Recent dark-sector results at Belle II

Paolo Branchini
INFN – Roma Tre
on behalf of the Belle II Collaboration

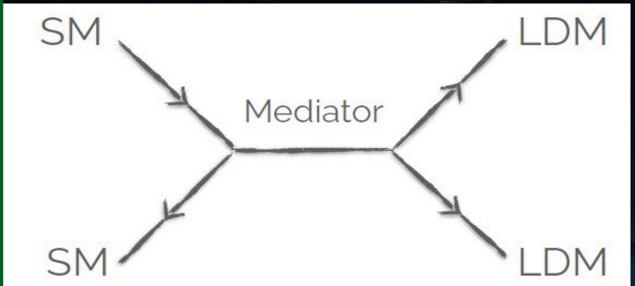
INFN ROMA TRE

Belle II

OUTLINE OF THE TALK

- ✓ Belle II and SuperKEKB
- ✓ Search of
  - ➢ Dark Higgsstrahlung
  - ➢ Z' to invisible **new**
  - ➢ Z', S, ALP $\rightarrow \tau\tau$ **new**
  - ➢ $\tau \rightarrow l\, \alpha$ **new**
- ✓ Perspectives & Summary

Dark matter hunt with a light sector



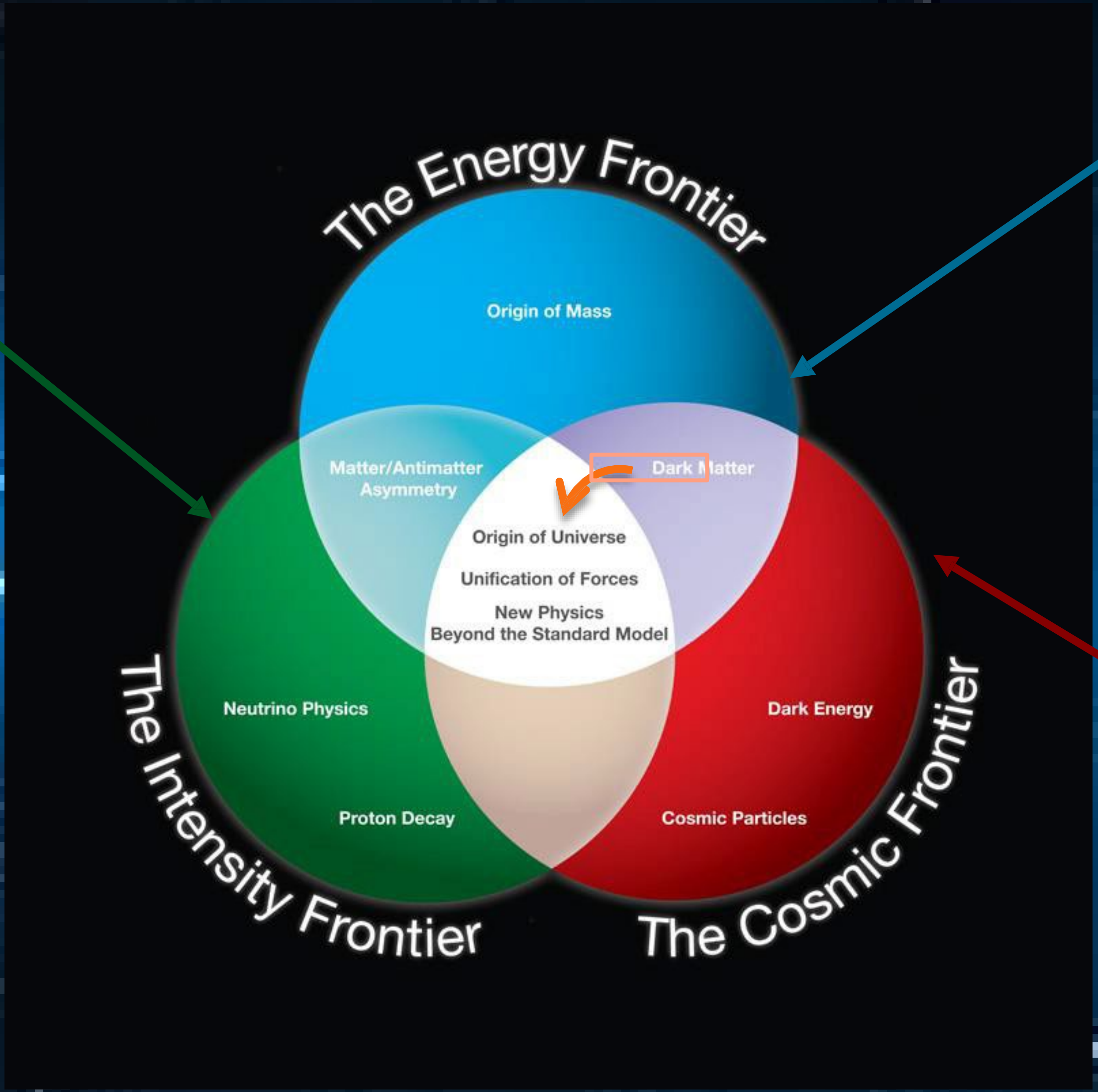
Light Dark Matter Mediators → portals

Vector portal
Dark photon, **Z’**, …

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

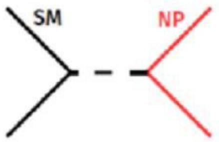
Scalar portal
Dark Higgs, **scalars**

Neutrino portal
Sterile neutrino



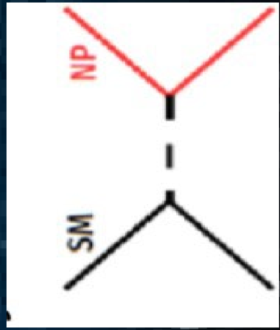
Energy frontier

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



Cosmic frontier

Direct effect search in (mostly) underground experiments



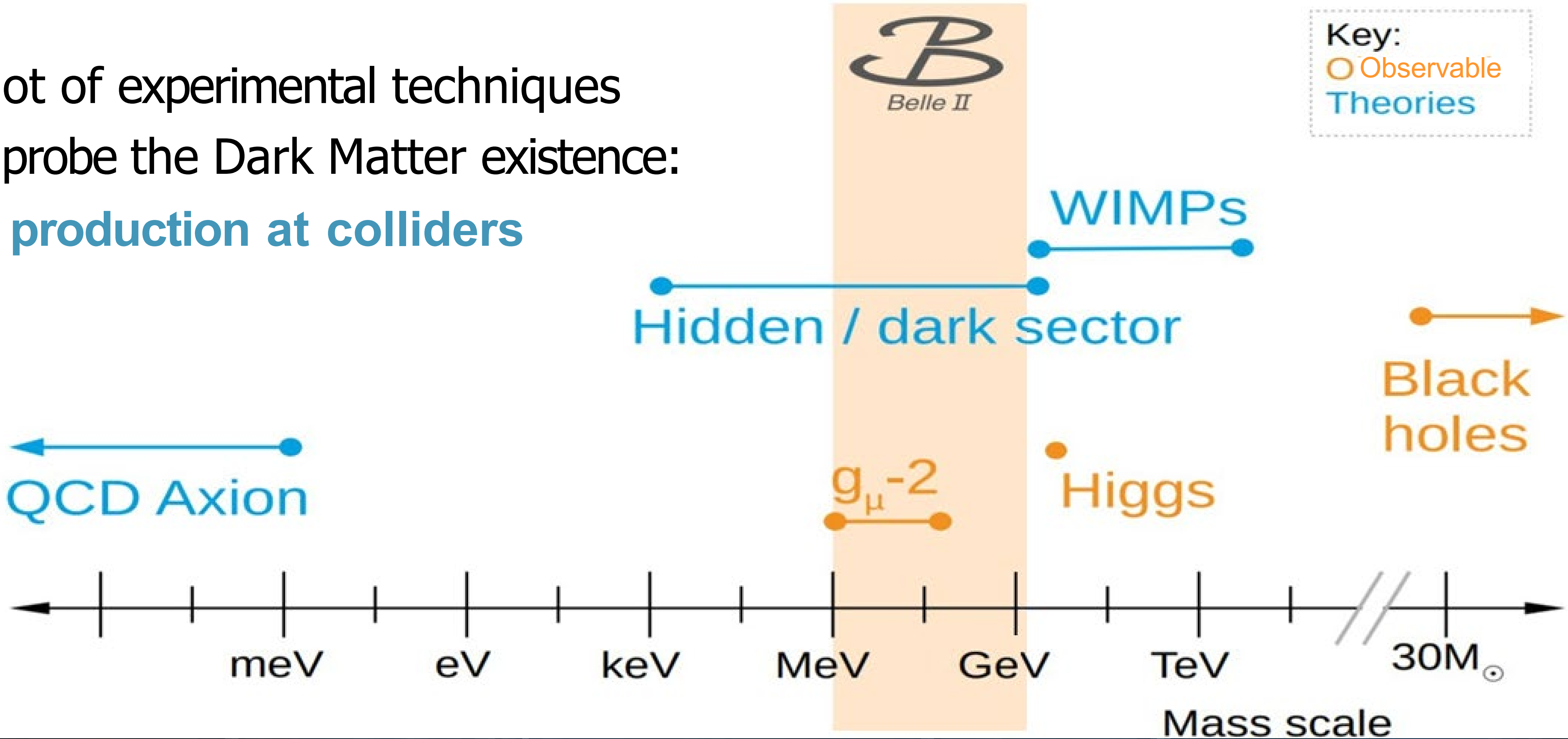
Dark Matter

It is "dark".

It exists…

A lot of experimental techniques
to probe the Dark Matter existence:

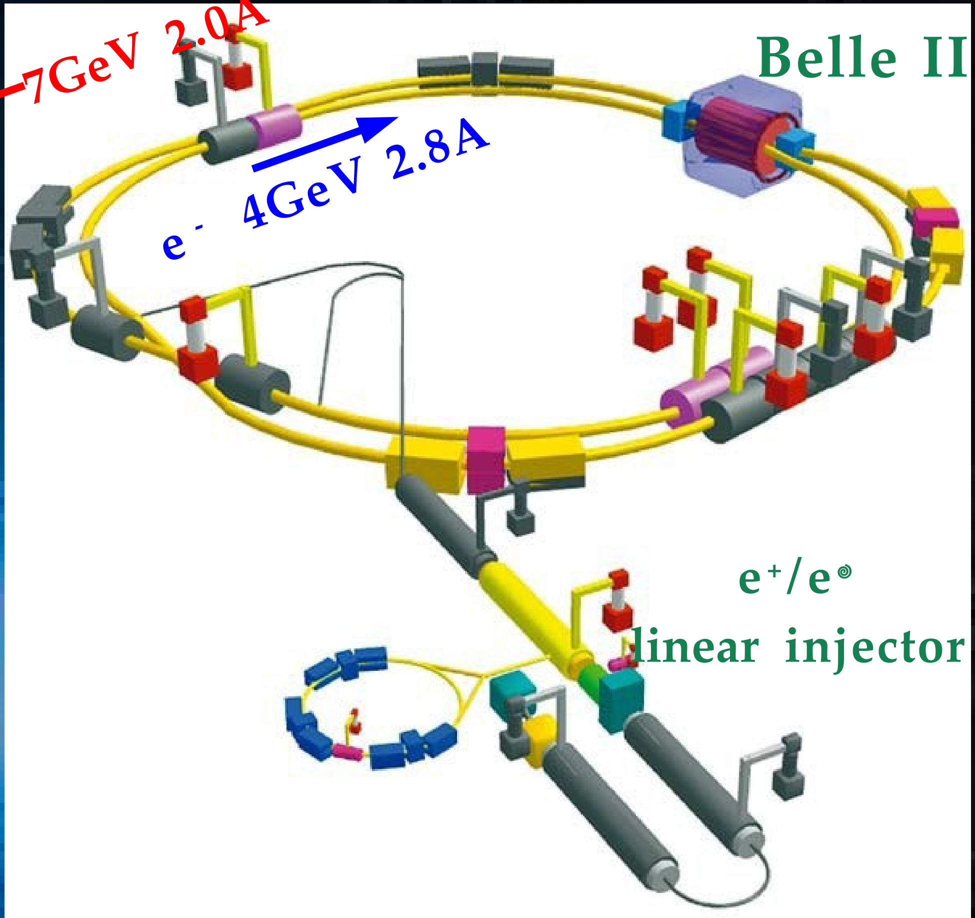
- **production at colliders**



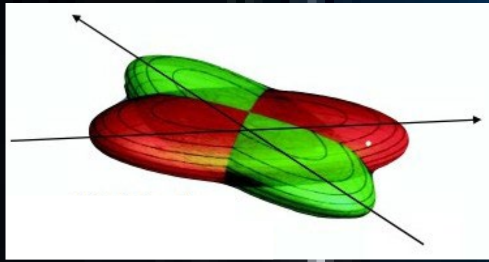
SuperKEKB: a new Intensity Frontier machine

SuperKEKB is a **super** B-factory
Located at KEK(Tsukuba, Japan)

It's an asymmetric e^+e^- collider operating mainly at **10.58 GeV**
(**Y(4S)**, but possible runs from Y(2S) to Y(6S))

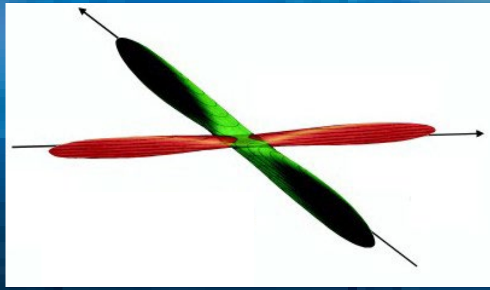


KEKB



nano-beam scheme

SuperKEKB

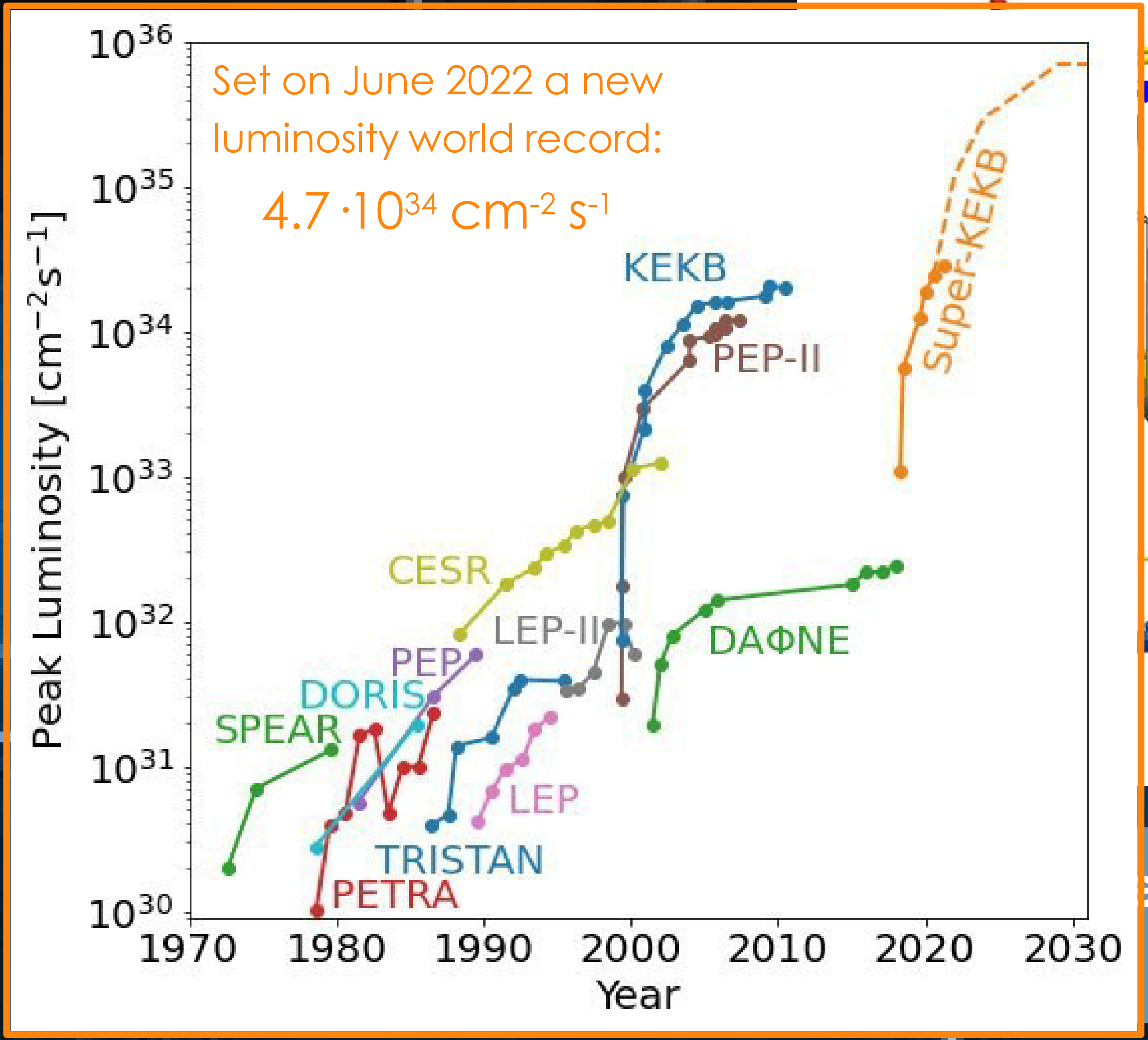


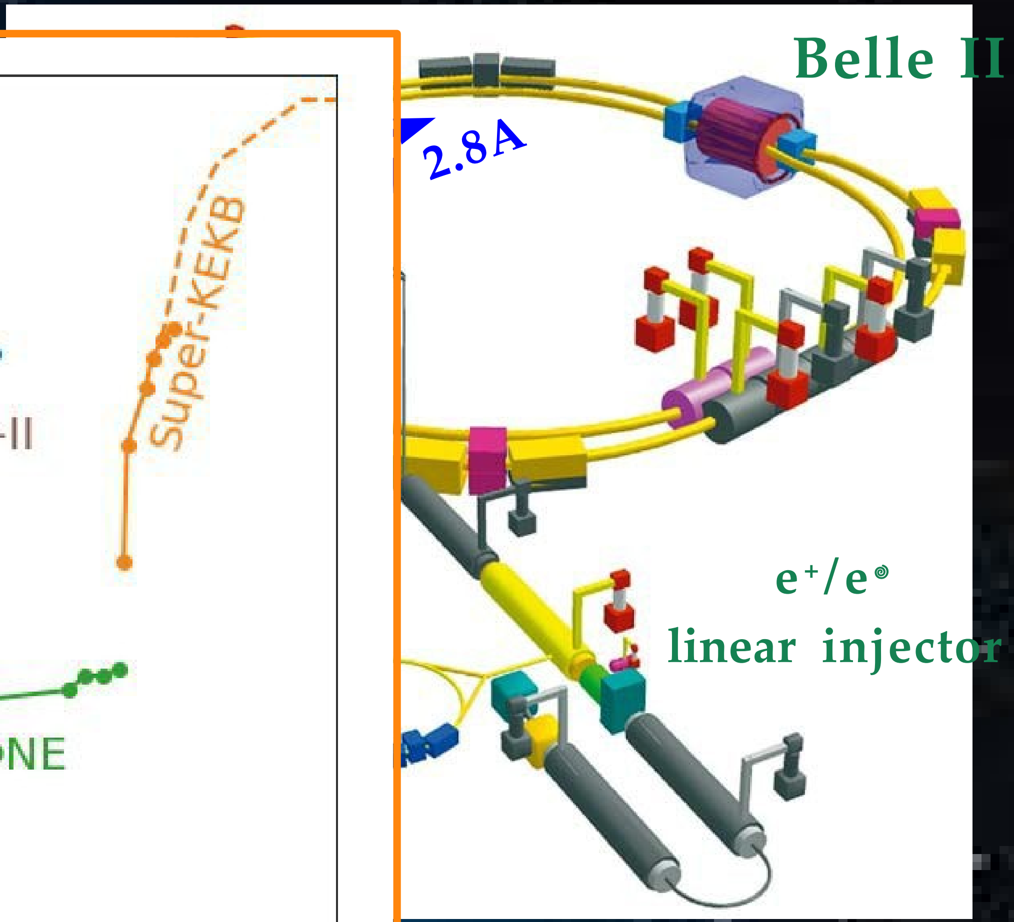
I (A): ~ 1.6/1.2
β^*_y (mm): ~ 5.9/5.9

I (A): ~ 2.8/2.0
β^*_y (mm): ~ 0.27/0.3

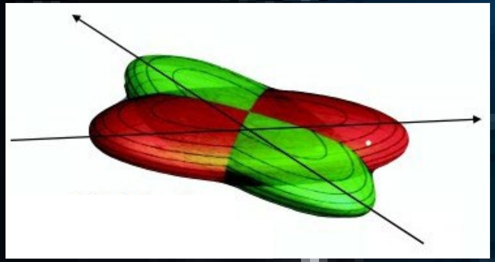
30x peak luminosity:
$6.3 \cdot 10^{35}$ cm^{-2} s^{-1}

SuperKEKB: a new Intensity Frontier machine





KEKB



I (A): ~ 1.6/1.2

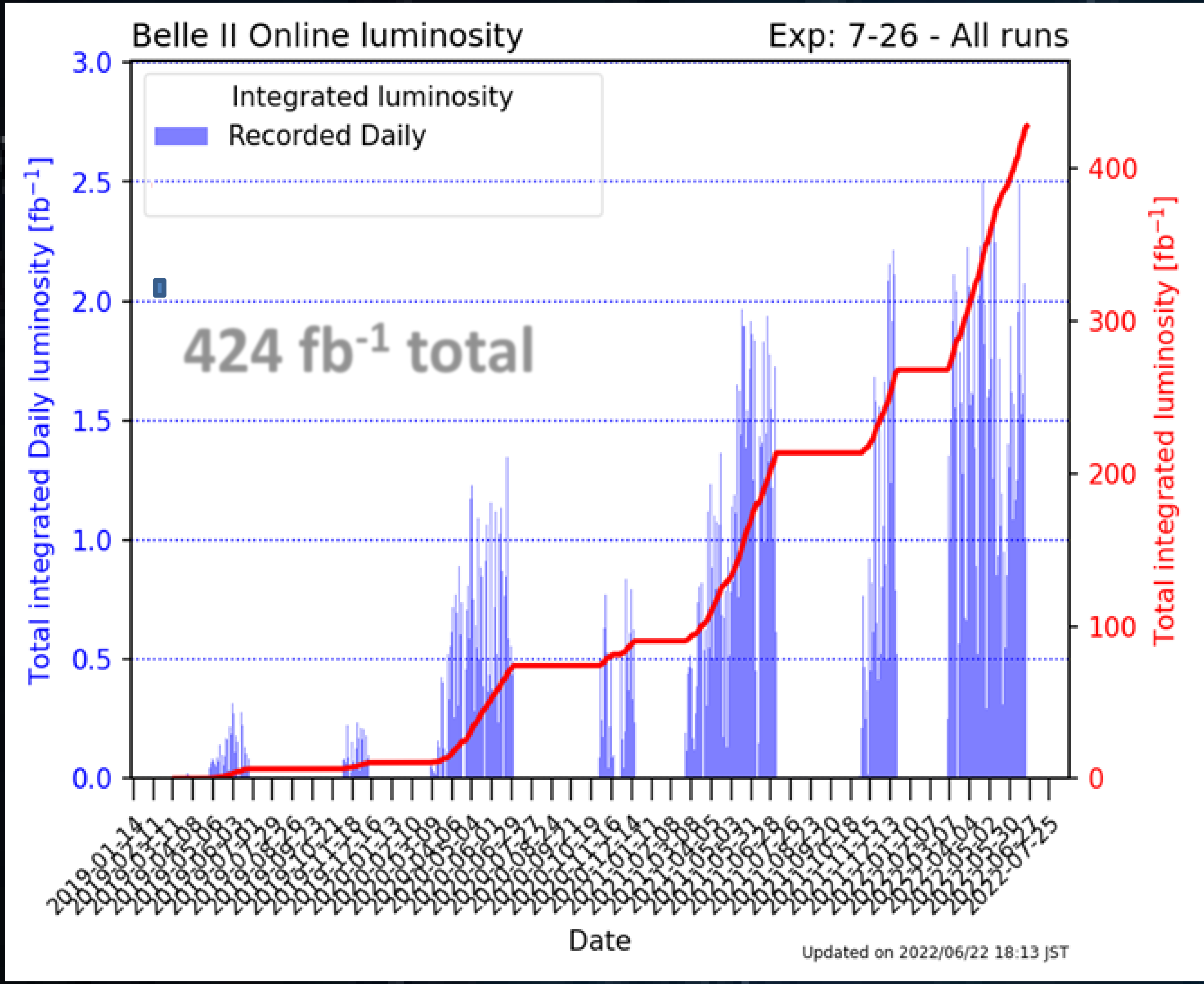
β^*_y (mm): ~ 5.9/5.9

eak luminosity:

· 10^{35} cm^{-2} s^{-1}

Where are we now?

