Perspective for DM searches @FCCee

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What we expect DM to look like

A. Strumia, talk @ FCCee workshop

https://agenda.infn.it/getFile.py/access?contribId=19&sessionId=7&resId=0&materialId=slides&confId=8830

- DM particles should be in some Z_2 symmetry making them stable (e.g. R-parity in SUSY)
    - Should be produced in pairs

Subject of this talk

- DM is not detectable with a typical collider detector
    - Main signature @FCCee is missing momentum/mass
    - some other object could be radiates (**monophoton**, **monojet, mono….**)
- Most likely, DM is part of a new sector, with other particles offering an easier path to discovery **Not covered today**

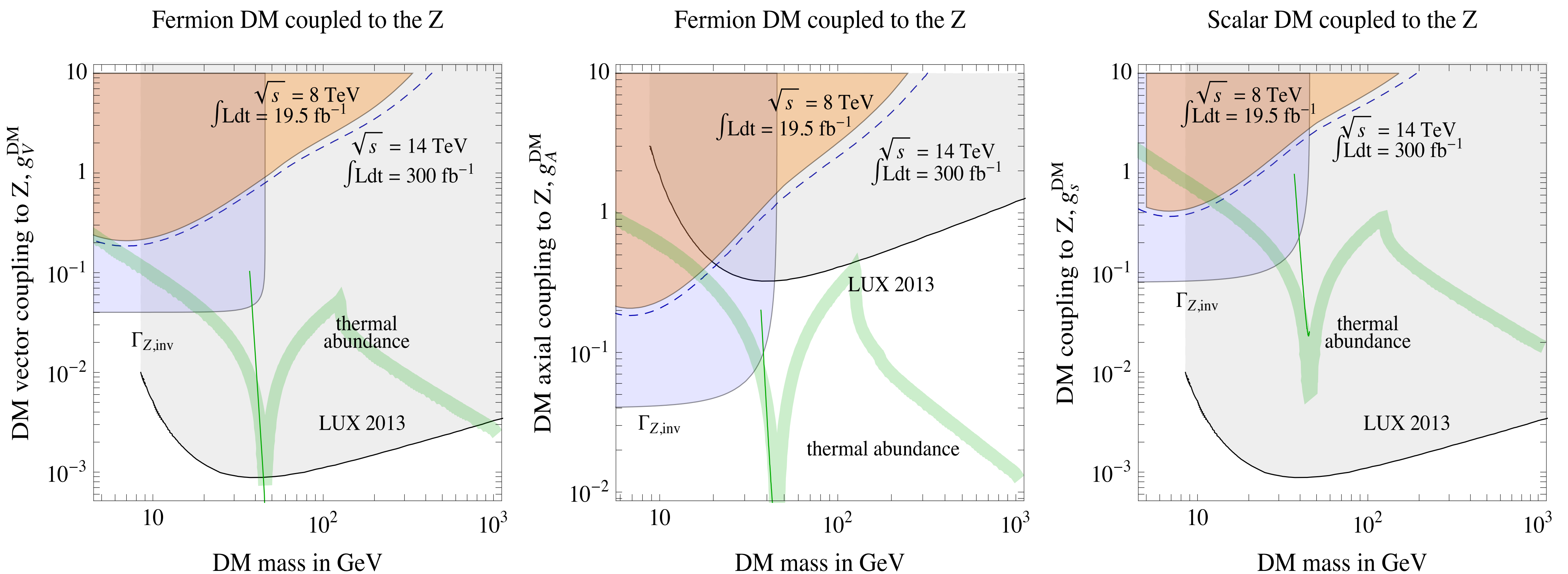
How could DM be produced

- SM mediator [De Simone et al. http://arxiv.org/abs/1402.6287](http://arxiv.org/abs/1402.6287)
  - DM couples to SM particles (Z, H, …)
  - Widths to invisible for Z and H play major role
- New heavy particles coupling both to SM and DM
  - off-shell mediator connect colliding ee to DM pair (s-channel or t-channel)
  - Effective field theory used in this case (and justified more than in other scenarios, e.g. LHC)
  - Nature of the mediator determines the effective operator that rules the interaction

DM mediated by SM particles

The Z portal option

[De Simone et al. http://arxiv.org/abs/1402.6287](http://arxiv.org/abs/1402.6287)

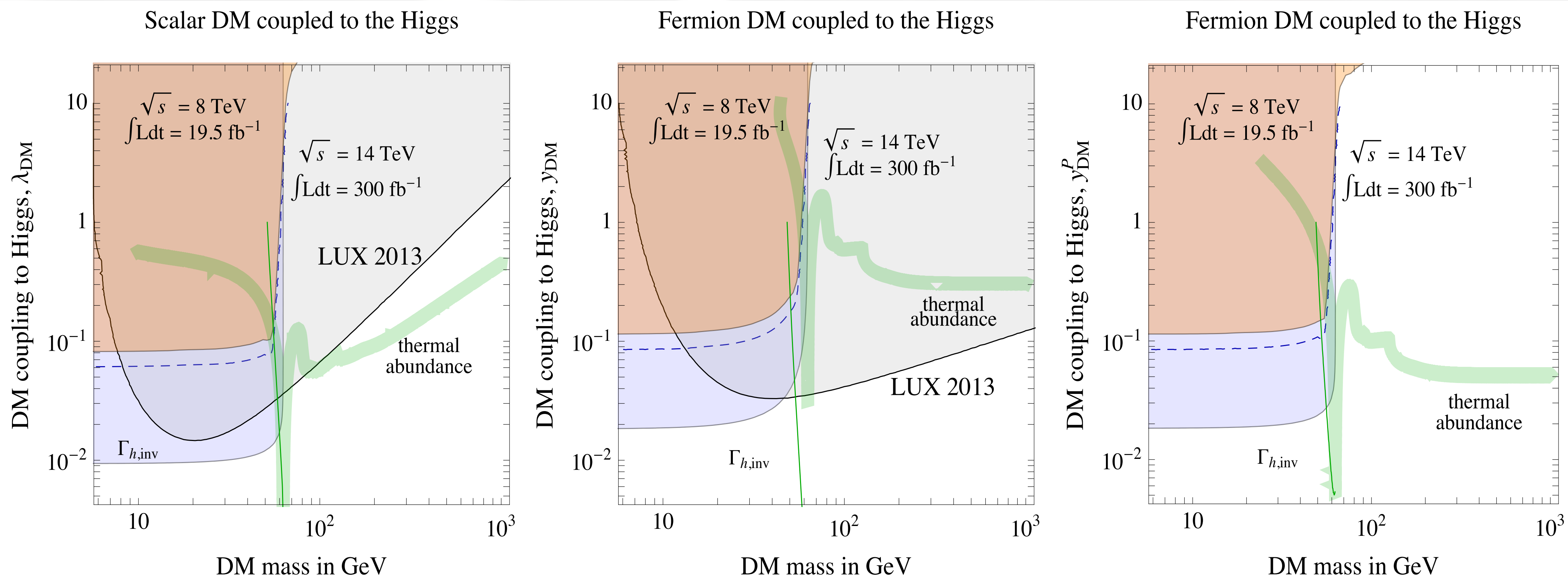


Red: LHC8 bound. Blue: Γ_Z^{inv} bound. Gray: direct detection bound.
Green: estimated band where the DM abundance is reproduced thermally.

