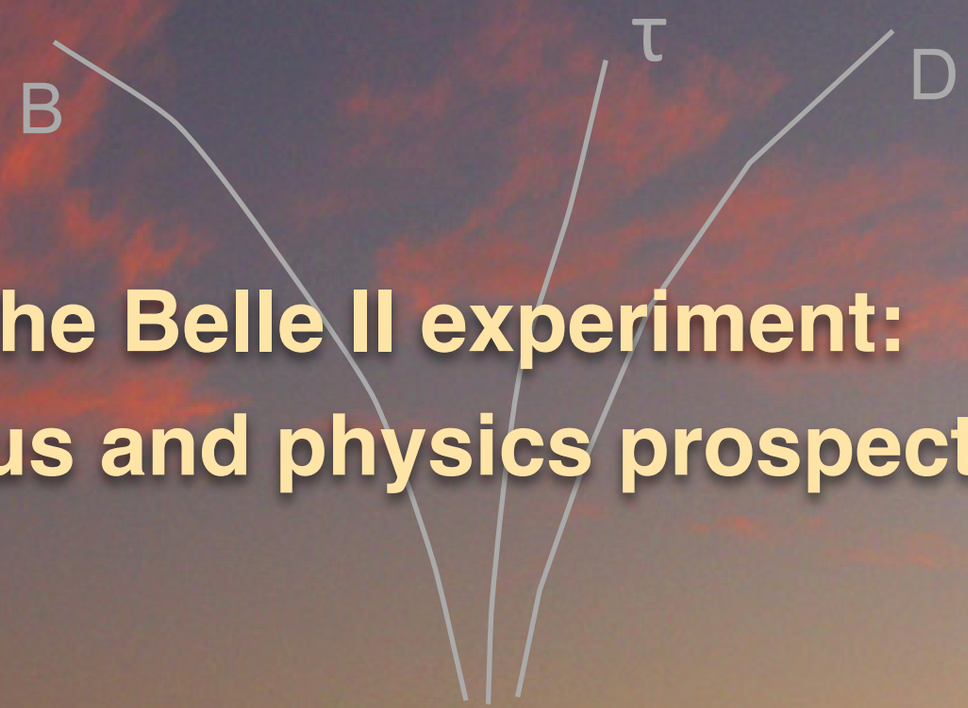
Isabelle Ripp-Baudot
GDR-InF workshop
1-2 February - CERN



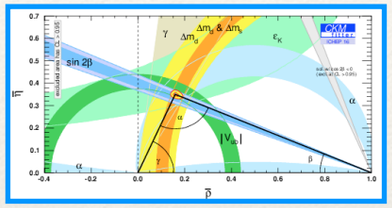
The Belle II experiment: status and physics prospects

Outline:

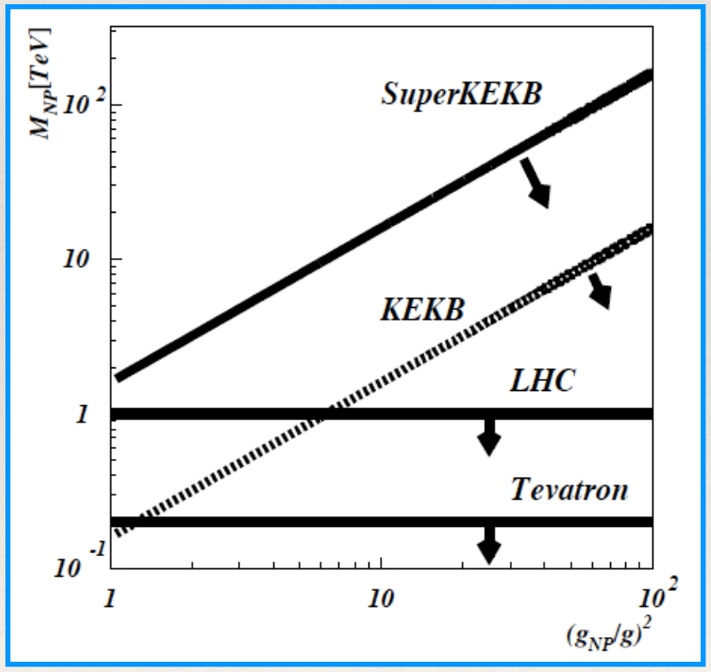
- Scientific motivation
- SuperKEKB
- Belle II commissioning (BEAST II)
- About B-Factory assets: flavour tagging,
  full event interpretation,
  beam constrained variables
- Expected sensitivity in few benchmark channels:
  $B \to K_{res}\gamma$, $B \to D^{(*)}\tau\nu$, cLFV τ decays.
- Conclusion

Scientific motivation (1)

- Search for new physics beyond the SM in the context of:
  - Current scientific landscape:
    - No new BSM particles discovered yet:
      limits ~3 TeV on new heavy gauge bosons and ~800 GeV on new vector-like fermions.
    - Legacy of BaBar, Belle, LHCb:
      NP contributions ~10% of SM still possible from UT achieved precision.



    - Observations:
      neutrino oscillations, additional CPV source needed, non baryonic dark matter, …
    - Unexpected measurements in the flavour sector hint a lepton non-universality.
    - Questions:
      additional Higgs bosons, FCNC, cLFV, V+A, …?
  - On-going LHC operation:
    - Direct searches at the energy frontier.
    - Searches for quantum manifestations of NP in LHCb.

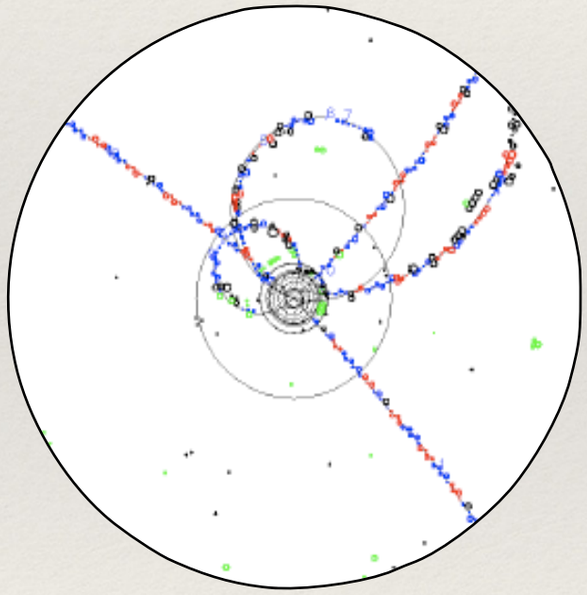


➛ Belle II: constructive complementarity & competition with LHC with an e^+e^- collider.

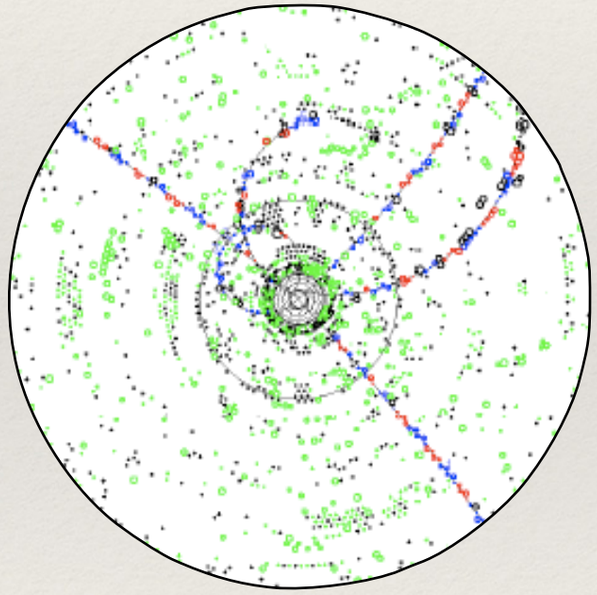
Scientific motivation (2)

- Belle II builds on the previous B-Factory experience, shifting focus to search for BSM physics, through measurements of unprecedented precision in the quark and charged lepton sectors.

- Excellent precision:
  - High statistics needed: high luminosity, targeting 50 ab^{-1}.
  - Optimised detectors and clean experimental environment: $e^+e^- \rightarrow B\bar{B}$, $\tau^+\tau^-$, $c\bar{c}$ @ $\sqrt{s} = M_{\Upsilon(4S)}$.



Belle at KEKB



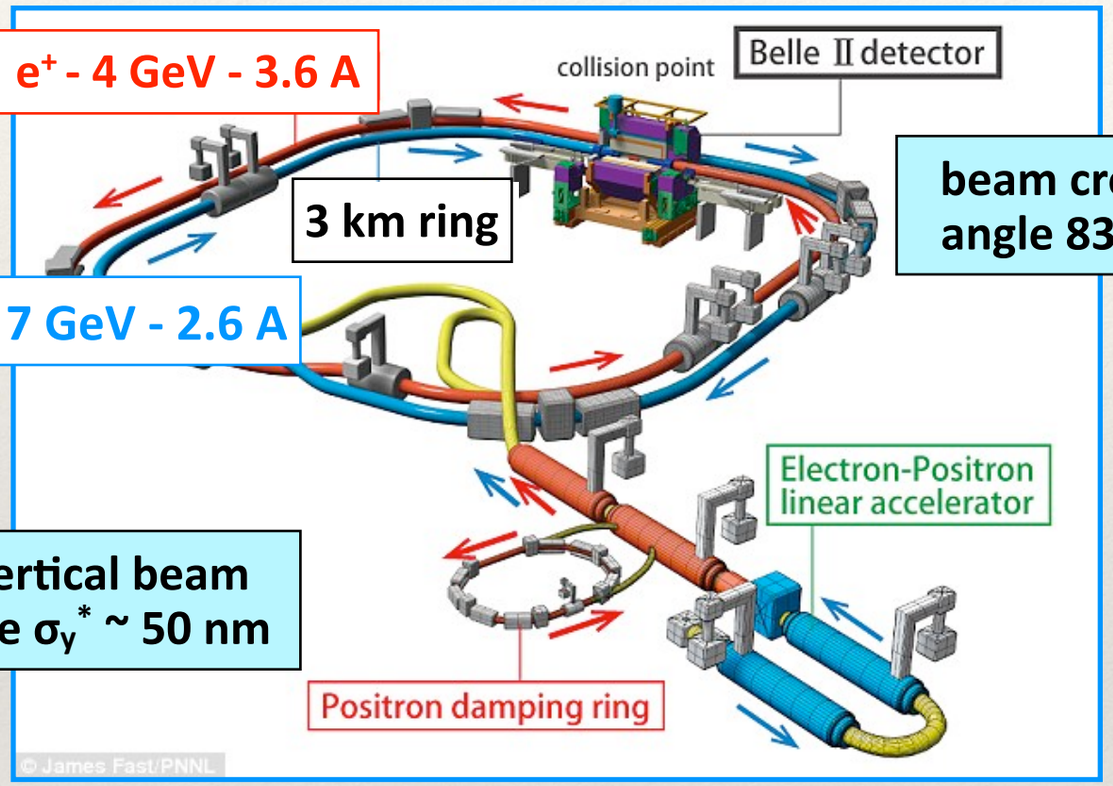
Belle at SuperKEKB

- High luminosity ➛ many parasite particles:
  - dominate occupancy in inner tracker,
  - damage detectors.

