BELLE-II: RARE DECAYS WITH MISSING ENERGY

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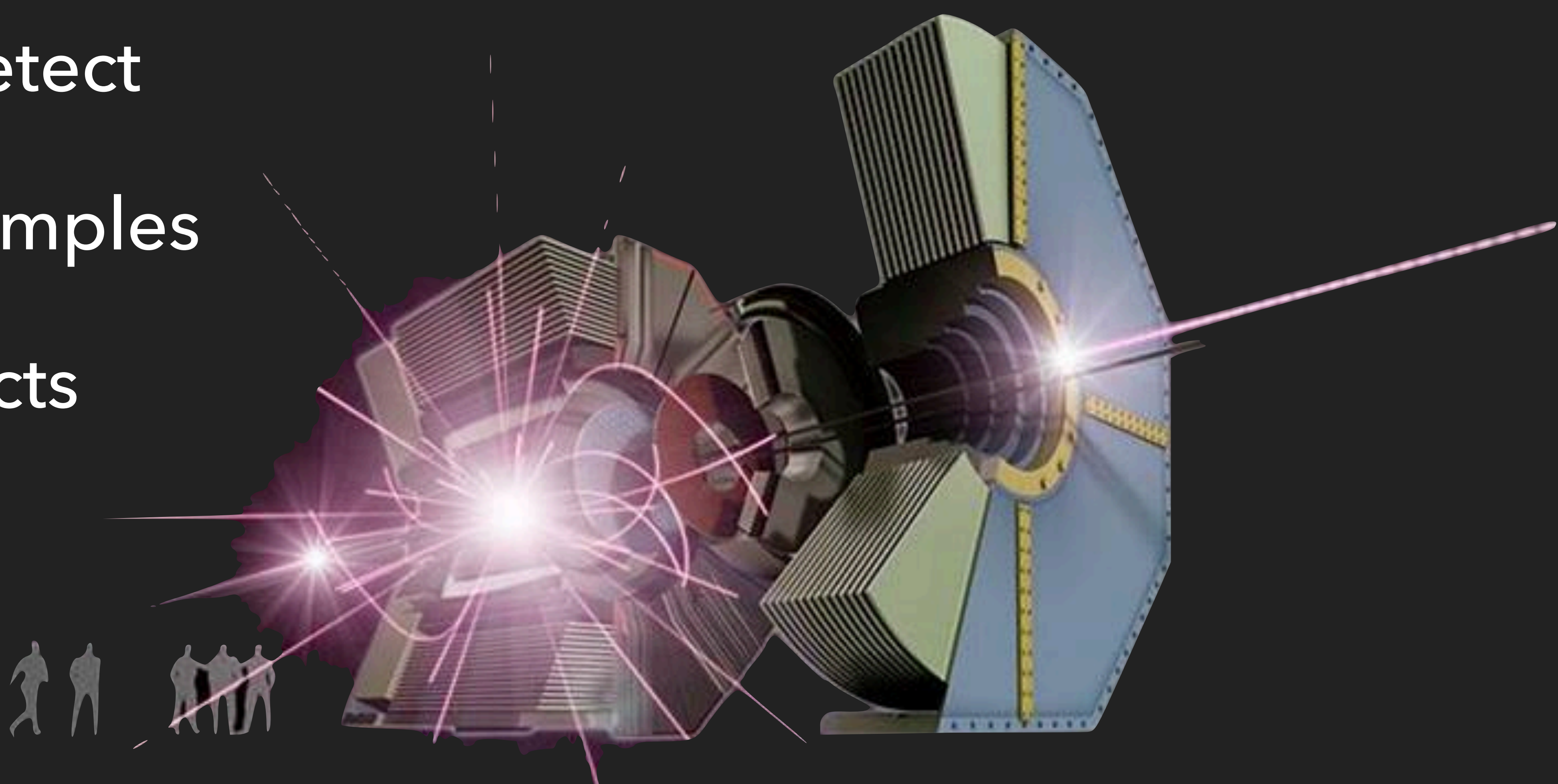
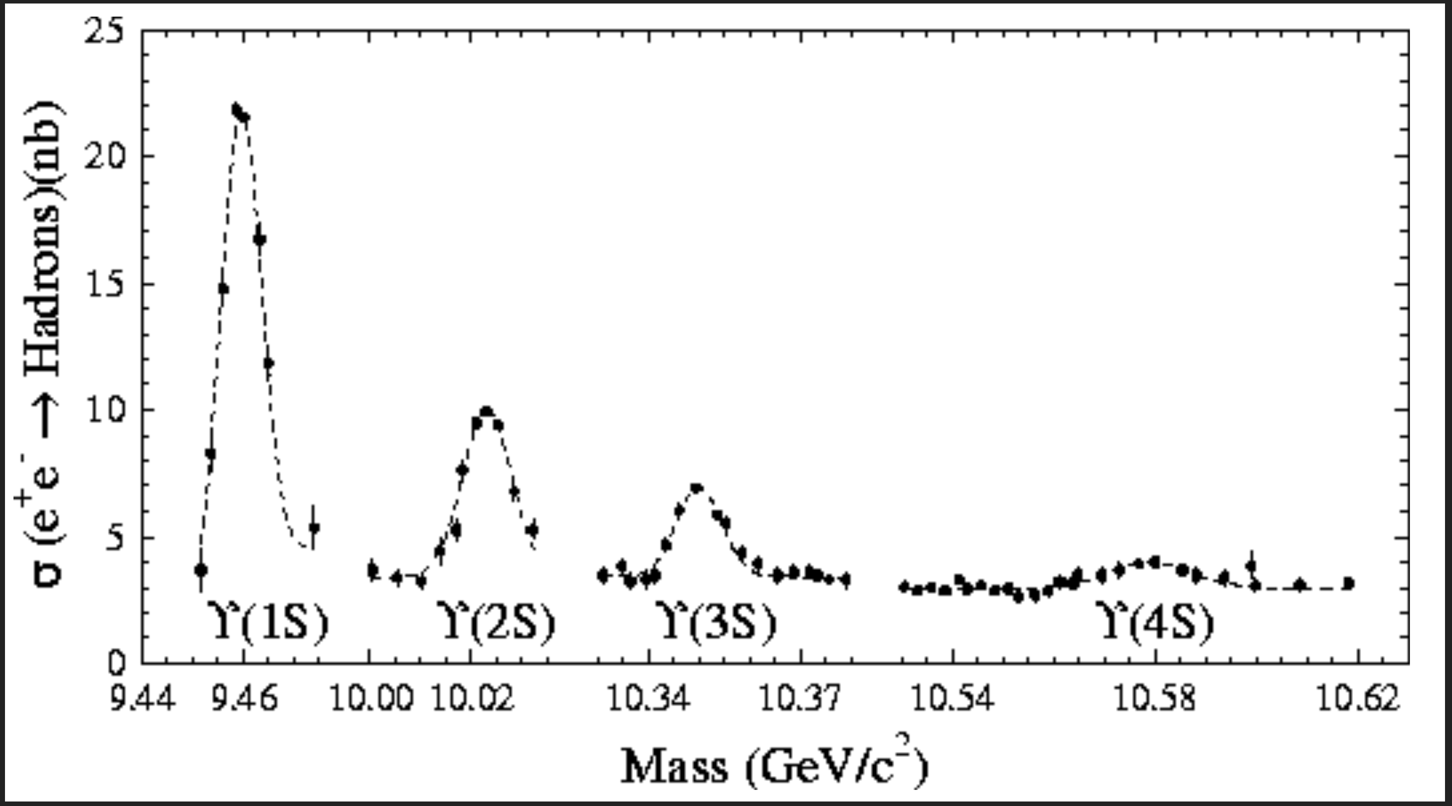
OVERVIEW

