Recent dark-sector results at Belle II

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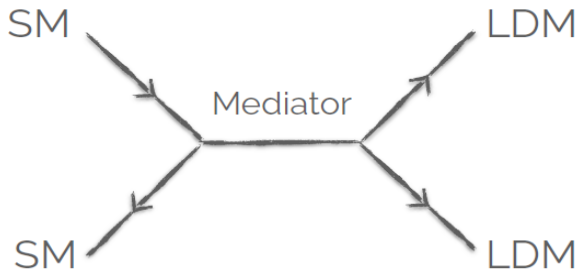
on behalf of the Belle II Collaboration

OUTLINE OF THE TALK

- ✓ Belle II and SuperKEKB
- ✓ Search of
  - ➢ Dark Higgsstrahlung
  - ➢ Z' to invisible **new**
  - ➢ Z', S, ALP →ττ **new**
- ✓ Perspectives & Summary

Dark matter hunt with a light sector



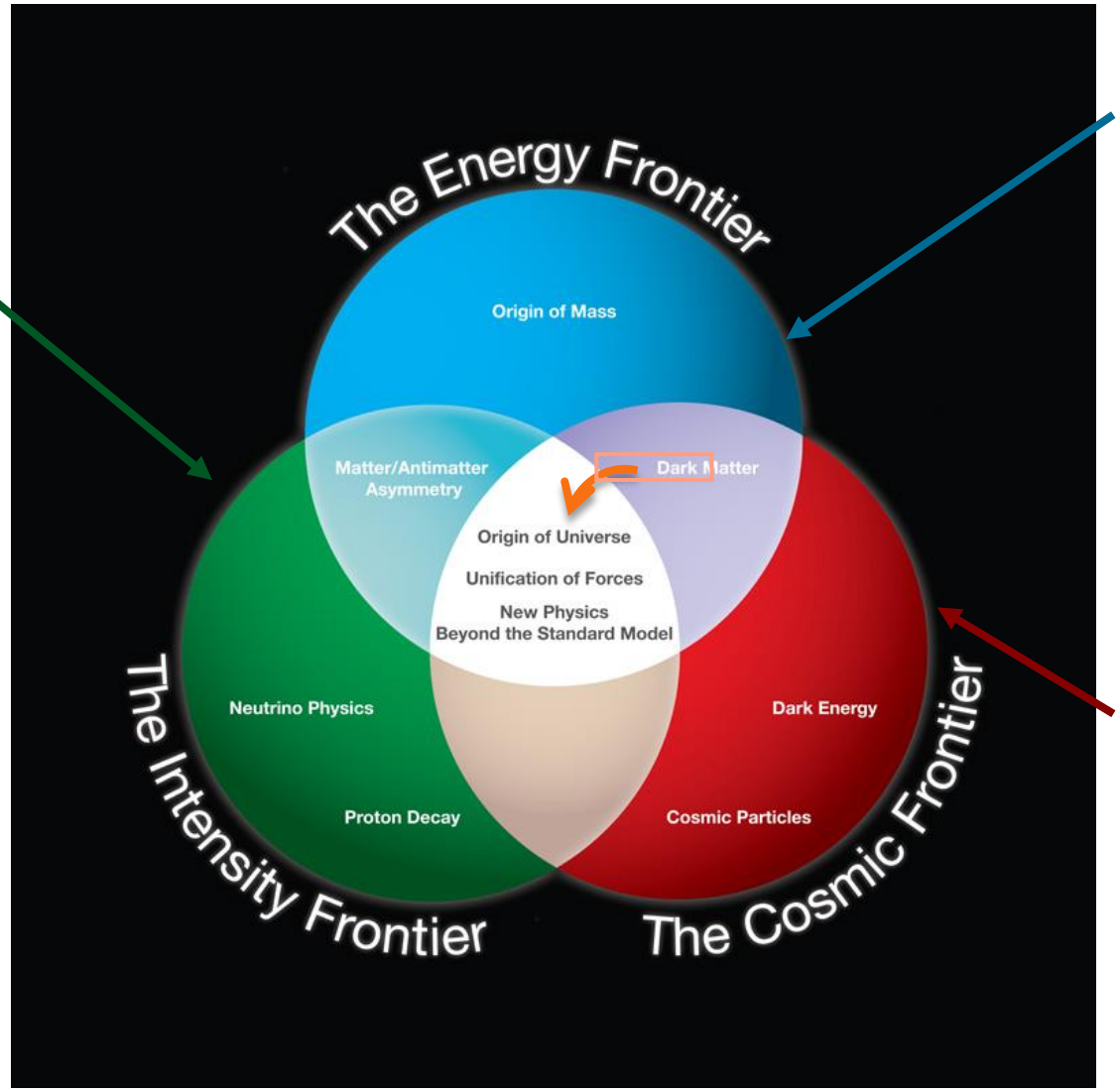
Light Dark Matter Mediators
→ portals

Vector portal
Dark photon, **Z'**, …

Pseudoscalar portal
QCD Axions, **ALPs**, …

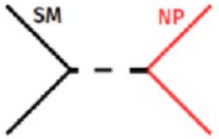
Scalar portal
Dark Higgs, **scalars**

Neutrino portal
Sterile neutrino



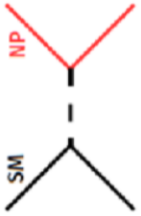
Energy frontier

Direct production of new particles - limited by beam energy
(LHC – ATLAS, CMS)



Cosmic frontier

Direct effect search in (mostly) underground experiments



From KEKB to SuperKEKB

- **Upgraded rings**
  - New e^+ damping ring
  - Increased currents

x2

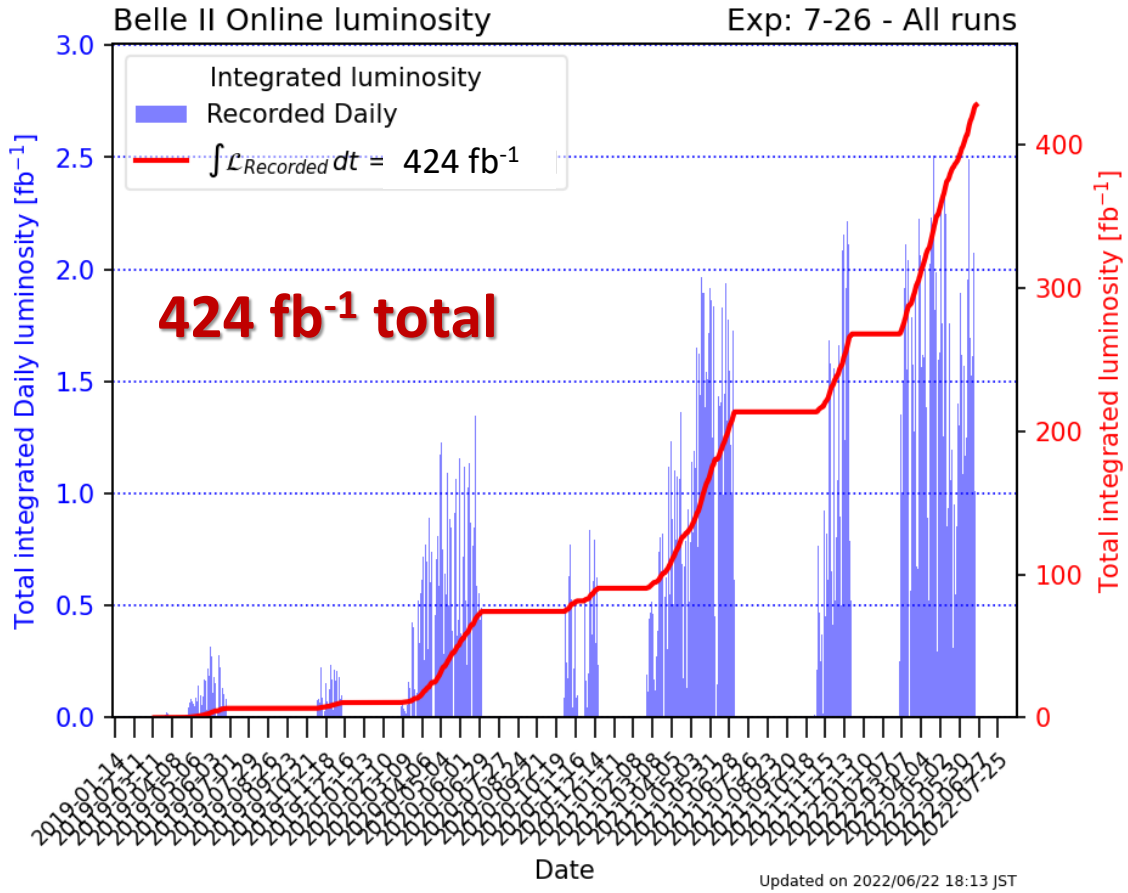
x15

x30

- **Nano-beam scheme**
  - New final focus magnets
  - Large crossing angle

Final goal : 50 ab^{-1}

Collected luminosity up to now: 2019-2022



Peak luminosity world record: **4.7 x 10^{34} cm^{-2} s^{-1}**

Resume physics run in fall 2023

Belle II detector

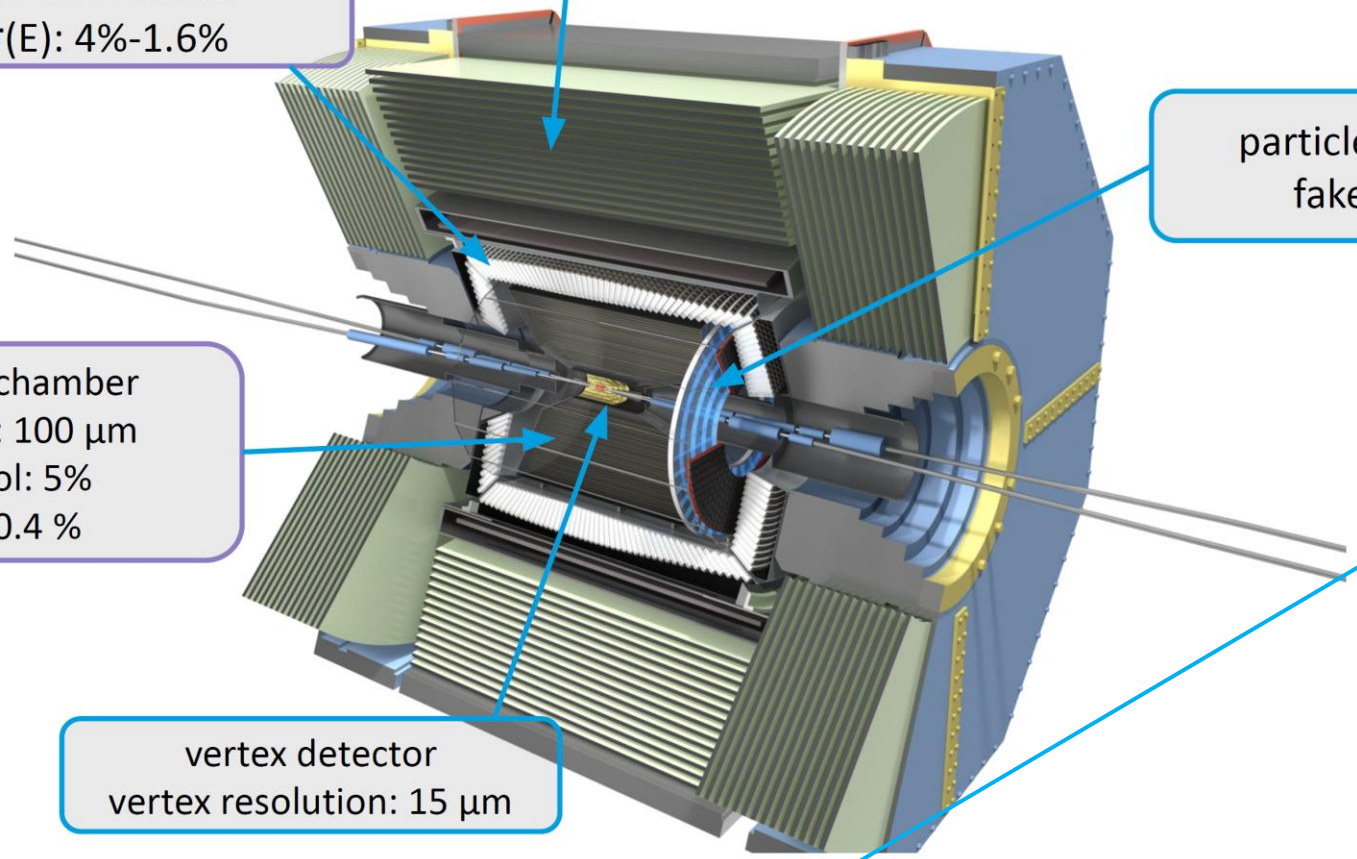
K_L and muon detector
μ ID-eff: ~90%

EM Calorimeter
σ(E): 4%-1.6%

particle identification
fake-π rate: 5%

central drift chamber
spacial resol: 100 μm
dE/dx resol: 5%
p_T resol: 0.4 %

vertex detector
vertex resolution: 15 μm



- Two-track trigger
- Three-track trigger
- E_{ECL}> 1 GeV trigger

Single muon
- Drift ch. + μ detector

Single track
- Neural based

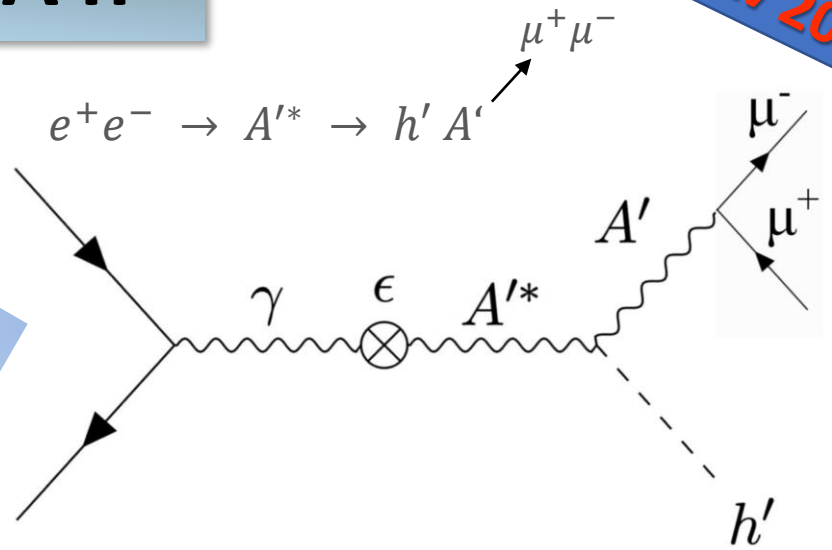
Single photon
- E_γ > 0.5, 1, 2 GeV

Key factors for dark sector physics: trigger, high backgrounds, precise knowledge of acceptance/vetoes, PID

Dark Higgsstrahlung: $e^+e^- \rightarrow A'h'$

New 2022

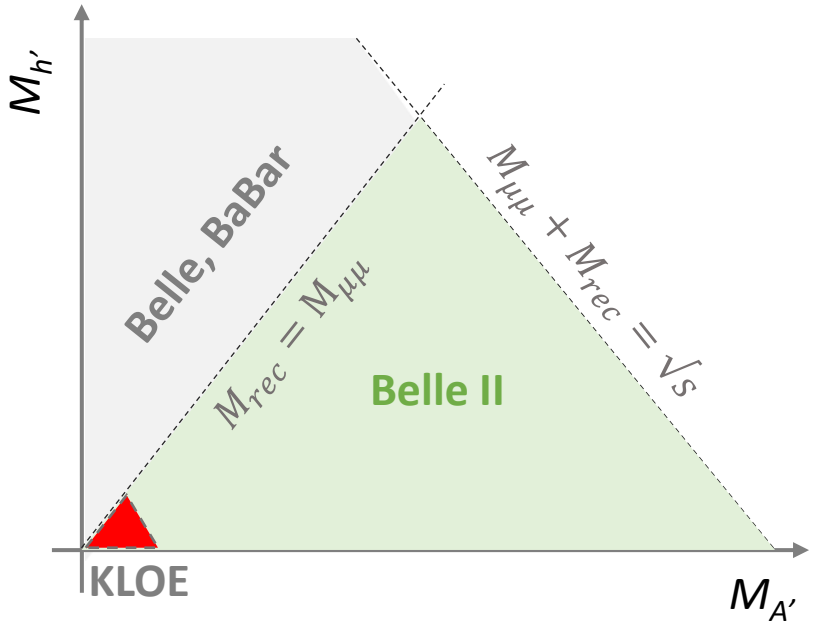
- U(1)' vector portal extension of SM → Phys. Rev D79, 115008 (2009)
  - dark photon A'
    - couples with kinetic mixing ε to SM
  - dark Higgs h'
    - gives mass to A' through SSB
    - no mixing of h' with SM Higgs
    - couples with α_D



