Missing Energy and Displaced Vertices at Belle II

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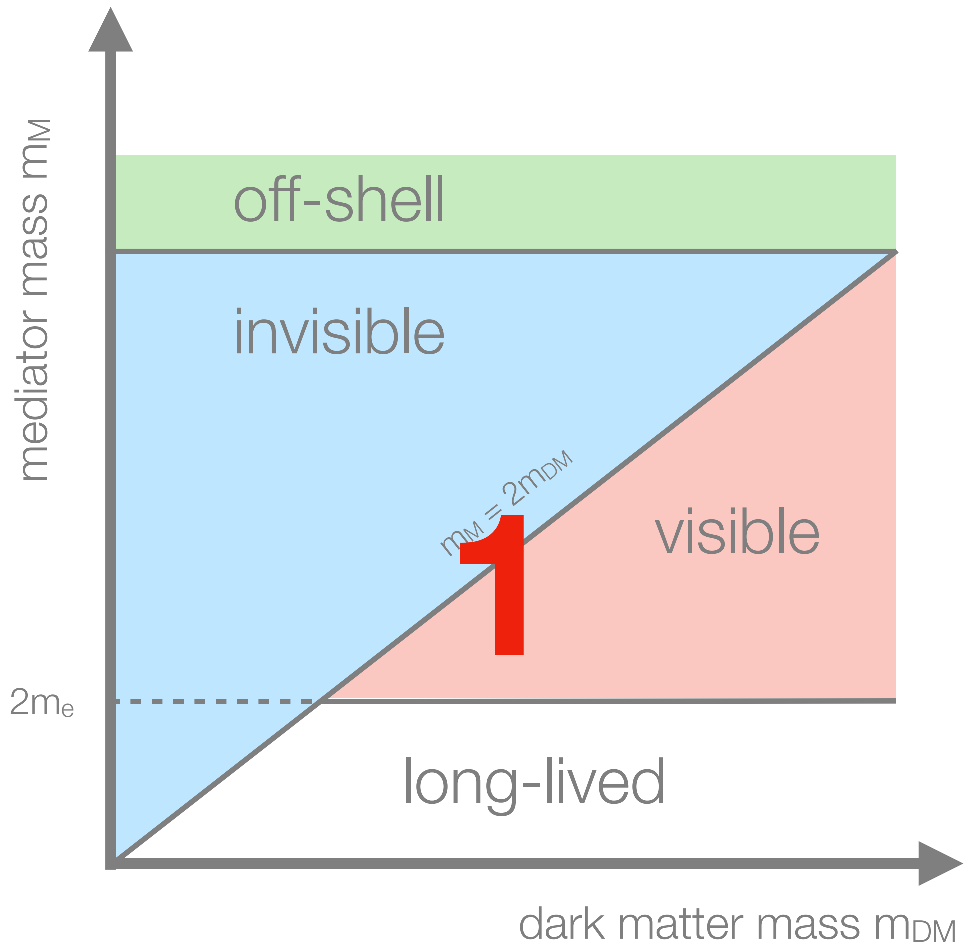
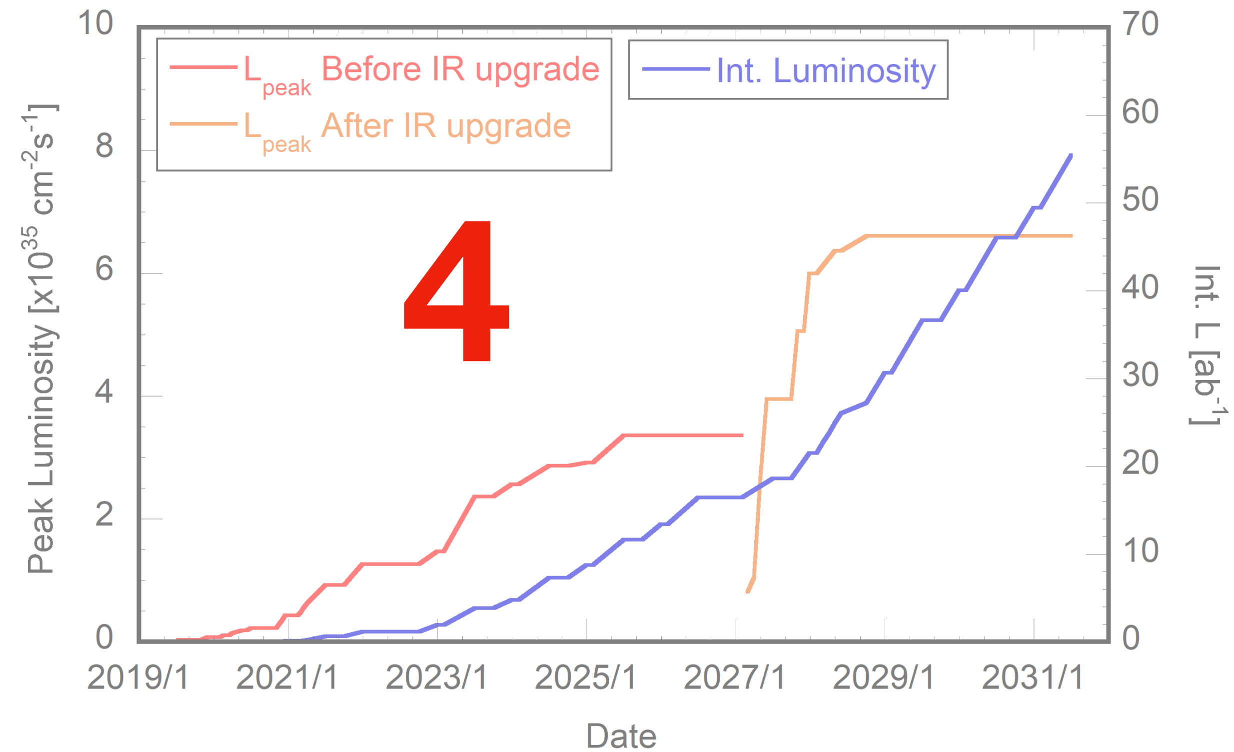
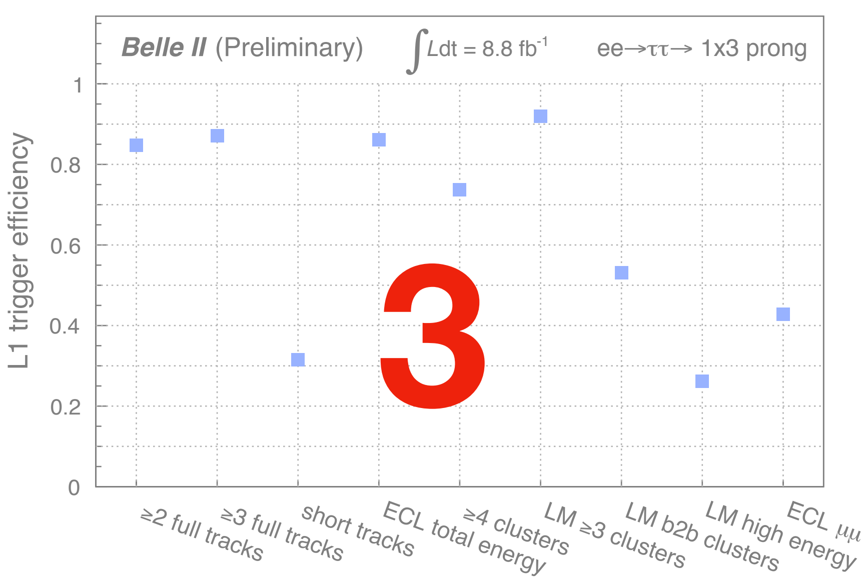
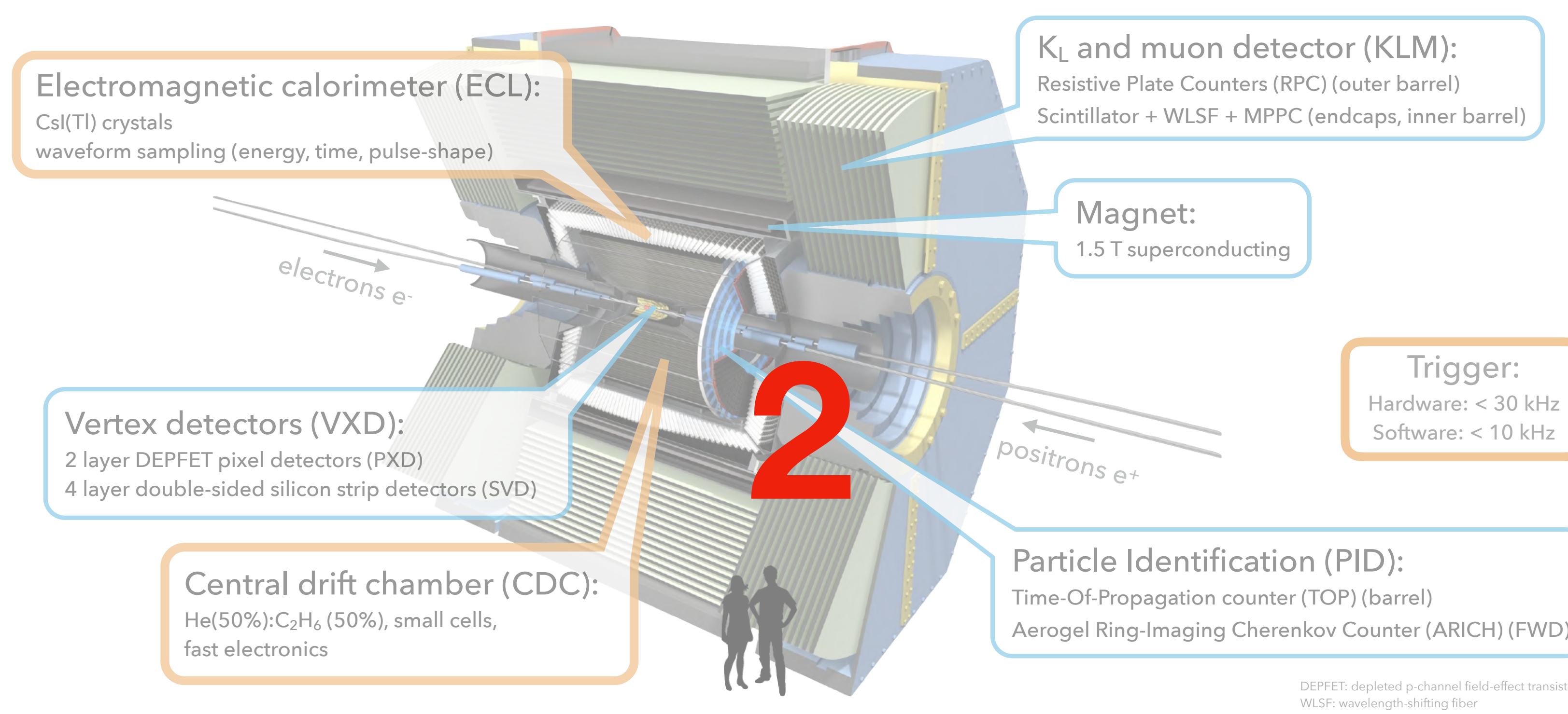
Anomalies and Precision in the Belle II Era
08/09/2021

