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New approach to DM searches with mono-photons

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Outline

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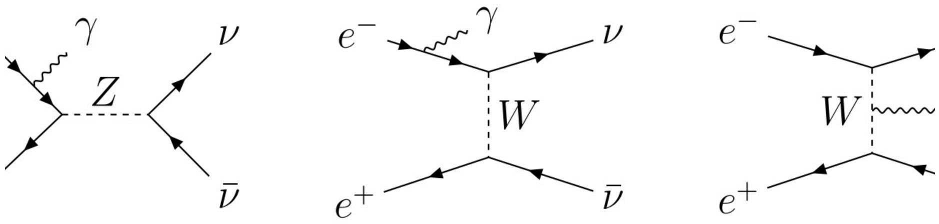
- Motivation
- Simulating mono-photon events with WHIZARD
  - new procedure for merging ISR structure function with ME
  - ArXiv: 2004.14486, **Eur. Phys. J. C (2020) 80: 634**
- New approach to DM searches with mono-photon signature
- Preliminary results
- Prospects

Motivation

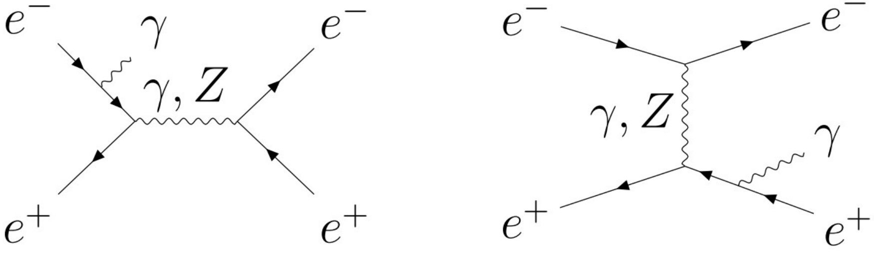
- Initial aim: preparation of background and signal samples for **Dark Matter analysis using a mono-photon signature. Following issues would need to be addressed:**
  - **To avoid double counting of photons from the ISR (γ^{ISR}) and those from matrix element (γ^{ME})**
  - **To have the same procedure for all backgrounds and DM signal,** successful generation of all processess in the first place: cutting out all of the singularities, stable cross sections calculations etc

- **Outcome: procedure general enough for any BSM searches with neutrino and Bhabha mono-photon events**
  - **NOTE: one cannot properly simulate all matrix element photons: t-channel W radiation events (mostly with high photon multiplicity) are not included in WHIZARD description of the ISR**

$e^+e^- \rightarrow \nu\bar{\nu}$



$e^+e^- \rightarrow e^+e^-$



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Simulating mono-photon events with WHIZARD

WHIZARD mono-photons

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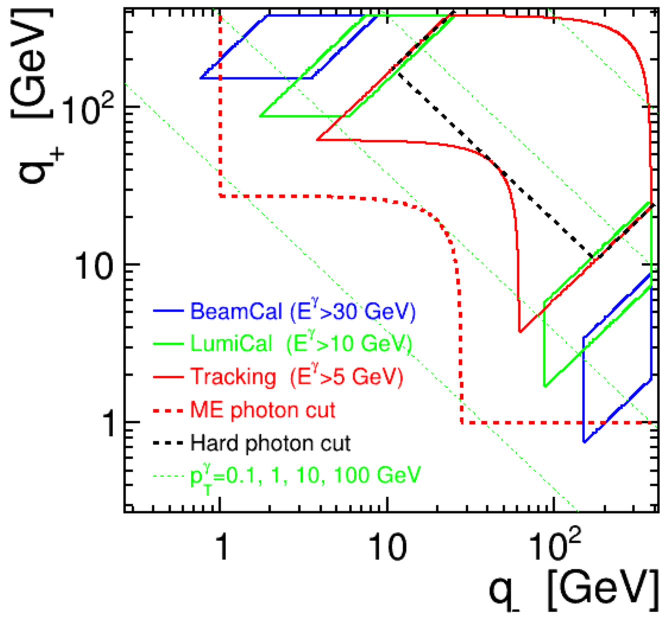
- **Lets define variables q^+ and q^- calculated for each photon in the event. e-/e+ fixed as beam energies:**

$$q_- = 2\sqrt{(E_{e_-} E_\gamma)}\sin(\frac{\theta_\gamma}{2})$$

$$q_+ = 2\sqrt{(E_{e_+} E_\gamma)}\cos(\frac{\theta_\gamma}{2})$$

- **Merging would be done for energy E^{min} and q^{min} : generated γ^{ME} should have q^+ and q^- above q^{min} and energy above E^{min}**
- **ISR photons accepted only below given E^{min} and q^{min} values**
- **Additional 'hard photon' selection: events with at least one γ having pT > 5 GeV and 7° < θ < 173°**

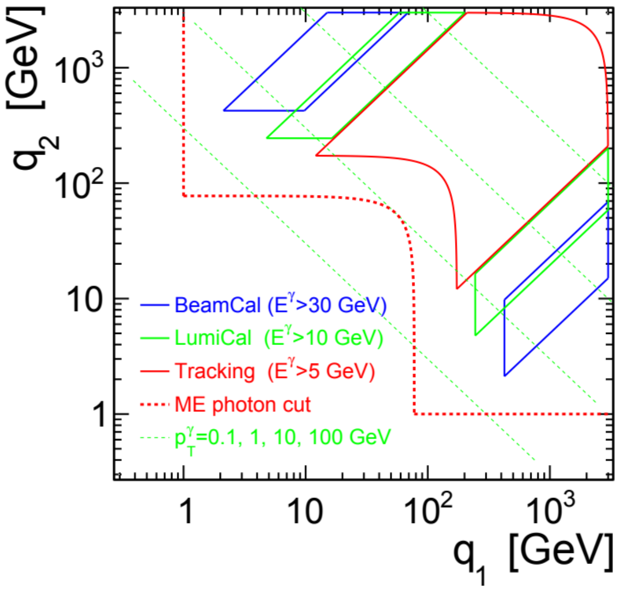


q^+/q^- phase space for √s of 380 GeV

(more cases in backup)

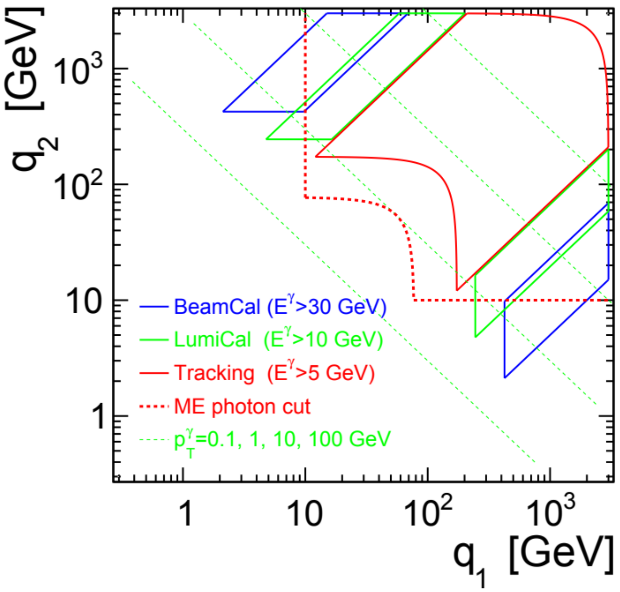
Merging ISR and ME photons

Using CLICdet design one can see that preferred value of q^{merge} is ~ 1 GeV: no ISR photons reach the BeamCal



q^{min} = 1 GeV

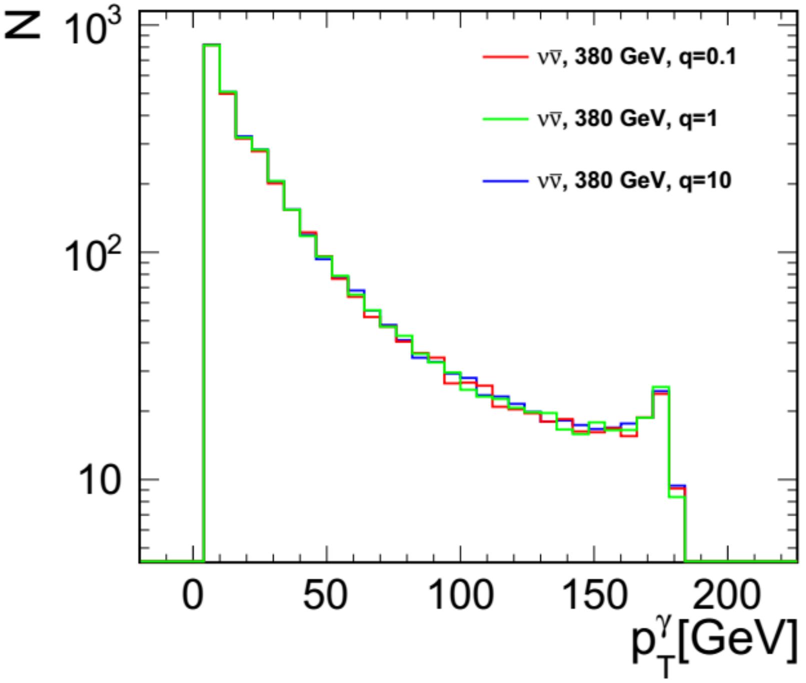
Plots for 3 TeV case



q^{min} = 10 GeV

Neutrino sample

$e^+e^- \to \nu\bar{\nu} + N\gamma$



Impact of q_{min} cut on cross section calculation: stable

$\sqrt{s}[GeV]$	$q_{min}[GeV]$	Whizard-2.8 $\sigma(e^+e^- \to \nu\bar{\nu})$ [fb]				$\sigma(e^+e^- \to \nu\bar{\nu})$ [fb] after ISR rejection
		$\nu\bar{\nu}$	$\nu\bar{\nu}+\gamma_{ME}$	$\nu\bar{\nu}+2\gamma_{ME}$	$\nu\bar{\nu}+3\gamma_{ME}$	
380	q_{min}=0.1	50900	16500	2600	220	50000
	q_{min}=0.5		12600	1600	110	50400
	q_{min}=1		10900	1200	55	50600
	q_{min}=5		7000	480	15	50700
	q_{min}=10		5300	270	7	50800

