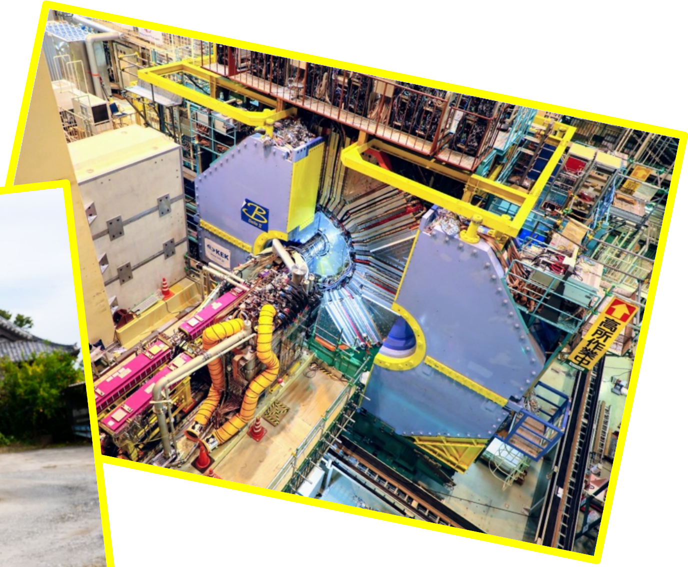
Recent Dark Sector results at Belle II



Giacomo De Pietro

INFN ROMA TRE

for the Belle II collaboration

Belle II

Identification of Dark Matter @ Vienna

18-22 September 2022

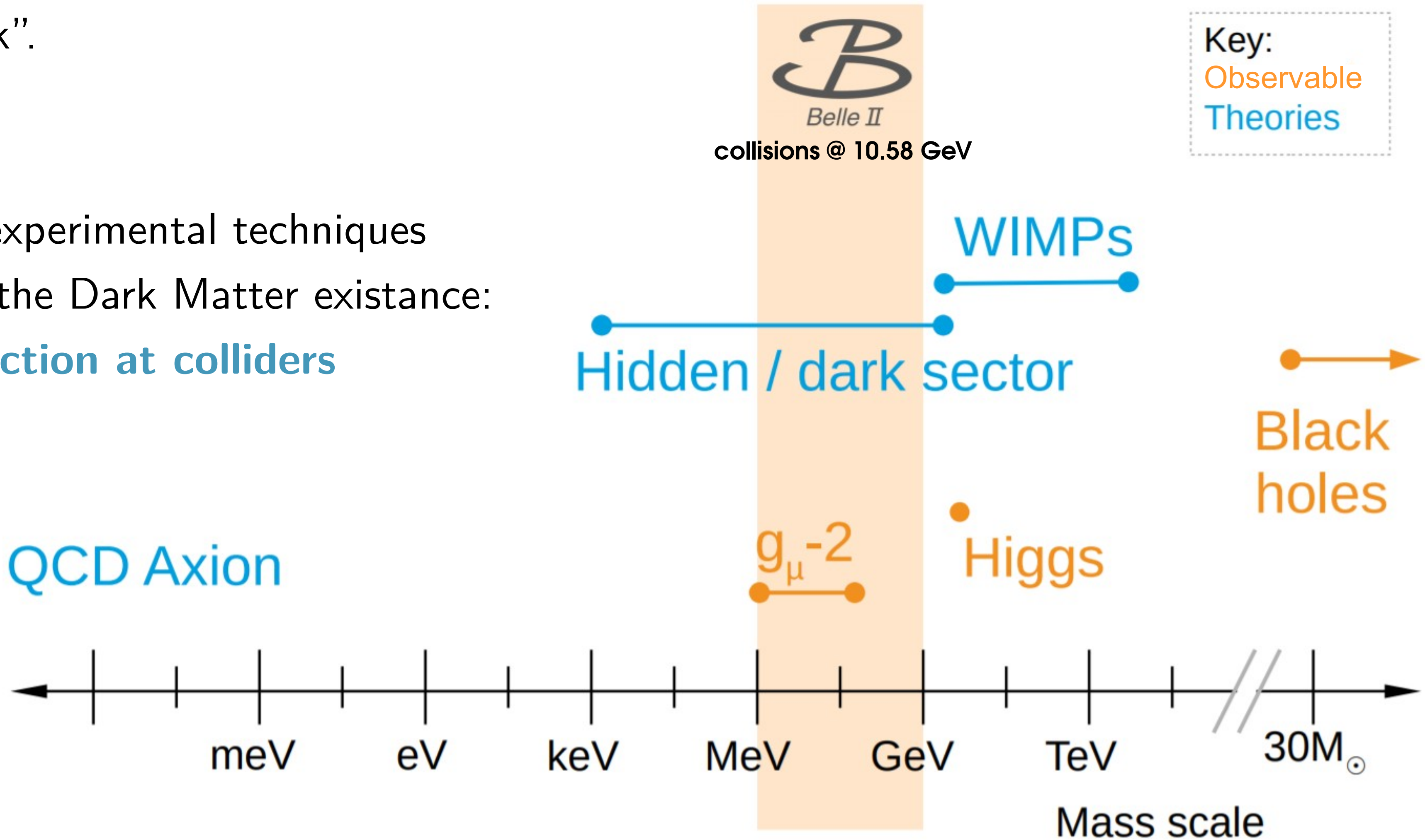
Dark Matter

It is "dark".

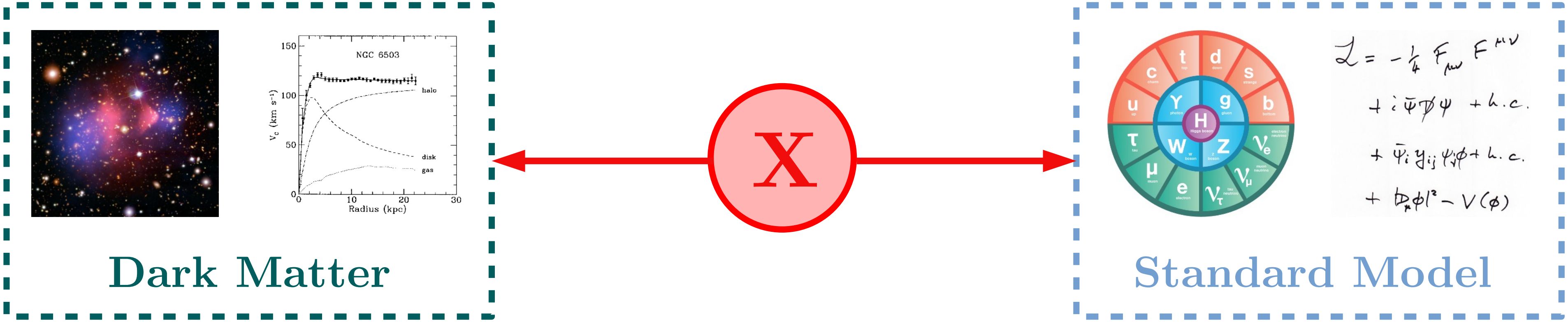
It exists...

A lot of experimental techniques to probe the Dark Matter existance:

- **production at colliders**



Dark Matter coupling to Standard Model



Different possible portals between **Dark Matter** and **Standard Model** depending on the **dark mediator X**:

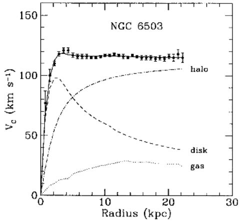
Vector portal → Dark Photon / Z'

Scalar portal → Dark Higgs / Dark Scalar

Pseudoscalar portal → Axion-Like Particles (ALPs)

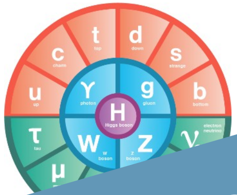
Neutrino portal → Sterile Neutrinos

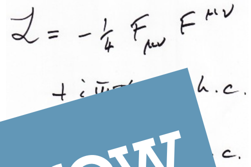
Dark Matter coupling to Standard Model



Dark Matter

X





Standard Model

Different possible p… Standard Model

…mediator **X**:

… portal → Dark Photon / Z'

Scalar portal → Dark Higgs / Dark Scalar

Pseudoscalar portal → Axion-Like Particles (ALPs)

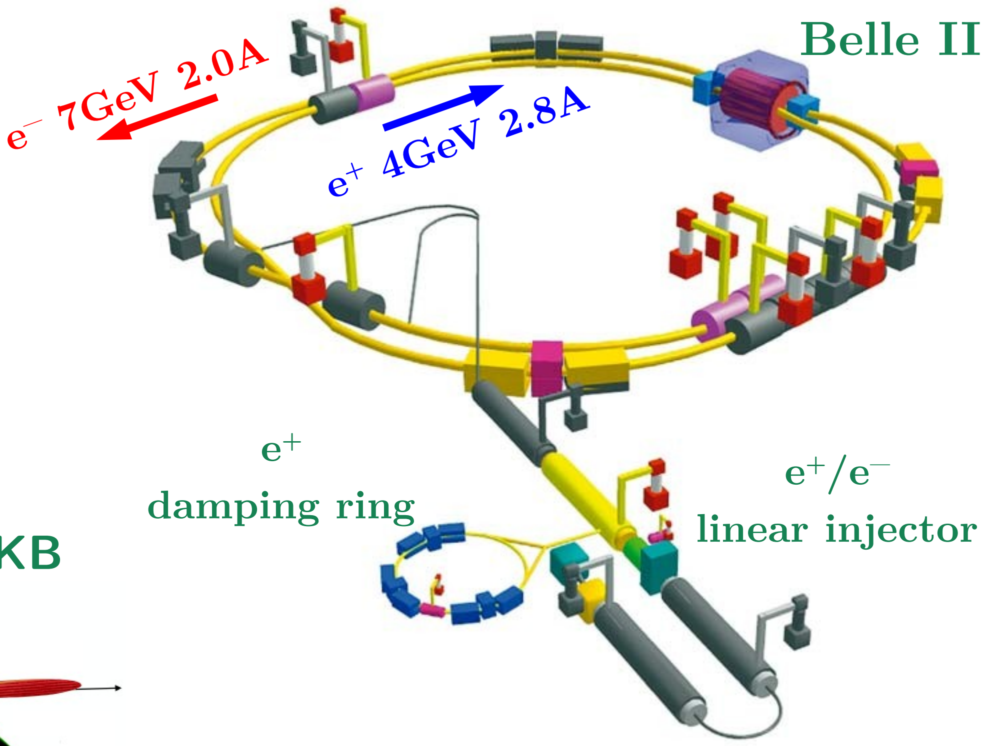
Neutrino portal → Sterile Neutrinos

More results will be presented tomorrow by M. Campajola during his plenary talk

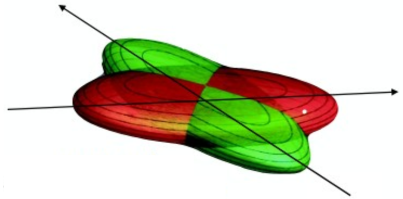
SuperKEKB: a new Intensity Frontier machine

SuperKEKB is a **super** B-factory
located at KEK (Tsukuba, Japan)