$e^+e^- \rightarrow \mu^+\mu^-$ + *missing energy*

Vector portal

- Mass hierarchy scenarios
  - $M_{h'} > M_{A'}$
    - $h' \rightarrow A'A'$, $e^+e^- \rightarrow A'A'A'$
    - probed by Babar and Belle
  - $M_{h'} < M_{A'}$ **this search**
    - Invisible h' (long-lived), mising energy
    - 2d peak in $M_{\mu\mu}$ and M_{recoil}
    - Probed by KLOE
    - Largely unconstrained

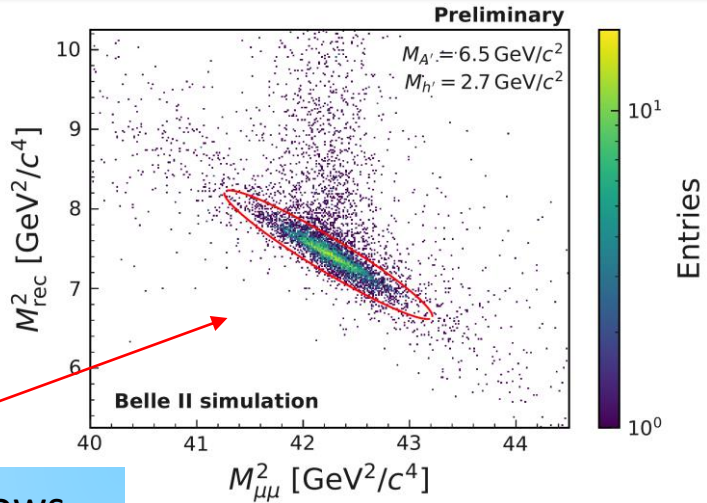


Dark Higgsstrahlung: analysis

New 2022

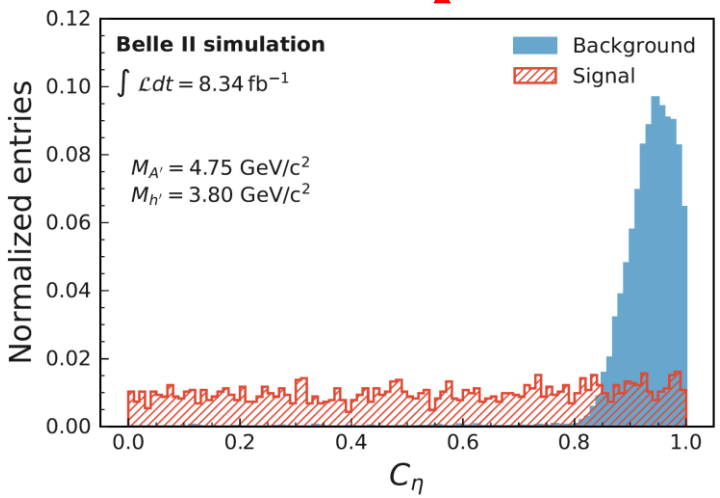
8.34 fb^{-1} (2019)

Two-track trigger
Two muons, $p_T^{\mu\mu} > 0.1$ GeV/c
Recoil points to barrel ECL
No extraenergy
Scan M_{recoil} vs $M_{\mu\mu}$



~9000 overlapping elliptical mass windows

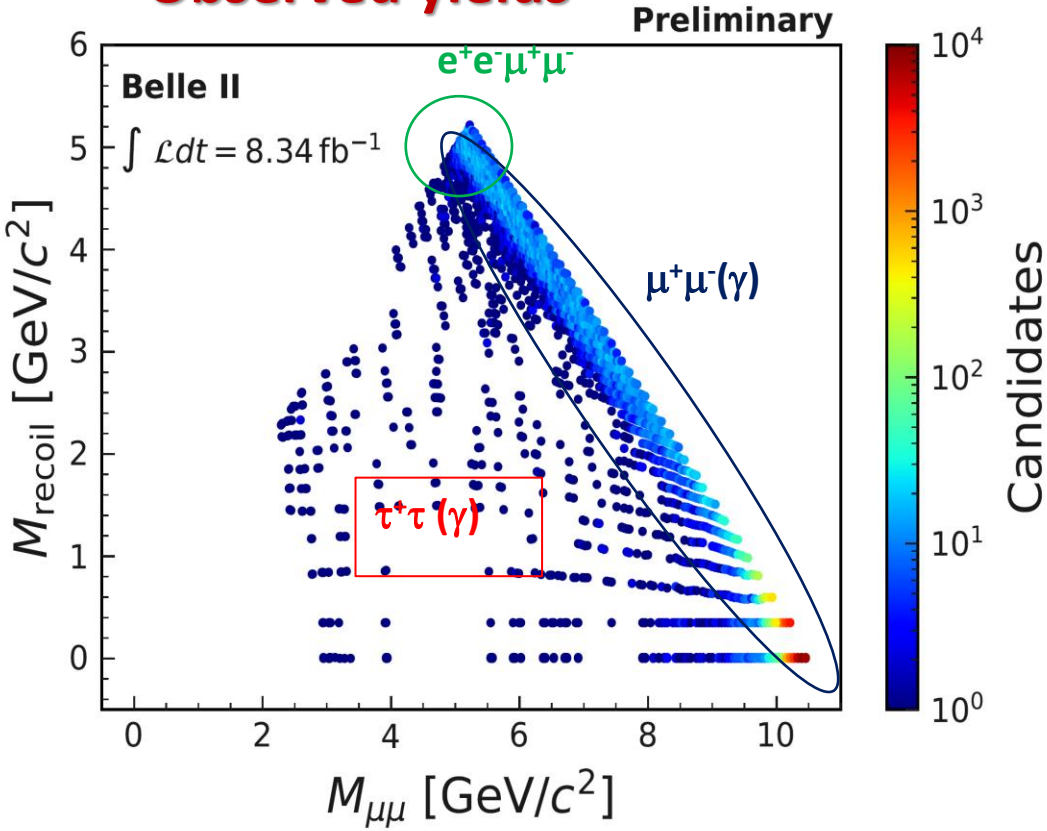
Helicity angle



Backgrounds

$\mu^+\mu^-(\gamma)$ 79%
$\tau^+\tau(\gamma)$ 18%
$e^+e^-\mu^+\mu^-$ 3%

Observed yields

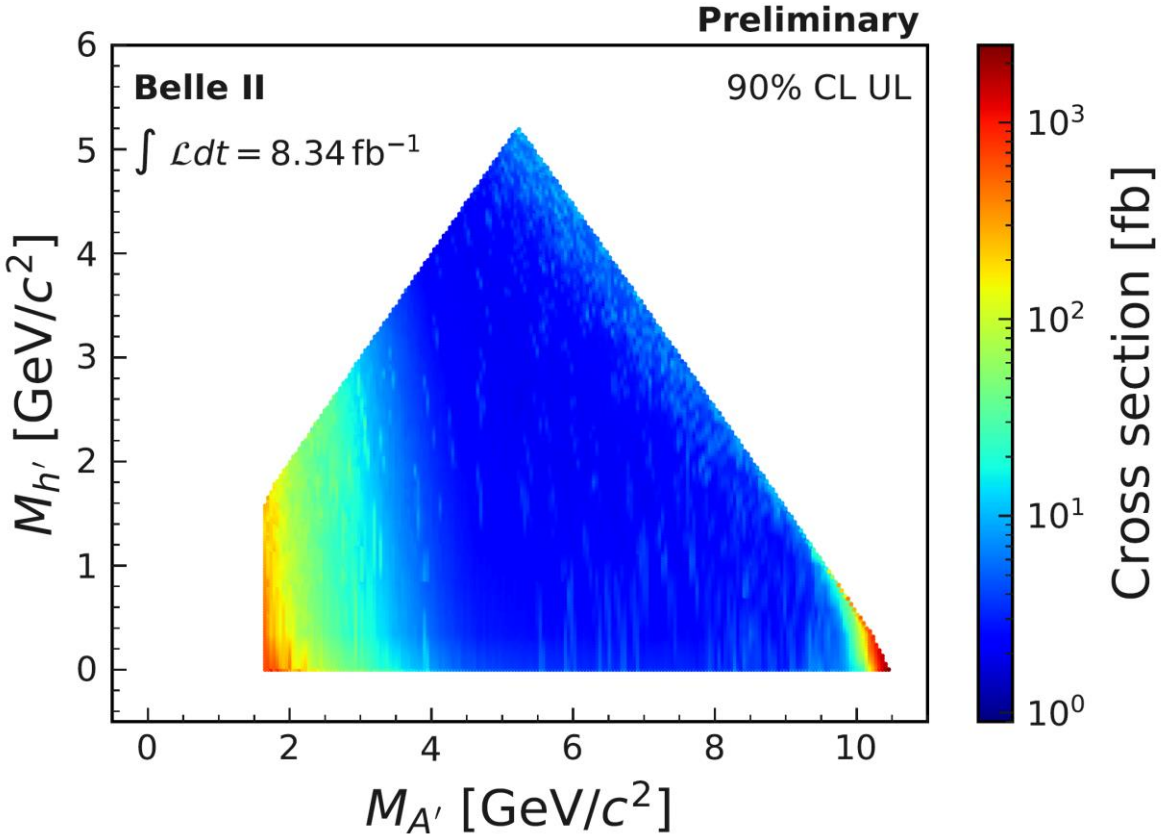


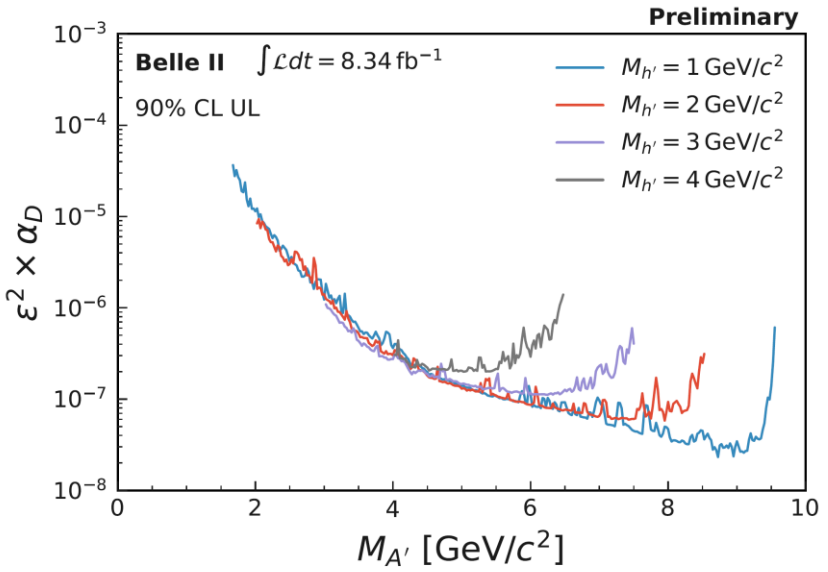
Dark Higgsstrahlung: results

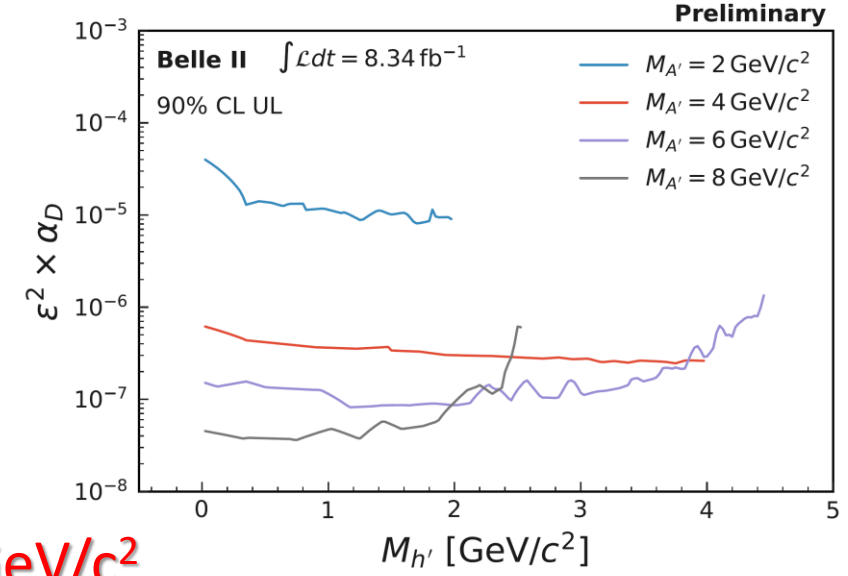
New 2022

No excess found
Upper limits on σ and $\varepsilon^2 \alpha_D$
most sensitive for $4 < M_{A'} < 9.7$ GeV/c^2

arXiv:2207.00509
submitted to PRL







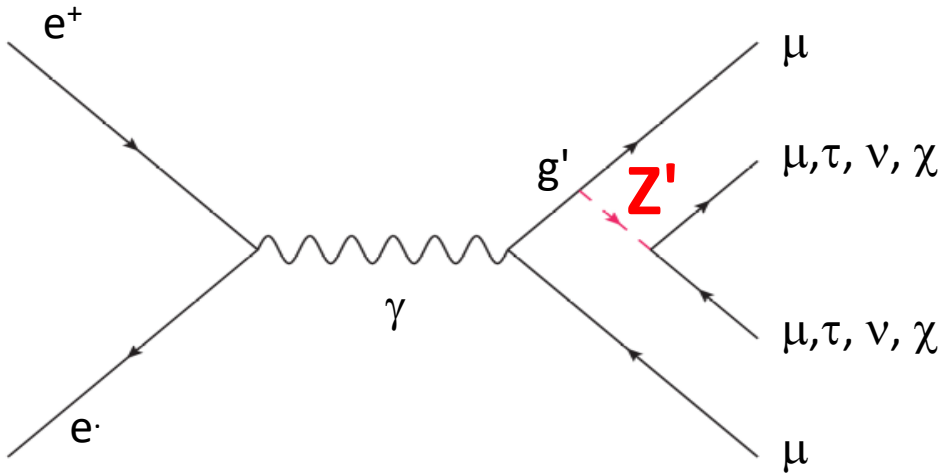
World first for $1.65 < M_{A'} < 10.51$ GeV/c^2

Z' L_μ - L_τ model

- Gauging L_μ - L_τ , the difference of leptonic μ and τ number
- A new gauge boson which couples only to the 2° and 3° lepton family
- Anomaly free (by construction)
- It may solve
  - **dark matter puzzle** → Sterile ν's / Light Dirac fermions
  - **$(g-2)_\mu$**
  - **$B \to K^{(*)}\mu\mu$, R_K, R_{K^*} anomalies**

Shuve et al. (2014), arXiv 1408.2727
Altmannshofer et al. (2016) arXiv 1609.04026