With 'hard photon' selection:

$\sqrt{s}[GeV]$	$q_{min}[GeV]$	Whizard-2.8 $\sigma(e^+e^- \to \nu\bar{\nu})$ [fb]			$\sigma(e^+e^- \to \nu\bar{\nu})$ [fb] after ISR rejection
		$\nu\bar{\nu}+\gamma_{ME}$	$\nu\bar{\nu}+2\gamma_{ME}$	$\nu\bar{\nu}+3\gamma_{ME}$	
380	q_{min}=0.1	3200	910	120	3000
	q_{min}=0.5	3200	670	55	3000
	q_{min}=1	3200	570	43	3100
	q_{min}=5	3200	340	10	3100
	q_{min}=10	3200	230	6	3100

$\nu\bar{\nu}$ sample: WHIZARD vs KKMC

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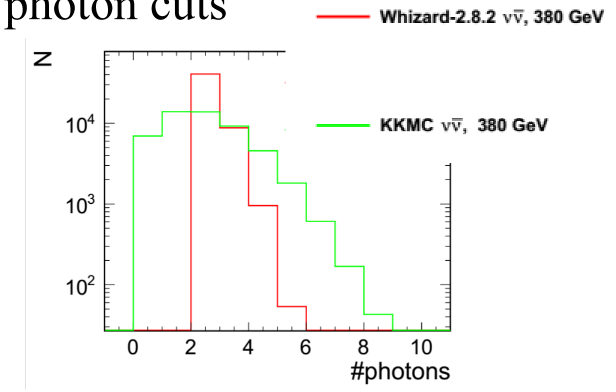
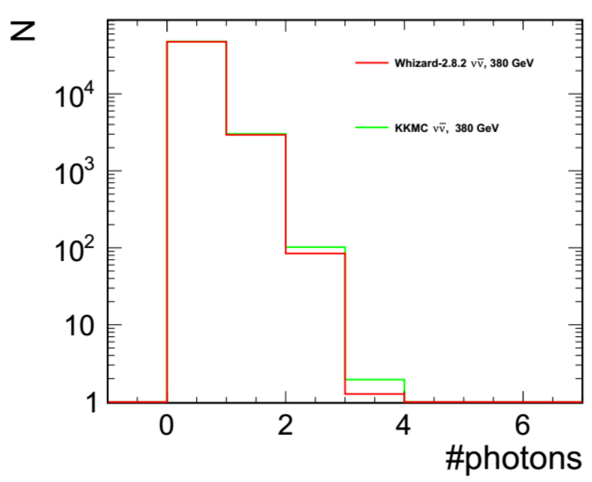
KKMC generator:
S. Jadach, B.F.L. Ward, Z. Wąs
Computer Physics Communications 130 (2000) 260–325

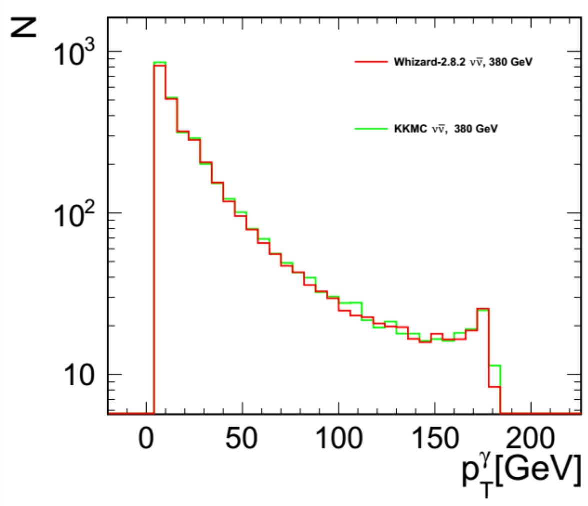
Comparison of WHIZARD and KKMC generators for neutrino sample at $\sqrt{s}$ = 380 GeV

- Using generators with different ISR/FSR descriptions
- no photon cuts



The same 'hard photon' selection imposed:

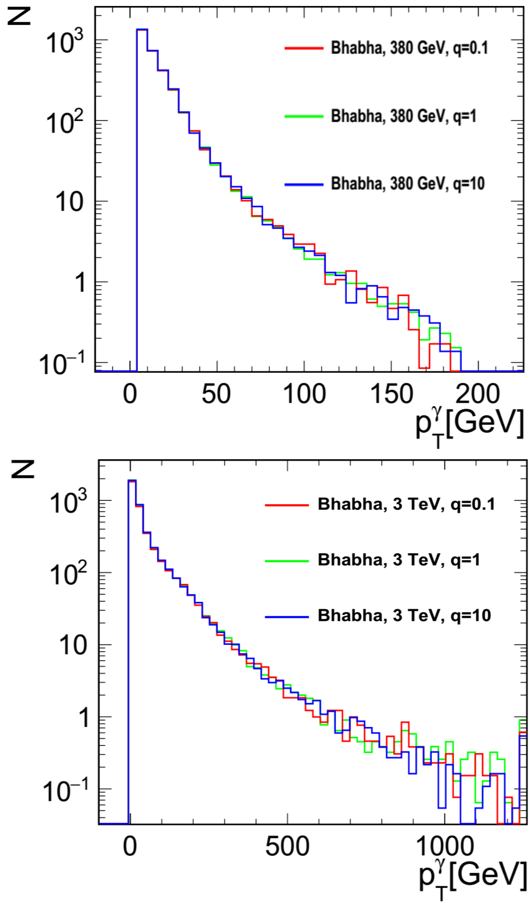




q^{min} set to 1 GeV

Bhabha sample and ISR/γ^{ME} merging

- **Comparison of pT spectra for energies of 380 GeV and 3 TeV for Bhabha background as a function of different merging parameters q^{min}**
- **Distributions show small impact on the shapes of the given spectra**
- **For further studies q^{min} value set to 1 GeV**



New approach to DM searches with mono-photon signature

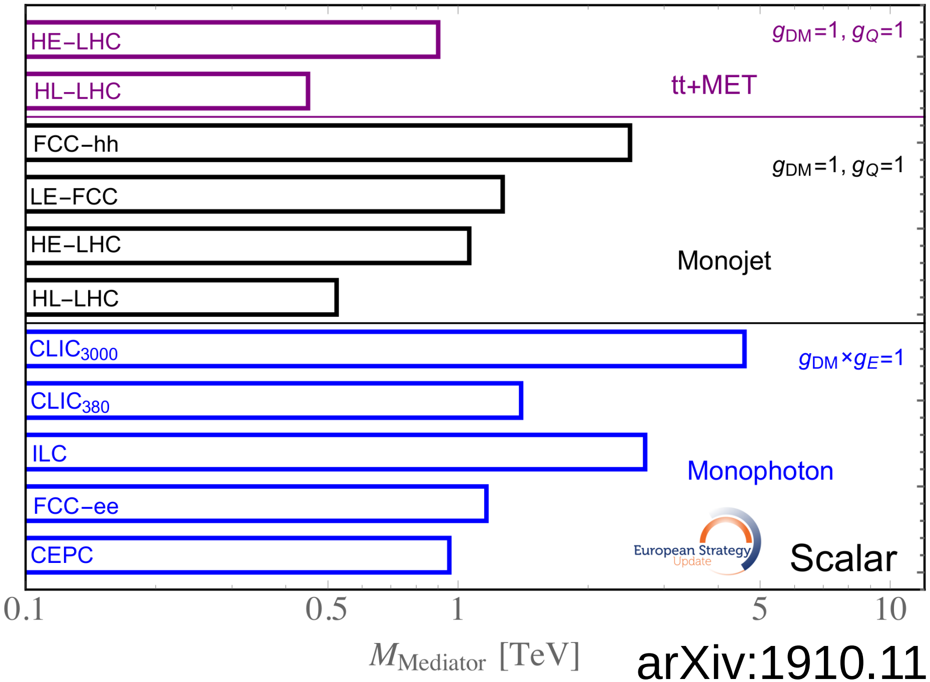
New approach to DM searches

- Common approach:
  setting limits on mediator mass for given coupling structure/values

- This approach is suitable,
  if we can assume

  $$M_{med} \gg \sqrt{s}$$

  but this does not need
  to be the case…

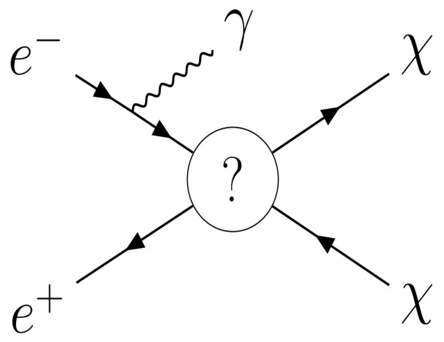


arXiv:1910.11775

- Different approach needed
  for mediator masses ~ $\sqrt{s}$

New approach to DM searches

- Experimental approach:
  set limits on the DM production cross section
  - as a function of the assumed **mediator mass and mediator width**
    DM mass not relevant, if sufficiently light
  - depends on the assumed **coupling structure**,
    but coupling values not relevant
  - most model independent limits
    can be then interpreted in different models