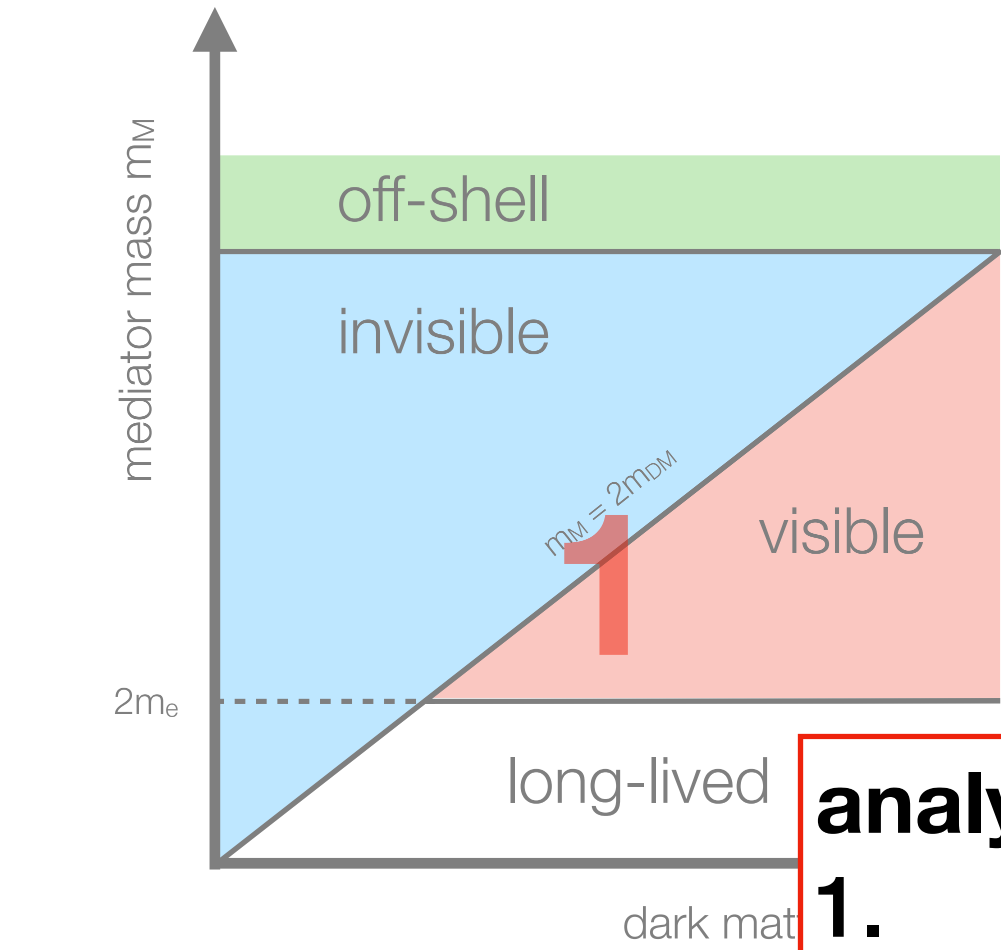
The main ingredients

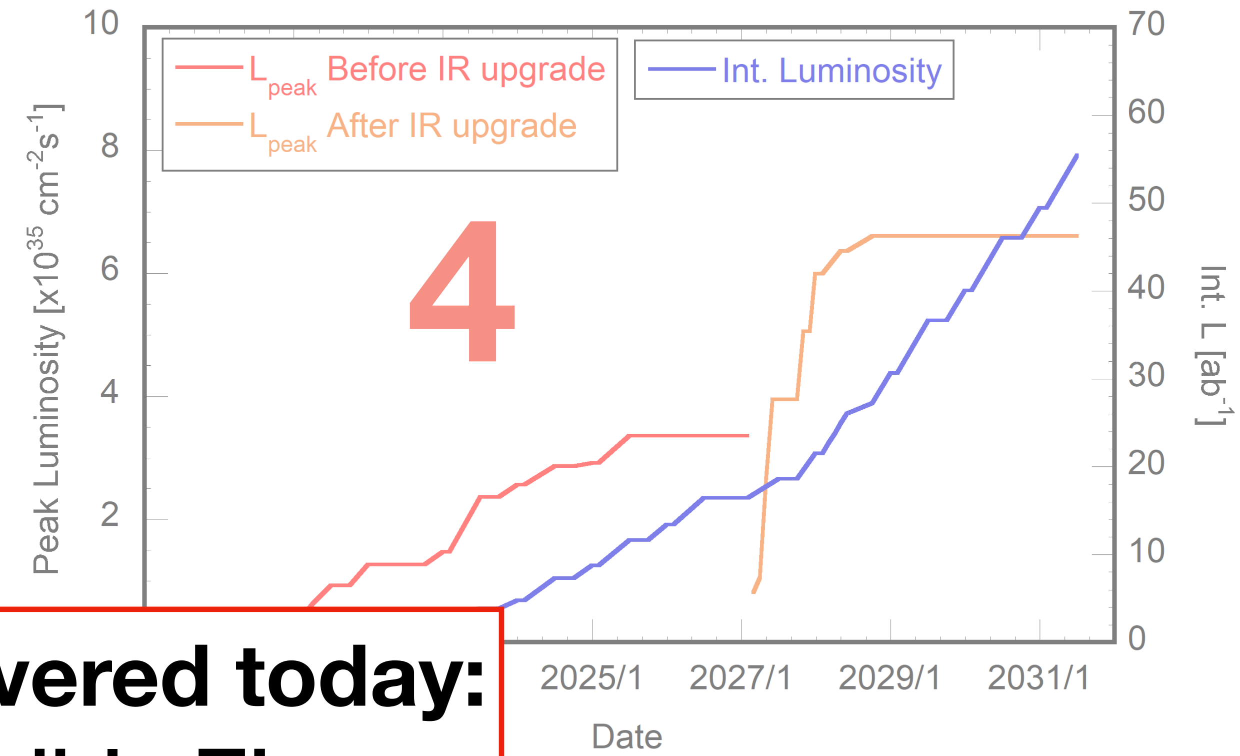

mediator mass mM
off-shell
invisible
mM = 2mDM
1
visible
2me
long-lived
dark matter mass mDM


Lpeak Before IR upgrade
Lpeak After IR upgrade
Int. Luminosity
4
Peak Luminosity [x10^35 cm^-2s^-1]
Int. L [ab^-1]
10
8
6
4
2
0
70
60
50
40
30
20
10
0
2019/1
2021/1
2023/1
2025/1
2027/1
2029/1
2031/1
Date


Belle II (Preliminary)
∫Ldt = 8.8 fb^-1
ee→ττ→ 1x3 prong
L1 trigger efficiency
1
0.8
0.6
0.4
0.2
0
3
≥2 full tracks
≥3 full tracks
short tracks
ECL total energy
≥4 clusters
LM ≥3 clusters
LM b2b clusters
LM high energy
ECL μμ

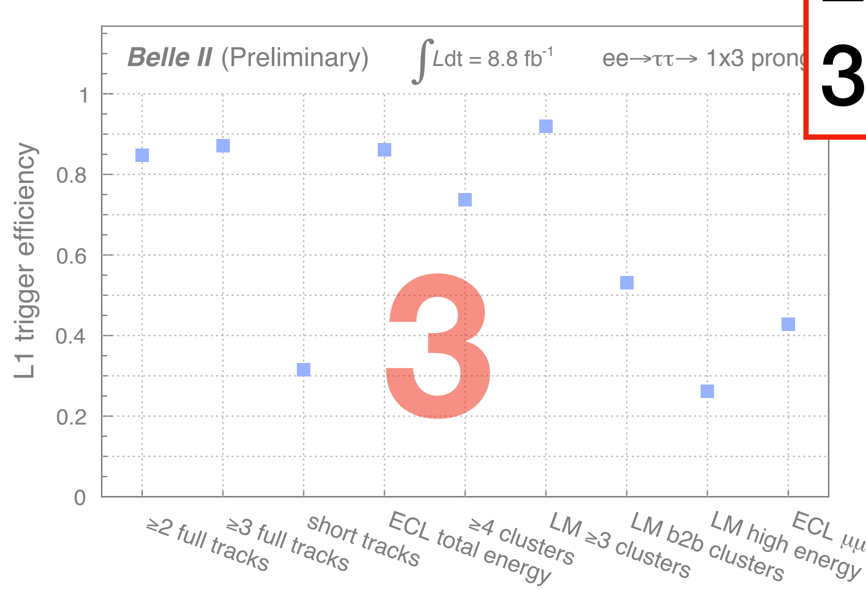

Electromagnetic calorimeter (ECL):
CsI(Tl) crystals
waveform sampling (energy, time, pulse-shape)
KL and muon detector (KLM):
Resistive Plate Counters (RPC) (outer barrel)
Scintillator + WLSF + MPPC (endcaps, inner barrel)
Magnet:
1.5 T superconducting
electrons e-
Trigger:
Hardware: < 30 kHz
Software: < 10 kHz
Vertex detectors (VXD):
2 layer DEPFET pixel detectors (PXD)
4 layer double-sided silicon strip detectors (SVD)
2
positrons e+
Central drift chamber (CDC):
He(50%):C2H6 (50%), small cells,
fast electronics
Particle Identification (PID):
Time-Of-Propagation counter (TOP) (barrel)
Aerogel Ring-Imaging Cherenkov Counter (ARICH) (FWD)
DEPFET: depleted p-channel field-effect transistor
WLSF: wavelength-shifting fiber
MPPC: multi-pixel photon counter

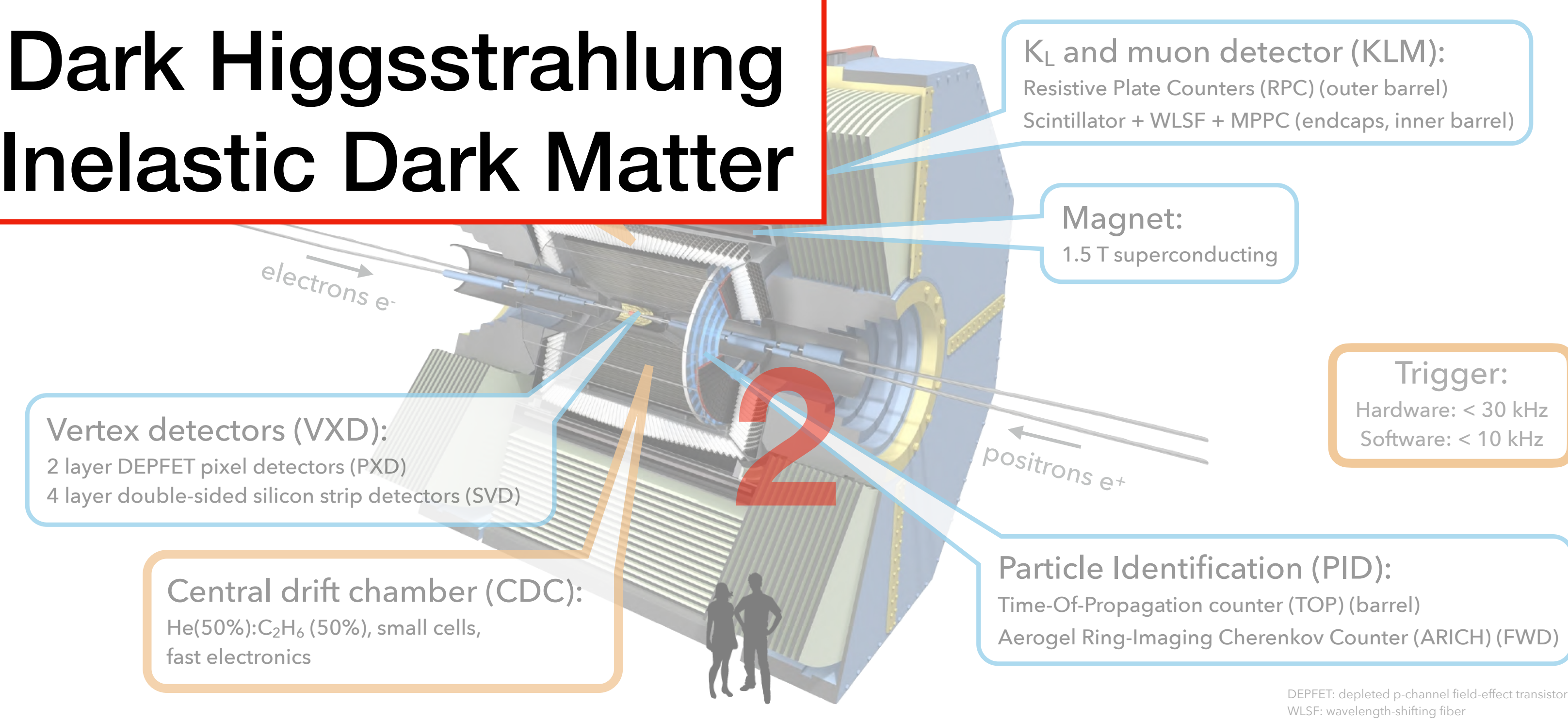




analysis covered today:

1. Invisible Z’
2. Dark Higgsstrahlung
3. Inelastic Dark Matter

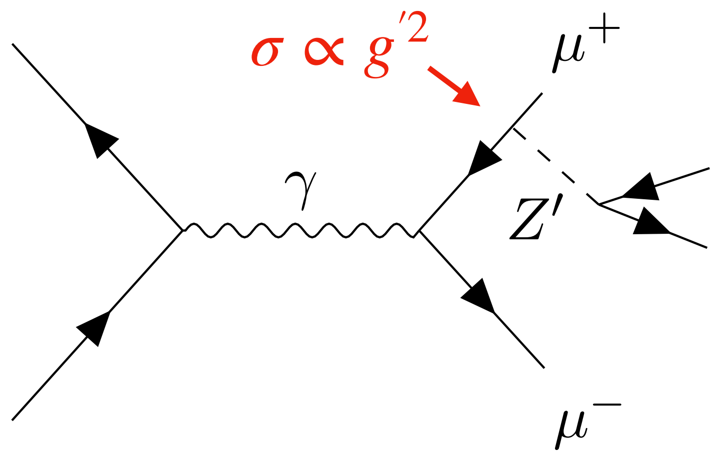




Invisible Z′

Invisible Z'

- extend SM by adding a U(1)' group
- new massive gauge boson Z' couples only to leptons of 2nd and 3rd generation
- Z' coupled to L_μ-L_τ via g'
- focus on invisible Z' decay produced with a pair of muons
- invisible decay channel explored for the first time



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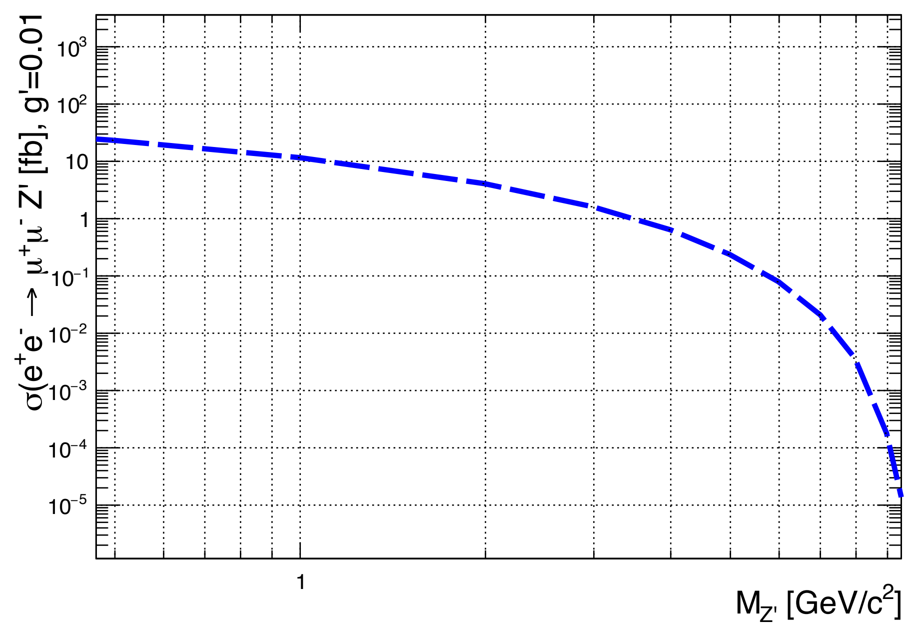
PRD 89, 113004 (2014)



$$M_{Z'} < 2M_\mu \implies BF[Z' \to \text{invisible}] = 1,$$
$$2M_\mu < M_{Z'} < 2M_\tau \implies BF[Z' \to \text{invisible}] \simeq 1/2,$$
$$M_{Z'} > 2M_\tau \implies BF[Z' \to \text{invisible}] \simeq 1/3.$$

