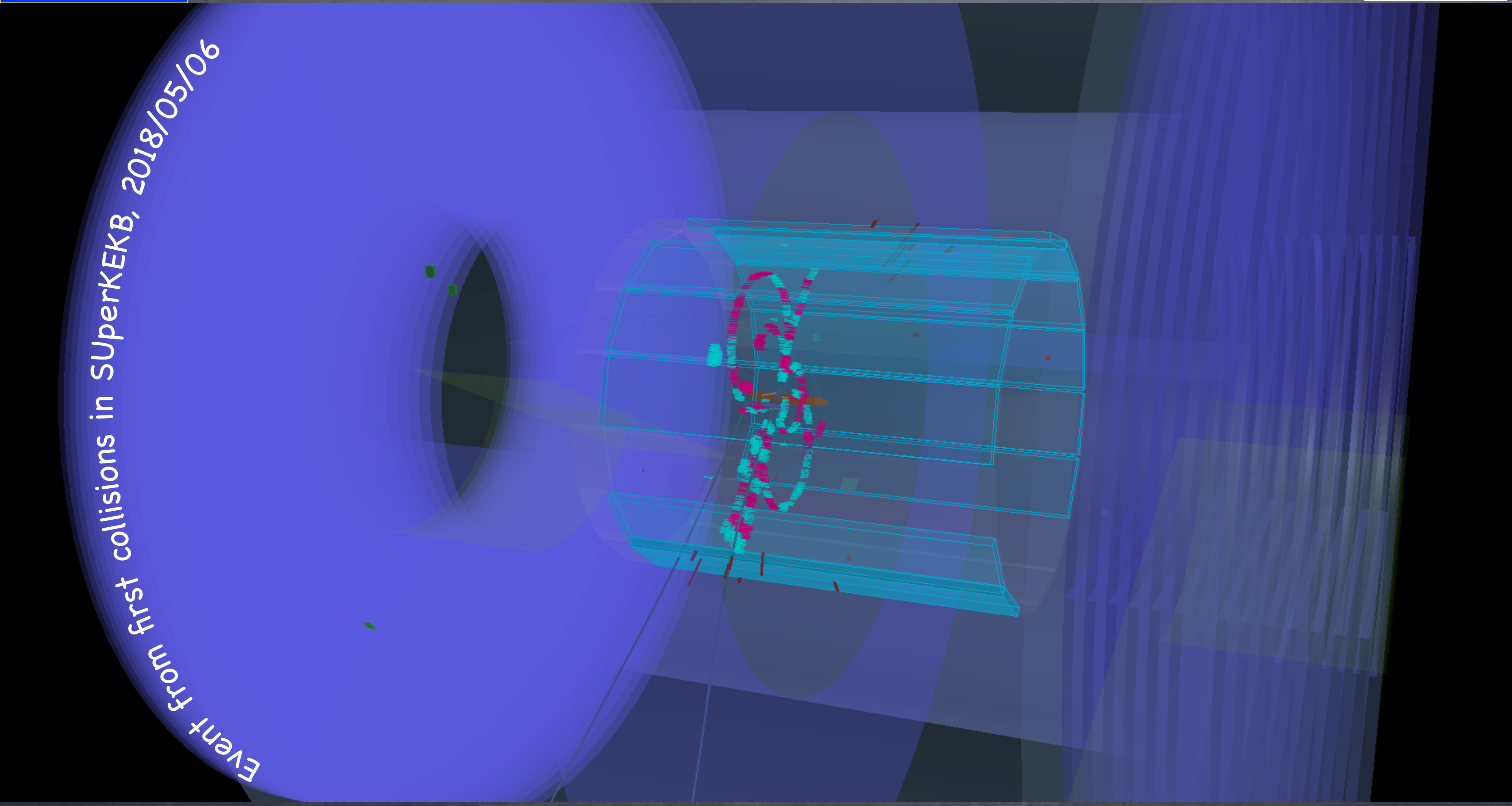
Physics Potential at the e^+e^- superKEKB-Factory

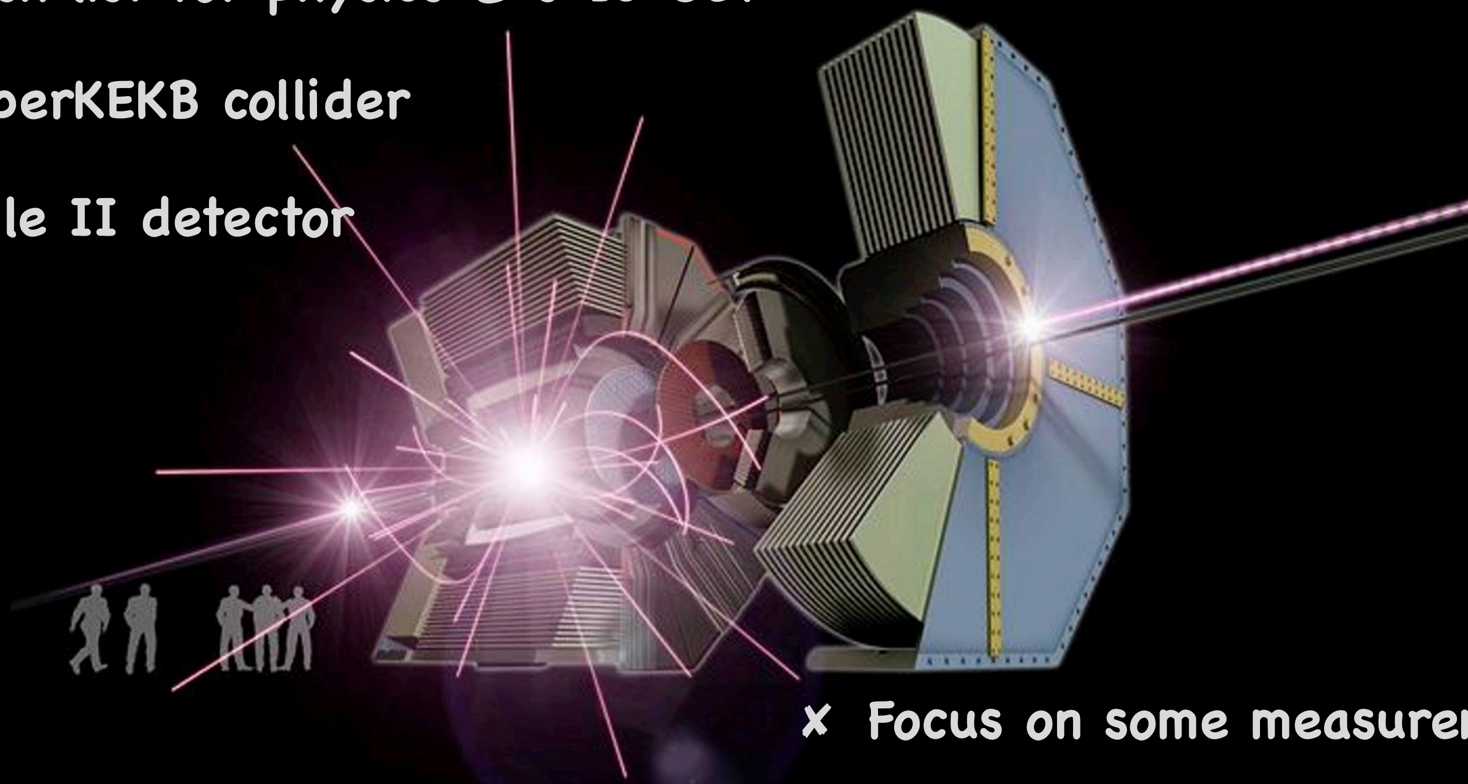


Jérôme Baudot
jerome.baudot@iphc.cnrs.fr

7th Linear Collider School
12 May 2018, Frauenhiemsee

Outline

- Legacy from B-factories & hot topics
- Wish list for physics @ s~10 GeV
- SuperKEKB collider
- Belle II detector



- Focus on some measurements
- Early physics program

Beyond SM effects at $\mathcal{O}(10)$ GeV

- "big" questions & flavor physics
- Whish list
- BaBar, Belle, LHCb legacy
- We have LHCb, why would we want another B-stuff ?

The "big" questions

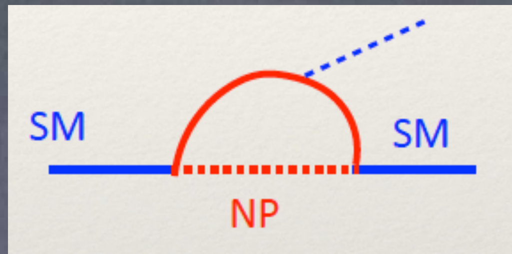
- Violations of known symmetry (ex: lepton flavour)
- New particles (fermions, bosons)
- New couplings (L-R symmetry, FCNC)
- Additional source of CP violation
- CKM matrix relation with mass

} Flavor physics

- Dark matter

- Strong force in binding hadrons

The quantum way

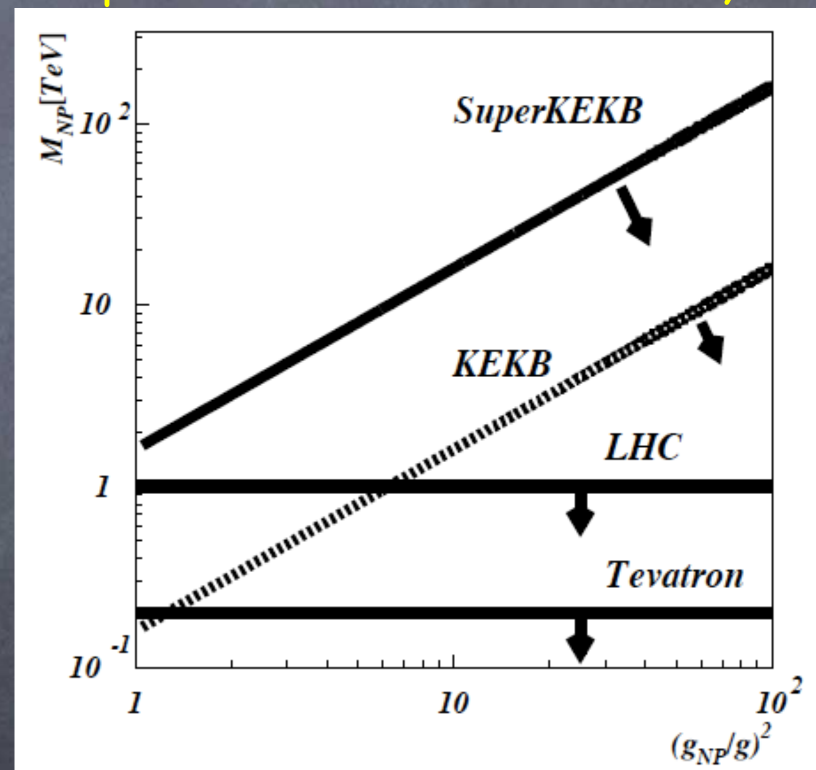
- **Loops** 

in the flavor sector

  - ➛ Effective lagrangian
    - Mass, coupling

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{g_{NP}}{\Lambda^2} O^{(6)}\,(\text{SM fields}) + \ldots$$

Simplistic scheme of discovery limit



- **Interest of rare processes**
  - Large modification expected from Beyond SM (BSM) wrt Standard Model (SM)
  - Not necessarily @ high energies

➡ LHCb, NA62, BES III, Belle II, …

The two frontiers

- **Energy frontier**
  - ➛ LHC & future LC or CC
  - ➛ Direct creation of BSM

- **Intensity frontier**
  - ➛ SuperKEKB
    (also LHC & future LC or CC)
  - ➛ Indirect effect of BSM

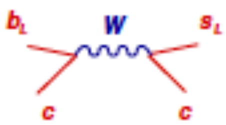
➢ How does BSM flavour coupling interfere with this naïve expectation?

Effective Field Theory

- Wilson development

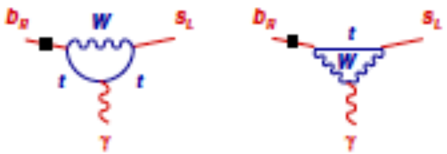
- CC (Fermi theory):

From J. MARTIN CAMALICH

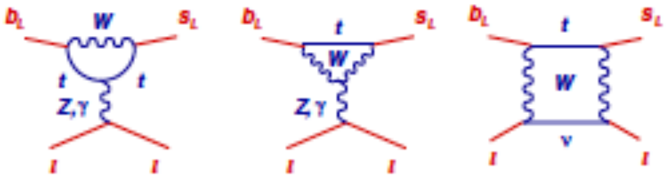


$$\Rightarrow \quad G_F V_{cb} V^*_{cs} C_2 \bar{c}_L \gamma^\mu b_L \bar{s}_L \gamma_\mu c_L$$

- FCNC:



$$\Rightarrow \quad \frac{e}{4\pi^2} G_F V_{tb} V^*_{ts} m_b C_7 \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$$



$$\Rightarrow \quad G_F V_{tb} V^*_{ts} \frac{\alpha}{4\pi} C_{9(10)} \bar{s}_L \gamma^\mu b_L \bar{\ell} \gamma_\mu (\gamma_5) \ell$$

- Wilson coefficients $C_k(\mu)$ calculated in P.T. at $\mu = m_W$ and rescaled to $\mu = m_b$

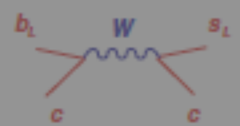
Complex !

- C_k are complex -> possible source of new CP-violated phase
- C_k(measured) = C_k(SM) + δC_k, with δC_k, standing for Physics Beyond SM

- Wilson development

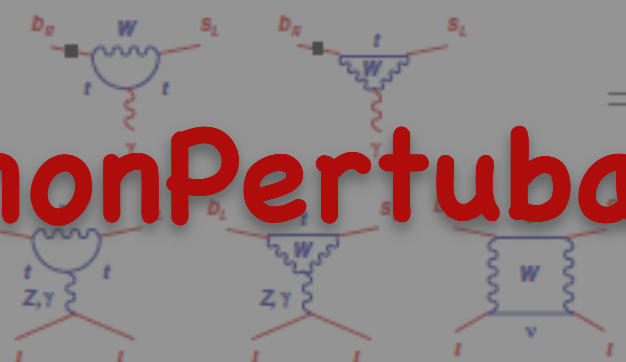
From J. MARTIN CAMALICH

- **CC** (Fermi theory):



$\Rightarrow \quad G_F V_{cb} V_{cs}^* C_2 \bar{c}_L \gamma^\mu b_L \bar{s}_L \gamma_\mu c_L$

- **FCNC**:



$\Rightarrow \quad \frac{e}{4\pi^2} G_F V_{tb} V_{ts}^* m_b C_7 \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$

nonPertubative QCD effects!

$\Rightarrow \quad G_F V_{tb} V_{ts}^* \frac{\alpha}{4\pi} C_{9(10)} \bar{s}_L \gamma^\mu b_L \bar{\ell} \gamma_\mu (\gamma_5) \ell$

- Wilson coefficients $C_k(\mu)$ calculated in P.T. at $\mu = m_W$ and rescaled to $\mu = m_b$

Complex !