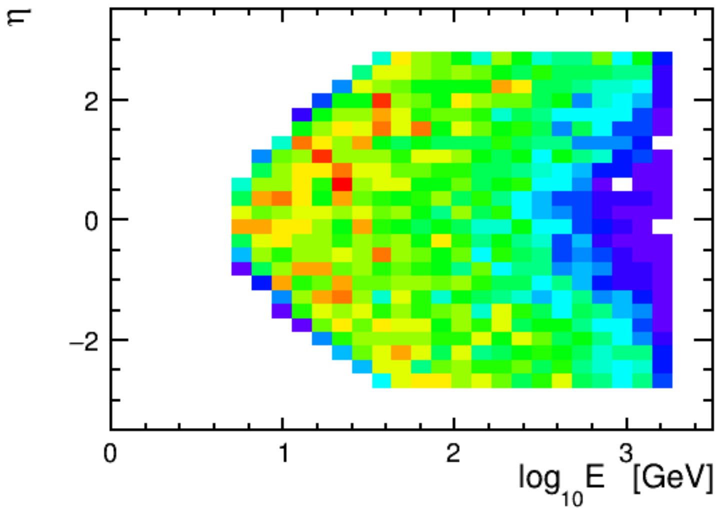


New approach to DM searches

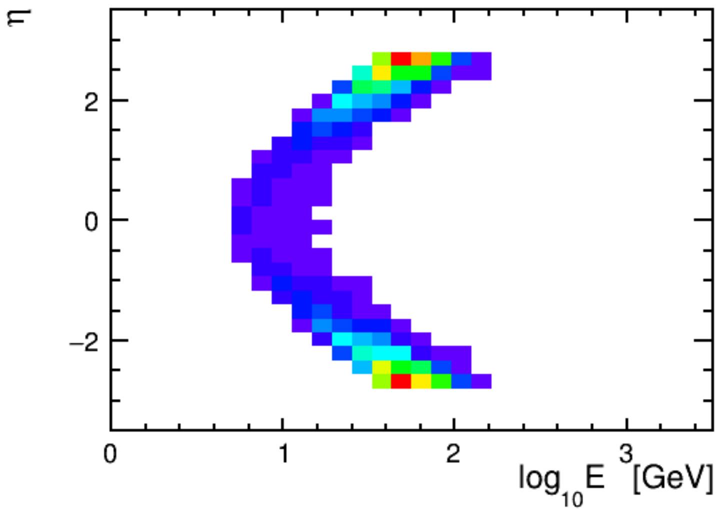
- Experimental approach:
  consider 2-D distribution of mono-photon event

- Main backgrounds (generator level cuts only) @ 3TeV CLIC:

$e^+e^- \longrightarrow \nu\nu$



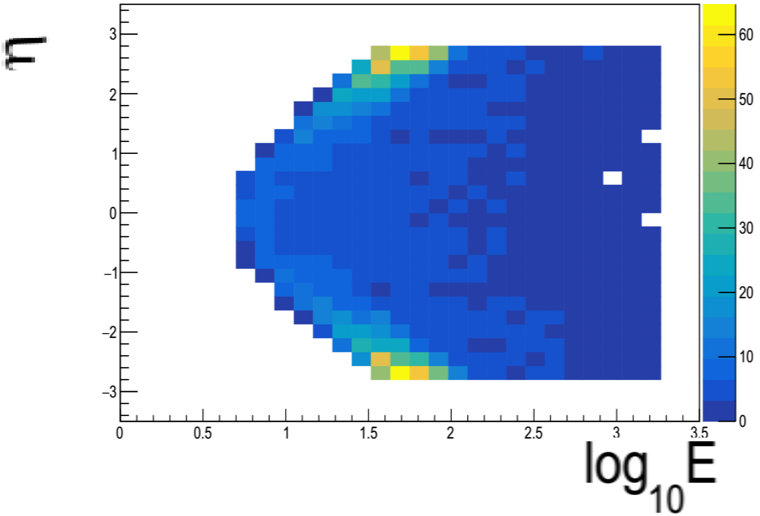
$e^+e^- \longrightarrow e^+e^-$

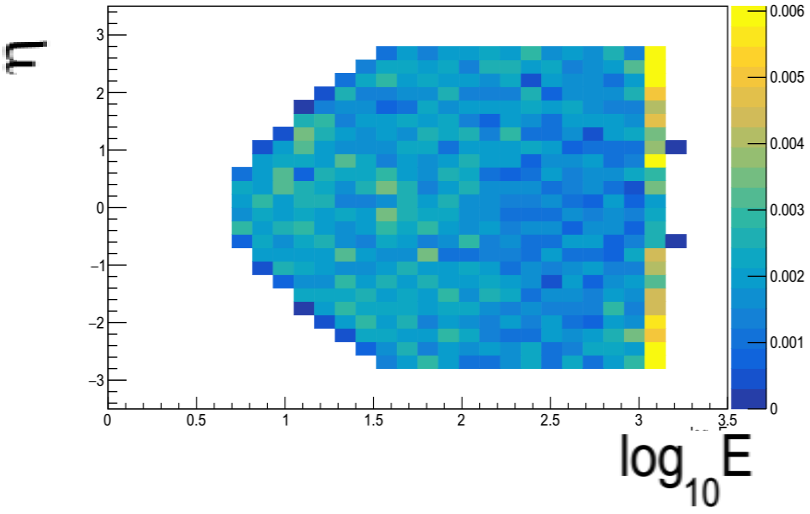


New approach to DM searches

- Experimental approach:
  consider 2-D distribution of mono-photon event

- Main backgrounds vs signal @ 3TeV CLIC
  $e^+e^- \to \nu\bar{\nu}$ & $e^+e^- \to e^+e^-$ M_{DM}=50GeV M_{med}=1TeV Γ_{med}=50GeV

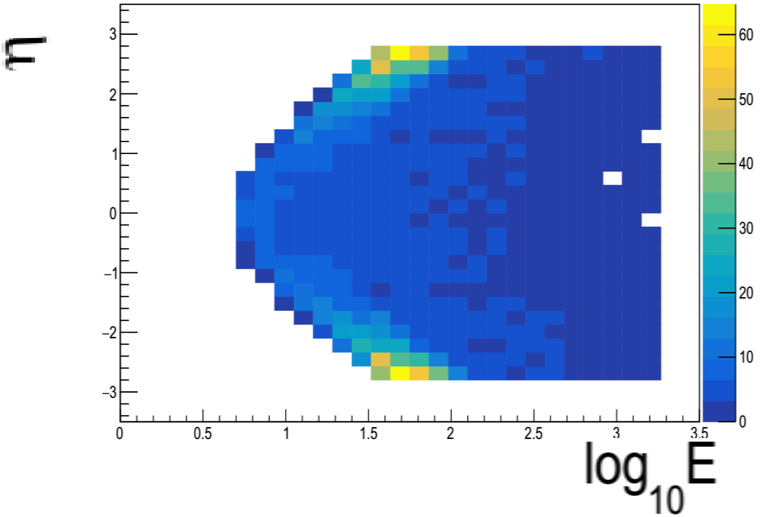


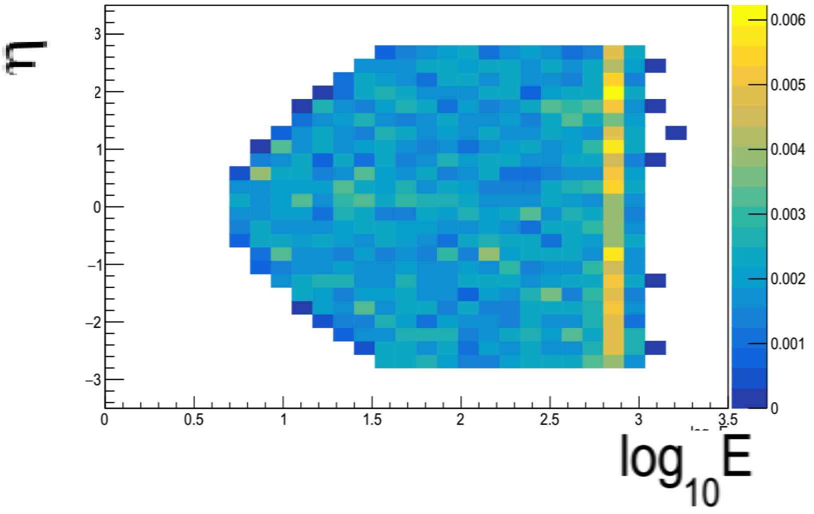


New approach to DM searches

- Experimental approach:
  consider 2-D distribution of mono-photon event

- Main backgrounds vs signal @ 3TeV CLIC
  $e^+e^- \rightarrow \nu\bar{\nu}$ & $e^+e^- \rightarrow e^+e^-$ M_{DM}=50GeV M_{med}=2TeV Γ_{med}=50GeV

