The Belle II Experiment at SuperKEKB

- Motivation
- SuperKEKB / Belle II Upgrade
- DESY contributions

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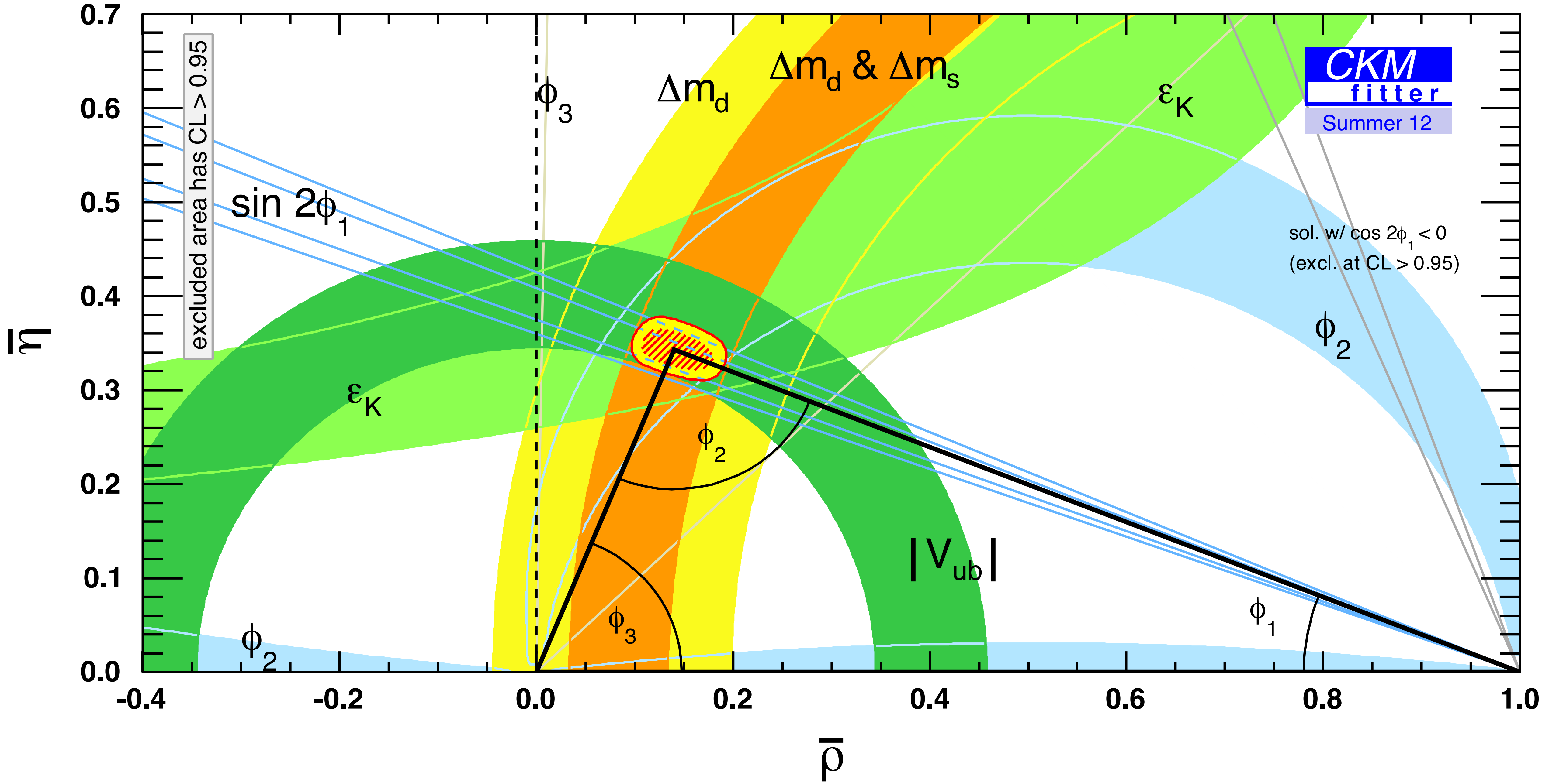
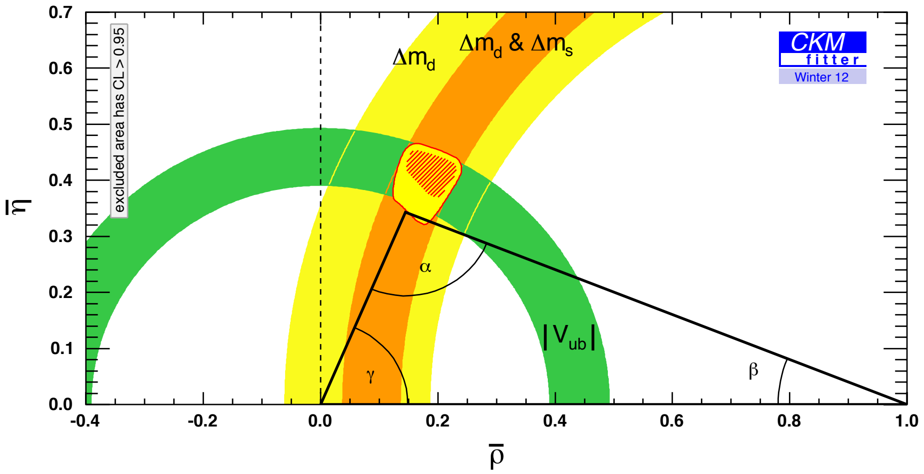
Current Constraints on Unitarity Triangle

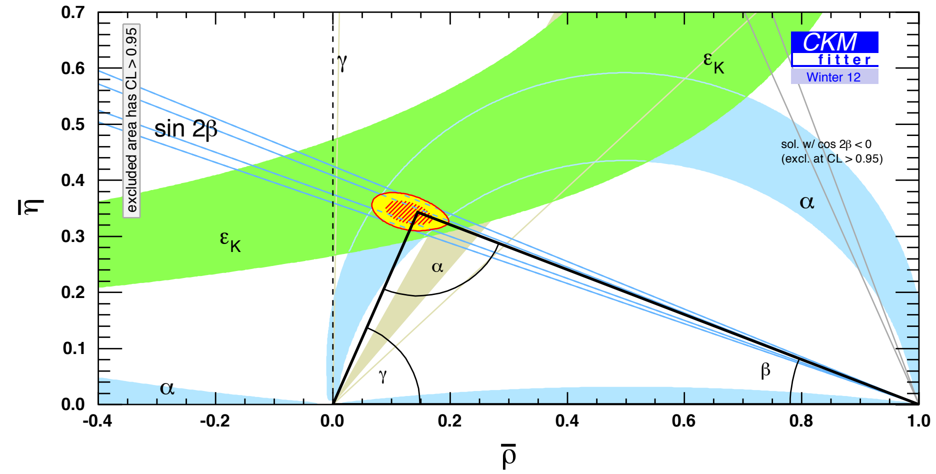


- Good consistency of all measurements and their agreement with CP violation in $K^0 - \overline{K}^0$ mixing, ε_K, and with SM predictions
- Spectacular confirmation of CKM model as dominant source of flavour and CP violation

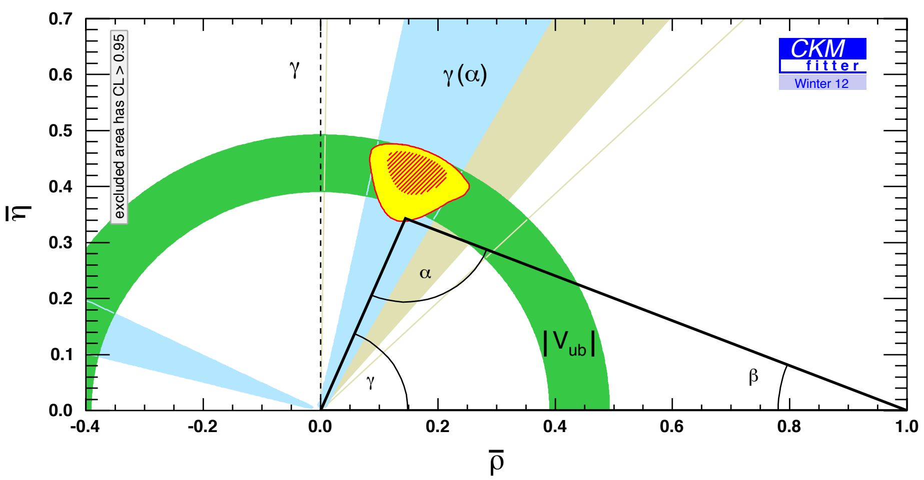
Consistency of Different Determinations



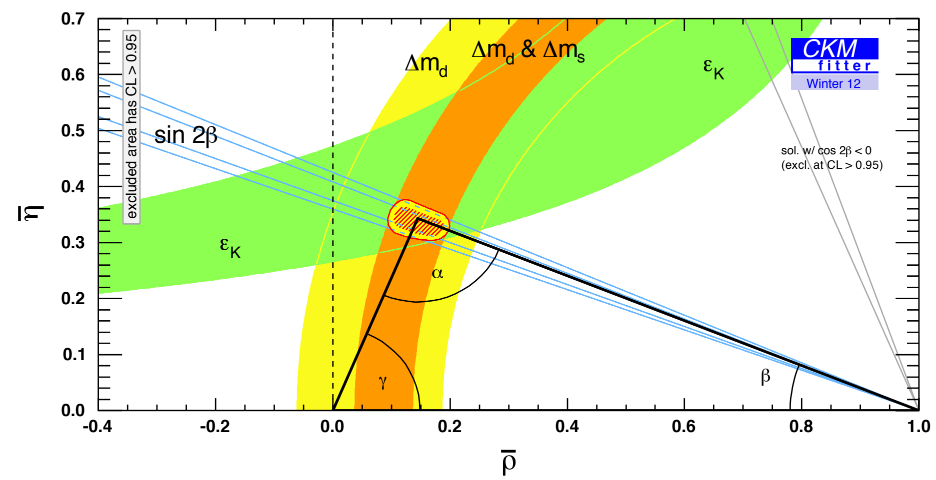
CP allowed only



CP violating only



Tree only

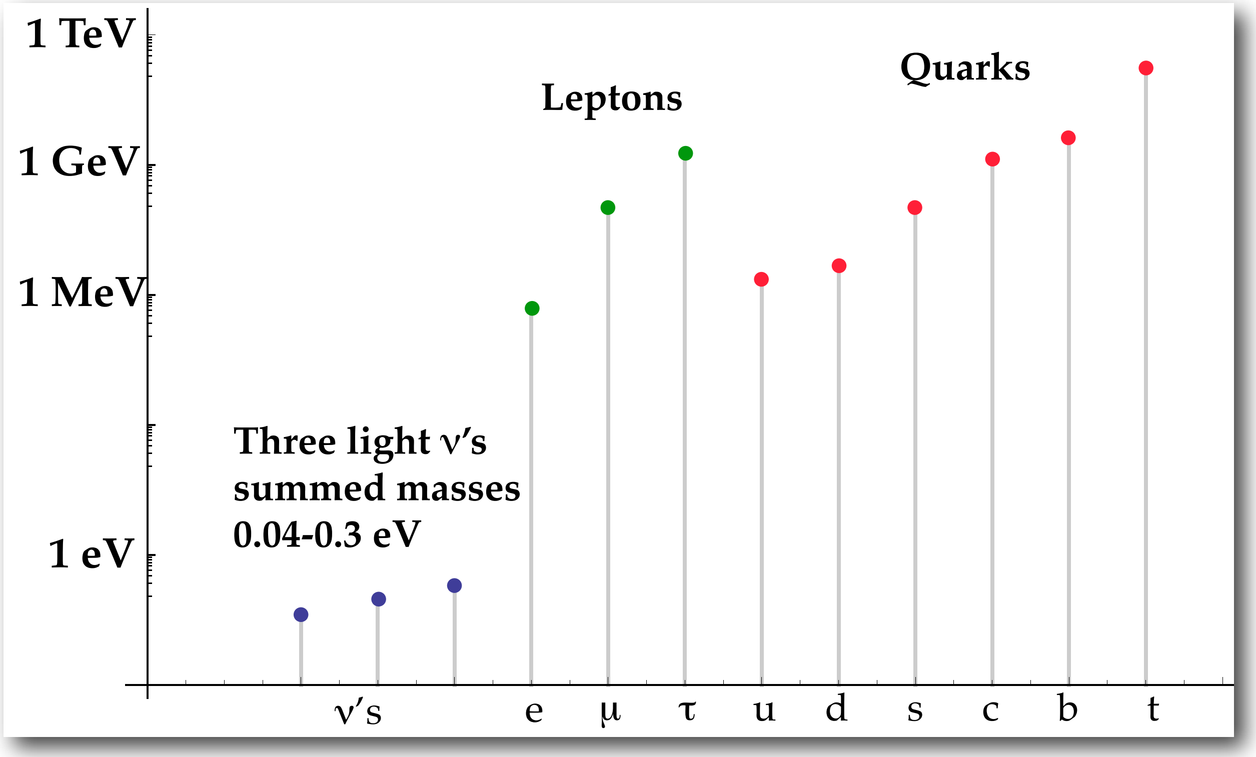


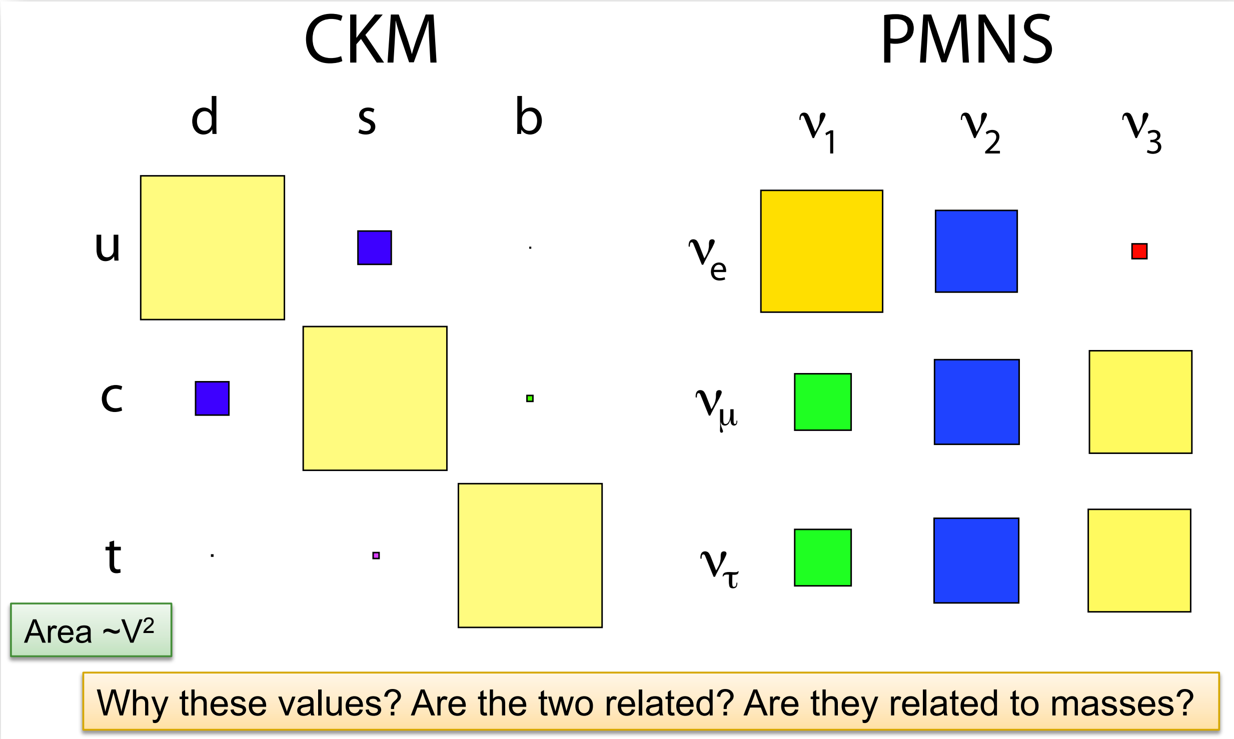
Loop only

- „New Physics flavour problem“ - i.e. tension between
  - relatively low (TeV) scale required to stabilize EW scale
  - high scale needed to suppress FCNC
- Any extension of SM must be able to preserve these features

Origin and Dynamics of Flavour ?