- Direct detection excludes large part of the coupling vs mass plane
- LHC searches complementary (can probe masses below the recoil threshold of direct detection)
- Bound from Γ(Z→inv) from LEP-SLD stronger than LHC where it applies (m_{DM}<45 GeV)

The H portal option

[De Simone et al. http://arxiv.org/abs/1402.6287](http://arxiv.org/abs/1402.6287)



Red: LHC8 bound. Blue: Γ_H^{inv} bound. Gray: direct detection bound.
Green: estimated band where the DM abundance is reproduced thermally.

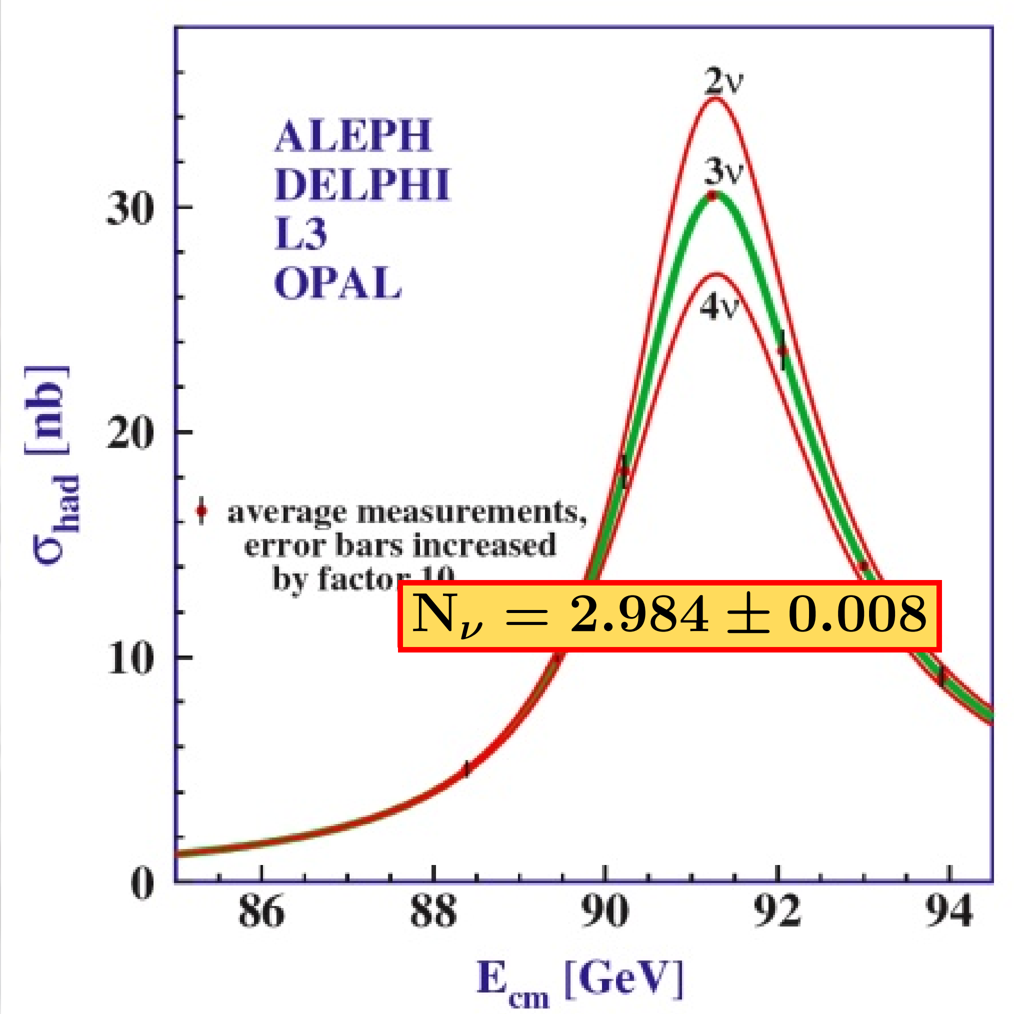
- Similar picture for Higgs portal
- LHC limit from monojet and H→inv
- Some scenario only probed at colliders

What can be done @FCCee?

- Γ(Z→inv) measured @LEP from Z lineshape
  - need to know shad precisely
  - need to control luminosity

Expected statistical precision on δN_ν

Mode	$N_{inv}(240)$	$N_{inv}(350)$	δN_ν	Efficiency
Z(ll)Z(inv)	$1.9 \cdot 10^5$	$0.4 \cdot 10^5$	0.013	CMS LEP3 [arXiv:1208.1662]
Z(bb)Z(inv)	$2.0 \cdot 10^5$	$0.4 \cdot 10^5$	0.012	21%, CMS LEP3 [arXiv:1208.1662]
H(bb)Z(inv)	$0.6 \cdot 10^5$	$0.1 \cdot 10^5$	0.022	21%, same as for Z(bb)Z(inv)
Total	$\mathbf{4.5 \cdot 10^5}$	$\mathbf{0.9 \cdot 10^5}$	**0.008**	
γZ(inv)	$3.6 \cdot 10^7$ (240+350)		0.001	100% eff., no bkg.



$$\delta N_\nu = 10.5\frac{\delta\sigma_{had}}{\sigma_{had}} \oplus 3.0\frac{\delta n_{lept}}{n_{lept}} \oplus 7.5\frac{\delta L}{L}$$

- This measurement will be systematic dominated @FCCee

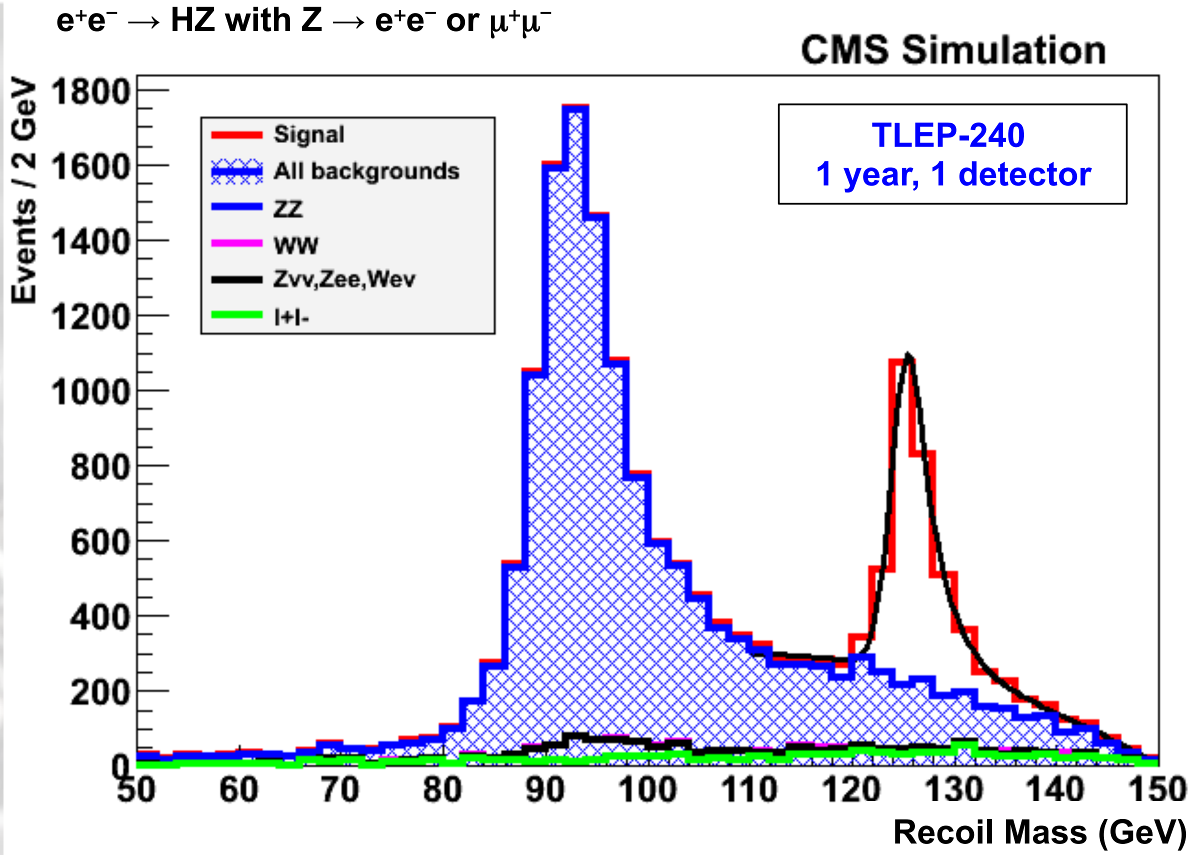
- The alternative would be a monophoton search, for which systematics could cancel in a ratio