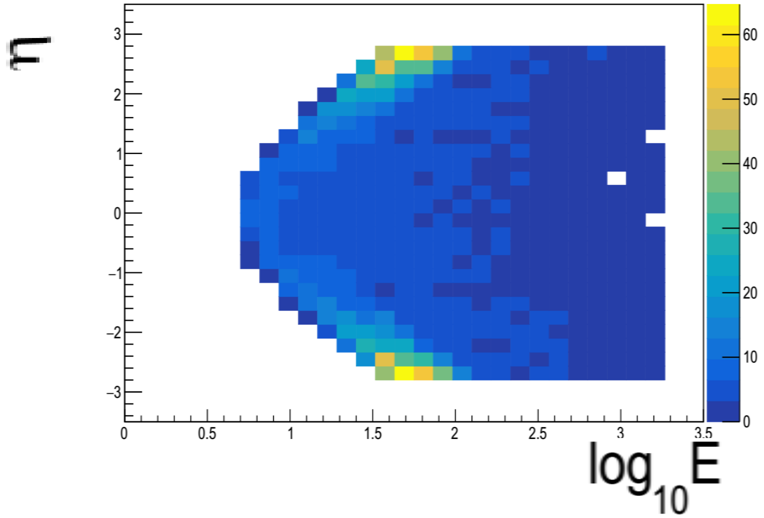


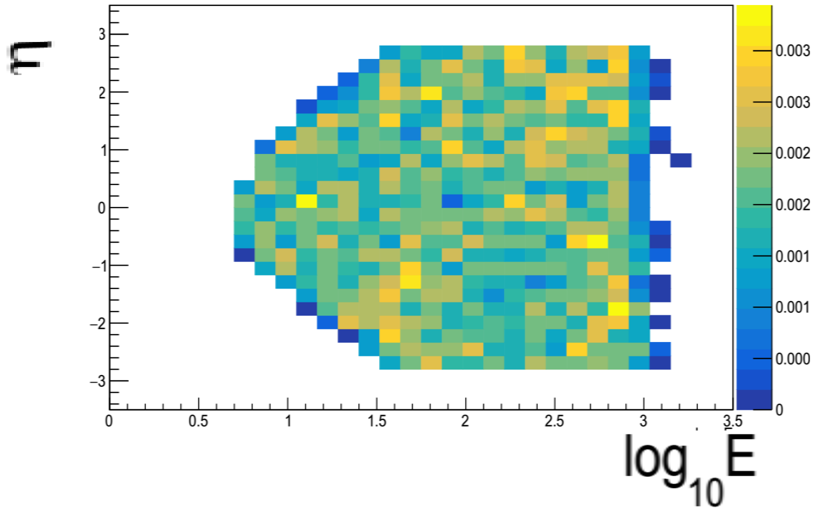


New approach to DM searches

- Experimental approach:
  consider 2-D distribution of mono-photon event

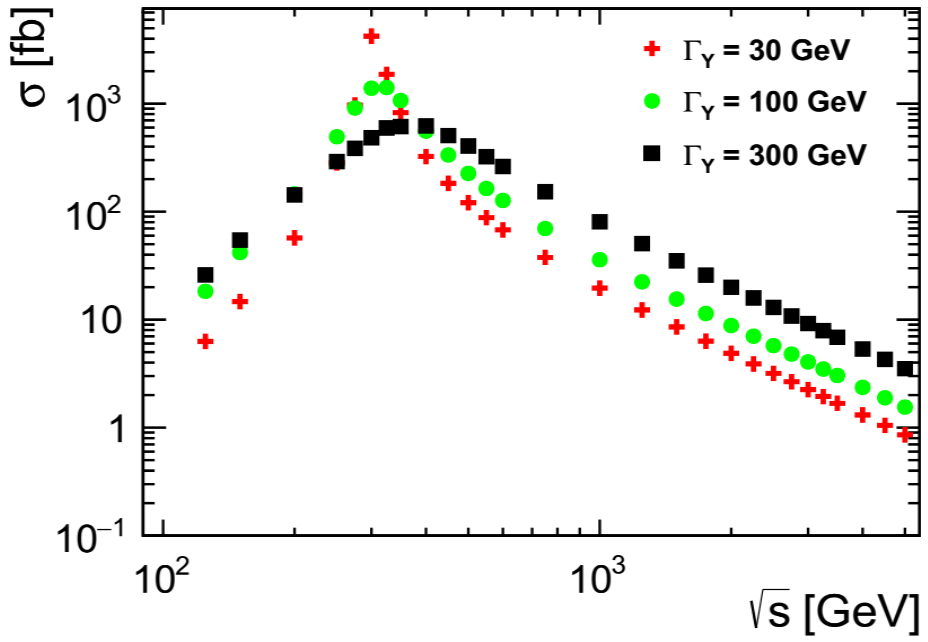
- Main backgrounds vs signal @ 3TeV CLIC
  $e^+e^- \rightarrow \nu\bar{\nu}$ & $e^+e^- \rightarrow e^+e^-$ M_{DM}=50GeV M_{med}=2TeV Γ_{med}=500GeV





Cross sections

- For now one scenario studied
  - Dirac Dark Matter of 50 GeV
  - Vector mediator with different masses and widths
- Example of cross section behaviour for different collision energies



Assumed mediator mass of 300 GeV

Cross sections as a function of mediator mass

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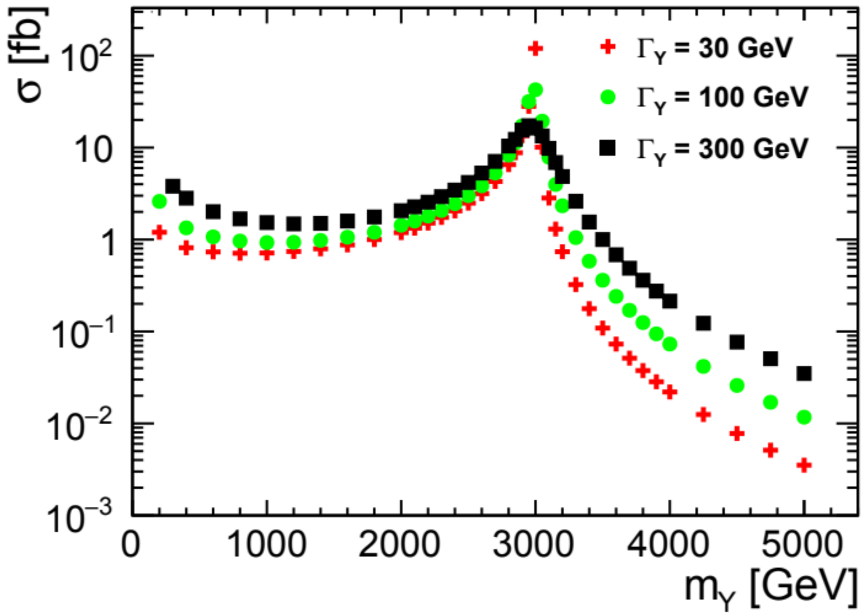
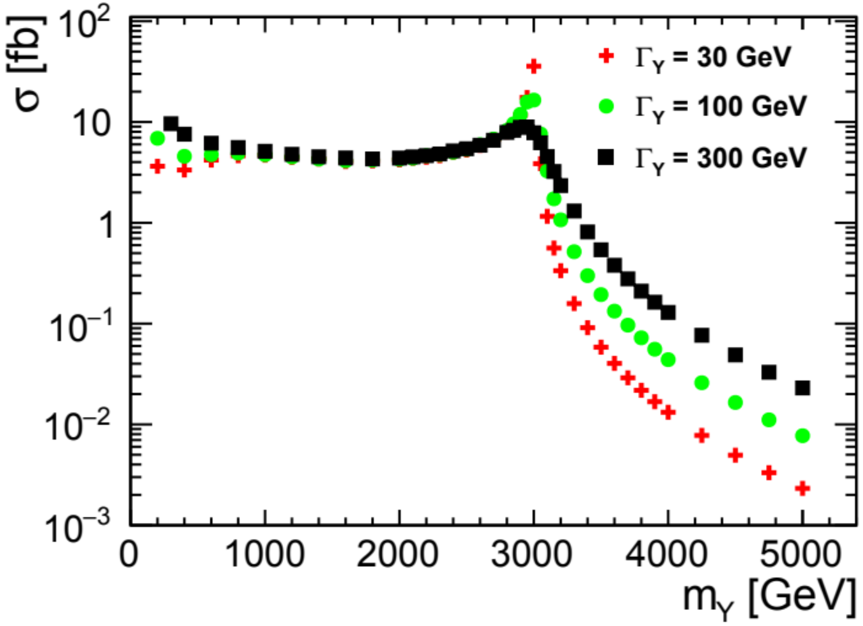
Without luminosity spectra



With luminosity spectra



For 3 TeV collision energy @ CLIC

Prospects on DM searches

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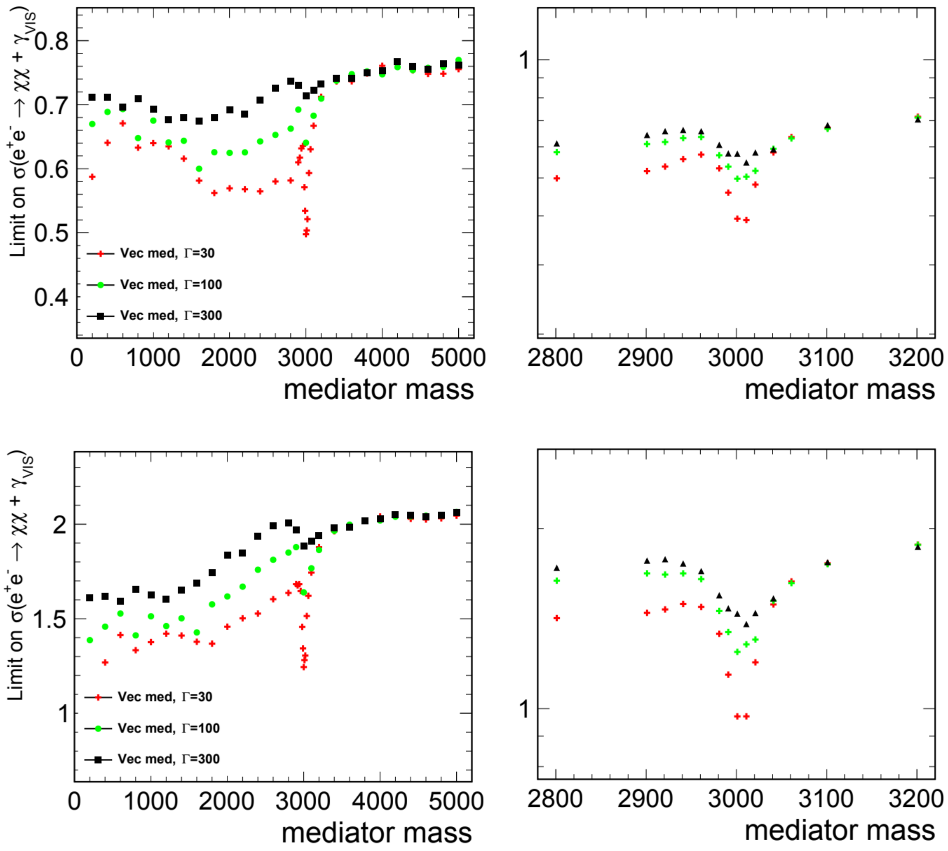
- Limits calculated with CLs method from 2D photon distributions
  - Assumed luminosity: 1 ab^{-1}
  - 3 TeV CLIC
  - Require only one photon in the detector (LumiCal and BeamCal veto)
  - Consider electron beam polarisation
  - Limits not corected for acceptance
- Stable cross section limits for a wide range of mediator masses
- Limits improve for narrow resonances



Positive pol.

