Search for dark photons at future e^+e^- colliders

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Second ECFA Workshop on e+e- Higgs/EW/Top Factories
October 11-13, 2023, Paestum (Salerno)

Introduction: Dark Matter

Bullet cluster

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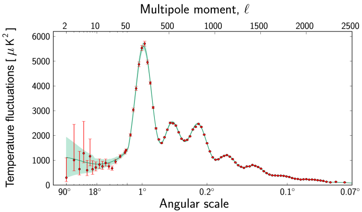

Plank CMB

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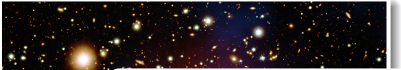

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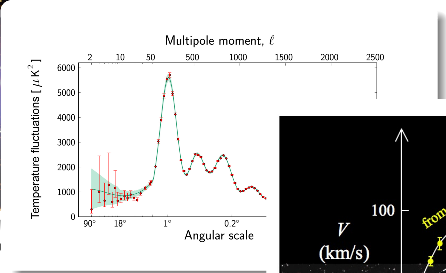

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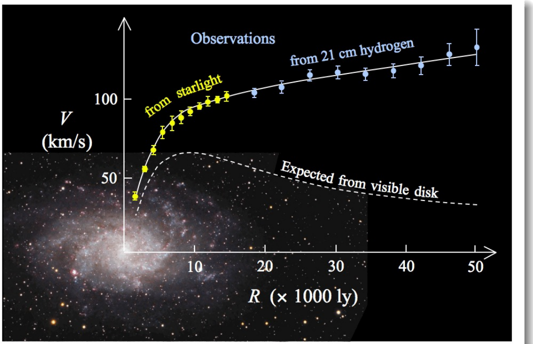

M33 rotation curve

Introduction: Dark Matter

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So ...

There *is* Dark Matter:

- WIMPs are still a good candidate....
- ... but still not seen.
- Other idea: Dark Matter lives in a dark, hidden sector $\Rightarrow$ FIPS.

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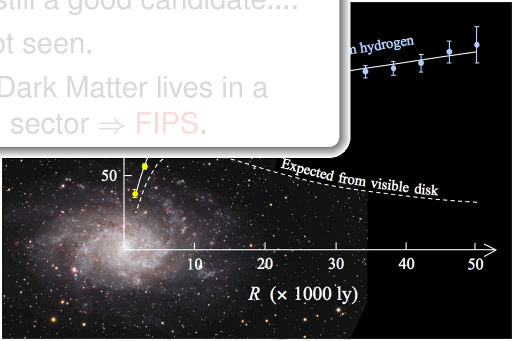

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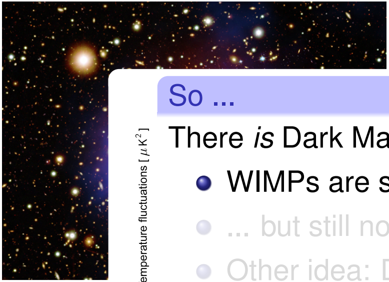

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Temperature fluctuations [μK^2]

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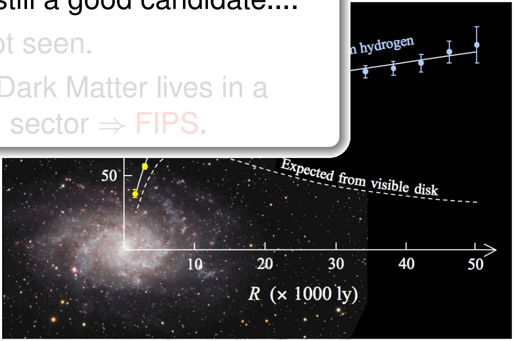

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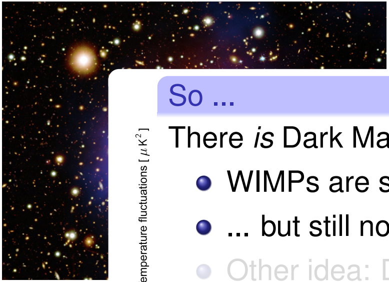