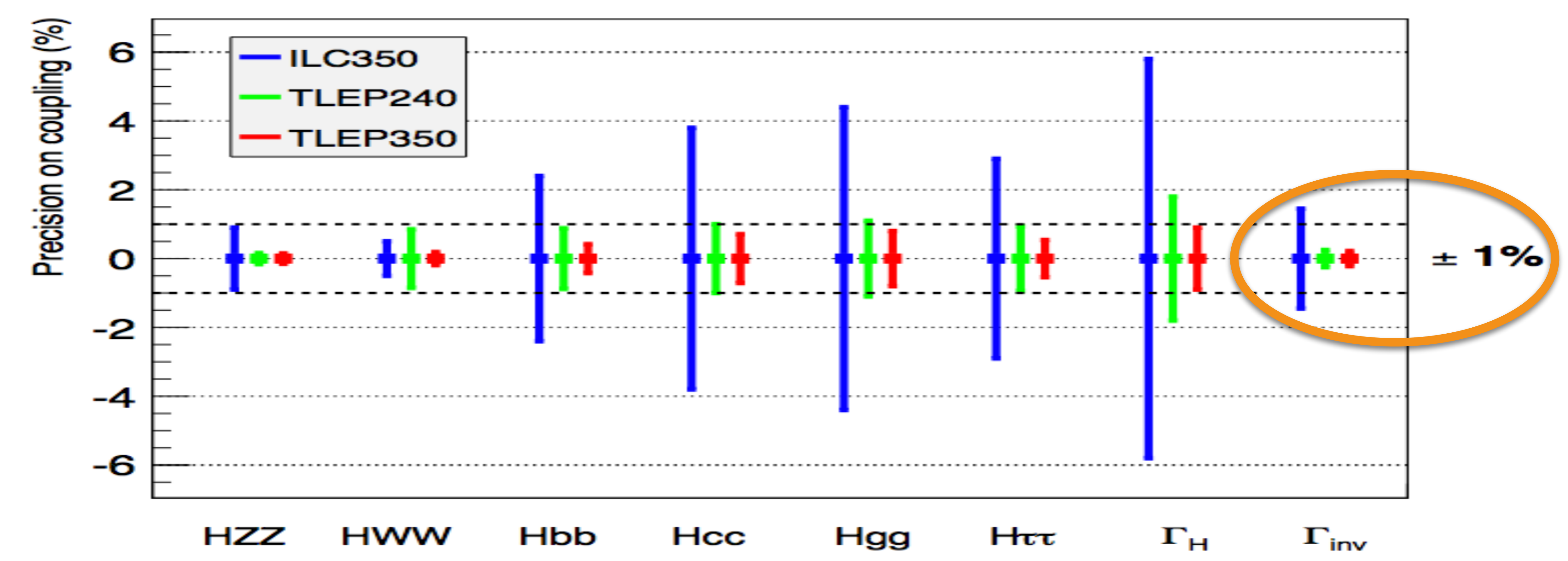
$$\boxed{N_\nu = \frac{N(\gamma Z_{inv})}{N(\gamma Z_{ee,\mu\mu})} / \left(\frac{\Gamma_{\nu_l}}{\Gamma_l}\right)_{SM}}$$

- In general, monophoton search is the DM probe @FCCee. More in next slides

What can be done @FCCee?

- Higgs boson production can be tagged from the Z
- One can then veto known Higgs final states
  - mono-Z search
- **Can reach sensitivity ~ 1%**

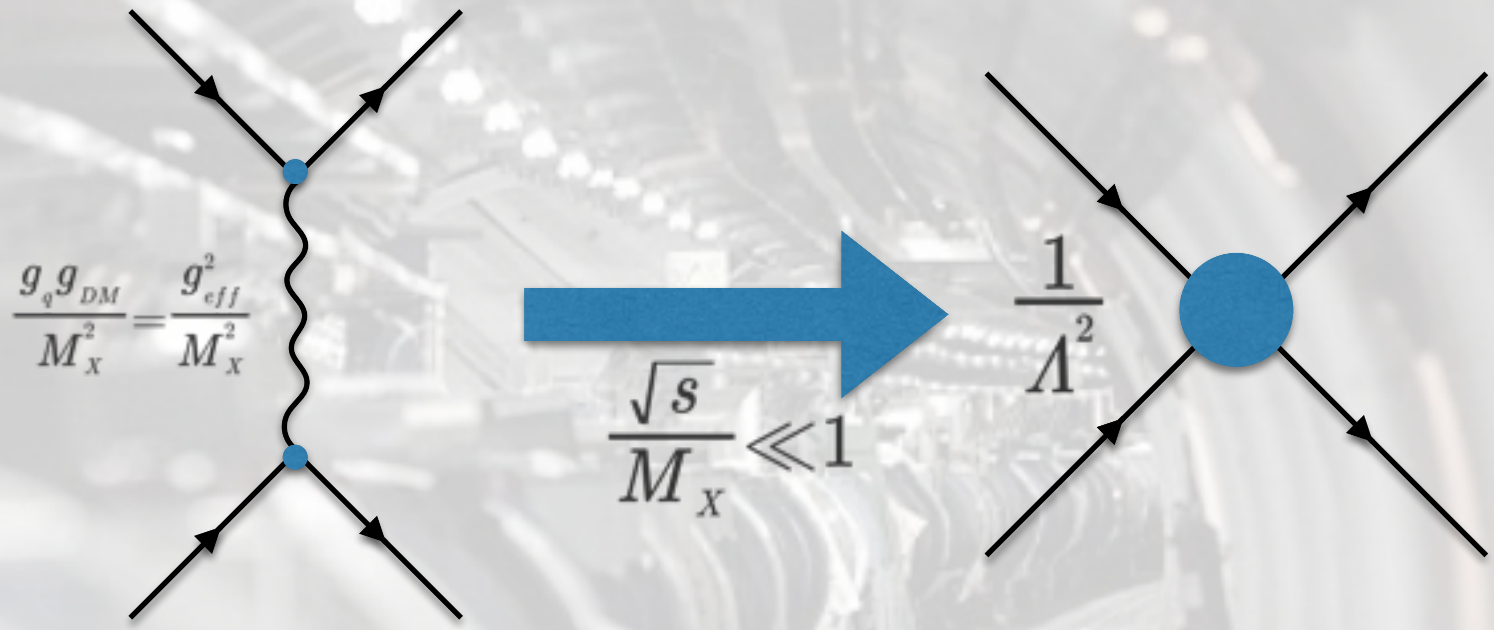




DM mediated by New Heavy Resonances

Effective Field Theory

- DM produced through a heavy mediator X
- In the low-energy limit, one expand the propagator (OPE) and describe the interaction as a local higher-order operator
- Similar to Fermi's description of β decays
  - Rather than a dimension-full operator (GF for Fermi), one introduces a new-physics scale Λ, where the UV completion of the theory (the W for Fermi) become relevant
- Different choices of the nature of X result in different effective operators