Negative pol.

Prospects on DM searches

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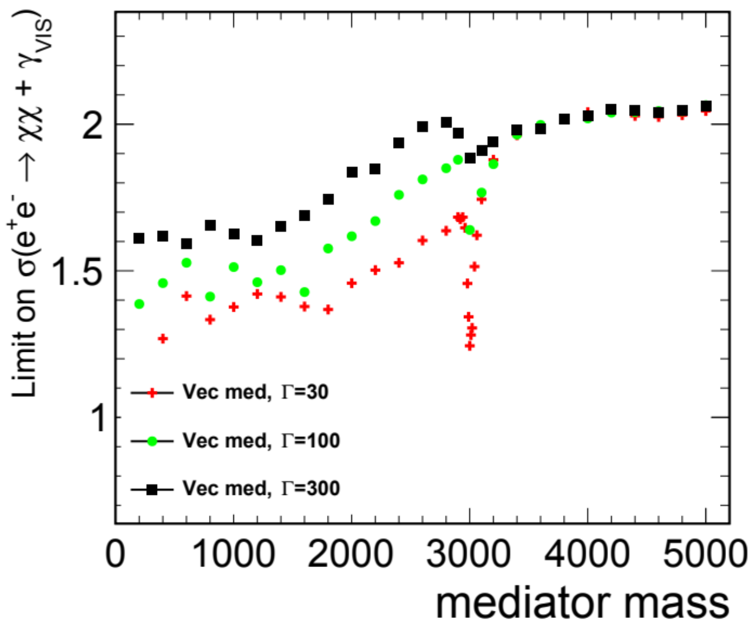
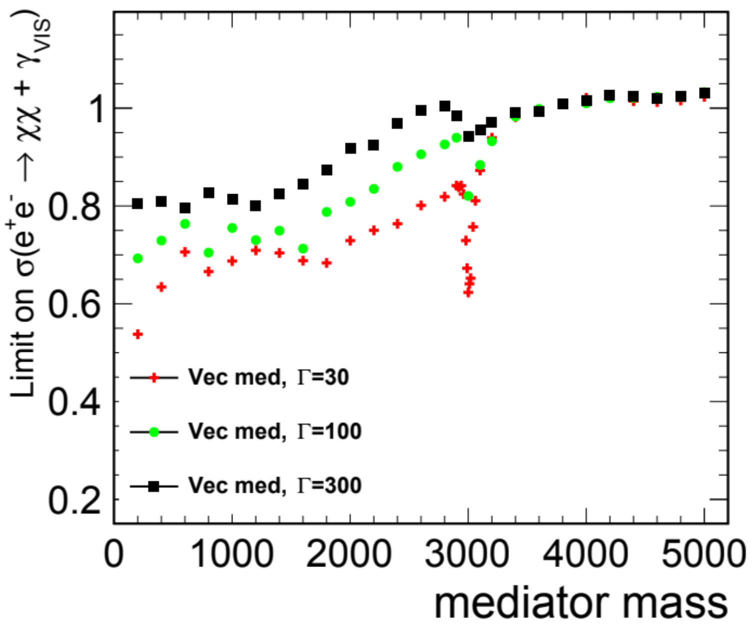
Impact of assumed luminosity
Negative polarisation

1 ab^{-1}



4 ab^{-1}

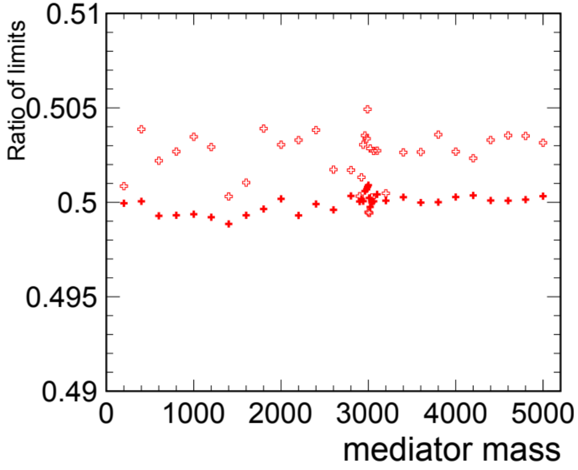


Ratios of limits

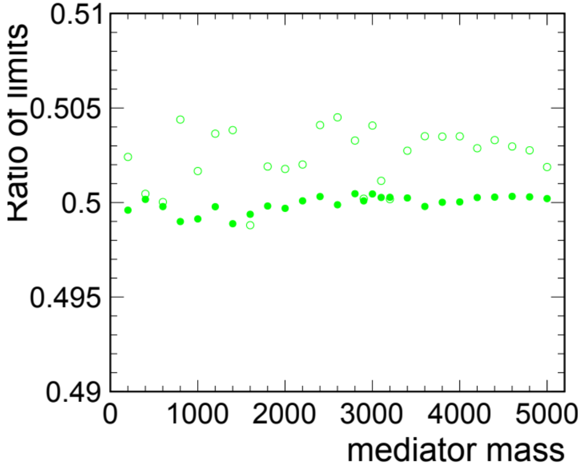
Ratios of limits calculated for assumed luminosity of 4 ab^{-1} with respect to 1 ab^{-1}

positive (open symbols) and negative (full) polarisation

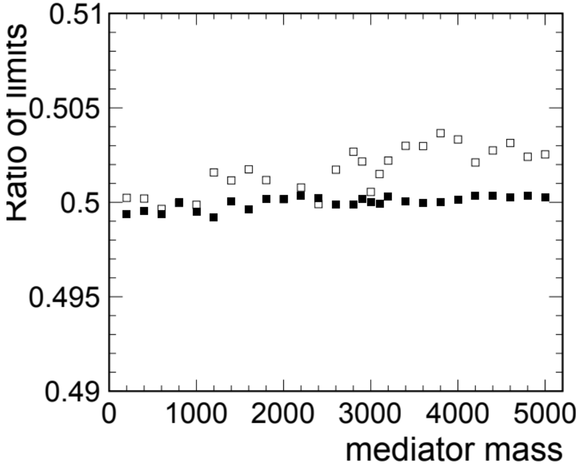
Γ = 30 GeV



Γ = 100 GeV



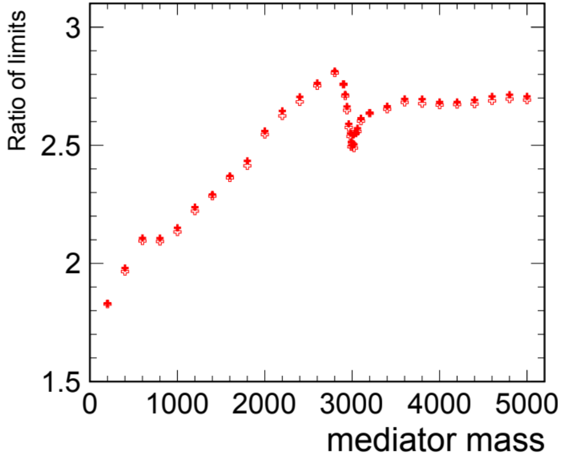
Γ = 300 GeV



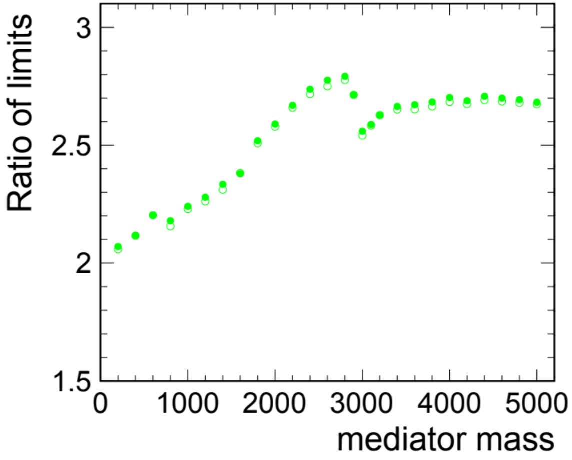
Ratios of limits

Ratios of limits calculated for negative polarisations to positive polarisation limits, for assumed luminosity of 1 ab^{-1}

