First physics results at Belle II: search for dark matter portals

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Outline

- Part I $\rightarrow$ physics motivation and experimental context
- Part II $\rightarrow$ the analysis strategy
- Part III $\rightarrow$ data validation and systematic uncertainties
- Part IV $\rightarrow$ results and conclusions

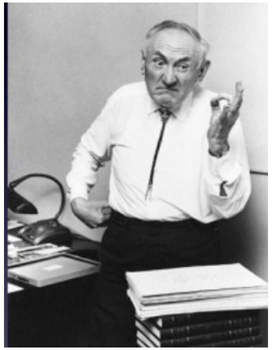
Part I

- Dark matter theoretical frameworks and searches
- The B-factory concept and the second generation:
  - SuperKEKB collider and Belle II experiment.

Introduction to dark matter

- Dark Matter (DM) is one of the most compelling issue for physics beyond the Standard Model. Many **astrophysics** and **cosmological observations** provide evidences for its existence:

F.Zwicky, 1933

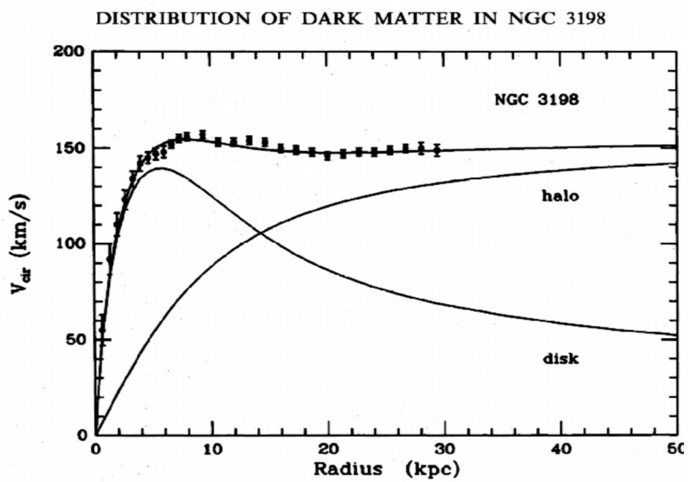


Virial Theorem:

$2E_{kine} = - U$

$<v(r)^2> = GM(r)/r$

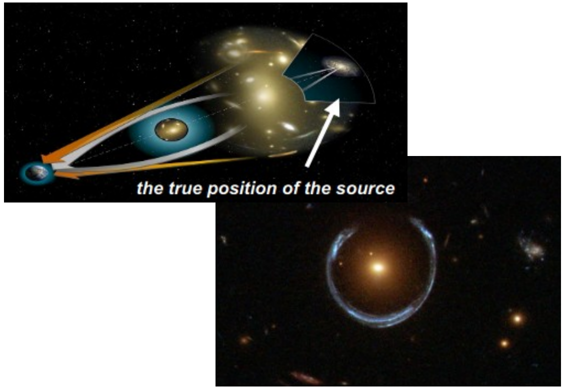
V.Rubin, 1970s

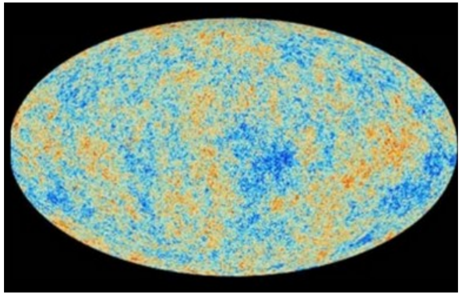


Flat rotational curves: $v(r) = const$

$\rightarrow$ mass distribution linearly growing with r (assuming $\rho(r)=1/r^2$)

Gravitational Lensing





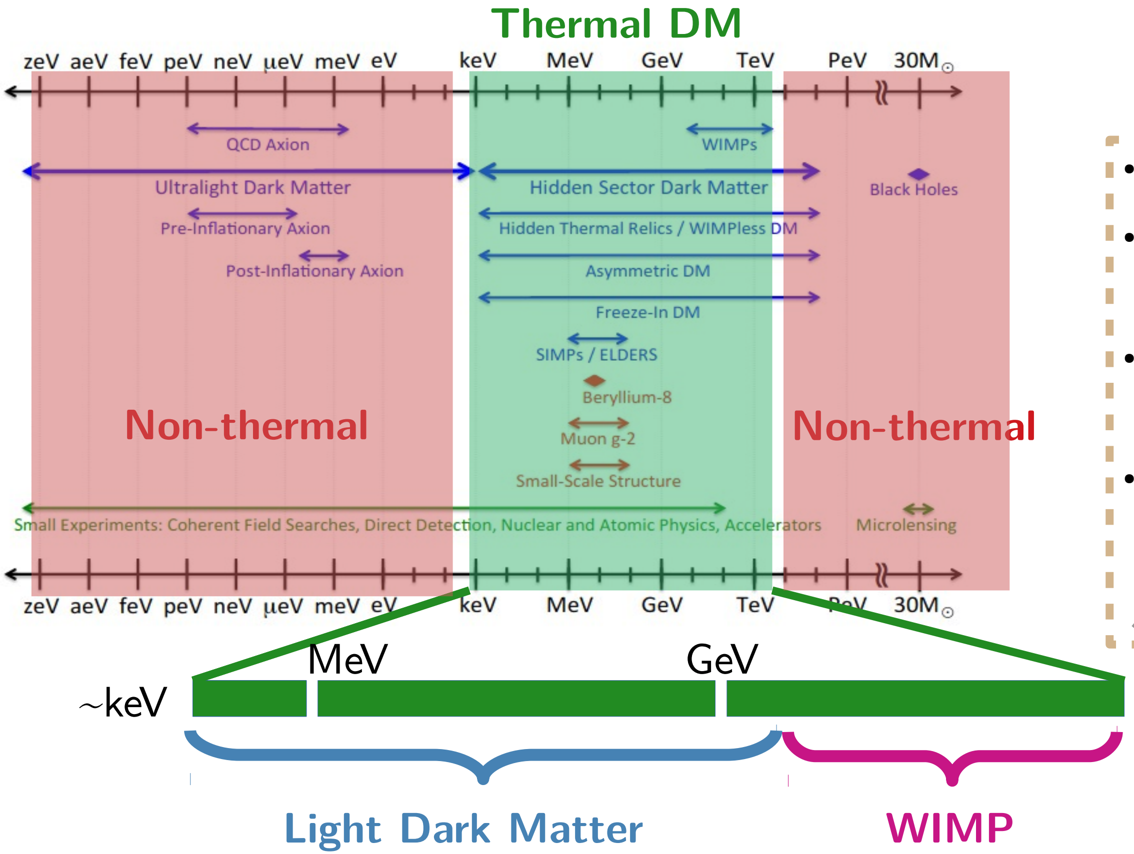
CMB Fluctuations

A large amount of not-luminous matter must populate galaxy bulks.

Dark matter candidates

- DM is an unsolved puzzle → Unknown origin and nature!

→ Modified Newtonian Gravity...
→ Non-particle candidates: MACHOs



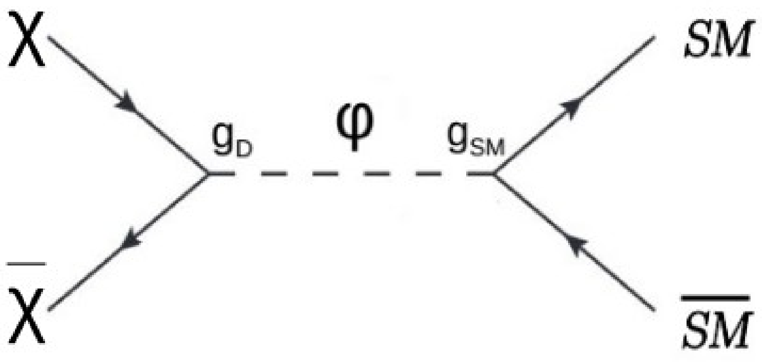
→ Particle candidates

- **Neutrinos** ✗ hot, relativistic candidates
- **QCD Axions** ✗ constrained by stellar cooling processes and supernovae dynamics, disfavoring thermal production
- **Sterile Neutrinos** ✓ observed DM abundance ✓ neutrino masses
- Weakly Interacting Massive Particles (**WIMPs**) ✓ match supersymmetric candidates (neutralino, *WIMP miracle*)

✗ null results from direct searches

Light dark matter scenarios

- No evidences for WIMP favor light DM hypotheses
- Possibility of *light dark sectors* motivates the search for a ***DM mediator (φ):***



Measured from cosmological observations

$$\langle \sigma v \rangle_{relic} \sim \frac{g_D g_{SM} m_\chi^2}{m_\phi^4}$$

<1 ($g_D g_{SM}$) → Experimentally constrained by current searches

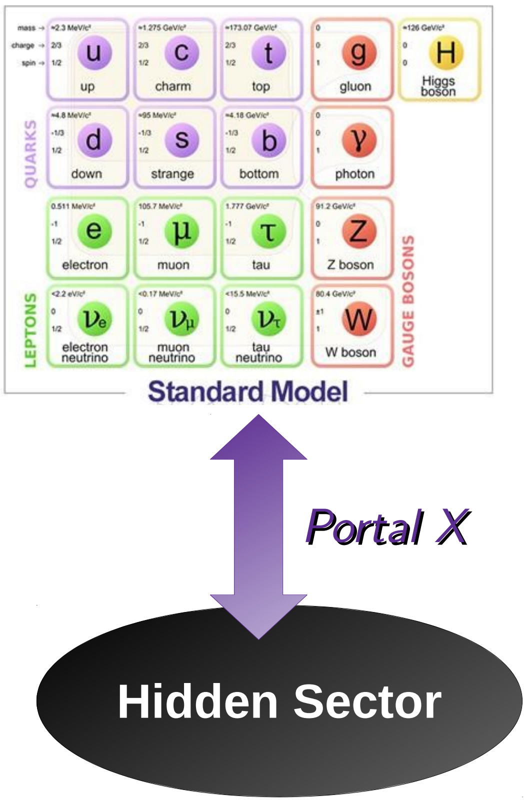
$$m_\phi^4 \leq \frac{m_\chi^2}{<\sigma v>} \text{ since g} < O(1)$$

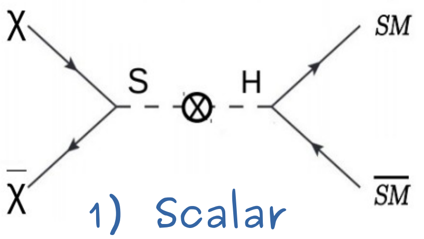
May be too small to be consistent with the mass of any known SM mediator

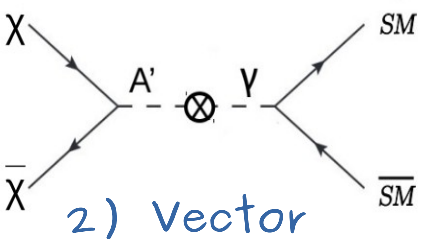
→ NEW PORTALS

Light dark sectors: portals

→ According to the spin and parity of new mediator, **3 renormalizable portals** with dimensionless couplings are allowed by Standard Model (SM) symmetries:

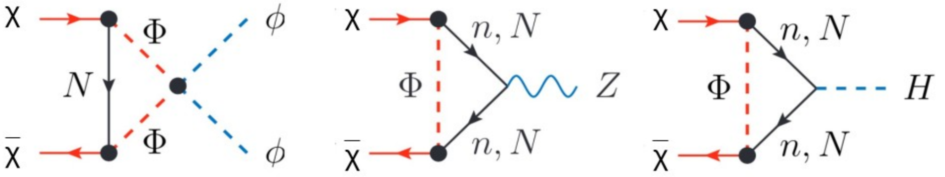






Naturally included in the context of light *dark sectors* → *much more generic*

3) Neutrino portal



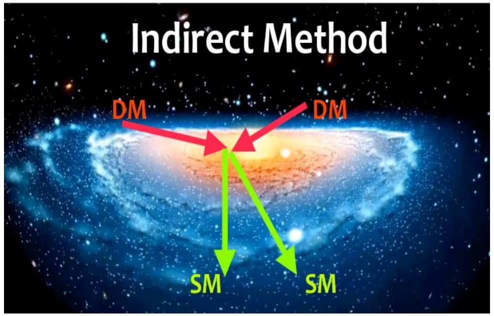
+ a not-renormalizable pseudo−scalar portal assuming Axion-Like Particles (ALPs) as mediators:

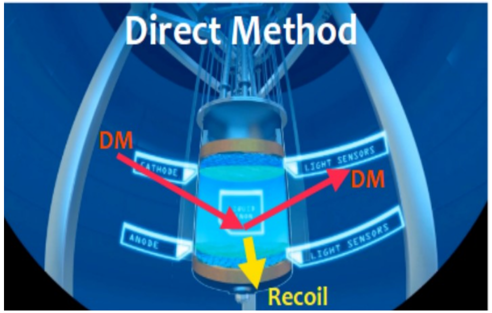
$$\mathscr{L}_a = \frac{1}{f_a} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

Dark matter detection

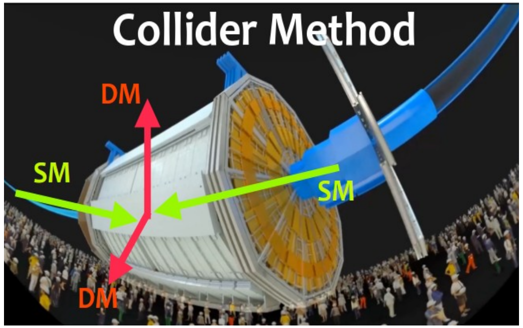
How to search for it?

1) Detect the energy of *nuclear(electron) recoil*



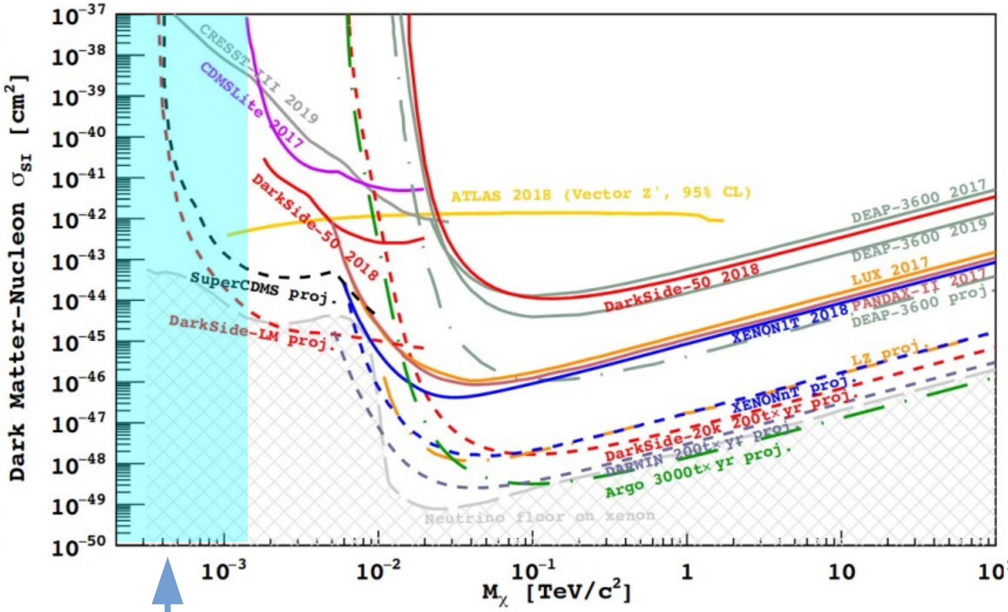


2) Detect the *flux of visible particles* produced by *DM annihilation*, *decays* or *conversions*



3) DM weakly couples to SM particles and it can be produced in *SM-particles annihilation* at ***accelerators***

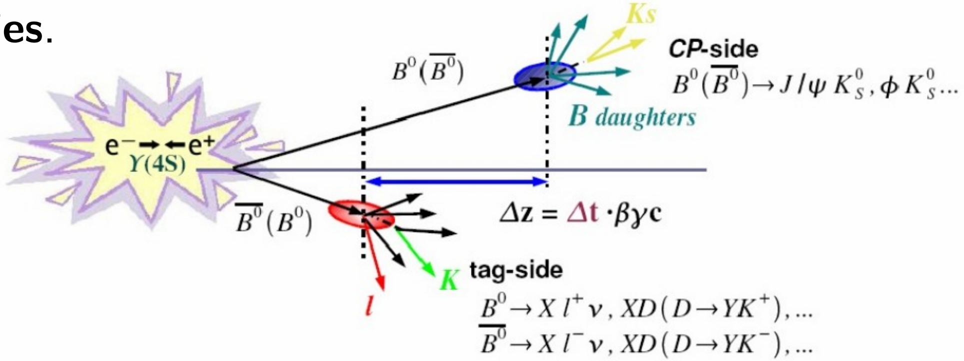
- Sensitivities and upper limits on WIMP-nucleon spin-independent scattering cross section (*European Strategy, Granada 2019*)



This presentation will focus on DM searches at B-factories

Experiments at B-factories

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

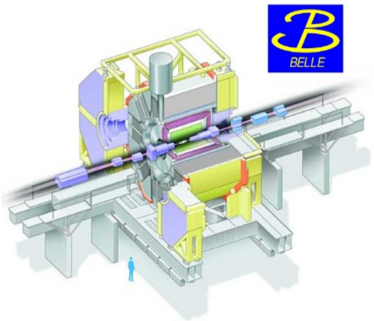


$$e^+e^- \rightarrow \Upsilon(4S)\ [10.58\ \text{GeV}] \rightarrow B\bar{B}$$

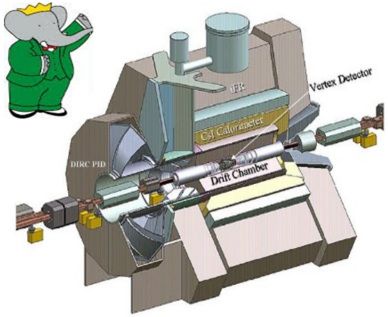
$\Upsilon(nS)$ = bound state of b quark and b anti-quark

- **Clean environment** → lower background, high resolution
- **Hermetic detector** with excellent PID capability
- Efficient reconstruction of **neutrals** (π^0, η, ...):
  - closed kinematics → study recoiling system and ***missing energy*** final states