Vector portal



Z'→μμ → **BABAR**, **Belle**, **CMS** $Z^0 \to Z'\mu\mu$

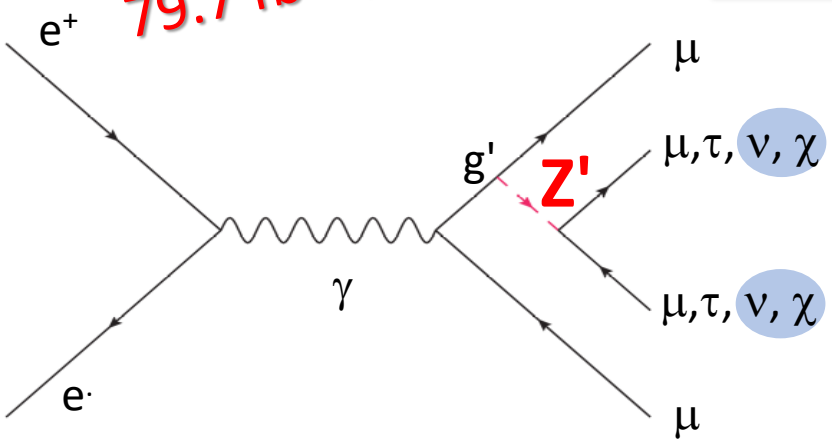
Z'→invisible → **Belle II 2020**, **Belle II** (new), **NA64-*e***

Z'→ττ → **Belle II** (new)

Z' to invisible: analysis

NEW

79.7 fb^{-1} (2019-2020)



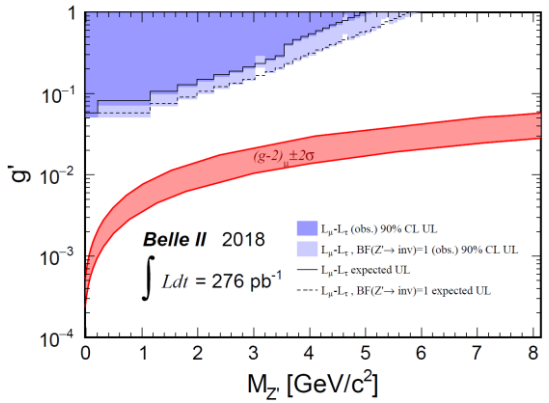
$e^+e^- \to \mu^+\mu^-$ + *missing energy*

Main backgrounds:

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

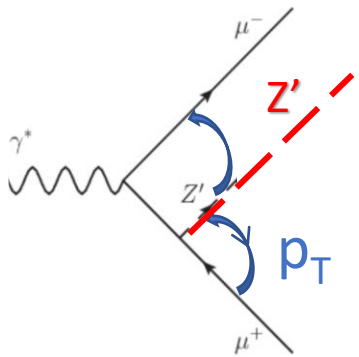
Old result

PRL 124 (2020), 141801



Look for bumps in recoil mass against a $\mu^+\mu^-$ pair

Two-track trigger
Two muons, $p_T^\mu > 0.4$ GeV/c
Recoil → barrel ECL $M_{recoil}<2$ GeV/c^2
No extraenergy, γ veto



FSR vs ISR + τ decay

NN trained to optimize Punzi FOM
Eur.Phys.J.C 82 (2022) 2, 121

Z' to invisible: analysis

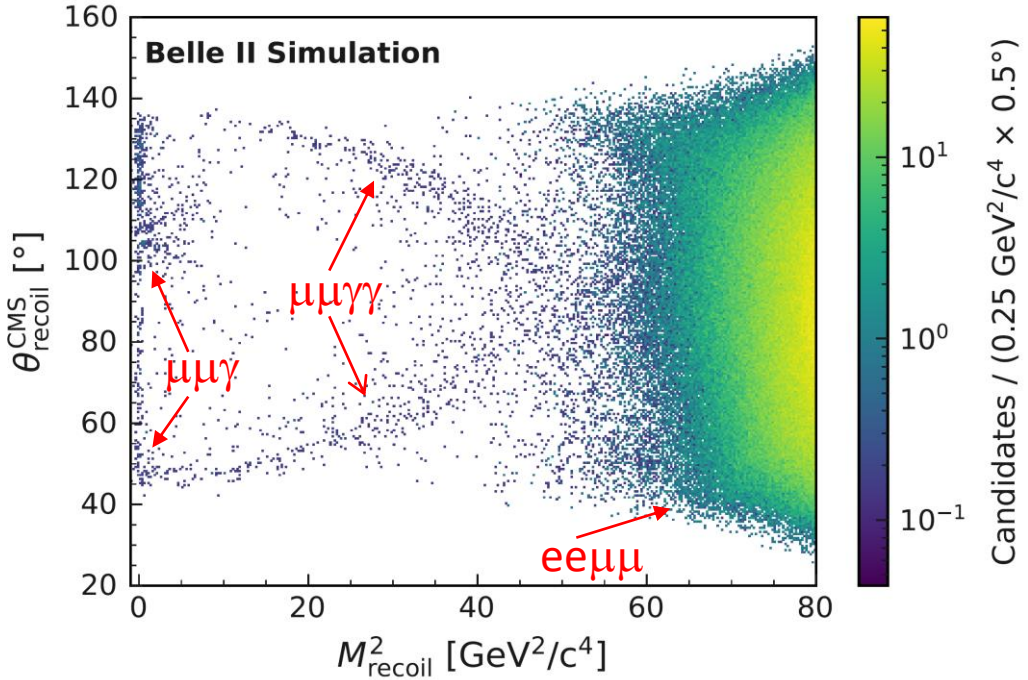
NEW

- $\tau^+\tau^-(\gamma)$ almost 100% suppressed
- $\mu^+\mu^-(\gamma)$ dominates up to ~7 GeV/c^2
- $e^+e^-\mu^+\mu^-$ dominates for high masses

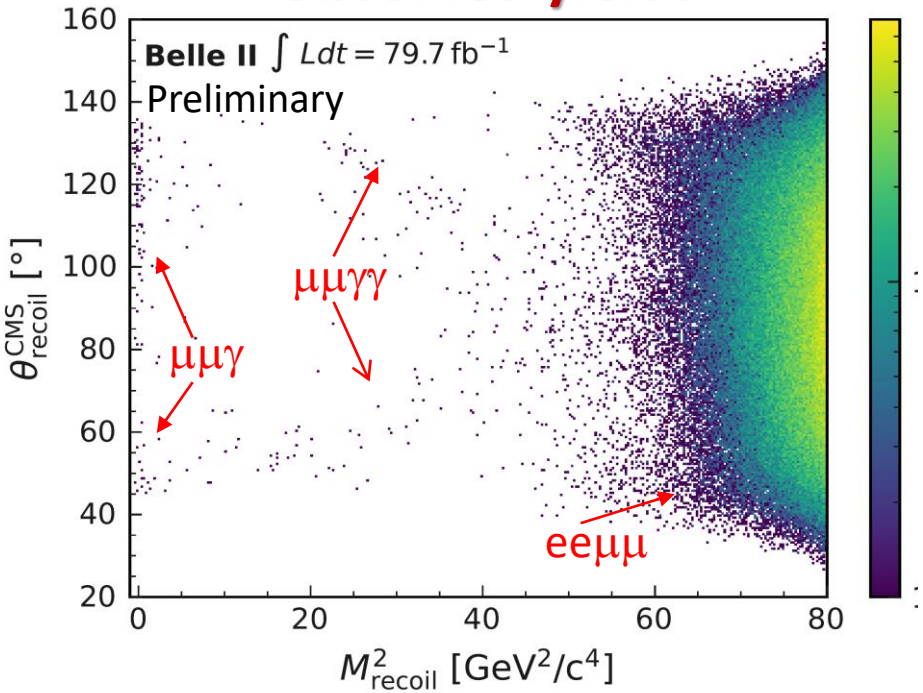
3 control samples

$\mu\mu\gamma$	selection+NN studies	low mass
$e\mu$	selection+NN studies	medium+high mass
$ee(\gamma)$	γ veto studies	

