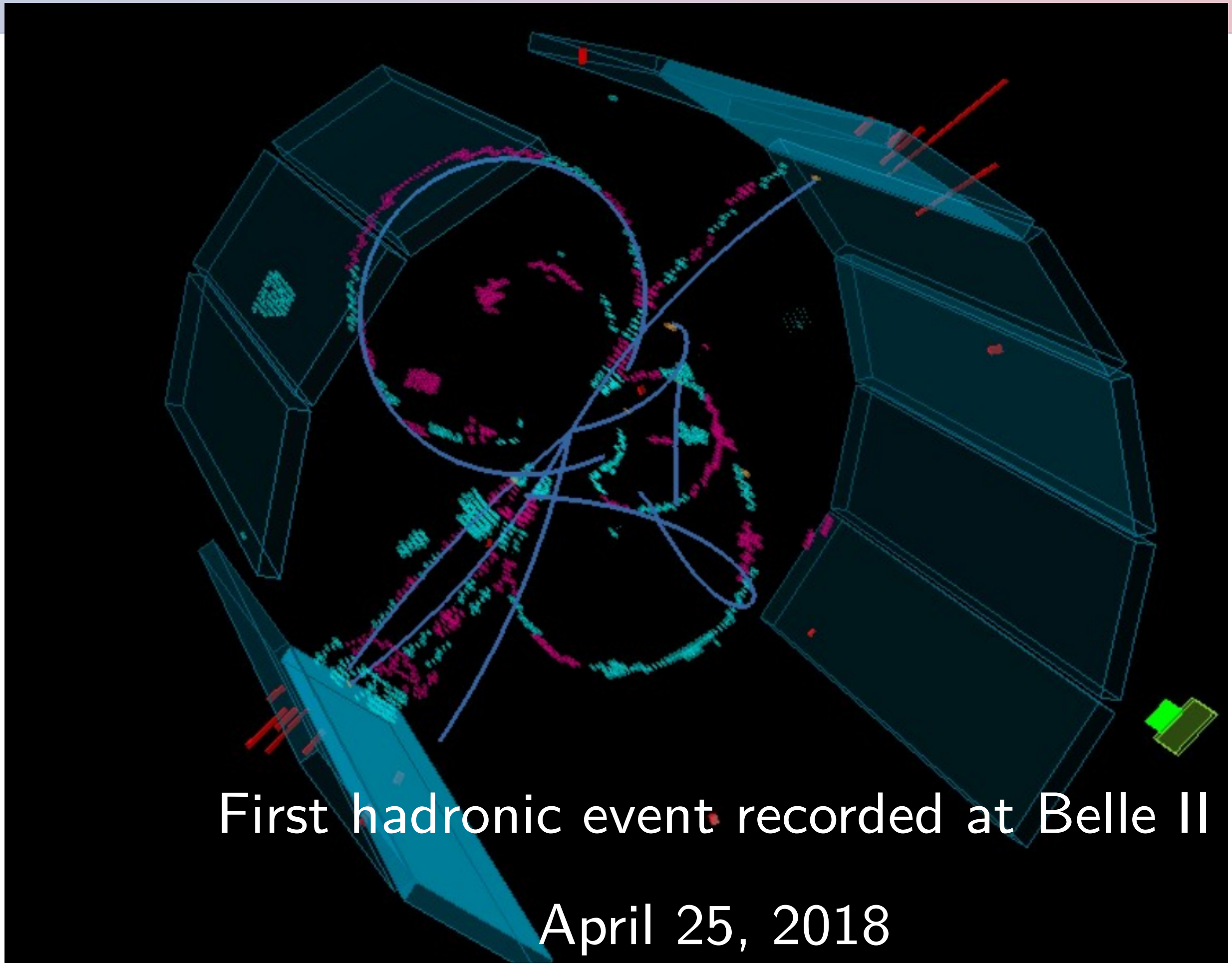
Search for invisible decays of the Dark Photon at Belle II



First hadronic event recorded at Belle II

April 25, 2018

Thesis project discussion for the Doctoral School in Physics

Laura Zani

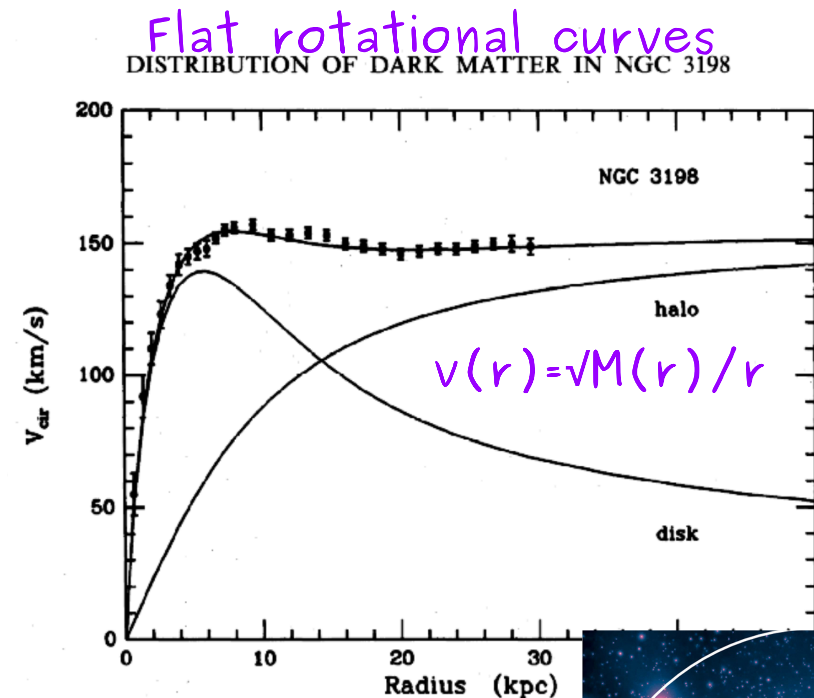
Pisa, 10/10/2018

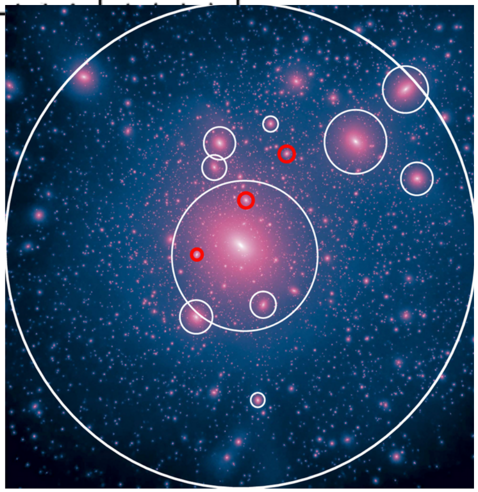
Outline

- Motivation for Dark Matter Searches
- Belle II experiment at SuperKEKB collider
- Analysis Strategy and Preliminary Results
- Summary & Outlook

Dark Matter

- Many astrophysical observations provide evidence for the existence of a kind of matter that does not interact with the SM (mostly just gravitational interaction) → ***dark matter***
- *Known* properties of this dark matter:
  - **Massive** → it interacts gravitationally
  - **Highly stable** → evidence for different presences at early stages of Universe formation
  - **Almost neutral under the SM** → not interacting strongly (limit from *Big Bang Nucleosynthesis*) nor electromagnetically (being "*dark*")
  - $\mathbf{v_{DM}}$ **(∼ 240 km/s)<< c** → crucial for observation of large structures



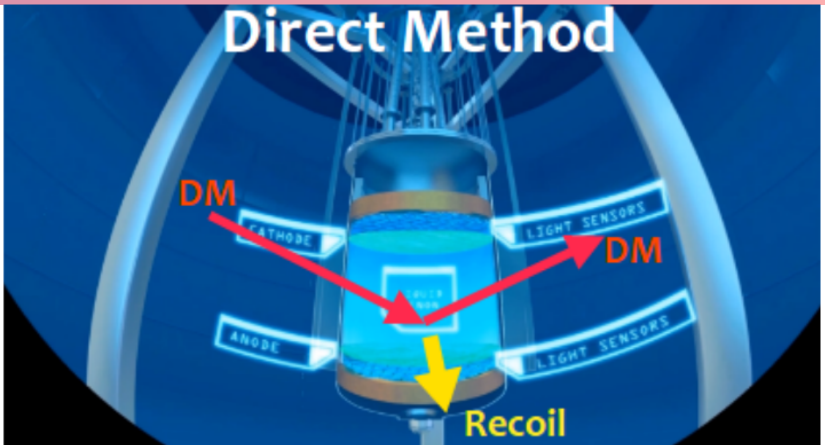


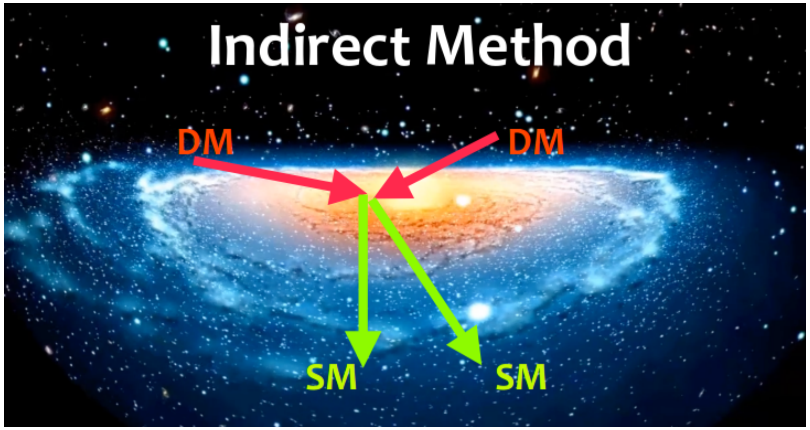
A Milky-Way-size dark-matter halo and its subhalos (circled), produced in simulations [Caterpillar Project, Griffen et al. 2016], AAS.

No such a kind of matter predicted by the SM → we have to look for New Physics and possibly a new type of particle as Dark Matter (DM) candidate.

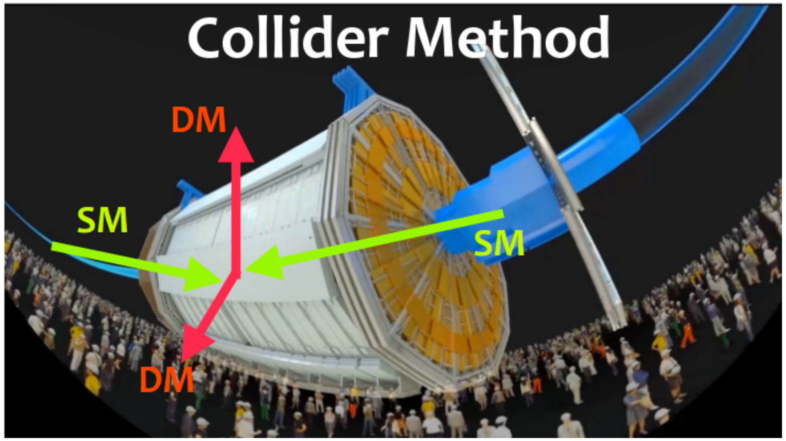
Dark Matter Searches

- Different *detection methods* are possible:
  - Detect the energy of *nuclear recoil* due to collision with DM particle from galactic halo in underground experiments → *direct detection*





  - Detect the *flux of visible particles* (electrons, positrons, protons, antiprotons, photons) produced by *DM annihilation* and decay (telescopes observations, satellite experiments)→ *indirect detection*
  - DM weakly couples to SM particles and therefore can be produced in *SM-particles annihilation* at colliders: several *signatures*, involving possible Dark Sector (DS) mediators→ *collider search*



→ In this presentation I will focus on the search at electron-positron colliders: Belle II experiment

B-Factories: the high intensity frontier

B-factories: dedicated experiments at *e^+e^- asymmetric-energy colliders* for the production of quantum coherent $B\bar{B}$ pairs → **CP Violation studies**.

$$e^+e^- \rightarrow \Upsilon(4S)\ [10.58\ \text{GeV}] \rightarrow B\bar{B}$$

First generation of B-factories

BELLE at the KEKB collider, (KEK, Japan)

BABAR at the PEP II collider (SLAC, California)

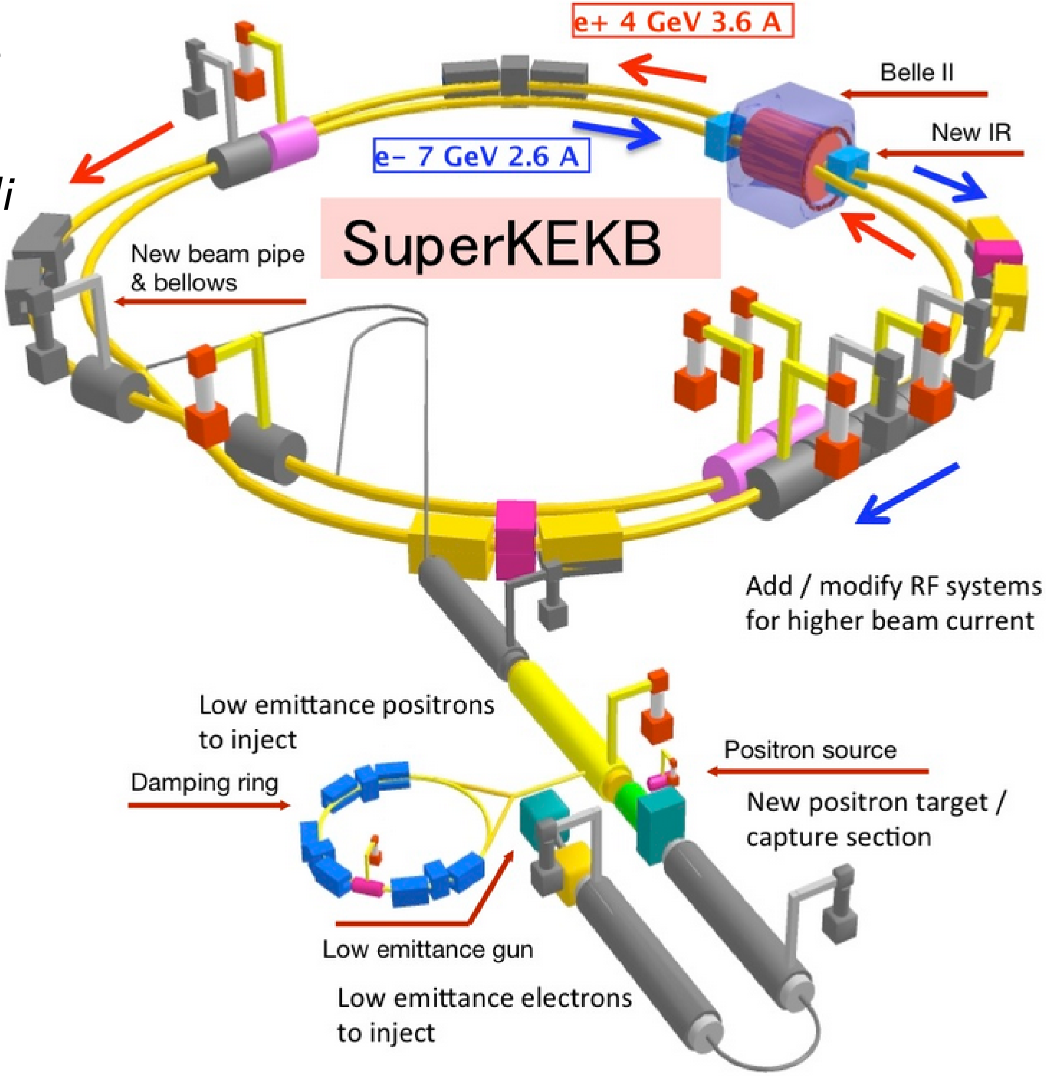
Belle II → x50 the data set of its predecessor!

