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

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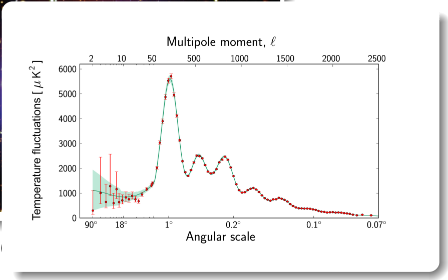
European Physical Society Conference on High Energy Physics,
August 20-25, 2023
Universität Hamburg

Introduction: Dark Matter

Bullet cluster

Introduction: Dark Matter

Bullet



Plank CMB

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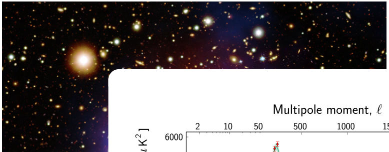

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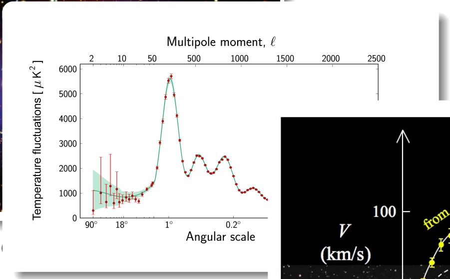

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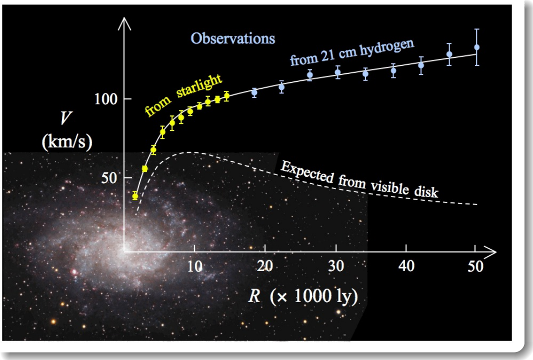

M33 rotation curve

Introduction: Dark Matter

Bullet (

Temperature fluctuations [μK^2]

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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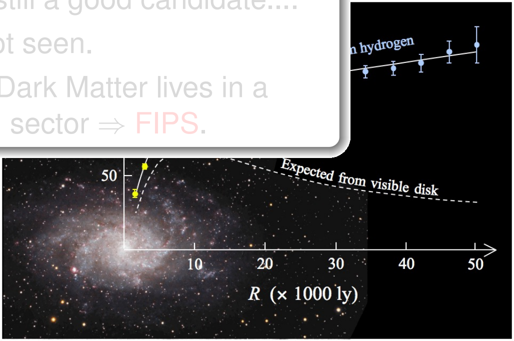

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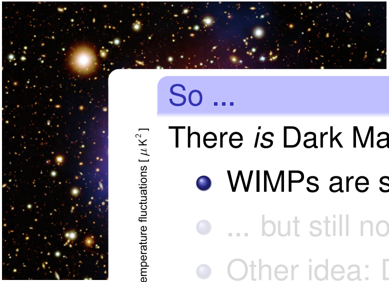

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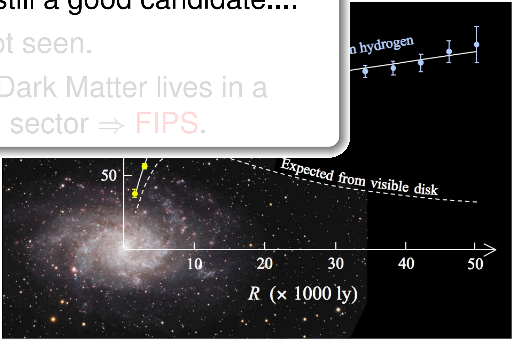

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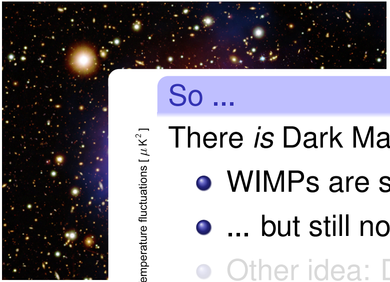