Look for bumps in θ_{recoil} vs M^2_{recoil}



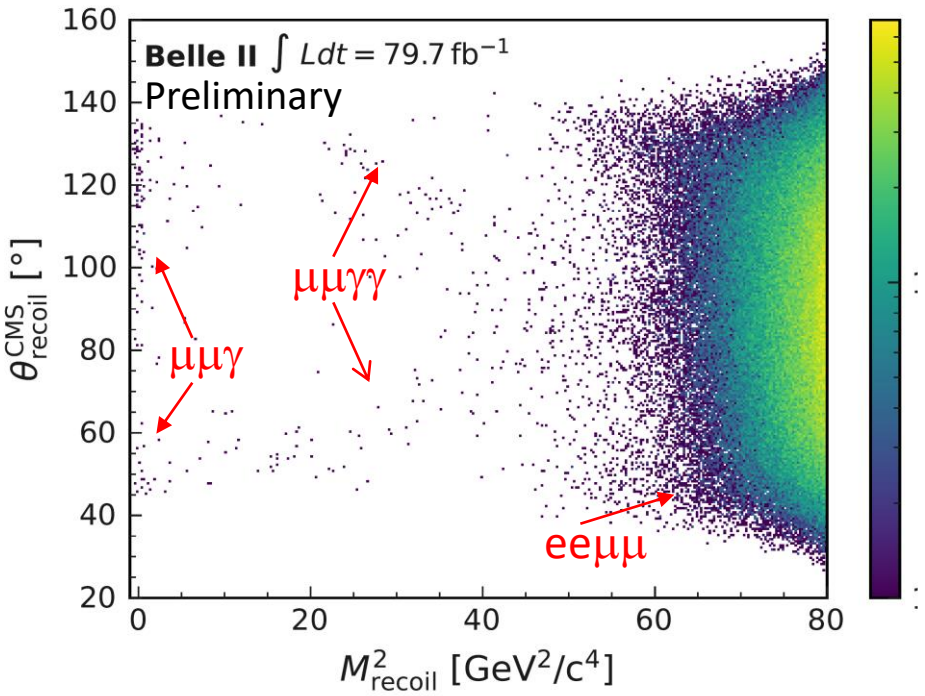
Observed yields

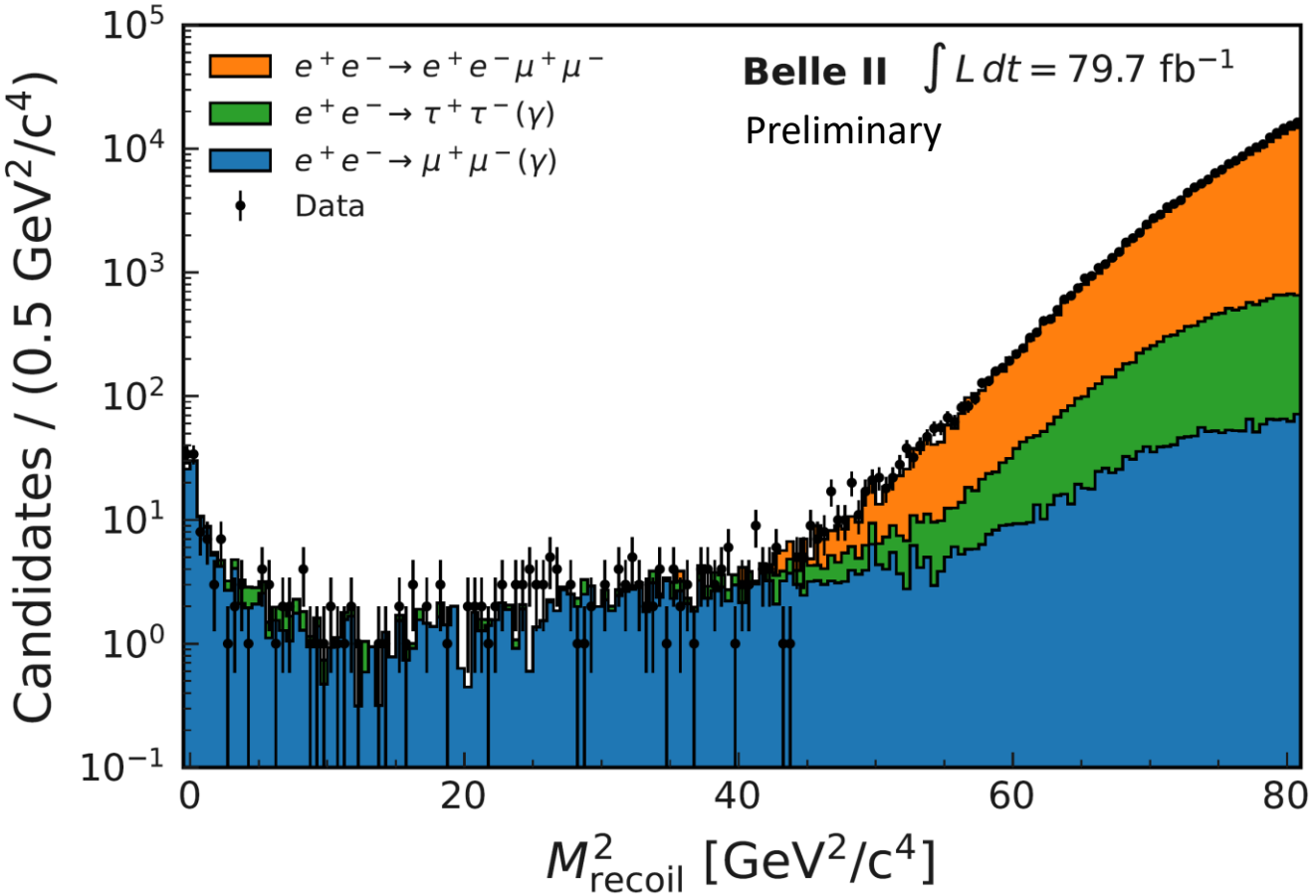


Z’ to invisible: observed yields

NEW

Look for bumps in θ_{recoil} vs M^2_{recoil}

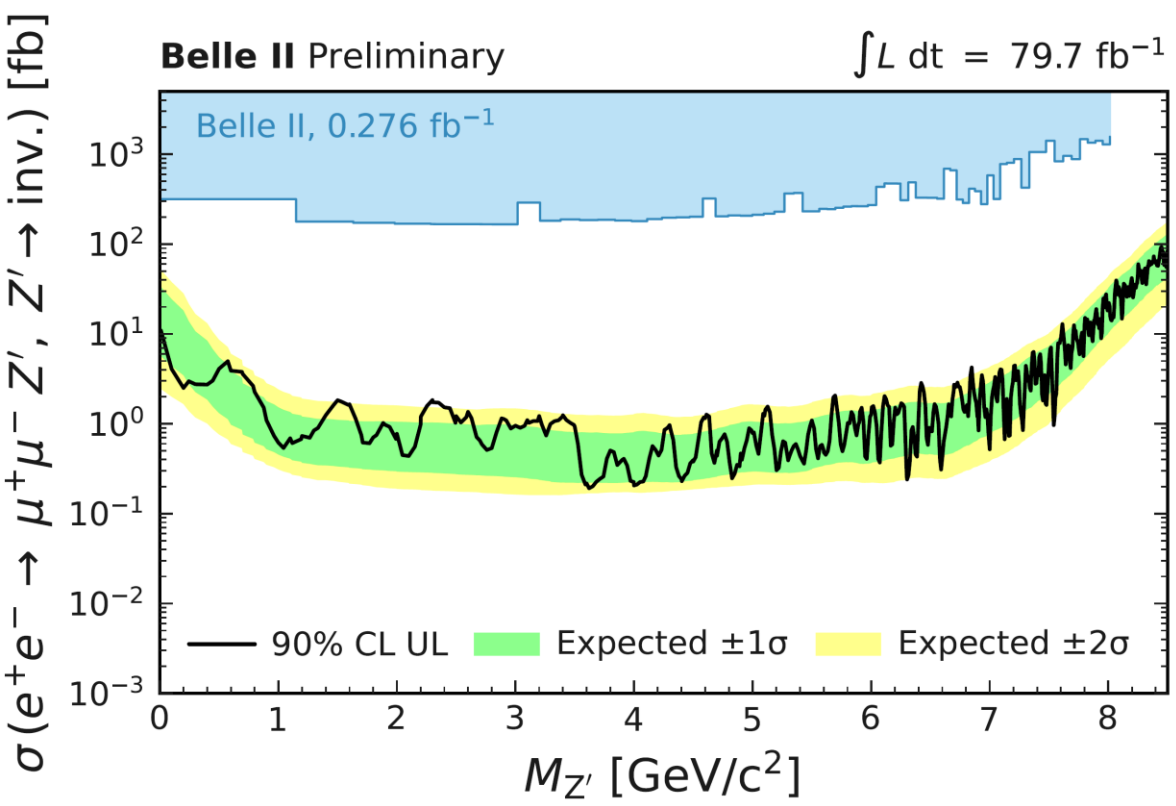


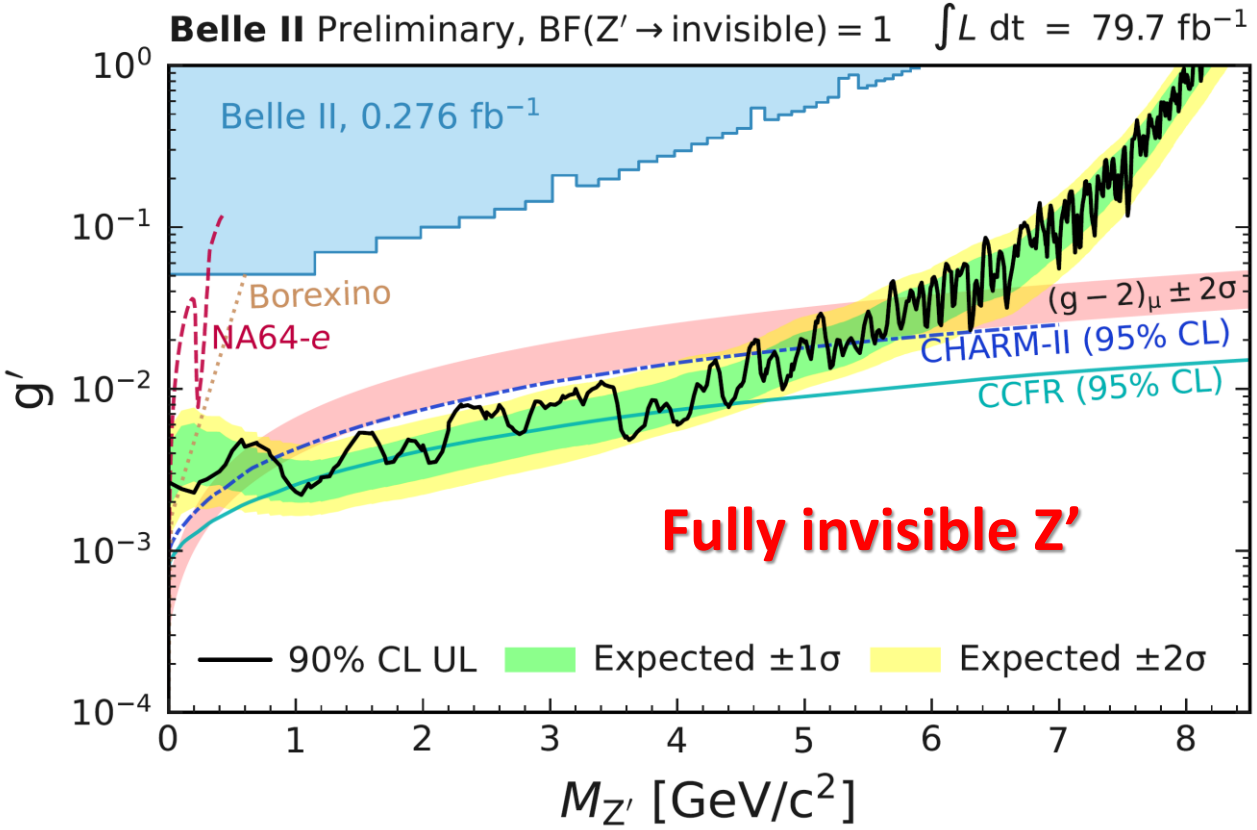


Z' to invisible: results

NEW

- No excess found
- Set 90%CL exclusion limits on cross section and coupling
  - Vanilla scenario: Z' decays to SM only
  - Fully invisible scenario

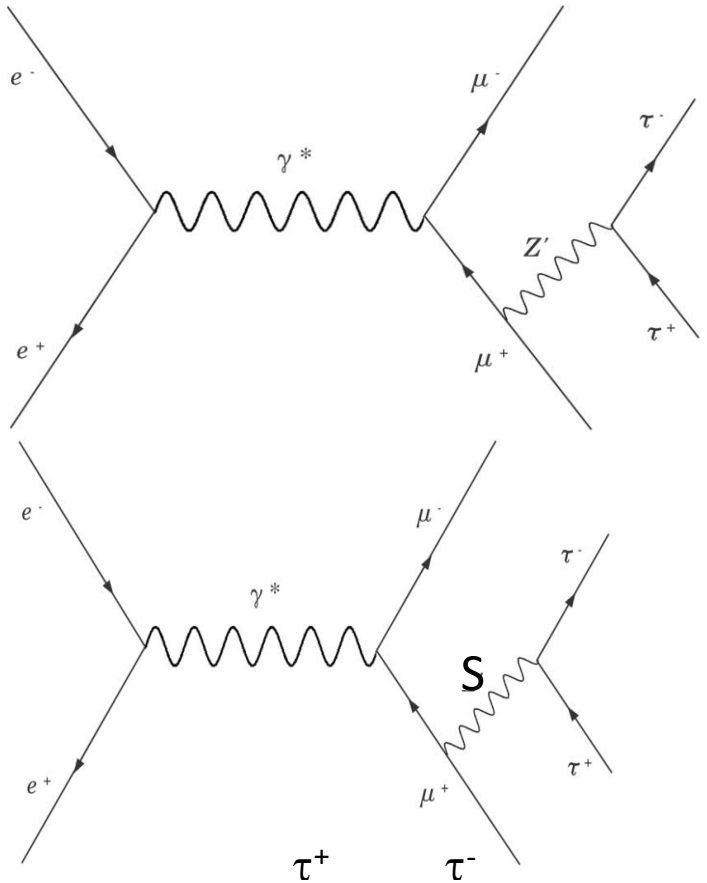




fully invisible Z' as origin of $(g-2)_\mu$ excluded for $0.8 < M_{Z'} < 5.0$ GeV/c^2

Z', S, ALP → ττ

NEW



Z' $L_\mu - L_\tau$ model

First time search in ττ

vector portal

Leptophilic scalar S model

Yukawa couplings

Contraints by BaBar in S→μμ

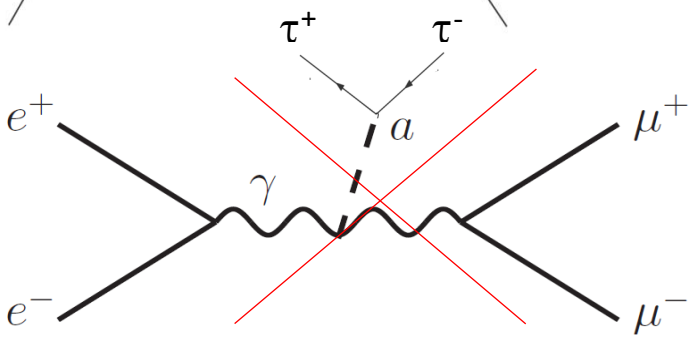
First time search in ττ

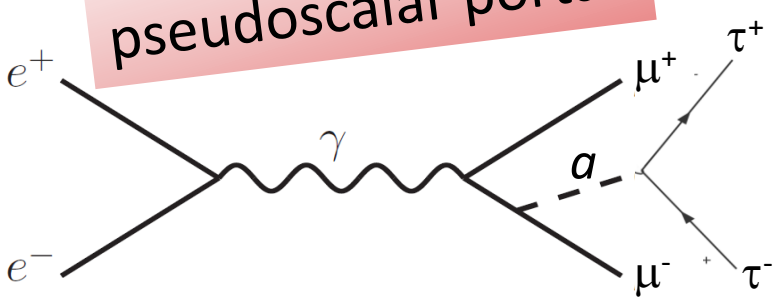
scalar portal

μμττ final states

$M_{Z',S,a} = M_{recoil}(\mu\mu)$

pseudoscalar portal





ALP → ττ

$C_{ee}=C_{\mu\mu}=C_{\tau\tau}$ $C_{\gamma\gamma}= C_{Z\gamma}=0$

Yukawa-like effective couplings

ALP-τ coupling unconstrained

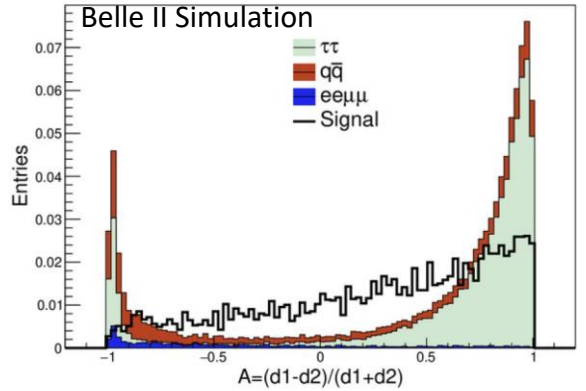
Z', S, ALP → ττ: analysis

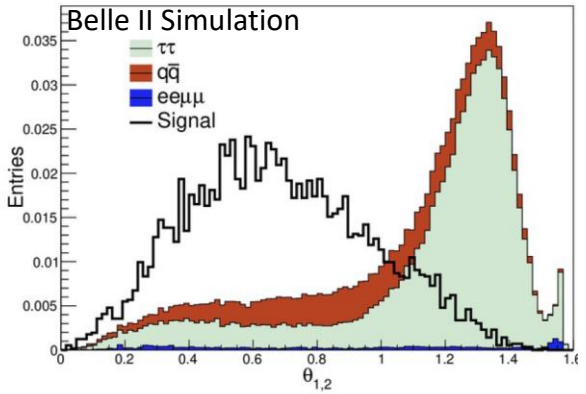
NEW

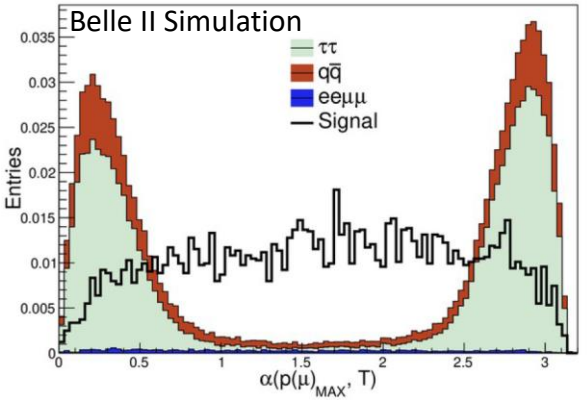
63.3 fb^{-1} (2019-2020)

3-track OR single muon trigger
1-prong τ decays (+ neutrals)
4-tracks
2 μ + 2x e/μ/π
M(4-track) < 9.5 GeV/c^2
Scan M_{recoil} (μμ)

Background suppression
NN MLP (Multi Layer Perceptron)
8 MLP ranges in M_{recoil} (μμ)
- resonance vs μμ
- FSR production
- ττ system







Optimize selections for Z' → ττ
99% background reduction

Control sample
2 π + 2x e/μ/π

Main backgrounds

$e^+e^- \to \tau^+\tau^-$ (γ) 1+3 prong
$e^+e^- \to qq$ (q=u,d,s,c)

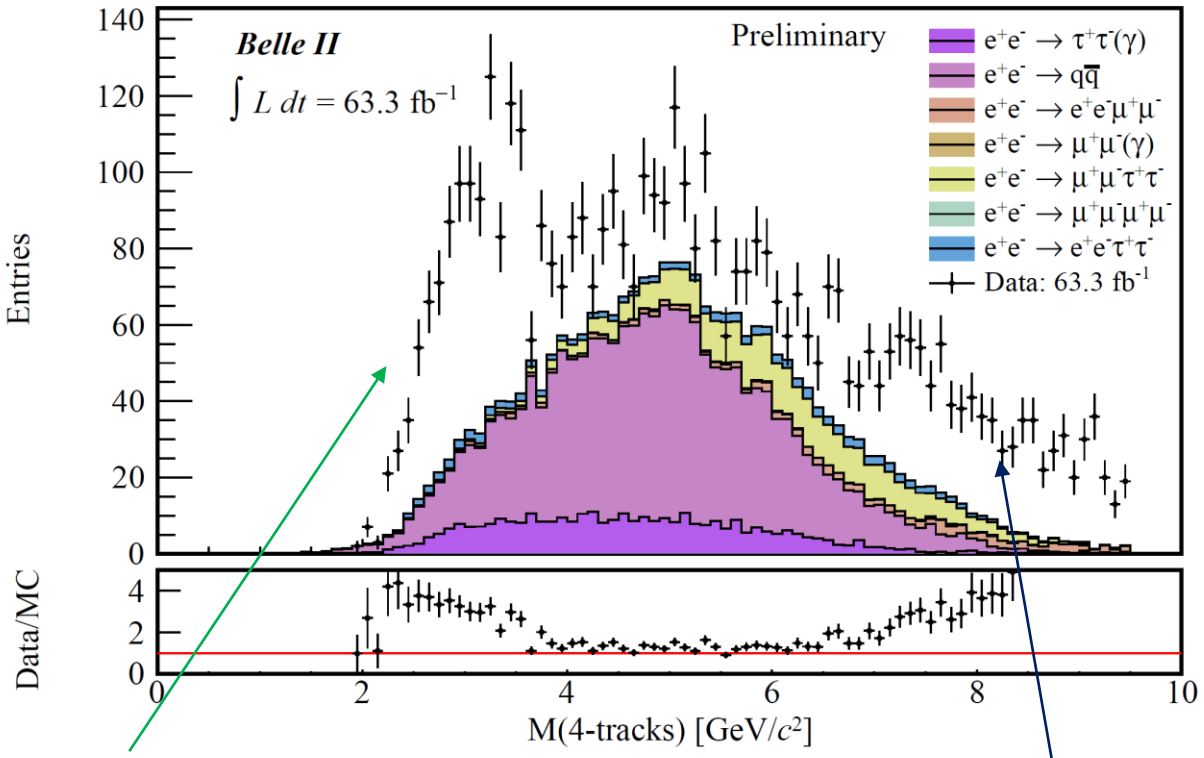
no ISR in simulation:
$e^+e^- \to e^+e^-\mu^+\mu^-$
$e^+e^- \to \mu^+\mu^-\tau^+\tau^-$
$e^+e^- \to e^+e^-\tau^+\tau^-$