It's an asymmetric e^+e^- collider
operating mainly at **10.58 GeV**
(**Υ(4S)**, but possible runs from Υ(2S) to Υ(6S))



KEKB



nano-beam
scheme

SuperKEKB

I (A): ~ 1.6/1.2
β^*_y (mm): ~ 5.9/5.9

I (A): ~ 2.8/2.0
β^*_y (mm): ~ 0.27/0.3

30x peak luminosity:
$6.3 \cdot 10^{35}$ cm^{-2} s^{-1}

SuperKEKB: a new Intensity Frontier machine

SuperKEKB is

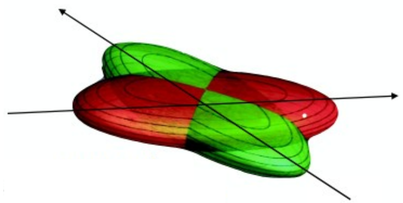
located at KEK

It's an asymme

operating mair

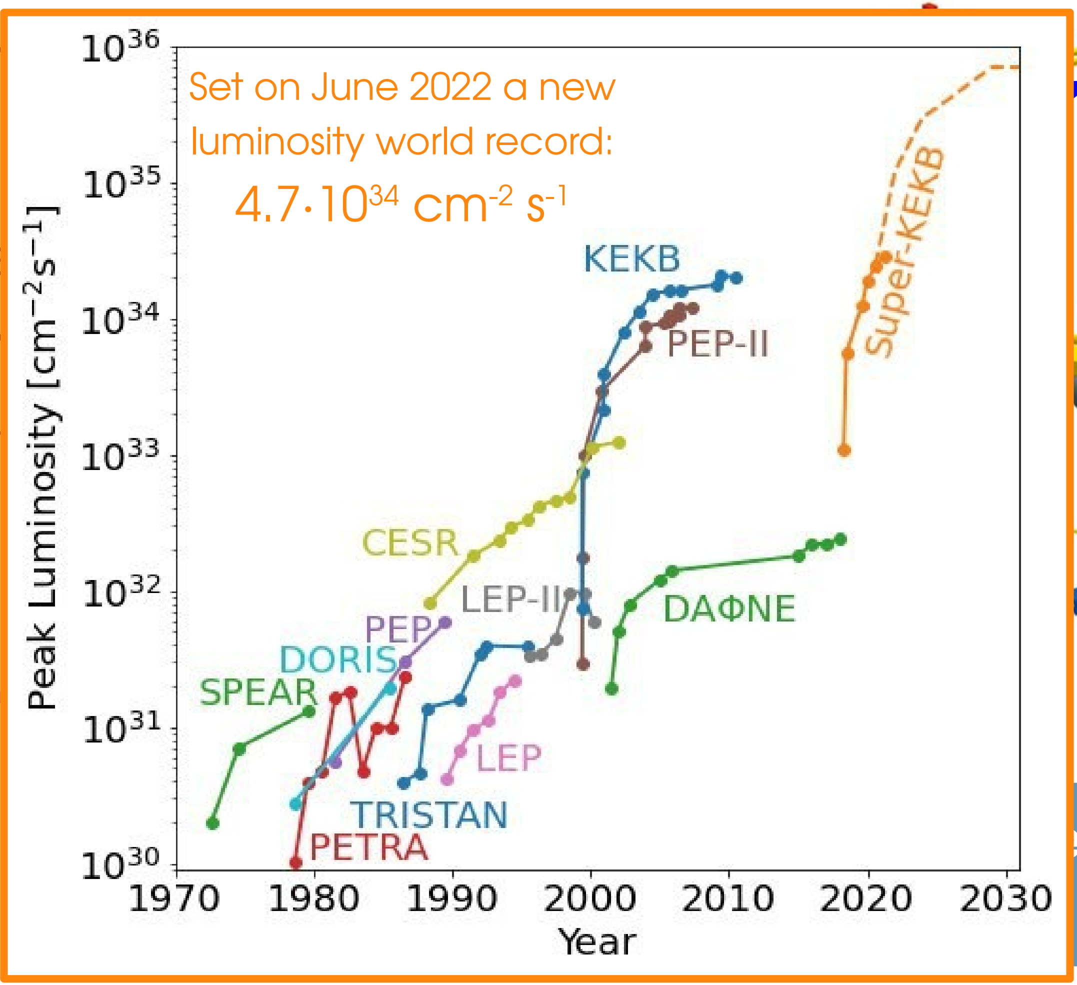
(Υ(4S), but possible ru

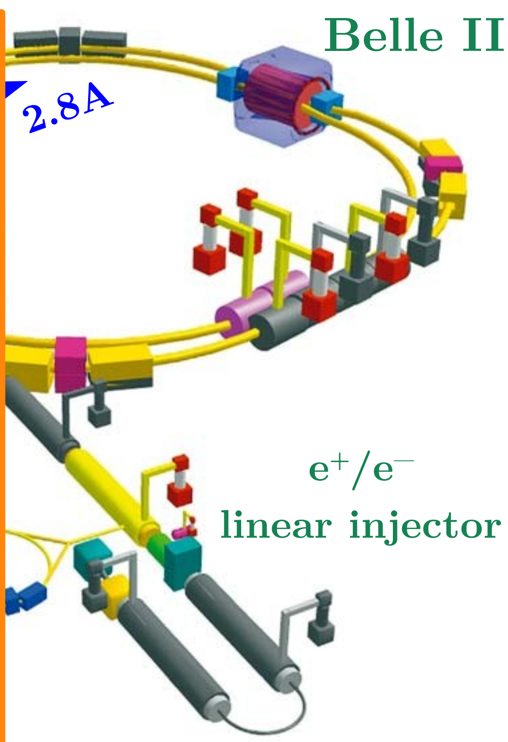
KEKB



I (A): ~ 1.6/1.2

β^*_y (mm): ~ 5.9/5.9





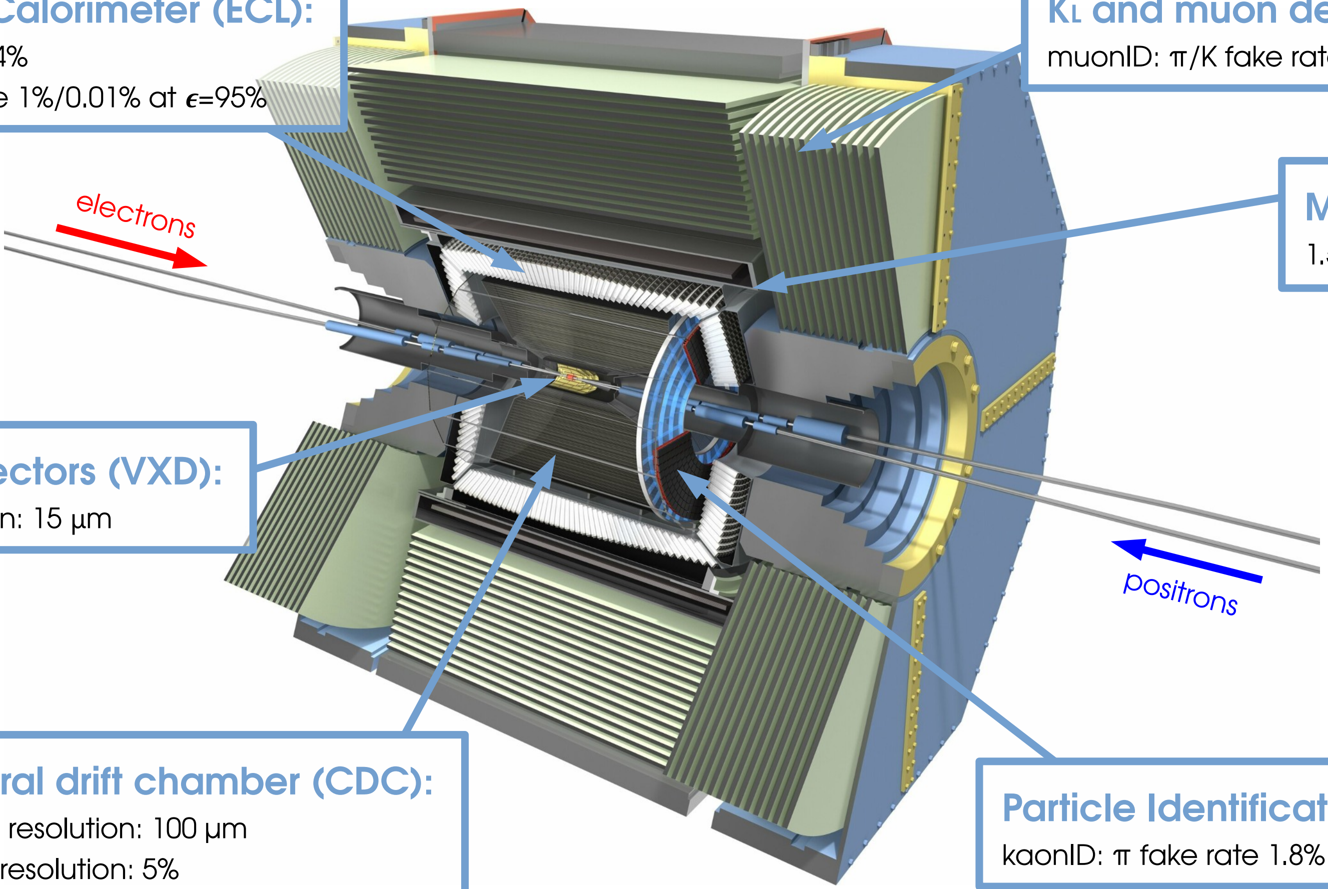
eak luminosity:

10^{35} cm^{-2} s^{-1}

Belle II: a new Intensity Frontier detector

Electromagnetic Calorimeter (ECL):
energy resolution: 1.6%-4%
electronID: π/K fake rate 1%/0.01% at ϵ=95%

K_L and muon detector (KLM):
muonID: π/K fake rate 2%/1% at ϵ(K)=95%



Magnet:
1.5 T superconducting

Vertex detectors (VXD):
vertex resolution: 15 μm

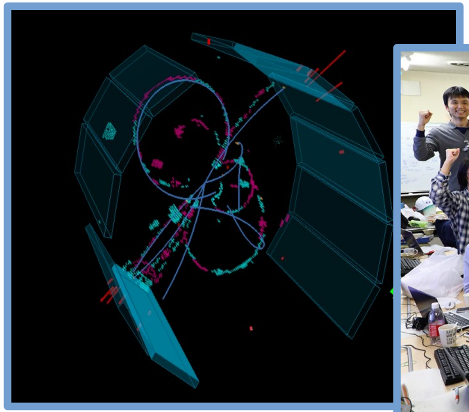
Trigger:
dedicated lines for
low multiplicity studies:
- single track
- single photon
- single muon

