DARK SECTORS AT BELLE II

Analysis Basics

BELLE II PHYSICS WEEK – 2024

14-18 October, 2024, KEK

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Outline

- Introduction
- Dark sector at Belle II
- Analysis basics... with one example
- Overview of some analyses at Belle II
- Summary & conclusions

Recalling concepts: a non-exhaustive introduction

Many more details in talks

- Prof. S. Gori, "Theory introduction to the dark sector"
- Dr. O. Sumensari "Connection between flavour and the dark sector"

DS

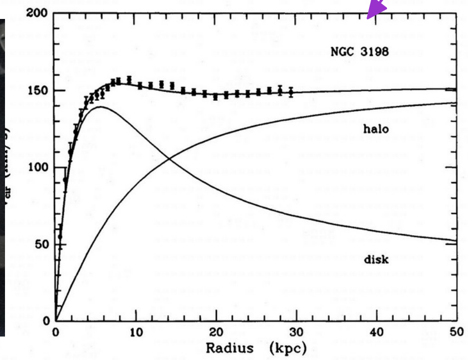
Evidences for dark matter

- Expected from virial theorem: $v(r) \sim 1/\sqrt{r}$
- **Observed:** $v(r) = const.$
  - → dark halo with $\rho \propto 1/r^2$, $M(r) \propto r$

- Many **astrophysics** and **cosmological observations** provide evidences for dark matter existence
  - → Flat rotational curves of galaxies
    - ▸ First **evidence of unseen mass**
  - → Gravitational lensing
  - → Cosmic Microwave Background anisotropy

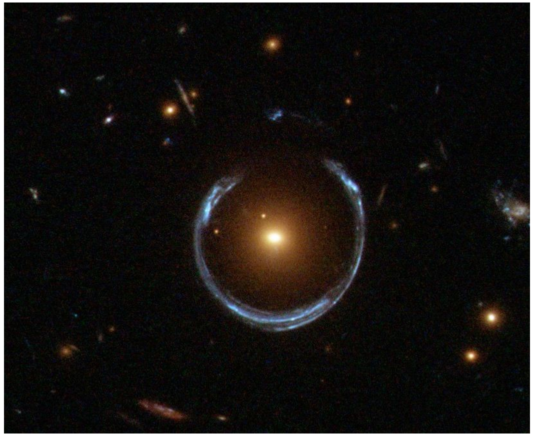
F. Zwicky in 1930s

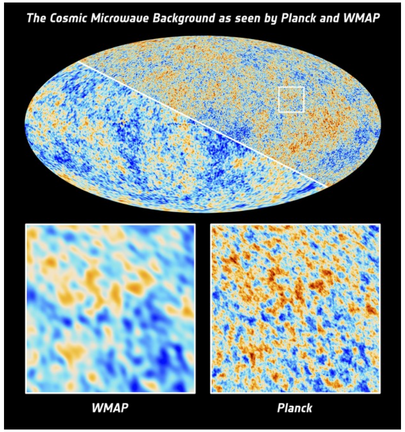
V. Rubin in 1970s



Dark matter

- Massive
- Stable on cosmological scales
- Dark
- 85% of the total mass in the universe

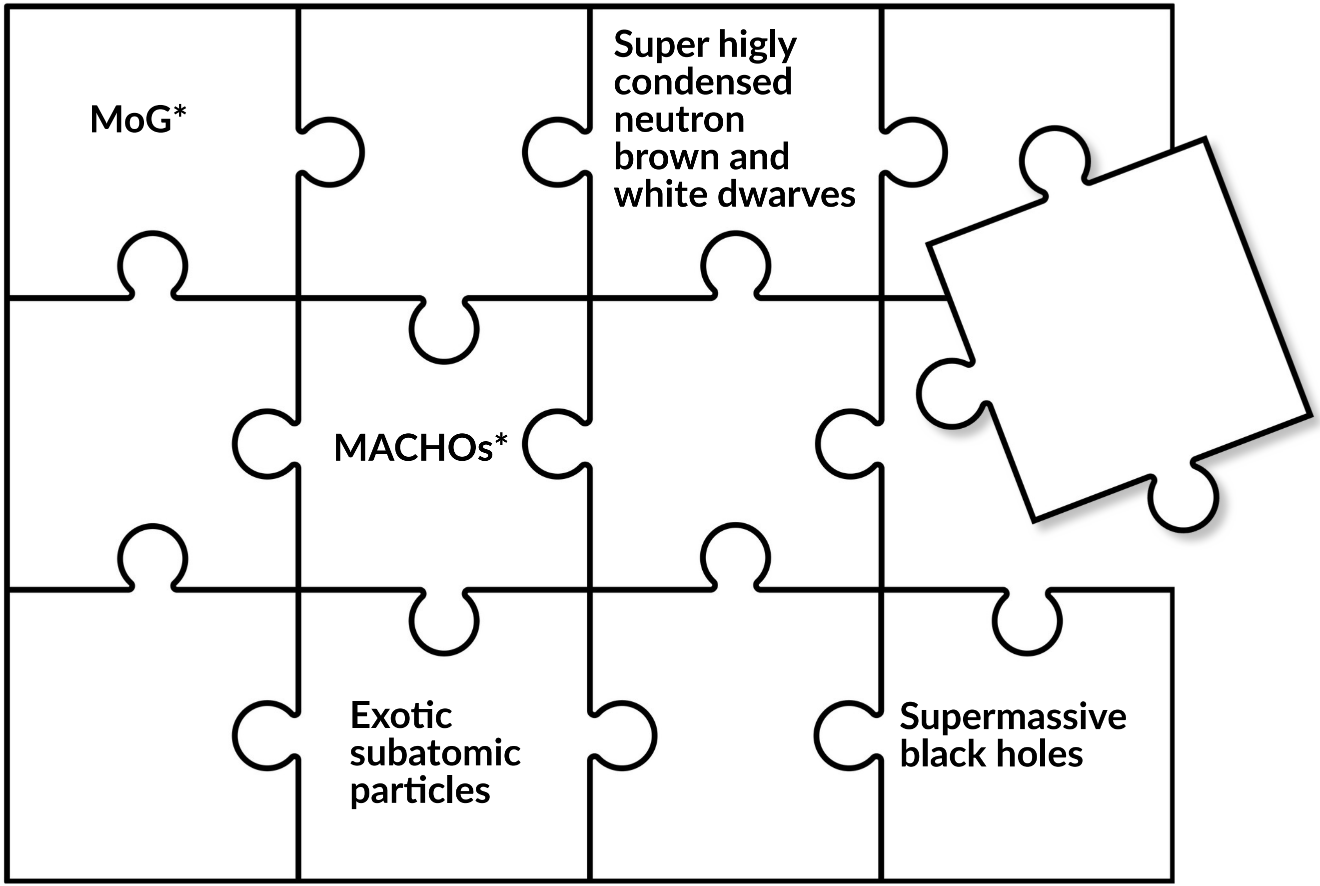




Dark matter puzzle

*Modified Gravity (MoG): Modified Newtonian Gravity (MoND), ...
*Massive Astrophysical Compact Halo Objects (MACHOs)

- Many hypoteses on the origin and nature of DM

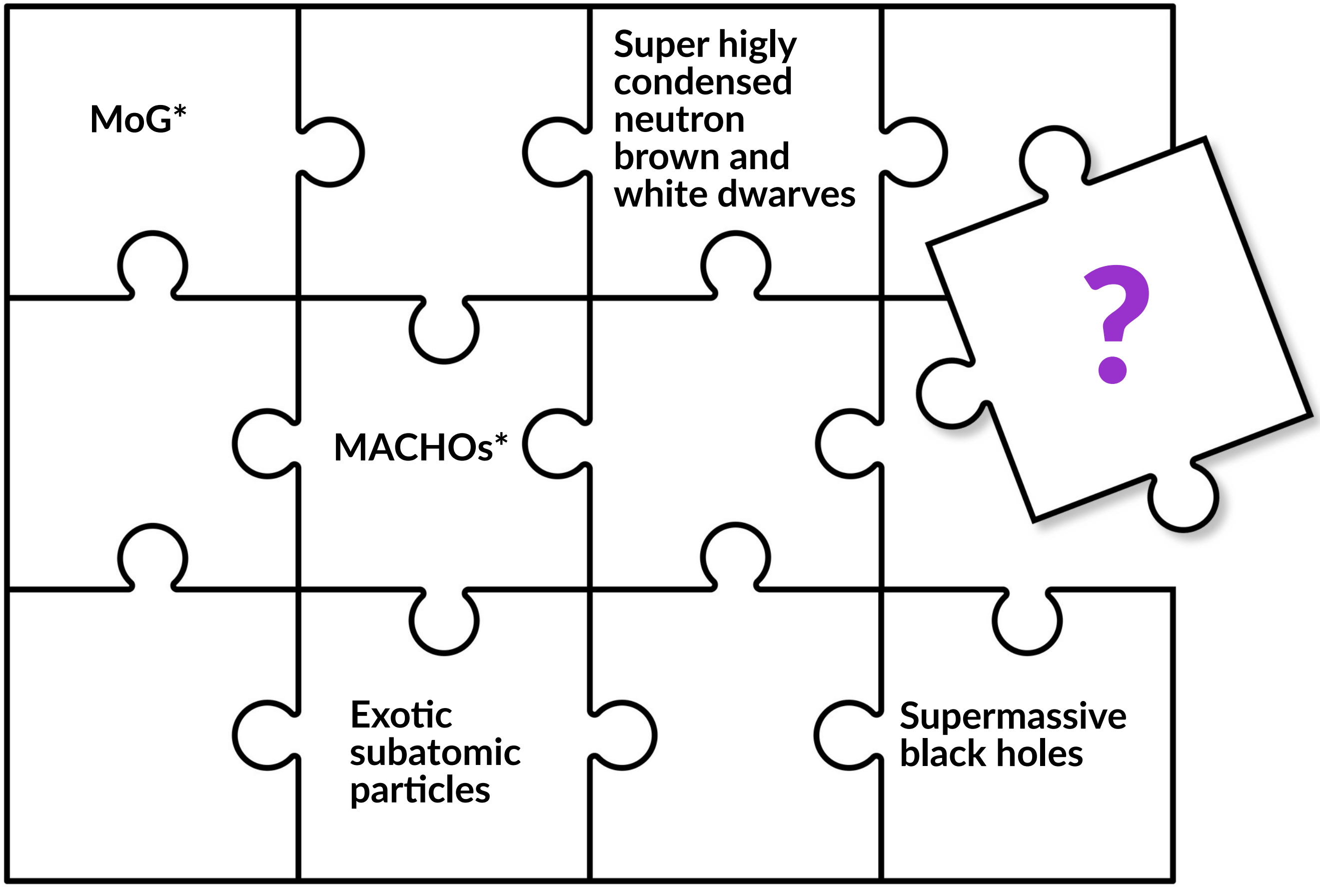


Dark matter puzzle

*Modified Gravity (MoG): Modified Newtonian Gravity (MoND), ...
*Massive Astrophysical Compact Halo Objects (MACHOs)

- Many hypoteses on the origin and nature of DM

- No solution yet
  - → DM nature is unknown
  - → Awaiting for discovery

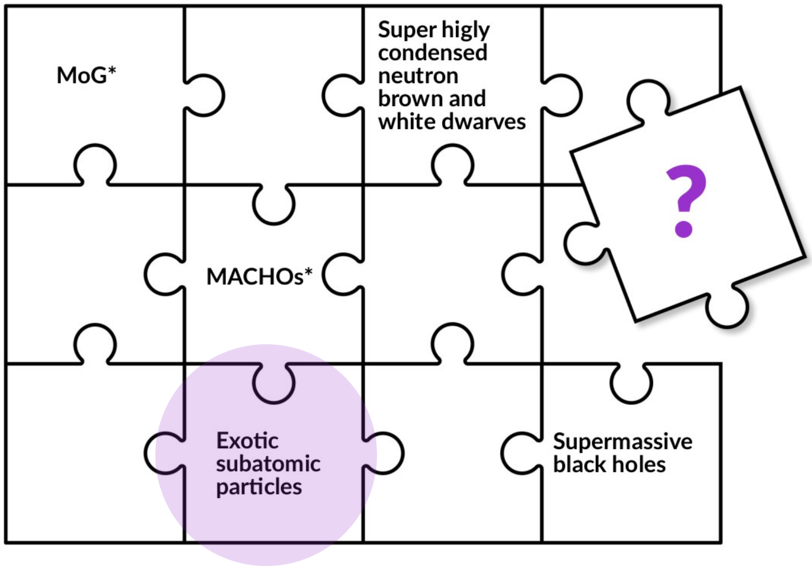


Dark matter as particle

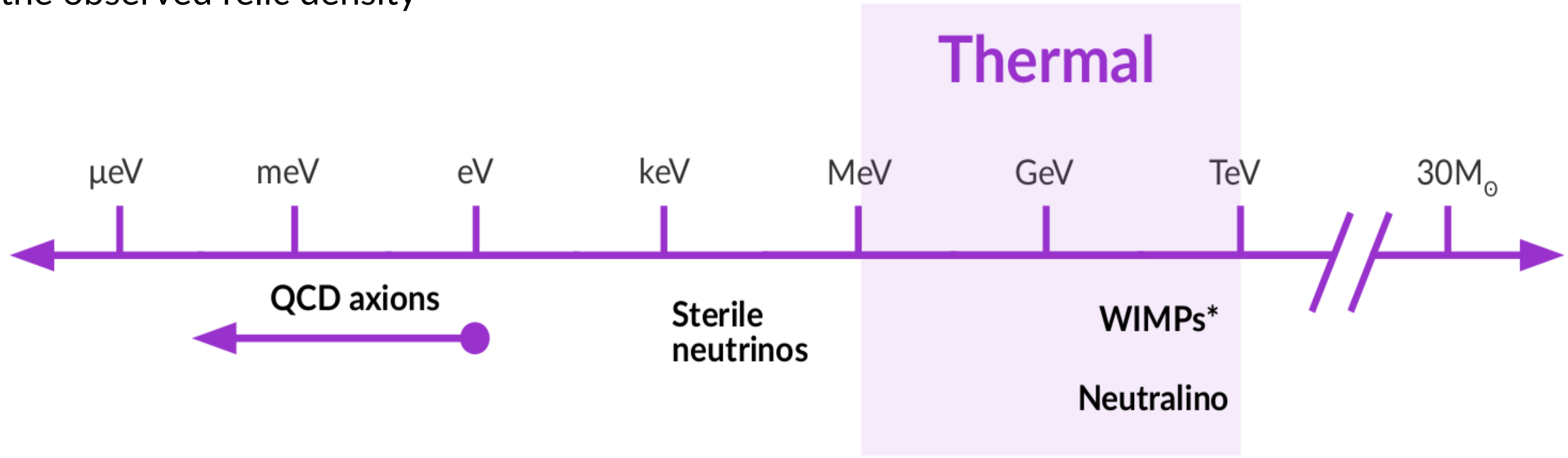
- **We do not know the DM mass scale**

DM candidate properties

- Stable on cosmological scales
- non-relativistic
- Only feeble interactions
- Provide the observed relic density



*Weakly Interacting Massive Particles (WIMPs)

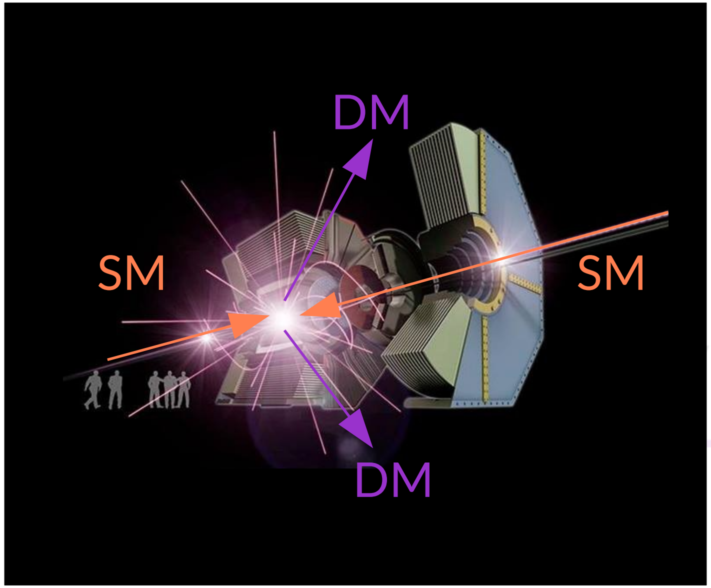


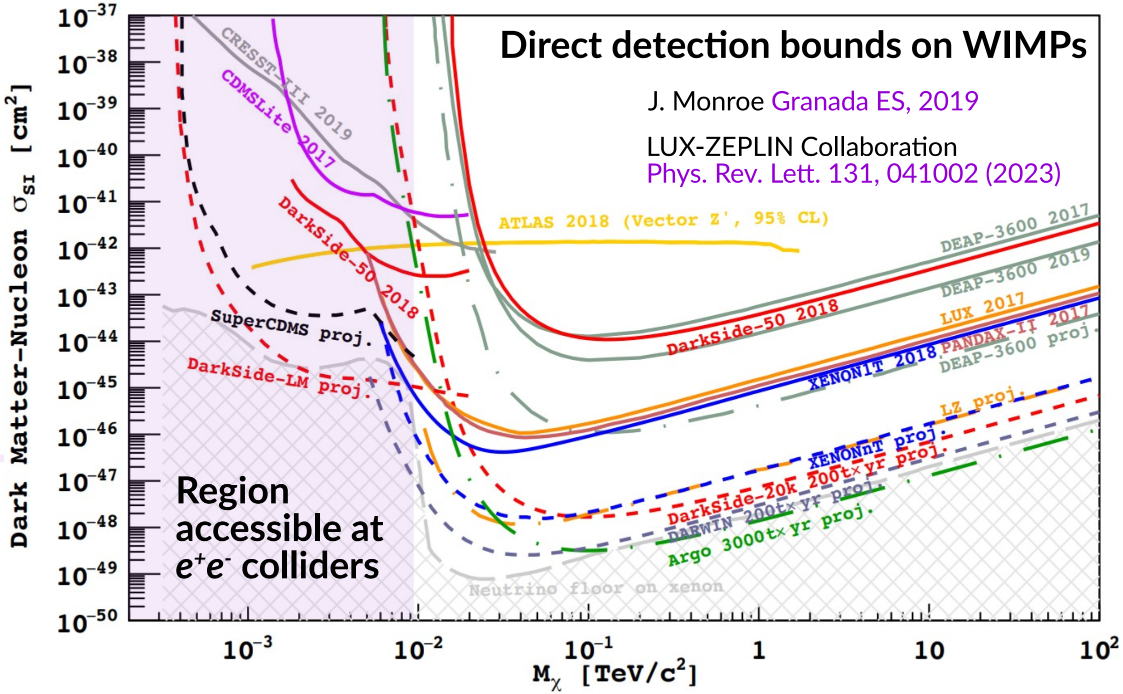
Dark matter as particle

If DM weakly couples to SM particles, it can be produced in SM particles annihilation at accelerators

→ **Involve dark sector mediators**

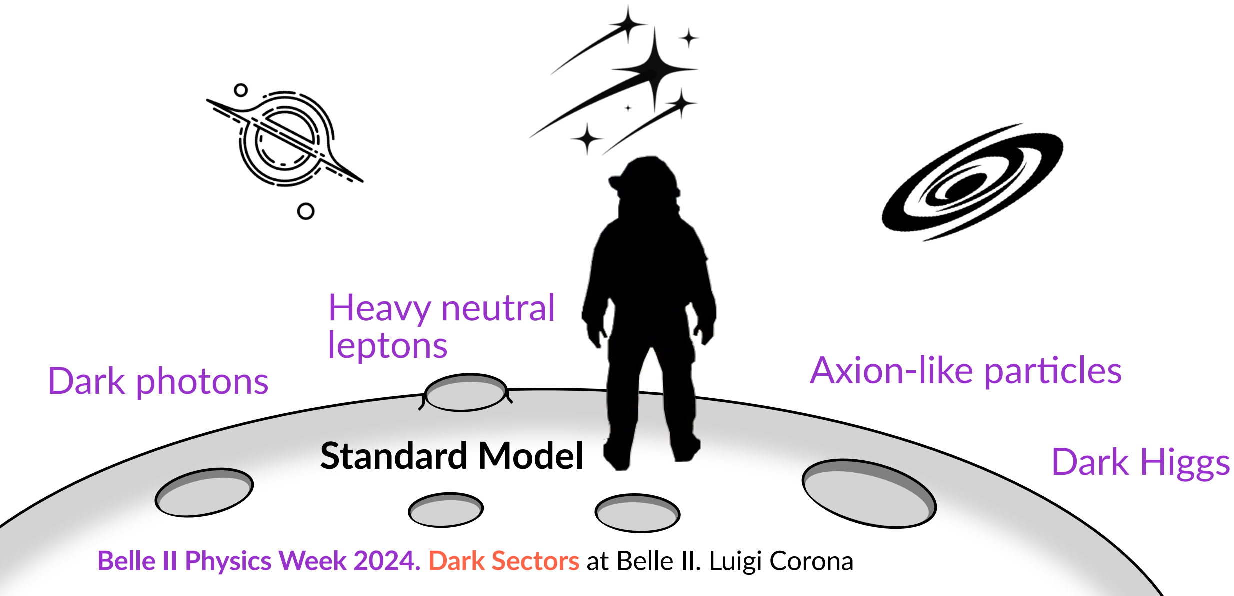
- Stable on cosmological scales



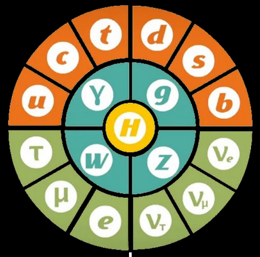


Dark sector landscape

- No evidence of DM at electro-weak scale in experiments
  - Light DM with **M ~ $\mathcal{O}$(MeV-GeV)** well motivated
    - They may **solve "DM puzzle"** and **explain observed anomalies** like the $(g-2)_\mu$
- **Light dark mediators** involved in the DM interaction with SM
  - "**portals**" of interaction



"Portals" of interaction

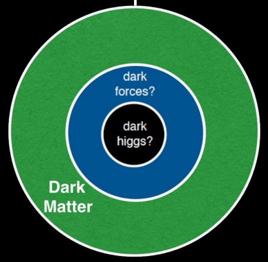


$$\mathcal{L}_{\text{vector}} \sim \varepsilon F^{\mu\nu} A'_{\mu\nu}$$

$$\mathcal{L}_{\text{scalar}} \sim |H|^2 \left(\kappa S + \lambda S^2\right)$$

$$\mathcal{L}_{\text{fermion}} \sim yHLN$$

$$\mathcal{L}_{\text{pseudo-scalar}} \sim \frac{1}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} a + \dots$$