First generation of B-factories

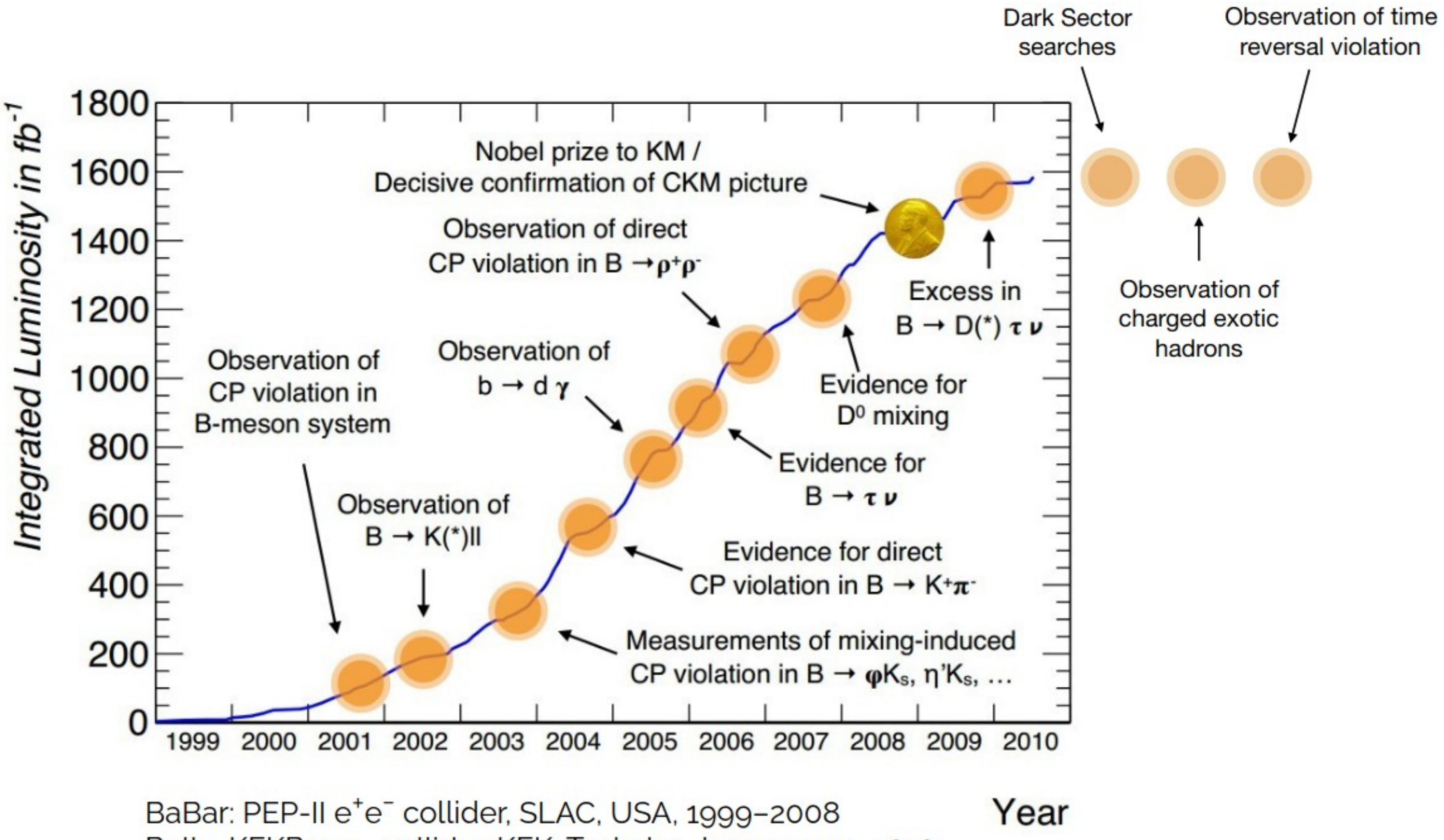


at the KEKB collider (KEK, Japan)



at the PEP II collider (SLAC, California)

Physics at B-factories

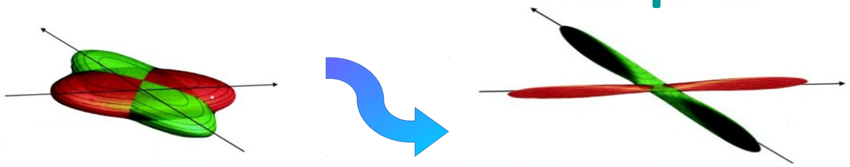


BaBar: PEP-II e^+e^- collider, SLAC, USA, 1999–2008
Belle: KEKB e+e– collider, KEK, Tsukuba, Japan, 1999–2010

SuperKEKB accelerator

- **World highest luminosity,** applying the large crossing angle (83 mrad) *nano-beam scheme* [arXiv:0709.0451].

KEKB **SuperKEKB**



I (A): ~ 1.6/1.2

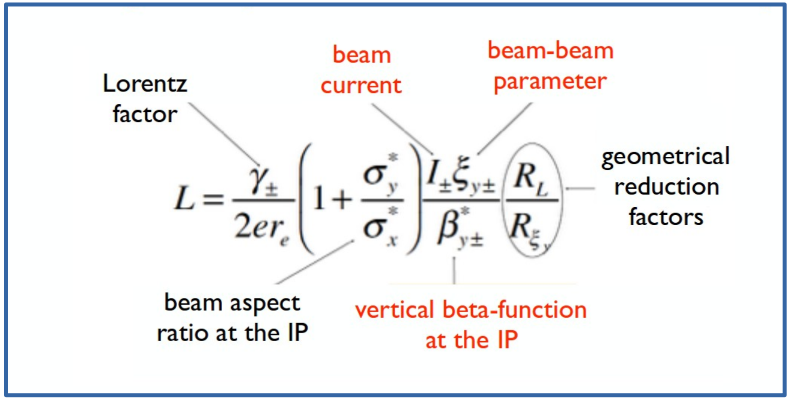
β^*_y (mm): ~ 5.9/5.9

I (A): ~ 3.6/2.6

β^*_y (mm): ~ 0.27/0.3

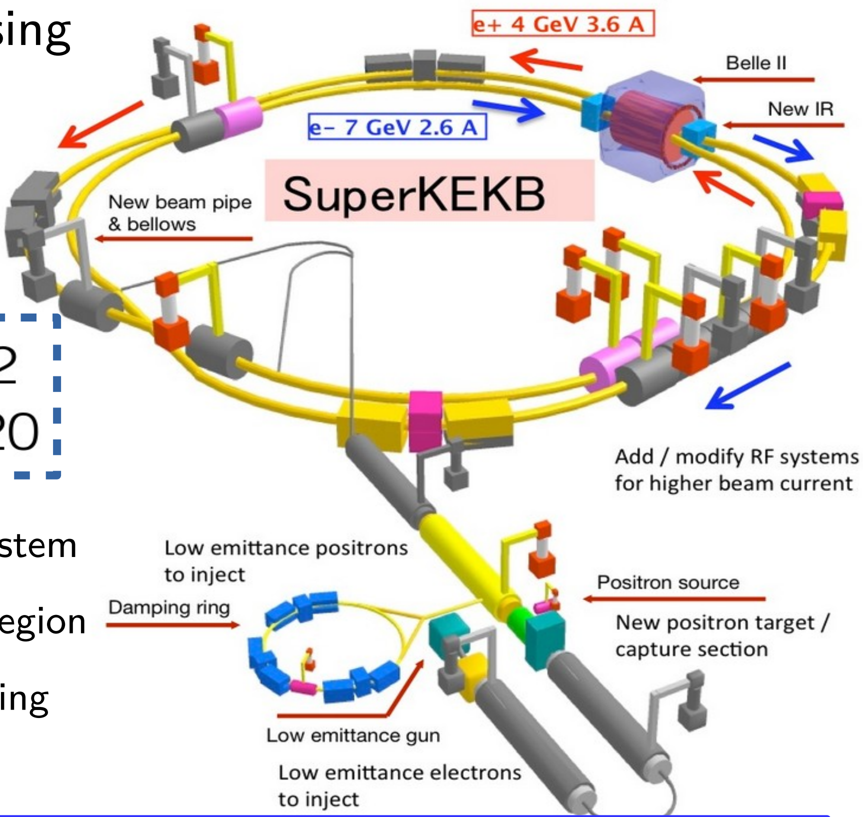
I ↑ x 2

β^*_y ↓ x 1/20



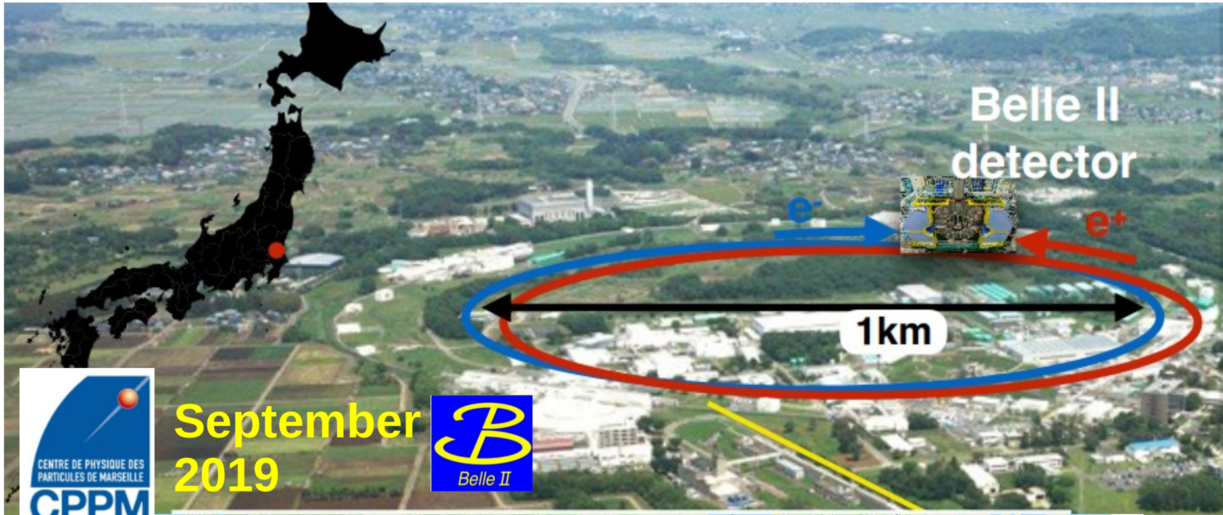
$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

- ✓ New final focus system
- ✓ New Interaction Region
- ✓ New e+ damping ring



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

Belle II collaboration



7 GeV e-, 4 GeV e+

E_{CM} Υ(4S) = 10.58 GeV + scans

Υ(4S) → B anti-B σ($b\bar{b}$) ~ 1.1 nb

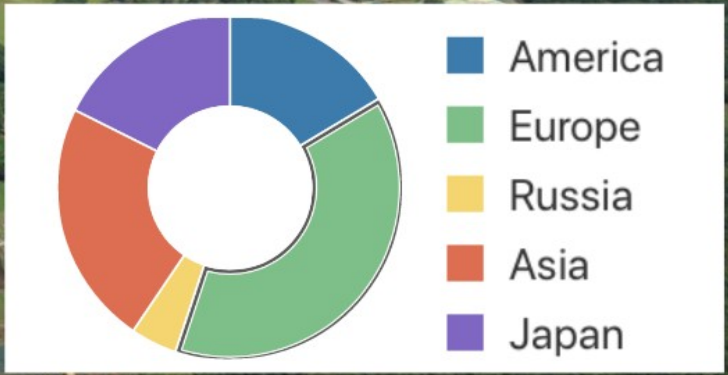
B + Charm + τ factory

September 2019

Members = 970

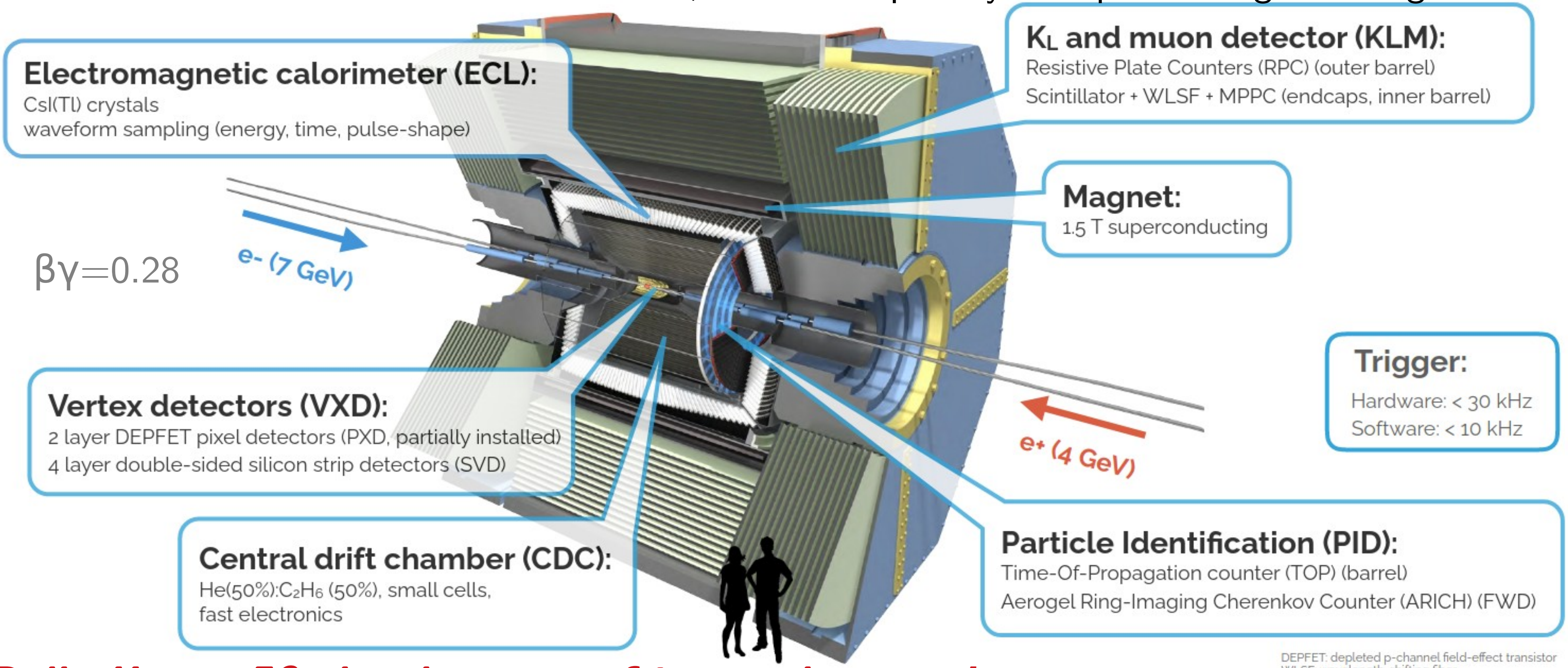
Countries = 26

Institutes = 112



Belle II detector

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



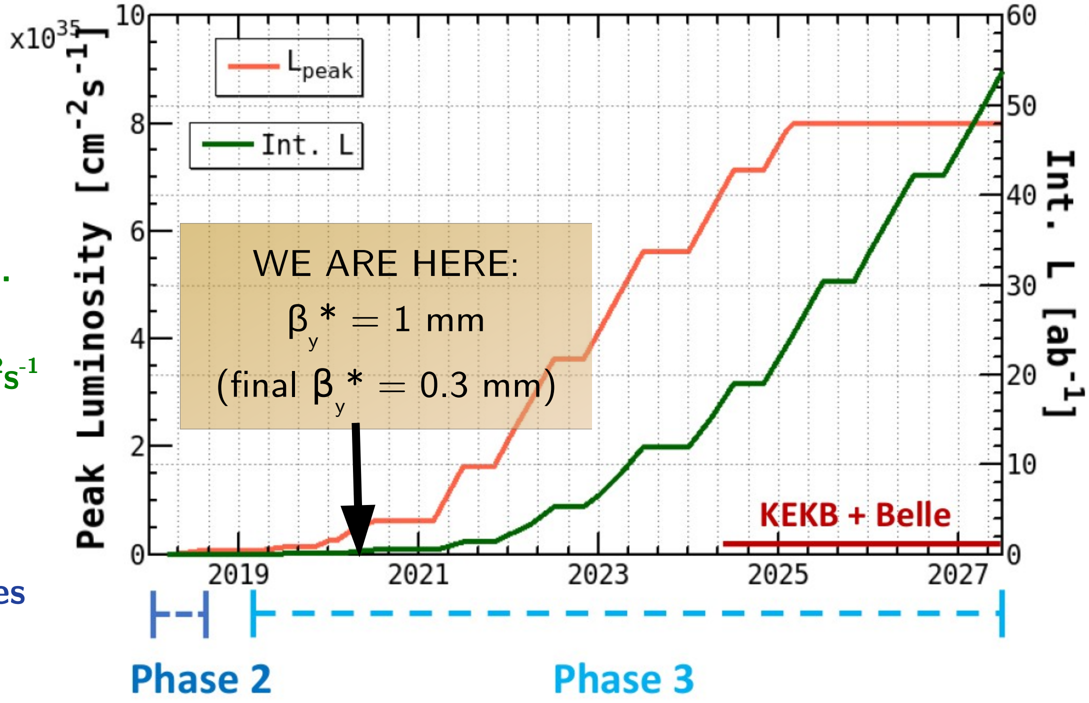
Belle II → x50 the data set of its predecessor!

Belle II data taking

Phase 2: April – July 2018

- Partial VXD installed (one ladder per each layer)
- Verify nano-beam scheme, commission the detector and the machine

- Reached inst. Luminosity 0.5×10^{34} $cm^{-2}s^{-1}$
- 0.5 fb^{-1} collected → suitable for Dark Searches



Phase 3: March 2019 – ... ~ 10 fb^{-1} collected in 2019

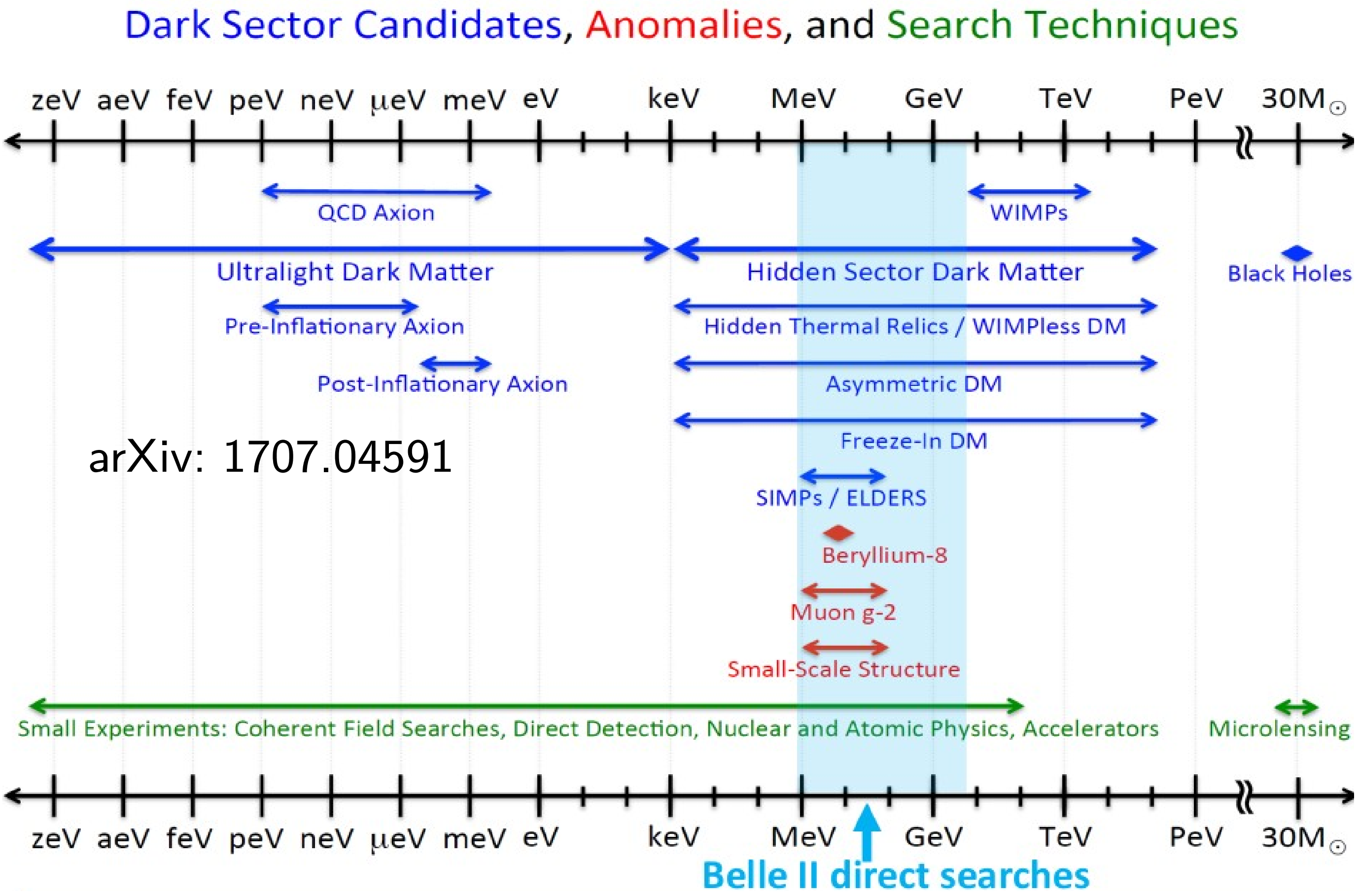
VXD detector installed

→ 4 full layers of silicon strips

→ 1 full of pixels +1/6 (installation finalized ~2021)