$e^+e^- \to \mu^+\mu^-\pi^+\pi^-$ not simulated

$e^+e^- \to e^+e^- X_{hadronic}$ not simulated

Z', S, ALP → ττ: observed yields

NEW

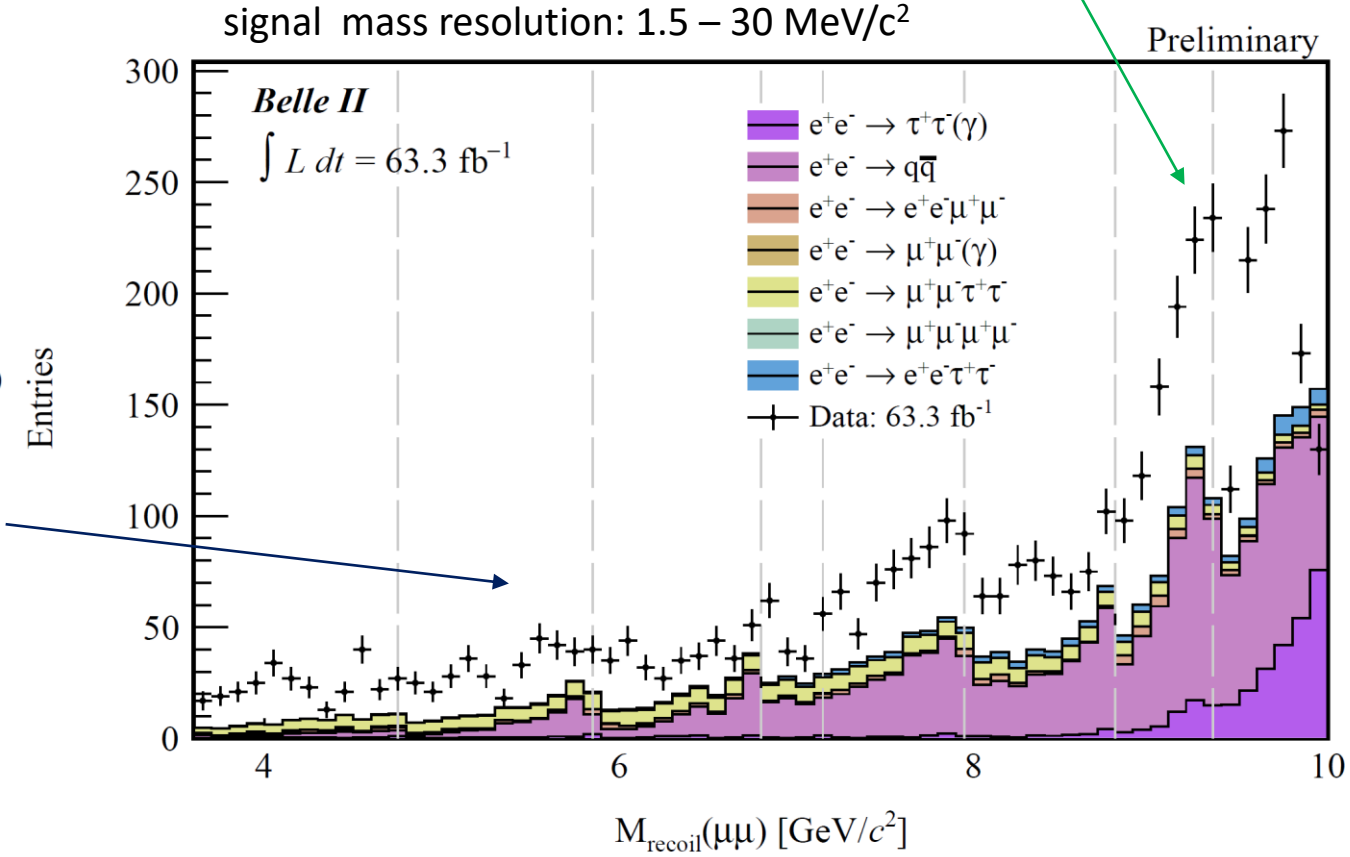


$e^+e^- \to e^+e^- X_{hadronic}$

Missing ISR

$e^+e^- \to e^+e^- X_{hadronic}$

signal mass resolution: 1.5 – 30 MeV/c^2



Discrepancies expected and understood

Non-peaking in M_{recoil} ($\mu\mu$)

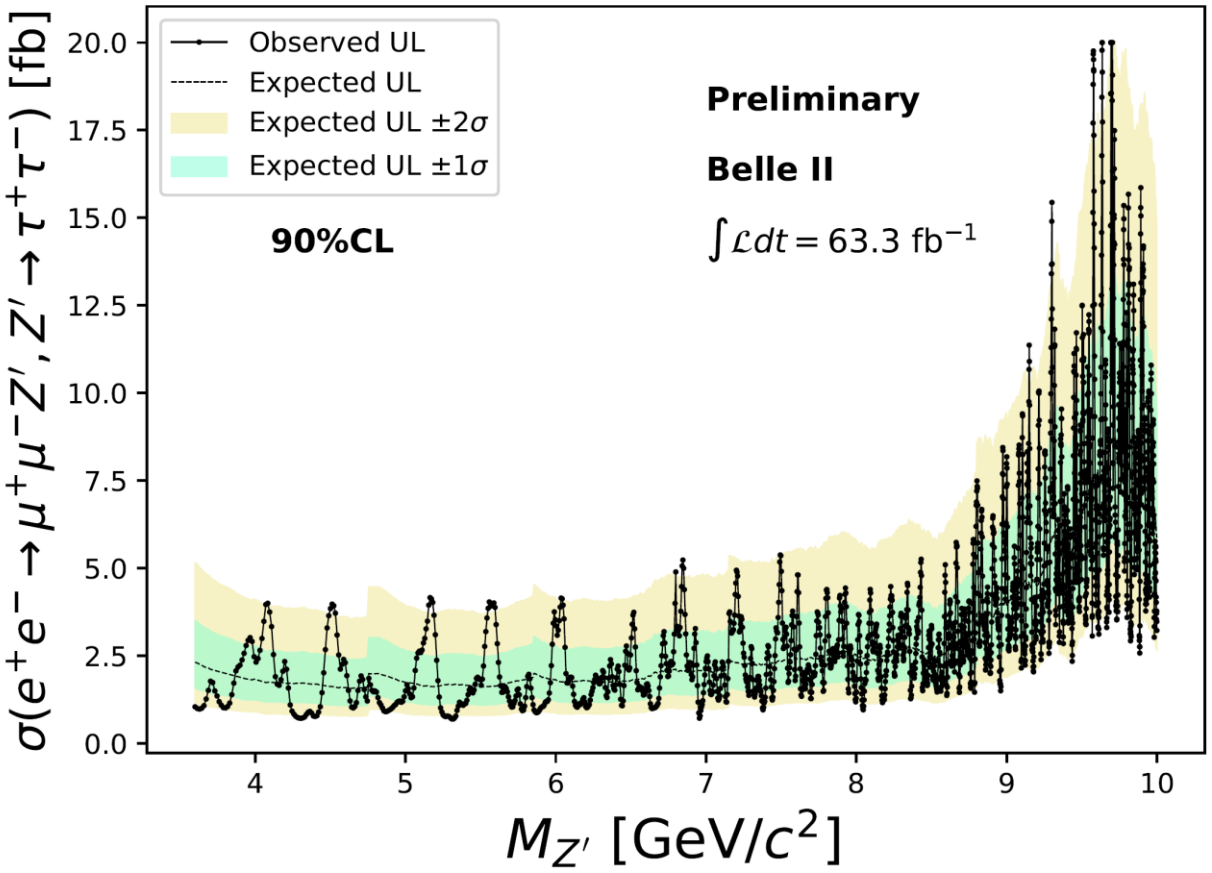
- signal mass resolution: 1.5 – 30 MeV/c^2

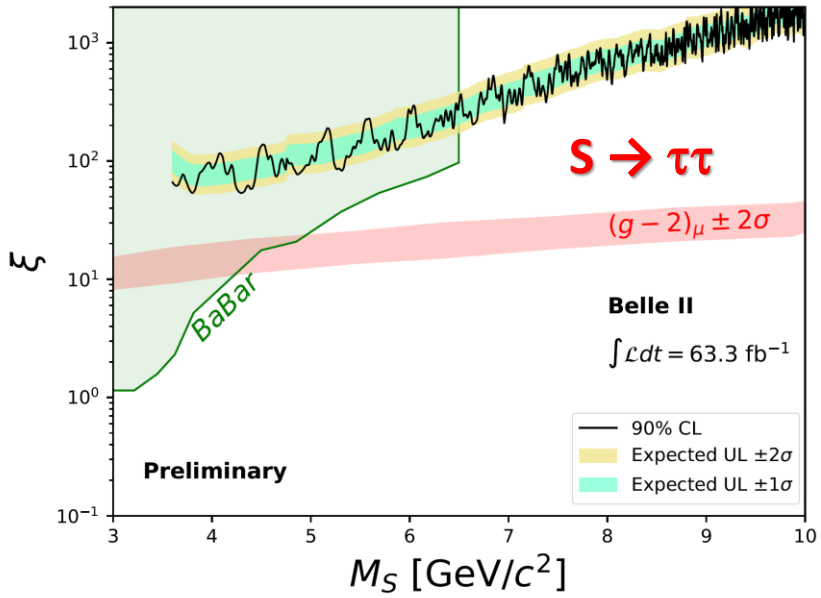
Background floated in the fit

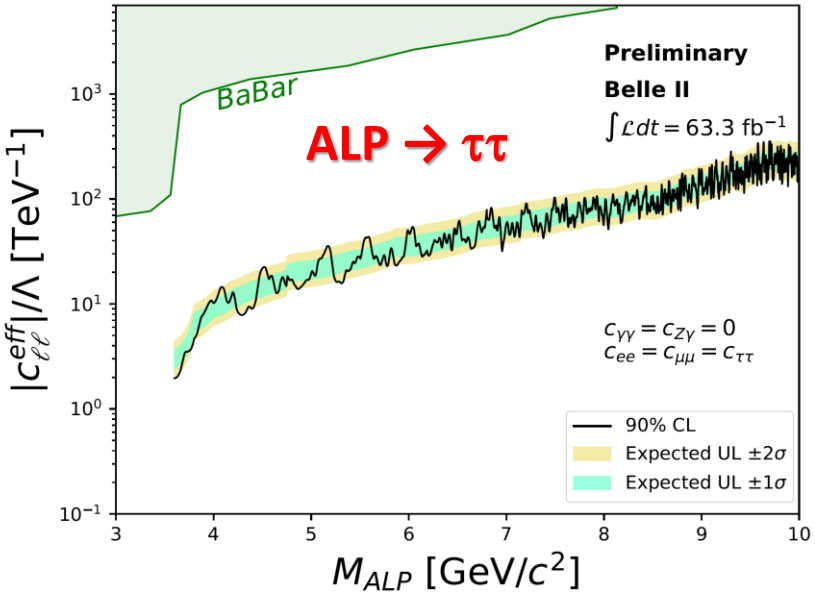
Z', S, ALP → ττ: results

NEW

- No excess found
- Set 90%CL exclusion limits on cross section and couplings
  - First constraints on S for $M_S > 6.5$ GeV/c^2
  - First direct constraints for ALP → ττ







Summary

- Negative results from LHC and direct search experiments → light dark sector scenario more and more attractive
- Belle II at SuperKEKB has great potential thank's to low-background collisions, hermeticity, dedicated triggers
- Belle II had two results with 2018 pilot run dataset: invisible Z' and ALP → $\gamma\gamma$
- **Belle II** started the physics run in 2019: 424 fb^{-1} collected up to now
- **Today @ ICHEP 2022 :** World-leading results for searches of:
  - Dark Higgsstralung $e^+e^- \rightarrow A'h'$, with $A' \rightarrow \mu\mu$ and h' invisible
  - Invisible Z' within the L_μ-L_τ model
  - $Z' \rightarrow \tau\tau$ within the L_μ-L_τ model
  - Leptophilic dark scalar S $\rightarrow \tau\tau$
  - Axion-like-particle a $\rightarrow \tau\tau$
- We expect to lead the light dark sector searches in the next decade

SPARE SLIDES

From KEKB to SuperKEKB

- New e^+ Damping Ring
- New Superconducting Final Focus (QCS)

Lorentz factor

Beam current

Beam-beam parameter

$$\xi_{y\pm} = \frac{r_e}{2\pi\gamma_\pm}\frac{N_\mp \beta_y^*}{\sigma_y^*(\sigma_x^* + \sigma_y^*)} R_{\xi_{y\pm}} \propto \frac{N_\mp}{\sigma_x^*}\sqrt{\frac{\beta_y^*}{\varepsilon_y}},$$

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

Classical electron radius

Beam size ratio@IP
1 ~ 2 % (flat beam)

Vertical beta function@IP

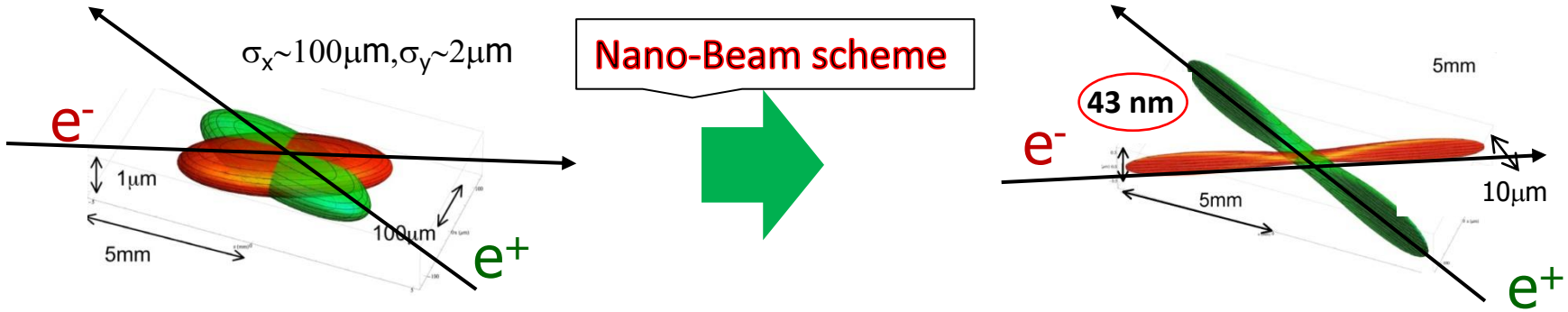
Lumi. reduction factor
(crossing angle)&
Tune shift reduction factor
(hour glass effect)
0.8 ~ 1
(short bunch)

x30

(1) Smaller β_y^*
(2) Increase beam currents
(3) Increase ξ_y

β^*_y=0.30/0.30 mm

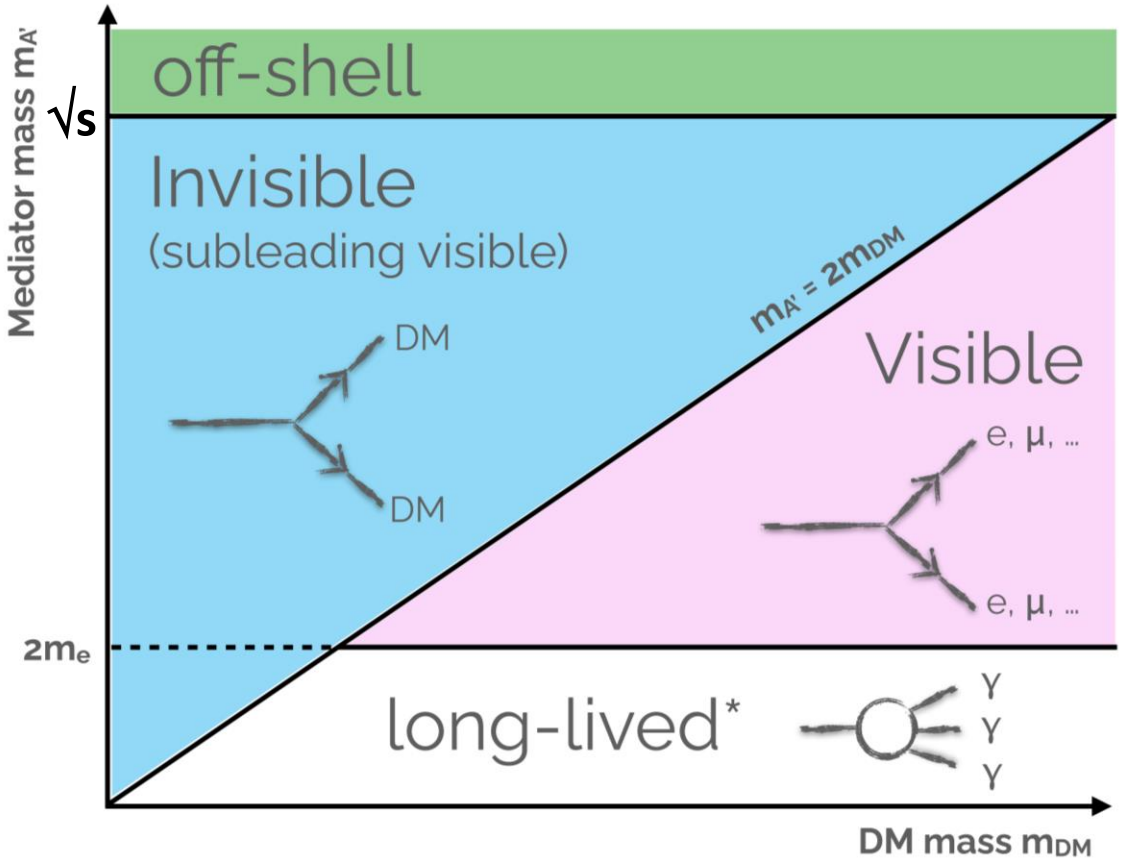
$I_{+/-}$=2.8/2.0 A



... For a 30x increase in intensity you have to make the beam as thin as a few x100 atomic layers