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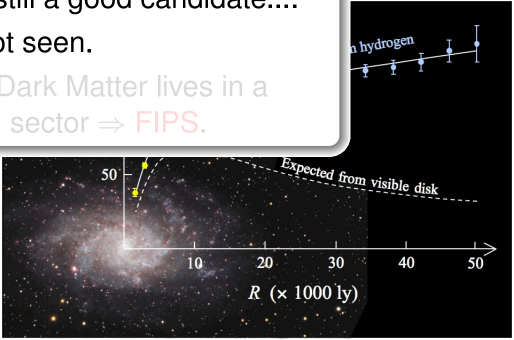

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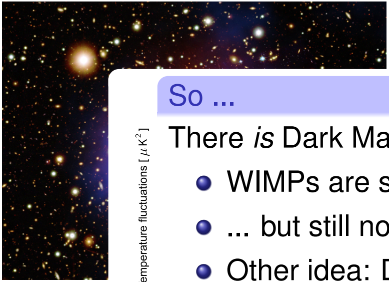

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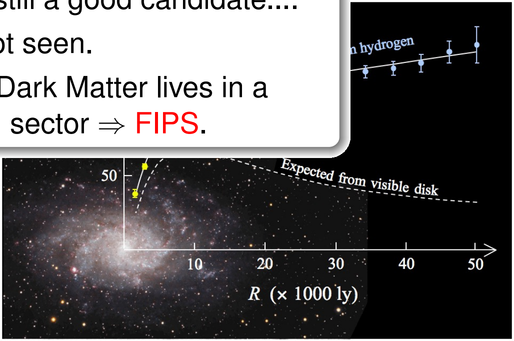

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Introduction: FIPS

Feebly interacting particles is a class of models explaining dark matter and why it's not yet been seen in a different way.

- Generically, FIPS are models where rather than having heavy new particles with sizeable couplings, the new physics might be light, but much more weakly coupled.
- So, the reason why the BSM has not yet been seen is not the lack of energy, but the lack of precision - be it luminosity, background contamination or detector performance.

Introduction: FIPS

Types of FIPS, and how to detect them

- The Higgs Portal: Dark Higgs
- The fermions Portal: Sterile Neutrinos.
- The Pseudoscalar Portal: Axions (and ALPS)

and

- The Vector Portal: Dark photons

which is what we will discuss here.

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The Vector Portal - Dark Photons, A_D

- Assume that there is a dark sector with a dark U(1) symmetry
- The relevant part of the Lagrangian is $\mathcal{L}_{gauge} = -\frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} - \frac{1}{4}\hat{Z}_{D\mu\nu}\hat{Z}_D^{\mu\nu} + \frac{1}{2}\frac{\epsilon}{\cos\theta_W}\hat{Z}_{D\mu\nu}\hat{B}^{\mu\nu}$. $\hat{B}$ is the ordinary U(1) field-strength tensor, and $\hat{Z}_D$ that of the dark U(1).
- The Dark Photon might mix with the photon by *kinetic mixing* - the $\hat{Z}_D\hat{B}$ term - , so that $e^+e^- \rightarrow A_D \rightarrow f\bar{f}$ is possible.
- The (arbitrary) mixing parameter ϵ must be small, so the coupling is weak. There will be few events, but the decay will form a very narrow peak, or even a displaced vertex.
- Note that the dark photon itself is not the dark matter, since it isn't stable ... Something else in the dark sector that is stable is needed in addition.

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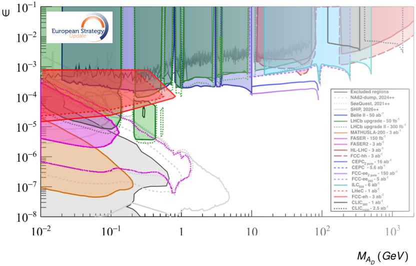
Dark Photon limits from the EPPSU

Current projections form the European Particle Physics Strategy Update of 2019

- All experiment, log mass-scale (from the EPPSU briefing book.)
- Masses up to $\sim$ 1 GeV: LLPs detected in Beam-dump experiments. Sensitive to very small couplings
- Beyond that: colliders
  - Up to 10 GeV: B factories - extremely high luminosity.
  - Then: e^+e^- up to their maximum energy
  - ... and beyond that pp colliders.