- C_k are complex -> possible source of new CP-violated phase
- C_k(measured) = C_k(SM) + δC_k, with δC_k, standing for Physics Beyond SM

A wealth of processes of interest

- CP asymmetries (also in charm)
- Electroweak penguin
- V_{ub}
- Rare B, K decays
- Lepton flavor violation
- And others
  - Tauonic B decay
  - Dark sector

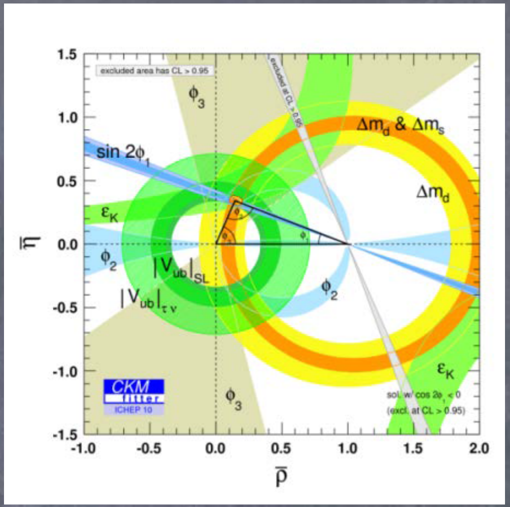
	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

Nucl. Phys. B830 (2010) 17-94

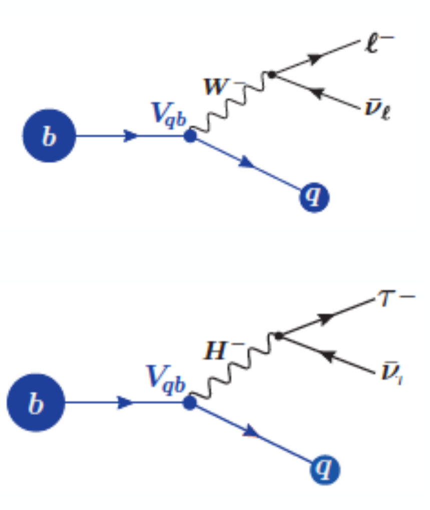
=> Identification of BSM model requires many measurements

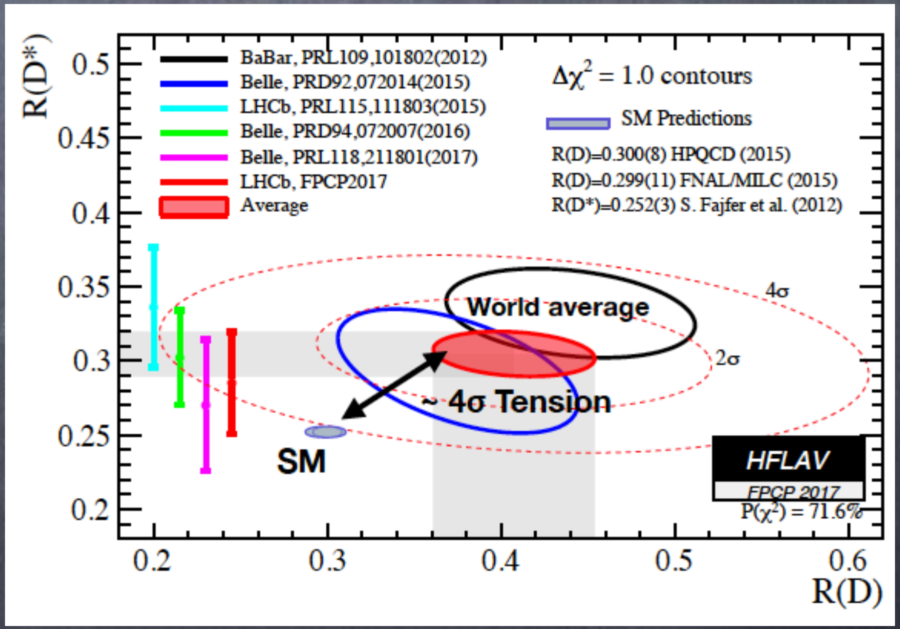
B-factories legacy



- **Data accumulated: ~1 ab^{-1} per factory**
  - PEP-II – BaBar, 1999-2008
  - KEKB – Belle, 1999-2010
- **CP violation measurements**
  - First at tree level b->ccbar transitions ($J/\Psi K_s$, 4%)
  - Then also at loop level b->s transitions (ΦK_s, $\eta' K_s$)
- **Tensions**
  - B->D$\tau\nu$ & B->D*$\tau\nu$
  - Also LHCb

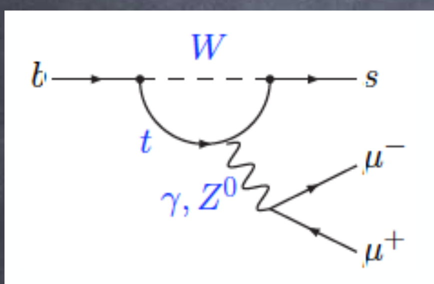
$$R = \frac{\mathcal{B}(b \to q\,\tau\,\bar\nu_\tau)}{\mathcal{B}(b \to q\,\ell\,\bar\nu_\ell)} \qquad \ell = e, \mu$$



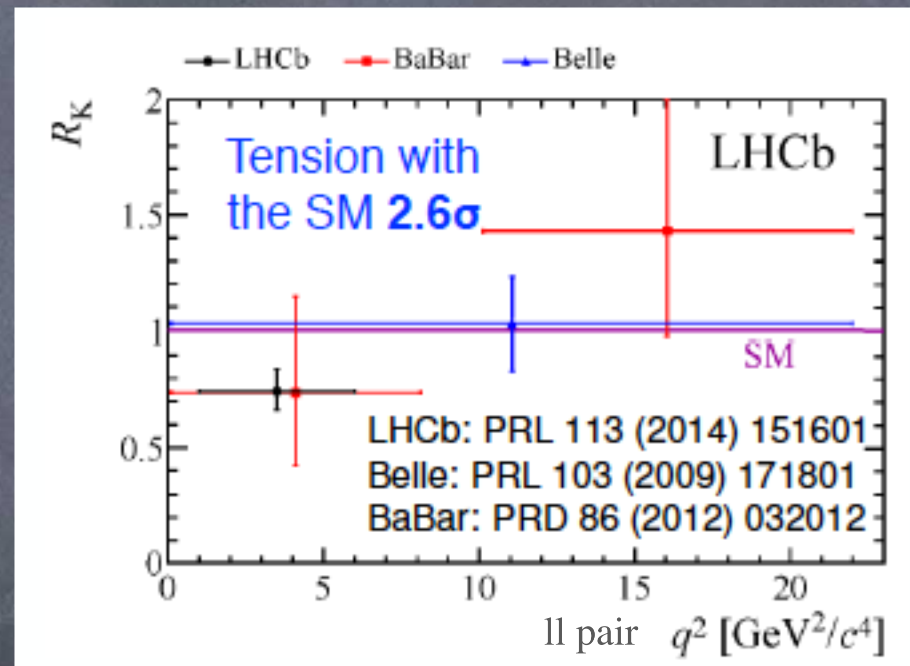


LHCb legacy

- **Data accumulated**
  - Run 1: 3 fb^{-1} + Run 2: 6 fb^{-1} (expected end of 2018)
  - Resume in 2021 with Run 3 for +15 fb^{-1} by 2024
- **Tensions in b->s transitions**
  - R(K*) = P(B->K*ee) / P(B->K*μμ)
  - Angular distribution of B->K*μμ



$$R = \frac{\mathcal{B}(b \to s\,\mu\,\mu)}{\mathcal{B}(b \to s\,e\,e)}$$



- **Tensions in leptonic transitions**
  - B->τμ (difference in estimatin from |Vub| wrt other channels)
    for tree level b->u / BaBar & Belle

Belle II - LHCb complementarity

LHCb

Initial states

- Extremely large Xsections for B_d, B_u, B_s, and Λ_b

Final states

- Crowdy events
- Large boost: easy vertexing
- Only self flavour tagging

Belle II

Initial states

- Mostly restricted to B_u, B_d
- B_s if gearing up to Y(5S)
- Initial energy known:
  - Missing mass, recoil techniques

Final states

- π^0, η, η', ρ, ν
- Isolated photons
- Low multiplicity (~1)
- Flavor tagging with other B
- Full event reconstruction
- Absolute Branching fraction (luminosity w Bhabha)

SuperKEKB collider & background

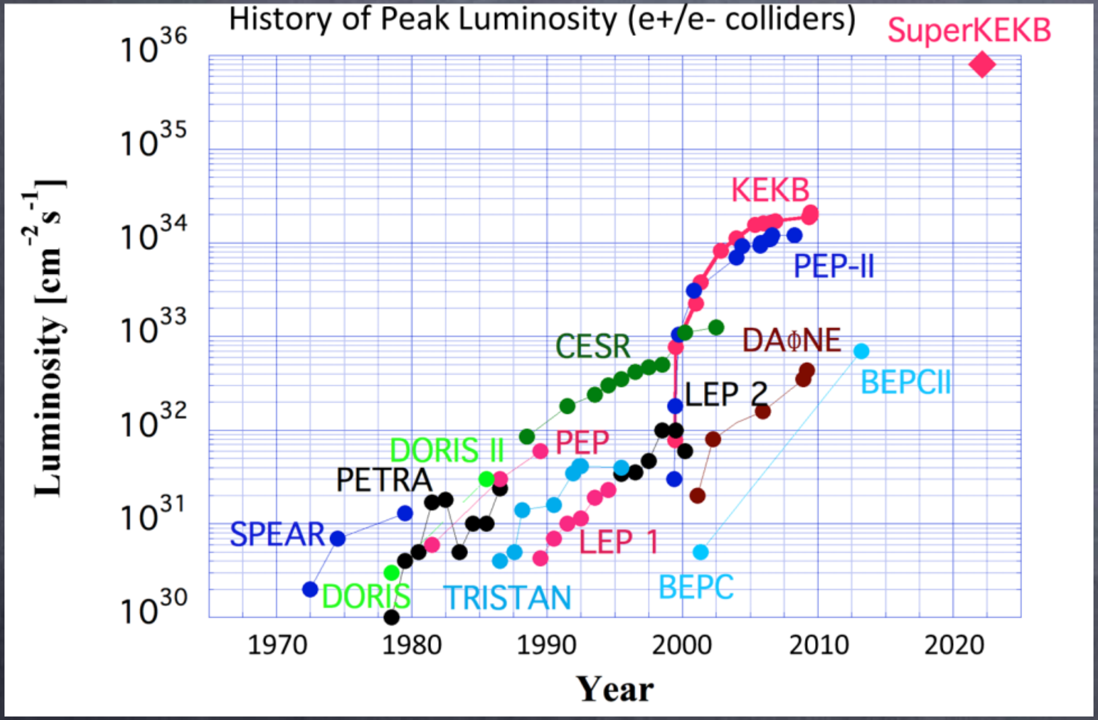
- Luminosity
- Asymmetric collisions
- Beam induced background

KEK @ Tsukuba, Japan

About luminosity

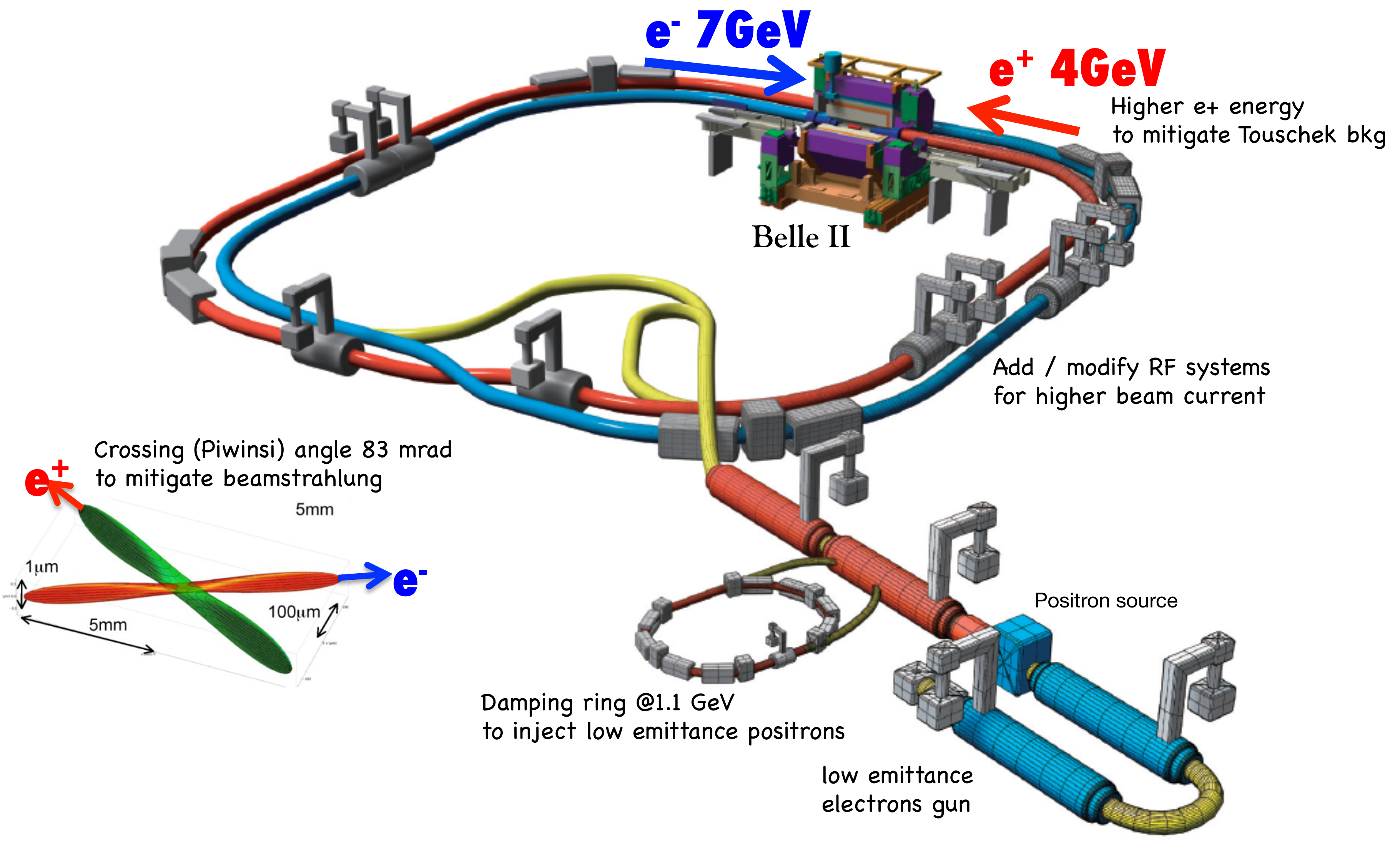
- Target instantaneous luminosity: $L = 8 \times 10^{35}\ cm^{-2}.s^{-1}$