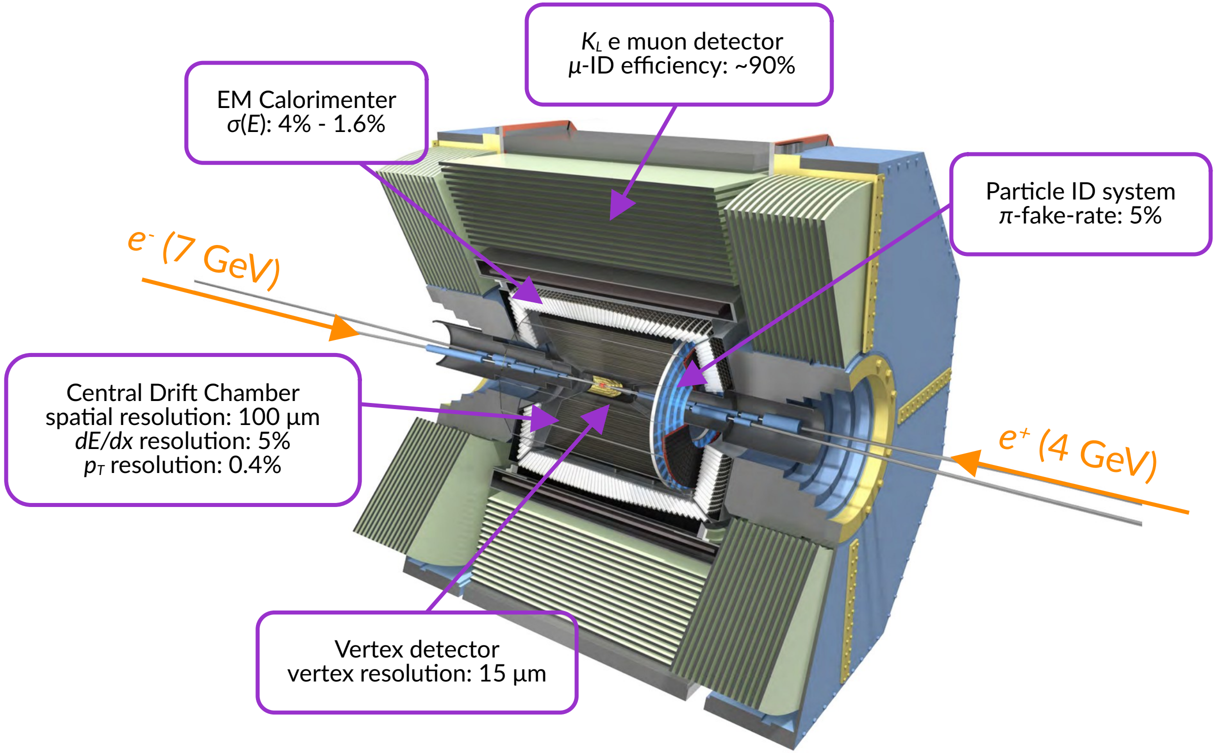


Exploring the dark sectors at Belle II

The Belle II experiment

Advantages of *B*-factories

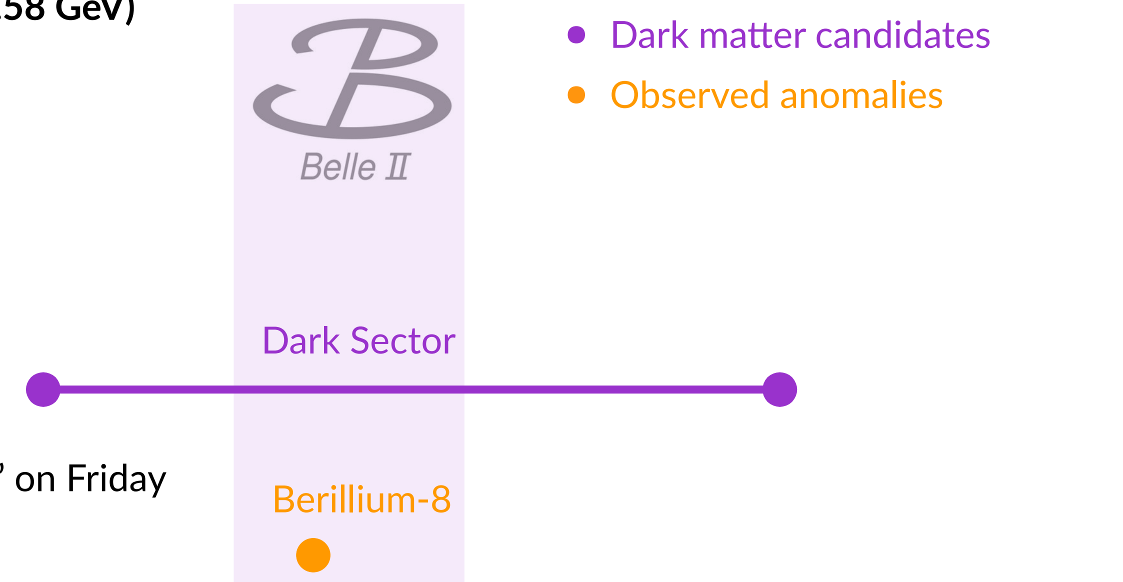
- **High luminosity**
  - 531 fb^{-1} collected so far
  - In next years, ~100 times the dataset collected so far
- Well **known initial state**
- **Clean environment** with low background
- **Hermetic detector** with excellent particle identification (PID) performance

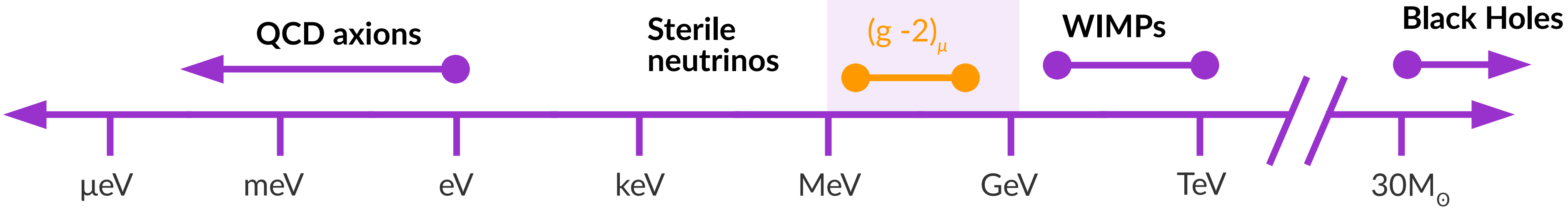


Excellent reconstruction capabilities for low multiplicities and missing energy signatures

Dark sector searches at Belle II

- **Collect data mainly at the Υ(4S) resonance (10.58 GeV)**
  - ➔ Sensitive in the **M ~ $\mathcal{O}$(MeV-GeV)**
- Search for **dark sector particles**
  - ➔ Produced **in e^+e^- annihilations**
  - ➔ Produced **in rare meson decays**
    - ▸ S. Stefkova,
      “Searching for the dark sector in B decay” on Friday
- **Dedicated low-multiplicity triggers at Belle II**

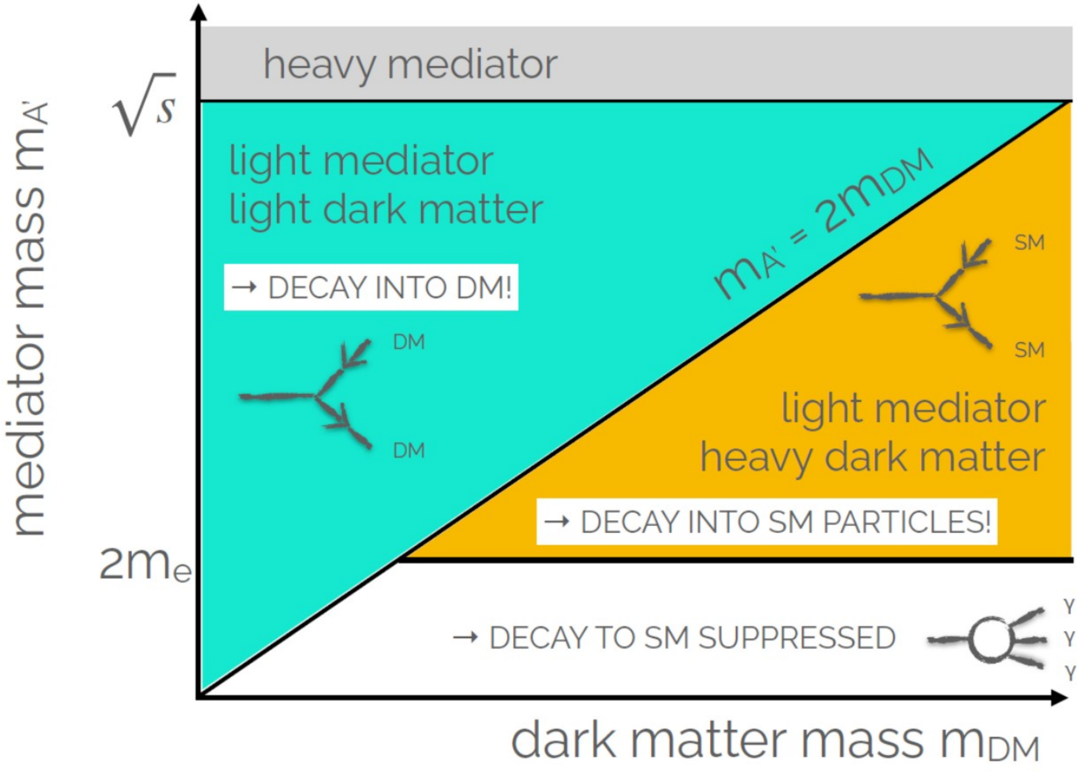




Dark sector signatures

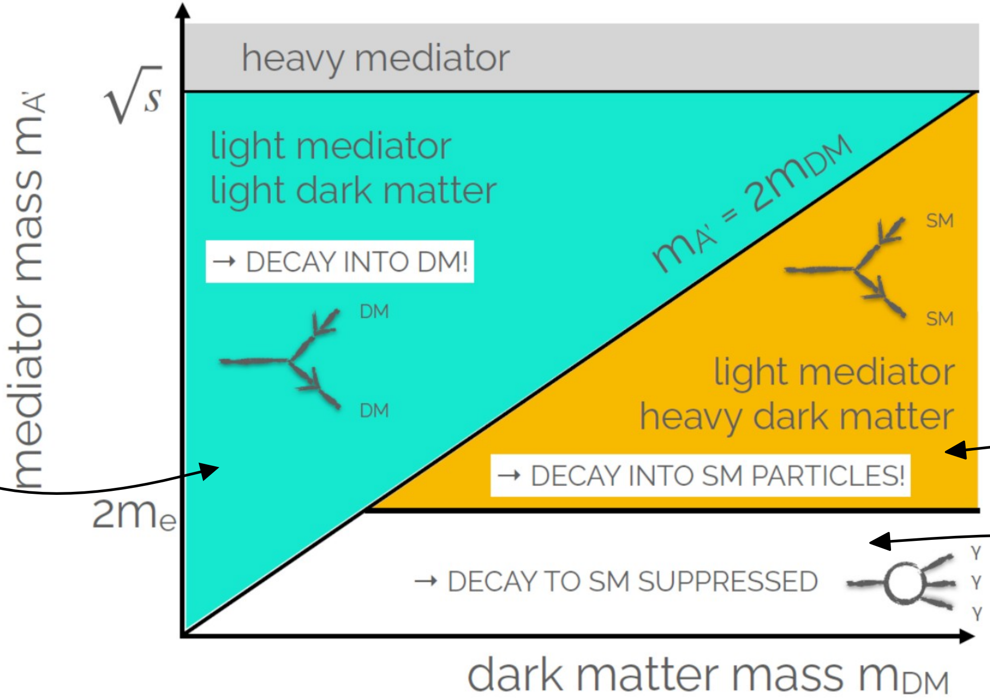
- The relationship between mass of the mediators and mass of DM candidates leads to different topologies

- **Negligible interaction probability of DM** with the detector
  - Search for final states with **missing mass**
  - Search for **mediators** (**visible** or **invisible**)
  - Search for both
- In models where decay to SM is suppressed
  - **Long-lived mediators**



Dark sector signatures: examples

- **Searches** are usually **driven by models** or proceed according to heuristic approaches



Invisible dark photon *A'*, *Z'*, ...

Visible dark photon *A'*, *Z'*, *ALP* → *γγ*, *ALP* → *ff*, ...

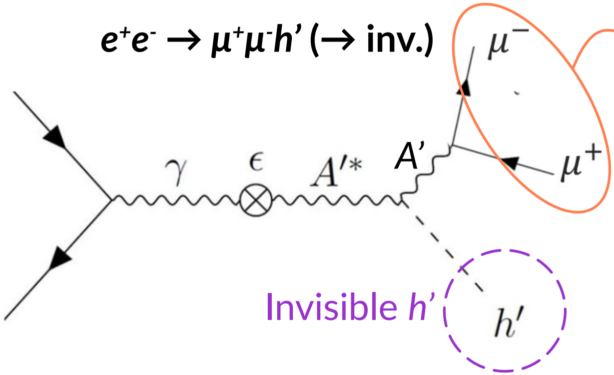
Inelastic DM, scalars, *h'*, ...

Visible or invisible?

- **Visible** or **invisible** dark sector particles produced in association with SM particles

Missing energy signatures

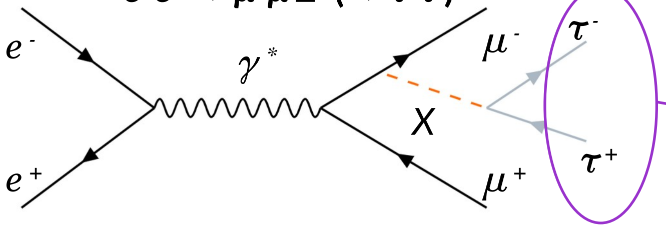
$e^+e^- \rightarrow \mu^+\mu^- h'$ (→ inv.)



Visible A'

Taus lead to missing energy signature because of neutrinos in τ decays

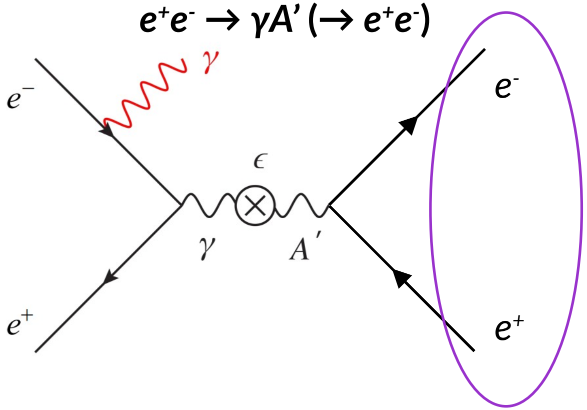
$e^+e^- \rightarrow \mu^+\mu^- Z'$ (→ $\tau^+\tau^-$)



- h' and Z' reconstructed as recoil to the dimuon system
- A' as dimuon system

No missing energy signatures

$e^+e^- \rightarrow \gamma A'$ (→ e^+e^-)



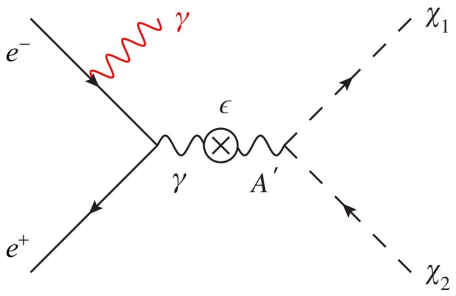
- A' reconstructed as dielectron system
  - $M_{A'} = M(e^+e^-)$
  - Generally direct invariant mass provides better resolution than recoil mass

Multiplicities

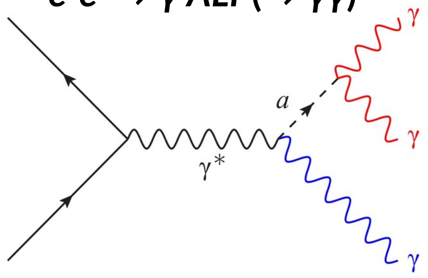
- Dark sector analyses are **low-multiplicity analyses,** from 0 to 6 charged particles (tracks); **generally 2 to 4**

No tracks

$e^+e^- \rightarrow \gamma A'(\rightarrow \text{inv.})$

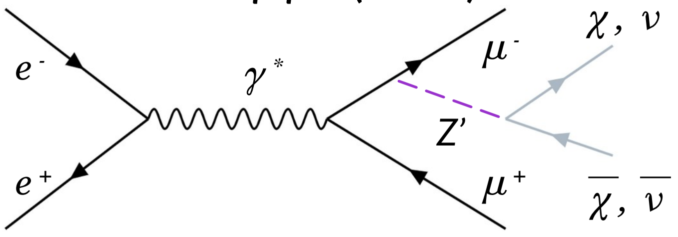


$e^+e^- \rightarrow \gamma\, ALP(\rightarrow \gamma\gamma)$



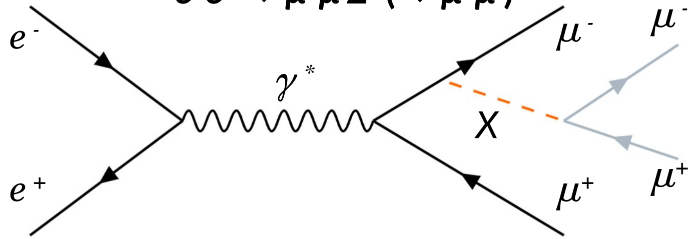
2 tracks

$e^+e^- \rightarrow \mu^+\mu^- Z'(\rightarrow \text{inv.})$



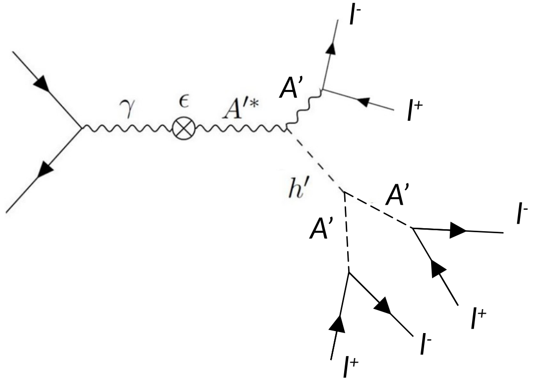
4 tracks

$e^+e^- \rightarrow \mu^+\mu^- Z'(\rightarrow \mu^+\mu^-)$



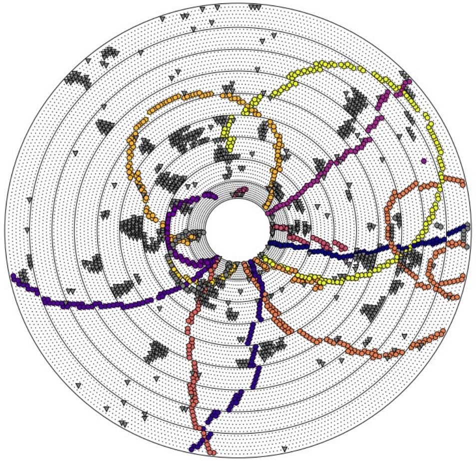
6 tracks

$e^+e^- \rightarrow A'\, h'(\rightarrow A'A'),\ A' \rightarrow l^+l^-$



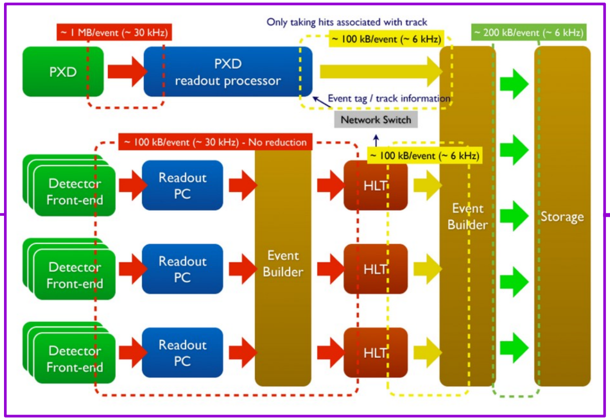
Low-multiplicity triggers

- Devised **specific low-multiplicity trigger lines**
  - **Suppress high-cross-section QED processes O(1 – 300 nb) without "killing" the signal < O(10 fb)**
  - **Precise knowledge of acceptance and efficiencies of the detector** required
  - Single-photon trigger (not available at Belle), single-muon trigger, single-track trigger, …
    - Makes the Belle II dataset world-unique



Credits to L. Reuter

Trigger & DAQ



S Lee et al., J. Phys. Conf. Ser. 331 022015 (2011)

SM
$e^+e^- \to e^+e^- (\gamma)$
$e^+e^- \to \mu^+\mu^- (\gamma)$
…
$e^+e^- \to e^+e^- ll$

$A' \to$ inv., $A' \to ll$,
$Z' \to$ inv., $Z' \to ll$,
ALP $\to \gamma\gamma$, ALP $\to ff$, …

Low-multiplicity triggers

- Final states with **only neutrals**, **only charged particles**, **both neutrals and charged particles** (tracks)
- Few examples of trigger lines currently used, or that will be used in planned analyses (and beyond)
- **Trigger efficiency may be < 100%, it needs to be determined**

tracks → drift chamber (CDC)
neutrals, electrons → calorimeter (ECL)
muons → K_L-muon detector (KLM)
lml = low-multiplicity

Not up to date

Analysis	Trigger lines
$e^+e^- \to \mu^+\mu^- h'$ (→ inv)	fy30, cdcklm, stt
$e^+e^- \to \mu^+\mu^- Z'$ (→ $\mu\mu$, $\tau\tau$)	fff/ffy, cdcklm, stt (fy30, fyo)
$e^+e^- \to \gamma_{ISR}$ A' (→ inv.)	hie, lml6, lml16 (lml1, prescaled)
$ALP \to \gamma\gamma$ (3 γ final state)	hie (high mass) , ggsel (low mass)
Inelastic DM (A', χ_1, χ_2) + Dark Higgs (h')	hie (lml12, stt [stt4/5])
Dark showers (ρ_D, …)	stt, stt-ecl, hie for electrons (displaced VTX)

Common SM background processes

- **Different contributions** depending on: the **number of tracks** in the final state, the presence of **missing energy**, the **mass region** we are investigating, the presence of **displaced vertices**

$e^+e^- \to B\bar{B}$

$e^+e^- \to q\bar{q}$

Low-multiplicity

Process	Cross section (nb)	Process	Cross section (nb)
$e^+e^- \to B^0\bar{B}^0$	0.510	$e^+e^- \to \mu^+\mu(\gamma)$	1.148
$e^+e^- \to B^+B^-$	0.540	$e^+e^- \to \tau^+\tau^-(\gamma)$	0.919
$e^+e^- \to u\bar{u}$	1.61	$e^+e^- \to e^+e^-\mu^+\mu^-$	18.9
$e^+e^- \to d\bar{d}$	0.40	$e^+e^- \to e^+e^-\tau^+\tau^-$	0.182
$e^+e^- \to s\bar{s}$	0.38	$e^+e^- \to \mu^+\mu^-\tau^+\tau^-$	0.143×10^{-3}
$e^+e^- \to c\bar{c}$	1.30	$e^+e^- \to \mu^+\mu^-\mu^+\mu^-$	0.342×10^{-3}

- **Conversions in the detector material**
  - Contribute mostly in low mass region and in searches with displaced vertices
- **SM resonances (K_S, Λ, ρ, J/ψ …)**
  - Contribute mostly in searches with displaced vertices
  - Peaking → they can emulate signal

- Some analyses need to develop an **aggressive background suppression** to **obtain competitive results**
  - $e^+e^- \to \mu^+\mu^- Z' (\to \mu^+\mu^-)$
- In other analyses the **SM background is ~zero** and are mainly **limited by statistics**
  - $e^+e^- \to A' h' (\to A'A'), A' \to l^+l^-$ (3 A' with same mass)

Belle II contributions… so far

- **Belle II has a unique sensitivity to light dark sector**
  - **Complementary** results **to higher energy colliders** and **beam-dump experiments**
  - **World-leading results** already **published** with partial datasets (< 427 fb^{-1})

Search for a $\tau^+\tau^-$ Resonance in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$ Events with the Belle II Experiment
I. Adachi *et al.* (Belle II Collaboration)
Phys. Rev. Lett. **131**, 121802 – Published 21 September 2023 PHYSICAL REVIEW LETTERS

Search for a Dark Photon and an Invisible Dark Higgs Boson in $\mu^+\mu^-$ and Missing Energy Final States with the Belle II Experiment
F. Abudinén *et al.* (Belle II Collaboration)
Phys. Rev. Lett. **130**, 071804 – Published 17 February 2023 PHYSICAL REVIEW LETTERS

Search for an Invisible Z' in a Final State with Two Muons and Missing Energy at Belle II
I. Adachi *et al.* (Belle II Collaboration)
Phys. Rev. Lett. **130**, 231801 – Published 7 June 2023 PHYSICAL REVIEW LETTERS

Search for Axionlike Particles Produced in e^+e^- Collisions at Belle II
F. Abudinén *et al.* (Belle II Collaboration)
Phys. Rev. Lett. **125**, 161806 – Published 14 October 2020 PHYSICAL REVIEW LETTERS

Search for a $\mu^+\mu^-$ resonance in four-muon final states at Belle II
I. Adachi *et al.* (Belle II Collaboration)
Phys. Rev. D **109**, 112015 – Published 14 June 2024 PHYSICAL REVIEW D

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
I. Adachi *et al.* (Belle II Collaboration)
Phys. Rev. Lett. **124**, 141801 – Published 6 April 2020 PHYSICAL REVIEW LETTERS

Search for a long-lived spin-0 mediator in $b \to s$ transitions at the Belle II experiment
I. Adachi *et al.* (Belle II Collaboration)
Phys. Rev. D **108**, L111104 – Published 21 December 2023 PHYSICAL REVIEW D

Many other analyses published at Belle and ongoig both at Belle and Belle II …

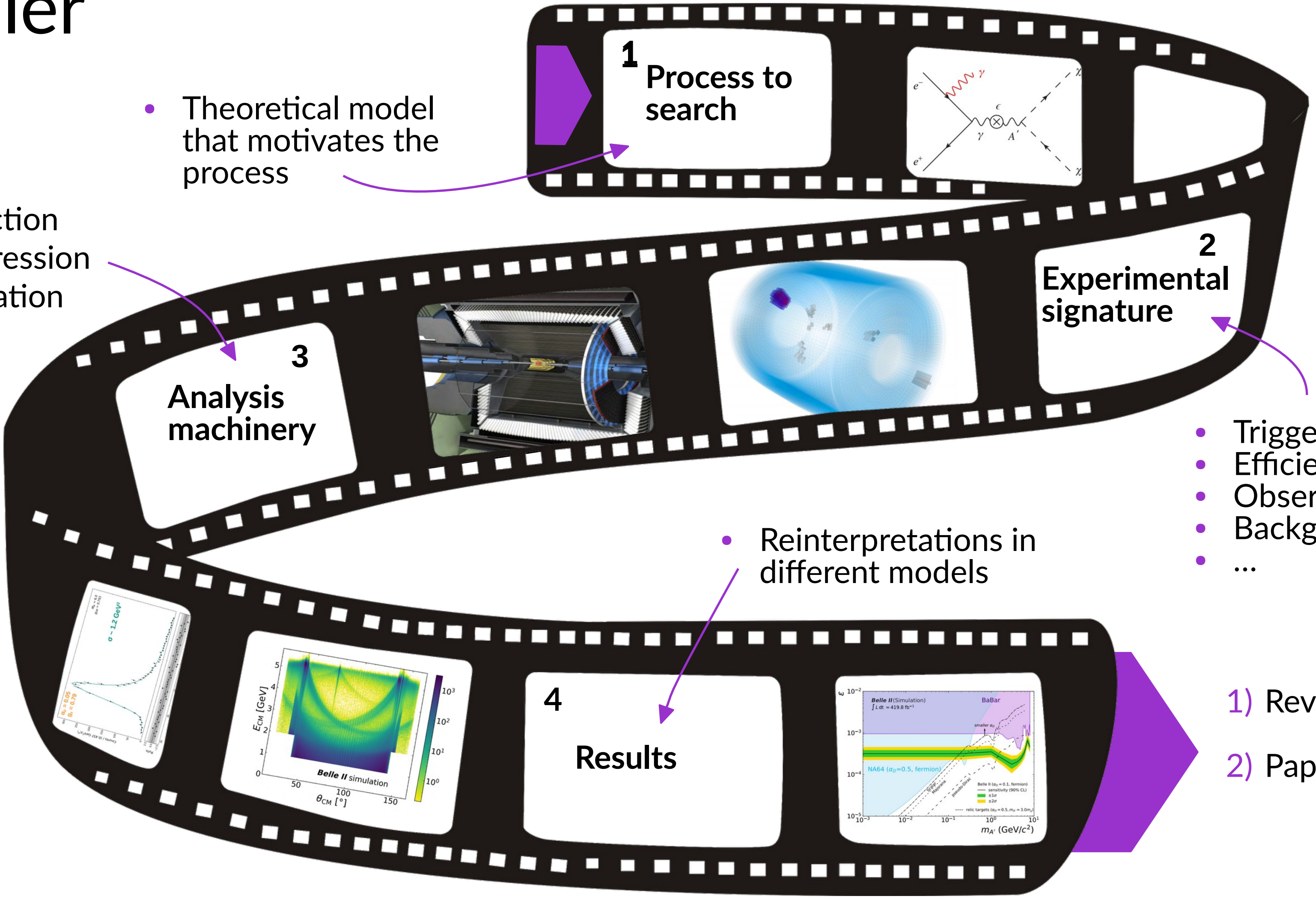
Let’s get into action!