➛ success of Belle II physics program relies on the control of the beam induced BG.

SuperKEKB collider (1)

- SuperKEKB targets world record luminosity of **8×10^{35} cm^{-2} s^{-1}** (world record ×40), based on a **new nano-beam scheme**.



$$\ell = \frac{\gamma_\pm}{2\, e\, r_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm\,\xi_{\pm y}}{\beta_y^*}\left(\frac{R_L}{R_y}\right)$$

Parameters (LER / HER)	KEKB crab cavities	SuperKEKB phase 2	SuperKEKB phase 3	
En. (GeV)	3.5 / 8.0	4.0 / 7.007	4.0 / 7.007	boost ×2/3
$\epsilon_x(nm)$	18 / 24	2.2 / 5.2	3.2 / 4.6	
σ_x^* (μm)	147 / 170	16.8 / 22.8	10 / 11	
σ_y^* (μm)	0.94 / 0.94	0.308 / 0.5	0.048 / 0.062	
β_x^* (mm)	1200 / 1200	128 / 100	32 / 25	
β_y^* (mm)	5.9 / 5.9	2.16 / 2.4	0.27 / 0.30	β_y^*/20
ξ_y	0.129 / 0.09	0.0240 / 0.0257	0.088 / 0.081	
$2\phi(mrad)$	22	83	83	
I_{beam} (A)	1.64 / 1.19	1.0 / 0.8	3.6 / 2.6	I×2
Nb bunches	1584	2500	2500	
$\mathcal{L}(10^{-34}cm^{-2}s^{-1})$	2.11	1	80	ℓ×40

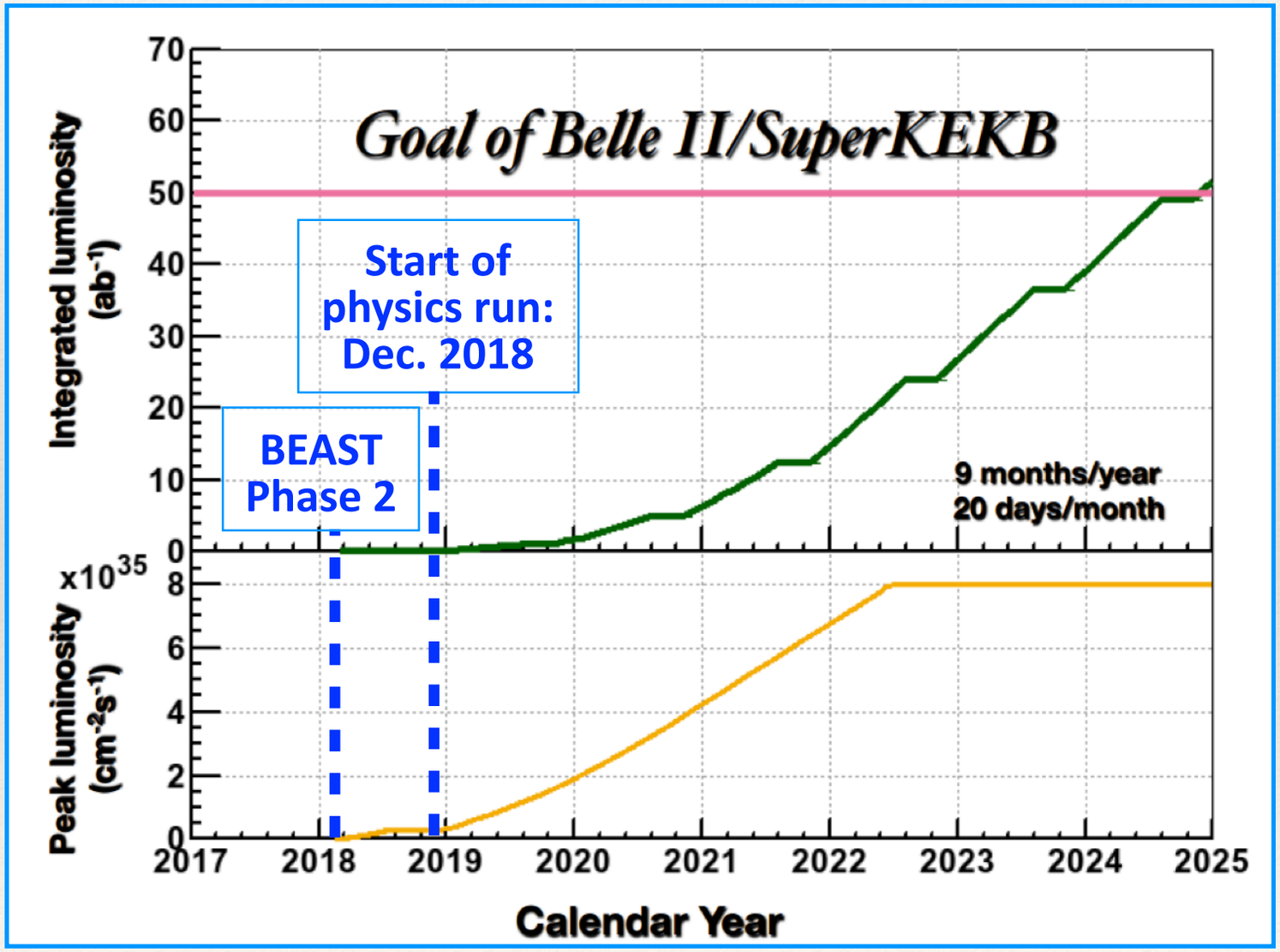
- $E_{collision}$ will range from Y(1S) to ~ Y(6S), limited to 11.24 GeV.
- Asymmetric beams.

SuperKEKB collider (2)

- SuperKEKB started in January 2016: circulation of single beams (BEAST Phase 1).
  First collisions will be delivered in Spring 2018 (BEAST Phase 2).
  Start of physics run scheduled in December 2018.

- Target integrated luminosities:
  - 2019: 1 ab^{-1} > present dataset.
  - 2021: 10 ab^{-1}.
  - 2024: 50 ab^{-1}

  ➔ 55×10^9 $B\bar{B}$,
  45×10^9 $\tau^+\tau^-$,
  65×10^9 $c\bar{c}$.



Experiment commissioning

- Commissioning in 2 phases:
  - Phase 1: single beams, BG and radiation level monitored, Jan.-June 2016.
  - Phase 2: collisions delivered, February-July 2018.

- Multi-target commissioning:
  - Operation of the whole Belle II detector (only part of the Inner Tracker System) and DAQ.
  - Fine tuning of beams to reach 10^{34} cm^{-2} s^{-1}, limiting machine induced BG.
  - Identify background hot spots to position shields.

- Characterisation of the machine induced background:
  - Validation of machine induced BG simulation, extrapolate predictions over ~2 orders of magnitude.
  - Insure safe operation of the vertex detector.
  - Contribution of IN2P3 (IPHC and LAL).

- Physics: ~25 fb^{-1} delivered?