Light Dark matter hunt

Different signatures depending on the DM ↔ mediator mass relation

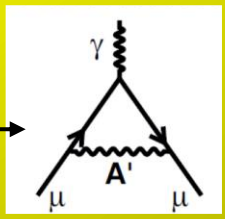


Probability of interaction of LDM detectors is negligible

- Search for mediators
- Search for missing energy signature
- Search for both

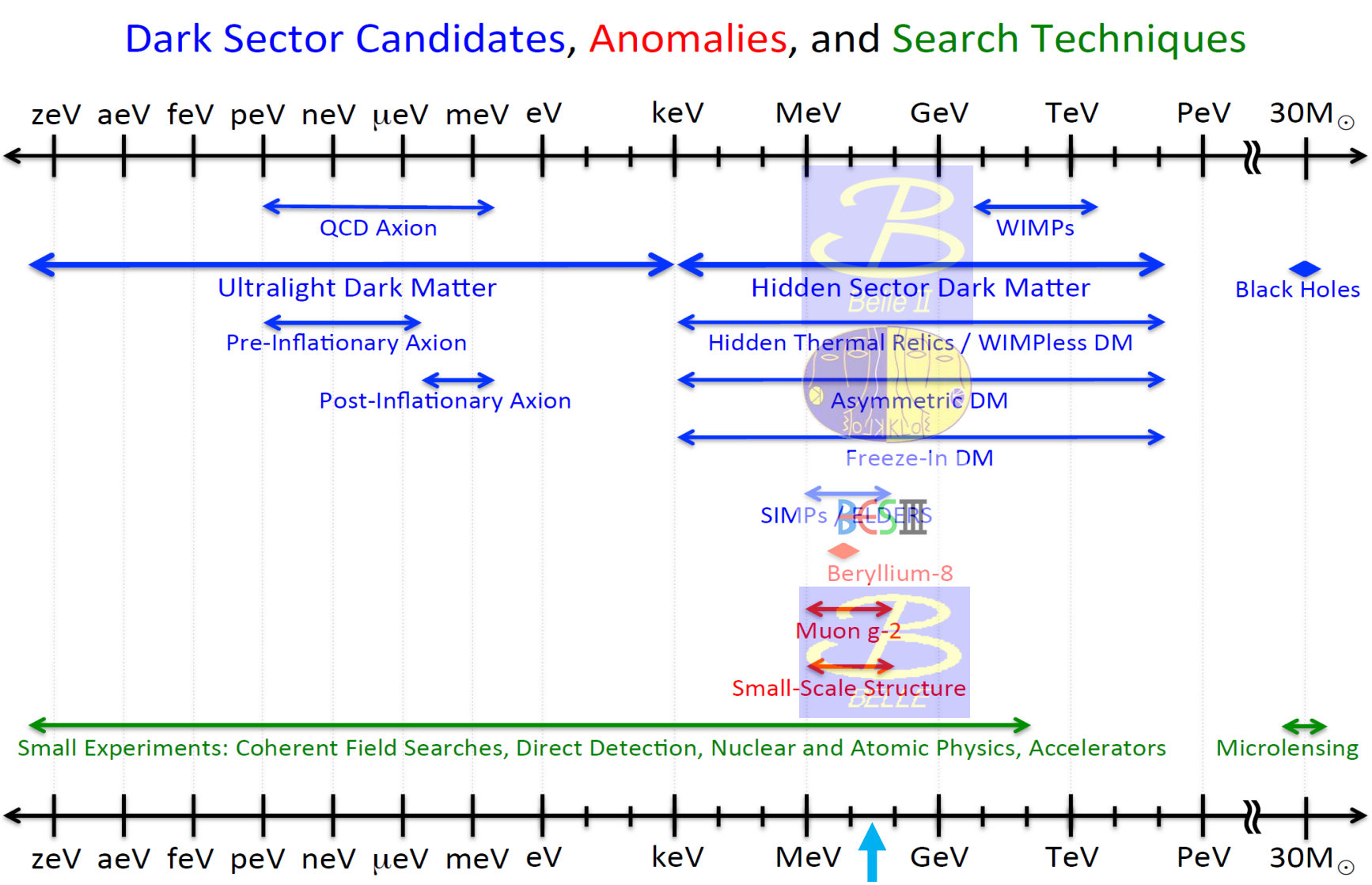
Additional benefits:

- Explanations of some astrophysics anomalies (PAMELA, AMS, FERMI, …)
- Explanation of the $(g-2)_\mu$ effect →



- Explanation (with additional hypotheses) of some flavour anomalies (LHCB, Belle, …)
- Some light mediators (not interacting with quarks) could escape direct search exclusion limits

Searching for dark matter



Dark matter/mediators

Vector portal

Dark photon, Z', …

Pseudoscalar portal

Axions, **ALPs**, …

Scalar portal

Dark Higgs, scalars

Neutrino portal

Sterile neutrino

Belle II trigger

Dark sector physics
- Low multiplicity signatures
- Huge backgrounds from beam, Bhabha, two-photon

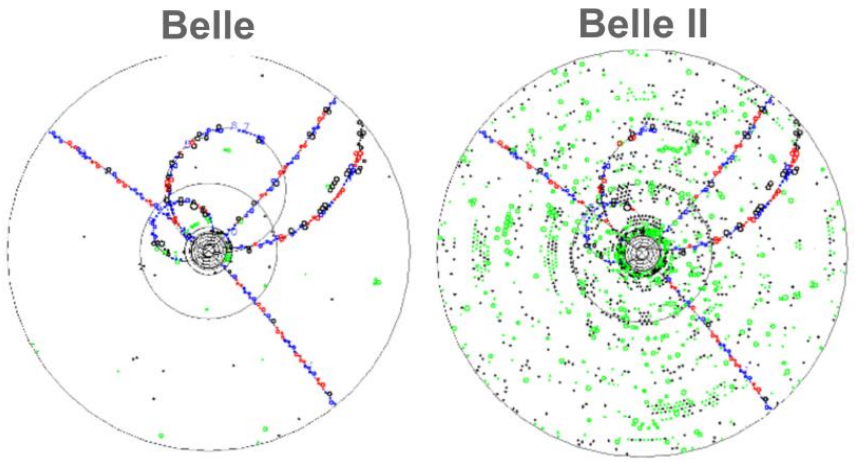
Level 1 hardware-based combines info from CDC, ECL, KLM
- Tracks, clusters, muons

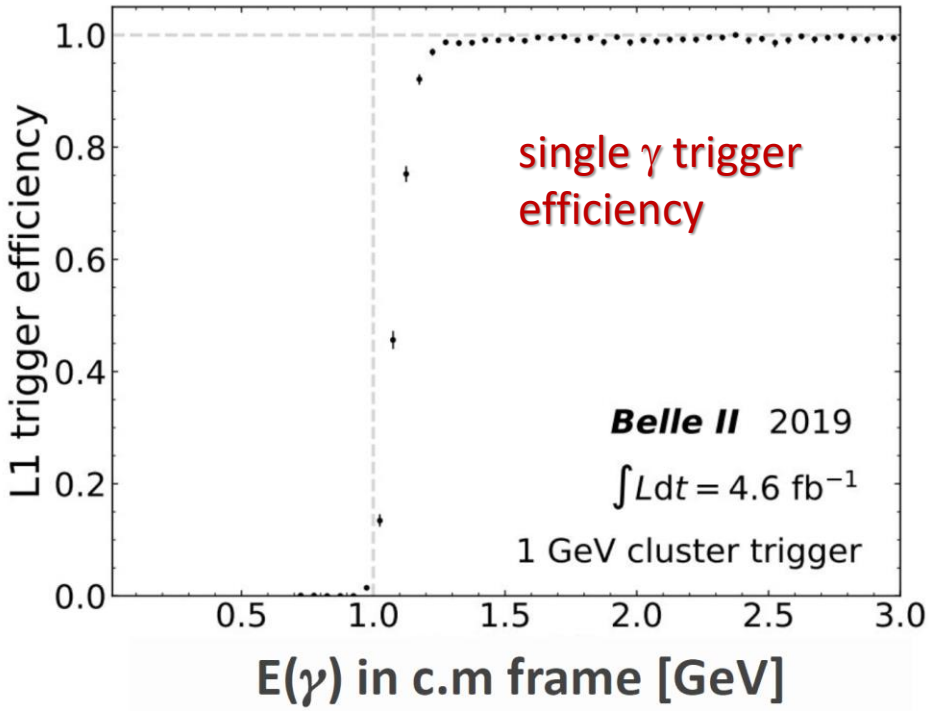
- Two-track trigger
- Three-track trigger
- E_{ECL}> 1 GeV trigger

Single muon
- CDC + KLM

Single track
- Neural based

Single photon
- E_γ > 0.5, 1, 2 GeV





Dark Higgsstrahlung: analysis

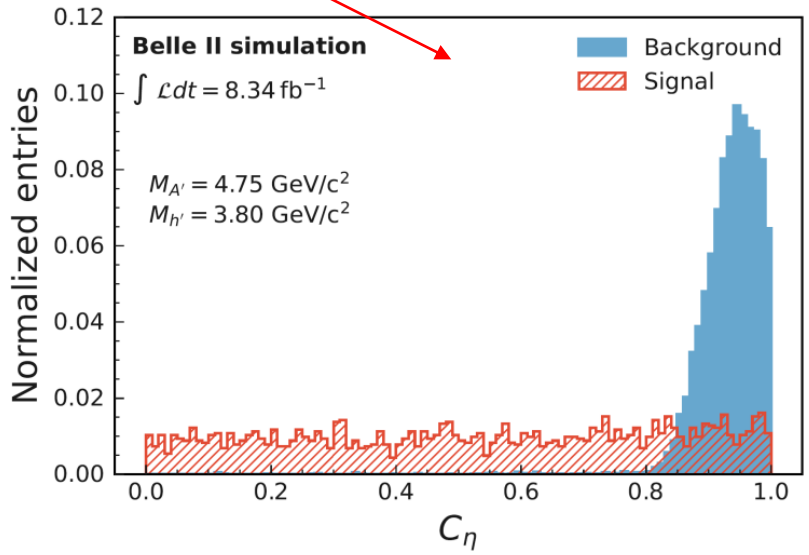
Moriond

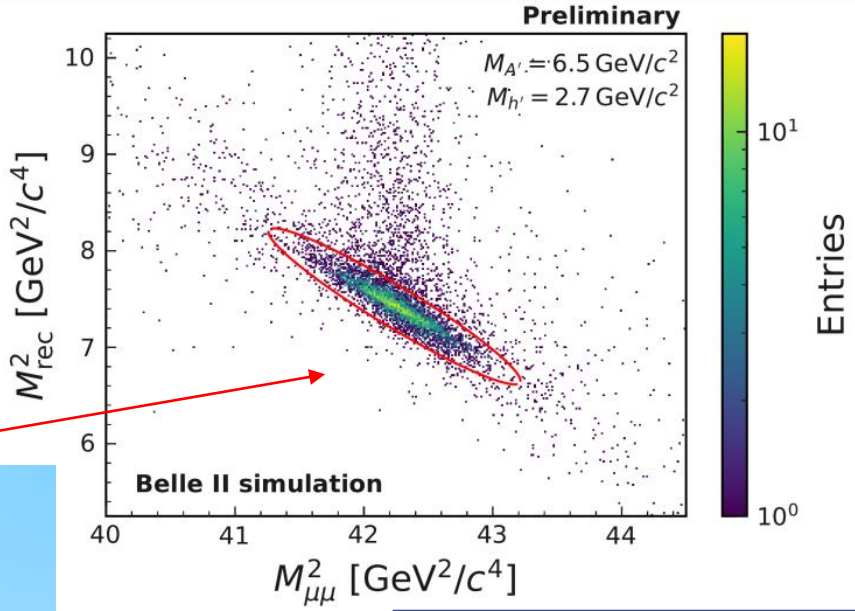
8.34 fb^{-1} (2019)

Two-track trigger
Two muons, $p_T^{\mu\mu} > 0.1$ GeV/c
Recoil points to barrel ECL
No extraenergy
Scan M_{recoil} vs $M_{\mu\mu}$

~9000 overlapping elliptical mass windows

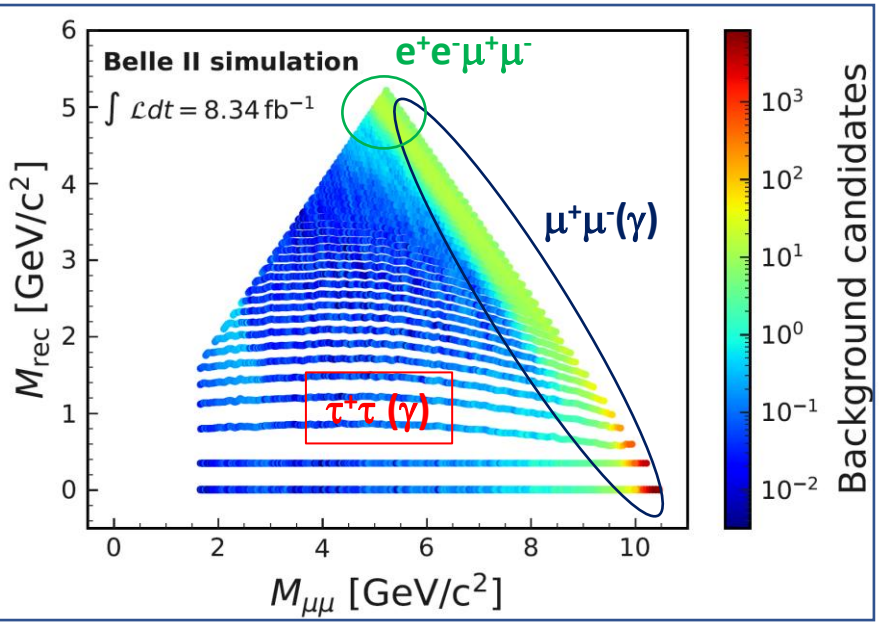
Helicity angle





Backgrounds

$\mu^+\mu^-(\gamma)$ 79%
$\tau^+\tau$ (γ) 18%
$e^+e^-\mu^+\mu^-$ 3%



Dark Higgsstrahlung: systematics

2 control samples

μμγ	μμ(γ) background
eμ	ττ background

Split mass plane into orthogonal macroregions

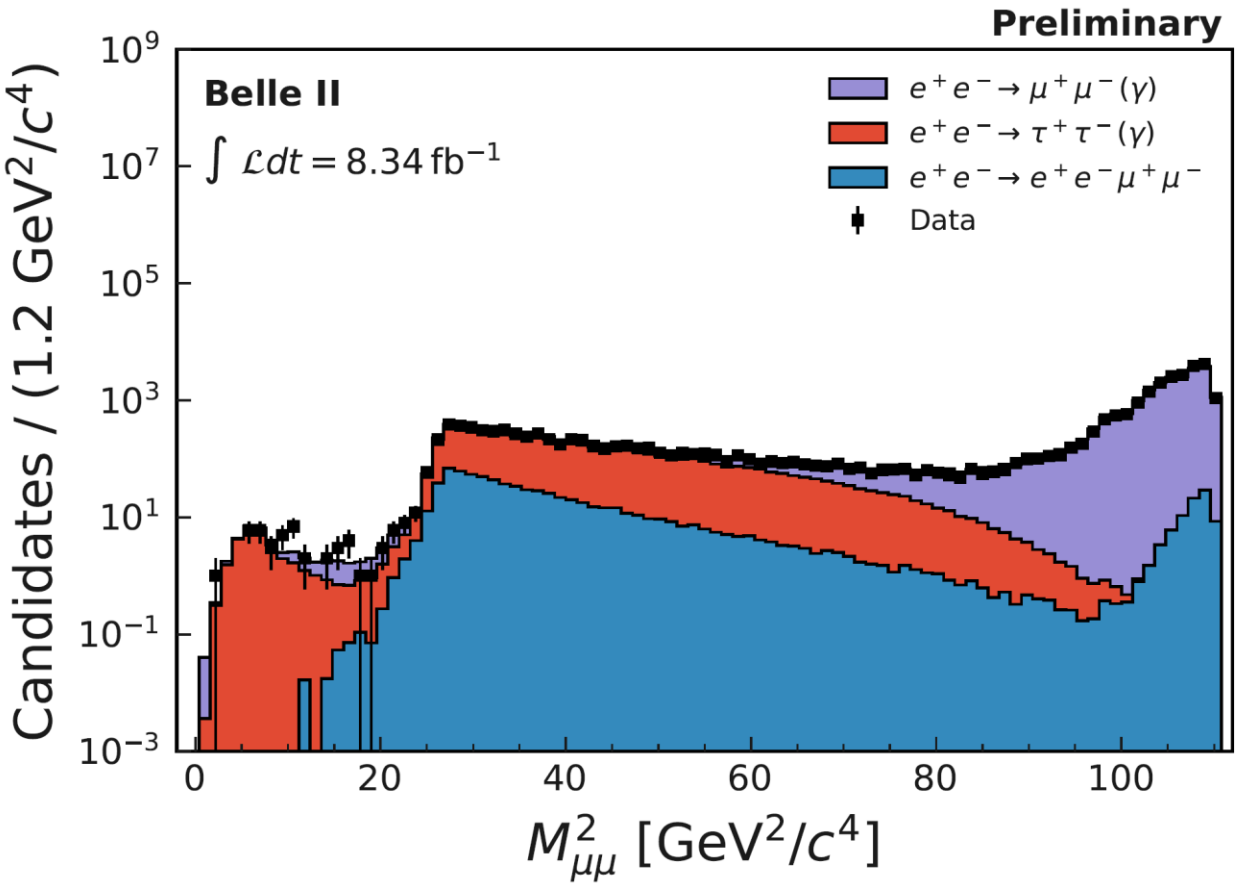
- Each dominated by a single background source
- Data/MC normalization + shape