The trailer

- Theoretical model that motivates the process

- Event reconstruction
- Backgroud suppression
- Analysis optimization
- Data validation
- Signal extraction
- …

Data & simulation



- Triggers
- Efficiencies
- Observables
- Backgrounds
- …

- Reinterpretations in different models

1) Review
2) Paper

Analysis strategy

Closed box analysis

- The signal region in data is kept hidden until the finalization of the analysis procedure to prevent experimenters' bias

Signal
- Signal generation & simulation
  - → MadGraph, EvtGen, …

Selection
- Reconstruction
- Event selection

Background
- Background characterization
- Background suppression
- Analysis optimization

Validation& Performance
- Data validation
- Detector performance studies

Extraction
- Signal yield extraction
- Statystical analysis
- Upper limit computation

Systematics
- Assess systematic uncertainties

Signal generators
- S. Banerjee, "Event generators for low multiplicity and tau"

Analysis strategy

Closed box analysis

- The signal region in data is kept hidden until the finalization of the analysis procedure to prevent experimenters' bias

- Signal generation & simulation
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- Background characterization
- Background suppression
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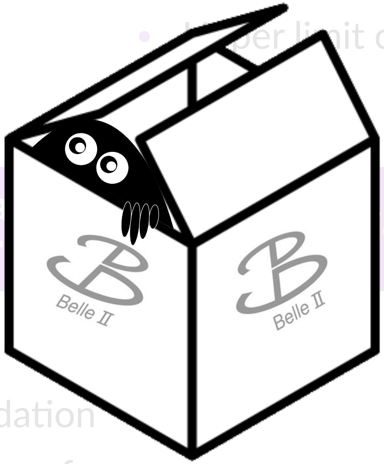
- Signal yield extraction
- Statystical analysis
- …per limit computation

Signal | Selec… | **Unboxing data** | Valida… Perfor… | …on | Systematics



- Reconstruction
- Event selection

- Data validation
- Detector performance studies

- Assess systematic uncertainties

Signal generators

- S. Banerjee, "Event generators for low multiplicity and tau"

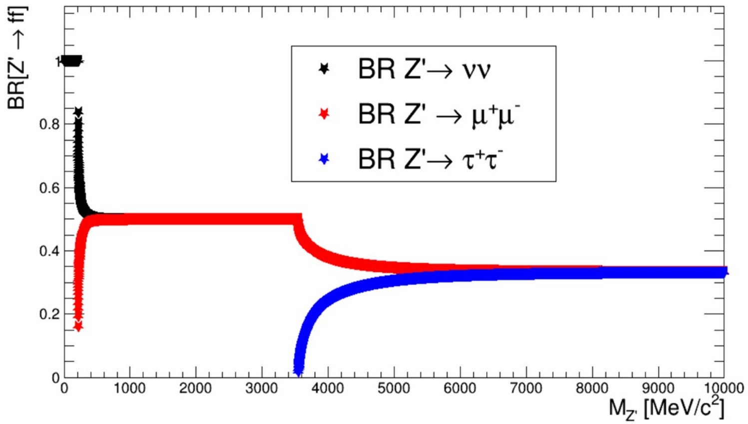
Example: invisible *Z'*

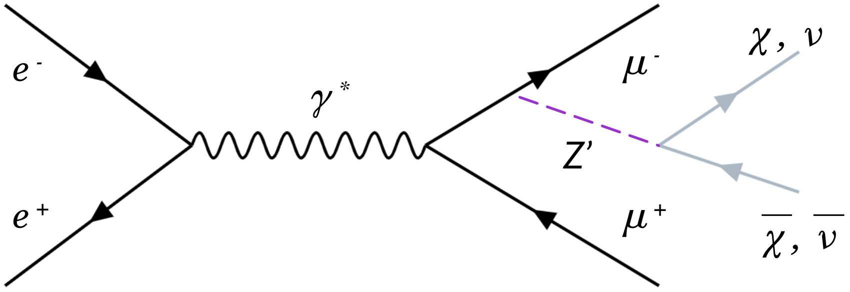
$L_\mu - L_\tau$ model

Shuve et al., Phys. Rev. D 89 , 113004 (2014)
D. Curtin et al., JHEP 02 (2015) 157
Altmannshofer et al., JHEP 106 (2016)

- **Massive Z' boson** with a **coupling g' only to leptons with μ- and τ-lepton numbers** ($L_\mu - L_\tau$ extension of the SM)
  - It may explain $(g-2)_\mu$ anomaly and DM abundance
- Possible decays:
  - $Z' \to$ invisible ($\nu\bar{\nu}$ or $\chi\bar{\chi}$), $Z' \to \mu\mu$, $Z' \to \tau\tau$
- **$Z' \to$ invisible** ($Z' \to \nu\bar{\nu}/\chi\bar{\chi}$)
  - If light **DM χ kinematically accessible** exists, **$BR(Z' \to$ invisible$)$ = 100%**
  - Profit from the **excellent Belle II capabilities for missing energy signatures**
  - Searched for through the process **$e^+ e^- \to \mu^+ \mu^- Z', Z' \to$ inv.**

$L_\mu - L_\tau$ model Z' branching ratios in leptons

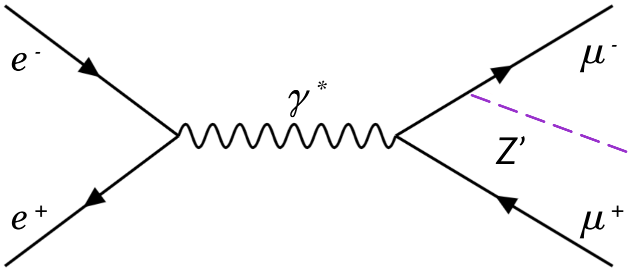




The invisible *Z'*

I. Adachi et al., Phys. Rev. Lett. 130, 231801 (2023)

- Search for an invisible resonance (*Z'*) in association with two muons in the final state
  - **$e^+e^- \rightarrow \mu^+\mu^-$ + missing energy**
  - **Signature**: two tracks compatible with muon hypothesis from the interaction point (IP) with missing energy, and nothing else



- **How do we reconstruct the *Z'*?**

The invisible *Z'*

I. Adachi et al., Phys. Rev. Lett. 130, 231801 (2023)

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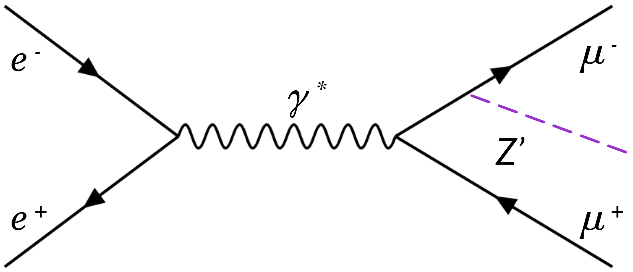

- **How do we reconstruct the *Z'*?**
  - Being invisible, the ***Z'* mass is reconstructed as a recoil to the two muons**
  - In signal events, we expect a **bump on M_{recoil}** correspondent to the mass of the *Z'*

$$M^2_{rec} = s + M^2_{\mu\mu} - 2\sqrt{s}E^{CMS}_{\mu\mu}$$

- **Which kind of background do we expect?**

The invisible *Z'*

I. Adachi et al., Phys. Rev. Lett. 130, 231801 (2023)

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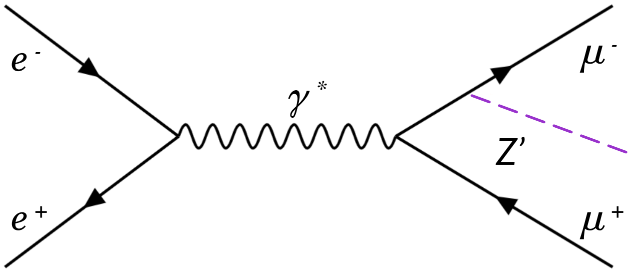

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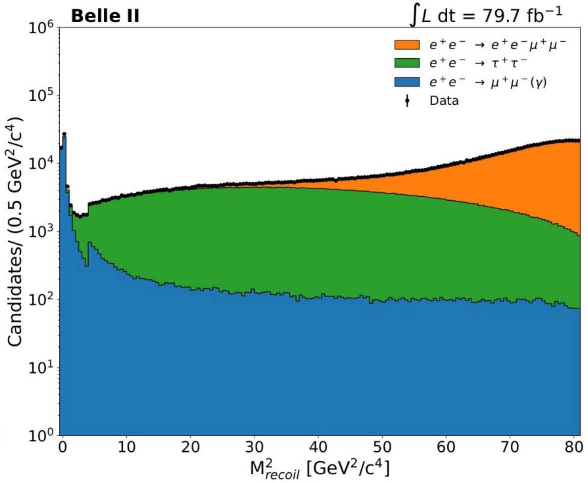
  - Being invisible, the ***Z'* mass is reconstructed as a recoil to the two muons**
  - In signal events, we expect a **bump on M_{recoil}** correspondent to the mass of the *Z'*

$$M^2_{rec} = s + M^2_{\mu\mu} - 2\sqrt{s}E^{CMS}_{\mu\mu}$$

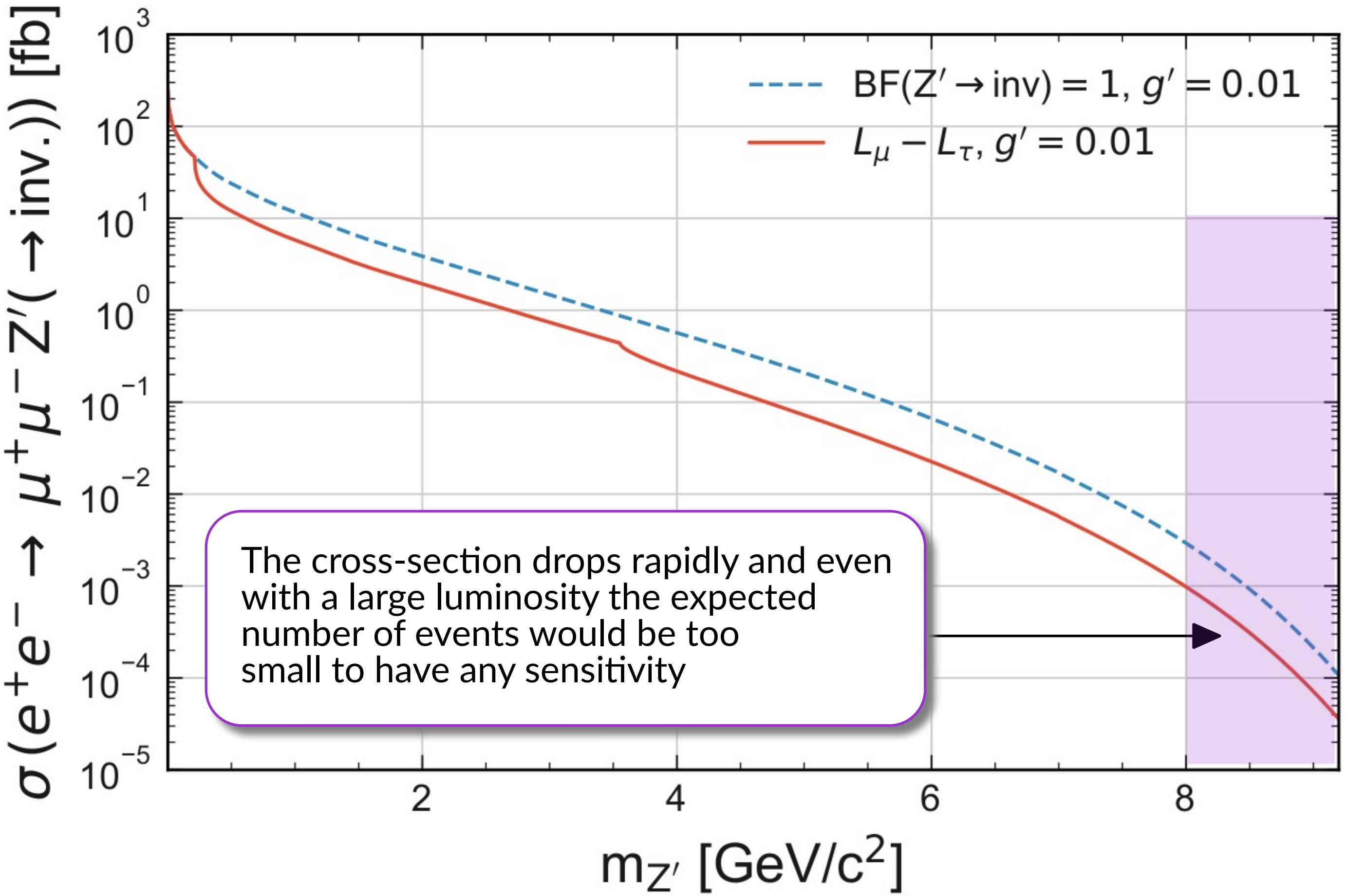


- **Which kind of background do we expect?**
  - **SM process with only two muons from IP** where **some particles** in the final state are **not detected**
    - $e^+e^- \to \mu^+\mu^-(\gamma)$, $e^+e^- \to \tau^+\tau^-(\gamma)$ with $\tau^- \to \mu^-\nu\bar{\nu}$, $e^+e^- \to e^+e^-\mu^+\mu^-$

Z' production in e^+e^- collisions

- How many events do we expect to produce in our experiment?

- Cross section from the generator
  - Model implemented in MadGraph5@NLO generator
  - Assuming $g' = 0.01$



The cross-section drops rapidly and even with a large luminosity the expected number of events would be too small to have any sensitivity

Data sets

- **Define a dataset**
  - In this case 78.7 fb^{-1} (2019+2020 dataset) are used

Large MC samples

- Study discriminating variables
- Optimize selections (train multi-variate analysis, ...)
- Compute signal efficiency and expected yields
- Estimate sensitivity

Data

- Validate the analysis procedure
- Measure detector efficiencies and systematic uncertainties
- Extract the final results

MC

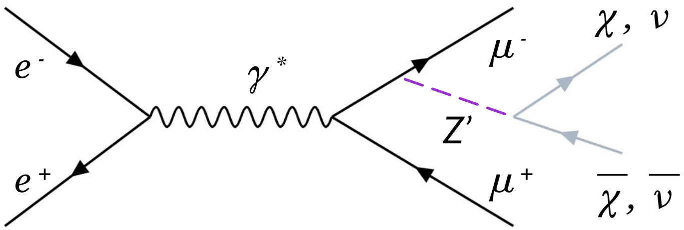
Process	N_{evts} ($\times 10^9$)	$\int Ldt$ (ab^{-1})
$e^+e^- \to \mu^+\mu^-(\gamma)$	1.148	1.0
$e^+e^- \to \tau^+\tau^-(\gamma)$	0.919	1.0
$e^+e^- \to e^+e^-(\gamma)$	29.58	0.1
$e^+e^- \to \pi^+\pi^-(\gamma)$	0.333	2.0
$e^+e^- \to K^+K^-(\gamma)$	0.033	2.0
$e^+e^- \to K^0\bar{K}^0(\gamma)$	0.018	2.0
$e^+e^- \to \pi^+\pi^-\pi^0(\gamma)$	0.048	2.0
$e^+e^- \to e^+e^-\mu^+\mu^-$	3.766	0.2
$e^+e^- \to e^+e^-\pi^+\pi^-$	1.895	1.0
$e^+e^- \to e^+e^-e^+e^-$	7.900	0.2
$e^+e^- \to e^+e^-K^+K^-$	0.160	2.0
$e^+e^- \to e^+e^-\tau^+\tau^-$	0.037	2.0
$e^+e^- \to \mu^+\mu^-\mu^+\mu^-$	7×10^{-4}	2.0
$e^+e^- \to \mu^+\mu^-\tau^+\tau^-$	3×10^{-4}	2.0

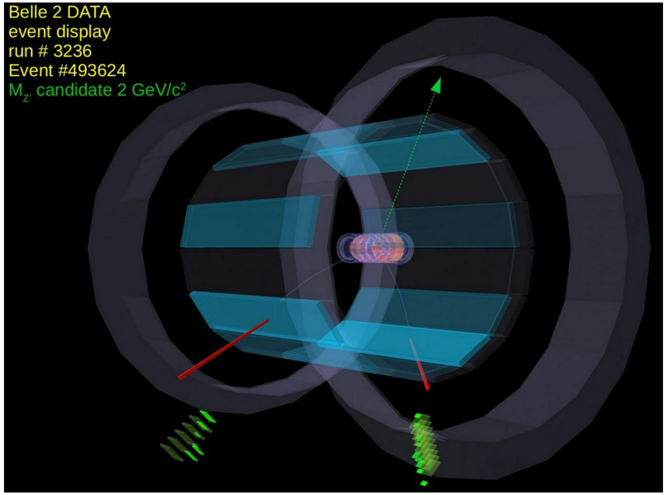
+ ~600 samples of signal MC

Data

Processing	Experiment	$\int Ldt$ on-res
Proc 12 - chunk 1	7, 8, 10	8.8 fb^{-1}
Proc 12 - chunk 2	12	53.9 fb^{-1}
Bucket 16	14	10.5 fb^{-1}
Bucket 16b	14	5.5 fb^{-1}
Total	7-14	78.7 fb^{-1}

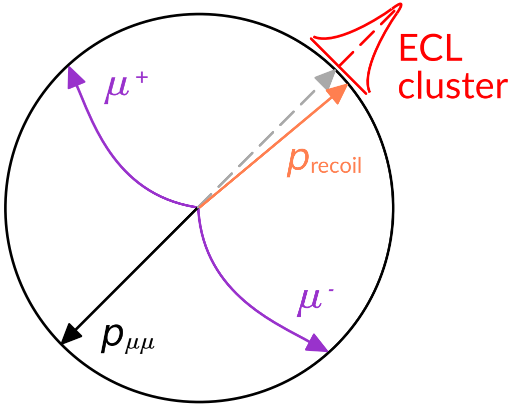
Event selection





- Signal signature: **peak in the recoil against a $\mu^+\mu^-$ pair ...**
  - Events with exactly two oppositely charged particles identified as muons from the IP
    - Not back-to-back (3D opening angle < 179.5° in the CMS frame)
  - CDC two-track trigger
- **... where nothing else is detected**
  - Recoil momentum within the ECL barrel excluding gap at 90°
  - No photon within 15° of the recoil momentum
  - No extra tracks in the rest-of-event and no extra energy > 0.5 GeV

Photon-veto



Signal modeling

- **Signal pdf**: sum of 2 Crystal-ball distributions (CB1 + CB2)
  - → **Extract mass peak width to define signal regions** (other strategies: sigma-68, …)
- Fit to the M^2_{recoil}

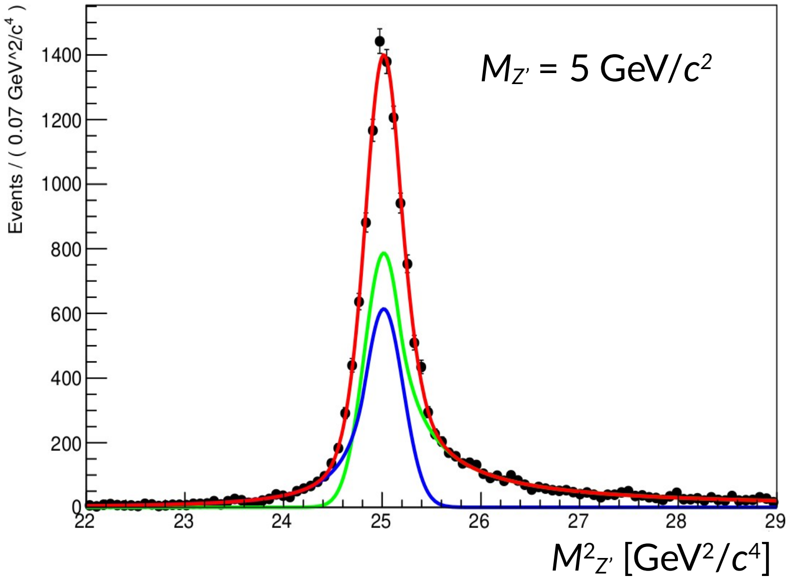
$$M^2_{rec} = s + M^2_{\mu\mu} - 2\sqrt{s}E^{CMS}_{\mu\mu}$$

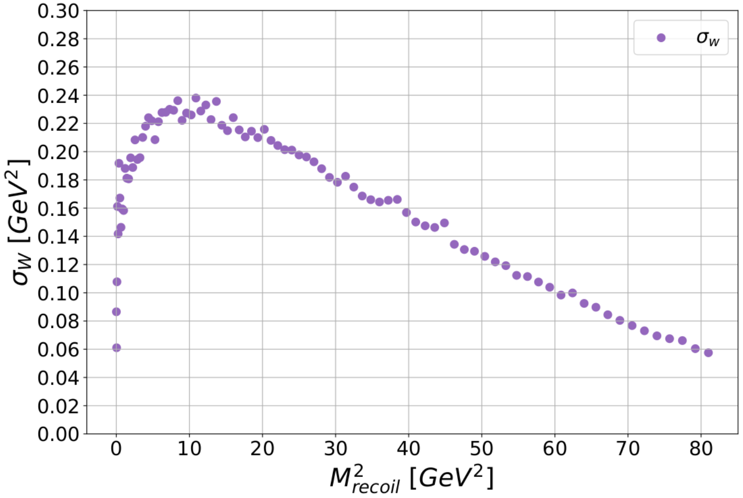
- **Resolution σ_W**

$$\sigma_W = \sqrt{f_{\text{CB1}}\sigma^2_{\text{CB1}} + (1 - f_{\text{CB1}})\sigma^2_{\text{CB2}}}$$

f_{CB1} = fraction of CB1

For the background rejection studies, only events within the signal region (±2σ from the nominal $M_{Z'}$) are used





Background suppression

G. Punzi, arXiv:physics/0308063 [physics.data-an] (2003)

- Identify **background sources**
- Study **signal features**
  - Define some **discriminating variables**
- Devise a method to **discriminate signal from background**
  - cut-based selection, multivariate-analysis techniques like applying neural networks, BDTs, ...
- **Optimize the selection**
  - Maximize a figure-of-merit, ...