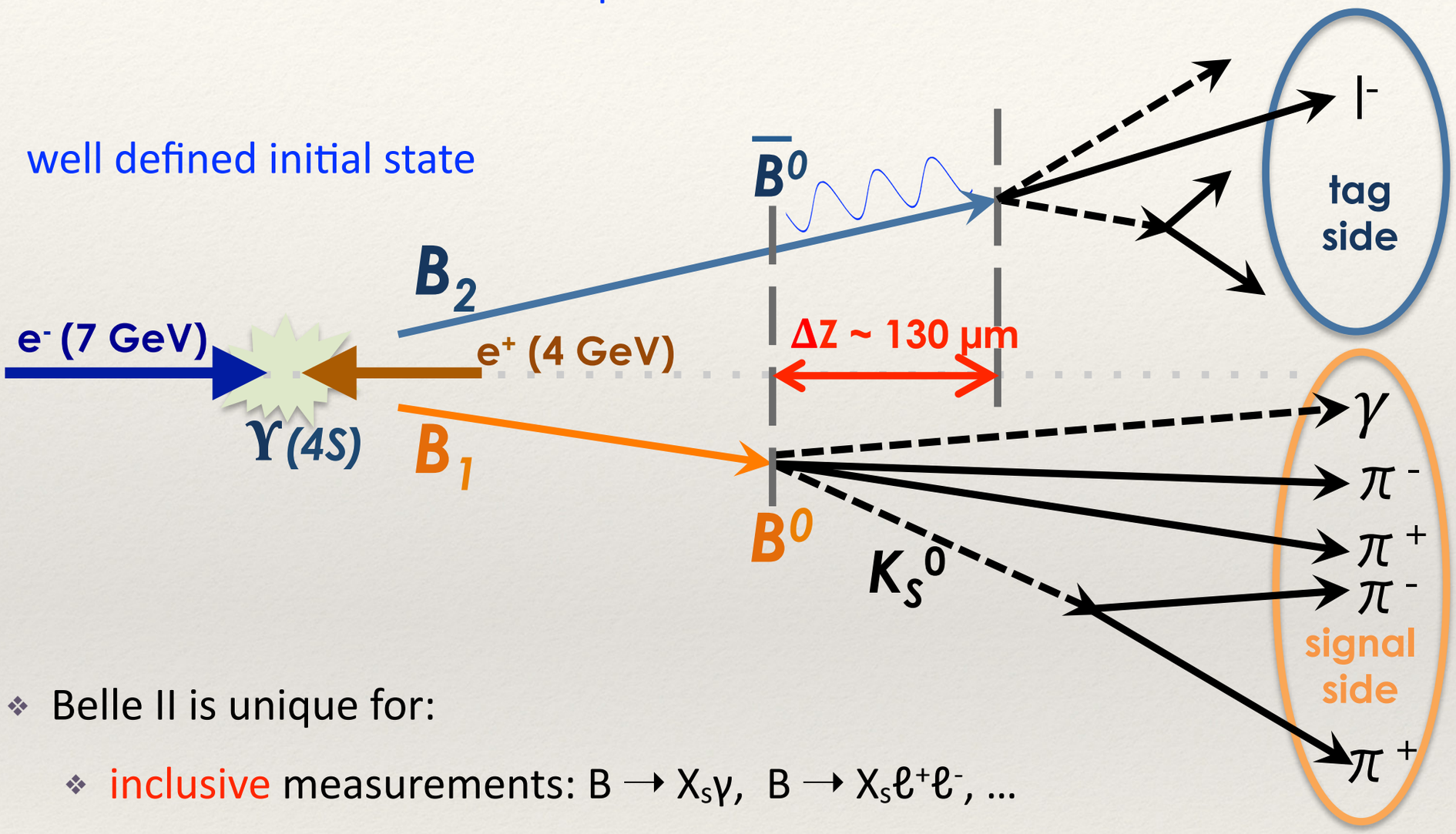
  Analyses w/o vertex detector and low stat:
  dark photon search, quarkonium studies, …

Beam **E**xorcism for **A** **ST**able BELLE **II** experiment

Belle II event

clean: only 2 B mesons produced

quantum correlated 1^{--} state



B_{SIG} flavour identified from companion meson

- Belle II is unique for:
  - inclusive measurements: $B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$, …
  - events with missing energy: $B^+ \to \tau^+\nu$, $B \to D^{(*)}\tau\nu$, …
  - events with neutrals: $B^0 \to \gamma\gamma$, $B^0 \to K_S^0\pi^0\gamma$, $B^0 \to K_S^0K_S^0K_S^0$, …

    ➛ interesting complementary with LHCb.

Flavour tagging

- Determined inclusively from flavour specific decay modes from companion meson, quantum entangled. Once B_{SIG} reconstructed, all remaining particles belong to B_{TAG}. No fragmentation.

- Many categories: leptons from $b \to c\, \ell^- \bar{\nu}$ and $b \to c \to s\, \ell^+ \nu$, π^+ from $\bar{B}^0 \to D^{*+}(\to D^0 \pi^+)X$, K^- and Λ^0 from $b \to c \to s$.

- Many inputs for each category: p, p^*, θ^*, M_{inv}, p-id, track χ^2, …

- Total effective tagging efficiency = $\sum \varepsilon_i \times (1 - 2\omega_i)^2$ = 37.2 %

  on Belle II MC, w.r.t. 33.6% with Belle II tagger algorithm on Belle data.

  ➔ Dilution factor r due to mis-tag ω:

  $r = 1 - 2\omega$ $\qquad$ $A_{CP}^{obs} = (1 - 2\omega)\, A_{CP}$

- ε_{eff} was 30.1 - 33.1 % in Belle and BaBar resp.

  Performance increased significantly with experiment lifetime.

  ➔ Improvement expected w.r.t. BaBar and Belle:

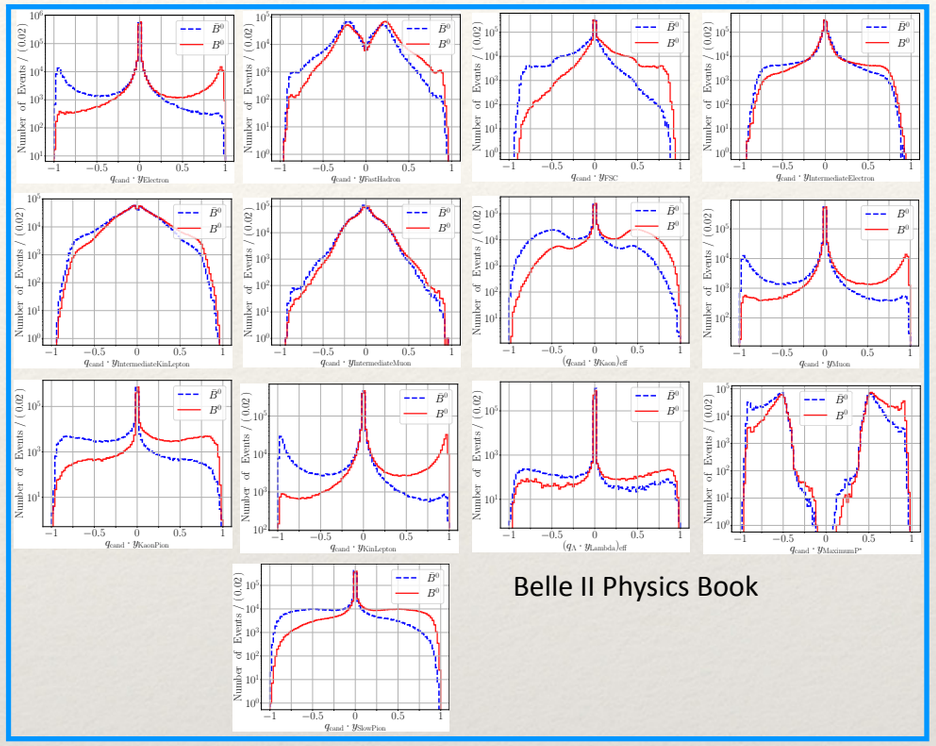
  - Additional categories included:

    Kπ, FastHadron, MaxP*, Fast-Slow-Correlations.

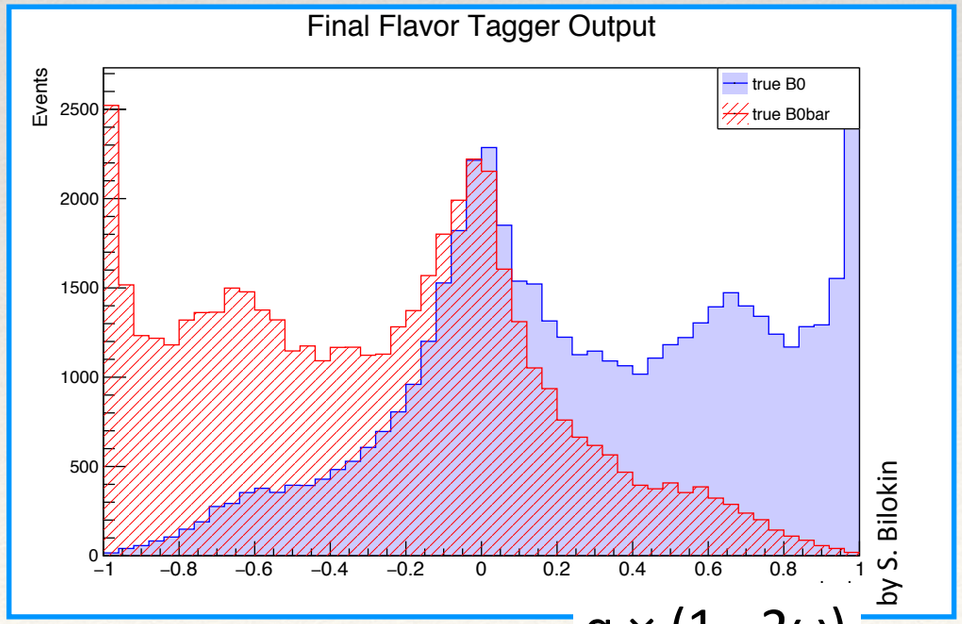
  - More input variables.

  - Deep NN combiner of sub-taggers.

- Impact of beam induced background.