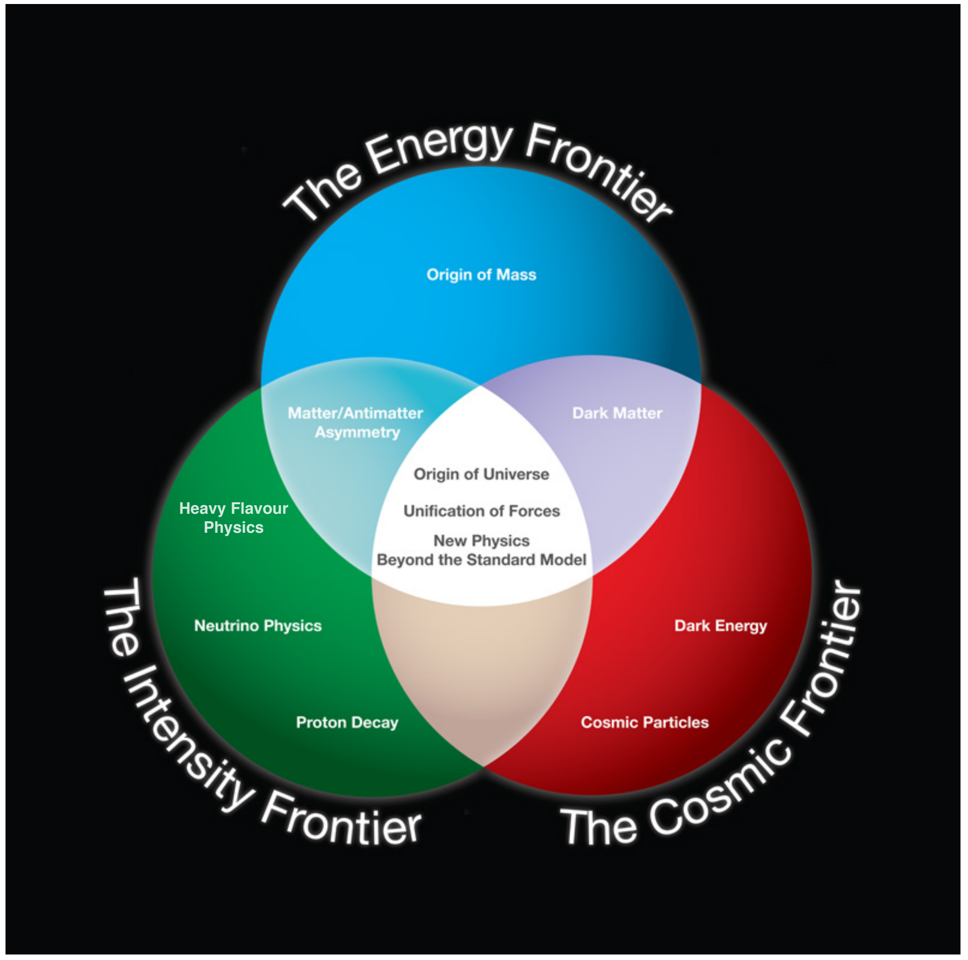
- While the SM describes flavour physics very accurately, it does not explain its mysteries
  - why are there three generations?
  - why does the fermion spectrum cover so many orders of magnitude?
  - why is mixing for quarks so different from that of neutrinos?
  - why is there this strong hierarchy?
  - why is the CP-violating phase of the CKM-matrix unsuppressed?





Two Frontiers to Search for New Physics

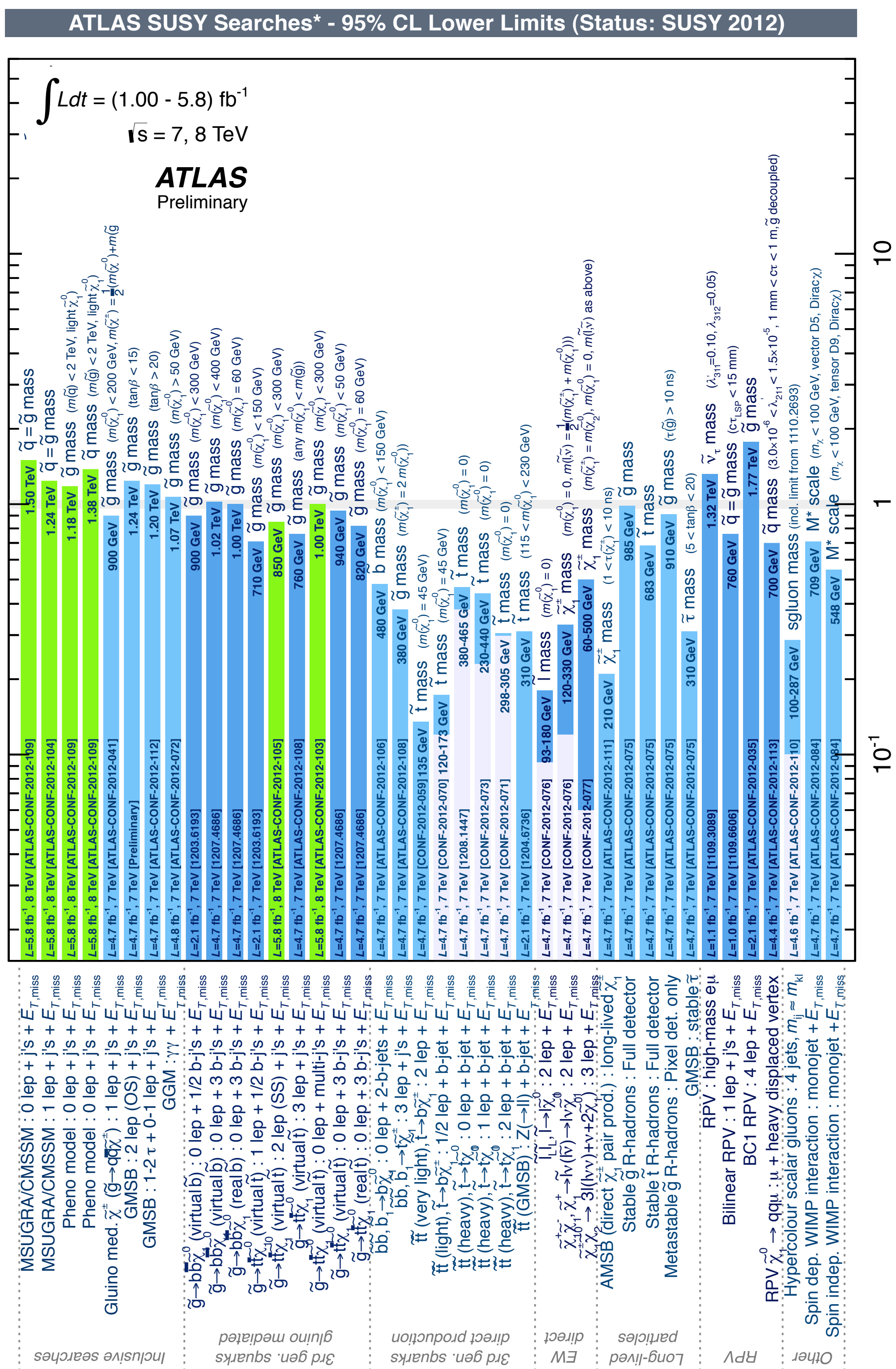
- Two complementary approaches to study shortcomings of the Standard Model and to search for so far unobserved processes and particles (i.e. New Physics). Energy frontier and intensity frontier



- Energy frontier:
  - direct search for production of unknown particles at the highest achievable energies
  - detection of „real“ new particles

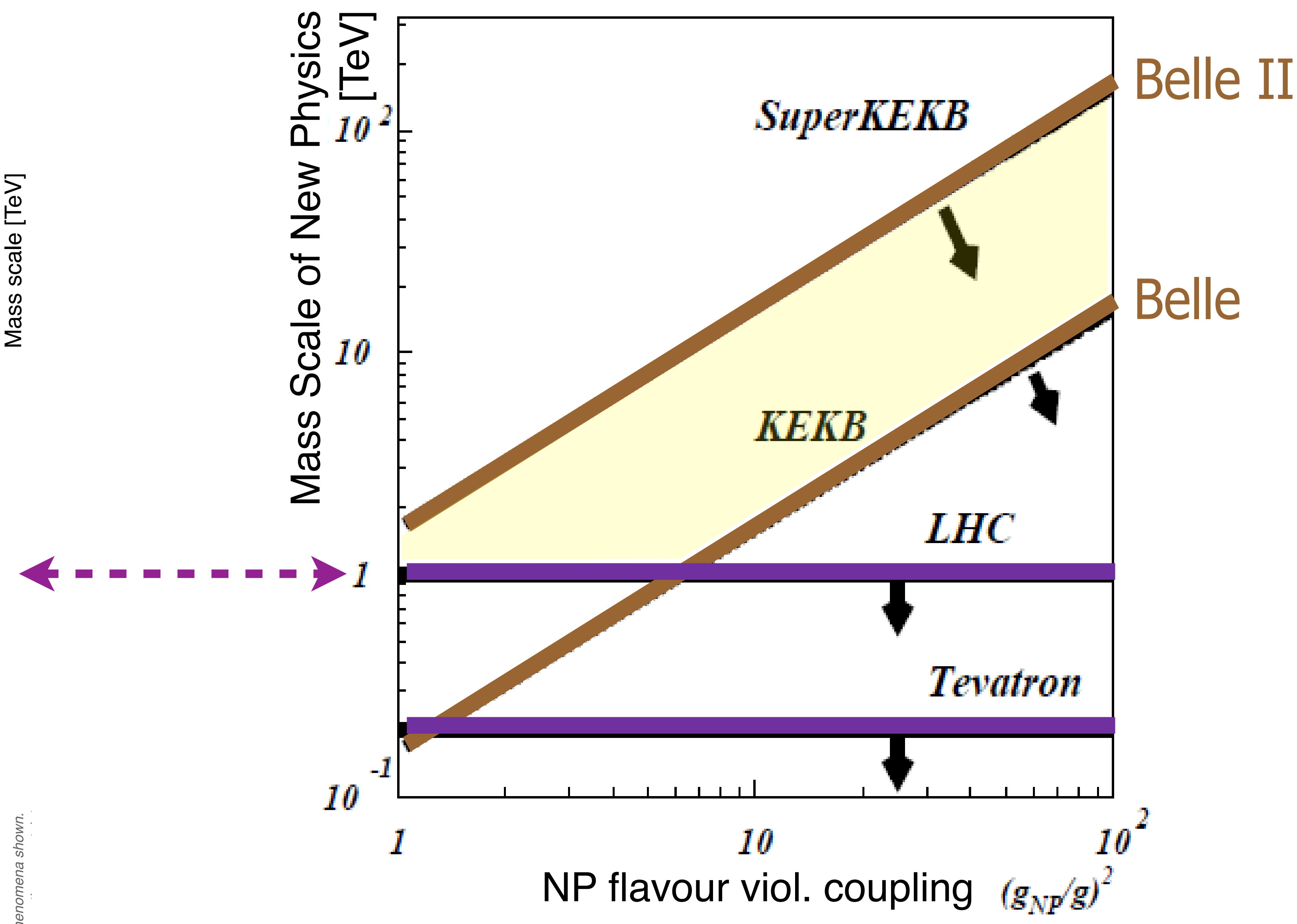
- Intensity frontier:
  - search for rare processes, deviations between theory predictions and experiments with ultimate precision
  - see effects of „virtual“ new particles in loops

Energy versus Intensity Frontier



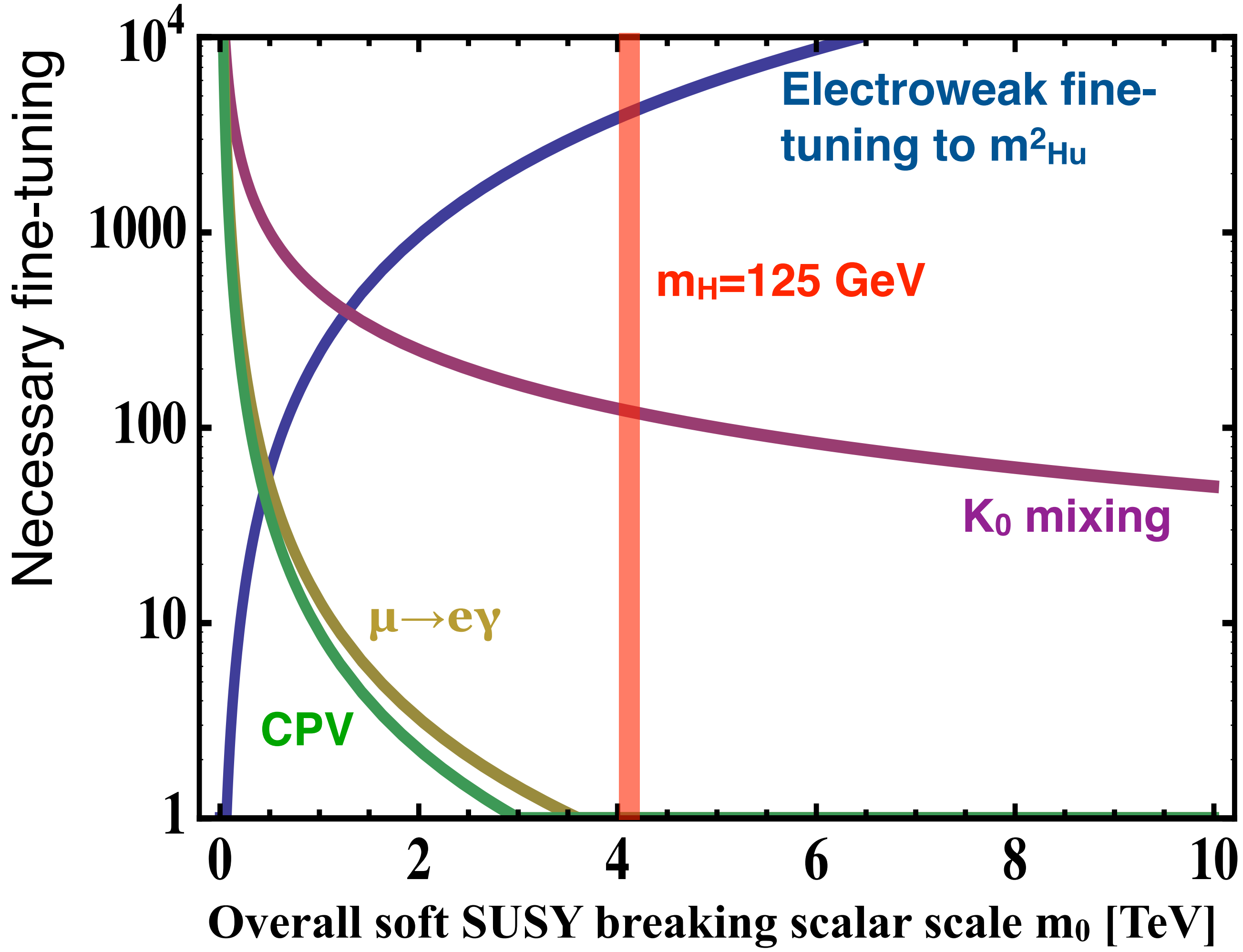
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/CombinedSummaryPlots

Illustrative sketch



Indirect discovery of New Physics in quantum loops via high precision measurements, searching for small deviations from the SM.