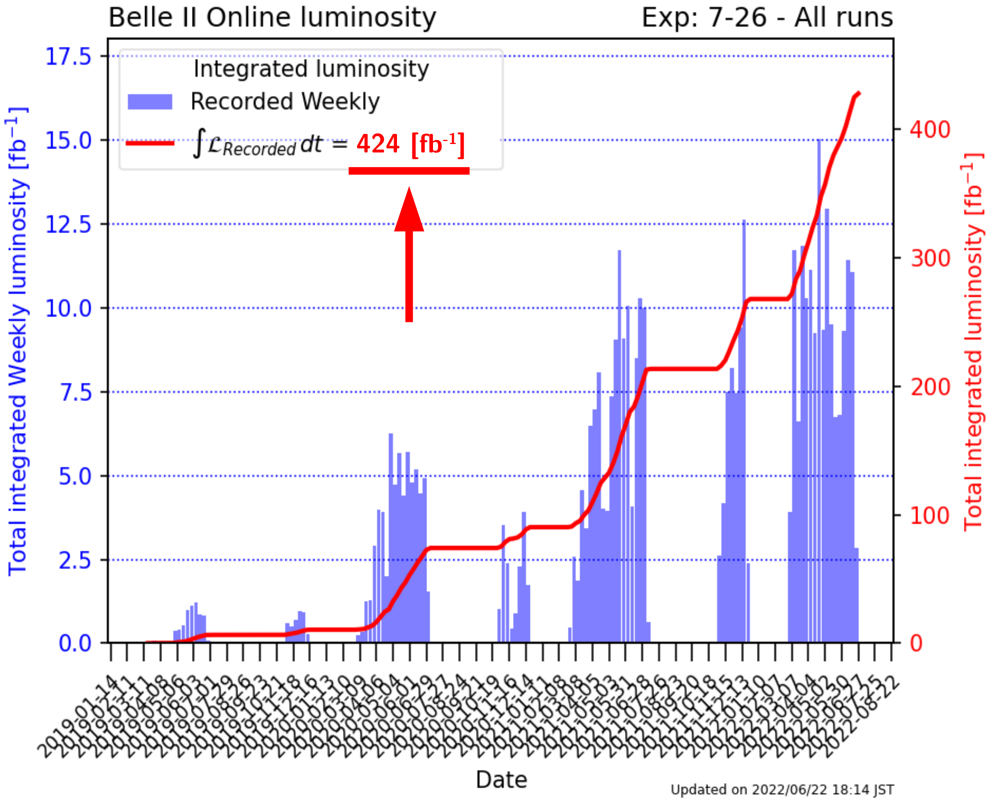
Central drift chamber (CDC):
spatial resolution: 100 μm
dE/dx resolution: 5%
pT resolution: 0.4%

Particle Identification (PID):
kaonID: π fake rate 1.8% at ϵ(K)=95%

SuperKEKB and Belle II operations

First collisions: 26th April 2018





Collected 0.5 fb^{-1} in 2018

- pilot run (without VXD detector)

Collected about 424 fb^{-1} since 2019

- 363 fb^{-1} at the $\Upsilon(4S)$ resonance
- 61 fb^{-1} off-resonance

Goal: integrate up to 50 ab^{-1} in a decade!

NEW – from ICHEP

$\tau^{\pm} \to (e^{\pm} / \mu^{\pm})\, \alpha\, ;\, \alpha \to$ invisible

Can enter from NP models such as light ALP

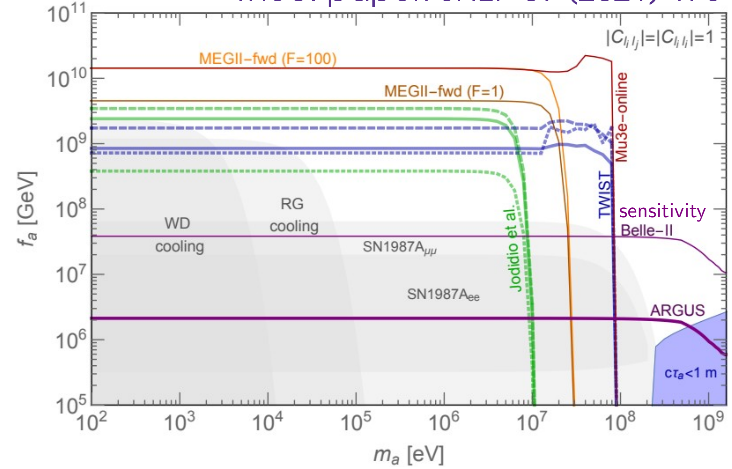
$\rightarrow$ our search is, however, spin-insensitive

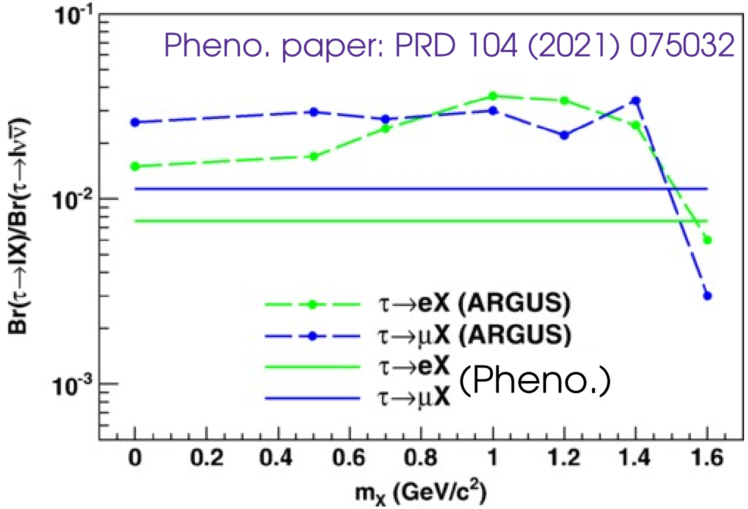
Best upper limits on $B(\tau \to l\alpha)/B(\tau \to l\nu\bar{\nu})$ from ARGUS (476 pb^{-1}, Z. Phys. C 68 (1995) 25)

From phenomenology: consistency of $B(\tau \to l\nu\bar{\nu})$ with SM predictions

With current data, Belle II can already set more stringent limits

Theo. paper: JHEP 09 (2021) 173



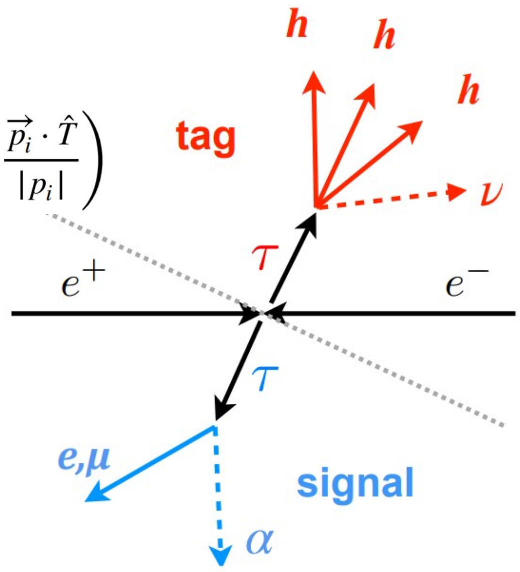


$\tau^{\pm} \to (e^{\pm}/\mu^{\pm})\,\alpha$ - Reconstruction

Dataset: 62.8 fb^{-1}

Split event in two emispheres across thrust axis

$$\vec{T} = max\left(\sum_i \frac{\vec{p_i}\cdot\hat{T}}{|p_i|}\right)$$



Require exactly 4 tracks:

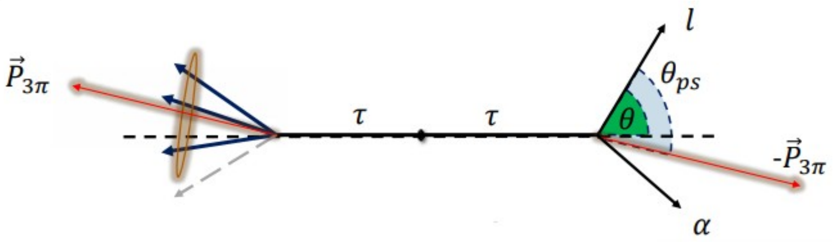
- 1 lepton on signal side
- 3 pions on tag side
- veto neutrals (γ, π^0) for reducing hadronic background

$\tau \to l\alpha$ events are indistinguishable from $\tau \to l\nu\bar{\nu}$ (irreducible background)

Look for a "peak" in lepton spectra computed in the τ pseudo-mass frame:

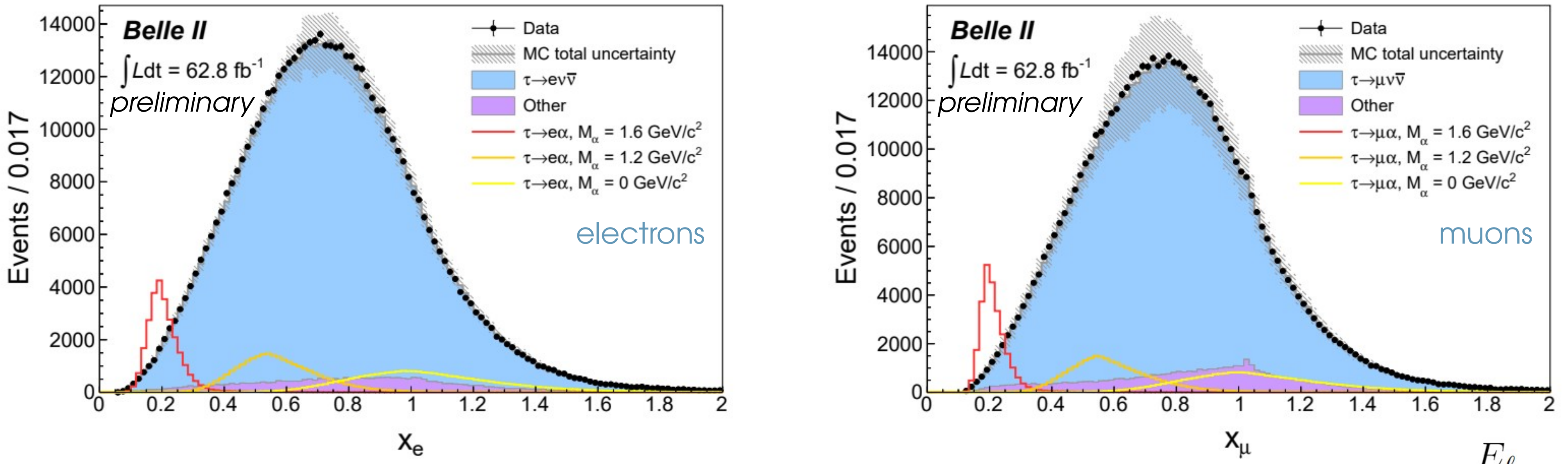
$$\hat{p}_\tau \approx -\frac{\vec{p}_{tag}}{|\vec{p}_{tag}|}$$

$$E_\tau \approx \sqrt{s}/2$$



$\tau^{\pm} \to (e^{\pm} / \mu^{\pm})\, \alpha$ – Data and MC spectra

Final spectra computed in the τ pseudo-mass frame: $\hat{p}_\tau \approx -\frac{\vec{p}_{tag}}{|\vec{p}_{tag}|}$ $E_\tau \approx \sqrt{s}/2$