Rich Physics Program

- SM test, precision flavor physics
- Rare/suppressed/forbidden processes
- Search for new light particle states
- *light DARK SECTOR*

SuperKEKB

- Second generation B-Factory, it will provide **the world highest luminosity,** applying the *large crossing angle nano-beams scheme. (P.Raimondi for SuperB)*



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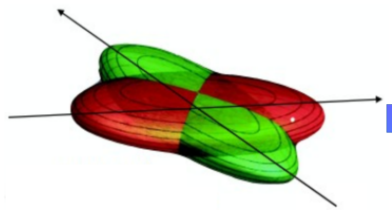
KEKB



I (A): ~ 1.6/1.2

β^*_y (mm): ~ 5.9/5.9

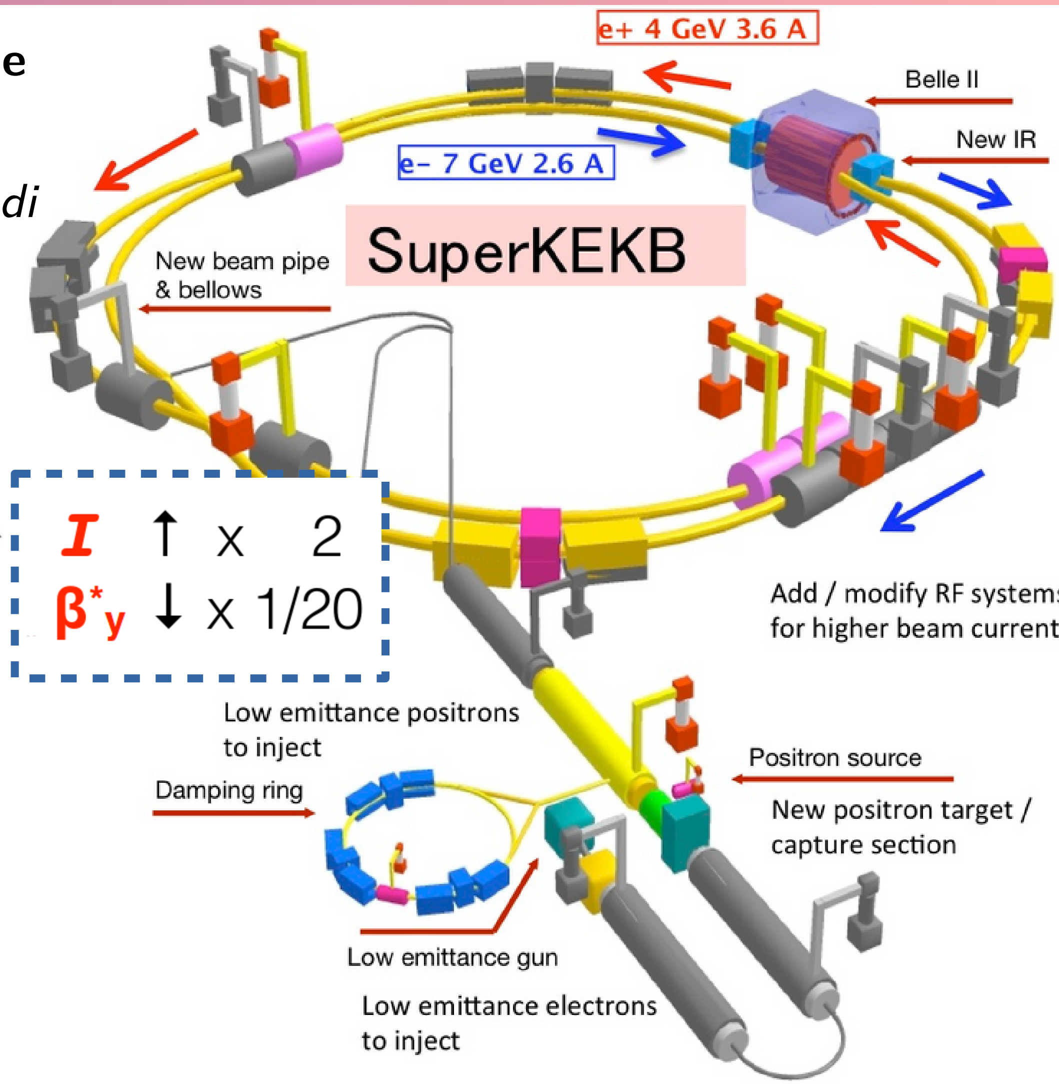
SuperKEKB

I (A): ~ 3.6/2.6

β^*_y (mm): ~ 0.27/0.3

$$L = \frac{\gamma_\pm}{2 e r_e}\left(1 + \frac{\sigma^*_y}{\sigma^*_x}\right)\frac{I_\pm \xi_{y\pm}}{\beta^*_{y\pm}}\left(\frac{R_L}{R_{\xi_y}}\right)$$

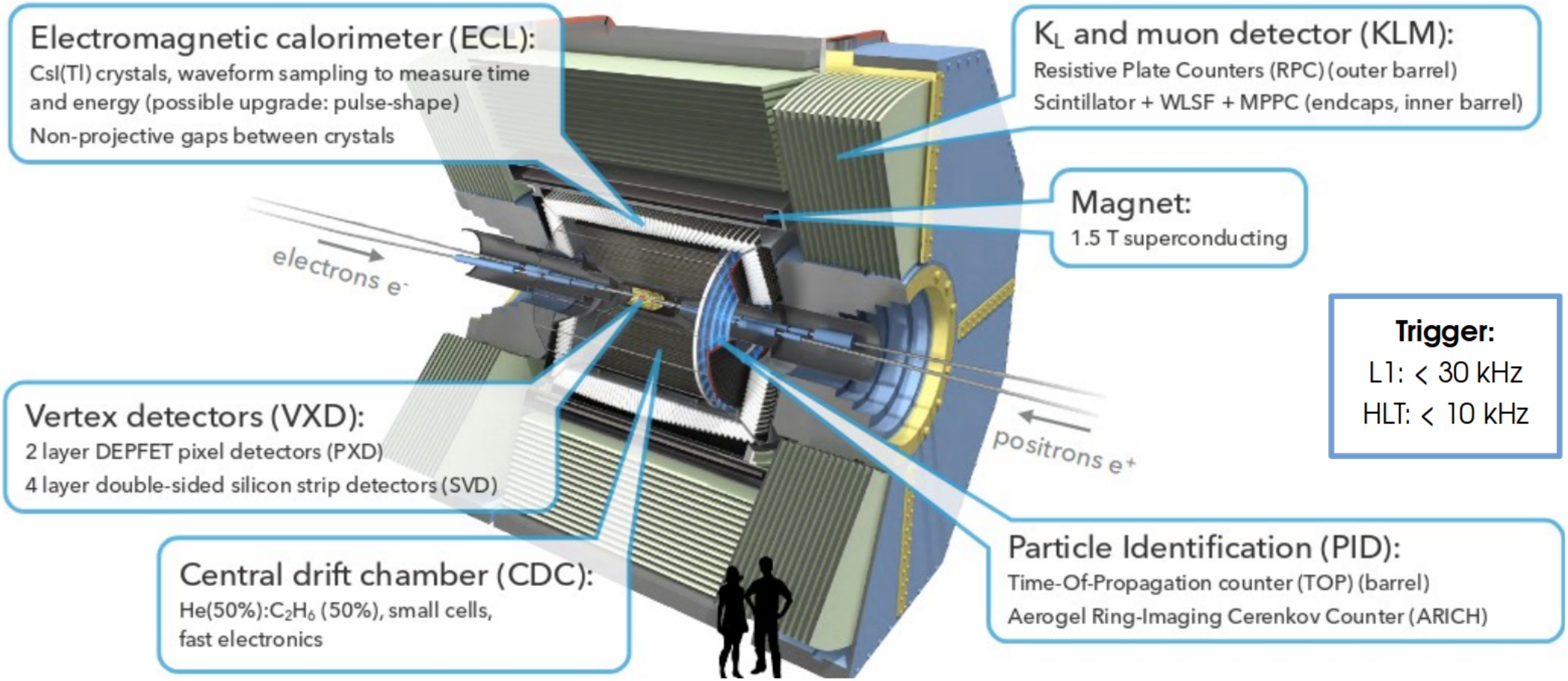
Lorentz factor; beam current; beam-beam parameter; geometrical reduction factors; beam aspect ratio at the IP; vertical beta-function at the IP



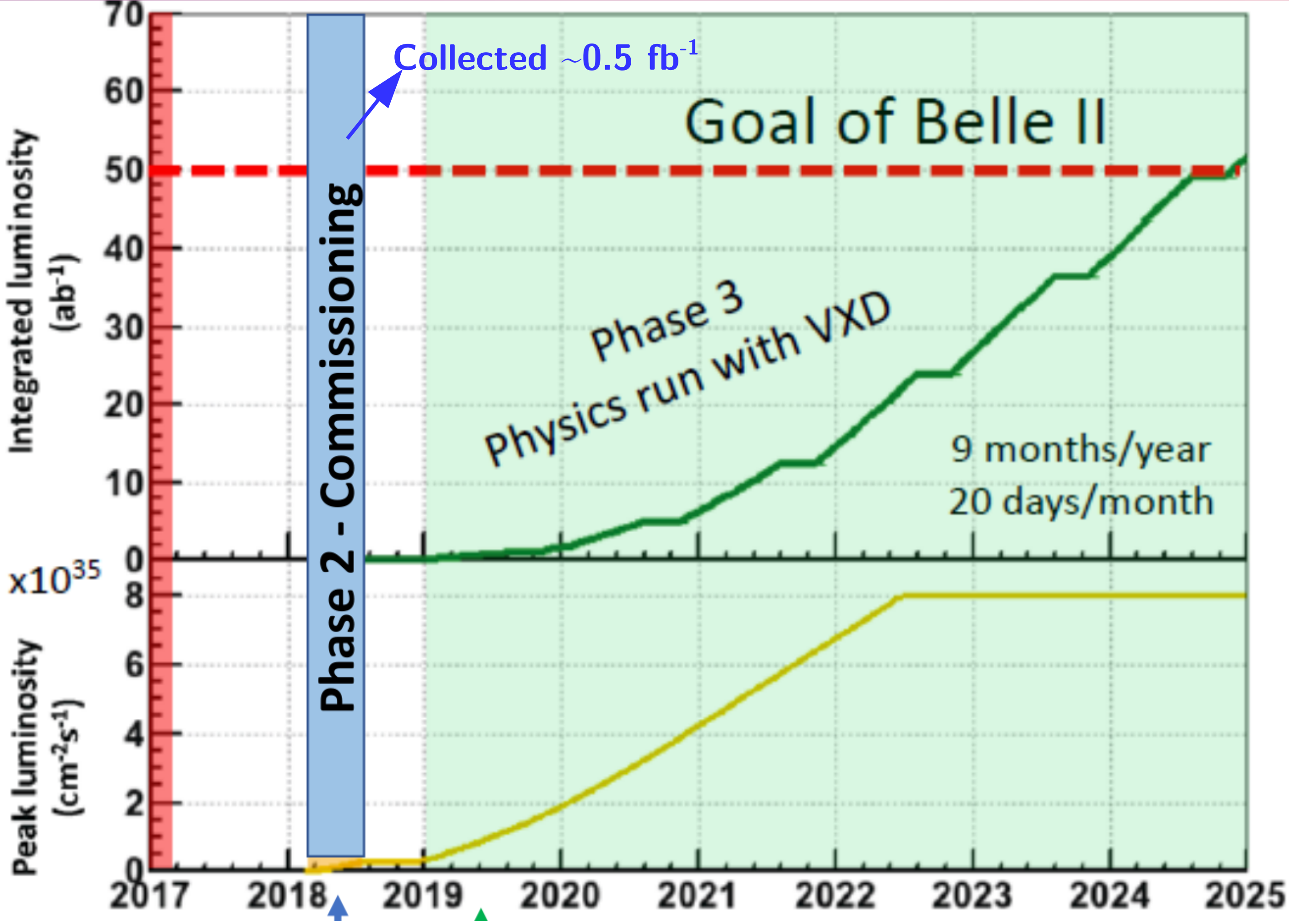
40x KEKB peak luminosity: $\mathcal{L} = 8 \cdot 10^{35}$ cm^{-2} s^{-1}

The Belle II Detector

- The Belle II detector has better resolution, Particle Identification (PID) and capability to cope with higher background



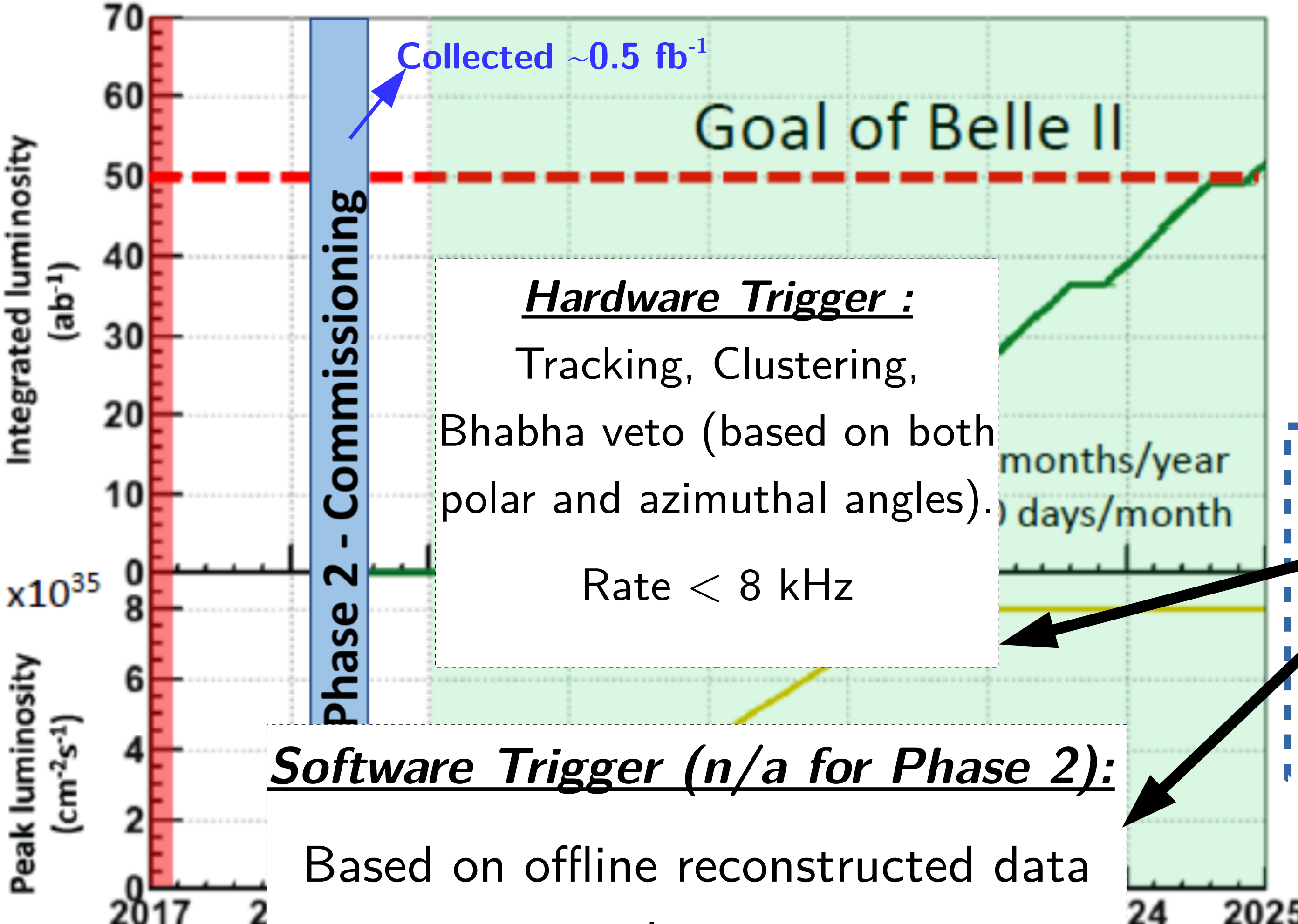
Belle II Data Taking: Phase 2



Phase 2 (April-July 2018): *Commissioning of the machine, detector and software*

- 1/8th VXD
- Lower backgrounds
- Flexible hardware triggers
- Pass-through software trigger

Belle II Data Taking: Phase 2



Hardware Trigger :

Tracking, Clustering, Bhabha veto (based on both polar and azimuthal angles).