Collected luminosity up to now: 2019-2022



Peak luminosity world record

4.7 x 10^{34} cm^{-2} s^{-1}

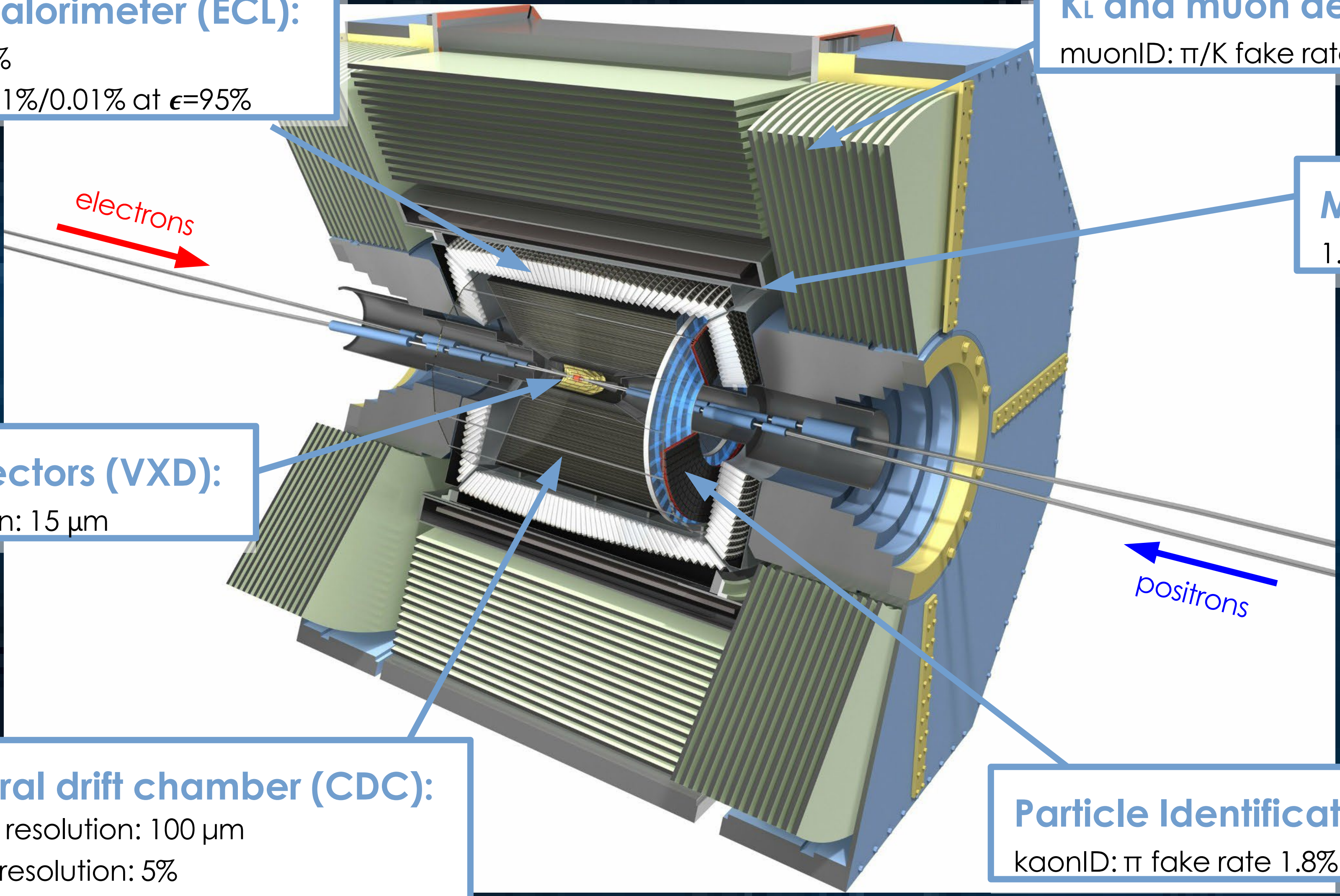
Resume physics run in fall 2023

Belle II: a new Intensity Frontier detector

Electromagnetic Calorimeter (ECL):
energy resolution: 1.6%-4%
electronID: π/K fake rate 1%/0.01% at ϵ=95%

K_L and muon detector (KLM):
muonID: π/K fake rate 2%/1% at ϵ(K)=95%

Magnet:
1.5 T superconducting



Vertex detectors (VXD):
vertex resolution: 15 µm

Trigger:
dedicated lines for low multiplicity studies:
- single track
- single photon
- single muon

Central drift chamber (CDC):
spatial resolution: 100 µm
dE/dx resolution: 5%
pT resolution: 0.4%

Particle Identification (PID):
kaonID: π fake rate 1.8% at ϵ(K)=95%

Belle II trigger

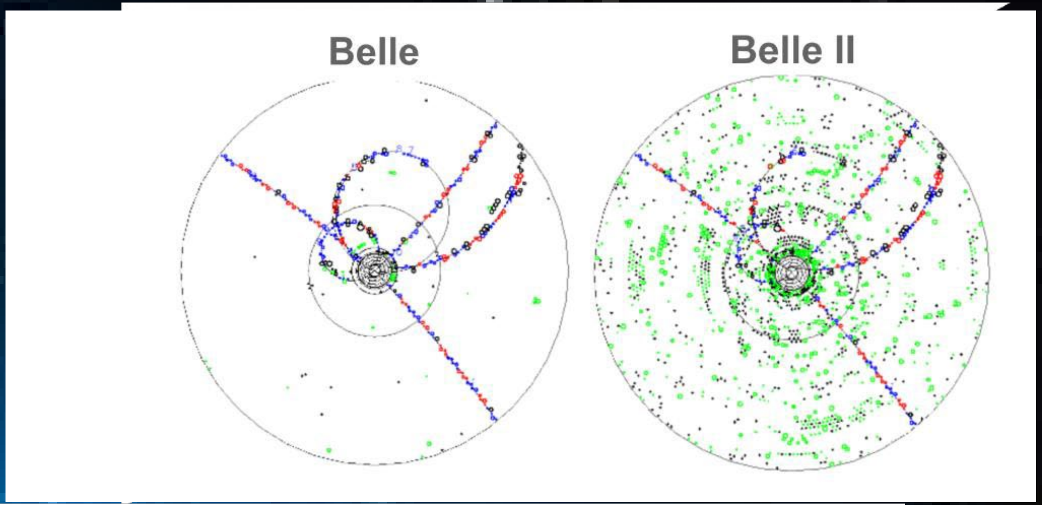
Dark sector physics
- Low multiplicity signatures
- Huge backgrounds from beam, Bhabha, two-photon

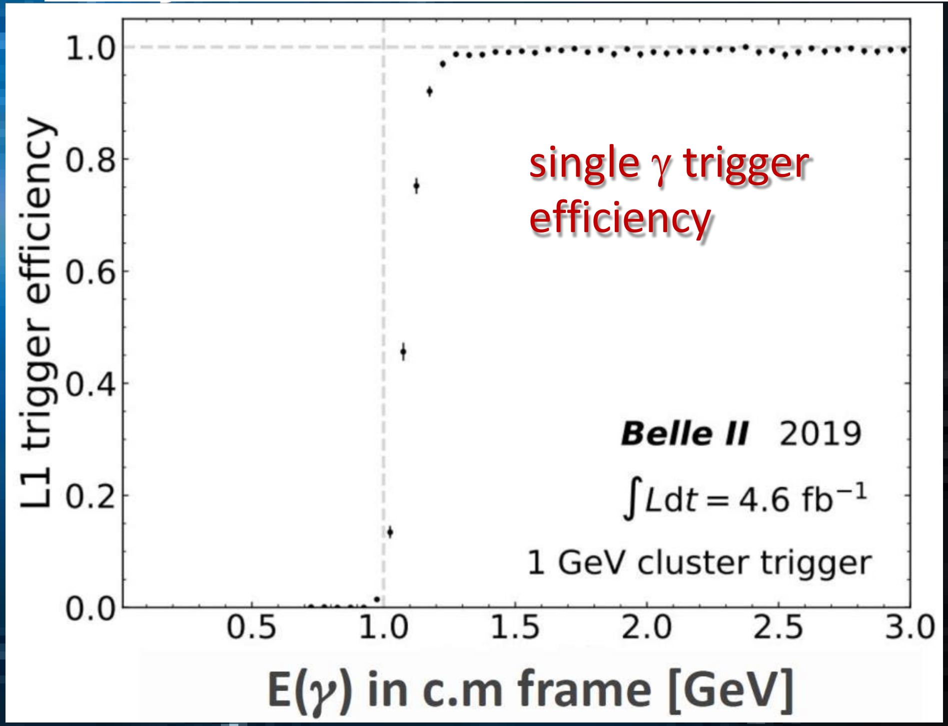
Level 1 hardware-based combines info from CDC, ECL, KLM
- Tracks, clusters, muons
- Two-track trigger
- Three-track trigger
- E_{ECL}> 1 GeV trigger

Single muon
- CDC + KLM

Single track
- Neural based

Single photon
- E_{γ} > 0.5, 1, 2 GeV

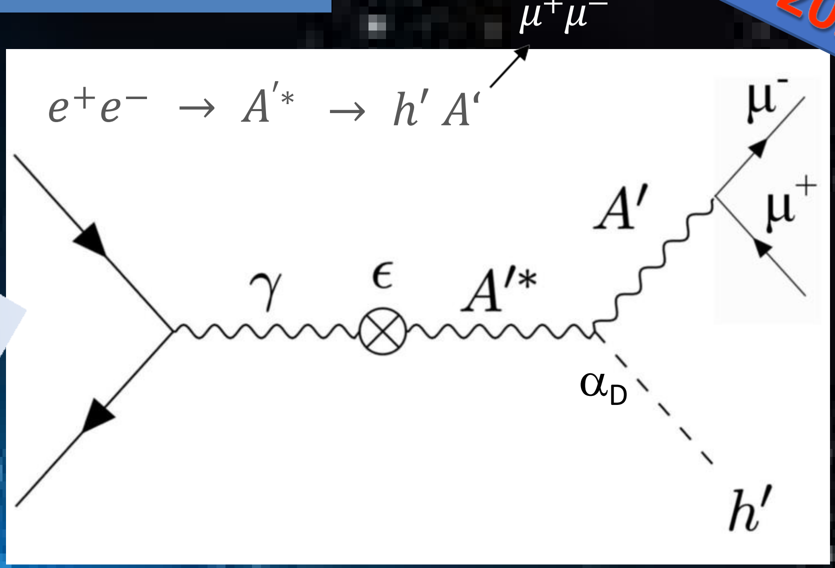




Dark Higgsstrahlung: $e^+e^- \rightarrow A'h'$

New 2022

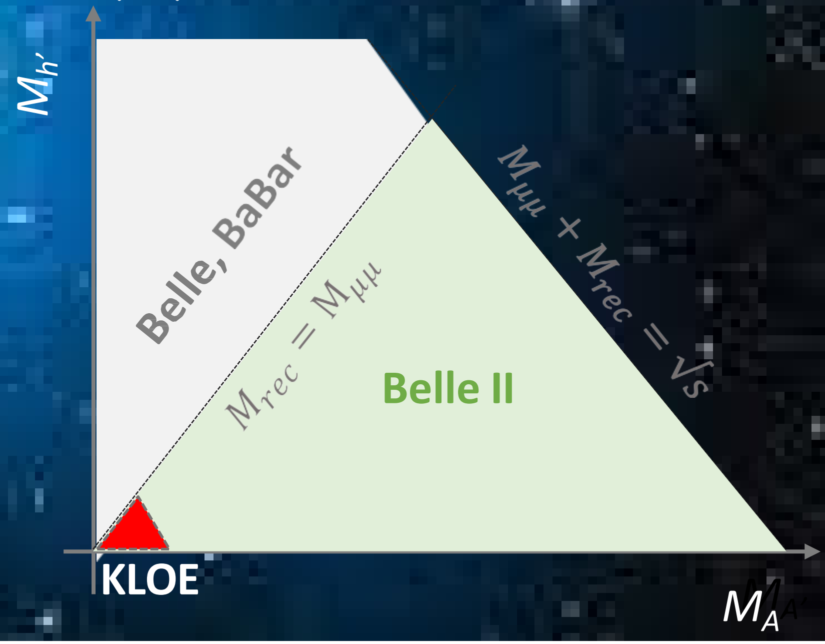
- **U(1)' vector portal extension of SM** ⟶ Phys. Rev D79, 115008 (2009)
  - dark photon A'
    - couples with kinetic mixing ε to SM
  - dark Higgs h'
    - gives mass to A' through SSB
    - no mixing of h' with SM Higgs
    - couples with α_D



Vector portal

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

- **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), missing energy
    - 2d peak in $M_{\mu\mu}$ and M_{recoil}
    - Probed by KLOE
    - Largely unconstrained

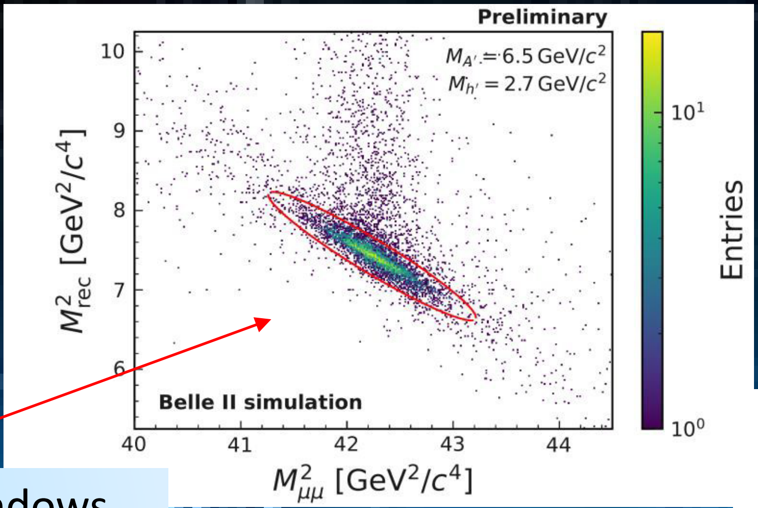


Dark Higgsstrahlung: analysis

New 2022

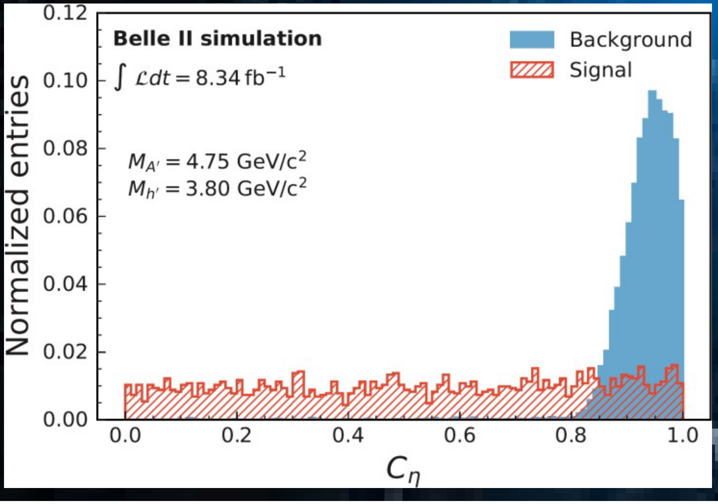
8.34 fb^{-1} (2019)