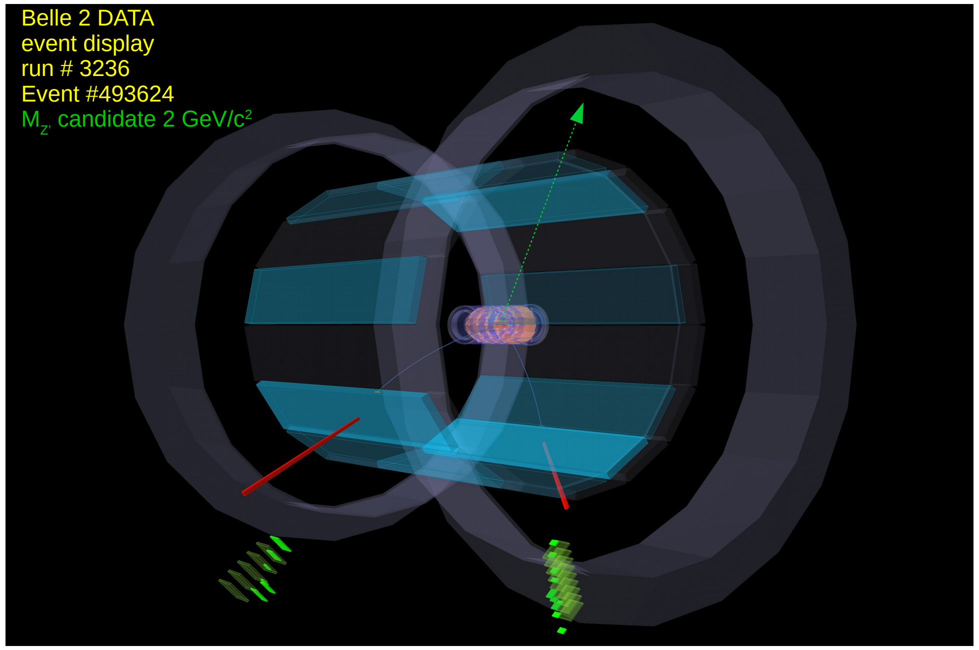
if $M_{Z'} > 2M_\chi$
$BF(Z' \to \chi\bar{\chi}) = 1$

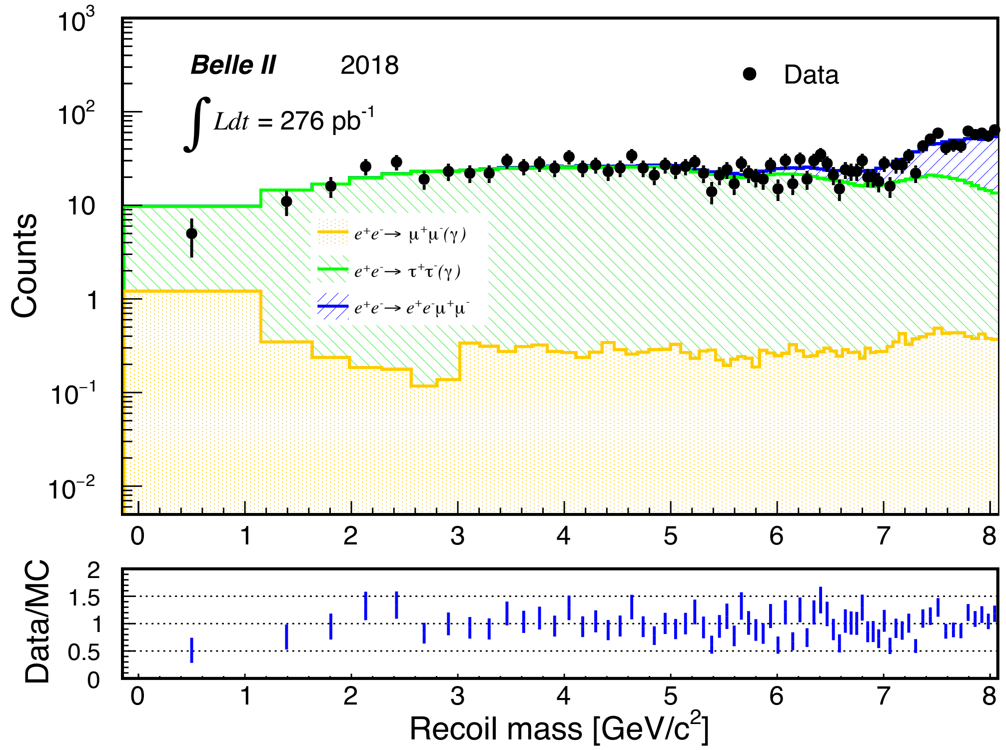
$$\mathcal{L} = \sum_\ell \theta g' \bar{\ell}\gamma^\mu Z'_\mu \ell$$

★ **may serve as mediator between SM and DS**
★ **may explain *(g-2)$_\mu$***
★ **may address anomalies in *b→sμ$^+$μ$^-$***

Invisible Z′

- reconstruct recoiling mass against μμ-pair, require nothing else to be in rest of event
- look for a peak in recoil mass distribution
- main bkgs arise from QED processes:
  - $\mu^+\mu^-(\gamma)$
  - $\tau^+\tau^-(\gamma)$, $\tau \rightarrow \mu\nu\nu$
  - $\mu^+\mu^- e^+e^-$





$$\boxed{M_r = s + M_{\mu\mu}^2 - 2\sqrt{s}E_{\mu\mu}^{CMS}}$$

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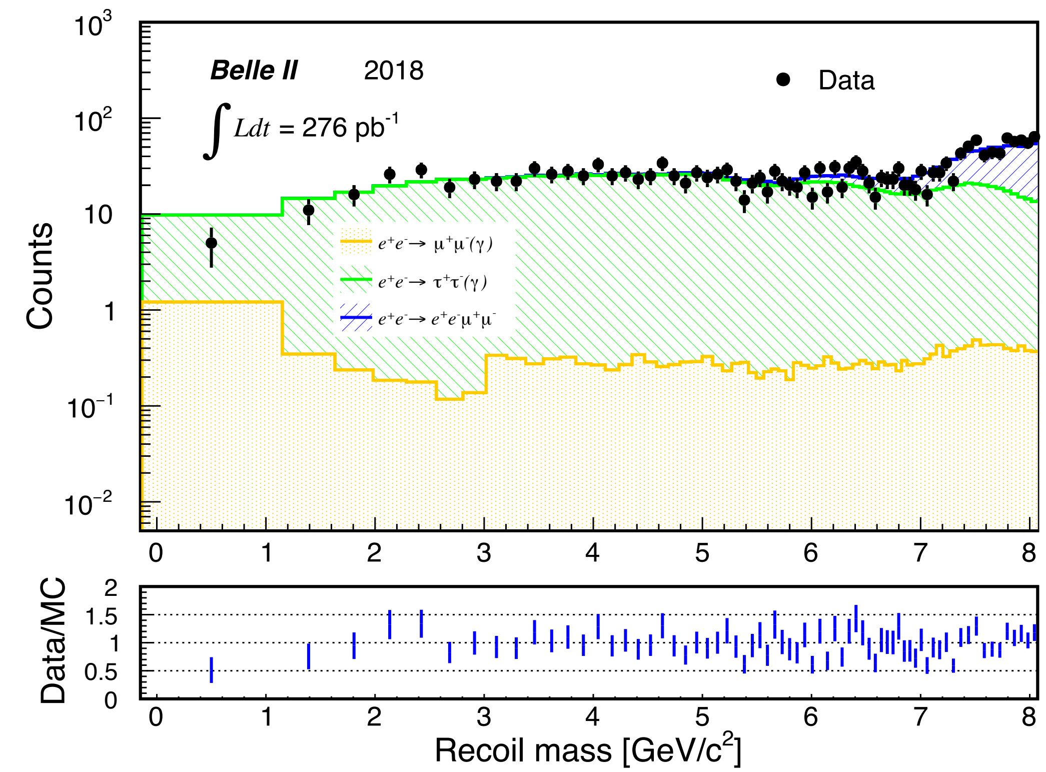
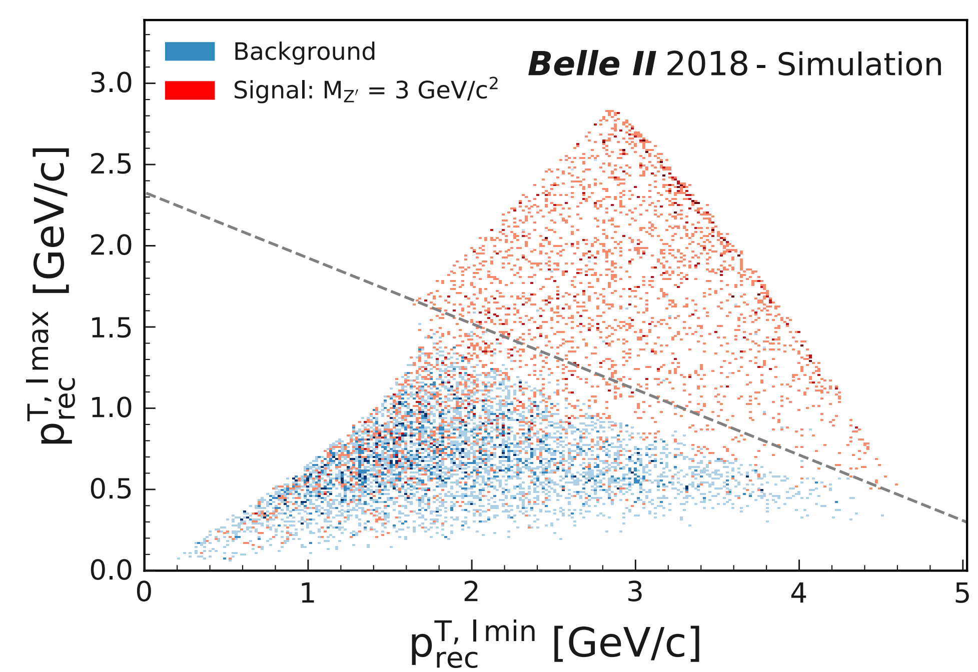
  - $\tau^+\tau^-(\gamma)$, $\tau \rightarrow \mu\nu\nu$
  - $\mu^+\mu^-e^+e^-$
- **main challenge:** tau-pair events give the biggest contribution
  - apply dedicated tau-suppression procedure
  - based on the different origin of missing momentum in sig and bkg

$$\textbf{Punzi FOM} = \frac{\epsilon_{sig}}{a/2 + \sqrt{N_{bkg}}}$$

(a=1.6 for CL=90%)





$p_{rec}^{T,lmax}$ ($p_{rec}^{T,lmin}$) : the transverse recoil momentum with respect to the lepton with the higher (lower) momentum

$p_{\mu\mu}^{T}$: the transverse momentum of the dimuon pair

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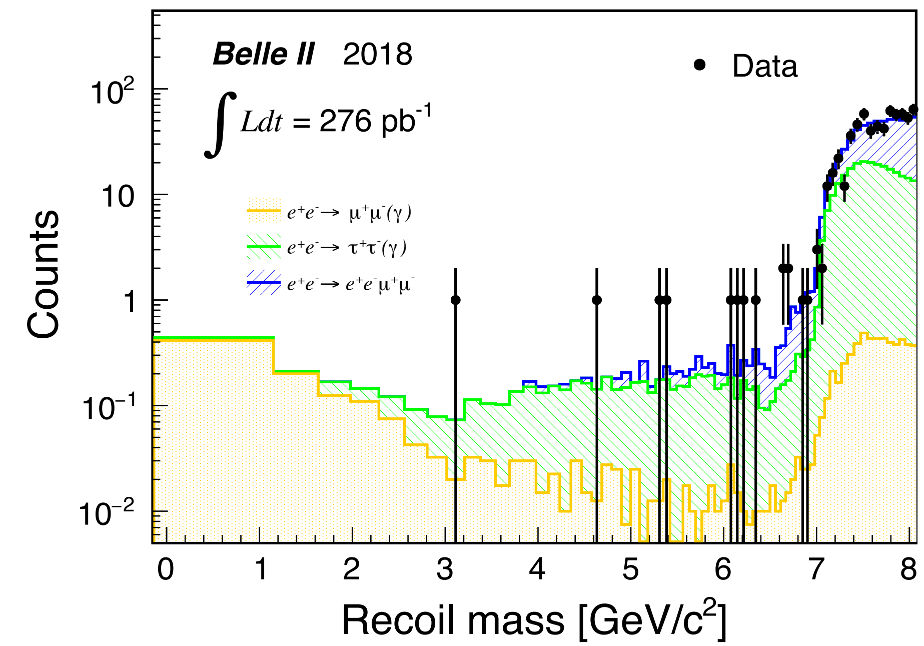
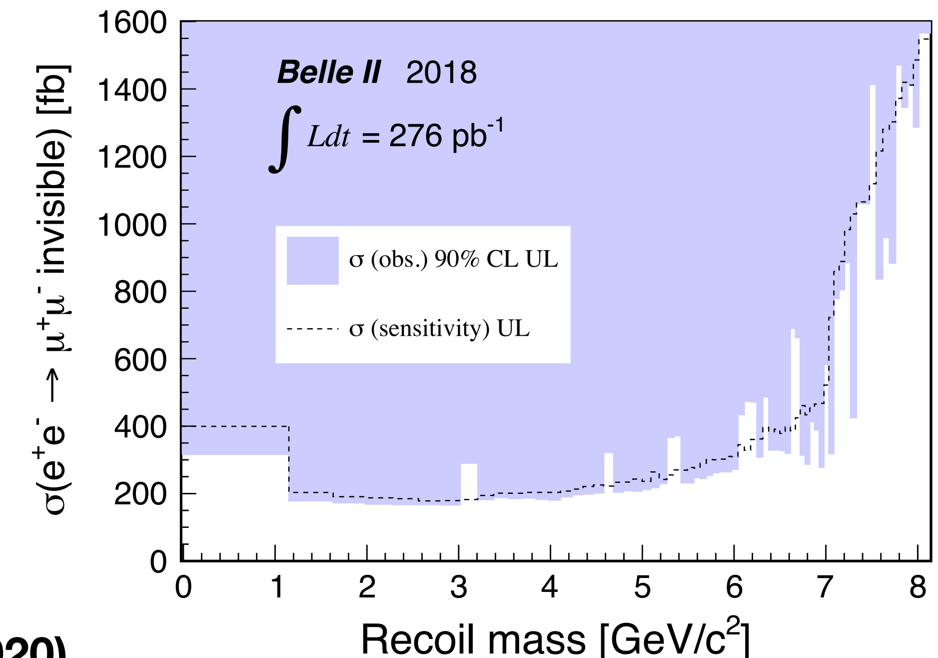
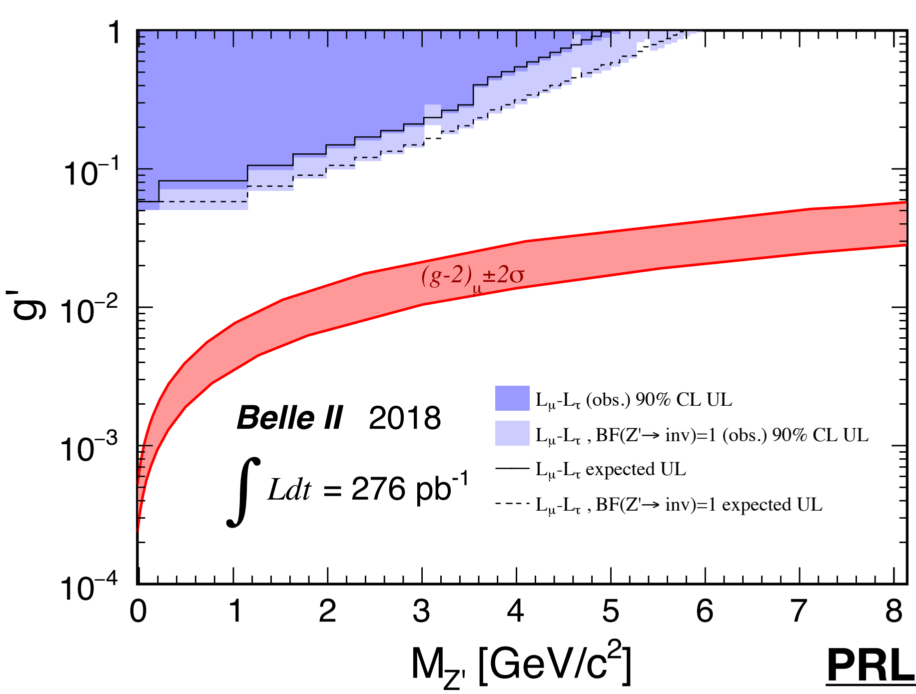
- **main challenge:** tau-pair events give the biggest contribution
  - apply dedicated tau-suppression procedure
  - based on the different origin of missing momentum in sig and bkg
- compute UL on production cross section and coupling constant g′







