LP2I9

29th International Symposium on
Lepton Photon Interactions at High Energies

Dark Sector Physics with Belle II

Marcello Campajola (University of Naples 'Federico II' and INFN)

marcello.campajola@na.infn.it

➢ ***on the behalf of the Belle II collaboration***

August 6th 2019, Toronto

Dark Sector Physics

➢ **Motivations**

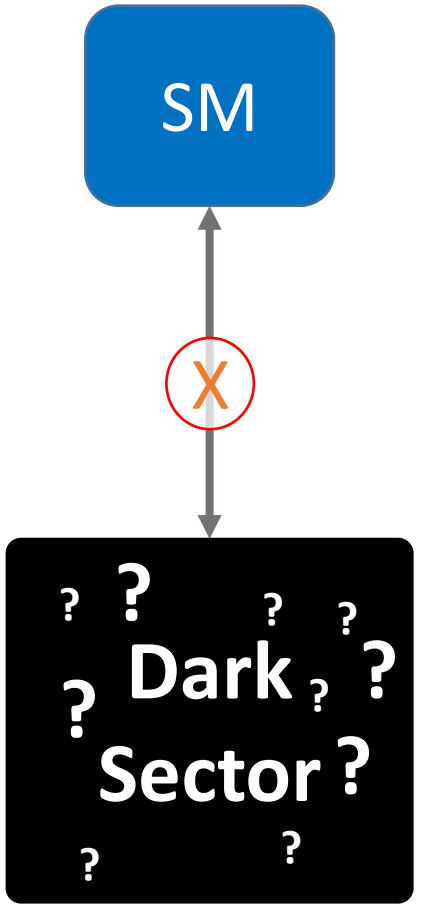
- Many astrophysical observations provide evidence for the existence of some kind of matter that interacts weakly with the Standard Model (SM) particles: ***dark matter.***

- Possible GeV and sub-GeV theoretical scenarios: Light-DM weakly coupled with SM through a light dark sector *mediator X*.

- Different possible **portals between Dark Sector and Standard Model** depending on the mediator X:

  - **Vector Portal** → Dark Photon A', Dark Z'
  - **Pseudo-scalar Portal** → Axion Like Particles
  - **Scalar Portal** → Dark Higgs / Dark Scalar
  - **Neutrino Portal** → Sterile Neutrinos

Covered Today

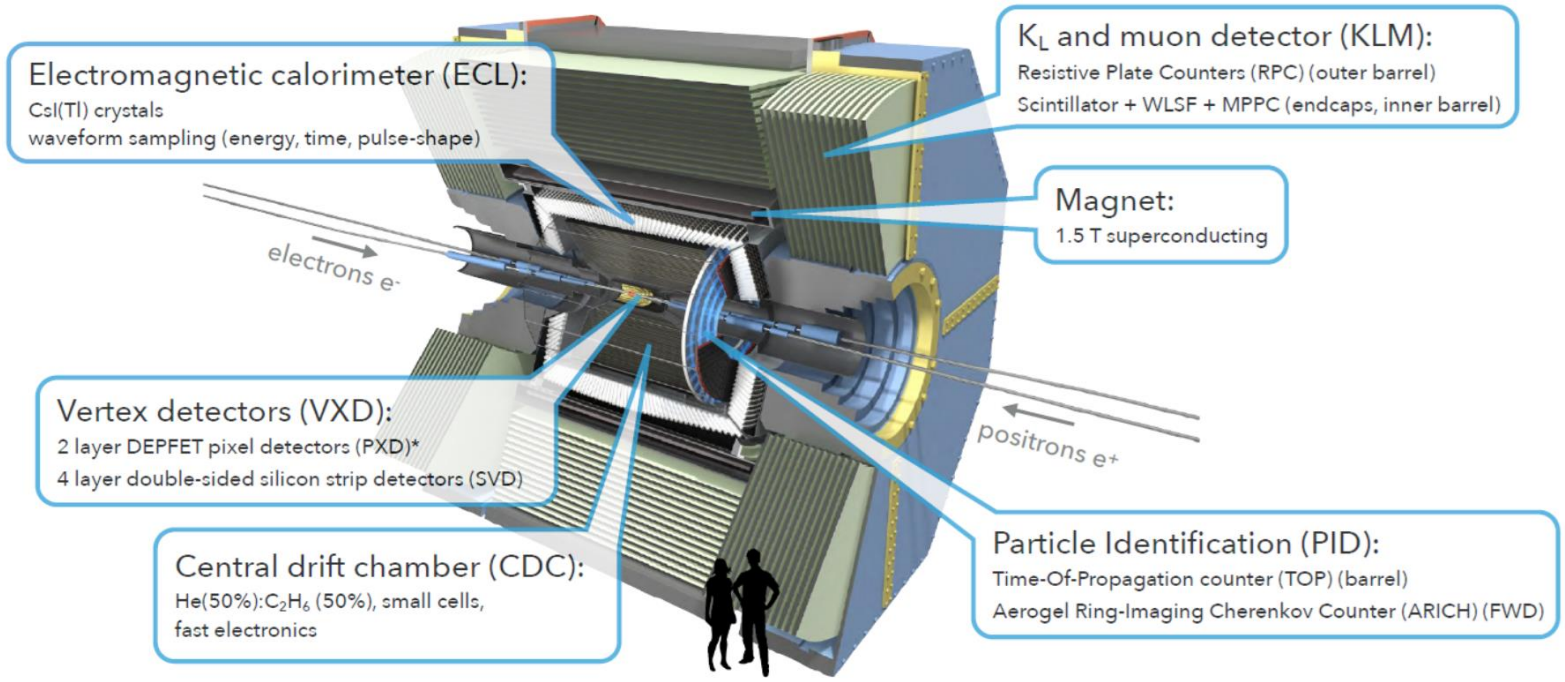


Belle II Experiment

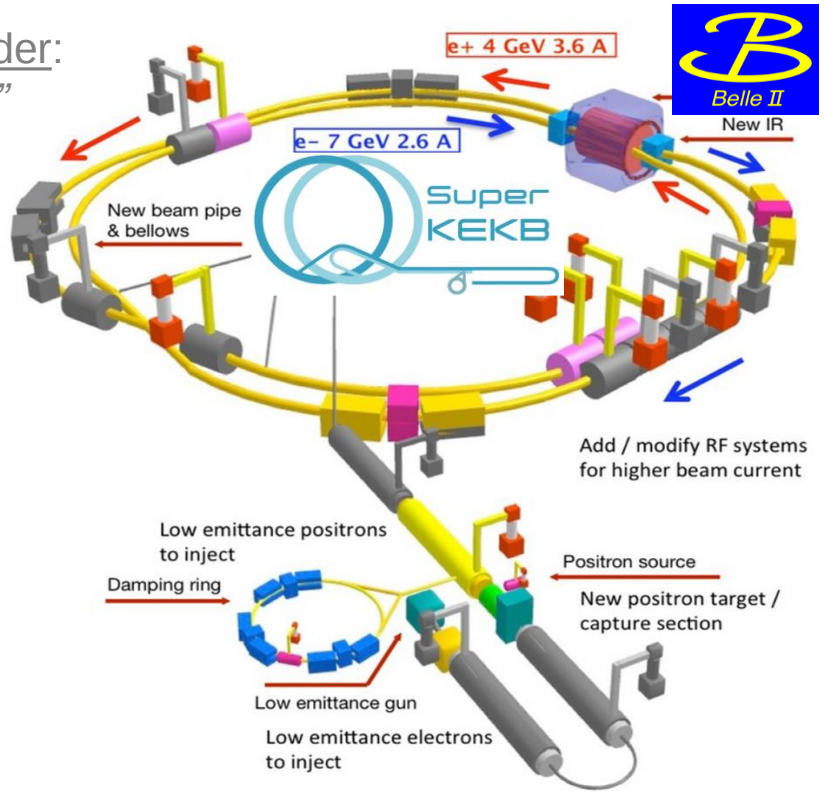
➢ **Inside the detector**

See yesterday talk by T. Browder:
"Recent News from Belle II"

- Located at IP of e^+e^- collider SuperKEKB in Tsukuba, Japan.
- Operated at 10.58 GeV $(= M_{\Upsilon(4s)})$
- Design luminosity 8×10^{35} $cm^{-2}s^{-1}$



* Some modifications for early data taking



SuperKEKB: second generation B-Factory. It will provide the ***world highest luminosity***, applying the *large crossing angle nano-beams scheme*.
(P.Raimondi et al., arXiv:0709.0451)

