY*** to apply the ChPT, while, at the same time, it is ***TOO LIGHT*** to trust the Heavy Quark Effective approach : ***HENCE IT IS NOT IMPOSSIBLE THAT THE SM IS ONCE AGAIN FINDING A WAYOUT TO SURVIVE!*** Golden, Grinstein 1989; Brod, Kagan, Zupan 2011

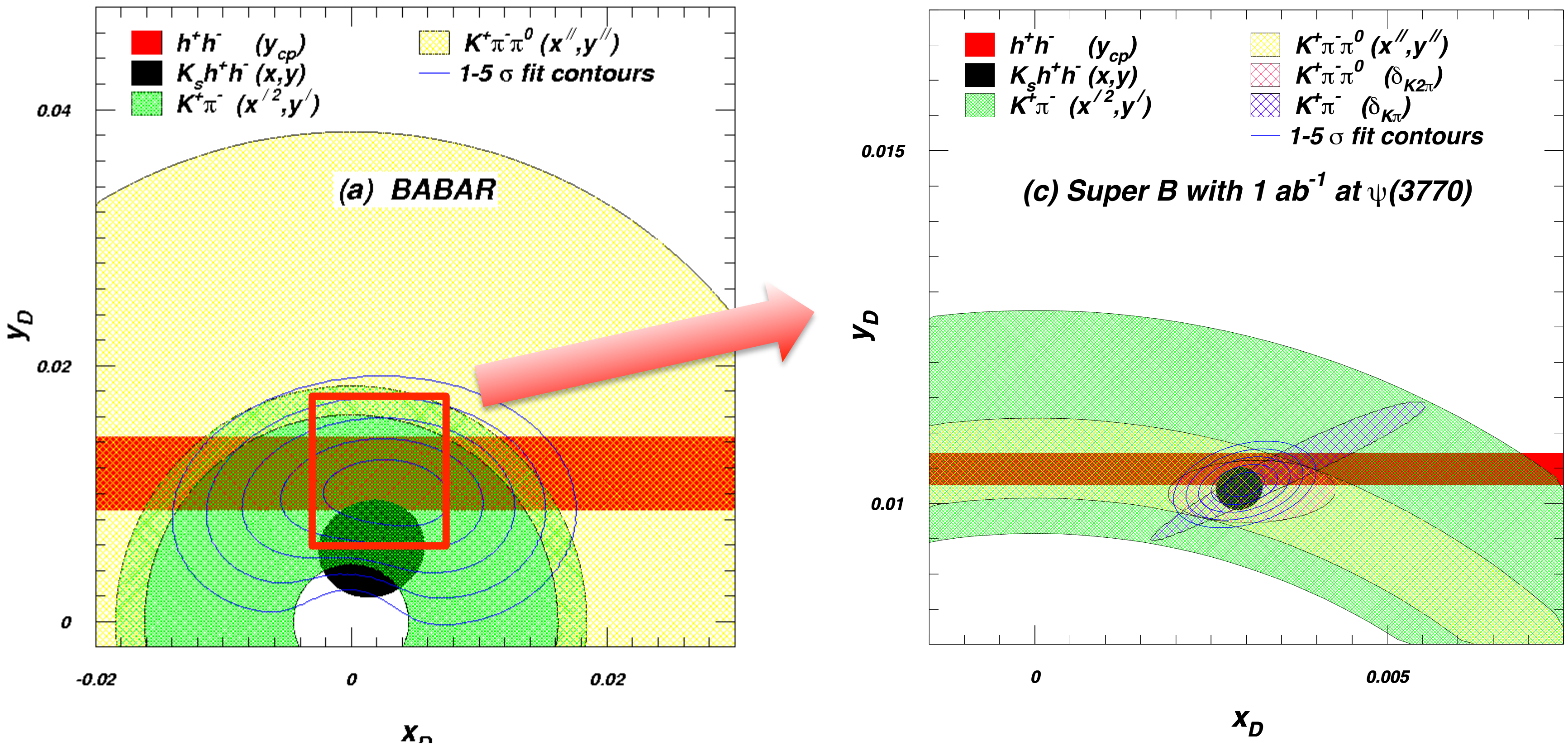
ON THE OTHER IT REMAINS POSSIBLE THAT NEW PHYSICS IS SHOWING UP... Giudice, Isidori, Paradisi 2012; Barbieri, Buttazzo, Sala e Straub 2012

POSSIBLE SURPRISES FROM THE KAON TOO → NA62 ?