$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{\ell}\gamma^\mu\ell)}{\Lambda^2}, \qquad \text{(vector, } s\text{-channel)}$$

$$\mathcal{O}_S = \frac{(\bar{\chi}\chi)(\bar{\ell}\ell)}{\Lambda^2}, \qquad \text{(scalar, } s\text{-channel)}$$

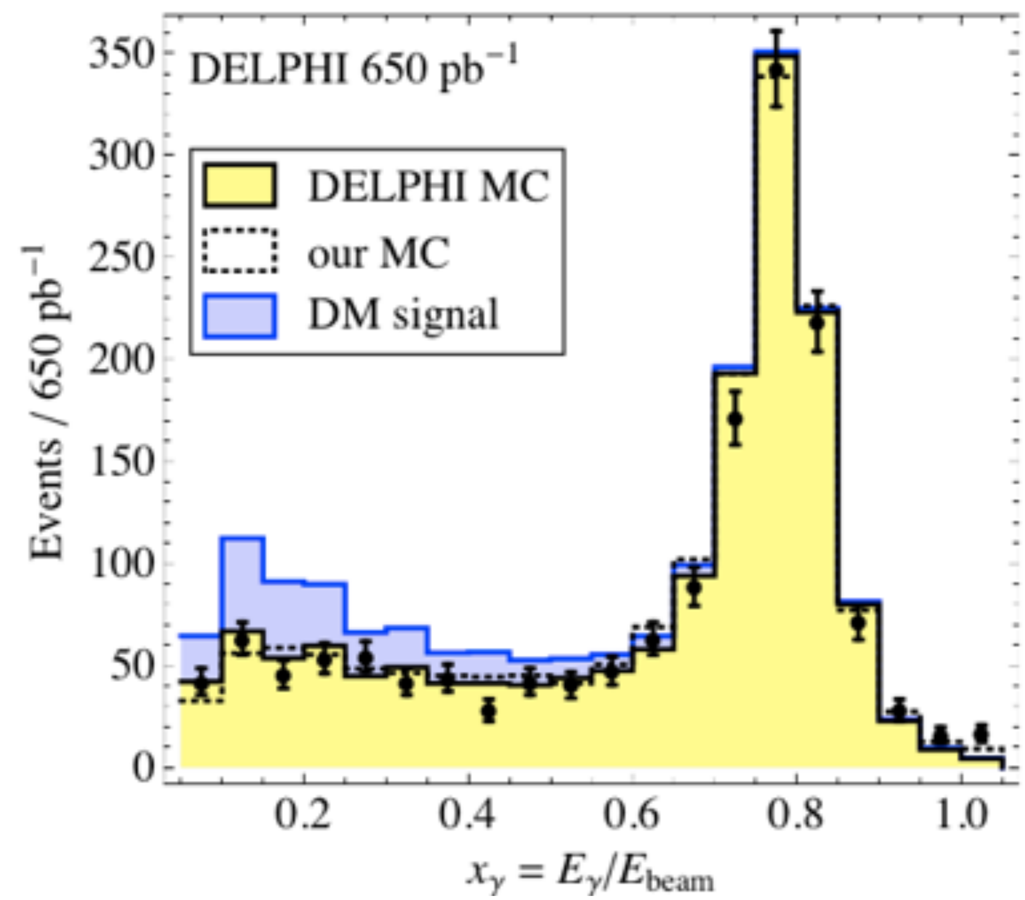
$$\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{\ell}\gamma^\mu\gamma_5\ell)}{\Lambda^2}, \qquad \text{(axial vector, } s\text{-channel)}$$

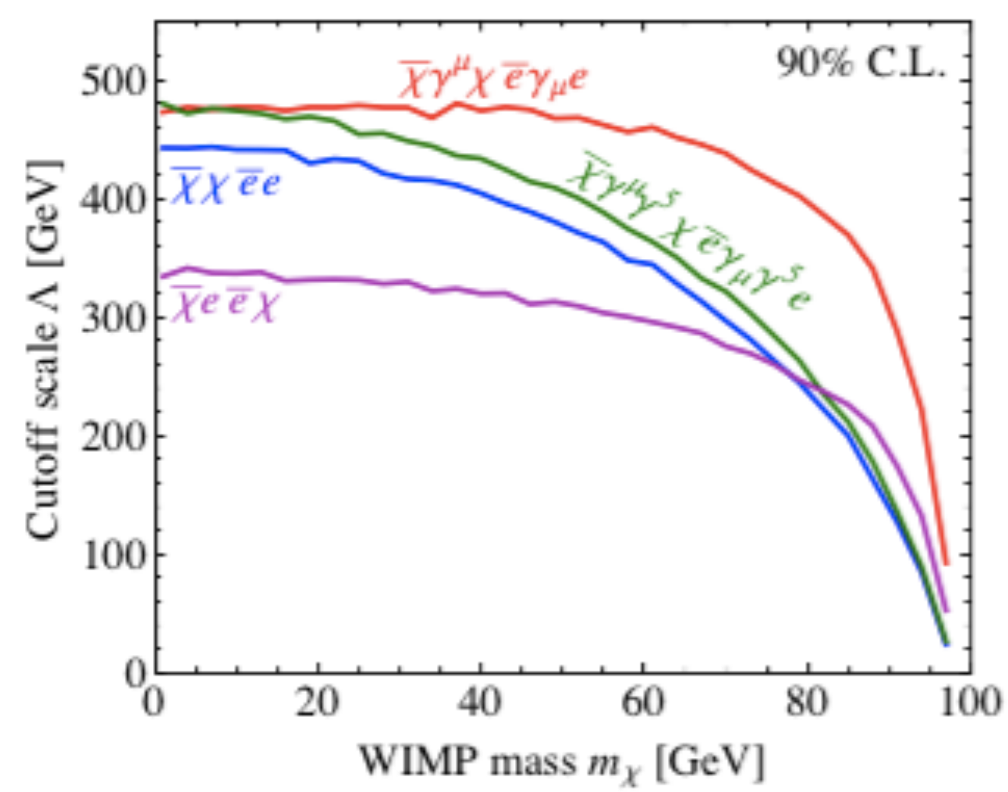
$$\mathcal{O}_t = \frac{(\bar{\chi}\ell)(\bar{\ell}\chi)}{\Lambda^2}, \qquad \text{(scalar, } t\text{-channel)}$$

DELPHI Monojet Search Recast

P. Fox et al. http://arxiv.org/abs/1103.0240

- Search for monophoton from LEP experiments
  - interpreted as SUSY searches
- Recast in EFT limit for different operators
  - reproduce DELPHI selection and plot
  - simulated DM sample for different EFT
  - Interpreted result as limit on Λ vs m_{DM}