Phase 3 FINAL GOAL : 50 ab^{-1}

Overview of dark searches at Belle II



arXiv: 1707.04591

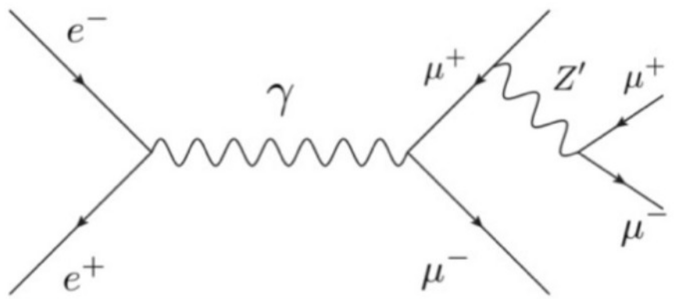
- Belle II can access the mass range naturally favored by ***light dark sectors***

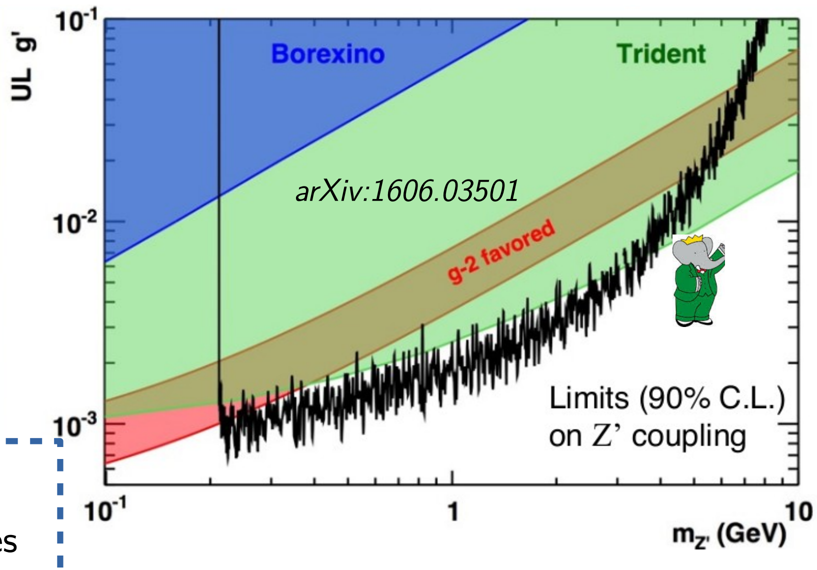
Early luminosity benchmark:

- *Vector portal:* dark photon A', **Z' boson**
- *Pseudo-scalar portal:* ALPs

Muonic dark forces: L_μ-L_τ model

- New gauge boson Z' coupling only to the **2nd and 3rd** generation of leptons (L_μ-L_τ symmetry): $\mathcal{L} = \sum_\ell \theta g' \bar{\ell} \gamma^\mu Z'_\mu \ell$
  - *If lighter accessible DM exists, Z' could decay to DM*
  - *May explain: DM abundance, $(g\text{-}2)_\mu$ and flavor anomalies $R(K^{(*)})$, $R(D^{(*)})$*
- Search for the process: $e^+e^- \to \mu^+\mu^- Z'$
- Existing limits on the Z' coupling (g'):
  - searches for visible decays $Z' \to \mu^+\mu^-$ (BaBar *arXiv:1606.03501*, CMS *arXiv:1808.03684*)
  - neutrino-nucleus scattering processes (*neutrino trident production*, CCFR experiment at Fermilab)





→ Muonic dark force at BaBar: search on 514 fb^{-1} for a peak in the dimuon invariant mass distribution in $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$ processes

Search for Z' to invisible

- Invisible signature investigated for the first time:

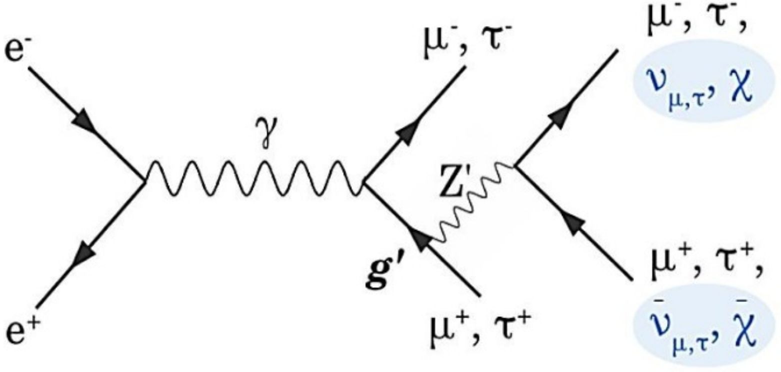
$$e^+e^- \to \mu^+\mu^- Z', Z' \to invisible$$

- Search for a peak in the mass spectrum of the recoil against a $\mu^+\mu^-$ pair in events where NOTHING else is detected.

Shuve et al. [arXiv:1403.2727]
Altmannshofer et al. [arXiv:1609.04026]

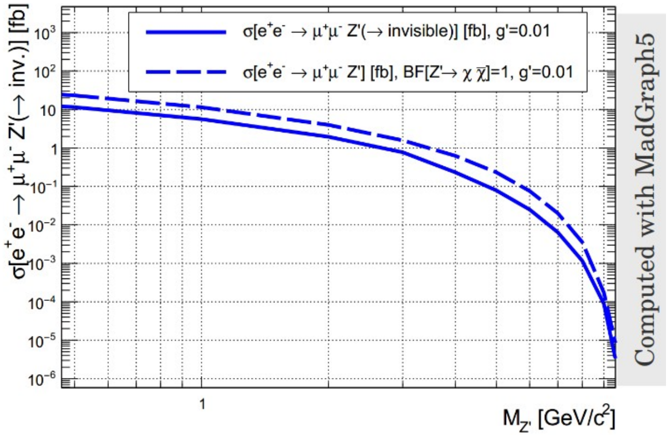
Branching ratios:

$$M_{Z'} < 2M_\mu \to \Gamma(Z' \to inv.) = 1$$
$$2M_\mu < M_{Z'} < 2M_\tau \to \Gamma(Z' \to inv.) \sim 1/2$$
$$M_{Z'} > 2M_\tau \to \Gamma(Z' \to inv.) \sim 1/3$$



$e^+e^- \to \mu^+\mu^- + missing\ energy$

- If lighter DM is accessible ($m_\chi < m_{A'}/2$), $BR(Z' \to \chi\bar{\chi}) = 1$ and SM final states are highly suppressed.



Search for LFV Z' to invisible

- Invisible signature investigated for the first time:

$$e^+e^- \rightarrow \cancel{\mu^+}\,e^+\mu^- Z', Z' \rightarrow invisible$$

- Search for a peak in the mass spectrum of the recoil against a *electron-muon* pair in events where NOTHING else is detected.

Shuve et al. [arXiv:1403.2727]

Altmannshofer et al. [arXiv:1609.04026]

Branching ratios:

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

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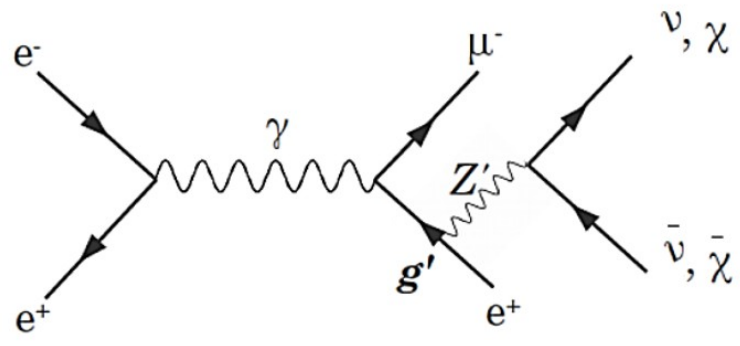


$e^+e^- \rightarrow e^\pm \mu^\mp + missing\ energy$

Galon et al. (2016), arXiv:1610.08060

- If lighter DM is accessible ($m_\chi < m_{A'}/2$), BR($Z' \rightarrow \chi\bar{\chi}$) = 1 and SM final states are highly suppressed.

- Z' could couple to leptons from different generation, allowing lepton flavor violation
- Byproduct of the flavor conserving (*standard*) Z' search
- Explore the invisible signature for the first time

Part II

- Analysis overview
- Signal study
- Background suppression
- Final selection

Why performing this search on **Belle II 2018 data**:

- No specific need of the vertex detector
- Looking for *dimuon(electron-muon) events* + *missing energy* is a model-independent, not yet explored signature
- Even with low statistics, new regions (< 212 MeV/c^2) of the Z' parameter space can be investigated

Analysis overview

BLIND ANALYSIS: the **recoil mass** spectrum has been kept hidden until the finalization of the analysis procedure to prevent any bias in the optimization.

recoil mass M_{rec}:

$$M_{rec}^2 = s + M_{\mu^+\mu^-}^2 - 2\sqrt{s}(E_{\mu^+}^* + E_{\mu^-}^*)$$

$$M_{rec} = \sqrt{M_{rec}^2}, \quad \text{if } M_{rec}^2 > 0;$$

$$M_{rec} = -\sqrt{-M_{rec}^2}, \quad \text{if } M_{rec}^2 < 0.$$

Analysis strategy: reconstruct the *recoil against* two muon tracks in events where nothing else is detected and look for a peak in the **recoil mass** over the expected background.

1) **Event selection and background suppression**: general selections against radiative QED processes + dedicated suppression procedure for $e^+e^- \to \tau^+\tau^- (\gamma)$ events

2) **Signal study:** extract the width of the simulated signal peak and compare to recoil mass resolution measured on data. Used to define the binning scheme.

3) **Data validation:** data and simulation are compared, using signal-free control samples to avoid any unintentional *unblinding*

4) **Detector performance studies**: compute efficiencies on data and assign systematic uncertainties

5) **Signal yield extraction** by applying a Poisson counting experiment technique per each **recoil mass** bin and **upper limits computation** in a Bayesian approach

Data sets

- Simulation (11th Monte Carlo production, **MC11**):
  - optimize the analysis procedure
  - compute signal efficiency and expected yields

Process	N_{evts} $[10^6]$	$\int Ldt$ $[\text{fb}^{-1}]$	Reference
$e^+e^- \to \mu^+\mu^-(\gamma)$	65	56.621	KKMC [80]
$e^+e^- \to \tau^+\tau^-(\gamma)$	36.8	40.044	KKMC
$e^+e^- \to e^+e^-\mu^+\mu^-$	140	7.406	AAFH [83]
$e^+e^- \to \pi^+\pi^-(\gamma)$	210	1372.539	PHOKHARA [84]
$e^+e^- \to e^+e^-(\gamma)$	60	0.198	BabaYaga@NLO [82]
$e^+e^- \to e^+e^-e^+e^-$	260.6	6.562	AAFH [83]

→ **Standard Z'** signal simulated with **MadGraph5**: 20k events x 18 mass samples for $m_{Z'}$ in the range [0.5 – 9] GeV/c^2 with 0.5 mass step

LFV Z' signal simulation not available → analysis optimization inherited from standard Z', model independent study on the product of cross section and efficiency ($\sigma \times \varepsilon$)

- Data: 6th reprocessing of 2018 collision data → usable luminosity for this analysis **276 pb^{-1}** due to trigger conditions
  - validate the analysis procedure
  - measure detector efficiencies and systematic uncertainties
  - extract the final results

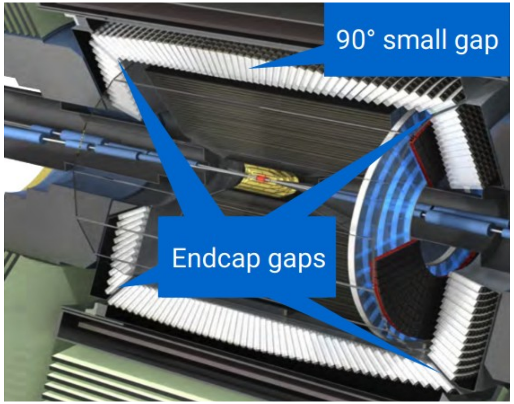
Belle II detector during Phase 2

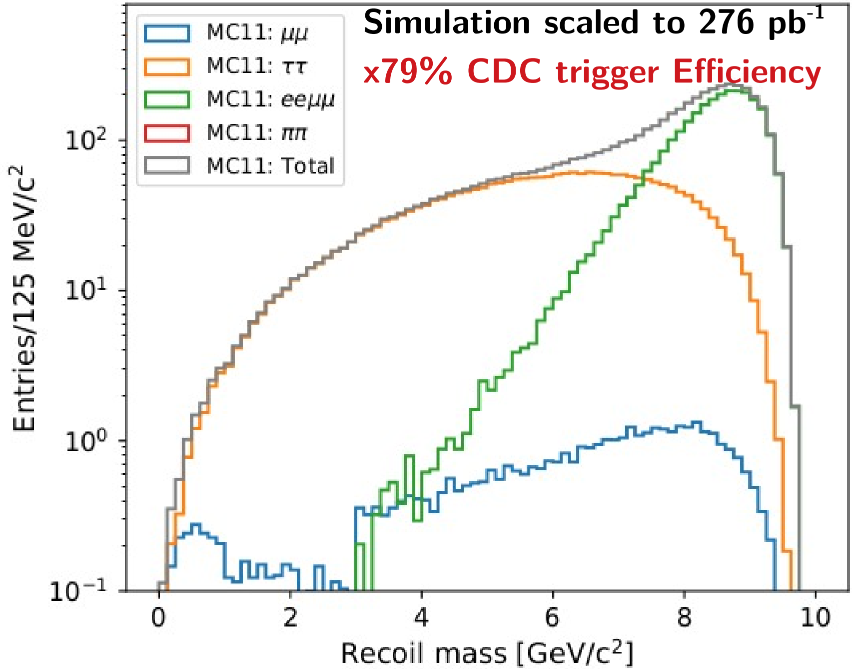
- Only 1/8 of VXD
- KLM firmware issues → no dedicated muon identification
- CDC Trigger firmware issues → reduce collection efficiency and data quality

Event selection

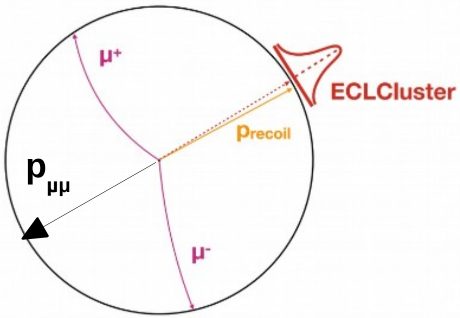
- Two good tracks coming from the interaction point and satisfying an ECL-based muon identification
  → *dimuon candidate*
- Tracks pointing to a fiducial ECL barrel region, $37° < \theta_\mu < 120°$, and similarly the recoil momentum
- **For $\mu\mu$ events CDC trigger fired in data and mimic the trigger effect in the selection: 2-track opening angle in the range [90°, 172°]**

Muon ID:
$0.15 <$ clusterE < 0.4 GeV
clusterE/p < 0.4





- Clean the ***Rest Of Event*** **(ROE):**
  → no ECL cluster (clusterE > 100 MeV) within 15° cone with respect to the reconstructed recoil momentum *(closest photon veto)*
  → no reconstructed π^0 candidate *(π^0 veto)*
  → no energy deposited in the ROE > 400 MeV *(extra energy veto)*



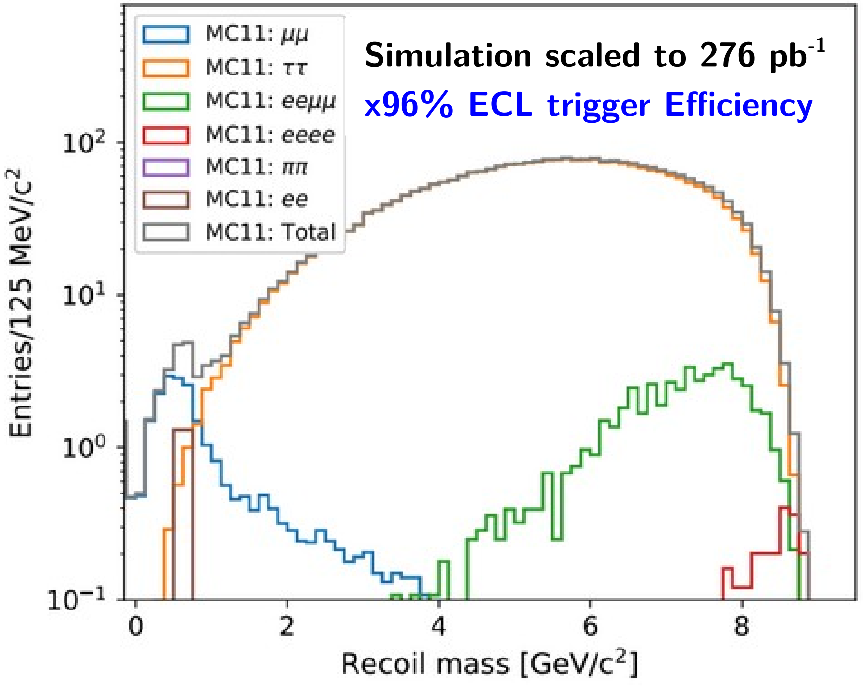
Event selection: LFV Z'

