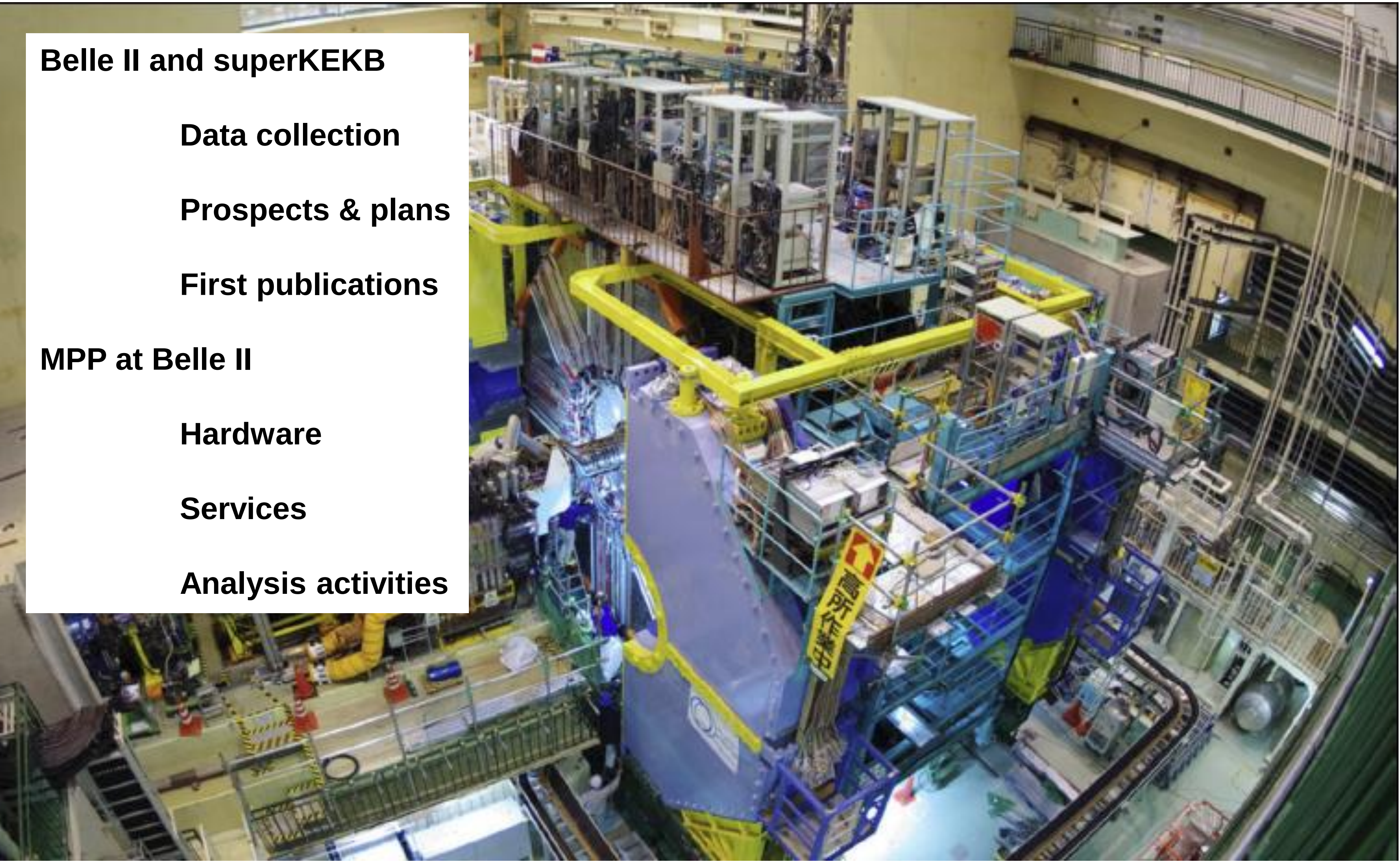
Belle II: Status and Prospects

Belle II and superKEKB

- **Data collection**
- **Prospects & plans**
- **First publications**

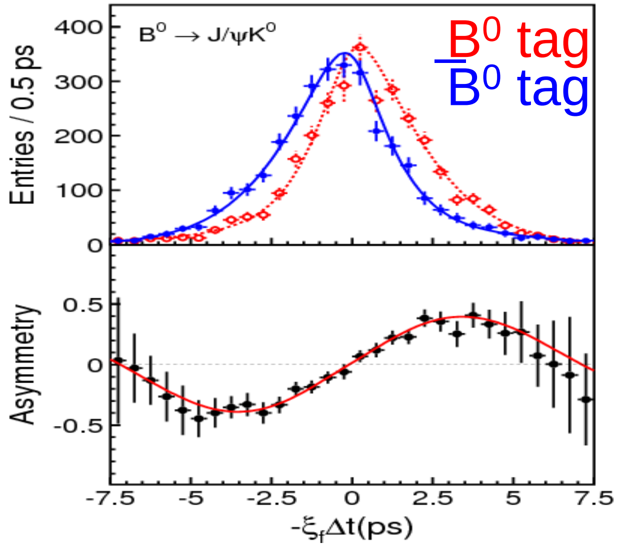
MPP at Belle II

- **Hardware**
- **Services**
- **Analysis activities**



Physics at B-factories

- CKM matrix elements and angles of the unitarity triangle
- Direct CP violation in B decays
- Rare decays (e.g., B -> K νν, B→τν, Dτν)
- b→s transitions: probe for new sources of CPV
- τ physics (EDM, MDM, rare decays)
- Spectroscopy, observation of new hadrons
- Low mass dark matter (dark sector)
- Lepton Flavour Violation
- ………



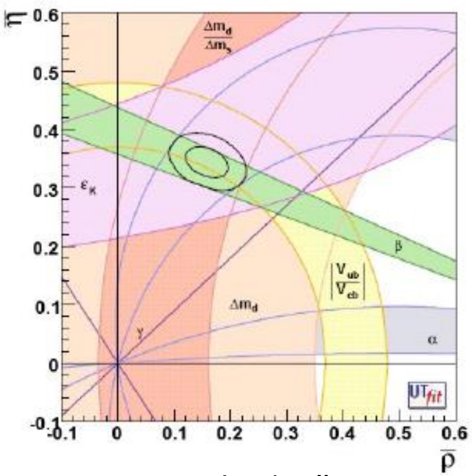
New Physics enters throuh loops

⇒ Sensitive to multi-TeV scales

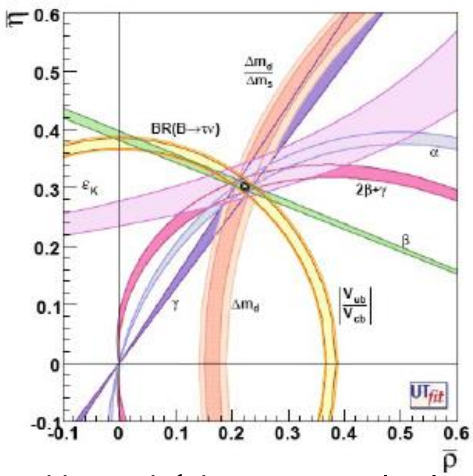
Predecessors

Babar ~500 fb^{-1}

Belle ~1000 fb^{-1}

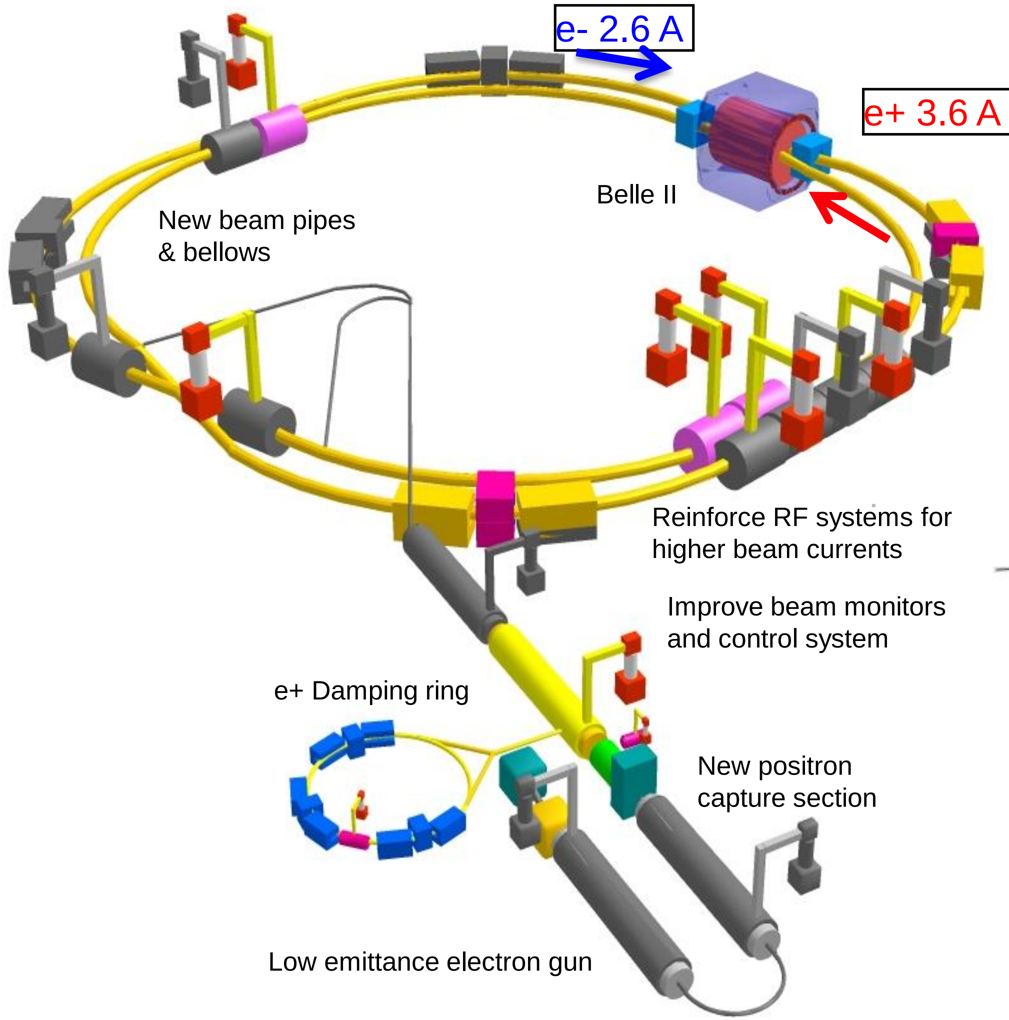


Babar/Belle



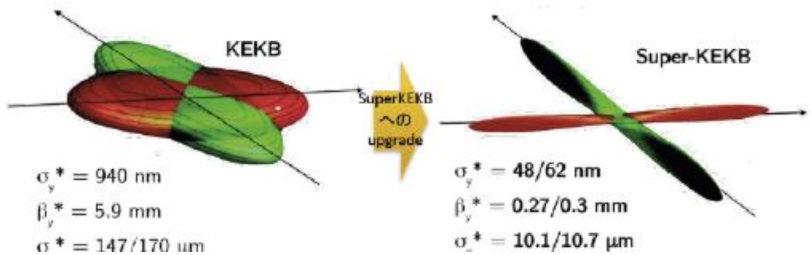
With 50 ab^{-1} (same central values)