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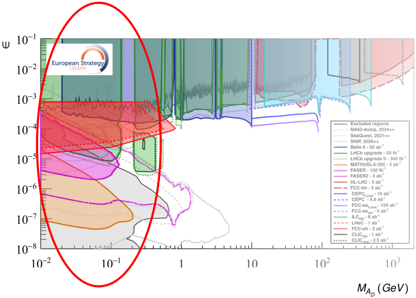

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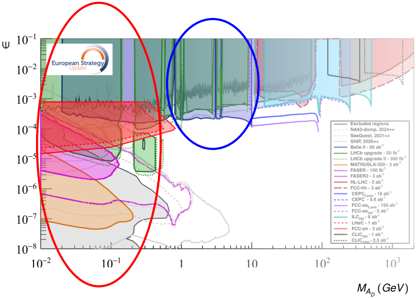

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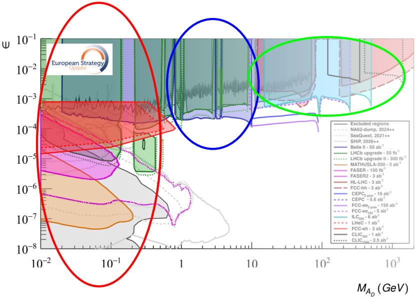

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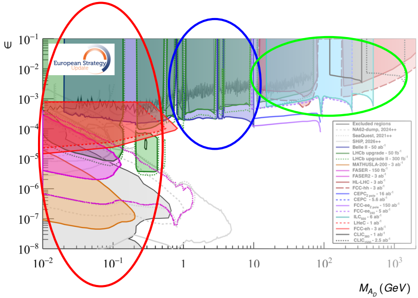

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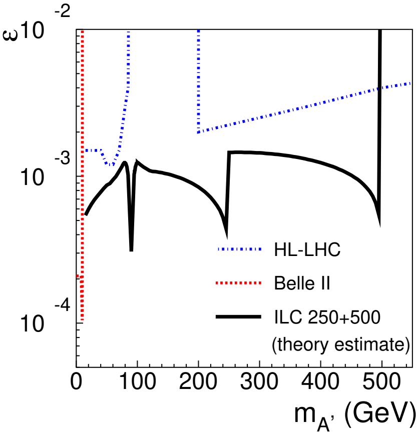

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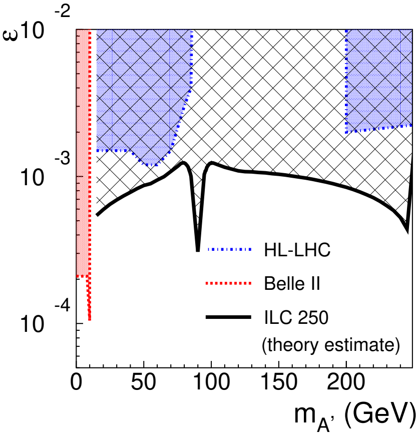

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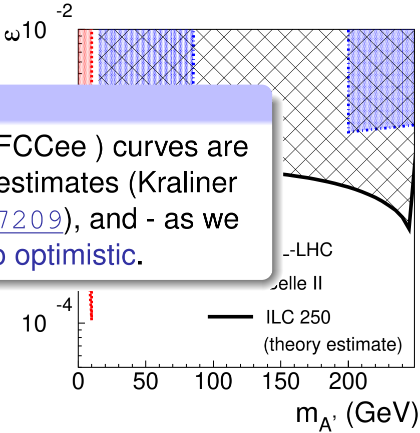


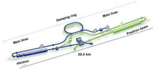
Attention !

The “ILC” (and CepC,FCCee) curves are very simplistic theory estimates (Kraliner & al. arxiv:1503.07209), and - as we will see - are much too optimistic.

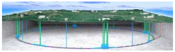
Higgs factories and beyond

The Bestiary of proposed future e^+e^- colliders, and their detectors

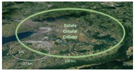
ILC



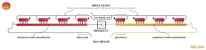
CEPC



FCC-ee

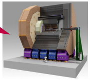


CLIC

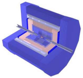


This talk uses ILD

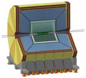
ILD



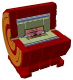
CEPC Baseline



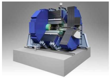
IDEA



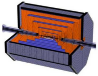
CLICdp



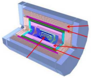
SiD



FST



CEPC 4th concept



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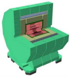


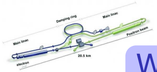
slide stolen from B. Dudar

The circular machines are Higgs (and Z) factories, the linear ones can extend far beyond in energy.