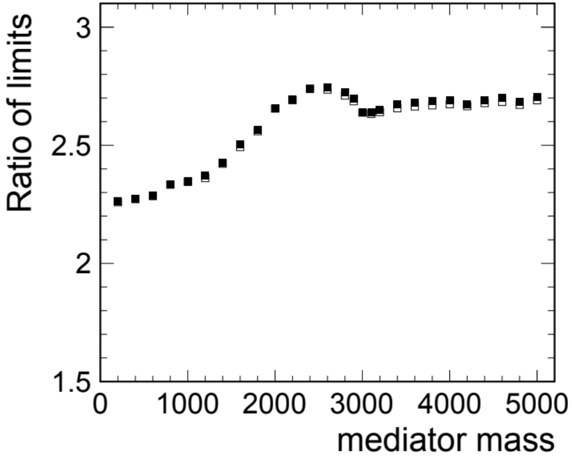
Γ = 30 GeV



Γ = 100 GeV



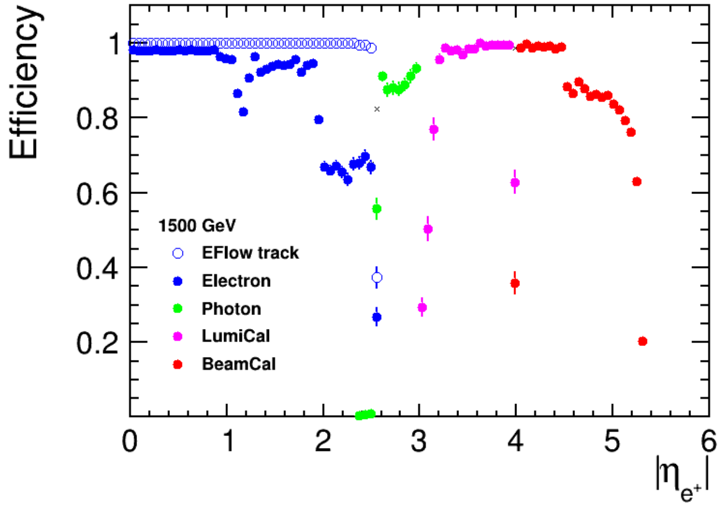
Γ = 300 GeV

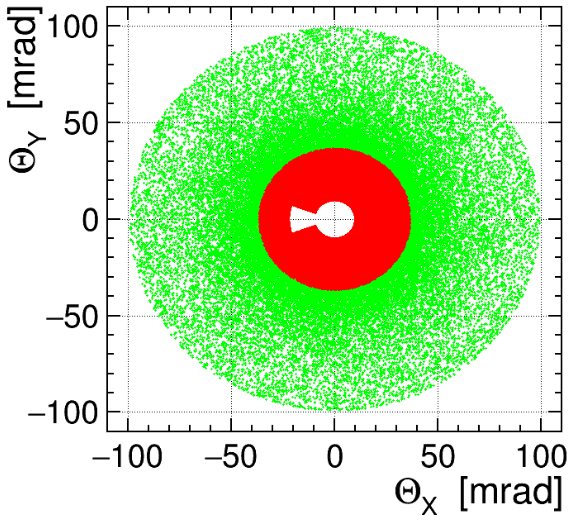


For the same luminosity, positive electron beam polarisation improves the sensitivitiy to DM production by about a factor of two

Prospects on DM searches

- All results so far based on generator level cuts
- Delphes model of CLICdet has beed modified to allow for better simulation of forward calorimeter acceptance





Conclusions

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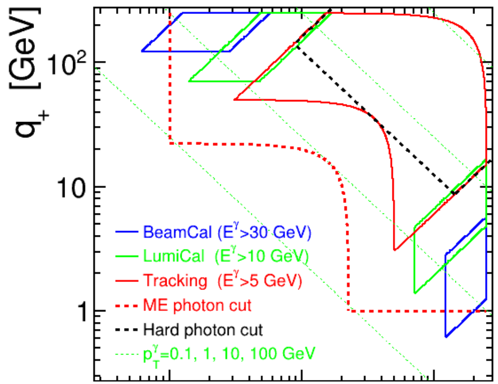
- **Presented merging procedure allows to treat two main backgrounds of mono-photon analysis with the same approach and obtain stable cross section calculations also for the Bhabha background. This procedure is general enough to be used for arbitrary BSM scenarios with mono-photon signature**

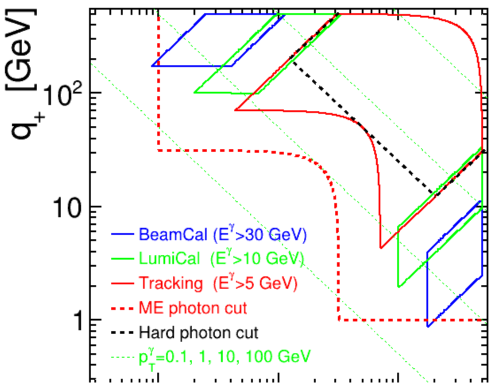
- **Working merging procedure allows to obtain model independent limits on Dark Matter production cross sections for different experimental setups**
  - **Only coupling structure needed**
  - **Impact of the mediator width on signal-to-background separation**
- **Scans of upper limits for a single DM scenario**
  - **Light mediators clearly distuingishable**
  - **Positive polarisation beam setup gives better limits**
- **Preliminary results based on generator level cuts, study based on Delphes detector model will follow**

Backup

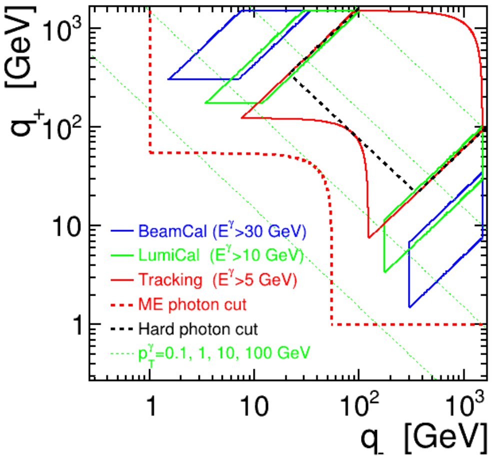
$\sqrt{s}$ = 250 GeV



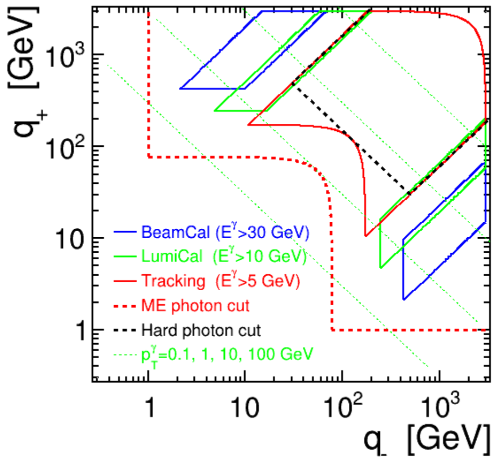
$\sqrt{s}$ = 500 GeV



$\sqrt{s}$ = 1.5 TeV



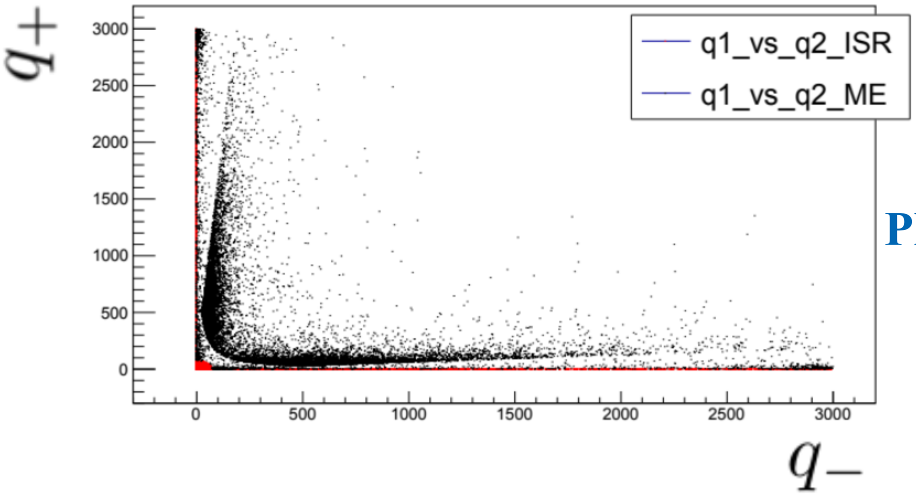
$\sqrt{s}$ = 3 TeV



Merging ISR and γ^{ME} for sample with Pt > 5 GeV cut

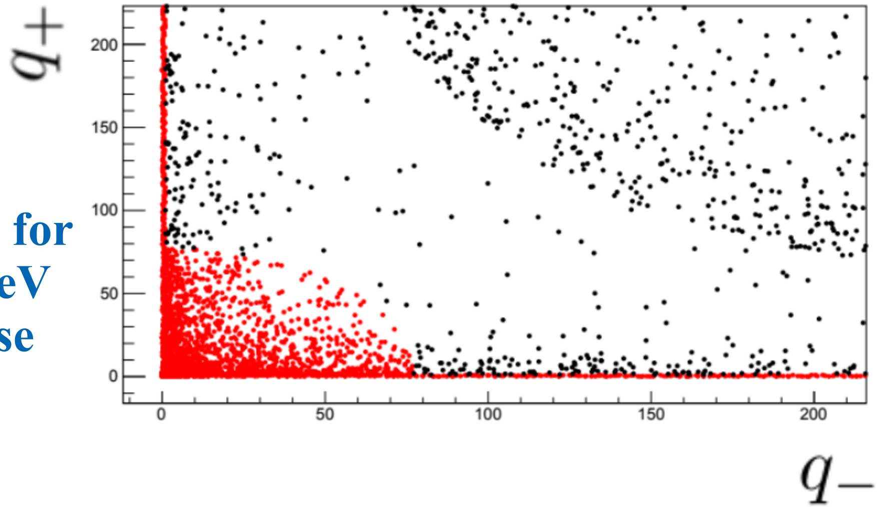
$q^{merge} = 1$ GeV

Bhabha sample



Plots for 3 TeV case

Zoom



Red – γ ISR

Black - γ^{ME}

$q^{merge} = 1$ GeV

Merging ISR and γ^{ME}

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Dependency of the neutrino sample on the merging parameter q^{min}