- Ikaros Bigi has told us many times that we need to test CP violation in the up-quark sector.
  - LHCb have paved the way with a deviation from expectation ($D^0 \rightarrow KK/\pi\pi$).
  - Belle also see a CP effect ($D^+ \rightarrow K_S pi^+$).
  - These are direct CPV measurements. "*Binary test of the SM*"
- The experimental community is slowly coming round to the fact that hadronic uncertainties are important.
- We need to:
  - Do time-dependent measurements (indirect CPV is clean[ish])
  - Measure sets of channels to constrain hadronic uncertainties.
  - e.g. a long list of things to do here: $D^0 \rightarrow \pi^+\pi^0$, ...

Charm Mixing Update

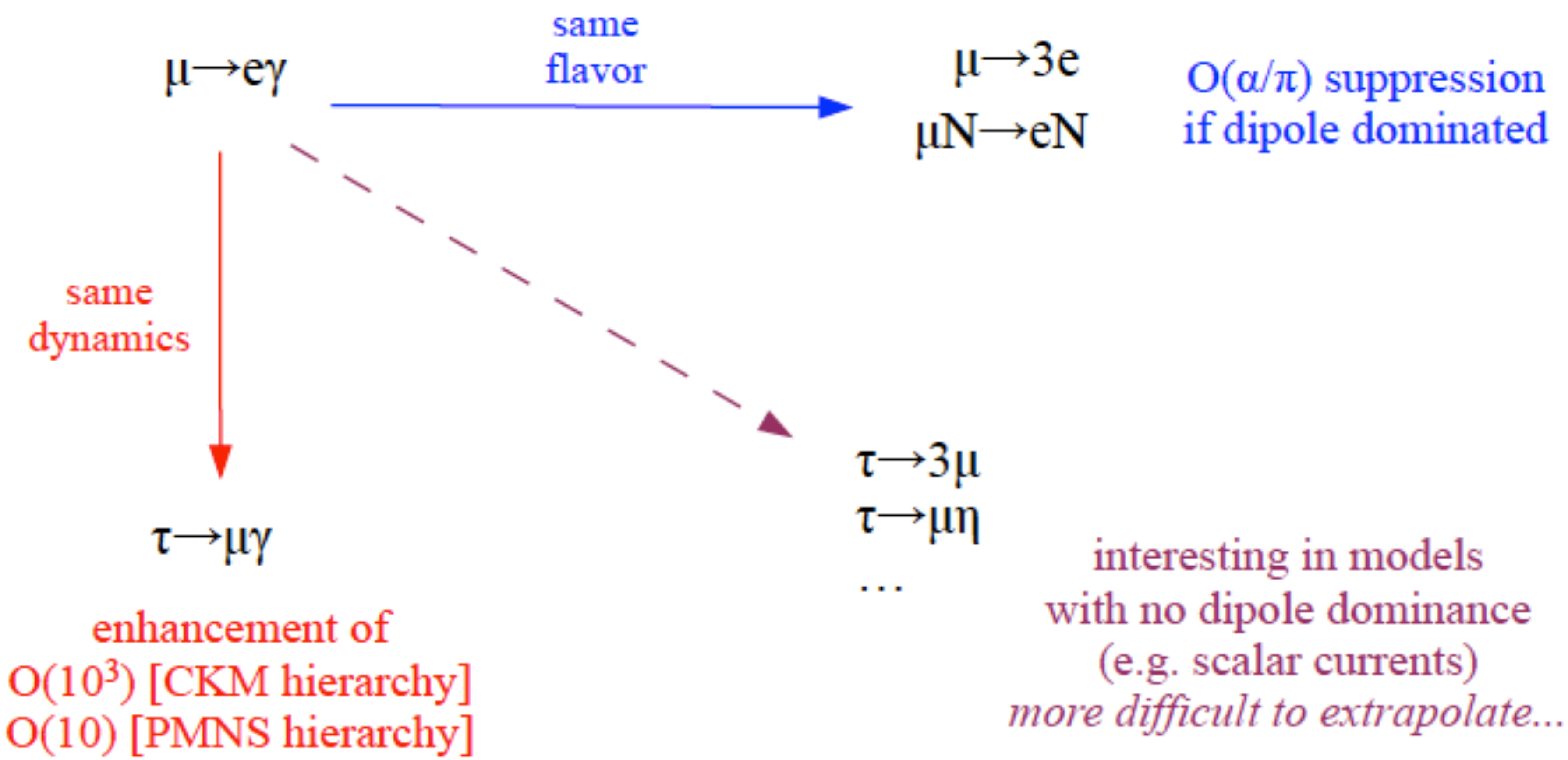
- Now assume $1ab^{-1}$ at $\psi(3770)$.