Rate < 8 kHz

Software Trigger (n/a for Phase 2):

Based on offline reconstructed data objects

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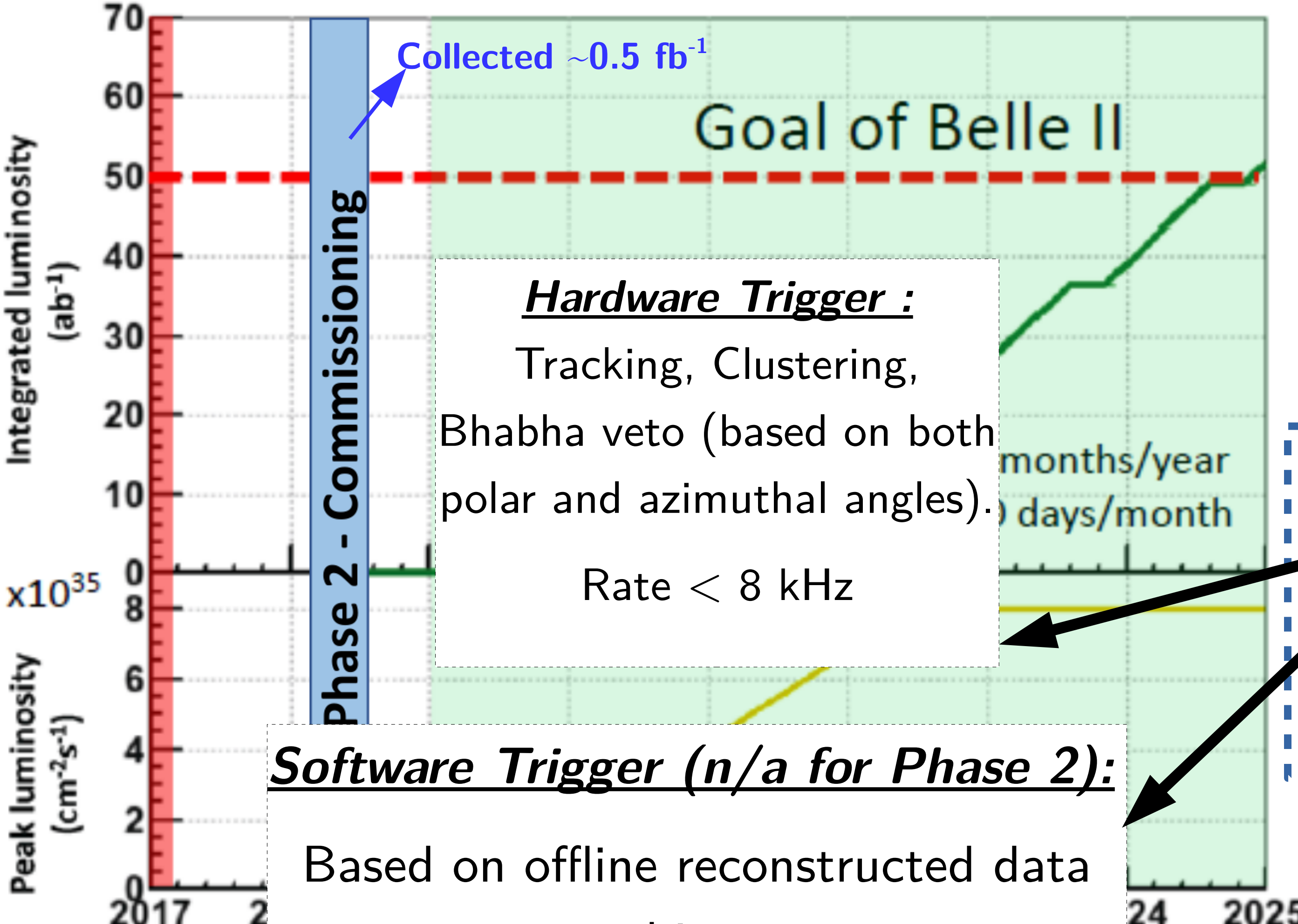
Good conditions for Dark Sector Searches

Belle II Data Taking: Phase 3



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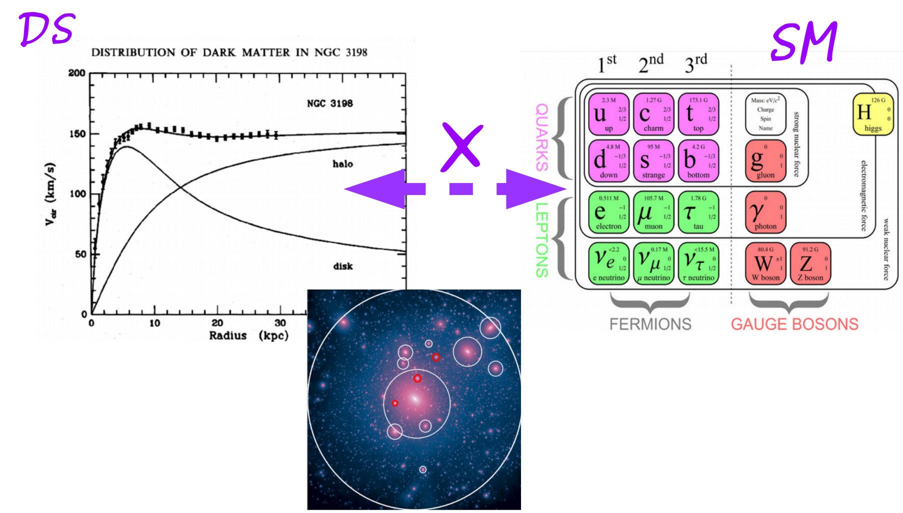
Good conditions for Dark Sector Searches

Phase 3: Run with full detector at peak luminosity, $L = 8 \cdot 10^{35}$ cm^{-2} s^{-1}

GOAL: collect 50 ab^{-1}

Light Dark Sector: Introduction

- Possible sub-GeV scale scenarios foresee the existence of a *light dark sector* weakly coupled to SM through a light ***mediator X:***
  - Vector portal → Dark Photon A'
  - Scalar portal → Dark Higgs/Scalars
  - Pseudo-scalar portal → Axion Like Particles (ALPs)
  - Neutrino portal → Sterile Neutrinos



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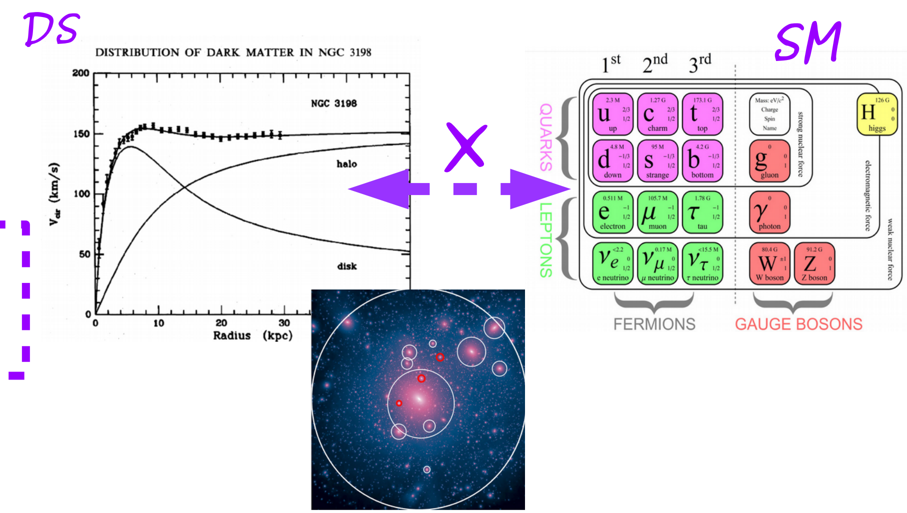
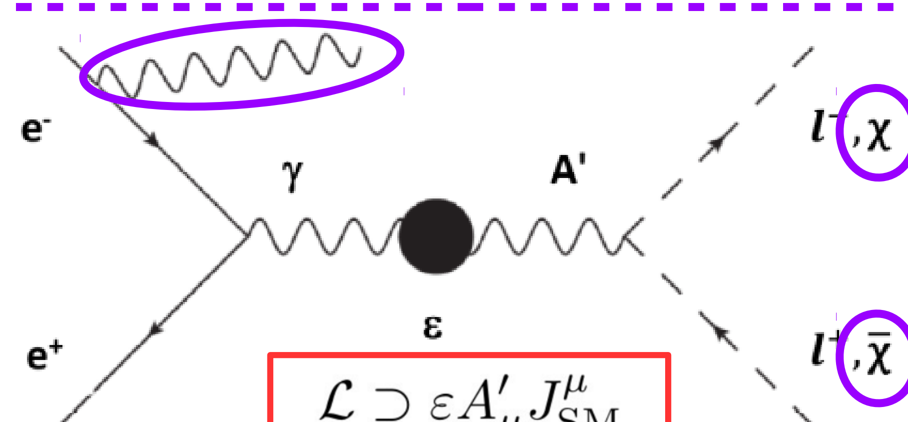
Phase 2 benchmark



- A possible extension of the SM include a new massive ($m_{A'}$) gauge boson A' of spin = 1 coupling to the SM through the kinetic mixing with strength ε → the ***dark photon***
- At e^+e^- colliders we investigate the ISR production $e^+e^- \to \gamma\, A'$.

Most promising signatures are the invisible final states, A' → χχ



$$\mathcal{L} \supset \varepsilon A'_{\mu} J^{\mu}_{\rm SM}$$

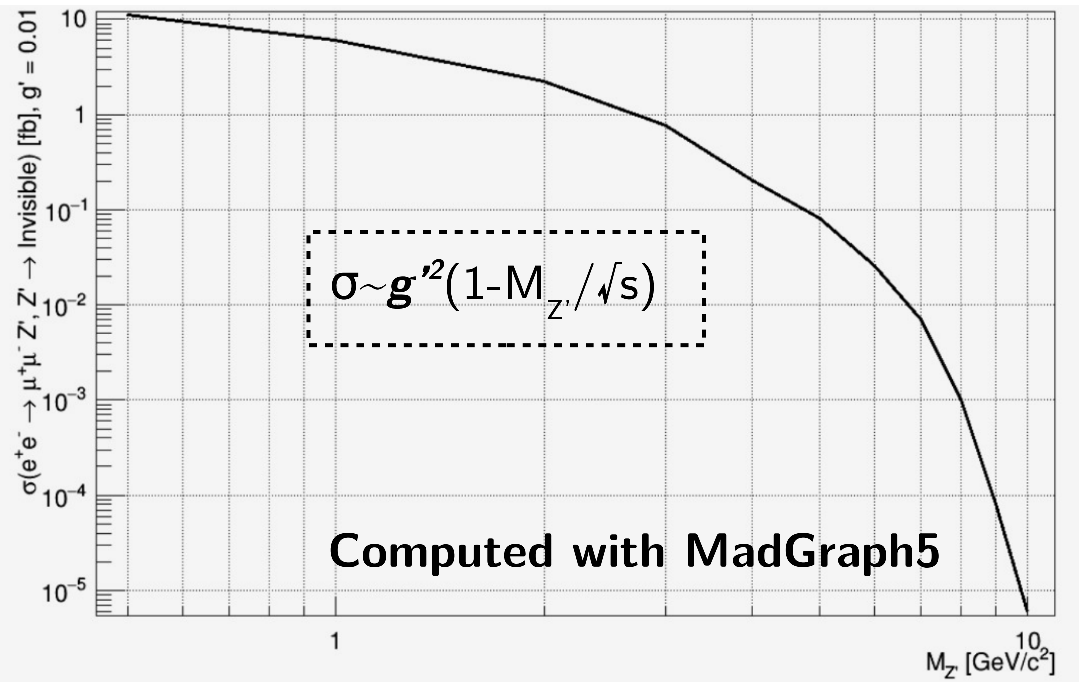
Batell et al. (2009), arXiv:0903.0363

Other SM extensions: Z' to invisible

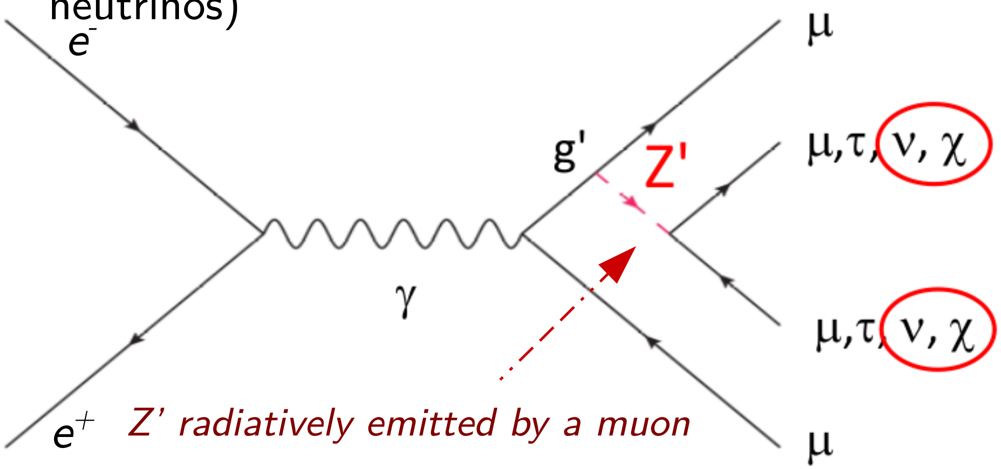
- New gauge boson Z' coupling only to the **2nd and 3rd** generation of leptons (minimal L_μ-L_τ model)

Detecting the L_μ-L_τ gauge boson at Belle II, arXiv:1702.01497

- Invisible signature investigated for the first time in the process $e^+e^- \rightarrow \mu^+\mu^- Z' +$ *missing momentum*
- May explain the $(g\text{-}2)_\mu$ anomaly
- BR(Z'$\rightarrow$ inv) may be enhanced by the presence of kinematically accessible DM (e.g. sterile neutrinos)