Higgs factories and beyond

The Bestiary of proposed future e$^+$e$^-$ colliders, and their detectors

ILC



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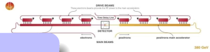

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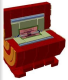
Why dark photons at Higgs factories ?

... when LEPII reached almost as high energies ?

- At least 1000 times the luminousity !
- and polarisation, triggerless running, 40 years for detector developnent ...
- $\Rightarrow$ Enormous increase in sensitivity !

CLICdp



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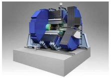

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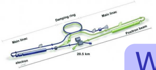

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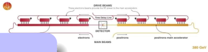

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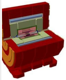

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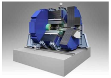

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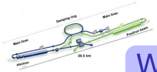

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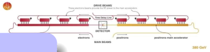

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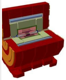

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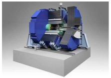

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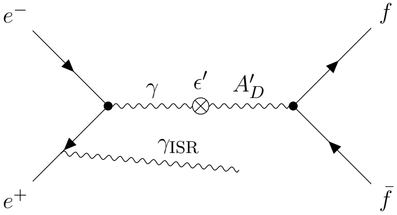
Dark Photons at e^+e^- beyond SuperKEKB

- Signal process: $e^+e^- \rightarrow \gamma_{ISR} A_D \rightarrow \mu^+\mu^-\gamma_{ISR}$, where E_{ISR} is such that the recoil-mass against the ISR is M_{A_D}



- Both σ and Γ scales with ϵ^2.
  - One could hope to exclude $\sigma > \mathcal{O}(1\ \mathrm{fb})$
  - For the corresponding ϵ^2, Γ is $\mathcal{O}(10\ \mathrm{keV})$ to $\mathcal{O}(10\ \mathrm{MeV})$.
  - $\Rightarrow$ detector resolution will determine the peak-width
  - $\Rightarrow$ decay is prompt ($c\tau < 1$ nm).

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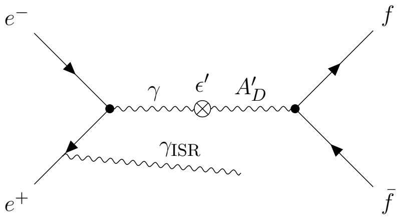

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- Signal process: $e^+e^- \to \gamma_{ISR} A_D \to \mu^+\mu^-\gamma_{ISR}$, where E_{ISR} is such that the recoil-mass against the ISR is M_{A_D}
- Both σ and Γ scales with ϵ^2.
  - One could hope to exclude $\sigma > \mathcal{O}(1 \text{ fb})$
  - For the corresponding ϵ^2, Γ is $\mathcal{O}(10 \text{ keV})$ to $\mathcal{O}(10 \text{ MeV})$.
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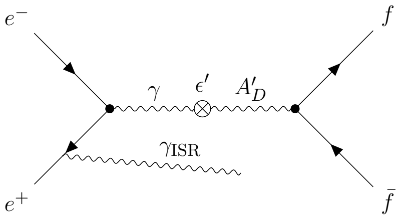

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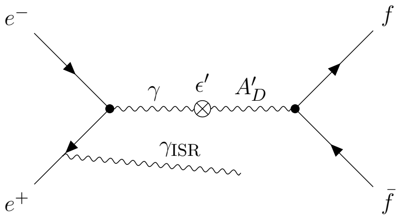

Properties of Dark Photon production and decay

Generate events using the UFO files describing the model of Curtin & al. (arxiv:1412.0018) interfaced to `Whizard` 3.0.