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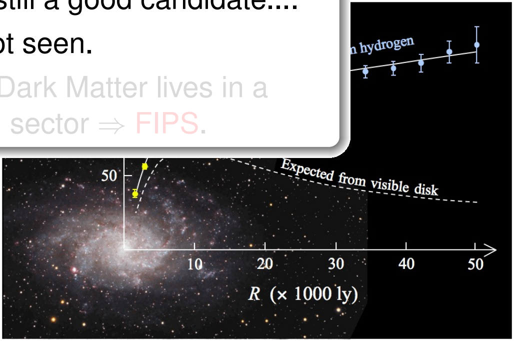

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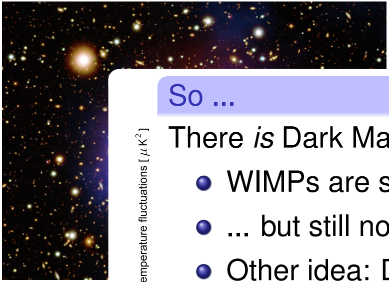

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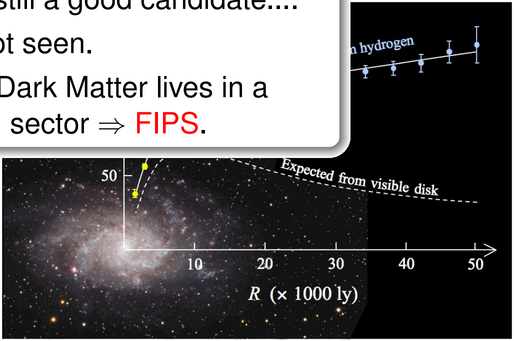

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Introduction: FIPS

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 $\mathrm{e^+e^-} \to A_D \to f\bar{f}$ 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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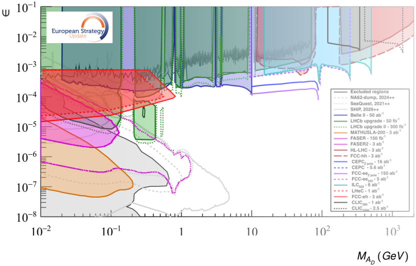
Dark Photon limits from the EPPSU

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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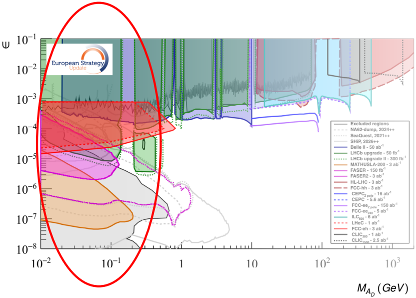

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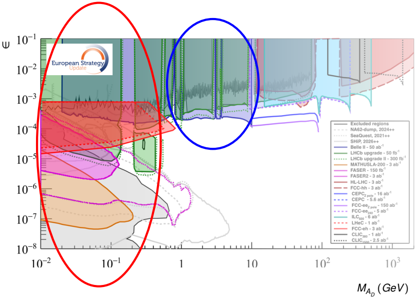

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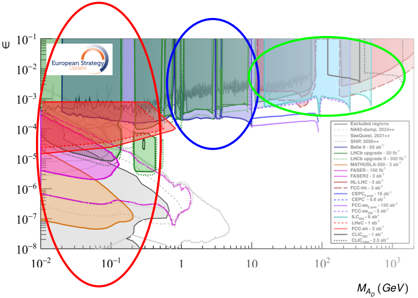

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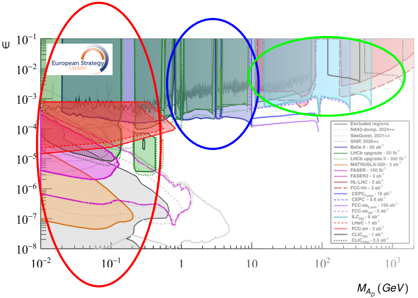