Shuve et al. (2014), arXiv:1403.2727



Z' radiatively emitted by a muon

Branching ratios:

$$M_{Z'} < 2M_\mu \rightarrow \Gamma(Z' \rightarrow inv.) = 1$$

$$2M_\mu < M_{Z'} < 2M_\tau \rightarrow \Gamma(Z' \rightarrow inv.) \sim 1/2$$

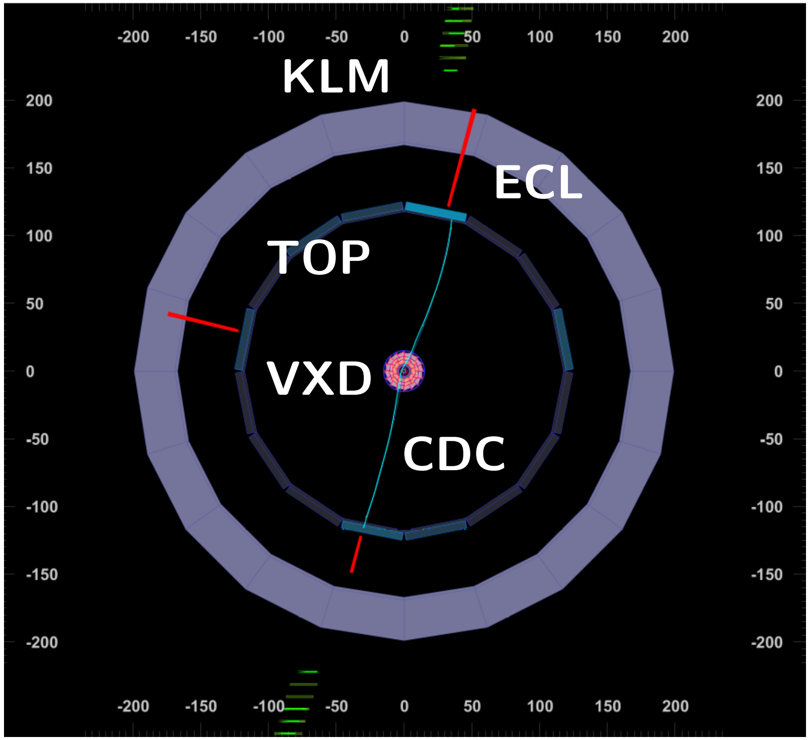
$$M_{Z'} > 2M_\tau \rightarrow \Gamma(Z' \rightarrow inv.) \sim 1/3$$

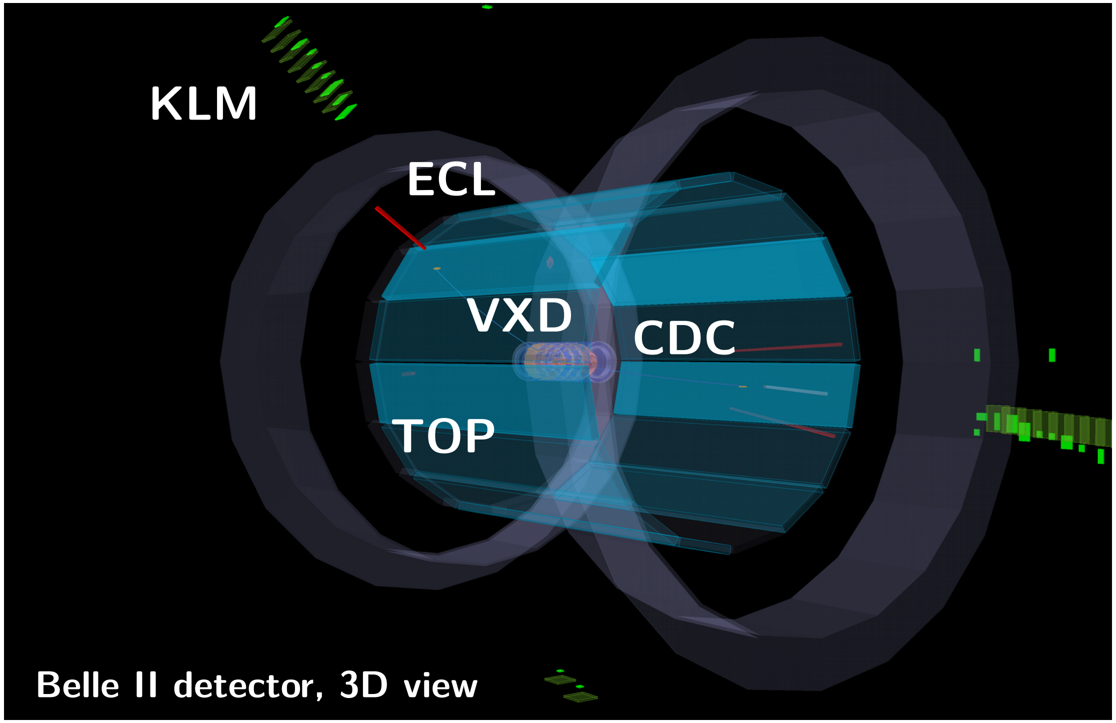
* If light DM is accessible, BR(Z'$\rightarrow$ DM)~1

Z' to Invisible: Analysis Strategy

- Reconstruct the recoil against a **$\mu^+\mu^-$ pair** (dimuon candidate) and look for a peak in the recoil mass spectrum. Additionally require **nothing** in the Rest Of Event (ROE) → MODEL INDEPENDENT SEARCH.
- Reject background (mainly QED radiative processes) by applying a signal-like selection on the distribution of the transverse momentum of the dimuon candidate
- Optimize the selection criteria on both MC simulation and data

Belle II detector, xy (transverse plane)

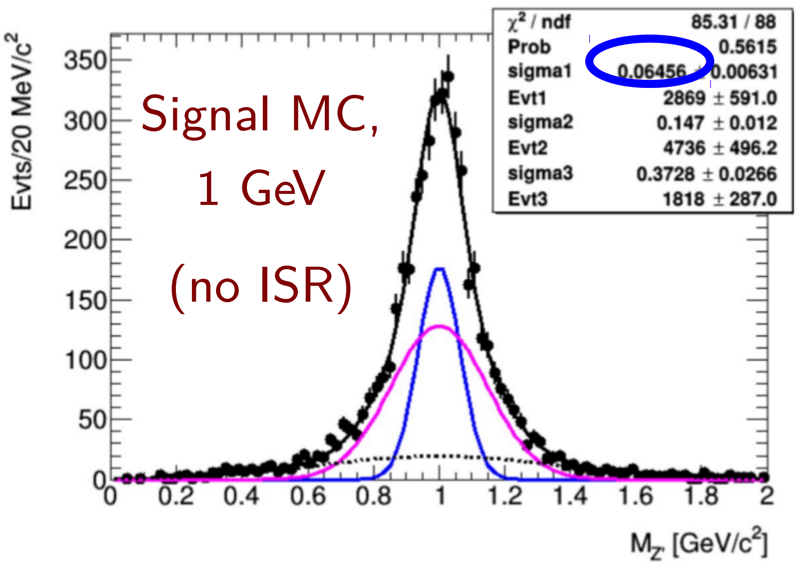


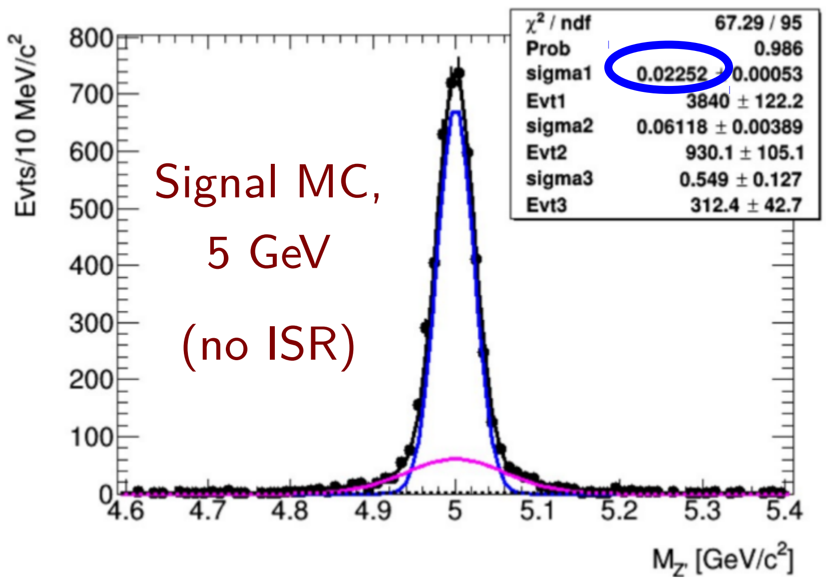


Belle II detector, 3D view

- Extract the signal yield by fitting the *recoil mass distribution*, in each mass bin defined for the simulated Z' masses.

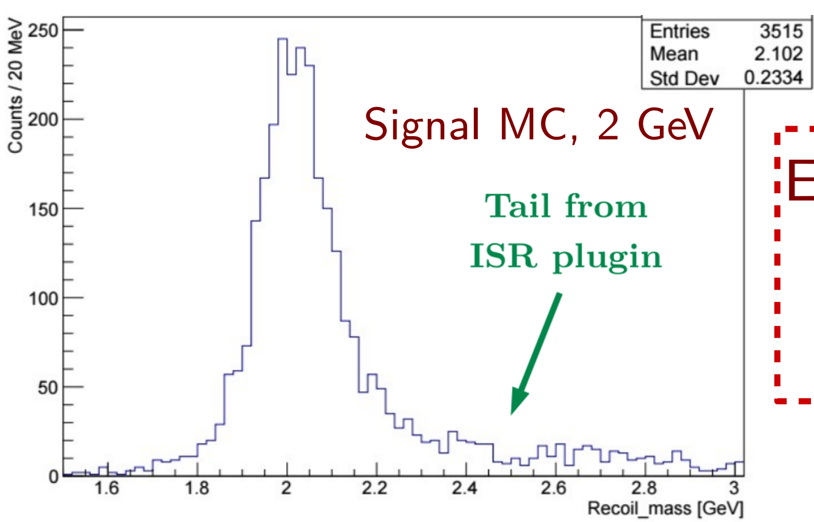
Signal Simulation



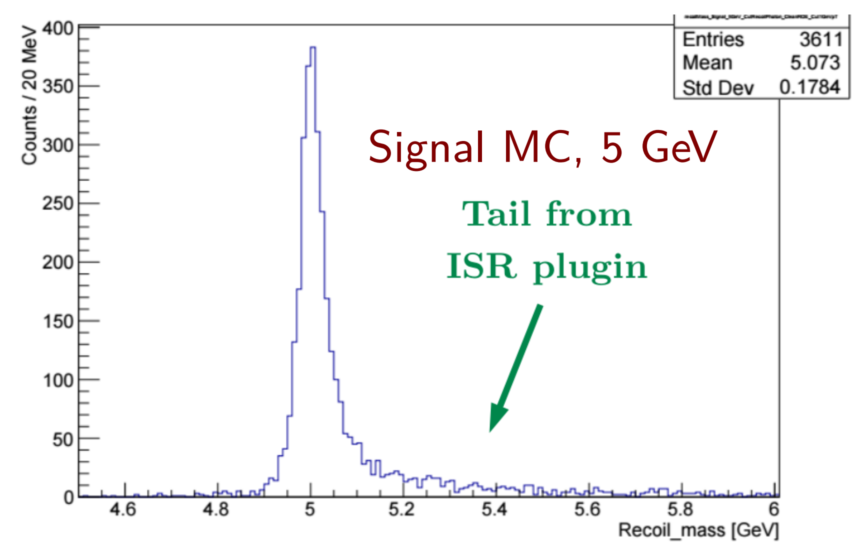


- Simulated and reconstructed ***10k events*** for several Z' masses between 0.1-10 GeV (1 GeV step size) assuming for the detector the *Phase 2 geometry*.

- To be done: study the signal shape with Initial State Radiation (ISR) effect included → signal component in final fit will be modeled by a *Crystal Ball function*



Expected worse resolution at lower masses



Background Rejection

- Backgrounds mainly from radiative QED processes: 10 fb^{-1} have been generated for each MC samples of $e^+e^- \to \mu^+\mu^-(\gamma)$, $e^+e^- \to \tau^+\tau^-(\gamma)$, $e^+e^- \to \mu^+\mu^-e^+e^-$

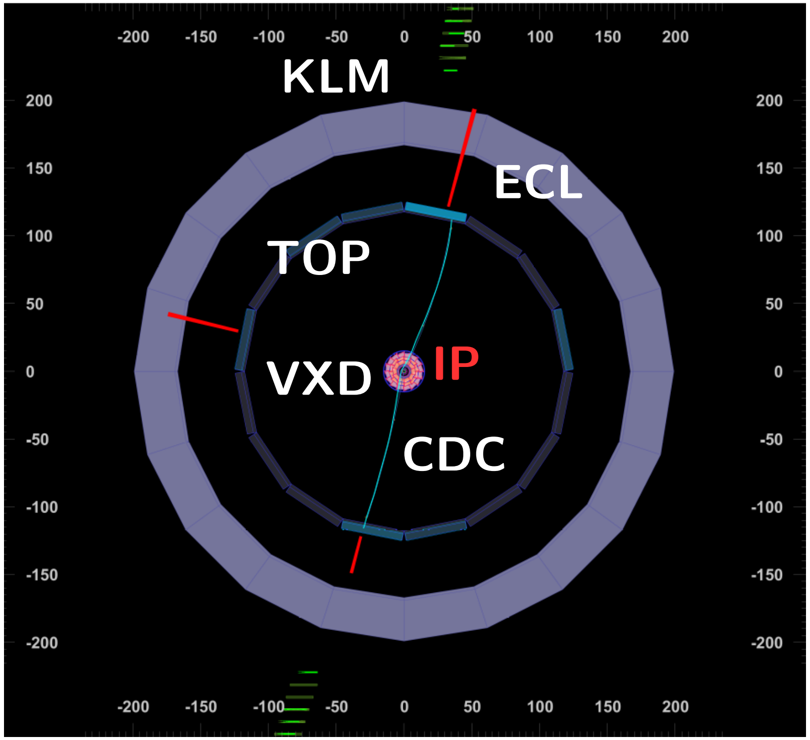
Reconstruction criteria:

1) ONLY 2 tracks coming from the interaction point (IP) and being identified as muon with a *Particle Identification (PID)* probability >0.9, kinematically fitted to a common vertex with a χ^2 probability > 0.1%

2) Exploit the close kinematic of lepton colliders and compute the **recoil four momentum** against the dimuon candidate in the center-of-mass (CM) frame.