- Production cross-section σ for fully polarised beams.
- BR($A_D \to \mu\mu$)
- "Effective" $\sigma \times$ BR (meaning: $N_{events} = \sigma_{eff} \times \int \mathcal{L}$) for
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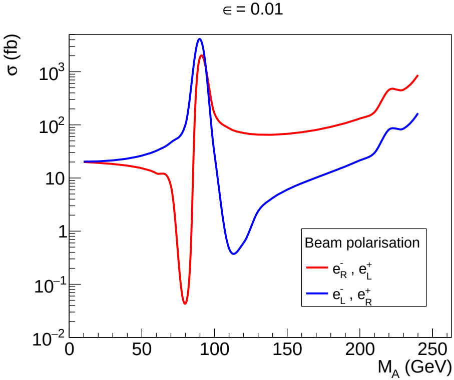

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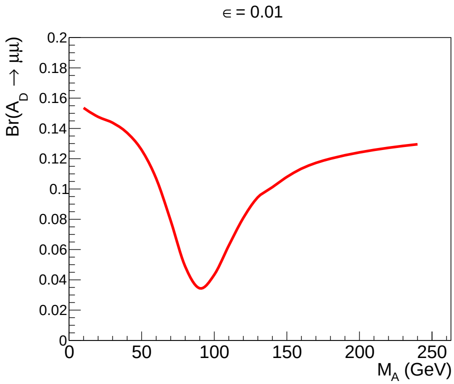

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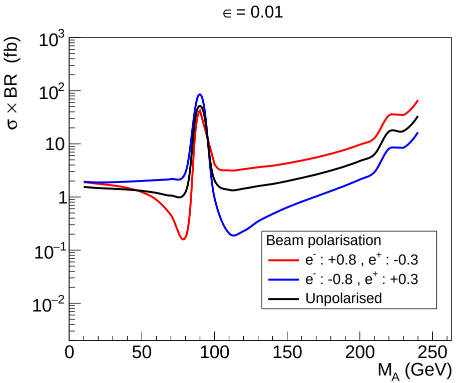

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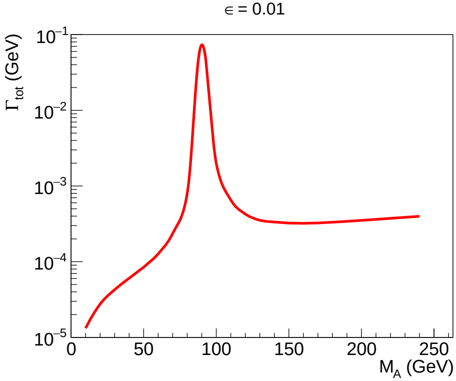

Dark Photons in a real detector

Pass such generated events through the full `Geant4`-based simulation (`ddsim`) and reconstruction (`Marlin`) of ILD.

- Select events with two muons, and possibly an isolated photon - nothing else.
- Include all (fully simulated) SM background.
- Look for an arbitrarily small peak in the $M(\mu\mu)$ distribution, with natural width $<< \delta_{det}(M)$, over the SM background
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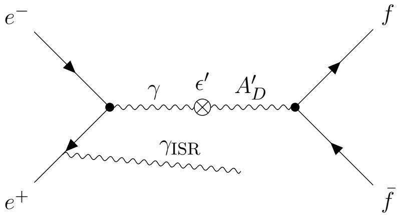
- The target.



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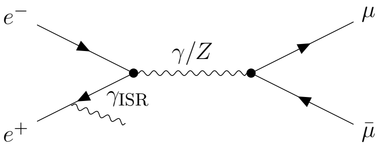

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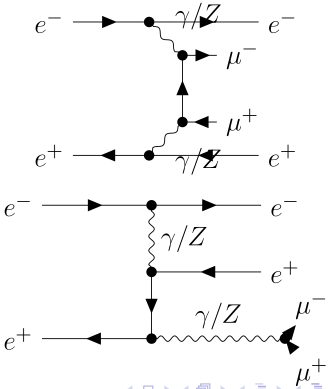

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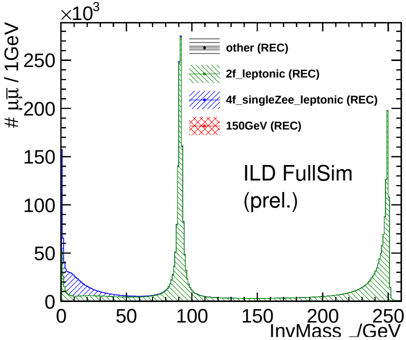