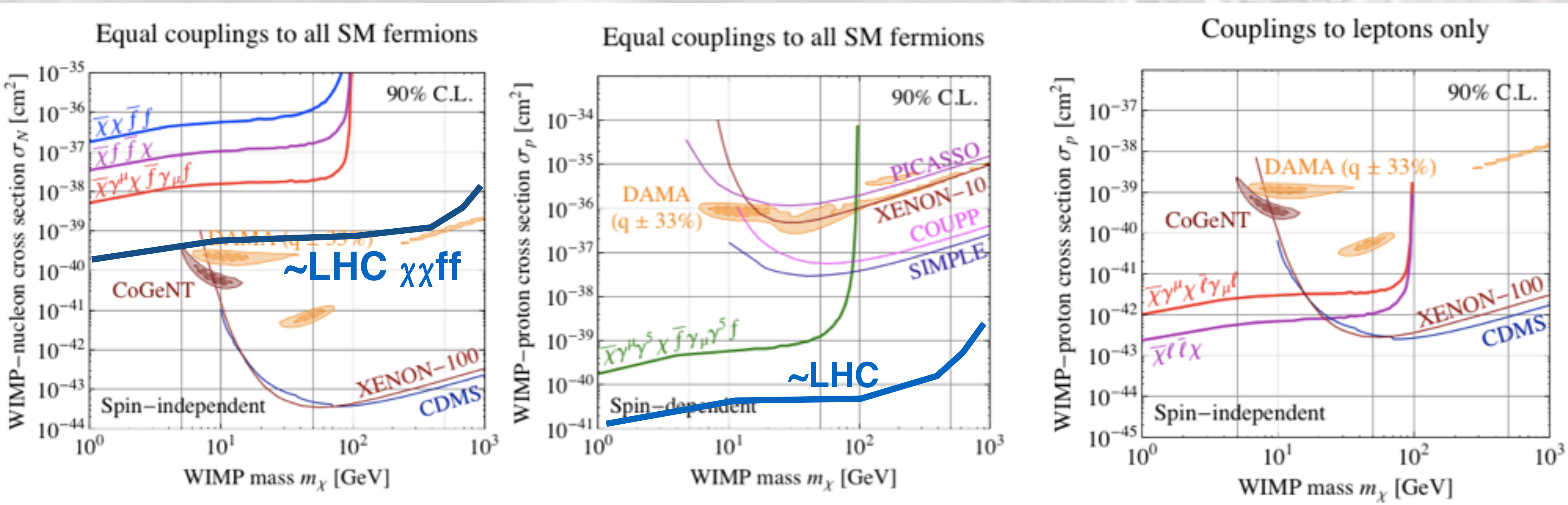




Limit on nucleon-DM scattering

P. Fox et al. http://arxiv.org/abs/1103.0240

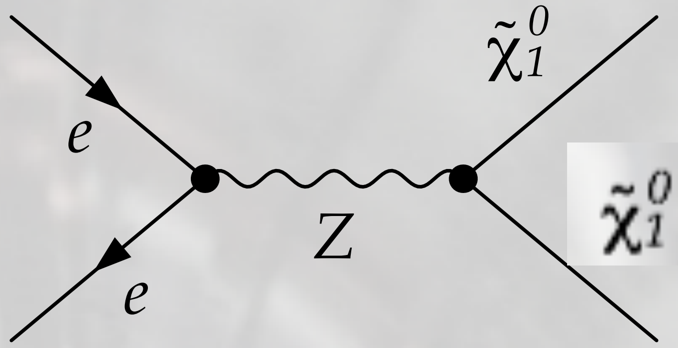
- When the result was presented, bound was relevant at small values of m_{DM}
- Limit less stringent than the LHC
- Need to push to exotic scenarios (DM coupling only to leptons) to cover unexplored territory

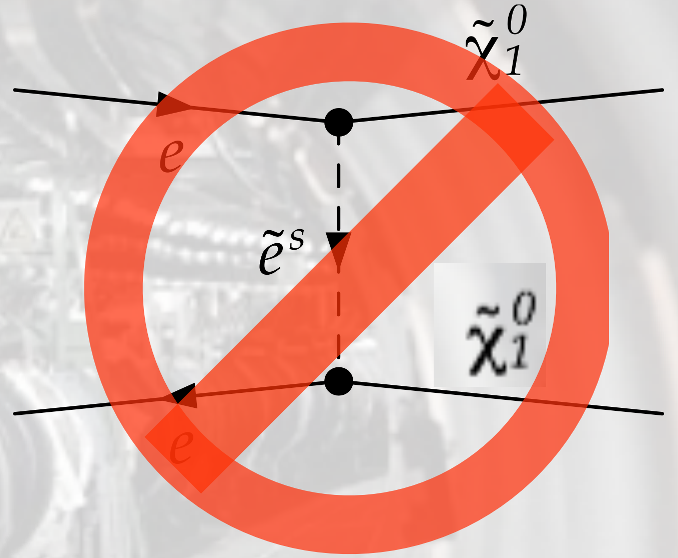


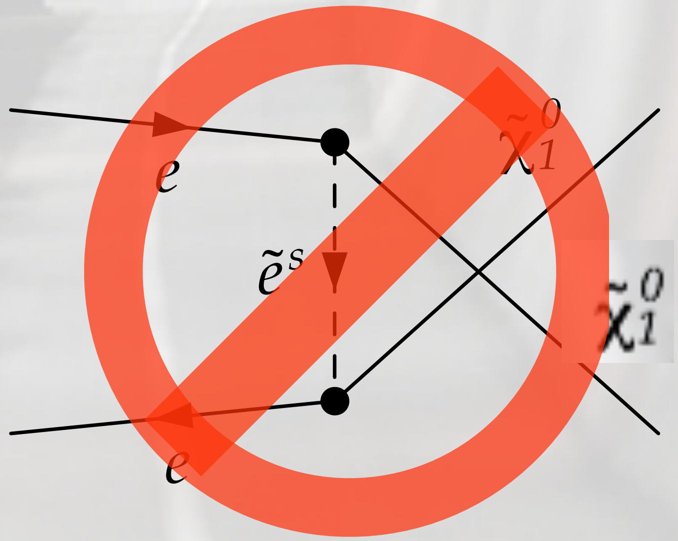
A MonoPhoton Search @FCCee

Samples

- Generated events with pythia8 at different $\sqrt{s}$
  - WW(160 GeV), HZ(240 GeV), and tt (350 GeV)
- No detector effects at this stage
- Only applied acceptance cut (see next slide)
- Simulated relevant SM processes and a prototype of DM signal (neutralino pair production) to derive plausible signal shapes
- For signal, used $\chi^0\chi^0$ production with other SUSY particles decoupled (essentially a Z-portal model)
  - To be extended to the models in the future (t-cannel, heavy mediator, etc)
  - No kinematic discrimination vs $\nu\nu\gamma$ for $2m_\chi<m_Z$