$\sqrt{s}[GeV]$	$q_{min}[GeV]$	Whizard-2.8 $\sigma(e^+e^- \to \nu\bar{\nu})$ $\nu\bar{\nu}$	$\nu\bar{\nu}+\gamma_{ME}$	$\nu\bar{\nu}+2\gamma_{ME}$	$\nu\bar{\nu}+3\gamma_{ME}$	$\sigma(e^+e^- \to \nu\bar{\nu})$ after ISR selection
380	q_{min}=0.1	50849	16500	2600	220	50000
	q_{min}=0.5		12600	1600	110	50400
	q_{min}=1		10900	1200	55	50600
	q_{min}=5		7000	480	15	50700
	q_{min}=10		5300	270	7	50800
	q_{min}=50		1400	21	0	50500
3000	q_{min}=0.1	53921	26200	6300	970	52200
	q_{min}=0.5		20700	4000	410	52300
	q_{min}=1		18500	3100	180	52400
	q_{min}=5		13000	1600	74	52700
	q_{min}=10		10700	1100	57	52600
	q_{min}=50		5200	260	2	52800

Merging ISR and γ^{ME}

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Dependency of the neutrino sample with a 'hard' γ^{ME} on the merging parameter q^{min}

$\sqrt{s}$[GeV]	q_{min}[GeV]	Whizard-2.8 $\sigma(e^+e^- \to \nu\bar{\nu})$ $\nu\bar{\nu}+\gamma_{ME}$	$\nu\bar{\nu}+2\gamma_{ME}$	$\nu\bar{\nu}+3\gamma_{ME}$	$\sigma(e^+e^- \to \nu\bar{\nu})$ after ISR selection
380	q_{min}=0.1	3200	910	120	3000
	q_{min}=0.5	3200	670	55	3000
	q_{min}=1	3200	570	43	3100
	q_{min}=5	3200	340	10	3100
	q_{min}=10	3200	230	6	3100
	q_{min}=50	1400	22	0	1400
3000	q_{min}=0.1	4200	1900	260	3700
	q_{min}=0.5	4200	1500	220	3900
	q_{min}=1	4200	1300	140	3900
	q_{min}=5	4200	850	66	3900
	q_{min}=10	4200	680	31	3900
	q_{min}=50	4000	240	2	3700

Merging ISR and γ^{ME}

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Dependency of the Bhabha sample with a 'hard' γ^{ME} on the merging parameter q^{min}
Bhabha background requires 'hard'-photon approach to have the cross setion calculations even converge

$\sqrt{s}[GeV]$	$q_{min}[GeV]$	Whizard-2.8 $\sigma(e^+e^- \to e^+e^- + N\gamma)$			$\sigma(e^+e^- \to e^+e^- + N\gamma))$ after ISR selection
		$e^+e^- + \gamma_{ME}$	$e^+e^- + 2\gamma_{ME}$	$e^+e^- + 3\gamma_{ME}$	
380	q_{min}=0.1	139500	29100	650	119800
	q_{min}=0.5	139200	20700	630	124900
	q_{min}=1	139300	17200	540	125600
	q_{min}=5	139700	9200	310	129400
	q_{min}=10	139400	4900	140	130000
	q_{min}=50	11200	150	2	11000
3000	q_{min}=0.1	8800	3600	74	6200
	q_{min}=0.5	9000	2800	73	6800
	q_{min}=1	8800	2700	33	7000
	q_{min}=5	8900	1800	30	7500
	q_{min}=10	8800	1200	22	7300
	q_{min}=50	7000	280	7	6000

Merging ISR/γ^{ME}

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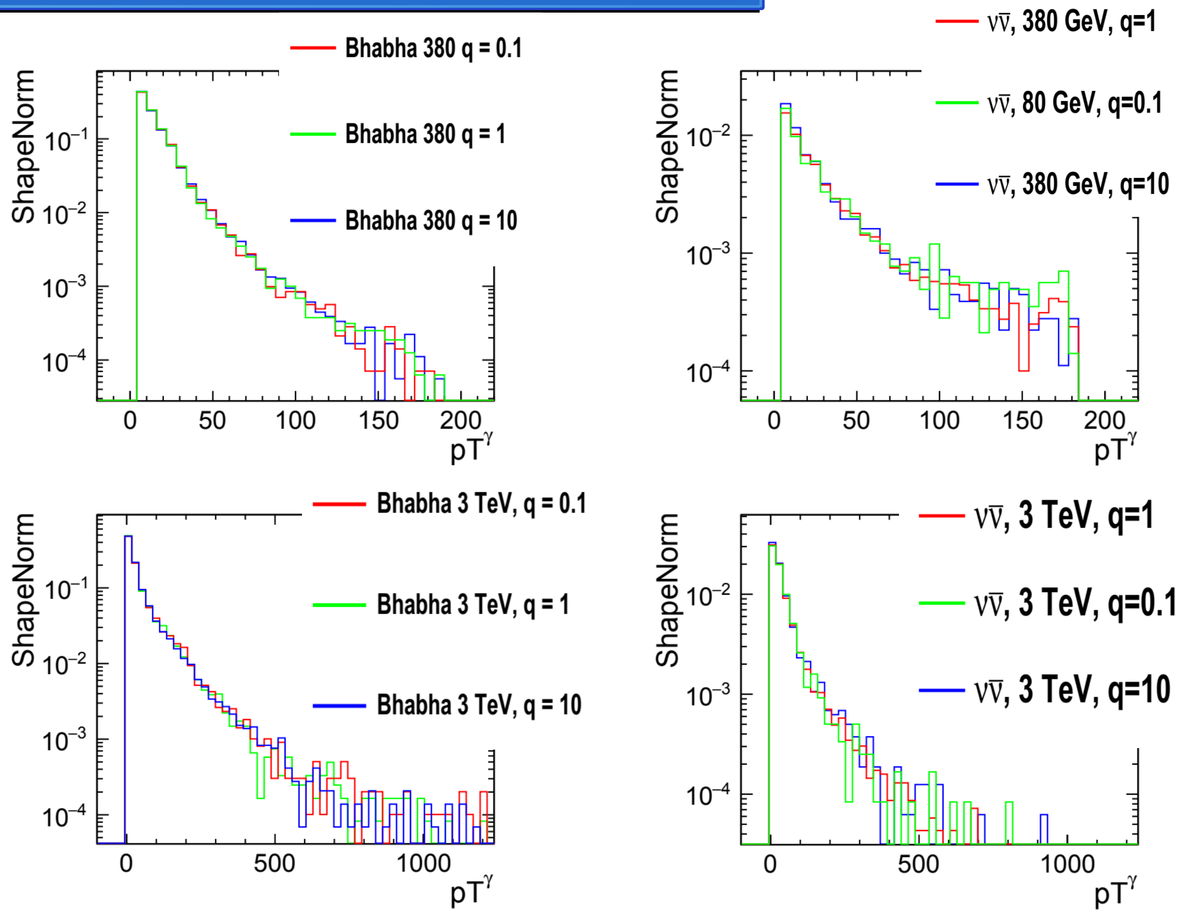
- **Comparison of pT spectra for energies of 380 GeV and 3 TeV for neutrino and Bhabha backgrounds as a function of different merging parameters q^{min}**
- **Distributions show small impact on the shapes of the given spectra**
- **For further studies q^{min} value set to 1 GeV**



More on σ and collision energy

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Backgrounds σ as a function of collision energy

Bhabha samples

$\sqrt{s}[GeV]$	Whizard-2.8 $\sigma(e^+e^- \to e^+e^- + N\gamma)$ $e^+e^- + \gamma_{ME}$	$e^+e^- + 2\gamma_{ME}$	$e^+e^- + 3\gamma_{ME}$	$\sigma(e^+e^- \to e^+e^- + N\gamma)$after ISR selection
240	233400	24900	480	216000
250	223600	24800	730	208100
380	139300	17200	540	125600
500	99300	14200	330	88800
1000	39900	7200	270	34000
1500	22900	4700	140	18800
3000	8800	2700	33	7000

neutrino samples

$\sqrt{s}[GeV]$	Whizard-2.8 $\sigma(e^+e^- \to \nu\bar{\nu})$ $\nu\bar{\nu} + \gamma_{ME}$	$\nu\bar{\nu} + 2\gamma_{ME}$	$\nu\bar{\nu} + 3\gamma_{ME}$	$\sigma(e^+e^- \to \nu\bar{\nu})$ after ISR selection
240	4200	730	37	4100
250	4100	700	48	3900
380	3200	570	43	3100
500	3100	590	48	3000
1000	3500	780	74	3300
1500	3800	940	98	3600
3000	4200	1300	140	3900

$\sqrt{s}[GeV]$	Whizard-2.8 $\sigma(e^+e^- \to \nu\bar{\nu})$ $\nu\bar{\nu}$	$\nu\bar{\nu} + \gamma_{ME}$	$\nu\bar{\nu} + 2\gamma_{ME}$	$\nu\bar{\nu} + 3\gamma_{ME}$	$\sigma(e^+e^- \to \nu\bar{\nu})$ after ISR selection
240	53900	12600	1300	64	53800
250	53300	12200	1300	60	53000
380	50900	10900	1200	55	50600
500	51200	11300	1200	75	51200
1000	52800	13600	1700	120	52200
1500	53300	15400	2200	170	52100
3000	53900	18500	3100	180	52400

Merging ISR/γ^{ME} and beamstrahlung

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Impact of beamstrahlung (BS in tables) on backgrounds' cross sections:

Cross sections for **neutrino** background samples are **not affected** by switching on the beam spectra

Beam spectra crucial for 3TeV Bhabha background

Note: values in [fb], rounded differently for each order of mag.