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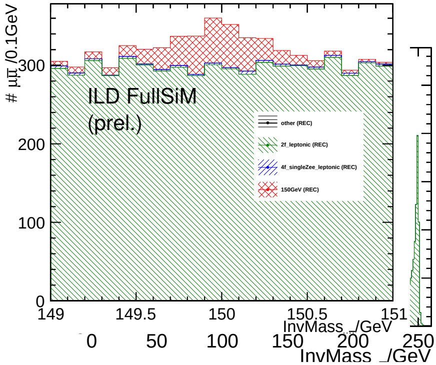
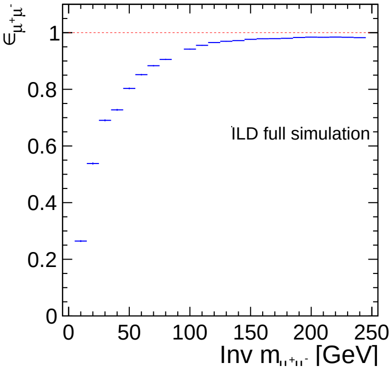


Dark Photons in a real detector

- Efficiency to find two muons.
- Why so low ? ILD track-finding is 100 % efficient down to $p_T \sim 300$ MeV and angles to the beam above $\sim 10°$!?
- Here's why: Angular distribution of the muons - we need to see both to get a pair, obviously!



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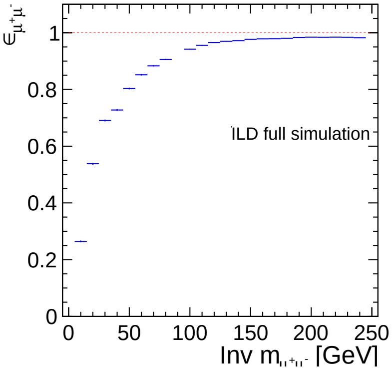

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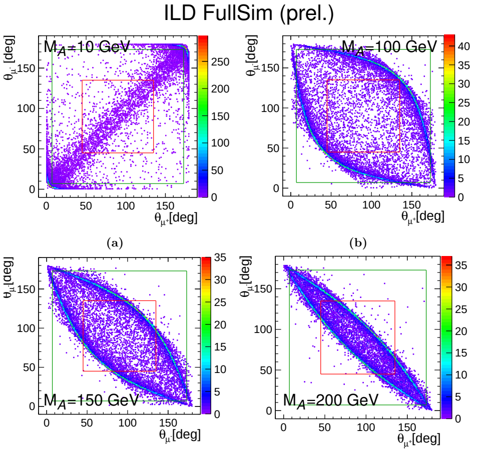

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- Mass resolution: $M = p_1 p_2 (1 - \cos\theta_{12})$, and the ISR is along the beam and $\sigma(1/p_T)$ vs. p is constant, so error-propagation gives $\sigma_M \propto M^2$, right ?
- Wrong.
  - Due to M.S., for $p \lesssim 100$ GeV, $\sigma(1/p_T)$ is not constant, rather $\propto p^{-1}$. Strong dependence on θ in the forward region.
  - and most muons are below 100 GeV
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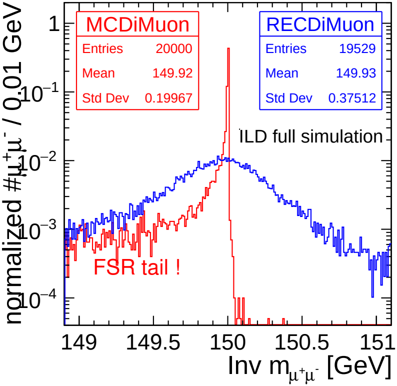

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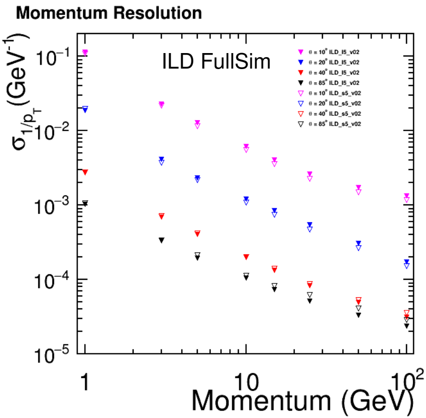