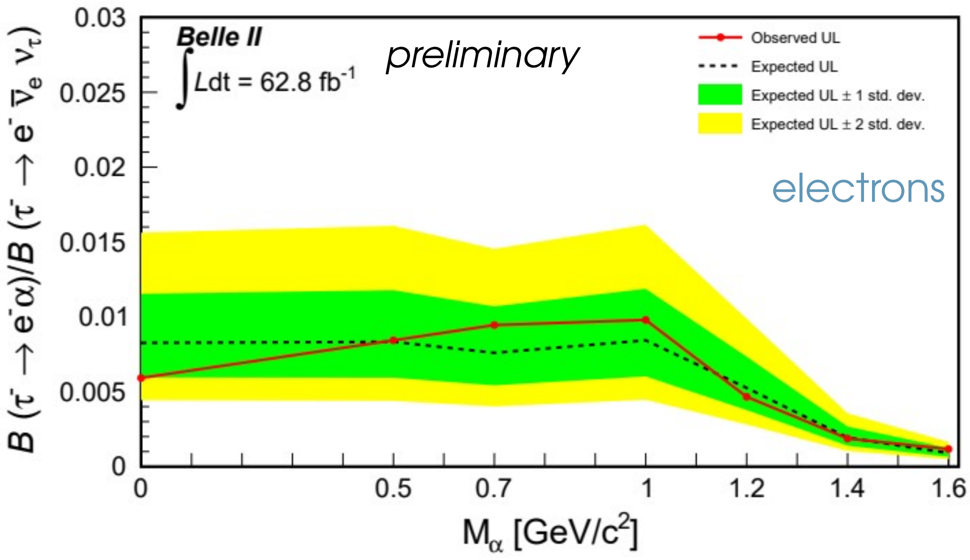
Arbitrary normalization for $\tau \to l\alpha$ events ($B(\tau \to l\alpha) = 5\%$) $x_\ell \equiv \frac{E_\ell}{m_\tau/2}$

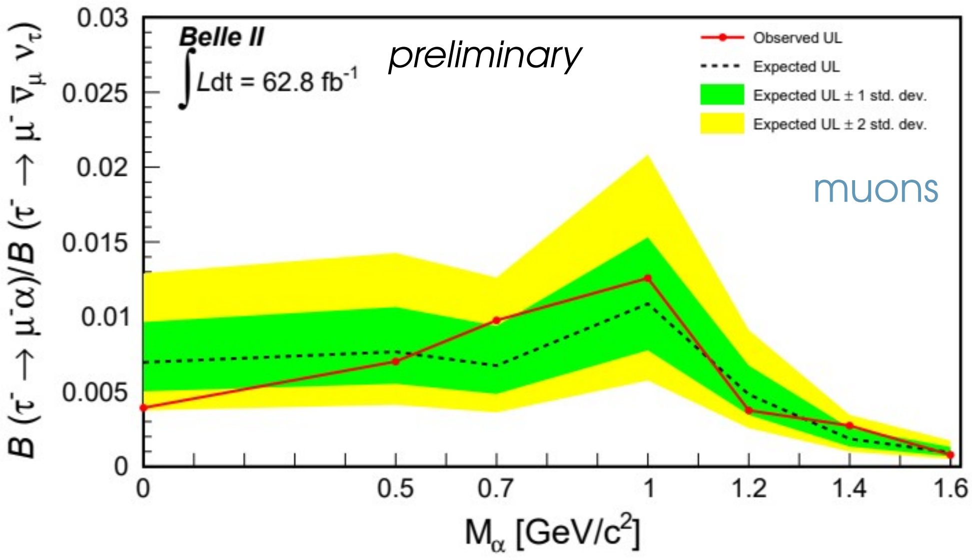
High purity (96% for electron channel, 92% for muon channel)

→ efficiency between 9% and 17% depending on M_α

$\tau^{\pm} \to (e^{\pm} / \mu^{\pm})\, \alpha$ – Results

No signal observed $\rightarrow$ set 95% CL upper limits





Largest systematics from particle identification

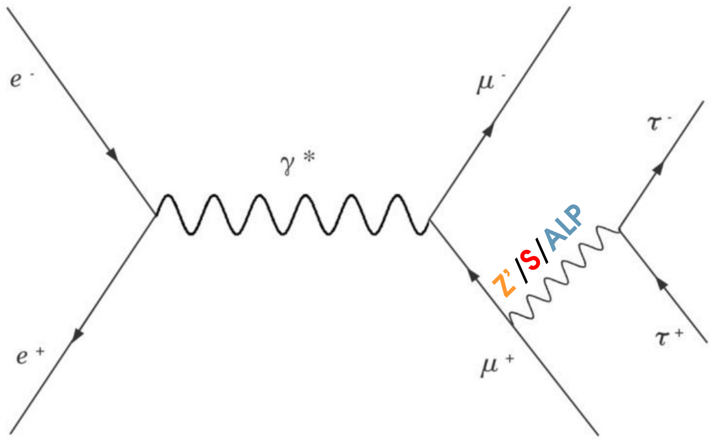
Most stringent measurements in these channels to date

NEW – from ICHEP

Z' / S / ALP → $\tau^+\tau^-$

We searched for a $\tau^+\tau^-$ resonance in $\mu^+\mu^-\tau^+\tau^-$ final states

$$\rightarrow M(\tau\tau) = M_{recoil}(\mu\mu)$$



We probed three different models:

Z' $L_\mu - L_\tau$ model

- JHEP 12 (2016) 106 (theo. paper)
- vector portal
- first time search in $\tau\tau$

Leptophilic dark scalar S model

- PRD 95 (2017) 075003 (theo. paper)
- Yukawa couplings
- constraints by BaBar in $S\rightarrow\mu\mu$
- first time search in $\tau\tau$

ALP → $\tau\tau$

- arXiv:2110.10698 (theo. paper)
- $C_{ee}=C_{\mu\mu}=C_{\tau\tau}$; $C_{\gamma\gamma}=C_{Z\gamma}=0$
- Yukawa-like effective couplings
- ALP-τ coupling unconstrained

Z' / S / ALP → $\tau^+\tau^-$ - Reconstruction

Dataset: 63.3 fb^{-1}

Basic selections:

- considering only 1-prong τ decays
  - → require 4 tracks
- $2\mu + 2e/\mu/\pi$
- M(4 tracks) $<$ 9.5 GeV
- allowed neutrals
- scan $M_{recoil}(\mu\mu)$

Main backgrounds:

- $\tau^+\tau^-(\gamma)$ (1x3-prongs events)
- $q\bar{q}$
- $l^+l^-l^+l^-$ (no ISR in our simulation)
- $\mu^+\mu^-\pi^+\pi^- + e^+e^-X_{had.}$ (not simulated)

Z' / S / ALP → $\tau^+\tau^-$ - Reconstruction

Dataset: 63.3 fb^{-1}

Basic selections:

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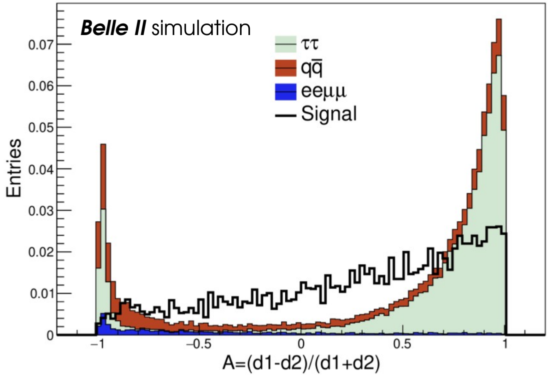
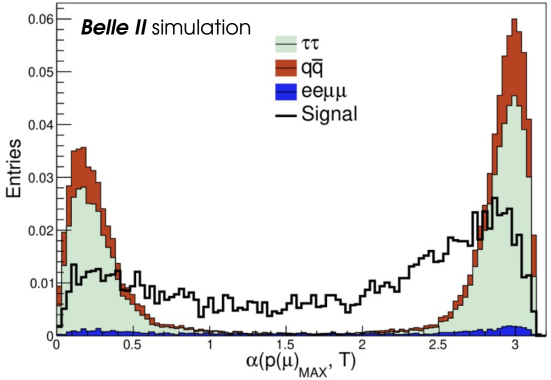
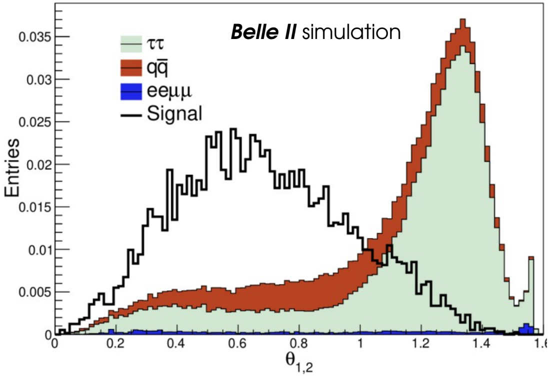
Background suppression via dedicated Neural Network

