The FCC-ee design study

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Processes with mono-photons in e+e- collisions: simulating SM background

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Motivation

Great expectations for New Physics at the LHC, but no direct evidence (yet?)

Outstanding questions remain + various BSM hints (DM, neutrinos,...)

A plausible scenario with dark matter candidate(s):

- all colored particles very heavy
- a few light EW particles, nearly mass-degenerate
- even charged states difficult to detect due to soft decay products
- dark matter cannot be seen directly

A future e+e- collider with:

- clean environment
- fixed CM frame
- polarized beams

can cope with such a difficult scenario via processes with a photon

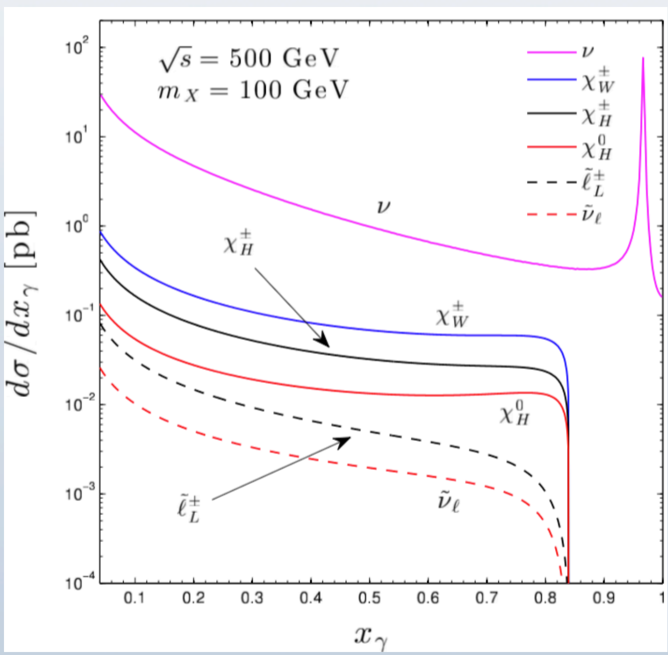
$$e^+e^- \to \chi\,\chi\,\gamma \to \gamma + E^{miss}$$

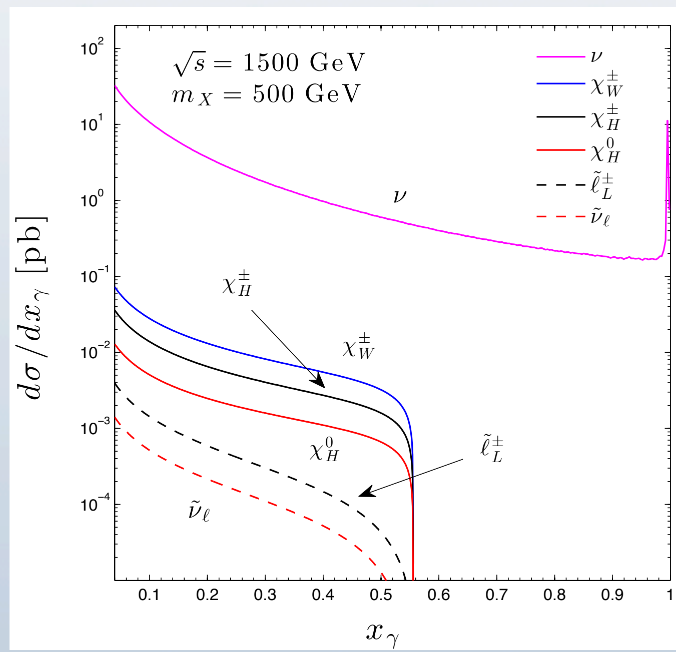
Motivation

Processes $e^+e^- \to \gamma + E^{miss}$ have been exploited in the past:

- counting neutrino families
- anomalous gauge couplings
- search for invisible states like lightest neutralino

e.g.previous studies: DM signal vs. neutrino background





S.Y. Choi, T. Han, JK., K. Rolbiecki and X. Wang, PRD 92(2015)095006

Motivation

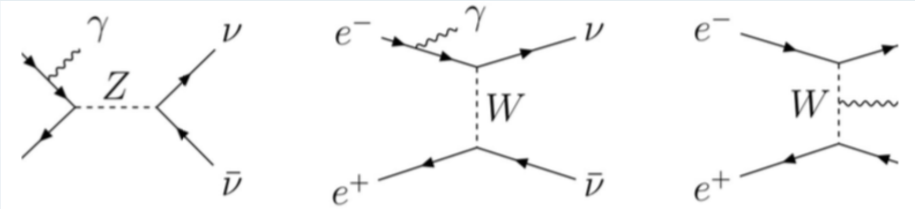
◆ Before assessing the discovery potential of the mono-photon processes