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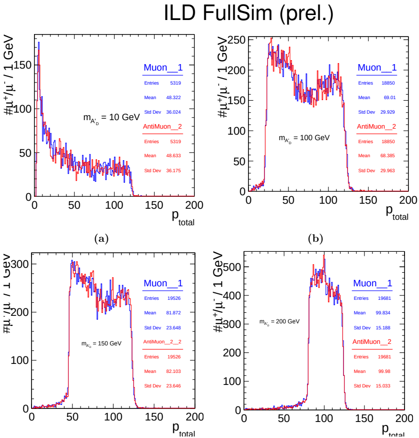

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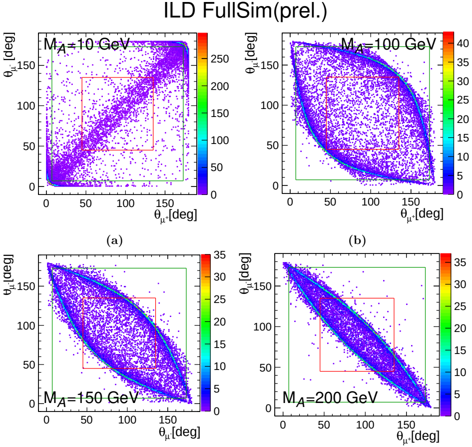
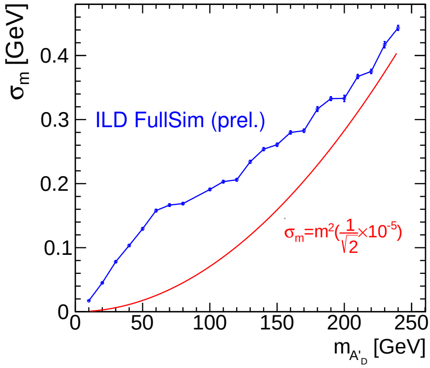


Dark Photons in a real detector

- Bottom line: None of the assumptions on the mass-resolution - the red curve - used for the EPPSU curve are valid. The correct full simulation values are the blue curve.
- The resolution will vary a lot event-by-event - with angle and momentum of the muons, and the angle of the ISR.
- ⇒ Event-by-event simulation is essential.



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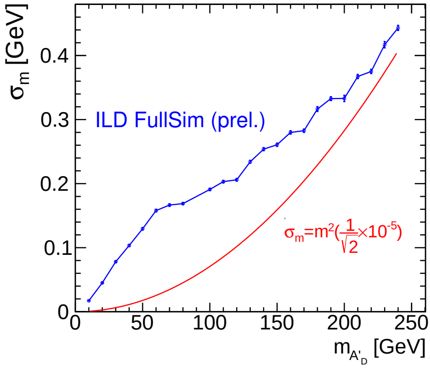

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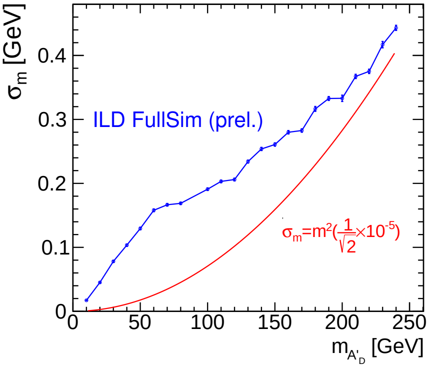

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- However, the uncertainty is known, event-by-event, since the track-fit covariance matrix is output from the fit !
- Use this to optimise the search:
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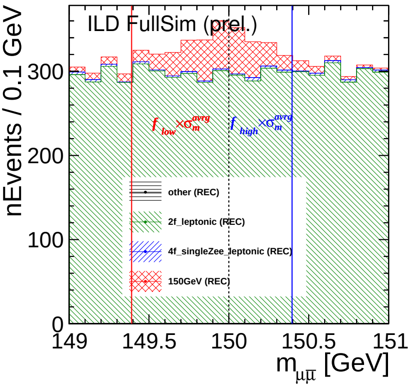

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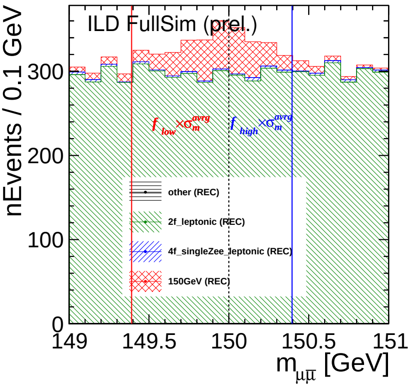