- Υ system
- Belle-II: The Detector
- Rare decays with missing energy
    - How to detect
    - Some examples
- Future prospects



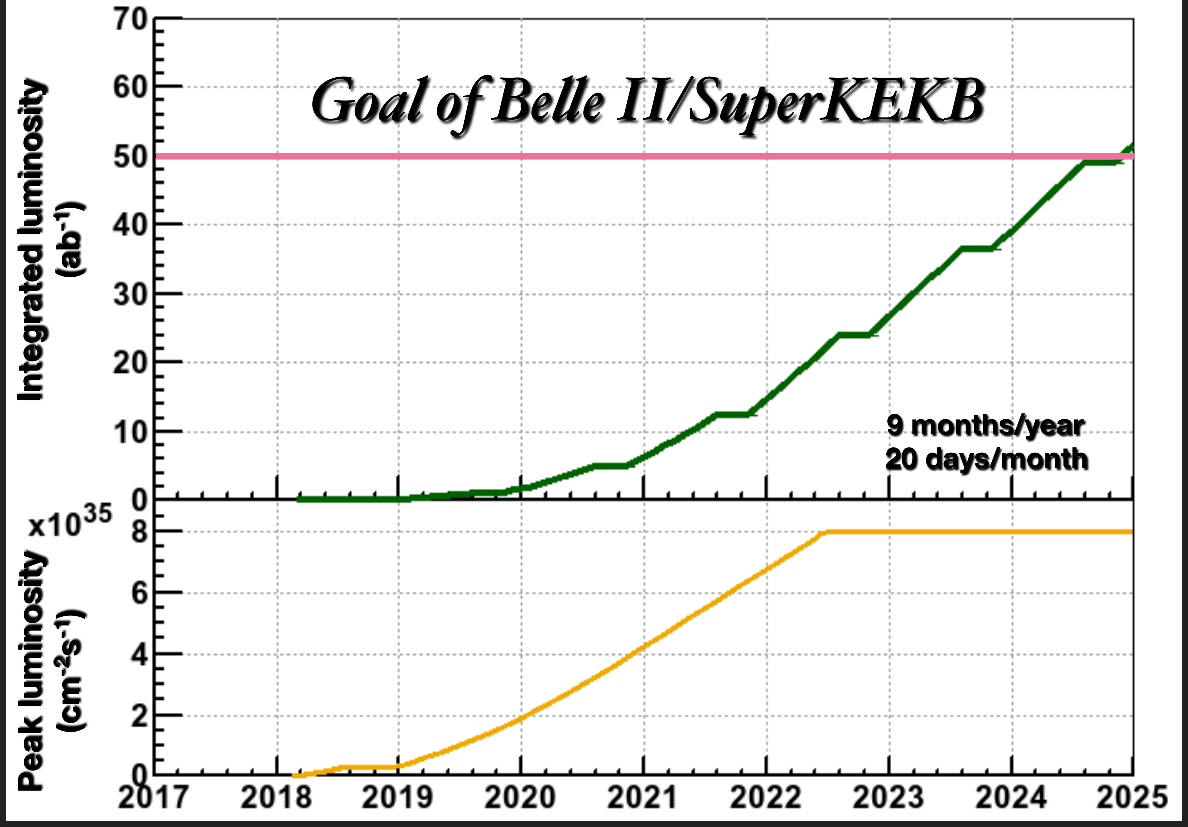
THE UPSILON (Υ) SYSTEM

- Υ system is the bound state of a b and anti-b quark
- By tuning accelerator energy, various resonances can be achieved
- The first 3 resonances can only decay through b anti-b annihilation
- 4th resonance ($4S$) has enough energy to create a light q pair, which then produce a B meson pair (without additional particles!)



BELLE-II: THE DETECTOR

- B mesons produced via $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B$ anti-B at SuperKEKB
  - Collided asymmetrically: E(e^+) = 4 GeV, E(e^-) = 7 GeV with CoM $\sqrt{s}$ = 10.58 GeV
- Luminosity frontier: $8 \cdot 10^{35}$ cm^{-2} s^{-1}
  - Integrated luminosity ~ 50 ab^{-1}
  - 55 billion B-anti B pairs, 47 billion $\tau^+ \tau^-$ pairs and 65 billion c anti-c



- Searches for New Physics (NP) by studying B, τ and charm decays (the flavour frontier) - indirectly reveals NP virtual particles in loops - probes the energy above 10 TeV

STATUS REPORT

Phase I (complete):

- Circulate beams without collision, Beam Background studies, optics tuning and vacuum scrubbing

Phase II (this year):

- First collisions, Beam Commissioning, Physics run with Belle II but without the Vertex Detector on $\Upsilon(4S)$ and maybe $6S$, New triggers for exotic dark signatures

Phase III (by 2019):