From KEKB to SuperKEKB



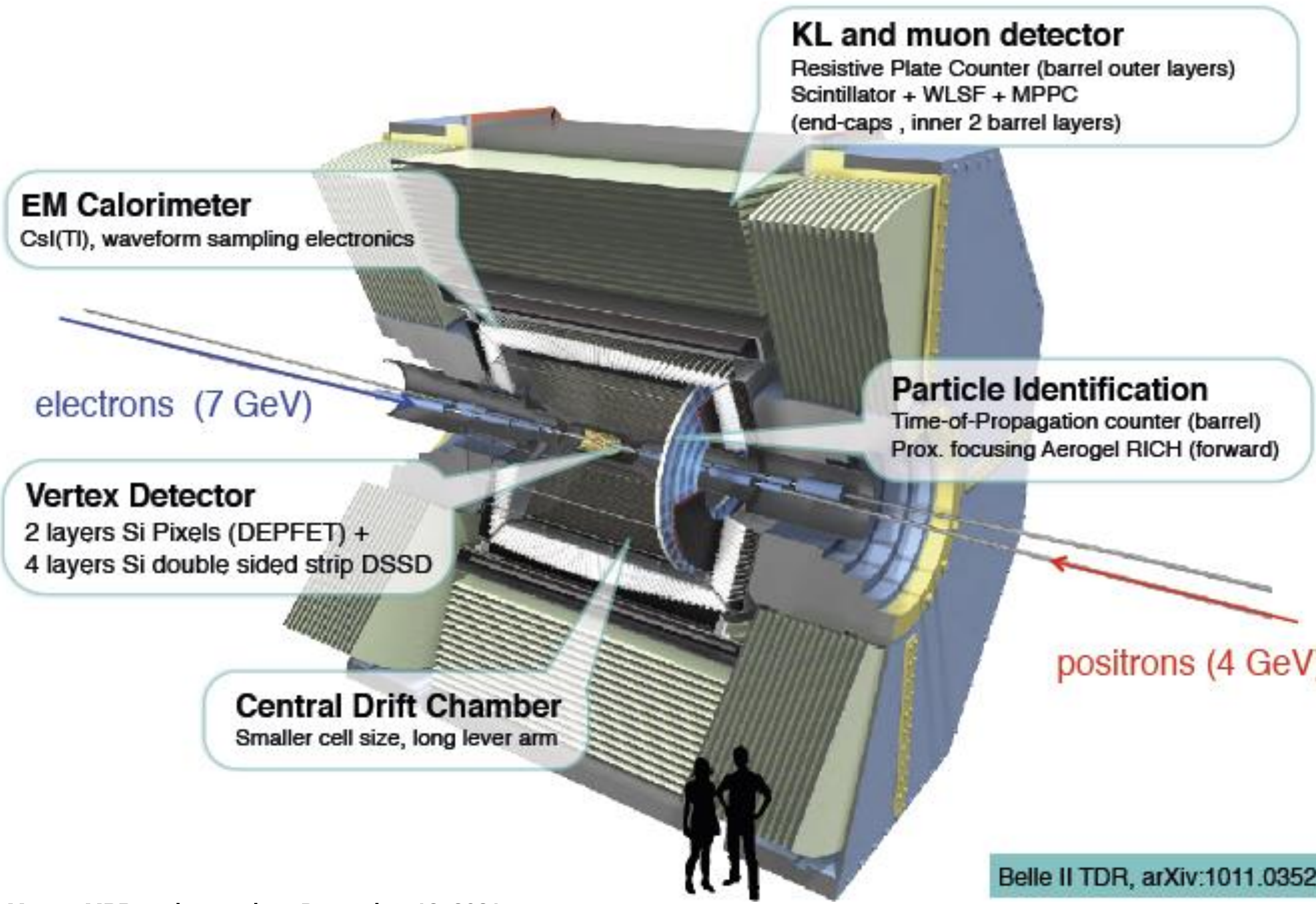
Upgrade KEKB to reach
L = 6.5 x 10^{35} $cm^{-2}s^{-1}$
(30 x luminosity of KEKB)

Nano Beams: 10µm x 50nm
Increase beam current (x2)



E_{cm} 10.58 GeV [Y(4s)] + scans

Belle II Detecotor

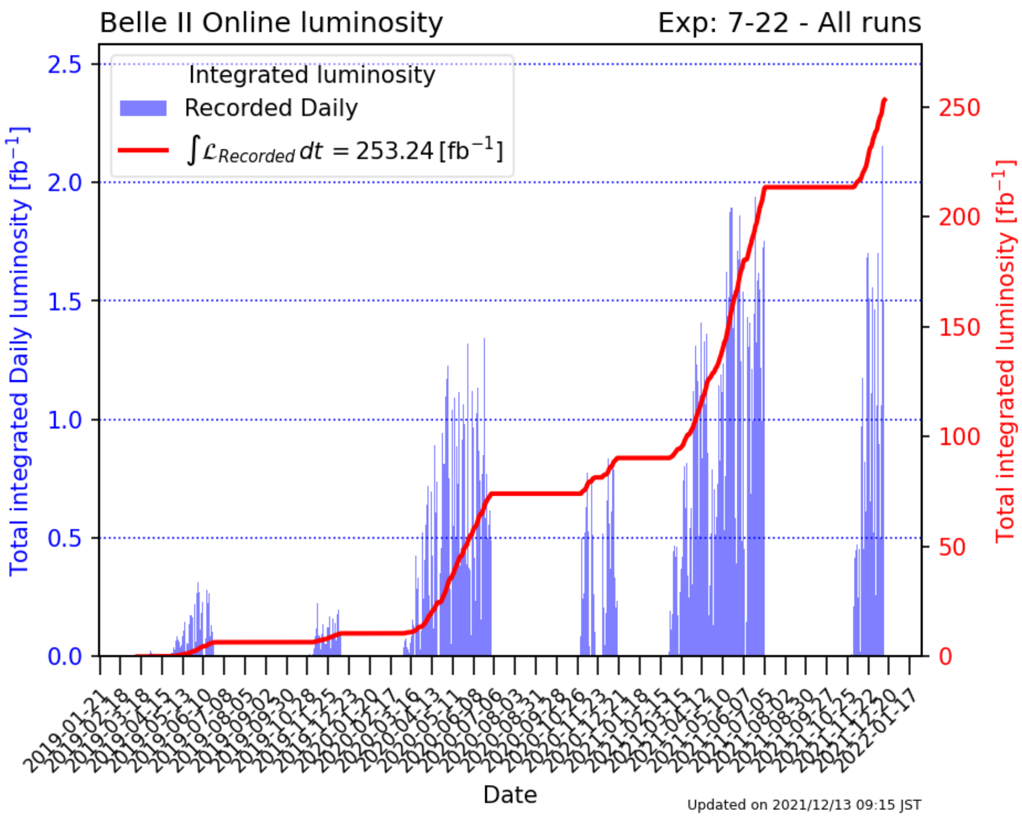


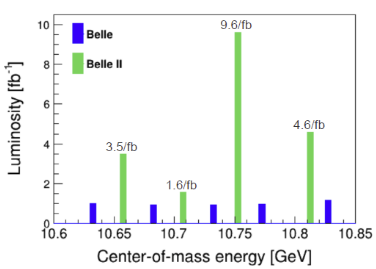
Belle II TDR, arXiv:1011.0352

Belle II Collaboration

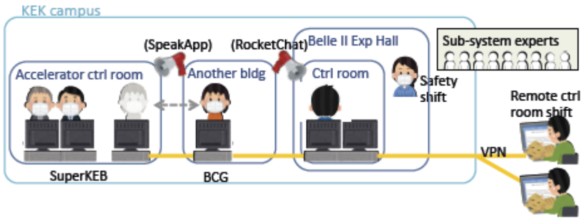
~1100 researchers 123 institutions 23 countries

SuperKEKB/Belle II Operation





Nov 21: scan
10.665 – 10.810 GeV
(~20 fb^{-1})



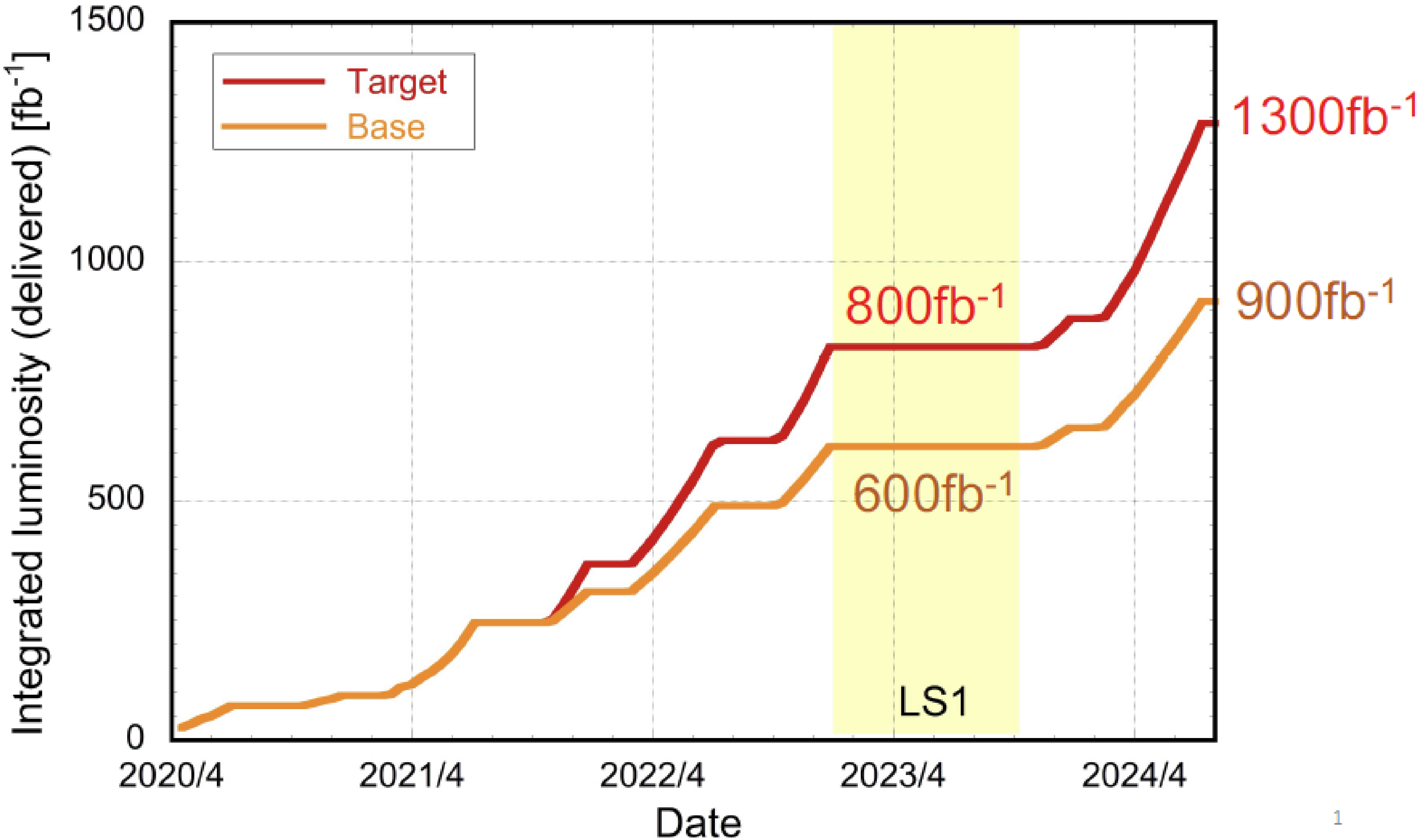
Successful running during Covid-19 pandemic
No travel to Japan possible
Remote shifts & small local team at KEK
DAQ efficiency 89.5%

Peak luminosity: 3.18 x 10^{34} $cm^{-2}s^{-1}$ (world record)

Luminosity still limited by large background (injections)
TOP aging and CDC currents

Total: 253 fb^{-1}

Prospects



Shutdown (LS1) to replace PXD (and TOP PMTs) postponed to 2023
Objective is to collect at least 600 fb^{-1} before long shutdown