→ 8 NN ranges in $M_{recoil}(\mu\mu)$



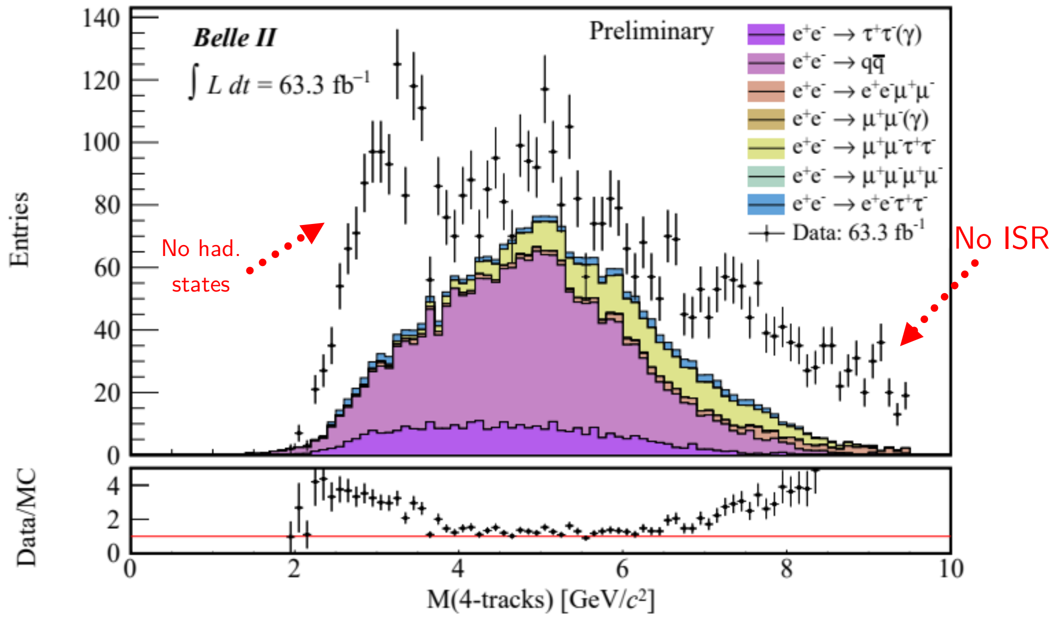


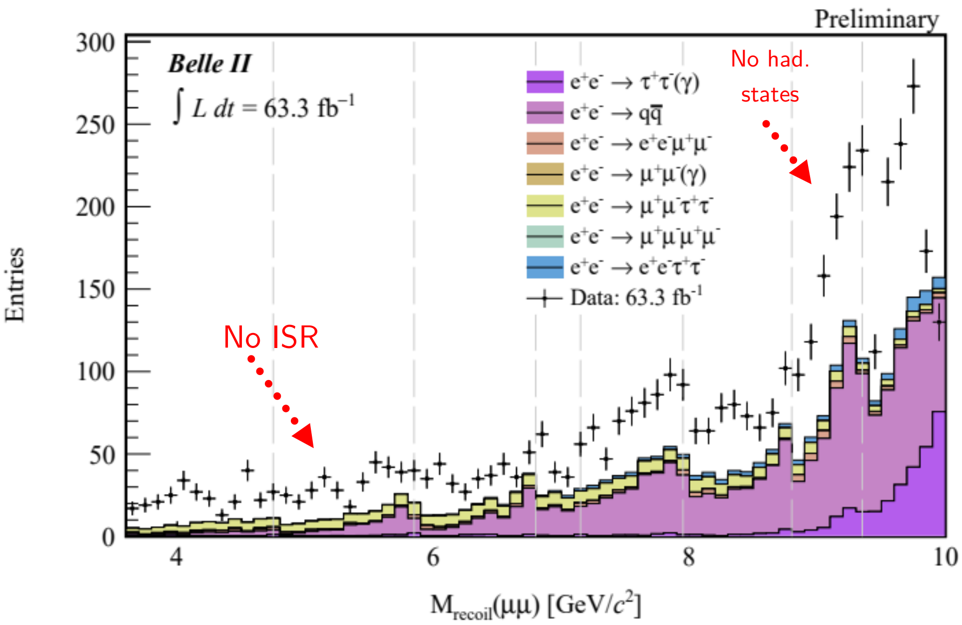


Selection optimized for $Z'\to\tau^+\tau^-$ signal

→ achieved 99% background reduction

Z' / S / ALP → $\tau^+\tau^-$ - Data and MC spectra





Discrepancies expected and understood due to missing features in simulation

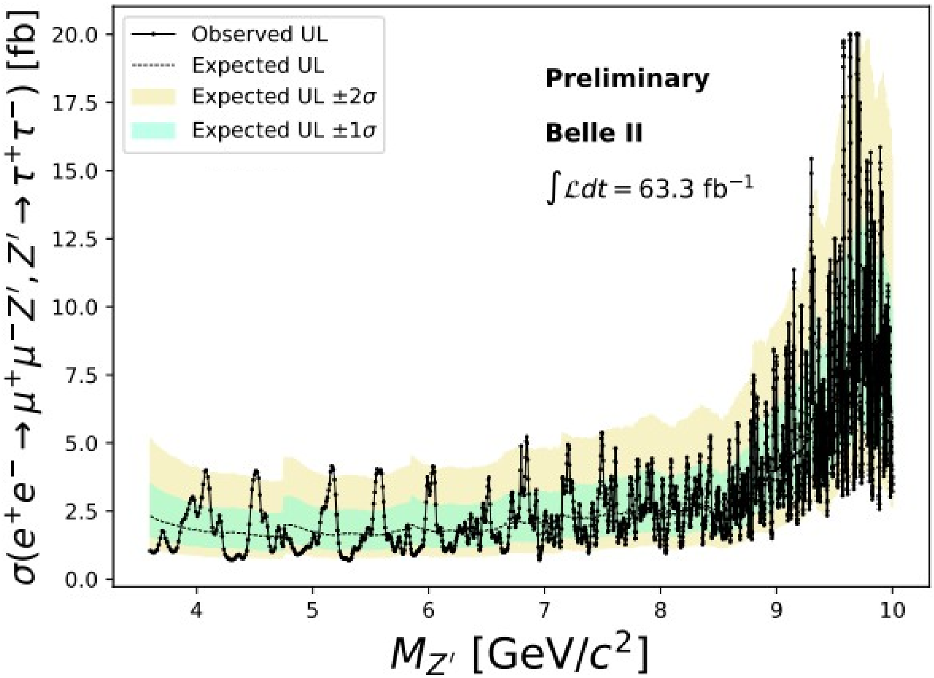
Smooth distribution and no peaking structures in $M_{recoil}(\mu\mu)$

→ NB: signal mass resolution from 1.5 MeV to 30 MeV

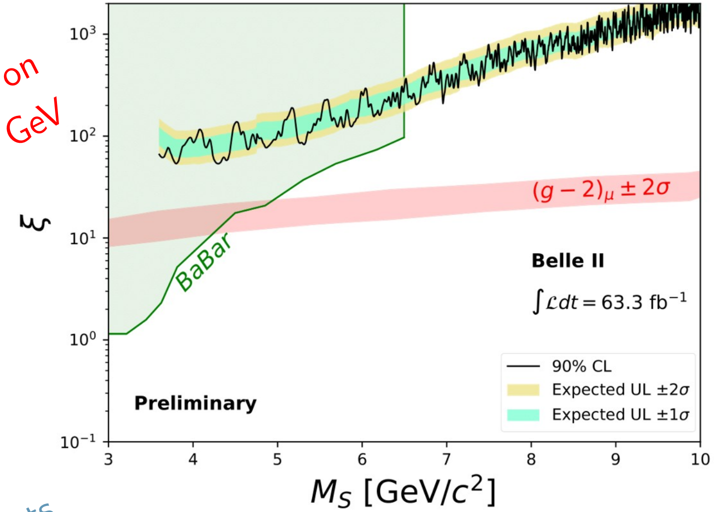
NEW – from ICHEP

Z' / S / ALP → $\tau^+\tau^-$ - Results

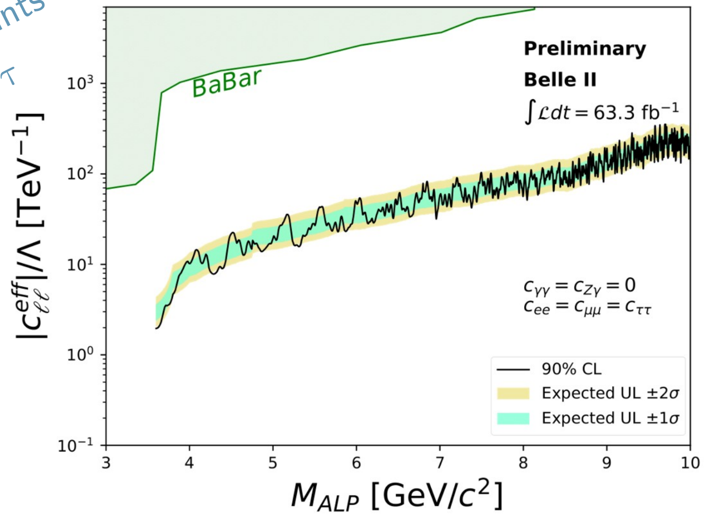
No signal observed → set 90% CL upper limits



First constraints on S for $M_S > 6.5$ GeV



First direct contraints on ALP → ττ



Z' → ττ ($L_\mu - L_\tau$ model) only used as benchmark

Summary

- Belle II collected about 424 fb^{-1} of collisions data
- Presented here world-leading results for searches of:
  - $\tau^{\pm} \to (e^{\pm} / \mu^{\pm})\ \alpha$, with $\alpha \to \mathrm{invisible}$
  - leptophilic dark scalar $S \to \tau^+\tau^-$ / $ALP \to \tau^+\tau^-$
- More results will be presented by M. Campajola in his plenary talk
  - Dark Higgsstralung $e^+e^- \to A'h'$, with $A' \to \mu^+\mu^-$ and h' invisible
  - Invisible Z' within the $L_{\mu} - L_{\tau}$ model
- Belle II will lead the field in the Dark Sector searches in the MeV-GeV mass range in the coming years

Thank you for your attention

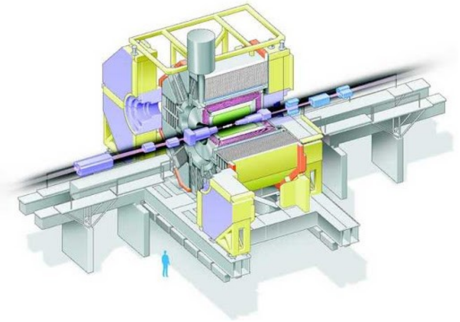
Backup slides

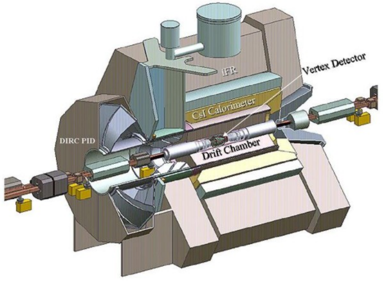
B-factories as Intensity Frontier experiments

B-factories are dedicated experiments at e^+e^- asymmetric-energy colliders for the production of quantum coherent $B\bar{B}$ pairs.

First generation of B-factories

(collected about 1.5 ab^{-1} of integrated luminosity)





BELLE

BABAR

The strenghts of a B-factory are:

- constrained kinematics;
- clean environment and lower background;
- hermetic detector;
- excellent PID capabilities;
- efficienct reconstruction of neutral particles.

B-factories as Intensity Frontier experiments

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First generation of B-factories

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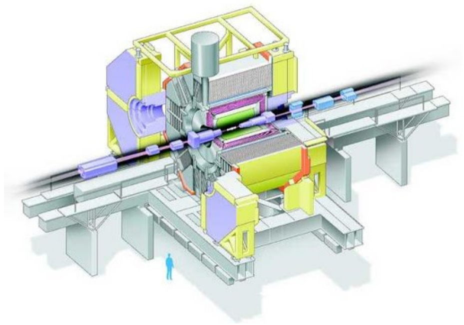
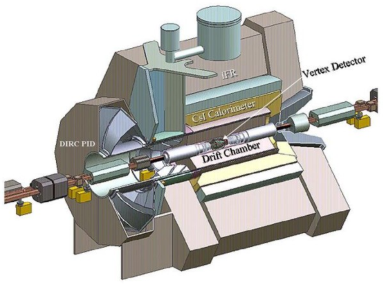
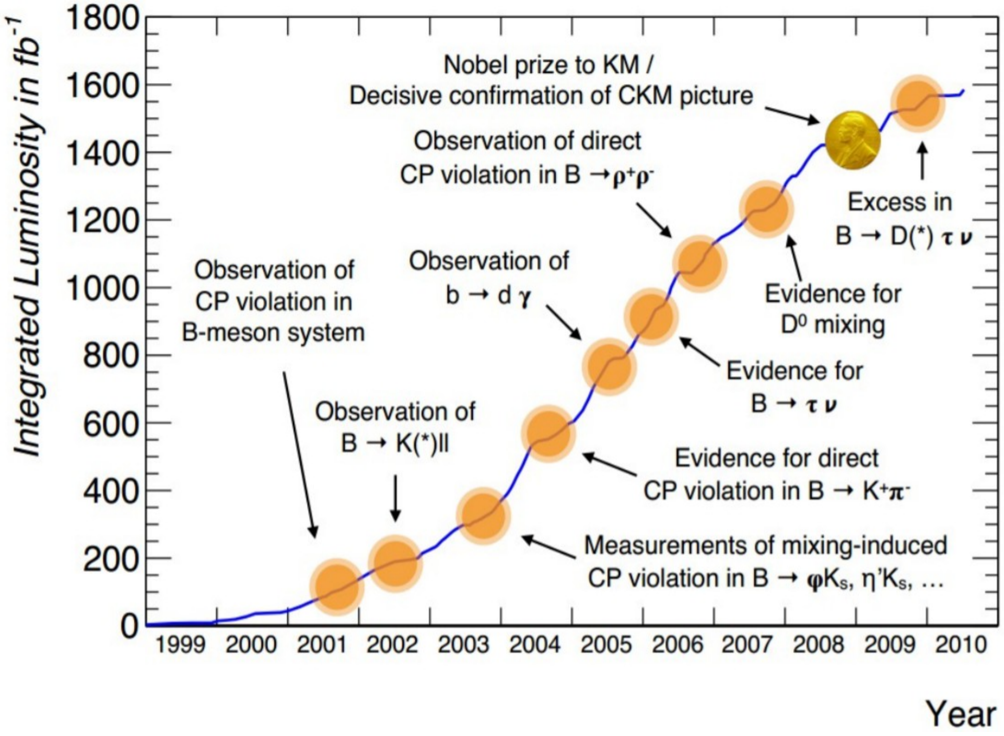