Fine-Tuning / Naturalness

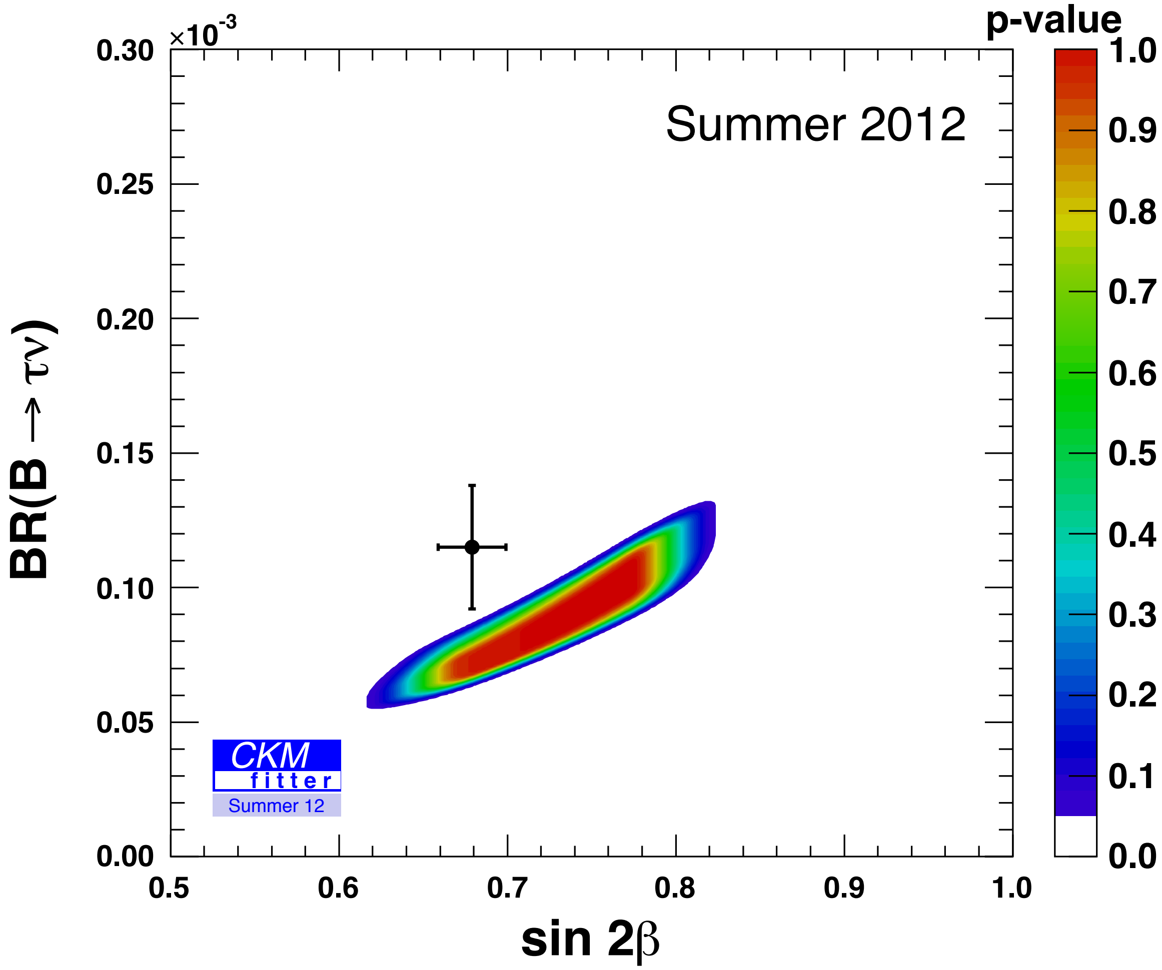


Jäckel / Khoze
arXiv: 1205.7091

- Recent LHC results push energy scale of New Physics higher
  - increased fine-tuning required for explanation of EW scale
- This, however, reduces the New Physics Flavour Problem
  - chances to see New Physics in flavour physics have in fact increased!

Hints of Deviations from SM at Intensity Frontier

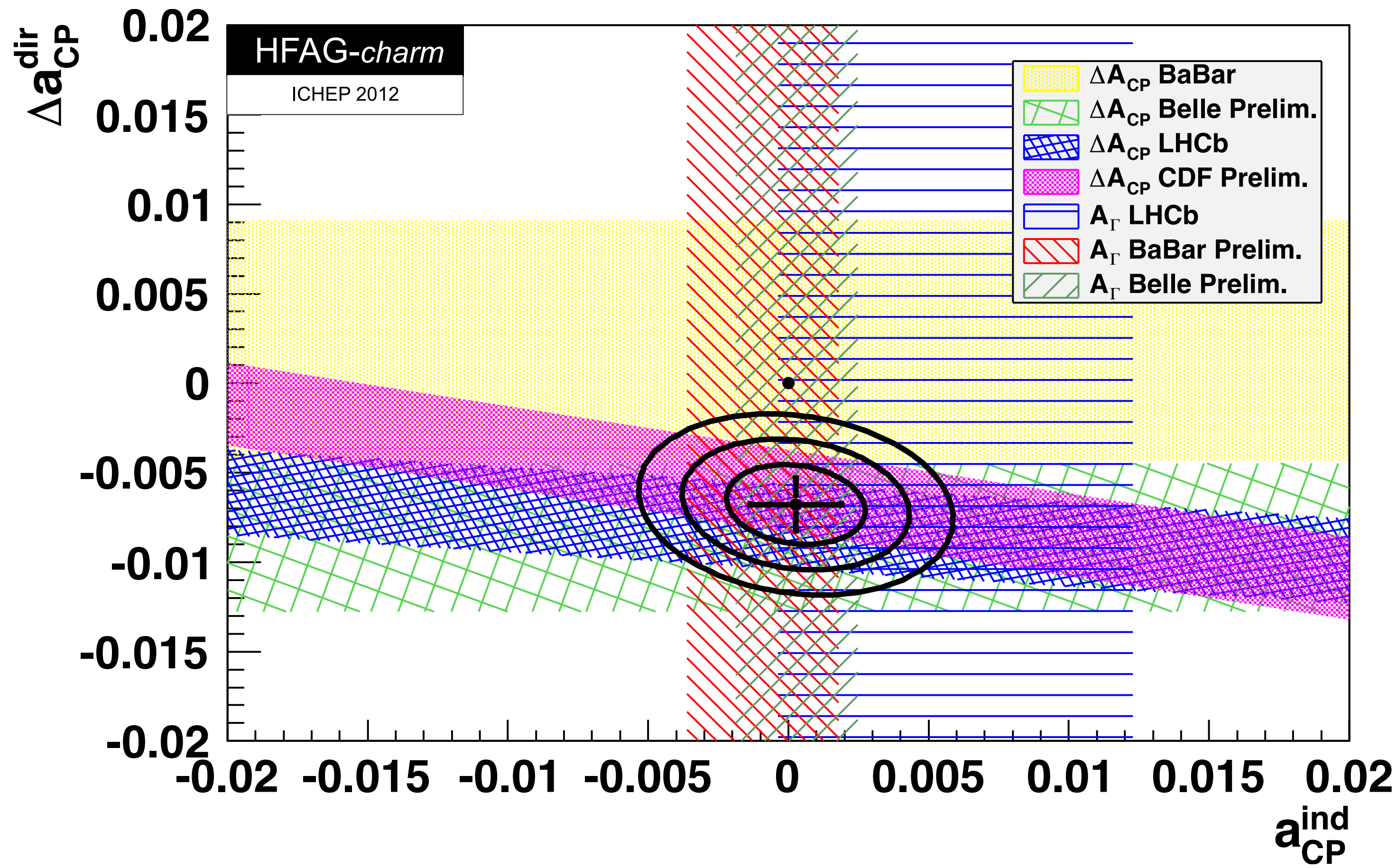
B mesons sector



$$\beta = \varphi_1 \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

Significance decreased w.r.t. 2011
(new hadronic tag Belle data)

C mesons sector



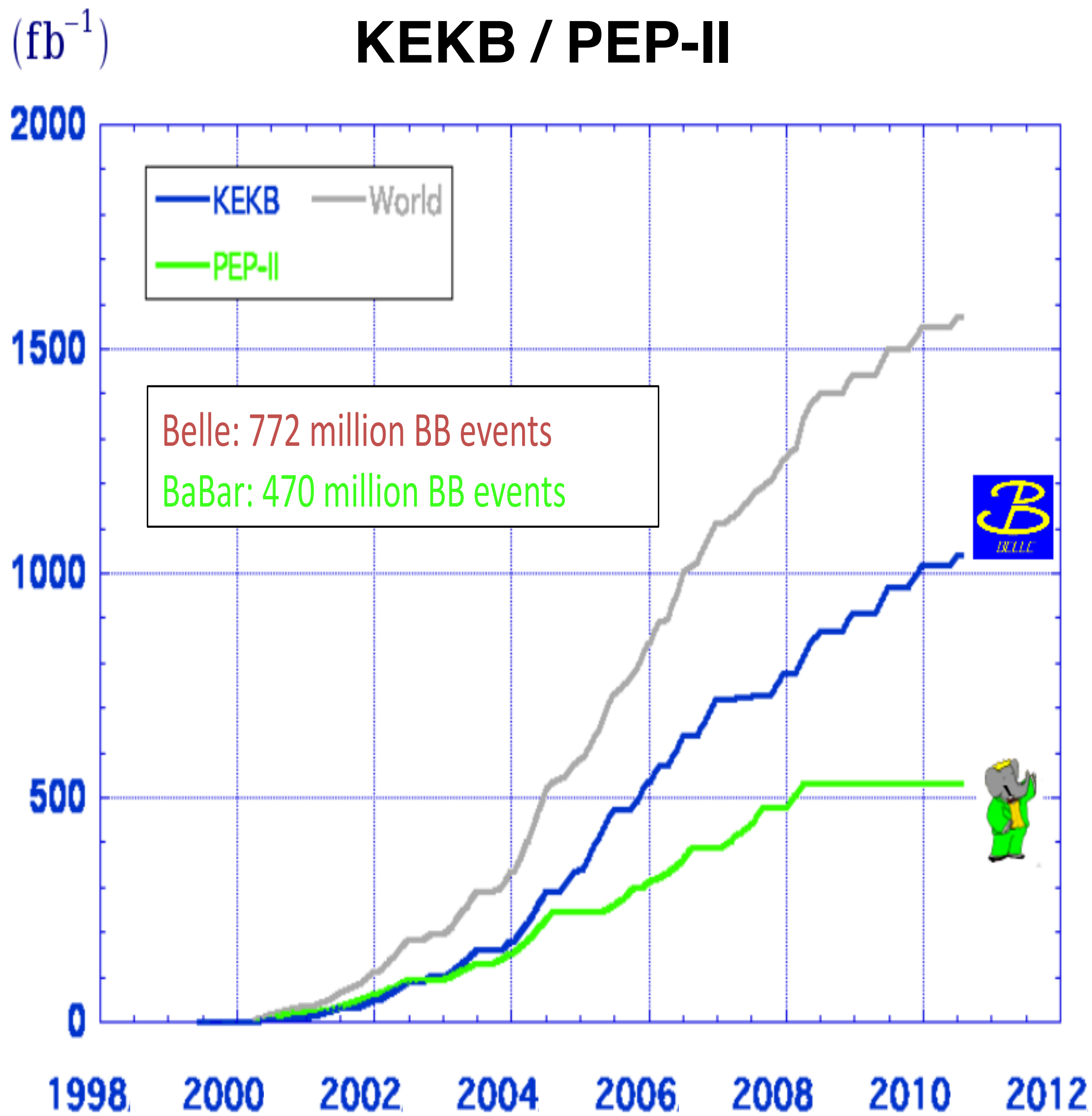
$a_{CP}^{ind} = (0.027 \pm 0.163)\%$
$\Delta a_{CP}^{dir} = (-0.678 \pm 0.147)\%$

Agreement with no CP violation CL = 2.0×10^{-5}
But not yet at 5σ level ...

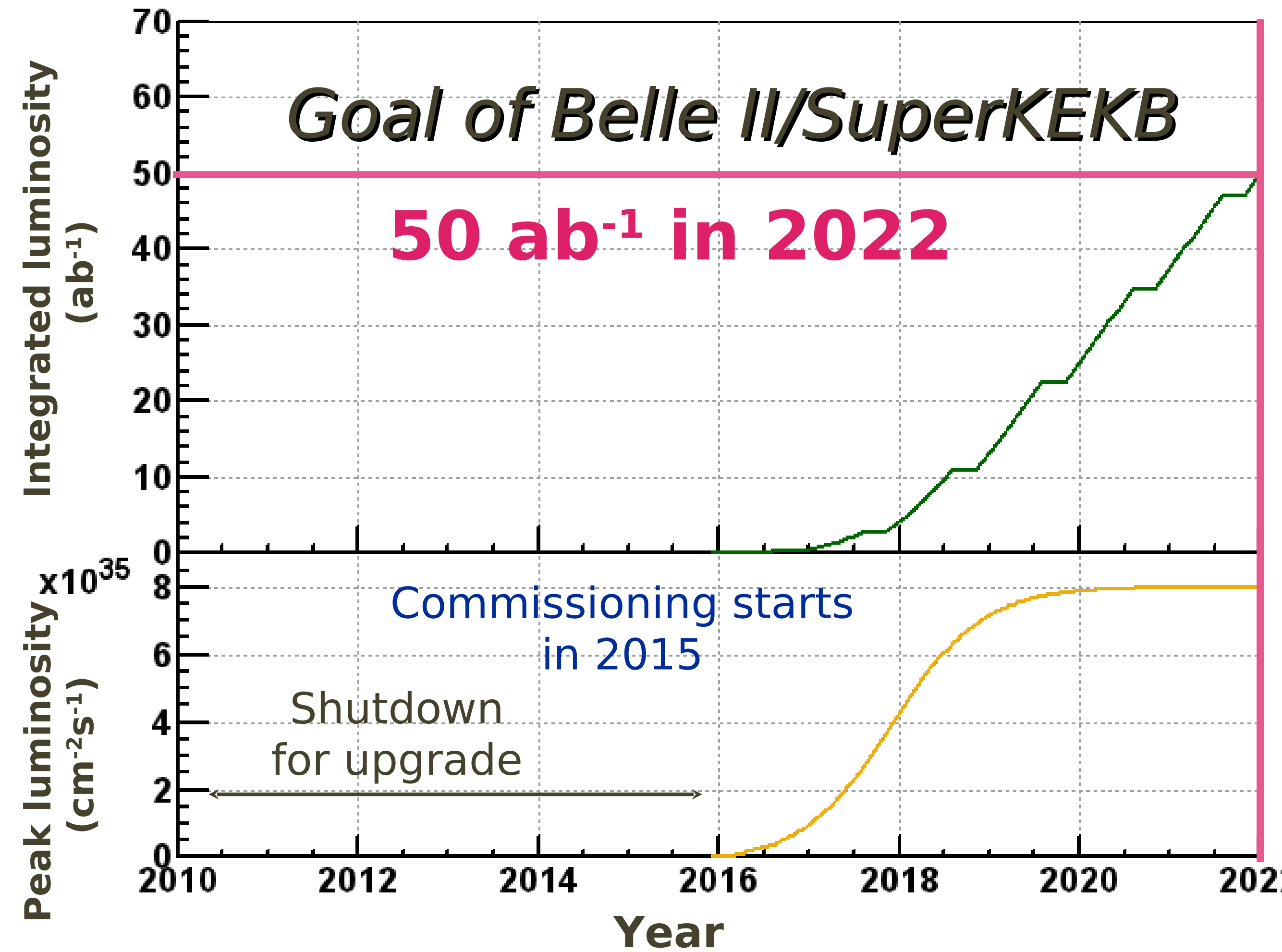
Significance increased w.r.t. 2011
(new time integrated $D^0 \rightarrow h^+h^-$ results from CDF)