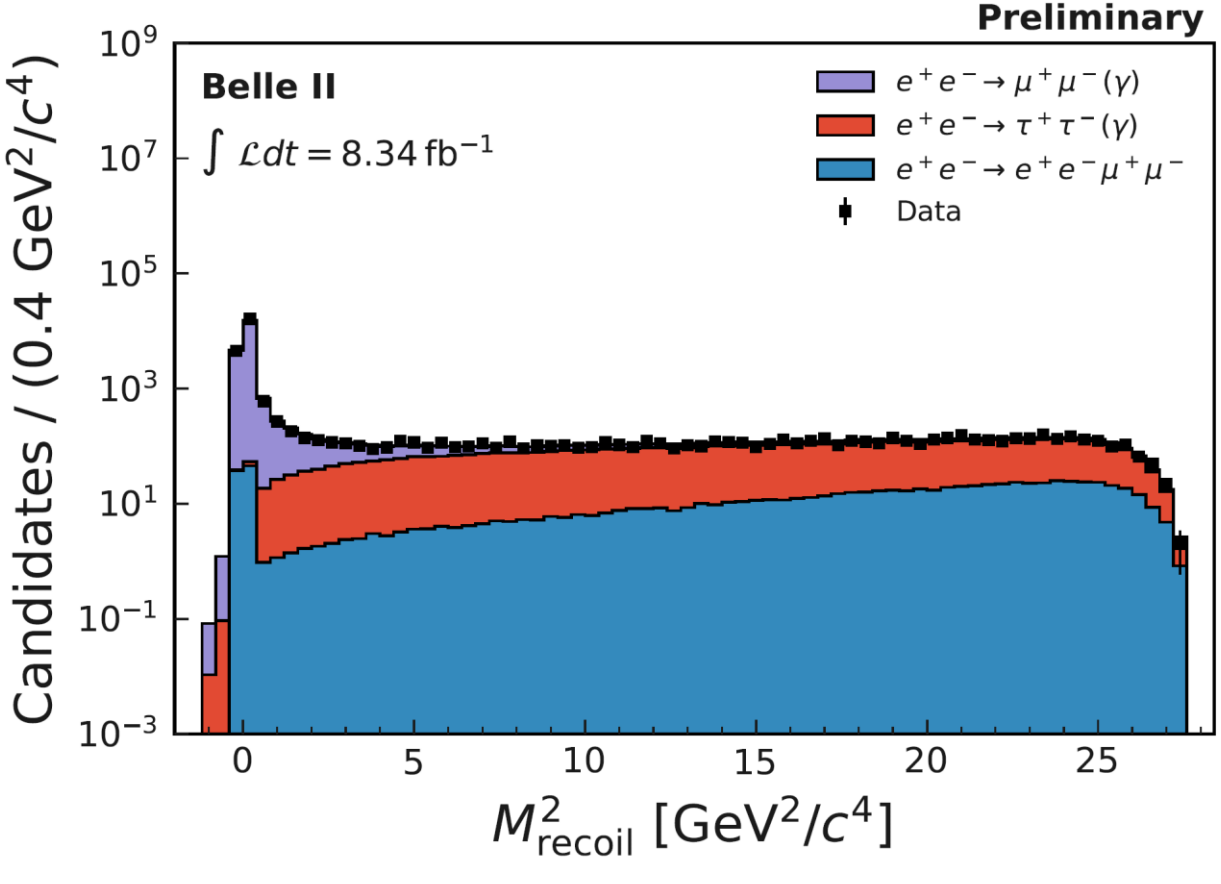
source	uncertainty	target
Pre-selections	**2 - 9.1%**	BKG & signal
BKG shape	**9.3%** (region specific)	BKG
C_η cut	**1%**	BKG
Mass resolution	**2.4%** (on average)	signal
Eff. Inside windows	**2 - 5%**	signal
Theory (BR A')	**4%**	signal

- Negligible effect on Uls (~1%)
- Exception is $M_{A'} > 9$ GeV/c^2 (~25%)

Dark Higgsstrahlung: data/MC

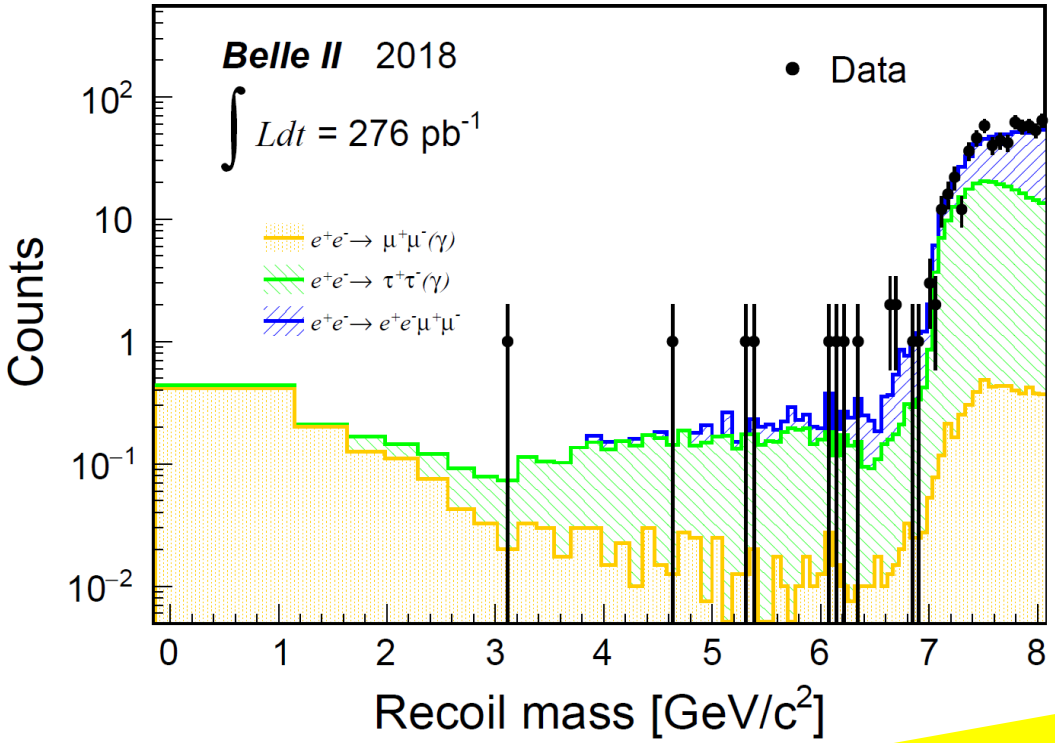
Moriond





Z’ to invisible: previous result

Pilot run physics results

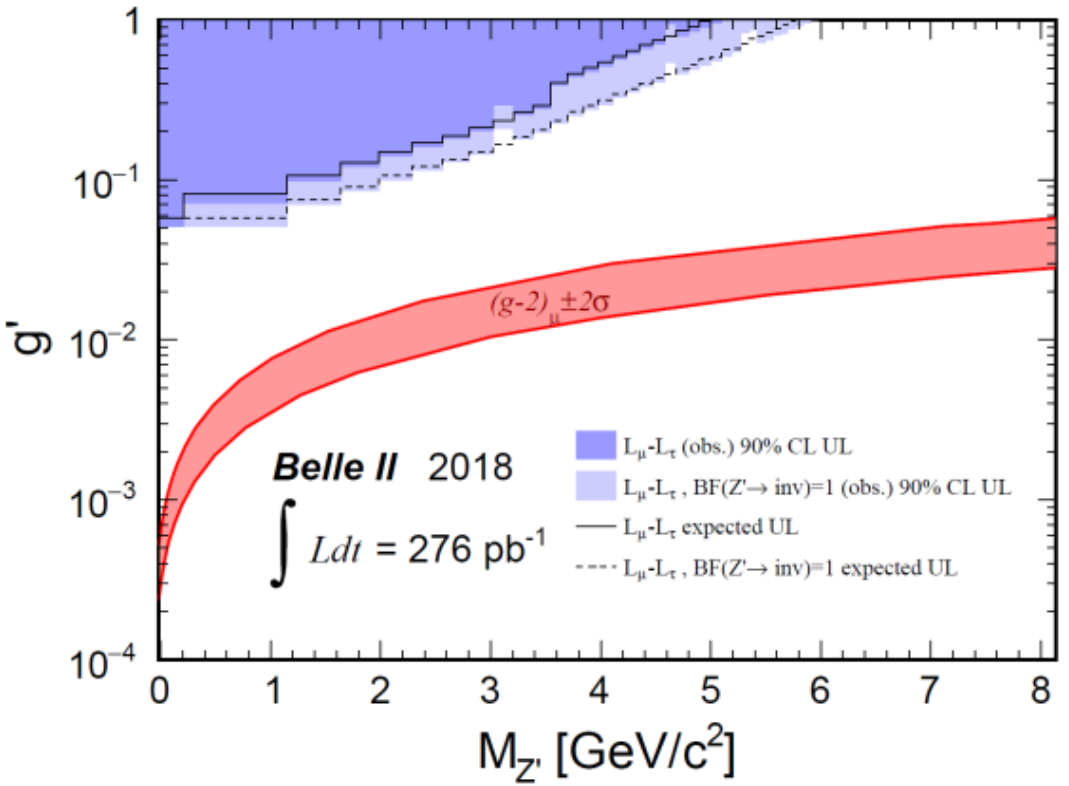


First physics paper by Belle II
PRL 124 (2020), 141801

Systematics

Source	Error
Trigger efficiency	6%
Tracking efficiency	4%
PID	4%
Luminosity	1.5%
Background before τ suppression	2%
τ suppression (background)	22%
Discrepancy in μμ yield (signal)	12.5%

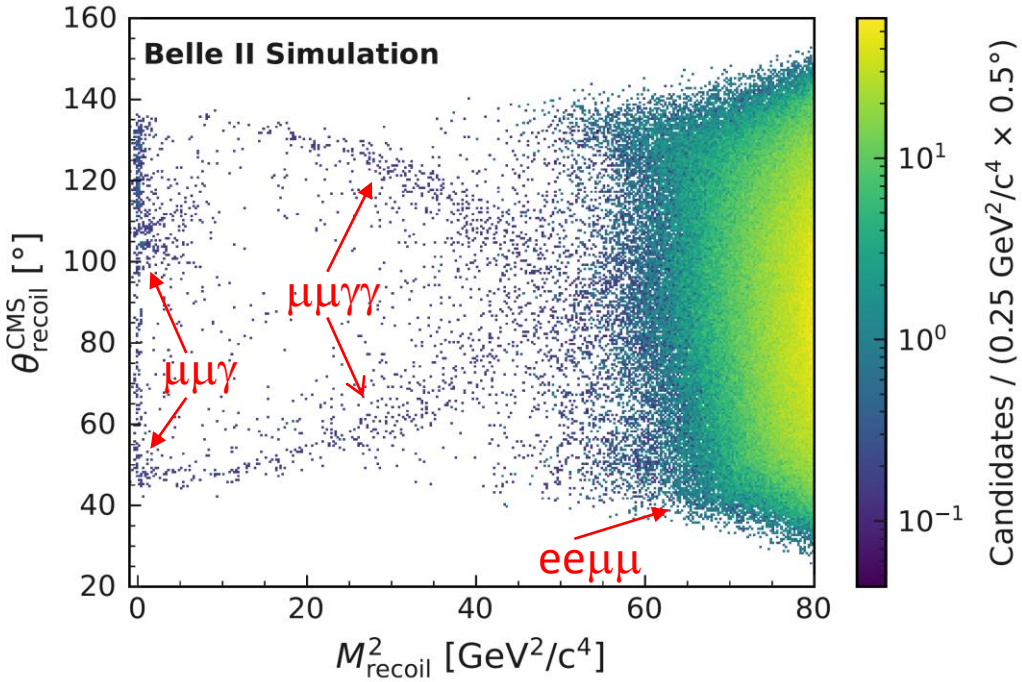
will decrease with new data



Z' to invisible: systematics

NEW

- $\tau^+\tau^-(\gamma)$ almost 100% suppressed
- $\mu^+\mu^-(\gamma)$ dominates up to ~7 GeV/c^2
- $e^+e^-\mu^+\mu^-$ dominates for high masses



Look for bumps in θ_{recoil} vs M^2_{recoil}

3 control samples

μμγ	selection+NN studies	low mass
eμ	selection+NN studies	medium+high mass
ee(γ)	γ veto studies	

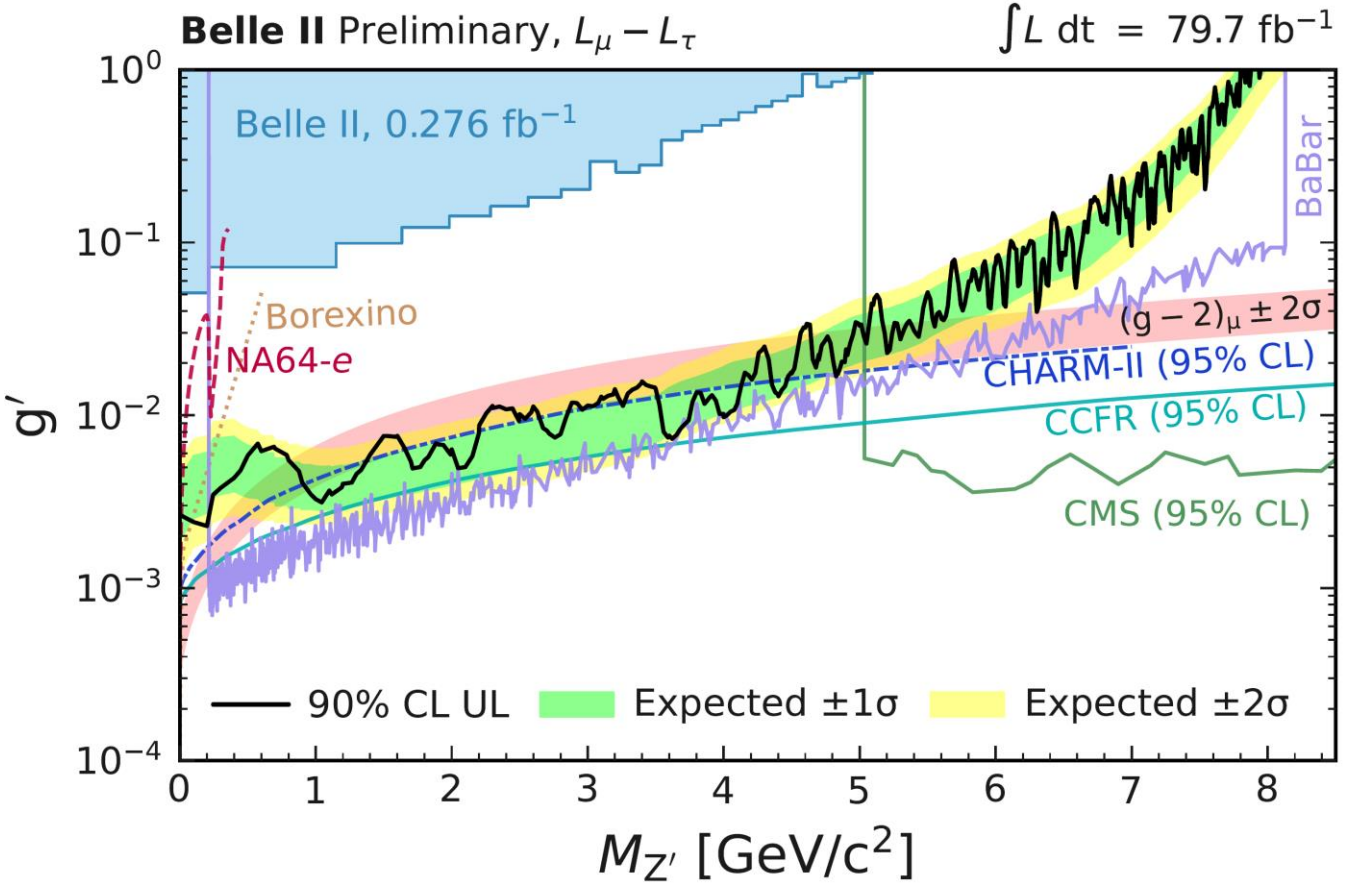
Systematics

Source	Low mass	Medium mass	High mass
selections	2.7%	6.5%	8.3%
Mass resolution	10%	10%	10%
Background shapes	3.2%	8.6%	25%
Photon veto	34%	5%	5%
luminosity	1%	1%	1%