SuperKEKB machine parameters

Parameter	KEKB Design	KEKB Achieved		SuperKEKB Design
Energy (GeV) (LER/HER)	3.5/8.0	3.5/8.0		4.0/7.0
β_y^* (mm)	10/10	5.9/5.9		0.27/0.30
β_x^* (mm)	330/330	1200/1200		32/25
ε_x (nm)	18/18	18/24		3.2/5.3
$\frac{\varepsilon_y}{\varepsilon_x}$ (%)	1	0.85/0.64		0.27/0.24
σ_y (μm)	1.9	0.94	1/20	0.048/0.062
ξ_y	0.052	0.129/0.090		0.09/0.081
σ_z (mm)	4	6/7		6/5
I_{beam} (A)	2.6/1.1	1.64/1.19	x2	3.6/2.6
$N_{bunches}$	5000	1584		2500
Luminosity ($10^{34} cm^{-2} s^{-1}$)	1.0	2.11	x40	80

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

Cross sections at a B-factory

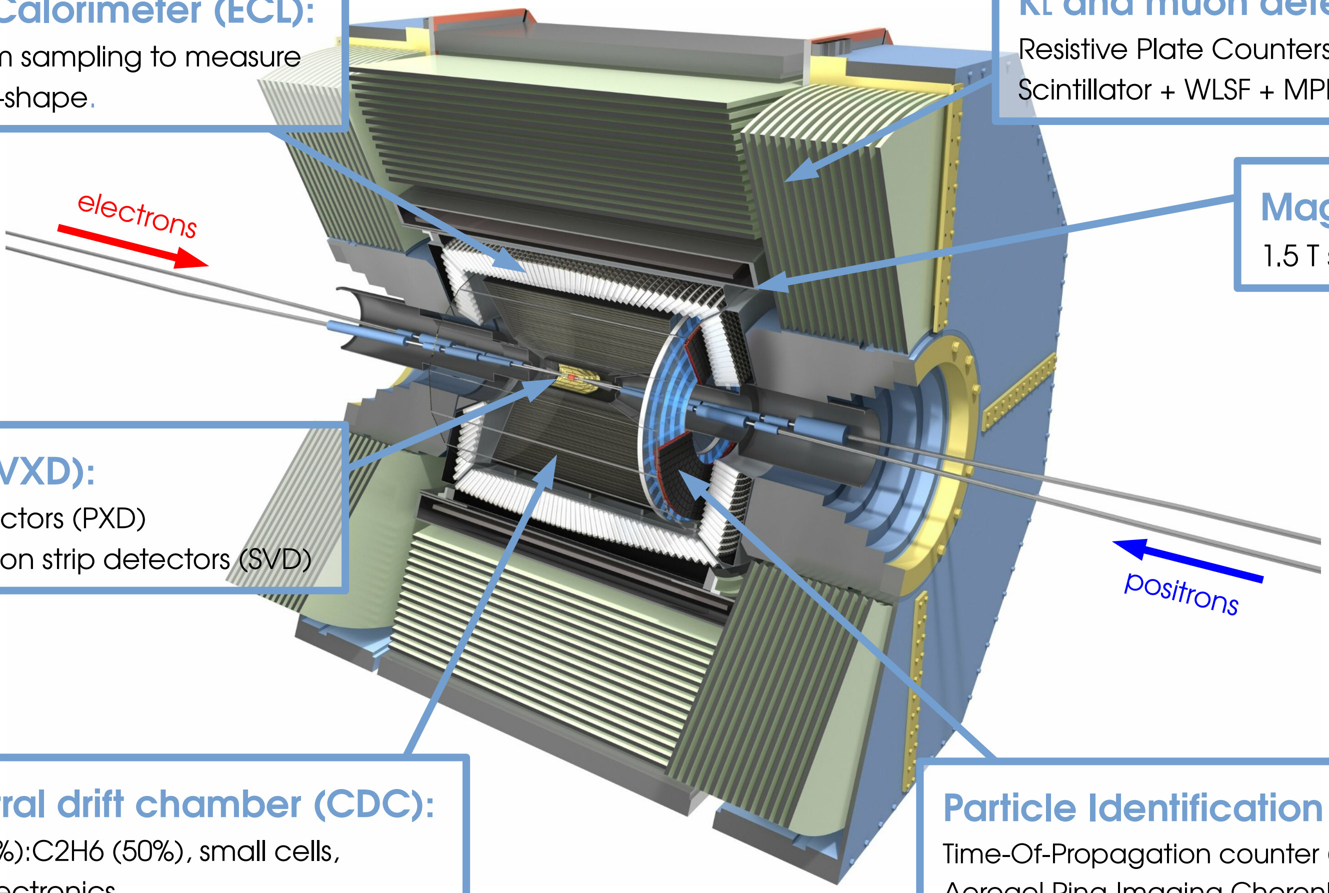
Physics process	Cross section [nb]	Selection Criteria	Reference
$\Upsilon(4S)$	1.110 ± 0.008	-	[2]
$u\bar{u}(\gamma)$	1.61	-	KKMC
$d\bar{d}(\gamma)$	0.40	-	KKMC
$s\bar{s}(\gamma)$	0.38	-	KKMC
$c\bar{c}(\gamma)$	1.30	-	KKMC
$e^+e^-(\gamma)$	300 ± 3 (MC stat.)	$10° < \theta_e^* < 170°$, $E_e^* > 0.15\,\mathrm{GeV}$	BABAYAGA.NLO
$e^+e^-(\gamma)$	74.4	$p_e > 0.5\,\mathrm{GeV}/c$ and e in ECL	-
$\gamma\gamma(\gamma)$	4.99 ± 0.05 (MC stat.)	$10° < \theta_\gamma^* < 170°$, $E_\gamma^* > 0.15\,\mathrm{GeV}$	BABAYAGA.NLO
$\gamma\gamma(\gamma)$	3.30	$E_\gamma > 0.5\,\mathrm{GeV}$ in ECL	-
$\mu^+\mu^-(\gamma)$	1.148	-	KKMC
$\mu^+\mu^-(\gamma)$	0.831	$p_\mu > 0.5\,\mathrm{GeV}/c$ in CDC	-
$\mu^+\mu^-\gamma(\gamma)$	0.242	$p_\mu > 0.5\,\mathrm{GeV}$ in CDC, $\geq 1\ \gamma\ (E_\gamma > 0.5\,\mathrm{GeV})$ in ECL	-
$\tau^+\tau^-(\gamma)$	0.919	-	KKMC
$\nu\bar{\nu}(\gamma)$	0.25×10^{-3}	-	KKMC
$e^+e^-e^+e^-$	39.7 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5\,\mathrm{GeV}/c^2$	AAFH
$e^+e^-\mu^+\mu^-$	18.9 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5\,\mathrm{GeV}/c^2$	AAFH

E. Kou, P. Urquijo et al.,
arXiv:1808.10567

Belle II: a new Intensity Frontier detector

Electromagnetic Calorimeter (ECL):
CsI(Tl) crystals, waveform sampling to measure time, energy, and pulse-shape.

K_L and muon detector (KLM):
Resistive Plate Counters (RPC) (outer barrel)
Scintillator + WLSF + MPPC (endcaps, inner barrel)



Magnet:
1.5 T superconducting

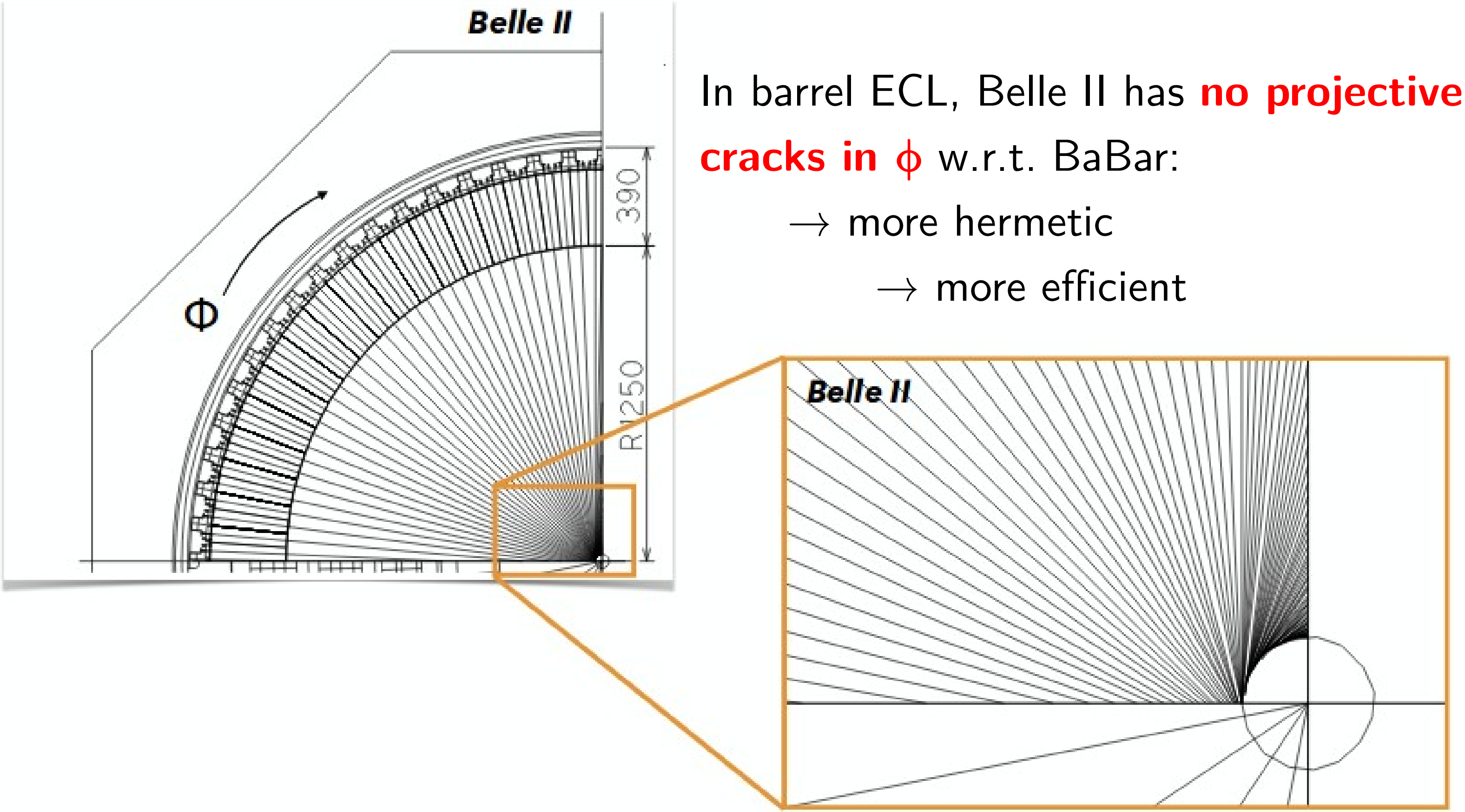
Vertex detectors (VXD):
2 layer DEPFET pixel detectors (PXD)
4 layer double-sided silicon strip detectors (SVD)