KEKB –> SuperKEKB Goals and Prospects

KEKB / PEP-II



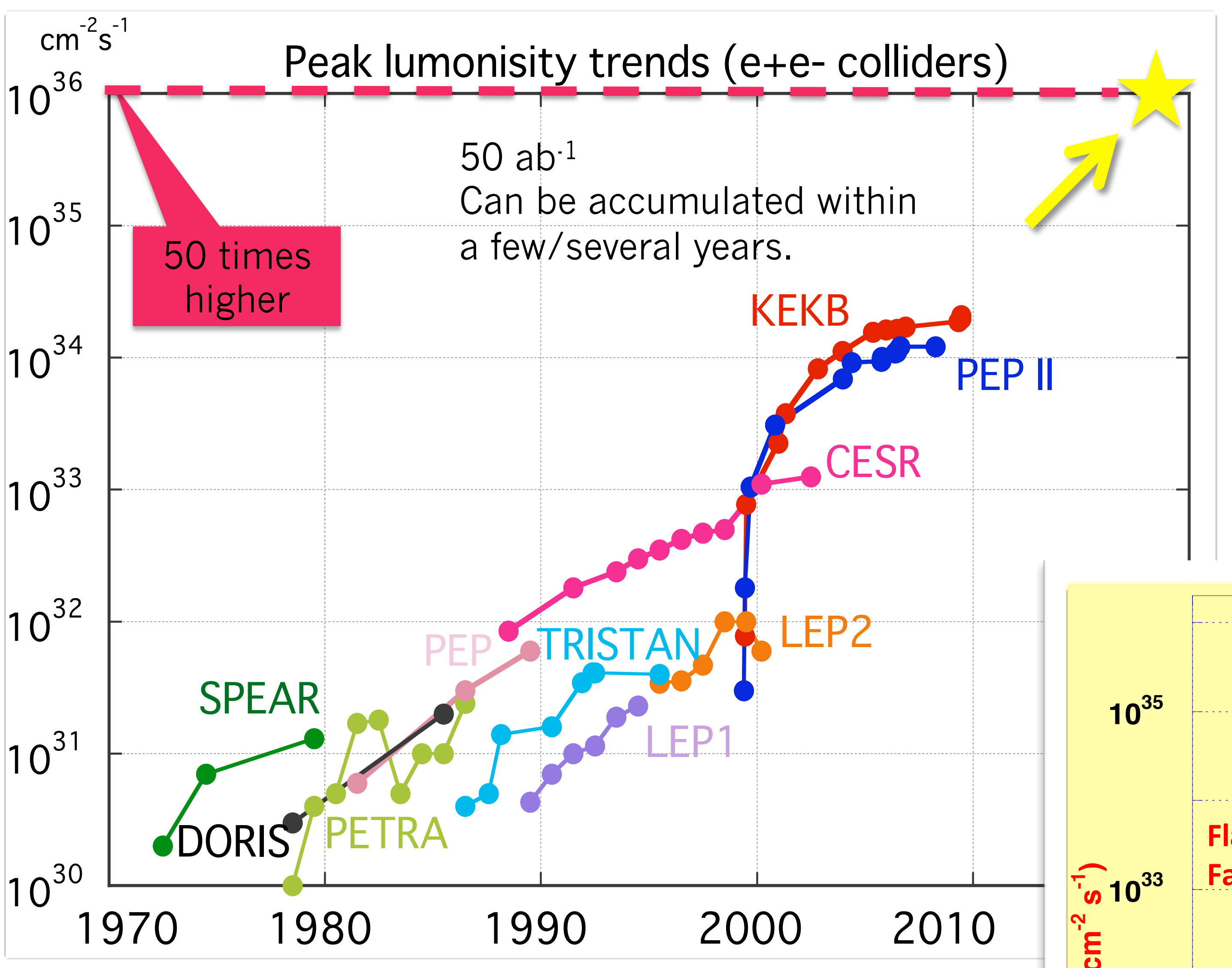
SuperKEKB

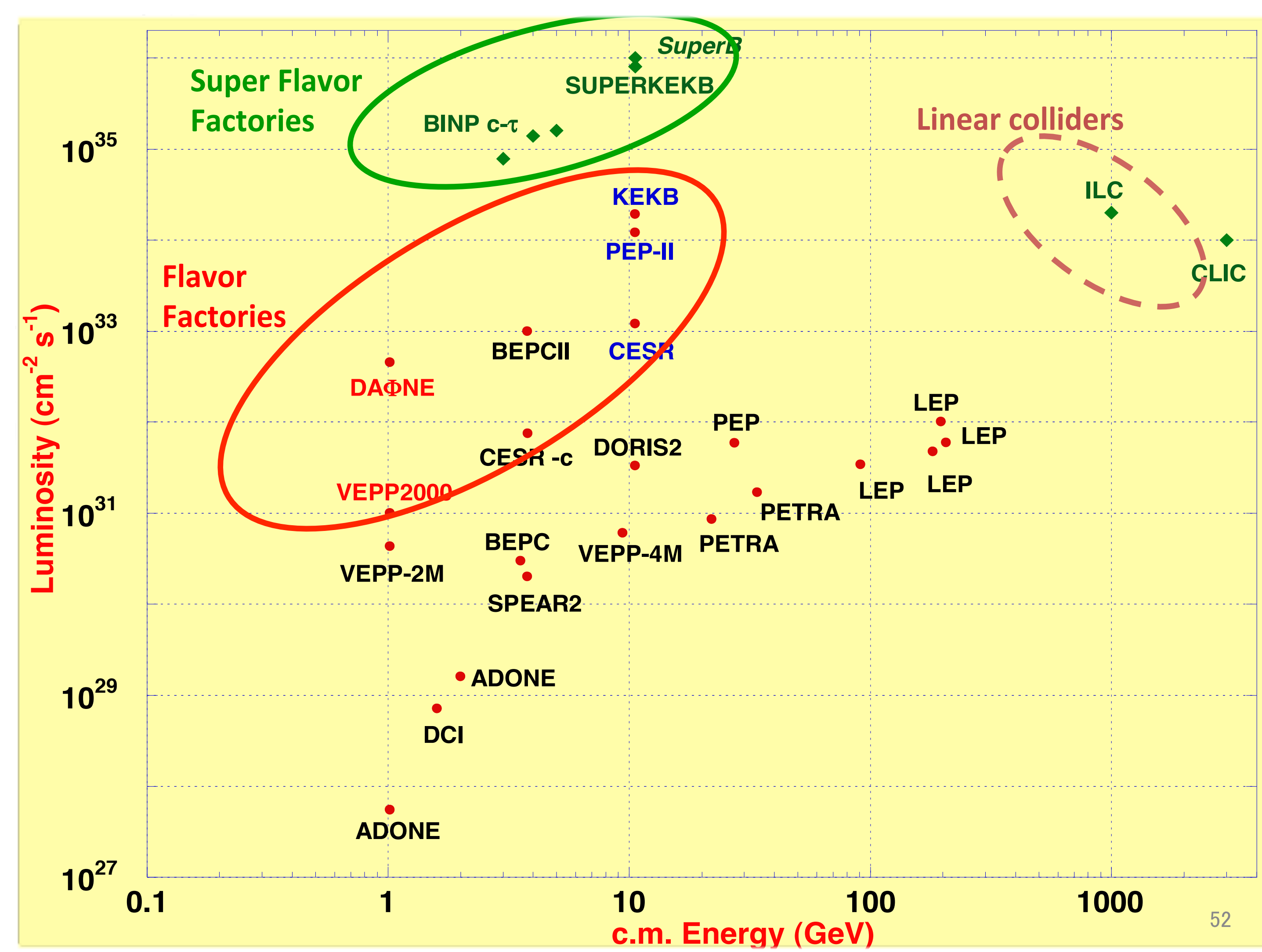


- check if KM scheme of SM correct
- provide quantitative test of KM mechanism of CP violation
- CKM parameters were known well enough to make a safe prediction of required luminosity

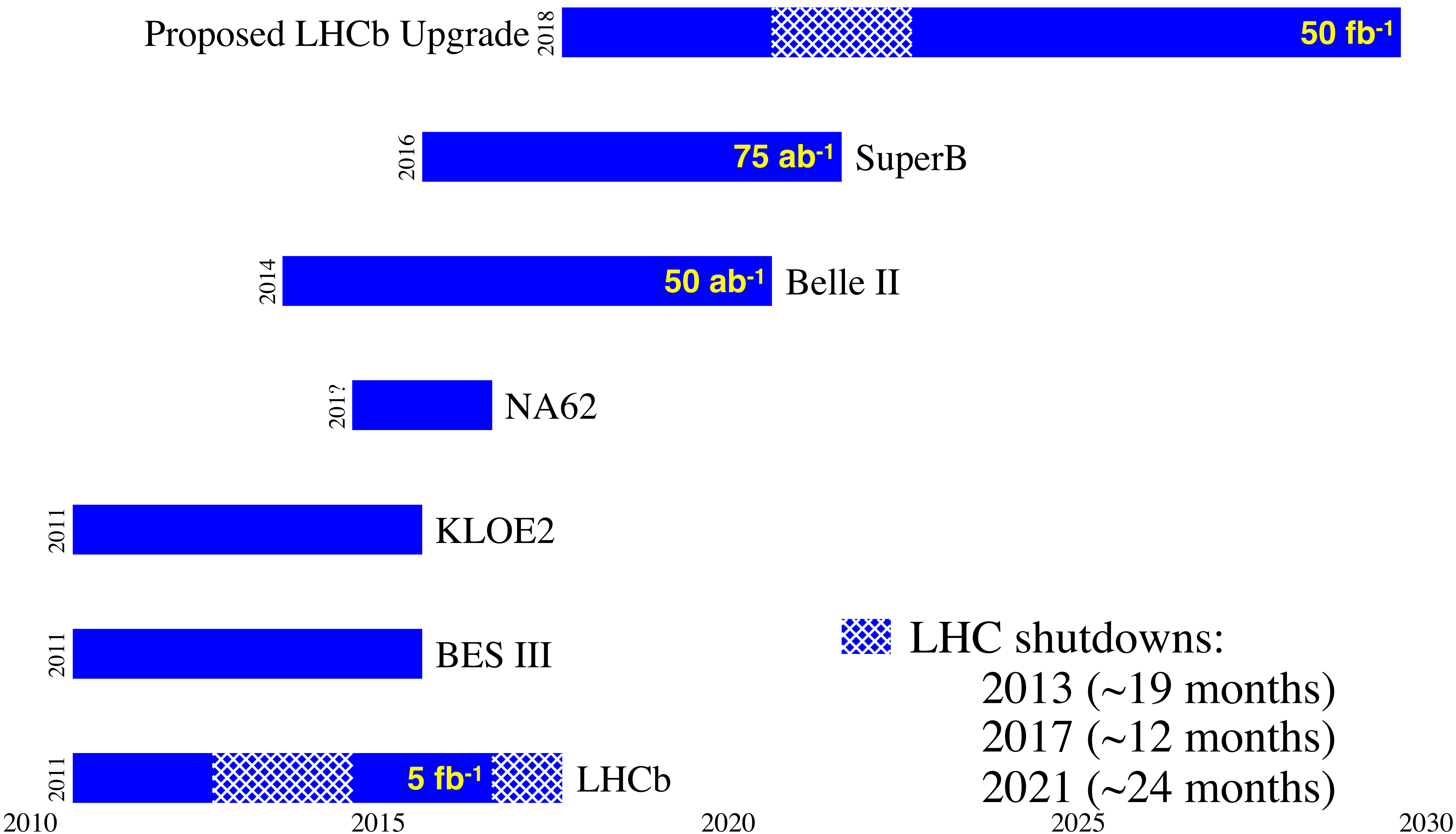
- understand origin of masses and mixing parameters and search for New Physics
- understand origin of matter-antimatter asymmetry in the universe
- no minimum luminosity for guaranteed success

Luminosity Goals of Super Flavour Factories



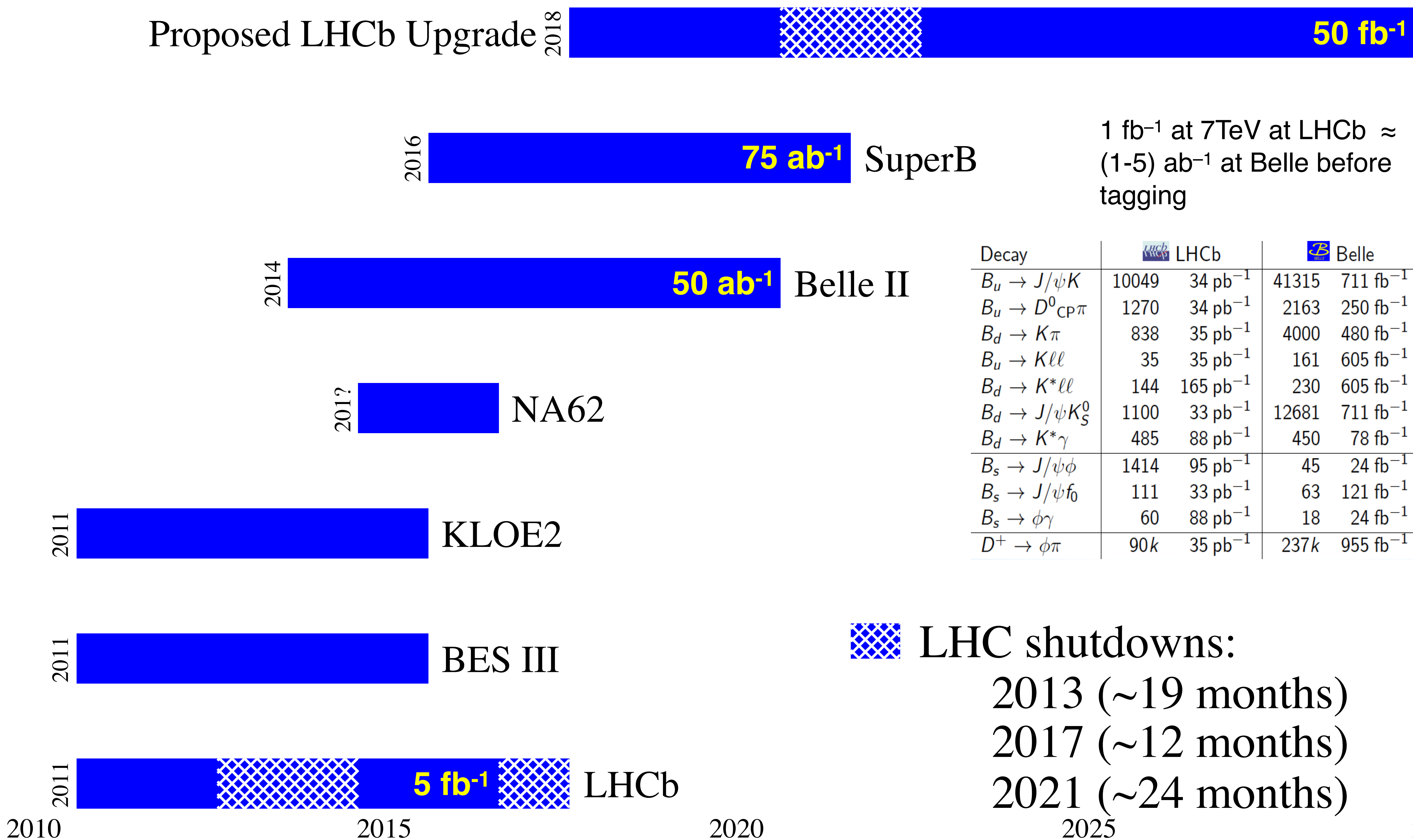


Experimental Flavour Landscape 2011 - 2030



arXiv:1109.5028v2

Experimental Flavour Landscape 2011 - 2030



1 fb^{-1} at 7TeV at LHCb ≈ (1-5) ab^{-1} at Belle before tagging

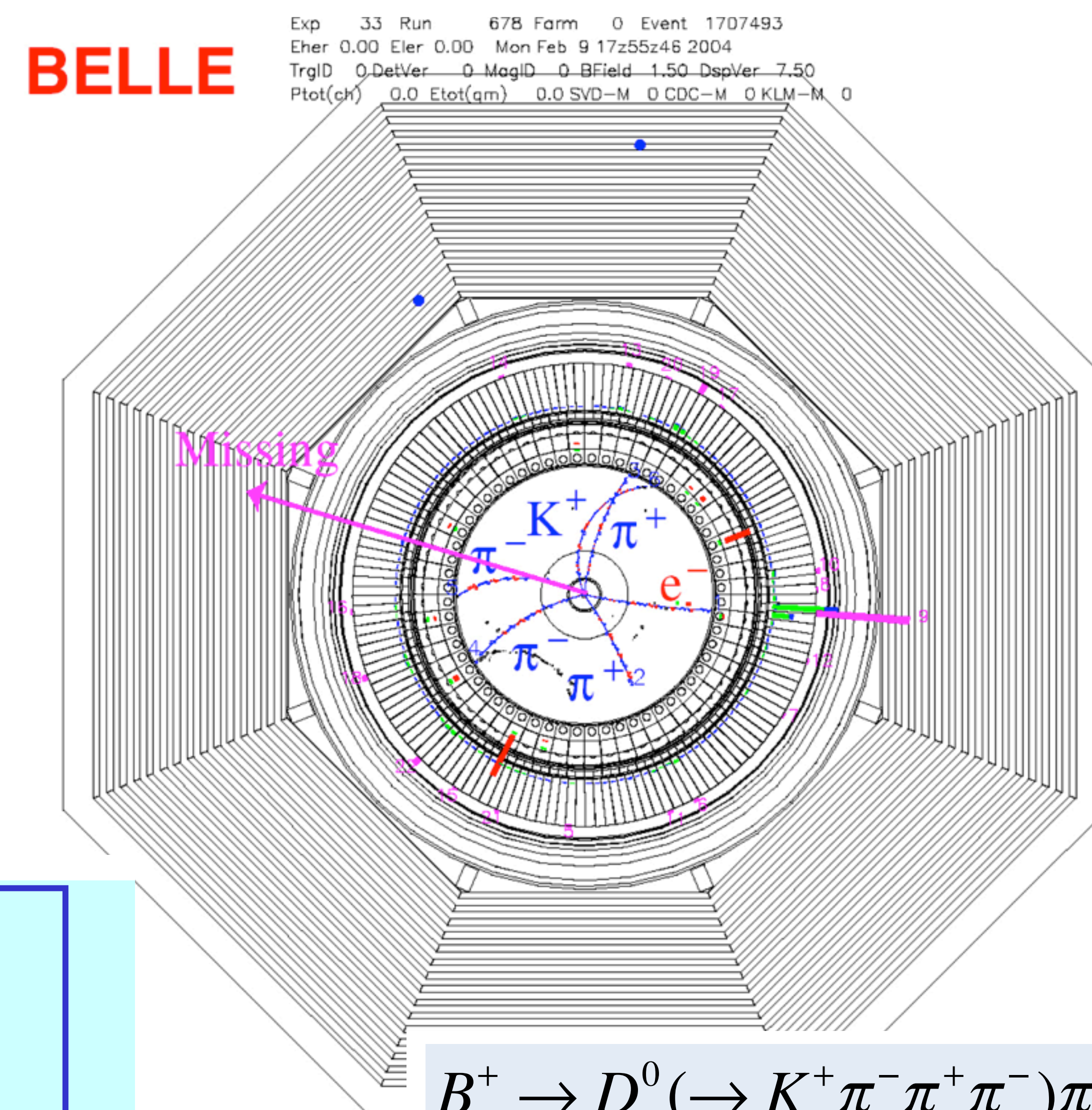
Decay	LHCb		Belle		Ratio
$B_u \to J/\psi K$	10049	34 pb^{-1}	41315	711 fb^{-1}	5.1
$B_u \to D^0{}_{CP}\pi$	1270	34 pb^{-1}	2163	250 fb^{-1}	4.3
$B_d \to K\pi$	838	35 pb^{-1}	4000	480 fb^{-1}	2.9
$B_u \to K\ell\ell$	35	35 pb^{-1}	161	605 fb^{-1}	2.6
$B_d \to K^*\ell\ell$	144	165 pb^{-1}	230	605 fb^{-1}	2.3
$B_d \to J/\psi K^0_S$	1100	33 pb^{-1}	12681	711 fb^{-1}	1.9
$B_d \to K^*\gamma$	485	88 pb^{-1}	450	78 fb^{-1}	1.0
$B_s \to J/\psi\phi$	1414	95 pb^{-1}	45	24 fb^{-1}	7.9
$B_s \to J/\psi f_0$	111	33 pb^{-1}	63	121 fb^{-1}	6.5
$B_s \to \phi\gamma$	60	88 pb^{-1}	18	24 fb^{-1}	0.9
$D^+ \to \phi\pi$	90k	35 pb^{-1}	237k	955 fb^{-1}	10