- Updated plots now available in the TDR.
- $K_S$hh Dalitz plot contribution helps shrink overall syst. error

* The key role of LFV and EDMs

The recent MEG bound, $BR(\mu\to e\gamma) < 2.4\times10^{-12}$, and its final sensitivity ($\sim10^{-13}$), can be taken as reference values to estimate potentially interesting levels for future LFV searches in different channels:



⁎ *The key role of LFV and EDMs*

The recent MEG bound, $BR(\mu\to e\gamma) < 2.4\times10^{-12}$, and its final sensitivity ($\sim10^{-13}$), can be taken as reference values to estimate potentially interesting levels for future LFV searches in different channels:

$\mu\to e\gamma$

$< 2\times10^{-12}$

same flavor

$\mu\to 3e$

$\mu N\to eN$

$O(\alpha/\pi)$ suppression
if dipole dominated

$\lesssim 10^{-14}$

same dynamics

$\tau\to\mu\gamma$ $\lesssim 4\times10^{-9}$

enhancement of
$O(10^3)$ [CKM hierarchy]
$O(10)$ [PMNS hierarchy]

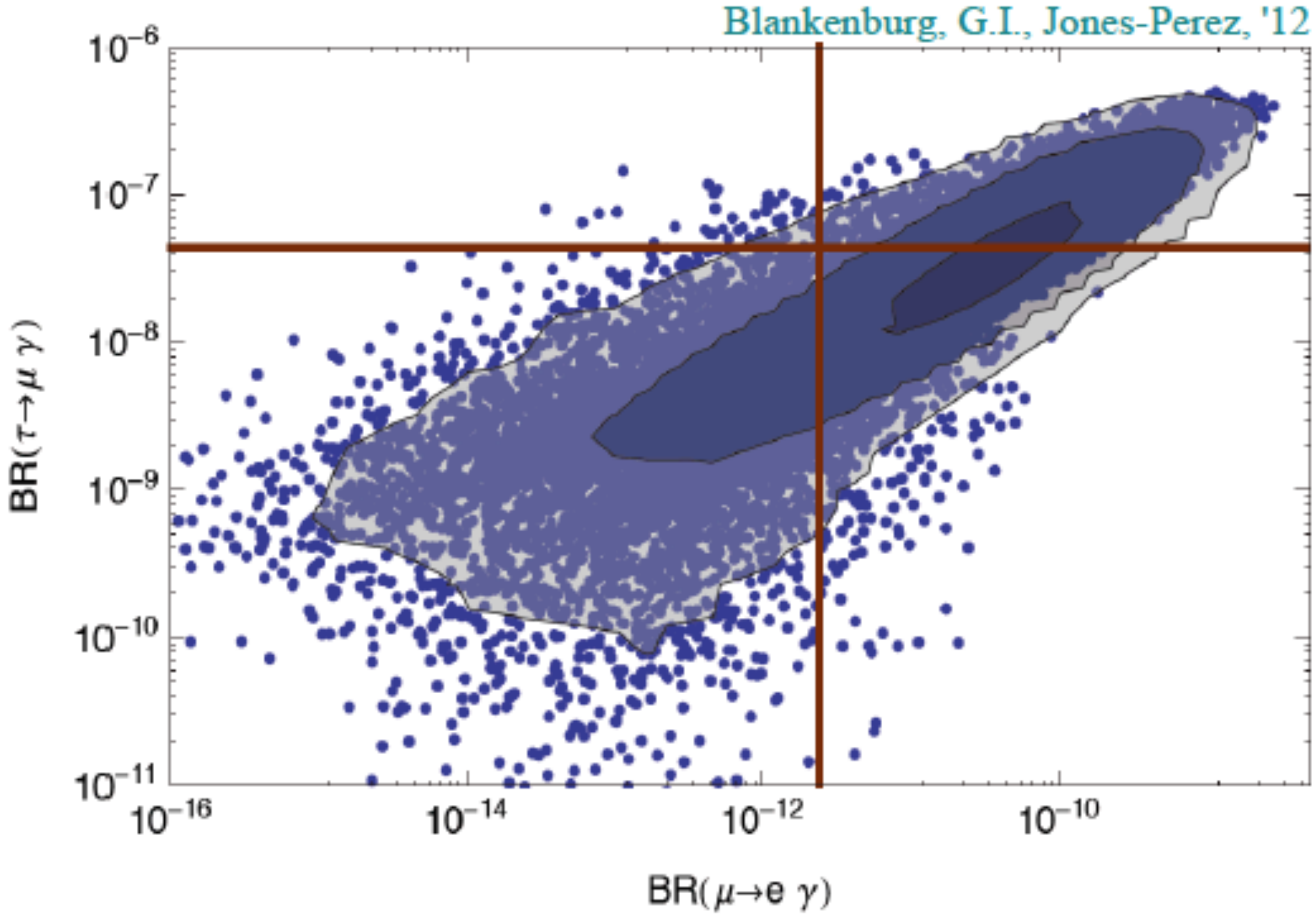
Key observables & planned exp. Limits:

- $\mu\to e\gamma$ 5×10^{-14} [PSI/MEG-II]
- $\mu\to 3e$ 10^{-16} [PSI/μ3e]
- $\mu N\to eN$ $10^{-15}\to10^{-18}$ [JPARC/COMET]; $10^{-15}\to10^{-18}$ [FNAL/Mu2e]
- $\tau\to\mu\gamma$ 2×10^{-9} [S-Bfactory ($50ab^{-1}$)]
- $\tau\to 3\mu$ 10^{-9}-10^{-10} [S-Bfact., S-LHCb]

⋆ *The key role of LFV and EDMs*

...and there is no doubt that if MEG will see a positive signal, then all other LFV searches would be extremely important to understand the nature of the effect.

E.g.: SUSY with minimally broken $U(3)^5$



Tau physics from a hadron machine

- LHCb showed some nice preliminary results on $\tau \to 3\mu$

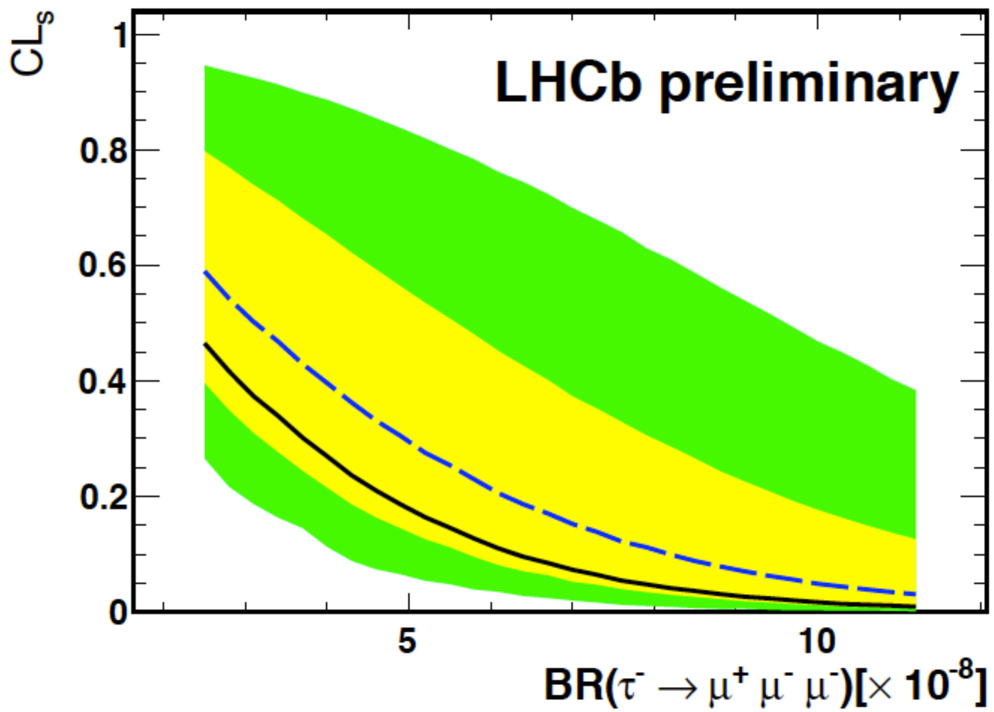
$$\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^-) < 6.3 \times 10^{-8} \text{ at } 90\% \text{ CL},$$
$$\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^-) < 7.8 \times 10^{-8} \text{ at } 95\% \text{ CL}.$$

- 3 times *worse* limit than the B Factories using 1fb-1 of data.