$L \propto I^2 / (\sigma_x \times \sigma_y)$

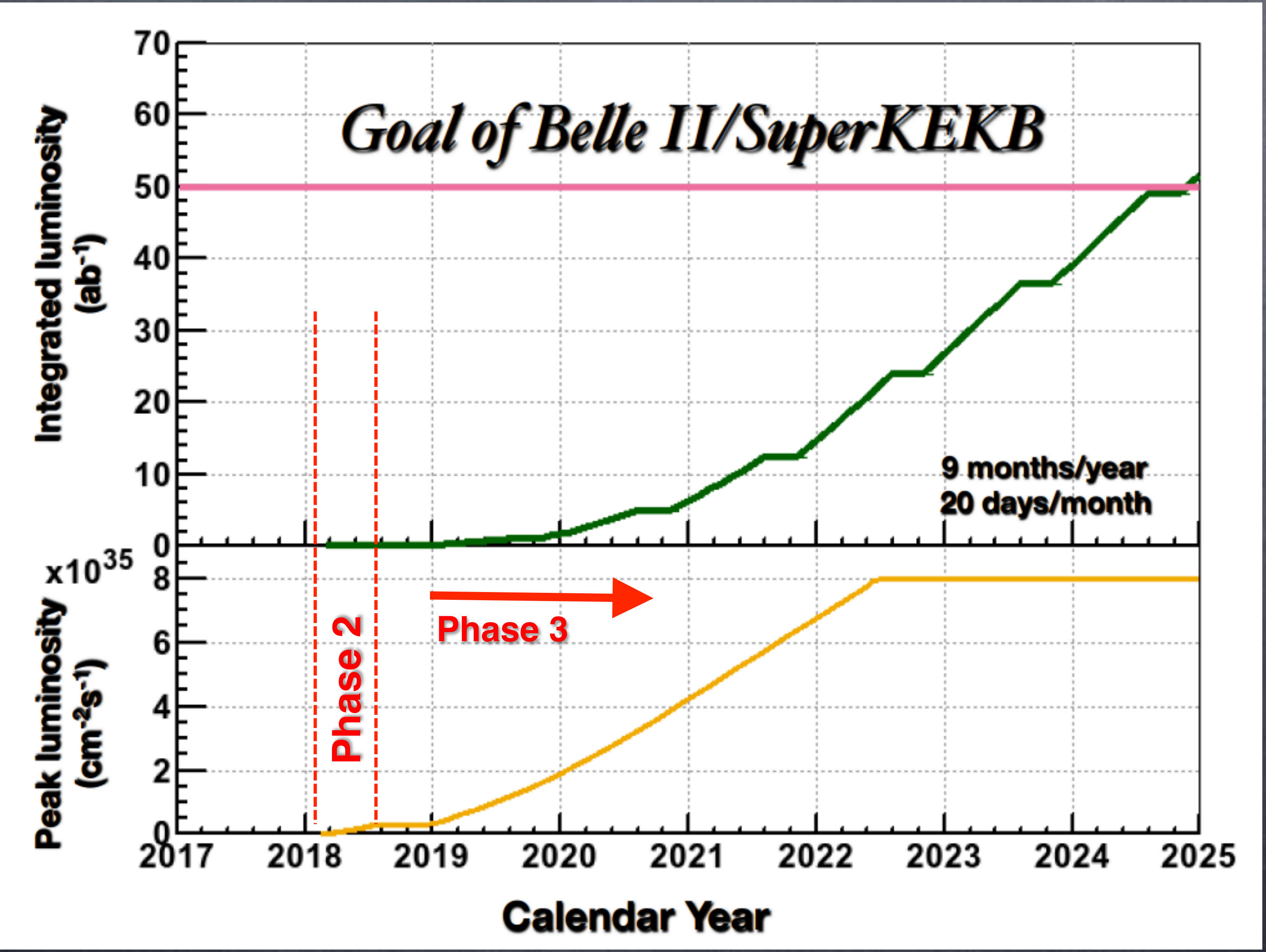


- KEKB → SuperKEKB
  - Currents I x2
    - I_{e+}=3.6A, I_{e-}=2.6 A
  - Beams size σ_y /20
    - $\sigma_x \times \sigma_y$ ~ 10μm × 60 nm
  - Crossing angle ϕ x4
    - ϕ = 83 mrad

➡ lumi x 40

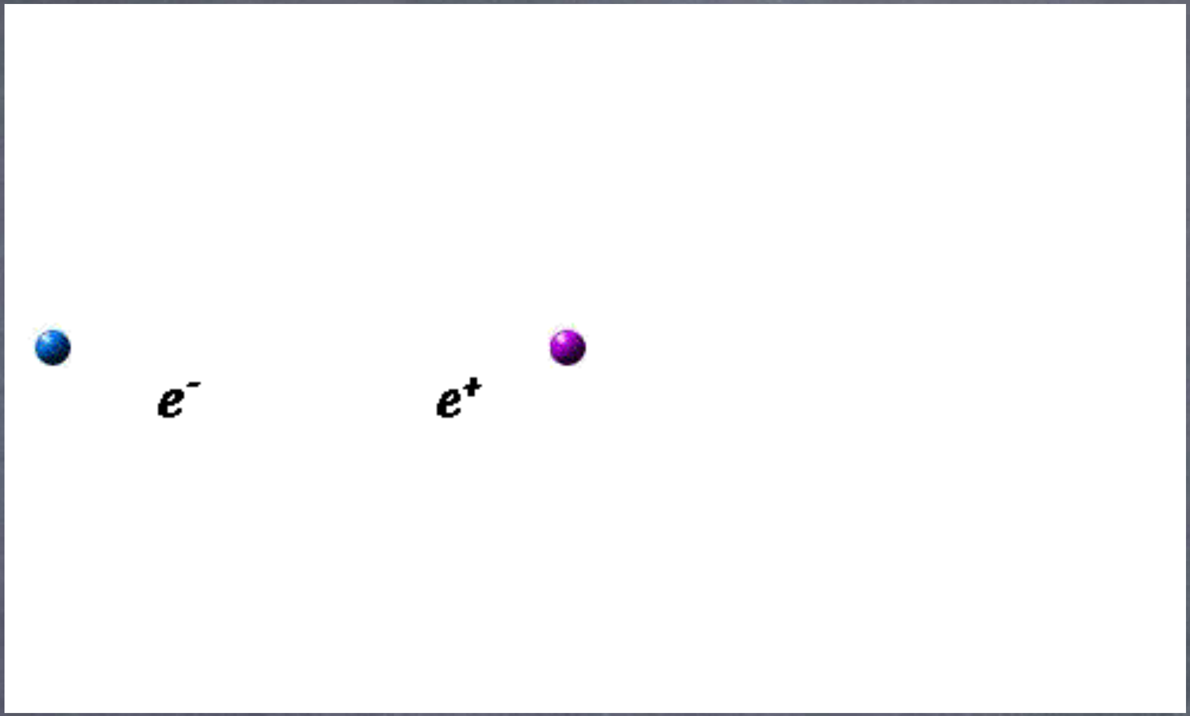

e- 7GeV
e+ 4GeV
Higher e+ energy
to mitigate Touschek bkg
Belle II
Add / modify RF systems
for higher beam current
Crossing (Piwinsi) angle 83 mrad
to mitigate beamstrahlung
e+
5mm
1μm
5mm
100μm
e-
Positron source
Damping ring @1.1 GeV
to inject low emittance positrons
low emittance
electrons gun

Running scenario



First beams in 2016 = Phase 1

$e^+ + e^-$ collisions @ Y(4S)



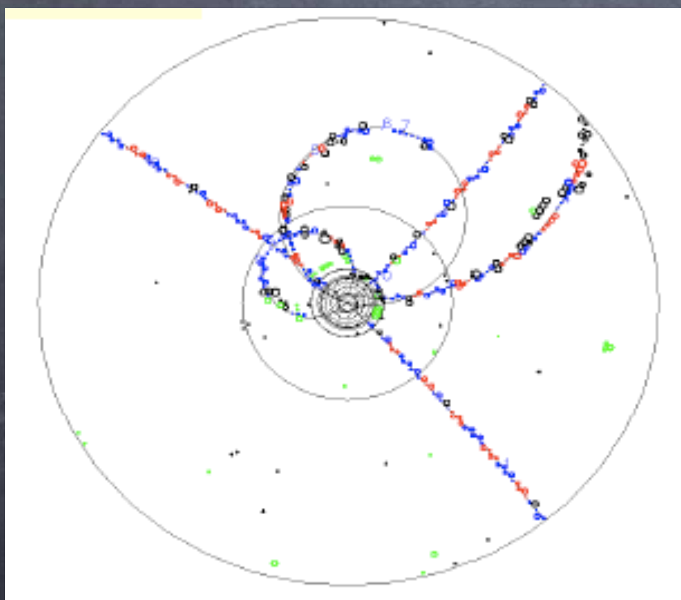
- **What is the energy asymmetry for ?**
  - Boost the B-Bbar syste and allows for Time Dependent Asymmetry measurements
- **Why cdm energy exactly Y(4S) mass**
  - Intricate the two B mesons
  - Avoid fragmentation regime for qq pairs

Beam induced background

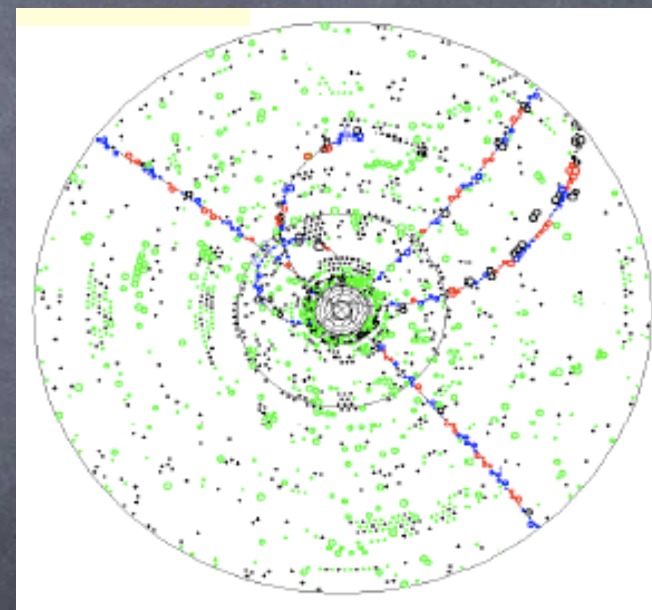
- ✘ **Luminosity increase has a cost**
  - ➛ Parasitic particles from beam x10 to x20

} Detector upgrades required
- Faster
- Tougher
- Higher precision

Belle



Belle II



➡ Similar effects for all $e^{+}+e^{-}$ machines: ILC, CLIC, CEPC, FCC-ee …

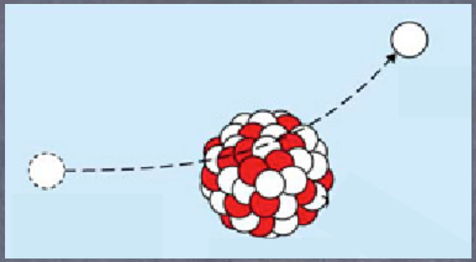
. .. but "details" are different (energy, colliding scheme)

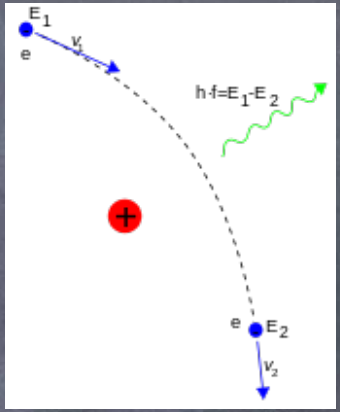
The physics of beam background

✘ Single beam effects

- ➣ Touschek: intra-beam scattering
  - Prob ∝ $I^2_{bunch} \times N_{bunch} / (\sigma_x \times \sigma_y) / E^3_{beam}$

- ➣ Beam gas (vacuum residue)
  - Prob ∝ $I^2 \times$ pressure

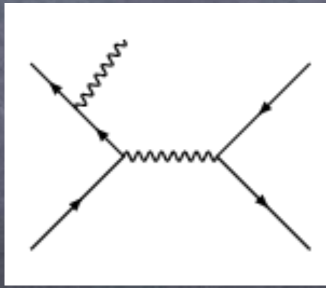




- ➣ Synchrotron radiation
  - Power ∝ E^4_{beam} / curvature

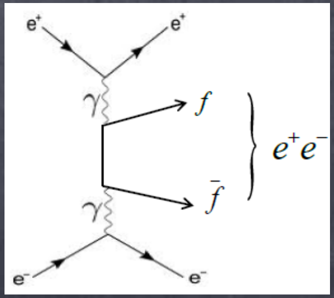
✘ Beam-beam effects (QED)

- ➣ Radiative Bhabha scattering
  - σ ~ 50 nb



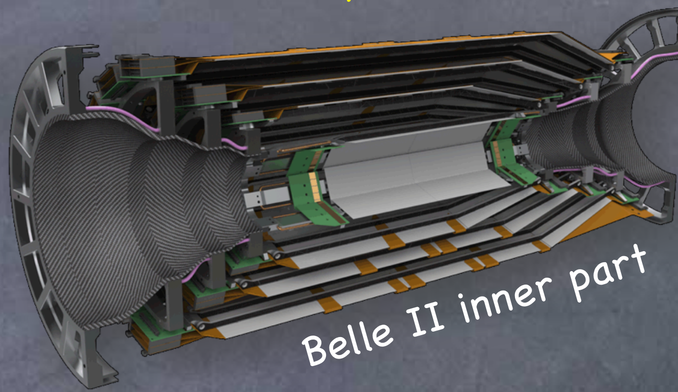
Both Prob ∝ Lumi

- ➣ Pair creation by two photons interactions
  - σ ~ 10^7 nb

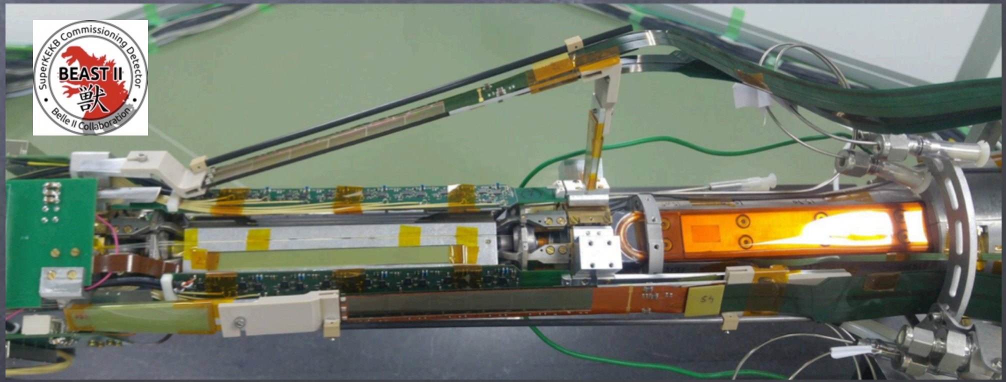


Control of the beam background

- **Phase 2 goals (2018 run)**
  - Validate background understanding @ 1/100 to 1/20 of max luminosity
  - Comparison measurement – simulation
  - Green light for final silicon det. installation
- **Dedicated detectors = BEAST**
  - 1 sector equipped with final Si sensors
    - Double sided strips + DEPFET pixels
  - Dose monitoring
    - PIN-diodes
    - Diamond sensors
  - Charged particle & Synchrotron
    - ATLAS-pixel
    - ILC-pixel PLUME
  - Neutron rate
    - Micro-TPC
    - He3-volume
  - Time structure
    - Fast scintillator + SiPM (ILC-calorimetry)