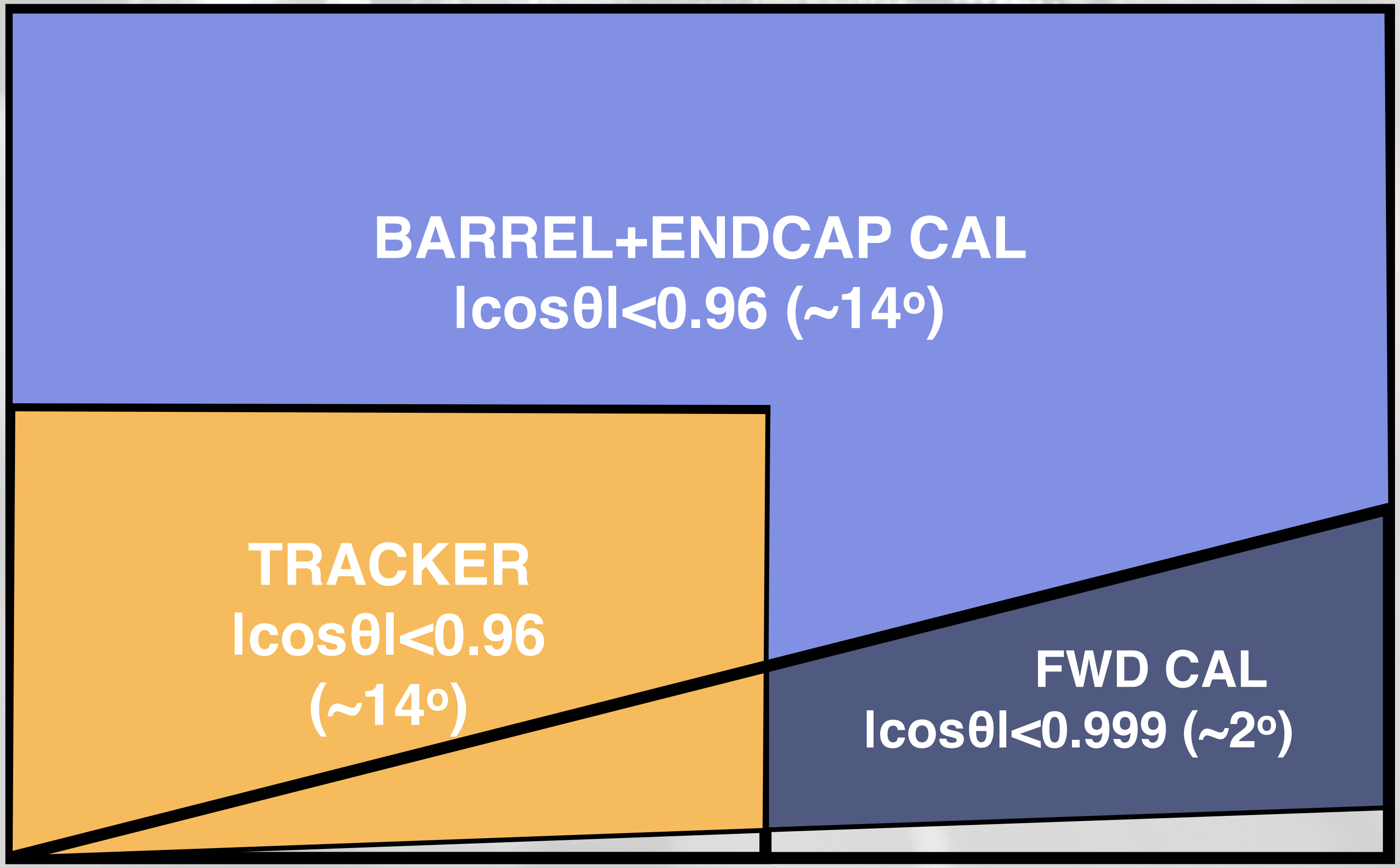






Analysis Selection

- Used the ALEPH analysis as a reference, simplifying the detector geometry
  - Required one photon within acceptance and pT>0.00357√s (θ>2°)
  - Veto on tracks within acceptance (θ>14)
  - Require less than 1GeV of additional energy within the acceptance (θ>14°)
  - Require no energy in the fwd part of the detector (2°<θ<14°)



Selection Efficiency

160 GeV	m_{DM} = 15 GeV	m_{DM} = 35 GeV	m_{DM} = 55 GeV
>1 γ and no track	16%	13%	2%
1 γ	15%	12%	2%
Etot<1 GeV	13%	11%	2%
No Efwd	11%	9%	2%
240 GeV	**m_{DM} = 15 GeV**	**m_{DM} = 35 GeV**	**m_{DM} = 55 GeV**
>1 γ and no track	15%	12%	3%
1 γ	15%	12%	3%
Etot<1 GeV	12%	10%	3%
No Efwd	10%	8%	2%
350	**m_{DM} = 15 GeV**	**m_{DM} = 35 GeV**	**m_{DM} = 55 GeV**
>1 γ and no track	15%	12%	4%
1 γ	14%	12%	4%
Etot<1 GeV	12%	10%	3%
No Efwd	10%	8%	3%

Used higgsino-like DM as a benchmark (too low xsec for Bino or Wino)