Trigger:
Dedicated lines for low multiplicity studies:
- single track
- single photon
- single muon

Central drift chamber (CDC):
He(50%):C_2H_6 (50%), small cells, fast electronics

Particle Identification (PID):
Time-Of-Propagation counter (TOP) (barrel)
Aerogel Ring-Imaging Cherenkov Counter (ARICH) (FWD)

Electromagnetic Calorimeter (ECL)



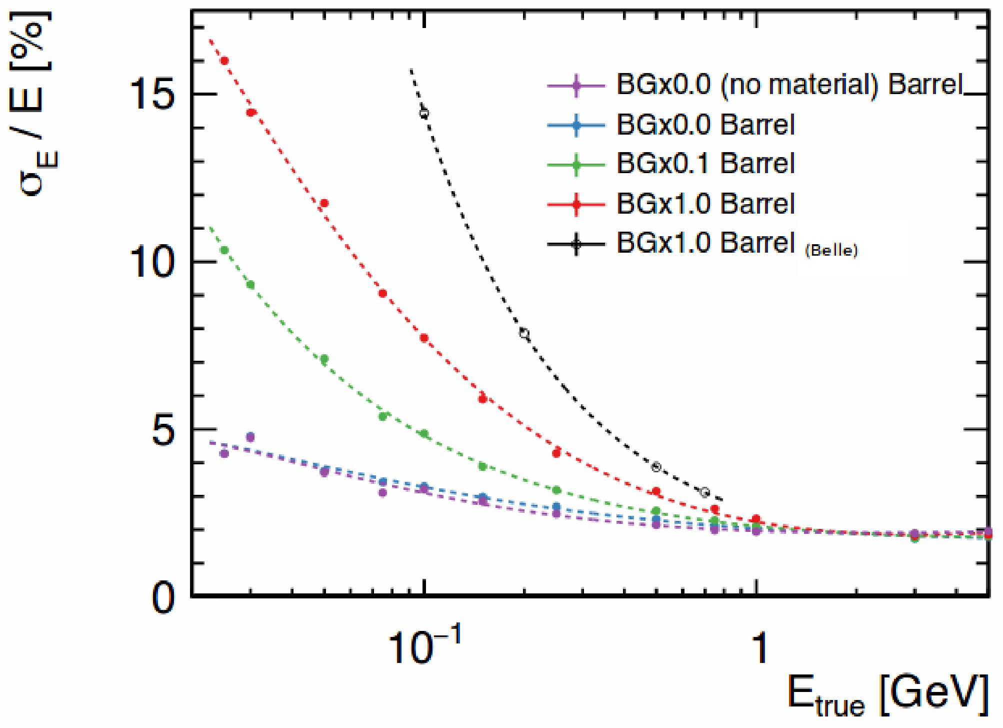
In barrel ECL, Belle II has **no projective cracks in ϕ** w.r.t. BaBar:

$\rightarrow$ more hermetic

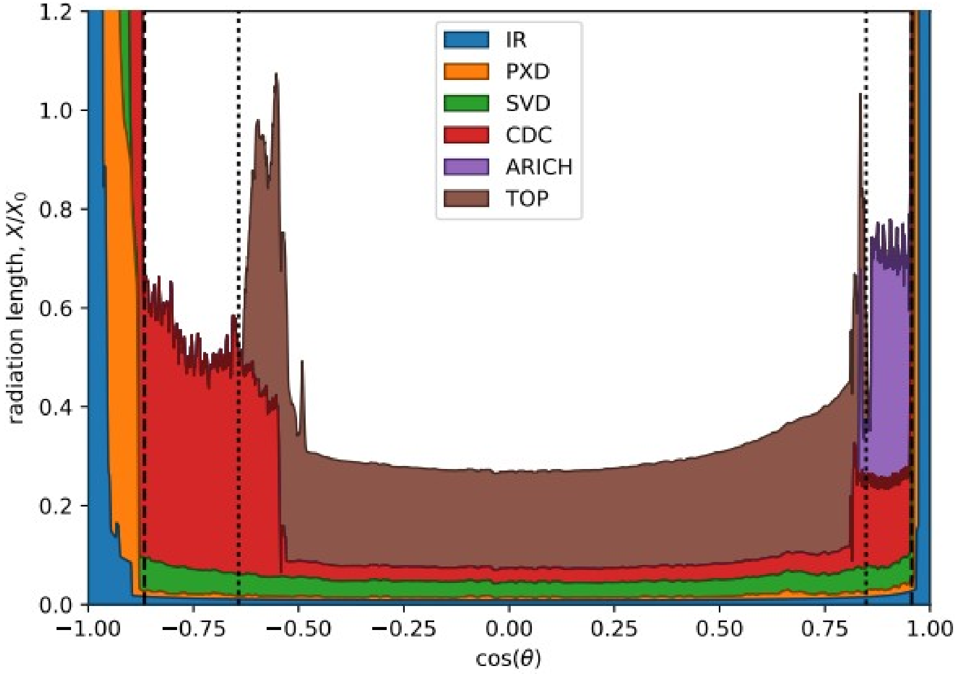
$\rightarrow$ more efficient

Electromagnetic Calorimeter (ECL)

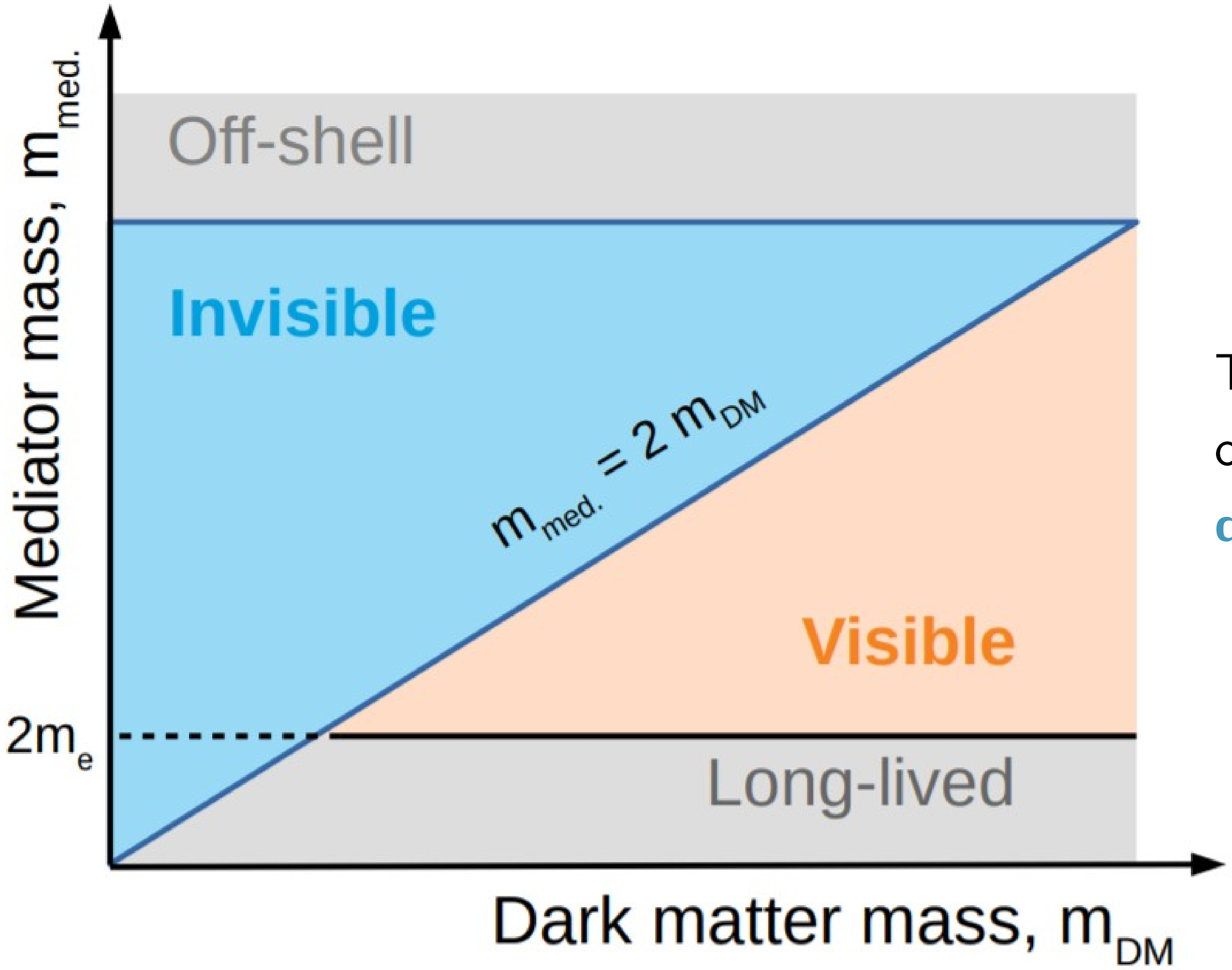
Energy resolution in Belle II barrel:



Material budget in front of ECL:



A rule of thumb...



The masses of the mediator and of the DM candidates lead to **different type of searches**.

ALP → γγ - Model

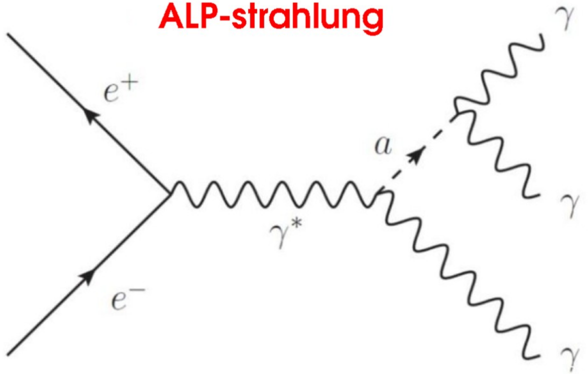
Axion-Like Particles (ALPs) are pseudoscalar particles (a) that couple to bosons.