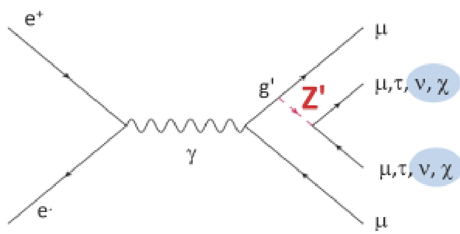
Recently Published

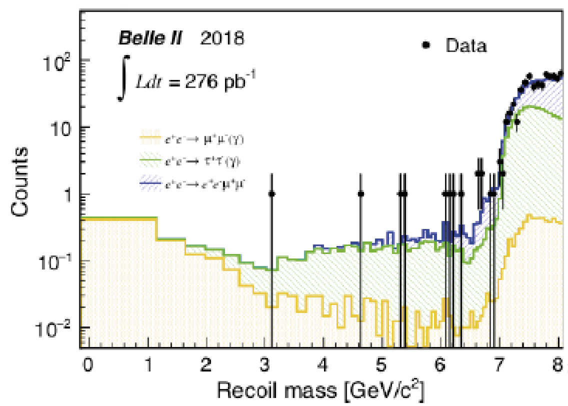
Dark Sector Search: Z‘ -> invisible [PRL 124, 141801] using 0.276 fb^{-1} (2018, commissioning)

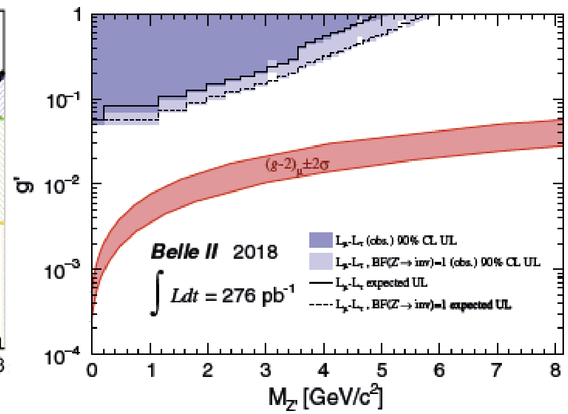
$L_\mu - L_\tau$ model
(coupling only to the 2nd and 3rd lepton generation)

Phy.Rev D89,113004 (2014)
JHEP12(2016)106]

$e^+ e^- \to \mu^+ \mu^- Z', (Z' \to invisible)$





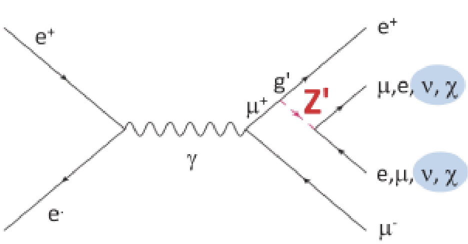


• The first experiment to set limits on Z’ coupling, g’. Will soon probe the region interesting for the (g-2)$_\mu$ anomaly.

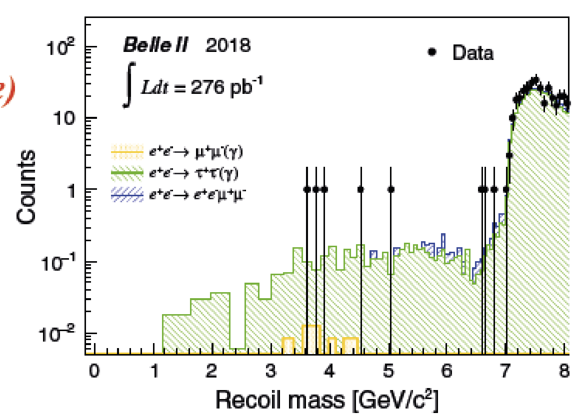
Z’ with *LFV*
$e-\mu$ coupling

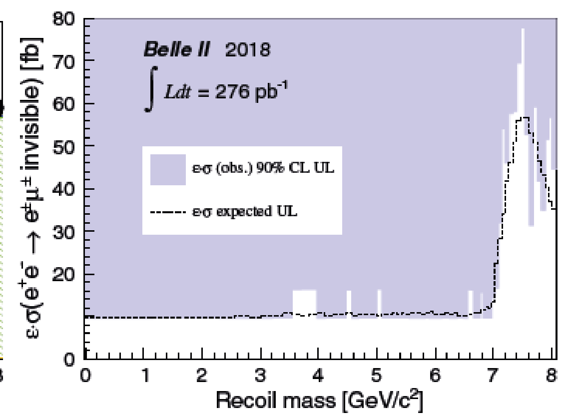
[JHEP05 (2017) 083,
JHEP03 (2017) 064]

$e^+ e^- \to e^\pm \mu^\mp Z', (Z' \to invisible)$



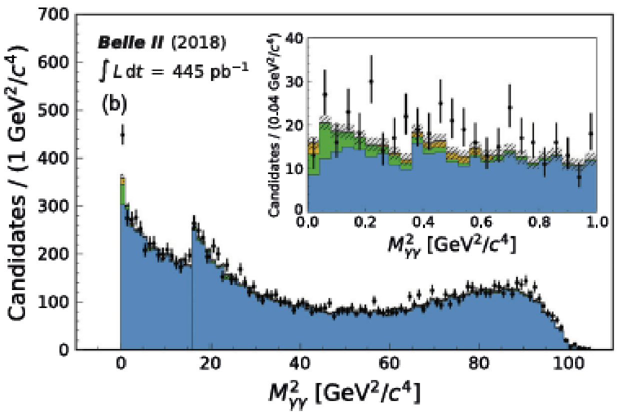
model independent search

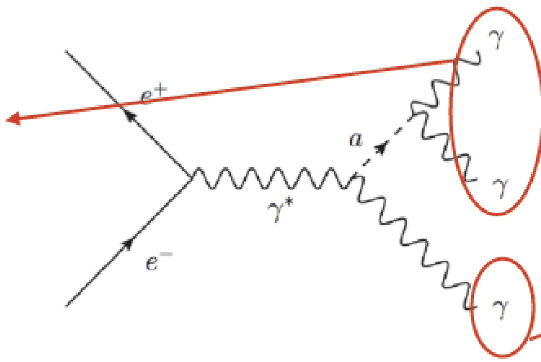


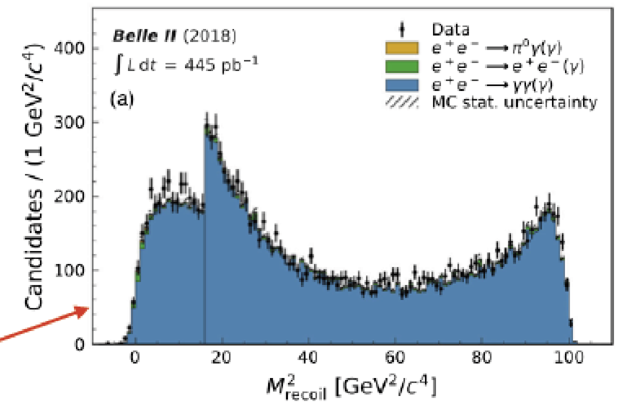


Recently Published

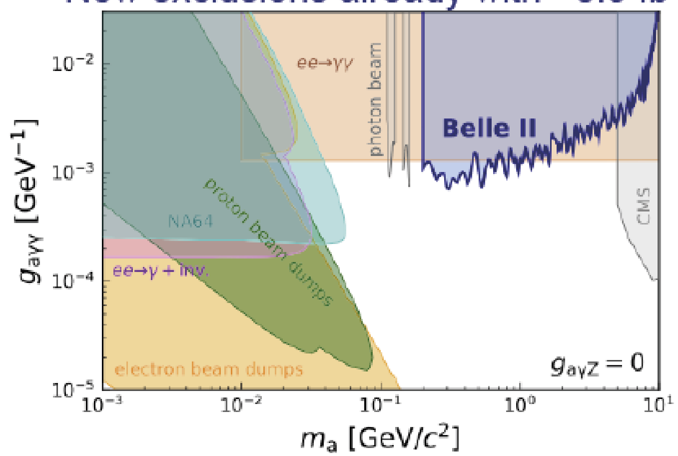
Dark Sector Search: Axion-Like Particle [PRL 125,161806 using 0.445 fb^{-1} (commissioning)







New exclusions already with ~0.5 fb^{-1}

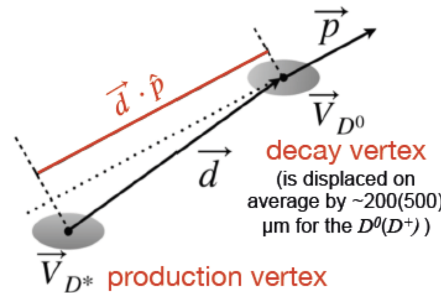


- A signal would be identified by a peak in the diphoton invariant mass ($M^2_{\gamma\gamma}$) (better for ALP masses < 6.5 GeV), or in the recoil invariant mass (M^2_{recoil}) (better for ALP masses > 6.5 GeV).
- No significant excess seen, limits set on ALP coupling to photons.

[PRL 125, 161806 (2020)]

D^0 and D^+ Lifetimes

Most precise measurements two decades ago (FOCUS [arXiv:hep-ex/0203037])
Test of effective models (heavy-quark expansion [arXiv:1405.3601])
Nothing from Belle, BaBar, LHCb ($\tau(D^+)$ used as reference)

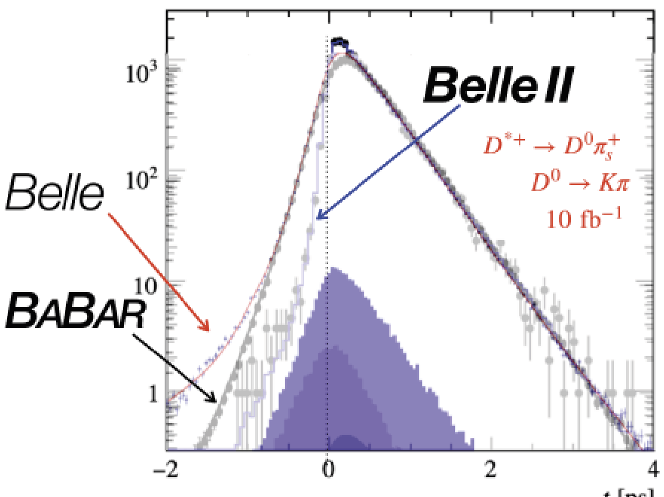


$e^+e^- \to c\bar{c} \to D^*X$ select $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^-$

	Belle II	World Average Value
$\tau(D^0)$ =	(410.5 ± 1.1 ± 0.8) fs	(410.1 ± 1.5) fs
$\tau(D^+)$ =	(1030.4 ± 4.7 ± 3.1) fs	(1040 ± 7) fs