All these studies are done in simulation and then validated in data using control channels

Punzi figure-of-merit

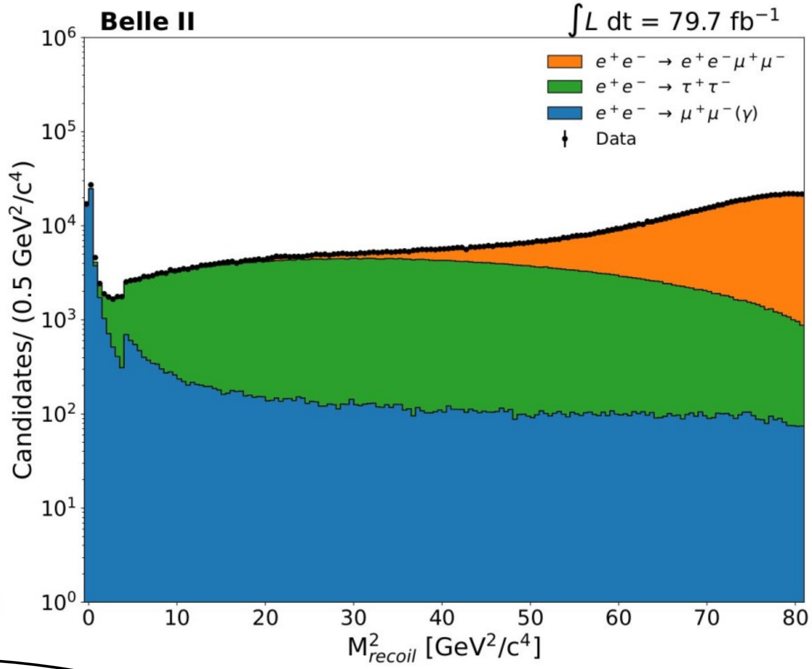
- Does not depends on number of signal events expected
  - Cross section is unknow
- Does not diverge for small number of background events

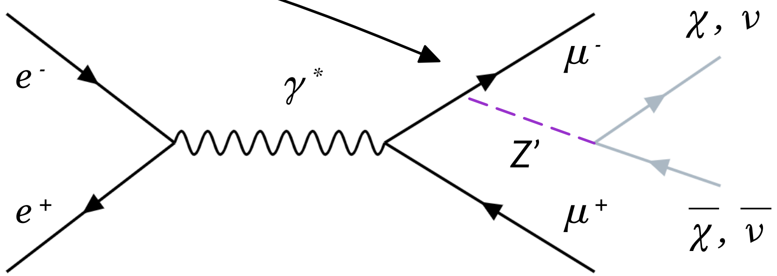
$$\mathrm{FOM_P} = \frac{\varepsilon_S(t)}{\frac{a}{2} + \sqrt{B(t)}}$$

t → selection
$\varepsilon_S(t)$ → signal efficieny given *t*
B(t) → number of background events passing *t*
a → number of sigmas is a one-tailed Gaussian test corresponding to the statistical significance for your analysis

Background in Z' → invisible

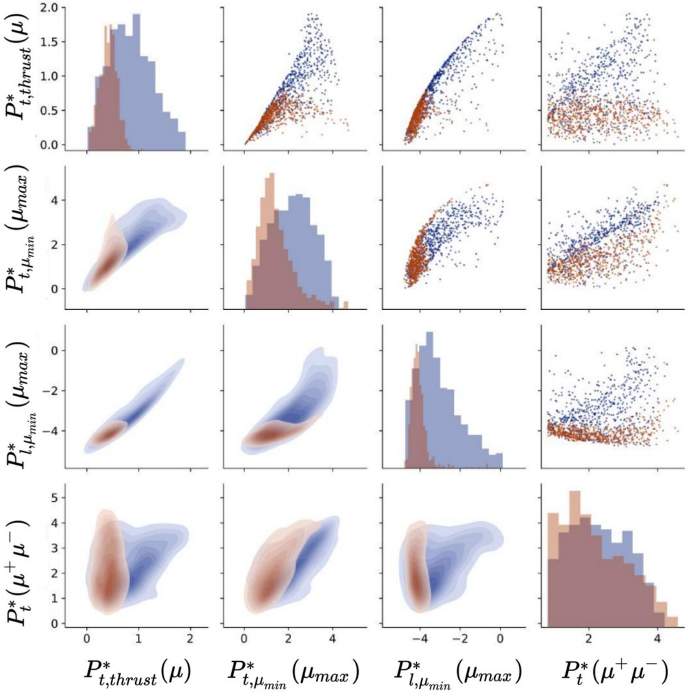
- **Main background components**
  - $e^+e^- \to \mu^+\mu^-(\gamma)$, when the photon is not detected
  - $e^+e^- \to \tau^+\tau^-(\gamma)$ with $\tau^- \to \mu^-\nu\overline{\nu}$, neutrino are not detected
  - $e^+e^- \to e^+e^-\mu^+\mu^-$, when both e^+e^- are not detected
- **Signal feature**
  - The Z' is radiated off one of the two muons in the final state as **final-state radiation**
  - **Different origin of missing energy** with respect to main background components
    - We expect some **difference in the distribution of kinematic variables of the two muons tracks** for signal and background





Background suppression in Z’ → invisible

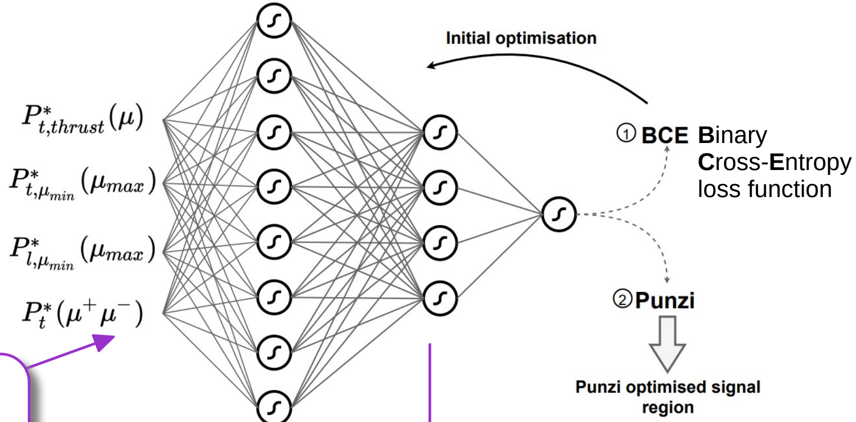
- **Set of variables** mostly **relating to the kinematics of the dimuon system** and the overall **event topology**
  - ➔ Sensitive to the **different origin of the missing momentum**



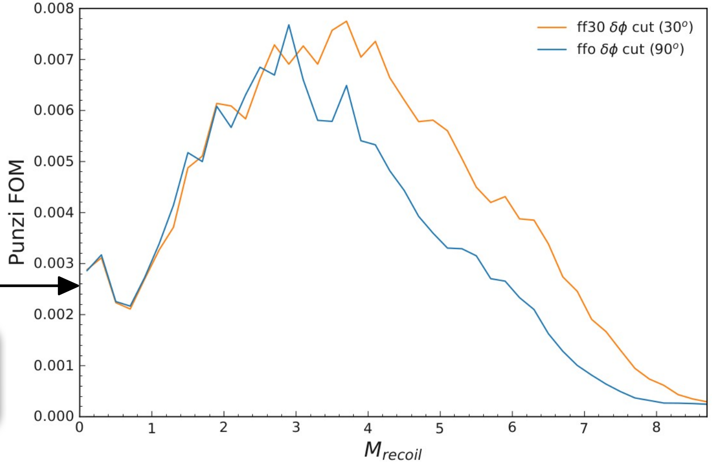
Signal
Background
$e^+e^- \to \tau^+\tau^-(\gamma)$

Fed to a **Punzi-network** specifically designed for this analysis

F. Abudinén et al., Eur. Phys. J. C 82, 121 (2022)



FOM$_P$ obtined at the optimal selection as a functon of M_{recoil}



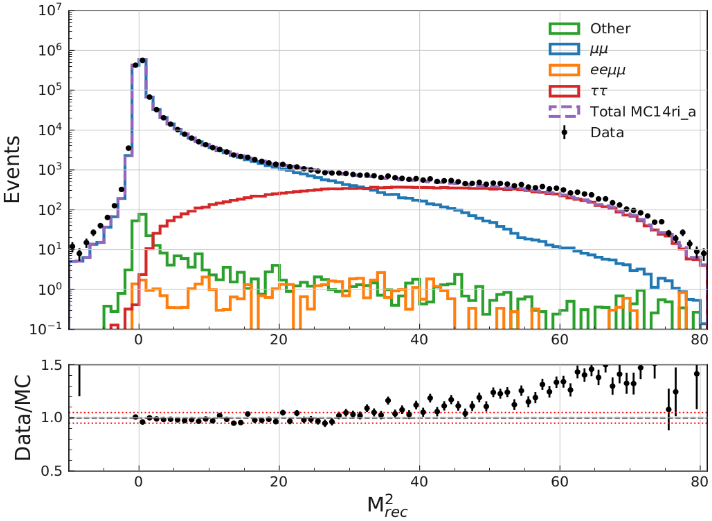
Signal efficiency of 5-7%

Data validation

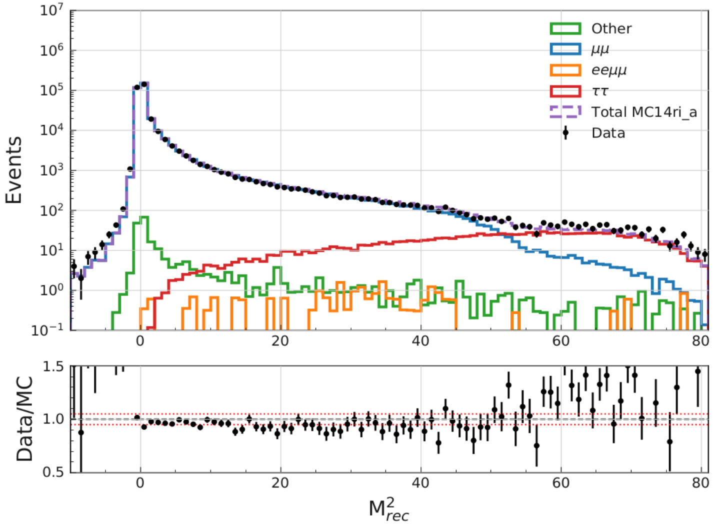
Signal free control channels

- Study **impact of the selections in data and simulation**
- **Extract corrections to MC** and **systematic uncertainties**
- $\mu^+\mu^-\gamma$ with a high energetic photon ($E\gamma$ > 1 GeV)
  - Recoil resolution study, trigger efficiencies, Punzi-net efficiency, background systematic estimation
- $e^\pm\mu^\mp$ sample, μID > 0.5 and eID > 0.5
  - Trigger efficiencies, Punzi-net efficiency, background systematic estimation
- e^+e^- sample, eID > 0.5
  - Measure the **photon veto inefficiency** in **data and simulation**
- **300 pb^{-1} of $\mu^+\mu^-$** data later **discarded from the analysis**

$\mu^+\mu^-\gamma$ before Punzi-net



$\mu^+\mu^-\gamma$ after Punzi-net



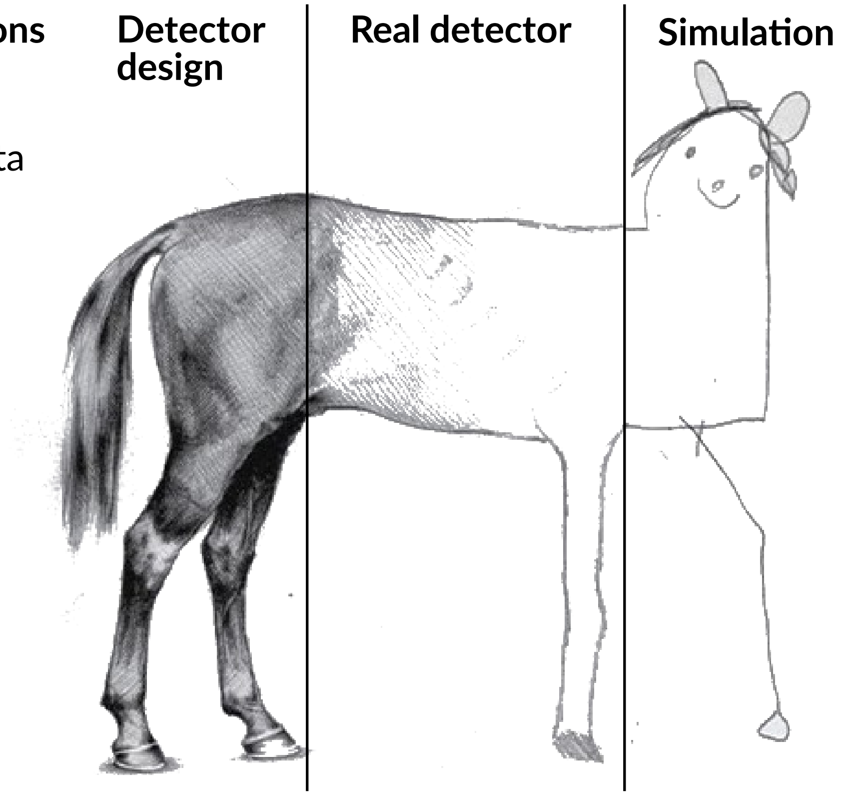
Unmodeled simulation

- Need to be carefully studied and understood

Detector performance studies

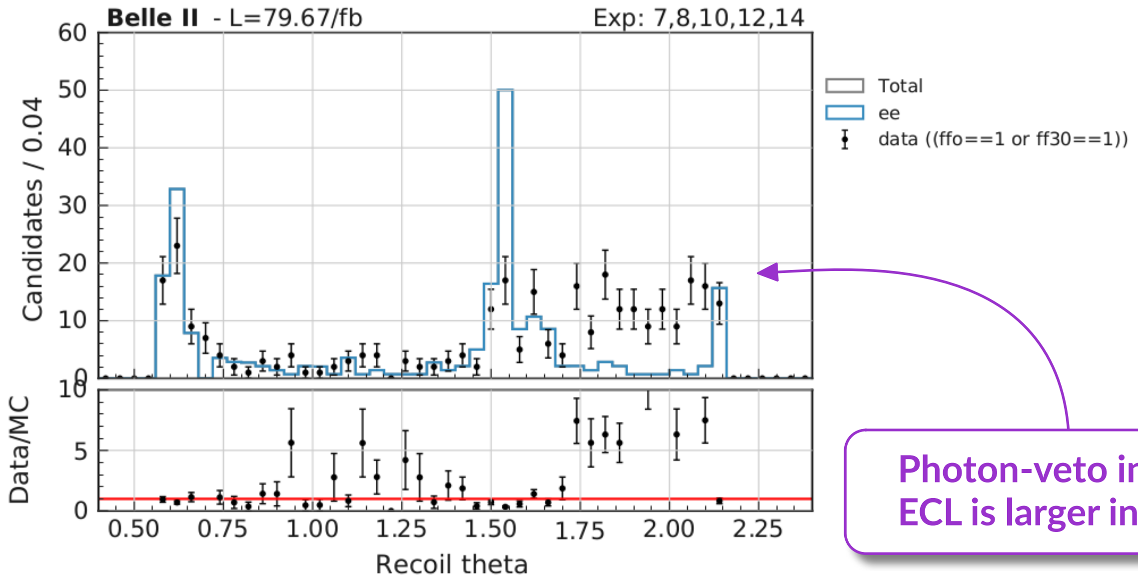
Real detector is different from the simulation

- **Estimate the discrepancy** in **detector efficiencies** and **resolutions** between **data and simulation**
  - → **Correct the simulation** for additional effects observed in data
  - → Assign **systematic uncertainties**
- In the ***Z'*** **→ invisible analysis**
  - → Trigger selection
  - → Tracking
  - → Particle identification (Lepton ID)
  - → Resolution on the recoil mass
  - → Photon-veto inefficiency



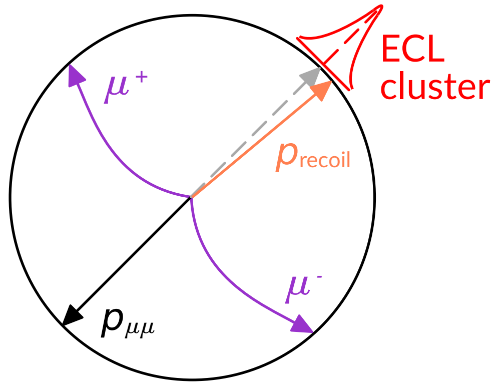
Photon veto inefficiency

- Signal free e^+e^- **control sample**
  - Select events with M^2_{recoil} < 1 GeV^2/c^4 (dominated by Bhabha events)
  - Measure the **photon veto inefficiency** in **data and simulation**
  - **Derive correction factors** to be used to correct the expected $\mu^+\mu^-$ background



Photon veto

- No photon within 15° of the recoil momentum
- No extra energy > 0.5 GeV

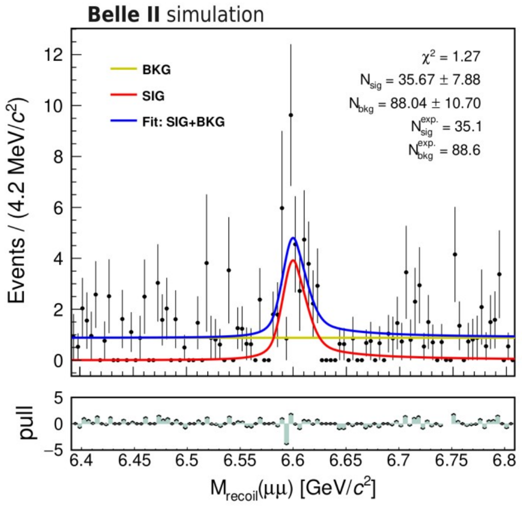


- **It relies on efficiency of ECL photon reconstruction …**
- … sometimes it fails
- … different in data and simulation

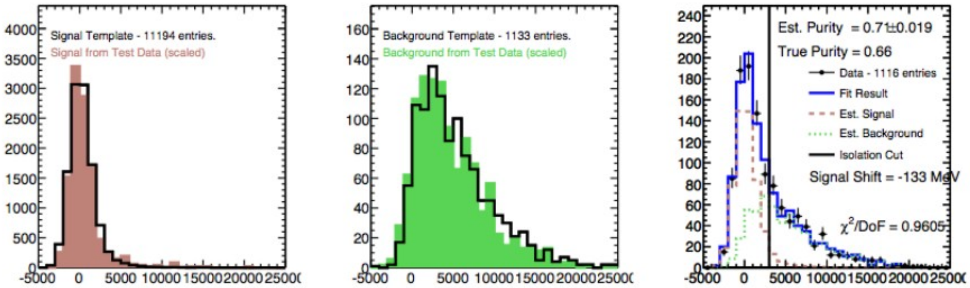
Photon-veto inefficiency in the backward barrel ECL is larger in data than that estimated in simulation

Signal yield extraction

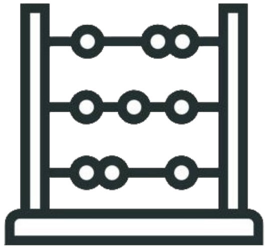
- **Fit using a PDF for signal and background**
  - Model the signal PDF parameters as a function of the mass hypothesis could be complicated



- **Template fits**
  - No analytical function
  - Shapes directly taken from simulation



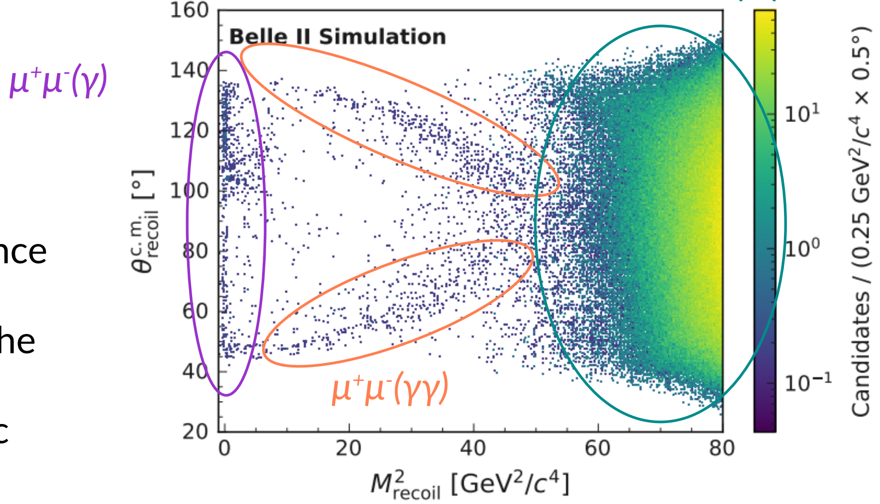
- **Cut-and-count technique**
  - No background to fit
  - Count the number of events observed in the signal region
  - Compare the counted number of events with background expectations to extract the signal yield

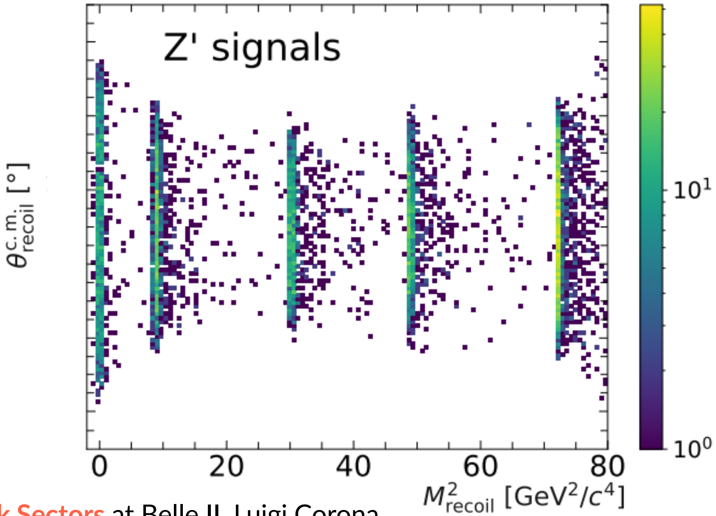


Signal extraction in Z’ → inv.