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

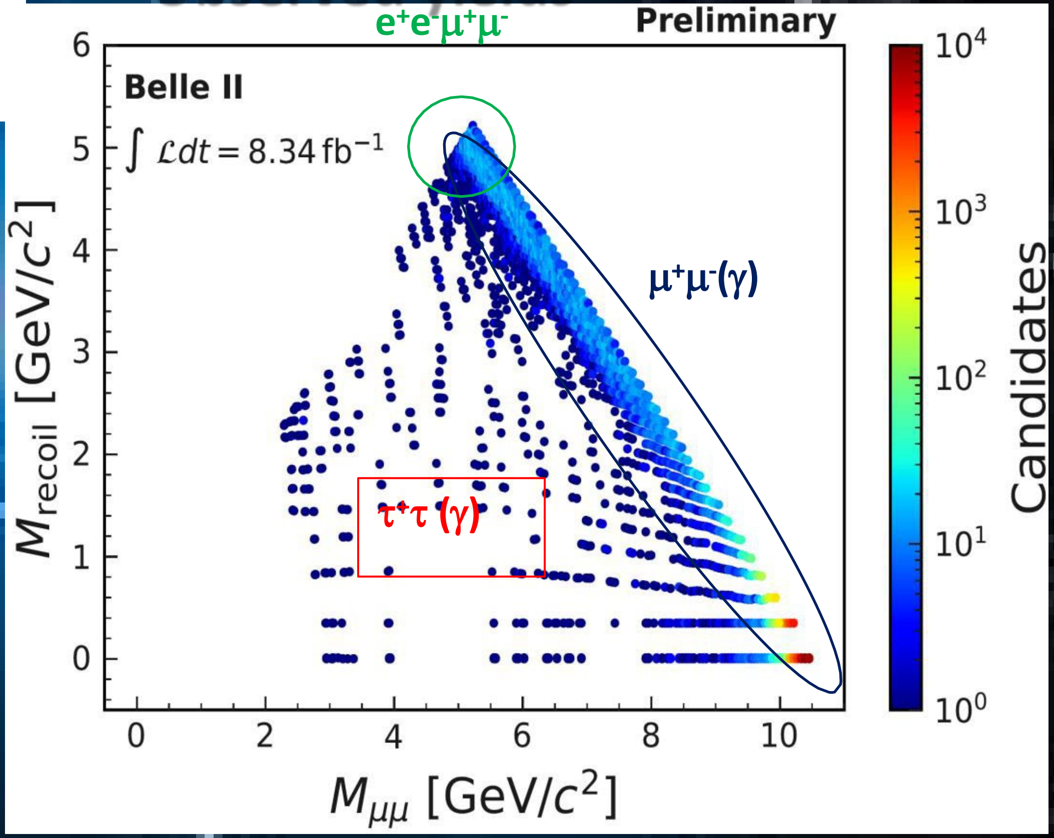
Helicity angle



Backgrounds

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

Observed yields

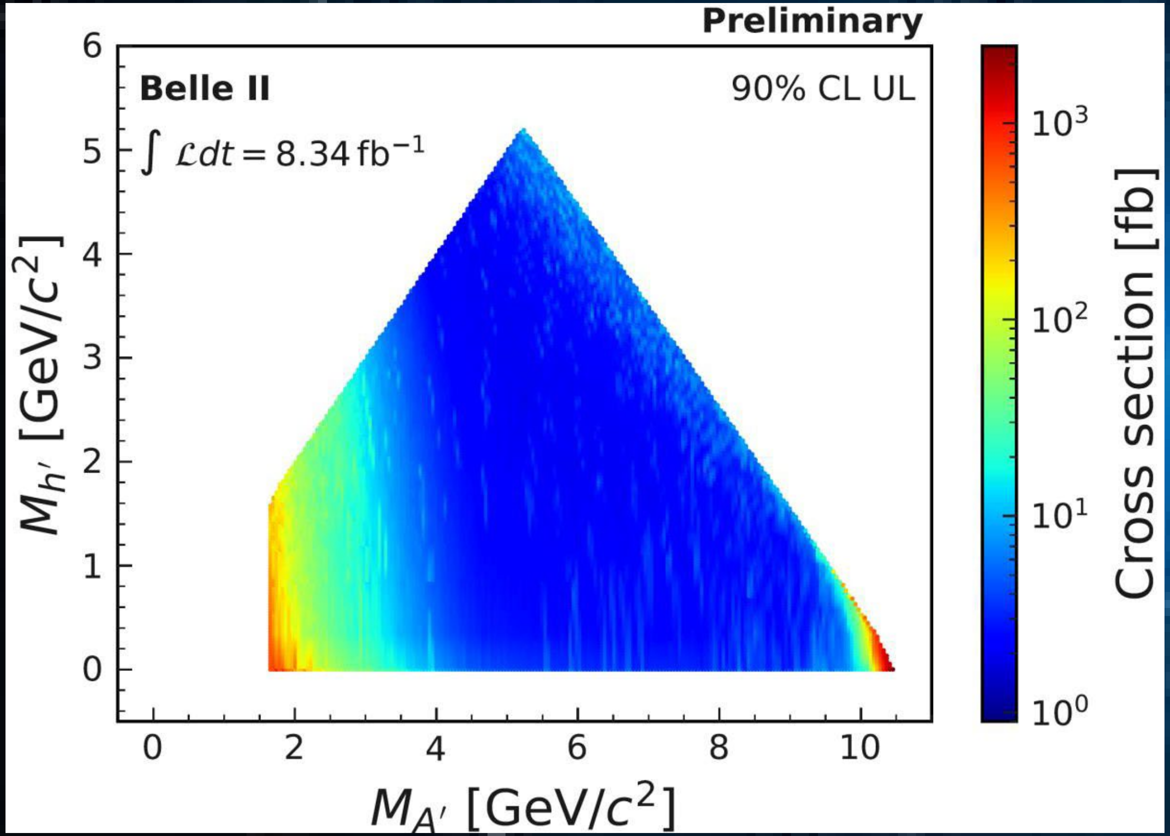


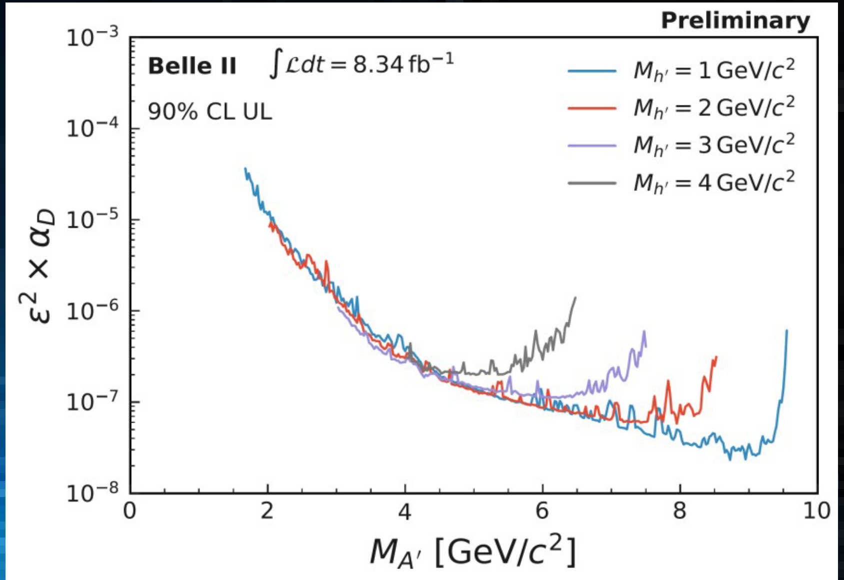
Dark Higgsstrahlung: results

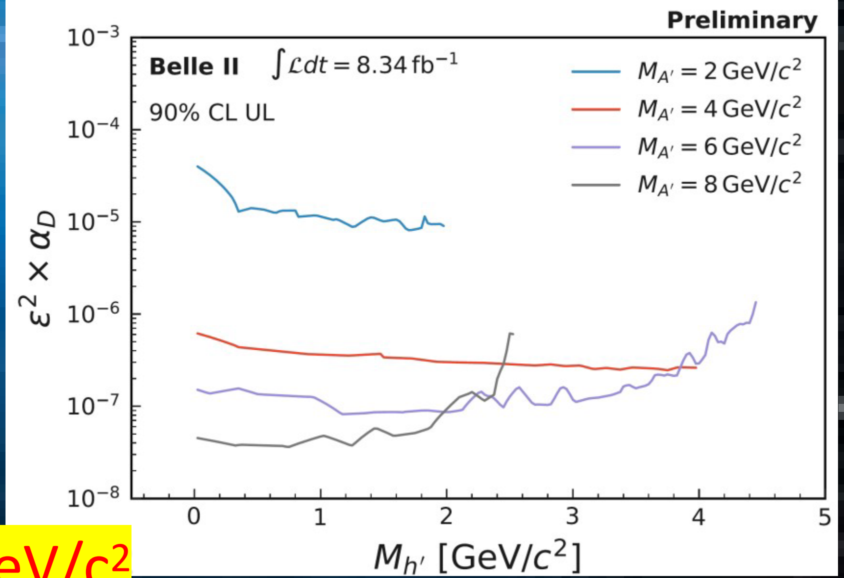
New 2022

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





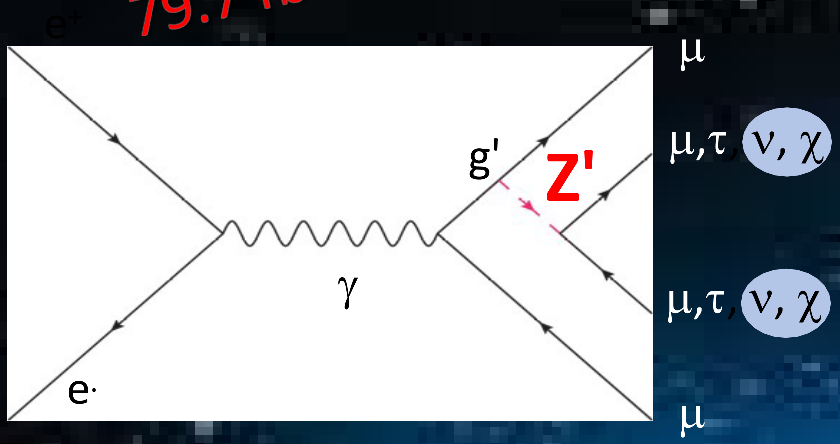


World first for $1.65 < M_{A'} < 10.51$ GeV/c^2

Z’ to invisible: analysis

NEW

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

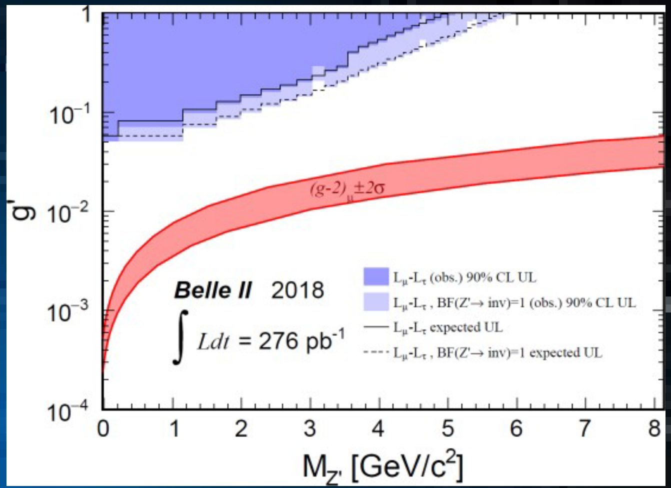


Main backgrounds

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

Old result

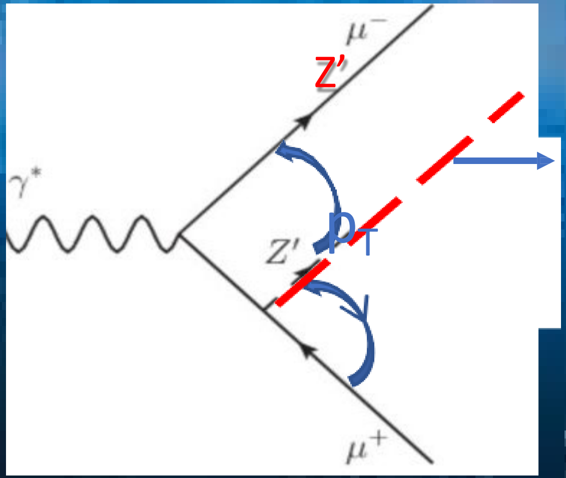
PRL 124 (2020), 141801



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

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/c²
No extraenergy, γ veto



FSR vs ISR + τ decay

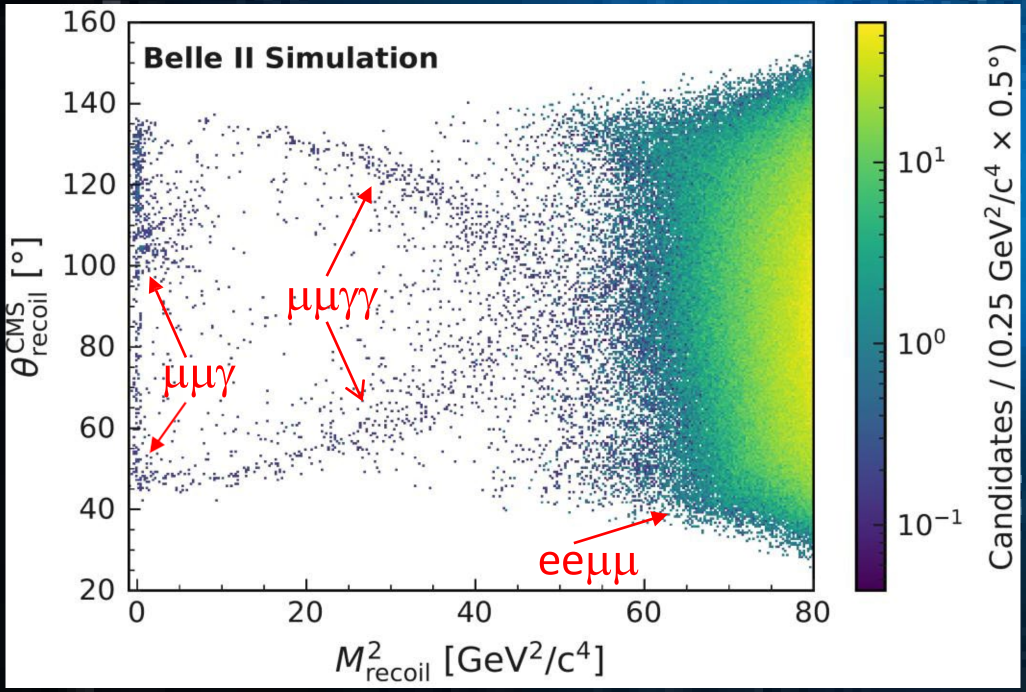
NN trained to optimize Punzi FOM
Eur.Phys.J.C 82 (2022) 2, 121

Z' to invisible: analysis

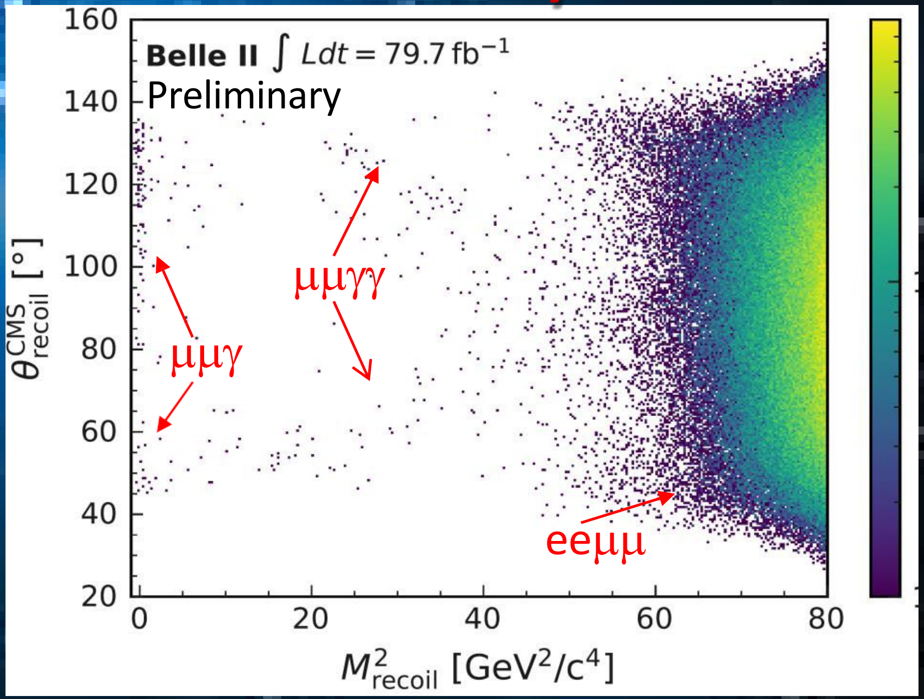
NEW

- $\tau^+\tau^-$ (γ) almost 100% suppressed
- $\mu^+\mu^-$ (γ) dominates up to ~7 GeV/c²
- $e^+e^-\mu^+\mu^-$ dominates for high masses

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



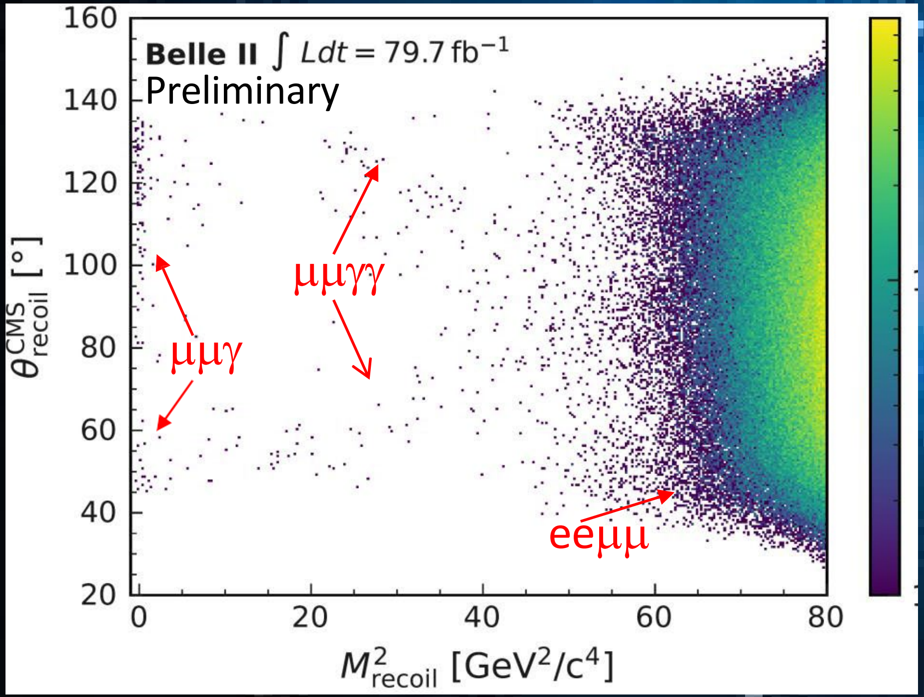
Observed yields

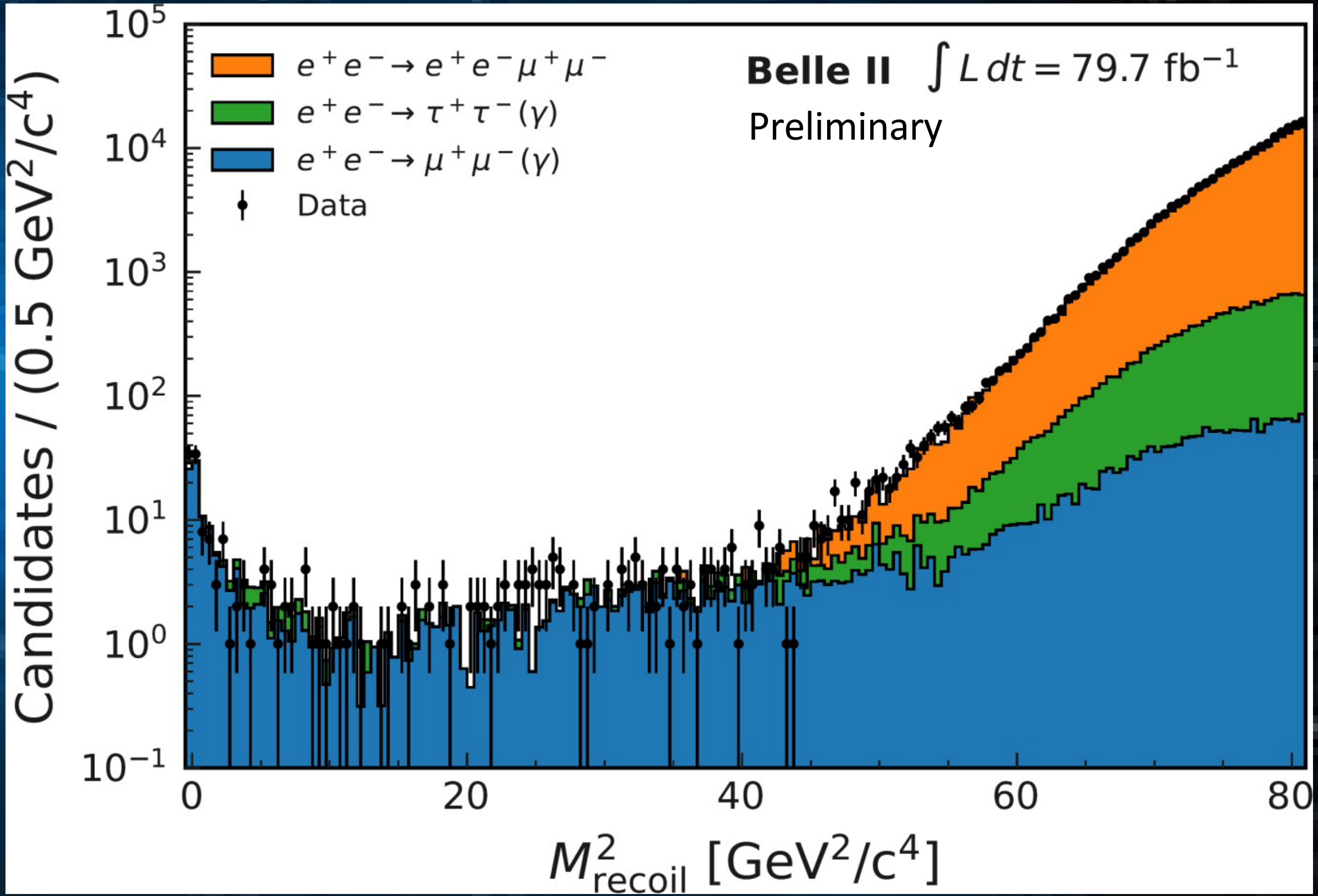


Z’ to invisible: observed yields

NEW

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

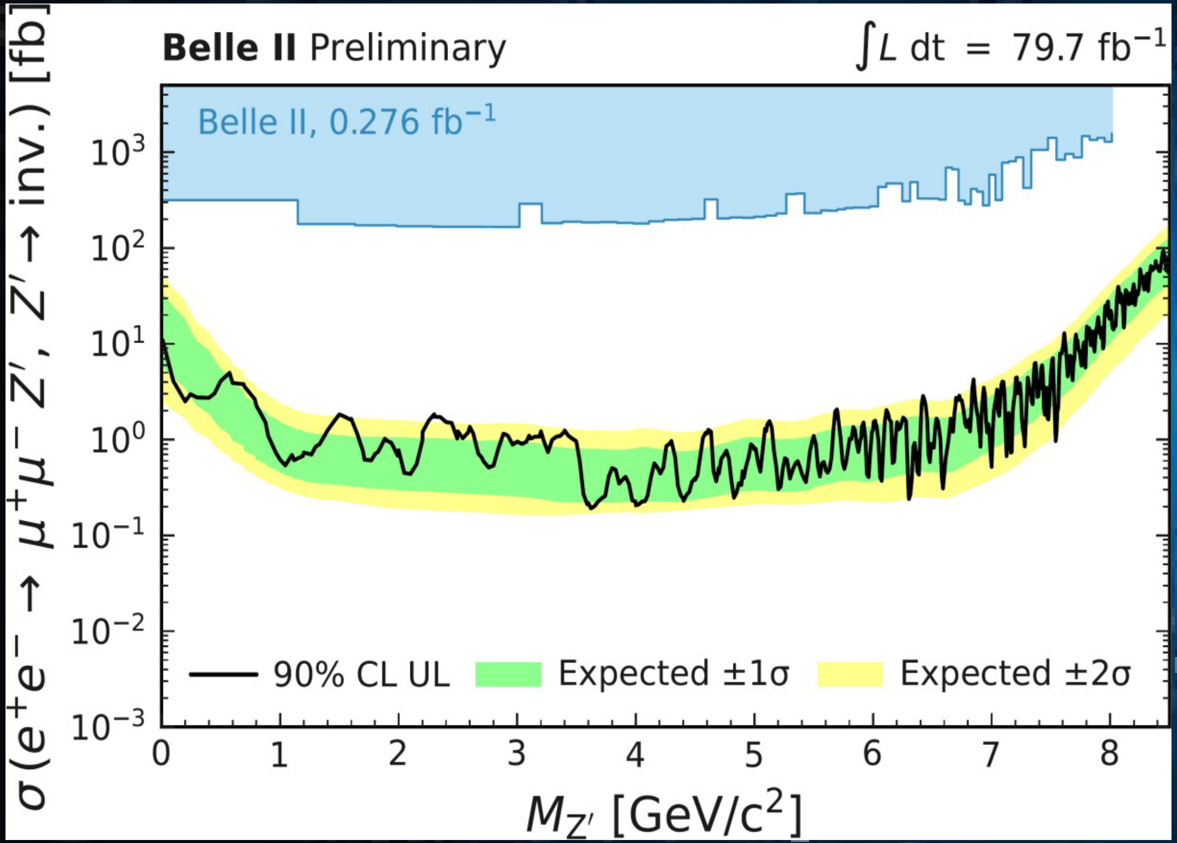


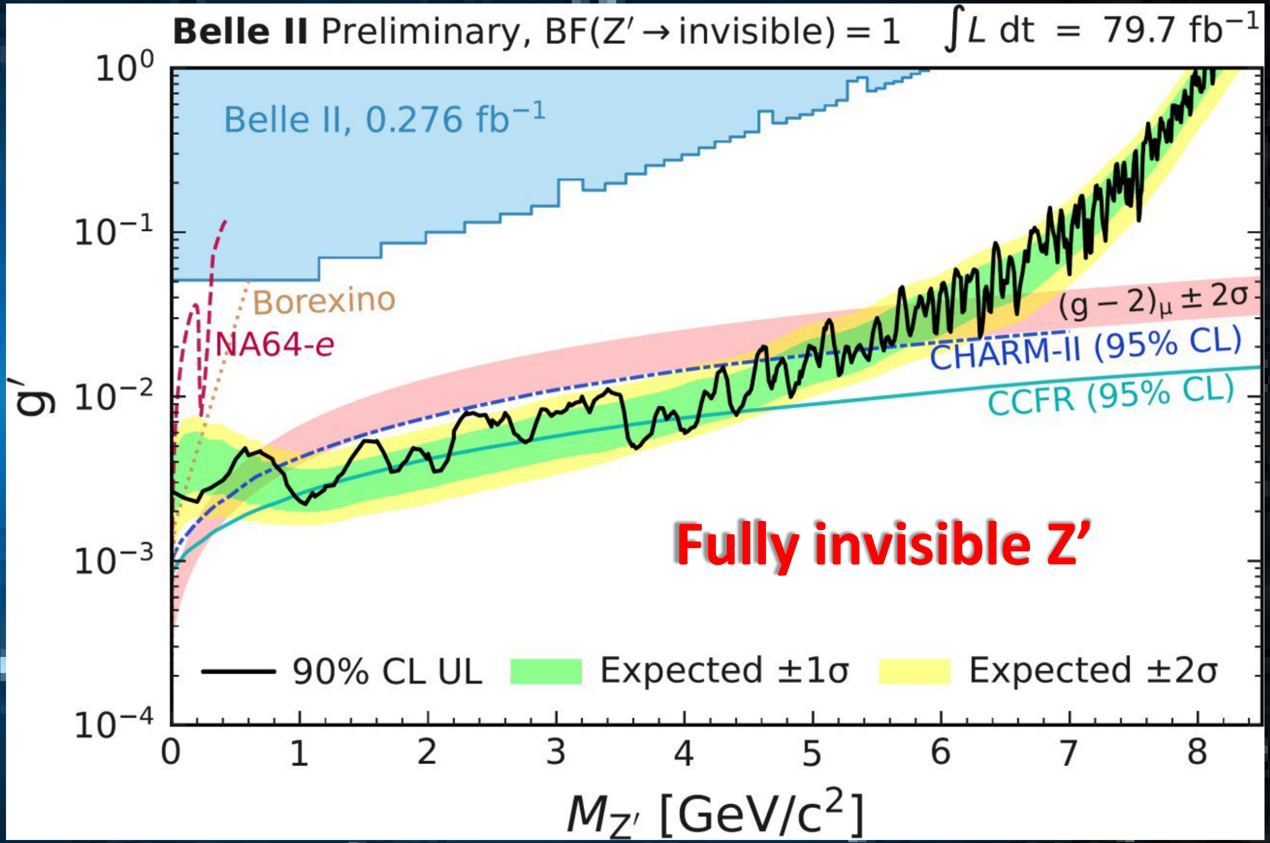


Z’ to invisible: results

NEW

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





fully invisible Z’ as origin of $(g\text{-}2)_\mu$ excluded for $0.8 < M_{Z'} < 5.0$ GeV/c²