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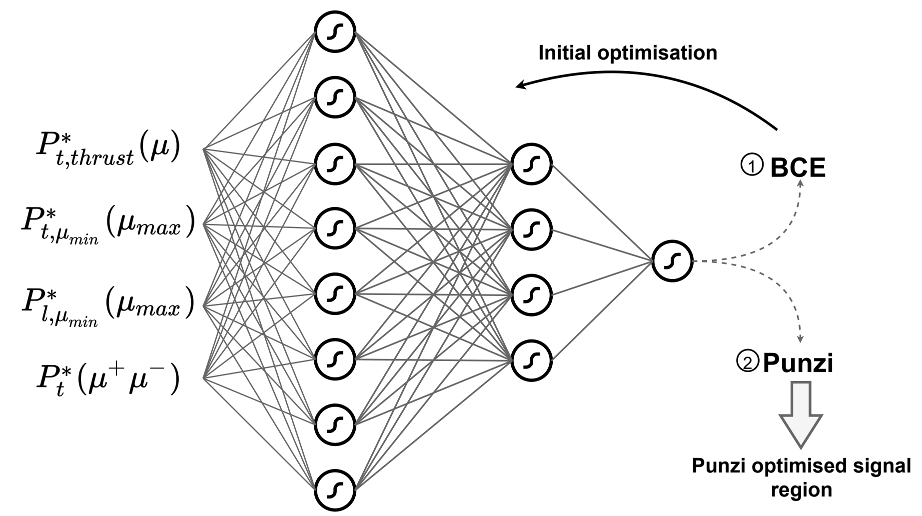
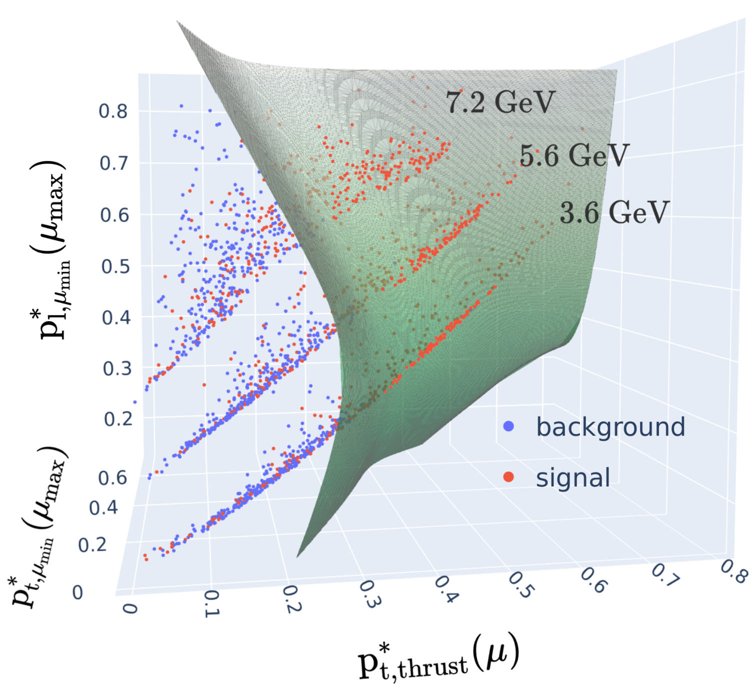
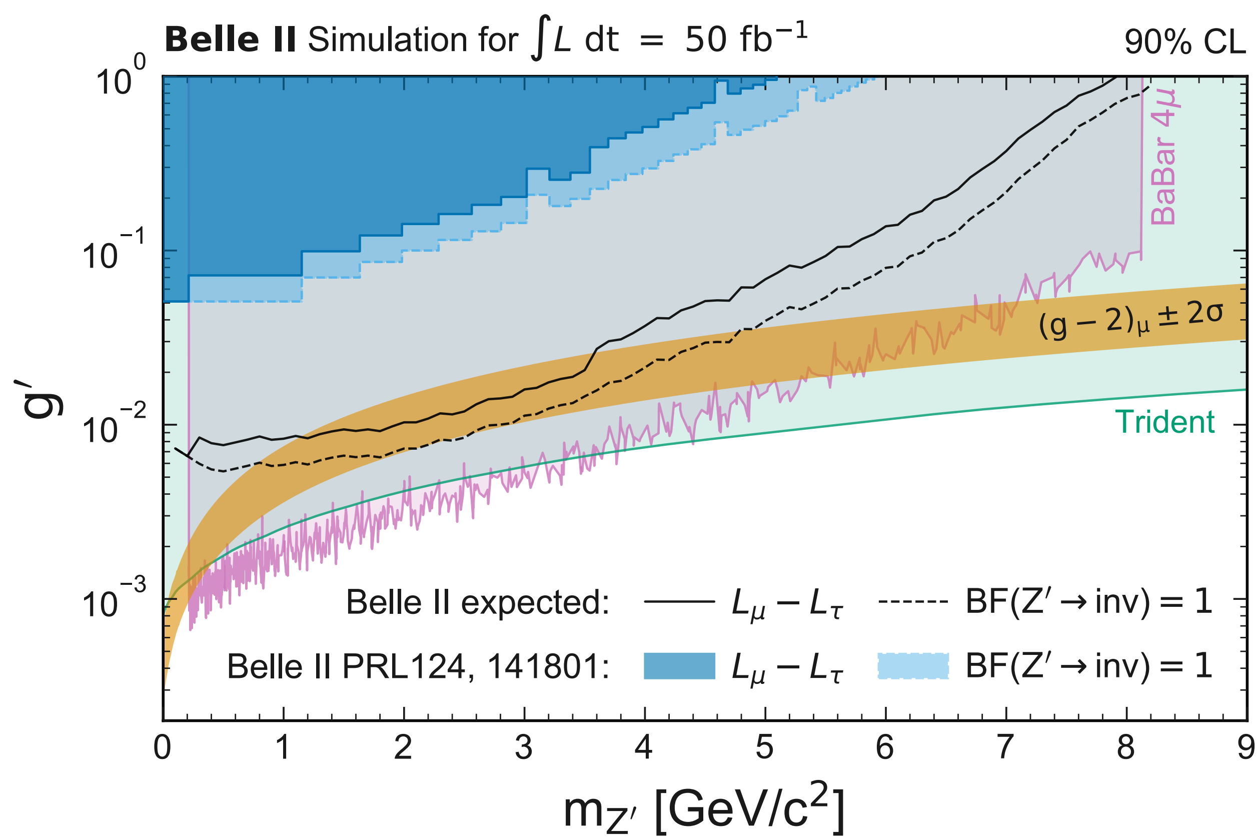
To the future and beyond

- the Z' searches allowed to demonstrate the capabilities of Belle II
- much more data has been recorded in the mean time (x1000)
- further progress:
  - deeper knowledge of the detector
  - improved particle identification
  - advanced MVA tools (Punzi-net)



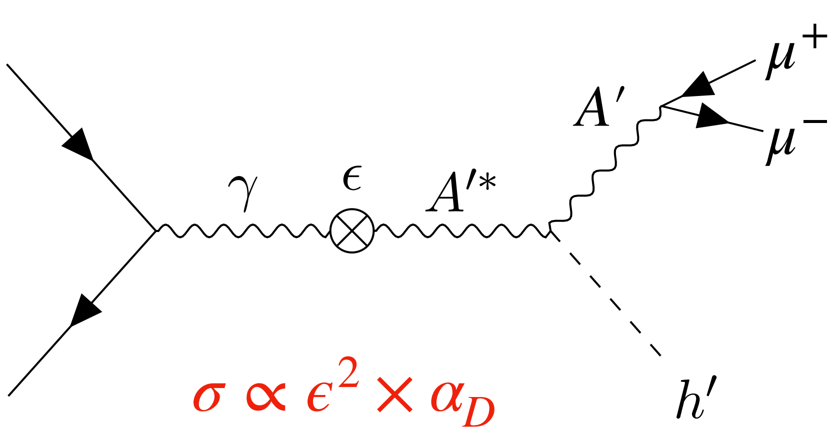


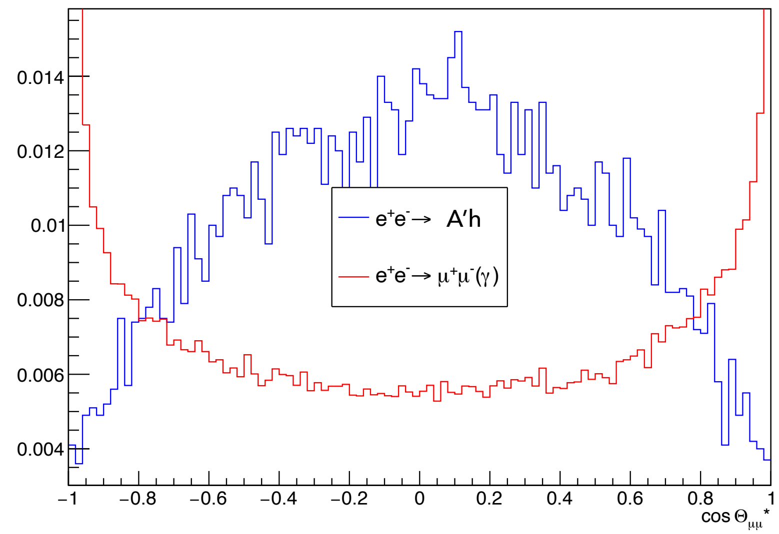


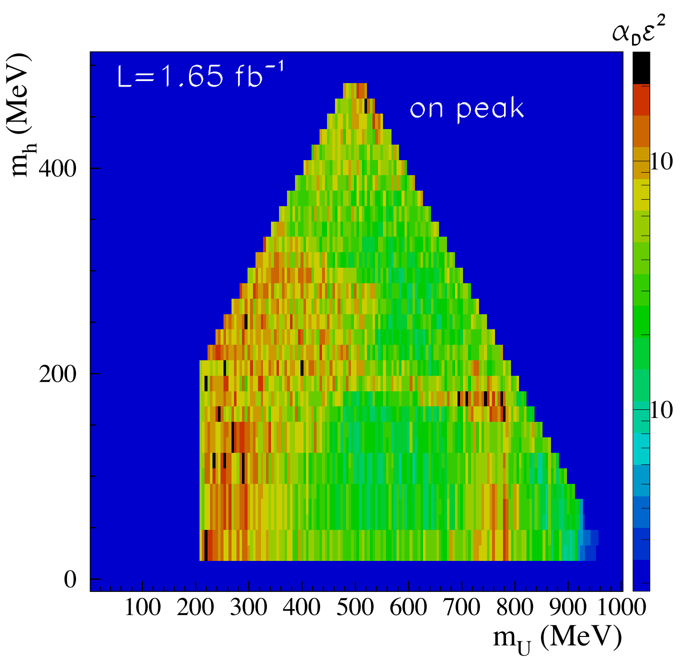
Dark Higgsstrahlung

What about a Dark Higgs?