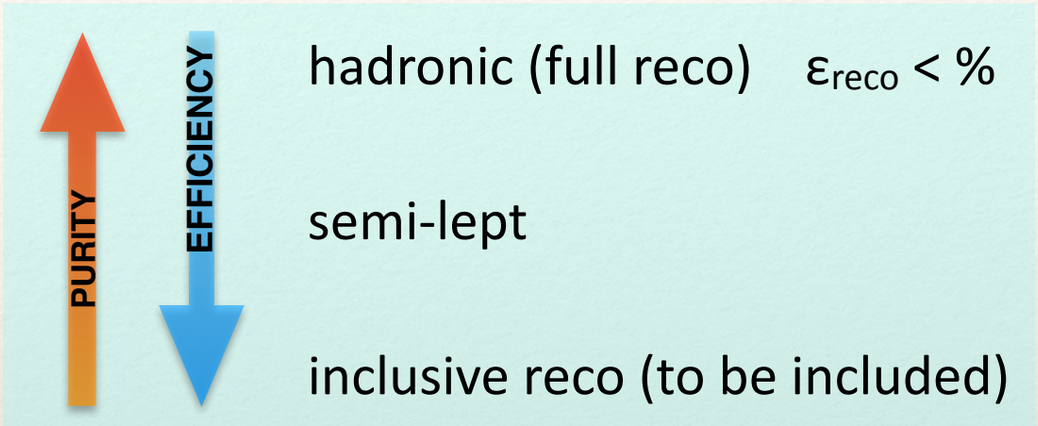
Belle II Physics Book



Full event interpretation

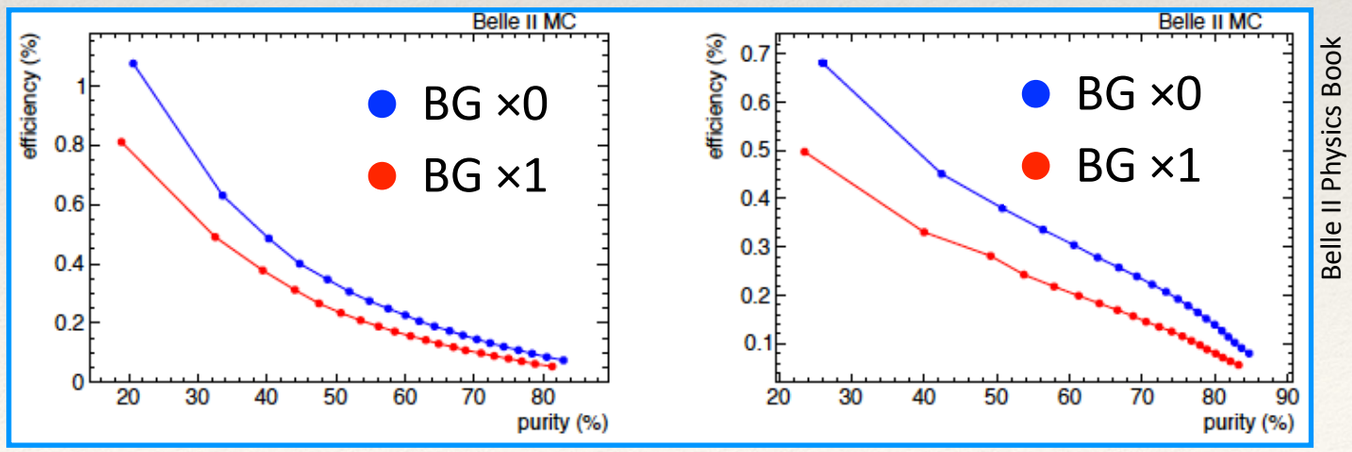
- Known initial state and reco of the rest of the event ➛ strong constraint on B_{sig}.
  Full Event Interpretation (FEI) is a unique asset at a B-Factory, for channels involving ν:
  $B^+ \to \tau\nu$ and $B \to D^{(*)}\tau\nu$, for inclusive measurements and for $|V_{ub}|$. Also used in τ physics.

- Reconstruction of companion B
  into several 1000s modes.
  Based on multivariate techniques.
  FEI includes hadronic and semi-leptonic
  (and soon also inclusive) taggings.



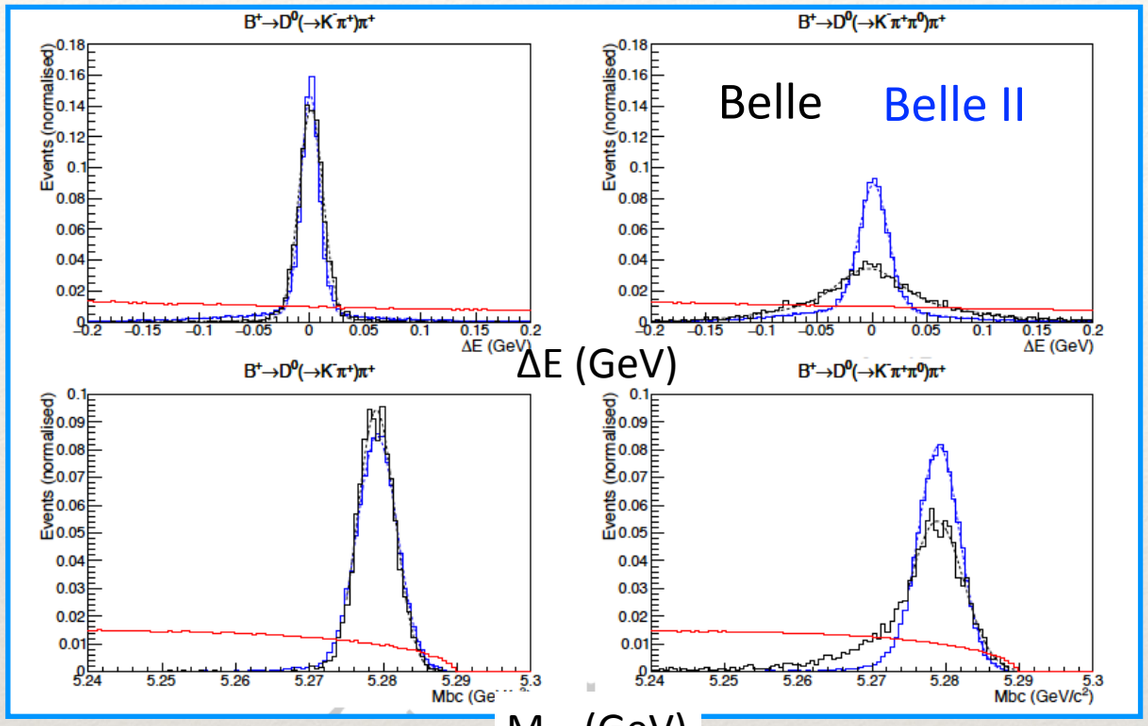
- Significant improvement w.r.t. Belle:
  - Speed optimised training algorithms (days instead of weeks).
  - CPU increase & parallel computing.
  - Two training modes:
    - Specific mode, w/ signal selection applied:
      suited to reconstruct B_{TAG} of channels
      e.g. $B^+ \to \tau\nu$, $B \to D^*\tau\nu$, $B \to \ell\nu\gamma$,
      $B \to K^*\nu\nu$, $B \to \nu\nu(\gamma)$.
    - Generic mode, w/o selection:
      suited in particular to inclusive analyses.

- Impact of beam induced background.



Beam constrained fits and observables

- Energy-like and mass-like variables used rather than B invariant mass to separate bkg from signal:



$$\Delta E = E_B^* - E_{beam}^* = (2p_B^\mu p_{boost}^\mu - s)/2\sqrt{s}$$

➔ Improvement w.r.t. Belle if π^0 are involved.

Expected gain is 50 % for this channel.

$$m_{bc} = \sqrt{{E_{beam}^*}^2 - {p_B^*}^2}$$

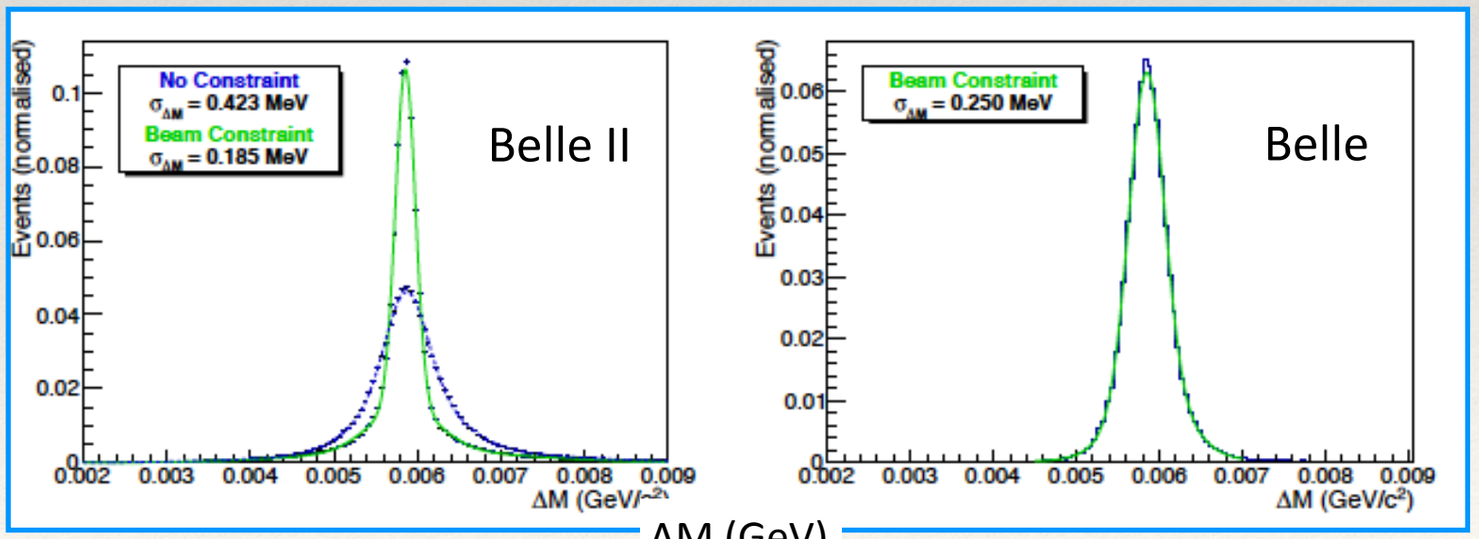
➔ Improvement w.r.t. Belle if π^0 involved.

Expected gain is 20 % for this channel.

- Better M_{inv} resolution with constrained vertex fit.

➔ Improvement w.r.t. Belle.

Expected gain is 27 % for $D^{*+} \rightarrow D^0\pi$.



Belle II Physics Book

Belle II sensitivity

Belle II Physics Book to be published soon: update of Belle II sensitivity studies.