3) Require the recoil momentum to point the central region of the ECL (best hermeticity) and ask for NO PHOTONS detected within a 15° cone

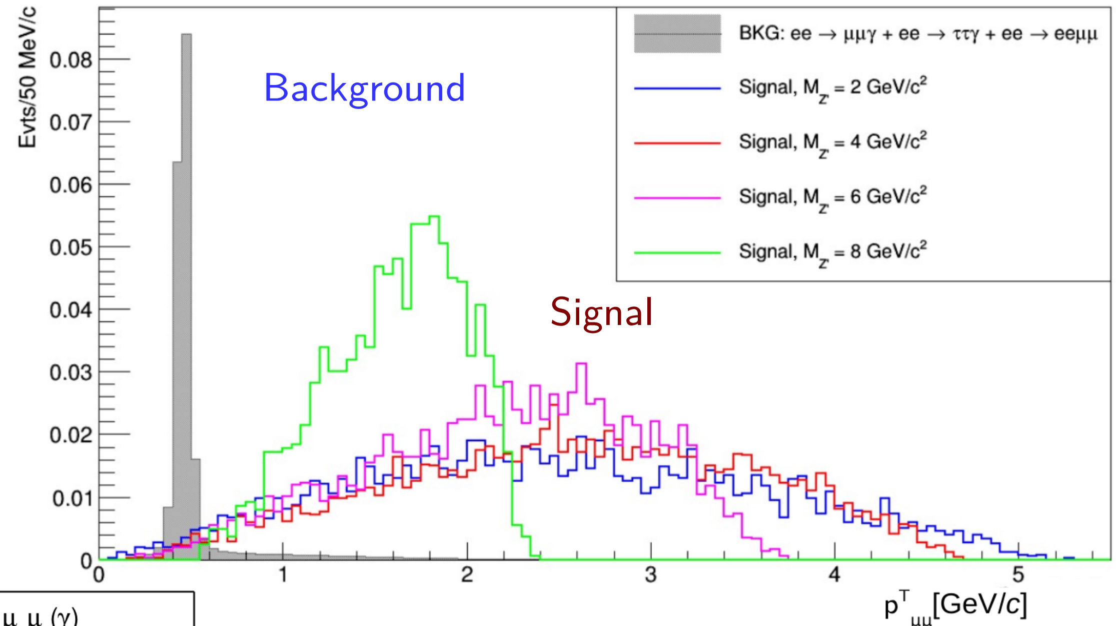
4) Nothing in the Rest Of Event (ROE)

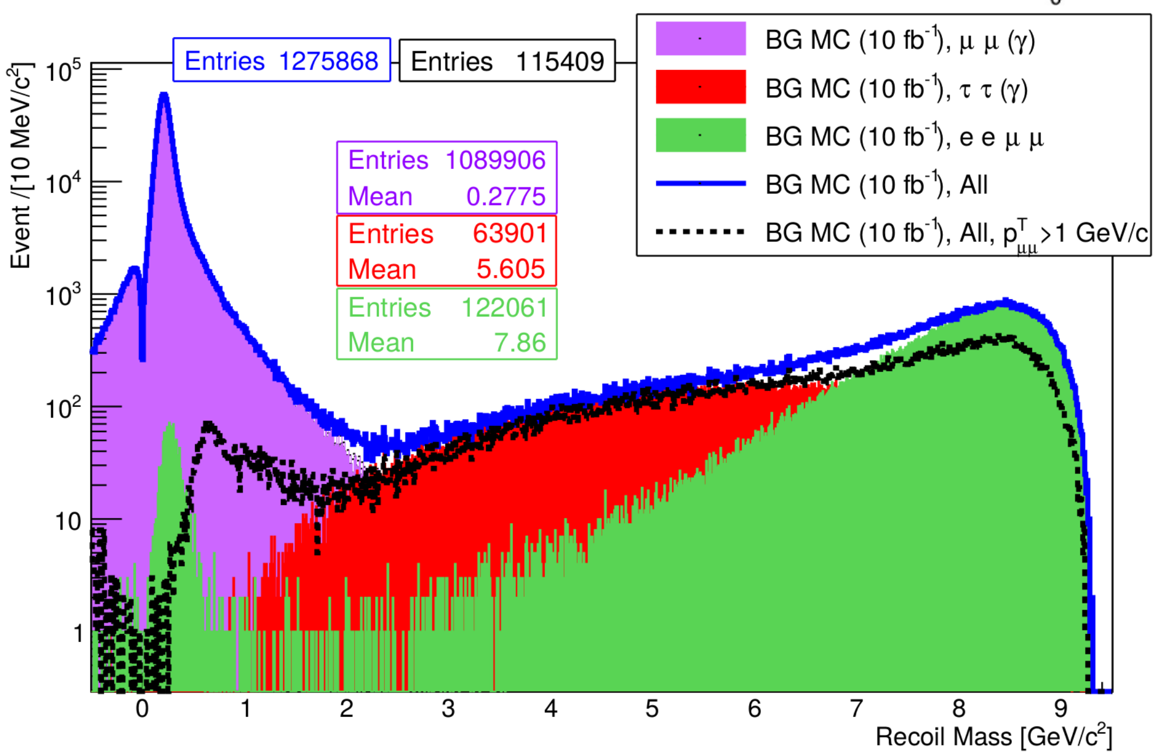


Belle II detector, xy (transverse plane): event display of a real event reconstructed from *Phase 2 data.*

Discriminant variables

- The transverse dimuon momentum $p^T_{\mu\mu}$ provides a good signal-background separation and the requirement $p^T_{\mu\mu} > 1$ GeV/c reject most of the $e^+e^- \to \mu^+\mu^-(\gamma)$ background peaking at low mass.





The average background reduction is ~91%

- Still contamination from $e^+e^- \to \tau^+\tau^-(\gamma)$
- Further discriminant variables and selection optimization is needed

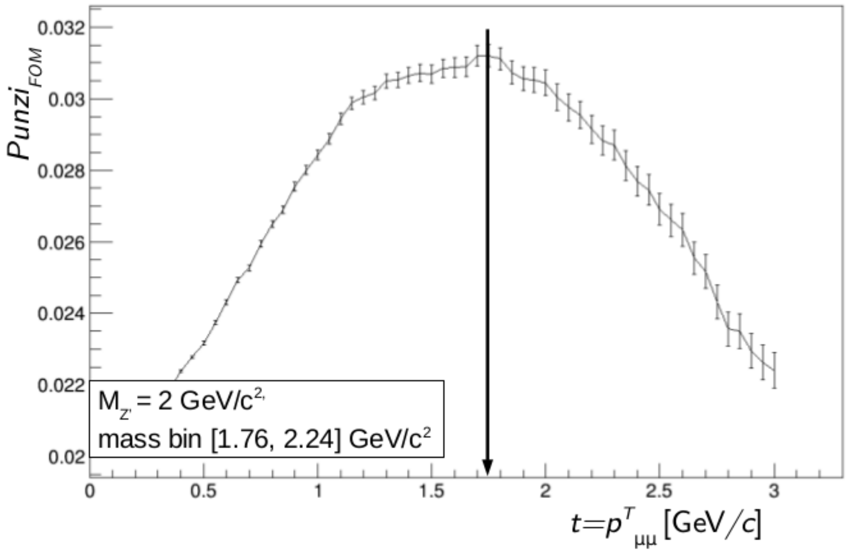
Selection Optimization

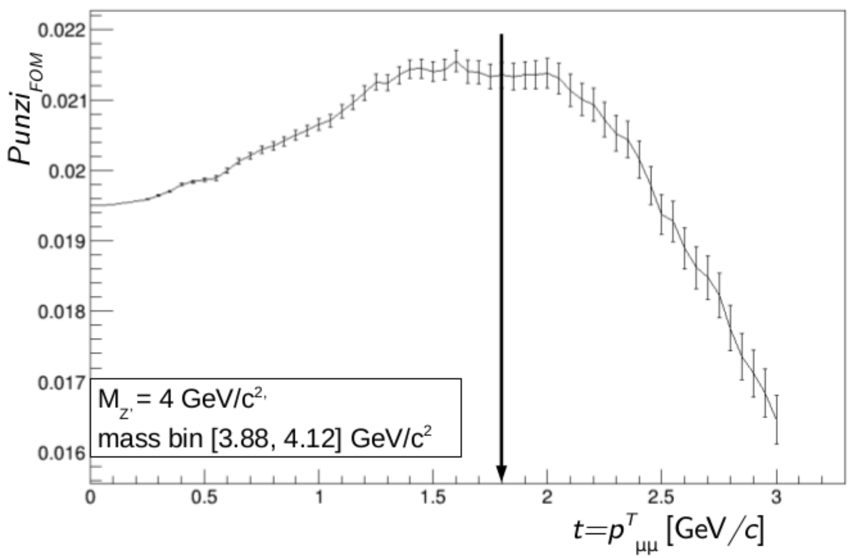
- Optimization strategy: maximize the Punzi Figure Of Merit,

$$Punzi_{FOM} = \varepsilon(t)/(a/2 + \sqrt{B(t)})$$

- Independent from unknown ***signal cross section*** and allows to optimize the ***significance*** (a, in unit of σ) ensuring the coverage of the desired ***Confidence Level (CL)***
- Function of the applied selection requirements t, mass bin-dependent

$\rightarrow$ *Preliminary studies: optimized $p^T_{\mu\mu}$ selection per each mass bin*

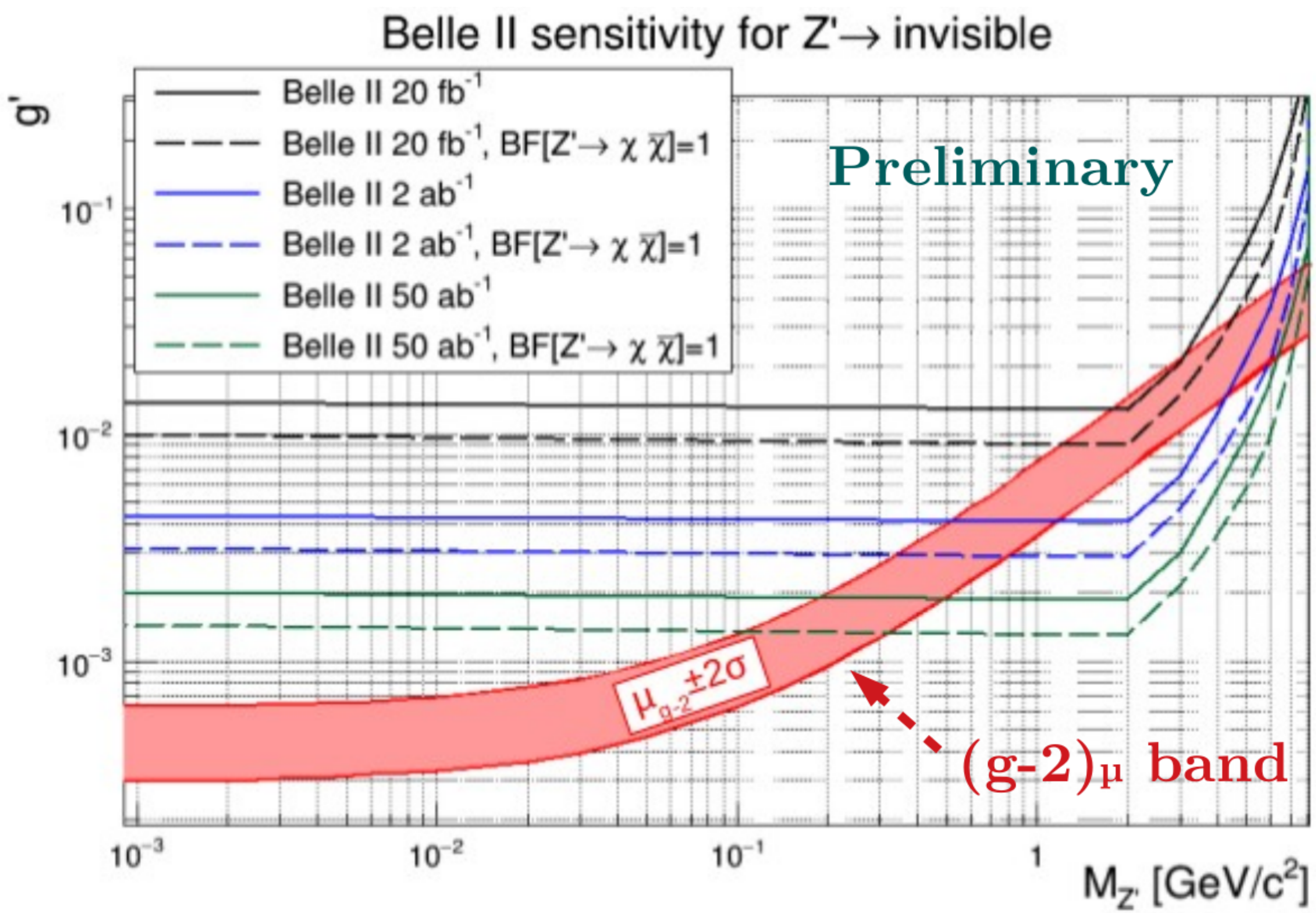




Expected Sensitivity

- The 90% CL upper limit is calculated as a basic Poisson counting experiment, considering background that survives all the selection criteria (*not Punzi-FOM optimized yet!*) per each mass bin.

- Sensitivity curves assume an average trigger efficiency of 82% from MC simulation and a signal efficiency dependent on the Z' mass, between 12% at 1 GeV and 1.2 % at 8 GeV.
- The mass bins are centered in a given Z' mass hypothesis$\pm 3\sigma$, with σ the standard deviation of the modeling of the Z' mass distribution in signal MC (simple Gaussian).

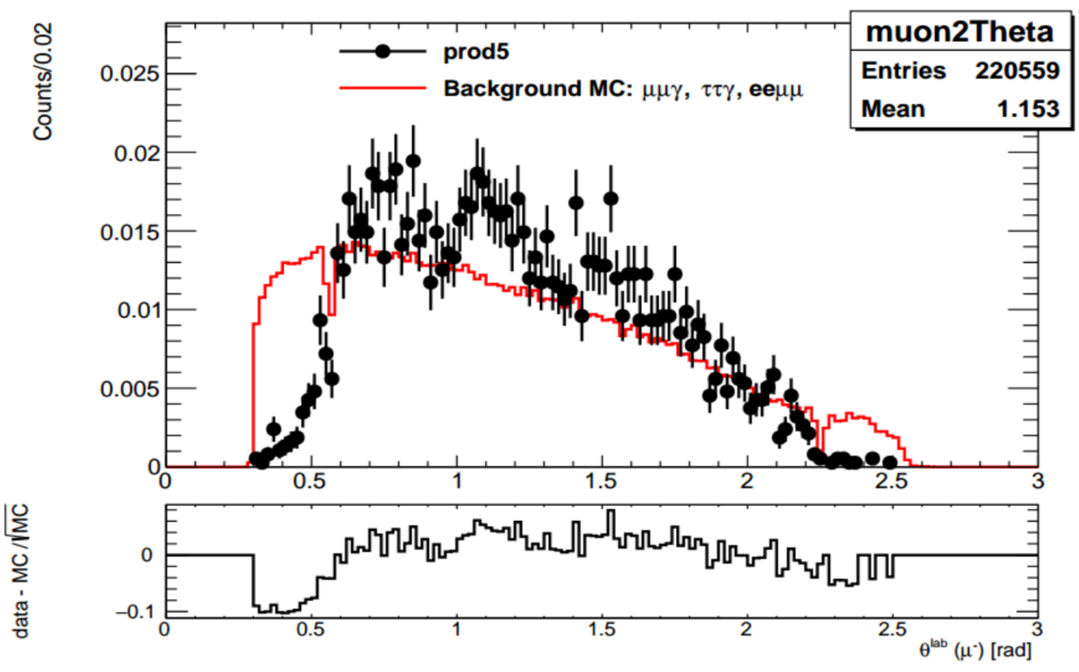


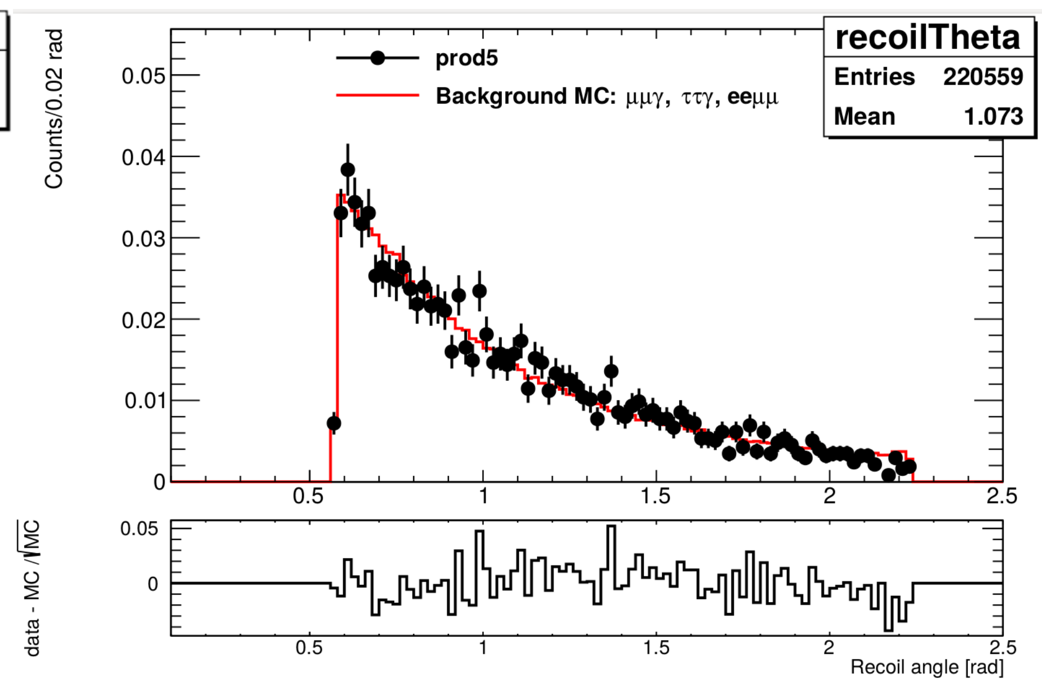
First look at data

Commissioning data are the first collected with a ***new detector*** at a ***new accelerator*** → good test for the experiment performance, but need to be understood! To reconstruct data **(Phase 2, ~0.5 fb^{-1})** we had to release some reconstruction criteria:

- ONLY 2 tracks coming from the interaction point (IP) and being identified as muon with a ~~PID probability >0.9, kinematically fitted to a common vertex with a χ^2 probability > 0.1%~~

- Muon selection is based on calorimeter information: 0. < clusterE < 0.4 GeV, ClusterE/p < 0.25 → PID variable not available yet
- Only partial VXD detector installed → release vertex fit





Summary and Outlook

The goals of this ***thesis project*** are:

- Development of measurement optimization for Phase 3 (on MC simulation)
- MC-data comparison on Phase 2
- MC-data comparison and performance/efficiency measurement on Phase 3 data
- Systematic uncertainty studies

Most likely not possible to include the final measurement on ***Phase 3 data*** due to the deadline of October 2019

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- *What's done:* full MC simulation for Phase 2, preliminary selection defined, performance on commissioning data tested

  → *small and flawed data set ~0.5 fb^{-1}*, no standard PID available and collected only with partial VXD, still crucial as ***proof of concept*** for the feasibility of this search at Belle II.

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- *What's next:* prepare the tools to ***perform the measurement on Phase 3 data***
  - Extend MC simulation to Phase 3
  - Finalize the selection optimization and signal modeling, define the limit setting strategy
  - Study the systematic uncertainties: data driven studies already started on Phase 2 data for the ***trigger efficiency, tracking efficiency, PID performance*** → to be extended to the new data set collected from ~February 2019.

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Phase 3 running for the Belle II experiment with the full detector installed, higher luminosity will start soon (February 2019) ...

STAY TUNED!

Thanks for attention

partial VXD, still crucial as ***proof of concept*** for the feasibility of this search at Belle II.

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Backup

Nano-beam Scheme

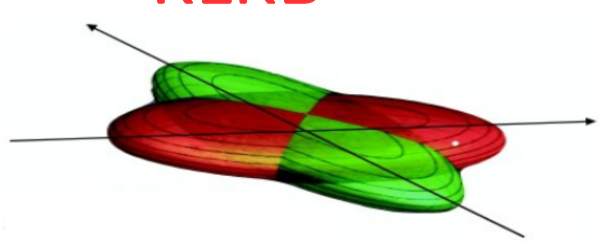
$$L = \frac{\gamma_{\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_{\pm}\xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

- Lorentz factor: $\gamma_{\pm}$
- Beam current: $I_{\pm}$
- Beam-Beam parameter: $\xi_{y\pm}$
- Vertical beta function at IP: $\beta_{y\pm}^*$
- Beam aspect ratio at IP ***(0.01-0.02)***: σ_y^*/σ_x^*
- Geometrical reduction factors (crossing angle, hourglass effect) ***(0.8-1.0)***: R_L/R_{ξ_y}

I ↑ x 2

β^*_y ↓ x 1/20

KEKB



I (A): ~ 1.6/1.2

β^*_y (mm): ~ 5.9/5.9

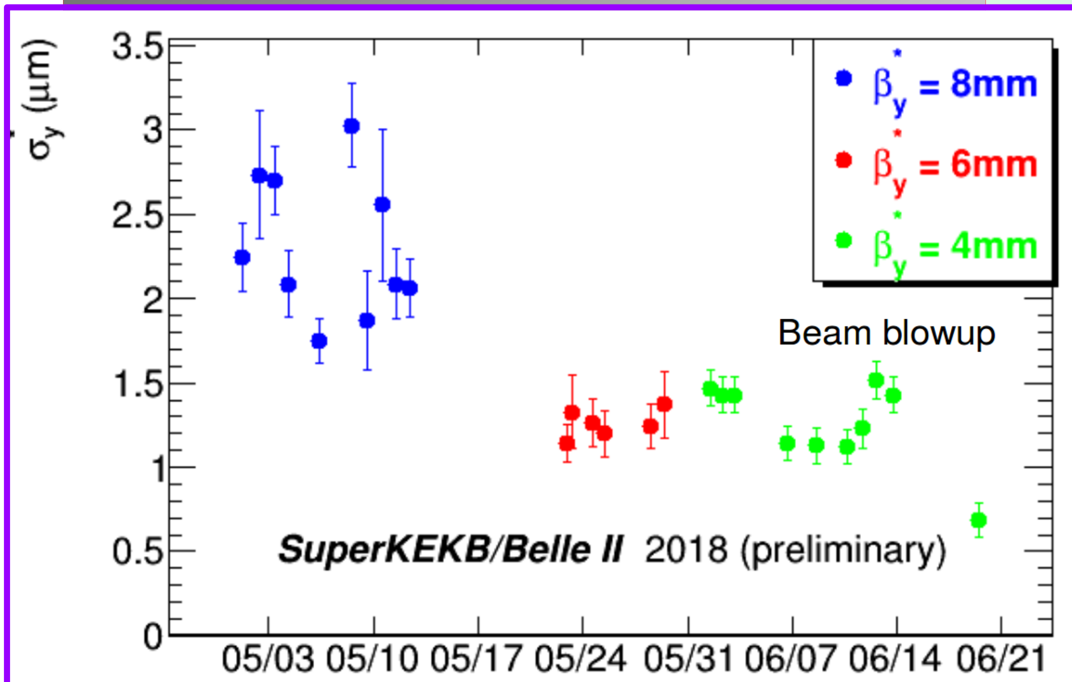
SuperKEKB

I (A): ~ 3.6/2.6

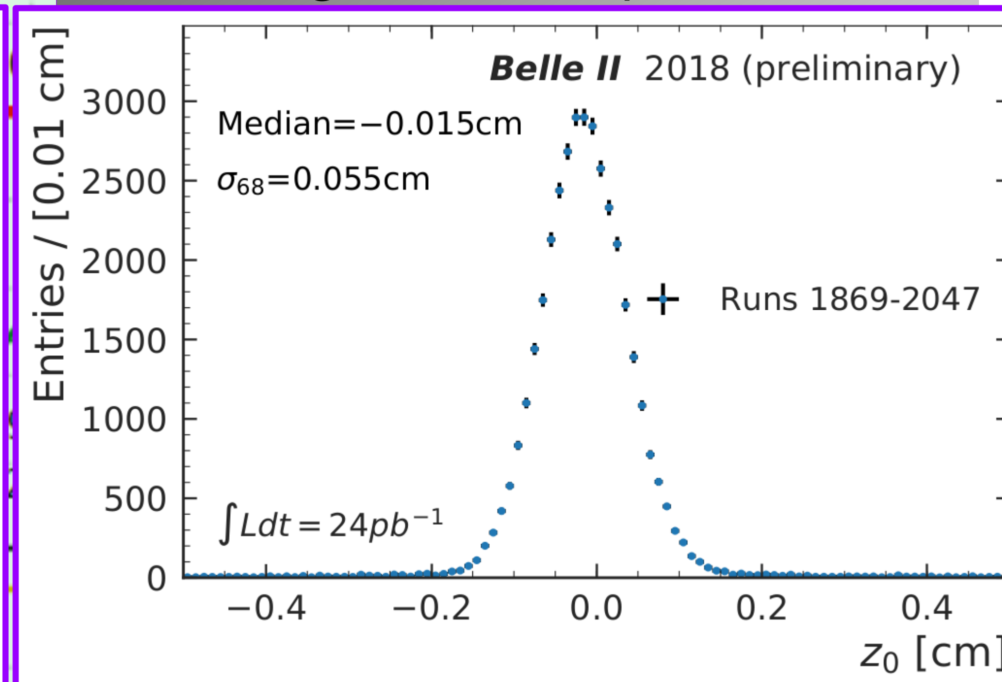
β^*_y (mm): ~ 0.27/0.3

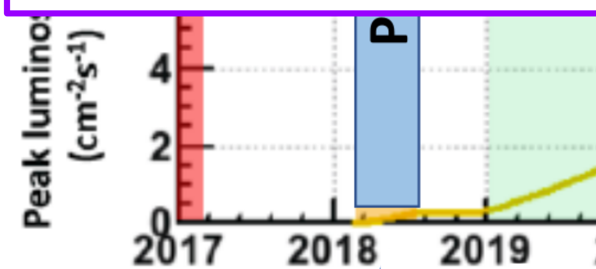
Belle II Performances: nano-beam scheme at work

Vertical beam size



Longitudinal IP position



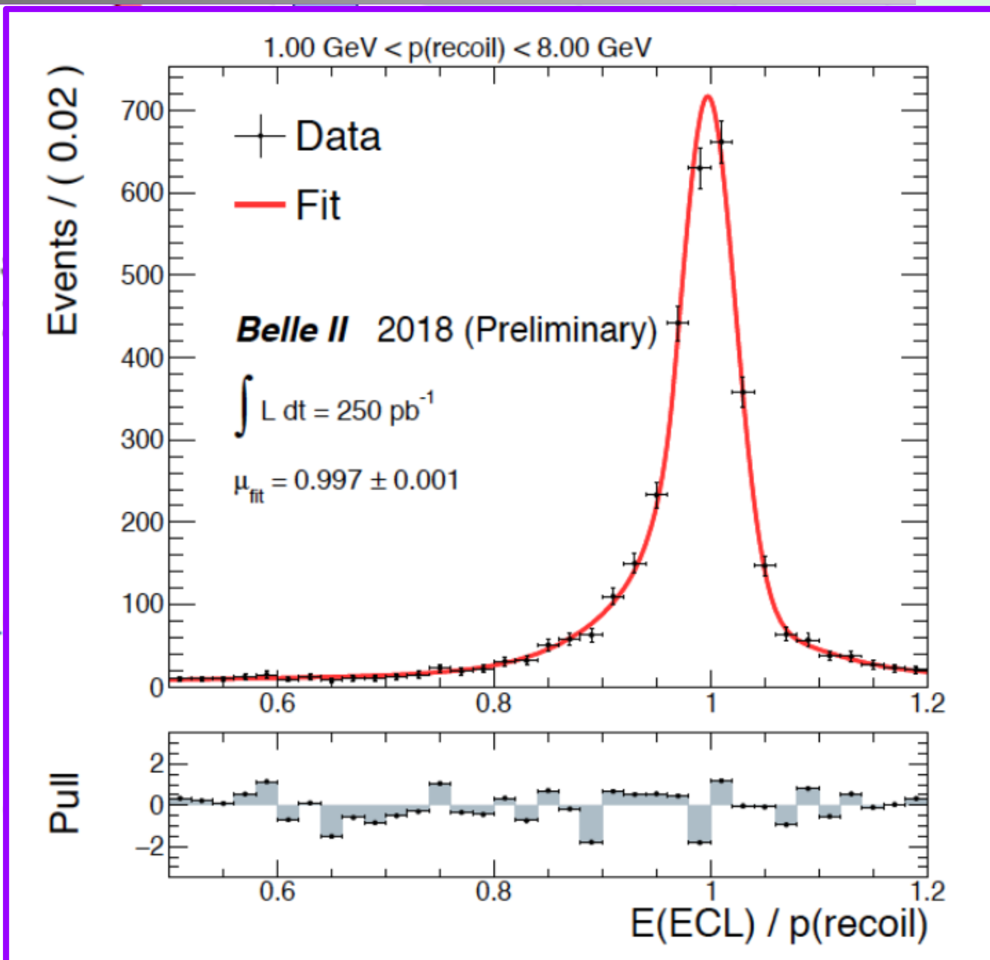


Ended July 17th , 9 am

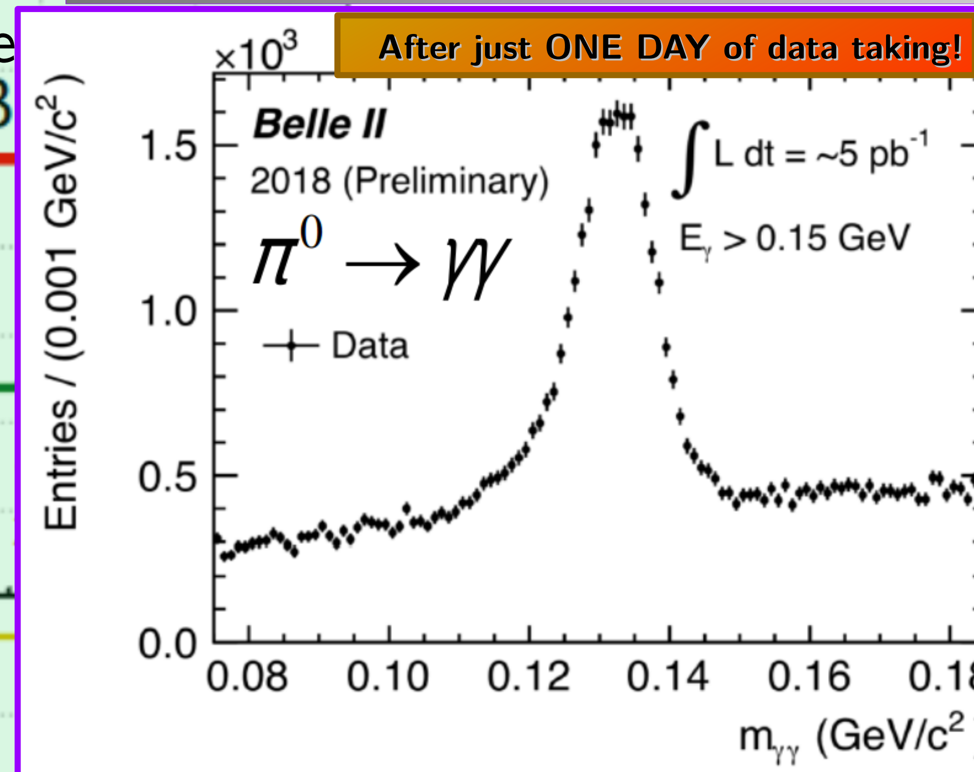
- ✔ **Nano-beam scheme work**
- ✔ **L = $5.5 \cdot 10^{33}$ cm^{-2} s^{-1}**
- ✔ **Collected 0.472 fb^{-1}**