$$e^+e^- \to \gamma + E^{miss}$$

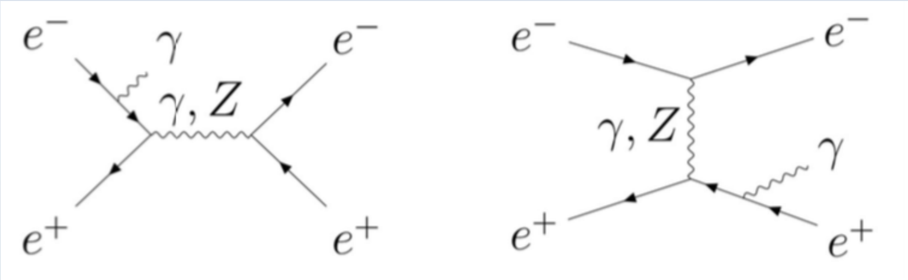
the SM background must be carefully studied

◆ Main SM background processes:

- radiative neutrino production



- radiative Bhabha scattering



◆ Goal: simulating mono-photon events with WHIZARD

Outline

◆ Simulating photons in Whizard

JK, W. Kotlarski, P. Sopicki, A.F. Zarnecki, EPJC80(2020)634

- photons in Whizard
- merging procedure for ISR and ME photons
- simulating mono-photons in (radiative) neutrino production
- simulating mono-photons in Bhabha scattering

◆ Prospects for future use

JK, W. Kotlarski, K. Mękała, P. Sopicki, A.F. Zarnecki, in progress

similar studies for ILC: M. Habermehl, J. List. M. Berggren, PRD101(2020)0705053

Photons in WHIZARD

- WHIZARD generator provides the ISR structure function option to account for soft photons radiated from initial leptons.
- It includes all orders of soft and soft-collinear photons as well as up to the third order in high-energy collinear photons.
- It allows for a proper modeling of the kinematics of hard scattering process
- WHIZARD ISR photons are not ordinary final state photons: they represent all photons radiated in the event from a given lepton line.

Photons in WHIZARD

- ISR structure function does not account for photons emitted from
  - internal lines, like from the t-channel W in neutrino pair production,
  - from the final states in the Bhabha process.
- The hard non-collinear photon emission should be included in the generation of the considered background process on the matrix element level

→ Must avoid double-counting of ISR and hard photons emitted in the same region of phase space

Photons in WHIZARD

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  - from the final states in the Bhabha process.
- The hard non-collinear photon emission should be included in the generation of the considered background process on the matrix element level

$\Rightarrow$ Must avoid double-counting of ISR and hard photons emitted in the same region of phase space

Goal: establish a procedure for simulating mono-photon events with WHIZARD

Merging procedure for ISR and ME photons

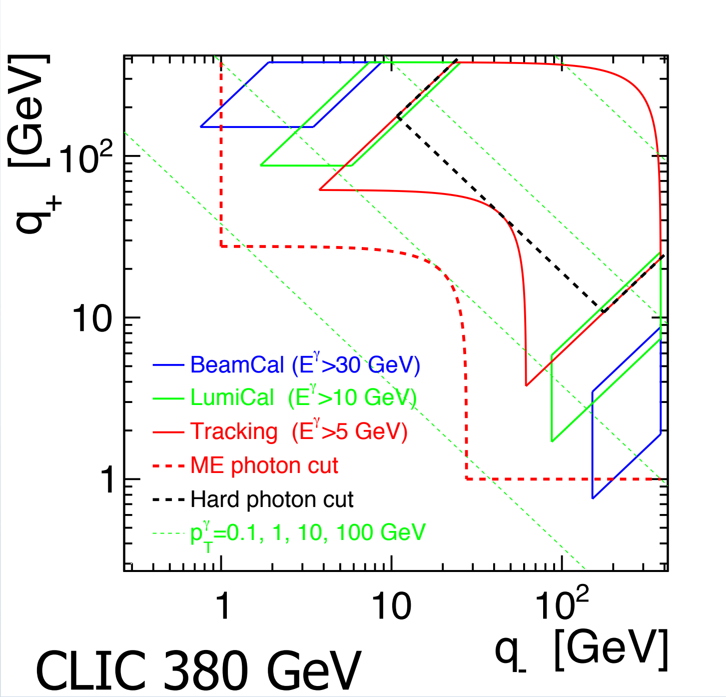
- Each emitted photon is characterized by two variables: its energy E_γ and polar angle θ_γ
- Define for <u>each</u> photon $q_- = \sqrt{4E_0E_\gamma}\,\sin\frac{\theta_\gamma}{2}, \quad q_+ = \sqrt{4E_0E_\gamma}\,\cos\frac{\theta_\gamma}{2}$