For further details see *The Belle II Physics Book*, arXiv:1808.10567

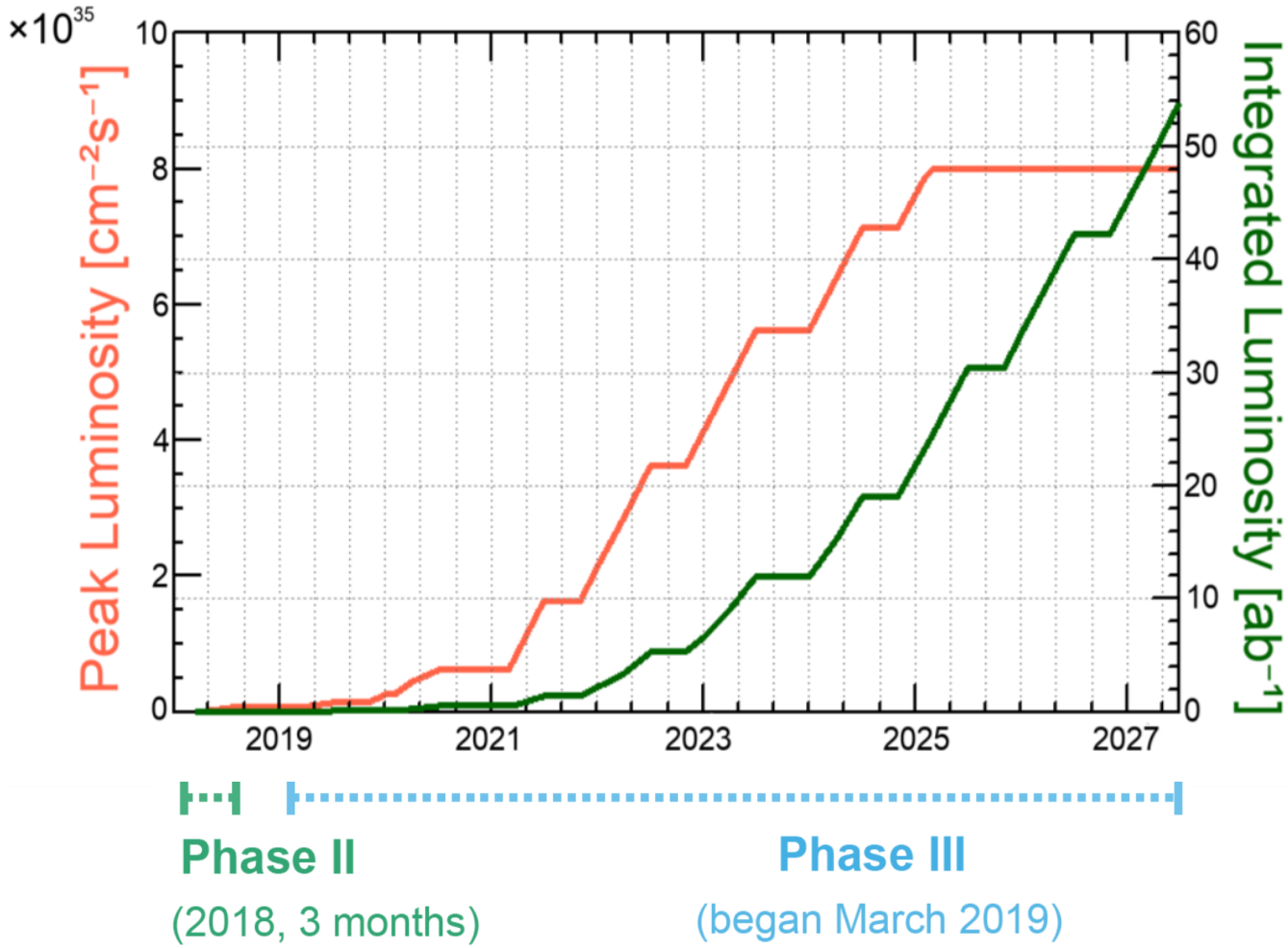
Belle II Experiment

➢ **Data Schedule**

- **Phase 2**: Last year
  - ✓ First physics data (500 pb^{-1}).
  - ✓ Incomplete detector (1/8 VXD)
  - ✓ Commissioning data.

- **Phase 3**: 2019 ->
  - ✓ Physics run started on March 2019
  - ✓ Up to now collected 6.5 fb^{-1}
  - ✓ Will continue 7-9 months/year

- **Goal:** integrate up to 50 ab^{-1}.
  x50 data set of its predecessor (Belle)



Dark Sector Physics

➢ **Outline of the presentation**

In this presentation I will focus on analyses competitive with available Phase 2 (0.5 fb^{-1}) or early Phase 3 (~20 fb^{-1}) data sets:

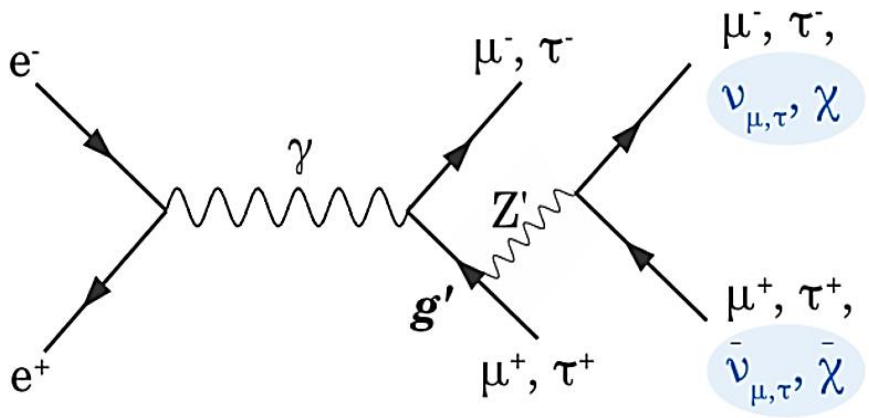
- **Z' to invisible ($L_\mu - L_\tau$ model)**
- **Dark photon to invisible**
- **Axion-like particles**

Z’ to invisible

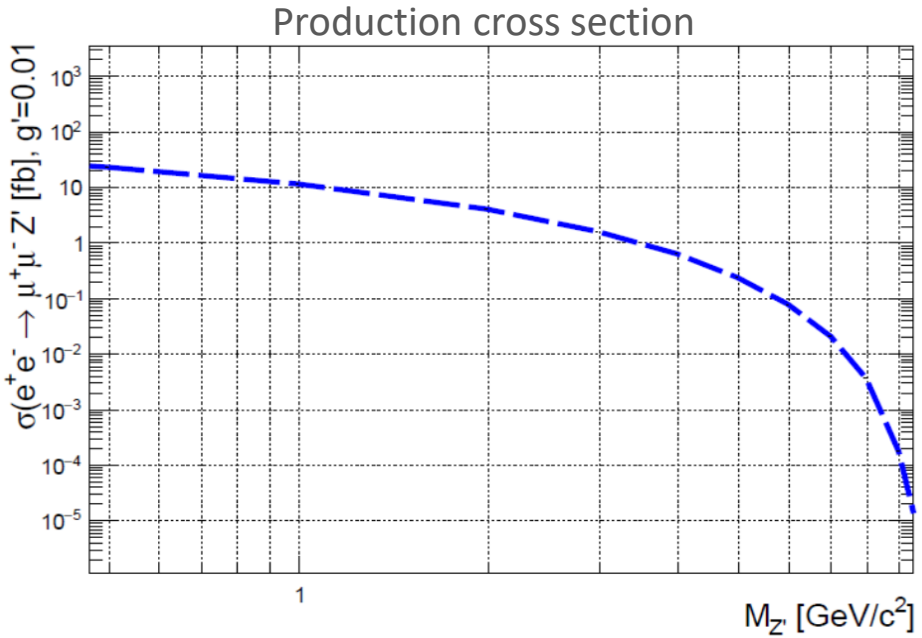
Shuve et al. (2014), arXiv:1403.2727
Altmannshofer et al. (2016) arXiv 1609.04026

➢ **Theory**

- New light gauge boson Z’ coupling only to the 2nd and 3rd generation of leptons *($L_\mu - L_\tau$ model);*
- Looking for an invisible Z’ decay produced with a pair of muons;



$$\mathcal{L} = \sum_{\ell = \mu, \tau, \nu_{\mu,L}, \nu_{\tau,L}} \theta g' \bar{\ell} \gamma^\mu Z'_\mu \ell$$



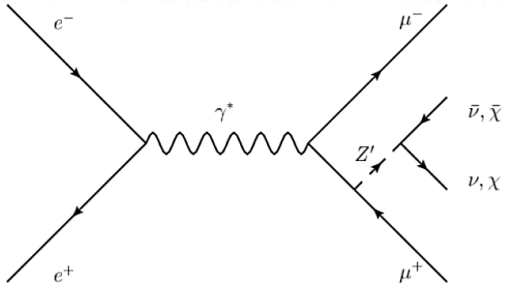
- If kinematically accessible, Z’ could decay to **DM** (sterile neutrinos, light Dirac fermions)
- May explain:
  - DM puzzle;
  - $(g\text{-}2)_\mu$ anomaly;
  - $B \to K(*)\mu\mu$, R_K, R_{K*} anomalies;

➢ Exploring the *invisible decay* for the first time.

$$e^+e^- \to \mu^+\mu^- + \textit{missing energy}$$

Z’ to invisible

➢ **Experimental Signature**

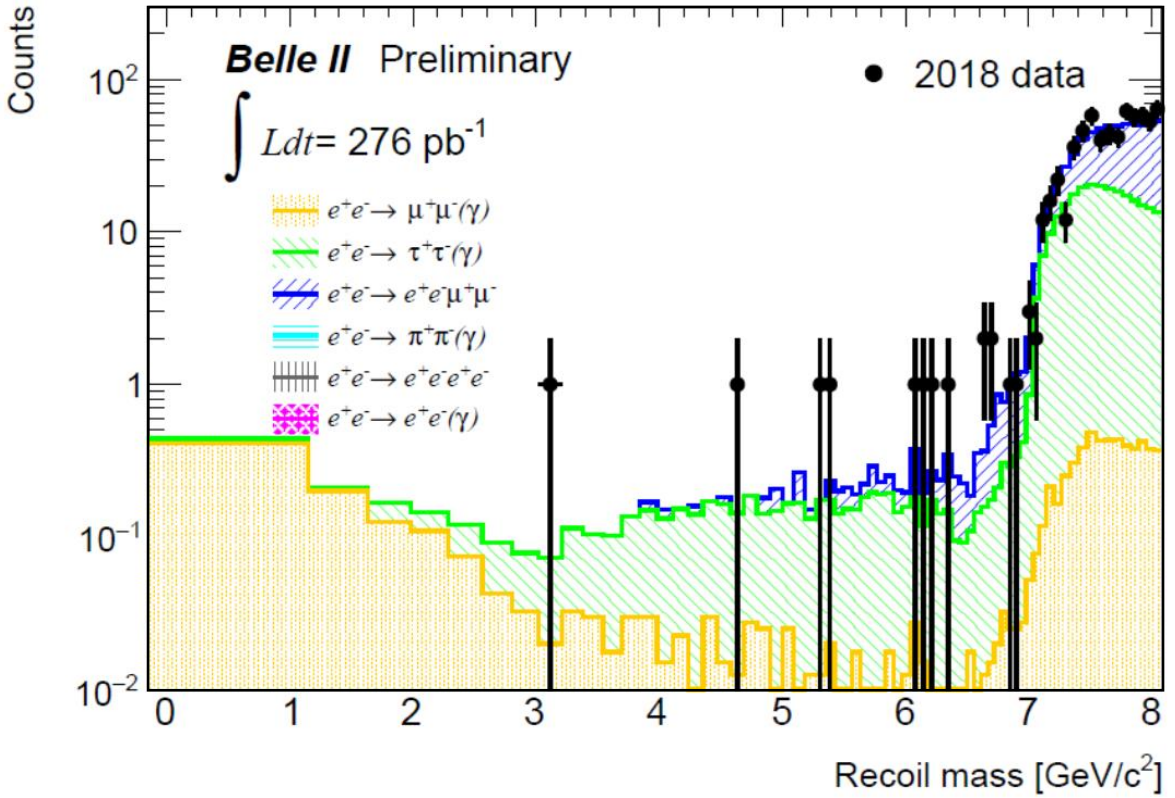


- Signal signature:
  - Bump in the **recoil mass** against $\mu\mu$ *pair*;
  - Nothing in the *rest of event*

- Background mainly from QED processes:
  - $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$;
  - $e^+e^- \rightarrow \tau^+\tau^-(\gamma), (\tau \rightarrow \mu\nu\nu)$;
  - $e^+e^- \rightarrow \mu^+\mu^-e^+e^-$;

- **Only 276 pb^{-1}** is usable due to trigger conditions for 2 tracks events.