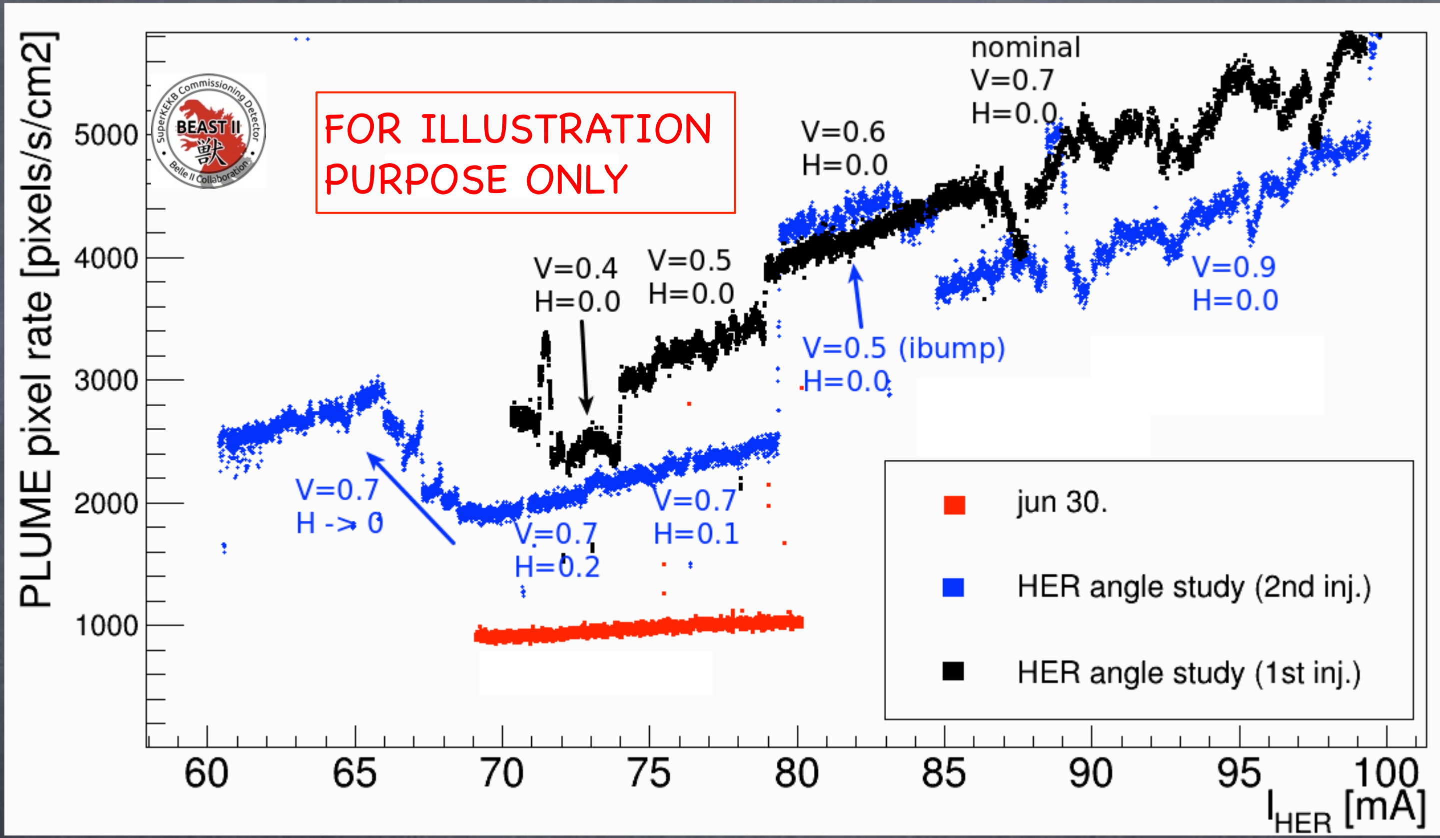
replaced by



Note: the rest of BELLE II is there!

SuperKEKB runs since March 16th

- Already various beam-background studies

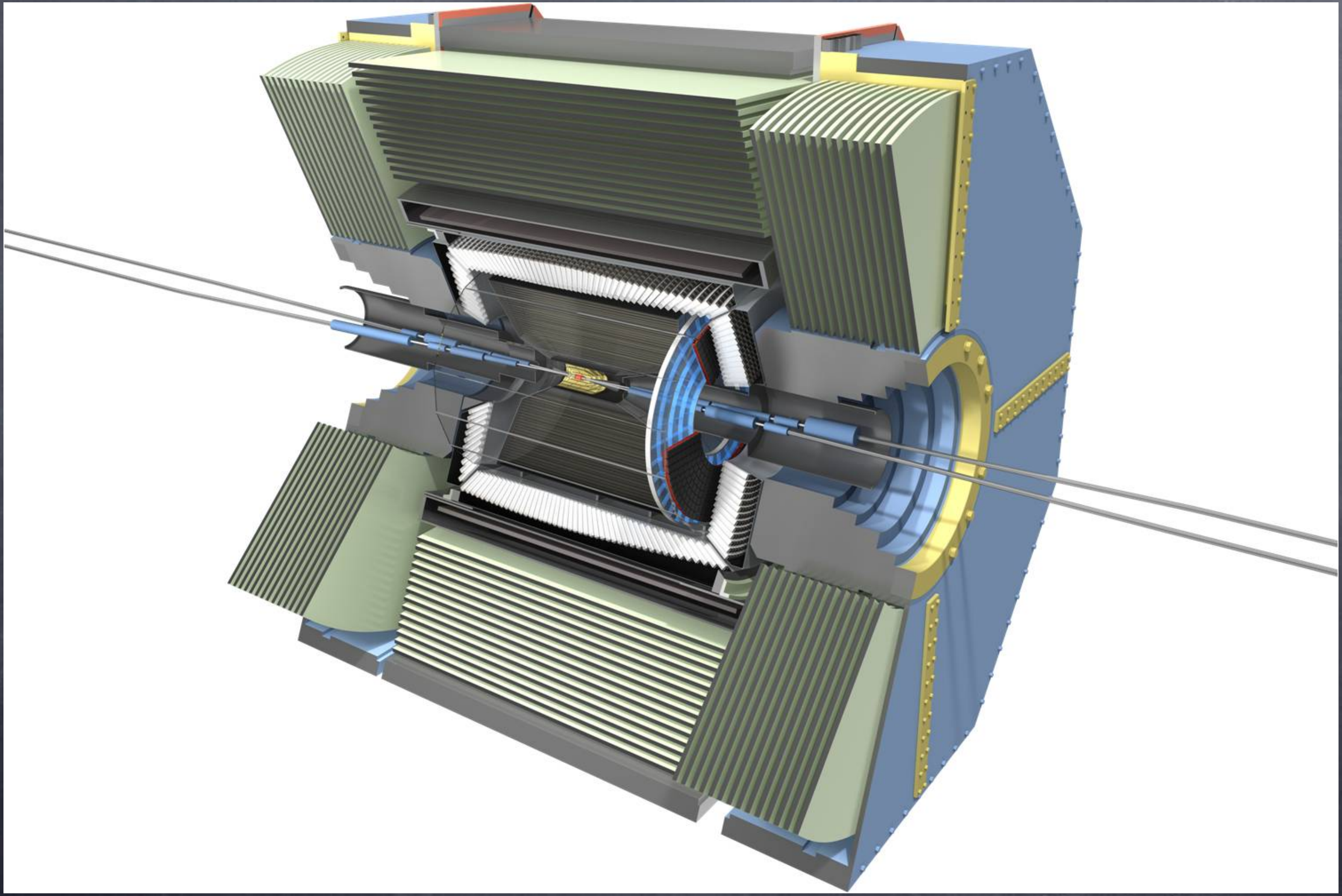


- **FIRST COLLISIONS recorded May 6th**
  - Luminosity in the 10^{31} -10^{32} cm^{-2}/s range, keeps increasing
  - Regular luminosity runs every day…expect fb^{-1} to accumulate in June-July

Belle II detector

- Extremely brief overview

$7.4 \times 7.1 \times 8\ m^3$

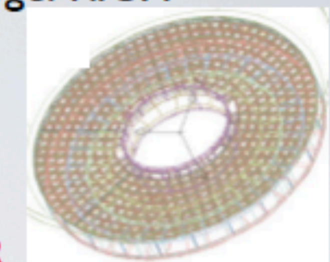


Le détecteur Belle-II

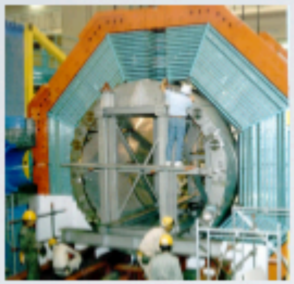
7.4 m × 7.1 m

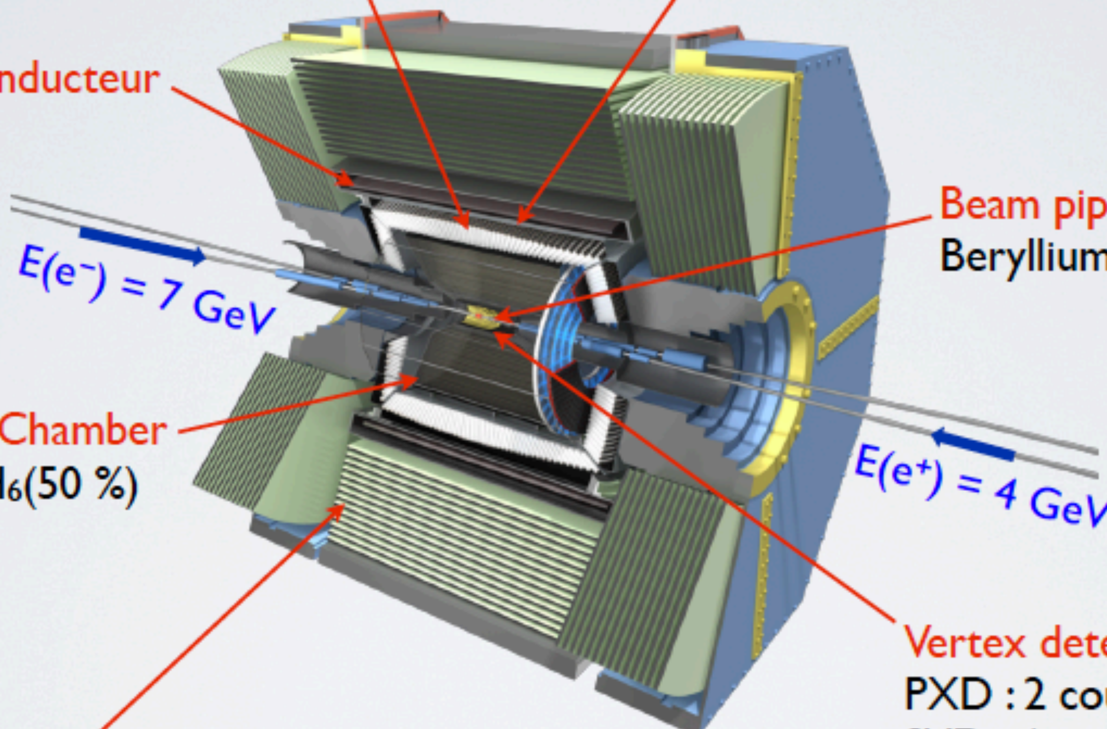
Calorimètre EM
barrel : CsI(Tl)
end-caps : pur CsI

Particle-Id
barrel : Time-of-Propagation
forward : focusing Aerogel RICH



Solénoïde supraconducteur

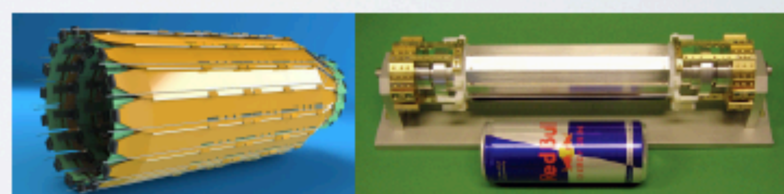




Beam pipe @IR
Beryllium, rayon = 1 cm

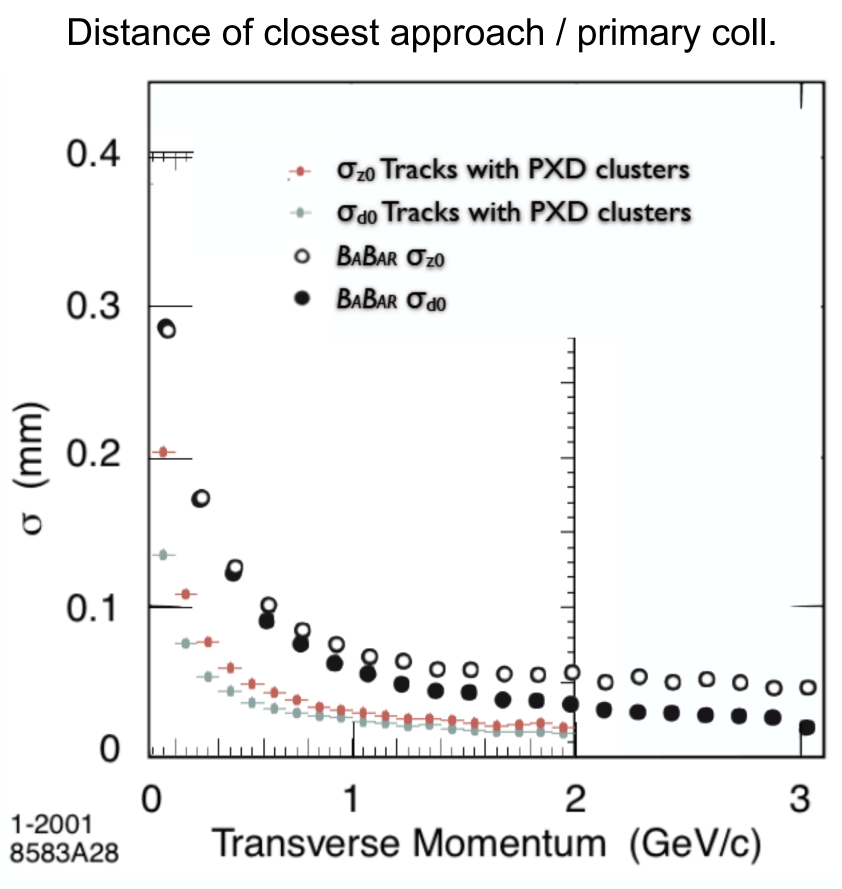
Central Drift Chamber
He(50 %):C_2H_6(50 %)