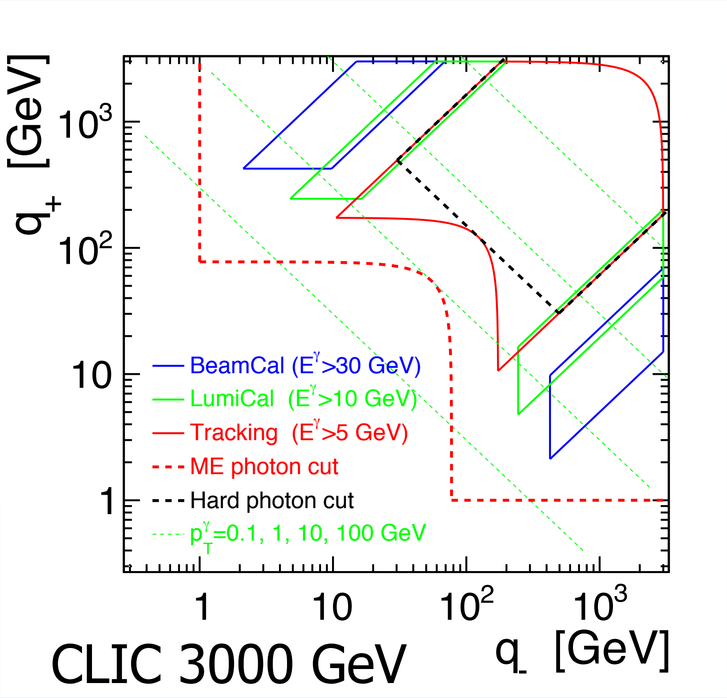
  for events with only one photon these variables would correspond to virtualities of electron and/or positron after photon emision

- Only photons with large enough $q_-,\ q_+$ can be measured in the detector
- Merging of ISR and ME photons at E_{min} and/or $q_-,\ q_+ = q_{min}$
- ISR photons are rejected above E_{min} and q_{min}

Merging ISR and ME photons

detector coverage in $q_-,\ q_+$ plane





$$E_{min} = 1\ \mathrm{GeV},\quad q_{min} = 1\ \mathrm{GeV}$$

Merging: neutrino sample

Testing the merging procedure

$\sqrt{s}[GeV]$	Whizard-2.8 $\sigma(e^+e^- \to \nu\bar{\nu})$ [fb]				$\sigma(e^+e^- \to \nu\bar{\nu})$ [fb] after ISR rejection
	$\nu\bar{\nu}$	$\nu\bar{\nu}+\gamma_{ME}$	$\nu\bar{\nu}+2\gamma_{ME}$	$\nu\bar{\nu}+3\gamma_{ME}$	
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

ISR radiation
before rejection

after ISR-ME
merging

$$E_{min} = 1 \text{ GeV}, \quad q_{min} = 1 \text{ GeV}$$

Merging: neutrino sample

Testing the merging procedure: impact of q_min value

$\sqrt{s}[GeV]$	$q_{min}[GeV]$	Whizard-2.8 $\sigma(e^+e^- \to \nu\bar{\nu})$ [fb] $\nu\bar{\nu}$	$\nu\bar{\nu}+\gamma_{ME}$	$\nu\bar{\nu}+2\gamma_{ME}$	$\nu\bar{\nu}+3\gamma_{ME}$	$\sigma(e^+e^- \to \nu\bar{\nu})$ [fb] after ISR rejection
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
	q_{min}=50		1400	21	0	50500
3000	q_{min}=0.1	53900	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

contributions of multi-photon events strongly depend on q_min,
while total cross section after ISR rejection is weakly dependent on q_min