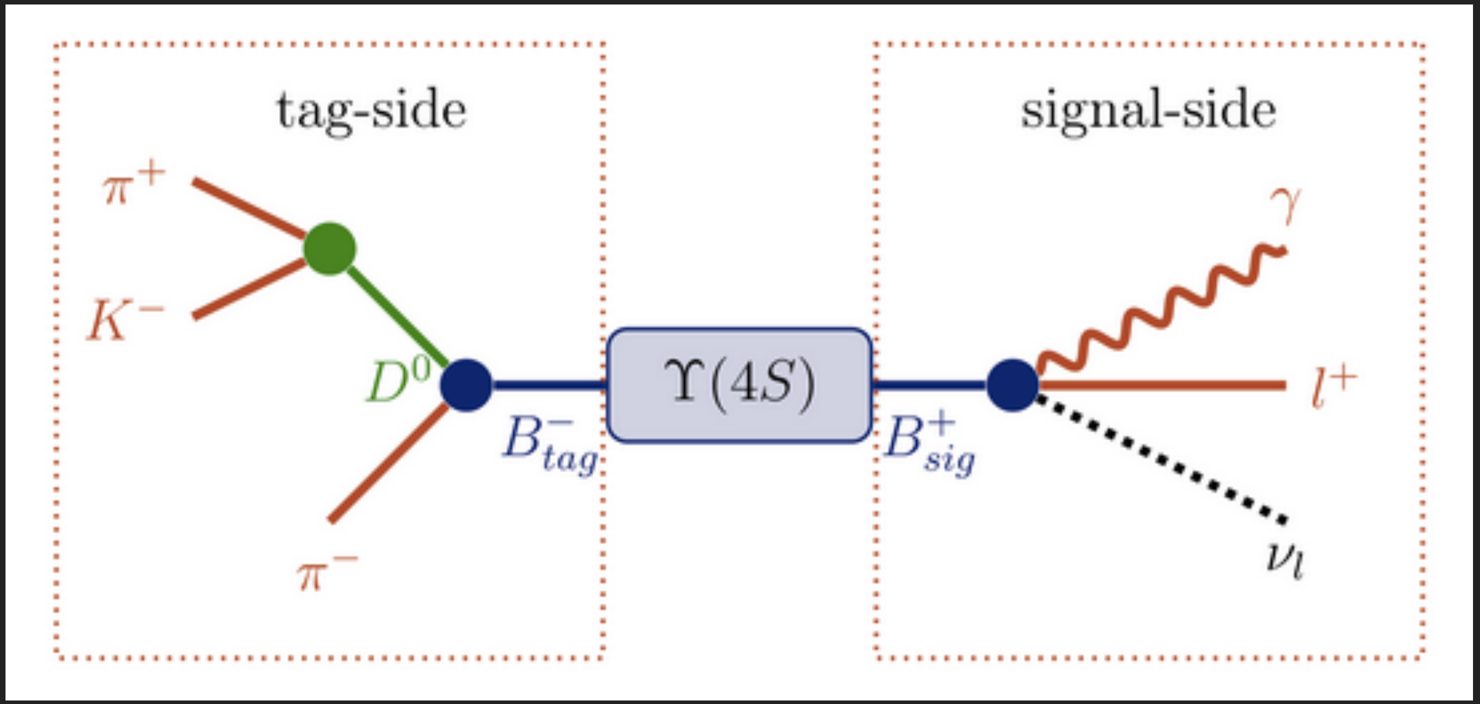
- Luminosity tuning, Physics run with FULL Belle II

RARE DECAYS WITH MISSING ENERGY

- Hermeticity of Belle II better than Belle and Babar
- Missing energy (i.e. νs) will hopefully allow us to probe for signs of physics beyond the SM: NP i.e. charged Higgs boson
- Anomalies already observed in data
- The luminosity at Belle II significantly improves the precision on measurements of B and D mesons and the τ lepton decays and should be able to resolve these observed anomalies!

EVENT RECONSTRUCTION

- B decays with missing energy (i.e. ν) are limited in their available kinematic information
- To identify the signal decay one has to exclusively reconstruct one of the B meson decays (the 'tagged B' or B_{tag})

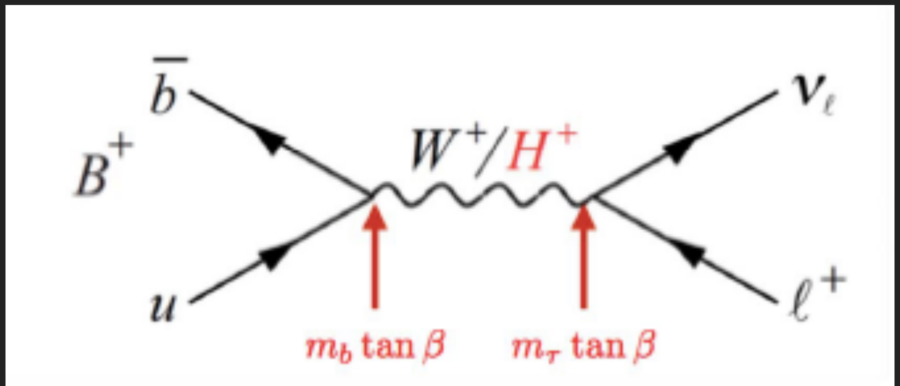


- This constrains the 4-mom and flavour of the other B (signal B) i.e. whether it was constructed from a b quark or an anti-b quark
  - Hadronic tagging: B_{tag} is fully reconstructed in numerous hadronic decays
  - Semileptonic tagging: B_{tag} is partially reconstructed in semileptonic decays