LHC shutdowns:
2013 (~19 months)
2017 (~12 months)
2021 (~24 months)

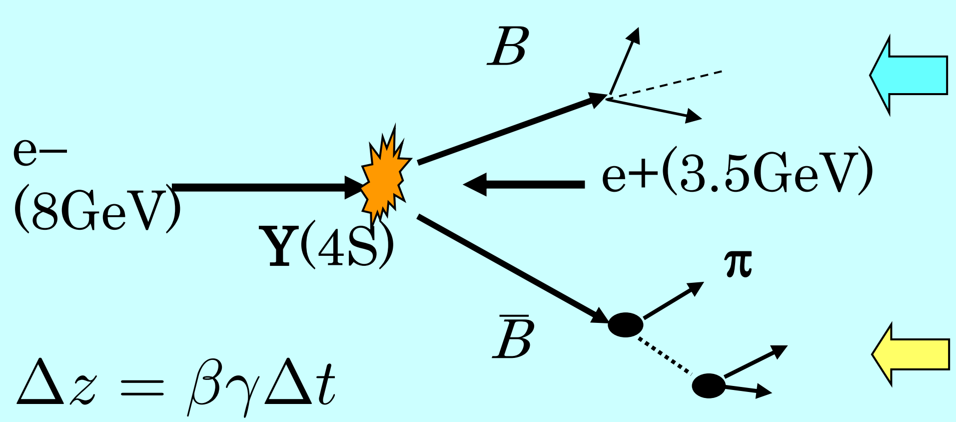
arXiv:1109.5028v2

Clean Environment at B-Factories

- Nearly hermetic detectors
- Fully reconstruct one of the B's to
  - tag B flavor/charge
  - determine B momentum
  - exclude decay products of one B from further analysis



$$B^+ \to D^0(\to K^+\pi^-\pi^+\pi^-)\pi^+$$
$$B^- \to \tau^-(\to e^-\nu\bar{\nu})\nu$$



Decays of interest
- $B \to X_u\, l\, \nu$,
- $B \to K\, \nu\, \nu$
- $B \to D\tau\nu,\ \tau\nu$

full reconstruction
$B \to D\pi$ etc. (0.1~0.3%)

→ Offline B meson beam!

Powerful tool for B decays with neutrinos

„Golden Modes“ of Super B Factories

Areas where Super B Factories can provide important insight into New Physics complementary to other experiments (LHCb):

E_{miss}:

$\mathcal{B}(B \to \tau\nu)$, $\mathcal{B}(B \to X_c\tau\nu)$, $\mathcal{B}(B \to h\nu\nu)$,...

Inclusive:

$\mathcal{B}(B \to s\gamma)$, $A_{CP}(B \to s\gamma)$, $\mathcal{B}(B \to sll)$, ...

Neutrals:

$S(B \to K_S\pi^0\gamma)$, $S(B \to \eta' K_S)$, $S(B \to K_SK_SK_S)$, $\mathcal{B}(\tau \to \mu\gamma)$, $\mathcal{B}(B_s \to \gamma\gamma)$, ...

A.G. Akeroyd et al., arXiv: 1002.5012

Physics at Super B Factory

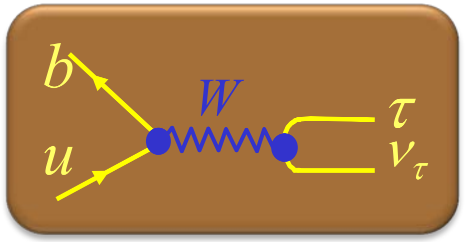
B. O’Leary et al., arXiv: 1008.1541

Super$B$

Progress Reports

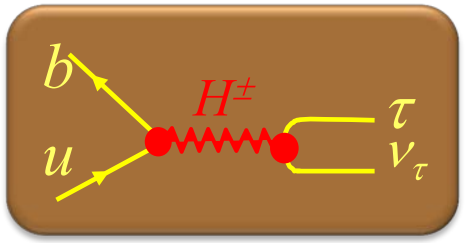
Physics

Example: Constraints on Charged Higgs from B $\rightarrow \tau\nu$



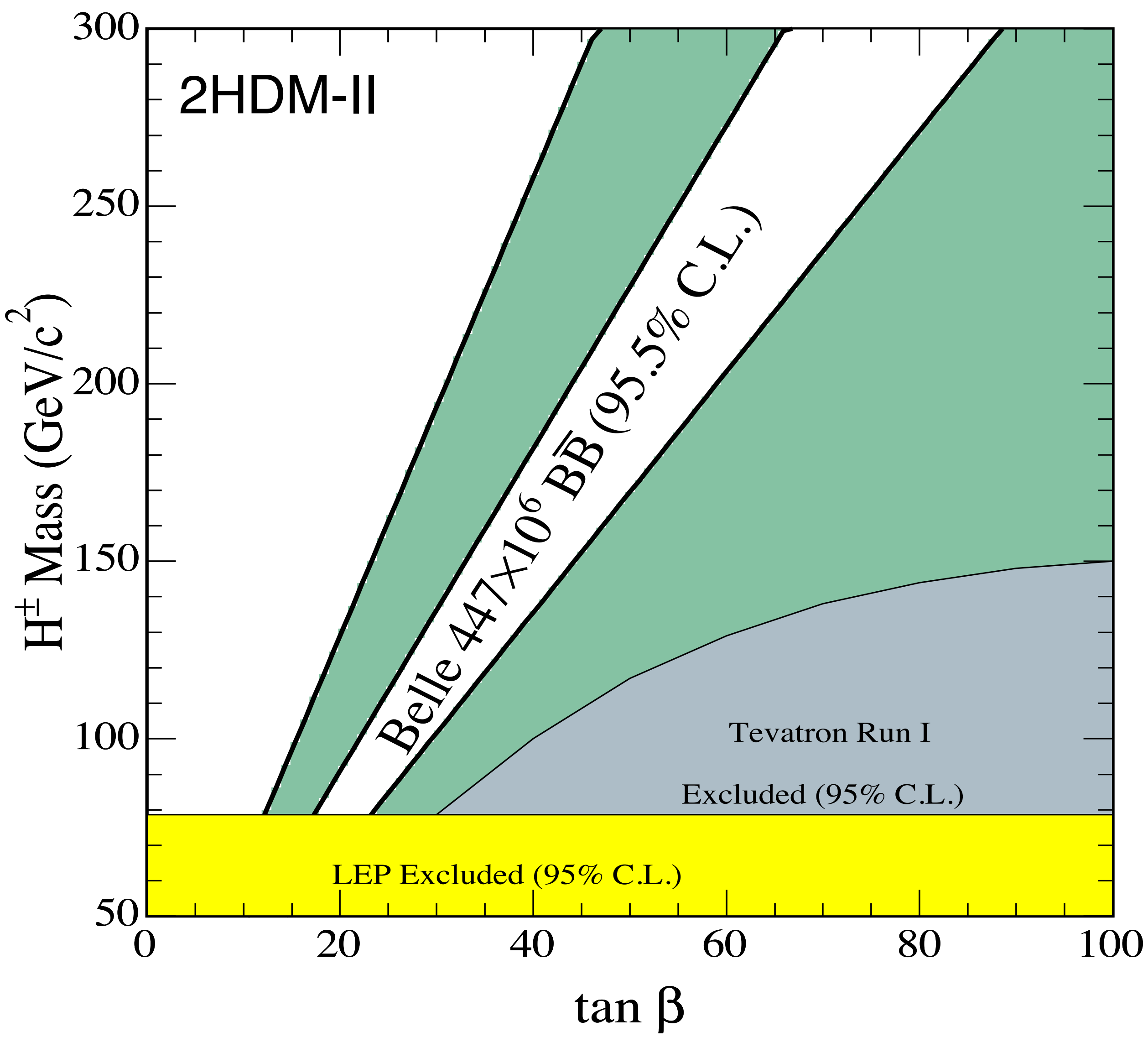
The rare decay $B^- \rightarrow \tau^- \nu_\tau$ is in SM mediated by the W boson

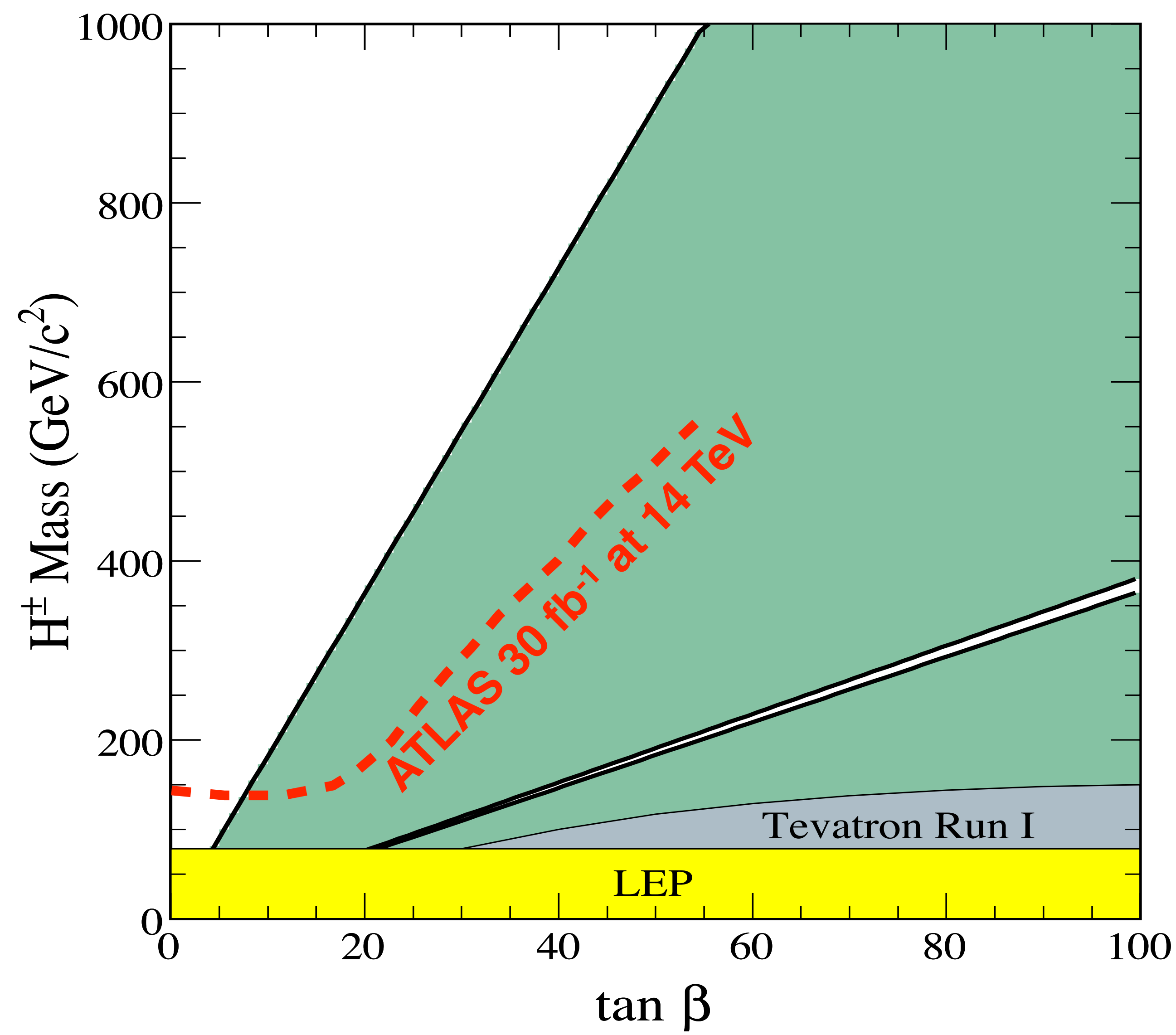
$$\frac{BR_{2HDM}}{BR_{SM}}(B \to l\nu) = \left[1 - \tan^2\beta \frac{m_b^2}{m_{H^\pm}^2}\right]^2$$



In some supersymmetric extensions it can also proceed via a charged Higgs

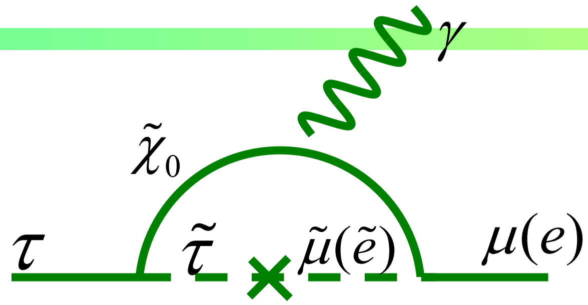
$$BR_{exp}(B^+ \to \tau^+\nu) = (1.67 \pm 0.30) \times 10^{-4}$$





Prospects for Lepton Flavour Violation

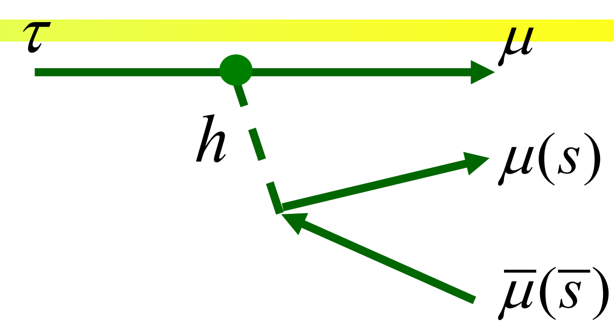
$\tau \to l\gamma$



- SUSY + Seasaw $(m^2_{\tilde{l}})_{23(13)}$
- Large LFV $Br(\tau \to \mu\gamma) = O(10^{-7\sim 9})$