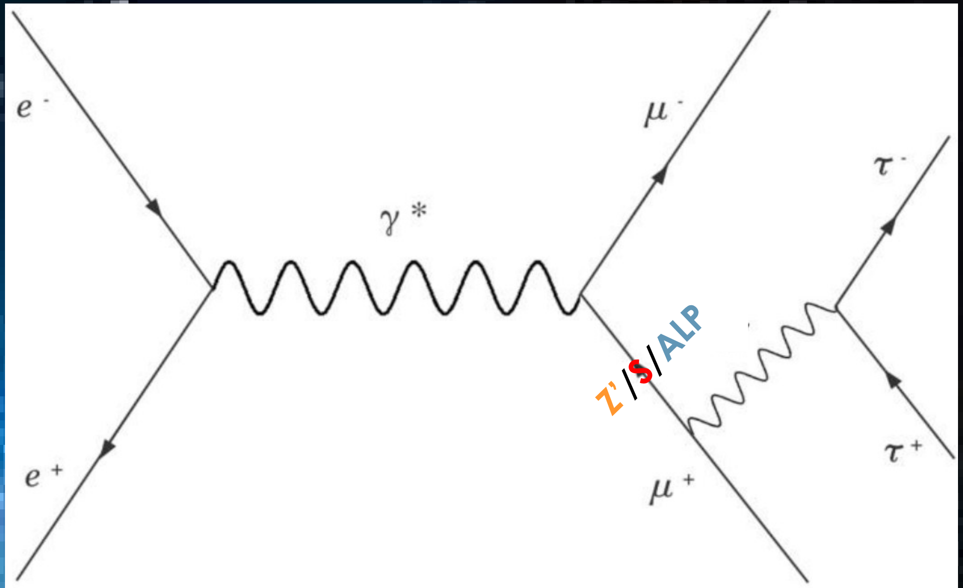
NEW – from ICHEP

Z' / S / ALP → $\tau^+\tau^-$

NEW

We searched for a $\tau^+\tau^-$ resonance in $\mu^+\mu^-\tau^+\tau^-$ final states

→ $M(\tau\tau) = M_{recoil}(\mu\mu)$



We probed three different models:

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

- JHEP 12 (2016) 106 (theo. paper)
- vector portal
- first time search in $\tau\tau$

Leptophilic dark scalar S model

- PRD 95 (2017) 075003 (theo. paper)
- Yukawa couplings
- constraints by BaBar in $S\to\mu\mu$
- first time search in $\tau\tau$

ALP → $\tau\tau$

- arXiv:2110.10698 (theo. paper)
- $C_{ee}=C_{\mu\mu}=C_{\tau\tau}$; $C_{\gamma\gamma}=C_{Z\gamma}=0$
- Yukawa-like effective couplings
- ALP-τ coupling unconstrained

Z' / S / ALP → $\tau^+\tau^-$ - Reconstruction

NEW

Dataset: 63.3 fb^{-1}

Basic selections:

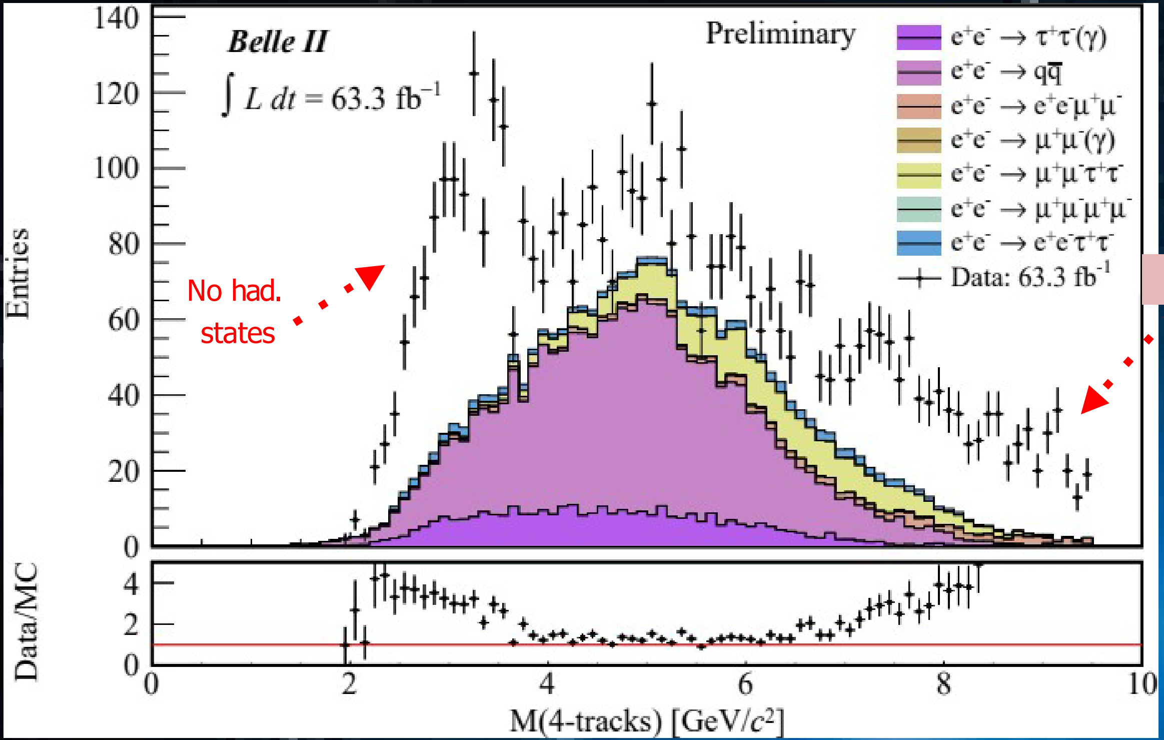
- considering only 1-prong τ decays
  - → require 4 tracks
- 2μ + 2$e/\mu/\pi$
- M(4 tracks) < 9.5 GeV
- allowed neutrals
- scan $M_{recoil}(\mu\mu)$
- NN selection to get rid of background

Main backgrounds:

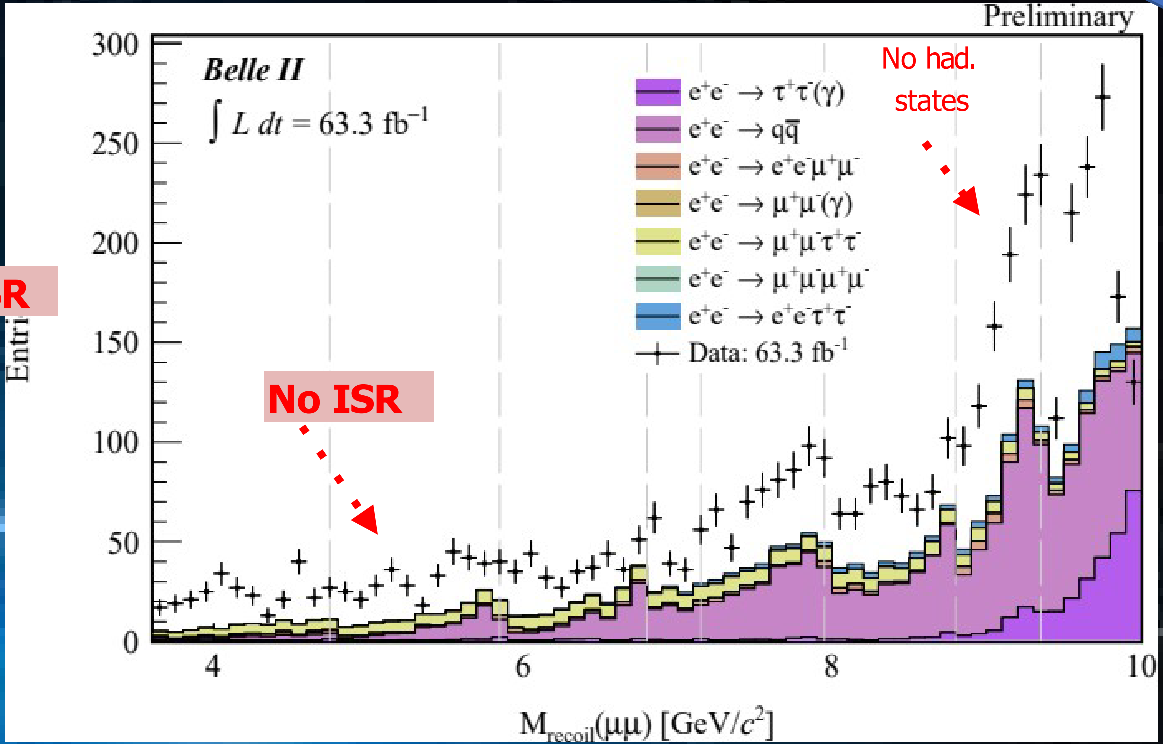
- $\tau^+\tau^-(\gamma)$ (1x3-prongs events)
- qq
- $l^+l^-l^+l^-$ (no ISR in our simulation)
- $\mu^+\mu^-\pi^+\pi^-$ + $e^+e^-X_{had.}$ (not simulated)

Z' / S / ALP → $\tau^+\tau^-$ - Data and MC specta

NEW



No ISR



Discrepancies expected and understood due to missing features in simulation

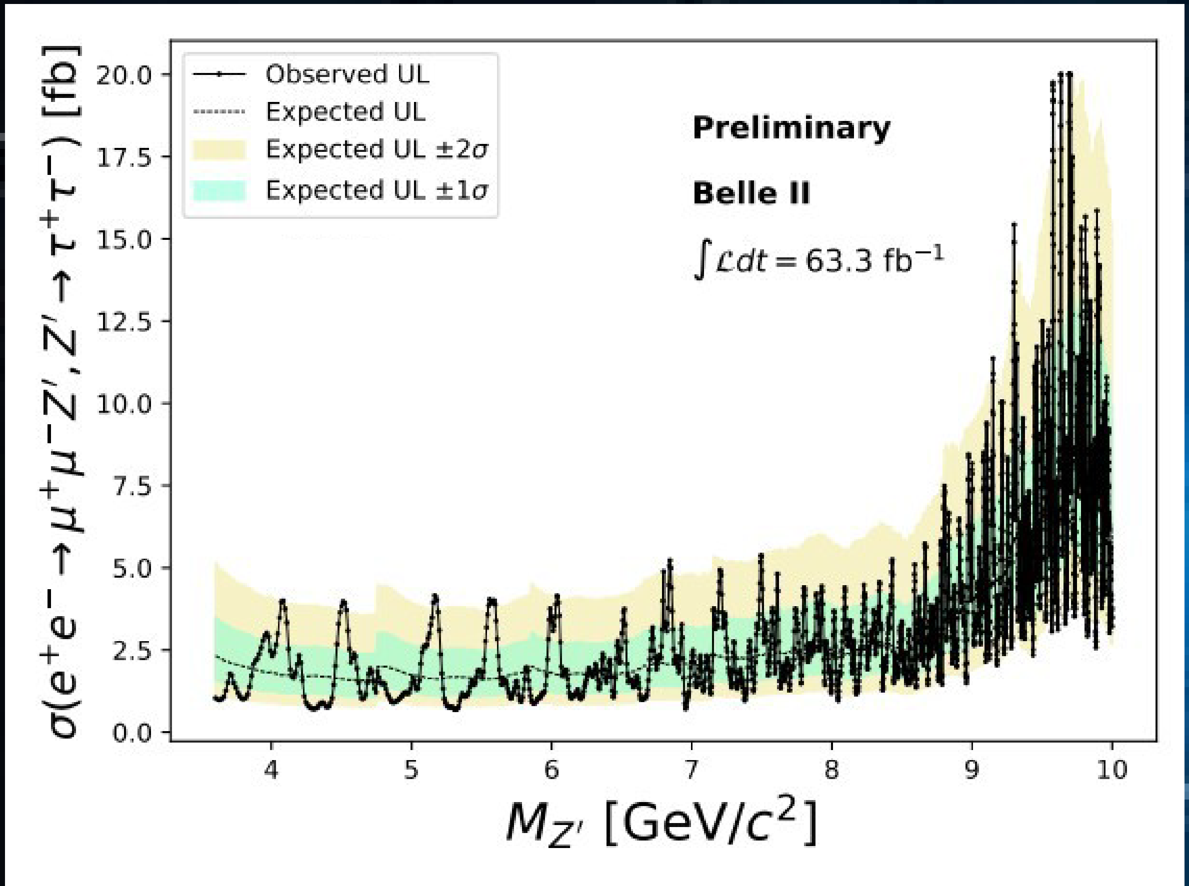
Smooth distribution and no peaking structures in $M_{recoil}(\mu\mu)$

→ NB: signal mass resolution from 1.5 MeV to 30 MeV

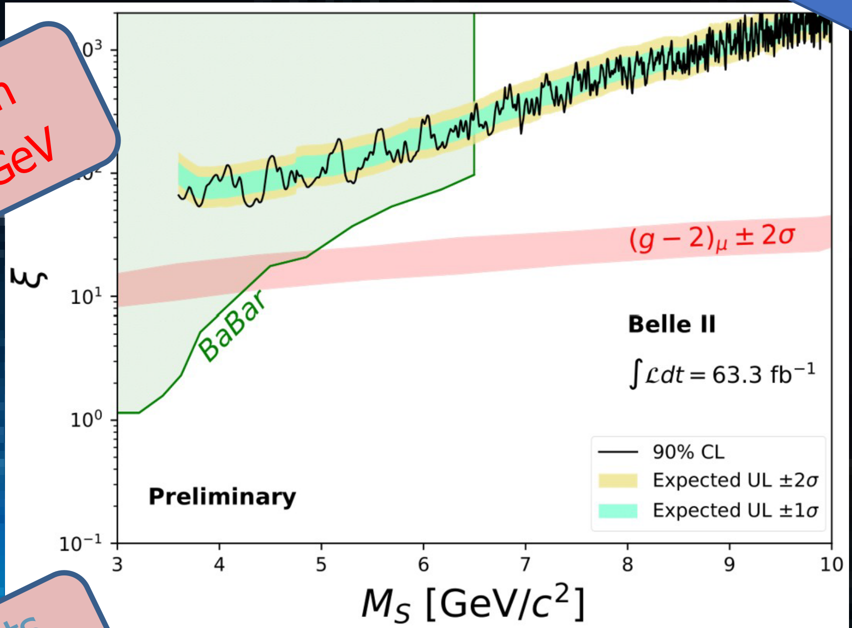
Z' / S / ALP → $\tau^+\tau^-$ - Results

NEW

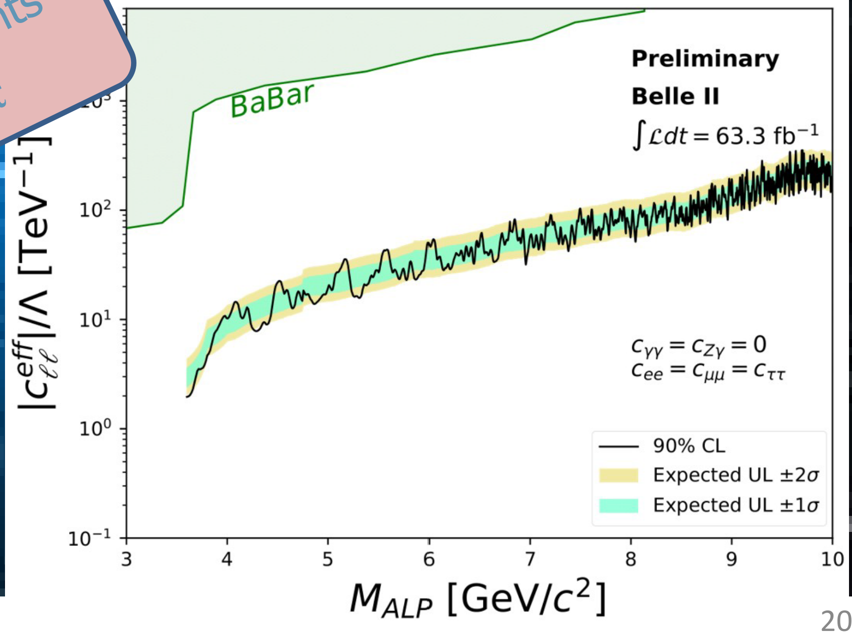
No signal observed → set 90% CL upper limits



First constraints on S for M_S > 6.5 GeV



First direct contraints on ALP → ττ



Z' → ττ ($L_\mu - L_\tau$ model) only used as benchmark

$\tau^\pm \to (e^\pm / \mu^\pm)\ \alpha$; $\alpha \to$ invisible

NEW

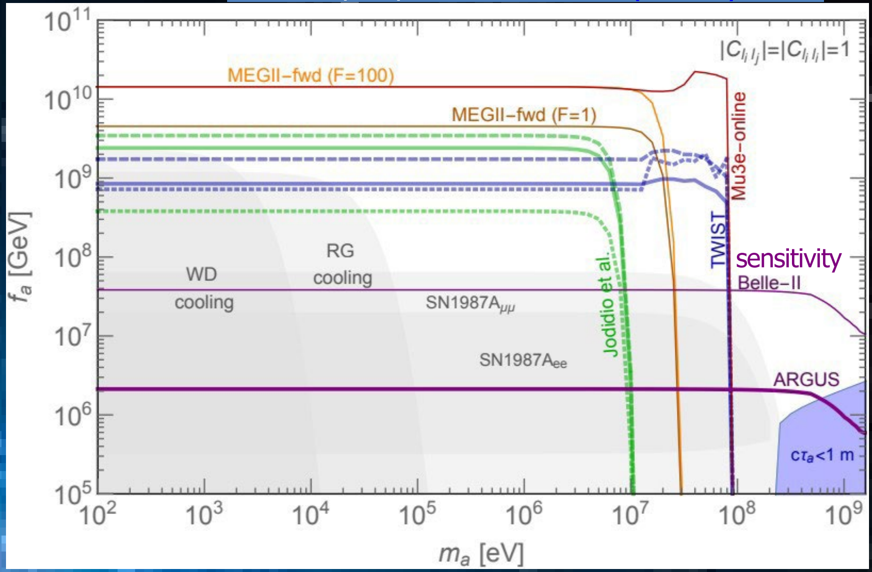
Can be relevant for NP models such as light ALP
→ our search is, however, spin-insensitive

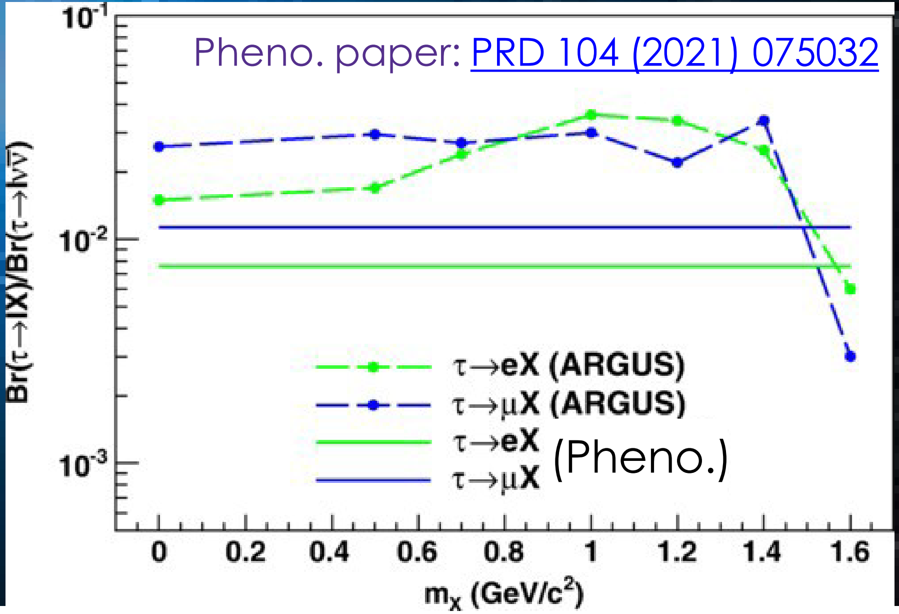
Best upper limits on $B(\tau\to l\alpha)/B(\tau\to l\nu\nu)$ from ARGUS (476 pb^{-1}, Z. Phys. C 68 (1995) 25)