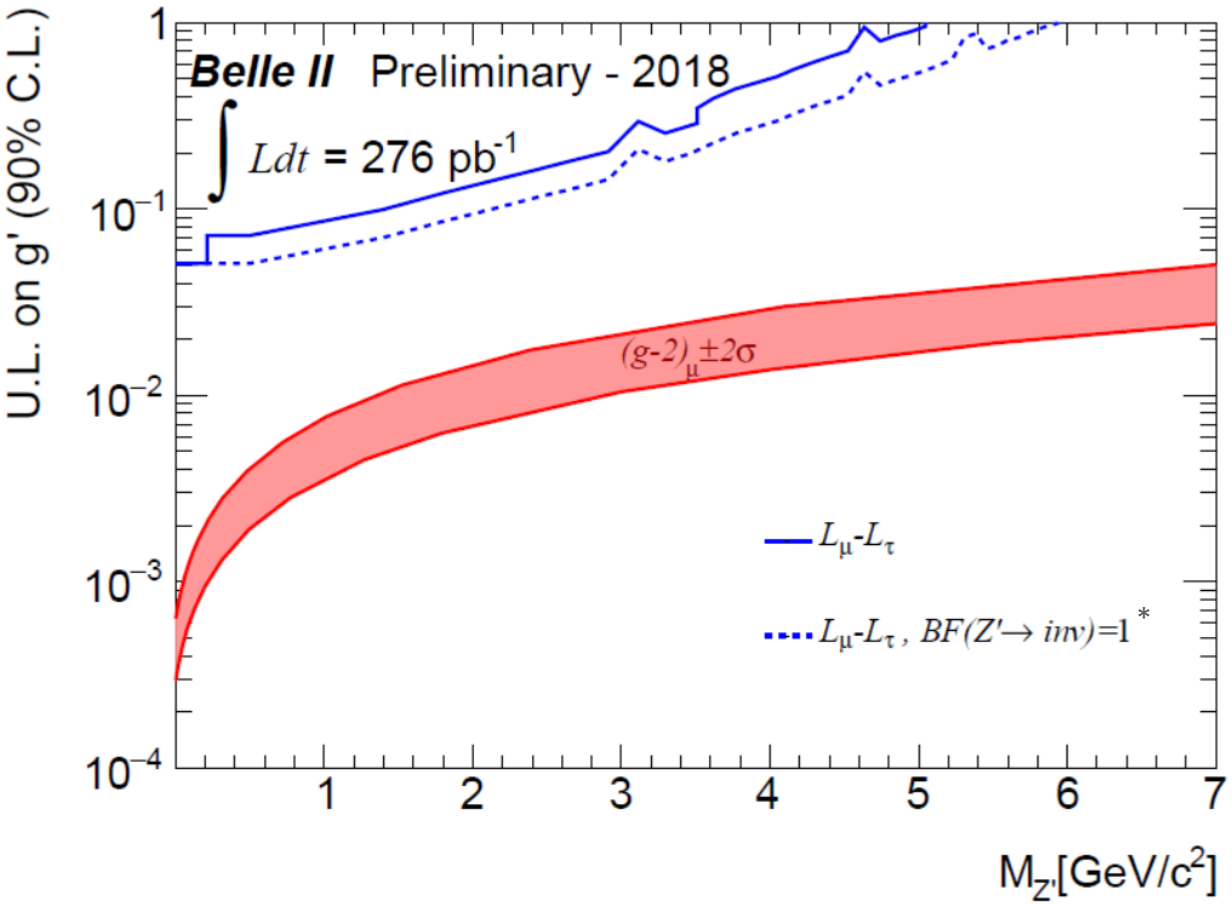
Recoil mass spectrum after selection



No sensitivity to the parameter space region for $M_{Z'} > 8$ GeV/c^2

Z’ to invisible

- **g’ upper limit**



- **First results ever** for the *Z’ to invisible decay*
- Measurement to be **published soon.**

List of systematic uncertainties

Tracking 4%
Trigger 4%
LeptonID 4%
Luminosity 1.5%
Analysis selections(background) 22%
muon yields(signal) 12.5%
muon yields(background) 2%

*If DM is kinematically accessible, it can be assumed *BR(Z’→ inv)~1*

LFV Z’

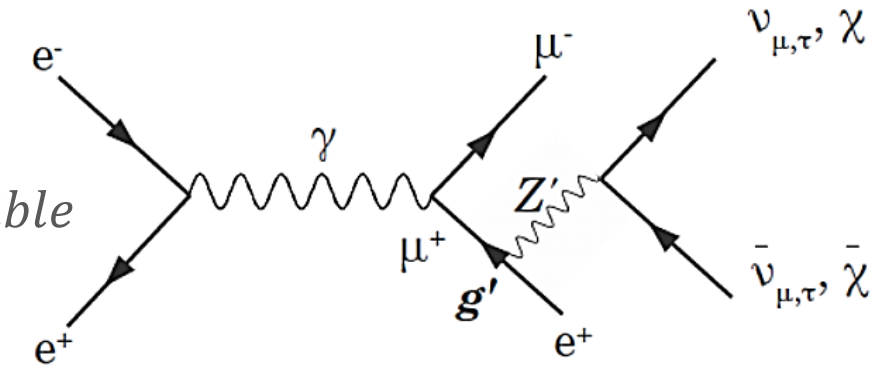
➢ **ε·σ upper limit**

For example I. Galon et al. (2016), arXiv:1610.08060

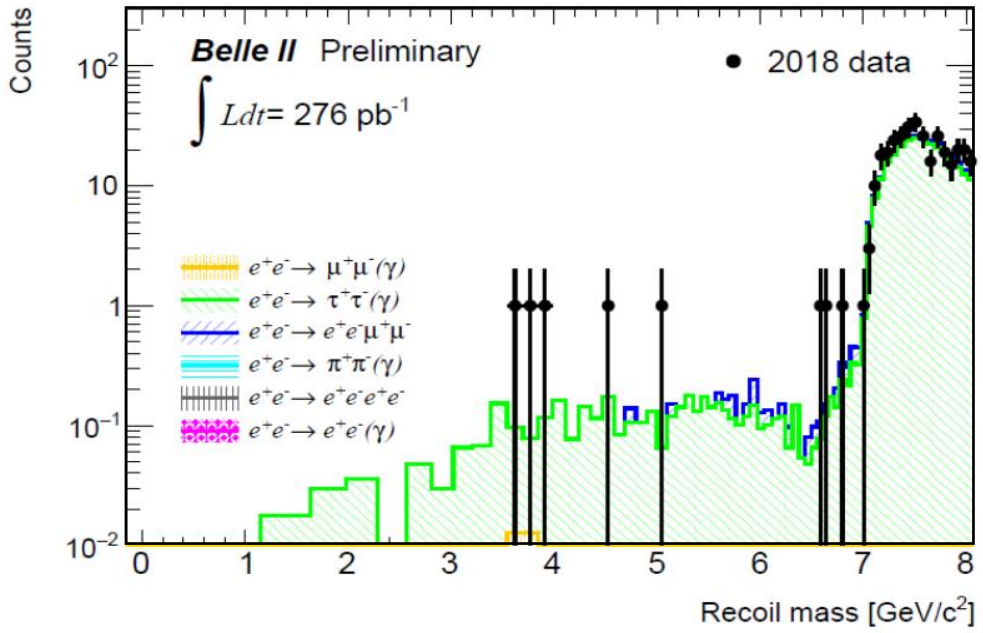
- Searching for a **Lepton Flavour Violating Z’** that couples to **eμ**:

$$e^+e^- \to e^+\mu^- Z'; Z' \to invisible$$

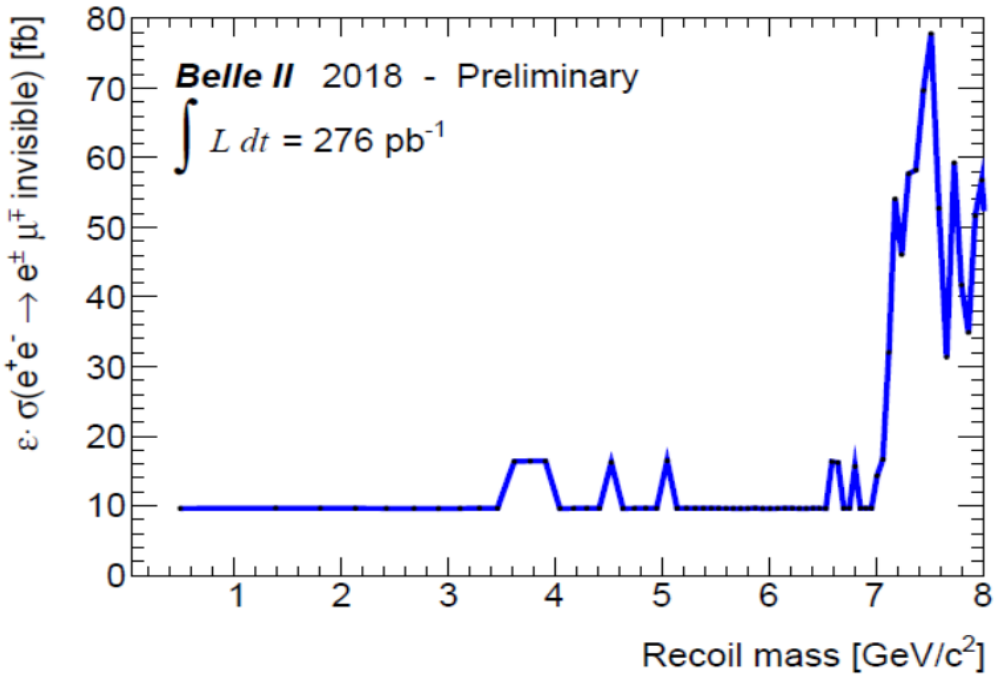
- Model independent search;
- Same analysis selection criteria of the *Z’ to invisible* search.