we take q_min = 1 GeV as a default value

Merging: neutrino sample

Only small fraction of photons can be measured in the detector

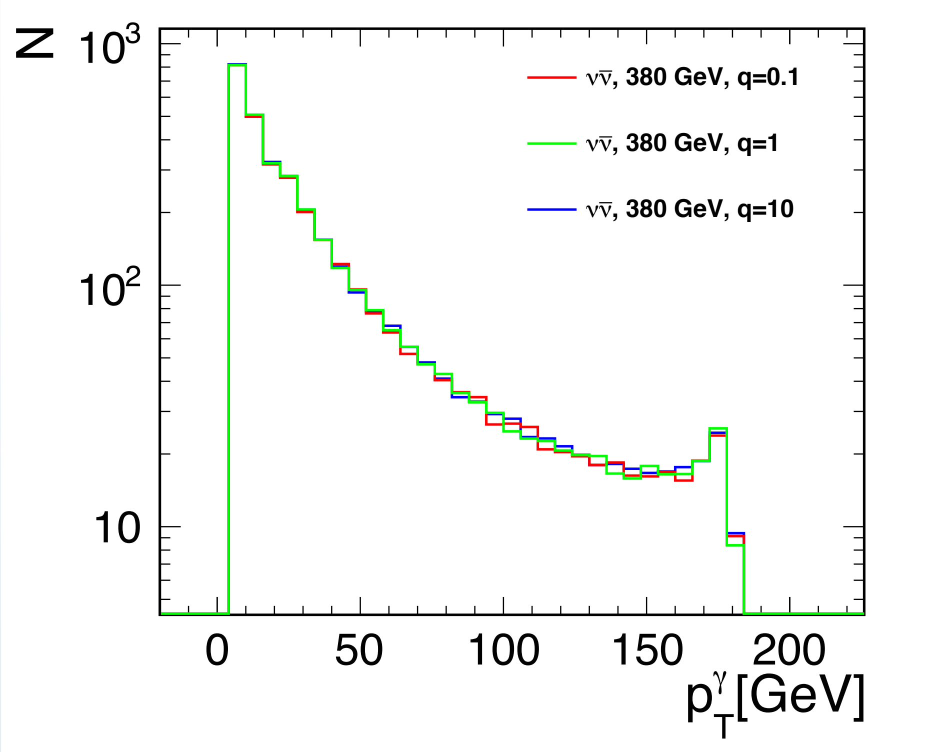
additional hard photon selection: $p_T > 5\ \mathrm{GeV}, \quad 7^o < \theta < 173^o$

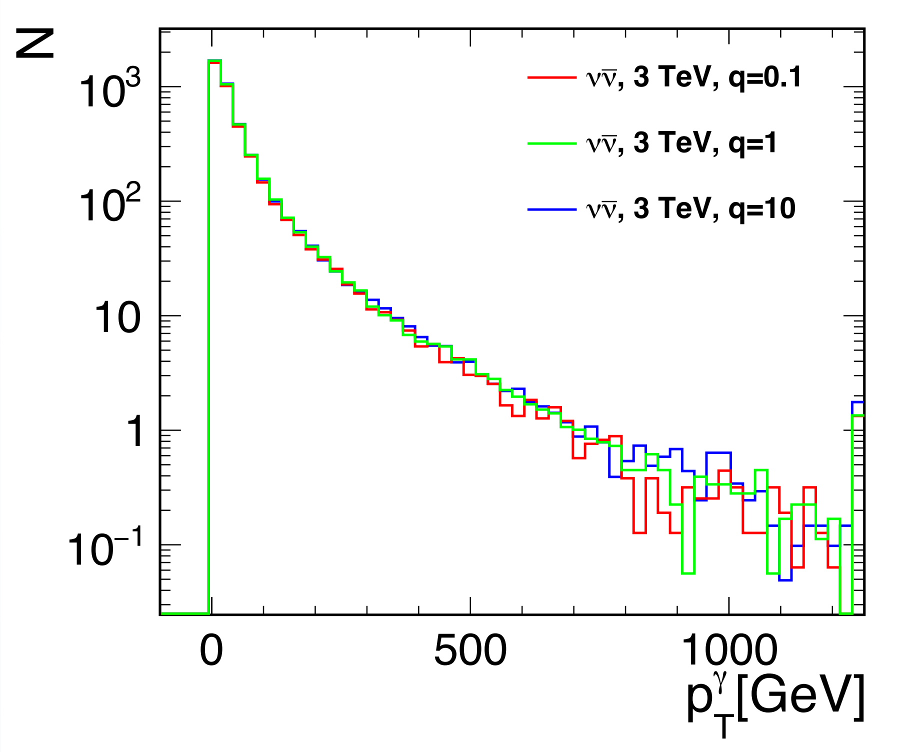
$\sqrt{s}[GeV]$	$q_{min}[GeV]$	Whizard-2.8 $\sigma(e^+e^- \to \nu\bar{\nu})$ [fb] $\nu\bar{\nu} + \gamma_{ME}$	$\nu\bar{\nu} + 2\gamma_{ME}$	$\nu\bar{\nu} + 3\gamma_{ME}$	$\sigma(e^+e^- \to \nu\bar{\nu})$ [fb] after ISR rejection
380	q_{min}=0.1	3200	910	120	3000
	q_{min}=0.5	3200	670	55	3000
	q_{min}=1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