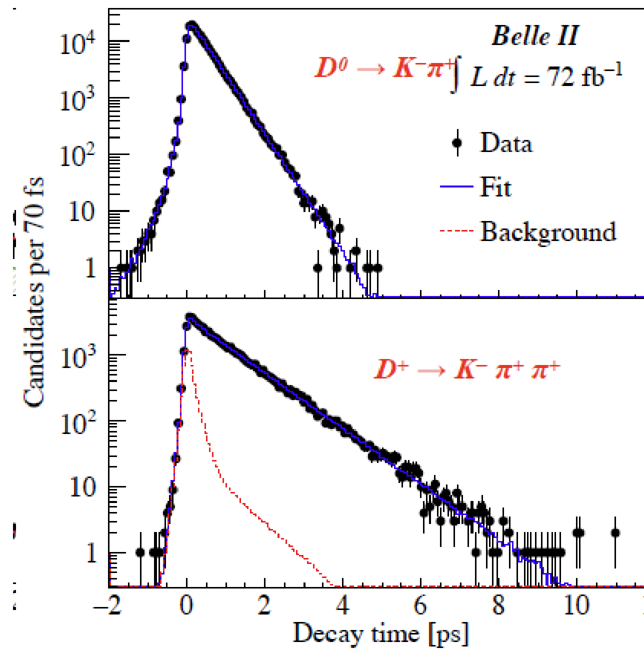
arXiv: 2108.03216, accept. by PRL

Belle II $\int\mathcal{L}dt$ = 72 fb^{-1}



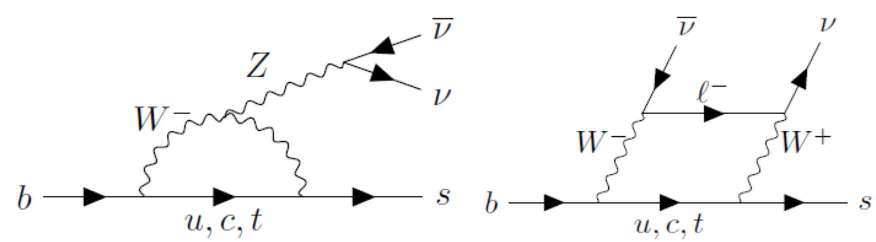
Demonstration of PXD performance

Twice as good as Belle & Babar



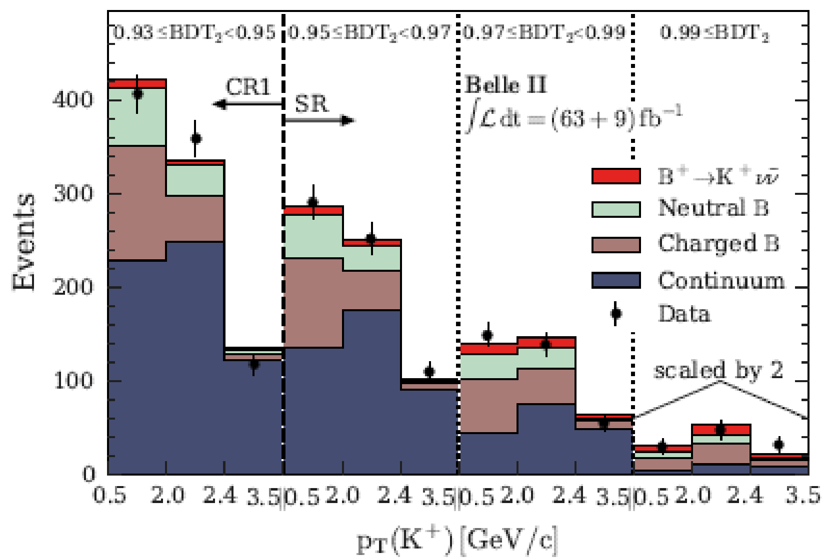
Recently Published

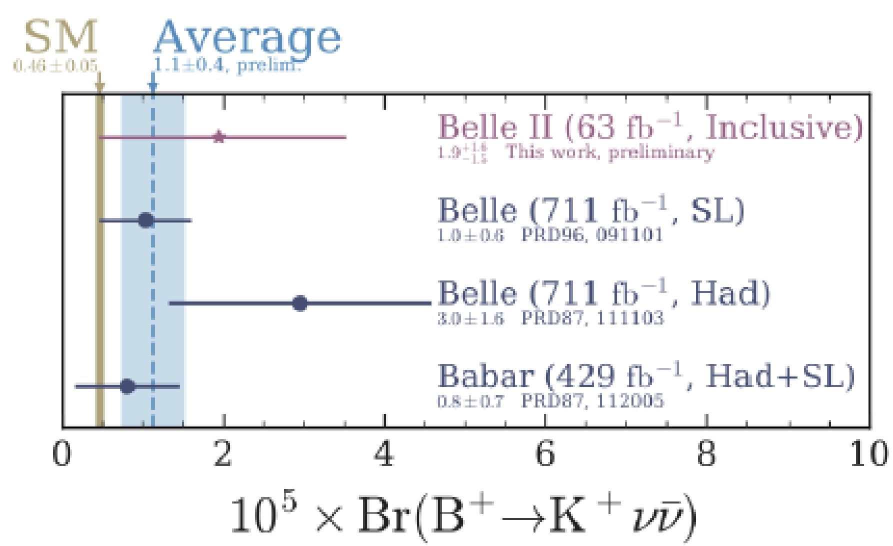
$B^+ \to K^+\nu\nu$ [PRL 127.181802] using 63 fb^{-1}



SM prediction: BF = 4.6 ± 0.5 10^{-6}
[Prog. Part. Nucl. Phys. 92, 50 (2017)]
Can give hints for Leptoquarks, Axions, DM
Best limits from Babar with hadronic & semi-leptonic tag (PRD 87, 112005)

New: Inclusive tagging using BDT for higher efficiency





BF < 4.1 x 10^{-5} @ 90% C.L. Already better systematic uncertainty than previous resutls

MPP: Team & Responsibilities

Director: Allen Caldwell
Project Leader: Hans-Günther Moser
Staff: Frank Simon (**F**uture **D**etectors), Stephan Paul (MPI Fellow)
Emeritus: Vladimir Chekelian, Christian Kiesling
Postdocs: Boqun Wang, Fabian Krinner (**S**tephan **P**aul), Thibaud Humair (FD)
PhD Students: *Philip Leitl*, Felix Meggendorfer, Benedikt Wach, Markus Reif,Hendrik Windel, Thomas Kraetzschmar (FD), Lukas Bierwirth (SP), Justin Skorupa
Master Students: Marton Nemeth-Csoka, Caspar Schmitt, Elia Schmidt
Bachelor Students: *Aniruddh Pawar, Paul Luger*

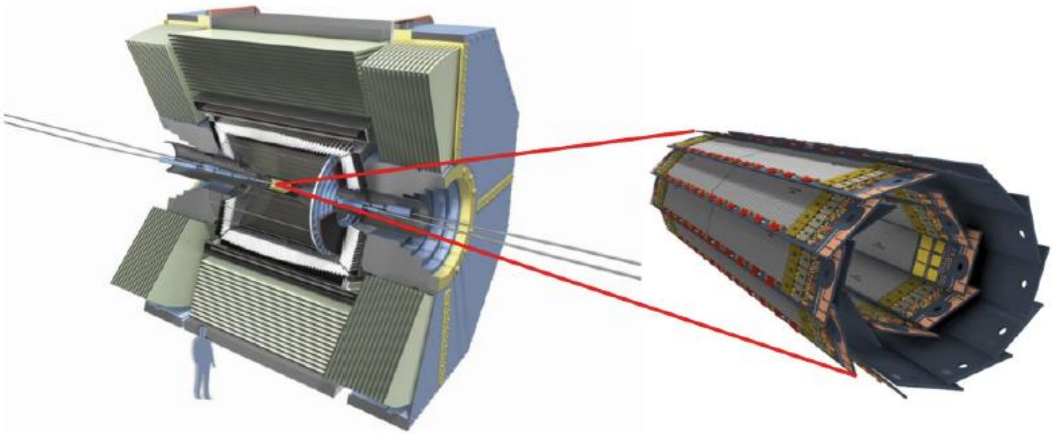
Technical Support: Ullrich Leis, Sven Vogt, Quirin Fischl, Enrico Töpper, Walter Kosmale, David Kittlinger, Andreas Wunderl, Janick Albrecht, Miriam Modjesch, Markus Fras, Stefan Horn, Carina Schlammer, Werner Haberer…….

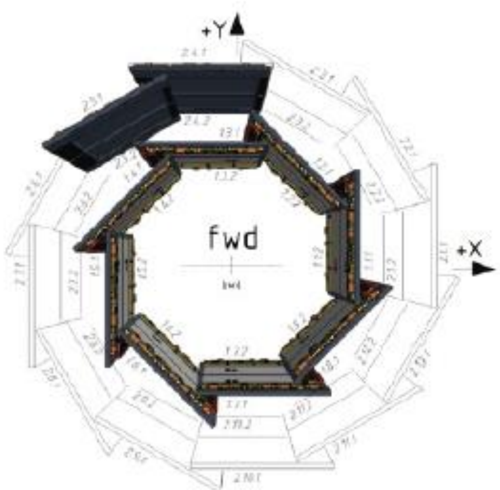
Responsabilities of MPP

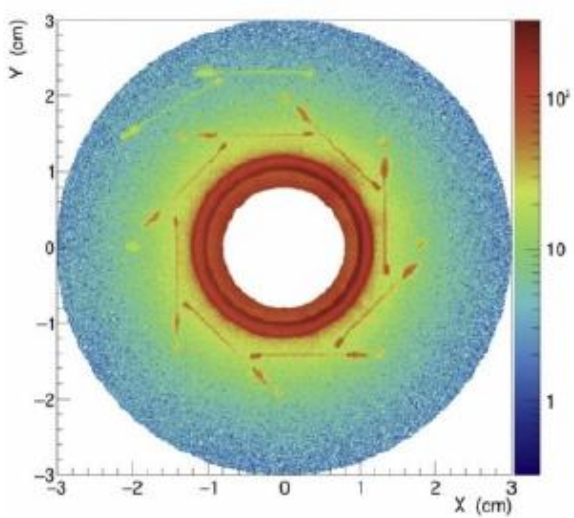
- PXD: Module Tests, Ladder assembly and mounting, services, installation, operastion
- IBBelle CO_2 Cooling System
- Neural Net Trigger (training)
- Computing (Tier II cluster at MPCDF, Garching)
- PXD Power supply maintenance & repair
- Management:

  PXD run coordination: Boqun Wang
  Speakers committee: Hans-Günther Moser
  TDCPV convener: Thibaud Humair
  Local shift coordinator: Frank Simon

PXD







Scatter plot from data

DEPFET pixel detector

0.21 % X_0/layer of material

MPP‘s main contribution to Belle II

(MPP, HLL, Bonn, Karlsuhe, Mainz, Gießen, Göttingen, DESY, LMU, TUM, Jülich, Krakow,..)

2 layers

8 inner ladders at r=14mm

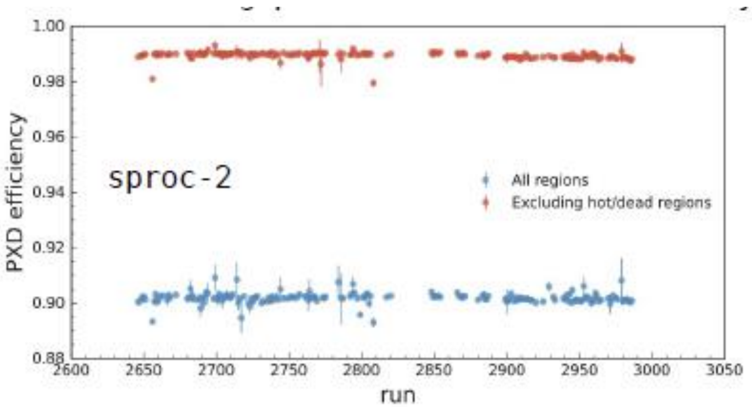
12 outer ladders at r=22mm (presently only 2 installed)

~8 Mpixels

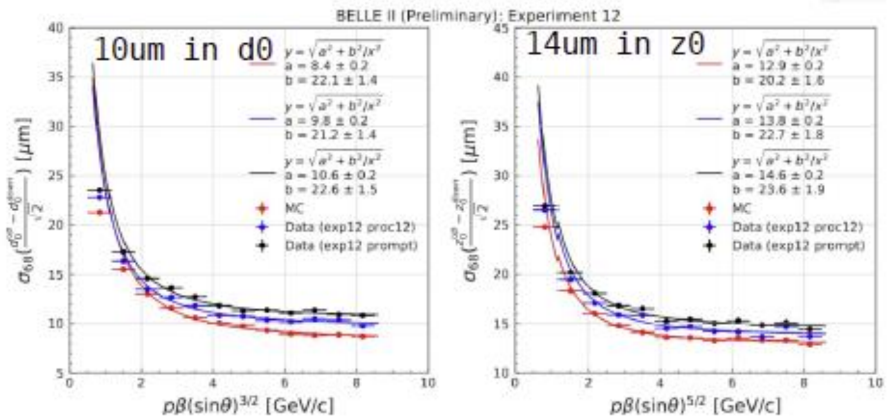
Completion in 2023

PXD Performance

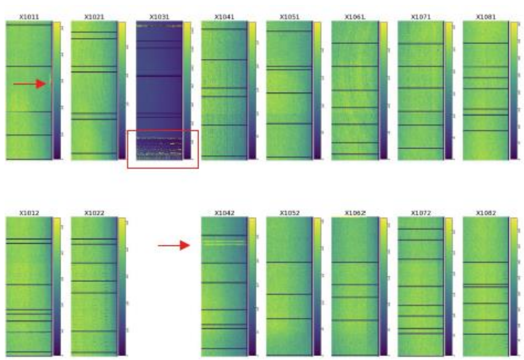
Efficiency: 99% for good areas
90% dead/noisy areas included