Belle II Performances: photon reconstruction

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



$\pi^0 \to \gamma\gamma$



- $e^+e^- \to \gamma\ X$
- $e^+e^- \to \gamma\ ALPS \to \gamma(\gamma\gamma)$

GOOD CONDITIONS for DARK SEARCHES

- ✔ Tracking and cluster L1 trigger
- ✔ Bhabha veto L1
- ✔ Single Photon L1 trigger

Dark Photon to Invisible

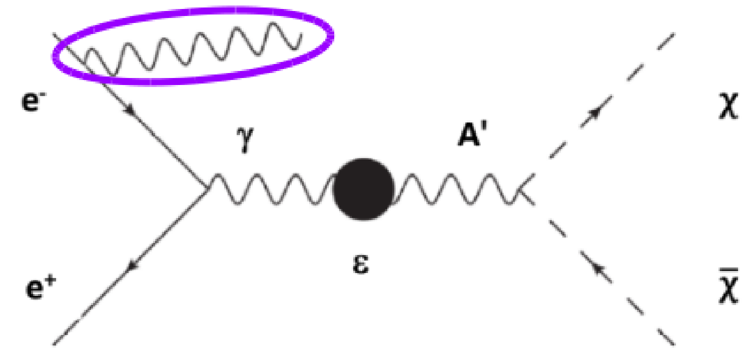
- Signal Signature:
  - select events with a single, monochromatic, high energetic *ISR photon*
  - Look for a bump in the reconstructed photon energy $E_\gamma = (s - m^2_{A'})/2\sqrt{s}$

    → only one photon in the detector requires a dedicated ***single photon trigger.***

(@Belle was not available, ~10% BaBar data)

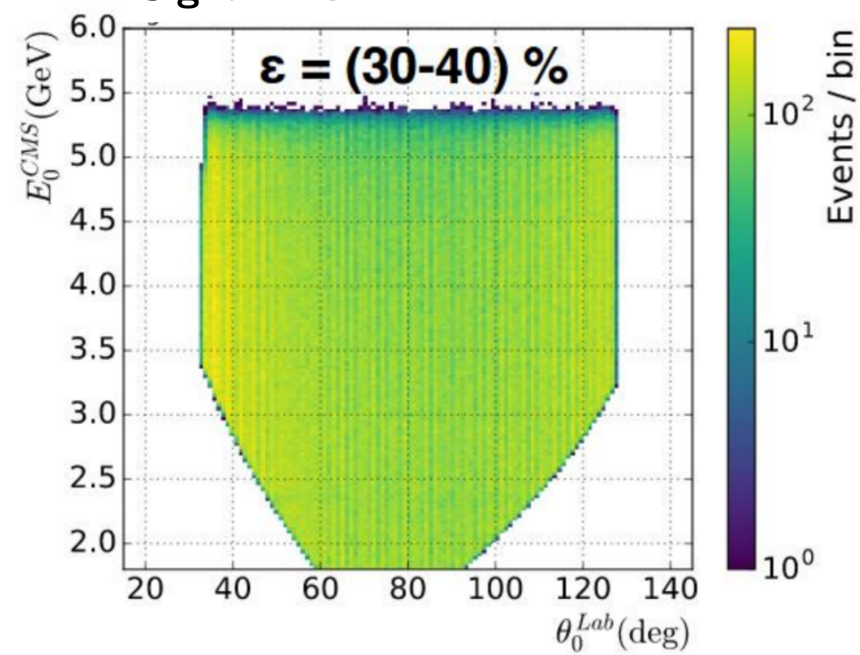
Trigger logic	L1 rate at full luminosity
E > 1 GeV + 2nd cluster E < 300 MeV	4 kHz (barrel) 7 kHz (endcaps)
E > 2 GeV + Bhabba & γγ vetoes	5 kHz (barrel)

Sustainable at Phase 3 full luminosity?



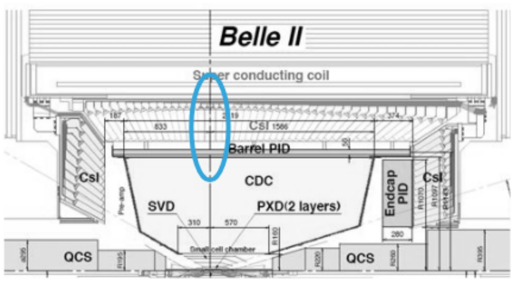
- Discriminant variables: E^*_γ, θ_γ

Signal MC

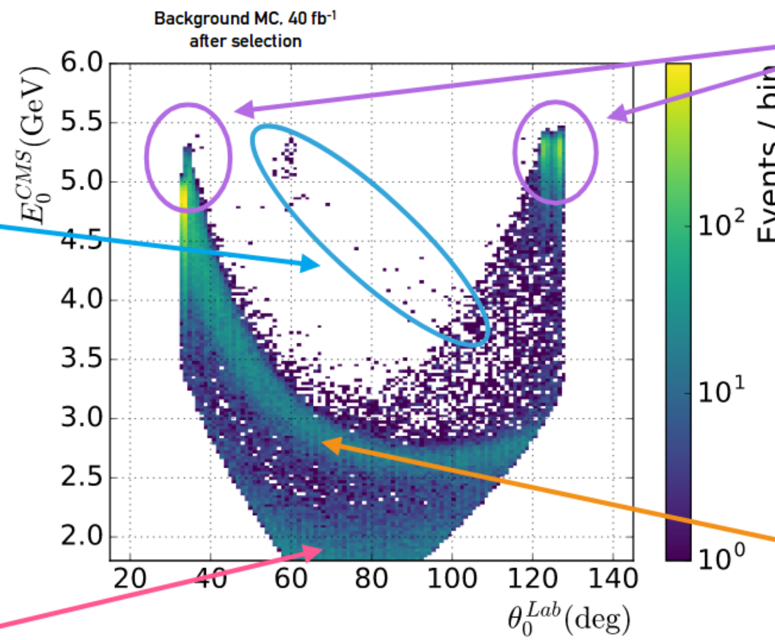


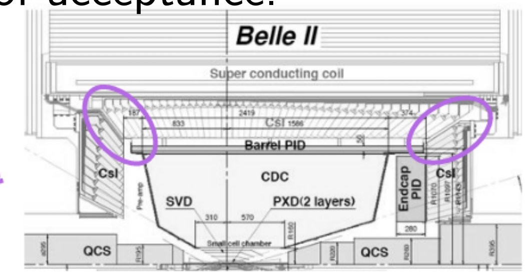
Dark Photon to Invisible: Backgrounds

- Background dominated by QED processes:
  - $e^+e^- \to \gamma\gamma(\gamma)$ where one photon is not detected (ECL gaps) and the second out of acceptance
  - radiative BhaBha $e^+e^- \to e^+e^-\gamma(\gamma)$ with the electron-positron pair out of acceptance.

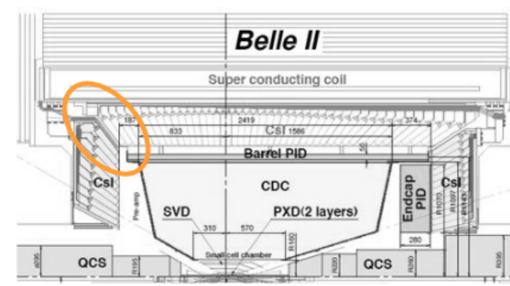


ee→2γ and 3γ
1γ in ECL 90° gap
1γ out of ECL acceptance





ee→2γ
1γ in ECL BWD or FWD gap

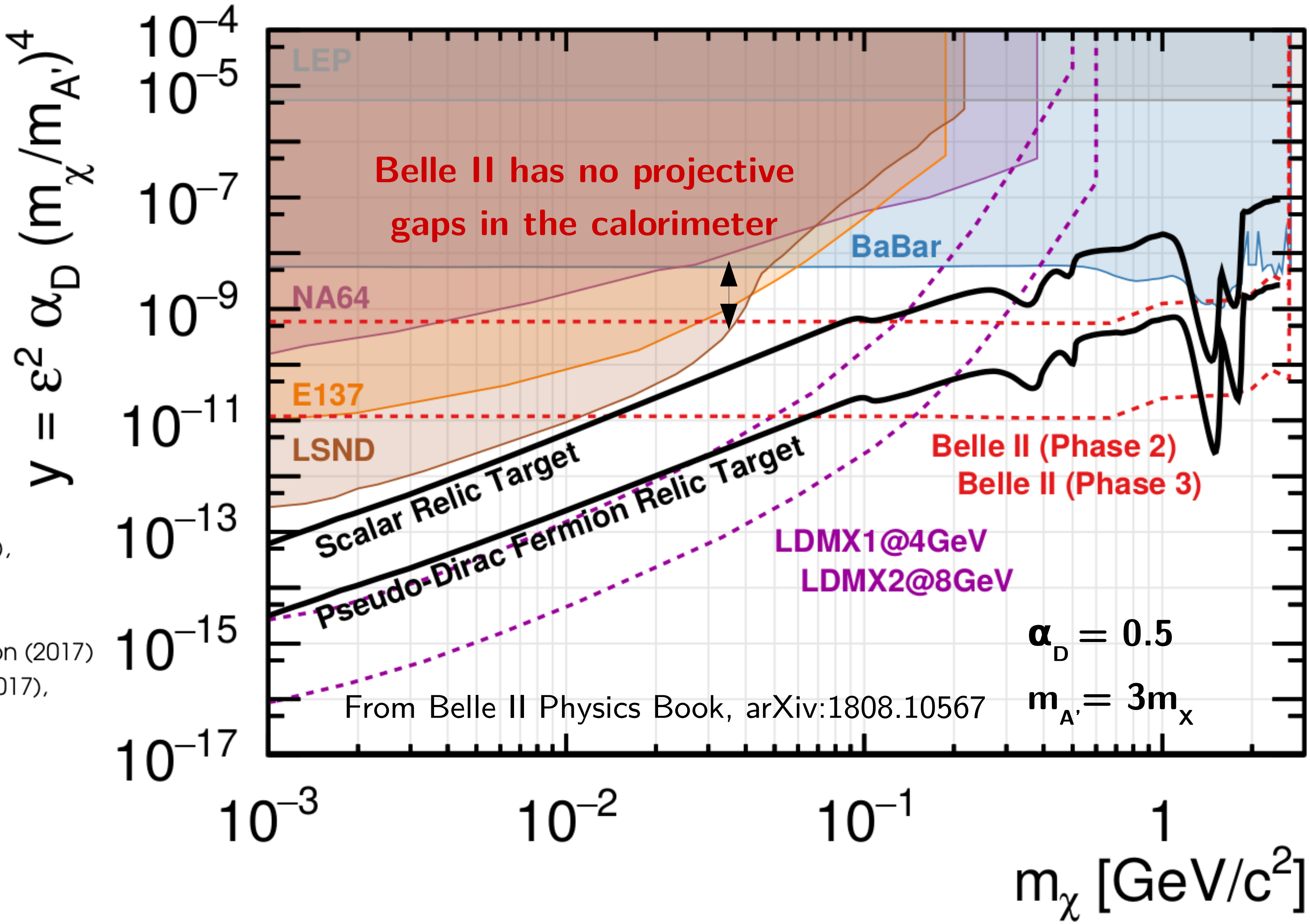


ee→3γ
1γ in ECL BWD gap
1γ out of ECL acceptance

ee→eeγ
both electrons
out of tracking acceptance

$e^+e^- \to \nu\nu\gamma$ negligible

Dark Photon to Invisible: Sensitivity



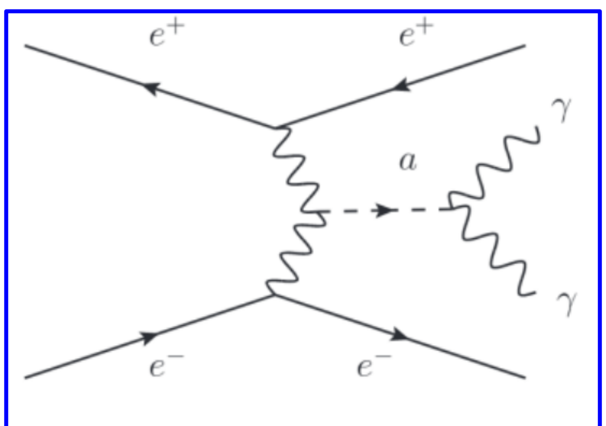
J. Alexander et al. (2016), arXiv:1608.08632

Natalia Toro, private communication (2017)

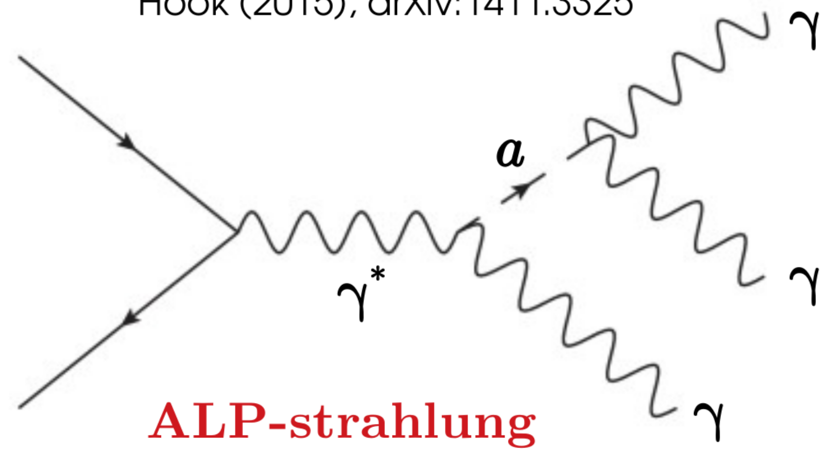
J. P. Lees et al., BaBar (2017), arXiv:1702.0332

Axion Like Particles (ALPs)

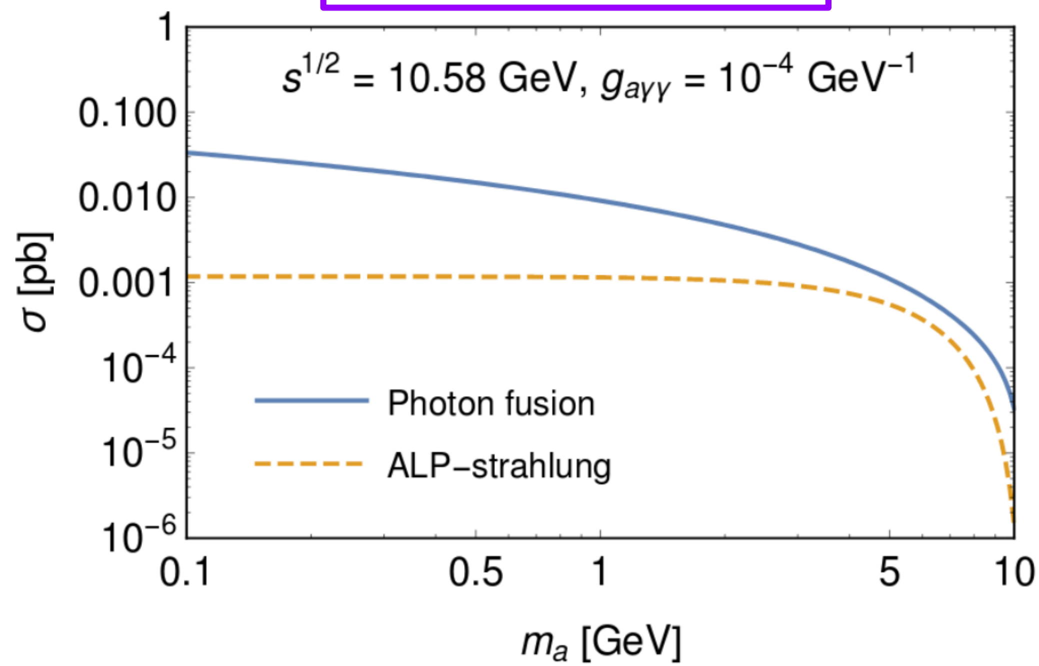
- Axion Like Particles are pseudo-scalars coupling to bosons
- Unlike for QCD Axions, there is no relation between the coupling and the mass
- Explored photon coupling $g_{a\gamma\gamma}$ in *ALP-strahlung* processes (*photon fusion: sensitivity under study*)
- $\tau = 1/m_a^2 g^2_{a\gamma\gamma}$