- extend SM by adding a U(1)' group
- new minimal model includes dark photon (A' boson), coupled to SM γ via kinetic mixing parameter ε
- introduce in analogy to SM a spontaneous symmetry breaking mechanism of U(1)' with new particle, dark Higgs h'
- $e^+e^- \rightarrow A'h'$ (Higgsstrahlung), distinguish different signatures according to mass hypothesis
  - $m_{h'} > 2m_{A'}$, h' decays to A' pair, six charged particle final state, investigated by BaBar and Belle
  - $m_{h'} < m_{A'}$, h' has large lifetime to escape detection, 2 charged particle final state plus missing energy, only investigated by KLOE







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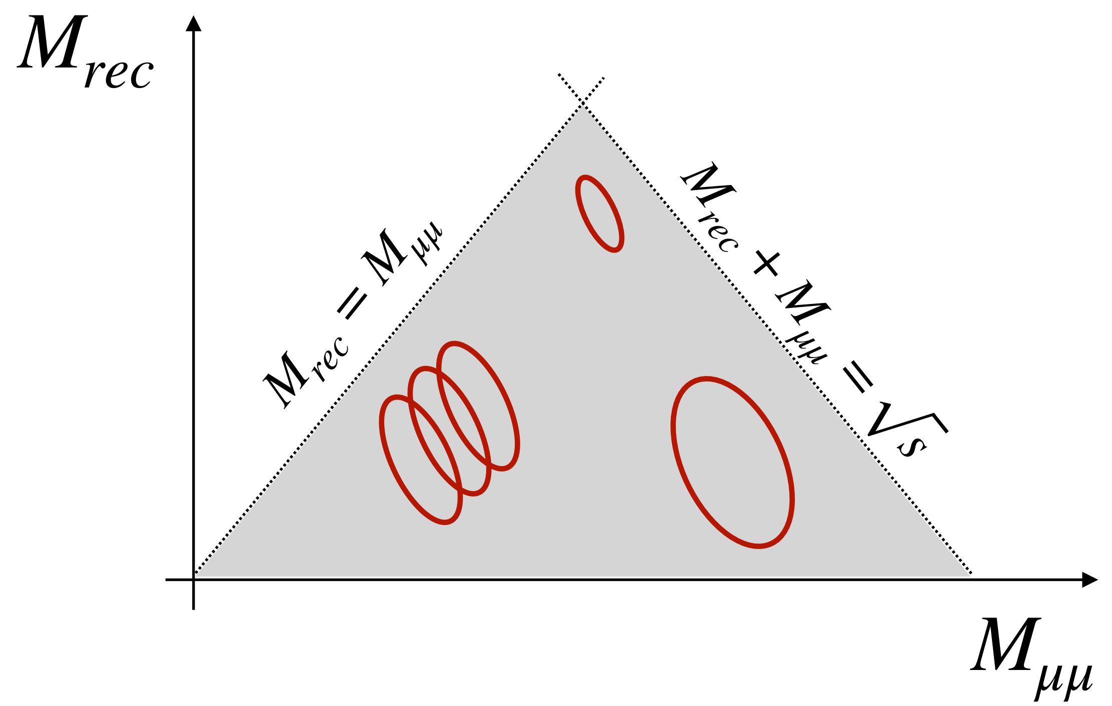
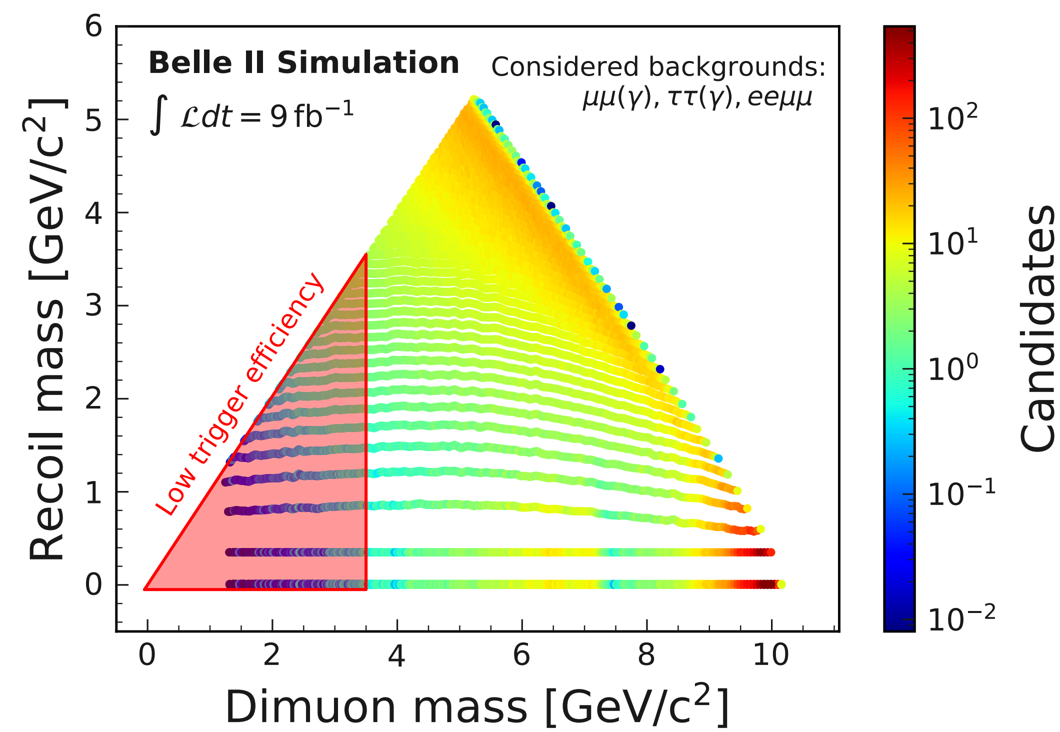
Dark Higgsstrahlung

- look for two oppositely charged muons plus missing energy
- find a peak in two dimensional distribution of recoiling mass vs dimuon mass
- main SM background contributions arise from
  - $\mu^+\mu^-(\gamma)$
  - $\tau^+\tau^-(\gamma)$
  - $e^+e^-\mu^+\mu^-$
- **main challenge:** measurement strategy
  - scan+count in elliptical mass windows
  - continuous grid of 9k (overlapping) ellipses





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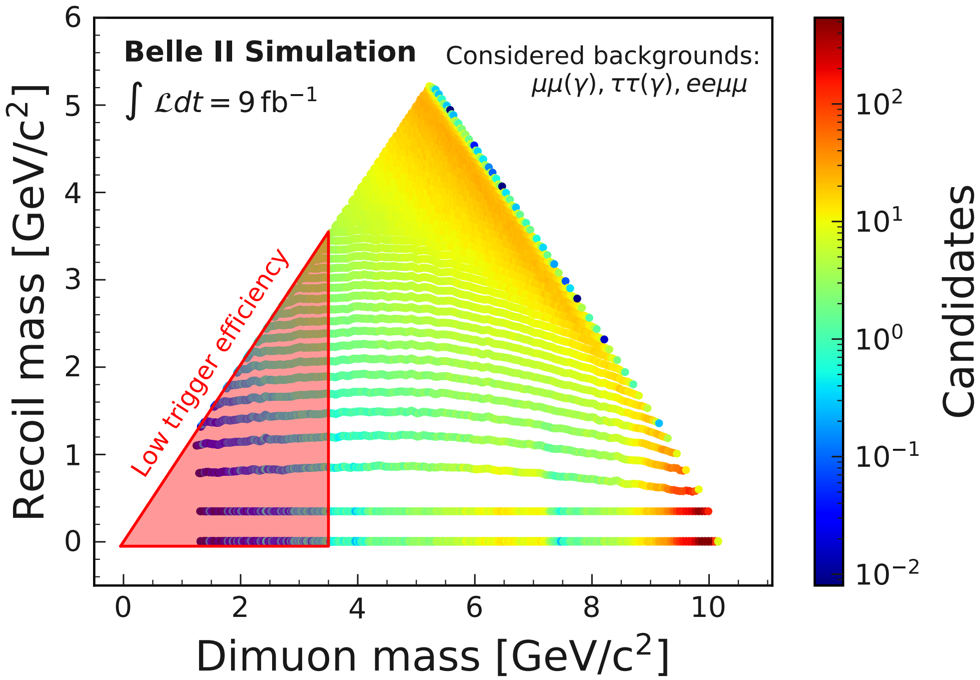

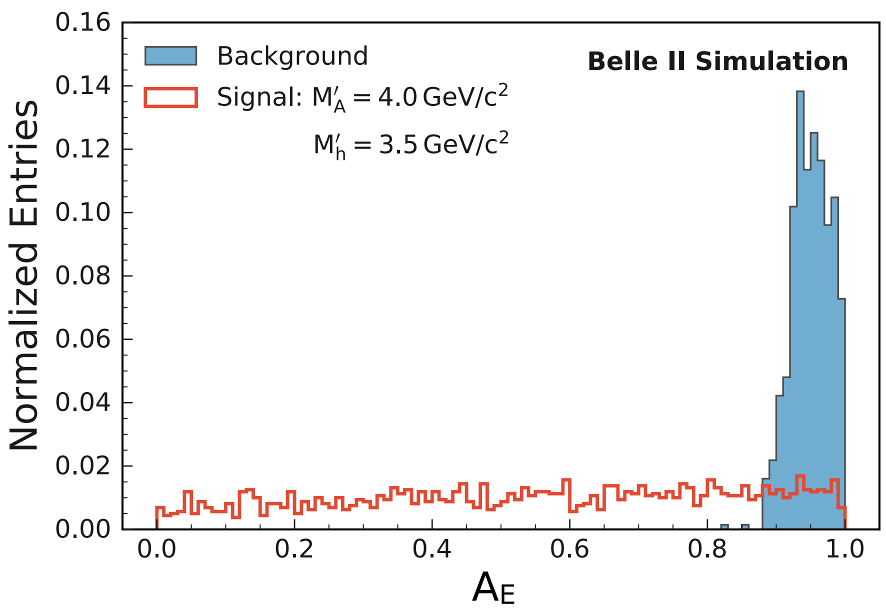

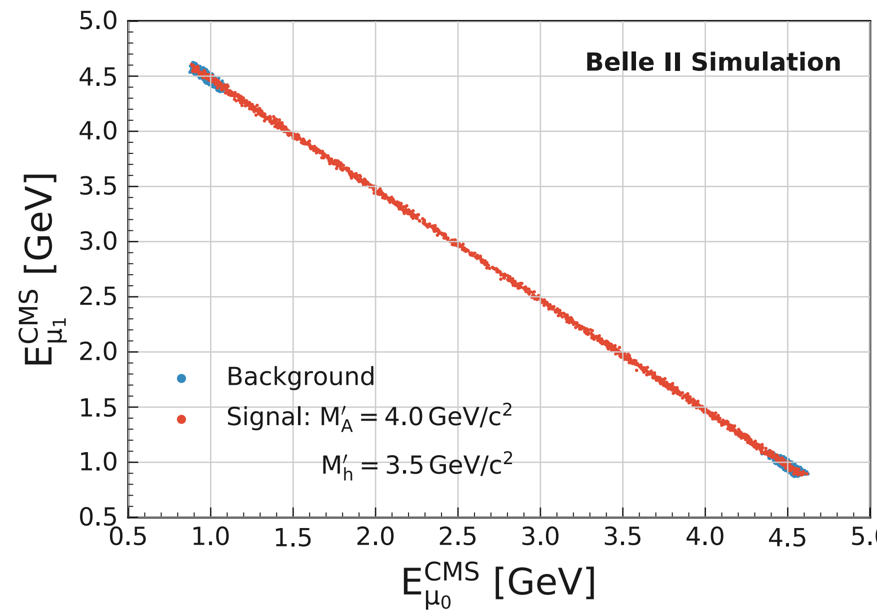

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- **main challenge:** measurement strategy
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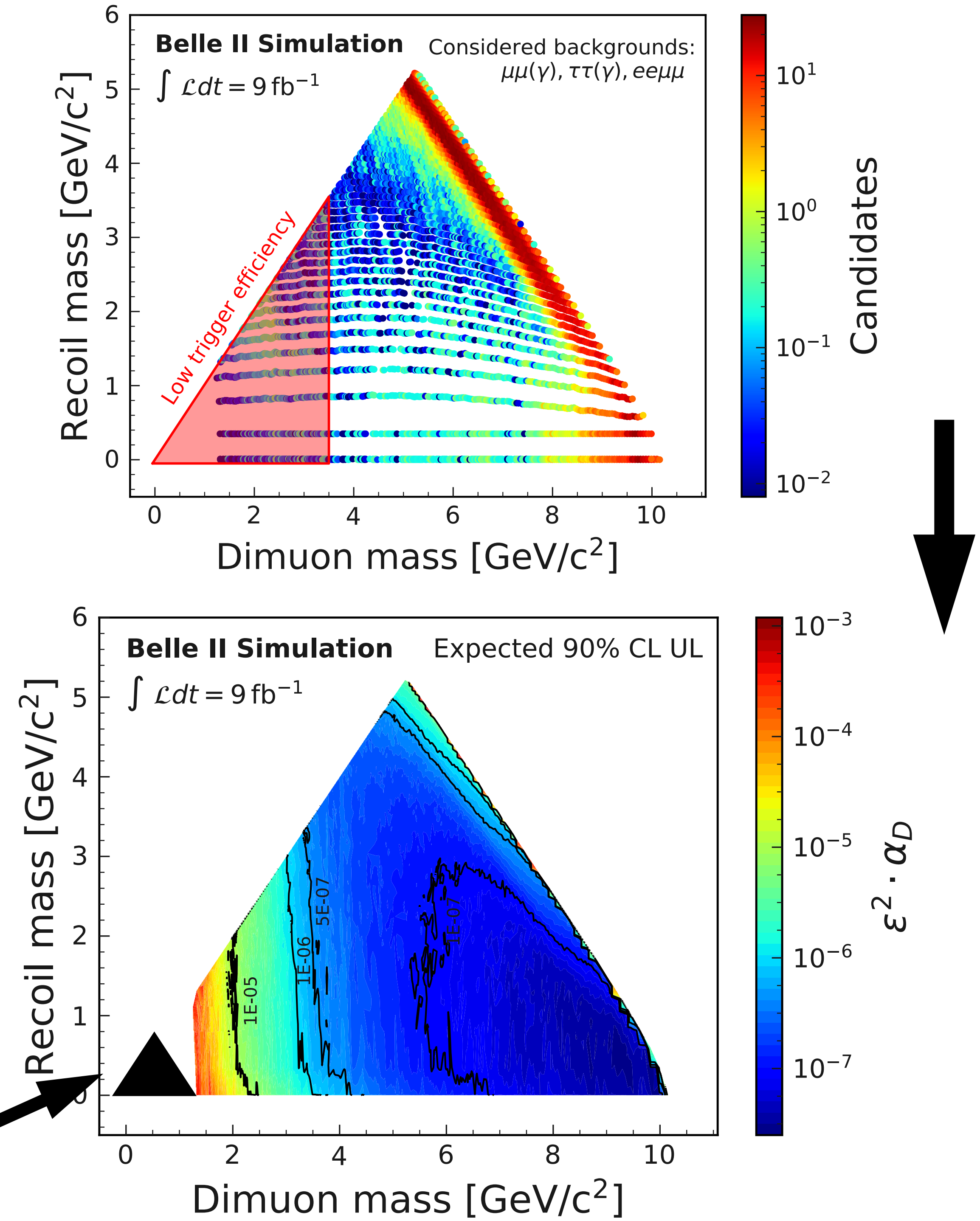
- background suppression based on helicity angle, energy asymmetry between muons
- set UL on the kinematic mixing parameter times dark coupling constant $\varepsilon^2\alpha_D$
- very promising result with „small" dataset
    - probing unconstrained regions in 2D mass plane
    - probing non trivial regions of $\varepsilon^2\alpha_D$
- expect huge LEE
- ongoing analysis, recently unblinded