FULL EVENT INTERPRETATION (FEI)

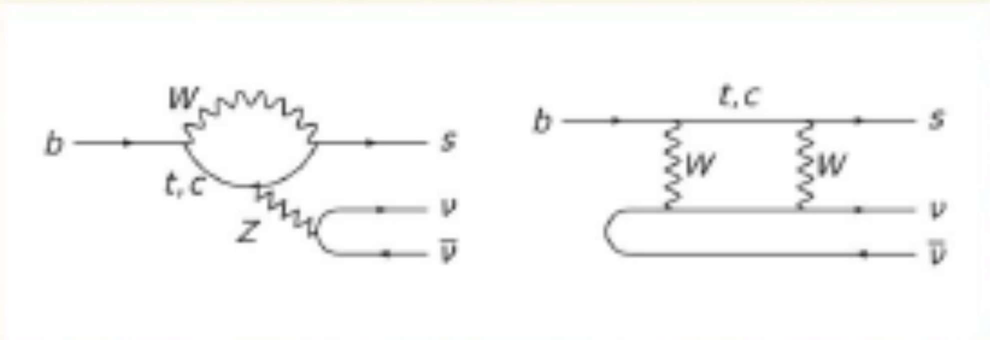
- How to detect missing kinematic information?
  - FEI unifies the hadronic and semi-leptonic tagging into a single algorithm
  - FEI partially recovers missing information and infers strong constraints on the signal candidates by automatically reconstructing the Rest of Event (ROE) in thousands of exclusive decay channels
  - More inclusive, more automation and analysis-specific optimisations. Multivariate classifier (MVC) has to be trained for intermediate and final state particle candidate classification
  - Combine all info into single value

$B^+ \to \tau^+ \nu$



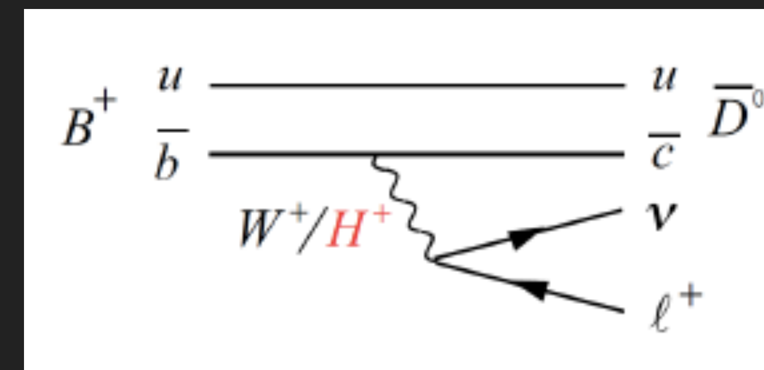
- Leptonic decay
- Branching ratio $\mathscr{B}r$ depends strongly on lepton mass
- sensitive to charged scalars (e.g. charged Higgs) → $\mathscr{B}r$ modification
- SM prediction: $\mathscr{B}r = (0.77 \pm 0.06)\text{x}10^{-4}$ (using CKM matrix $|V_{ub}|_{excl} = (3.55 \pm 0.12) \times 10^{-3}$, B decay constant $f_B=(186 \pm 4)$MeV)
- Current measurements approach: $\mathscr{B}r = (0.821 \pm 0.003)\text{x}10^{-4}$
- FEI good for the measurement of $B \to \tau\, \nu$ as it allows precise measurement of the $\mathscr{B}r$, which would be sensitive to NP
- If there are no NP, it provides a direct determination of f_B and $|V_{ub}|$.