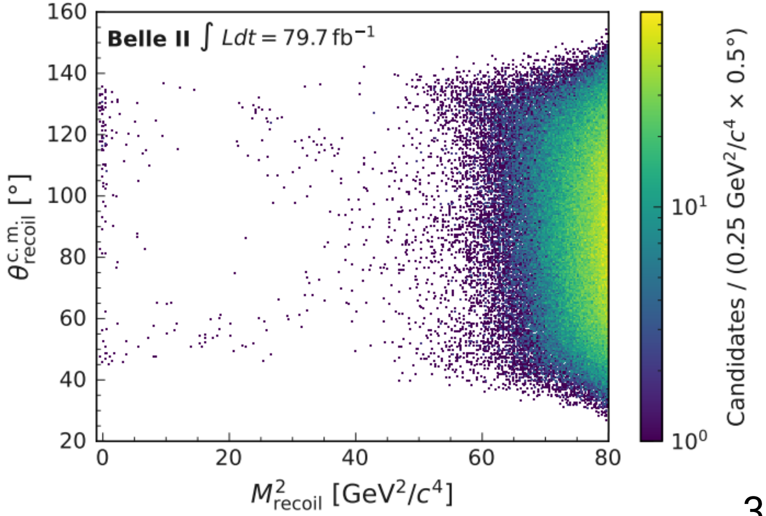
- **2D binned likelihood fit to M^2_{recoil} vs θ^{CMS}_{recoil}**
  - Template for background and signal combined
  - Systematic uncertainties are introduced in the fit via nuisance parameters
  - Nuisance parameters constrained with Gaussian terms in the likelihood
  - Standard deviation σ_ν of Gauss is the associated systematic uncertainty
  - Mass window of ±10σ in M^2_{recoil}

Expected yields



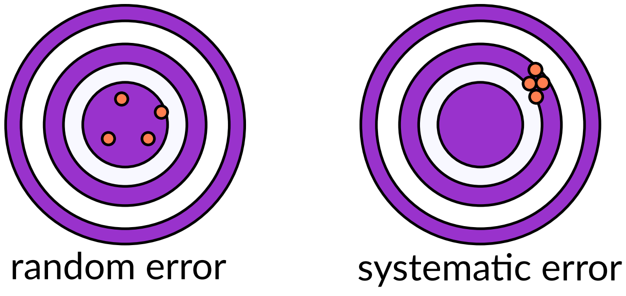


Observed yields



Assess systematic uncertainties

- Lepton-ID, hadrond-ID, tracking efficiency, ...
  - Evaluated from **differences measured in data and simulation in performance studies** as a function of the momentum, polar angle, ...
  - **Are provided by the performance group**
  - Documented in internal technical notes



- **Other systematic uncertainties to assess**
  - Usually studied on data using **signal free control samples**
  - Every **arbitrary choices** you consider in the analysis **need to be studied** (selections, signal and background models, fit, ...)
    - Check the **effect on your signal efficiency** and **background predictions**

Usually in dark sector analysis we set upper limits to theoretical models, which are mainly limited by statics

- **Upper limits on cross section scale with luminosity (~ √L)**

However systematics affect the upper limits and are crucial if something is observed

Systematic uncertainties in the invisible *Z'*

- **Systematic uncertainties** on the **signal efficiency** and on the **signal and background template shapes**
- Studied by **comparing data and simulation** in the ***μμγ, ee***, and ***eμ* control samples**
  - ➔ Provide complementary coverage of M^2_{recoil} in three ranges [-0.5; 9], [9; 36], [36; 81] GeV^2/c^4 (for which we have a different contribution from the three main backgrounds)

M^2_{recoil} range [GeV$^2/c^4$]			[-0.5; 9]	[9; 36]	[36; 81]
Source	Affected quantity	Sample used	Uncertainty		
Data-simulation comp.	ε_S	$\mu\mu\gamma$, $e\mu$	2.2%	1%	4.2%
Punzi-net efficiency	ε_S	$\mu\mu\gamma$, $e\mu$	1.6%	6.4%	7.2%
Recoil mass resolution	Signal shape	$\mu\mu\gamma$	10%	10%	10%
Background shape	Background	$\mu\mu\gamma$, $e\mu$	3.2%	8.6%	25%
Integrated luminosity	Global		1%	1%	1%
M^2_{recoil}			< 1 GeV$^2/c^4$	> 1 GeV$^2/c^4$	
Photon-veto inefficiency	Background shape	ee	34%	5%	

Data-simulation comparison includes

- Mismodeling in trigger efficiency
- Tracking efficiency
- Lepton-ID
- Background cross sections
- Effect of the selections

Generally provided by the performance group

- Integrated luminosity uncertainty from luminosity paper

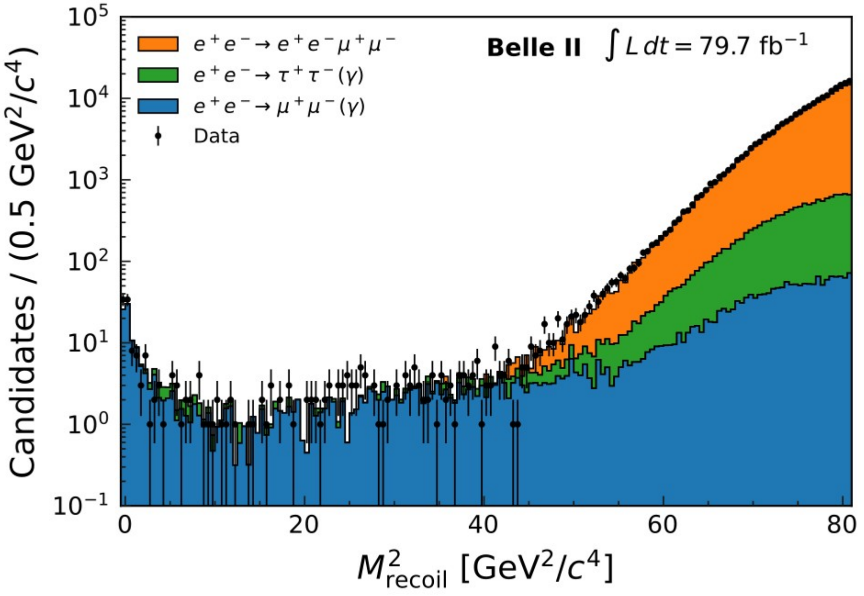
F. Abudinén et al., Chin. Phys. C 44, 021001 (2020)

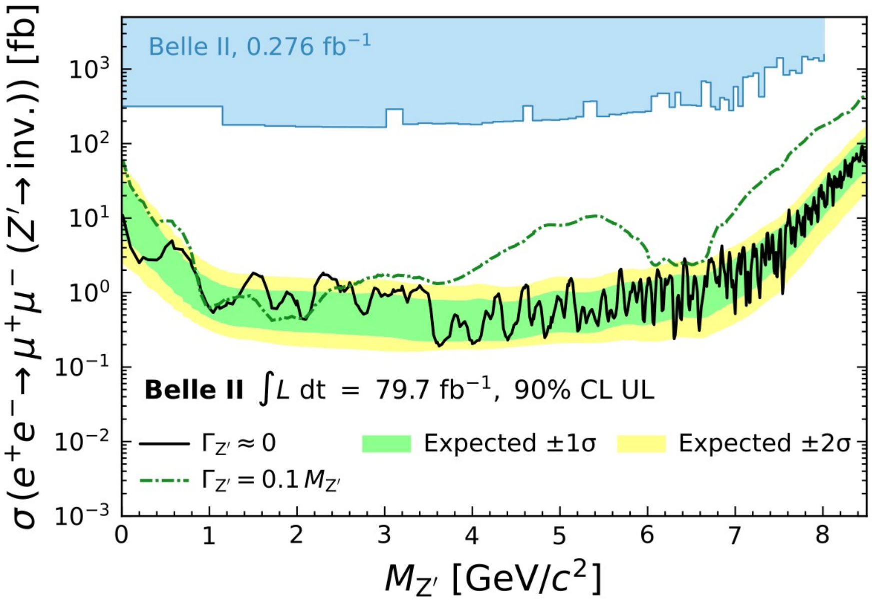
Unboxing data

I. Adachi et al., Phys. Rev. Lett. 130, 231801 (2023)

How to compute upper limits?
- E. Graziani, "Limit setting: how to" (next talk)
- S. Stefkova, G. Stark, L. Gaertner "pyhf-tutorial"

- **No significant excess compatible with signal found**
- **Set 90% CL upper limits** to the cross section of the process $e^+e^- \to \mu^+\mu^- Z'$, $Z' \to$ invisible
  - Our upper limits are mainly limited by luminosity → Currently, same analysis is ongoing on 362 fb^{-1}



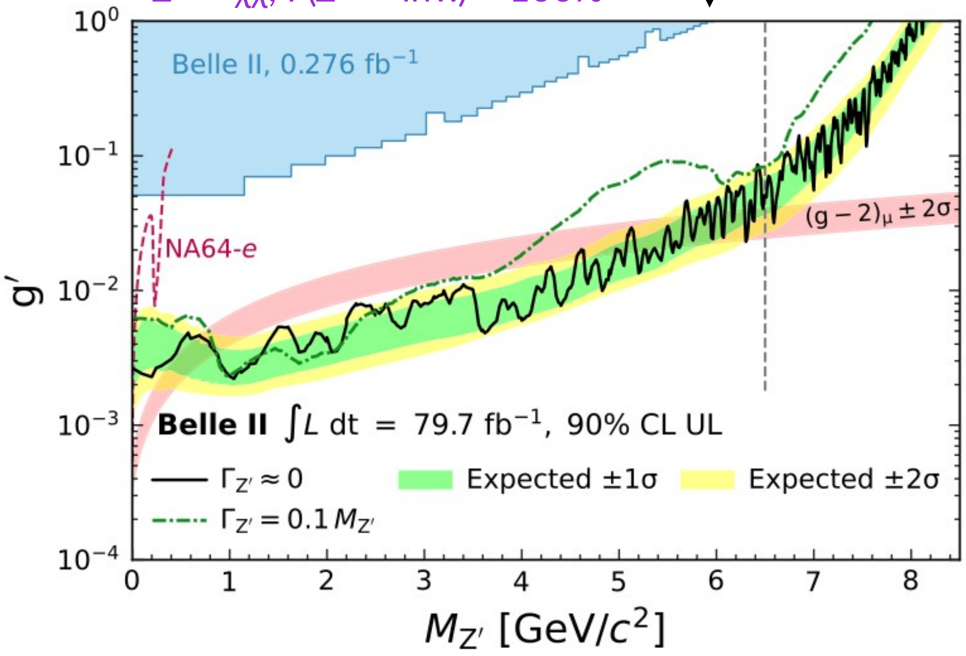


Interpretation in the *Z'* models

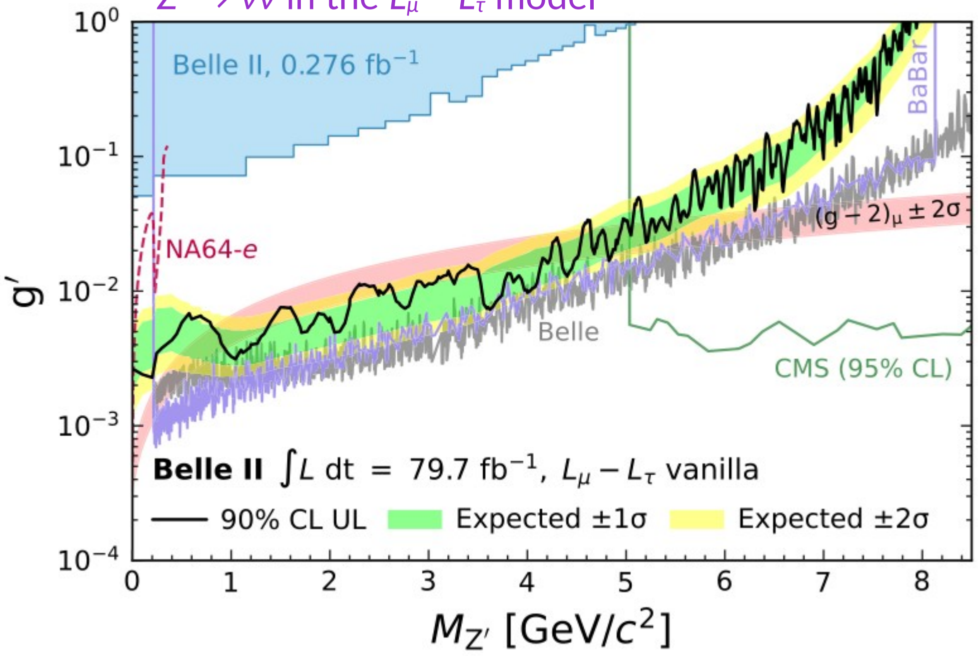
I. Adachi et al., Phys. Rev. Lett. 130, 231801 (2023)

- **$(g - 2)_\mu$ favored region escluded for $M_{Z'} \in (0.8, 5.0)$ GeV/c^2 for $\Gamma(Z' \to$ inv.) = 100%**

$Z' \to \chi\bar{\chi}$, $\Gamma(Z' \to \text{inv.}) = 100\%$



$Z' \to \nu\bar{\nu}$ in the $L_\mu - L_\tau$ model



General comments

- **The steps are generally the same …**
- **… but there are significant differences depending on the analysis**
  - → Different reconstruction
  - → Different backgrounds
  - → Different vetoes
  - → Different triggers
  - → Different control channels
  - → Different signal yield extraction
  - → …

Signal
- Signal generation & simulation
  - → MadGraph, EvtGen, …

Selection
- Reconstruction
- Event selection

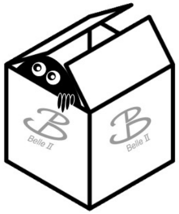
Background
- Background characterization
- Background suppression
- Analysis optimization

Validation& Performance
- Data validation
- Detector performance studies

Extraction
- Signal yield extraction
- Statystical analysis
- Upper limit computation

Systematics
- Assess systematic uncertainties

Unboxing data



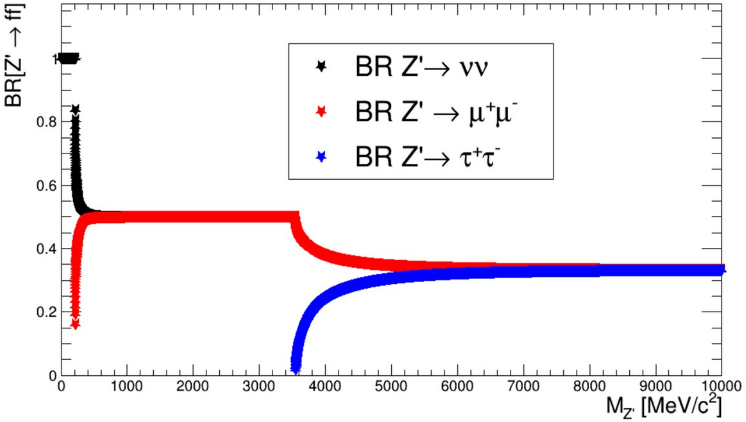
Let's see few examples in the next slides

More on the analyses and results

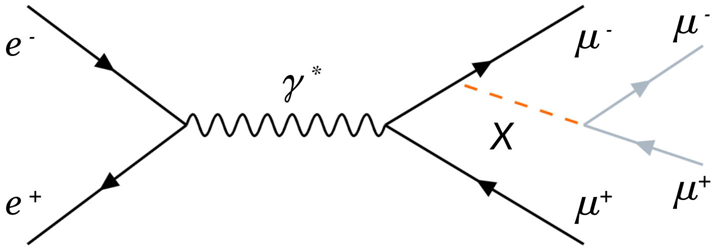
Other *Z'* searches

- In the $L_\mu - L_\tau$ **framework**
  - *Z'* boson couples only to leptons with μ- and τ-lepton numbers
  - $Z' \rightarrow \mu\mu$, $Z' \rightarrow \tau\tau$

$L_\mu - L_\tau$ model *Z'* branching ratios in leptons

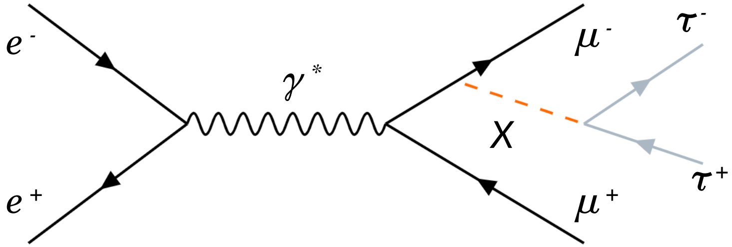


Search for a $\mu\mu$-resonance in $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$



- Reinterpret the results in different models
  - $X = Z'$, muonphilic dark-scalar

Search for a $\tau\tau$-resonance in $e^+e^- \rightarrow \mu^+\mu^-\tau^+\tau^-$

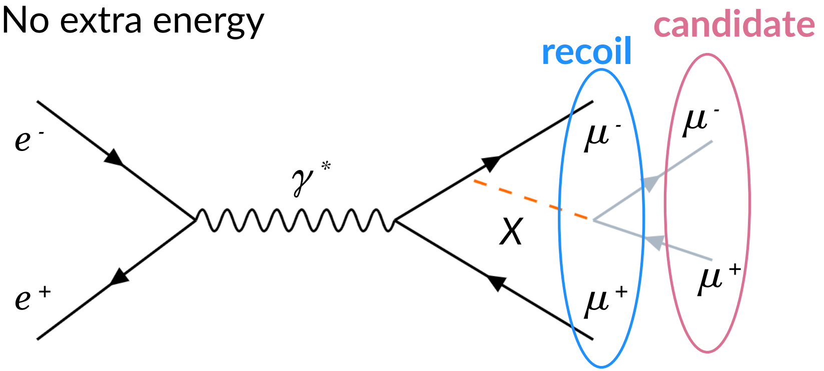


- Reinterpret the results in different models
  - $X = Z'$, axion-like particle *ALP*, leptophilic dark scalar

Search for a $\mu\mu$-resonance in $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$

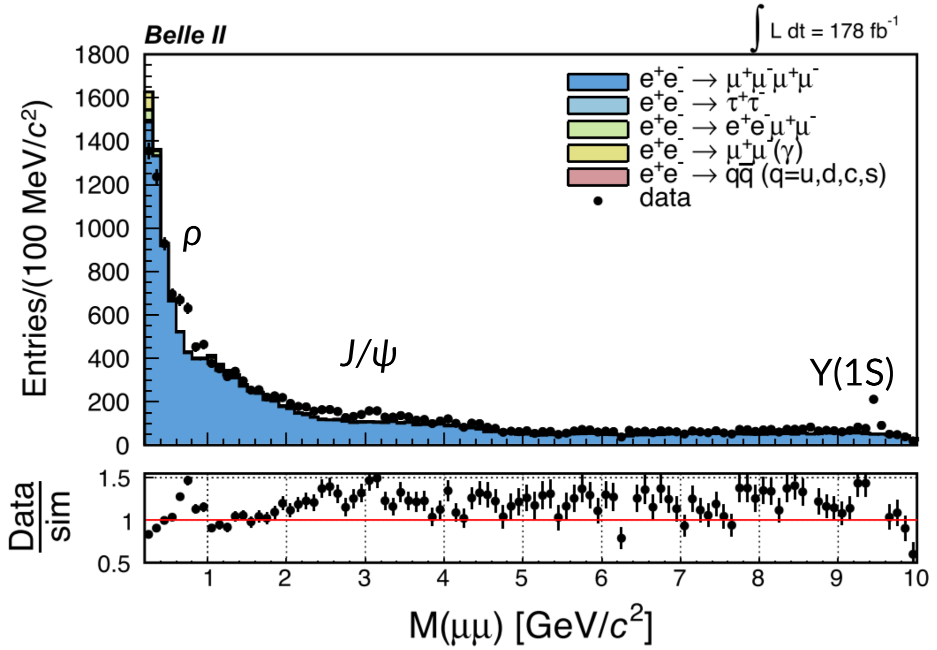
I. Adachi et al., Phys. Rev. D 109, 112015 (2024)

- ***$e^+e^- \to \mu+\mu$-$Z'(\to \mu^+\mu^-)$***
  - Four-track final state with at least **three identified as muons**
  - Four-track invariant mass compatible with collision √s
  - No extra energy



- **Presence of a resonance in both candidate and recoil muon pairs**
  - Exploited in the background suppression through neural networks → Challenging aggressive suppression of main **SM background $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$**

- Signal signature is a **narrow peak in the opposite-charge dimuon mass *M(μμ)***
- Signal extracted through **fit scan to *M(μμ)***



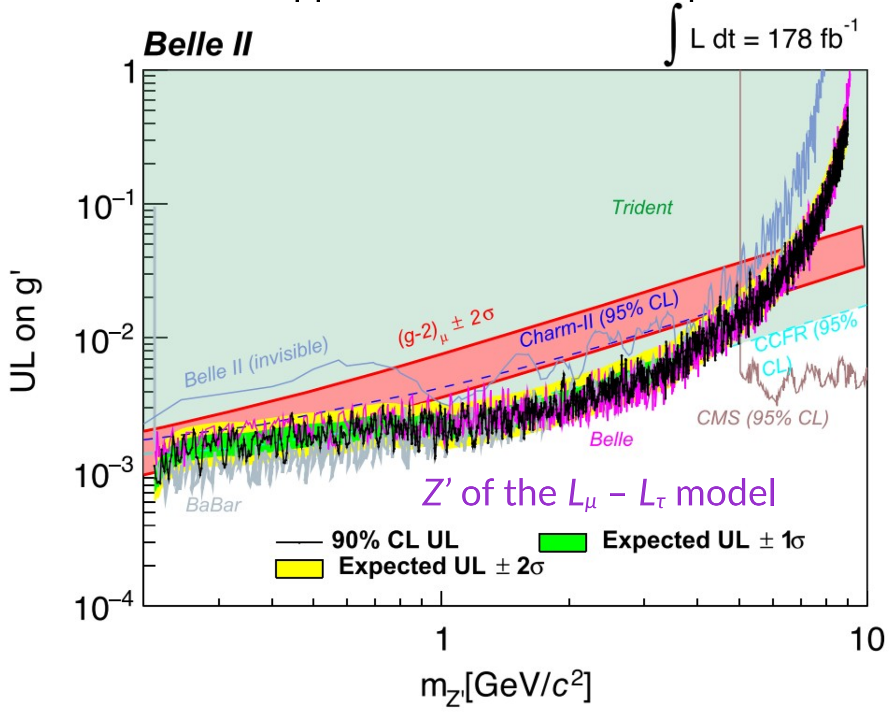
Search for a $\mu\mu$-resonance in $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$

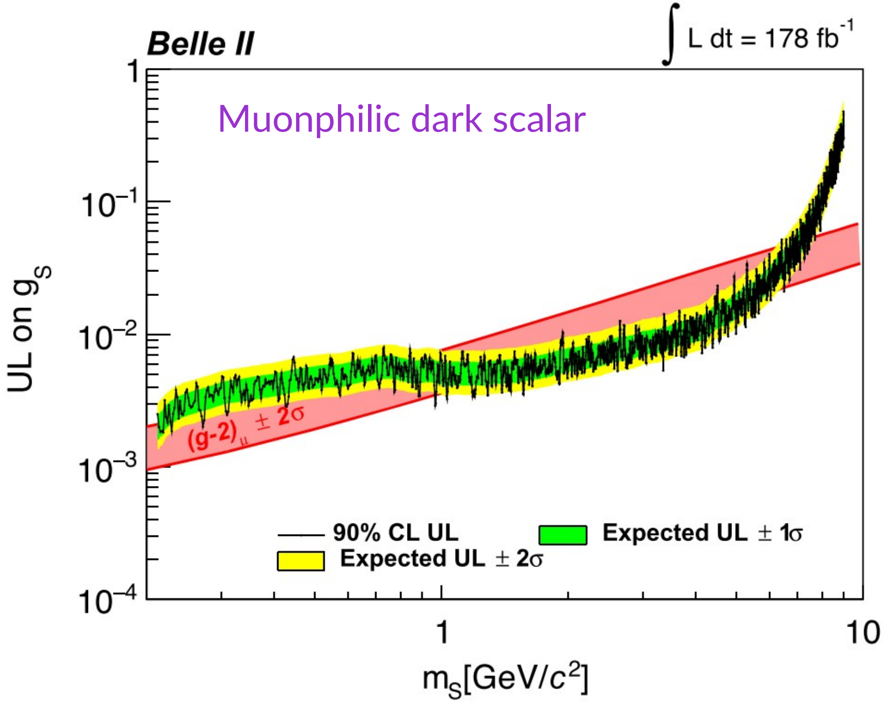
I. Adachi et al., Phys. Rev. D 109, 112015 (2024)

P. Harris et al., arxiv-2207.08990 (2022)
S. Gori et al., arxiv-2209.04671 (2022)

- **No significant excess found in 178 fb^{-1}**
  - Competitive 90% CL upper limits on the g' coupling of the $L_\mu - L_\tau$ model (Z') with BaBar (> 500 fb^{-1}) and Belle (> 600 fb^{-1}) results
  - First 90% CL upper limits for the muonphilic scalar model from a dedicated search

Example of limit recast to a different model!