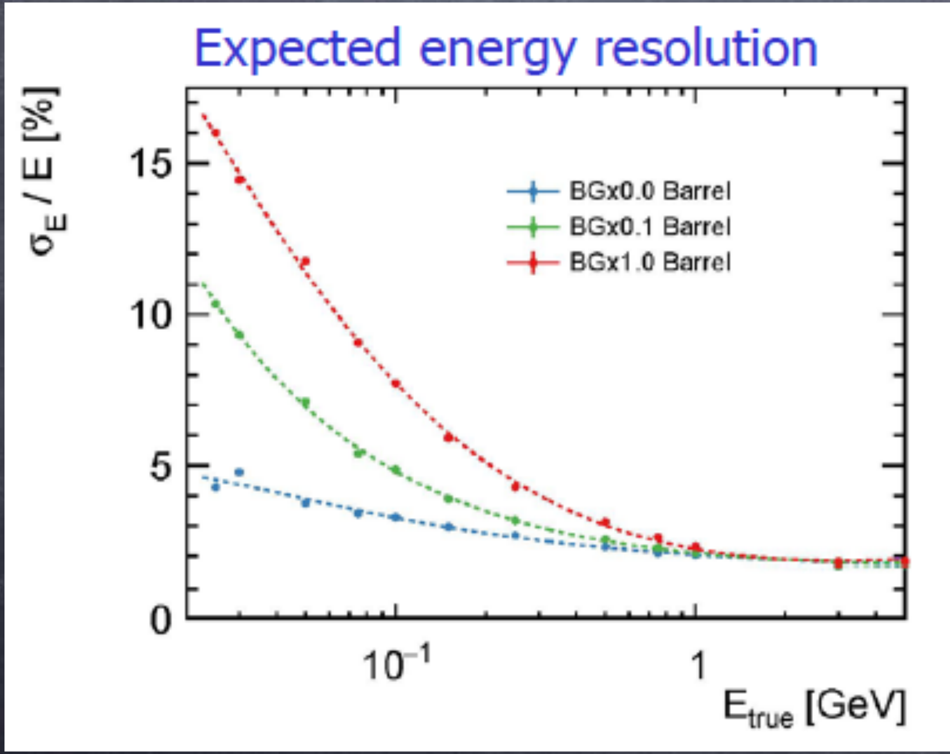
Vertex detector
PXD : 2 couches pixels DEPFET
SVD : 4 couches strips double-faces



K_L and μ detector
outer barrel : RPC
end-caps + inner barrel : scintillateur + Si-PM

Some simulated performances

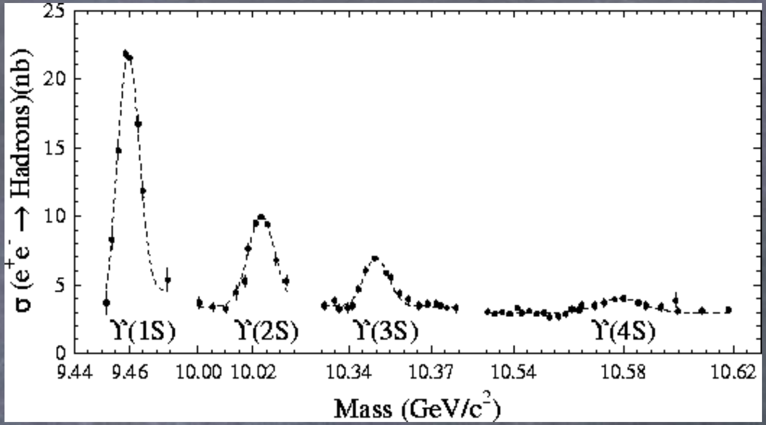




Statistics for physics

- B factories at $\mathcal{O}(10)$ GeV

$$e^+ + e^- \to \Upsilon(4S) \to B\bar{B}$$



  - per 1 ab^{-1} of integrated luminosity:
    - 1.1 $\times 10^9$ $b\bar{b}$
    - 1.3 $\times 10^9$ $c\bar{c}$
    - 0.9 $\times 10^9$ $\tau^+\tau^-$

- From the 2000s
  - BaBar (SLAC)
    - 454 fb^{-1}
  - Belle (KEK)
    - 711 fb^{-1}

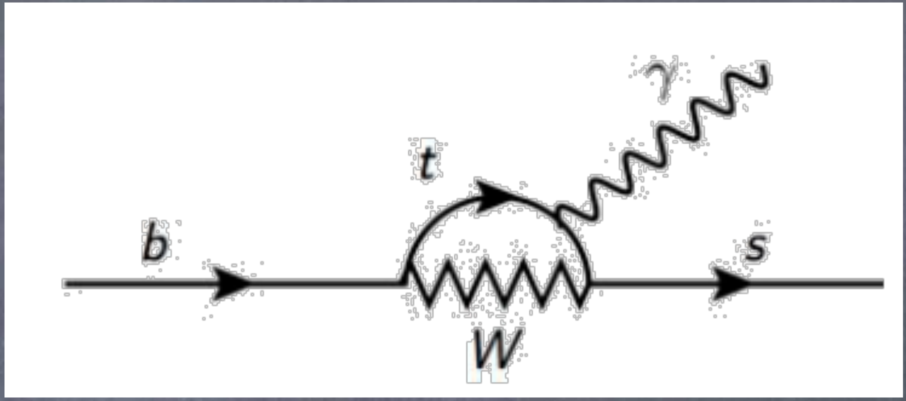
- Expected in the 2020s…
  - Belle II SuperKEKB
    - 50 ab^{-1}
  - 3.6% of luminosity for Y(nS), n≠4

Detailed focus

- Test of V+A coupling in radiative penguins B decays

Photon polarisation to sign BSM

✗ Radiative penguin diagram



- ➛ Penguin diagram ⟺ loop
  - Sensitivity to new particle / coupling
- ➛ Radiative decay ⟺ photon polarisation
  - Sensitivity to V-A structure

✗ The photon polarisation is constrained in SM: why ?

- ➛ 2 basic ingredients
  - Only left-handed fermions are coupled to W
  - spin S and its projection S_z are both conserved
- ➛ 2 "tricks"
  - Helicity = chirality
  - Possibility to flip helicity with probability ∝ mass

$$\frac{P(b_L \to s_R + \gamma_R)}{P(b_R \to s_L + \gamma_L)} \approx \frac{m_s}{m_b} \sim 0$$

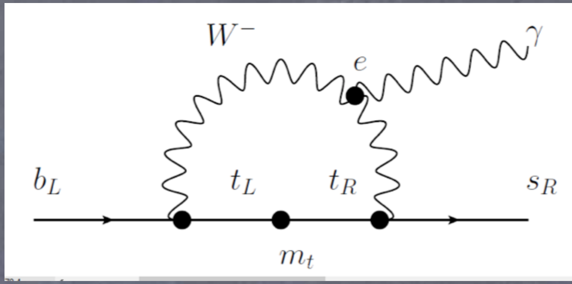
⇓

$$B^0(\bar{b}d) \to \text{Right-handed } \gamma$$

$$\bar{B}^0(b\bar{d}) \to \text{Left-handed } \gamma$$

Expectation on photon polarisation

- **New physics with Left-Right symmetry**
  - Helicity flip on top quark line! $P(t_L \rightarrow t_R) \propto m_t >> m_s$
  - Non-zero probability for right-handed γ in anti-B decay

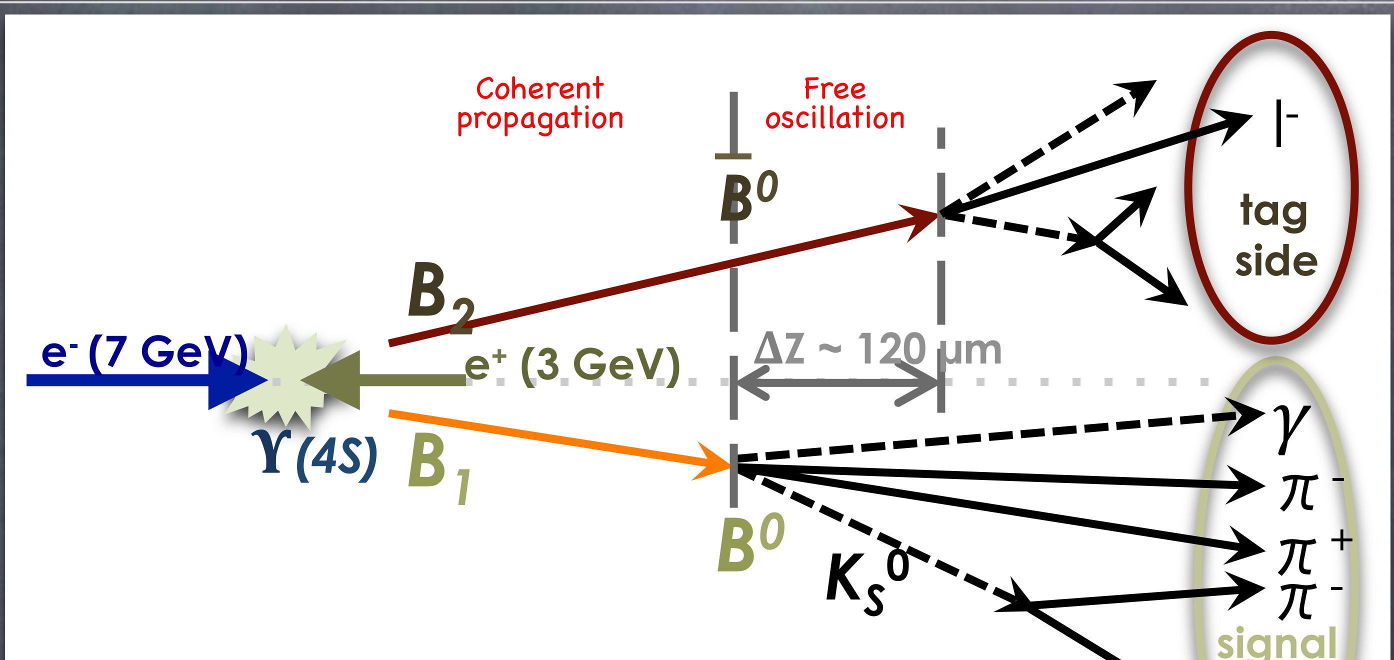


- **How can we access the photon polarisation?**

- **Direct measurement with 3 body decays**
  - $B^+ \to K^+\pi^-\pi^+\gamma$
  - Requires a lot of data & Dalitz analysis of $K\pi\pi$ resonnances

- **Indirect measurement in time dependent CP violation**
  - Indirect CP violation requires interference in final states of f_B and f_{Bbar}
  - In SM are different since not the same photon polarisation => NO Cpviolation
  - New physics might change the result within $\lesssim$ 10%

Time dependent asymmetries



$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to f) - \Gamma(B^0(t) \to f)}{\Gamma(\bar{B}^0(t) \to f) + \Gamma(B^0(t) \to f)}$$

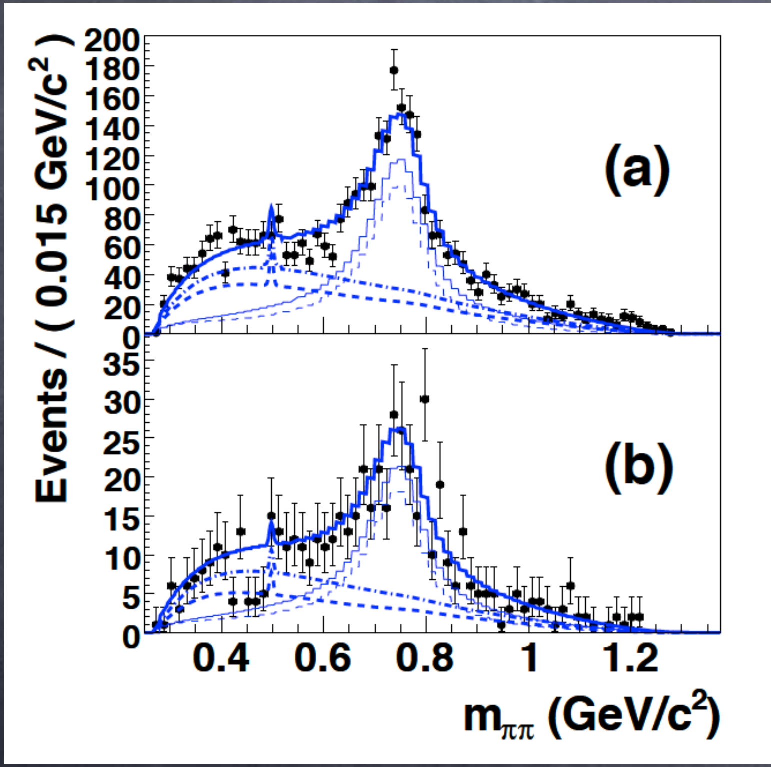
- **From detector**
  - Identify final state on signal side (B1)
  - Measure Δt from Δz and B-momentum ⬅ excellent vertex detector
  - Tag B_2 to get B_1 flavor ⬅ complex algorithm (machine learning)