See Belle II Theory Interface Platform: https://confluence.desy.de/display/BI/B2TiP+WebHome

- Inclusive and exclusive Leptonic and Semi-leptonic B decays, $|V_{ub}|$ and $|V_{cb}|$:

  $B\to\tau\nu$, $B\to\mu\nu$, **$B\to D^{(*)}\tau\nu$**, $B\to\pi\tau\nu$, $B\to X_c\tau\nu$, $B\to D^{**}\ell\nu$, $B\to\pi\ell\nu$, $B_s\to K\ell\nu$, $B\to X_u\ell\nu$, $B_{(s)}\to X_c\ell\nu$, …

- Radiative and electroweak Penguin B decays:

  $B\to X_{s,d}\gamma$, $B_{(s)}\to V\gamma$, $B_{(s)}\to\gamma\gamma$, $B\to X_s\gamma\gamma$, $B\to X_{s,d}\ell\ell$, $B\to K^{(*)}\ell\ell$ (inclunding $\tau\tau$), $B_{(s)}\to\tau\tau$, $B\to K^{(*)}\nu\nu$, $B_{d,s}\to\nu\nu$, $b\to q\tau\tau$, …

- Time Dependent CPV, β and α:

  $B\to J/\psi K_S$, $B\to J/\psi\pi^0$, $B\to\phi K^0$, $B\to\eta' K^0$, $B\to\omega K_s$, $B\to K_S\pi^0$, **$B\to K_S\pi^0\gamma$**, $B\to\pi\pi$, $B\to\pi^0\pi^0$, $B\to\rho\rho$, $B\to\rho\pi$,…

- Determination of γ:

- Charmless hadronic B decays and direct CPV:

  $B\to\rho K^*$, $B\to K^*\pi$, …

- Charm physics:

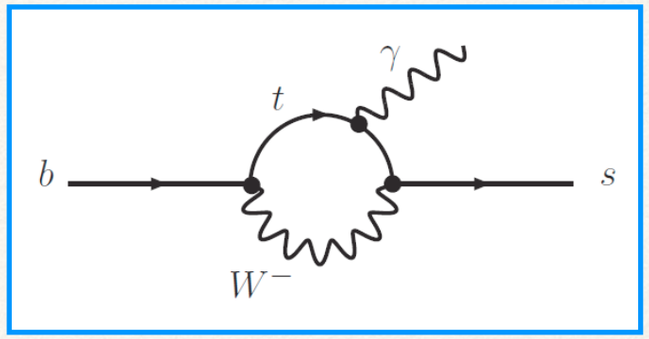
- Quarkonium(like) physics:

- τ physics: **cLFV decays**, …

- Dark sectors and Light Higgs:

photon helicity in $B \to K_{res}\gamma$

- Right helicity-γ suppressed in b→sγ process:
  ➔ sensitive to BSM V+A contribution (coeff. C'_7).



- $B^+ \to K_{res}\gamma \to K^+\pi^+\pi^-\gamma$ channel:
  - photon helicity directly from A_{ud} through γ angular distribution measurement.
  - LAL analysis, synergy with interest in Particle-Id.

- $B^0 \to K_{res}\gamma \to K_S^0\pi^+\pi^-\gamma$ channel:
  - photon helicity probed in Time Dependent CP Asymmetry measurement.
    No $B^0 \to f_{CP}\gamma_{right}$ and $B^0 \to \bar{B}^0 \to f_{CP}\gamma_{left}$ interference in SM and Asymmetry is suppressed by m_s/m_b.
  - IPHC analysis, synergy with interest in tracking, vertexing and K_s^0 reconstruction.
  - Also $B^0 \to K_{res}\gamma \to K_s^0\pi^0\gamma$ channel.

- Difficulties:
  - Limited knowledge of Kππ amplitudes (not all contributions are CP eigenstates)
    ➔ will be improved with Belle II higher stat.
  - QCD corrections in calculation of TDCPA.

- See J. Baudot @ GDR InF workshop 29-31 March 2017:
  https://indico.in2p3.fr/event/14159/contributions/16972/attachments/14113/17321/belleII-France_when-what.pdf

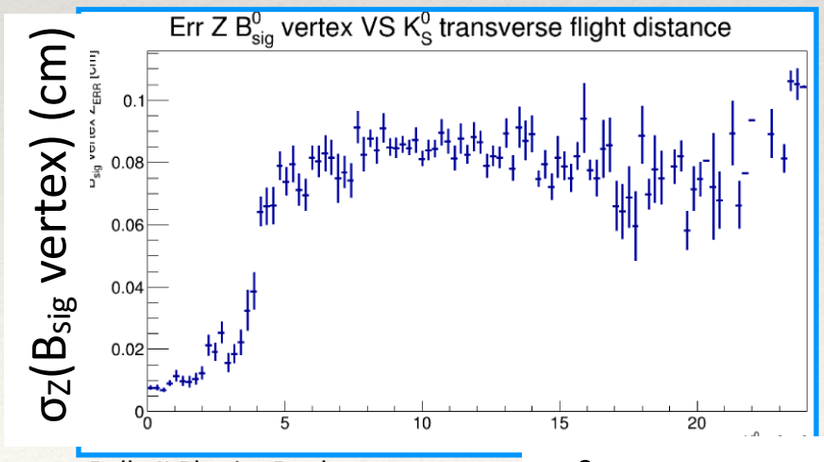
TDCPA of $B \to K_S^0 \pi^0 \gamma$ decays

- TDCPA of $B^0 \to K_S^0 \pi^0 \gamma$ decays: golden mode, no competition from LHCb.
- Published: Belle 0.495 ab^{-1} $S_{K_S\pi^0\gamma} = -0.10 \pm 0.31 \pm 0.07$ [PRD74 (2006)]
  BaBar 0.427 ab^{-1} $S_{K_S\pi^0\gamma} = -0.78 \pm 0.59 \pm 0.09$ [PRD78 (2008)]
- Prospects:

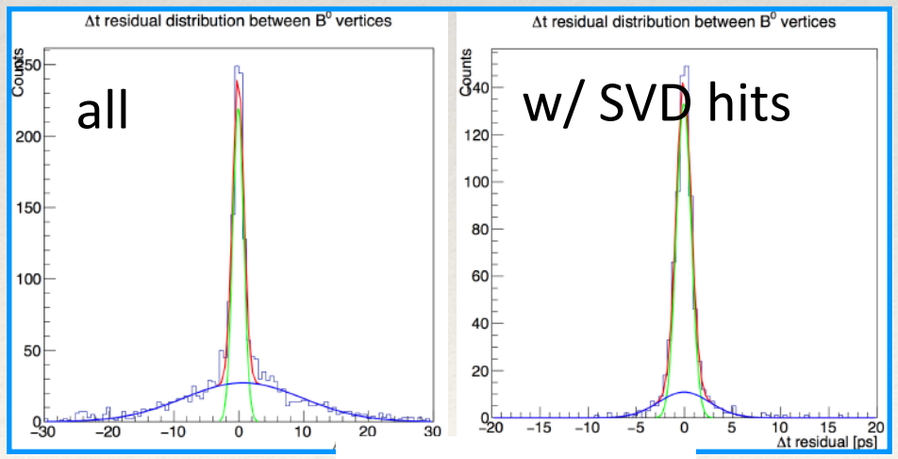
L (ab	σ(S)
2	0.15
5	0.10
10	0.07
50	0.03

With Belle II data set:
stat. ~ syst. ~ SM prediction.

- Difficulty to reconstruct B_{sig} decay vertex.
  Intersection of reconstructed K_S^0 4-mom with *iptube* (xy beam-spot constraint).



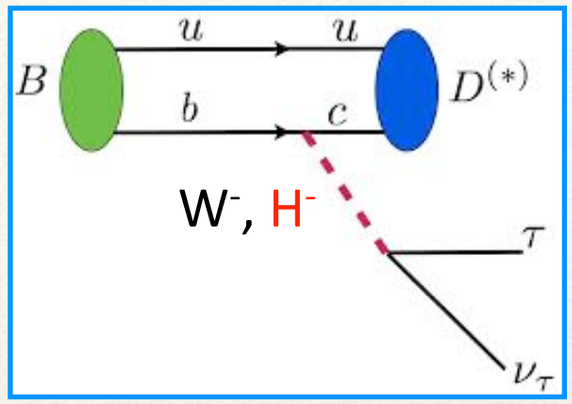
Belle II Physics Book



➔ Room for improvement on K_S^0 reconstruction.
IPHC started to work on it.

$B \to D^{(*)} \tau \nu$ (1)

- $B \to D^{(*)} \tau \nu$ sensitive to BSM H^+, with H-b-c coupling. Tree-level diagram.



- SM predictions suffer from form factor and $|V_{cb}|$ uncertainties
  ➛ yield ratio is a more powerful probe of NP:

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)} \tau \nu_\tau)}{\mathcal{B}(B \to D^{(*)} \ell \nu_\ell)}$$

- Investigate discrepancy w.r.t. SM prediction, observed by Belle, BaBar and LHCb is one of the primary goal of Belle II.

- Higher statistics in Belle II ➛ additional observables will help clarifying the NP structure:
  τ and D^* polarisations, $q^2 = (p_\tau + p_\nu)^2$ spectrum, $p(D^*)$ and $p(\ell)$ spectra, …

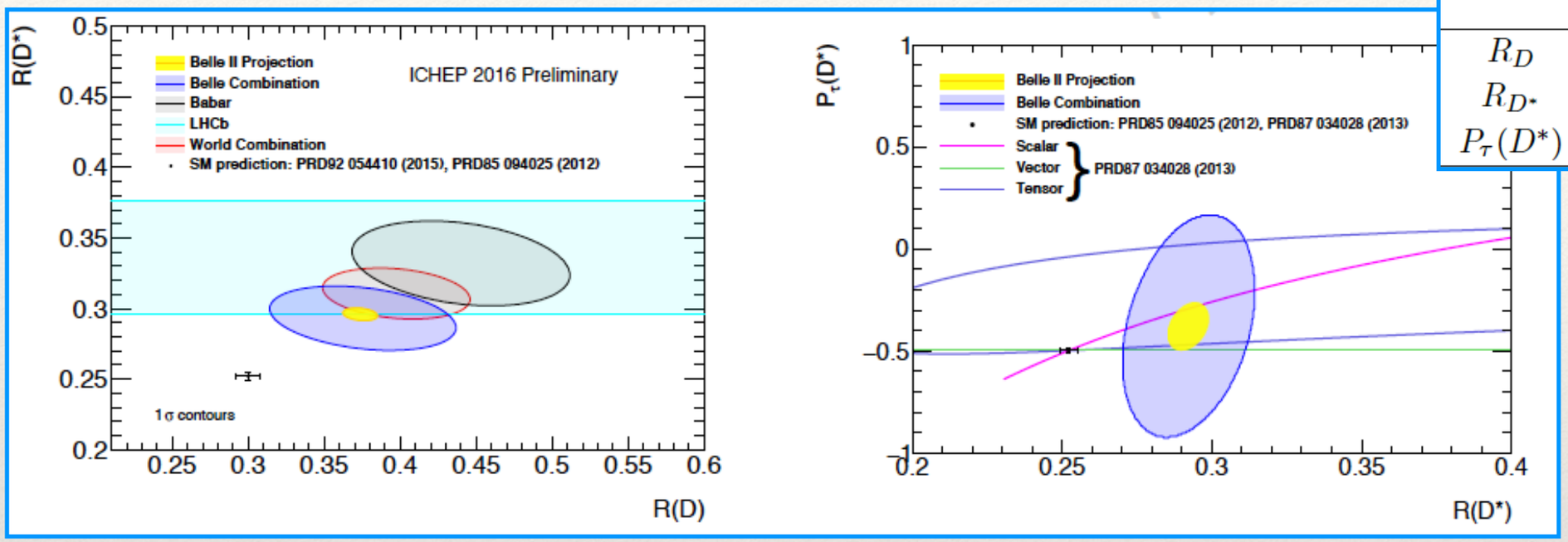
- $\tau \to h\nu$ decays ($h = \pi, \rho$) were also used in Belle for $R(D^*)$ ➛ τ polarisation measurement.