Recoil mass spectrum after selection



90% CL upper limits to ε·σ

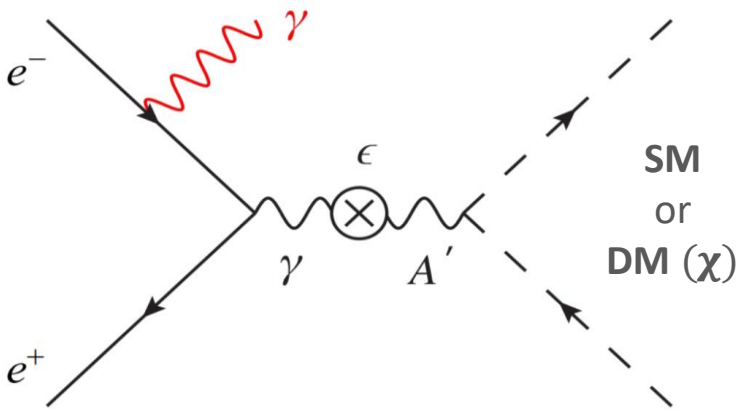


Dark Photon to invisible

➢ **Theory**

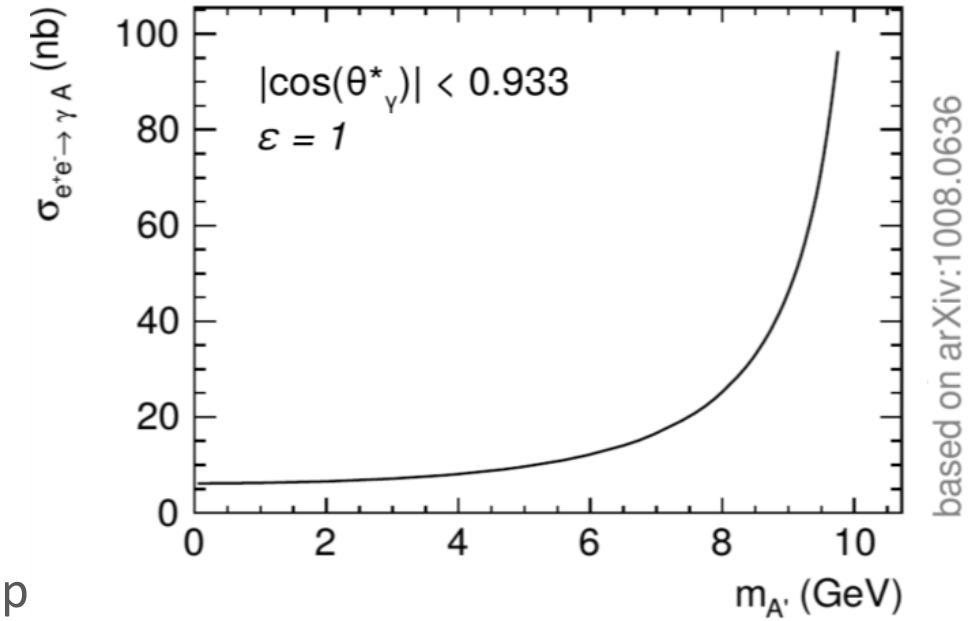
P. Fayet, Phys. Lett. B **95**, 285 (1980),
P. Fayet, Nucl. Phys. B **187**, 184 (1981).

- A possible extension of the SM includes a new massive gauge boson *A'* of spin = 1 coupling to the SM through the kinetic mixing with strength ε, called ***dark photon***.
- At e^+e^- colliders: $e^+e^- \rightarrow \gamma_{ISR}\, A'$



$$\mathcal{L} \supset \epsilon g_D A'_\mu J^\mu_{\mathrm{EM}}$$

Production cross section

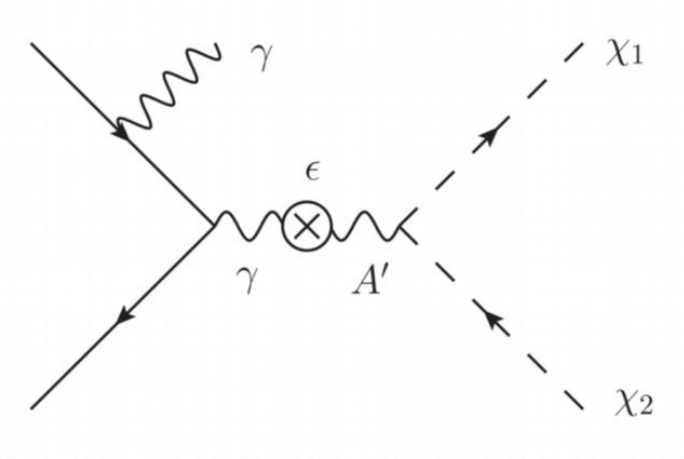


- Two basic scenarios depending on A' vs DM masses relationship
  - $m_x > \frac{1}{2} m_{A'} \rightarrow$ A' **visible decays** to SM particles;
  - $m_x < \frac{1}{2} m_{A'} \rightarrow$ A' **invisible decays to LDM**;

➢ exploring the invisible decay:
$e^+e^- \rightarrow \gamma_{ISR} A' \rightarrow \gamma_{ISR}\, \chi\bar{\chi}$

Dark Photon to invisible

➢ **Analysis strategy**



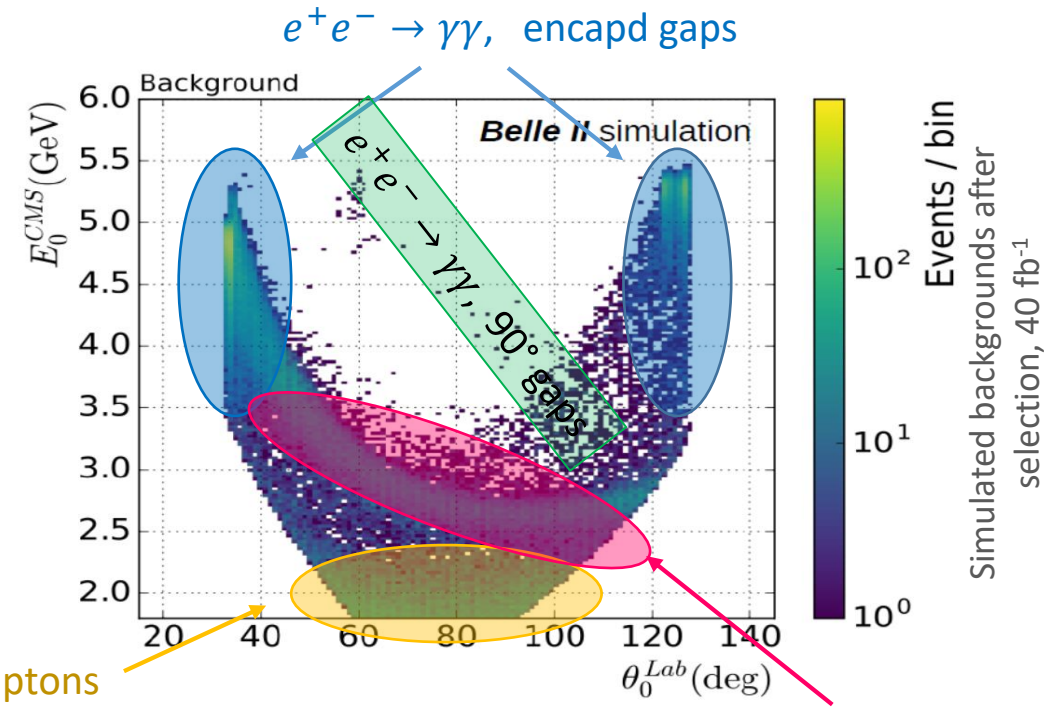
- Signal Signature:
  - **Only one mono-chromatic, high-E photon γ_{ISR}** in the detector.
  - No tracks, no other good photons.
  - Bump in the photon energy: $E_\gamma = \frac{s - M_{A'}^2}{2\sqrt{s}}$ (*on−shell*)

- Discriminant variables: E_{CMS} vs. polar angle of "single photon"

- Needs a special **single photon trigger**

  (not available in Belle, ≈ 10% of data in BaBar)

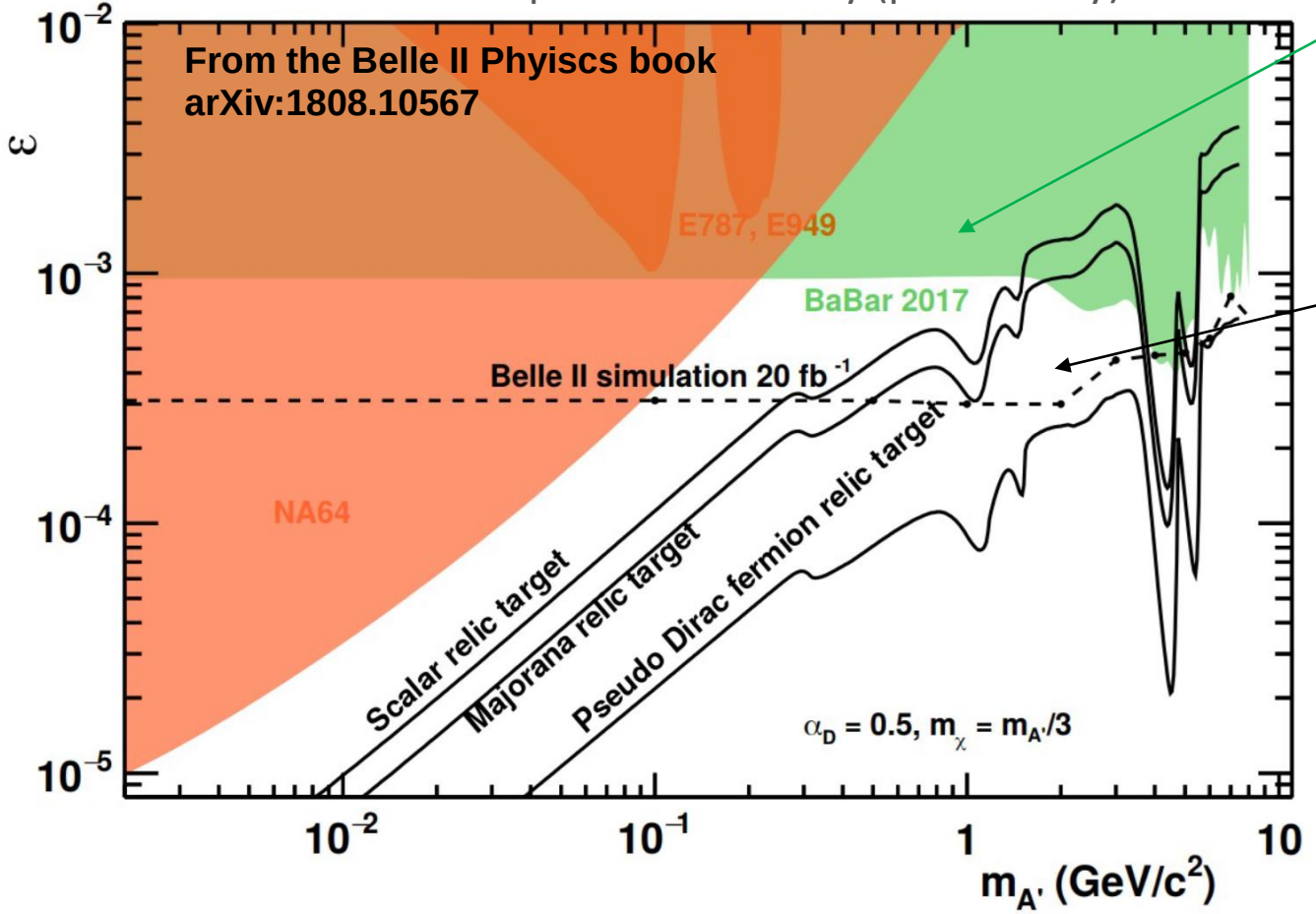
- SM backgrounds:
  - $ee \to \gamma\gamma(\gamma)$
  - $ee \to ee(\gamma)$
  - Cosmics not negligible