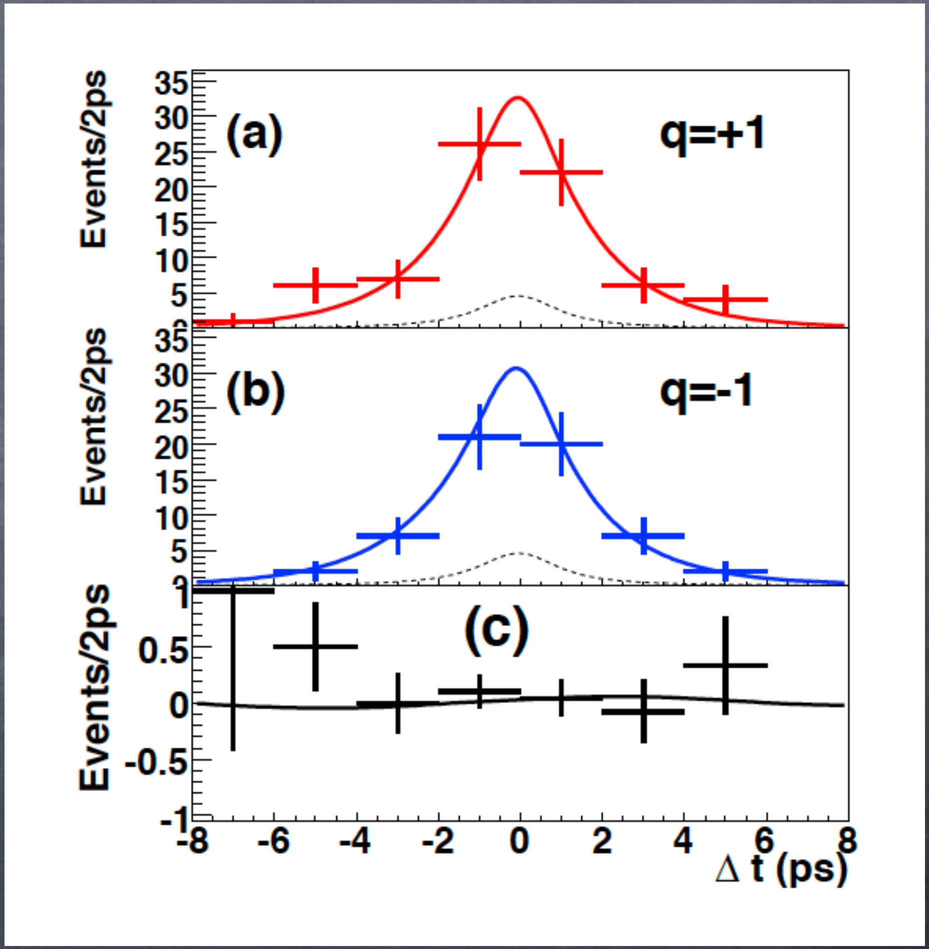
REQUIRED

Example of Belle analysis

PRL101 (2008)

$$B^0 \to K_1(1270) + \gamma \to K_S^0 + \pi^+ + \pi^- + \gamma$$





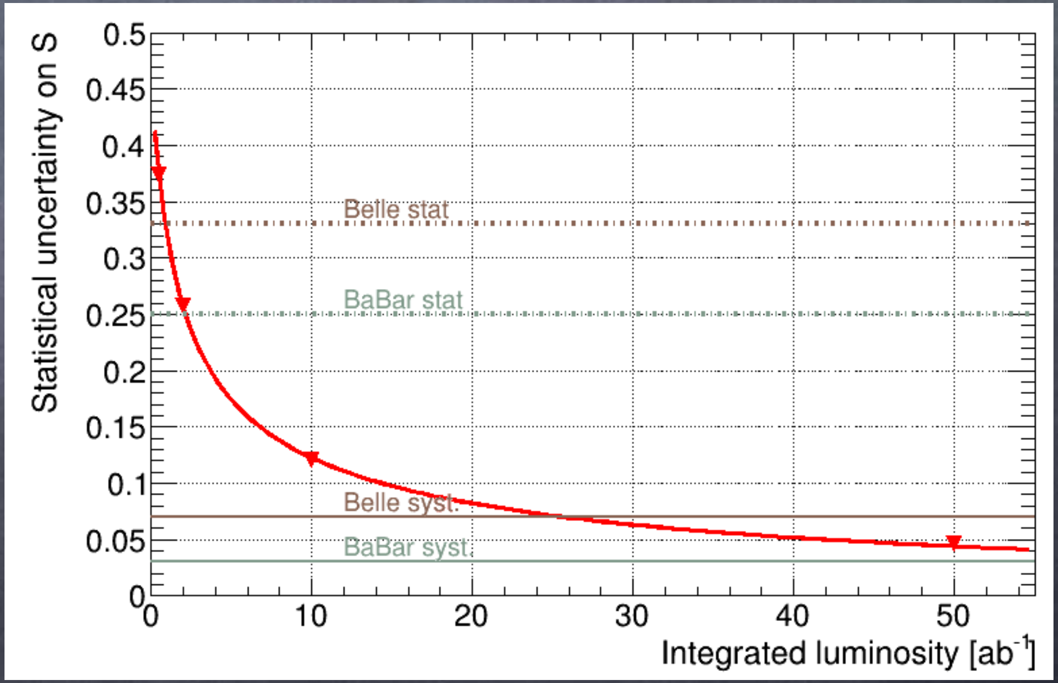
$$K_1(1270) \to \pi^+ + \pi^-$$

Time dependent asymmetries

- **Golden channel $B^0 \to K_s \pi^0 \gamma$**
  - LHCb cannot compete (π^0)
  - Uncertainty: statistical ~ systematics already around 10 ab^{-1}
  - Difficult part, vertex resolution with only K_s => exploit known boost direction
  - Relative uncertainty expectation @ 50 ab^{-1}: 3%

- **Also possible with $B^0 \to K_s \pi^+ \pi^- \gamma$**
  - Easier vertex resolution with
  - Statistics lower
  - Might be difficult to interpret
    - Need connection with $B^+ \to K^+ \pi^- \pi^+ \gamma$

Toy Monte Carlo study, S.Bilokin et al. 2018



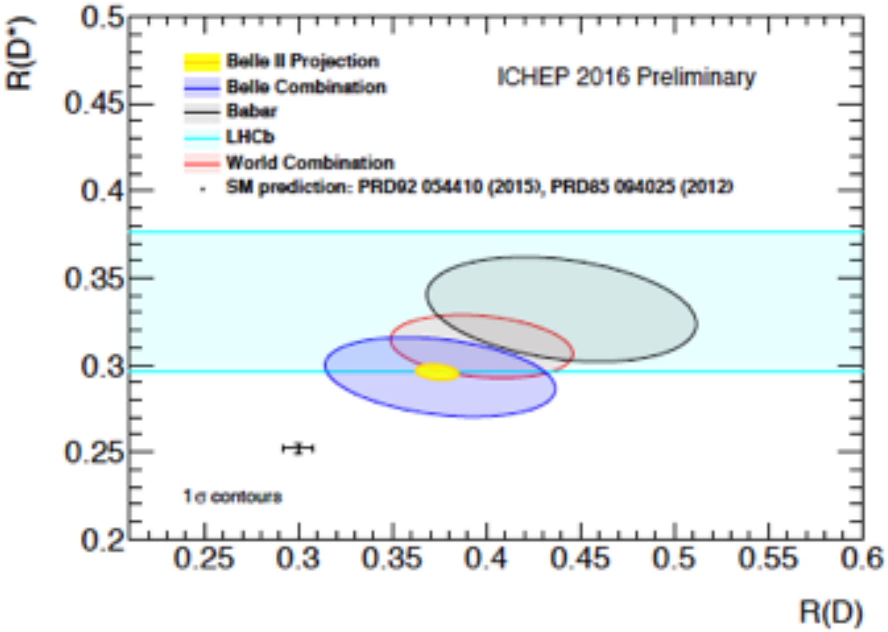
Short focus

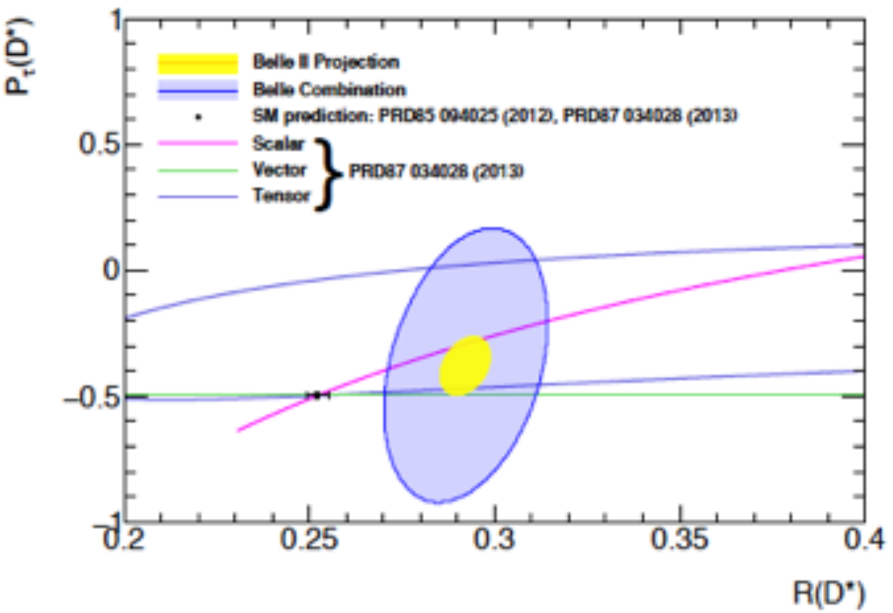
- Tau anomaly
- Lepton flavour violation

Anomaly in tau?

- **Belle II can**
  - Measure R(D*), R(D) and τ polarisation simultaneously
  - With 50 ab^{-1}, SM could be ruled out by 9σ

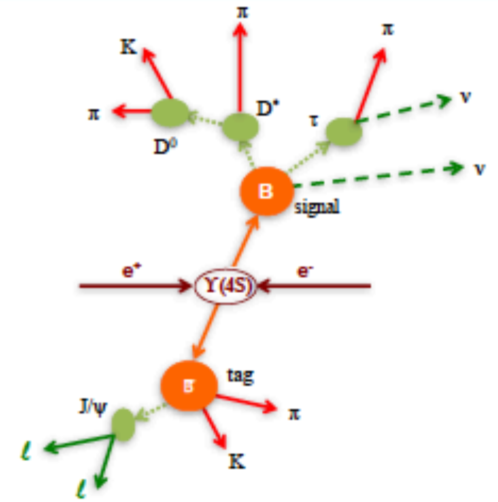
$$R = \frac{\mathcal{B}(b \to q\,\tau\,\bar{\nu}_\tau)}{\mathcal{B}(b \to q\,\ell\,\bar{\nu}_\ell)} \quad \ell = e, \mu$$