Efficiency computed wrt all events, i.e. not all events have a photon

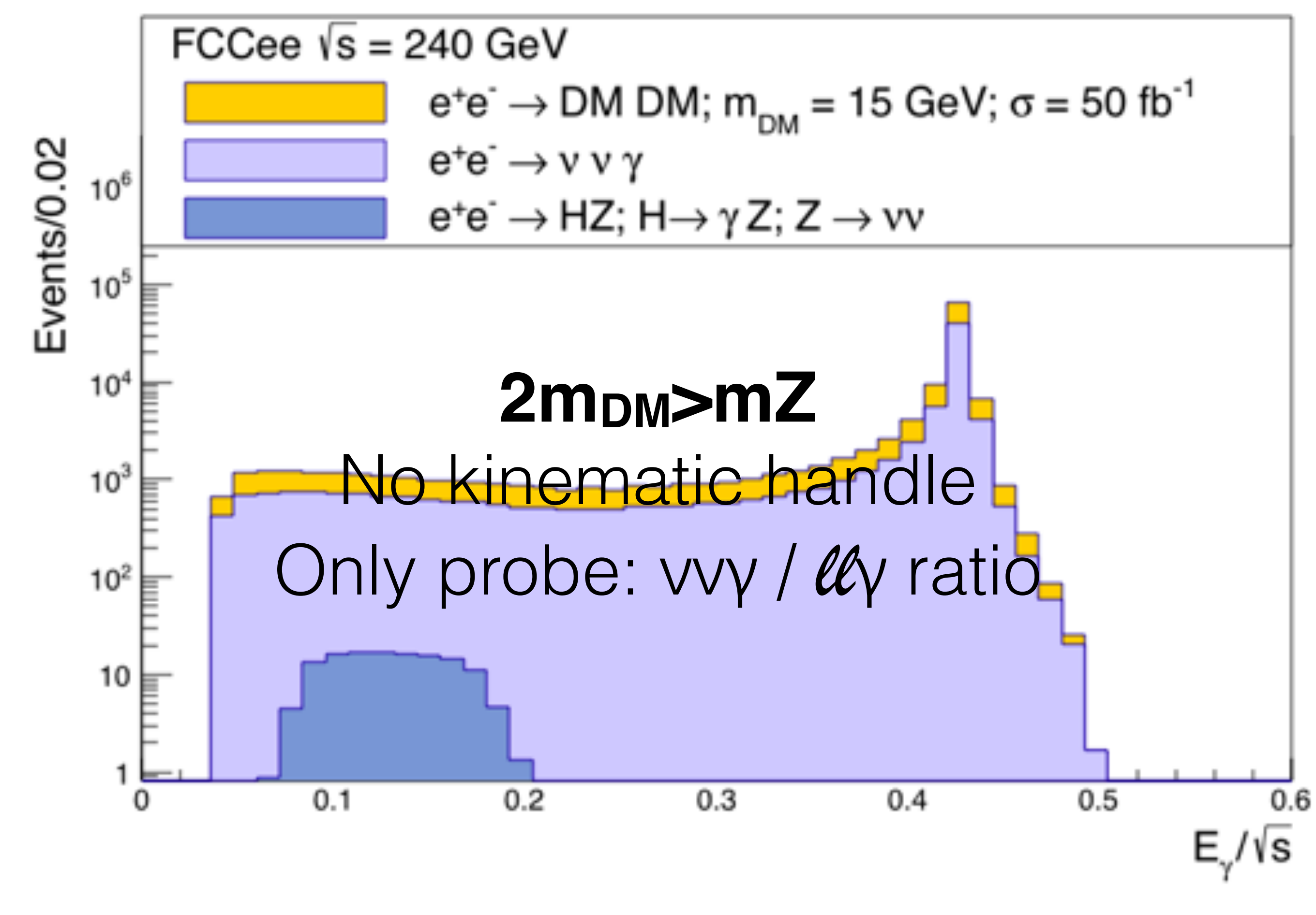
Background Efficiency

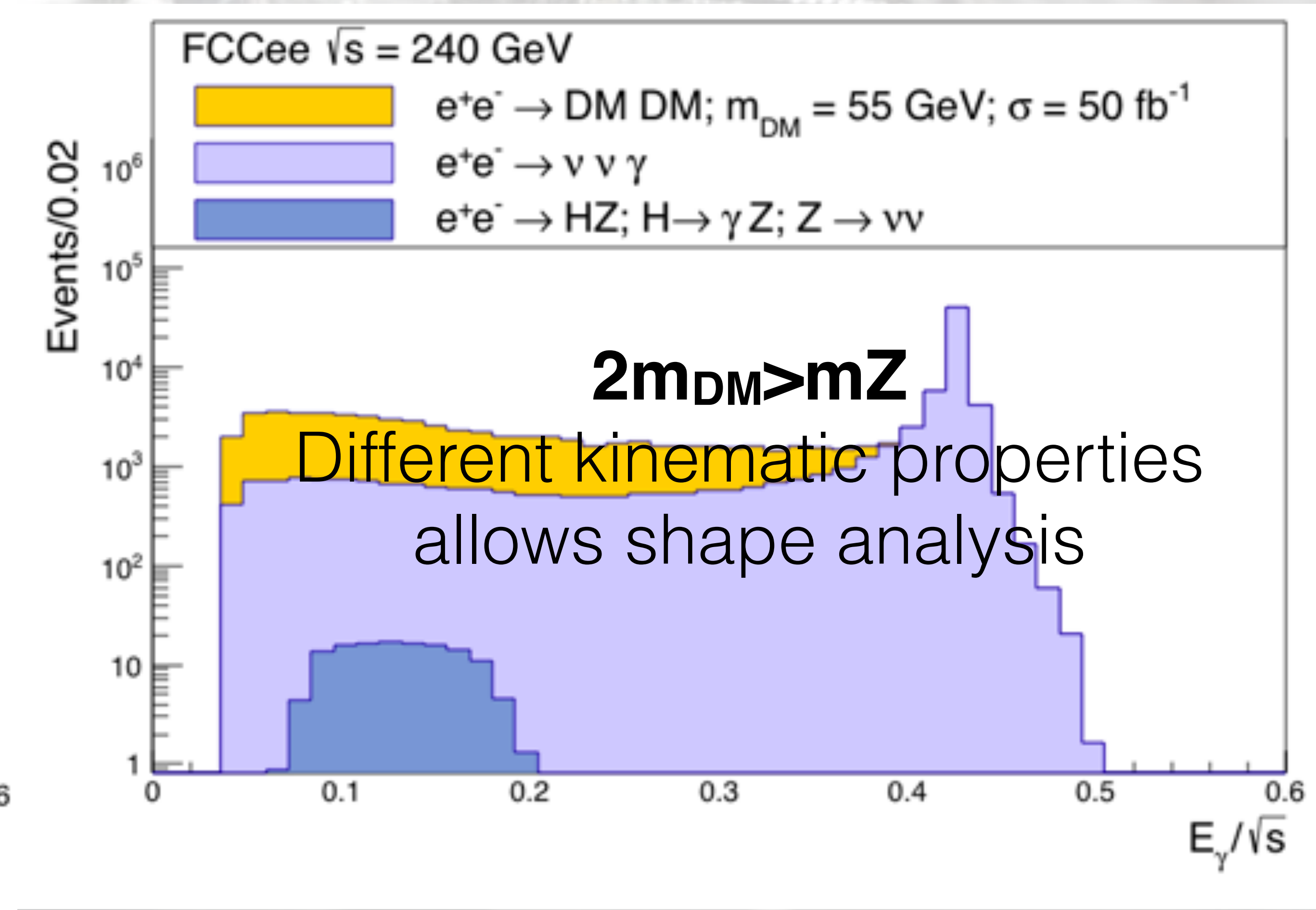
ννγ	160 GeV	240 GeV	350 GeV
>1 γ and no track	39%	32%	28%
1 γ	38%	32%	28%
Etot<1 GeV	33%	26%	23%
No Efwd	27%	22%	19%
H(γγ)Z(νν)	**160 GeV**	**240 GeV**	**350 GeV**
>1 γ and no track	92%	94%	94%
1 γ	4%	7%	8%
Etot<1 GeV	0.03%	0.1%	0.08%
No Efwd	0.03%	0.1%	0.06%
H(γZ)Z Z→νν	**160 GeV**	**240 GeV**	**350 GeV**
>1 γ and no track	93.0%	91.3%	84.1%
1 γ	92.8%	90.8%	81.4%
Etot<1 GeV	87%	79.4%	66.5%
No Efwd	71%	64.3%	54.1%

Other backgrounds (qqγ, γγ,llγ) have $<10^{-6}$ efficiency (neglected for now)
Very loose selection on E_γ: expected large bkg to be reduced
(due to shape separation)

Expected Background

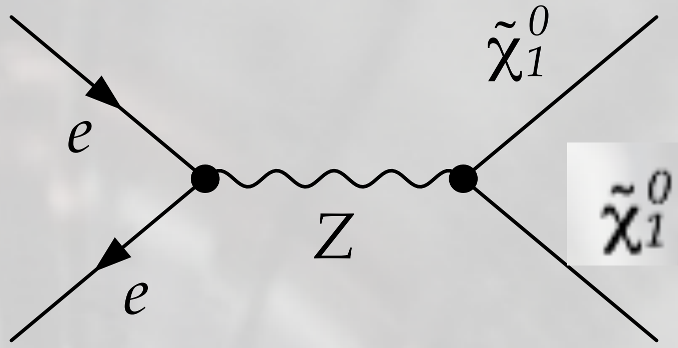
Ebeam	Run time [year]	# IPs	$\int L \cdot dt$	$N_{\nu\nu\gamma}$	$N_{H(\gamma Z)Z\ Z\to\nu\nu}$
160 GeV	1	4	42 ab^{-1}	8.9E+05	-
240 GeV	5	4	11 ab^{-1}	7.3E+04	134
350 GeV	5	4	3 ab^{-1}	8.3E+03	22