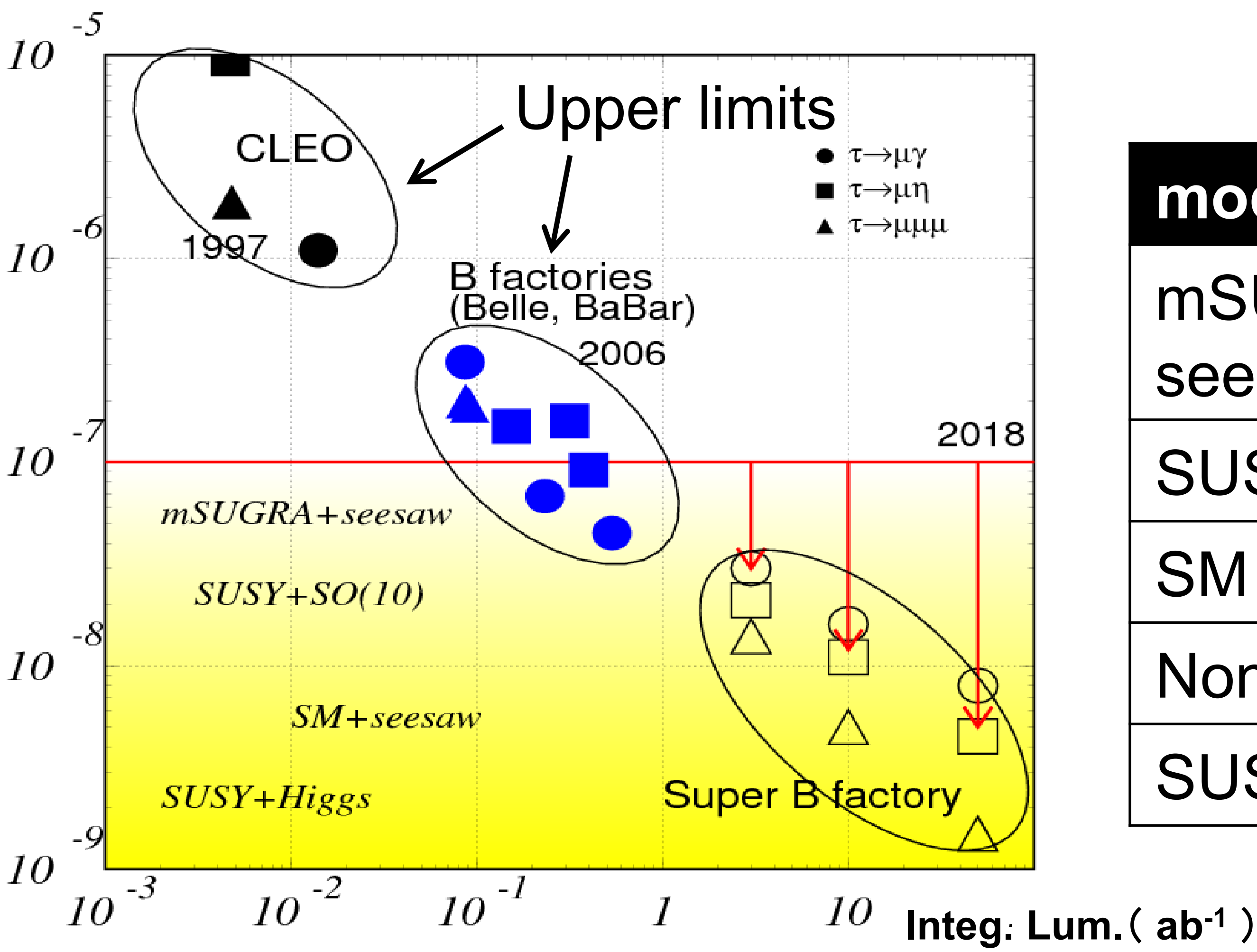
$$Br(\tau \to \mu\gamma) = 10^{-6} \times \left(\frac{(m^2_{\tilde{L}})_{32}}{\bar{m}^2_{\tilde{L}}} \right) \left(\frac{1\,TeV}{m_{SUSY}} \right)^4 \tan^2\beta$$

$\tau \to 3l, l\eta$



- Neutral Higgs mediated decay.
- Important when MSUSY >> EW scale.

$$Br(\tau \to 3\mu) = 4 \times 10^{-7} \times \left(\frac{(m^2_{\tilde{L}})_{32}}{\bar{m}^2_{\tilde{L}}} \right) \left(\frac{\tan\beta}{60} \right)^6 \left(\frac{100GeV}{m_A} \right)^4$$



mode	$Br(\tau \to \mu\gamma)$	$Br(\tau \to 3l)$
mSUGRA + seesaw	10^{-7}	10^{-9}
SUSY + SO(10)	10^{-8}	10^{-10}
SM + seesaw	10^{-9}	10^{-10}
Non-universal Z'	10^{-9}	10^{-8}
SUSY + Higgs	10^{-10}	10^{-7}

Nano-Beam Scheme for SuperKEKB

Lorentz factor

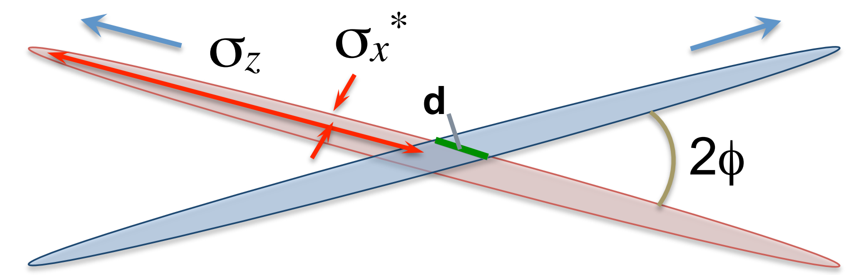
beam current (x 2)

$$L = \frac{\gamma_{e^\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e^\pm}\xi_y^{e^\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

Lumi reduction factor
cross angle&tune shift red.
(hourglass effect) 0.8-1

vertical beta function @ IP (x 20)

$$\sigma_{x,y} = \sqrt{\varepsilon_{x,y}\beta_{x,y}}$$



Half crossing angle: ϕ

$$d = \frac{\sigma_x^*}{\phi}$$

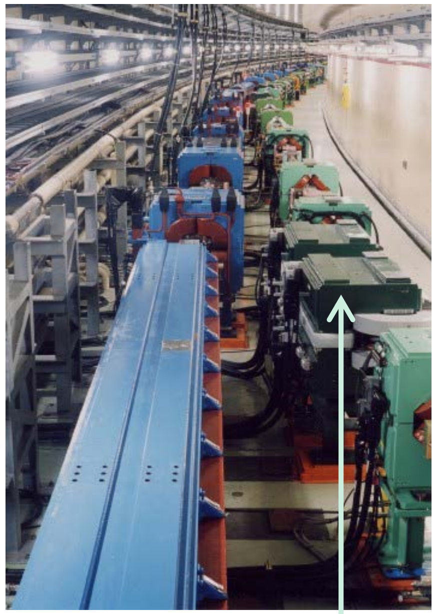
overlap region (≠ bunch length)

„Nano-Beam“ scheme (P. Raimondi, DAΦNE):
Squeeze vertical beta function at the IP (β^*_y) by minimizing longitudinal size of overlap region of the two beams at the IP, which generally limits effective minimum value of β_{y^*} through hourglass effect.

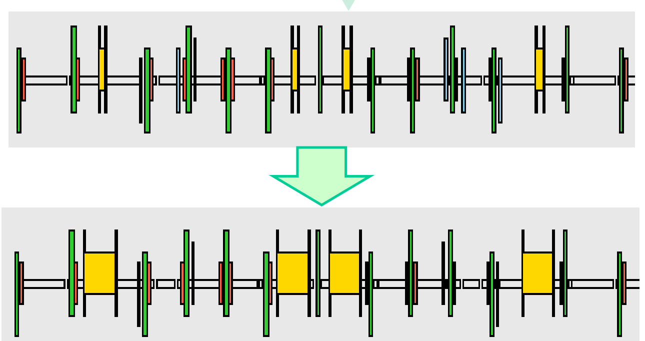
Parameter	KEKB LER	KEKB HER	SuperKEKB LER	SuperKEKB HER
Beam energy [GeV]	3.5	8	4	7
Half crossing angle [mrad]	11		41.7	
Horizontal emittance [nm]	18	24	3.2	5.0
Emittance ratio [%]	0.88	0.66	0.27	0.25
Horizontal beta function at IP [mm]	1200		32	25
Vertical beta function at IP [mm]	5.9		0.27	0.31
Beam currents [A]	1.64	1.19	3.60	2.60
Beam-beam parameter	0.129	0.090	0.0886	0.0830
Luminosity [10^{34} cm^{-2}s^{-1}]	2.1		80	

- Reduced energy asymmetry
  - HER 8 –> 7 GeV: reduced synrad, E_c
  - LER 3.5 –> 4 GeV: better beam lifetime $\tau_{Touschek} \propto \gamma^3$
  - smaller Lorentz boost: need better vertex resolution $\Delta z = \beta\gamma\Delta t$

From KEKB to SuperKEKB

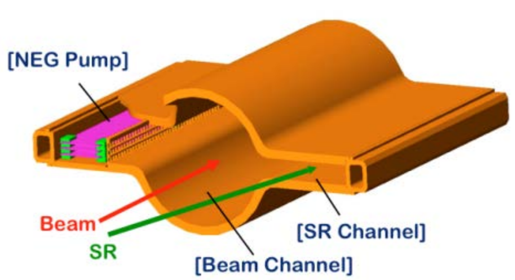


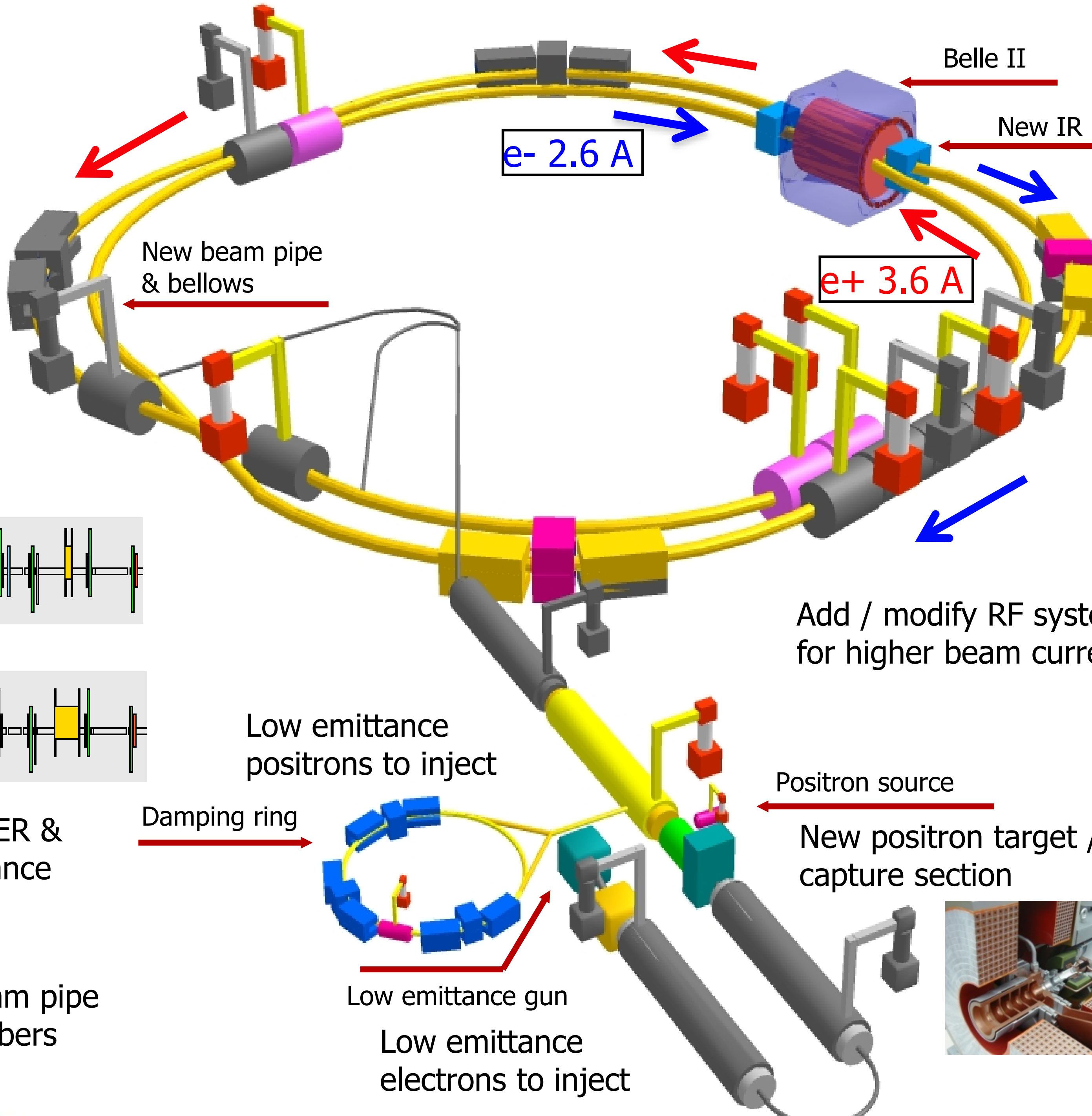
Replace short dipoles with longer ones (LER)



Redesign the lattices of HER & LER to squeeze the emittance

TiN-coated beam pipe with antechambers





Belle II

New IR

New beam pipe & bellows

Low emittance positrons to inject

Damping ring

Low emittance gun

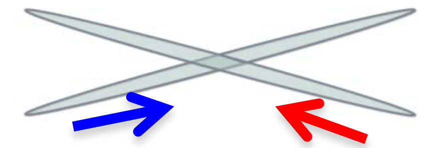
Low emittance electrons to inject

Positron source

New positron target / capture section

Add / modify RF systems for higher beam current

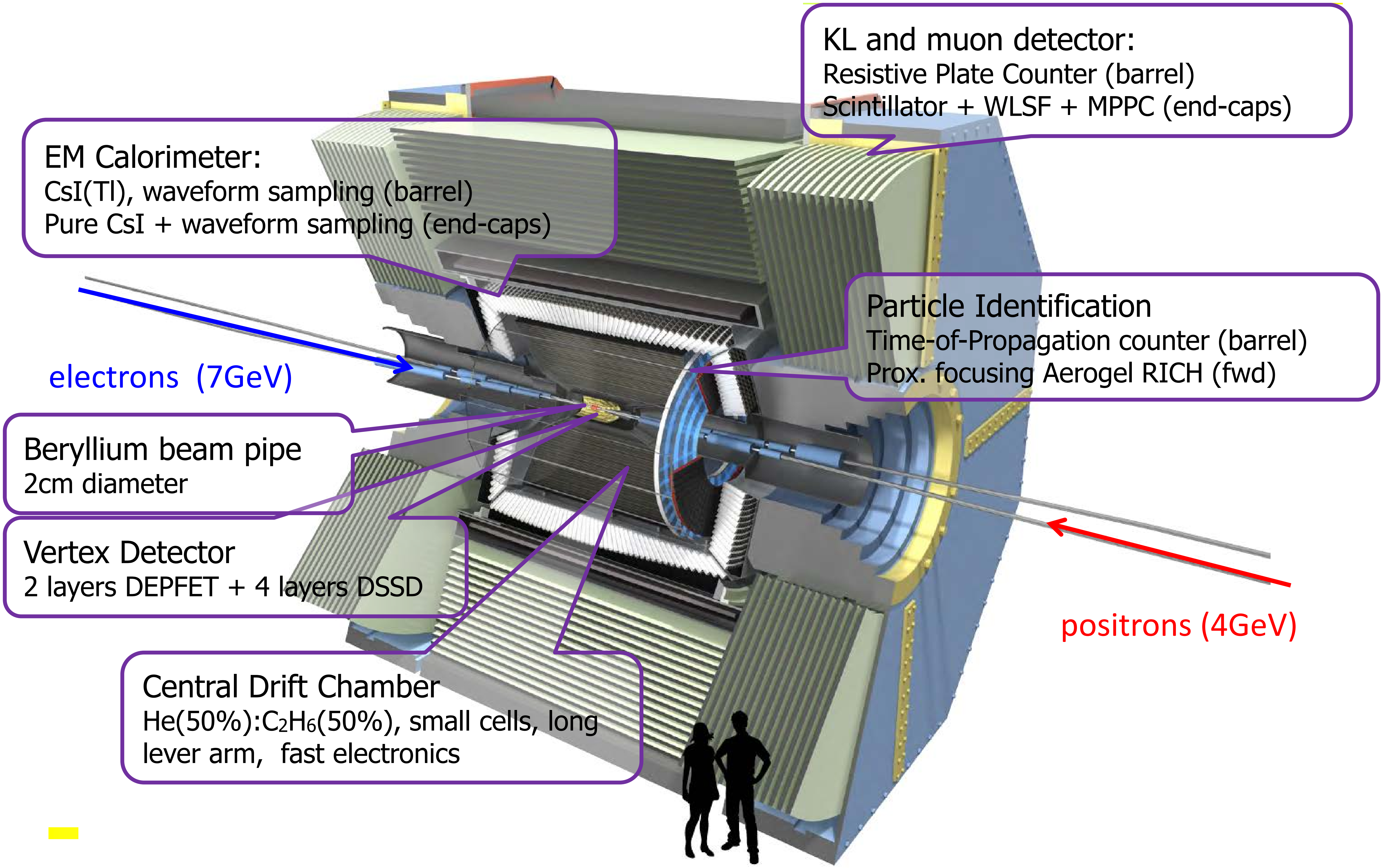
Colliding bunches



New superconducting /permanent final focusing quads near the IP

To get x40 higher interaction rate

Belle II Detector



Belle II Collaboration

20 countries, 67 institutions, ~450 collaborators

Germany second largest after Japan

German contribution: Pixel Detector PXD

DESY joined Belle II in November 2011

MEMORANDUM OF UNDERSTANDING
between

the Belle II International Collaboration
at the High Energy Accelerator Research Organization, KEK