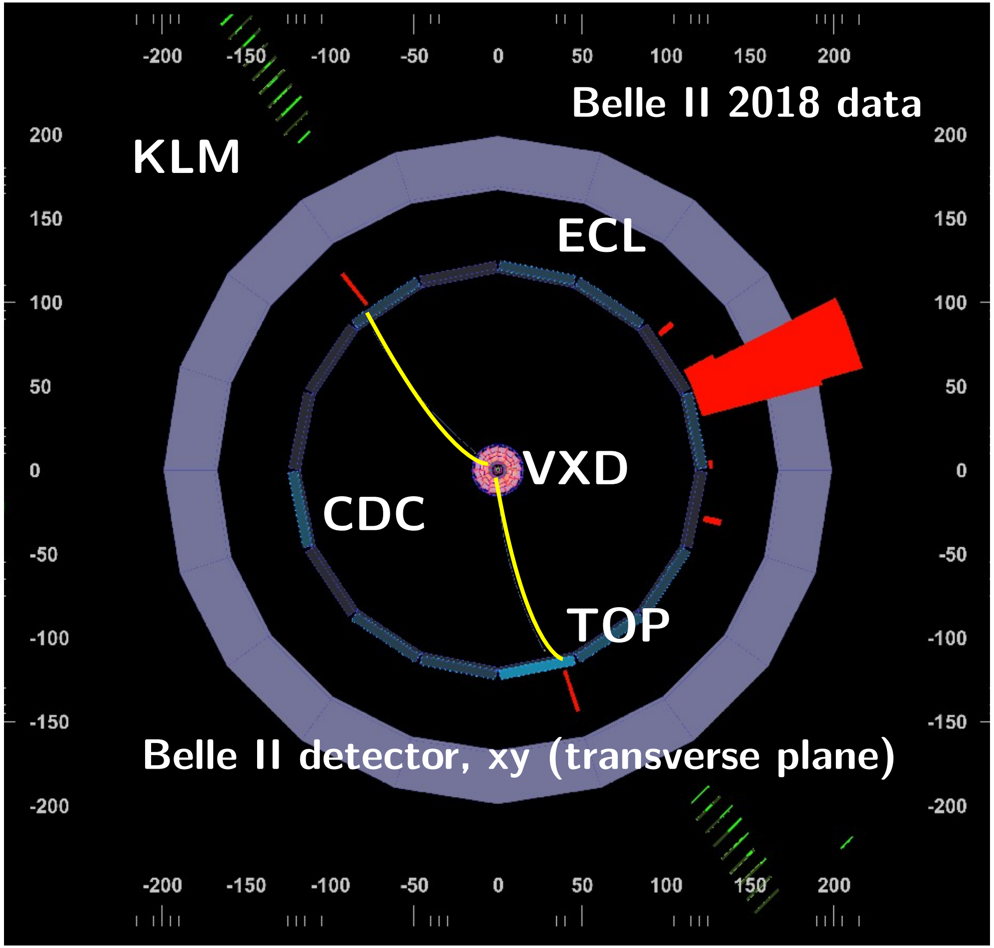
- LFV Z' inherits the same selections, replacing a muon with an electron
- **For eμ events ECL trigger fired in data and mimic the trigger effect in the selection: ECL cluster energy for electron track $>$1.5 GeV**
- Same vetos (*closest photon*, π^0 , *extra energy veto*) applied to clean the ***Rest Of Event*** (**ROE**)

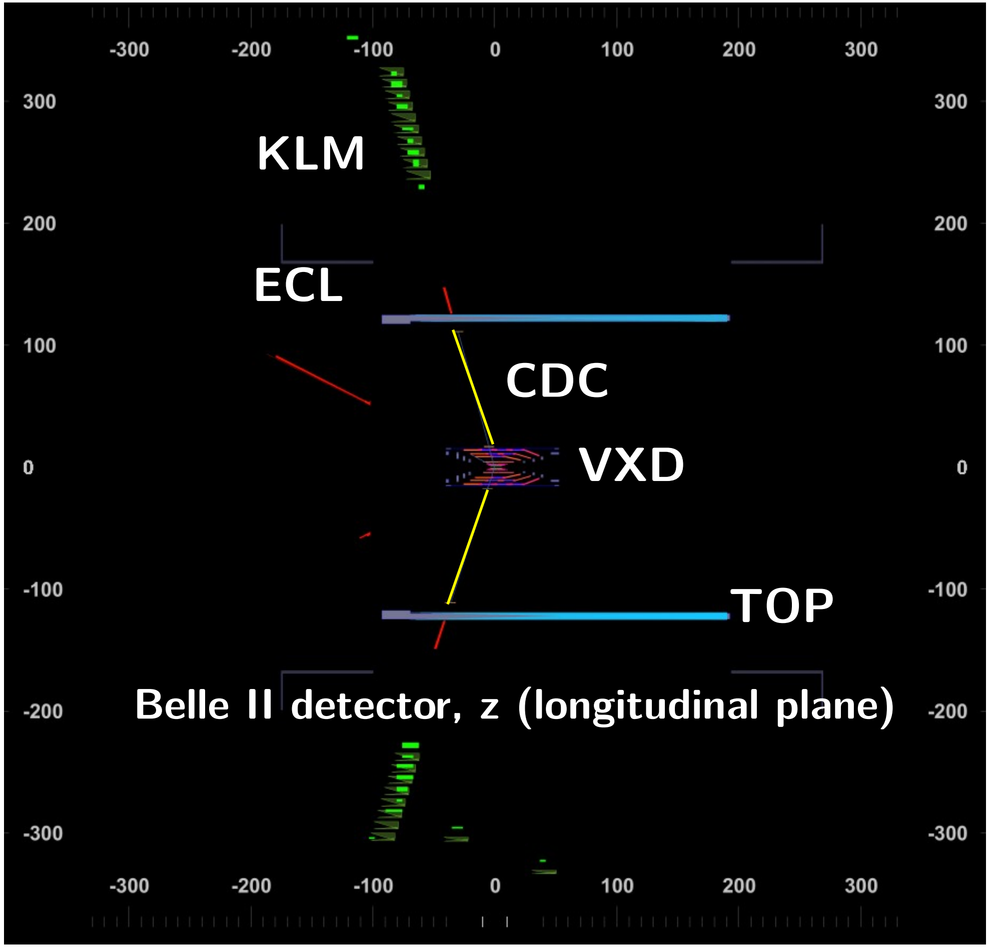
Muon ID:
clusterE/p $<$ 0.4

→

Electron ID:
0.8 $<$ clusterE/p $<$ 1.2




Belle II 2018 data
KLM
ECL
VXD
CDC
TOP
Belle II detector, xy (transverse plane)


KLM
ECL
CDC
VXD
TOP
Belle II detector, z (longitudinal plane)

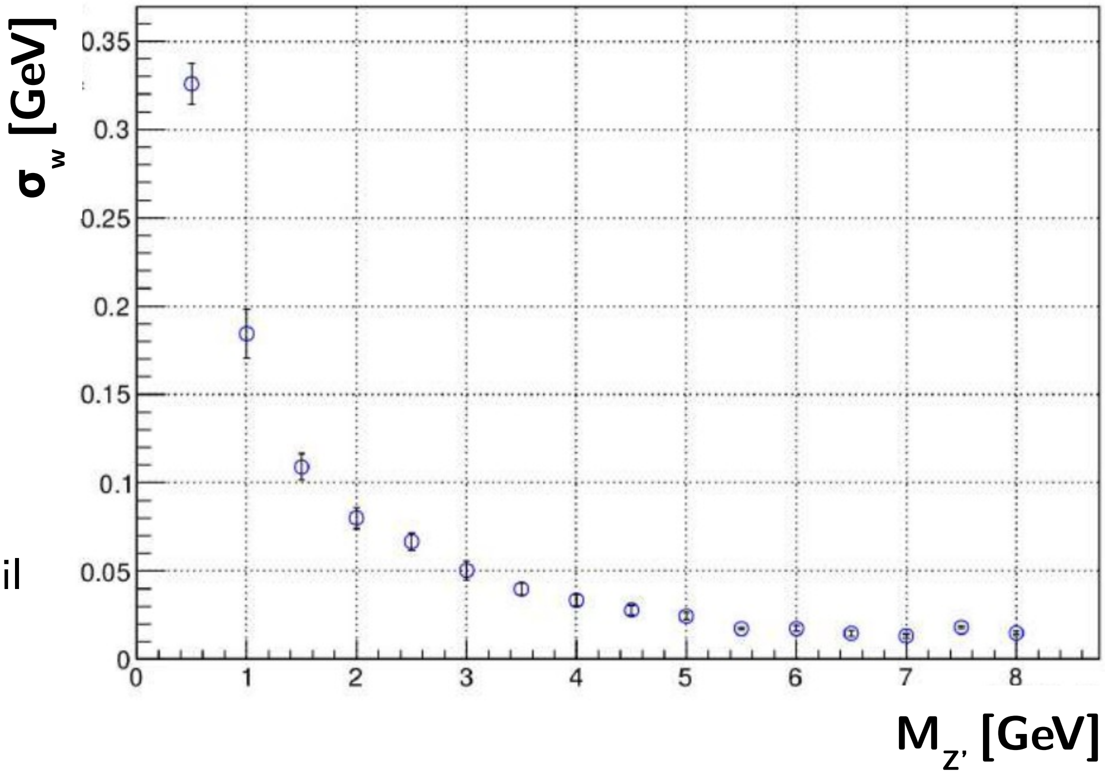
Signal shape study

- Fit the signal recoil mass spectrum (Z' peak, per each generated mass point) on MC simulation after general selections:

Fitting model: Crystal ball shape function (CB) + Gaussian function
Extract the signal peak width:

$$\sigma_w = \sqrt{frac \times \sigma^2_{\text{CB}} + (1 - frac) \times \sigma^2_{\text{Gauss}}}$$

- Compare the recoil mass resolution between data and simulation on μμγ control samples → MC simulation found consistent with data
- Recoil mass resolution used to define the recoil mass windows where to count events (*binning scheme*)



Background rejection

Background from QED processes that can mimic the final state of 2 muons + missing mass because of acceptance or undetected particles:

- $e^+e^- \to \mu^+\mu^- (\gamma)$,
- $e^+e^- \to \tau^+\tau^- (\gamma)$, $\tau \to \mu\nu\nu$
- $e^+e^- \to \mu^+\mu^- e^+e^-$

> - affects the low mass range $M_{rec} < 3$ GeV, rejected by general selections
> - **Dominant contribution in the recoil mass range ~ 3-7 GeV → needs dedicated suppression**
> - Affects high mass spectrum $M_{rec} > 7$ GeV where sensitivity is also limited by the decreasing production cross section

- Selections optimization by maximizing the *Punzi figure of merit* in each recoil mass bin.

$$FOM_{Punzi} = \varepsilon/(a/2 + \sqrt{B}),\ a=1.64\ (90\%\ CL)$$

- Number of surviving events and signal efficiencies computed for each recoil mass bin →

Binning scheme:

I. Contiguous bins have been defined interpolating the fitted σ_w to cover all the recoil mass spectrum

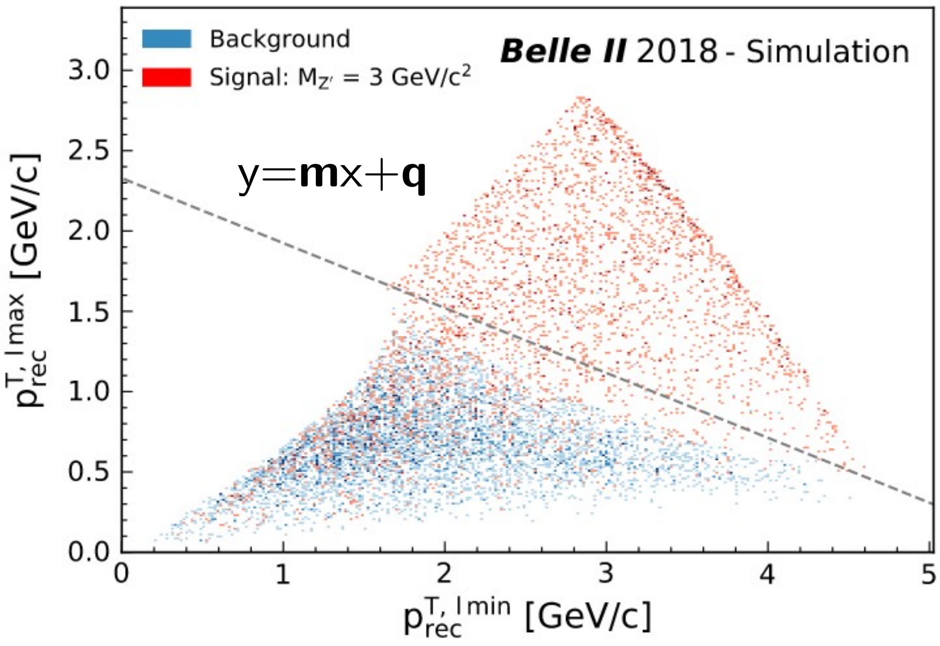
II. Punzi-optimized bin-widths = $\pm 2\sigma_w$

τ-suppression procedure

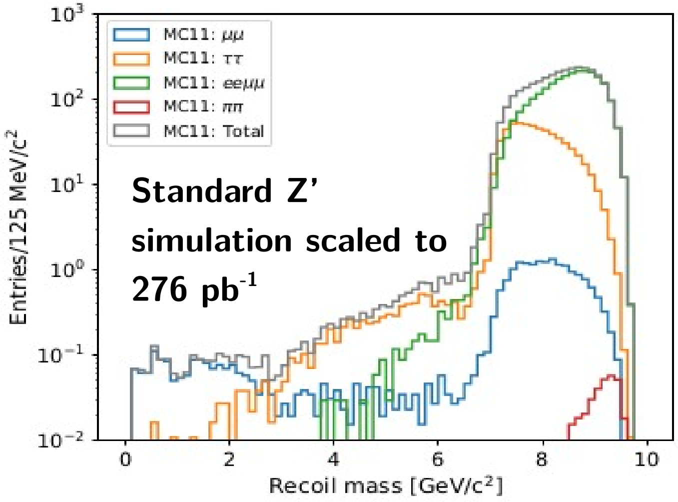
- **Discriminant variables:**
  - $\mathbf{p^{T,max}}_{\mathbf{rec}}$, $\mathbf{p^{T,min}}_{\mathbf{rec}}$, transverse component of recoil momentum along the direction of the maximum/minimum lepton momentum
  - $\mathbf{p^{T}}_{\mathbf{\mu\mu}}$, dimuon candidate transverse momentum

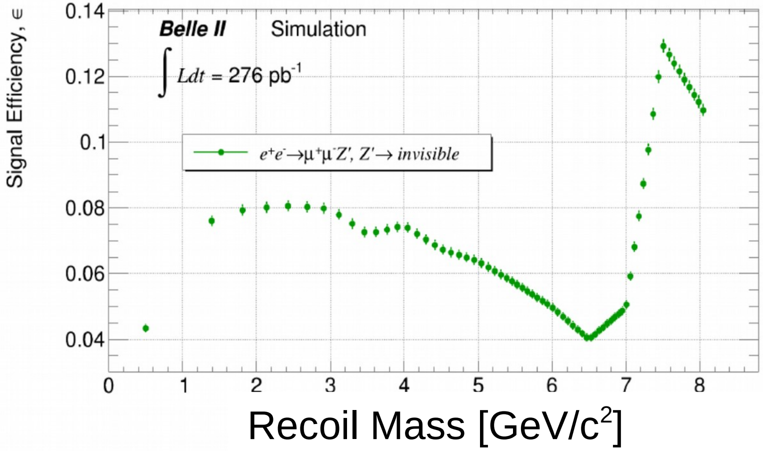
- Optimal selections found by simultaneously maximizing the Punzi FOM
- Interpolated as a function of M_{rec}
- Achieved rejection factor ($N_{bkg}^{before}/N_{bkg}^{after}$) up to 400; relative efficiencies ~40-70%

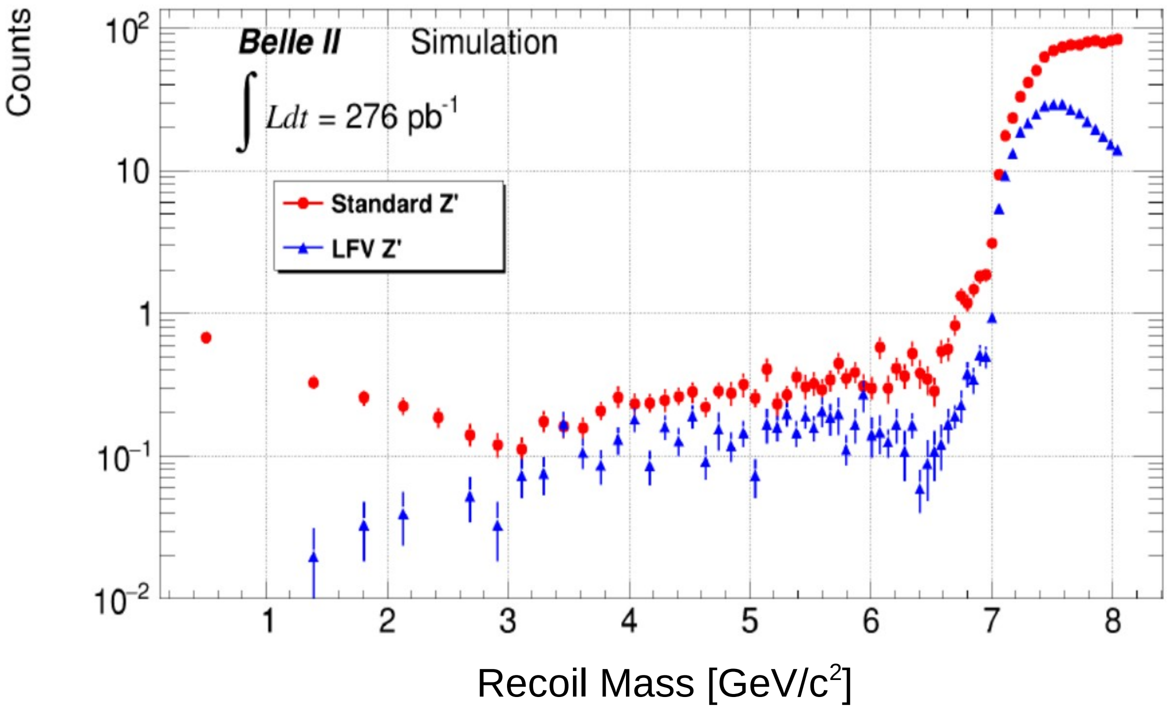
➔ Z' is *final state radiation* from one muon leg, missing momentum in ττ events is due to neutrinos from both muons



Final selection results







Part III

- Data validation
- Systematic uncertainty evaluation

Data validation: overview

- Impact of the selections studied on signal-free **control samples** in data and MC:

1) **ee sample: Bhabha events, $\tau\tau$ ($\tau \to$ e) pairs**

- check τ pair background ($3 < M_{rec} < 7$ GeV)
- assign a systematic for the τ suppression procedure

→ unintentional unblinding avoided by complementary ECL PID for electrons

2) **$\mu\mu\gamma$, *eeγ*, *e$\mu\gamma$ samples: r*adiative dilepton events**

- check low recoil mass region, $M_{rec} < 3$ GeV
- validate the trigger by using the complementary ECL line ($>$ 1 GeV energy deposit)

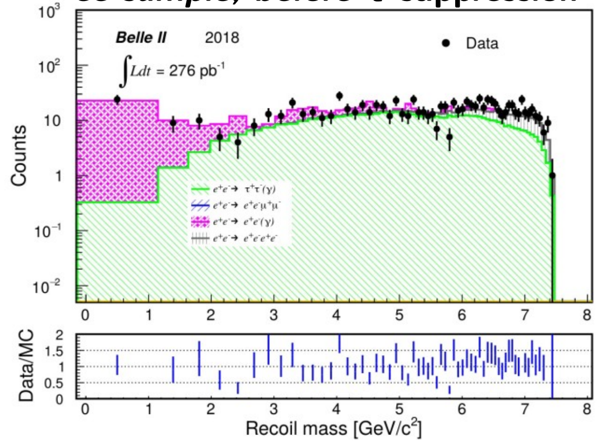
→ unintentional unblinding avoided by explicitly asking for a reconstructed photon

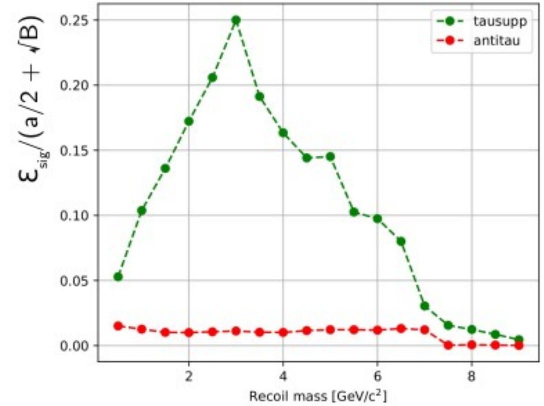
3) **$\mu\mu$, *eμ samples* with reversed τ-suppression procedure**