Unlike QCD Axions, ALPs have no relation between mass and coupling.

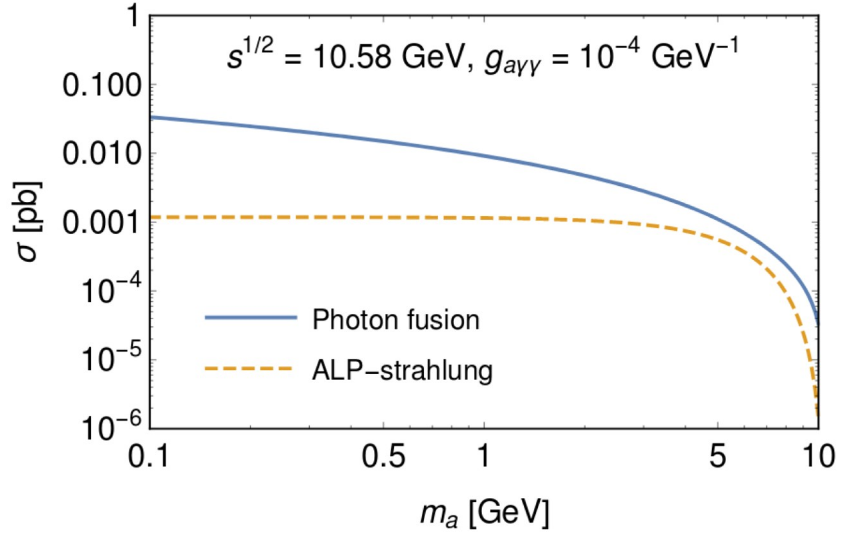
Belle II focused on the **coupling to photons**:

$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad \tau_a \sim 1/g_{a\gamma\gamma}^2 m_a^3$$

ALP-strahlung



Dolan et al. (2017), *arXiv:1709.00009*



Investigating the photon coupling $g_{a\gamma\gamma}$ in ALP-strahlung

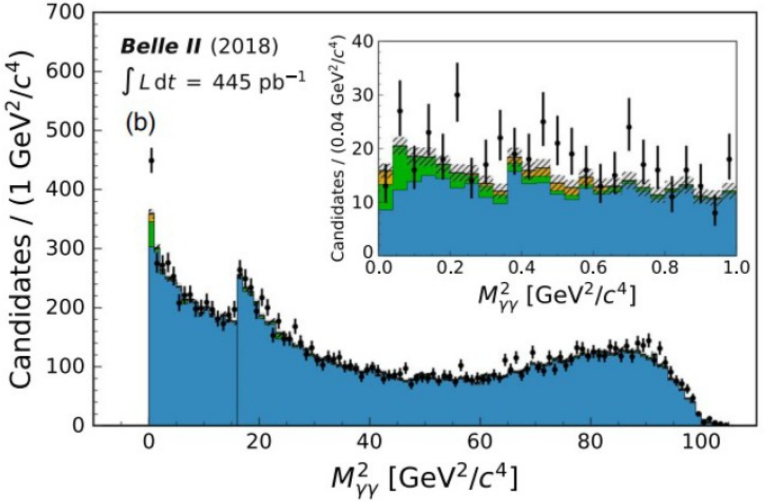
First search at B-factories

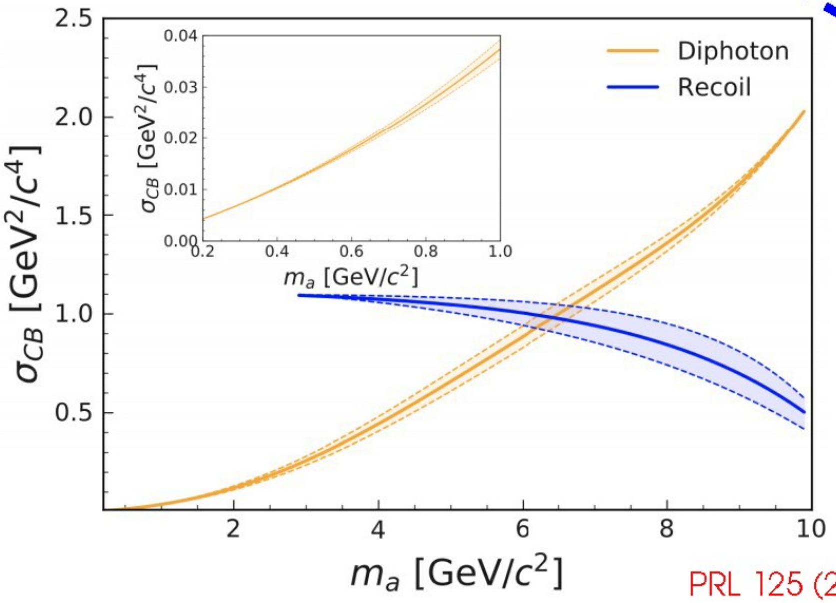
ALP → γγ – Reconstrunction & Data/MC spectra

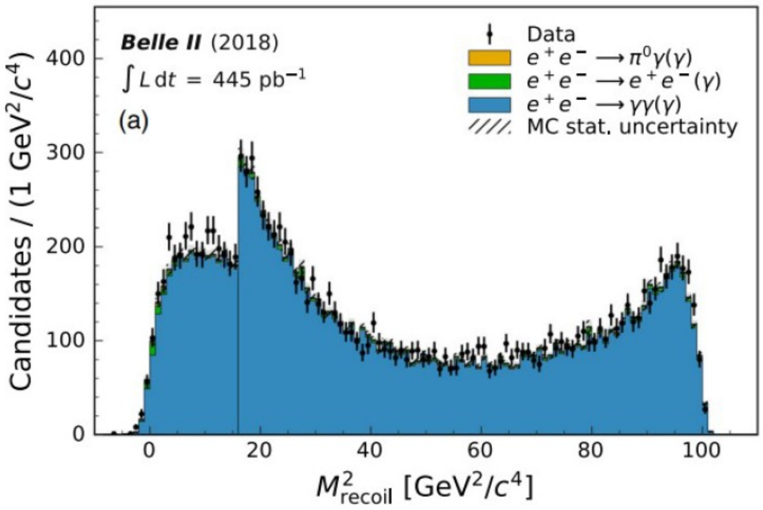
Select events with no charged tracks consisting of 3 isolated photons with a total invariant mass consistent with $s^{1/2}$.

Search strategy optimized to maximize ALP sensitivity:

- low ALP mass → diphoton mass spectrum;
- high ALP mass → recoil mass spectrum.







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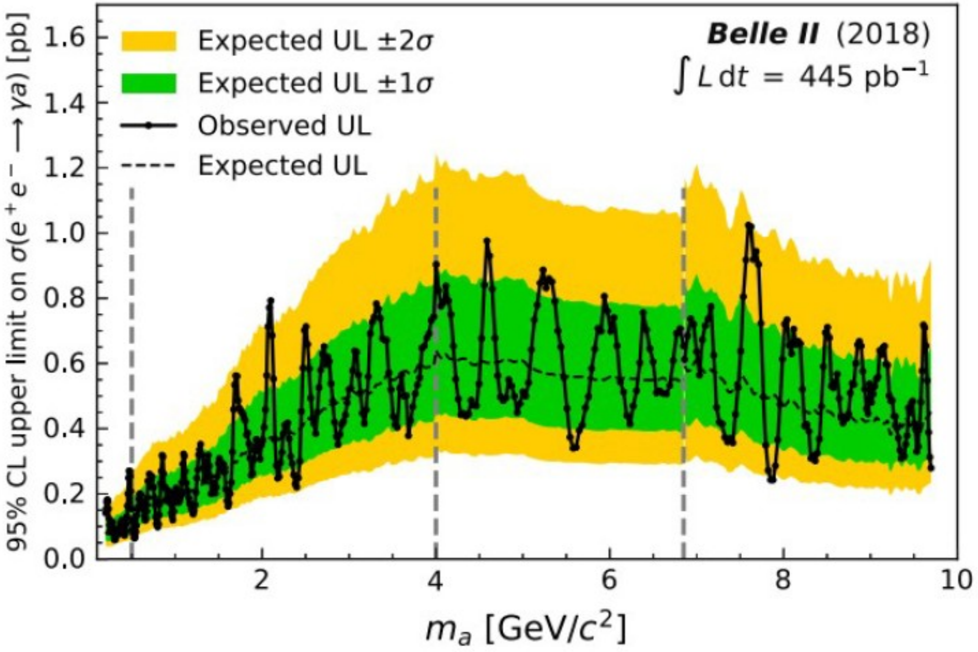
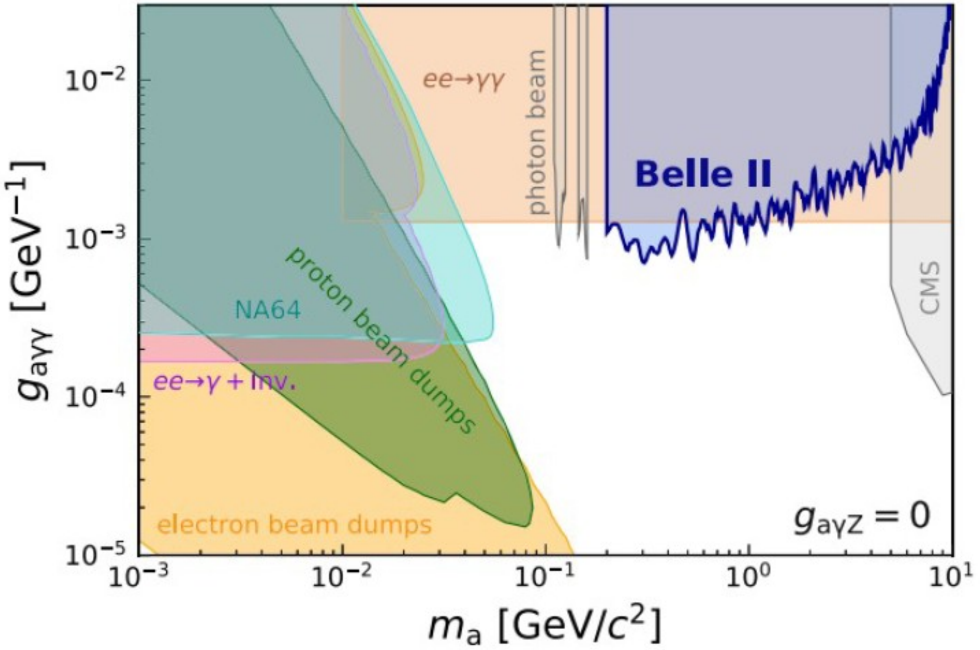
ALP → γγ - Results

Search conducted with 445 pb^{-1} of 2018 pilot run data:

- 500 fits in sliding ranges with steps of half mass resolution;
- no excess observed (largest local significance: 2.8 σ).

$$\sigma_a = \frac{g_{a\gamma\gamma}^2 \alpha_{\rm QED}}{24}\left(1 - \frac{m_a^2}{s}\right)^3$$





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