From phenomenology: consistency of $B(\tau\to l\nu\nu)$ with SM predictions

With current data, Belle II can already set more stringent limits

Theo. paper: JHEP 09 (2021) 173





$\tau^\pm \rightarrow (e^\pm / \mu^\pm)\ \alpha$ - Reconstruction

NEW

Dataset: 62.8 fb^{-1}

Split event in two hemispheres across thrust

axis Require exactly 4 tracks:

- 1 lepton on signal side
- 3 pions on tag side
- veto neutrals (γ, π^0) for reducing hadronic background

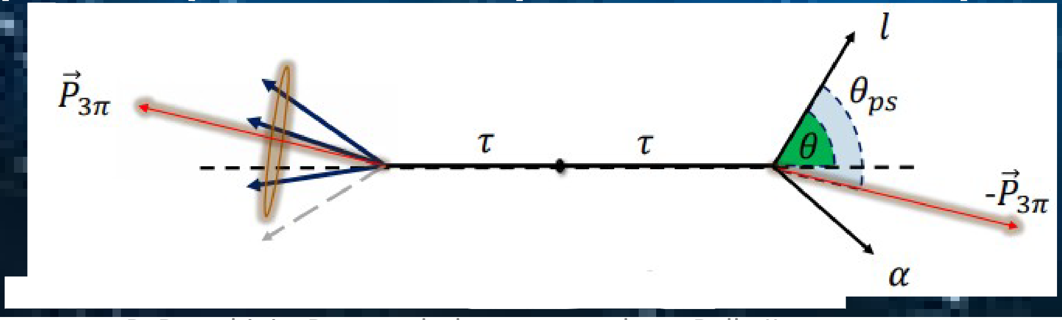
$\tau \rightarrow l\alpha$ events are indistinguishable from $\tau \rightarrow l\nu\nu$ (irreducible background)

Look for a "peak" in lepton spectra computed in the τ pseudo-mass

frame:

$$\hat{p}_\tau \approx -\frac{\vec{p}_{tag}}{|\vec{p}_{tag}|}$$

$$E_\tau \approx \sqrt{s}/2$$

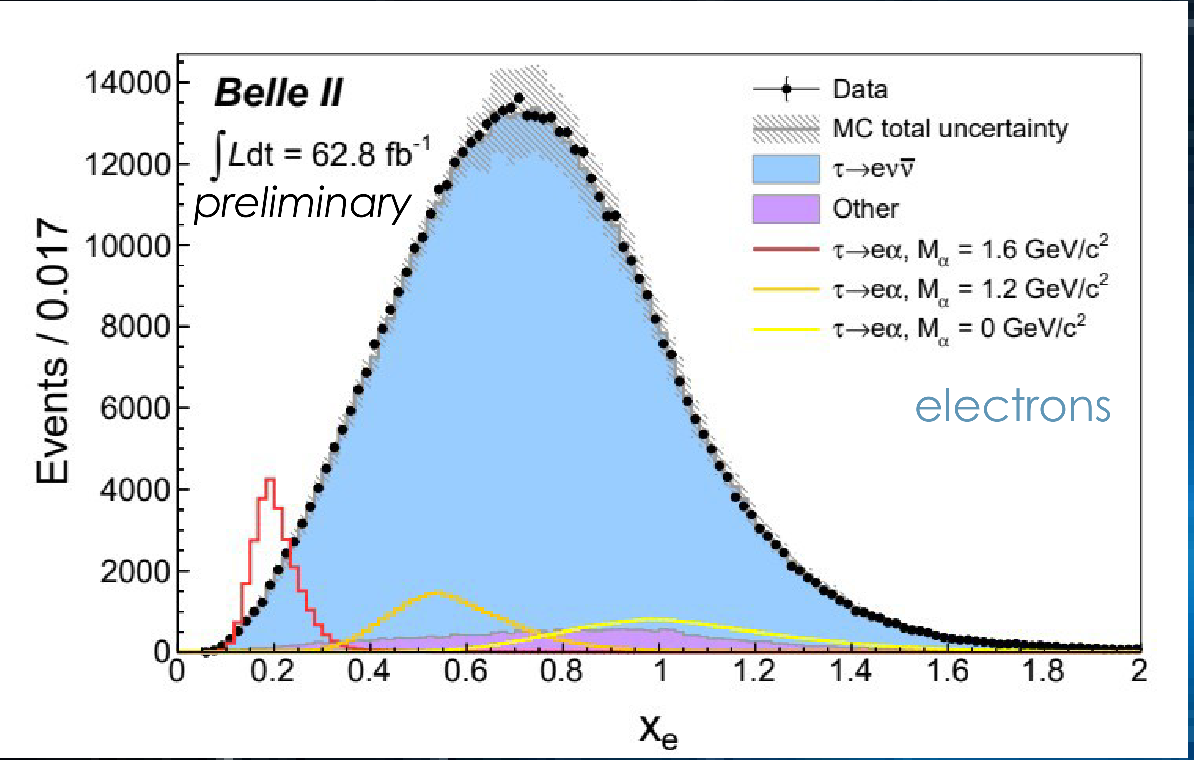


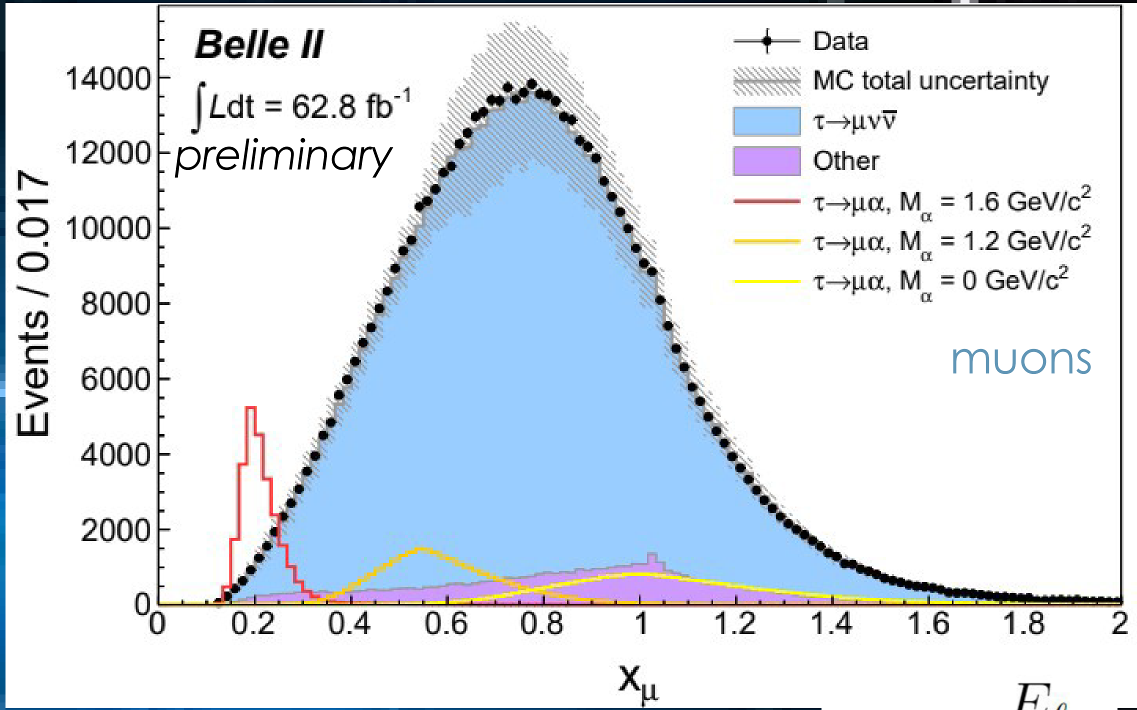
$\tau^\pm \to (e^\pm / \mu^\pm)\ \alpha$ – Data and MC spectra

NEW

Final spectra computed in the τ pseudo-mass frame:

$$\hat{p}_\tau \approx -\frac{\vec{p}_{tag}}{|\vec{p}_{tag}|}\,, \quad E_\tau \approx \sqrt{s}/2$$





$$x_\ell \equiv \frac{E_\ell}{m_\tau/2}$$

Arbitrary normalization for $\tau\to l\alpha$ events ($B(\tau\to l\alpha)$ = 5%)

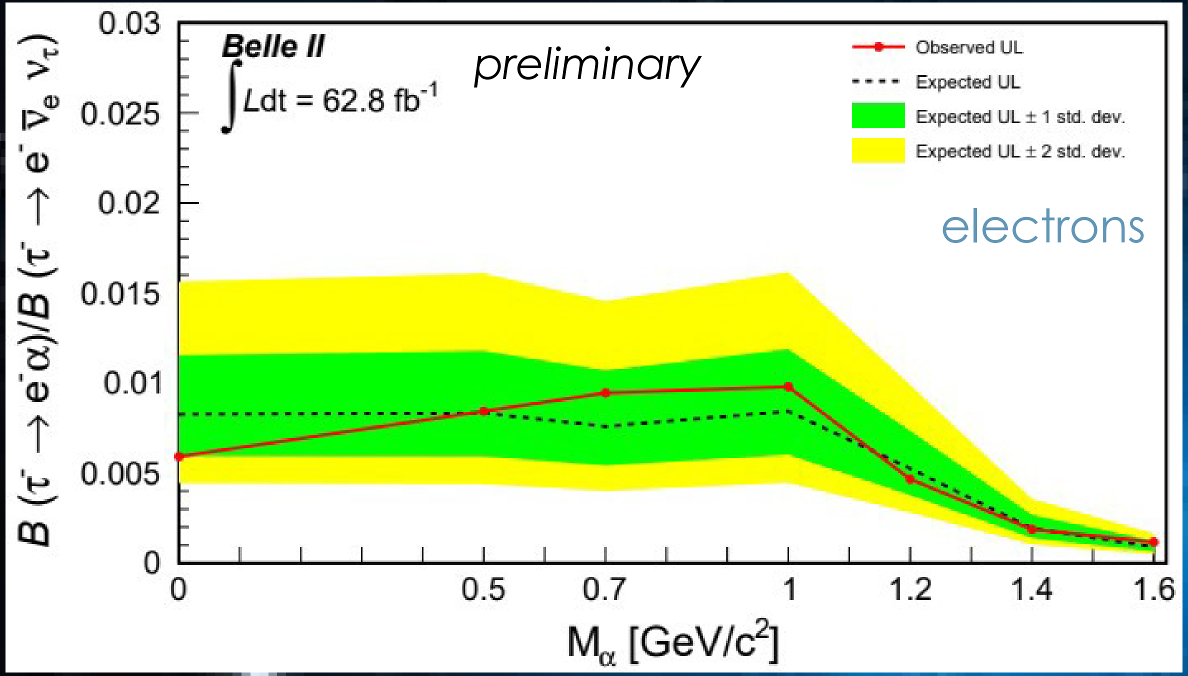
High purity (96% for electron channel, 92% for muon channel)

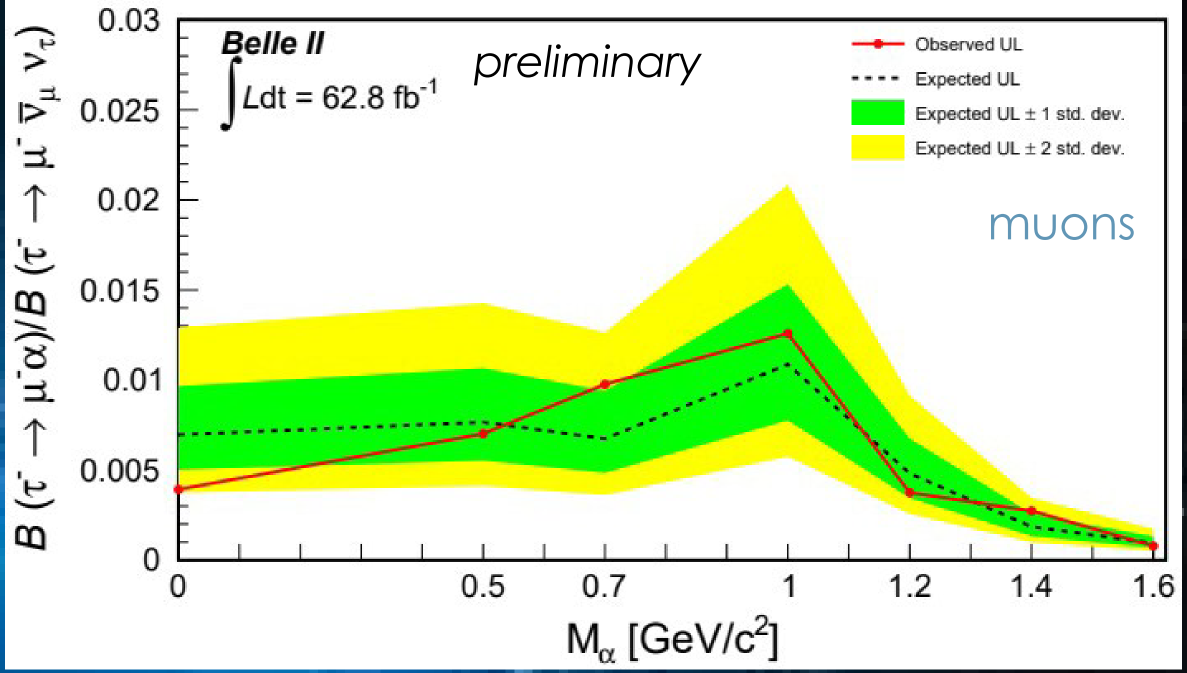
→ efficiency between 9% and 17% depending on Mα

$\tau^{\pm} \rightarrow (e^{\pm} / \mu^{\pm})\ \alpha$ – Results

NEW

No signal observed → set 95% CL upper limits





Largest systematics from particle identification

Most stringent measurements in these channels to date

Summary

- Negative results from LHC and direct search experiments → light dark sector scenario more and more attractive

- Belle II at SuperKEKB has great potential thanks 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

Summary

- Today World-leading results for searches of:
  - Dark Higgsstralung $e^+e^- \to A'h'$, with $A' \to \mu\mu$ and h' invisible
  - Invisible Z' within the L_μ-L_τ model
  - $Z' \to \tau\tau$ within the L_μ-L_τ model
  - Leptophilic dark scalar $S \to \tau\tau$
  - Axion-like-particle $a \to \tau\tau$
  - $\tau^\pm \to (e^\pm / \mu^\pm)\ \alpha,\ \alpha \to$ invisible
  - New seaches going on in B decays ($B^+ \to K^+ + S$ and $B^+ \to K^+ + A$)

  so… stay tuned!
- We expect to lead the light dark sector searches in the next decade

SPARE SLIDES

Z' / S / ALP → $\tau^+\tau^-$ - Reconstruction

NEW

Dataset: 63.3 fb^{-1}

Basic selections:

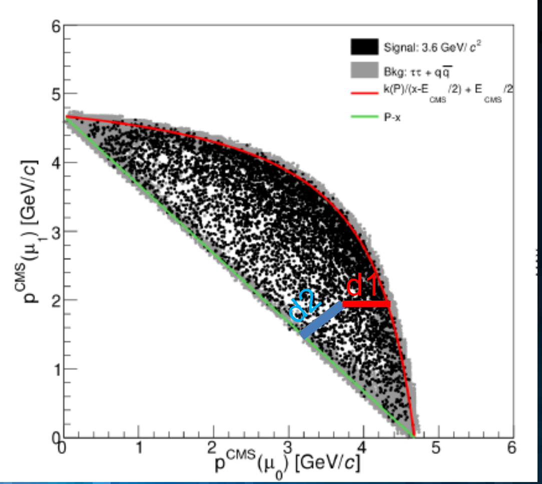
- considering only 1-prong τ decays
  → require 4 tracks
- $2\mu + 2e/\mu/\pi$
- M(4 tracks) < 9.5 GeV
- allowed neutrals
- scan $M_{recoil}(\mu\mu)$

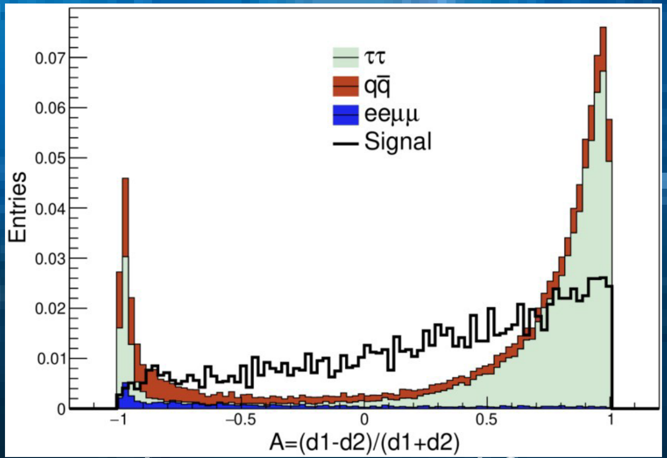
Main backgrounds:

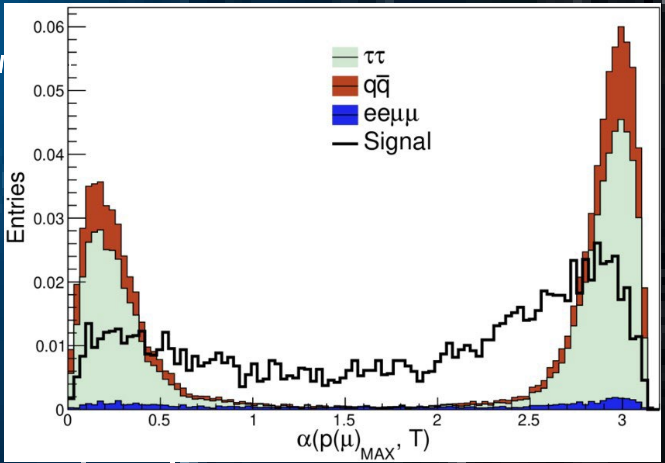
- $\tau^+\tau^-(\gamma)$ (1x3-prongs events)
- qq
- $l^+l^-l^+l^-$ (no ISR in our simulation)
  $\mu^+\mu^-\pi^+\pi^-$ + $e^+e^-X_{had.}$ (not simulated)

Background suppression via dedicated Neural Network
→ 8 NN ranges in $M_{recoil}(\mu\mu)$

Belle II simulation

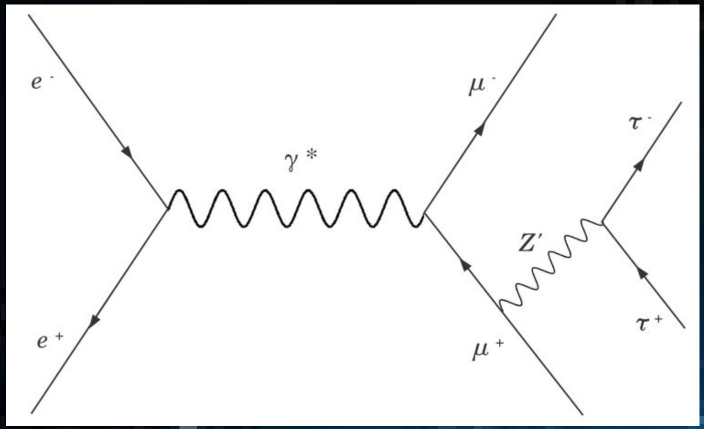






Selection optimized for $Z' \to \tau^+\tau^-$ signal
→ achieved 99% background reduction