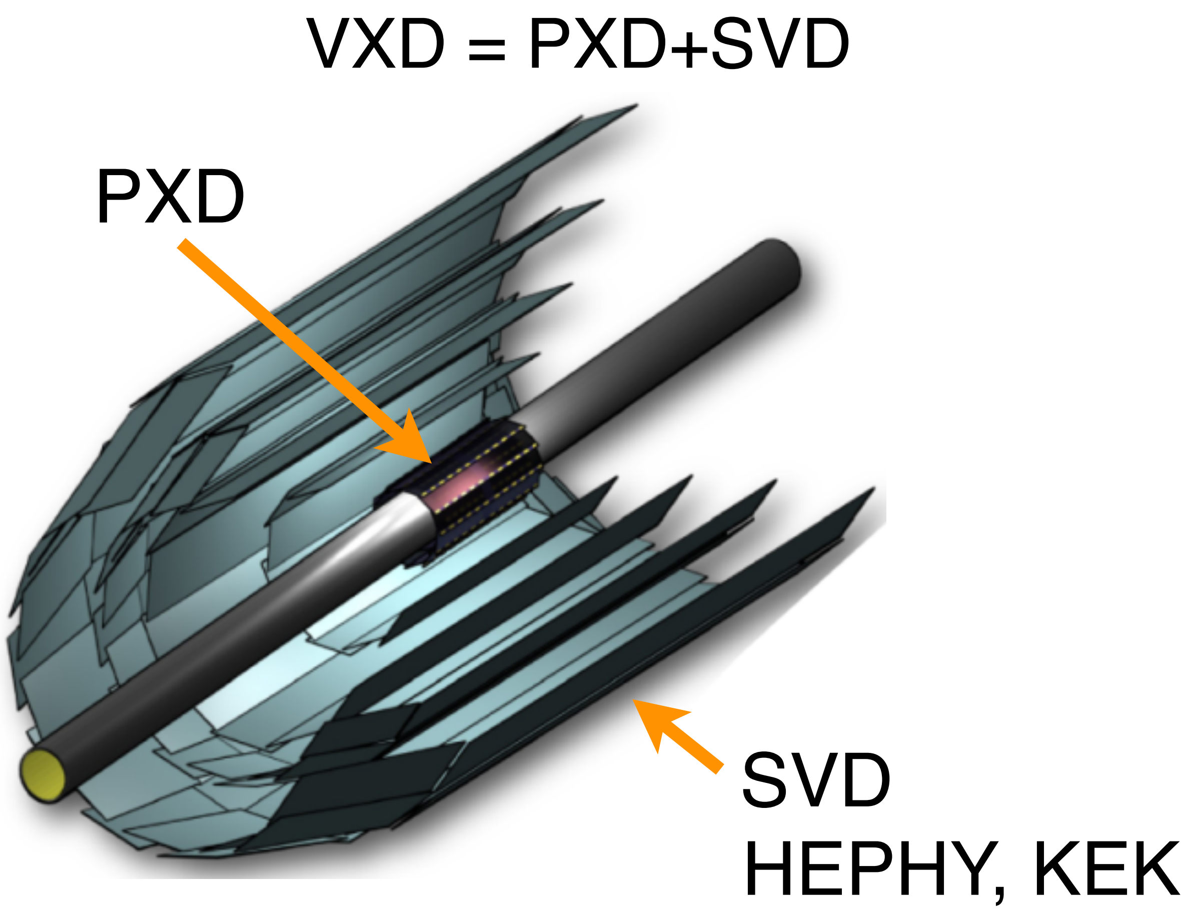
High Energy Accelerator Research Organization, KEK
1-1 Oho, Tsukuba-shi
Ibaraki 305-0801, Japan

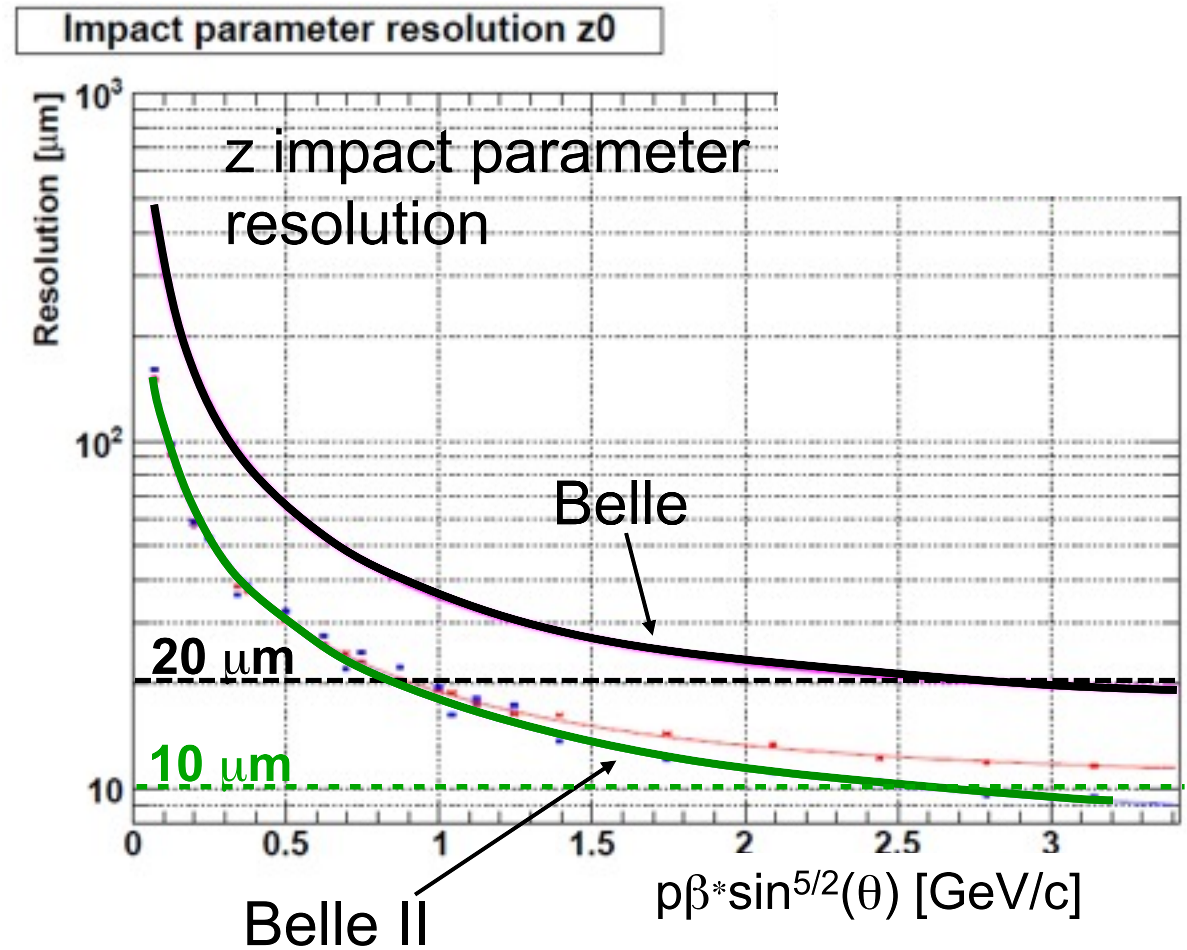
the Federal Ministry of Education and Research
Heinemannstr. 2, 53175 Bonn

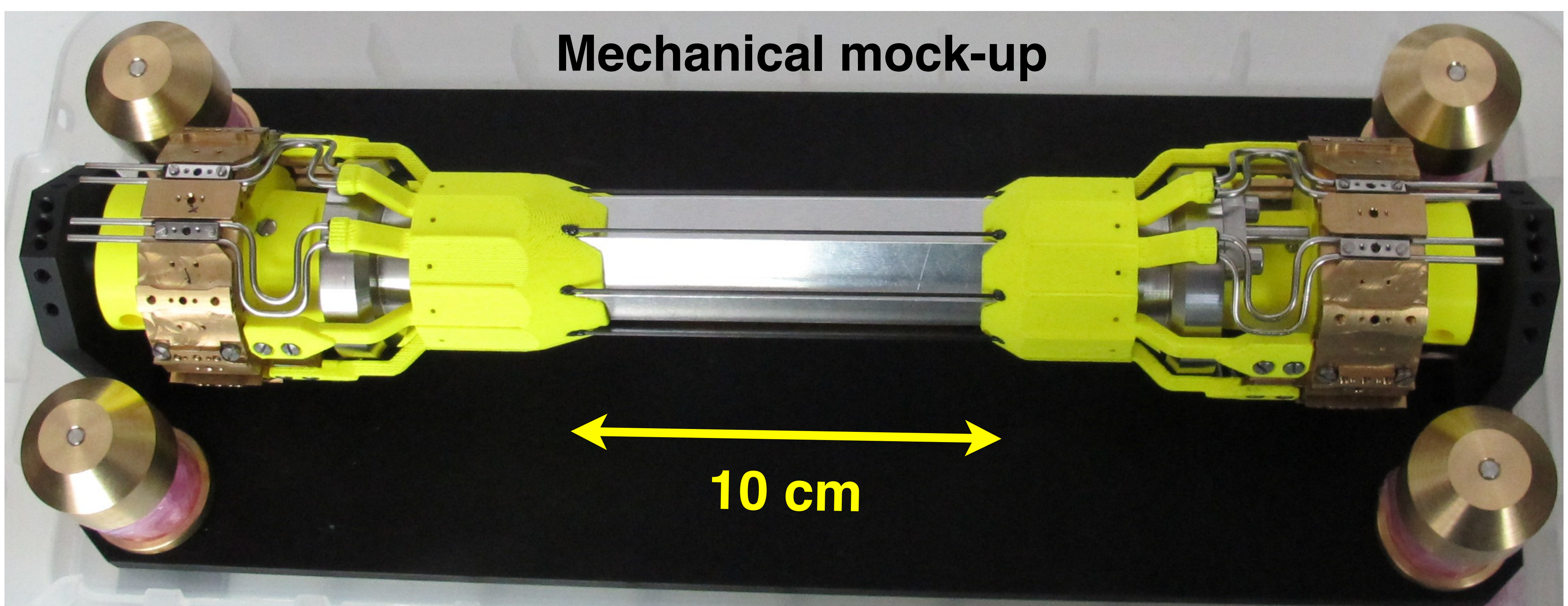
the Deutsches Elektronen-Synchrotron
Notkestraße 85, 22607 Hamburg

the Max-Planck-Gesellschaft
Hofgartenstr. 8, 80539 München

PXD Overview







2 layers: @1.4(2.2) cm

Thickness: **75 µm, 0.4%X_0**

Installation in Belle II: 08/2015

DEPFET Principle

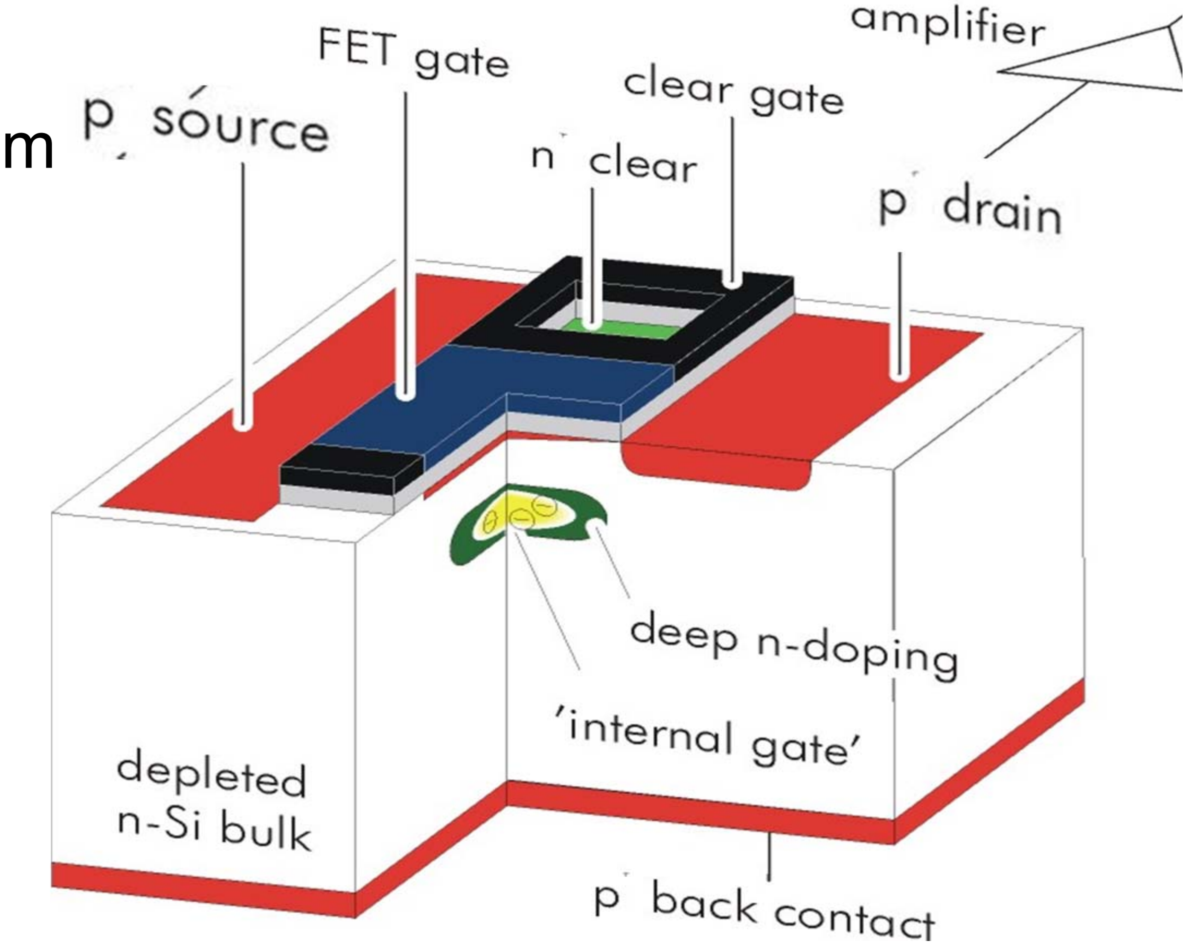
p-channel FET on a completely depleted bulk invented at MPI, produced at HLL

A deep n-implant creates a potential minimum for electrons under the gate (“internal gate”)

Signal electrons accumulate in the internal gate and modulate the transistor current (g_q ~ 400 pA/e^-)

Accumulated charge can be removed by a clear contact (“reset”)

Depleted p-channel FET



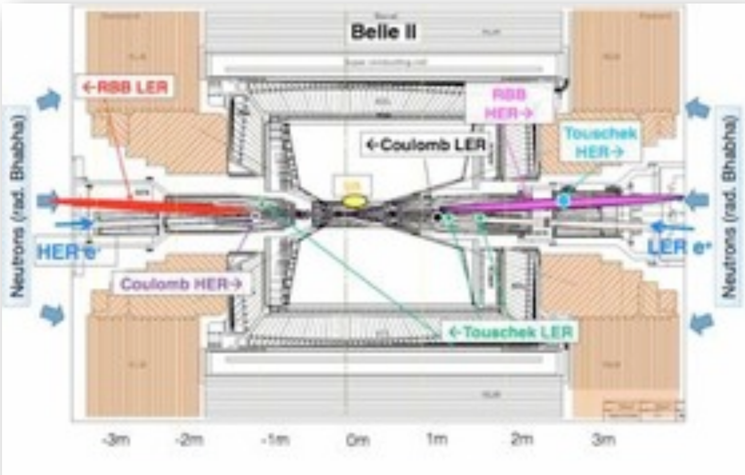
Fully depleted: → large signal, fast signal collection