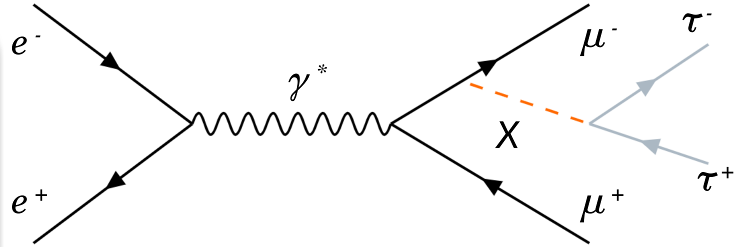




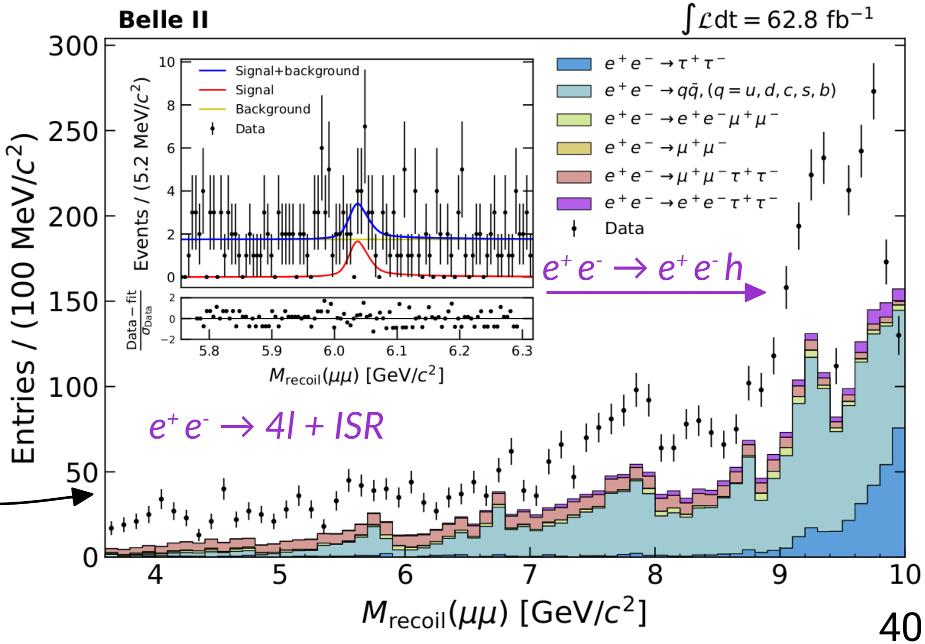
Search for a $\tau\tau$-resonance in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$

I. Adachi et al., Phys. Rev. Lett. 131, 121802 (2023)

- **Four-track final state:** τ decay in $\tau \to l\nu\bar{\nu}$, $\tau \to h\nu\bar{\nu}$
  - With missing energy; **intermediate between $Z' \to$ inv. and $Z' \to \mu^+\mu^-$**
- Signal peaks in the **recoil mass of $\mu^+\mu^-$ $M_{recoil}(\mu\mu)$**



- Challenging **background rejection to reduce event contamination with missing energy not associated with signal signature**
  - Eight classifiers trained on different regions of recoil mass
- **Signal extracted through fit scan to $M_{recoil}(\mu\mu)$** distribution
  - **Background measured directly on data** to minimize impact of not correctly simulated backgrounds
  - **Smooth background** on the scale of signal resolution (~10 MeV) → not problematic



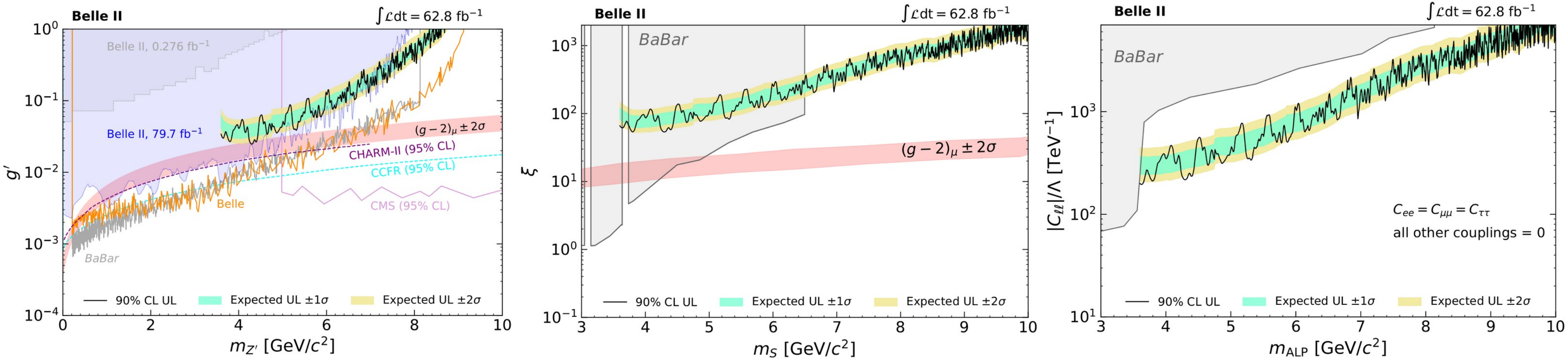
Search for a $\tau\tau$-resonance in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$

I. Adachi et al., Phys. Rev. Lett. 131, 121802 (2023)

Example of limit recast to different models!

- **No significant excess found in 62.8 fb^{-1}**
  - First **limits at 90% CL for a leptophilic dark scalar *S*** model with m_S > 6.5 GeV/c^2
  - First **direct limits at 90% CL for axion-like particle *ALP* → $\tau\tau$**

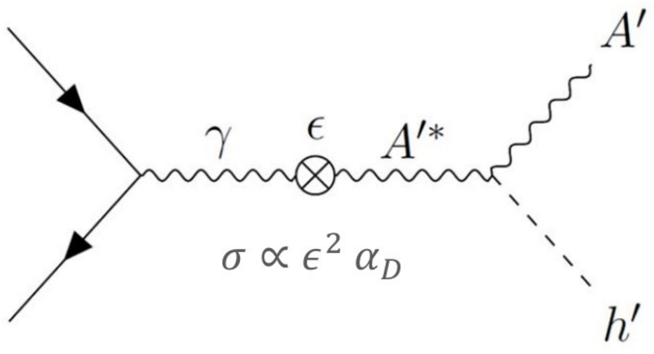
Z' of the $L_\mu - L_\tau$ model — Leptofilic dark scalar *S* — Axion-like particle *ALP*



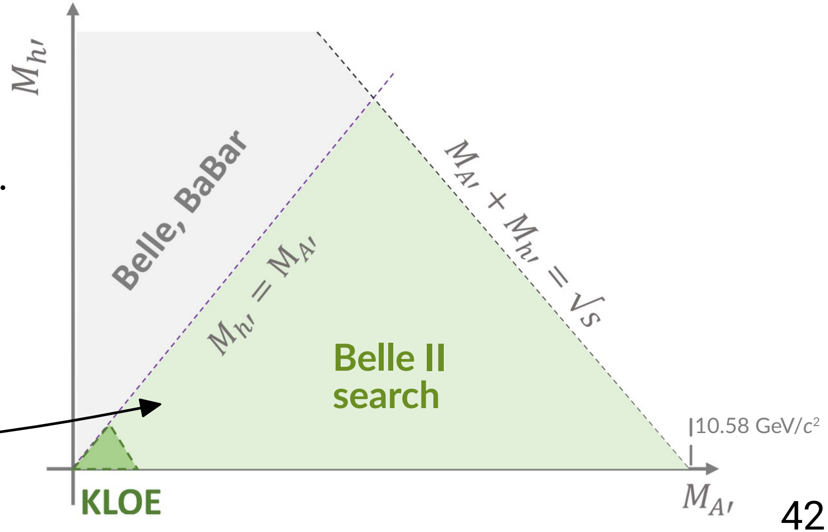
J. P. Lees et al., PhysRevLett.125.181801 (2020)
M. Bauer et al., JHEP09-056 (2022)

Dark Higgsstrahlung

P. Fayet, Nucl. Phys. B 187, 184 (1981)
Batell et al., Phys. Rev. D 79, 115008 (2009)



- **Dark photon *A'***
  - kinetic mixing with SM photon with strength ε
  - mass produced by the Higgs mechanism involving a dark Higgs boson
- **Dark higgs *h'***
  - couples to *A'* with α_D
  - does not mix with SM Higgs
- Dark higgsstrahlung process: $e^+e^- \to A'^* \to A'\,h'$
- **Different signatures depending on *h'* mass**
  - $M_{h'} > M_{A'}$: prompt decay $h' \to A'A'$, up to 6 tracks in the final state. Investigated by BaBar(2012) and Belle(2015)
  - $M_{h'} < M_{A'}$: *h'* is long-lived, thus invisible. Investigated by KLOE(2015)
- **Belle II searched for an invisible *h'***

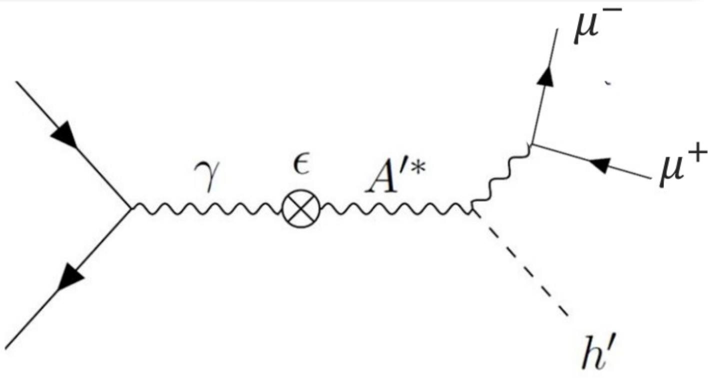


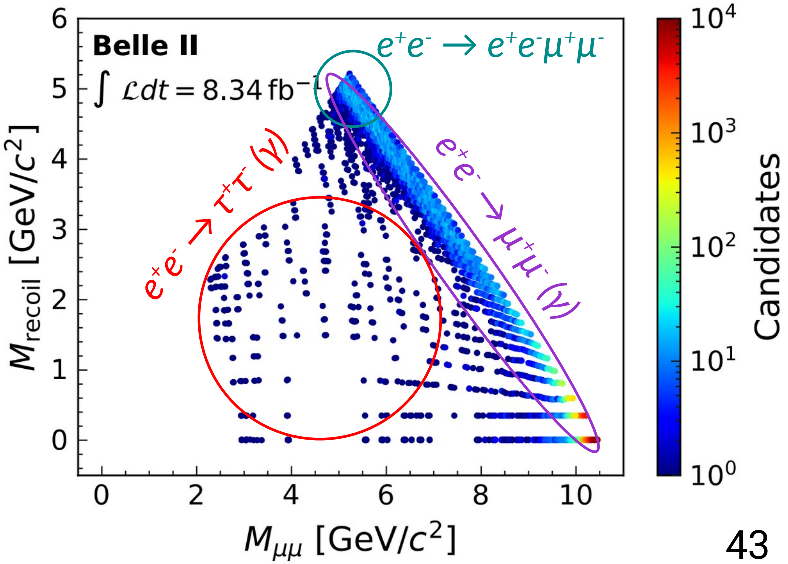
Dark Higgsstrahlung at Belle II

F. Abudinén et al., Phys. Rev. Lett. 130, 071804 (2023)

A' reconstructed from $\mu^+\mu^-$ invariant mass; h' reconstructed as recoil against $\mu^+\mu^-$

- ***$e^+e^- \to A'h'$, $A' \to \mu\mu$, $h' \to$*** **invisible**
  - **Same final state as for the invisible *Z'***, similar backgrounds: $e^+e^- \to \tau^+\tau^- (\gamma)$, $e^+e^- \to \mu^+\mu^- (\gamma)$, $e^+e^- \to e^+e^-\mu^+\mu^-$
  - **Inherit from *Z'* → invisible analysis**
- Signal signature is a **2D peak in the recoil mass vs the dimuon mass**
- **Event selection**
  - Two reconstructed muons, $p_T^\mu > 0.1$ GeV/c
  - Recoil momentum in the ECL barrel, no nearby photon
  - **Cut on dimuon helicity angle** → efficiently suppress background
- **Signal extraction** through cut-and-count **in M_{recoil} vs $M_{\mu\mu}$** plane

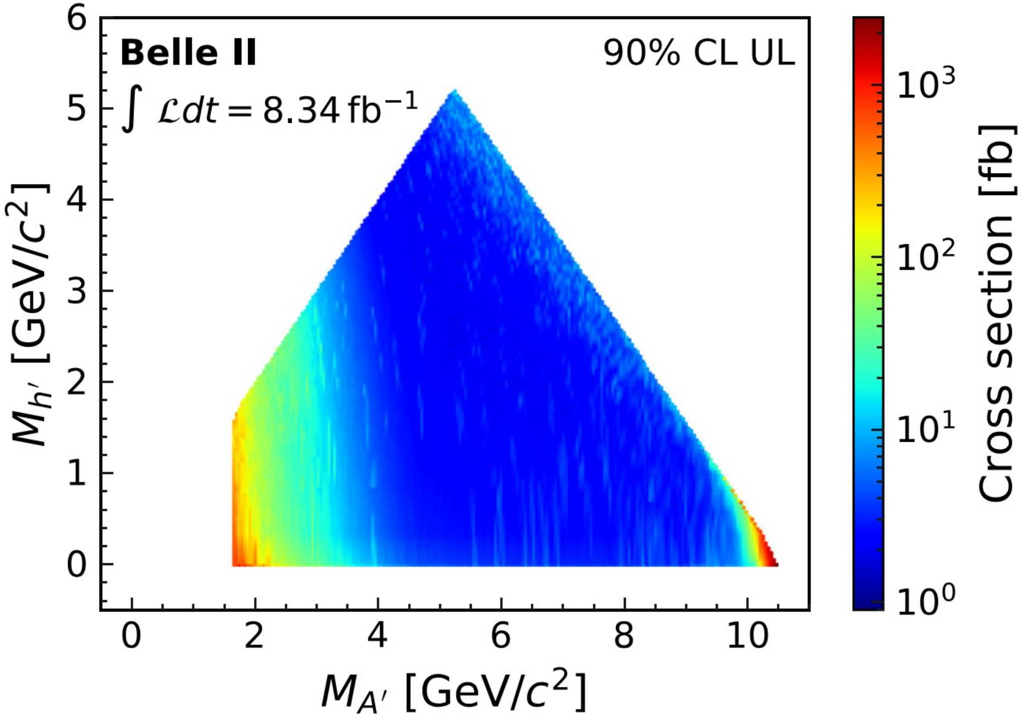


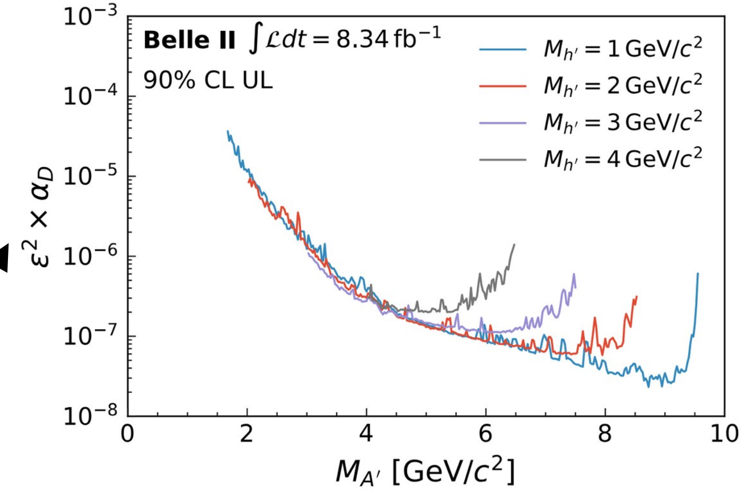


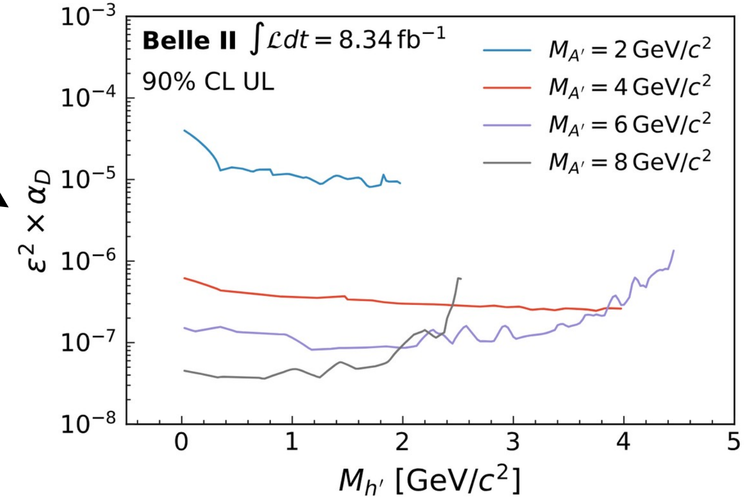
Dark Higgsstrahlung at Belle II

F. Abudinén et al., Phys. Rev. Lett. 130, 071804 (2023)

- **No significant excess in 8.34 fb^{-1}**
  - 90% CL upper limits and world leading limits for $1.65 < M_{A'} < 10.51$ GeV/c^2







More complicated model …

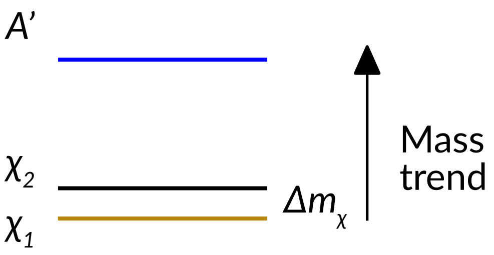
Inelastic dark matter …

- Expanded dark sector with **two dark matter states** with a **small mass splitting** and a **dark photon**
  - **χ_1 is stable** (relic candidate), **χ_2 is long-lived**
- Focus on $m_{A'} > m_{\chi 1} + m_{\chi 2}$
  - the decay $A' \rightarrow \chi_1 \chi_2$ is favored

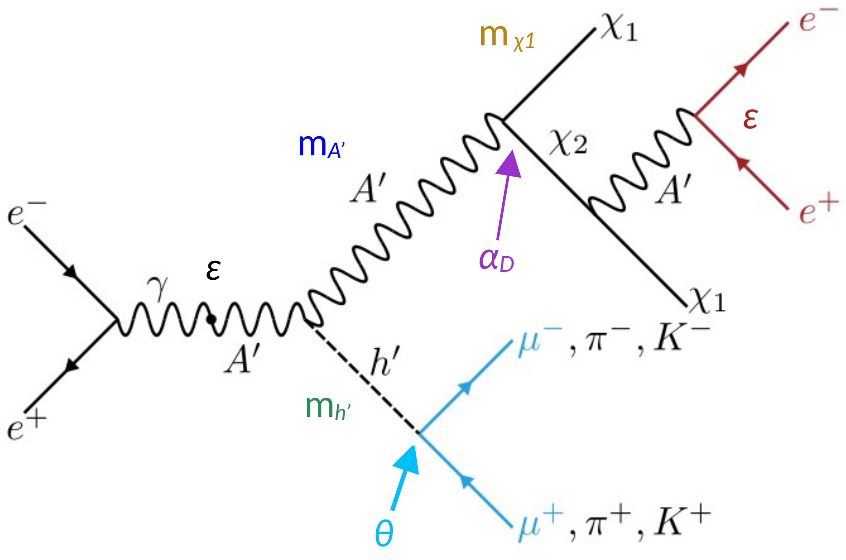
… let's add a dark higgs (provide mass to *A'*)

- ***h'* mixes with Standard Model Higgs** with θ
  - ***h'* is natural long-lived** (LLP) for small θ

- We have 4 dark sector particles: A', h', χ_1 and χ_2
- We have 7 parameters: $m_{A'}$, $m_{h'}$, $m_{\chi 1}$, Δm_χ, θ, ε, α_D



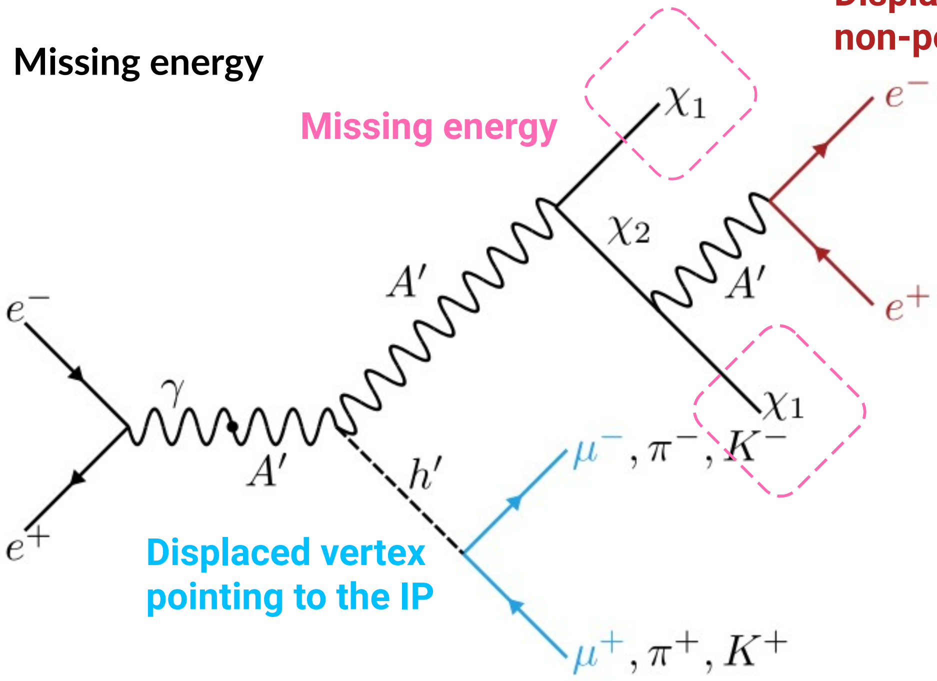
$e^+e^- \rightarrow h'(\rightarrow t^+t^-)A'(\rightarrow \chi_1\chi_2(\rightarrow \chi_1 e^+e^-), t = \mu, \pi, K$

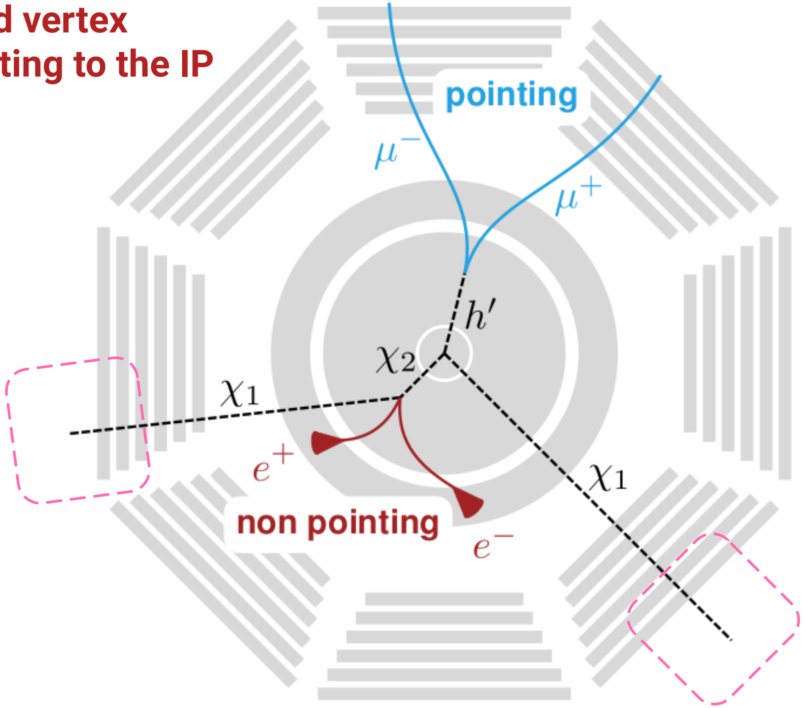


… More complicated signature

- **Four tracks in the final state**
  - 2 forming a **pointing displaced vertex** →
  - 2 forming a **non-pointing displaced vertex**
- **Missing energy**