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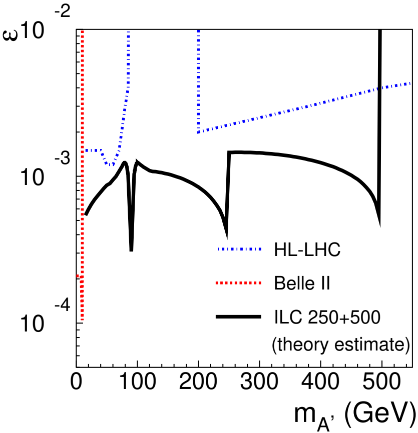

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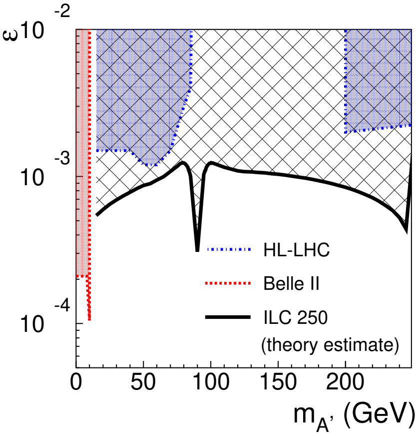

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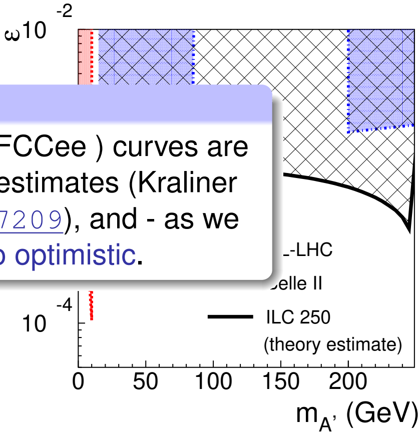


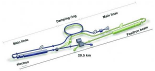
Attention !

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.

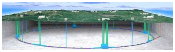
Higgs factories and beyond

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

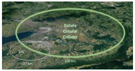
ILC



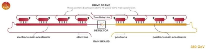
CEPC



FCC-ee

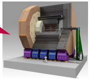


CLIC

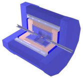


This talk uses ILD

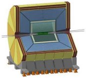
ILD



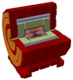
CEPC Baseline



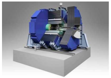
IDEA



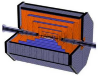
CLICdp



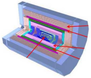
SiD



FST



CEPC 4th concept



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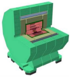

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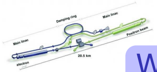
The circular machines are Higgs (and Z) factories, the linear ones can extend far beyond in energy.

Higgs factories and beyond

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

ILC



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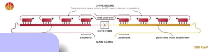

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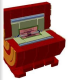
Why dark photons at Higgs factories ?

... when LEPII reached almost as high energies ?

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

CLICdp



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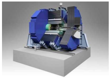

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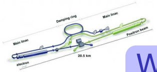

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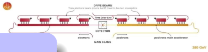

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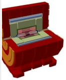

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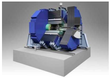

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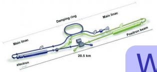

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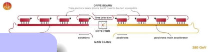

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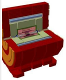

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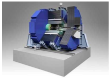

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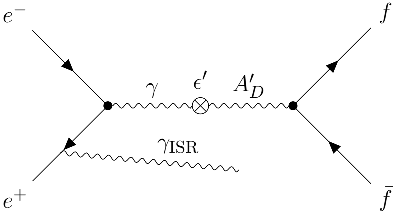
Dark Photons at e^+e^- beyond SuperKEKB

- 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 $\sigma > \mathcal{O}(1\text{ fb})$
  - For the corresponding ϵ^2, Γ is $\mathcal{O}(10\text{ keV})$ to $\mathcal{O}(10\text{ MeV})$.
  - $\Rightarrow$ detector resolution will determine the peak-width
  - $\Rightarrow$ decay is prompt ($c\tau < 1$ nm).