- Background plays a role, so one has to take care extrapolating limits.

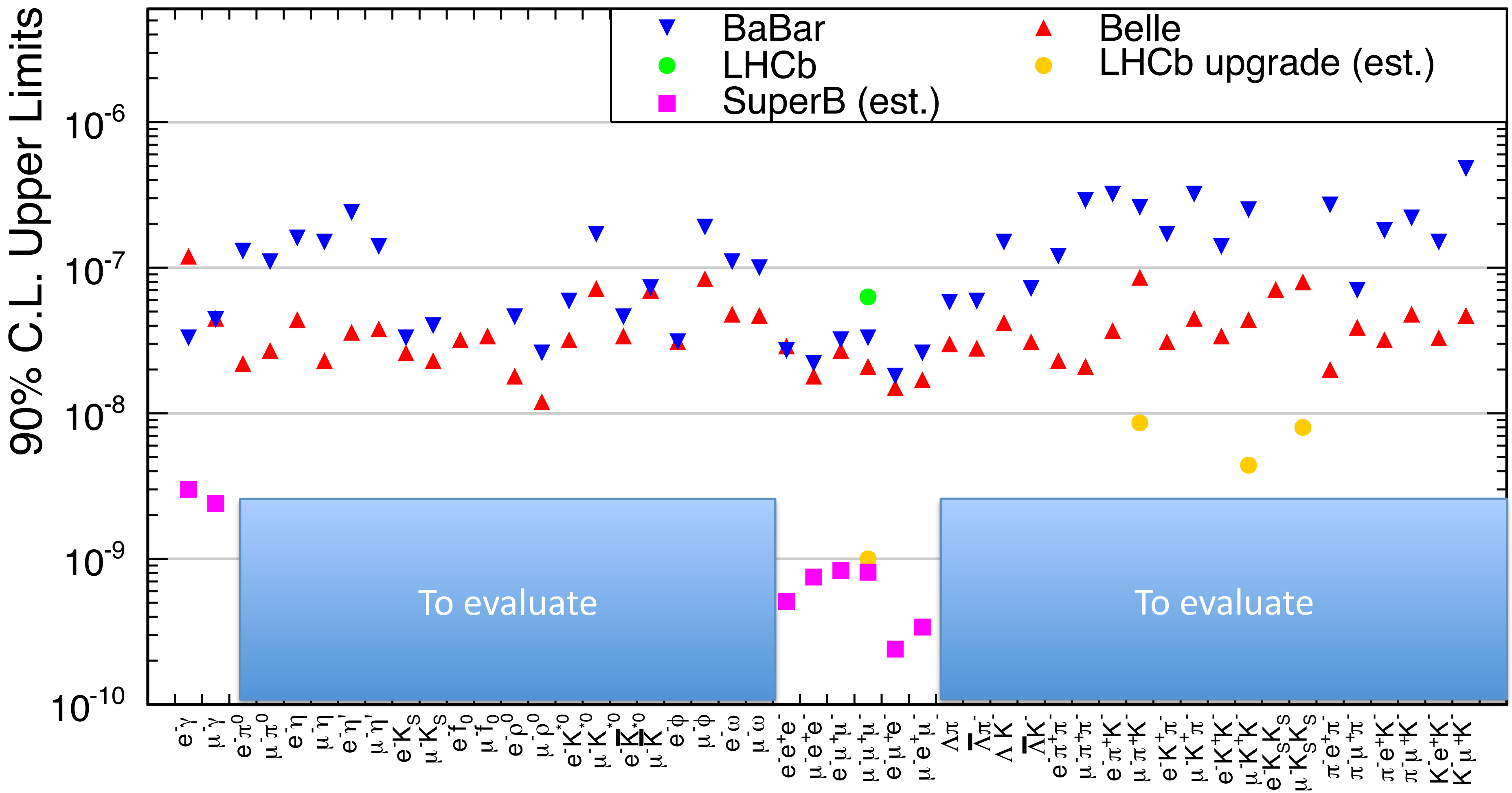
- Expect some improvement in method when extrapolating beyond this level.

- See LHCb-CONF-2012-015



(personal opinion: Unfortunately LHCb succumbed to using CLs)

τ LFV



90% C.L. Upper Limits
BaBar
Belle
LHCb
LHCb upgrade (est.)
SuperB (est.)
To evaluate
To evaluate