Dark Photon to invisible

- **Sensitivity**

Belle II expected sensitivity (preliminary)



BaBar limit, 50 fb-1
Phys. Rev. Lett. 119, 131804 (2017)

Belle II projection, 20 fb-1
KEK-2018-27, arXiv: 1808.10567

Why Belle II is expected to perform better than BaBar?

- **no ECL cracks** pointing to the interaction regions
- Smaller boost and larger calorimeter ⇒ **larger acceptance**

*If astronomical dark matter is due to the dark sector, parameters will lie along one of these lines.
Derived from E. Izaguirre, G. Krnjaic, P. Schuster, N. Toro, Phys. Rev. Lett. 115, 251301 (2015)

Axion Like Particles

JHEP 1712 (2017) 094 arXiv:1709.00009

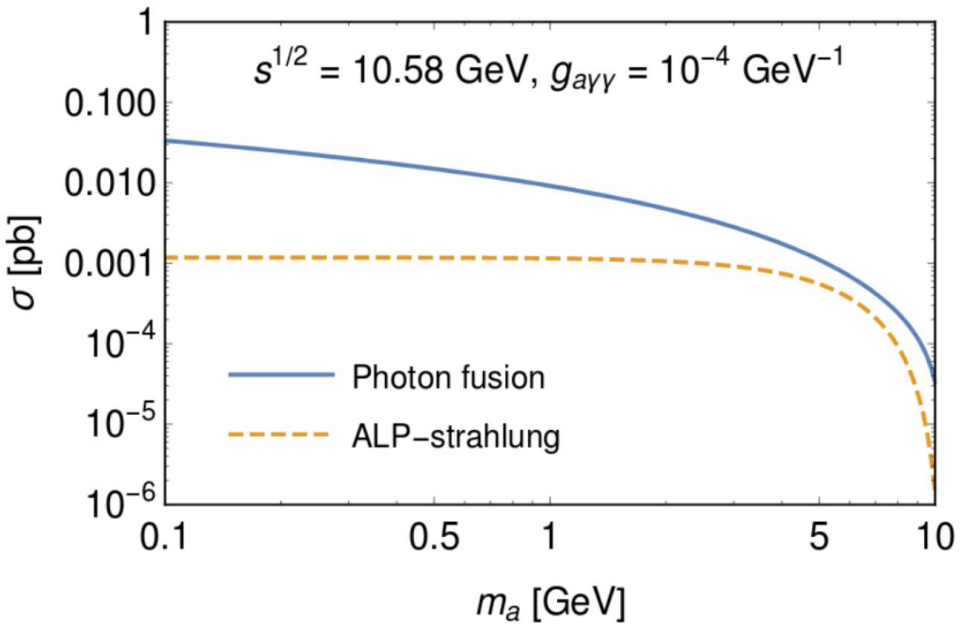
➢ **Theory**

- ***ALPs*** are pseudo-scalars particles (a) that couple to bosons.
- No strict relationship between coupling and mass.
- Focus on coupling to photons:

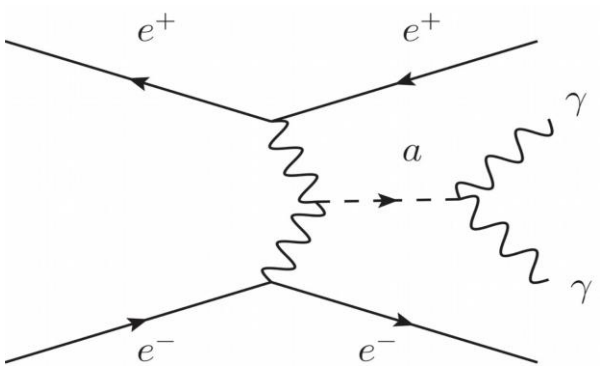
$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

- Two possible production processes:
  - *Photon fusion*
  - *ALP-strahlung*

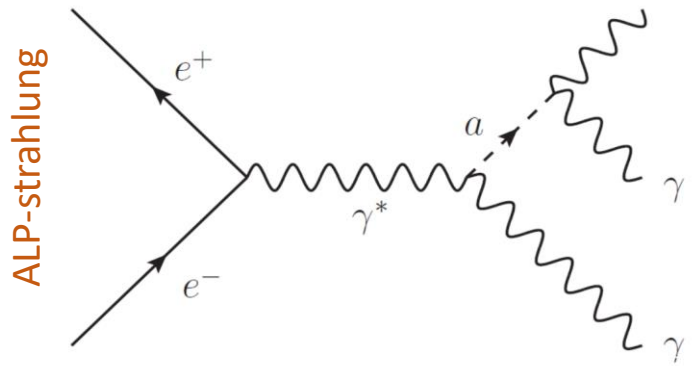
Production cross section



Photon fusion



ALP-strahlung



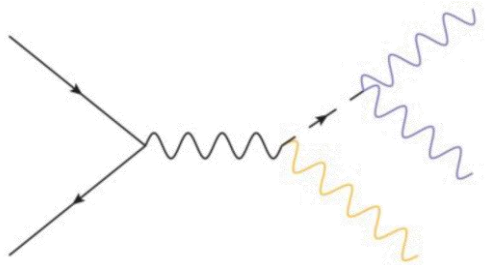
Sensitivity under study

➢ No results at B-factories yet

➢ exploring photon coupling $g_{a\gamma\gamma}$ in ***ALP-strahlung***

Axion Like Particles

➢ **Experimental Signature**



- Several topologies depending on (m_a, $g_{a\gamma\gamma}$) parameters;

$$\tau \sim 1/g_{a\gamma\gamma}^2 M_a^2$$

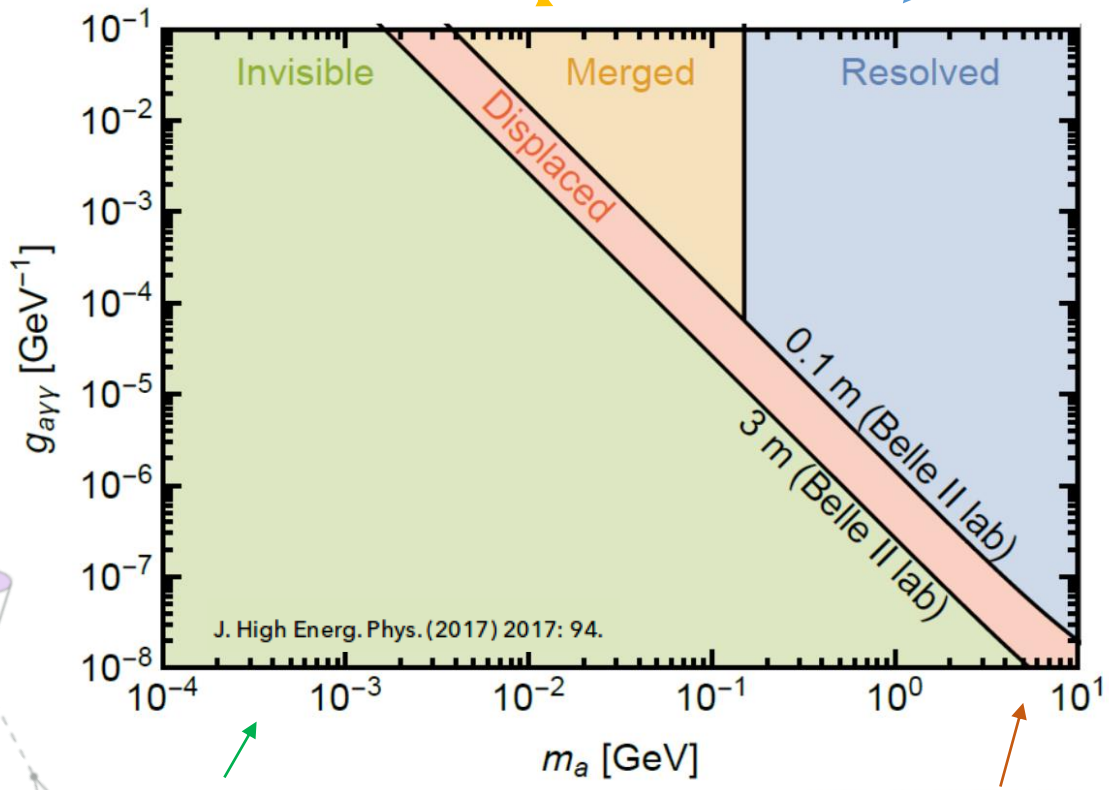
- ALPs can also decay to **DM**;

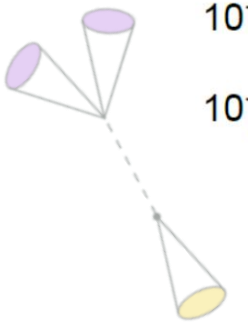
- Final state:
  - 3γ that add up to the beam energy;
  - Zero tracks;
  - **bump on di-photon mass**;

- Background from SM is large and partially peaking:
  - $e^+e^- \rightarrow \gamma\gamma(\gamma)$;
  - $e^+e^- \rightarrow e^+e^-(\gamma)$;
  - $e^+e^- \rightarrow P\,\gamma(\gamma),\ P = \pi^0, \eta, \eta'$;

Two of the photons overlap or **merge**.