$B \rightarrow K(*)\, \nu\, \nu$

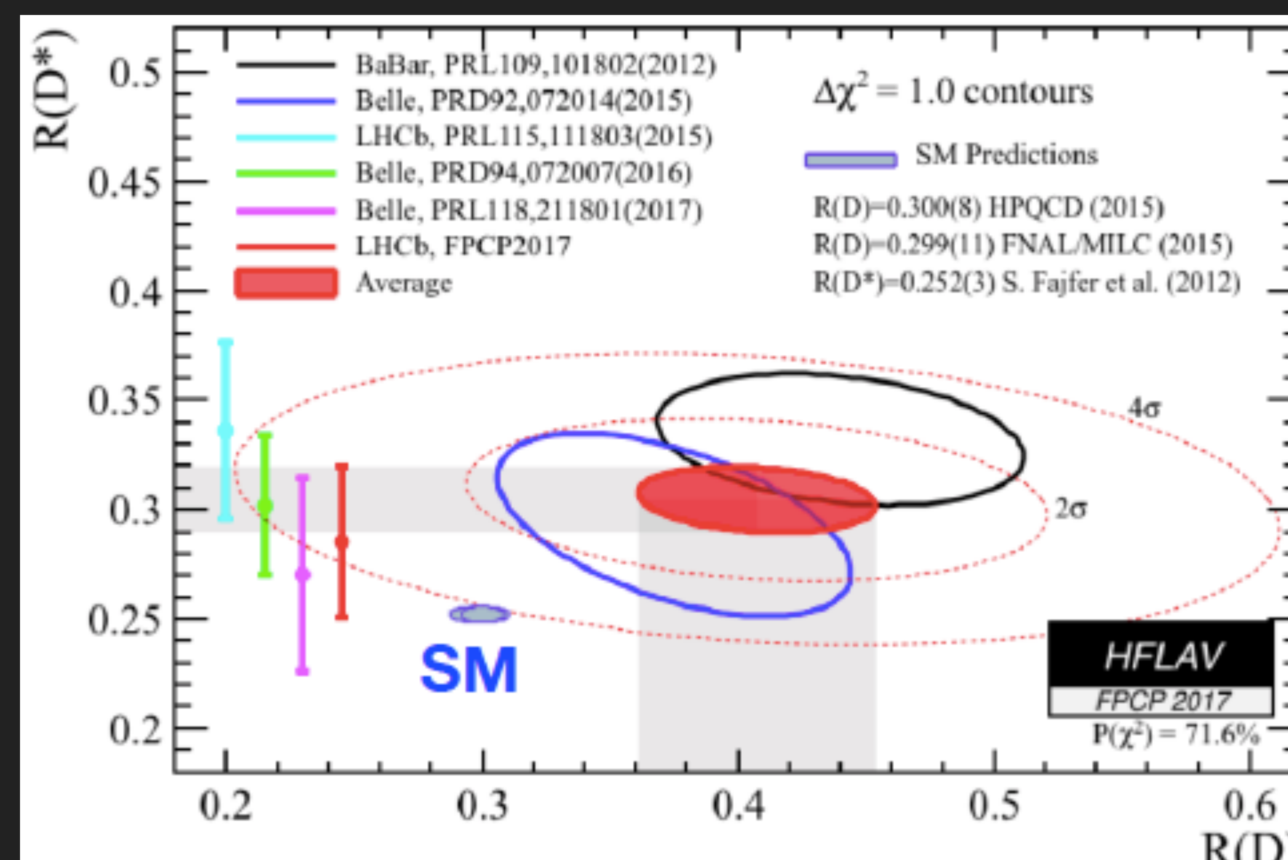


- $\mathscr{Br}$ < 1.3x10^{-5}, CL =90%
- Flavour changing neutral current (FCNC). Prohibited at the tree level in the SM
- Clean decay to examine
- So far no signal evidence
- Potentially observable with 18 ab^{-1} of data, and with 50ab^{-1} the sensitivities of the $\mathscr{Br}$ would be 12 and 11% respectively

$B \to D(*)\, \tau\, \nu$



- Semileptonic decay is sensitive to BSM physics (Larger $\mathscr{Br}$ in the SM: ~1%)
- SM prediction:
    - $R(D)_{SM} = 0.297 \pm 0.017$
    - $R(D^*)_{SM} = 0.252 \pm 0.003$
- World average for $R(D^{(*)})$ was in ~4.1σ deviation from SM but recent Belle and LHCb results consistent with SM for $B \to D^{*-}\, \tau\, \nu$
- Lepton universality test: electroweak couplings of leptons to gauge bosons independent of flavour?



FUTURE PLANS

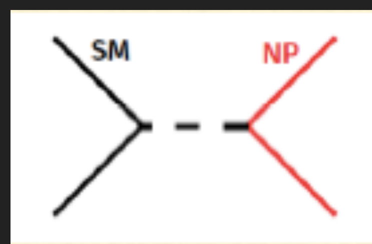
- To investigate further the deviation from /consistency with the SM of $B^+ \to \tau^+ \nu$ and $B \to D^{(*)} \tau \nu$ (which can be resolved with just a few ab^{-1} of data!)
- Prospects for these modes:
  - $B^+ \to \tau^+ \nu$: Belle II at $50ab^{-1}$ is expected to reach ~6% precision
  - $B \to K^{(*)} \nu \nu$: To approach the SM prediction for $B \to K^{(*)} \nu \nu$ (which can be probed at the 5σ level with $50ab^{-1}$). Once observed the measurements of differential $\mathscr{Br}$ and polarisation of K* will be focussed on next.
  - $B \to D^{(*)} \tau \nu$: Belle II can reach 3% sensitivity for R(D(*)) at 50 ab^{-1}.