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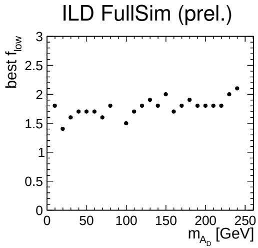

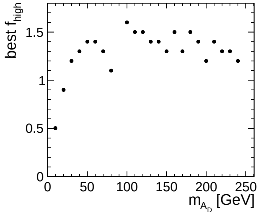

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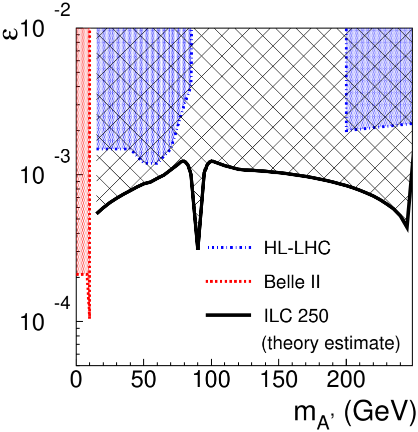
- Compared to the theory curve ...
- ... this is the (current) result with full simulation.
- At the highest mass, the correct limit is a factor two higher, a factor four at 100 GeV.
- This is due to the correct estimate of the error.
- Below M_Z, the difference is larger, and HL-LHC limits are expected to be stronger.
- Here, the reason is both the correct error-estimate, but also the much larger background from non-$Z \to \mu\mu$ processes.



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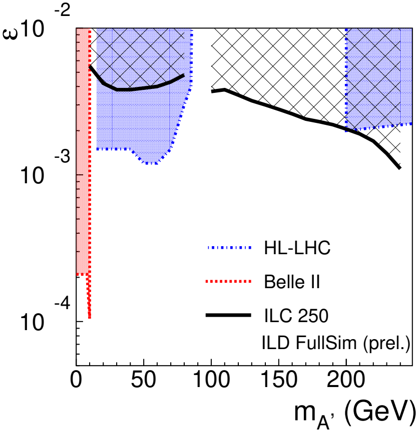

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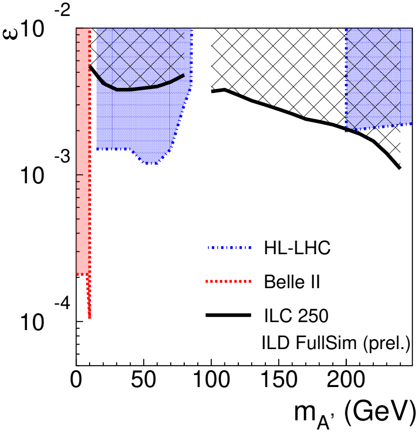

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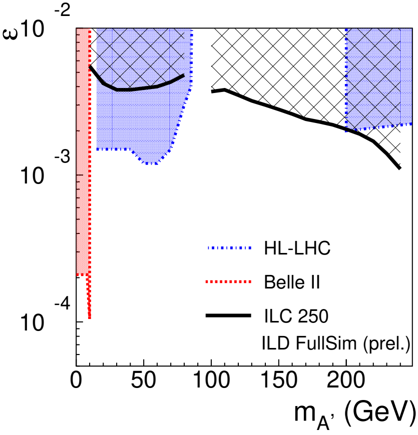

Conclusion and outlook

Uptake:

- Even for - or maybe in particular for - the most simple topology full simulation is needed.
- Because in these cases, precision is the most important aspect.
- Even though the correctly evaluated reach is significantly less than the theory estimate, e^+e^- colliders will probe lower dark photon couplings than HL-LHC, at least for masses above M_Z.

Outlook:

- Several non-trivial ameliorations are possible
  - LR weighting of the samples with different polarisations.
  - Include $A_D \to e^+e^-$: Need methods to compensate for brems-strahlung to get good enough mass-resolution.
  - No use of the ISR photon made. Can it be used ? Background reduction at low M_X, or even better resolution?
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Thank You !

Backup

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