Hook (2015), arXiv:1411.3325

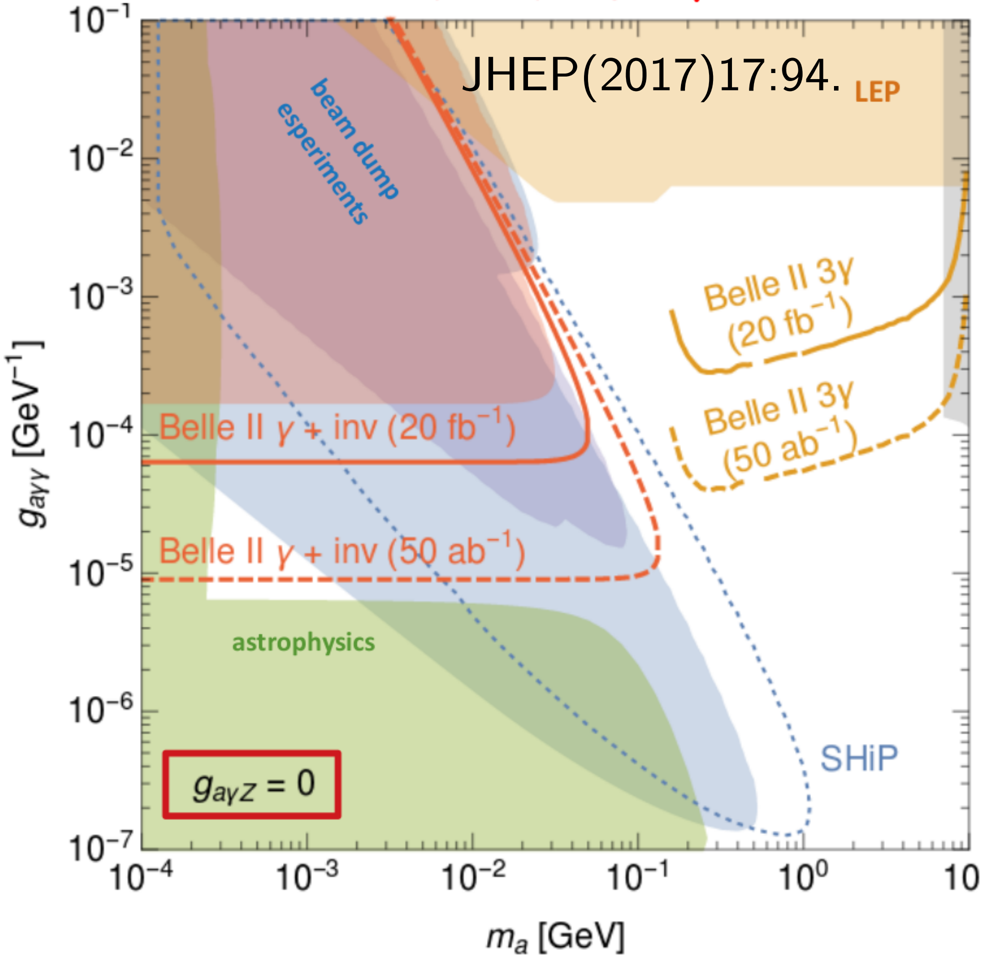


$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

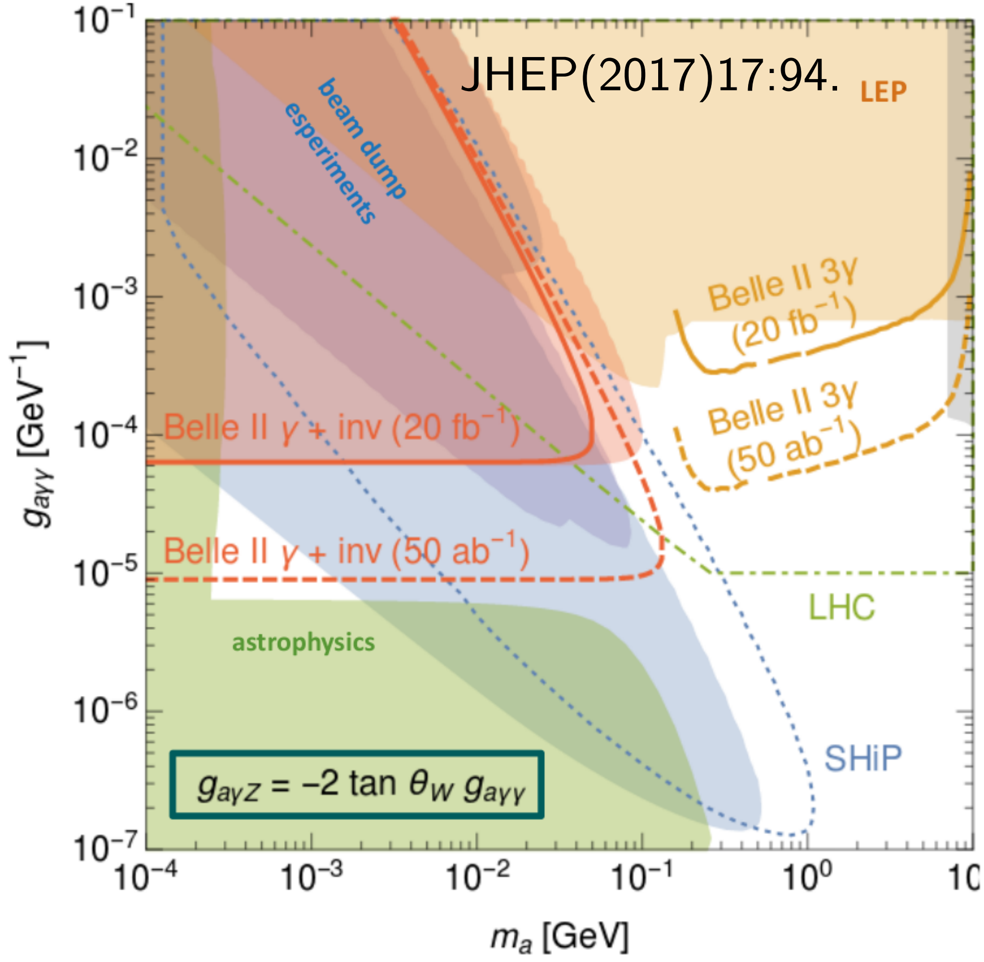


ALPs: Sensitivity

Only coupling to γ



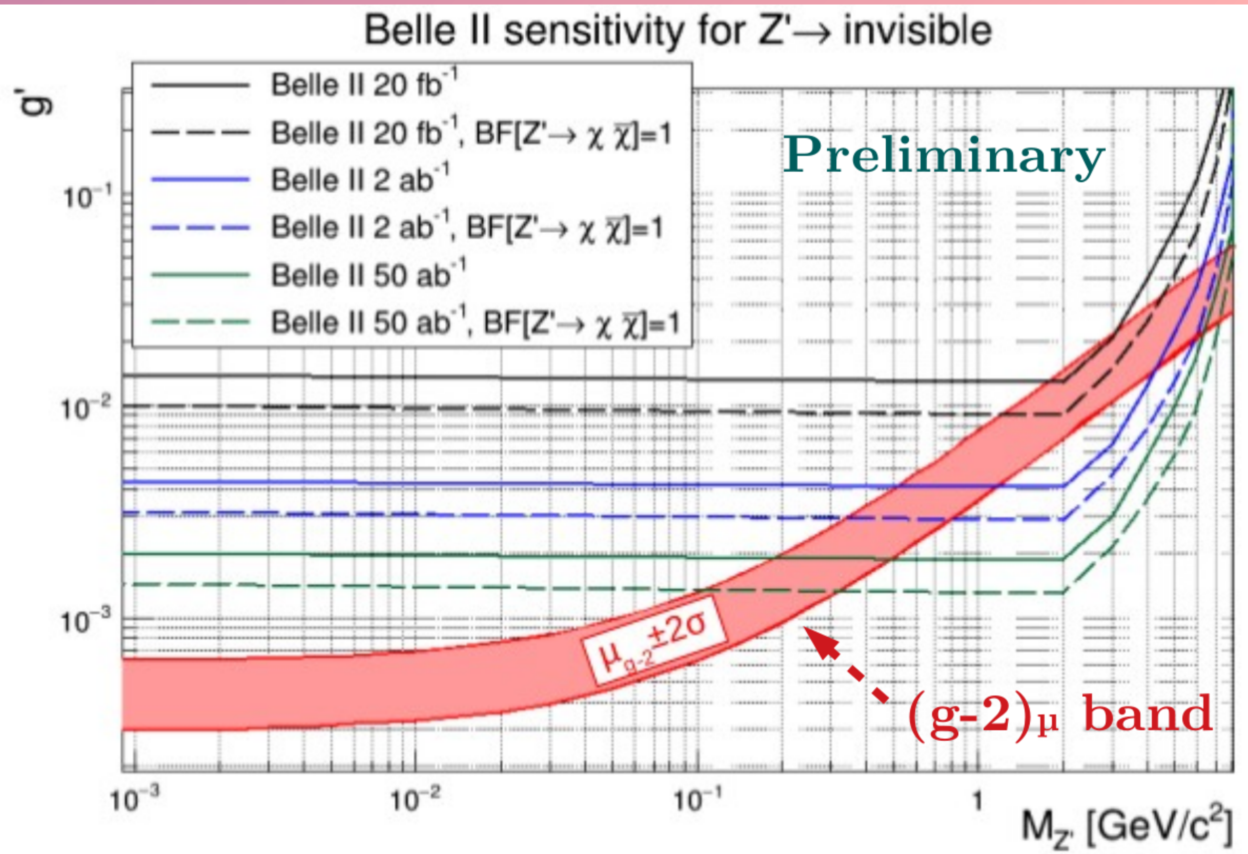
With coupling to Z



Z' to Invisible: Experimental Signature

- Reconstruct the recoil against a $\mu^+\mu^-$ pair and looks for a peak in the recoil mass spectrum. (Additionally require nothing in the rest of event)
- Simulated and reconstructed several Z' masses between 0.1 -10 GeV
- Backgrounds mainly from radiative QED processes:

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



- Furthermore, it will be possible to search for a **Lepton Flavor violating Z'**:

LFV Z' (eμ coupling)

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

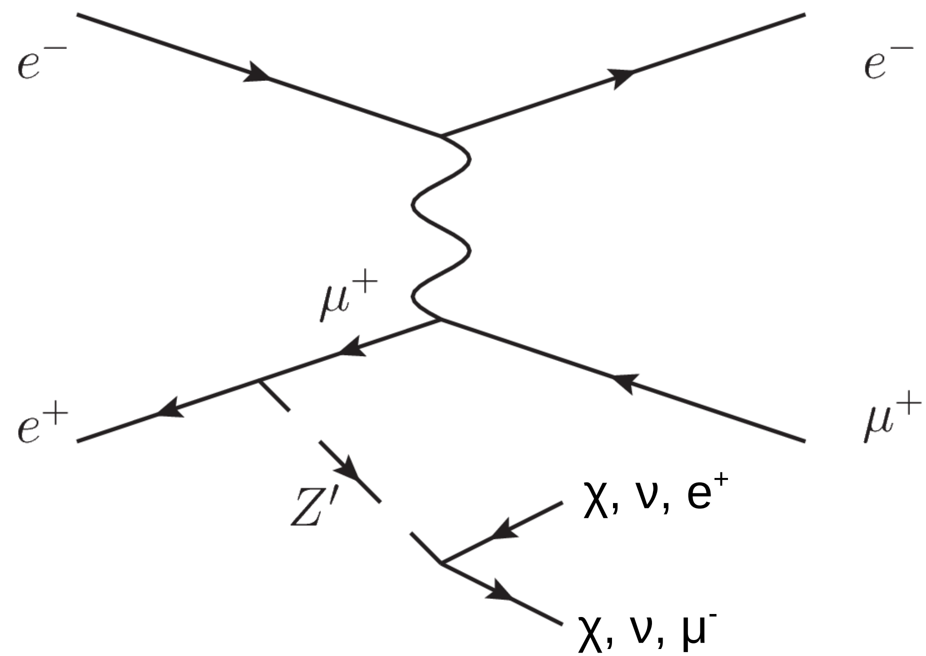
$e^+ e^- \to e^+ \mu^- Z'$; $Z' \to e^+ \mu^-$ (no SM background)

LFV Z': invisible and visible channel

What if symmetries of SM are not kept in the Dark Sector?

What if DM violates Lepton Flavour?

One can imagine, for example, $e\mu$ coupling



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

Dominant background: $e^+e^- \rightarrow \tau^+\tau^- (\gamma)$, $\tau^\pm \rightarrow \mu^\pm, e^\pm \nu\nu$

$e^+e^- \rightarrow e^+\mu^{-}Z'$; $Z' \rightarrow e^+\mu^-$ **+ c.c.**

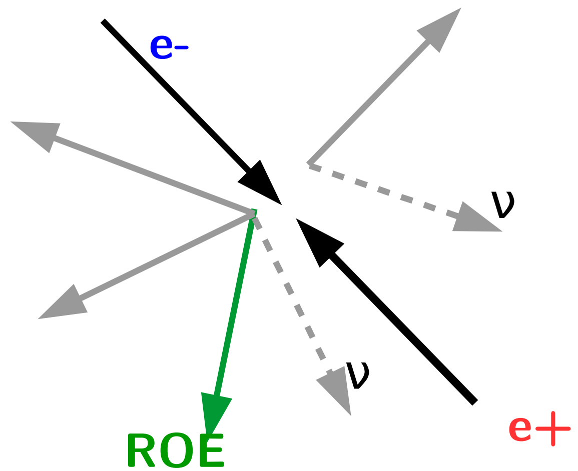
no SM background

Tracking efficiency study

→ exploit charge conservation and kinematic constrains on simple (= with a well recognizable topology) **τ-pairs events** to deduce the existence of a track. "*Track finding efficiency in BaBar*" https://arxiv.org/abs/1207.2849

BaBar strategy was based on *Tau31 events selection:*

- one τ is required to decay leptonically (17.36%), the other semi-leptonically to a 3-prong final state (14.56%) → ***5% of total events***



- Tracking efficiency:
  - $\varepsilon \times A = N4/(N3+N4)$
    - N4 = Tau31 events where the 4th track has been found
    - N3 = Tau31 as reconstructed in the 1+2 selection (further details in the next slide) where the 4th is not found.
- MC-data difference in tracking efficiency is then given by:
  - $\Delta = 1 - \varepsilon_{MC}/\varepsilon_{data}$

  With ε the tracking efficiency evaluated respectively on MC/data, including the detector acceptance A.