KLOE result

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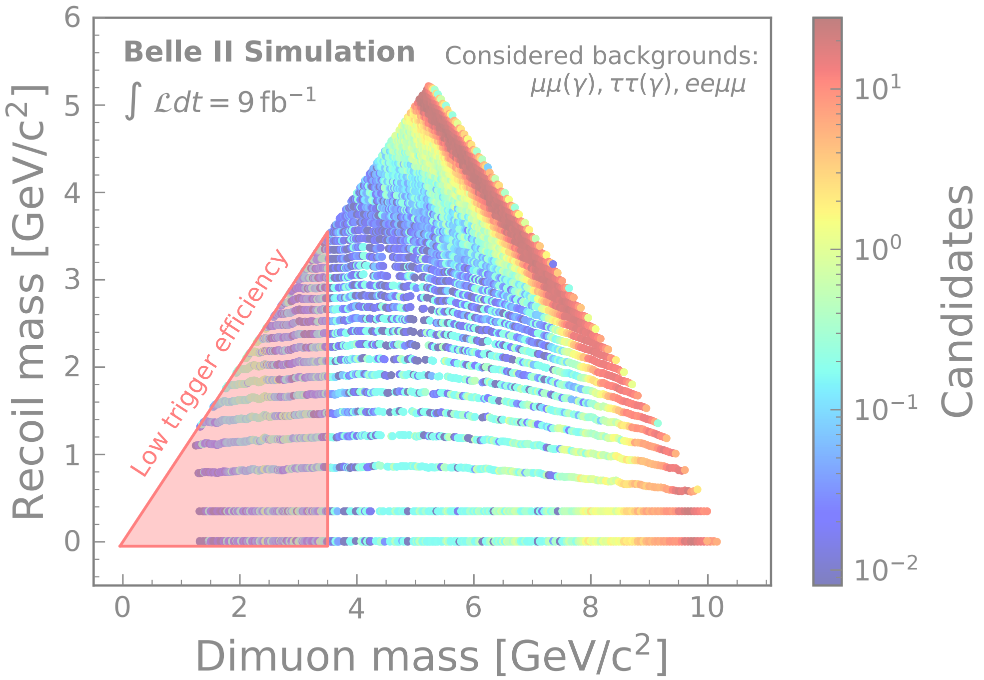
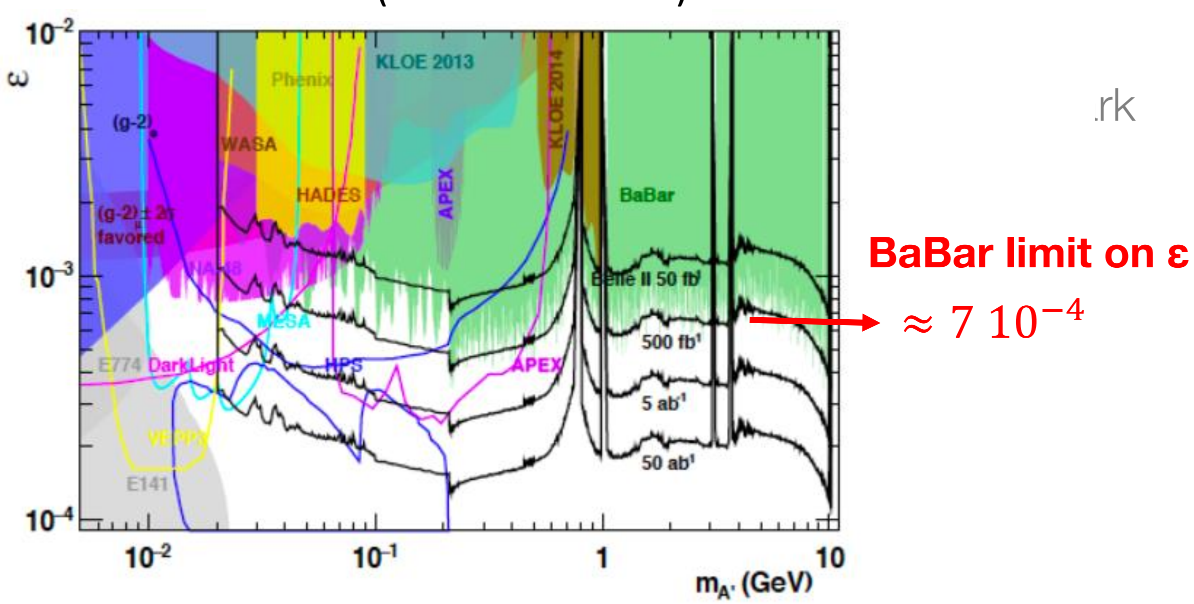


UL on ϵ (visible searches)



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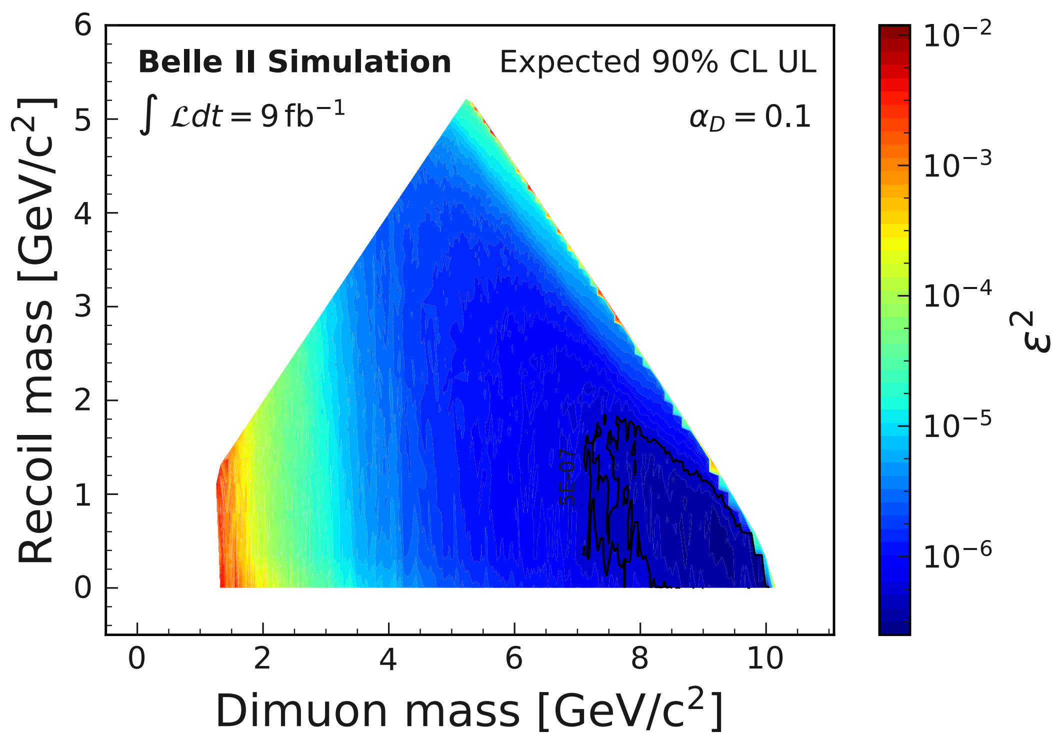
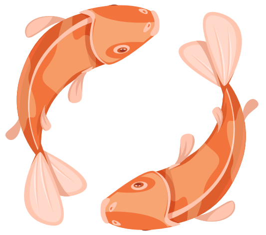
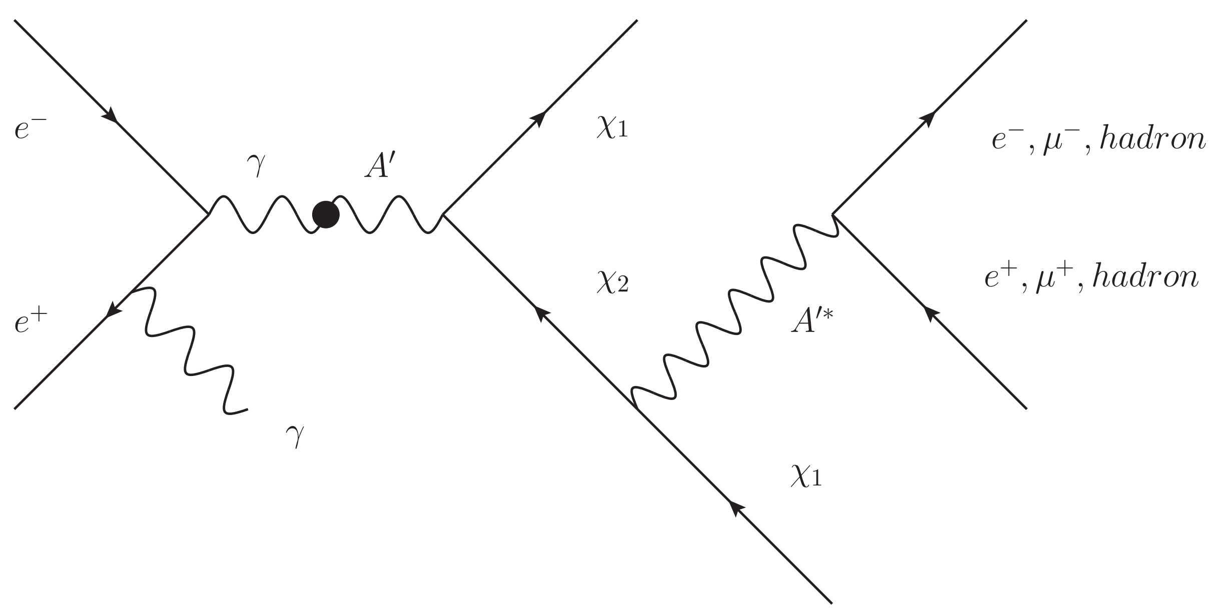


Inelastic Dark Matter



Inelastic Dark Matter (iDM)

- model introduces a dark photon A' and two dark matter states χ_1 and χ_2 with a small mass splitting
  - χ_1 is stable (relic)
  - χ_2 is long-lived at small values of kinetic-mixing coupling
- unconstrained by direct detection experiments, as both inelastic and elastic scattering suppressed
- focus on $m_{A'} > m_{\chi 1} + m_{\chi 2}$, such that $A' \rightarrow \chi_1 \chi_2$ is dominant decay channel
- production at Belle II via ISR



5 parameter model:
$m_{A'}$ (fixed relative to $m_{\chi 1}$)
$m_{\chi 1}$ (scan)
mass difference $\Delta = m_{\chi 2} - m_{\chi 1}$ (categorical)
dark coupling α_D (fixed to benchmarks)
kinetic mixing parameter ε (limit)