- Main syst. will decrease with larger stat:
  B.R.($B \to D^{**} \ell \nu$), B.R.($B \to$ hadrons) and MC stat. (depending on channel).

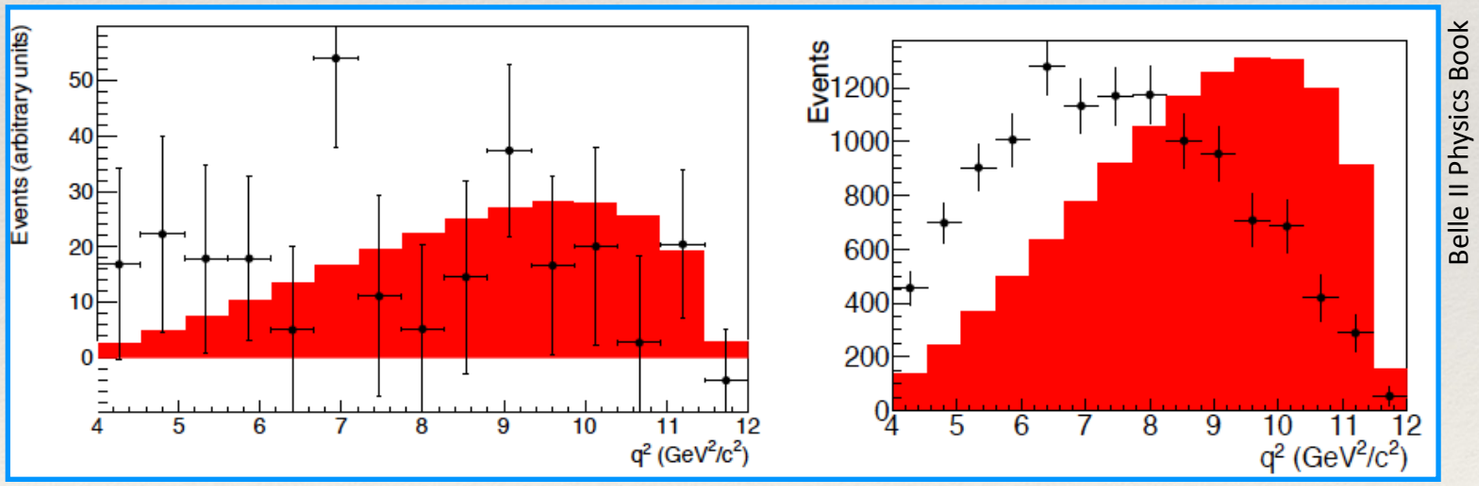
- Impact of beam induced background needs to be controlled.
  In particular on E_{ECL} discriminating and fit variable (extra energy in em calorimeter).

$B \to D^{(*)} \tau \nu$ (2)

- Belle II expected sensitivity (based on existing Belle results and expected improvements):



	$5\ \mathrm{ab}^{-1}$	$50\ \mathrm{ab}^{-1}$
R_D	$(6.0 \pm 3.9)\%$	$(2.0 \pm 2.5)\%$
R_{D^*}	$(3.0 \pm 2.5)\%$	$(1.0 \pm 2.0)\%$
$P_\tau(D^*)$	0.18 ± 0.08	0.06 ± 0.04



Belle 0.711 ab^{-1}

hadronic tag, $\tau \to h\nu$ analysis

[PRD92(7), 072014 (2015)]

Belle II 50 ab^{-1}

SM expectation

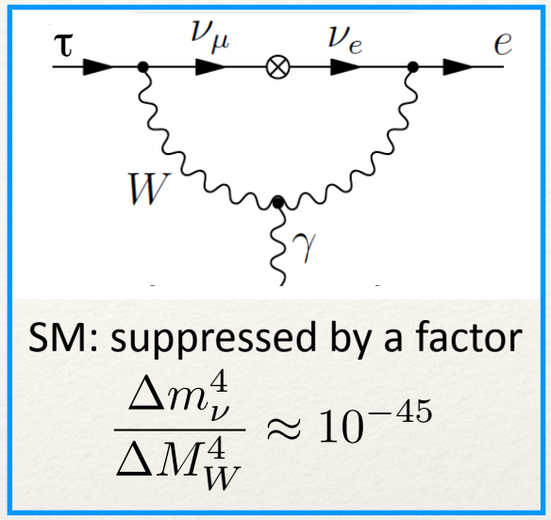
red = 2HDM of type II

with $\tan(\beta) = 0.5\ \mathrm{GeV}^{-1}$

τ physics

- Belle II is a unique place for τ physics:
  - 45×10^9 pairs $\tau^+\tau^-$ produced by SuperKEKB in 50 ab^{-1}.
  - Skills of Belle II for decays involving ν.

- Many interesting studies:
  τ and B cLFV decays, lepton universality, QCD, CPV in τ decays, τ EDM, …
  With τ→hadrons:
  quark-lepton LFV couplings, baryon number violation.

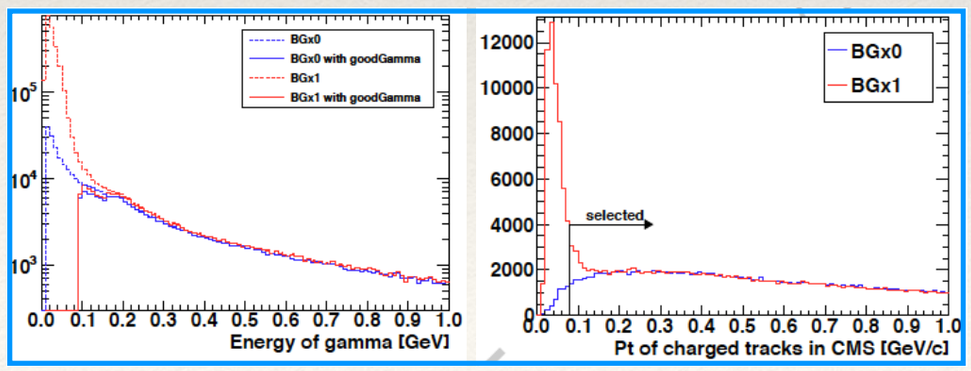


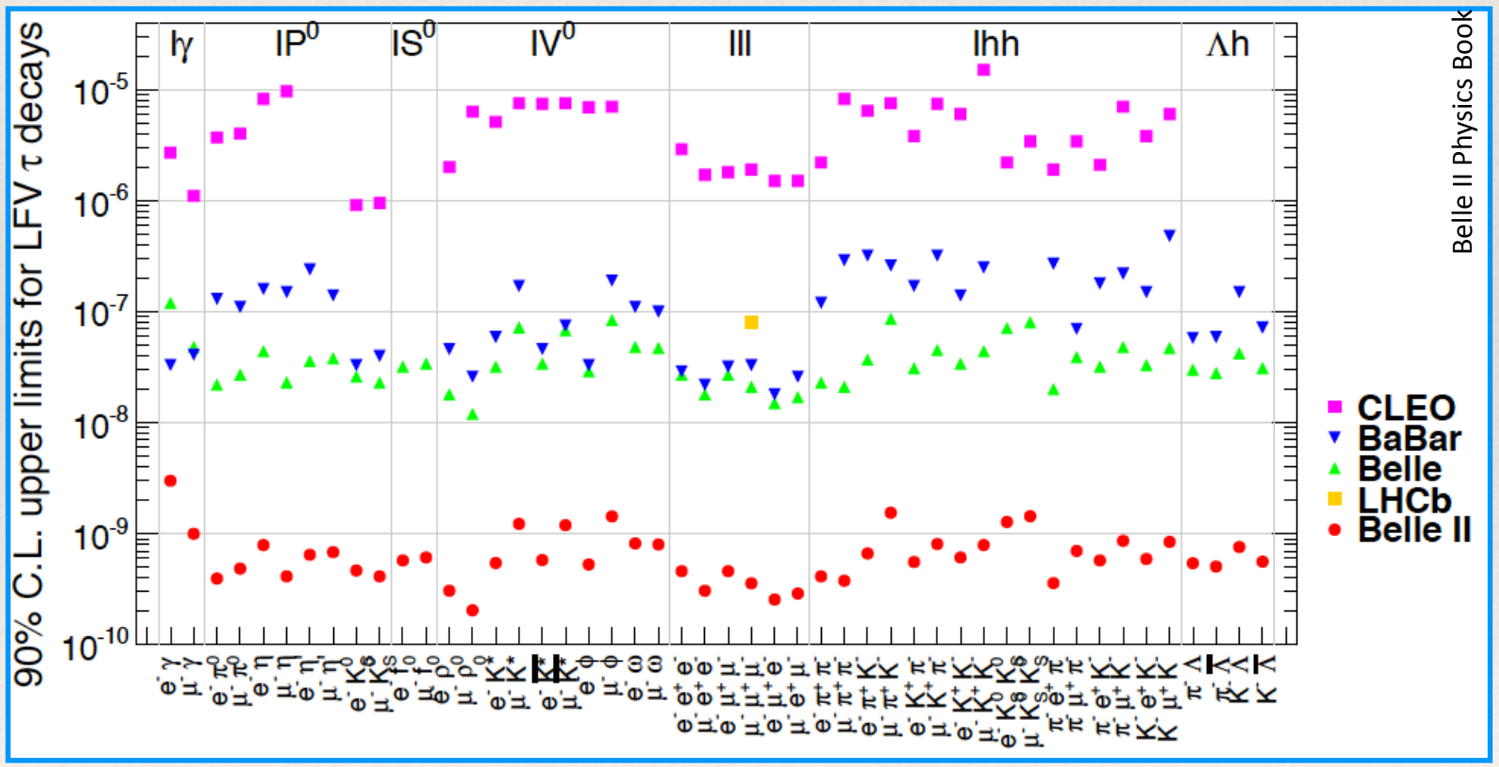
SM: suppressed by a factor

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

- Belle: 46 τ cLFV decays searched.
  Limits ~ few 10^{-8}.