- analogous to the background expected for unblinded samples
- assign a systematic uncertainty on the expected background level

→ signal efficiency negligible, select sideband

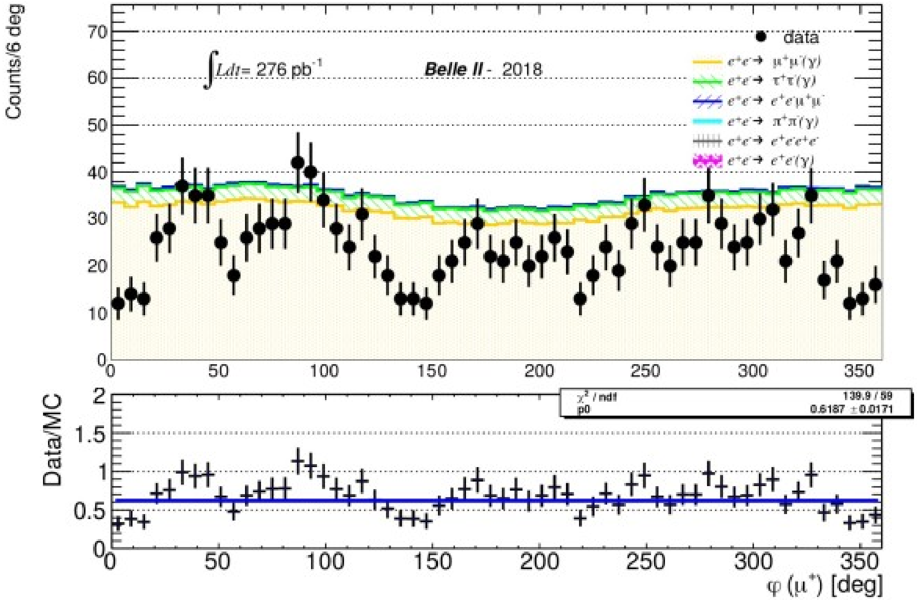
***ee sample, before* τ-suppression**





Data validation: results

- Observed data-MC discrepancy of **-35% in μμ events** (*standard Z'*), **-10% in eμ events** (*LFV Z'*);
- 10% data-MC difference understood and assigned to track finding performances;
- For μμ events, residual **–25%** data-MC mismatch **unexplained.**



➔ Scale the MC simulations by **0.65 for μμ events** and **0.90 for eμ events**

Detector performance studies

- Real detector $!=$ simulated detector

$\rightarrow$ GOAL: Estimate the **discrepancy** in detector efficiencies and resolutions between data and simulation, and based on this measurement:

  - correct for additional inefficiencies observed in data or not simulated detector effects
  - assign a systematic uncertainty

...for the Z' analysis, three main contributions affect the selection efficiency:

- Trigger selection
- Track reconstruction efficiency
- Particle identification selection

$\rightarrow$ Phase 2 data mainly exploited to understand a new detector at a new machine
$\rightarrow$ Wide program of performance studies in parallel to the analysis effort

Systematic uncertainties

- List of systematic uncertainties entering the cross section measurement for the μμ and eμ channels respectively:

$$\sigma_{Z'} = \frac{N_{\rm obs} - B_{\rm exp}}{L \times \epsilon_{\rm sig}}$$

Source	Affected quantity	$\mu\mu$	$e\mu$
Trigger efficiency	ϵ_{sig}	6%	1%
Tracking efficiency	ϵ_{sig}	4%	4%
PID	ϵ_{sig}	4%	4%
Luminosity	L	0.7%	0.7%
τ suppression (background)	B_{exp}	22%	22%
Background before τ suppression	B_{exp}	2%	2%
Discrepancy in $\mu\mu$ yield (signal)	ϵ_{sig}	12.5%	-

- ✓ Trigger, Tracking and Particle ID: from performance studies
- ✓ from offline luminosity measurement [arXiv:1910.05365]
- ✓ τ-suppression: from validation on ee sample (statistically dominated)
- ✓ Background yields: from data-MC agreement in control samples with reversed τ-suppression selection

- Conservatively assign half of the measured data-MC discrepancy due to an unknown source (→ **±12.5%**) as systematic uncertainty in the **signal efficiency.**

Part IV

- Upper limit computation
- Phase 2 results
- Summary and outlook

Upper limit computation

- Signal yields extracted by applying a Poisson counting experiment technique, in each recoil mass bin, after the final selections
- Upper limits on the cross-section $\sigma_{Z'}$ are computed in a Bayesian approach

$\rightarrow$ after τ-suppression, expected events scaled to data luminosity < 1
$\rightarrow$ too low statistics to fit the recoil mass distribution

Upper limit computation in the Bayesian approach

(BAT software framework: https://doi.org/10.1016/j.cpc.2009.06.026)

- N_{obs}, B_{exp}: Poissonian likelihood
- Prior distribution for Z' cross section: positive, flatly distributed in 0-10^5 fb

$$\sigma_{Z'} = \frac{N_{\text{obs}} - B_{\text{exp}}}{L \times \epsilon_{\text{sig}}}$$

- Systematic uncertainties: modeled with Gaussian functions with width equal to the size of the estimated effect

  $\rightarrow$ integrate over nuisance parameter priors (*marginalization*)

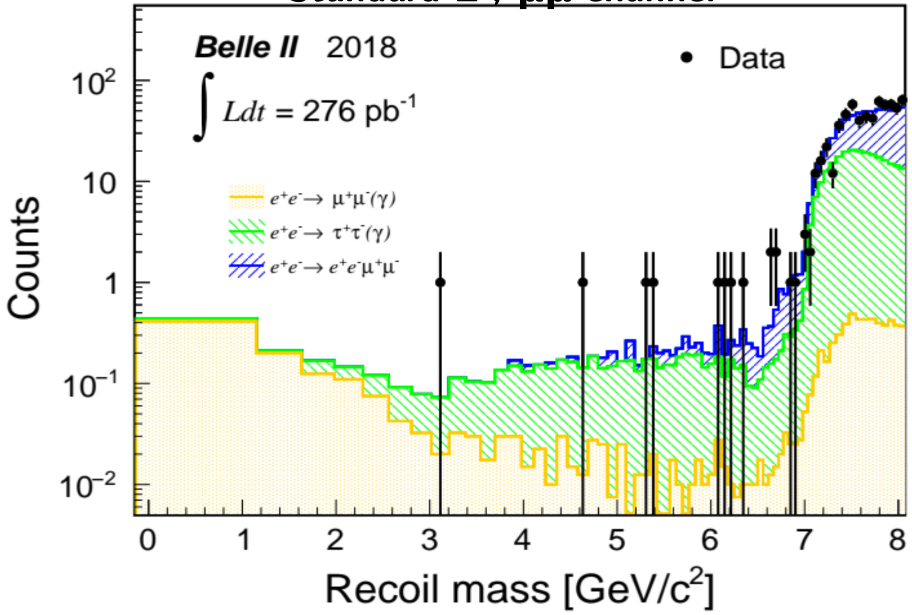
  $\rightarrow$ integrate the likelihood until the value of the integral reaches the wanted credibility level (0.90)

Results on Phase 2 data

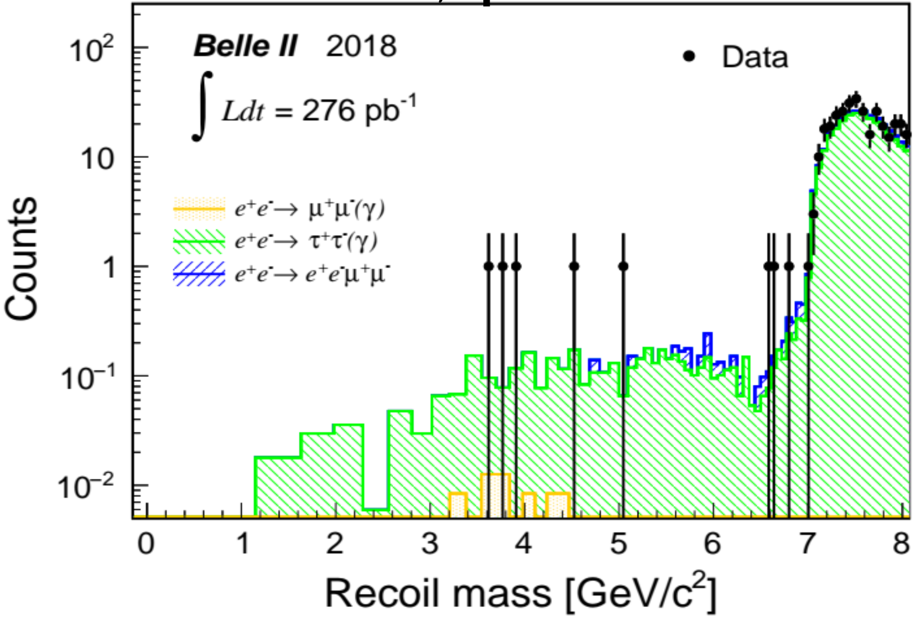
BOX OPENING

- Recoil mass spectra after the final selections for Belle II 2018 data and MC:

Standard Z', μμ channel



LFV Z', eμ channel



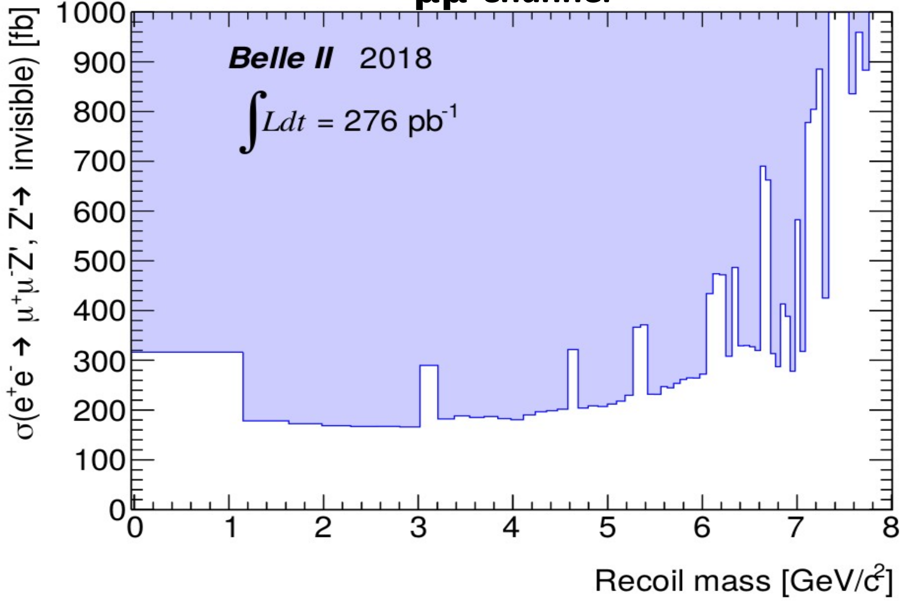
→ μμ (eμ) expected yields scaled for the measured trigger efficiency of 0.79(0.96) and data/MC ratio of 0.65(0.90) from validation studies

Phys. Rev. Lett. 124, 141801 – Published 6 April 2020

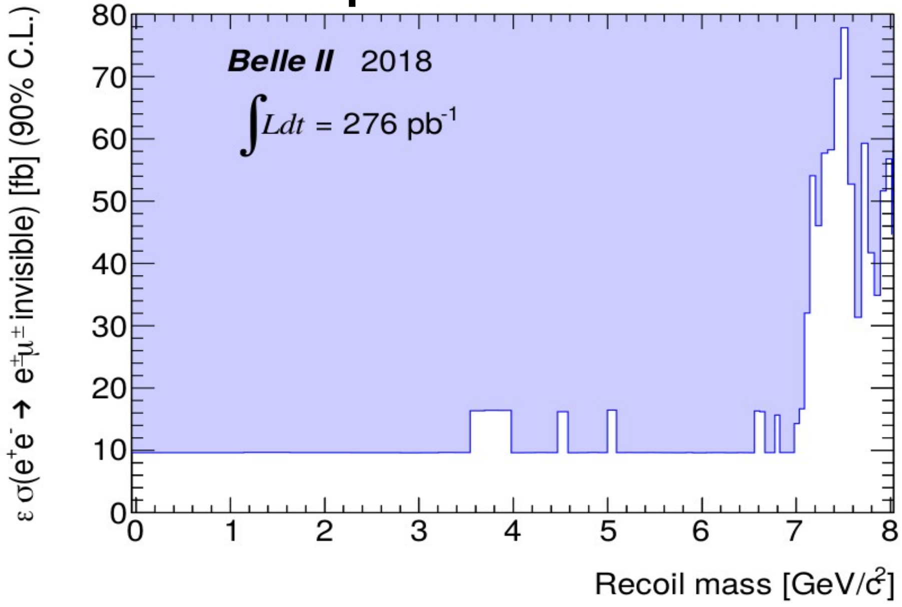
Upper limits: results

- First upper limits on the cross section for the processes $e^+e^- \rightarrow \mu^+\mu^- +$ ***missing energy*** and first model-independent constrain on the product of (efficiency x cross section) for the process $e^+e^- \rightarrow e^+\mu^- +$ ***missing energy***

μμ channel



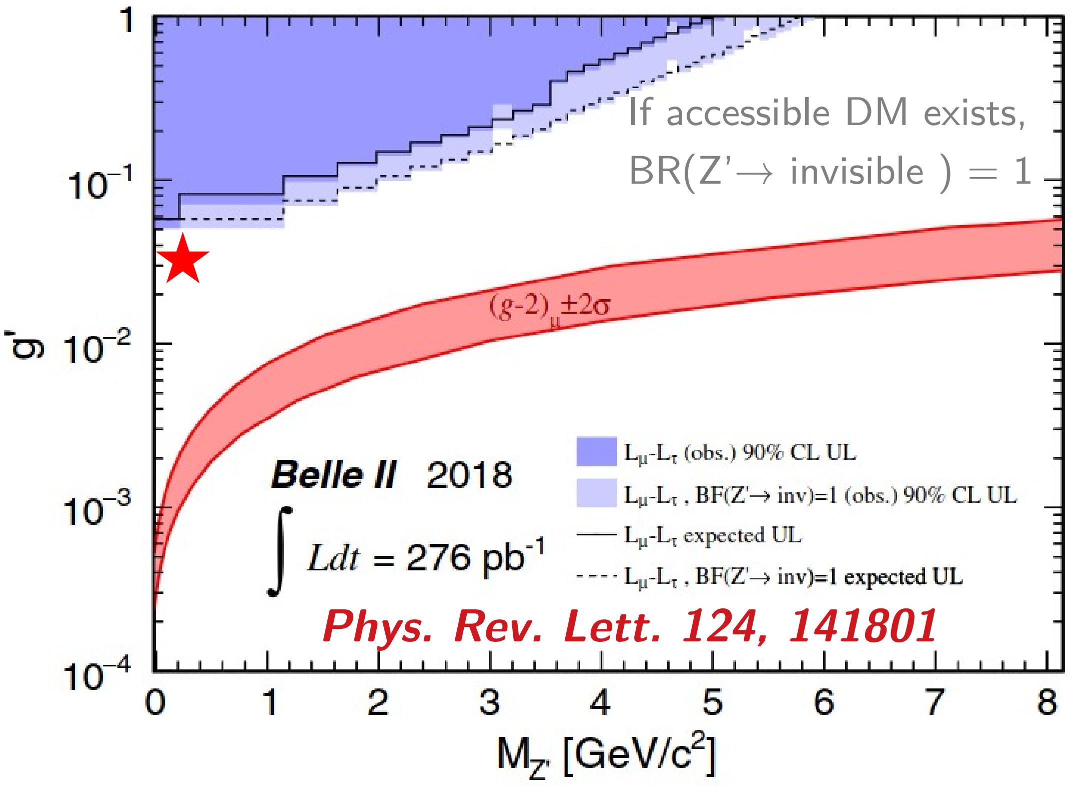
eμ channel



Phys. Rev. Lett. 124, 141801 – Published 6 April 2020

First invisible Z' upper limits

- Upper limits on the cross section for the processes $e^+e^- \rightarrow \mu^+\mu^-$ + ***missing energy*** translated in terms of ***invisible Z'*** coupling constant g' (using MadGraph5 for numerical computation)



★ *Already with few statistics a new region of the Z' parameter space (L_μ-L_τ model) can be explored*

→ never reached before by visible searches ($M_{Z'}$ < 212 MeV)

Summary

- This search is the **first physics result from the Belle II experiment**

PHYSICAL REVIEW LETTERS **124,** 141801 (2020)

Editors' Suggestion | Featured in Physics

Search for an Invisibly Decaying Z' Boson at Belle II in $e^+e^- \to \mu^+\mu^-(e^\pm\mu^\mp)$ Plus Missing Energy Final States

Belle II

→ First upper limits on the production cross section for processes **$e^+e^- \to \mu^+\mu^-(e^+\mu^-)$ + missing energy** are measured

→ First upper limit on Z' coupling constant g' within the L_μ-L_τ model below the dimoun invariant mass threshold

Results on 2018 data are mostly limited by the low statistics and the performances of the Phase 2 detector.

Phase 3 has started → larger statistics and better data quality are coming...

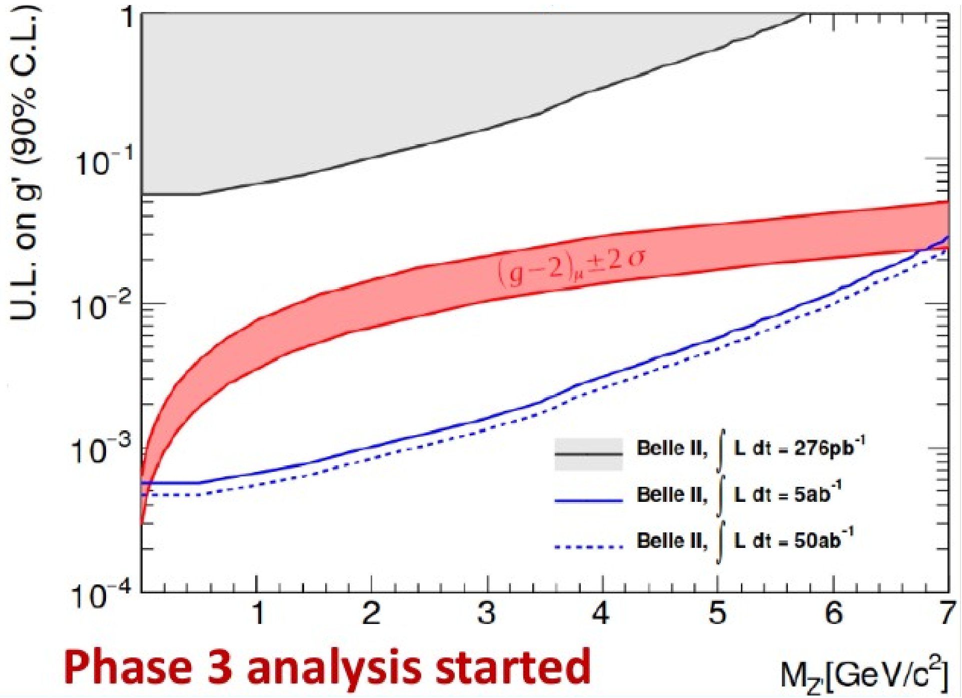
Outlook

Phase 3 prospects

- Luminosity increase (in 2020 collected > 13/fb ... x40 Phase 2 data set)
- Complete detector installed
- Solved firmware issues

  → *improved data quality*

  → *improved data-MC agreement, reduced systematic uncertainties*



Phase 3 analysis started

The unprecedented statistics of the full Belle II data set will allow to pursue a rich program in flavor physics as well as in dark sector searches (Z' parameter space fully explored, dark photons, ALPs and much more on ***The Belle II Physics Book, arXiv:1808.10567***)

LUMINOSITY
IS
COMING

Thanks for your attention.