Challenging for tracking and trigger
Almost zero background analysis





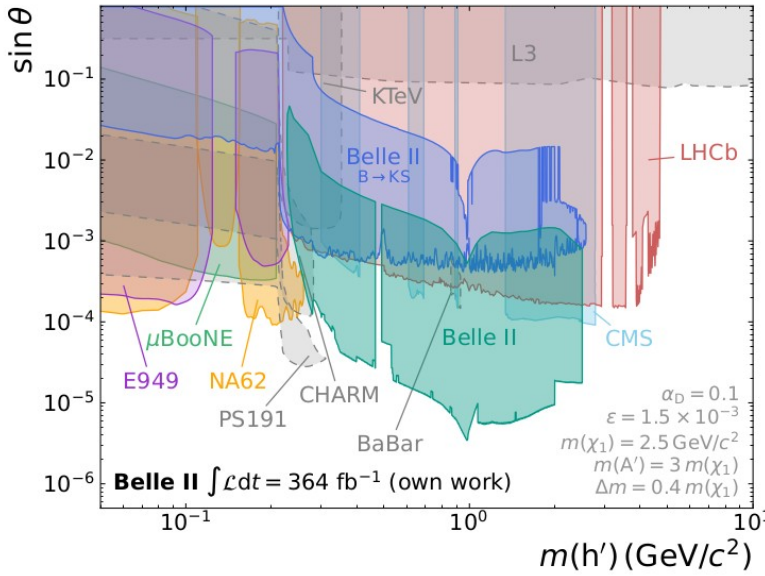
Preliminary results

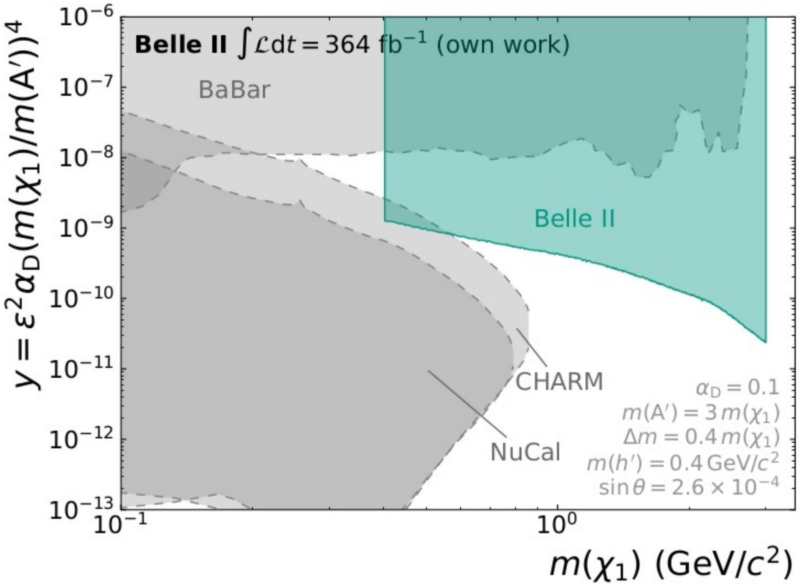
Analysis under Collaboration Wide Review

- **Cut-and-count strategy** for extracting signal yields
- **Expected background estimated in data** from sidebands to not rely on MC
  - Data/MC discrepancy due to not well modeled contributions, as $e^+e^- \to e^+e^- \Phi(\to K_S K_L)$ missing in simulation
- **No significant excess found** in the individual final states or the combination → **place 95% CL upper limits**

Note that the region corresponding to the K_S is vetoed in h' masa

Example for one configuration of model parameters

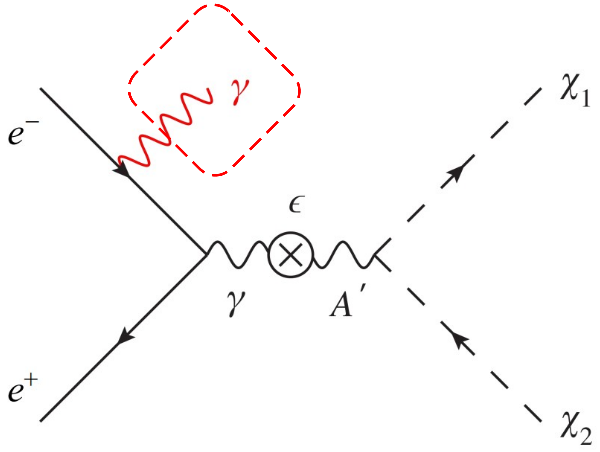




Easier signature… challenging analysis

Single photon search, $e^+e^- \rightarrow A'\gamma$

- For $m_{A'} > m_\chi \rightarrow$ **$A' \rightarrow \chi\bar{\chi}$ in 100%** of cases



B. Batell et al., Phys. Rev. D 79, 115008 (2009)

Dark photon field

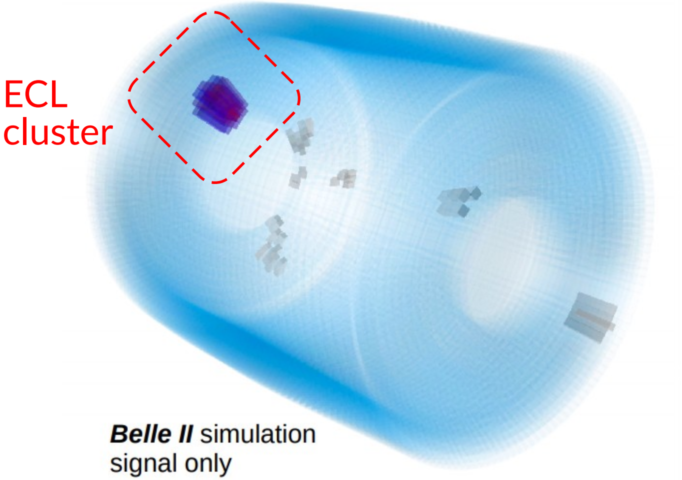
$$\mathcal{L}_{int} = e\varepsilon A'_\mu J^\mu_{em}$$

Interation stenght

Electromagnetic current

Signature

- **Events with nothing but a single high energetic ISR photon**
- **Dedicated single photon trigger needed**, not available at Belle and only on 10% of Babar data



- Look for a **bump in the reconstructed photon energy**

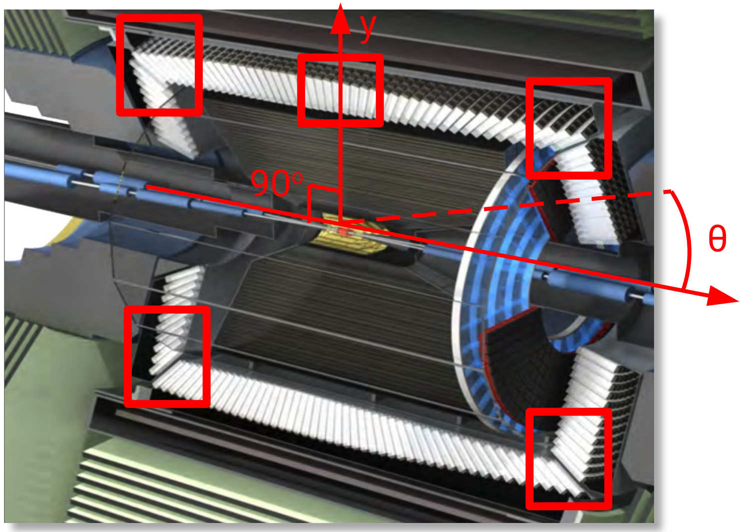
$$E_\gamma = \frac{s - M^2_{A'}}{2\sqrt{s}}$$

Easier signature... challenging analysis

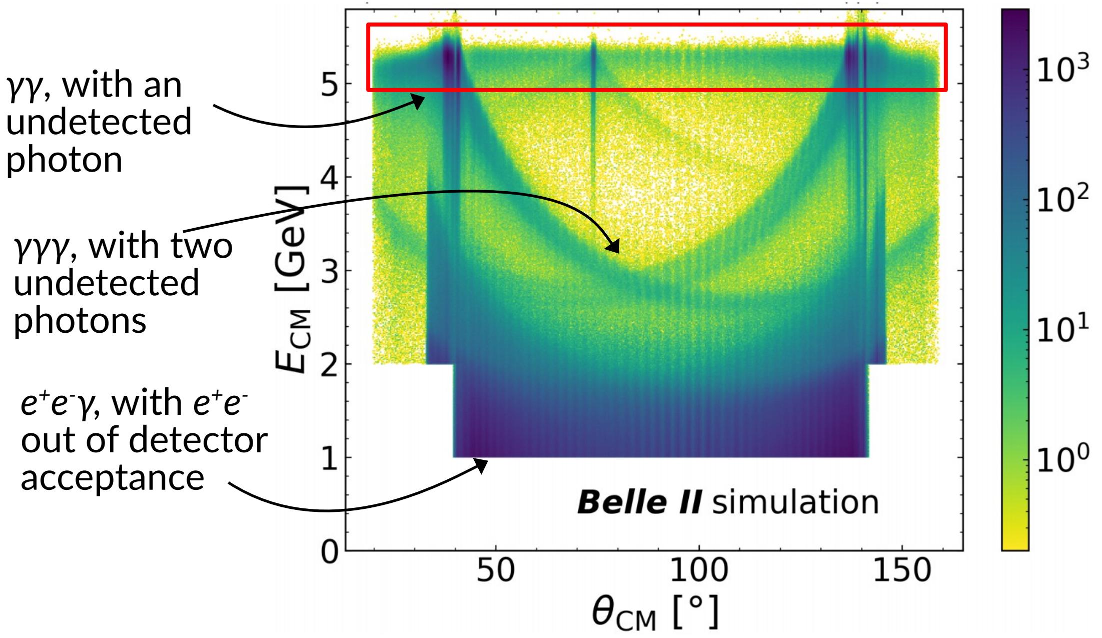
Main Backgrounds

- ***$e^+e^- \rightarrow e^+e^-(\gamma)$***: electrons out of acceptance
- ***$e^+e^- \rightarrow \gamma\gamma(\gamma)$***: photons lost in e.m. calorimeter (ECL) inefficient regions (gaps)
- **cosmic rays**

Crucial to devise photon veto to compensate for detector inefficiencies that could mimic monophoton signal



Background simulation assuming 20 fb^{-1}



The end

Summary & conclusions

Belle II has unique sensitivity to dark sectors

Complementary results to high-energy and beam-dump experiments

- **World-leading results already published**

Margin of improvements

- Higher statistics
- New analysis techniques
- New triggers for displaced (or even more exotic) topologies

Thank you!

... any questions?

Backup slides

Evidences for dark matter

- Many **astrophysics** and **cosmological observation**s provide evidences for dark matter existence
  - ➔ **Flat rotational curves of galaxies**

- F. Zwicky in 1933
  - ➔ Applied virial theorem to the Coma cluster
  - ➔ **Evidence of unseen mass**

Virial theorem

- $2\langle T\rangle = -\langle U\rangle$
- $\langle v(r)^2\rangle = GM(r)/r$

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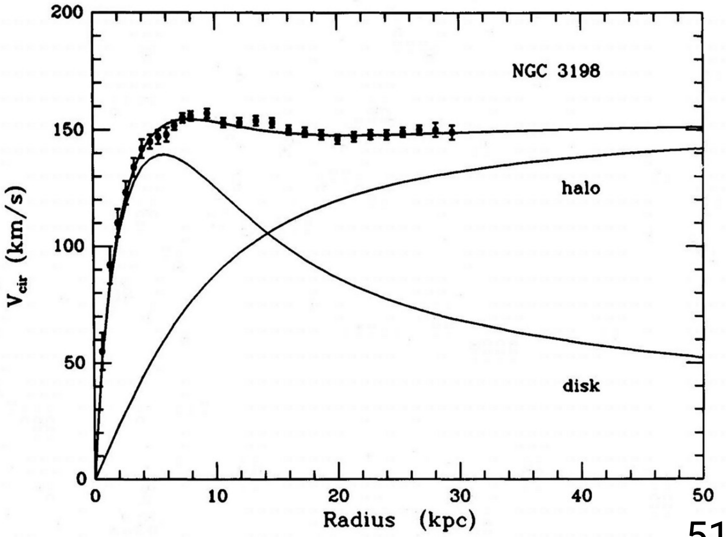
Virial theorem

- $2\langle T \rangle = - \langle U \rangle$
- $\langle v(r)^2 \rangle = GM(r)/r$

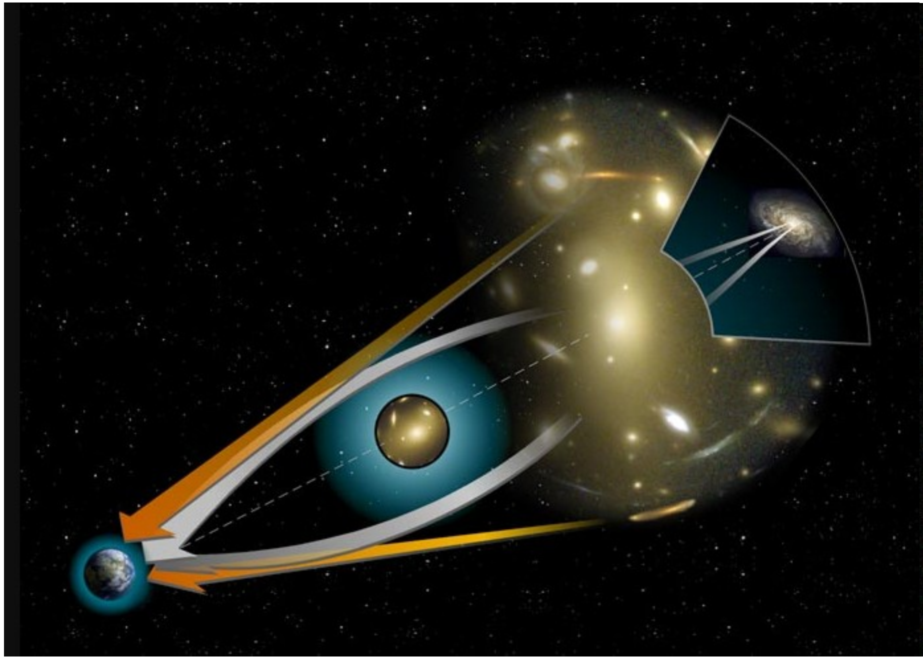


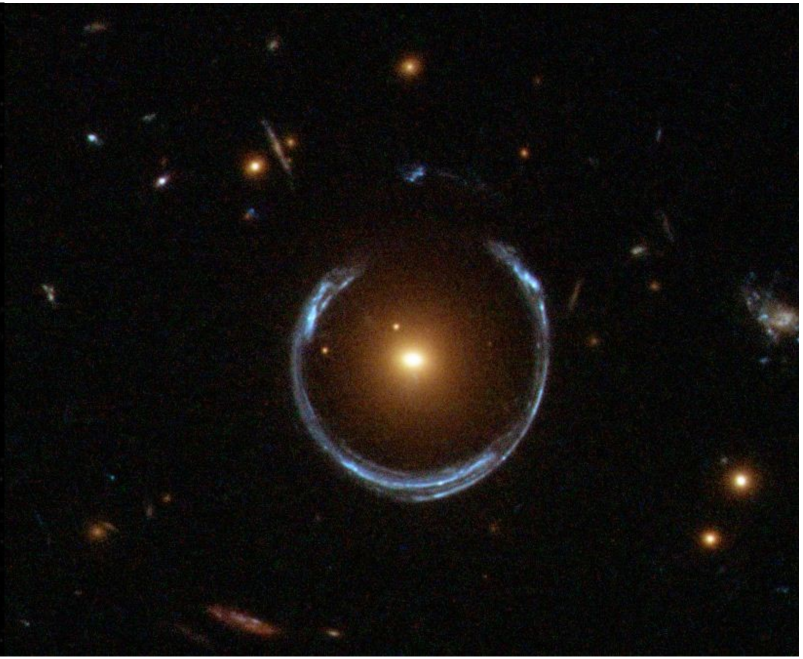
- V. Rubin in 1970s
  - ➔ **v(r) = const**
  - ➔ dark halo with $\rho \propto 1/r^2$, $M(r) \propto r$

Evidences for dark matter

- Many **astrophysics** and **cosmological observations** provide evidences for dark matter existence
  - → Flat rotational curves of galaxies
  - → **Gravitational lensing**

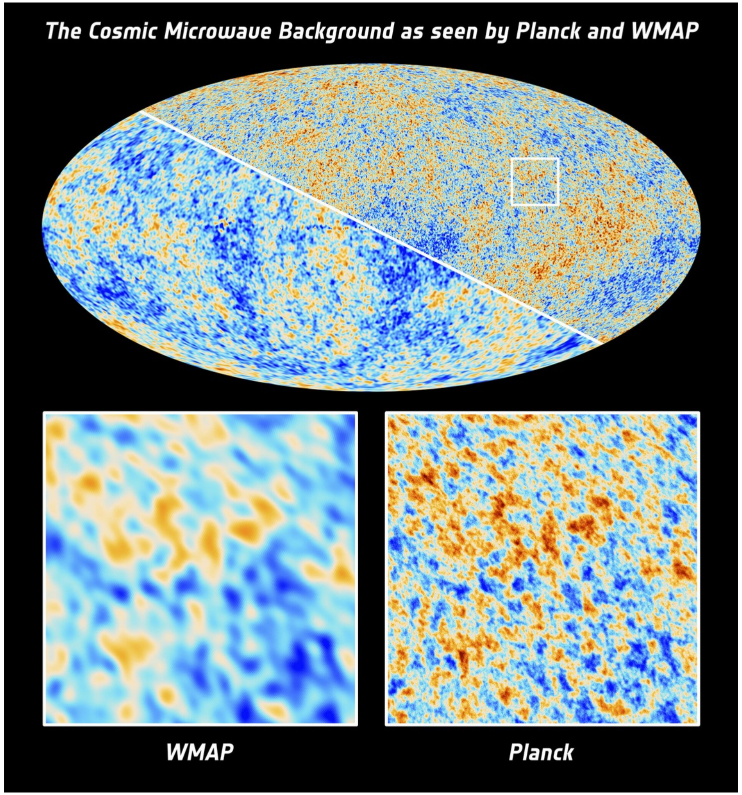
Evidence of unseen mass
→ It is dark





Evidences for dark matter

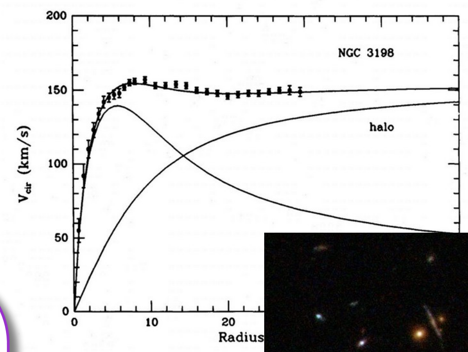
- Many **astrophysics** and **cosmological observations** provide evidences for dark matter existence
  - → Flat rotational curves of galaxies
  - → Gravitational lensing
  - → **Cosmic Microwave Background anisotropy**

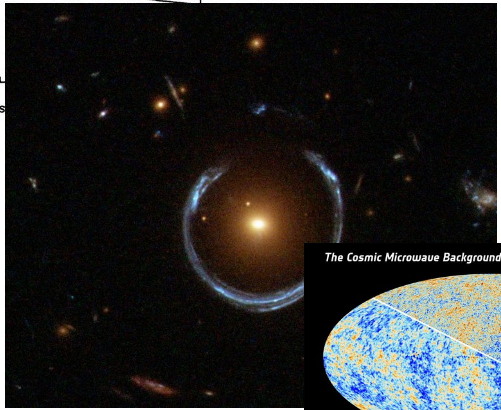


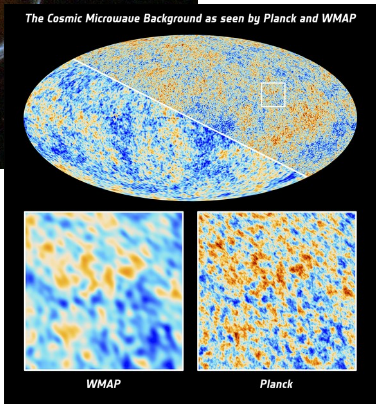
In agreement with DM models
DM stable on cosmological scale

Evidences for dark matter

- Many **astrophysics** and **cosmological observations** provide evidences for dark matter existence
  - Flat rotational curves of galaxies
  - Gravitational lensing
  - Cosmic Microwave Background anisotropy

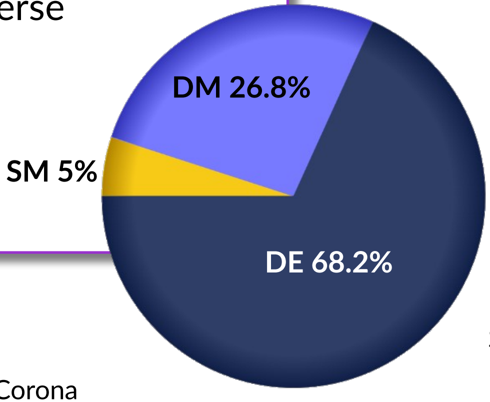






Dark matter

- Massive
- 85% of the total mass in the universe
- Stable on cosmological scales
- Dark

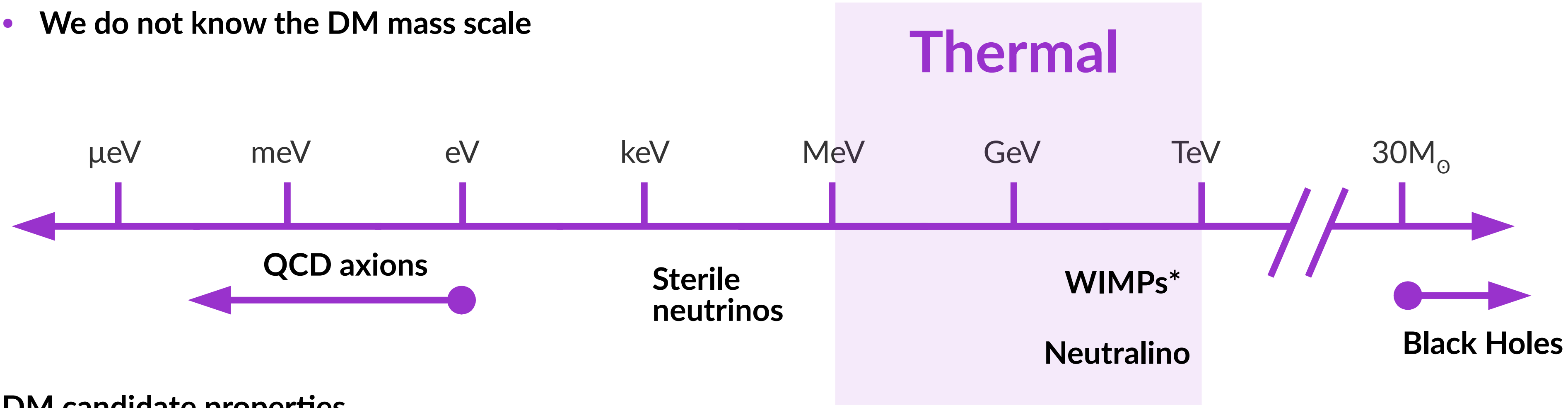


Dark matter (DM)
Dark energy (DE)
Standard Model (SM)

Dark matter candidates (examples)

*Weakly Interacting Massive Particles (WIMPs)

- **We do not know the DM mass scale**



DM candidate properties

- Stable on cosmological scales
- non-relativistic
- Only feeble interactions
- Provide the right relic density

Universe expands

Thermal relic density

- For example, freeze-out mechanism
  1) DM+DM ↔SM+SM equilibrium
  2) DM+DM ← SM+SM suppressed
  3) Equilibrium lost, DM decouples → relic density: $<\sigma v> = 10^{-26}\ cm^3\ s^{-1}$

How to search for dark matter?