Bhabha

$\sqrt{s}[GeV]$	$q_{min}[GeV]$	Whizard-2.8 $\sigma(e^+e^- \to e^+e^- + N\gamma)$: $e^+e^- + \gamma_{ME}$	$e^+e^- + 2\gamma_{ME}$	$e^+e^- + 3\gamma_{ME}$	$e^+e^- + 4\gamma_{ME}$	$\sigma(e^+e^- \to e^+e^- + N\gamma))$ after ISR selection
380	noISR+noBS	128100	16700	1100	2	145900
	BS	407600	29600	640	4	437800
	ISR	139200	17600	520	3	125100
	BS+ISR	144900	18200	530	0	131700
3000	noISR+noBS	5800	2200	77	0	8100
	BS	221600	15100	88	2	236800
	ISR	8900	2500	74	0	6900
	BS+ISR	20400	3800	100	0	15900

Neutrinos

$\sqrt{s}[GeV]$	$q_{min}[GeV]$	Whizard-2.8 $\sigma(e^+e^- \to \nu\bar{\nu})$: $\nu\bar{\nu} + \gamma_{ME}$	$\nu\bar{\nu} + 2\gamma_{ME}$	$\nu\bar{\nu} + 3\gamma_{ME}$	$\nu\bar{\nu} + 4\gamma_{ME}$	$\sigma(e^+e^- \to \nu\bar{\nu})$ after ISR selection
380	noISR+noBS	3000	550	48	1	3600
	BS	3000	560	45	1	3600
	ISR	3200	570	48	0	3100
	BS+ISR	3200	580	43	2	3100
3000	noISR+noBS	4300	1300	150	4	5700
	BS	4100	1200	130	1	5400
	ISR	4200	1300	140	2	3900
	BS+ISR	4000	1200	130	1	3800

$\nu\bar{\nu}$ sample: WHIZARD vs KKMC

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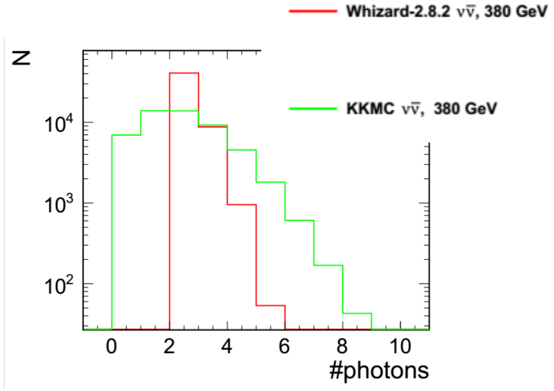
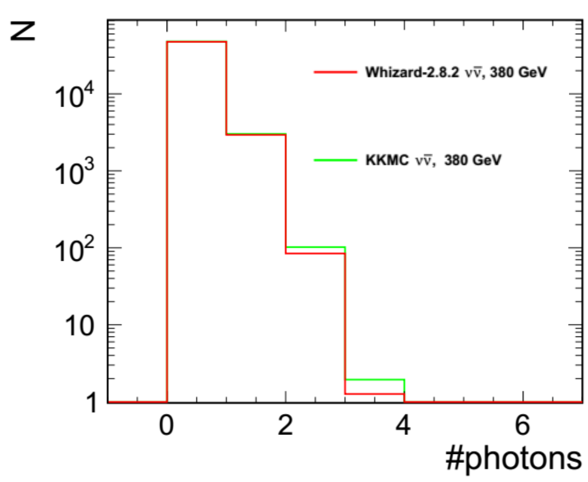
Comparison of WHIZARD and KKMC generators for neutrino sample at $\sqrt{s}$ = 380 GeV

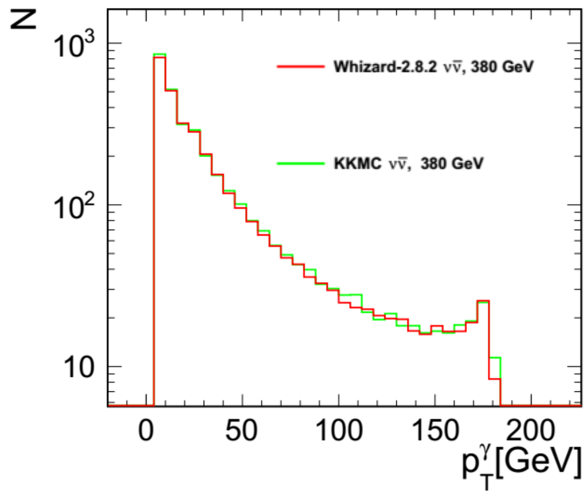
KKMC generator:
S. Jadach, B.F.L. Ward, Z. Wąs
Computer Physics Communications 130 (2000) 260–325

- Using generators with different ISR/FSR descriptions
- no photon cuts



The same 'hard photon' selection imposed:

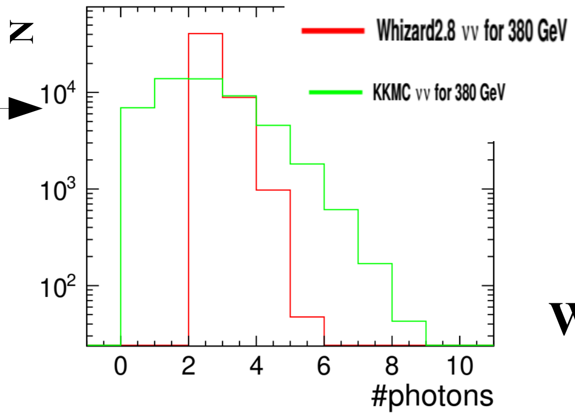


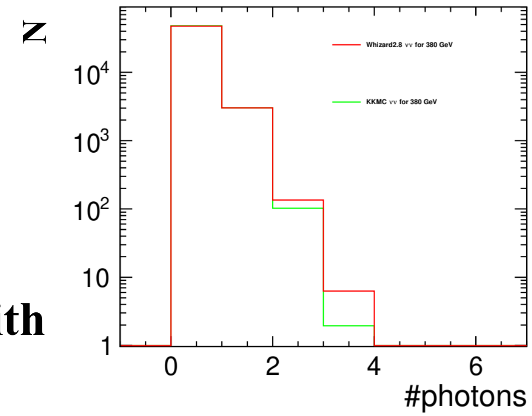


q^{min} set to 1 GeV

Comparison with KKMC

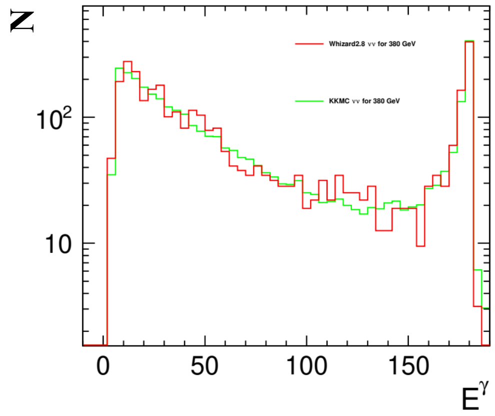
Before selection





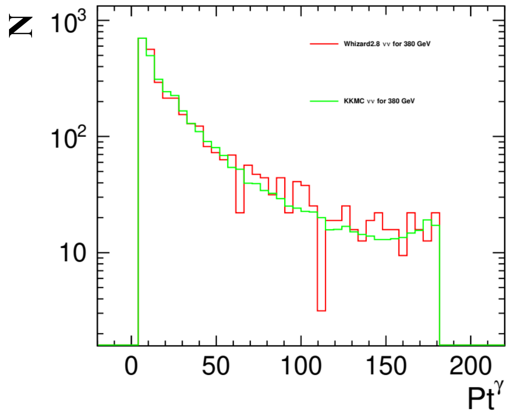
After selection

Whizard sample with basic merging



Selecting photons:

pT > 5 GeV
7° < θ < 173°



Comparison with KKMC

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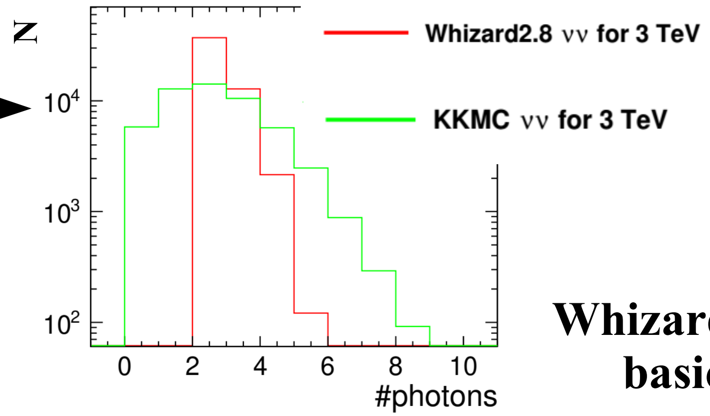
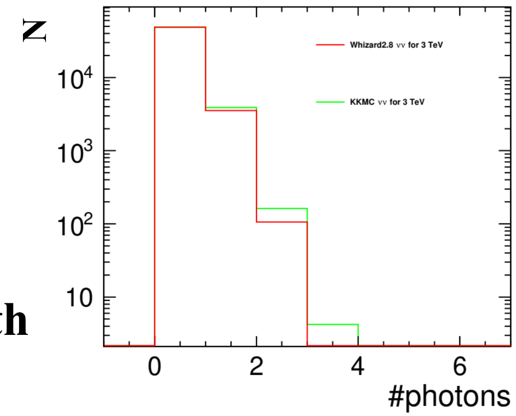
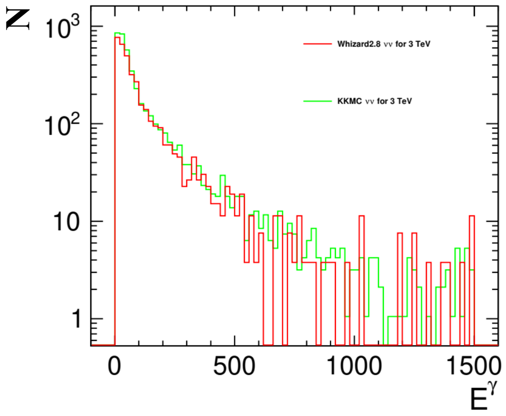
Before selection



After selection



Whizard sample with basic merging



Selecting photons:

$p_T > 5$ GeV
$7° < \theta < 173°$