SUMMARY

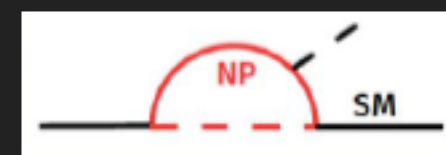
- Belle II is a very competitive and unique environment to study B decays with missing energy
- Potentially sensitive to indirect NP effects
- The improvements in analysis strategy and the larger data sample will allow us to probe further these possible effects

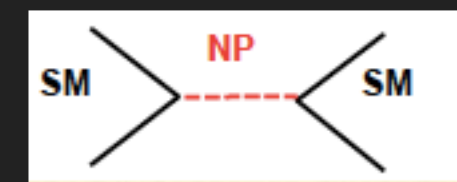
BACK-UP

Energy frontier: direct production of new particles - limited by beam energy (LHC - ATLAS, CMS)



Intensity frontier: new virtual particles in loops/trees transitions, deviation from SM expectations (B factories, LHCb)





Why asymmetric? The B meson pairs are created with a Lorentz boost $\beta\gamma$ of 0.425, allowing measurements of the B meson decay times via the distance from the (known) collision point.

LHCb is better when it comes to decays that involve muons, but Belle II takes precedence when it come to missing energy.

Expected errors with the Belle full data sample, and 5 ab^{-1} and 50 ab^{-1} of Belle II data.

	Statistical	Systematic (reducible, irreducible)	Total Exp
$\mathcal{B}(B \to \tau\nu)$ (had. tagged)			
711 fb^{-1}	38.0	(14.2, 4.4)	40.8
5 ab^{-1}	14.4	(5.4, 4.4)	15.8
50 ab^{-1}	4.6	(1.6, 4.4)	6.4
$\mathcal{B}(B \to \tau\nu)$ (semileptonic tagged)			
711 fb^{-1}	24.8	$(18, ^{+6.0}_{-9.6})$	$^{+31.2}_{-32.2}$
5 ab^{-1}	8.6	$(6.2, ^{+6.0}_{-9.6})$	$^{+12.2}_{-14.4}$
50 ab^{-1}	2.8	$(2.0, ^{+6.0}_{-9.6})$	$^{+6.8}_{-10.2}$

For the $B \to D^{(*)} \tau \nu$ decay

Extrapolation of the Babar result. Errors are given in percent.

	Statistical	Systematic (reducible, irreducible)	Total Exp
$R(D)$			
423 fb^{-1}	13.1	(9.1, 3.1)	16.2
5 ab^{-1}	3.8	(2.6, 3.1)	5.6
50 ab^{-1}	1.2	(0.8, 3.1)	3.4
$R(D^*)$			
423 fb^{-1}	7.1	(5.2, 1.9)	9.0
5 ab^{-1}	2.1	(1.5, 1.9)	3.2
50 ab^{-1}	0.7	(0.5, 1.9)	2.1

	Limit or total error
$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = (4.4 \pm 1.5) \times 10^{-6}$	
0.711 ab^{-1}	$< 5.5 \times 10^{-5}$
5 ab^{-1}	$< 2.1 \times 10^{-5}$
50 ab^{-1}	$< 0.7 \times 10^{-5}$
$\mathcal{B}(B^0 \to K^0_S\nu\bar{\nu}) = (2.2 \pm 0.8) \times 10^{-6}$	
0.711 ab^{-1}	$< 9.7 \times 10^{-5}$
5 ab^{-1}	$< 3.7 \times 10^{-5}$
50 ab^{-1}	$< 1.2 \times 10^{-5}$
$\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu}) = (6.8 \pm 2.0) \times 10^{-6}$	
0.711 ab^{-1}	$< 5.5 \times 10^{-5}$
5 ab^{-1}	$< 2.1 \times 10^{-5}$
50 ab^{-1}	$< 0.7 \times 10^{-5}$

- Touschek effect
  - Intra bunch scattering
  - Dominant with highly compressed beams