Three **resolved**, high energetic photons.





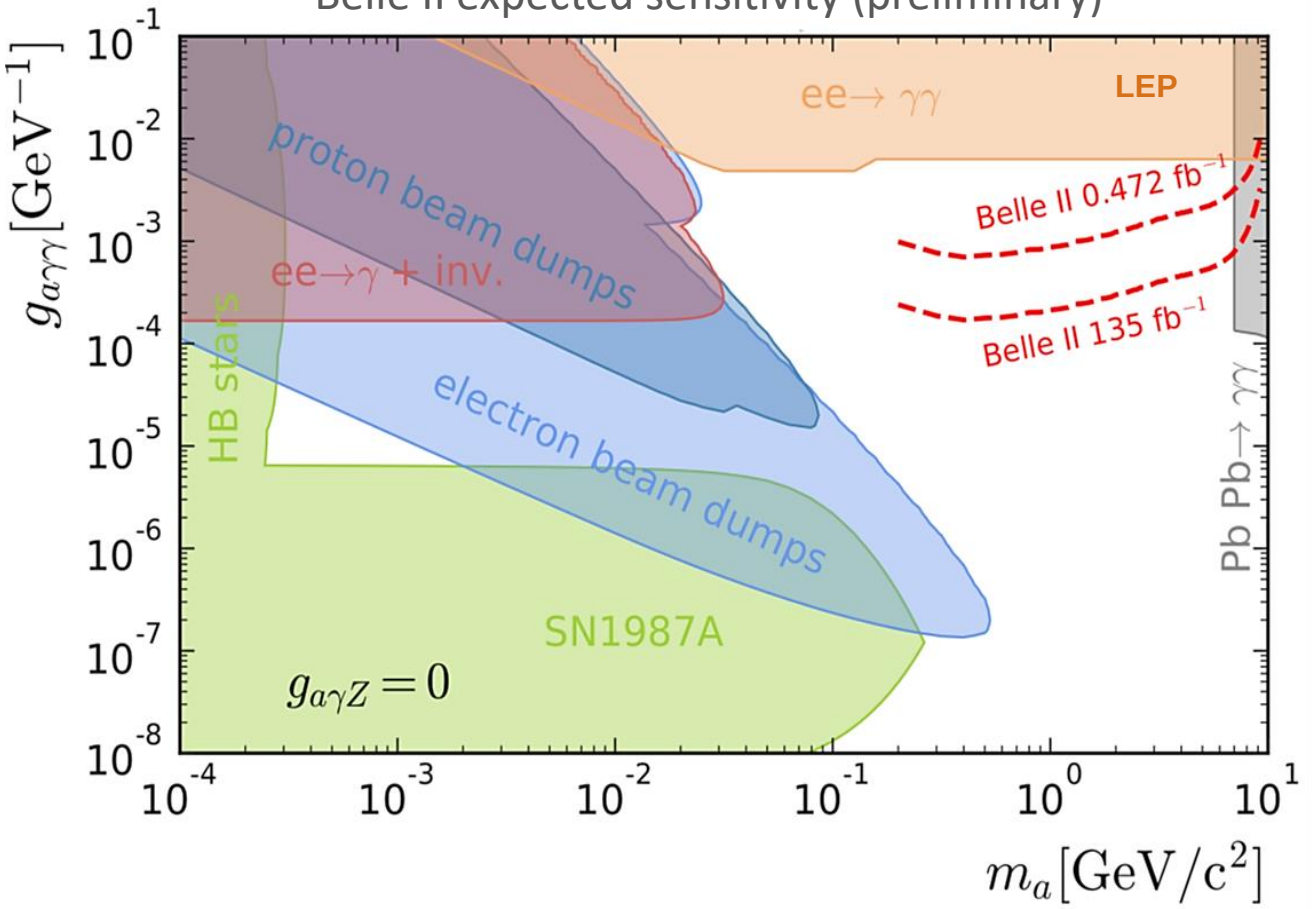
ALP decays outside of the detector or decays into **invisible** particles: Single photon final state

The searches for invisible and visible ALP decays veto this region.

Axion Like Particles

- **Sensitivity**

Belle II expected sensitivity (preliminary)*



- ***Belle II*** can be competitive with Phase2 dataset (500pb^{-1}).
- Goal: measurement with Phase 2 data to be **published soon**

*No systematics.
Only (dominant) ee→γγγ background included
135fb^{-1} assumes no γγ trigger veto in the barrel

Conclusions

- Discovering dark matter is today one of the biggest and interesting challenges we are facing.
- Although designed mainly for B-physics, the ***Belle II experiment*** has a broad and active program to explore the ***Dark Sector Physics***;
- It started operations in 2018 (Phase 2). Successful commissioning of the machine and 0.5fb^{-1} of data collected;
- Phase 3 started physics data taking on March 2019. Up to now 6.5fb^{-1} collected.
- First results for the ***Z' to invisible*** search, and many other searches ongoing (***A', ALPs***) with good prospects even with early data.
- Possibility to explore many more dark sector models;

For further details see *The Belle II Physics Book*, arXiv:1808.10567

Stay tuned…. More results are to be released soon!

Contact:

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marcello.campajola@na.infn.it

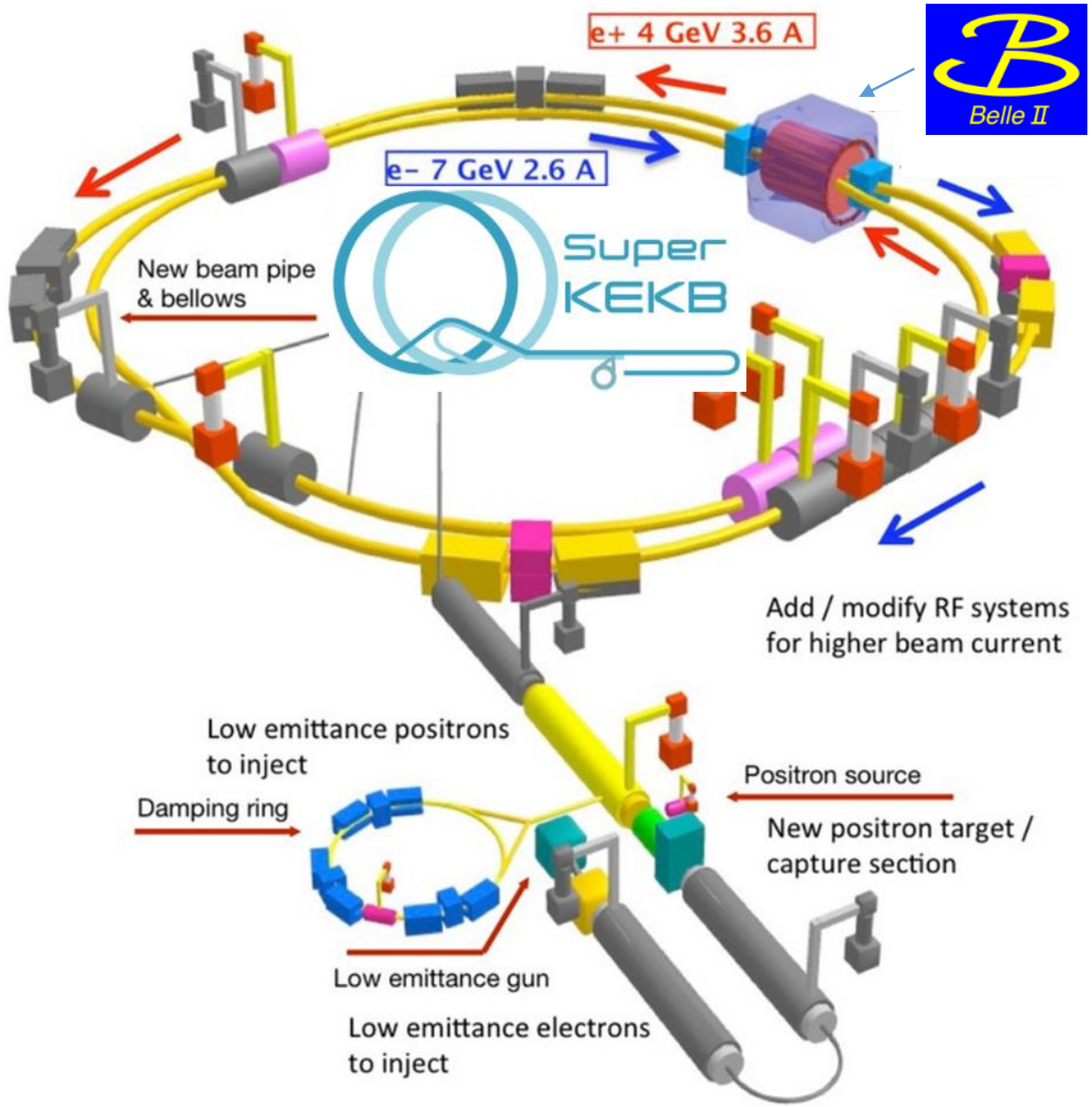
SuperKEKB

➢ **an 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** (*Y(4S)*)
- World highest luminosity**,** applying the *large crossing angle nano-beam scheme.*

(P.Raimondi for SuperB, M. Bona et al., arXiv:0709.0451)

- A factor **40** increase wrt KEKB in instantaneous luminosity: $L = 8 \cdot 10^{35}\ cm^{-2}\ s^{-1}$
  - ×2: from higher beam current
  - ×20: reduce β* from final focus magnets