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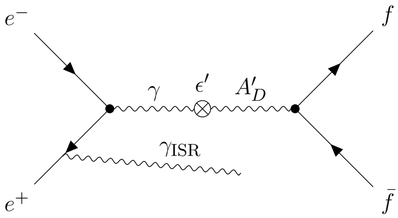

Dark Photons at e^+e^- beyond SuperKEKB

- 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 $\sigma > \mathcal{O}(1\text{ fb})$
  - For the corresponding ϵ^2, Γ is $\mathcal{O}(10\text{ keV})$ to $\mathcal{O}(10\text{ MeV})$.
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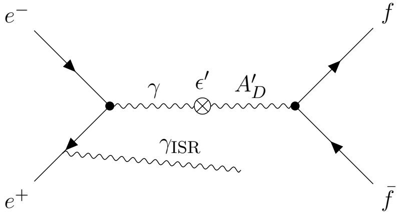

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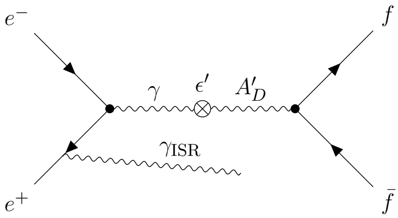

Properties of Dark Photon production and decay

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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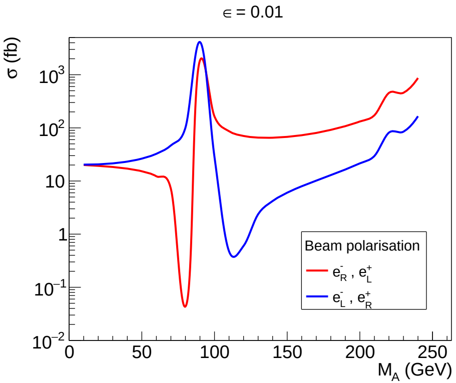

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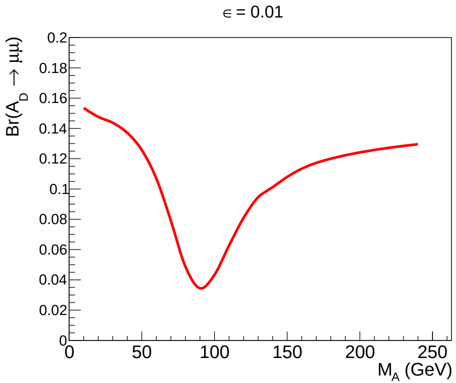

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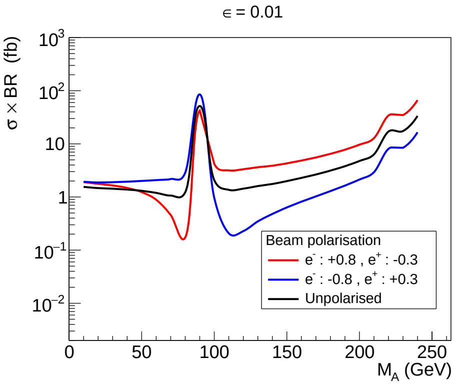

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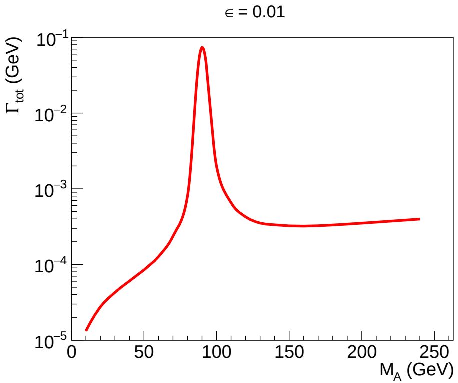

Dark Photons in a real detector

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.
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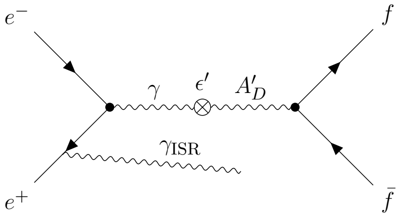
- The target.