Z', S, ALP → ττ



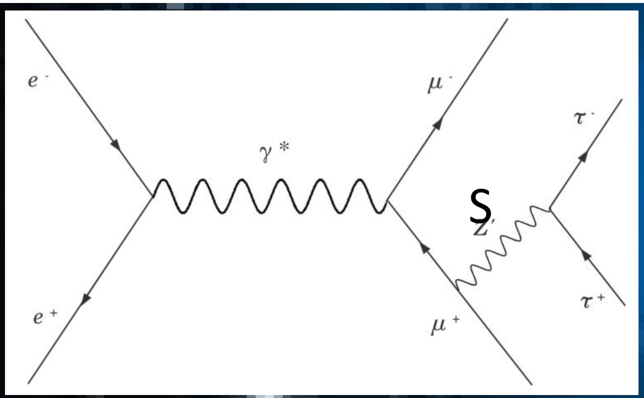
Z' L_μ - L_τ model

First time search in ττ

vector portal

μμττ final states

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



Leptophilic scalar S model

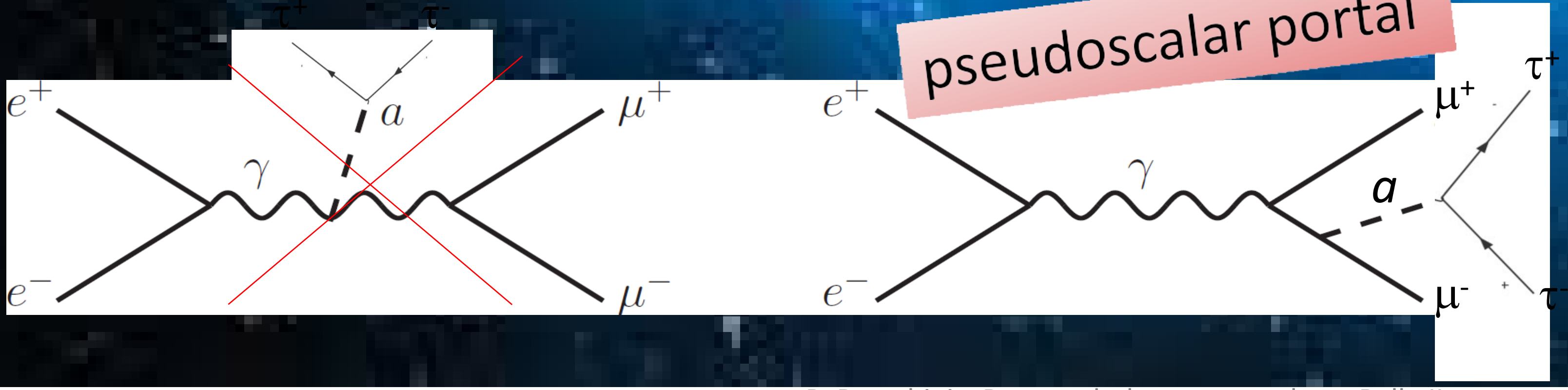
Yukawa couplings

Contraints by BaBar in S→μμ

First time search in ττ

scalar portal

pseudoscalar portal



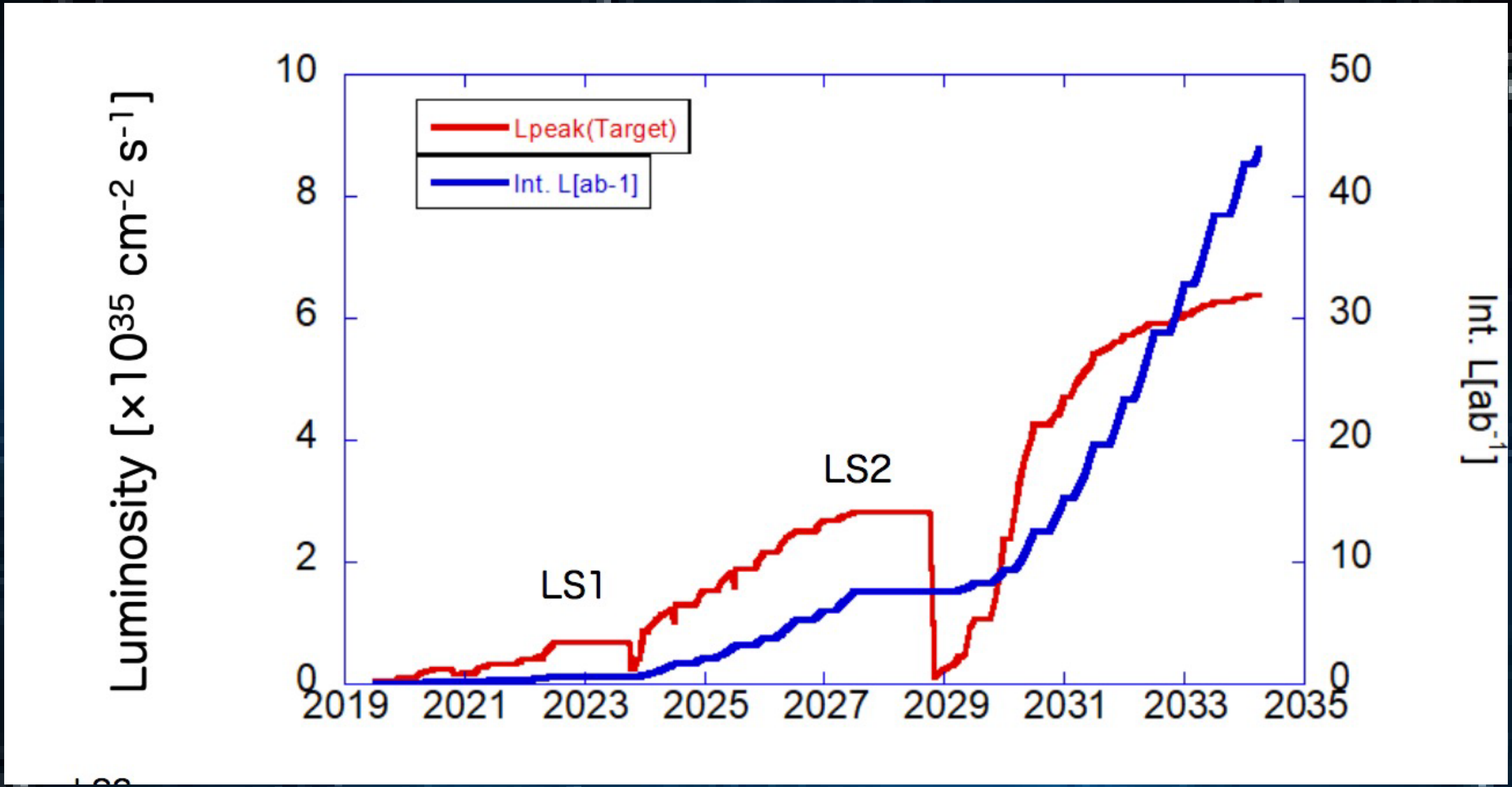
ALP → ττ

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

Yukawa-like effective couplings

ALP-τ coupling unconstrained

From KEKB to SuperKEKB: long term plan



Final goal : 50 ab^{-1}

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

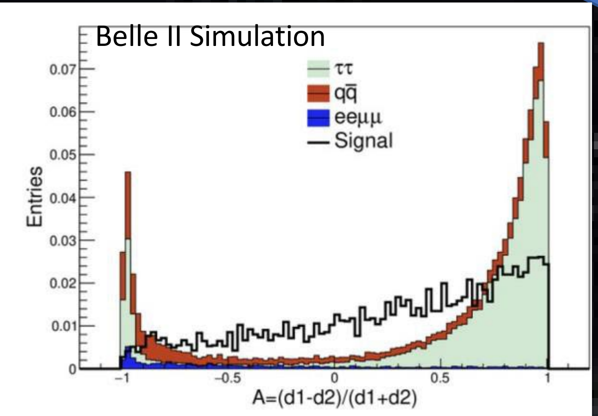
Main backgrounds

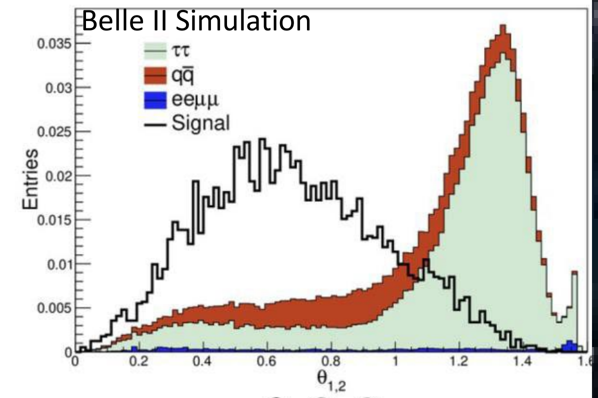
$e^+e^- \to \tau^+\tau^- (\gamma)$ 1+3 prong
$e^+e^- \to q\bar{q}$ (q=u,d,s,c)

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

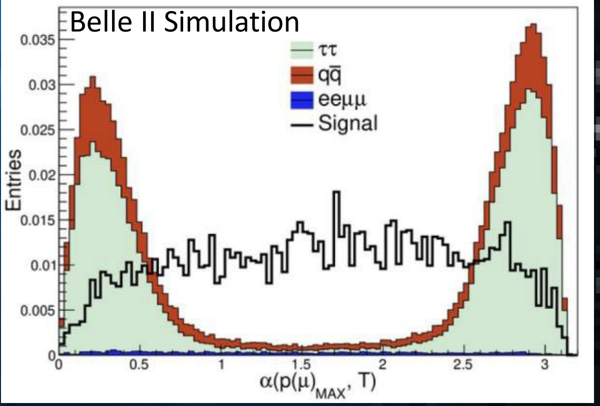
$e^+e^- \to \mu^+\mu^-\pi^+\pi^-$ not simulated

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



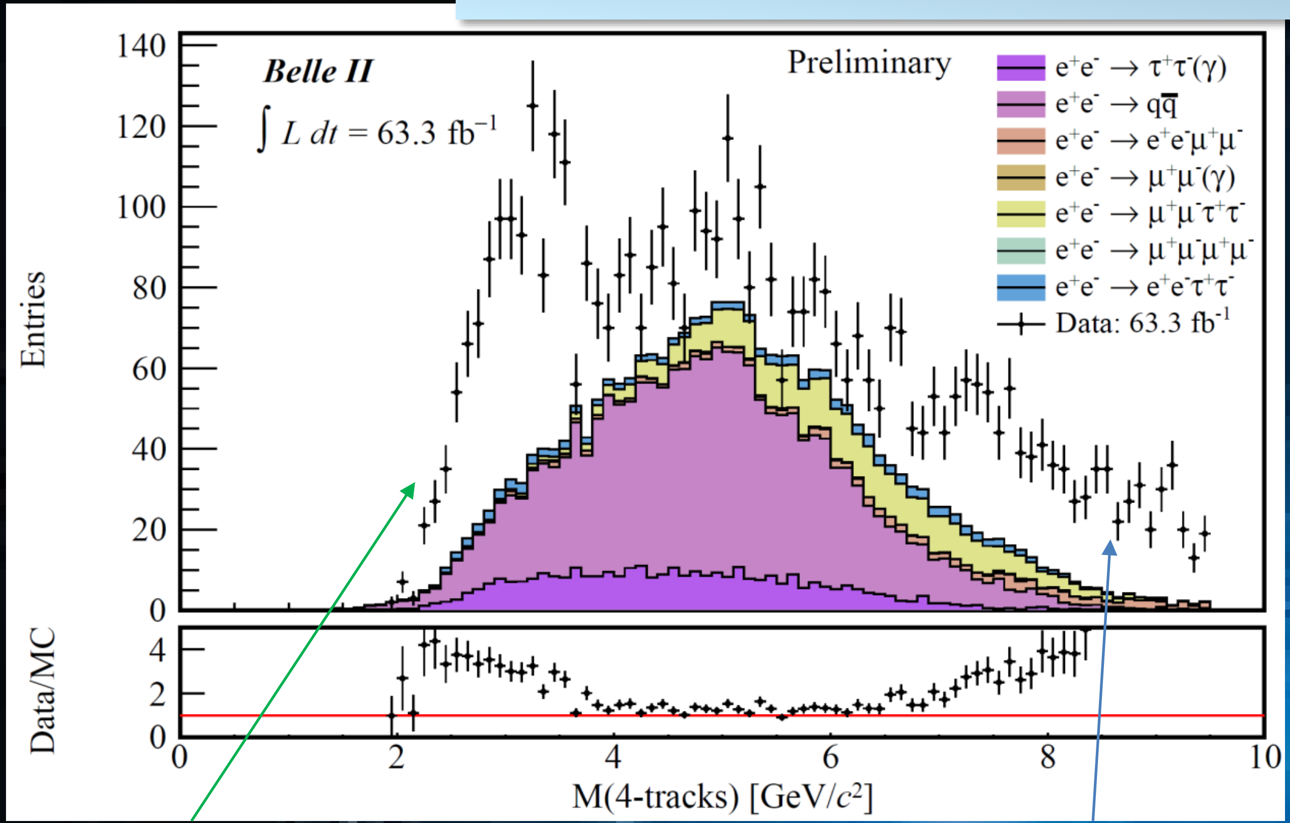


• • •



Z', S, ALP → ττ: observed yields

NEW

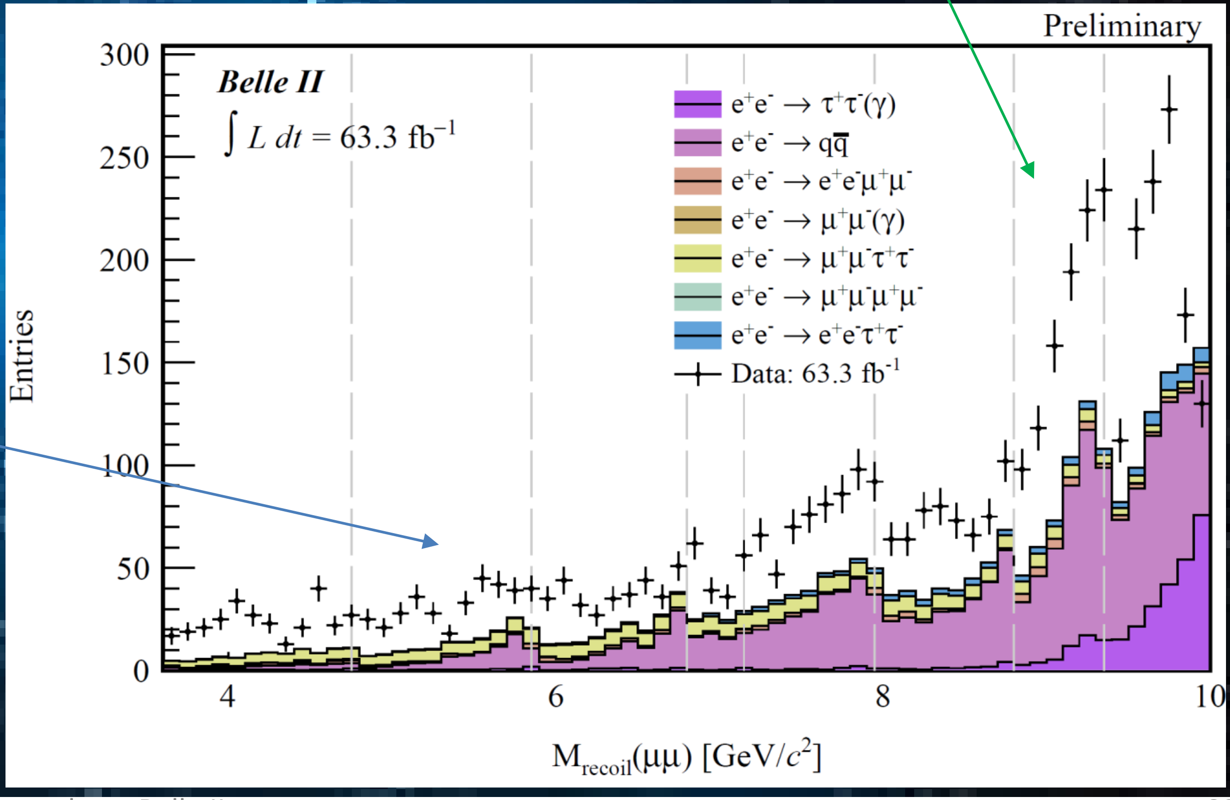


$e^+e^- \to e^+e^-\ X_{hadronic}$

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 $M_{recoil}(\mu\mu)$

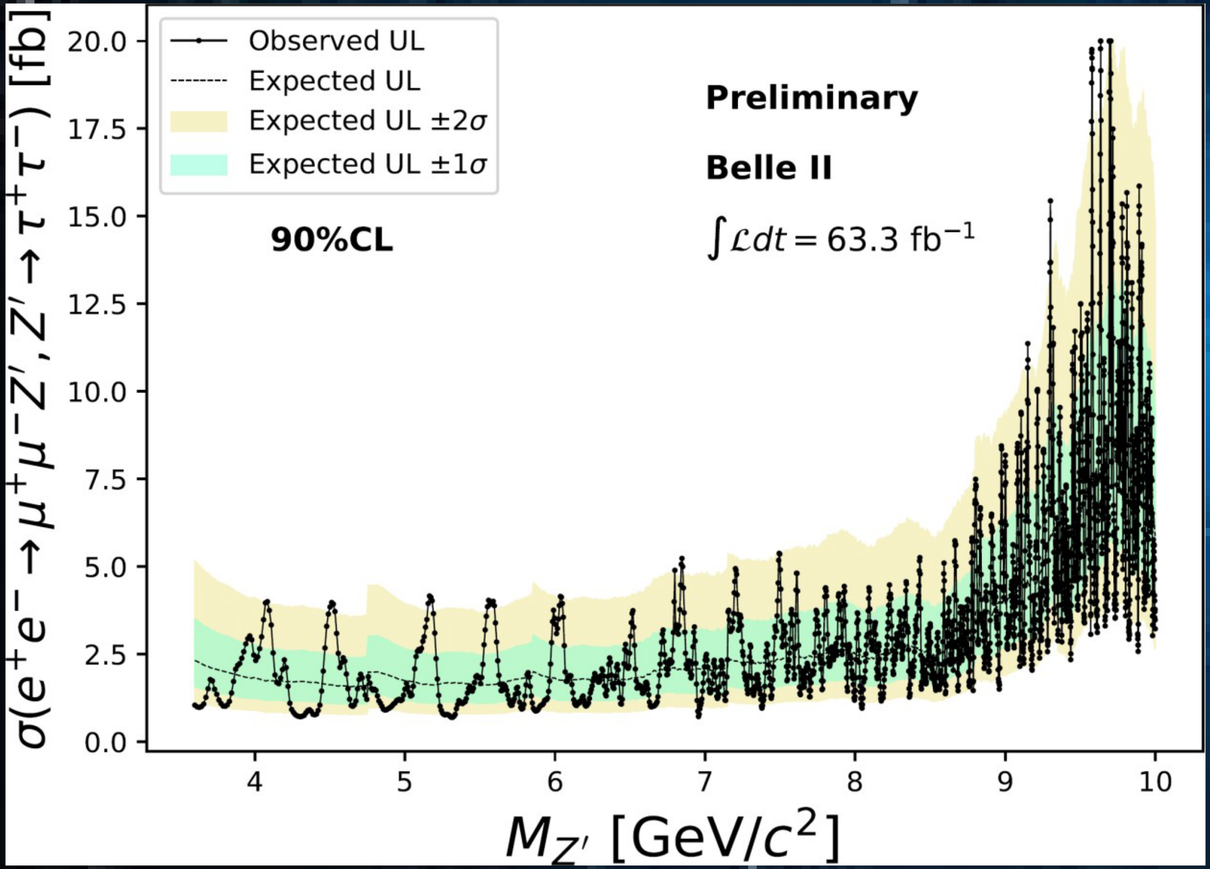
- signal mass resolution: 1.5 – 30 MeV/c^2

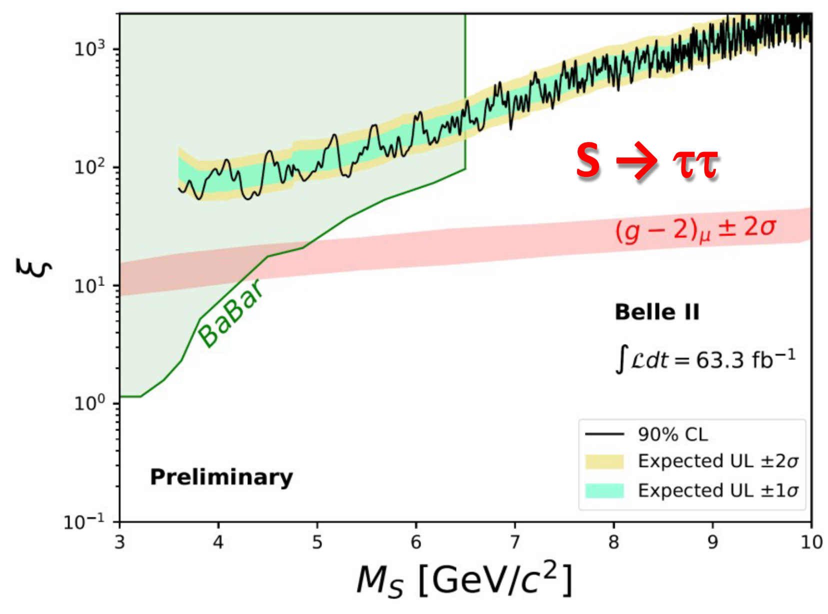
Background floated in the fit

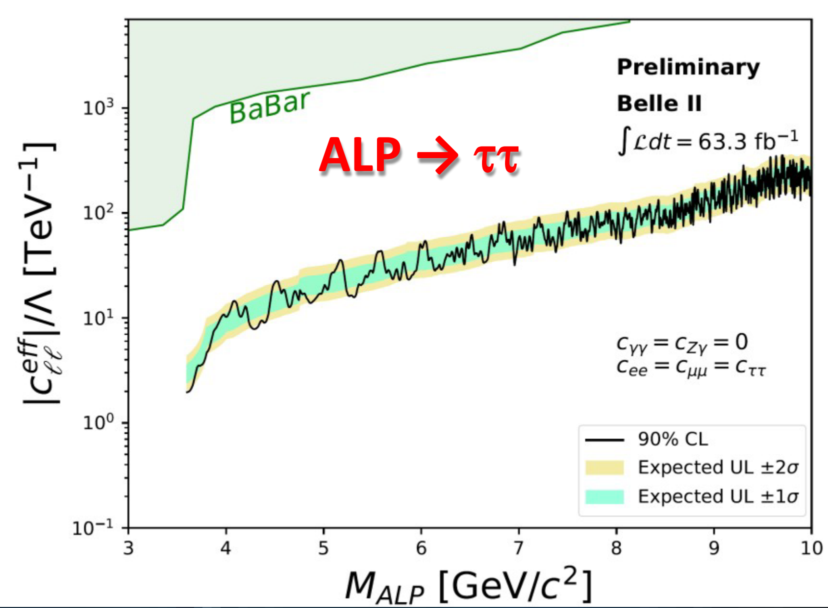
Z', S, ALP → ττ: results

NEW

- No excess found
- Set 90%CL exclusion limits on cross section and couplings
  - First constraints on S for $M_S > 6.5$ GeV/c²
  - First direct constraints for ALP → ττ







From KEKB to SuperKEKB

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

Lorentz factor

Beam current

Beam-beam parameter

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

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

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

Classical electron radius

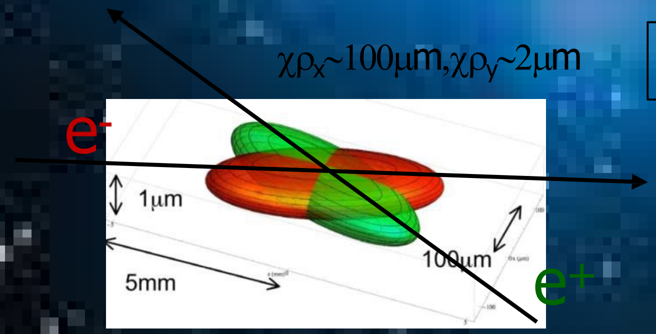
Beam size ratio@IP
1 ~ 2 % (flat beam)