Z’ to invisible results

NEW

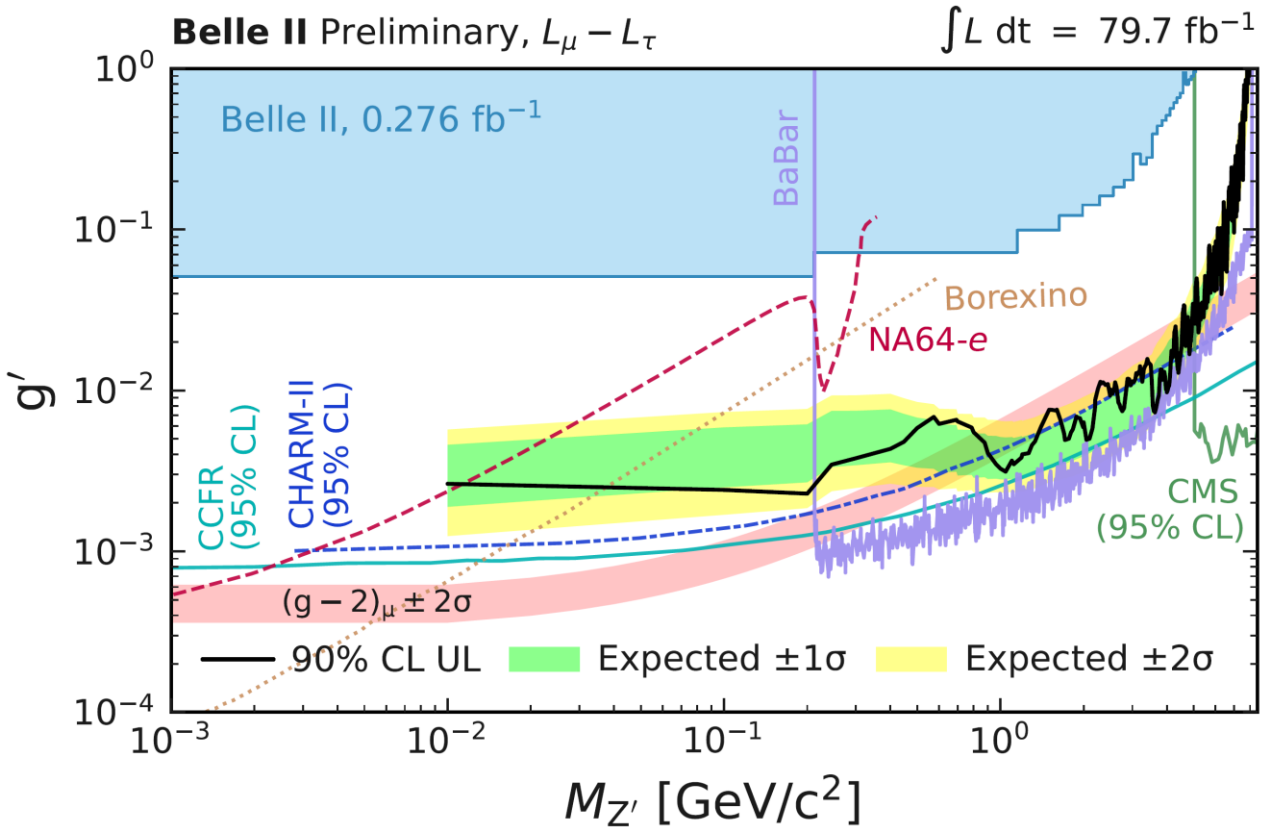
Vanilla model invisible Z’



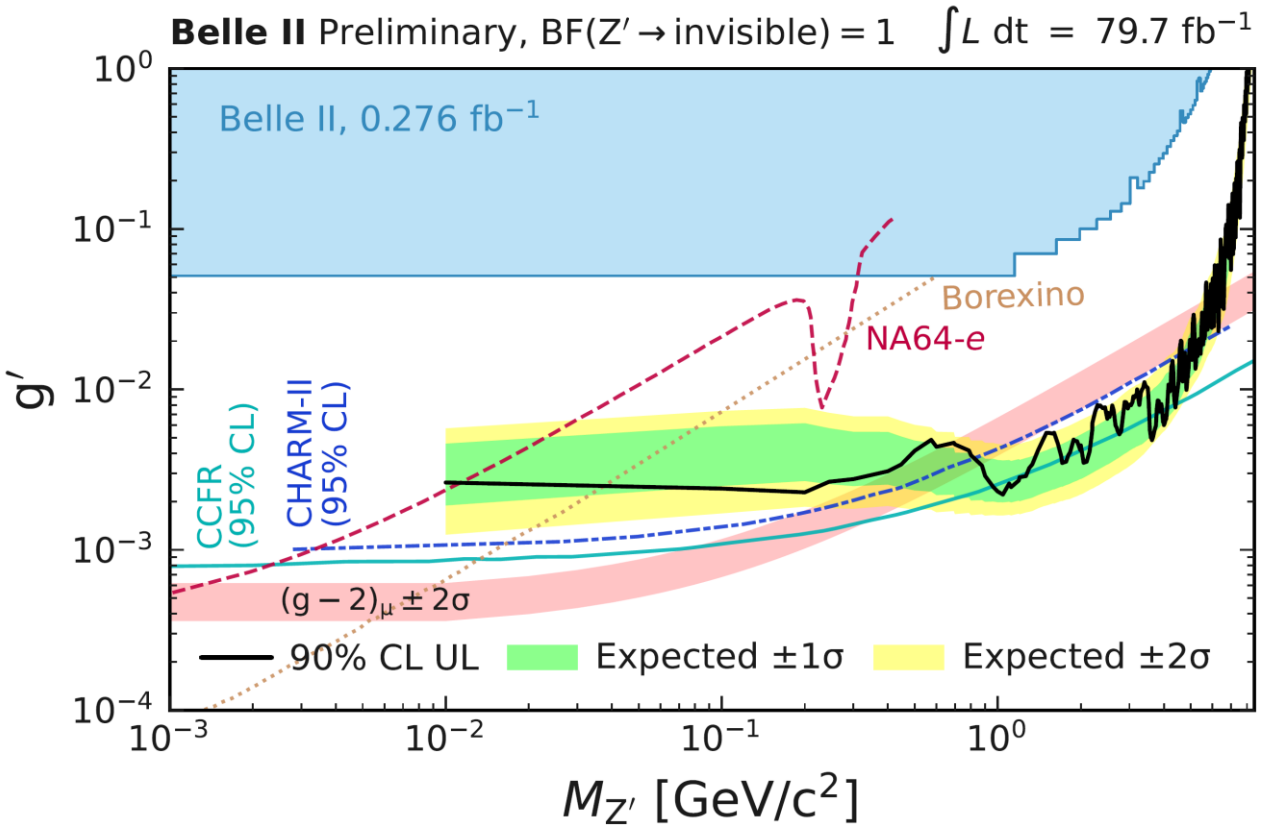
Z’ to invisible results

NEW

Vanilla model invisible Z’



Fully invisible Z’

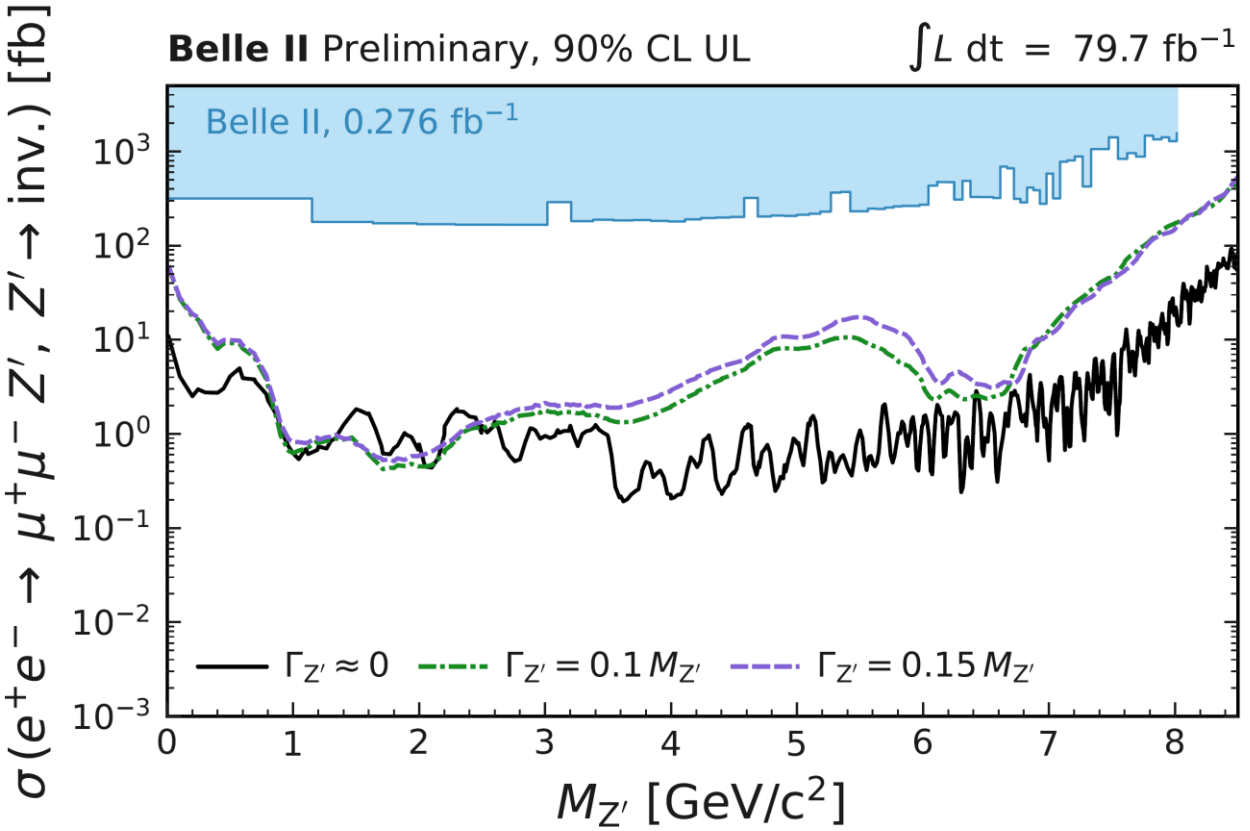


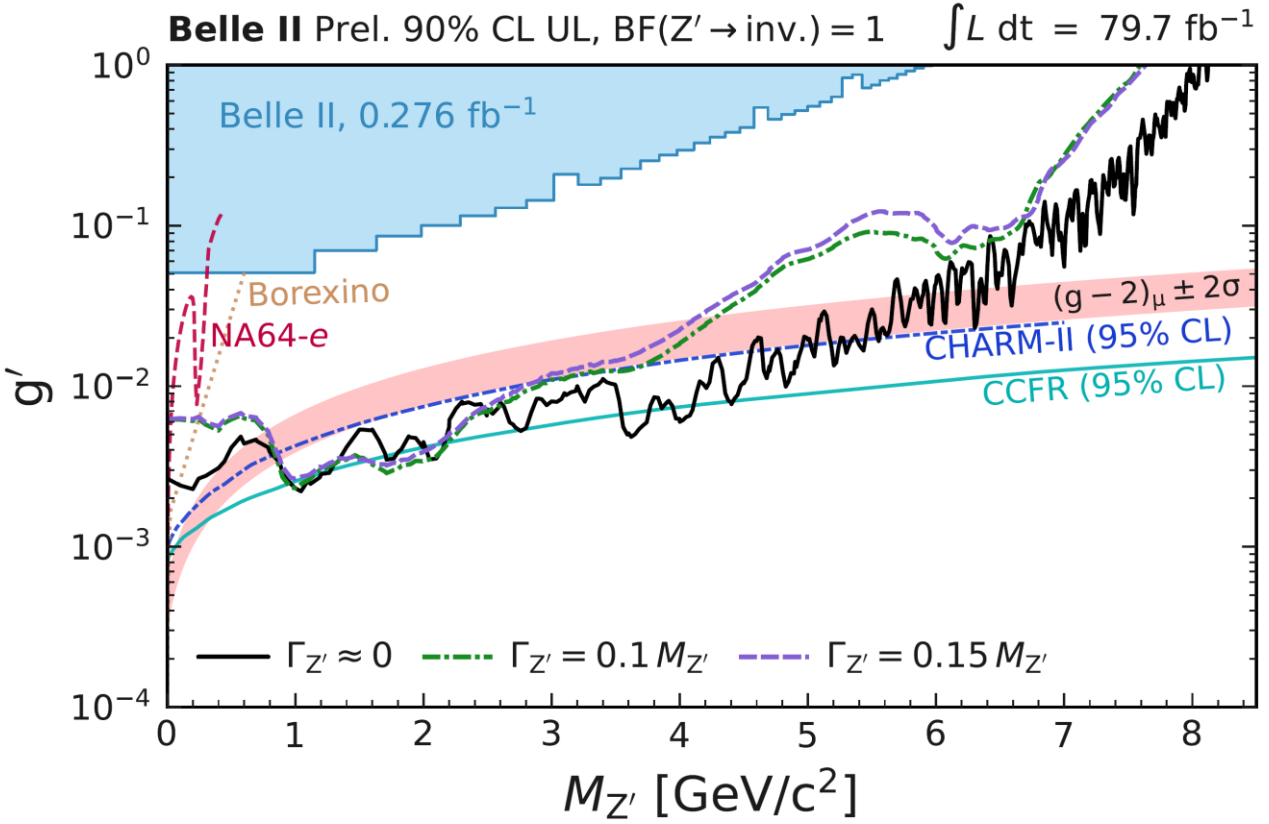
Z’ to invisible results

NEW

- Invisible Z’ with non negligible intrinsic width

- $\Gamma_{Z'} = 0.1\ M_{Z'}$, $0.15\ M_{Z'}$





Z', S, ALP → ττ: systematics

NEW

source	Uncertainty (%)
trigger	2.7
Particle ID	3.9-6.2
Tracking	3.6
Fit bias	4
MLP selection	2.8
Mass resolution	3
Efficiency interpolation	2.5
Luminosity	1
other	1
Total	**8.8-9.9**

Negligible effect on sensitivity and Uls → 1%