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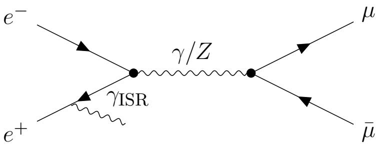

(a)

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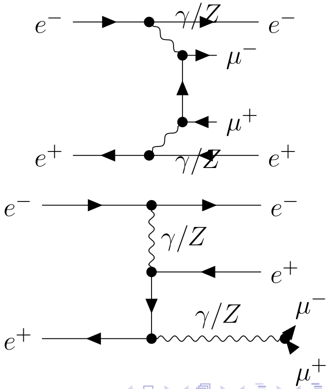

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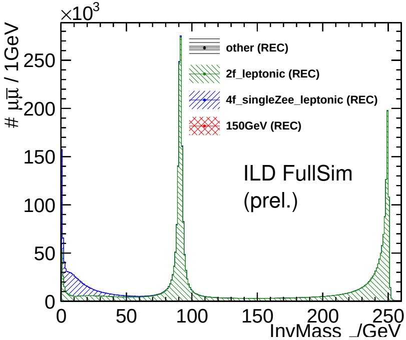

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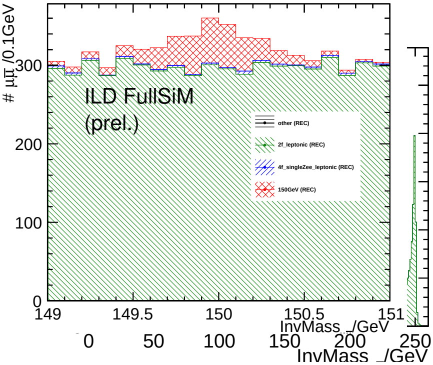
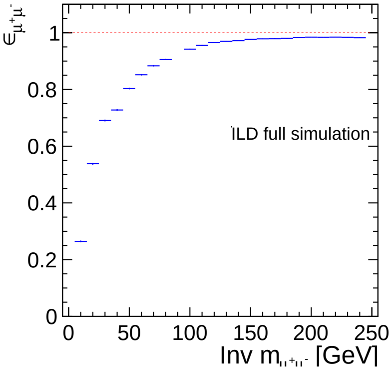


Dark Photons in a real detector

- 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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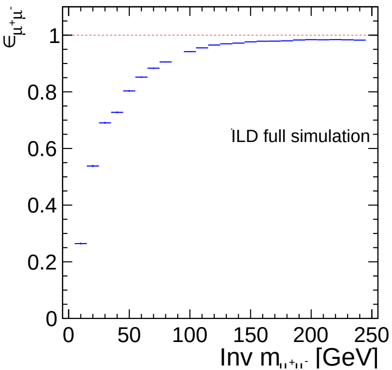

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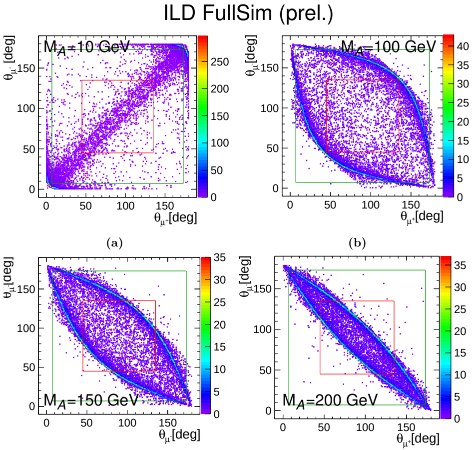

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- Mass resolution: $M = p_1 p_2(1 - \cos\theta_{12})$, and the ISR is along the beam and $\sigma(1/p_T)$ vs. p is constant, so error-propagation gives $\sigma_M \propto M^2$, right ?
- Wrong.
  - Due to M.S., for $p \lesssim 100$ GeV, $\sigma(1/p_T)$ 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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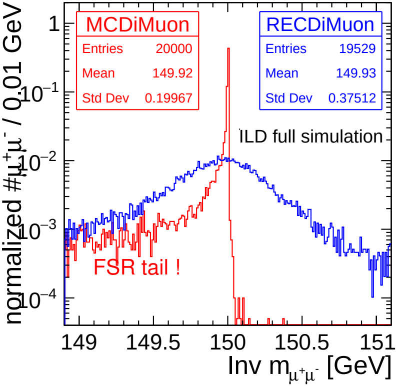