Vertical beta function@IP

x30

β^*_y=0.30/0.30 mm
$I_{+/-}$=2.8/2.0 A

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



Nano-Beam scheme

Final goal : 6×10^{35} $cm^{-2}s^{-1}$ 50 ab^{-1}

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

From KEKB to SuperKEKB

Super KEKB
uest for BSM

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

Beam-beam parameter

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

Lorentz factor

Beam current

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

Classical electron radius

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

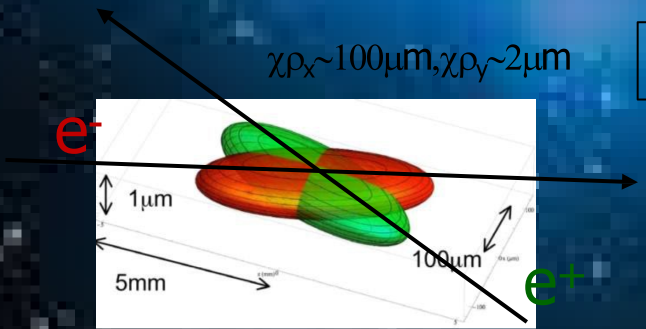
Vertical beta function@IP

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

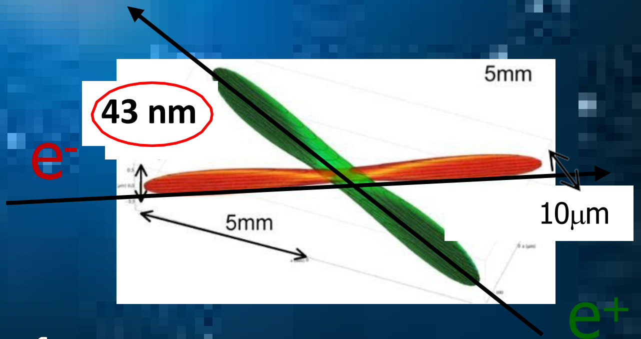
x30

β^*_y=0.30/0.30 mm
$I_{+/-}$=2.8/2.0 A

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



Nano-Beam scheme



Final goal : $6x10^{35}$ $cm^{-2}s^{-1}$ 50 ab^{-1}

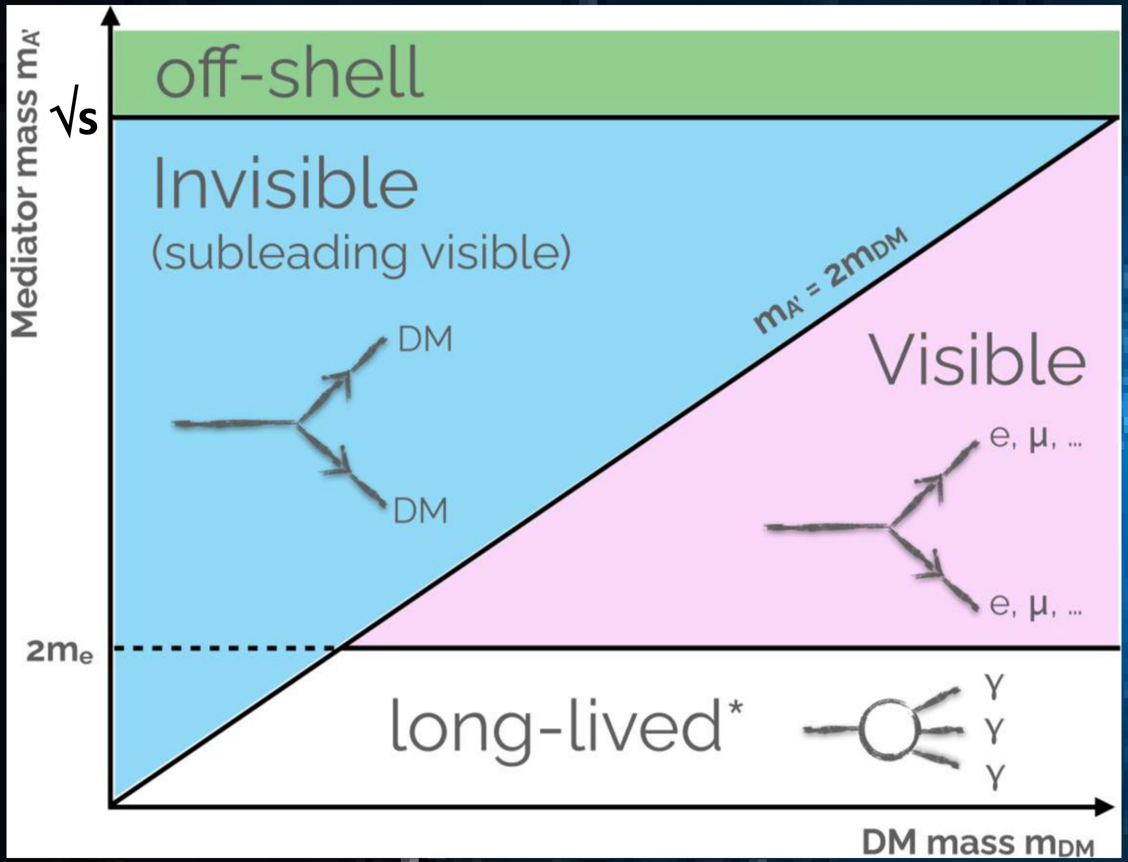
... For a 30x increase in intensity you have to make the beam as thin as a few x100 atomic layers

Limitation found so far

- Shorter beam lifetime than expected
  - As a result, the maximum bunch currents are limited by the balance between the lifetime and the injection power.
- Lower bunch-current limit than expected due to TMCI
  - Due to higher impedance of beam collimators, in which the apertures are smaller than the design values to suppress high background.
- Beam-beam effect (vertical beam size blow-up)
  - Relaxed by the crab-waist collision scheme, but still remains.
- Low operation efficiency
  - Operation efficiency during 2021a, b is almost 0.5, lower than expected one, 0.65.
  - Machine tunings, machine troubles, maintenance, etc.
- Aging of hardware and facilities, and so on.

Light Dark matter hunt

Different signatures depending on the DM ↔ mediator mass relation

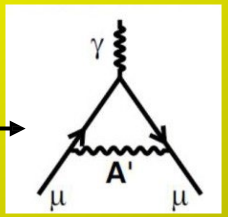


Probability of interaction of LDM detectors is negligible

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

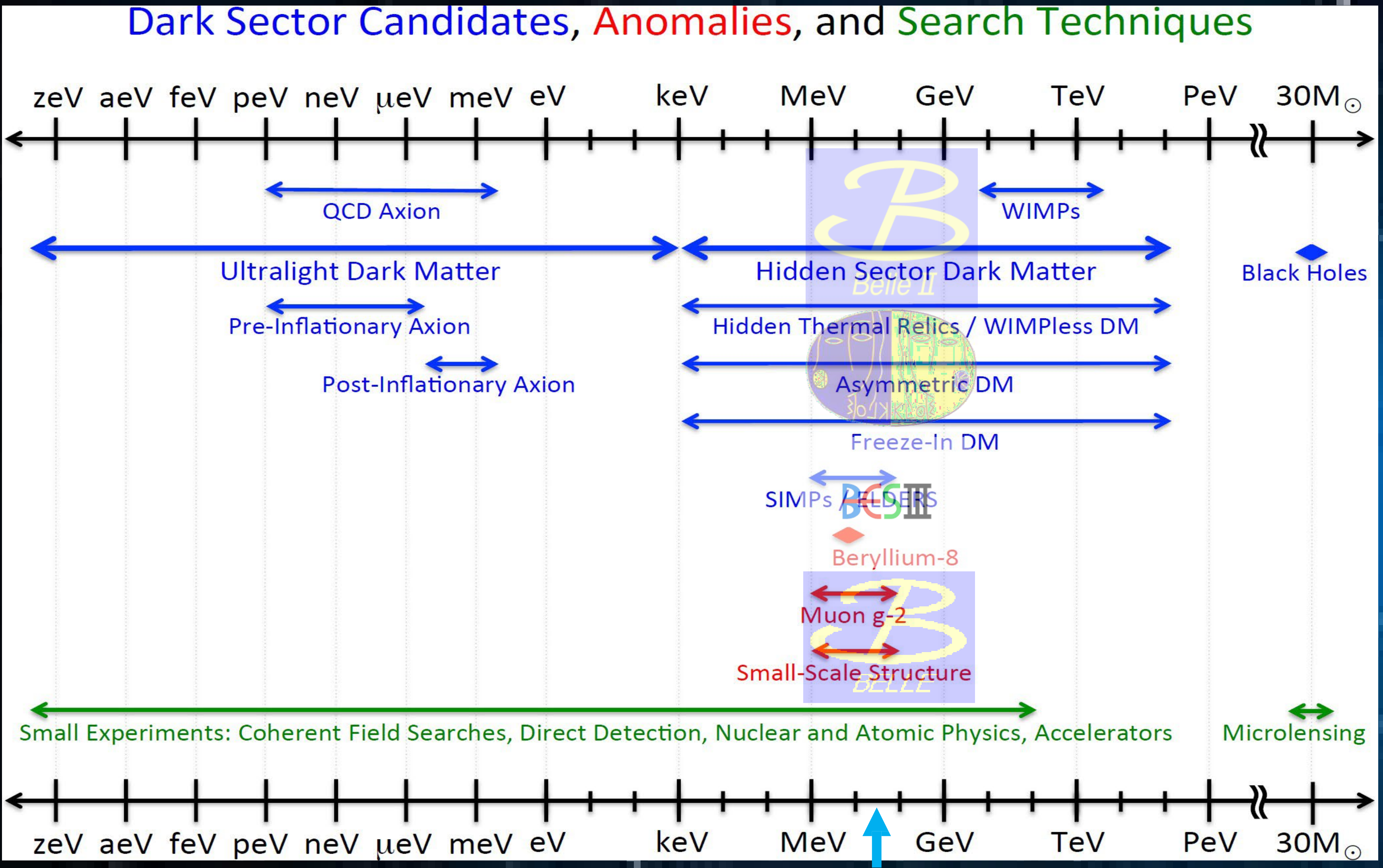
Additional benefits:

- 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

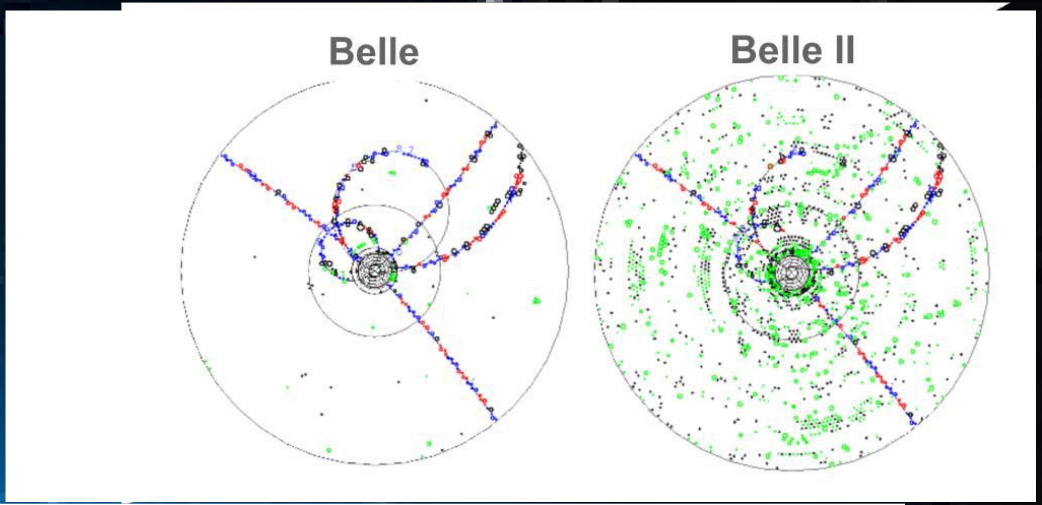
Level 1 hardware-based combines info from CDC, ECL, KLM
- Tracks, clusters, muons

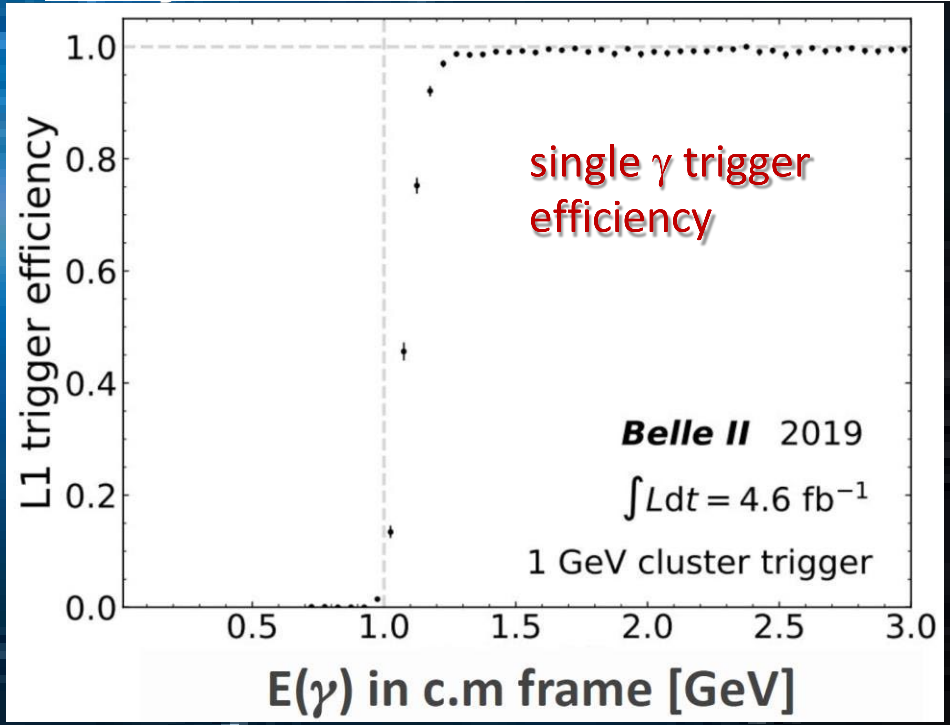
- Two-track trigger
- Three-track trigger
- E_{ECL}> 1 GeV trigger

Single muon
- CDC + KLM

Single track
- Neural based

Single photon
- E_γ > 0.5, 1, 2 GeV



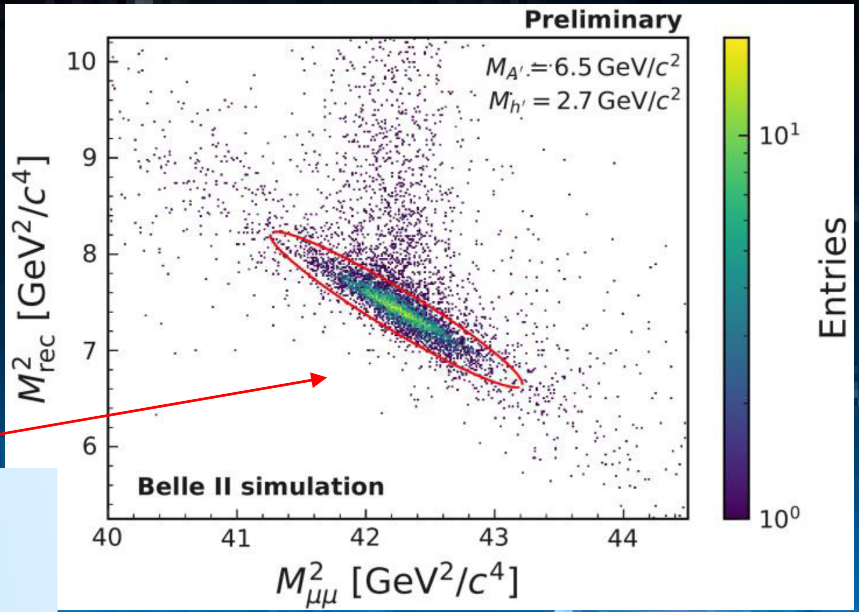


Dark Higgsstrahlung: analysis

Moriond

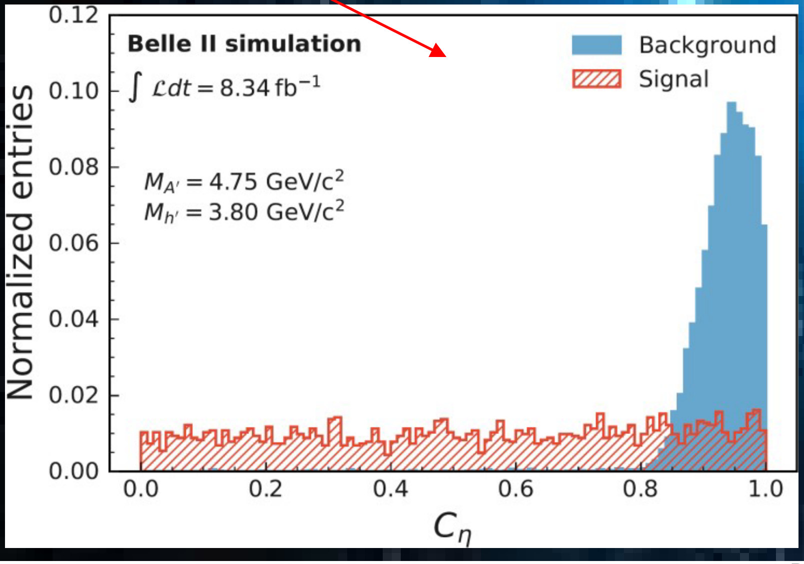
8.34 fb^{-1} (2019)

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



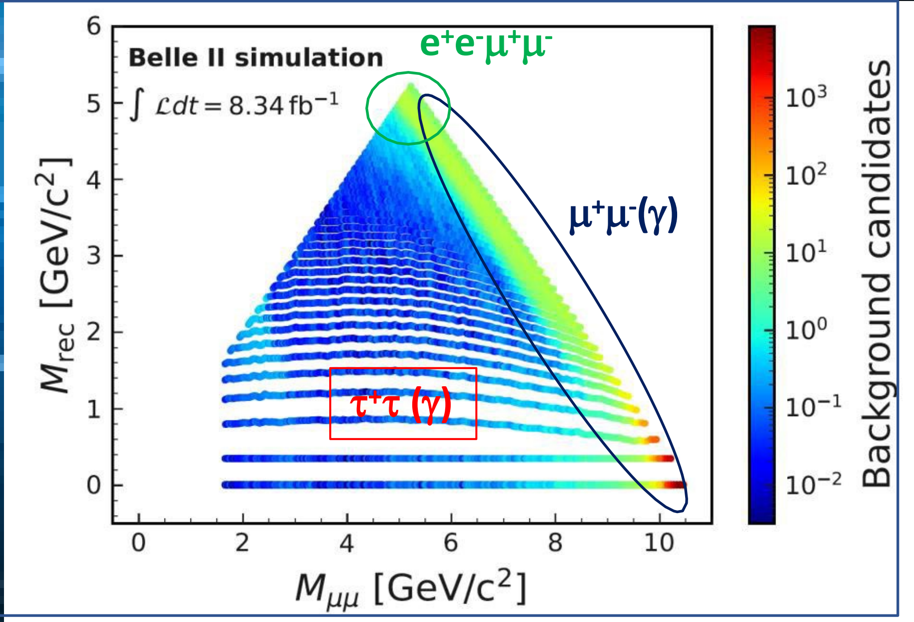
~9000 overlapping elliptical mass windows

Helicity angle



Backgrounds

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



Dark Higgsstrahlung: systematics

2 control samples

μμγ μμ(γ) background
eμ ττ background

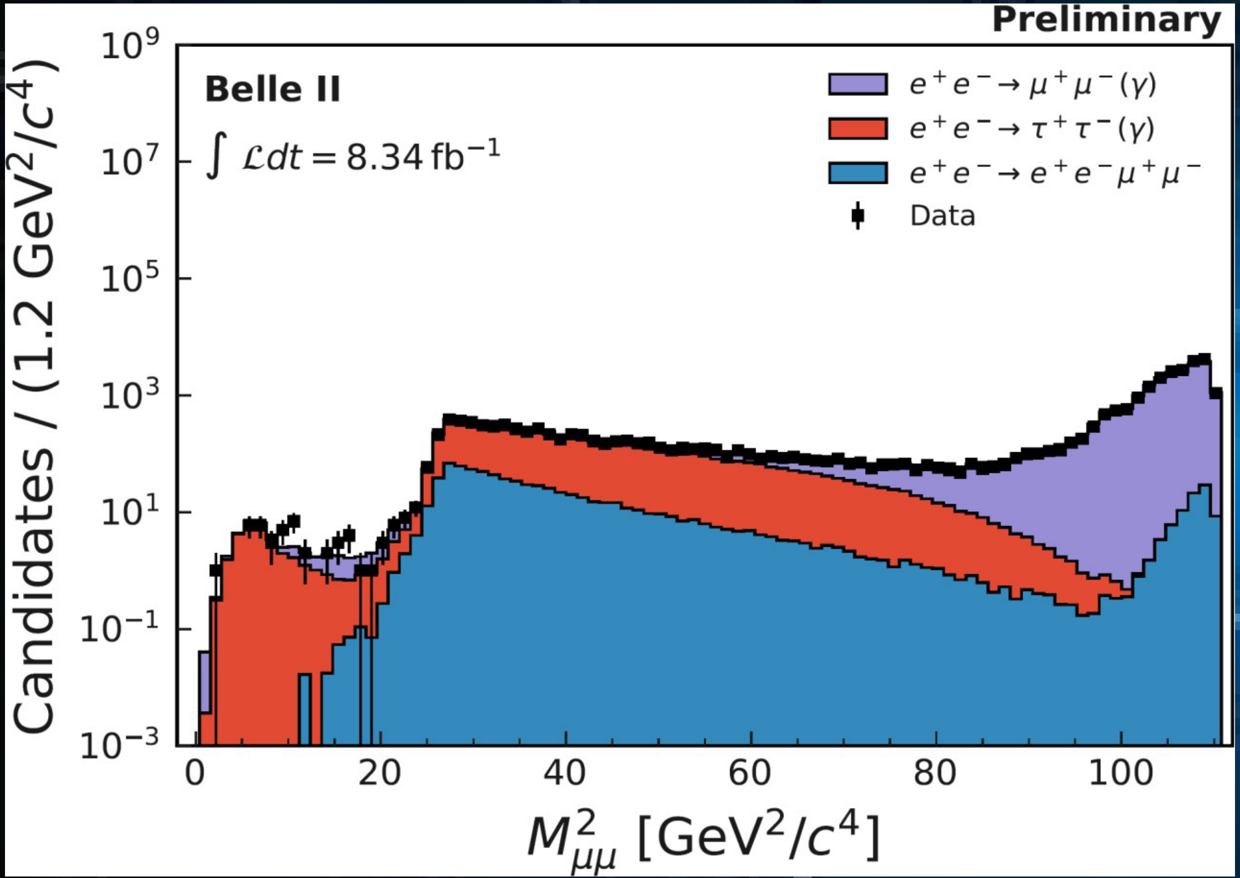
Split mass plane into orthogonal macroregions
- Each dominated by a single background source
- Data/MC normalization + shape