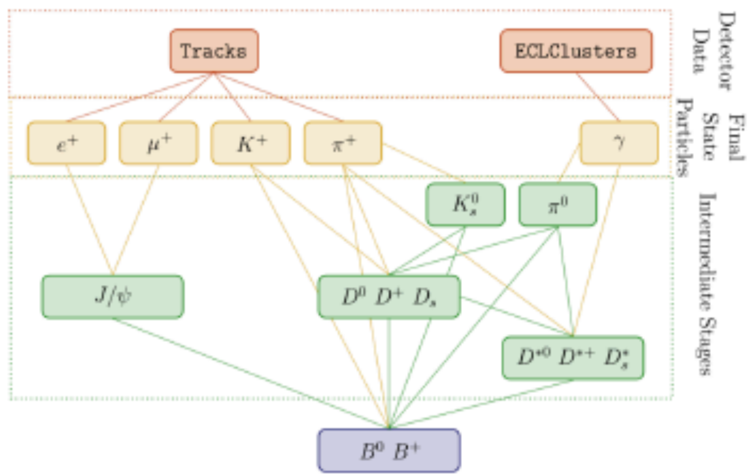


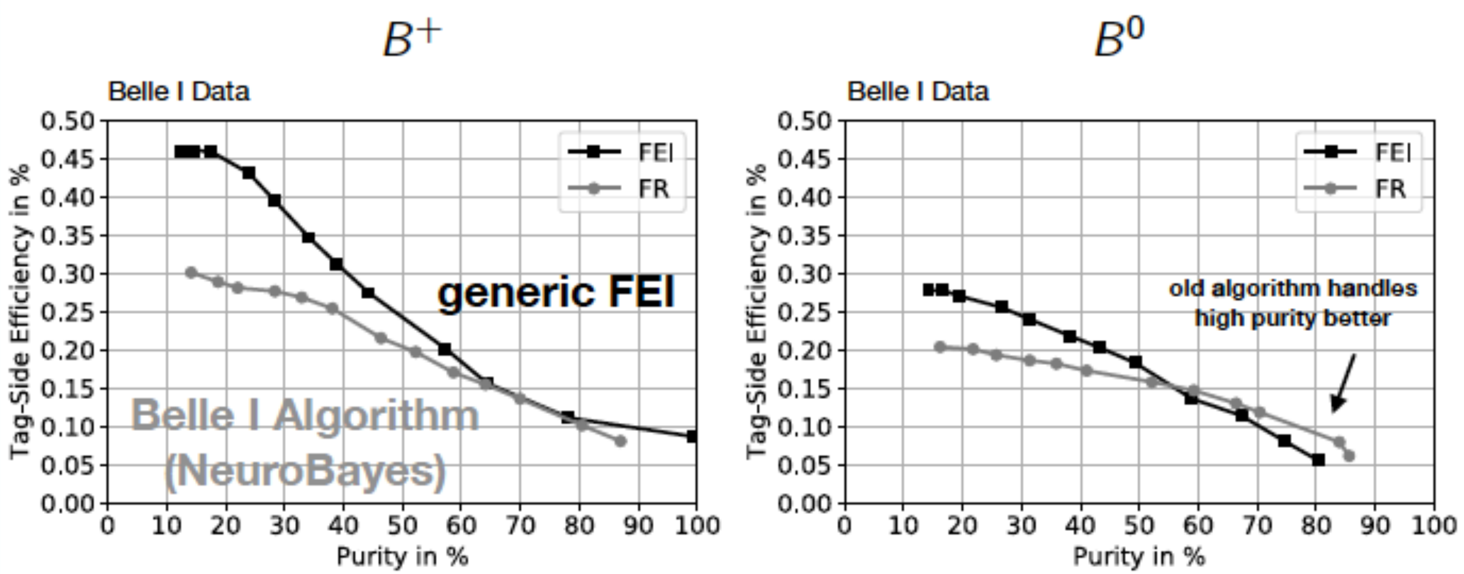


Full event interpretation

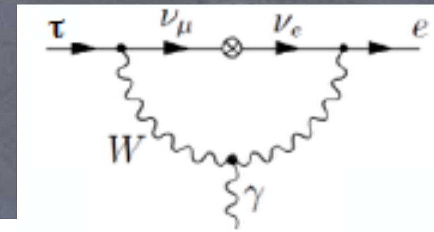
From Thomas KECK, 2017





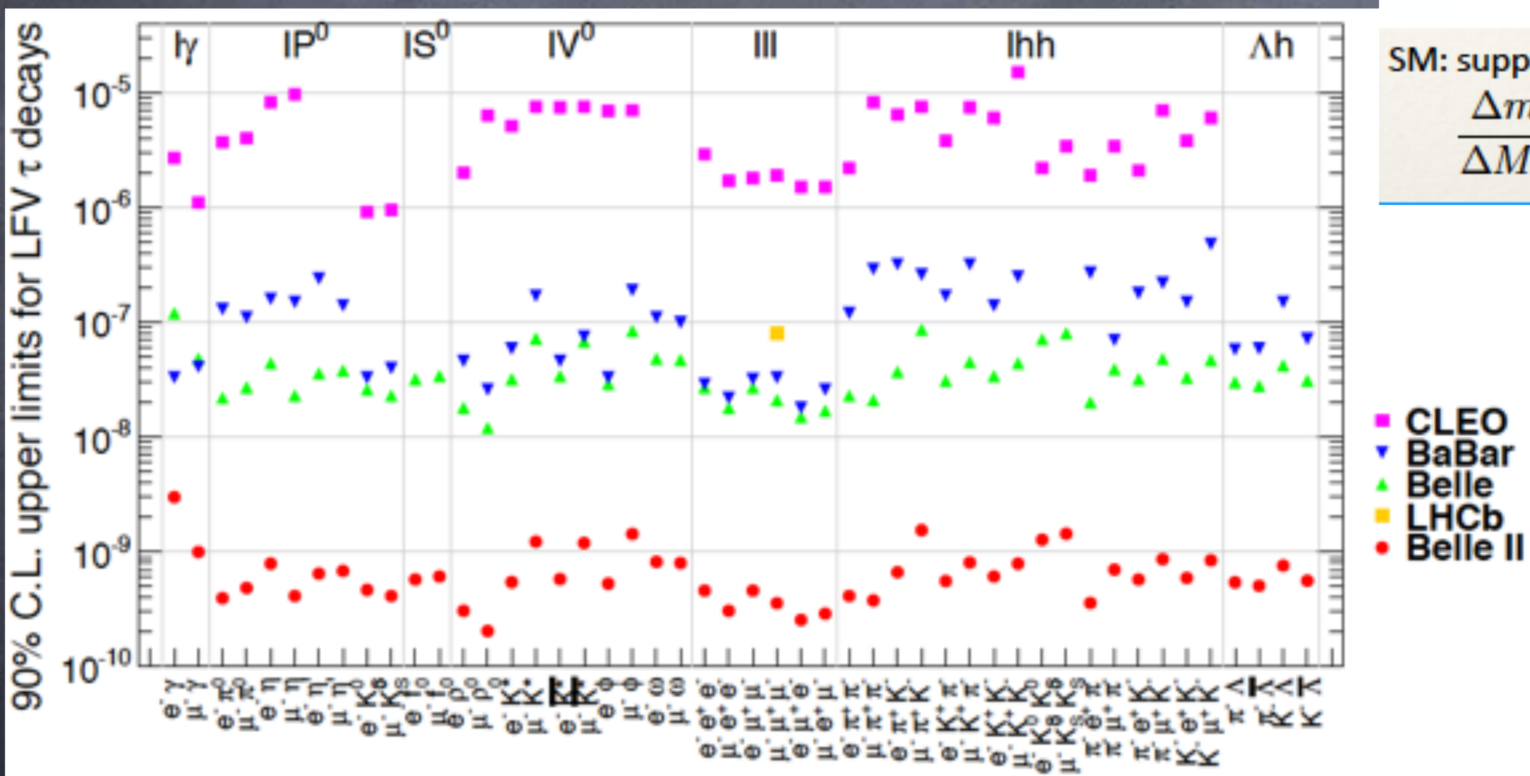


- Reconstruct as many tau decays as possible
  - $\tau \to$ hadrons doable
  - Some very clean: $\tau \to \mu\mu\mu$ background free



SM: suppressed by a factor

$$\frac{\Delta m_\nu^4}{\Delta M_W^4} \approx 10^{-45}$$

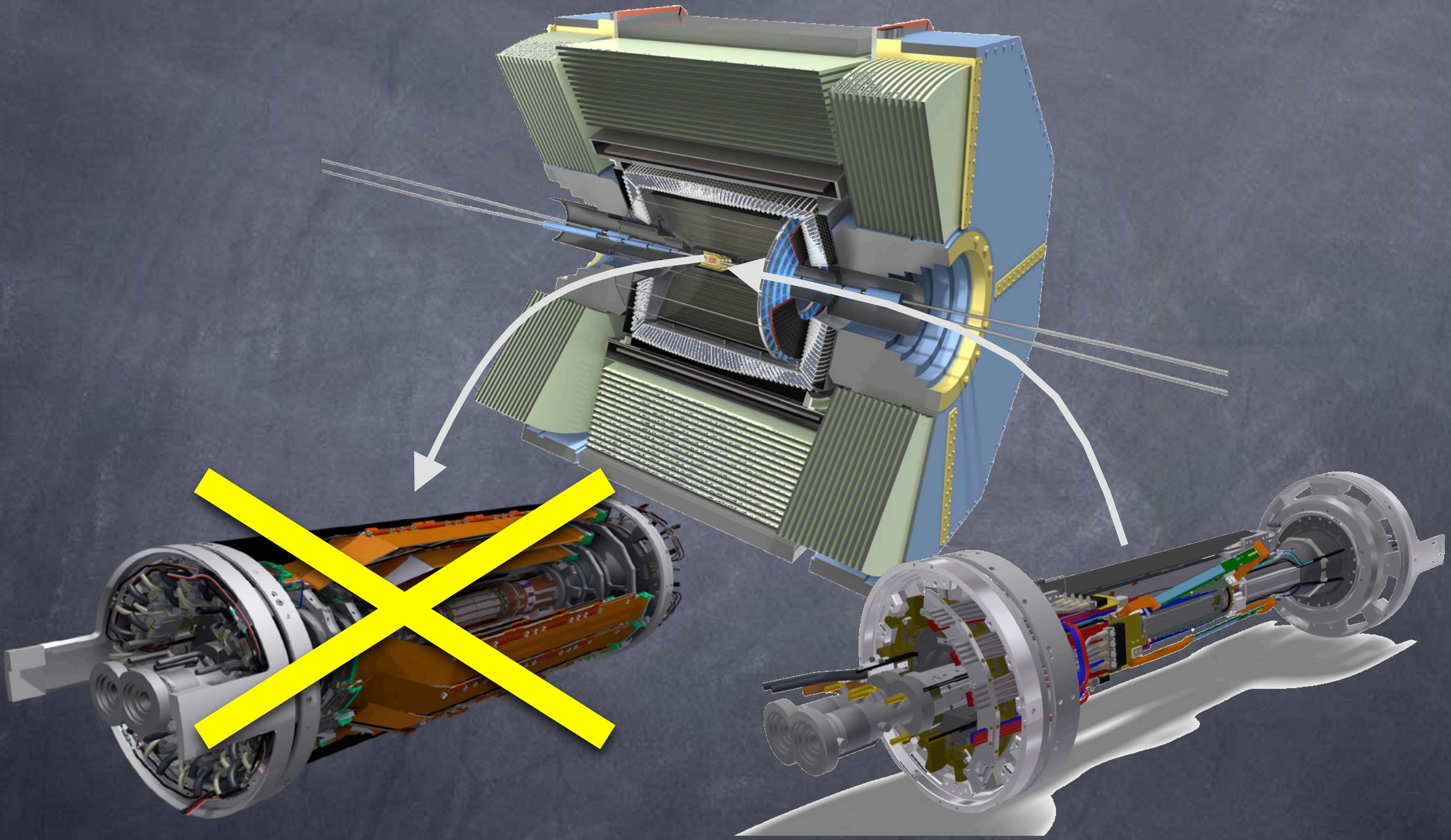


In the early program…

…but of course not only

- Year 0 (2018), 20 fb^{-1} expected
- Dark sector
- Bottomium

Reminder on Phase 2 (2018)



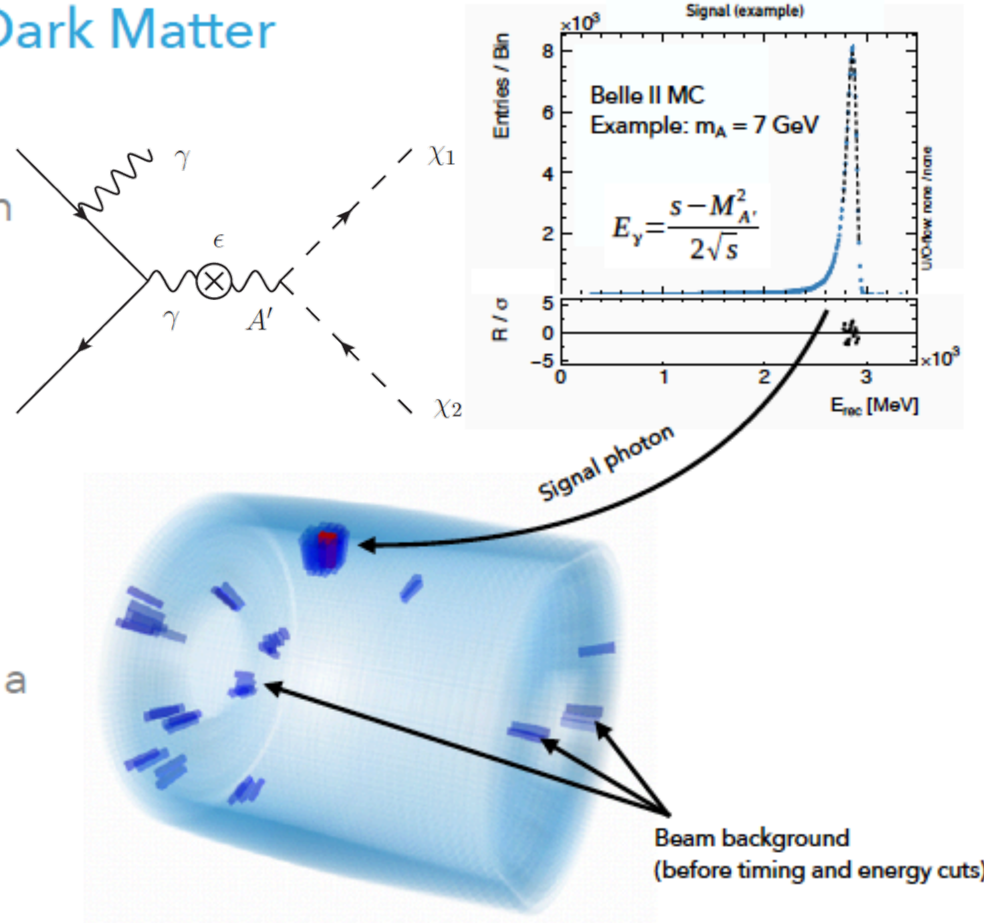
No vertex det. => no Δt measurement

Still: γ, leptons, K^0, π^0, D, B

From Thorsten FERBER, Feb'2018

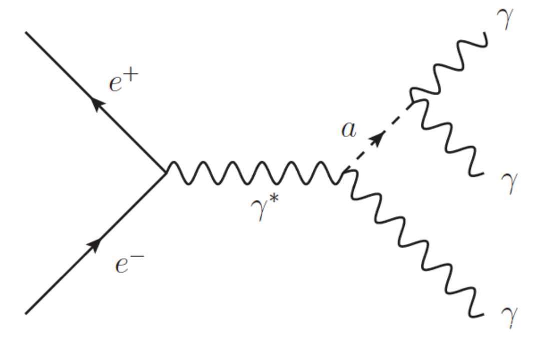
Dark photon decaying into light Dark Matter

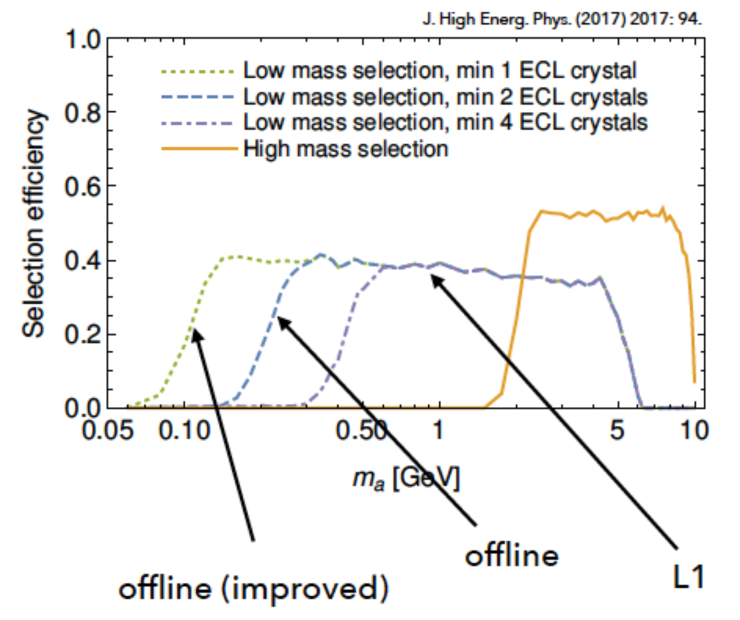
- In the so called Vector Portal, a (massive) Dark Photon A can mix with the SM photon with strength ε.
- If there is a sufficiently light Dark Matter (DM) particle, the A will dominantly decay into DM: Invisible final state.
- Search for $e^+e^- \to A\gamma$ by searching for a single, high energetic photon: Bump-hunt in recoil mass energy (or photon energy).



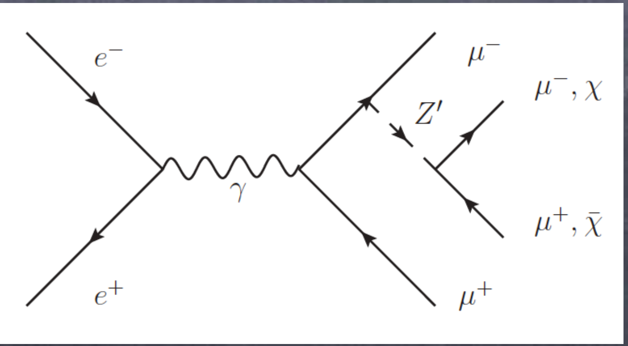
Many other searches

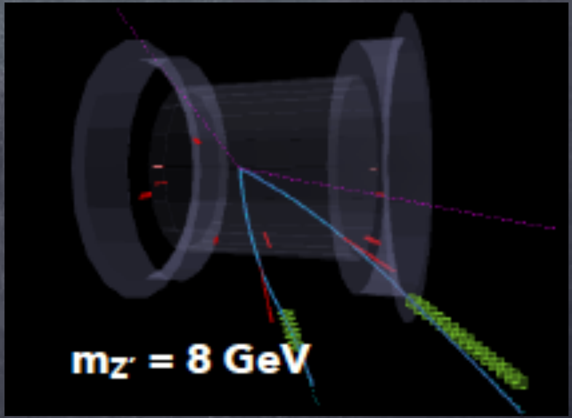
- **Axion-like particles**
  - 3 g event