Backup

My contributions

- The analysis effort has been shared with the Z' analysis group which includes master and PhD students and dark sector experts among the Belle II members.
- Being one of the 2 PhD students that has developed this search as thesis project, I have been working on almost all the analysis steps:
  1) Event reconstruction, general selections and *ntuple* production
  2) Study of the discriminant variable (comparing signal and background distributions for different variables)
  3) Validation procedure: control sample selection, comparison between data and simulation, results
  4) Trigger validation on radiative dilepton samples

$\rightarrow$ For the detector performance studies, I have been the main author of the measurement of the track reconstruction efficiency discrepancy between data and simulation, on τ pair events

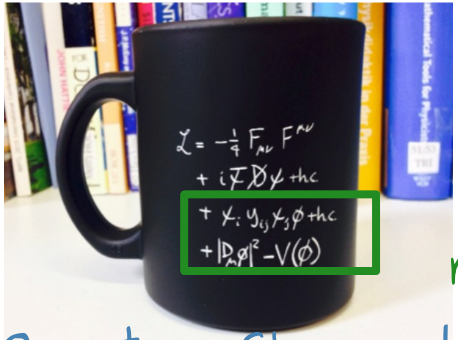
$\rightarrow$ I am working at the Phase 3 analysis preparation, devising the new background yields estimation directly from data (*sideband extrapolation technique*)

$\rightarrow$ I am working at track reconstruction efficiency study also on early Phase 3 data

Standard model and beyond

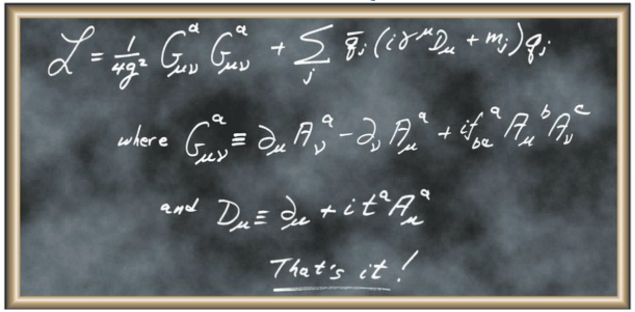
- The Standard Model (SM) of elementary particles successfully describes the matter content of our Universe and its interactions:

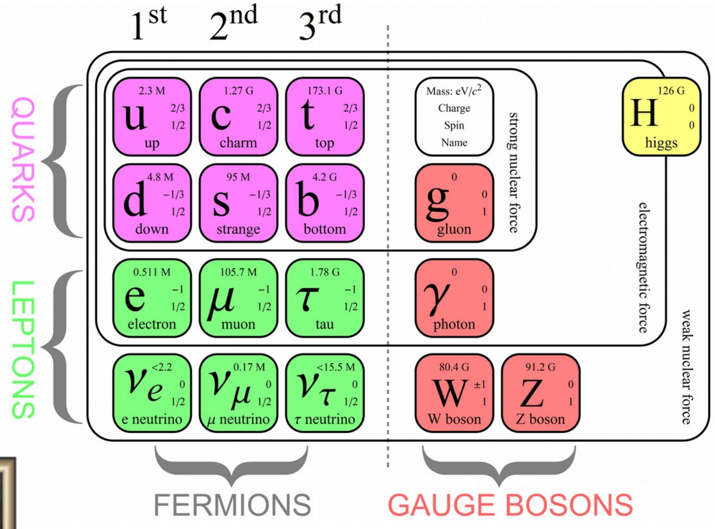
Electro-weak unification



\+ Higgs mechanism

Quantum Chromodynamics





- BUT it is still an incomplete theory, leaving many open issues unexplained:
  - Gravity not included
  - Neutrino masses
  - Baryon-antibaryon asymmetry
  - Mass hierarchy problem
  - **23% of Universe matter seems not to interact with SM particles if not gravitationally, hence being *dark***

Searching for physics beyond the SM is a well motivated effort.

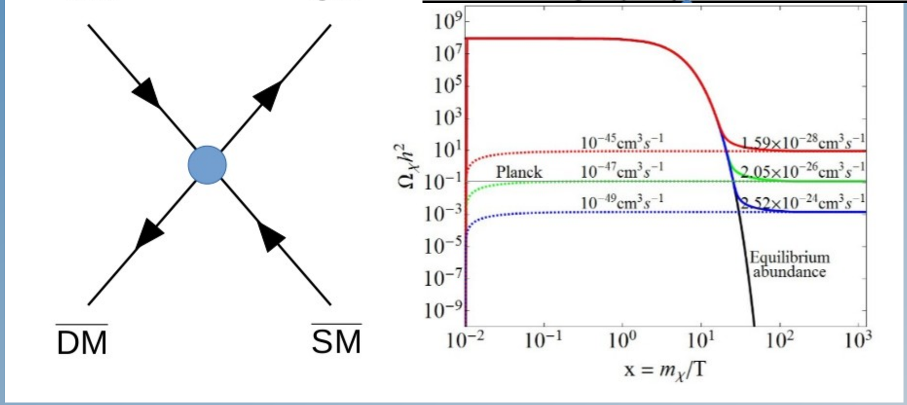
Dark matter puzzle

- DM origin and nature is still unknown:
  - I. Modified Newtonian Gravity
  - II. Something completely different and unexpected (not-particle DM candidates)
    - $\rightarrow$ **M**assive **A**strophysical **C**ompact **H**alo **O**bjects (*MACHOs*): highly condensed object as neutron stars, brown and white dwarfs, **primordial black holes** [arXiv:1906.05950]
  - III. Exotic subatomic candidates: similarly to the SM, rich *dark sectors* with new particles content may exist.

Thermal relic density: *freeze out* mechanism

- In the early universe SM particles are in equilibrium with DM

$$n_{\rm DM}^{(\rm eq.)} = \int \frac{d^3p}{(2\pi)^3} \frac{g_i}{e^{E/T} \pm 1} \sim T^3$$



- As the universe expands, the DM number density is exponentially suppressed $\rightarrow$ no more DM annihilations are possible
- DM abundance is frozen at the **relic density**:

Thermal DM $\langle\sigma v\rangle = 10^{-26}\ \mathrm{cm^3 s^{-1}}$

Dark matter candidates

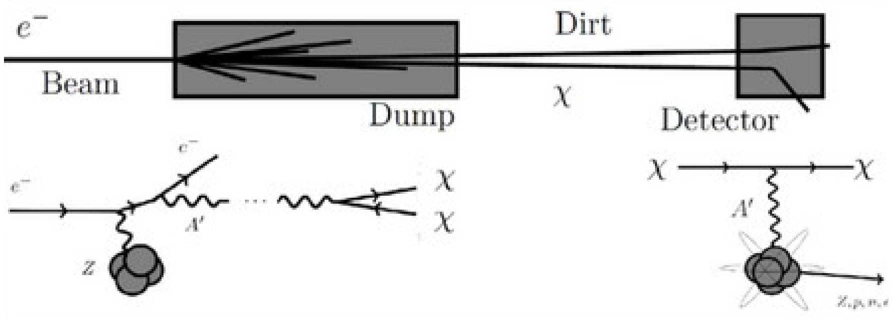
Prerequisites:

- ✓ Provide the right *relic density*
- ✓ Average velocity of a self-gravitating sphere $<v> \sim 235$ km/s (assumed Boltzmann distribution)
- ✓ Cold, non-relativistic candidate
- ✓ Stable on a cosmological time-scale
- ✓ Only very weakly interactions (*dark*)

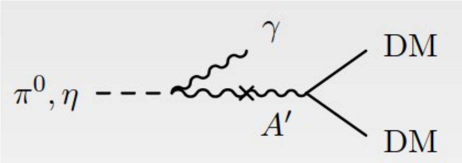
- **Neutrinos:** relativistic (hot) candidates
- **Sterile Neutrinos:** cold DM that may explain the neutrino masses problem
- Weakly Interacting Massive Particles (**WIMPs**): match new particle candidates from supersymmetric models (*neutralino*)
- **QCD Axions:** Peccei-Quinn solution to QCD fine-tuning problem

Dark matter production at accelerators

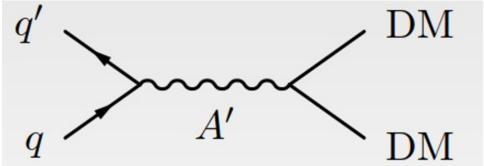
- Fixed-target experiment
  - Electron beam dump



  - Proton beam dump (DM at neutrino facilities)



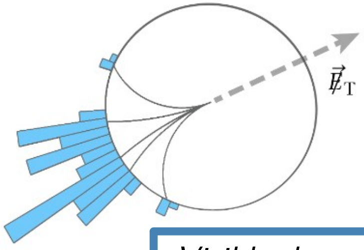
Via meson production

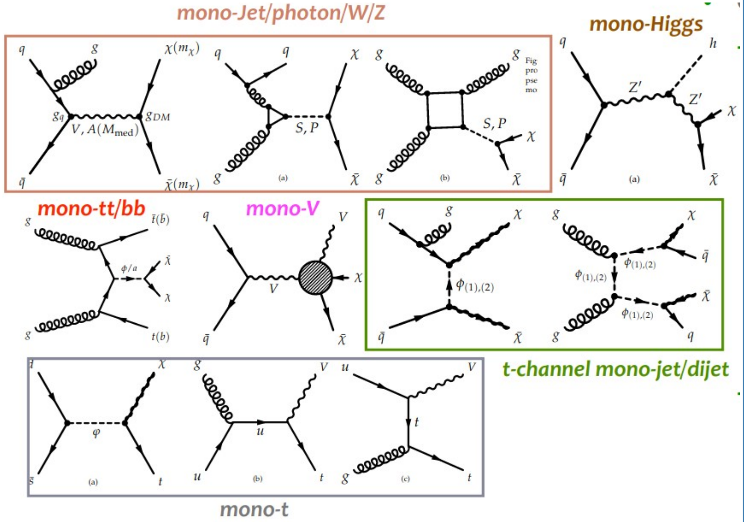


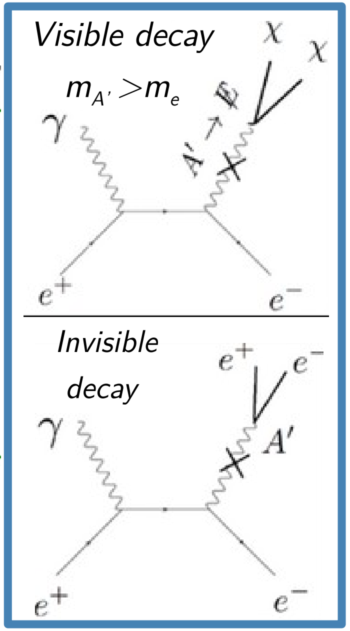
Direct production

- Colliders

Mono-X searches: detect a well-reconstructed SM object (ISR photon, jets..) + missing energy

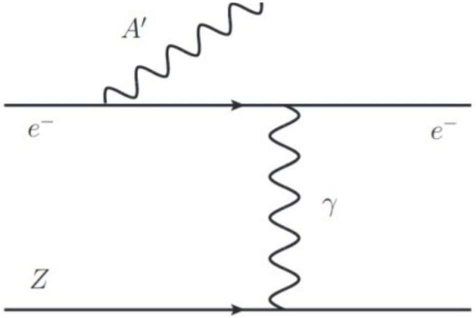






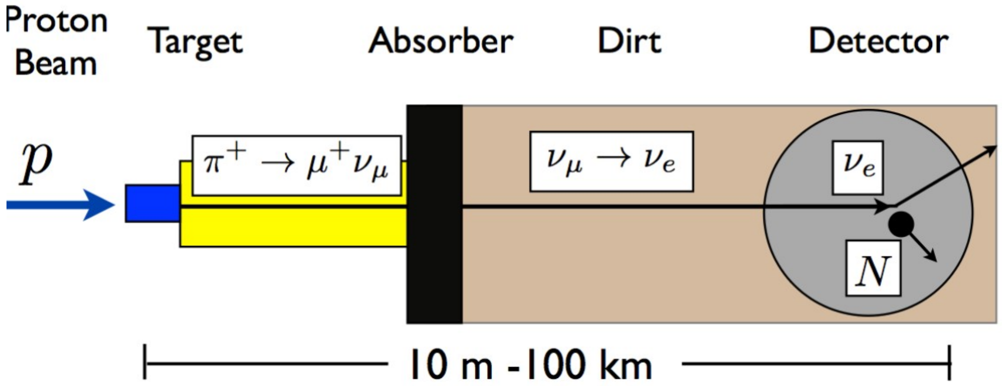
Dark matter searches at fixed-target

- Electron beam dump



  - Suitable to investigate *vector* portals for mediator masses $2m_e < m_{A'} <$ GeV
  - Larger luminosity
  - Scattering cross section enhanced by nuclear charge coherence
  - Compact special-purpose detectors (dual-arms spectrometer @JLAB, MAMI, forward vertexing spectrometer @HPS)

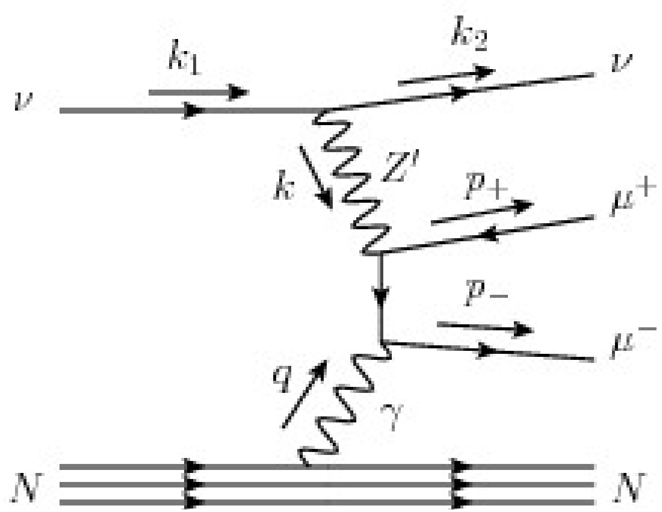
- Proton beam dump: exploiting neutrino facilities

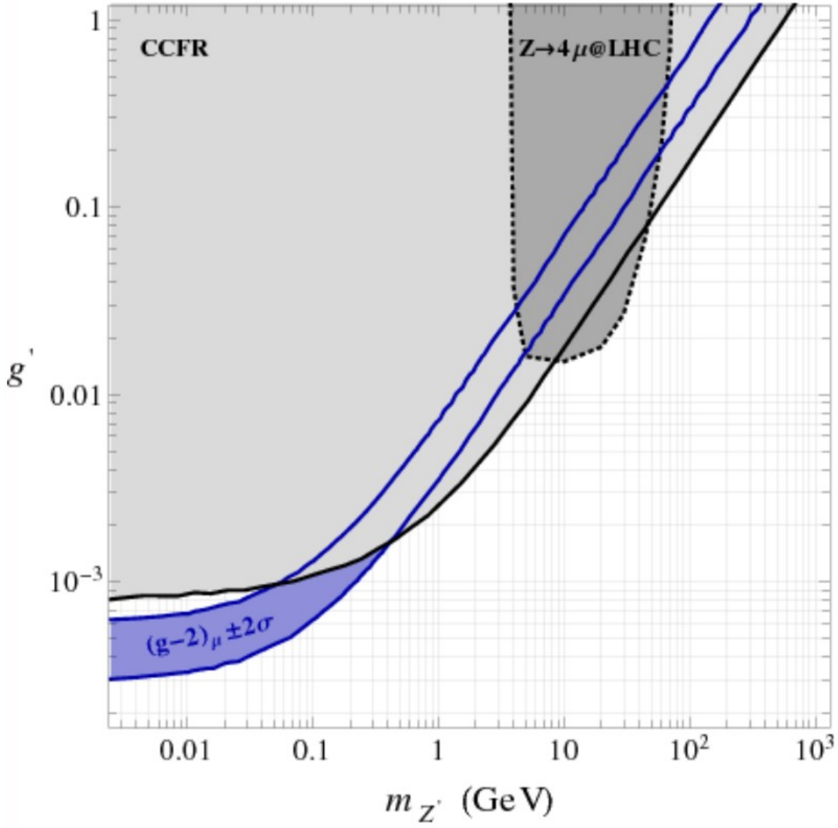


  - Exploit existing neutrino facilities
  - Look for neutral pion conversions to photons that may kinetically mix with the dark photon
  - Signal signature: dilepton resonances, long-lived particle, missing energy

Neutrino trident production

- Neutrino trident production with a Z' boson





Cross section in e$^+$e$^-$ collision at 10.58 GeV

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

The Belle II Physics Book

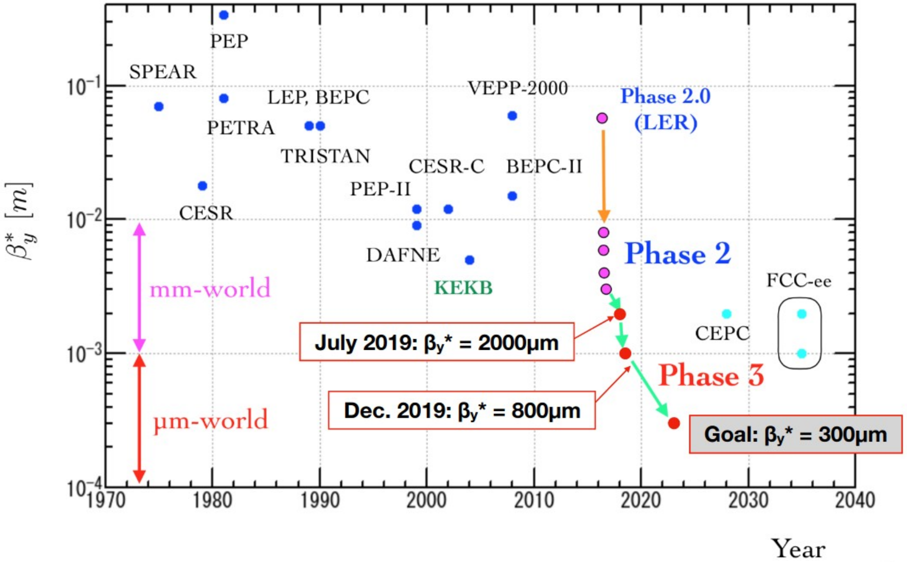
[arXiv:1808.10567]

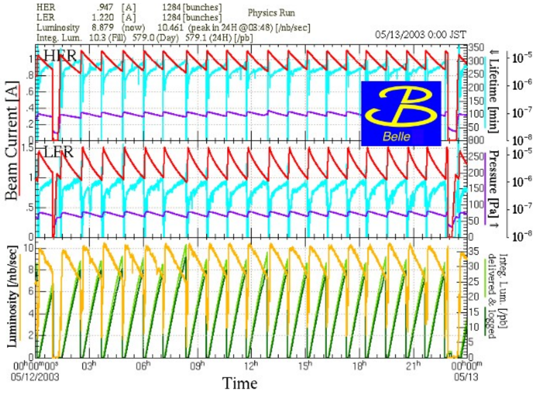
- Low multiplicity event cross sections rapidly diverge compared to hadronic ones
- Selections applied at MC generator level to reduce the effective cross section (acceptance, particle momentum selections)
- W_{ll} is the minimum invariant secondary fermion pair mass