SuperKEKB

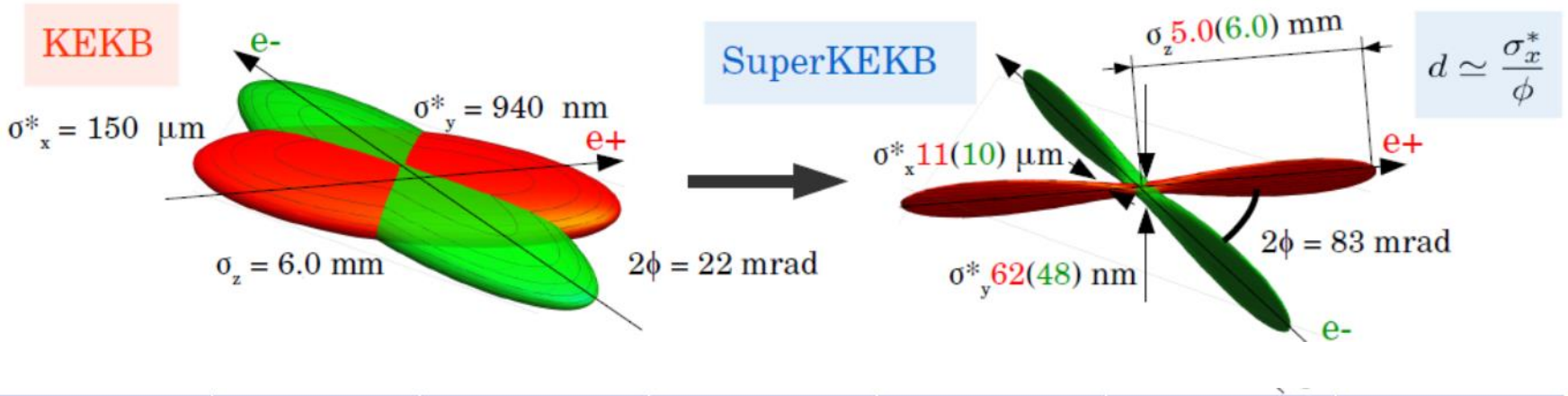
- **Nano-beam scheme**

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

currents; beam-beam parameter; geometrical reduction parameter ~0.8-1

Ratio between the y and x dimension of the beam 0.01 – 0.02

vertical beta function at IP

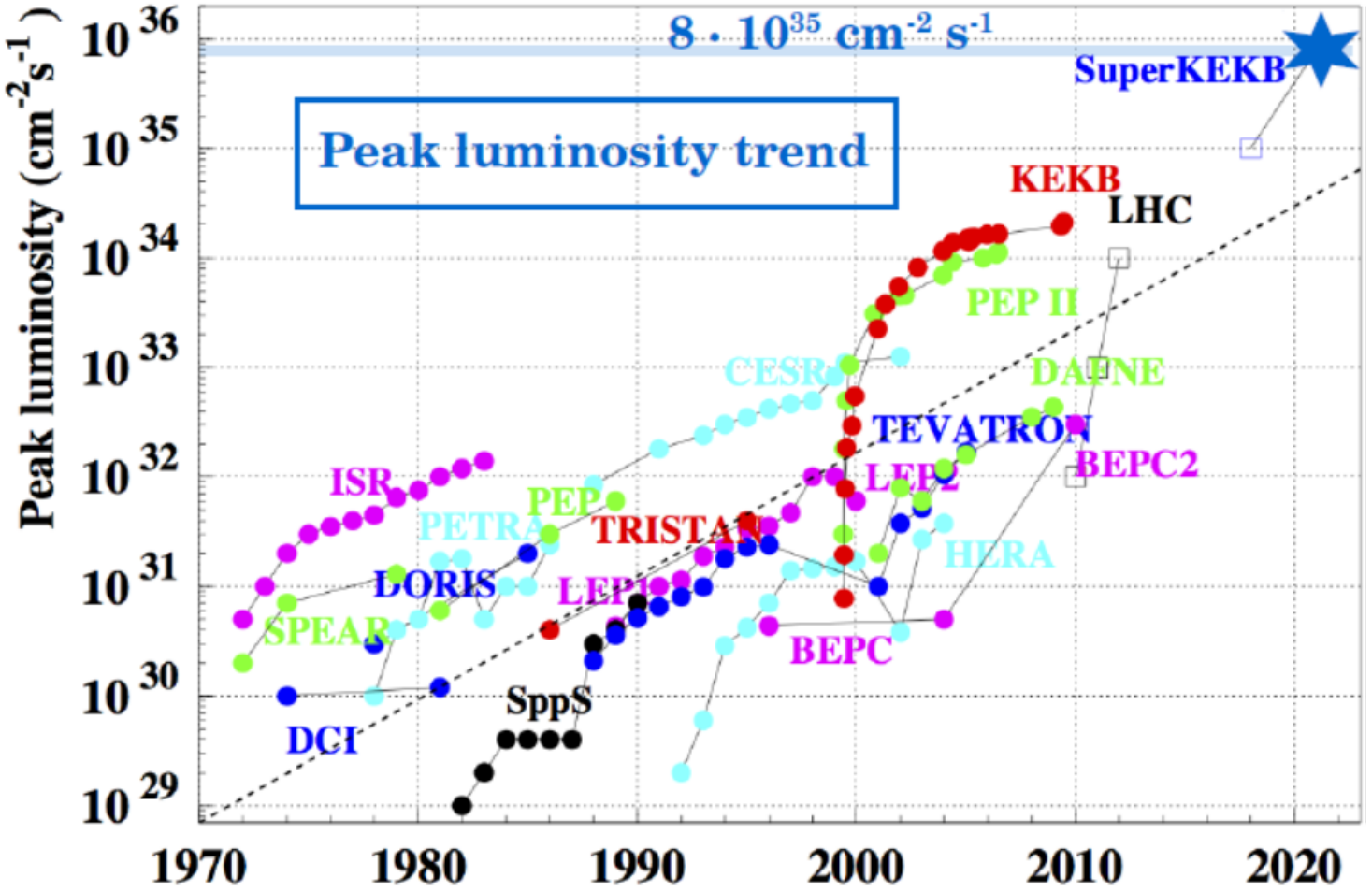


	E (GeV) LER/HER	β*y (mm) LER/HER	β*x (cm) LER/HER	ϕ (mrad)	I(A) LER/HER	L(cm⁻²s⁻¹)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	$2.1 \cdot 10^{34}$
SuperKEKB	4.0/7.0	0.27/0.30 x1/20	3.2/2.5	41.5	3.6/2.6 x2	$80 \cdot 10^{34}$ x40

SuperKEKB

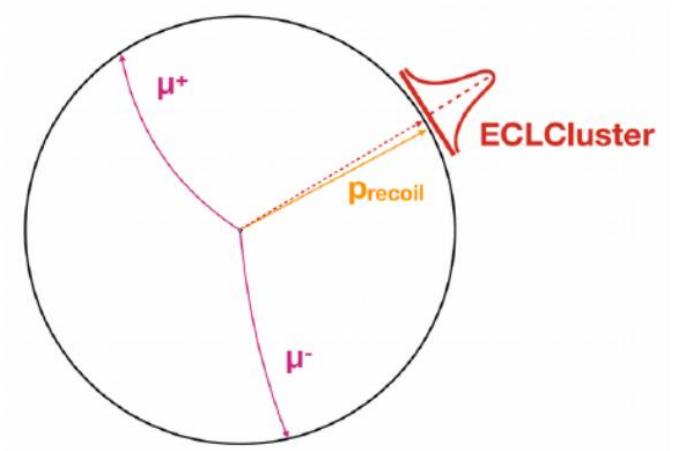
➢ an Intensity Frontier machine

- **Flavor physics and SM Test:**
  - CKM parameters
  - CPV in *B* decays
  - $B/D/\tau$ physics
- **BSM physics:**
  - rare or suppressed or forbidden processes in the SM
- **Search for:**
  - new light particles
  - light Dark Sector