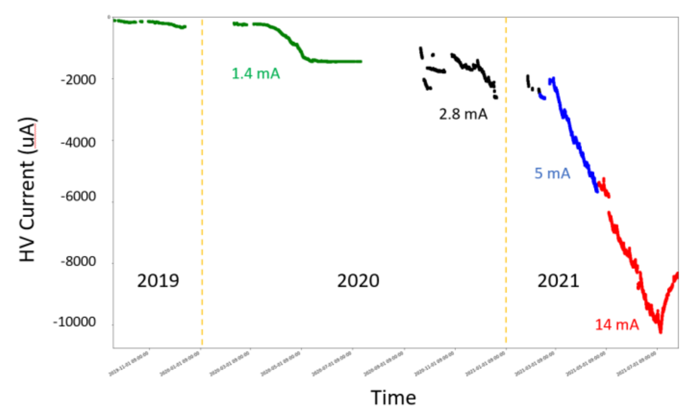
Resolution: 10µm in r-Φ 14 µm in z



Dead/noisy areas due to uncontrolled beam losses
(4 large losses so far)



HV Current Trend of Module 1082
(radiation damage)



CLAWS system to detect losses (by MPP)
⇒ Fast beam dump
⇒ HV emergency off
See talk by Swathi Sasikumar (future detectors)

Parasitic currents: no problem for performance
Current limit of PS needs to be increased
=> Hardware modification (B. Wang)

Detector Production for PXD 2022

Due to problems in the ladder assembly only 2 out of 12 modules were installed in layer 2.
The PXD will be completely replaced (including layer 1 which suffered damage due to beam losses)

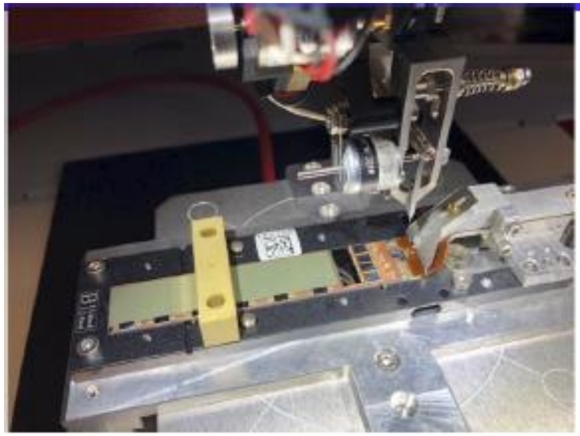
Module assembly:
- Sensors + ASICs from HLL
- Soldering of Kapton tape to sensors
- Wire bonding
- Testing and characterisation

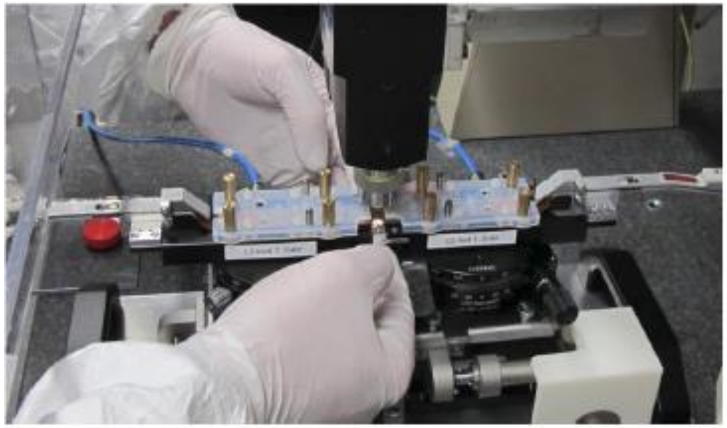
Assembly of two modules to a ladder
- Assembly procedure has been re-designed to avoid any touching of delicate sensor areas (no losses since)

Mounting of ladders on support structure
- Test assembly with dummies completed
- Hot assembly in spring 2022

Installation of new PXD early 2023

D.Kittlinger, E. Töpper, C. Schlammer, Q. Fischl, M. Modjesch





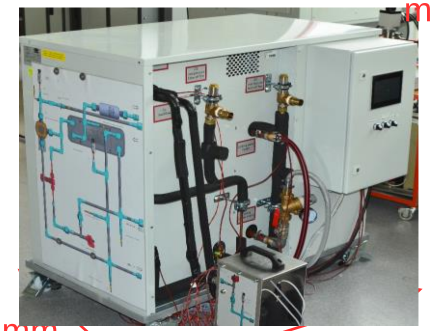
CO_2 Cooling

PXD and SVD cooled by 2-phase CO_2: 3kW at -20°C (-30°C possible)
IBBelle CO_2 plant designend by CERN and MPP, produced at MPP, working at KEK reliably since 2018
However:

- Single point of failure – no backup
- Maintenance difficult (no revision in 2020 and 2021 due to Covid-19)

IBBelle
cooling Belle II inner detector

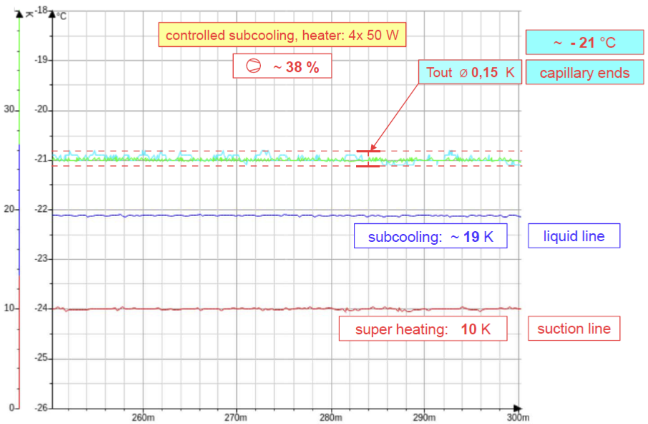
Carrier
basic commercial unit



Affordable (<1/4 costs of IBBELLE) ommercial units are now available, single circuit (no Freon), compact

Carrier unit tested at MPP

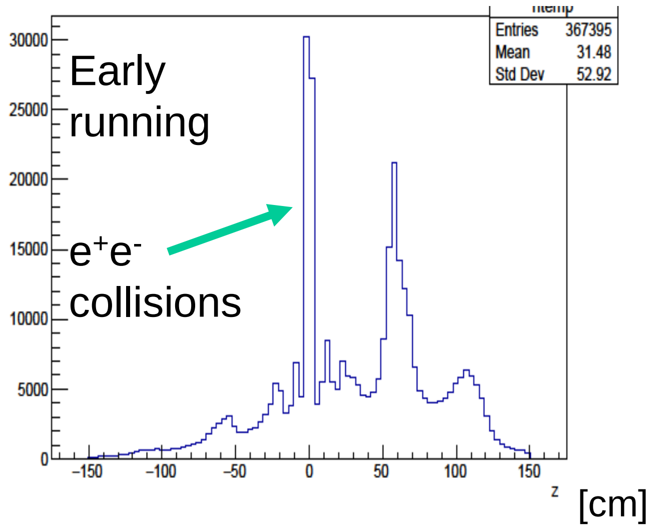
- suitable in terms of capacity and stability
- Next step: chiller with specifications based on our test
- Backup
- operation of PXD 22 during commissioning



U. Leis, S. Vogt, S. Horn

NN Trigger

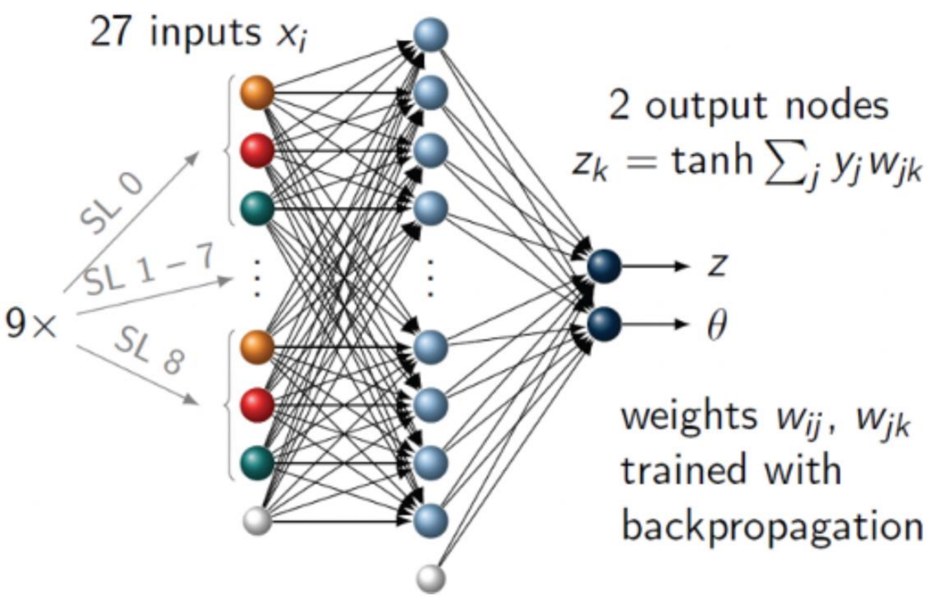
z-vertex distribution (offline) :



Belle II: majority of (beam background) events originate from outside of the interaction region (IP) (|z| >> 1 cm): only ~10% from IP

Saturate DAQ bandwidth

=> „z-vertex“ trigger mandatory



L1 Track Trigger FPGA pipeline:

CDC — Sense wire patterns

↓

Track Segment Finder (TSF)
(Axial TS and Stereo TS)

↓

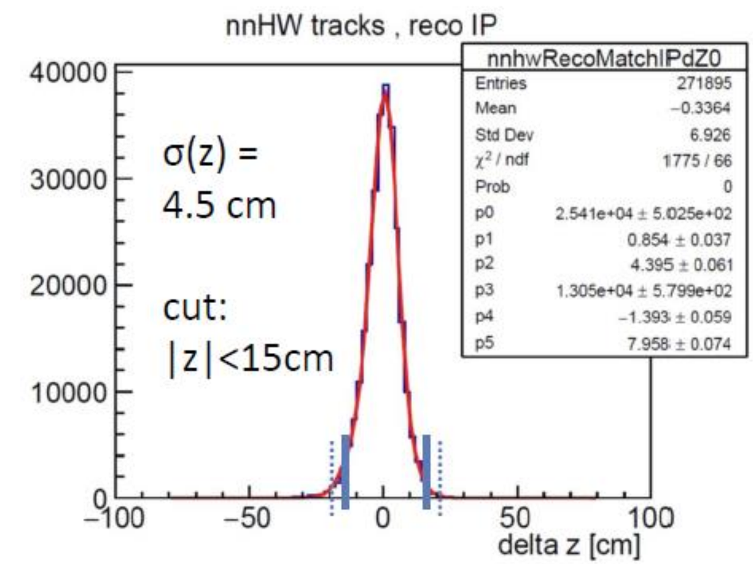
Hough-Transform with ATS (2D)
(-> Standard 2D Trigger)