SuperKEKB Numbers

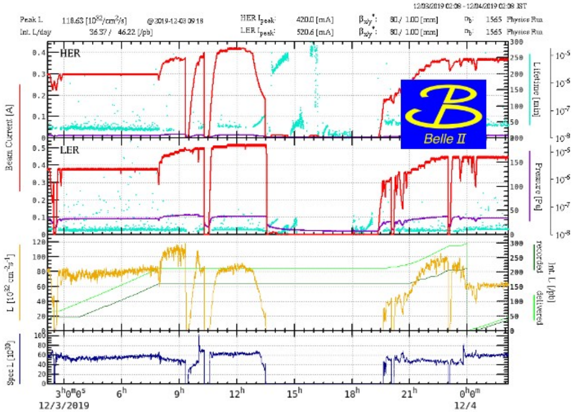
2017/September/1	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(1.5)	nm/pm	():zero current
Coupling	0.27	0.28		includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	mm	
Crossing angle	83		mrad	
α_p	3.20×10^{-4}	4.55×10^{-4}		
σ_δ	$7.92(7.53)\times10^{-4}$	$6.37(6.30)\times10^{-4}$		():zero current
V_c	9.4	15.0	MV	
σ_z	6(4.7)	5(4.9)	mm	():zero current
ν_s	-0.0245	-0.0280		
ν_x/ν_y	44.53/46.57	45.53/43.57		
U_0	1.76	2.43	MeV	
$\tau_{x,y}/\tau_s$	45.7/22.8	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	8×10^{35}		$cm^{-2}s^{-1}$	

World highest luminosity with nano beams





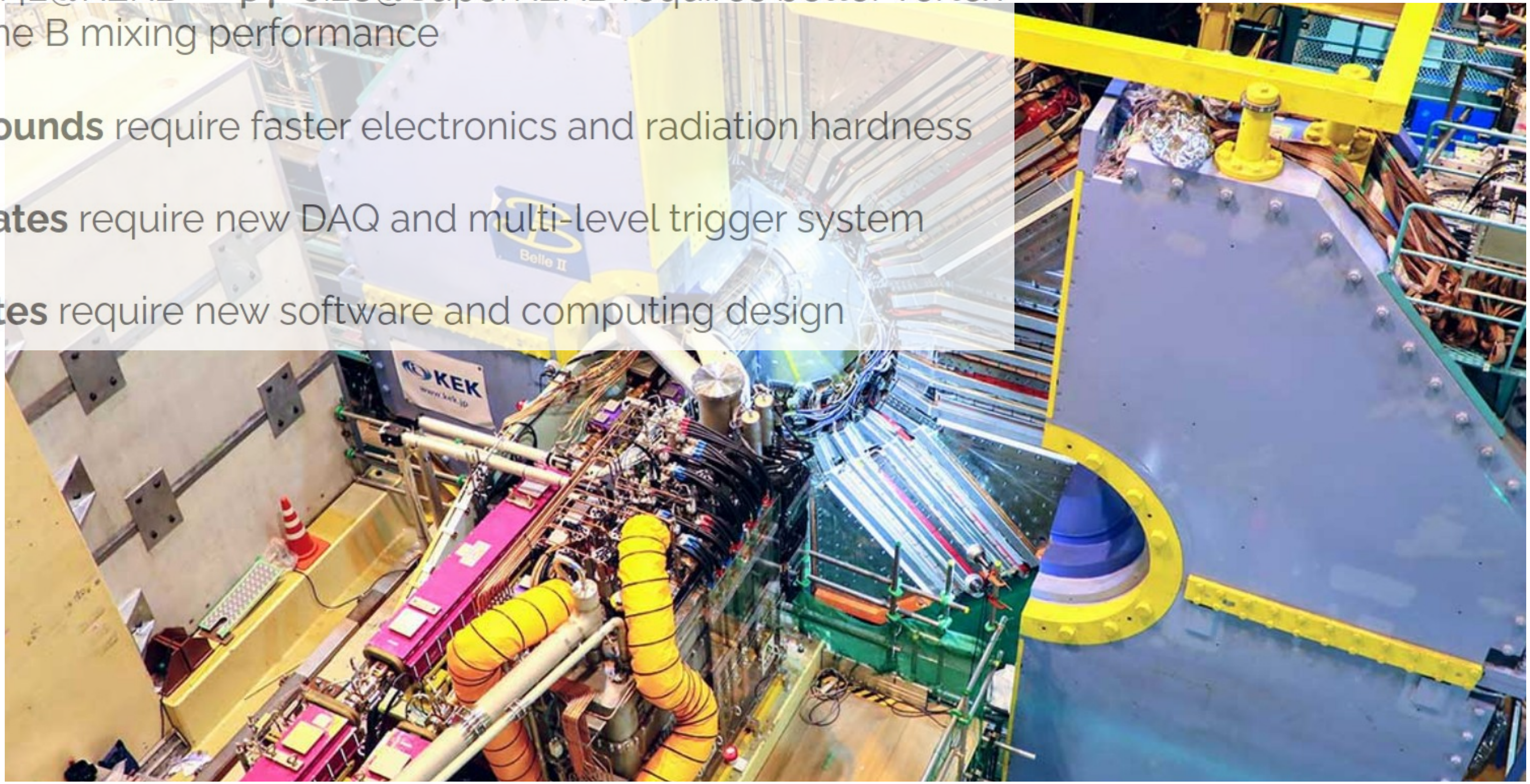
13.05.2003: β_y^* = 5.0 mm
I_{LER} = 1.2A, I_{HER}=0.95A



03.12.2019: β_y^* = 0.8 mm
I_{LER} = 0.52A, I_{HER}=0.42A

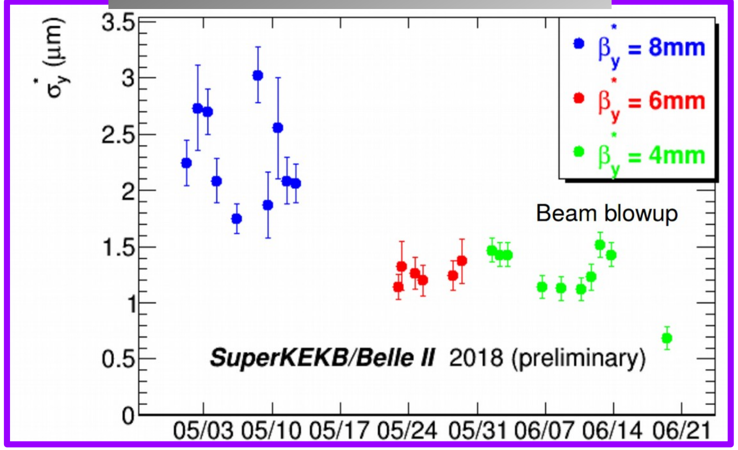
Belle II Challenges

- **Reduced boost** $\beta\gamma$=0.42@KEKB → $\beta\gamma$=0.28@SuperKEKB requires better vertex resolution for the same B mixing performance
- Much **higher backgrounds** require faster electronics and radiation hardness
- Much **higher event rates** require new DAQ and multi-level trigger system
- Much **higher data rates** require new software and computing design

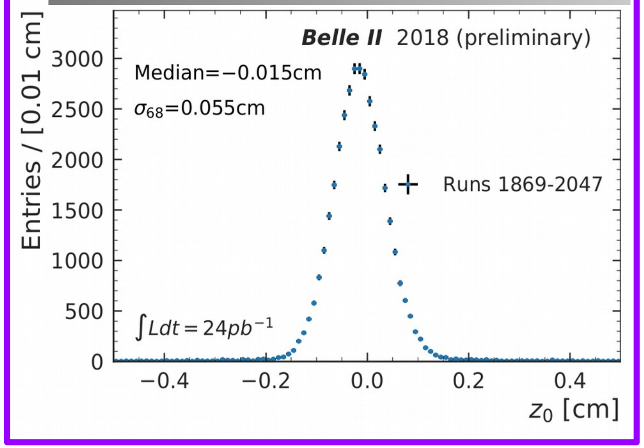


Belle II Performances in Phase 2

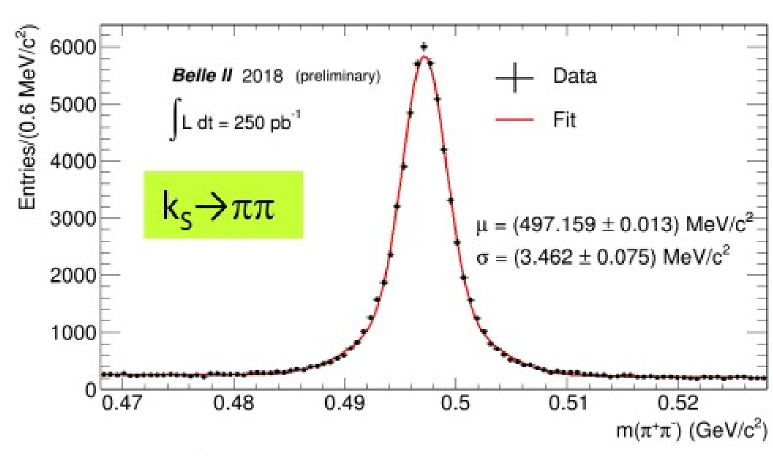
Vertical beam size

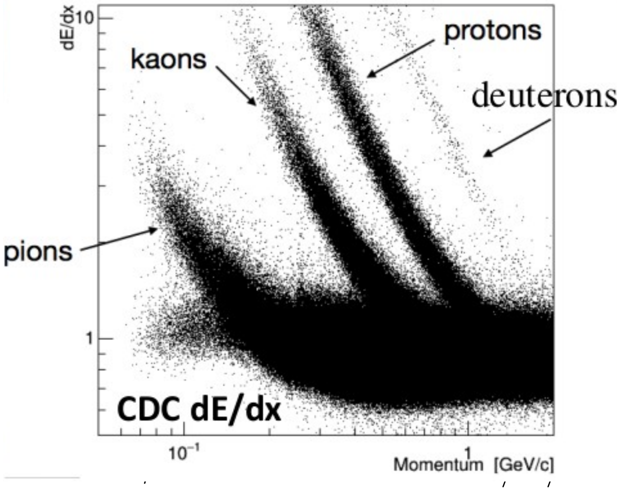


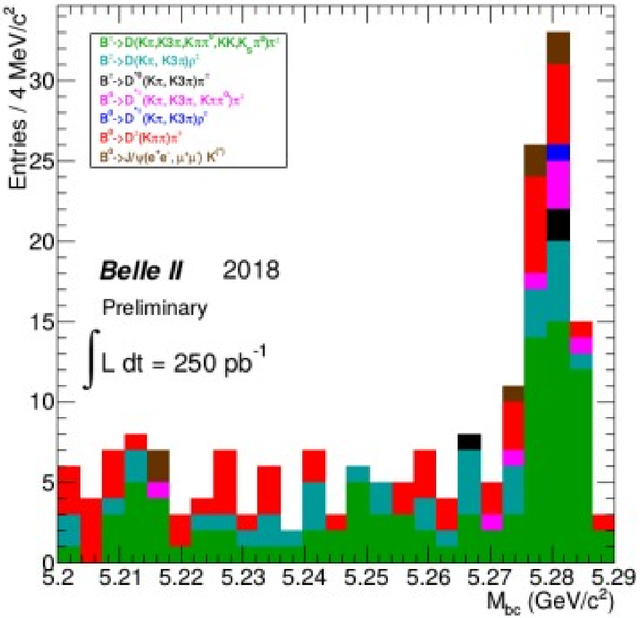
Longitudinal IP position



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

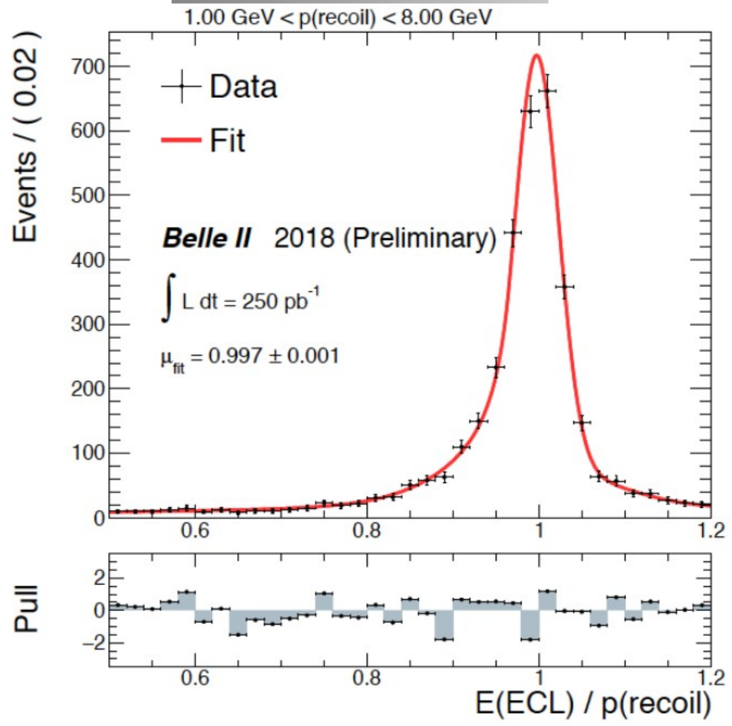




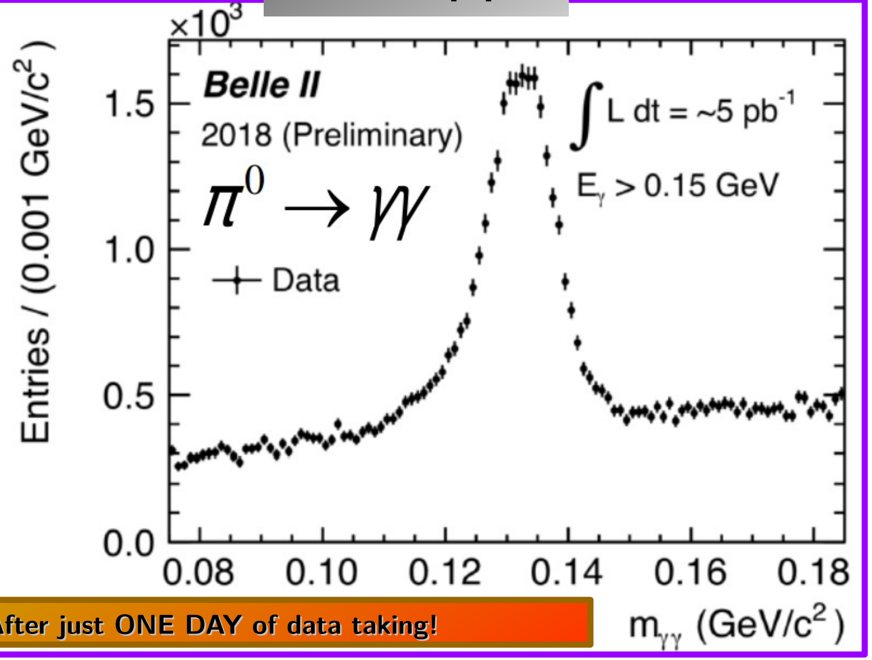


Belle II Performances in Phase 2: photon reconstruction

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



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



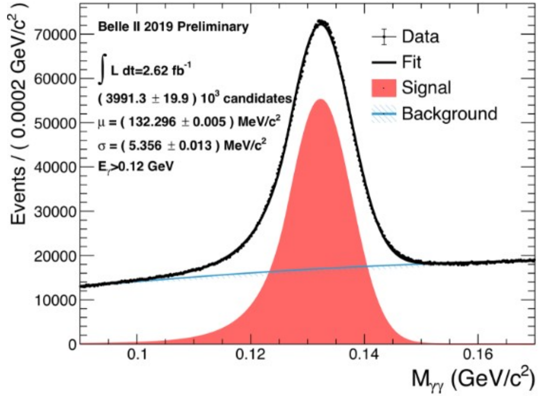
After just ONE DAY of data taking!

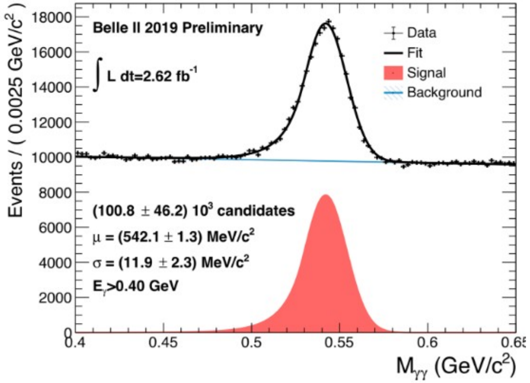
$e^+e^- \to \gamma\ X$

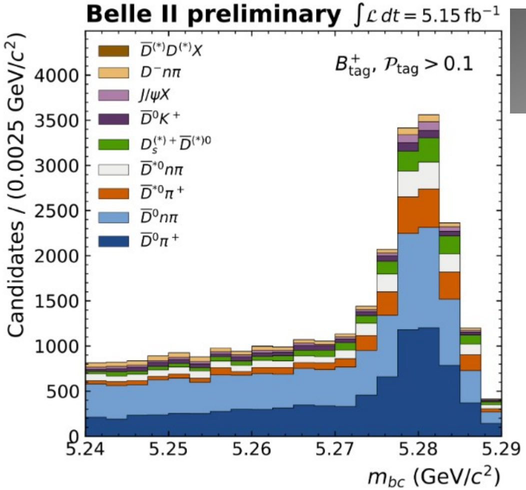
$e^+e^- \to \gamma\ ALPS \to \gamma(\gamma\gamma)$

Belle II Phase 3 snapshot

π^0, $\eta \to \gamma\gamma$

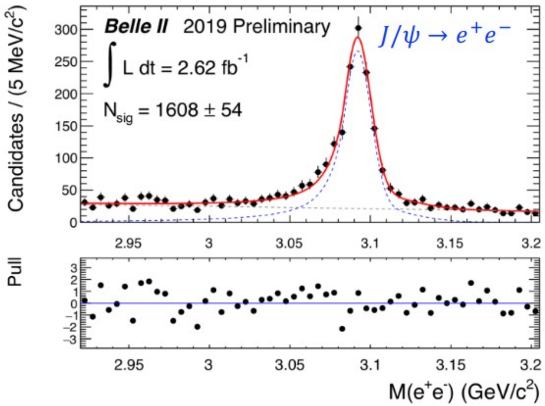


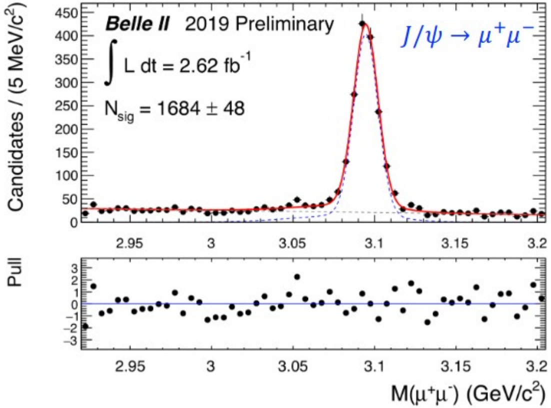


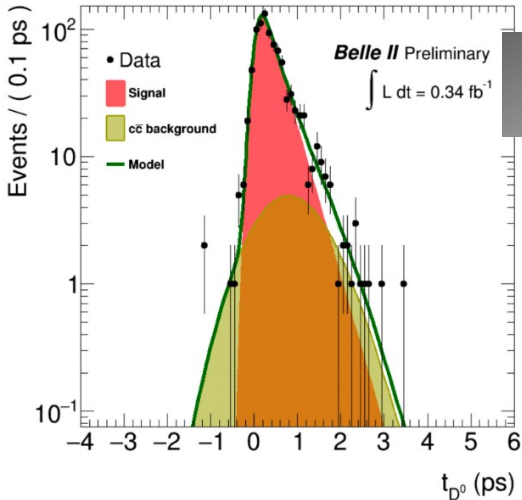


FEI, B tagging

- *Important B factory techniques to reconstruct decay with neutrinos and do inclusive searches*