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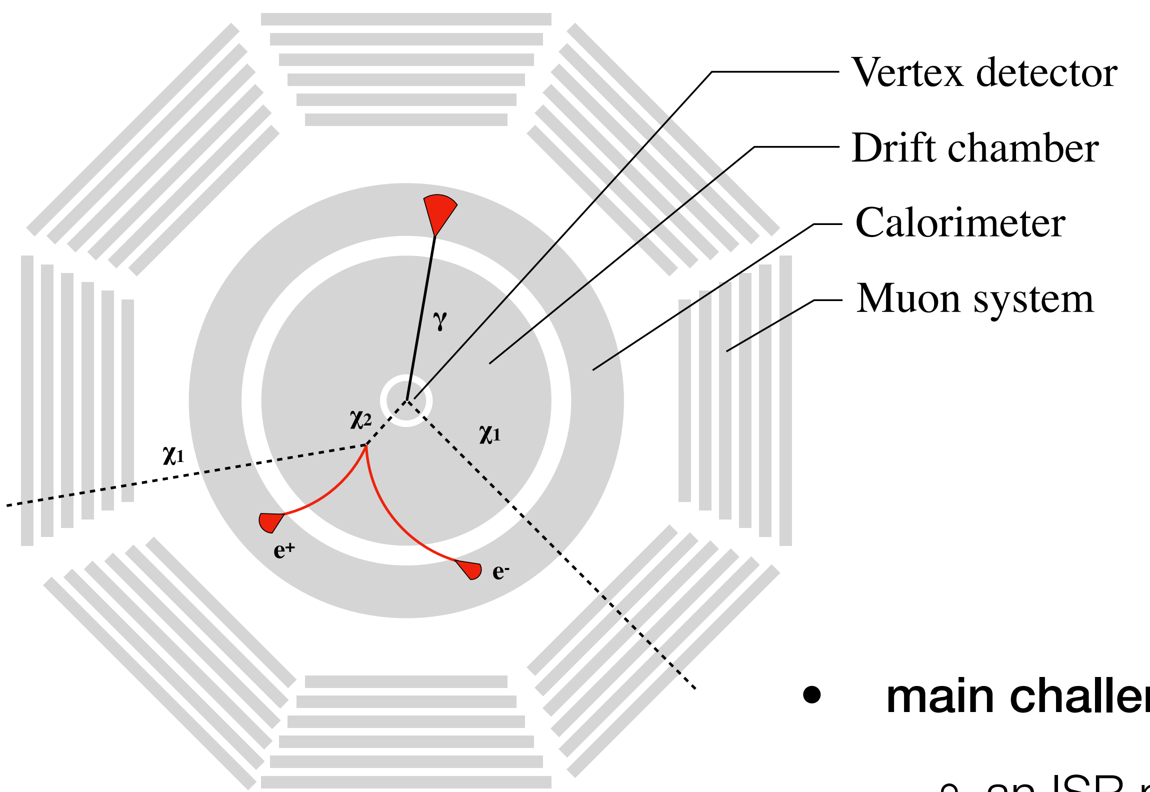
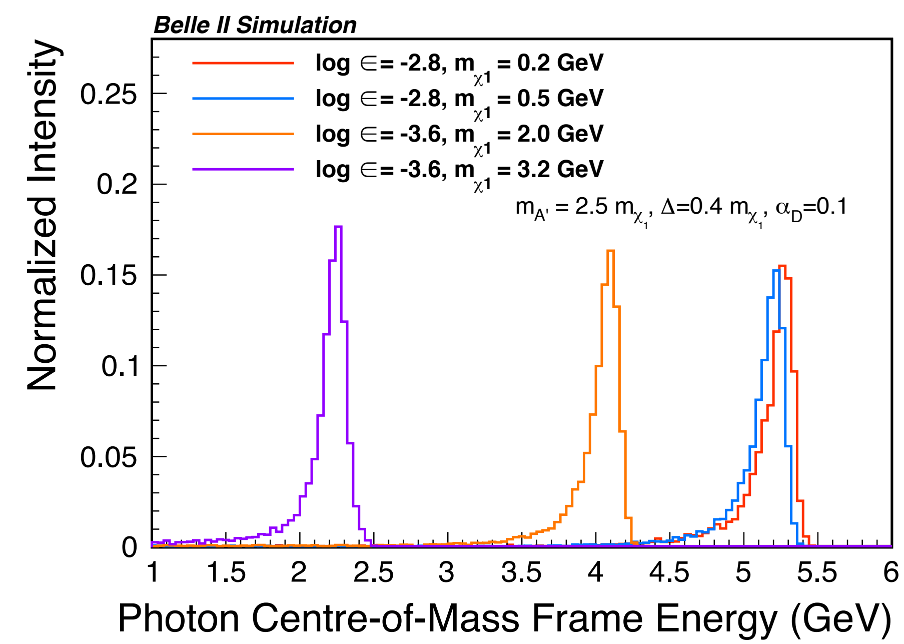
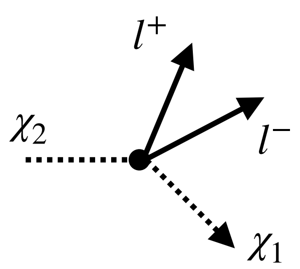
iDM signature

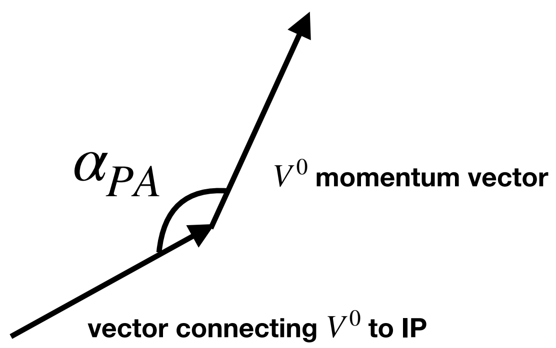




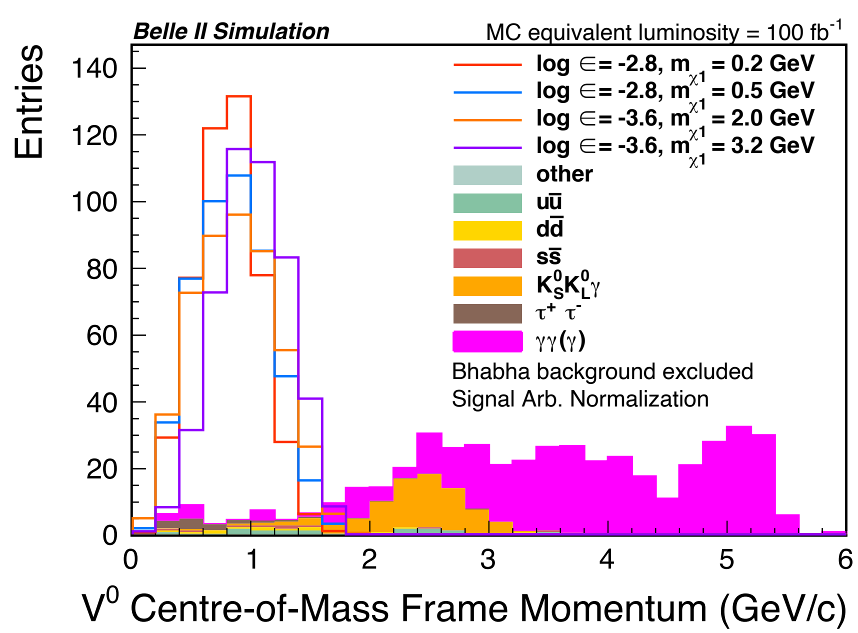
- **main challenge:** detector signature includes
  - an ISR photon
  - a displaced vertex which is non-pointing
  - missing energy
- search for a peak in the photon CMS energy distribution
- bkg contribution arise from
  - photon conversion: $e^+e^- \to \gamma\gamma(\gamma)$, $\gamma \to e^+e^-$
  - meson decays: $e^+e^- \to K^0_S K^0_L(\gamma)$, K^0_S decays

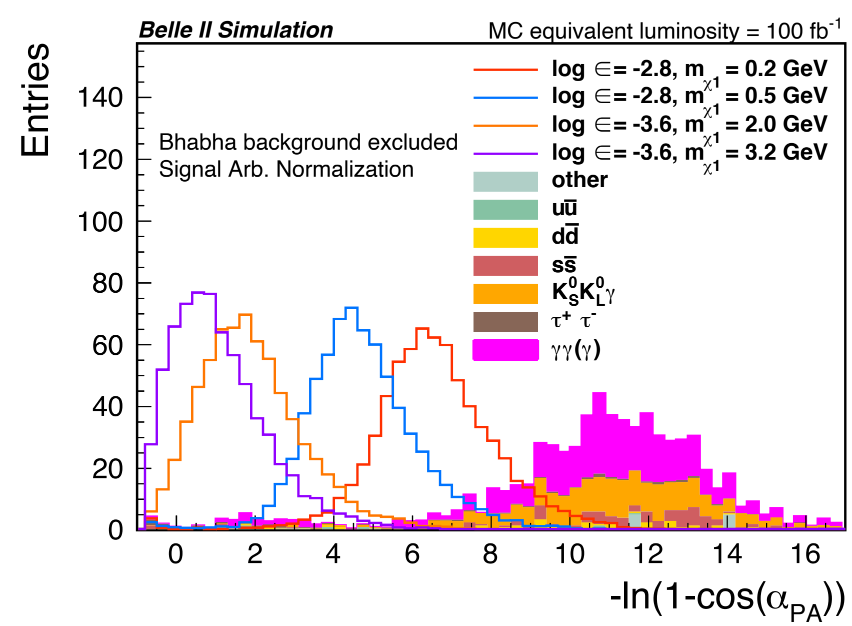
iDM background suppression





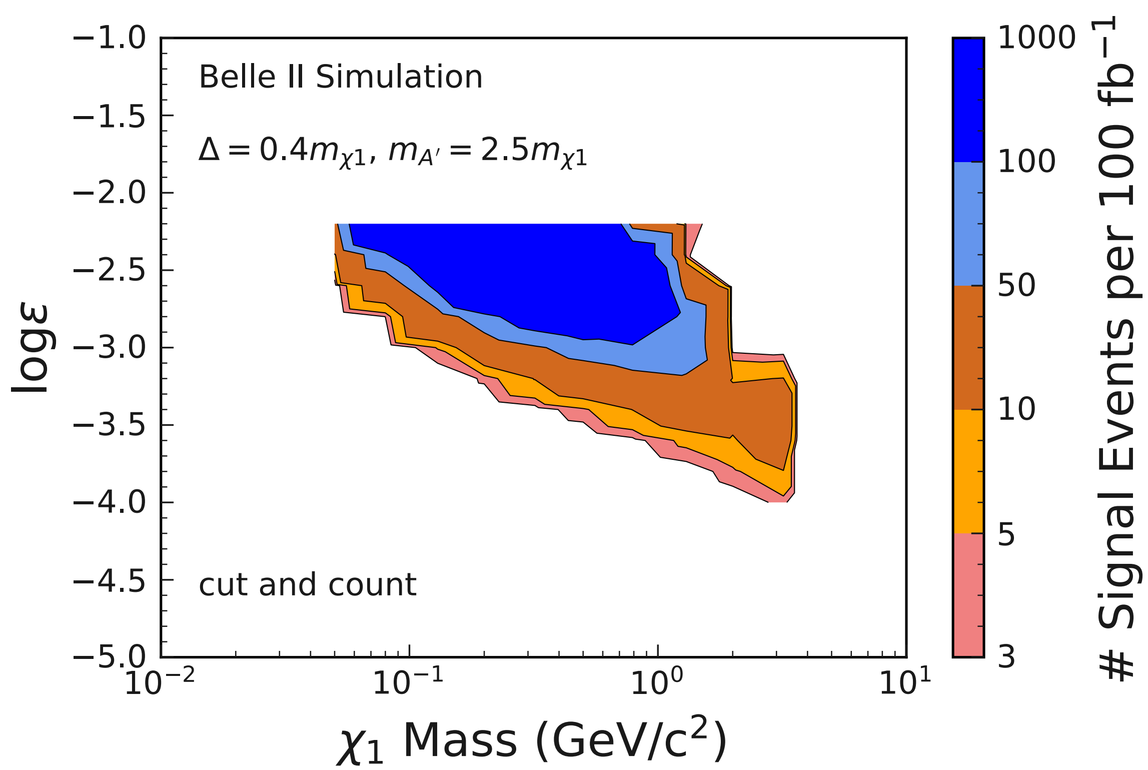
- most of prompt $l^+l^-(\gamma)$ background is rejected by requirement of displaced vertex
- cut on V^0 momentum can be very effective
  - undetected χ_1 lowers signal V^0 momentum w.r.t background
- the pointing angle α_{PA} offers further discriminating power
  - the 3-body iDM decay leads to a non-pointing V^0
  - most of the considered backgrounds are 2-body processes





Inelastic Dark Matter (iDM)

- estimate signal yield by counting events in ISR photon window (final analysis will use template fit)
- maximum reach of χ_1 is determined by 2GeV trigger threshold
- new displaced vertex trigger under consideration
- Belle II can explore a large region of new iDM parameter space



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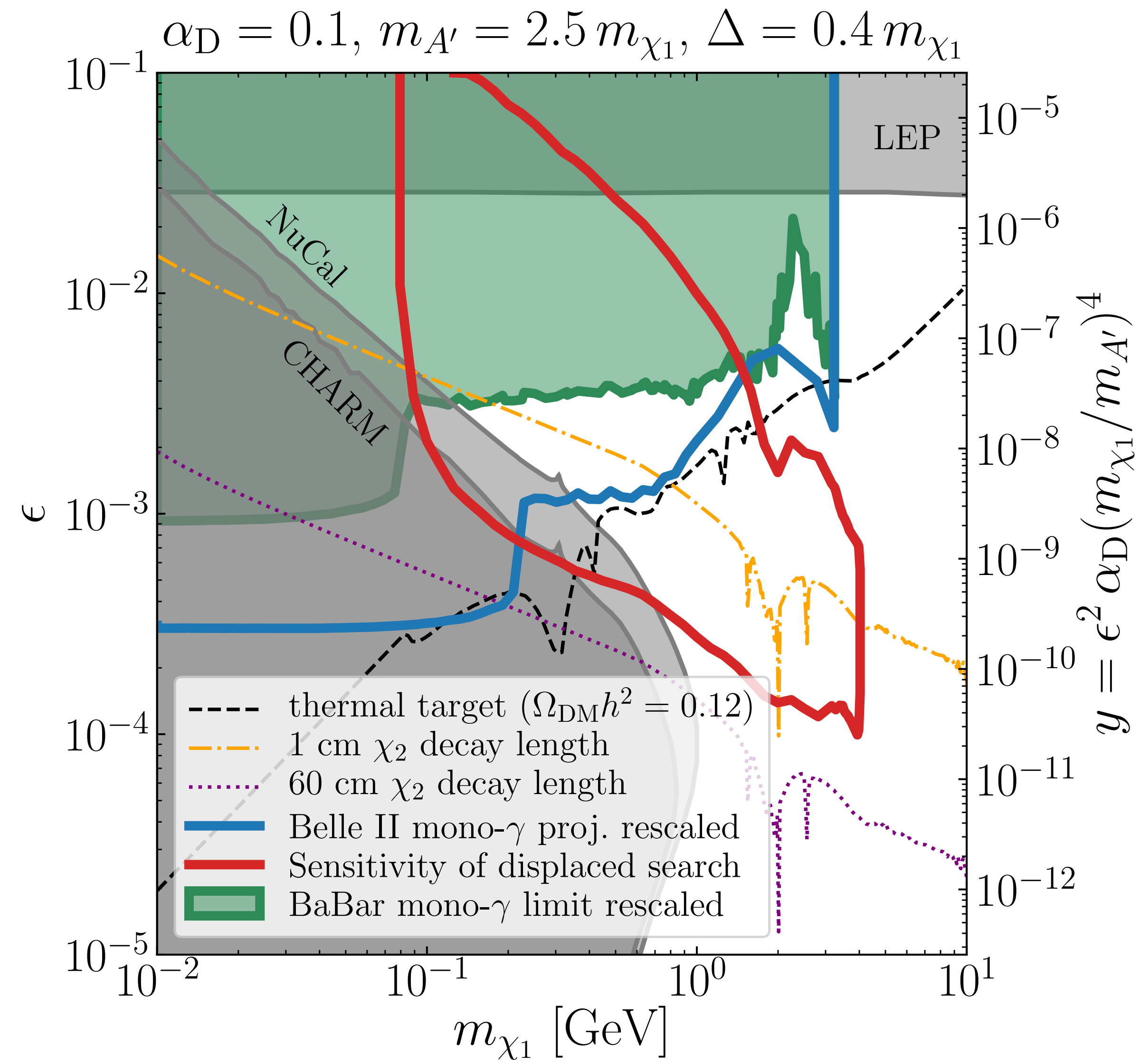
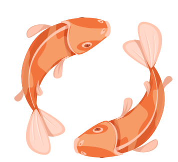