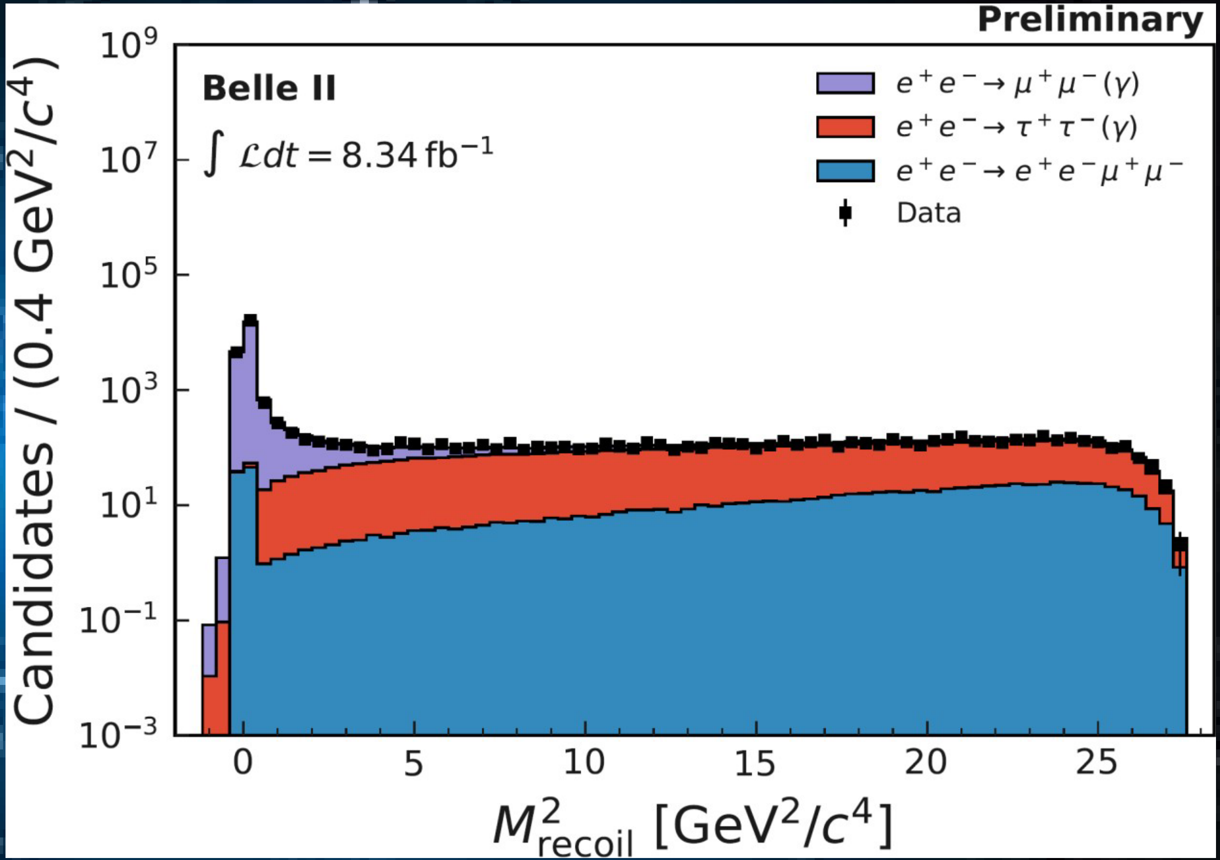
source	uncertainty	target
Pre-selections	**2 - 9.1%**	BKG & signal
BKG shape	**9.3%** (region specific)	BKG
C_η cut	**1%**	BKG
Mass resolution	**2.4%** (on average)	signal
Eff. Inside windows	**2 - 5%**	signal
Theory (BR A')	**4%**	signal

- Negligible effect on ULs (~1%)
- Exception is $M_{A'}$ > 9 GeV/c² (~25%)

Dark Higgsstrahlung: data/MC

Moriond

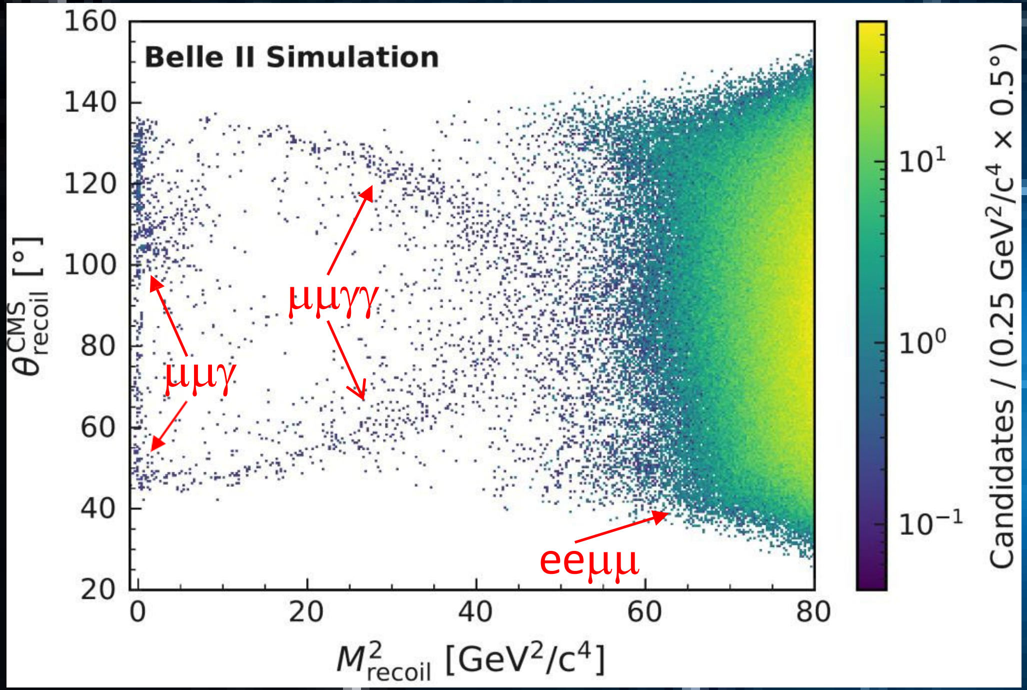




Z' to invisible: systematics

NEW

- $\tau^+\tau^-(\gamma)$ almost 100% suppressed
- $\mu^+\mu^-(\gamma)$ dominates up to ~7 GeV/c²
- $e^+e^-\mu^+\mu^-$ 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	

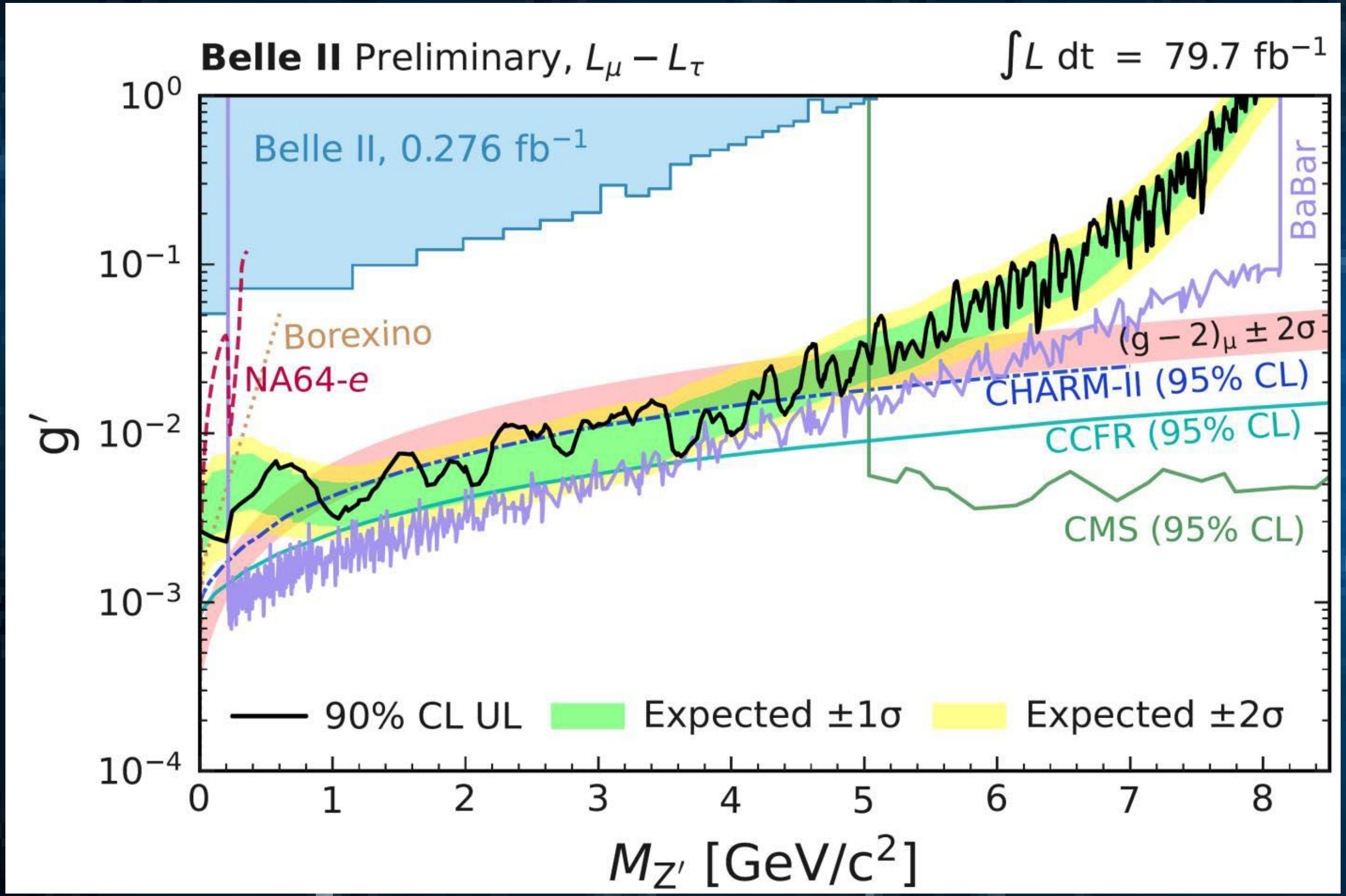
Systematics

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

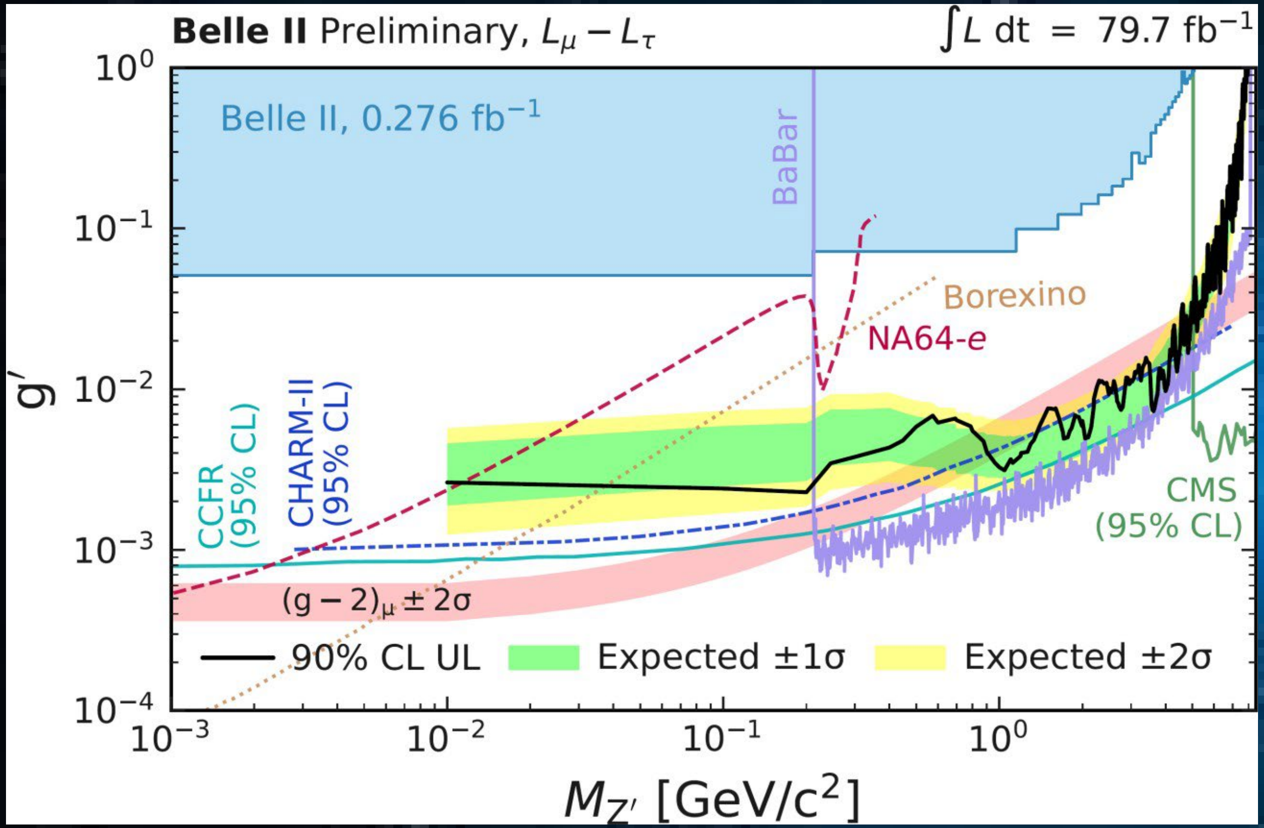
Vanilla model invisible Z'



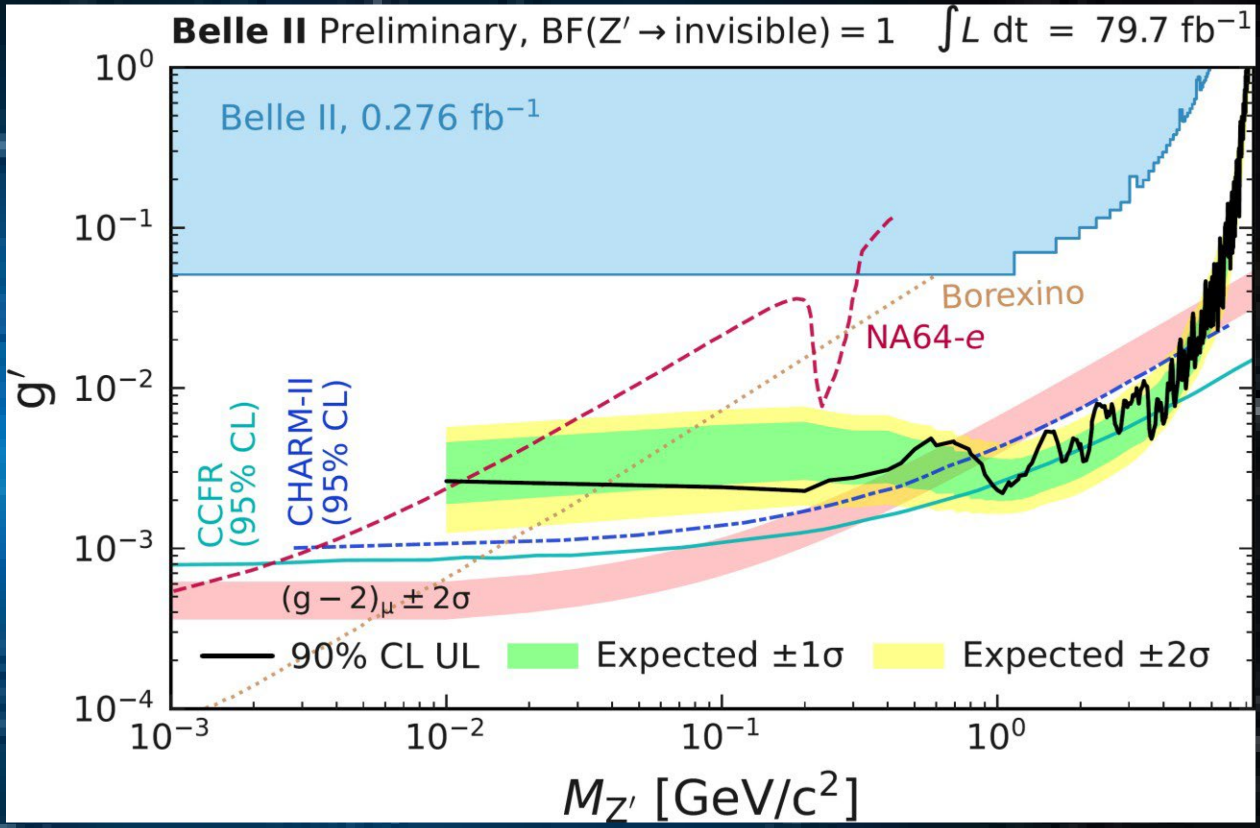
Z' to invisible results

NEW

Vanilla model invisible Z'



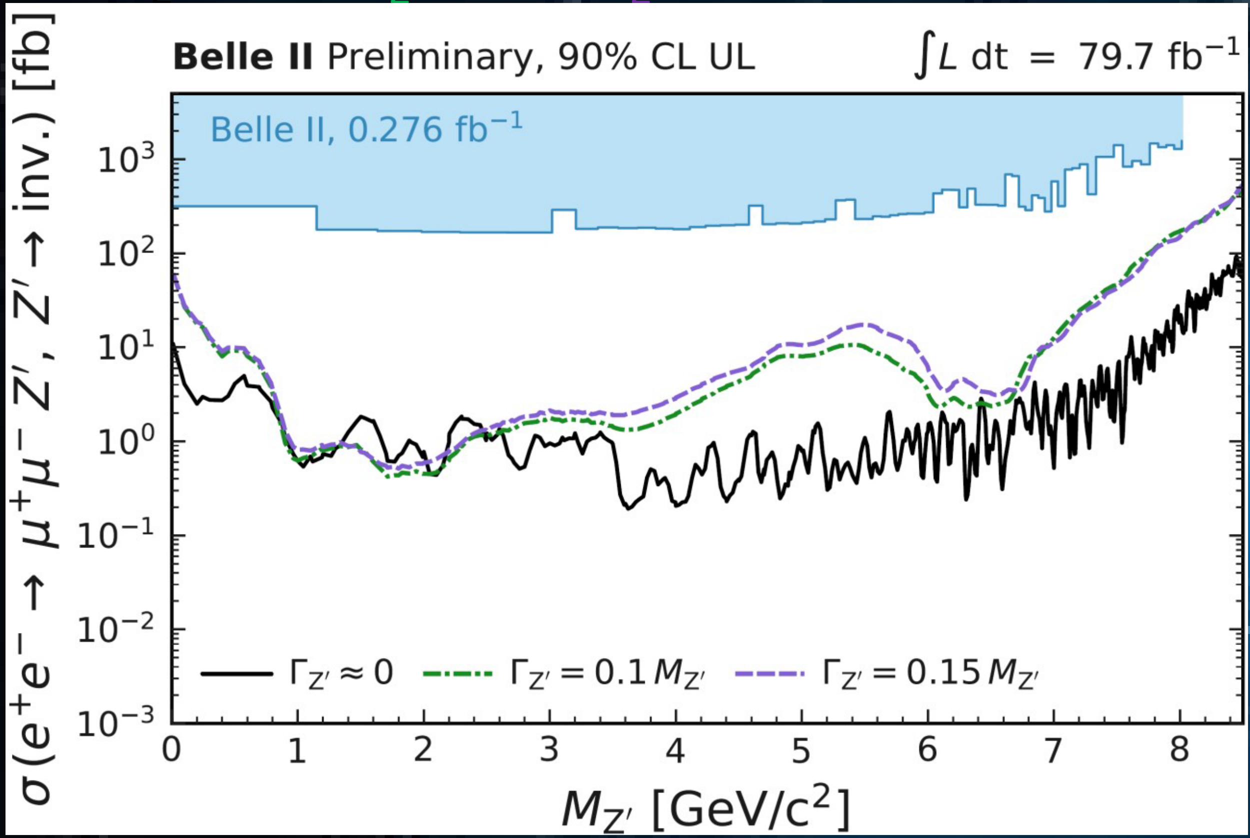
Fully invisible Z'

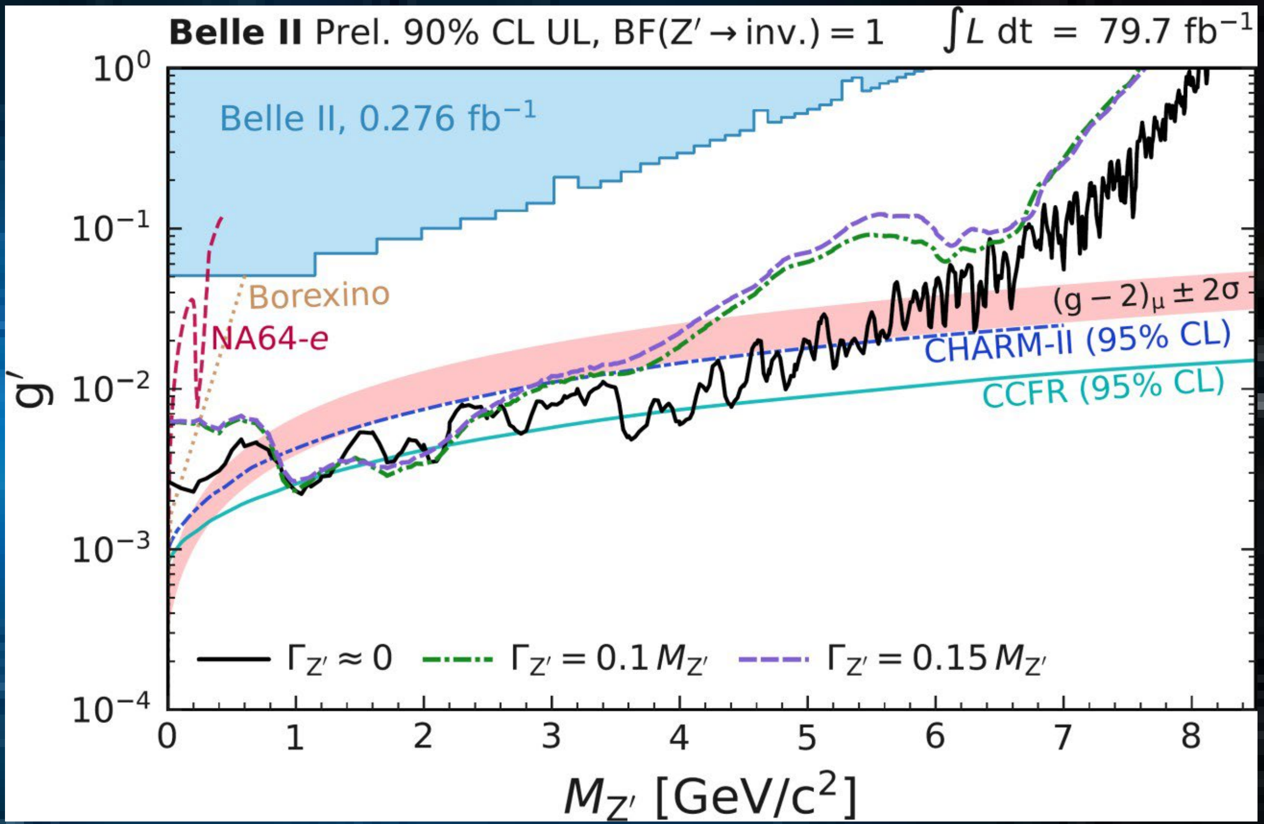


Z' to invisible results

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%