Low capacitance,
internal amplification
→ low noise

Transistor on only during readout:
→ low power

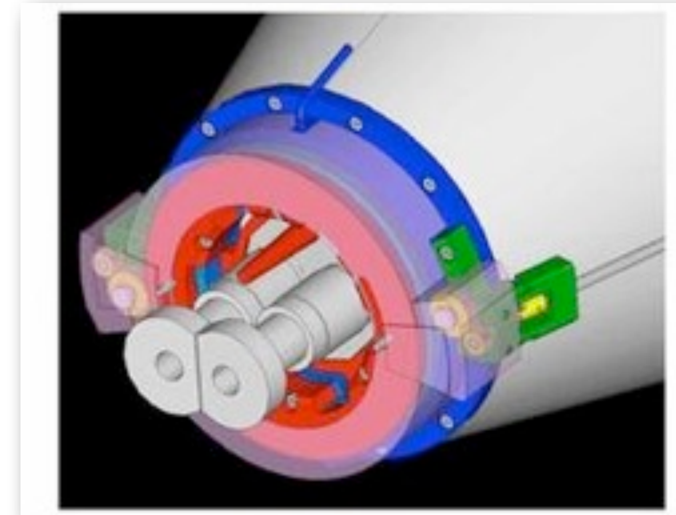
DESY Activities around Belle II PXD

SynRad Background MC

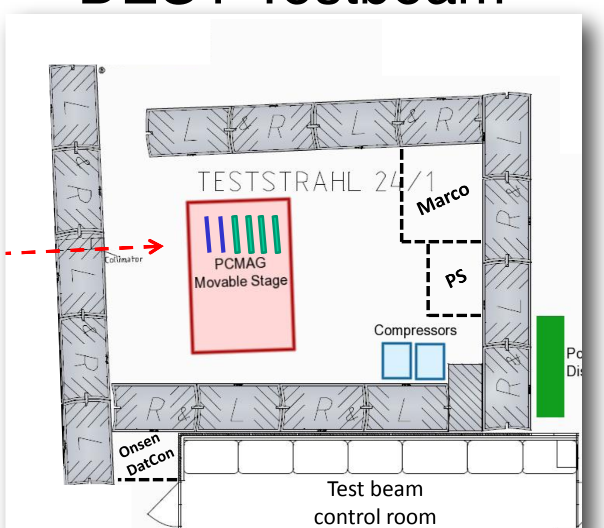


CO_2 System

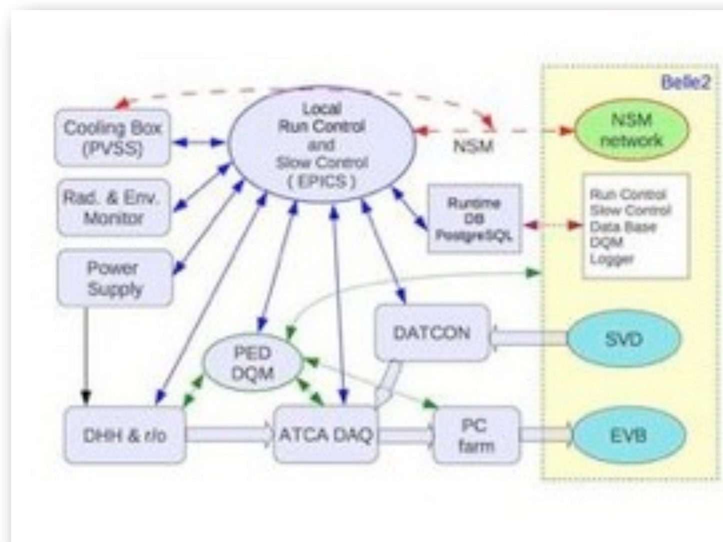
Remote Vacuum Connection



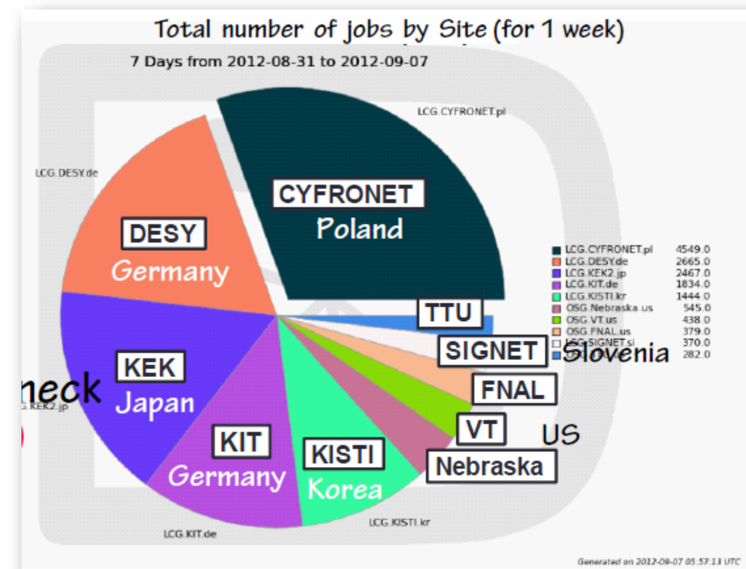
DESY Testbeam



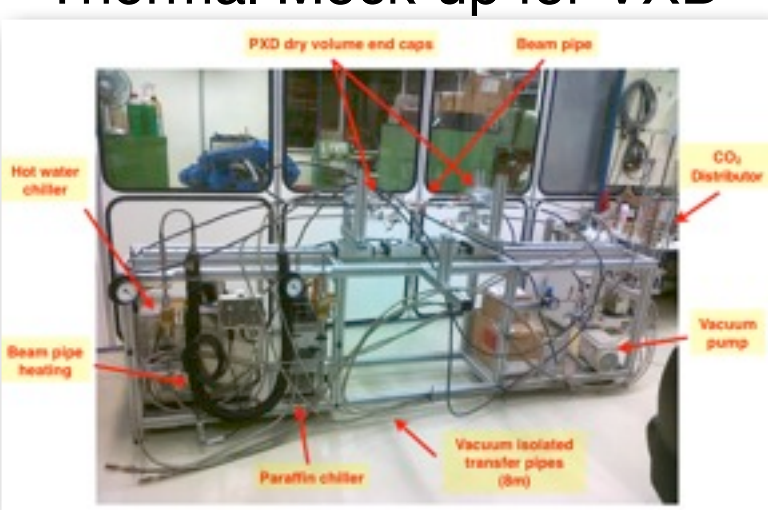
Slow Control & DAQ



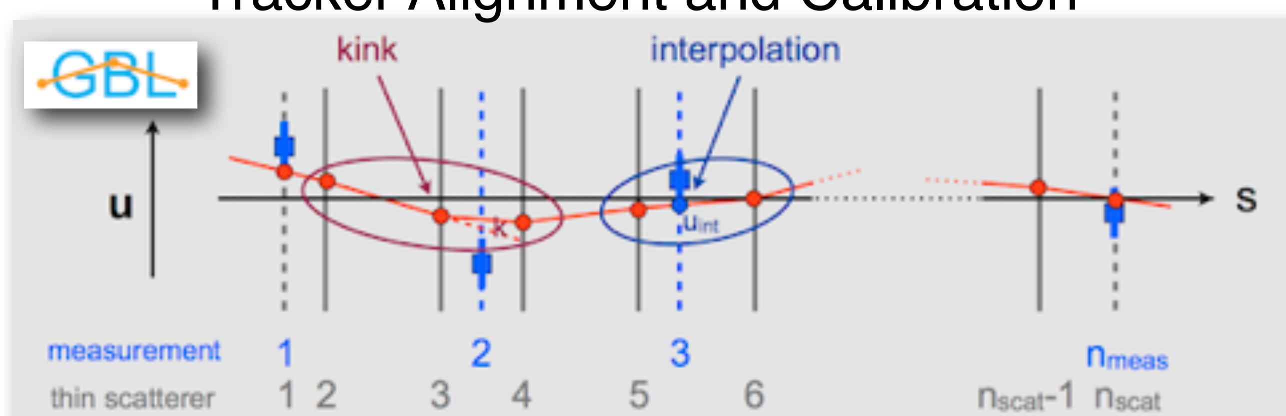
Grid/NAF/Data Preservation



Thermal Mock-up for VXD



Tracker Alignment and Calibration



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Summary

- SuperKEKB / Belle II offer very rich physics potential
  - start of physics run in 2016
  - collect 50 ab^{-1} by ≈ 2022
  - physics program complementary both to ATLAS/CMS and to LHCb

- Interesting and very challenging upgrade projects

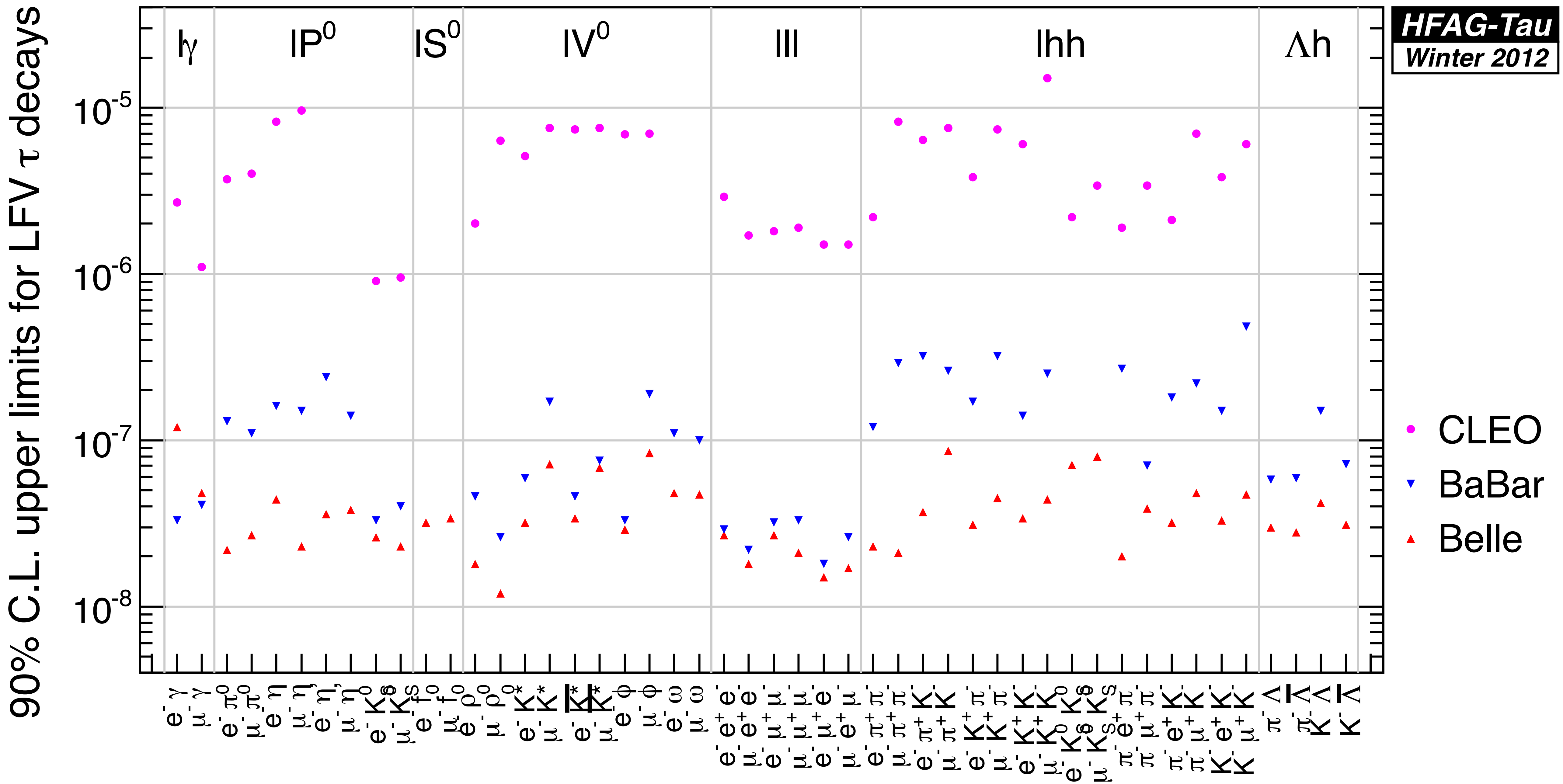
- DESY joined Belle II in November 2011 and Belle in July 2012
  - DESY activities center around PXD project as support for German university groups
  - despite having joined relatively late DESY has already gained quite some visibility by taking over responsibilities in several important areas
  - physics analyses of Belle data just starting at DESY as preparation for Belle II analyses
    - explore feasibility of Weinberg angle measurement
    - studies of CPV/mixing in charm sector
    - ...

Additional Material

Projected Sensitivities at SFF versus LHCb+

Observable/mode	Current now	LHC*b* (2017) 5 fb^{-1}	Super*B* (2021) 75 ab^{-1}	Belle2 (2021) 50 ab^{-1}	LHC*b* upgrade (10 years of running) 50 fb^{-1}	theory now
			τ Decays			
$\tau \to \mu\gamma$ ($\times 10^{-9}$)	< 44		< 2.4	< 5.0		
$\tau \to e\gamma$ ($\times 10^{-9}$)	< 33		< 3.0	< 3.7 (est.)		
$\tau \to \ell\ell\ell$ ($\times 10^{-10}$)	$< 150 - 270$	< 244	$< 2.3 - 8.2$	< 10	< 24	
			$B_{u,d}$ Decays			
BR($B \to \tau\nu$) ($\times 10^{-4}$)	1.64 ± 0.34		0.05	0.04		1.1 ± 0.2
BR($B \to \mu\nu$) ($\times 10^{-6}$)	< 1.0		0.02	0.03		0.47 ± 0.08
BR($B \to K^{*+}\nu\bar{\nu}$) ($\times 10^{-6}$)	< 80		1.1	2.0		6.8 ± 1.1
BR($B \to K^{+}\nu\bar{\nu}$) ($\times 10^{-6}$)	< 160		0.7	1.6		3.6 ± 0.5
BR($B \to X_s\gamma$) ($\times 10^{-4}$)	3.55 ± 0.26		0.11	0.13	0.23	3.15 ± 0.23
$A_{CP}(B \to X_{(s+d)}\gamma)$	0.060 ± 0.060		0.02	0.02		$\sim 10^{-9}$
$B \to K^*\mu^+\mu^-$ (events)	250	5000	10-15k	7-10k	65,000	-
BR($B \to K^*\mu^+\mu^-$) ($\times 10^{-6}$)	1.15 ± 0.16		0.06	0.07		1.19 ± 0.39
$B \to K^*e^+e^-$ (events)	165	400	10-15k	7-10k	5,000	-
BR($B \to K^*e^+e^-$) ($\times 10^{-6}$)	1.09 ± 0.17		0.05	0.07		1.19 ± 0.39
$A_{FB}(B \to K^*\ell^+\ell^-)$	0.27 ± 0.14		0.040	0.03		-0.089 ± 0.020
$B \to X_s\ell^+\ell^-$ (events)	280		8,600	7,000		-
BR($B \to X_s\ell^+\ell^-$) ($\times 10^{-6}$)	3.66 ± 0.77		0.08	0.10		1.59 ± 0.11
S in $B \to K^0_S\pi^0\gamma$	-0.15 ± 0.20		0.03	0.03		-0.1 to 0.1
S in $B \to \eta' K^0$	0.59 ± 0.07		0.01	0.02		± 0.015
S in $B \to \phi K^0$	0.56 ± 0.17	0.15	0.02	0.03	0.03	± 0.02
			B^0_s Decays			
BR($B^0_s \to \gamma\gamma$) ($\times 10^{-6}$)	< 8.7		0.3	$0.2 - 0.3$		0.4 - 1.0
A^s_{SL} ($\times 10^{-3}$)	-7.87 ± 1.96		4.			0.02 ± 0.01
			D Decays			
x Charm mixing	$(0.63 \pm 0.20\%$	0.06%	0.02%	0.04%	0.02%	$\sim 10^{-2}$
y	$(0.75 \pm 0.12)\%$	0.03%	0.01%	0.03%	0.01%	$\sim 10^{-2}$ (see above).
y_{CP}	$(1.11 \pm 0.22)\%$	0.05%	0.03%	0.05%	0.01%	$\sim 10^{-2}$ (see above).
$\lvert q/p \rvert$	$(0.91 \pm 0.17)\%$	10%	2.7%	3.0%	3%	$\sim 10^{-3}$ (see above).
arg$\{q/p\}$ (°)	-10.2 ± 9.2	5.6	1.4	1.4	2.0	$\sim 10^{-3}$ (see above).
			Other processes Decays			
$\sin^2\theta_W$ at $\sqrt{s} = 10.58\,\mathrm{GeV}/c^2$			0.0002			clean

Status Lepton Flavour / Number Violation for τ's



- 48 LFV/LNV modes searched
- All limits are below 10^{-7}, some are almost reaching 10^{-8}

$\overline{\text{MS}}$