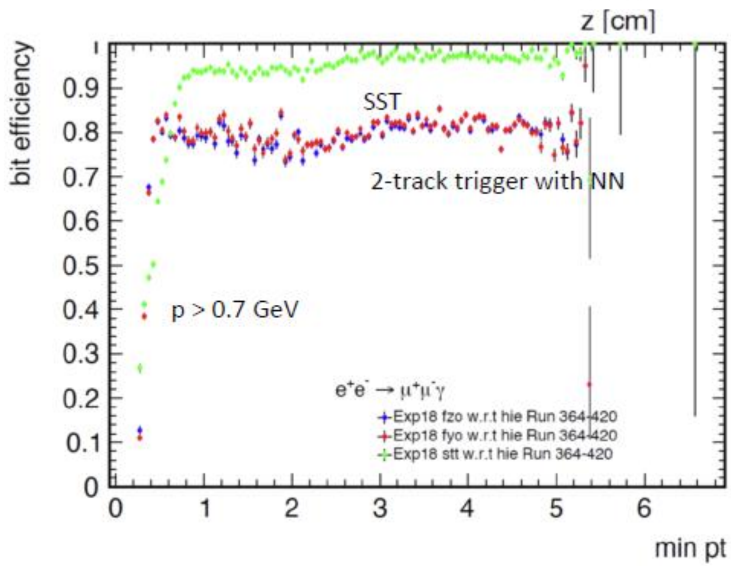
↓

Neural Networks
2D ATS + 3 (4) STS -> 3D tracks

Total L1 latency 5 µs, **NN: 300 ns**

NN Trigger





z-vertex track: |z|< 20cm: active since March 2021

Since April 2021:
All track triggers (>=2 tracks) require a NN track
(rate reduction of track trigger by ~60-70%)

Single Track Trigger
operational since April 2021

STT outperforms all other track triggers

Very important for low multiplicty events:
- τ–physics
- Dark Sector

C. Kiesling, F. Meggendorfer, M. Nemeth-Csoka, P. Luger (with KIT and TUM)

Slow Pion Reconstruction

Importance of „Slow Pions“ from D* decay:

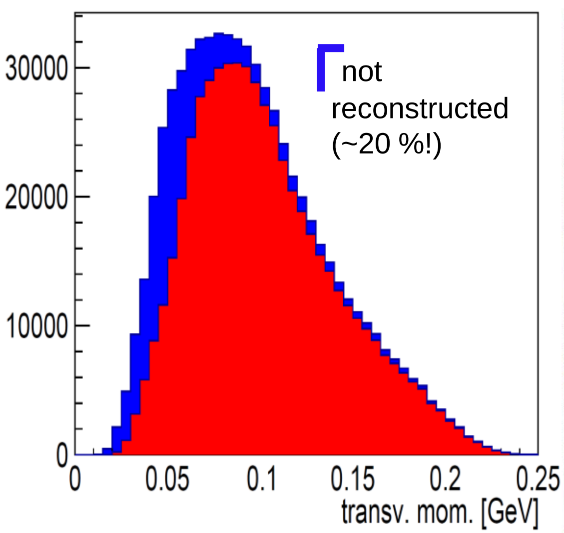
- as flavor taggers
- important tag for LFV searches, e.g. BF(B -> D* μν) / BF(B-> D* τν)

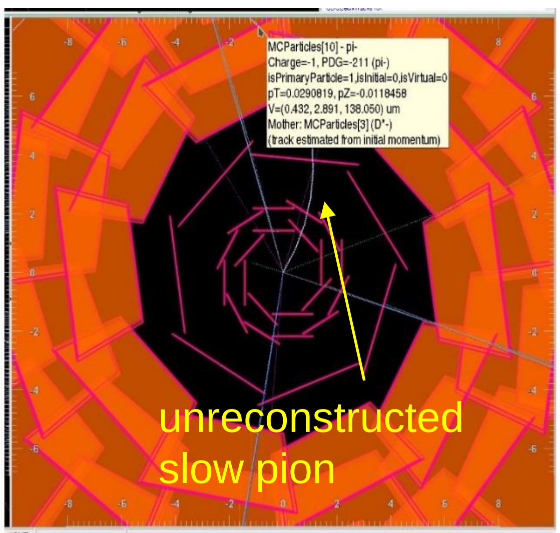
- rarely reach CDC => reconstructed only in SVD + PXD
- PXD hits dominated by huge background from QED electrons (combinatorics)
- At high luminosity: PXD hits lost due to ROI selection

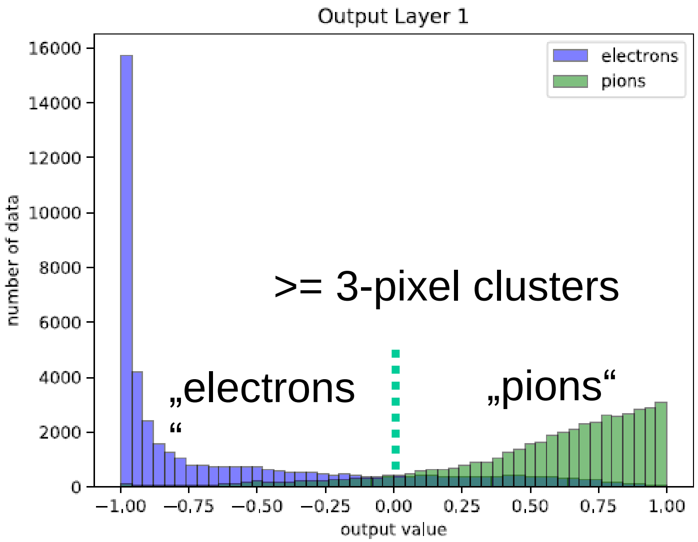
- distinguish hits from slow pions against electrons by cluster parameters
- multivariate methods, e.g. NN algorithm in DAQ FPGA
- Together with TUM (Stephan Paul)

C. Kiesling, M. Varela

p_t spectrum of slow Pions

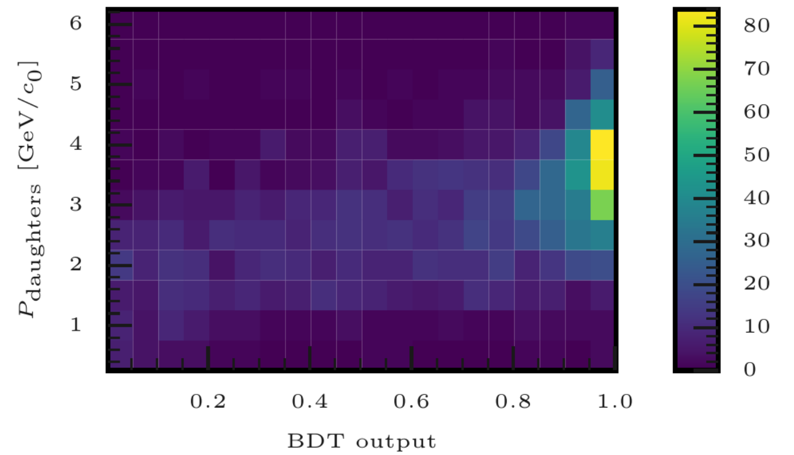


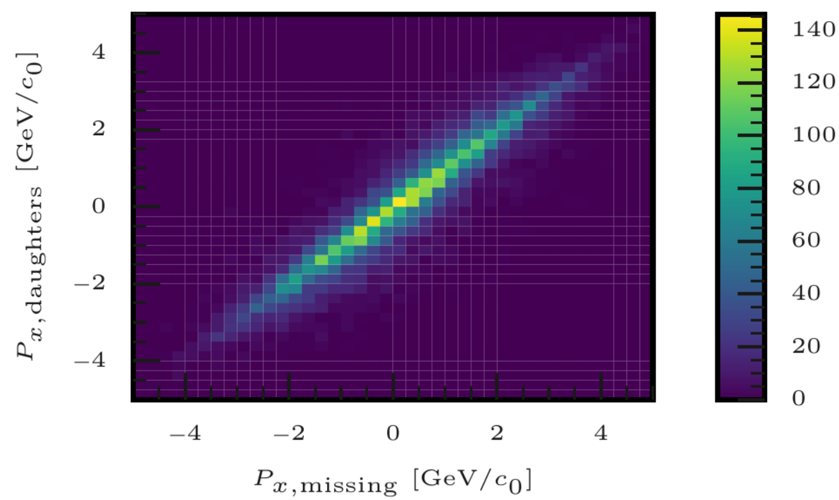




Charm Tagger

- A tool to study charm decays involving missing particles or many neutrals in final state
- Motivation:
  - (semi-) leptonic D decays
  - $D^0 \rightarrow$ invisible, $D^0 \rightarrow \gamma\gamma$
- Identify signal meson by missing four momentum → reconstruct full event
- Principle:
- reconstruct tag-side charm hadron in various channels
- Combine with remaining tracks (charmless system)
- BDT to separate signal from background
- Benchmark channel $D^+ \rightarrow \pi^+ \pi^0$
- Compare momentum of daughters and missing momentum

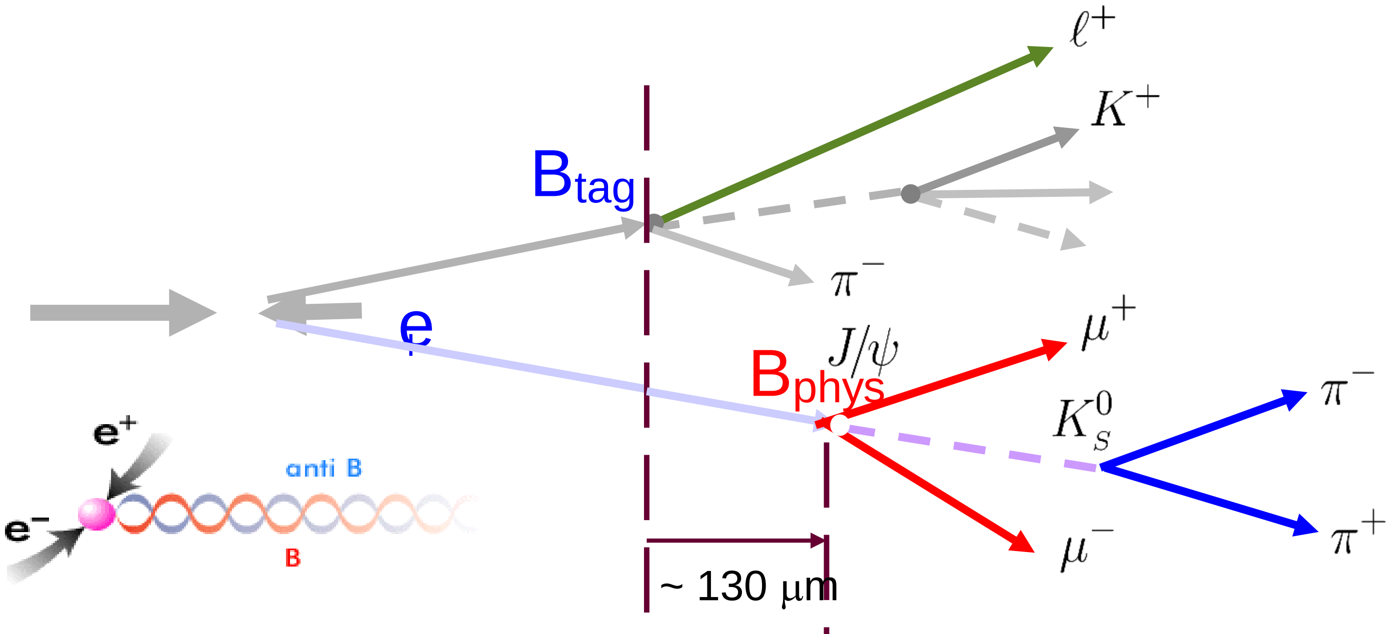




L. Bierwirth

Time dependent measurements of CP violation

Resolution on Δt will be dominated by the resolution of the tagging side vertex



Quantum entangled neutral B meson pair production

Δt probability parametrization $\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 + q\left(\mathcal{A}_{CP}\cos\Delta m_d\Delta t + \mathcal{S}_{CP}\sin\Delta m_d\Delta t\right)\right]$

Time-dependent analyses

Last year, our group observed first hint of time-dependent CP-violation in the B^0 system at Belle II, using $B^0 \to J/\varphi K_S$ decays.

Since then: focused on precise measurement of the B^0 lifetime and mixing frequency using B^0 hadronic decays.