D^0 lifetime

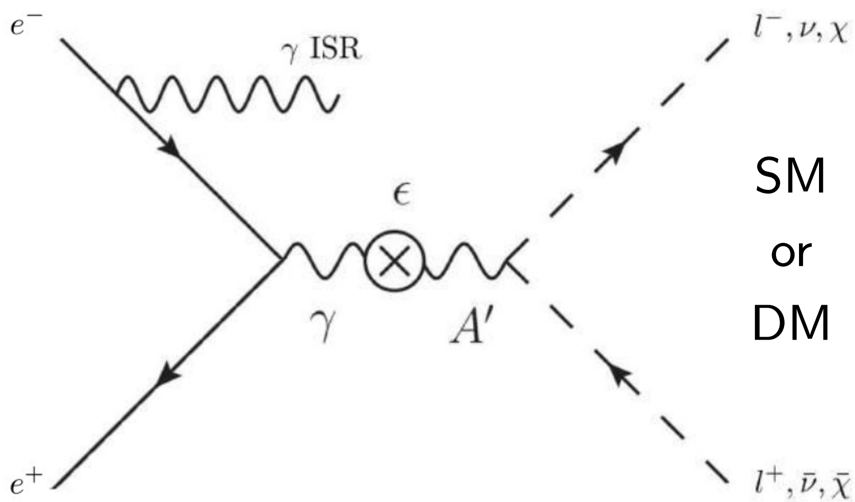
$\tau = (370 \pm 40)$ fs

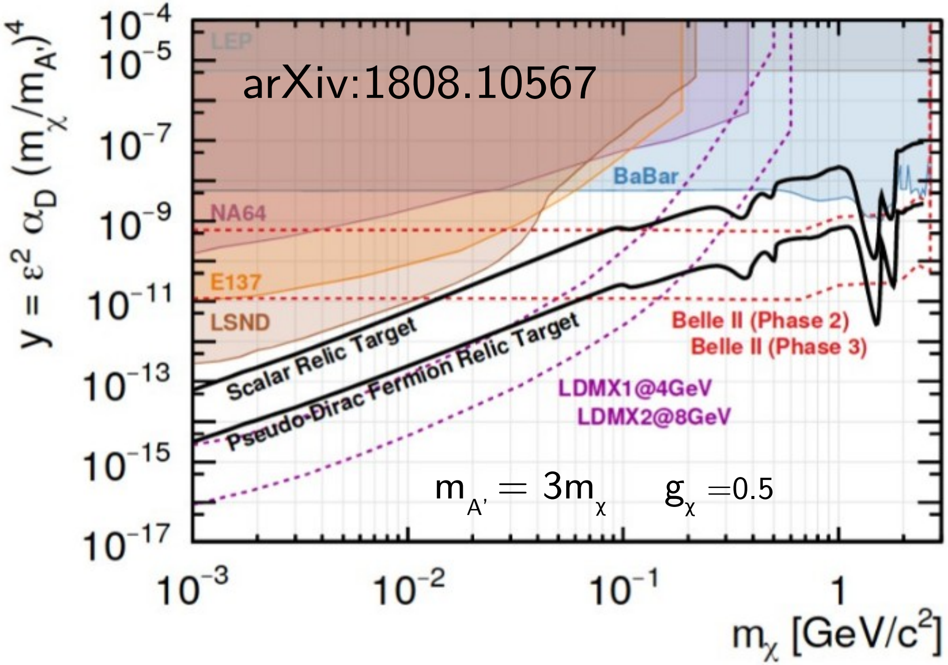
PDG average:

(410.1 ± 1.5) fs

Vector portal: dark photons

- Dark sectors are more generic than light DM and *a priori* unconstrained in their structure
- Common to assume U(1) gauge group with an associated spin-1 massive boson A'→ the ***dark photon***
- Interaction with the SM particles are mediated by the *kinetic mixing* with the SM photon with a strength ε: $\mathscr{L}_{A',\gamma} = \frac{\epsilon}{2} B_{\mu\nu} F'^{\mu\nu}$

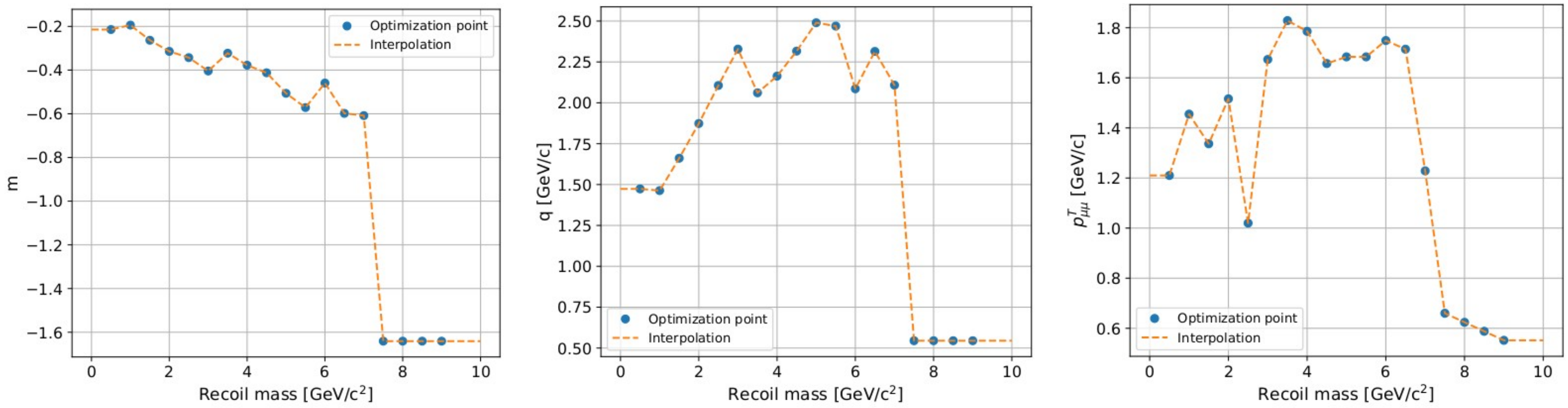




Promising signature @B-factories: Initial State Radiation production of an invisibly decaying dark photon A'

Analysis optimization

- Optimal selection values for the τ-suppression parameters: m(M_{rec}), q(M_{rec}) and $pT_{\mu\mu}$(M_{rec}) interpolated as a function of the recoil mass



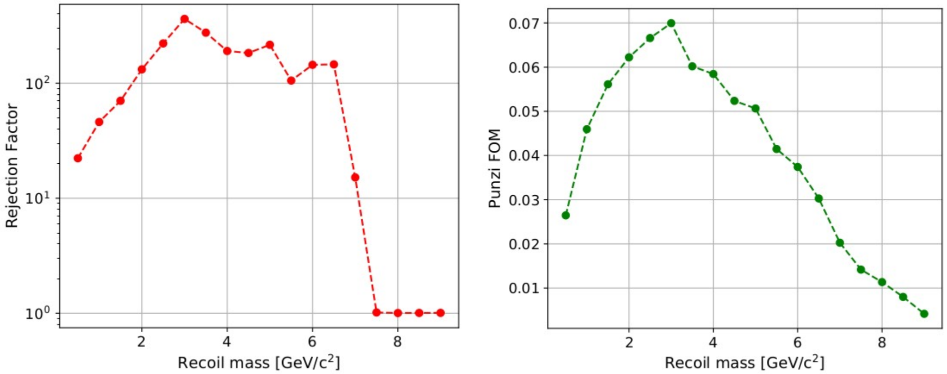


Figure 4.12: Background rejection factor defined as the bin by bin ratio in the recoil mass spectrum of the number of events before and after the τ suppression procedure only (left). Punzi FOM as a function of the recoil mass after the optimization process (right).

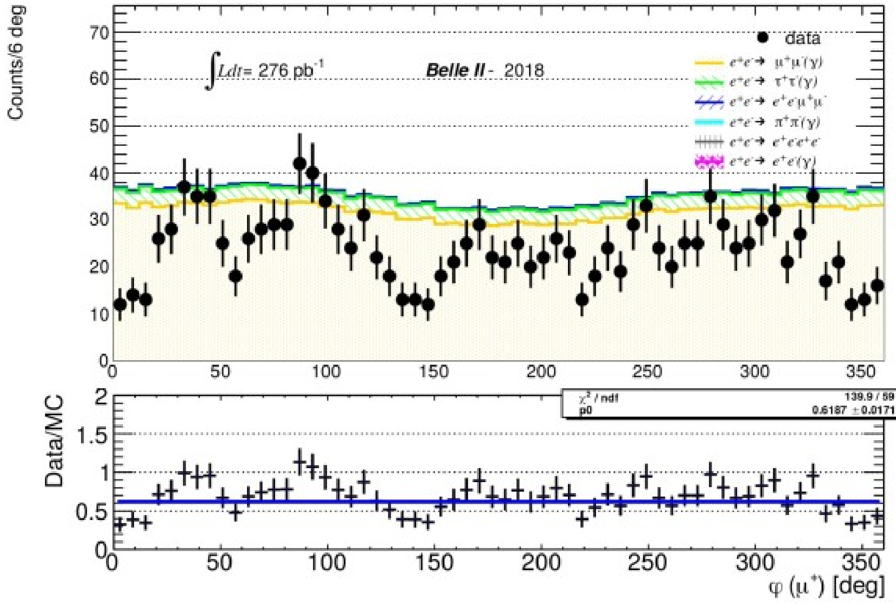
Data validation: results

- Observed data-MC discrepancy of **-35% in μμ events** (*standard Z'*), **-10% in eμ events** (*LFV Z'*)
- 10% data-MC difference understood
- For μμ events, residual **–25%** data-MC mismatch **unexplained**

Investigation effort on dimuon yield mismatch:

- ✓ All checked distributions show flat data/MC ~ 0.65
- ✓ Shape distortion in azimuth angle (φ) distributions for μμ events and ascribed to the effect of CDC trigger selection
- ✓ 35% discrepancy persists in μμγ sample selected with ECL trigger and with different MC generators (KKMC, BagaYaga@NLO)

NO clear hint for a culprit → CDC trigger seems to be the most suspicious candidate.



➔ Scale the MC simulations by **0.90 for eμ events** and **0.65 for μμ events**

Trigger efficiency

- Two orthogonal trigger lines:
  - CDC two-track trigger for μμ events (standard Z'): Bhabha veto and at least 2 tracks within CDC acceptance, with opening angle $> 90°$

$$\epsilon_{CDC} = \frac{N(\mathrm{bit_{CDC}\ AND\ bit_{ECL}})}{N(\mathrm{bit_{ECL}})}$$

  - ECL trigger for eμ events (LFV Z'): Bhabha veto and minimum energy deposit of 1 GeV

$$\epsilon_{ECL} = \frac{N(\mathrm{bit_{CDC}\ AND\ bit_{ECL}})}{N(\mathrm{bit_{CDC}})}$$

- Select good runs (ε_{CDC} >50%) and CDC fiducial regions in bins of polar angle and momentum and compute final trigger efficiency of 79% as:

$$\epsilon_{CDC} = \frac{\sum_i \epsilon_i^{\mathrm{bit_{CDC}}} \times \mathcal{L}_i}{\sum_i \mathcal{L}_i}$$

- Systematic uncertainty is evaluated as the relative variation of average efficiency in bins of θ, pT, #CDChits: 6%

  → **ε_{CDC} = (79 ± 6)%**

Used to scale expected bkg MC yields

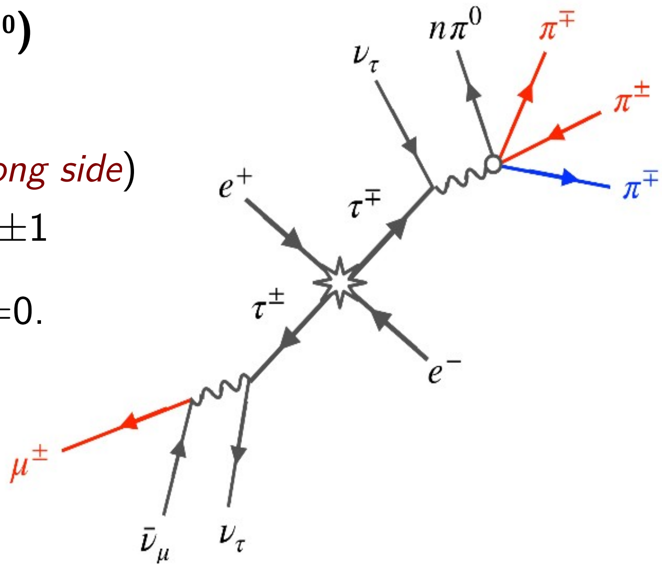
- Validated with the CDC trigger (assume same good runs luminosity of 276 pb^{-1}) on μμγ events
- Found to be flat in the fiducial ECL barrel region

  → **ε_{ECL} = (96 ± 1)%**

Track reconstruction efficiency

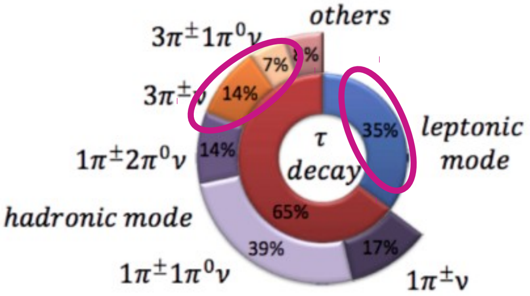
Tag & probe method on $e^+e^- \to \tau\tau \to (l + \nu\bar{\nu})(3\pi^\pm + \nu + n\pi^0)$

(BaBar, arXiv:1207.2849)



TAG: one isolated *good* track consistent with a *electron/muon* hypothesis (*1-prong side*) + two *good* hadronic tracks on the opposite side (*2-prong side*), satisfying $\Sigma q = \pm 1$

PROBE: 4th track in the event, satisfying loose selection requirement and $\Sigma q = 0$.



$\sigma_{\tau\tau}$ (10.58 GeV) ~ 0.9 nb → (xBF) 50k evt

- Count the number of events with the probe track (**N4**) and without (**N3**)
- Compute $\varepsilon \cdot$ **A = N4/(N4 + N3)** in data and simulation and estimate the calibrated discrepancy δ :

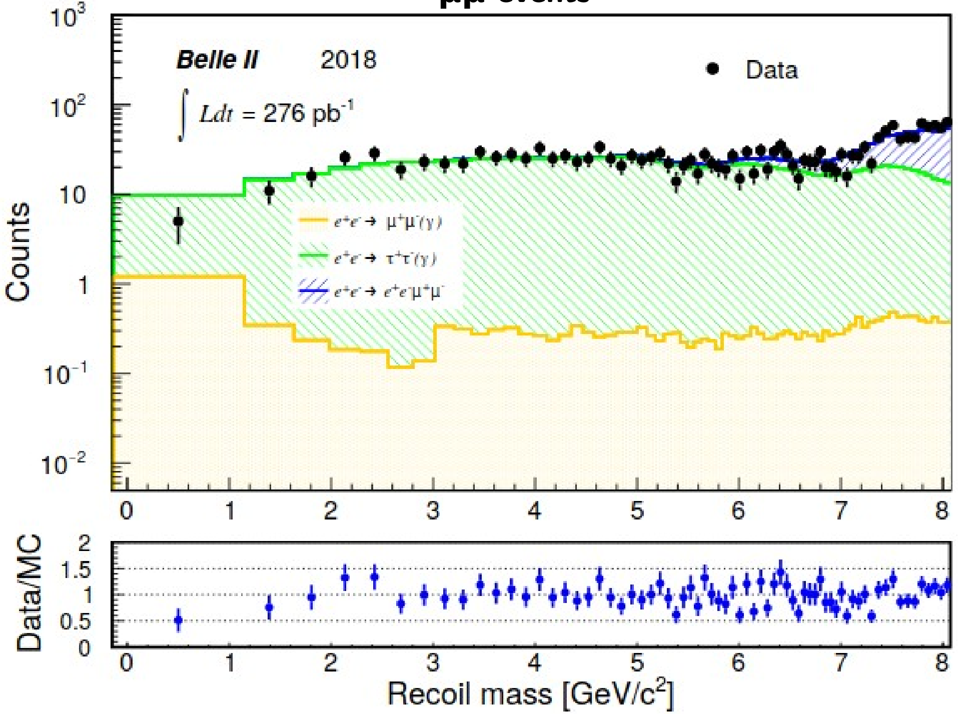
$$1/k \cdot \left(1 - \frac{\epsilon^{Data}_{meas}}{\epsilon^{MC}_{meas}}\right)$$

Phase 2 data, 381 pb^{-1} due to trigger conditions (ECL trigger to provide unbiased samples)

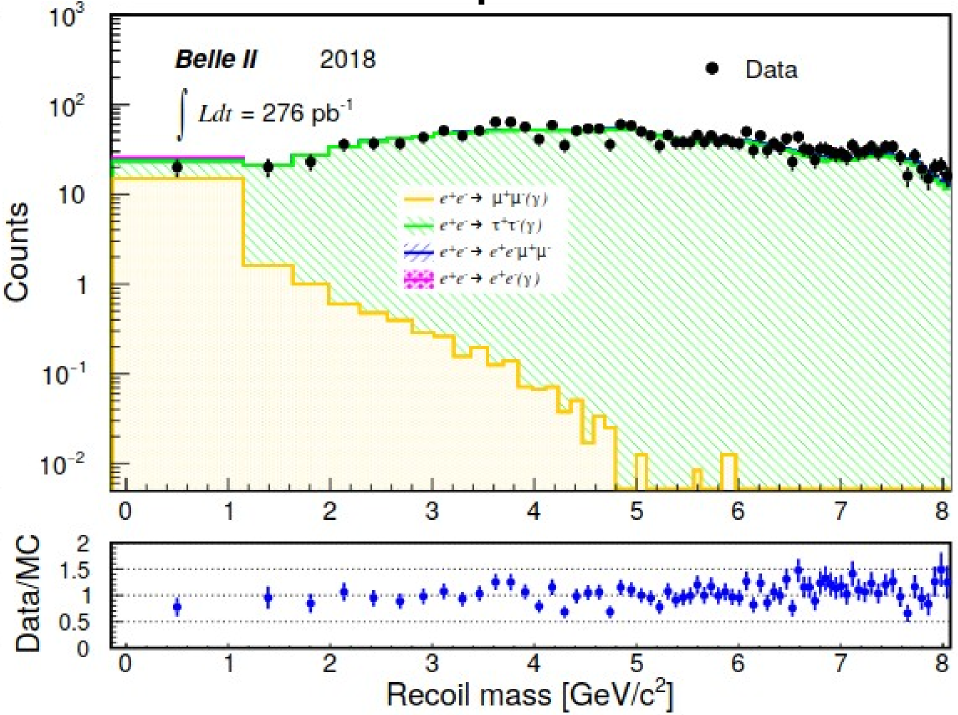
Phase 2 results

- Recoil mass spectra before the τ-suppression procedure, 0.75 scale factor applied to simulation yields in **μμ events** to match the measured data/MC ratio:

μμ events



eμ events



Phase 3 improvements

- The full VXD will improve the recoil mass resolution (~40%) → reduce mass windows and surviving background
- Muon detection improved thanks to KLM performances