- Important impact of beam induced BG.
  Expected limits ~ few 10^{-10}-10^{-9}.





Golden channel τ→μμμ is BG free:
limit improves faster than luminosity.

Conclusion

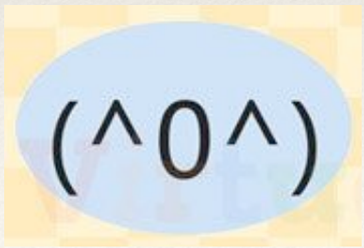
- Belle II will start in 2018.

- Search for quantum manifestations of physics beyond the SM relying on:
  - Accumulated experience from previous generation of B-Factories.
  - Stat × 40.

- Expected experimental performances often improve w.r.t. Belle despite 20× higher beam induced background and lower boost, thanks in particular to:
  - Pixelated innermost tracking detector,
  - Improved P-Id,
  - Optimised algorithms and deep learning, increasing CPU.

- With 50 ab^{-1}, many measurements will start to be syst. limited ➛ lots of work ahead!

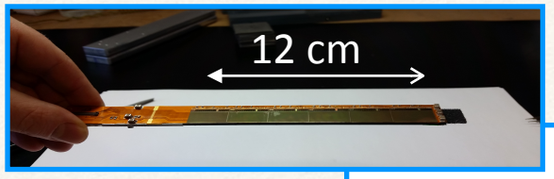
- IN2P3 has joined the Belle II collaboration with already recognised contributions and looking forward to welcoming new French collaborators.
  Excellent support from IN2P3.

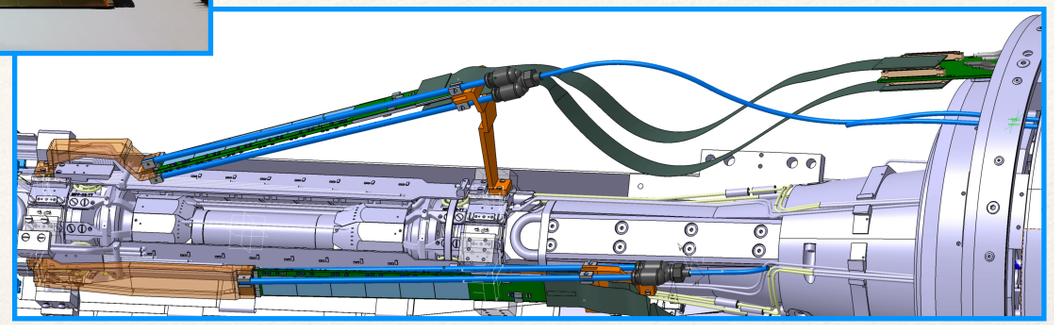


thank you for your attention

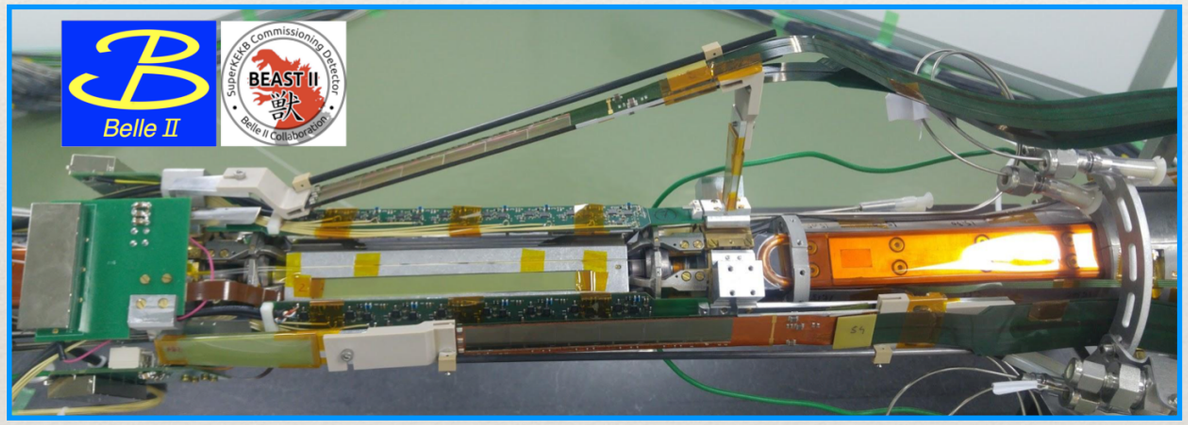
Study of machine induced background at IPHC

- Study of machine induced BG in inner tracker volume, @IPHC:
  - Conception + construction of a CMOS detector of 16×10^6 pixels, based on PLUME ILC R&D.
    Very light self-stiffened detector: 0.4 % of X_0.



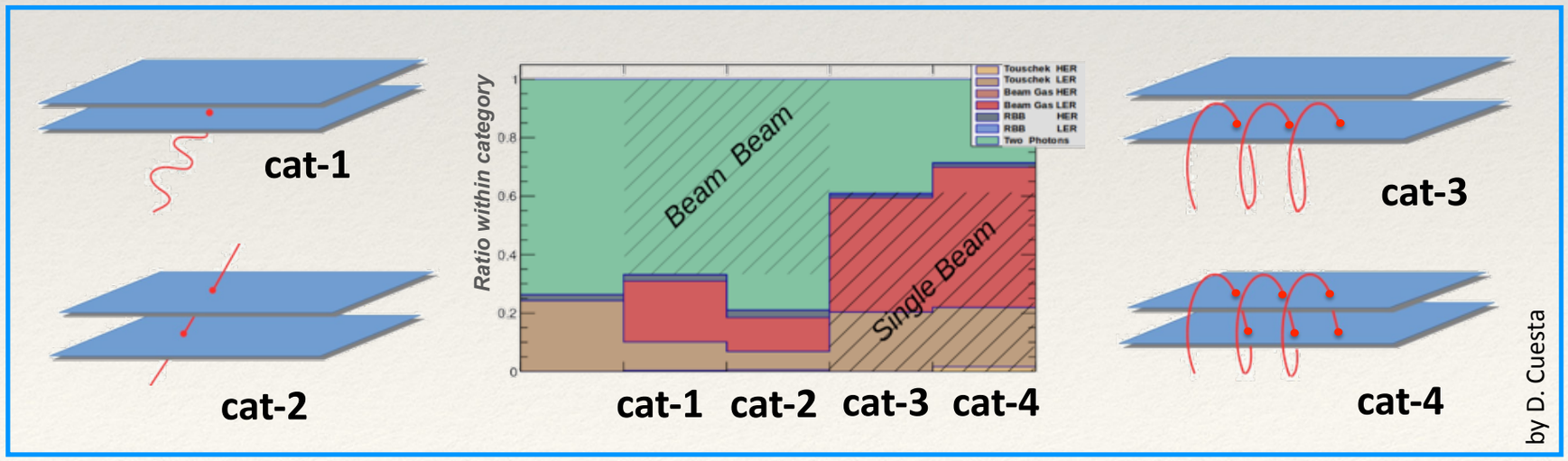


  - PLUME is a standalone mini- tracker: unique information on machine induced background.
  - Successful installation in Belle II in December 2017, ready to take data.



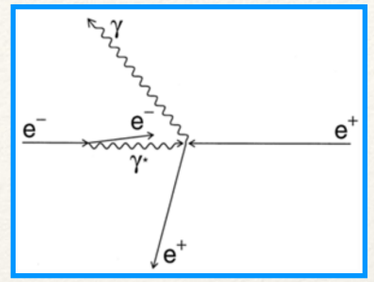
2 CMOS ladders around the beam pipe:
- one inclined: scan background in the whole vertex detector radius range.
- one ~ // to beam pipe: fit of helix tracks.

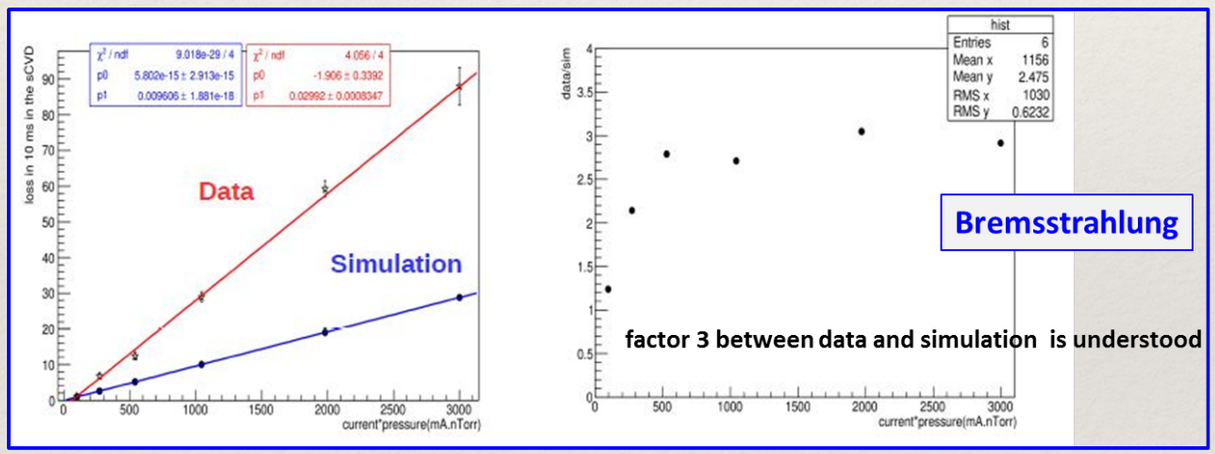
Sensitivity to the process origin.