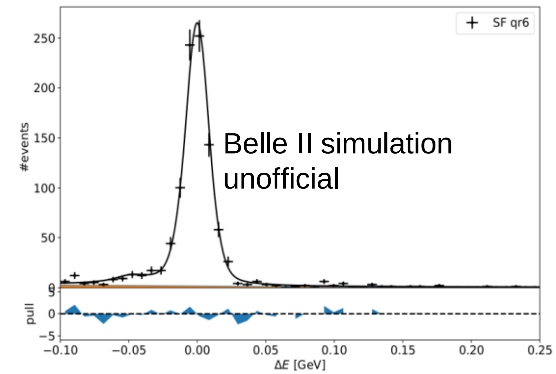
Moriond 2022 with greatly improved analysis techniques:

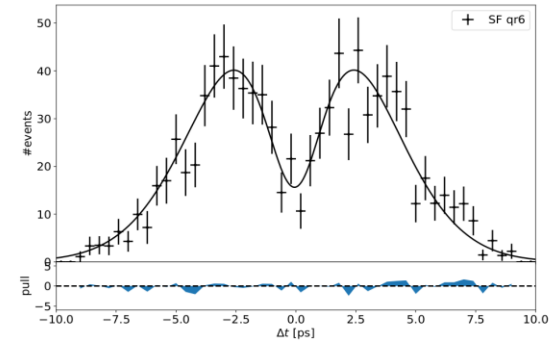
- Refined background studies (Caspar's Master's thesis);
- Improved vertex resolution using beam spot size measurement
- Time-dependent fit uses improved modelling of the detector response, taking into account various smearing effects;
- Detailed study of the impact of the detector mis-alignment (in collaboration with Charles university, Prague).

Updated measurement of time-dependent CP-violation and of the CKM angle β (ϕ_1) to follow shortly after.

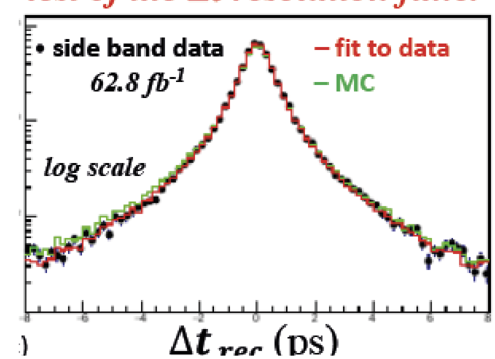
Long term: refined treatment of resolution function

Vladimir Chekelian, Thibaud Humair, Caspar Schmitt



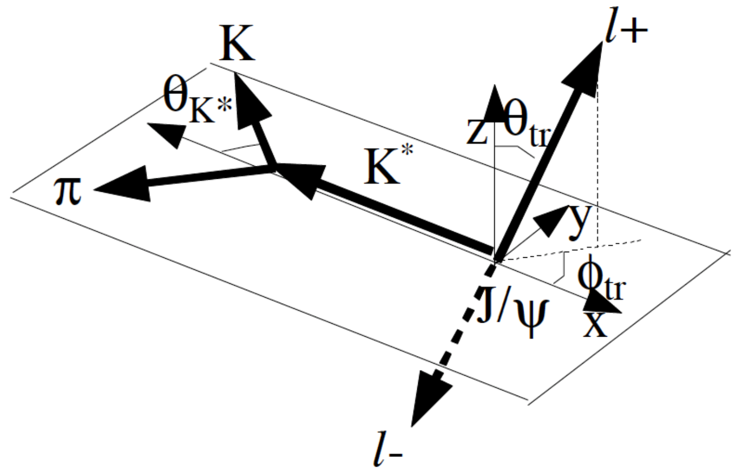


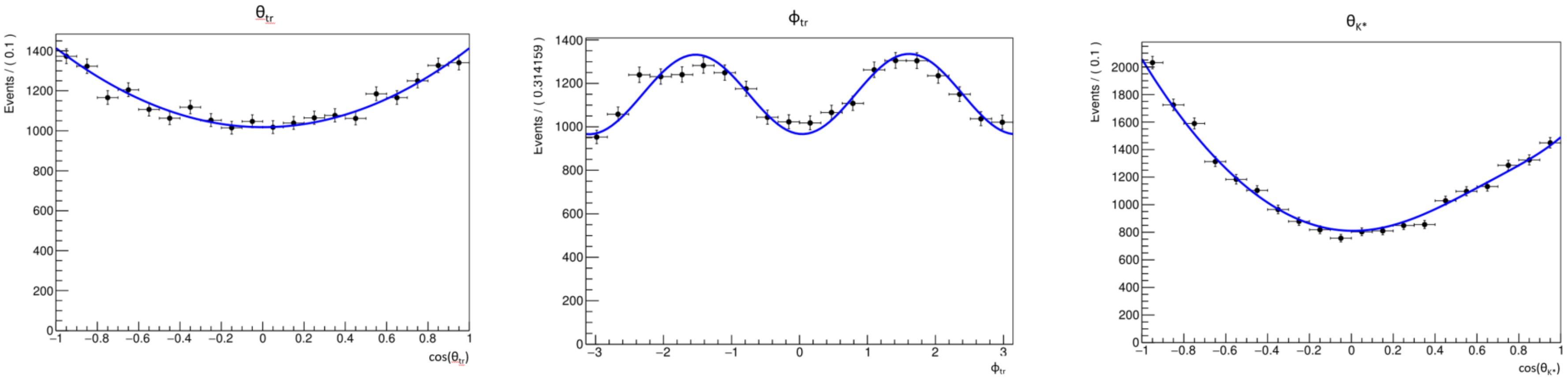
test of the Δt resolution func.



Angular Analysis $B^0 \rightarrow J/\Psi\ K^{*0}\ (K_S\ \pi^0)$

- Decay $B^0 \rightarrow J/\Psi\ K^{*0}\ (K_S\ \pi^0)$ contains mixture of CP-eigenstates.
- Fitting angular observables and decay time can extract TDCPV parameters.
- Disentangle the components of each CP-eigenstates for the measurement of the width difference of B^0 mass eigenstates $\Delta\Gamma_d$.
- SM prediction is $\Delta\Gamma_d^{SM} / \Gamma_d^{SM} << O(10^{-12})$.





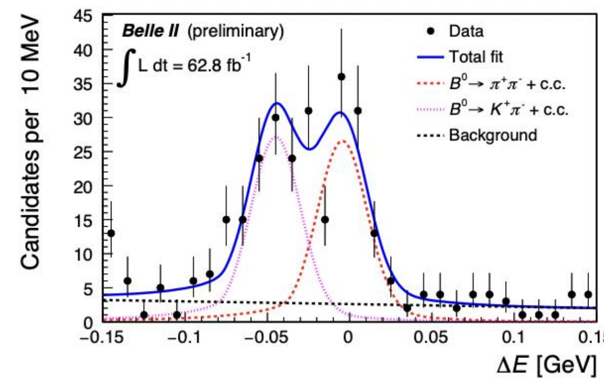
B. Wang

Charmless B-decays

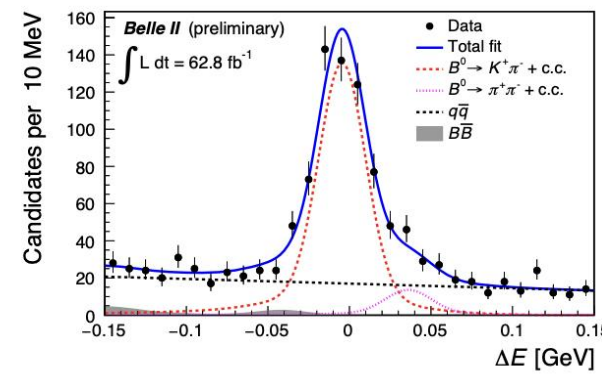
» Branching ratio measurements of B decays not involving a charm quark allow the extraction of CKM angle α (ϕ_2);

» Several charmless decays are studied at Belle II, big contribution from MPP students;

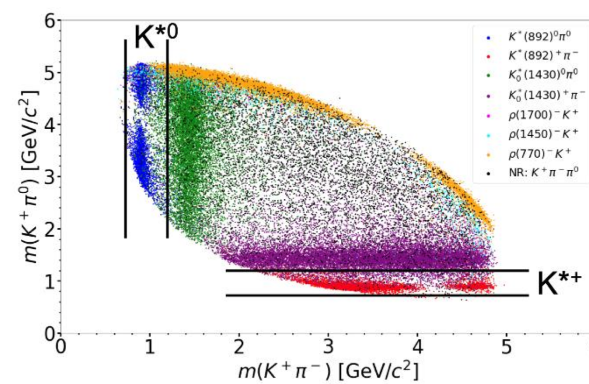
» Latest results were shown at Moriond 2021, currently analyses are refined for Moriond 2022.



$B^0 \rightarrow K^+\pi^-\pi^0$:
For Moriond focus on $K^*\pi$; full Dalitz long term.



$B^0 \rightarrow \pi^+\pi^-$ (time dependent):
Time-integrated measurement for Moriond;
Then time-dependent measurement for extraction of ϕ_2



M. Reif, J. Skorupa, B. Wach

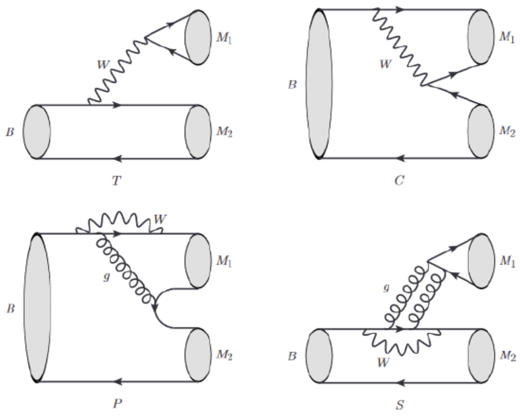
Isospin Sum Rule/K-π puzzle

$B^+ \to K^0\pi^+$ $$A^{0+} = -P'_{tc} + P'_{uc}e^{i\gamma} - \frac{1}{3}P'^{C}_{EW}$$

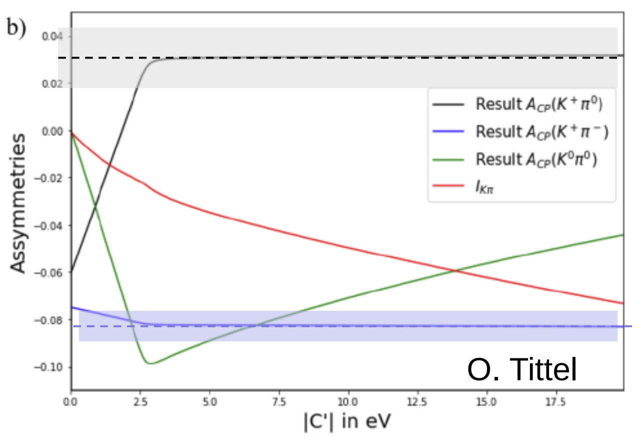
$B^+ \to K^+\pi^0$ $$\sqrt{2}A^{+0} = -T'e^{i\gamma} - C'e^{i\gamma} + P'_{tc} - P'_{uc}e^{i\gamma} - P'_{EW} - \frac{2}{3}P'^{C}_{EW}$$

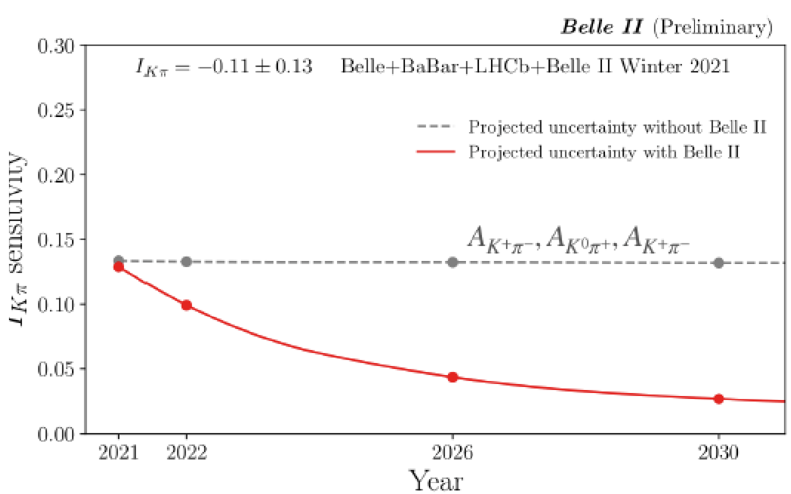
$B^0 \to K^+\pi^-$ $$A^{+-} = -T'e^{i\gamma} + P'_{tc} - P'_{uc}e^{i\gamma} - \frac{2}{3}P'^{C}_{EW}$$