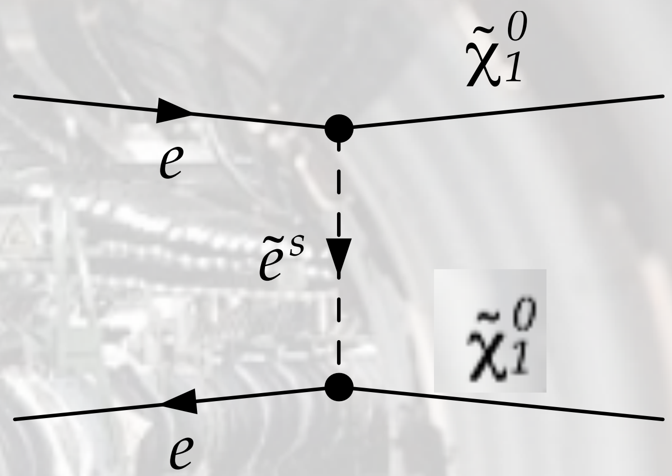


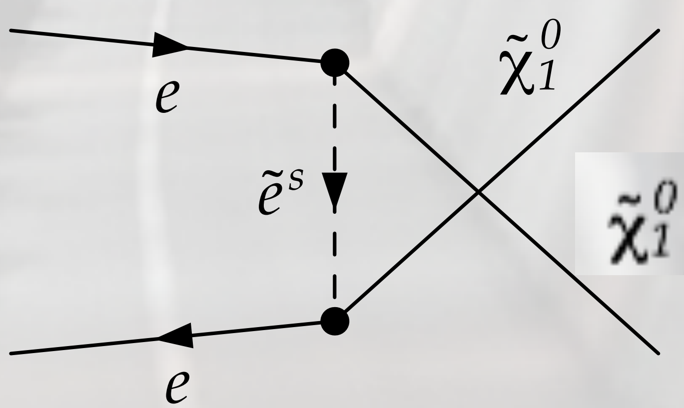


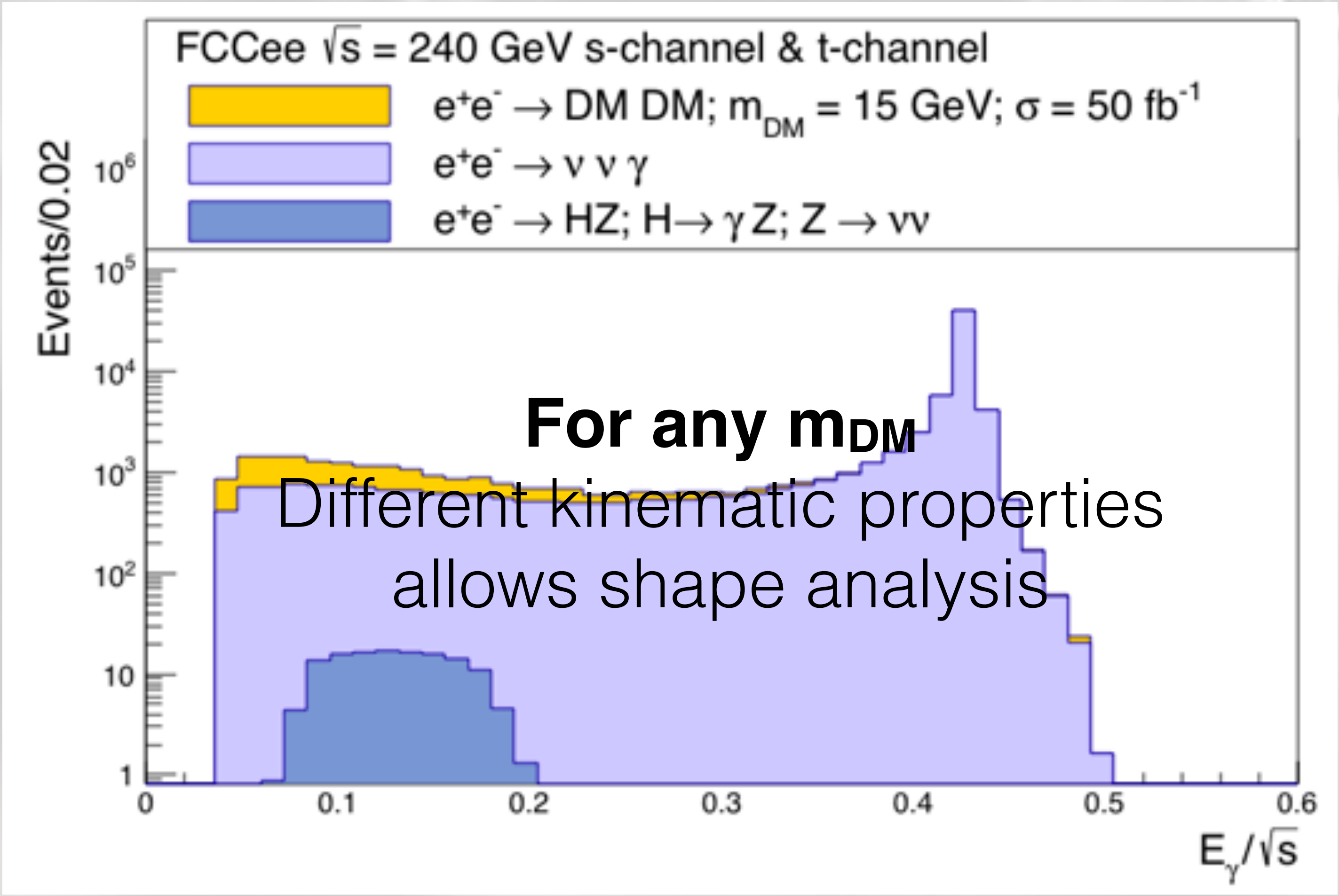
Adding the t-channel

- Allow for selections (eL and eR) at 500 GeV
  - No impact on Higgsino-like DM
  - Large xsec increase for Wino-like DM
  - t-channel provides for extra kinematic separation
  - Small efficiency at small masses
  - Shape barely depends on DM mass









Benchmark Needed

- At this point, any statement on DM sensitivity would be premature
    - strong dependence on the model
    - strong dependence on the rest of NP spectrum (heavy mediator, heavy (s)leptons, etc)
- <u>We need to establish a minimal set of simplified models to work with</u>
    - Follow the work happening between ATLAS and CMS
    - Work on obvious minimal models (Z and H portals) requiring no extra BSM particle
- This work could then be pushed beyond DM itself (SUSY simplified models, etc)

Summary

- Dark Matter could be produced at colliders
  - through some new heavy mediator which also couples to SM particles
  - coupling directly to SM particles (e.g. Z or H portals)
- Existing bounds from LEP put interesting bounds already
  - Measurement of $\Gamma(Z\to\text{invisible})$
  - Monophoton search
- Improved sensitivity @FCCee, thanks to large target ∫Lumi
  - $\Gamma(Z\to\text{invisible})/\Gamma(Z\to\ell\ell)$ @ Z pole
  - $\sigma(\nu\nu\gamma)/\sigma(\ell\ell\gamma)$ above Z pole with monophoton (Z portal)
  - Study photon spectrum for monophoton events (other DM models)
  - Add extra sensitivity with $H\to$invisible search
- Quantitative conclusions are model dependent: need to establish benchmark simplified models