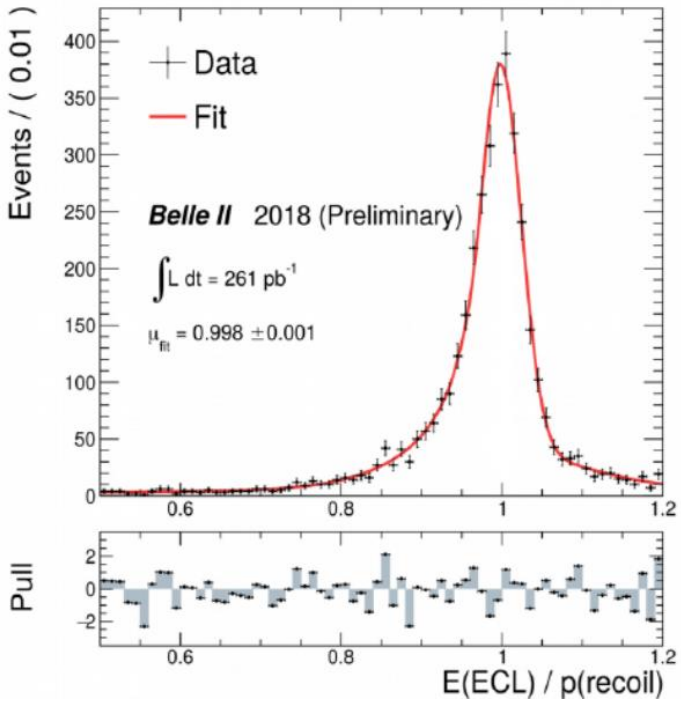


Highlights from Phase2

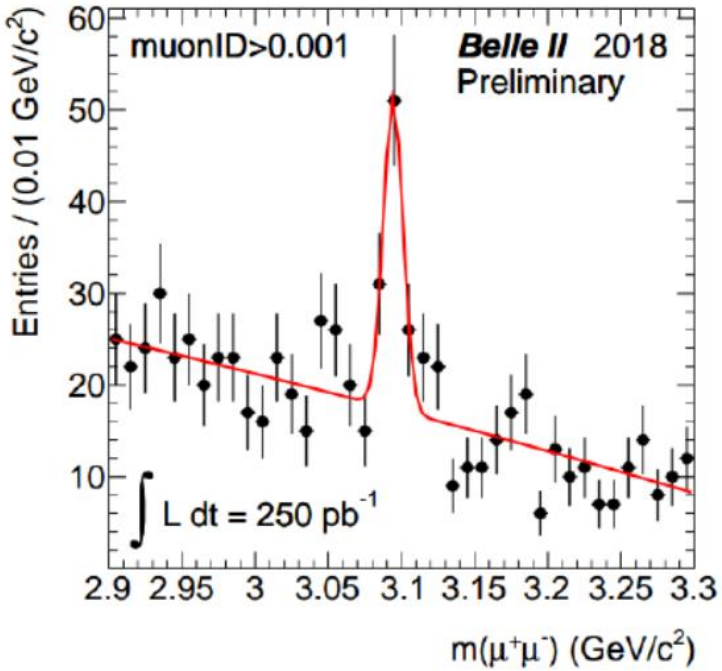
- **Belle II performances**



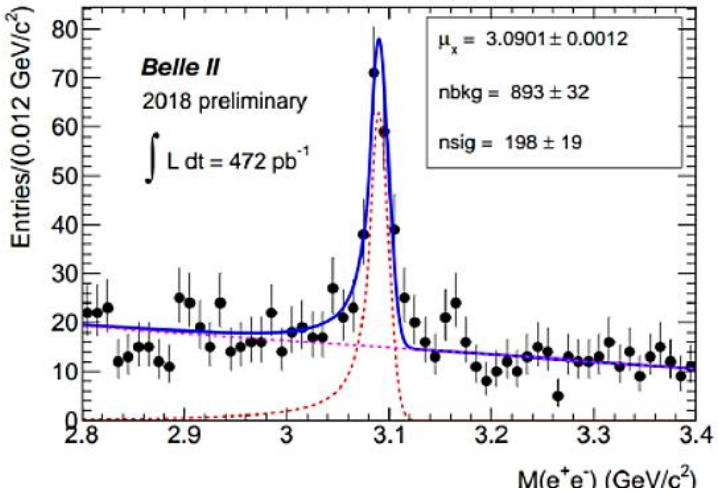
$e^+e^- \to \mu^+\mu^-\gamma$



$J/\Psi \to \mu^+\mu^-\gamma$



$J/\Psi \to e^+e^-\gamma$



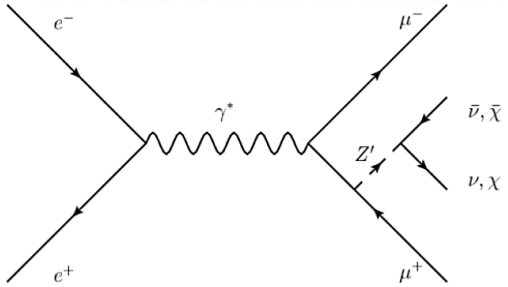
Others Dark Sector searches

- Visible dark photon decays
- Off-shell dark photon decays
- Muonic dark force: $e^+e^- \rightarrow \mu^+\mu^- Z',\ Z' \rightarrow \mu^+\mu^-$
- Dark scalar: $e^+e^- \rightarrow \tau^+\tau^- S,\ S \rightarrow l^+l^-$
- Magnetic monopoles with small magnetic charges
- Invisible Y(1S) decays via Y(3S) → Y(1S)$\pi^+\pi^-$
- Dark Higgs/Higgstrahlung

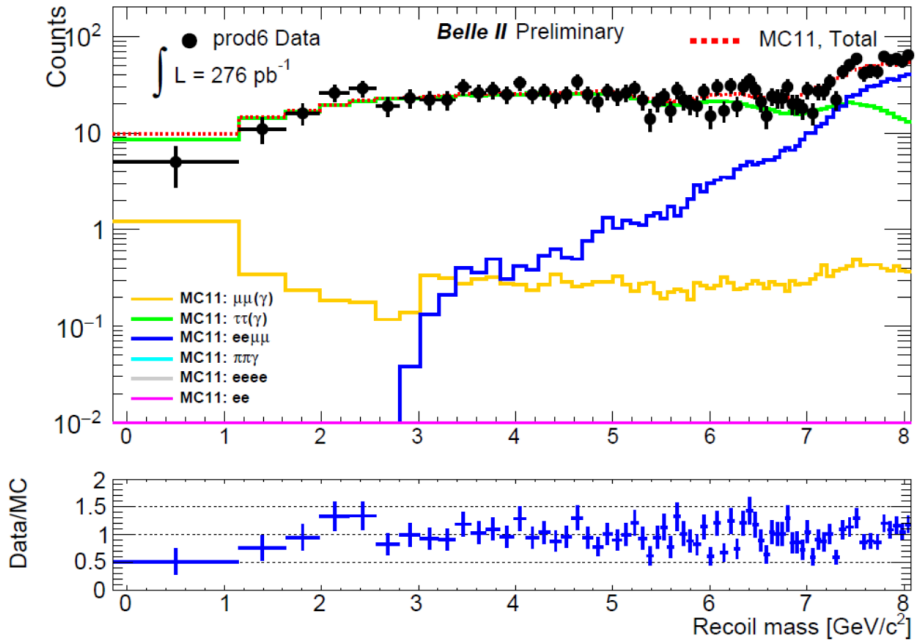
For further details see *The Belle II Physics Book*, arXiv:1808.10567

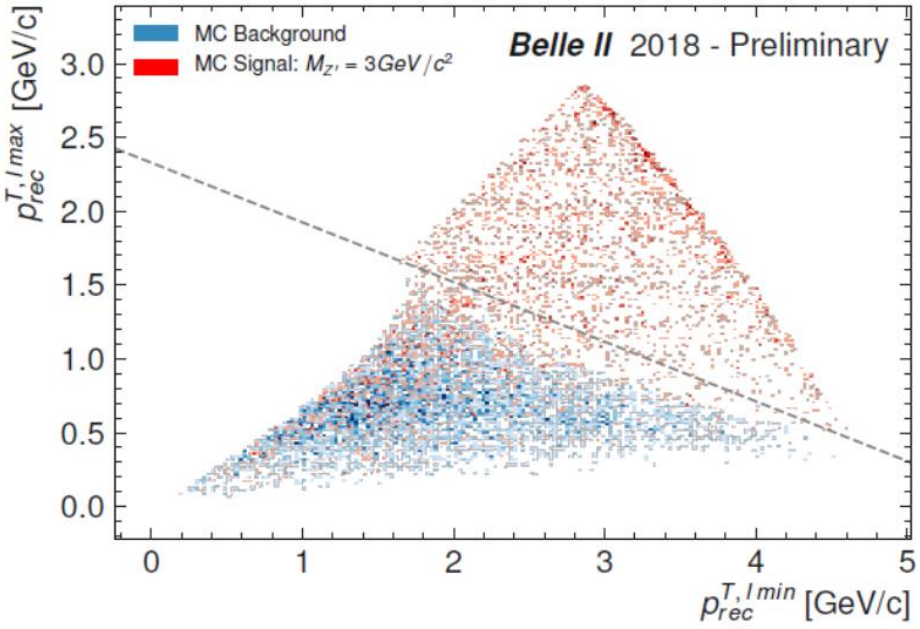
Z' to invisible

➢ **Analysis strategy**



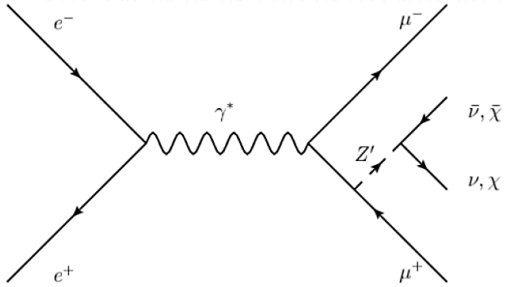
- Signal signature:
  - Two opposite-charged muon tracks;
  - Bump in the recoil mass against $\mu\mu$ *pair*;
- Further requirements:
  - 'Nothing' in the rest of events;
  - p_{rec} to point into the calorimeter barrel.
- Reduce $\tau^+\tau^-$ background with kinematic cuts on transverse momenta of Z'(missing momentum) wrt max and min momentum muons;



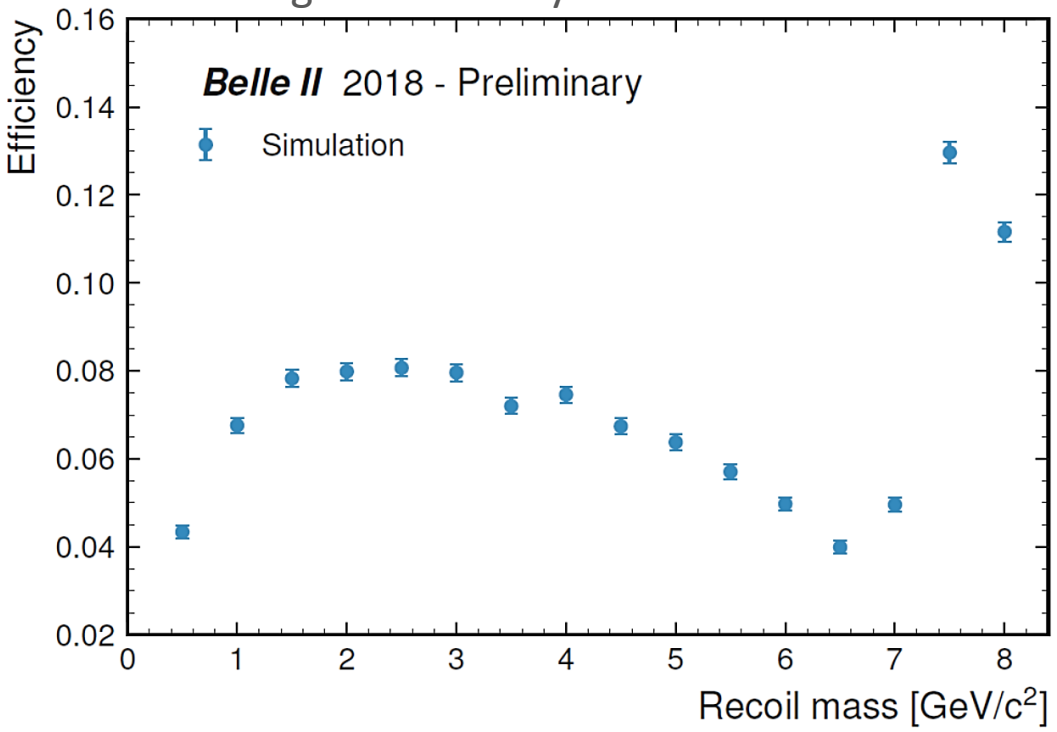


Z' to invisible

- **Analysis strategy**



Signal efficiency after selection



Recoil mass spectrum after selection