$B^0 \to K^0\pi^0$ $$\sqrt{2}A^{00} = -C'e^{i\gamma} - P'_{tc} + P'_{uc}e^{i\gamma} - P'_{EW} - \frac{1}{3}P'^{C}_{EW}$$



$$I_{K\pi} = A^{+-}_{CP} + A^{0+}_{CP}\frac{BR(0+)}{BR(+-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2A^{+0}_{CP}\frac{BR(+0)}{BR(+-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2A^{00}_{CP}\frac{BR(00)}{BR(+-)}$$





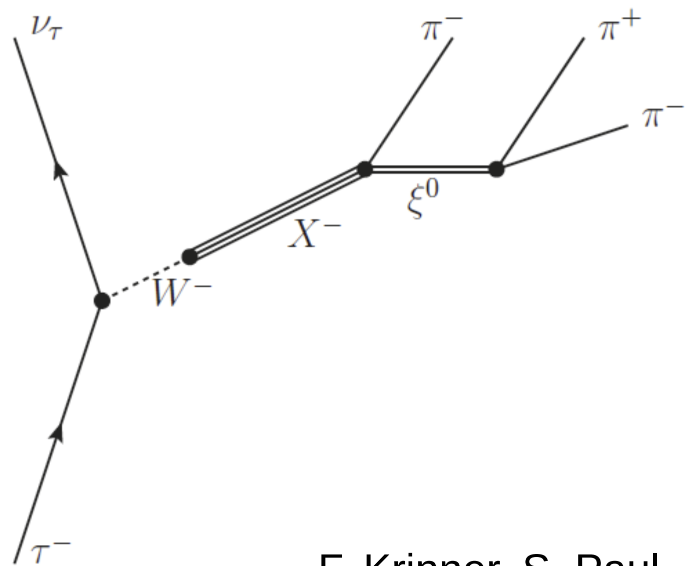
τ-Physics

Partial wave analysis of $\tau^- \to 3\pi^\pm \nu_\tau$

- Model process via resonances:

  $$X^- \text{ and } \xi^0$$

- Main question:
  - Which X^- (e.g. $a_1(1260)$)?
  - Which ξ^0 (e.g. $\rho(770)$)?
  - Strengths and phases?
- Current status: Verify on MC:
  - Without background ✓
  - With background ✗
  - Problem: background parametrization



F. Krinner, S. Paul

Electric and magnetic dipole moments of the τ

- τ coupling to E.M. field:

$$\Gamma^\mu = F_1(q^2)\gamma^\mu + \frac{iF_2(q^2)}{2m_\tau}\sigma^{\mu\nu}q_\nu + \frac{F_3(q^2)}{2m_\tau}\sigma^{\mu\nu}\gamma^5 q_\nu$$

- $F_1(0) = 1$ Dirac form factor, standard model
- $F_2(0) = (g_\tau - 2)/2$ Pauli f.f., anomalous magnetic moment (MDM)
- $F_3(0) = \frac{2m_\tau}{e} d_\tau$, electric dipole moment (EDM), CP-violating

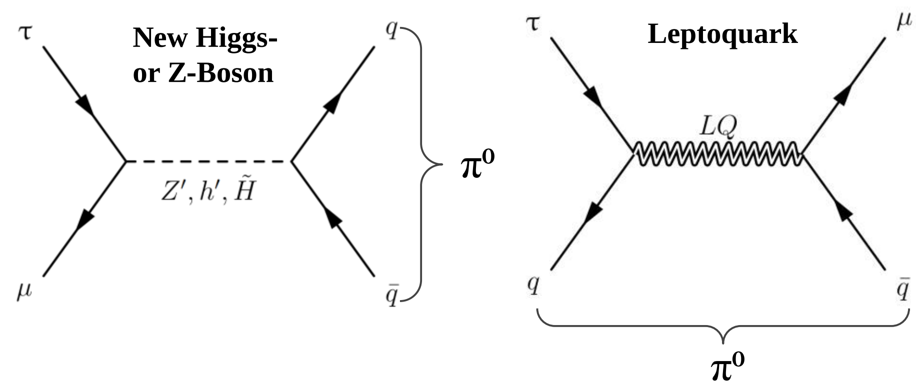
Spin correlations of τ^+ and τ^- are sensitive to F_2 and F_3

✓ Machinery set up
✓ Data MC comparison

arXiv 2112.01980

Status and prospects on $\tau \to \mu\pi^0$

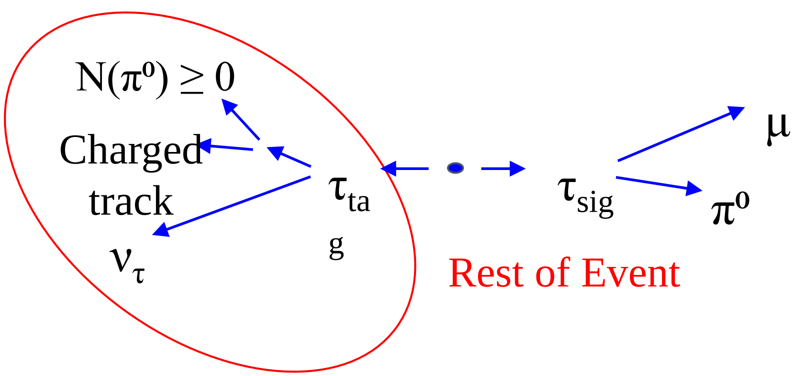
- New Physics at tree level
- 1-1 topology: two charged tracks only
- BF < 4.4 10^{-8} (BaBar, 104.021802, 2009)



New inclusive approach:

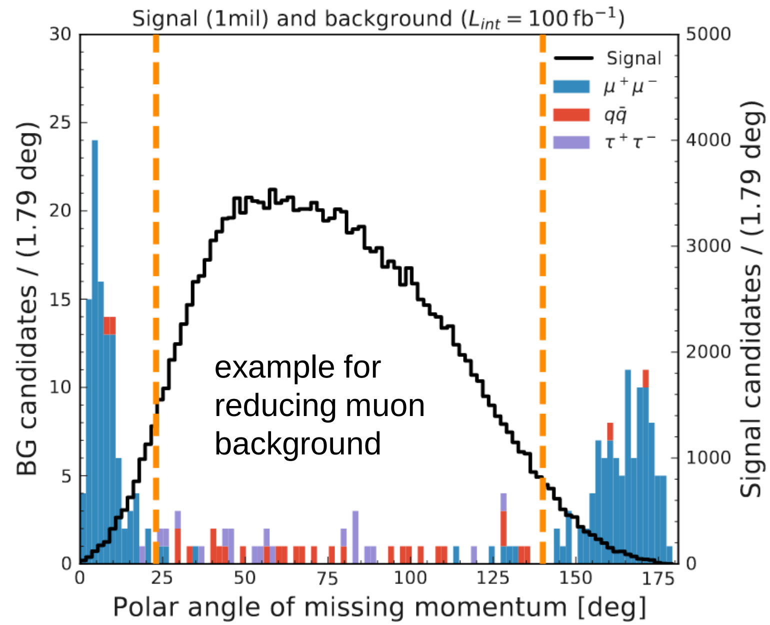
→ No direct reconstruction of τ on tag-side

→ Combine all particles not used for signal and build RestOfEvent object



MC-analysis on 100fb⁻¹ sample results:

- Fully suppressed background
- 5.3% signal efficiency (Belle 4.2%)
- NN trigger increases efficiency further
- competitive witrh 800 fb^{-1} (end of 2022)

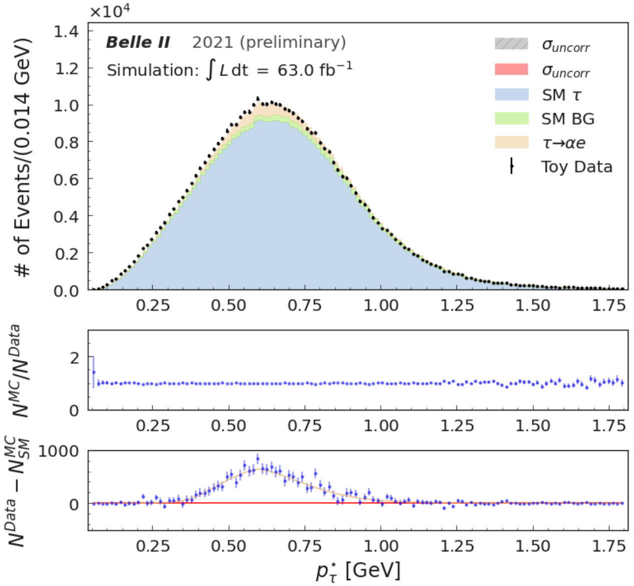


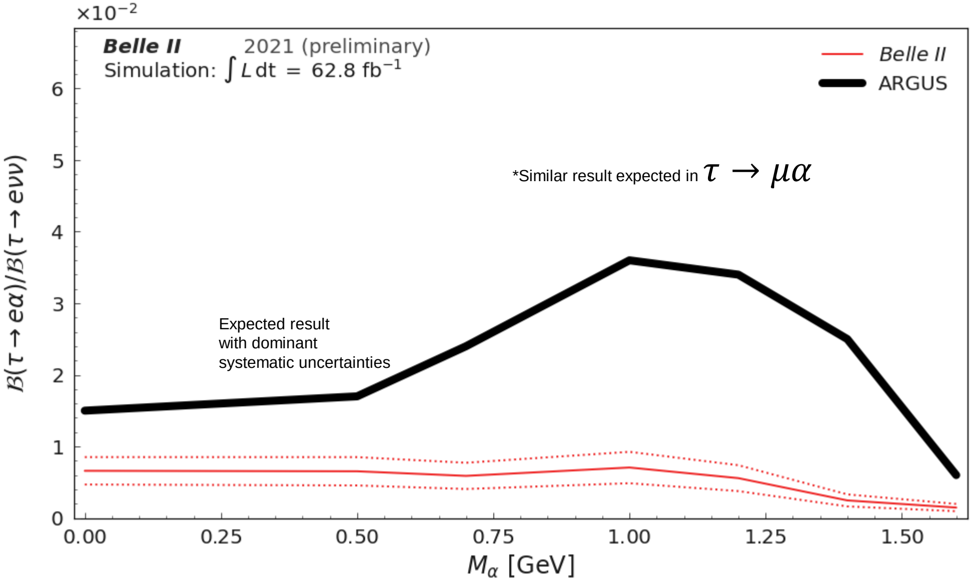
C. Kiesling, F. Meggendorfer, M. Nemeth-Csoka

$\tau \rightarrow l + \alpha(\text{invisible})$

» Invisible boson manifests as a peak in the pseudo-rest-frame of the τ

» Unblinding work in Progress ⟶ Result scheduled for Moriond





Problem: reconstruction of rest frame of τ due to missing ν
Special tool developed: ‚Generalised Known Kinematics‘ arXiv 2109.14455

T. Kraetzschmar

Summary

Main activities at MPP for Belle/Belle II:

Service Tasks

Preparations of PXD replacement
CO_2 cooling
Computing (Tier III)
NN trigger
Tracking (slow pion rescue)

Physics Analyis

Time dependent CP violation
Charmless B-decays
τ-Physics

First papers already published
Many more analyses in preparation
Expect world leading results for low mass dark matter and τ
Belle II will reach the break even with Belle/Barbar end of 2022