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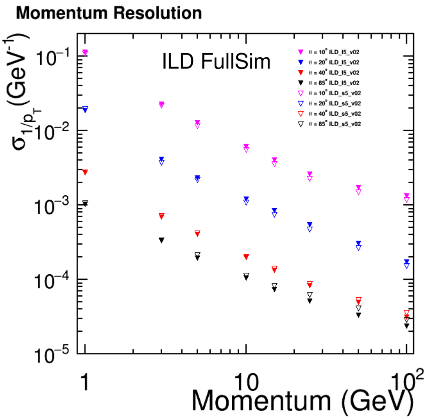

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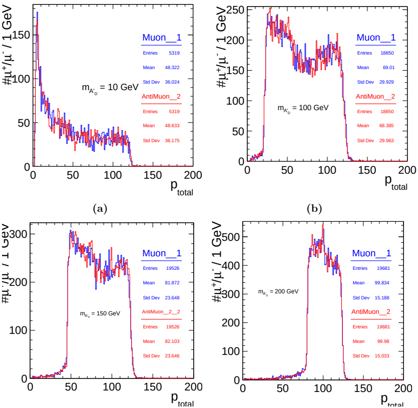
ILD FullSim (prel.)



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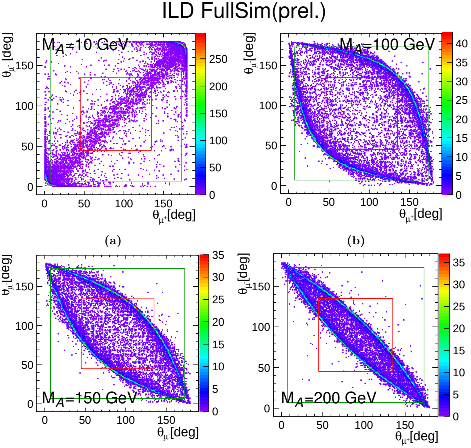
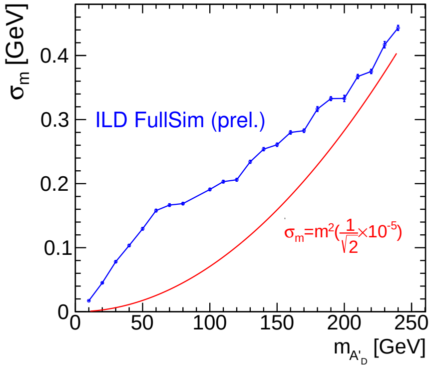


Dark Photons in a real detector

- 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.
- $\Rightarrow$ Event-by-event simulation is essential.



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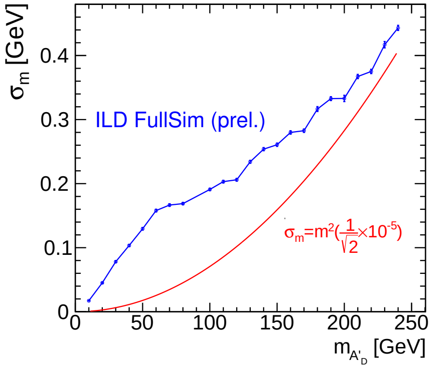

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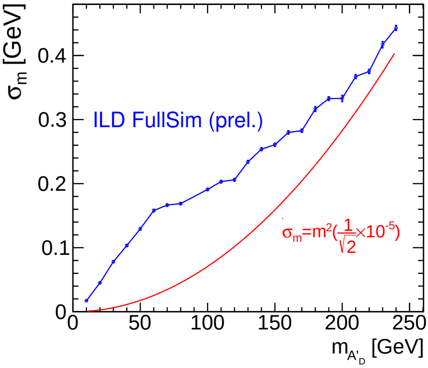