Direct detection (XENON, LUX, DarkSide, …)

- Detect the energy of nuclear (electron) recoil

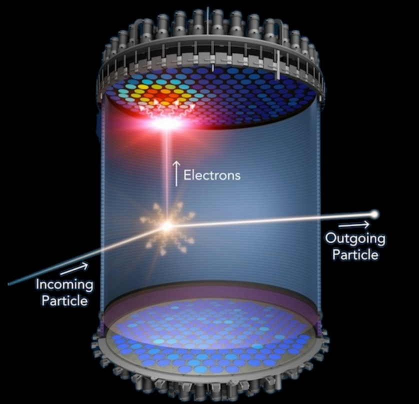
Indirect detection (IceCube, Fermi LAT, …)

- Detect the flux of visible particles produced by DM annihilation, decays or conversions

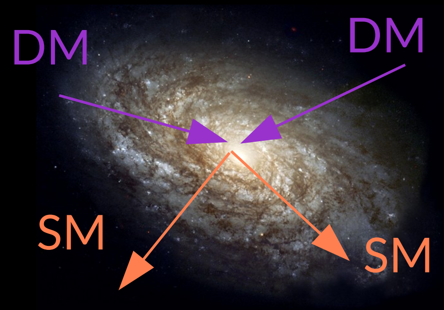
Searches at colliders

- DM weakly couples to SM particles and it can be produced in SM particles annihilation at accelerators
  - → several signatures involving light **dark sector mediators** too

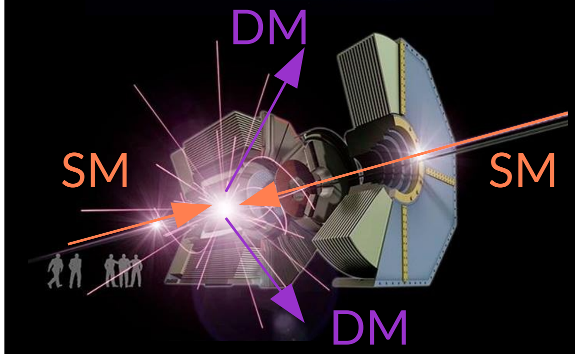
Direct detection



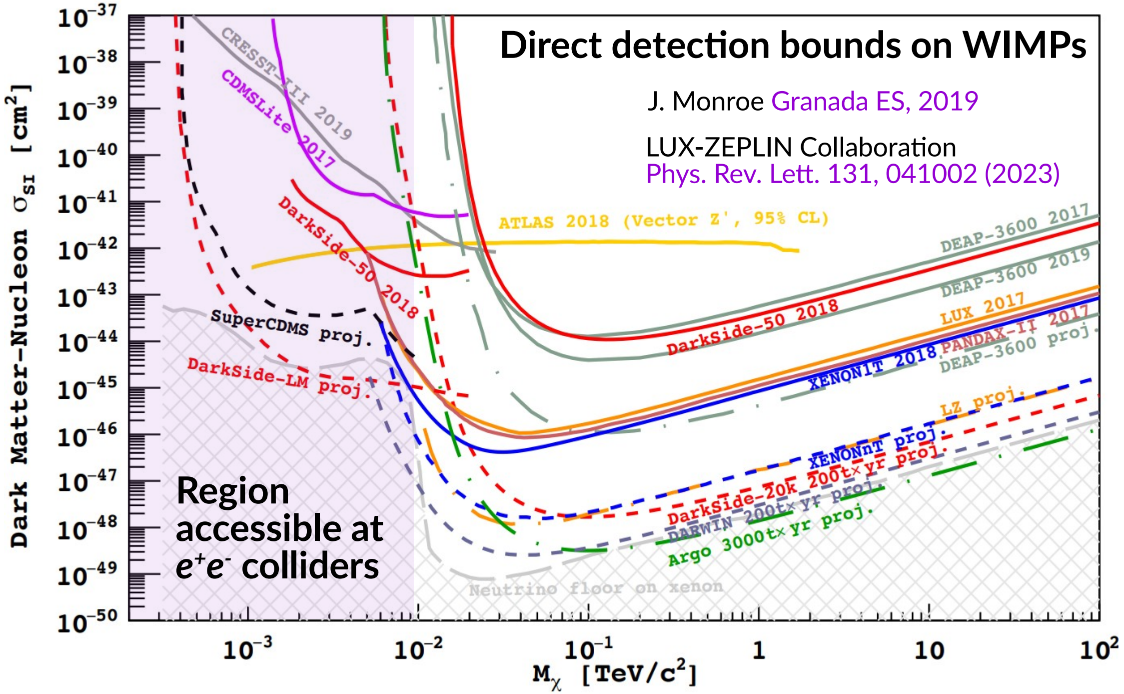
Indirect detection



Colliders



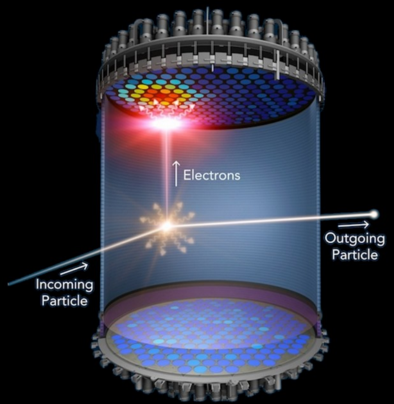
How to search for dark matter?



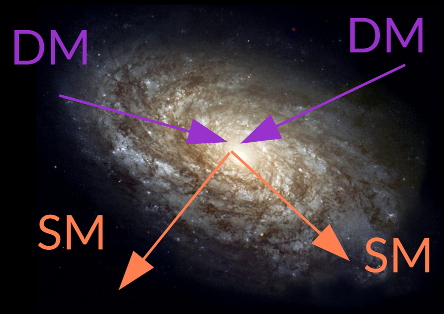
Searches at colliders (LHC, *B*-factories)

- DM weakly couples to SM particles and it can be produced in SM particles annihilation at accelerators
  - several signatures involving light **dark sector mediators** too

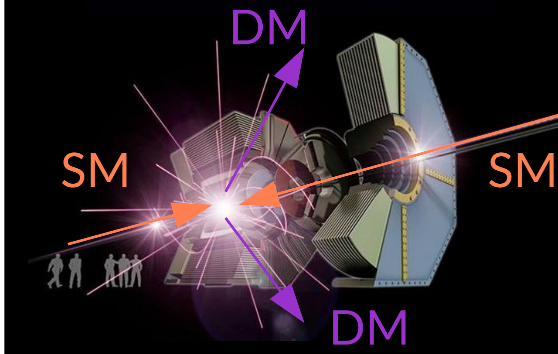
Direct detection



Indirect detection



Colliders



Data sets

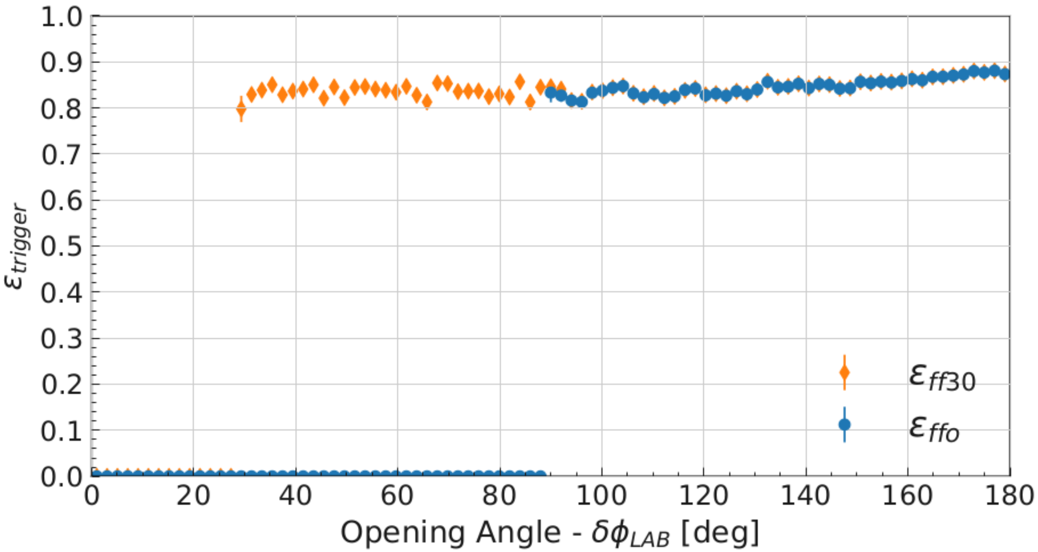
About MC simulation

- **Simulation** might be **missing/incomplete**, **mis-model** the **data**
- Some **detector effect not simulated**
- **Use MC run dependent**
  - Simulated with data taking conditions
- **Signal MC** for **dark sector** is **not centrally produced**
  - Models with **too many possible parameter configurations** (different masses, dfferent couplings, ...)
  - A tool is available
  - How to produce so much MC? How to keep track of the samples? ...

Detector performance studies: examples

Trigger selection efficency

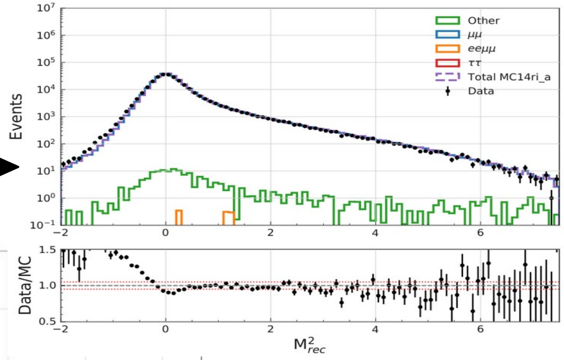
- $\mu^+\mu^-\gamma$ and $e^\pm\mu^\mp$ control samples
- Directly **measured on data** as a function of the azimuthal opening angle of the two tracks, minimum transverse momentum and polar angle and recoil mass
- **Used to scale simulation**

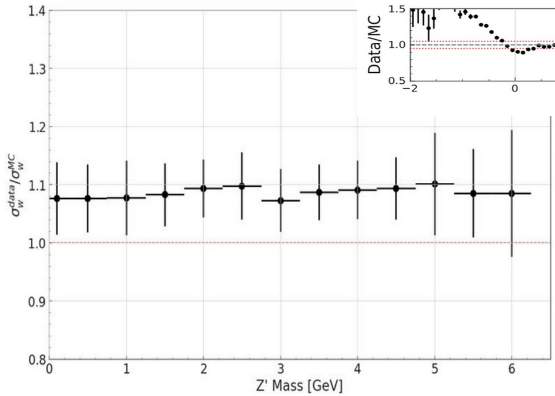


Recoil mass resolution

- $\mu^+\mu^-\gamma$ control sample
  - → **Event kinematics constrained to ϒ(4S)** (10.18 < E($\mu^+\mu^-\gamma$) < 10.98 GeV) & Punzi-net applied
  - → Width σ from a **fit with to M^2_{recoil}** the sum of 2 Crystal-ball pdfs

Data/simulation comparison →

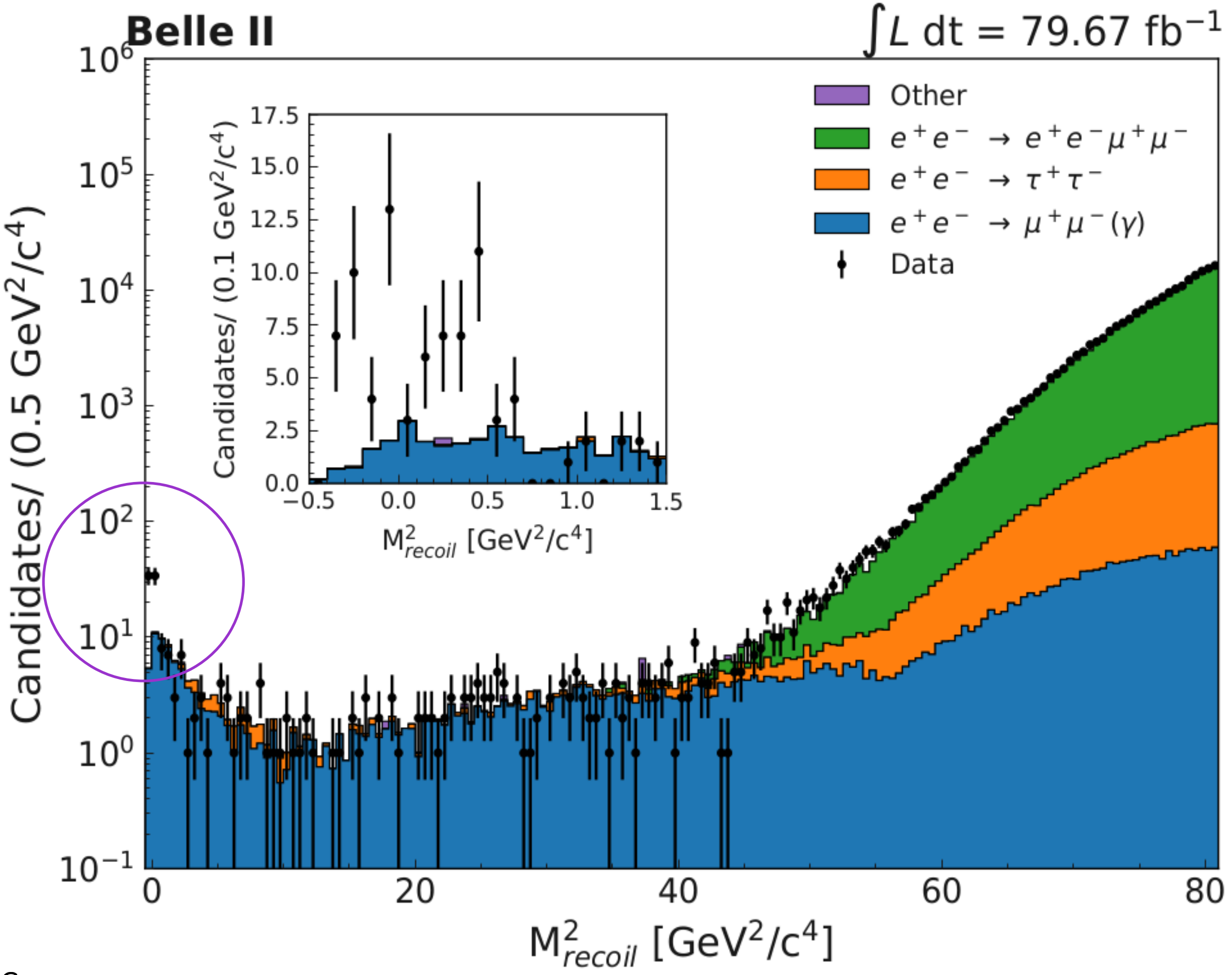




← **Correction $\sigma^{Data}/\sigma^{MC}$ as a function of the *Z'* mass**

Unboxing data

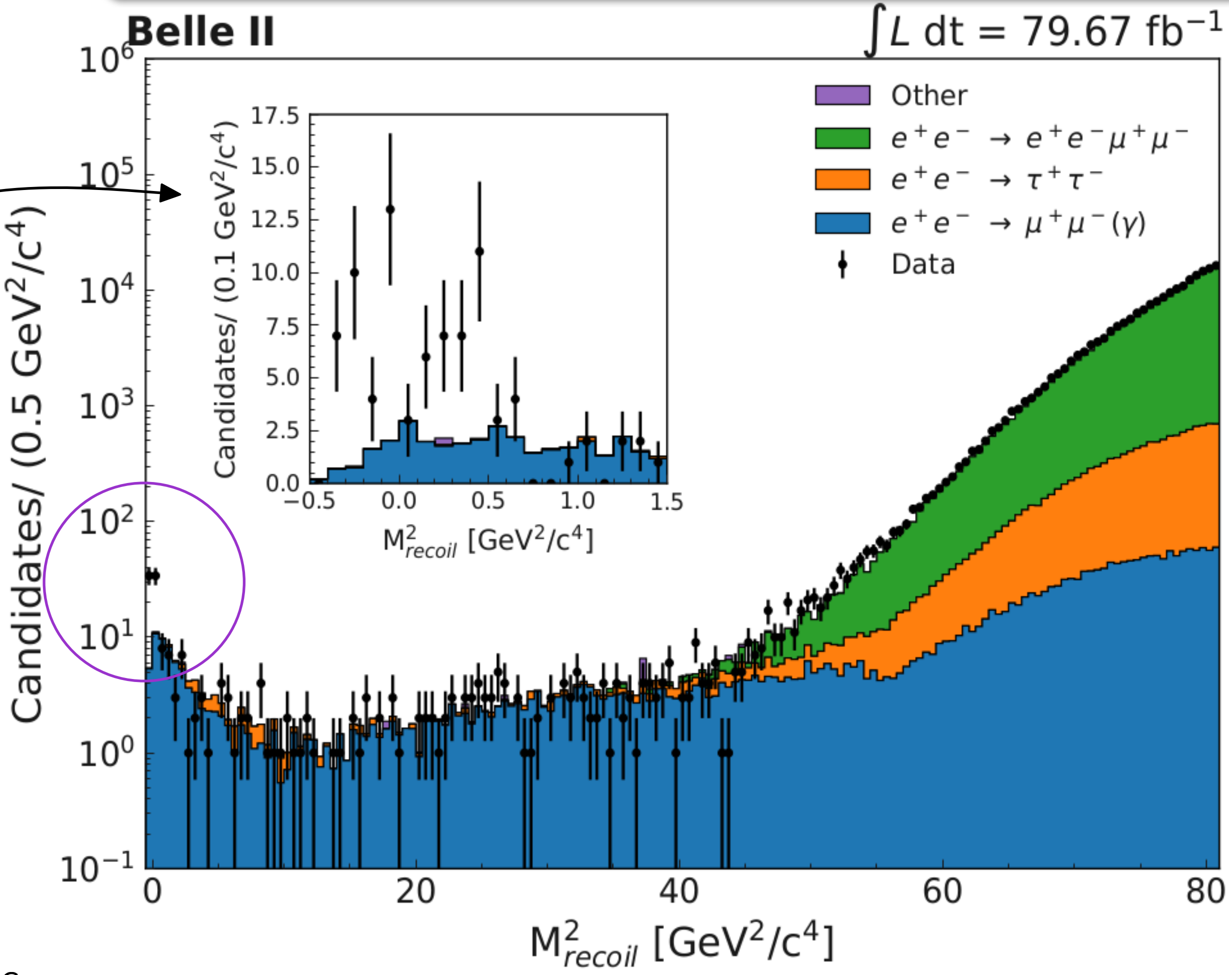
- Excess found at small M^2_{recoil}
  - ➔ **Have we really found DM?**



Unboxing data

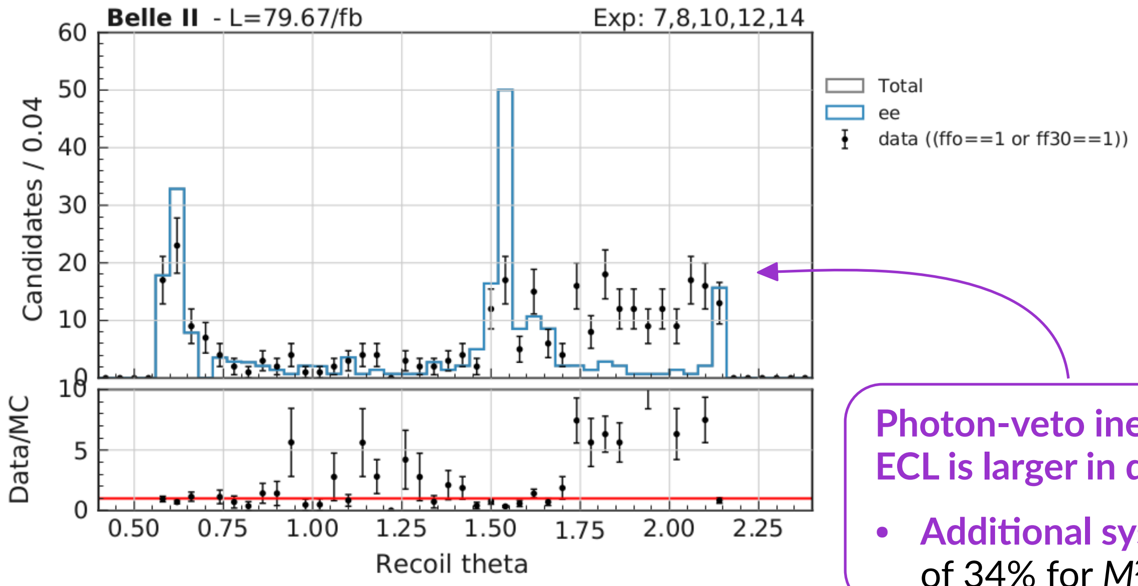
Before unboxing data, make sure to have carefully checked and considered all possible effects of your selections in data and MC

- Excess found at small M^2_{recoil}
  - **Have we really found DM?**
    - **No!**
      It does not look like signal (narrow peak)
    - **Instrumental effect**



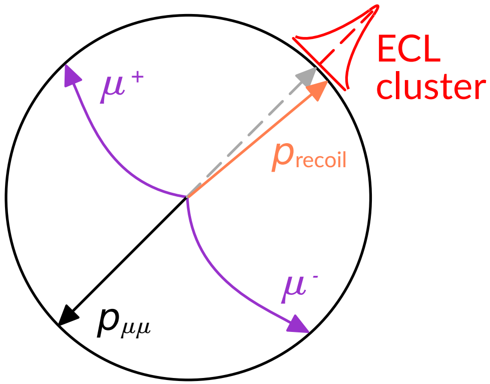
Photon veto inefficiency

- **One step back, re-check the analysis**
- Signal free ***e^+e^-*** **control sample**
  - Select events with $M^2_{recoil} < 1$ GeV$^2/c^4$ (dominated by Bhabha events)
  - Measure the **photon veto inefficiency** in **data and simulation**
  - **Derive correction factors** to be used to correct the expected $\mu^+\mu^-$ background



Photon veto

- No photon within 15° of the recoil momentum
- No extra energy > 0.5 GeV



- **It relies on efficiency of ECL photon reconstruction …**
- … sometimes it fails
- … differently in Data and simulation

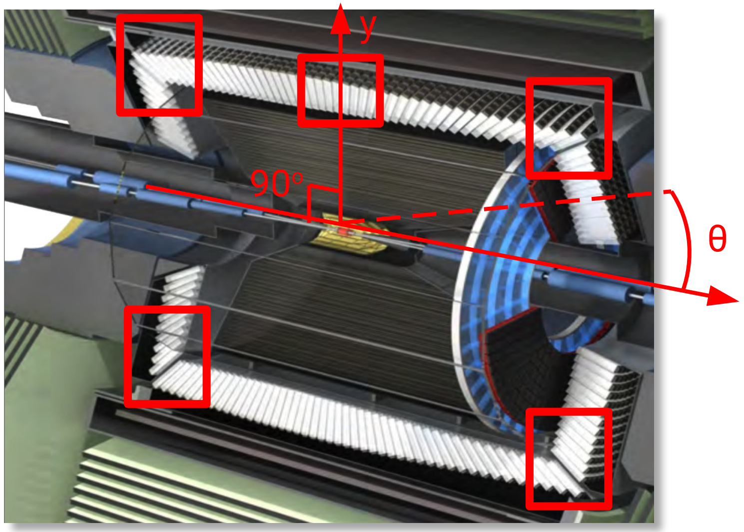
Photon-veto inefficiency in the backward barrel ECL is larger in data than that estimated in simulation

- **Additional systematic** to the background template shape of 34% for $M^2_{recoil} < 1$ GeV$^2/c^4$ and 5% above 1 GeV$^2/c^4$

Easier signature… challenging analysis

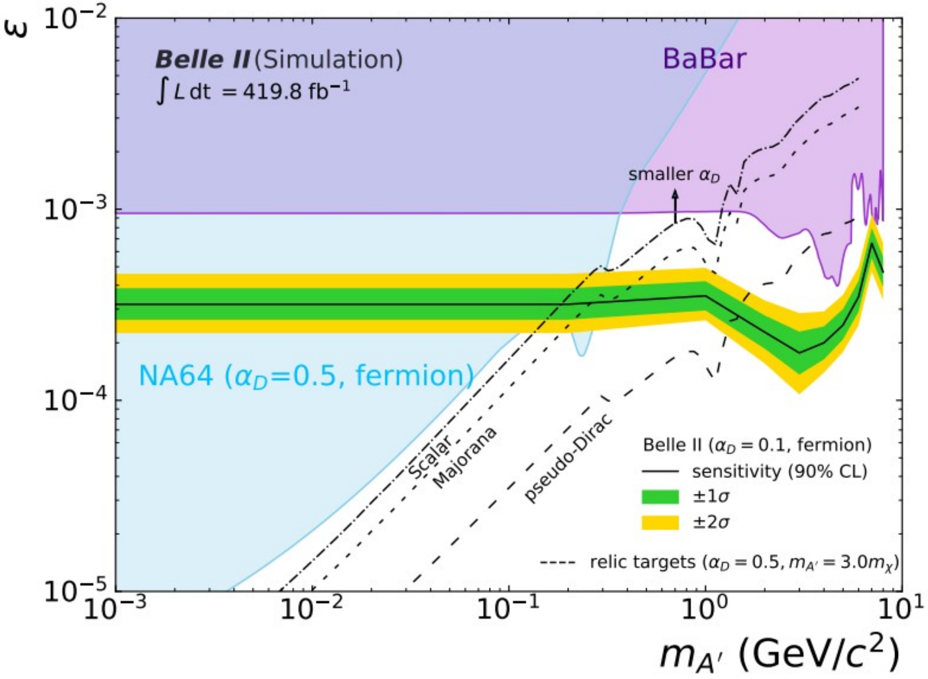
Main Backgrounds

- ***$e^+e^- \to e^+e^-(\gamma)$***: electrons out of acceptance
- ***$e^+e^- \to \gamma\gamma(\gamma)$***: photons lost in e.m. calorimeter (ECL) inefficient regions (gaps)
- **cosmic rays**



Crucial to devise photon veto to compensate for detector inefficiencies that could mimic monophoton signal

Very very very … preliminary from simulation



Summary & conclusions

Dark sectors

Evidences of an unseen mass in the Universe

- **In agreement with DM models**

DM nature is unknown

- **Interest from the scientific community in shedding light on DM nature**

No experimental observations at the electroweak scale

- **Dark sectors**
  - Explain DM puzzle and experimental results in tension with SM predictions

Belle II

Unique sensitvity to dark sectors

Complementary results to high-energy and beam-dump experiments

- **World-leading results already published**

Margin of improvements

- Higher statistics
- New analysis techniques
- New triggers for displaced (or even more exotic) topologies