Conclusion

- broad and active program of DS physics at Belle II
- available phase-space is probed with many different models
- further analysis with displaced vertices include B→Ka, B→Kh'…
- advanced MVA tools developed
- first results published and more to come

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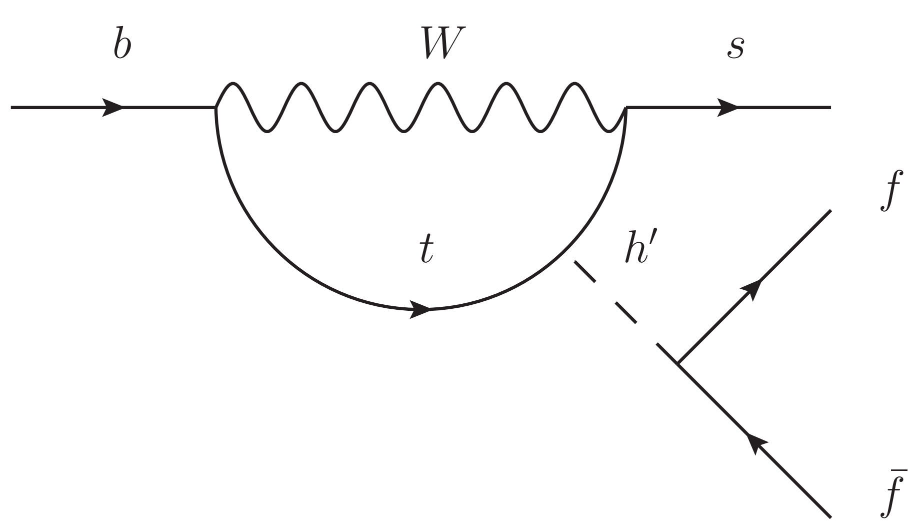
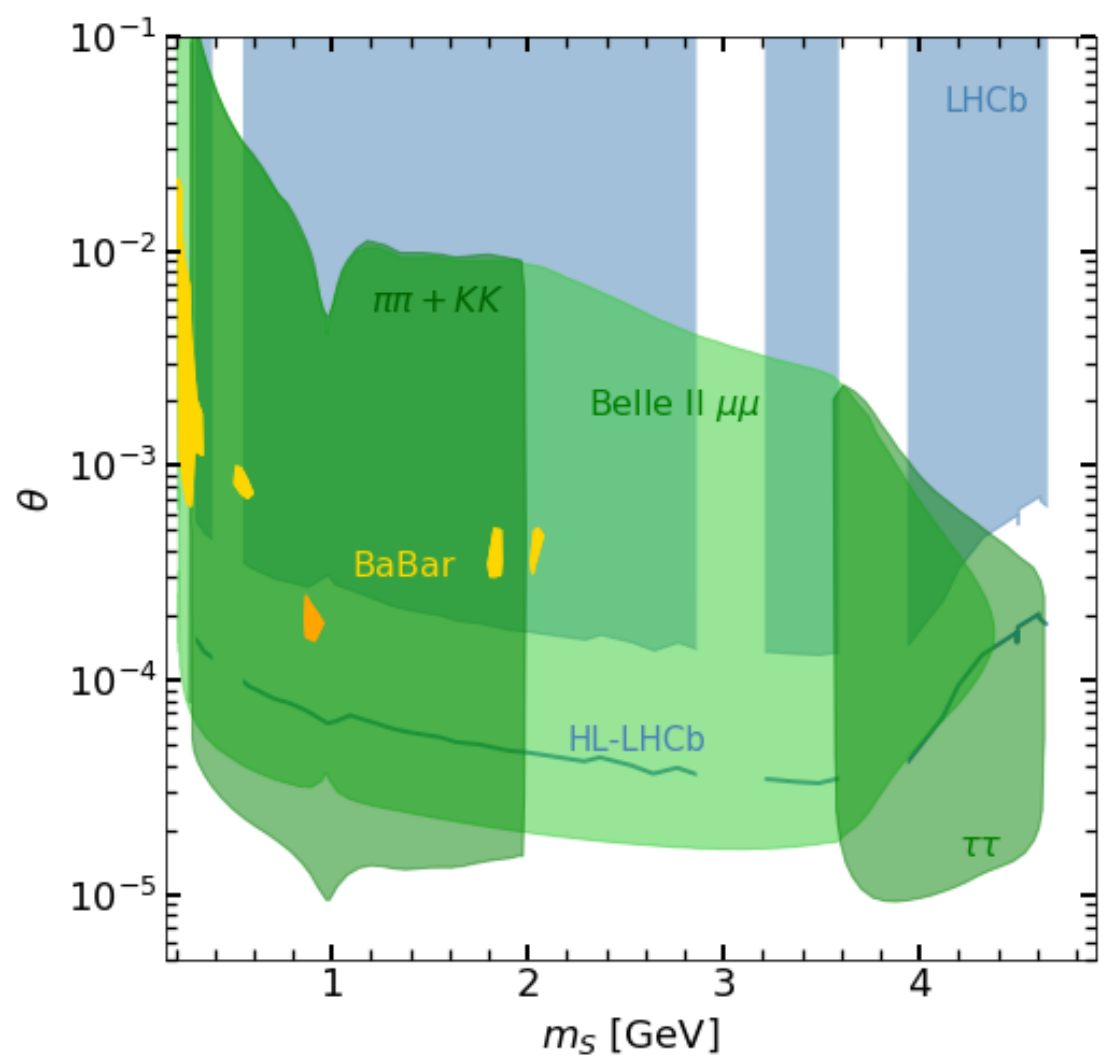
Backup

Additional searches : B→Kh'

- Search for long-lived scalar in rare B meson decays
    - B→Kh', h'→μμ,ππ,KK
    - generic scalar that mixes with the Higgs sector
    - LHCb and Belle II complementary due to different B momenta
    - reach towards even smaller mixing angle by searching for B→K+invisible





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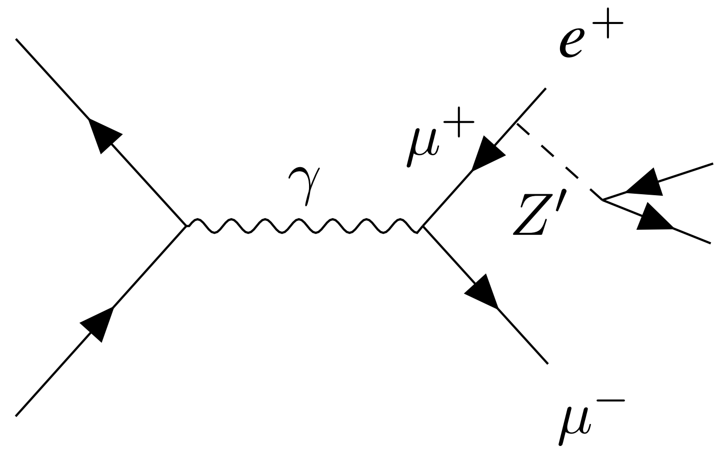
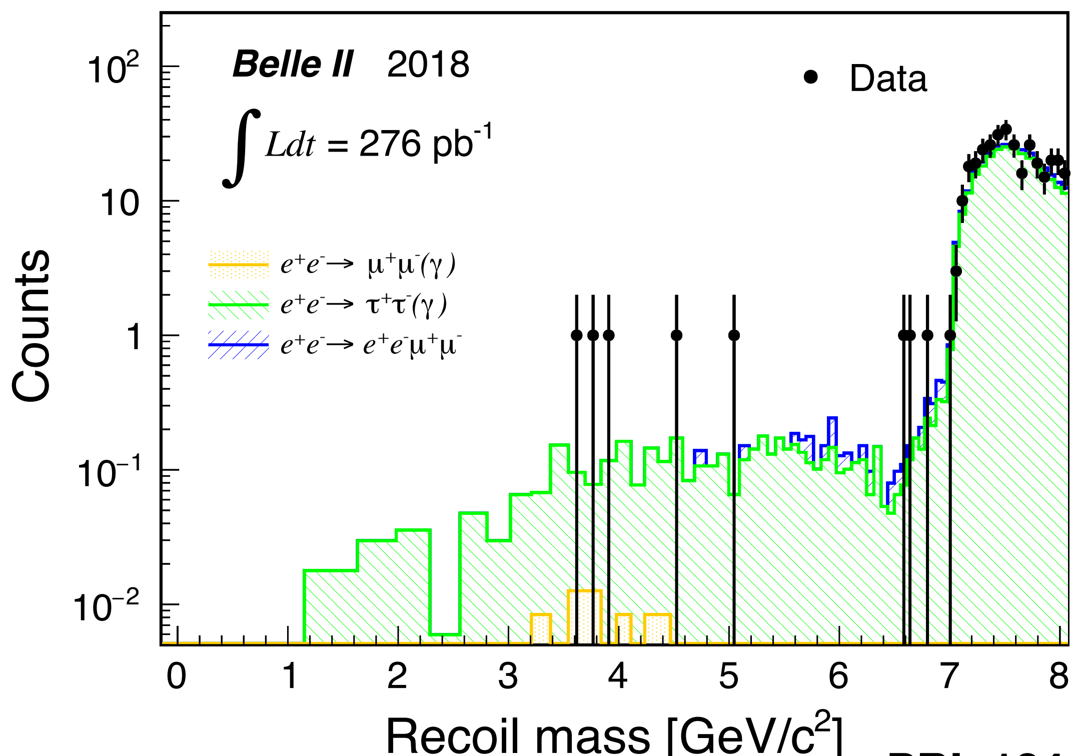
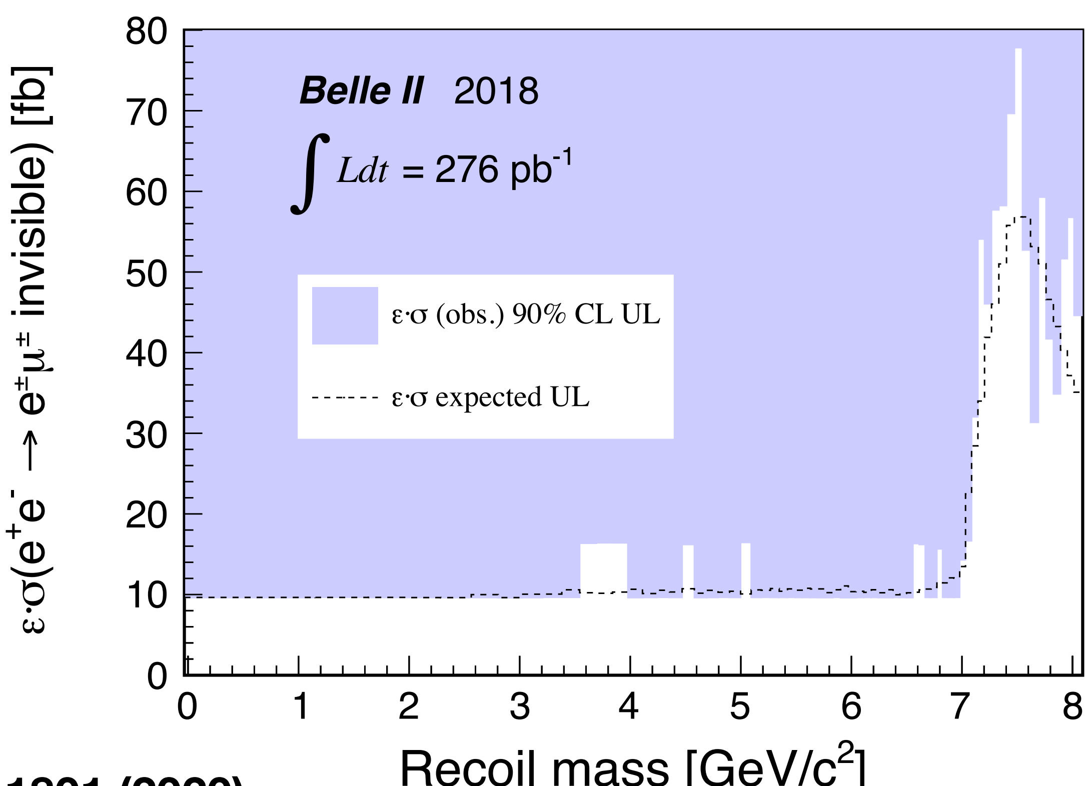
Invisible Z' - LFV



- look for LFV Z' that couples to eμ
- model-independent search with same selection criteria
- included in same publication





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