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- However, the uncertainty is known, event-by-event, since the track-fit covariance matrix is output from the fit !
- Use this to optimise the search:
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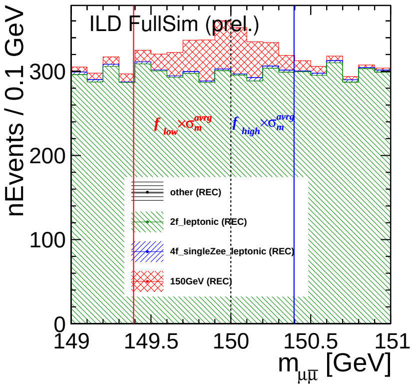

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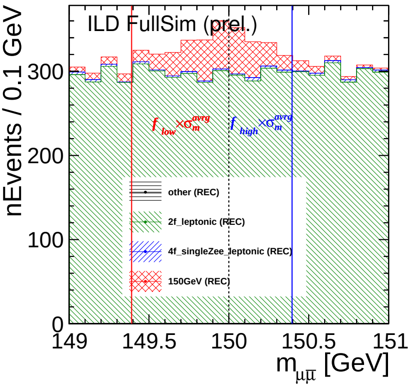

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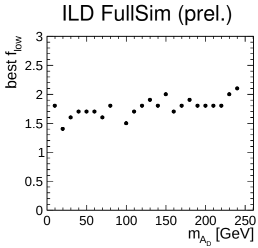

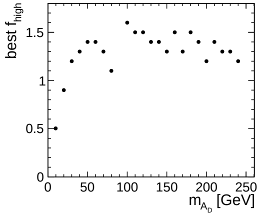

Dark Photons in a real detector

- 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.
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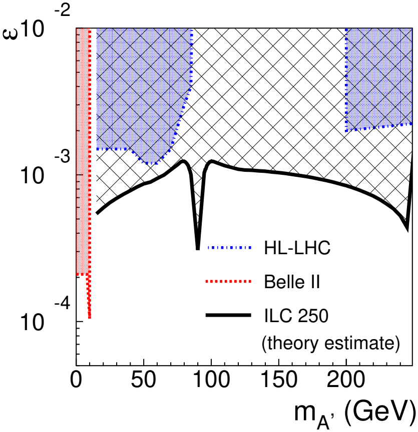

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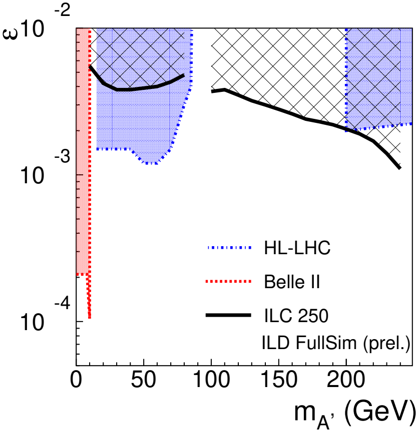

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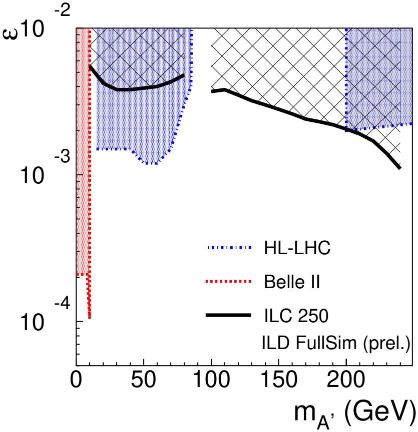

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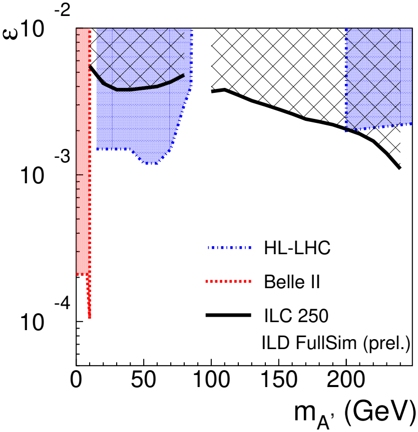

Conclusion and outlook

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.

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  - 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

BACKUP SLIDES