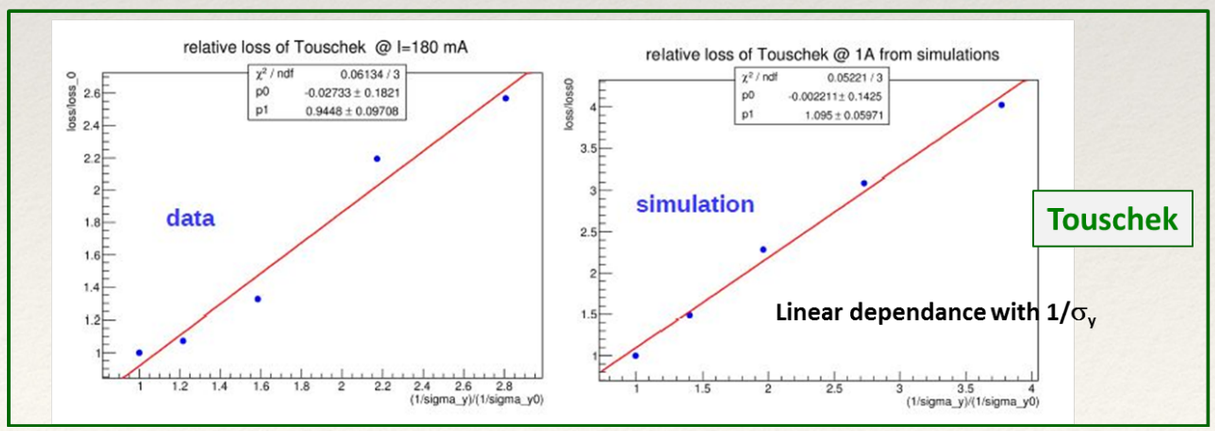


R&D for a luminosity monitor at LAL

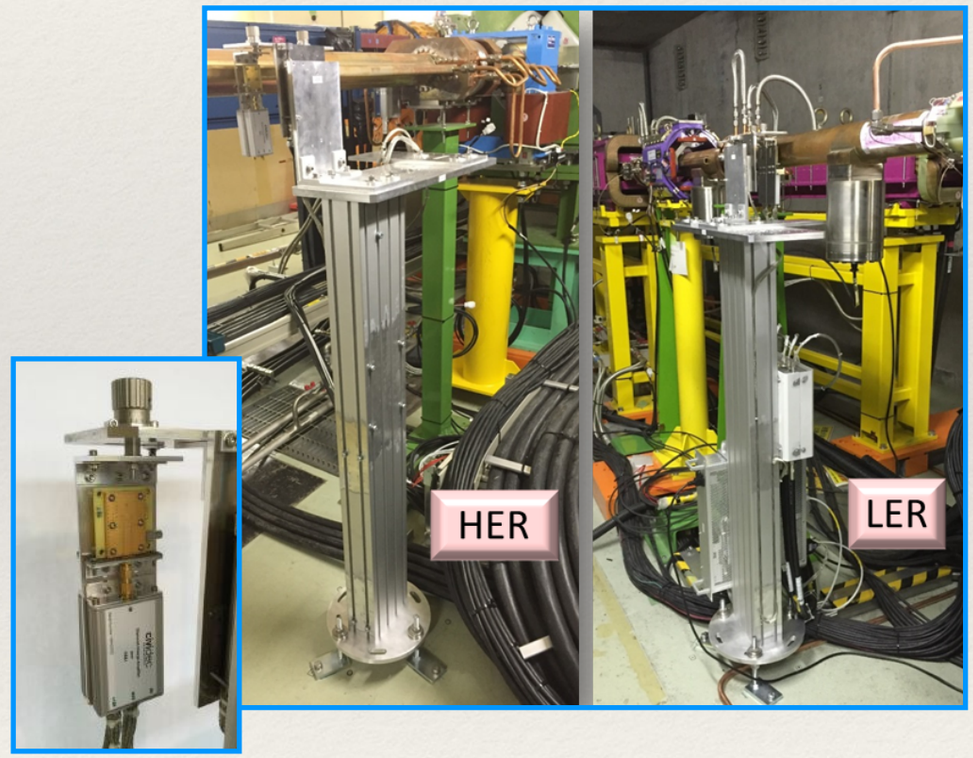
- Realisation of a fast luminosity monitor and measurement of radiative Bhabha process, @LAL:
  - Aimed precision: $\delta L/L \sim 10^{-2}$ to 10^{-3} in 1 to 10 ms.
  - Fast signal : monitor for each bunch crossing every 4 ns.
  - Measurement of radiative Bhabha process at 0º photon scattering angle.
  - Setup: 2 sets of 2× 5x5 mm^2 diamond sensors coupled to fast charge amplifiers.
  - Commissioning of the luminometer during Phase 1 and background measured: 5 TB of data collected.







by D. El Khechen

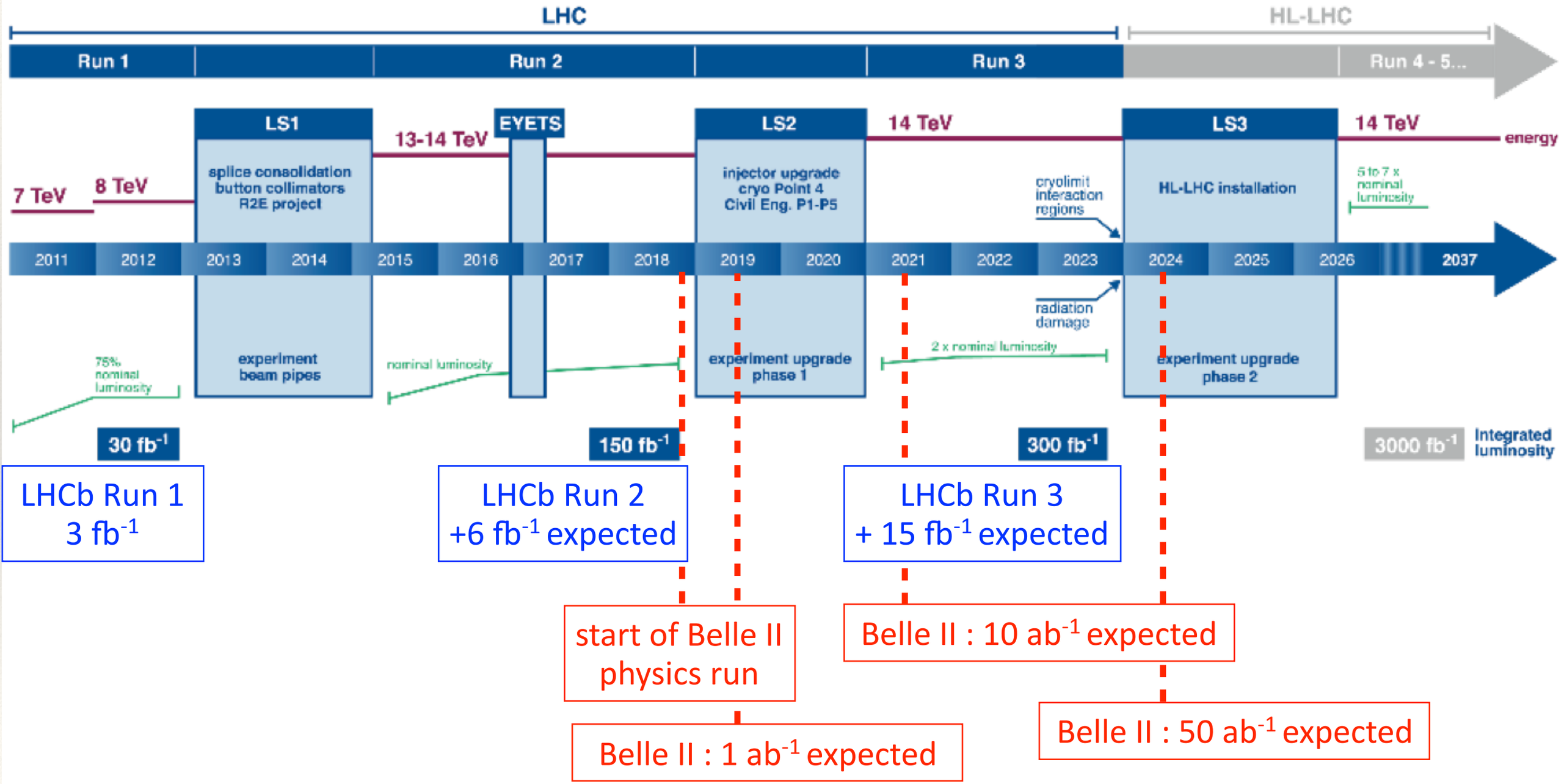


HER: photon detected 30 m downstream the IP

LER: scattered e^+ detected 11.9 m upstream the IP

LHCb vs. Belle II schedules

LHC / HL-LHC Plan



LHCb Run 1
3 fb^{-1}

LHCb Run 2
+6 fb^{-1} expected

LHCb Run 3
+ 15 fb^{-1} expected

start of Belle II physics run

Belle II : 1 ab^{-1} expected

Belle II : 10 ab^{-1} expected

Belle II : 50 ab^{-1} expected