Rate ∝ inverse beam size, # of bunches

- Beam gas
  - Coulomb and bremsstrahlung scattering (neg.) by residual gas atoms

Rate ∝ vacuum level and beam current

- Synchrotron radiation
  - γ emitted by charged particles when deflected in B field

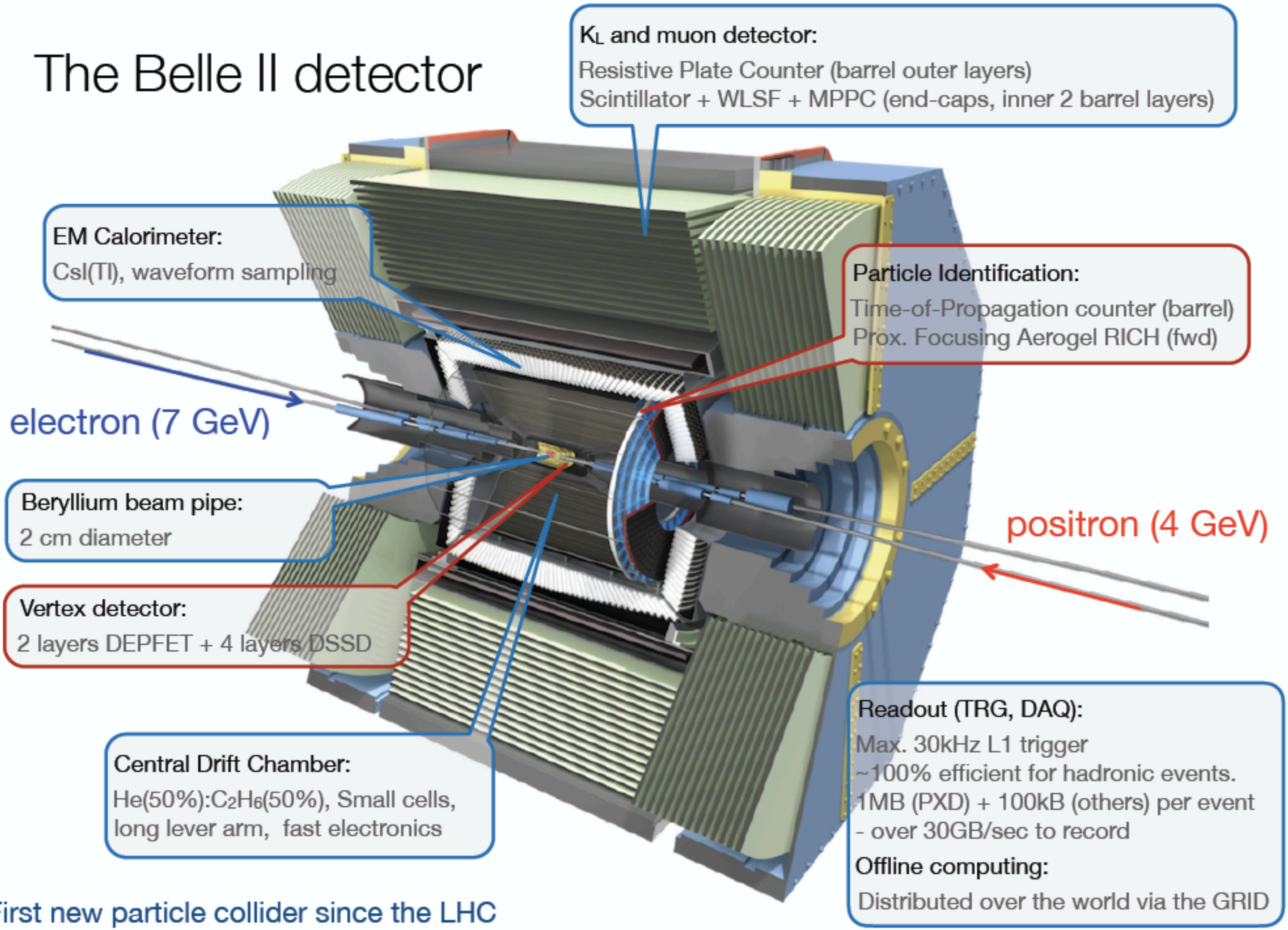
Rate ∝ beam energy squared and magnetic field squared

- Physical backgrounds (Collisions - phase 2)
  - Radiative Bhabha process $ee \to (\gamma)ee$ before or after Bhabha scattering

    interaction with iron in magnets gives n background!
  - Two photon process: $ee \to eeee$

Rate ∝ luminosity

The Belle II detector



First new particle collider since the LHC