- **Invisible Z′ decay**
  - μ or τ but no e
  - Recoil technique

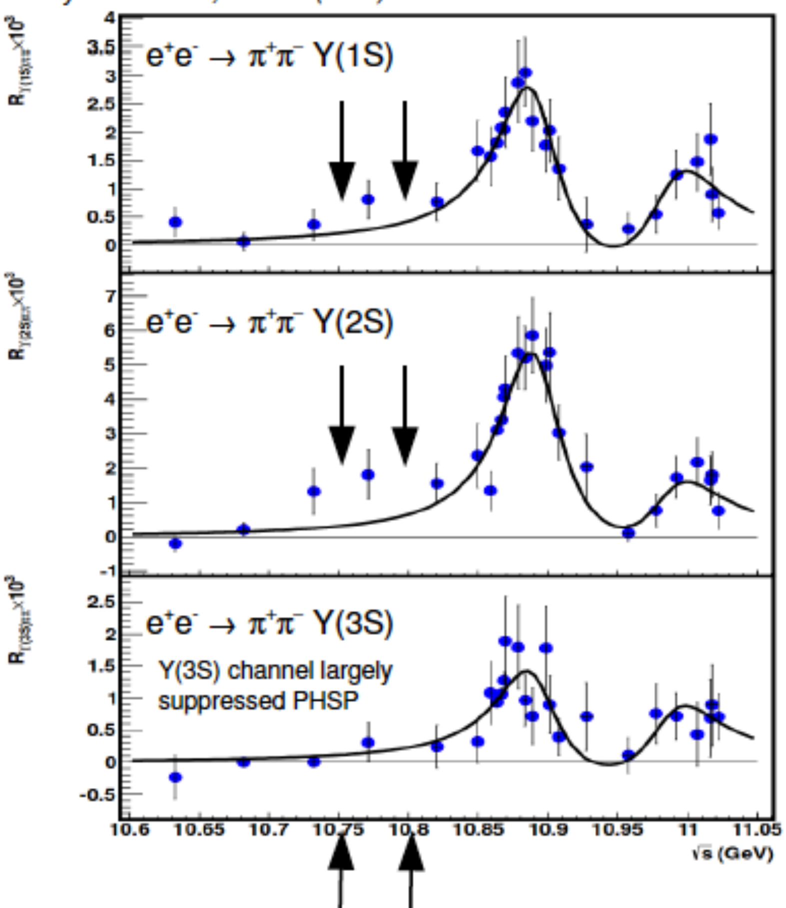




Bottomium states

From Umberto TAMPONI, Feb'2018

Phys. Rev. D 93, 011101 (2016)



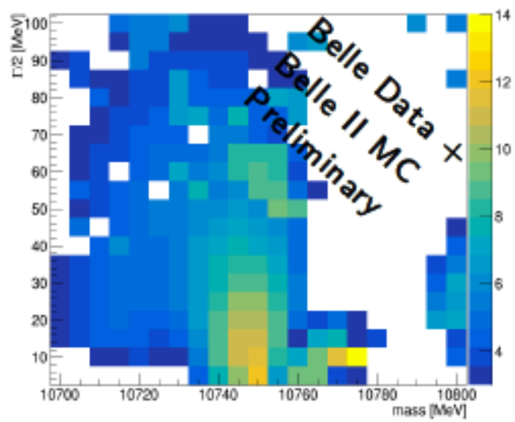
Belle II phase II prospects:

→ Hints of a resonance around 10.750 GeV?

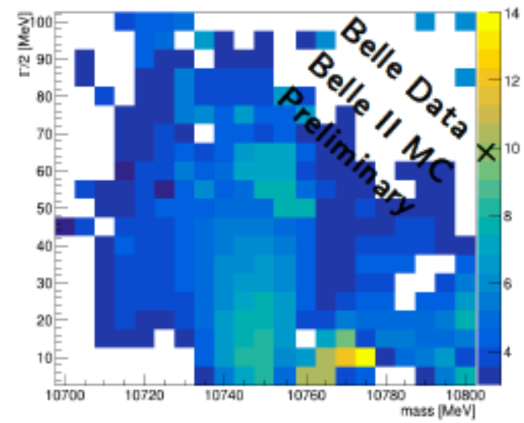
→ Run in Phase II at 10.750 GeV and/or at 10.800 GeV

→ Combine Belle and Belle II data

Expected local significance of an extra resonance (> 3σ only)



20 fb^{-1} at 10.750 GeV



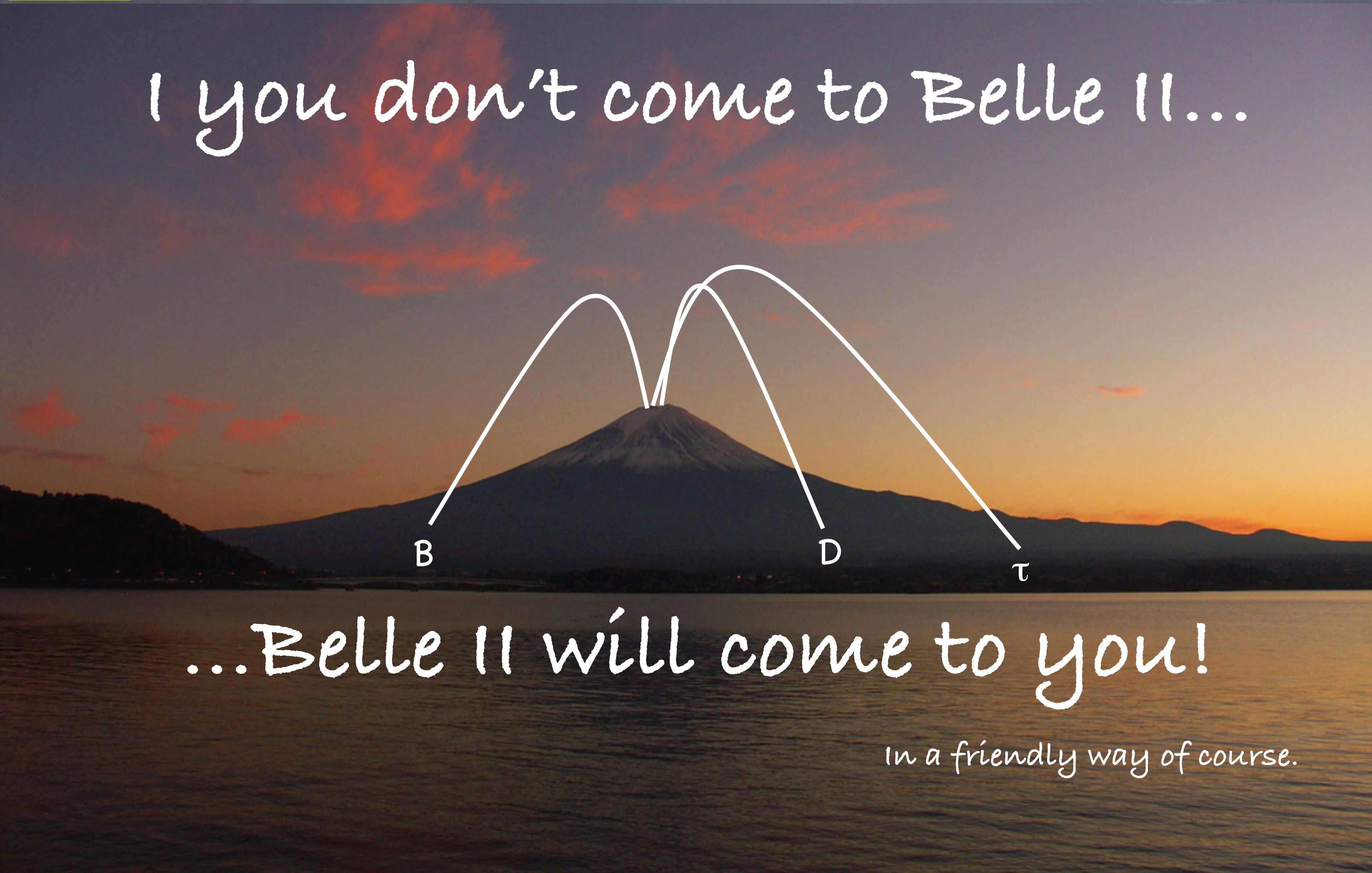
10 fb^{-1} at 10.750 GeV +
10 fb^{-1} at 10.800 GeV

26

Note: Belle II is the last chance to investigate the Υ familly

As a conclusion:

I you don't come to Belle II…



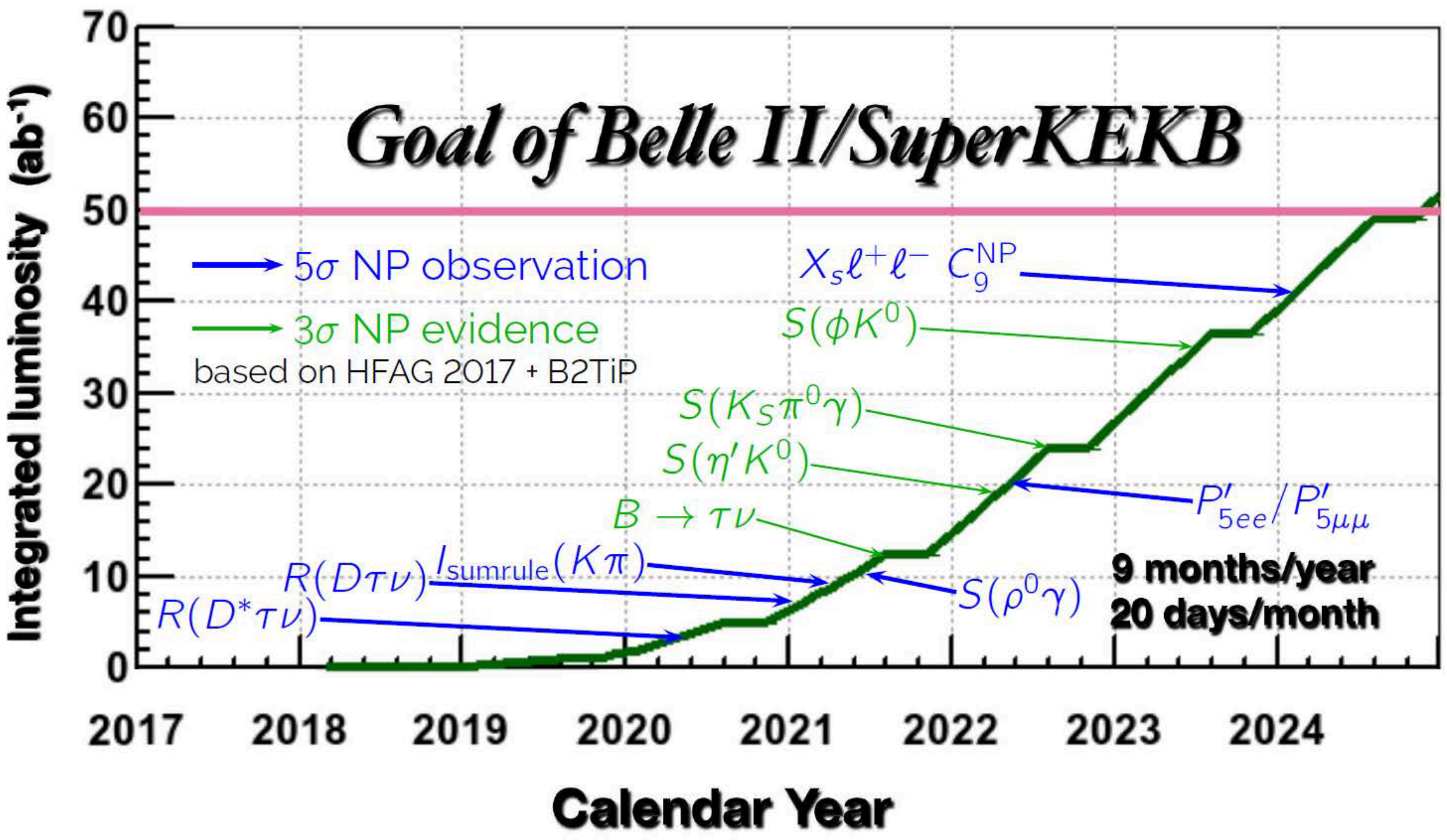
…Belle II will come to you!

In a friendly way of course.

References

- Belle II status and potential, by P.Krizam @ Alps2018
  https://indico.cern.ch/event/645588
- Belle II TheoryInterfacePlatform (B2TiP), to be published in PTEP
  https://confluence.desy.de/display/BI/B2TIP+WebHome
- Physics at B Factories, Eur. Phys. J. C74 (2014) 3026
- Physics at Super B Factory, arXiv:1002.5012 (Belle II)
- SuperB Progress Reports: Physics, arXiv:1008.1541 (SuperB)

BACKUPs



Using "current" central values, and extrapolated stat+syst errors

Effective theory in b->sγ transitions

From David STRAUB, Oct'2017

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \Bigg(-\frac{V_{ub}V_{us}^*}{V_{tb}V_{ts}^*} \sum_{i=1}^{2} C_i Q_i^u + \sum_{i=1}^{2} C_i Q_i^c$$

current-current (tree!)

$$+ \sum_{i=3}^{6} C_i Q_i + C_{iQ} Q_{iQ}$$

QCD & EW penguin

$$+ \sum_{i=7}^{8} C_i Q_i + C_i' Q_i' + \text{h.c.} \Bigg)$$

dipole

$$Q_1^p = (\bar{s}_L \gamma_\mu T^a p_L)(\bar{p}_L \gamma^\mu T^a b_L) \qquad Q_2^p = (\bar{c}_L \gamma_\mu p_L)(\bar{p}_L \gamma^\mu b_L)$$

$$\dots \qquad \dots$$

$$Q_7^{(\prime)} = \frac{e}{16\pi^2} m_b (\bar{s}_{L(R)} \sigma_{\mu\nu} b_{R(L)}) F^{\mu\nu} \qquad Q_8^{(\prime)} = \frac{g_s}{16\pi^2} m_b (\bar{s}_{L(R)} \sigma_{\mu\nu} T^a b_{R(L)}) G^{a\mu\nu}$$

$$C_7^{\text{eff, SM}}(\mu = m_b) = -0.2915 \qquad C_7'^{\text{SM}} = \frac{m_s}{m_b} C_7^{\text{SM}}$$

Time dependent asymmetries

- CP violation in decays to CP eigenstate
  - Direct violation $\Gamma(B\to X) \neq \Gamma(\bar{B}\to\bar{X})$
  - Indirect (interference with mixing)

$$\Gamma(B\to f_{CP}) + \Gamma(B\to\bar{B}\to f_{CP}) \neq \Gamma(\bar{B}\to\overline{f_{CP}}) + \Gamma(\bar{B}\to B\to\overline{f_{CP}})$$

- The formulas $\eta_{CP}(B)=+1$, $\eta_{CP}(\text{anti-}B)=-1$

$$\Gamma(B^0(t)\to f) = g_{\eta_{CP}} = Ne^{-\Gamma_{B^0}|\Delta t|}[1+\eta_{CP}(C_f\cos(\Delta M\Delta t)+S_f\sin(\Delta M\Delta t))]$$

$$\Gamma(\bar{B}^0(t)\to f) = g_{\eta_{CP}} = Ne^{-\Gamma_{B^0}|\Delta t|}[1+\eta_{CP}(C_f\cos(\Delta M\Delta t)+S_f\sin(\Delta M\Delta t))]$$

- The measurement = asymmetry

$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0(t)\to f)-\Gamma(B^0(t)\to f)}{\Gamma(\bar{B}^0(t)\to f)+\Gamma(B^0(t)\to f)}$$

  - Time is needed, otherwise effect vanishes !

List of topics

- (semi-) leptonic B decays
- CKM matrix elements: $|V_{ub}|$, $|V_{cb}|$
- Radiative and electroweak penguins B decays
- CKM matrix/triangle angles with TD-CPV, α, β, γ
- Charmless hadronic B decays and direct CPV
- Charm physics: CPV, ?
- Quarkonium physics
- Tau physics, lepton flavor violation
- Dark sector, light Higgs