one “hard” photon required

Merging: neutrino sample

Testing the merging procedure: hard photon transverse momenta

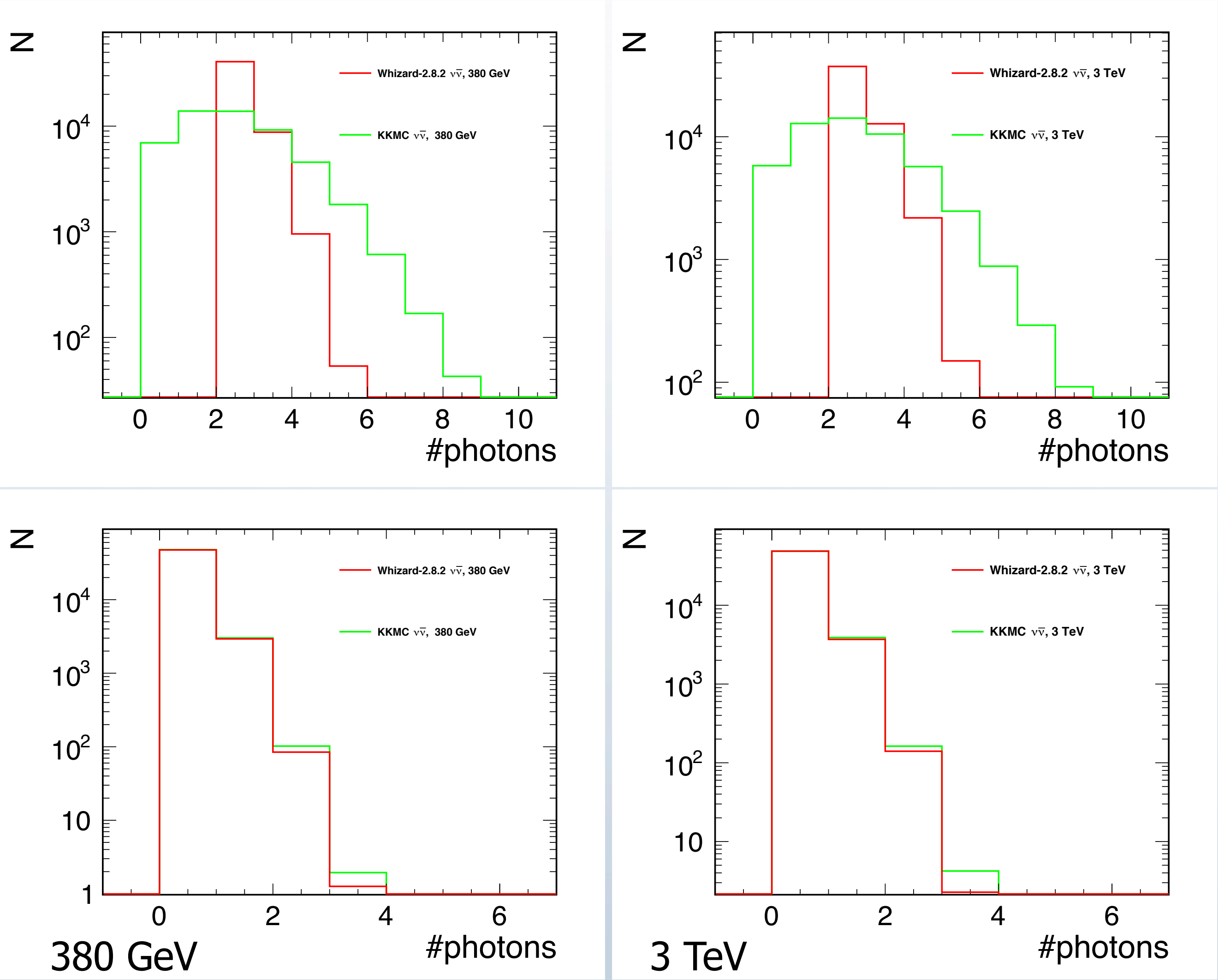




after hard photon selection the distributions are not sensitive to q_min

Comparison with *KK* MC: photon multiplicity

*KK*MC: soft photon resummation in CEEX + exact O(Born + $\alpha^{3/2}$)

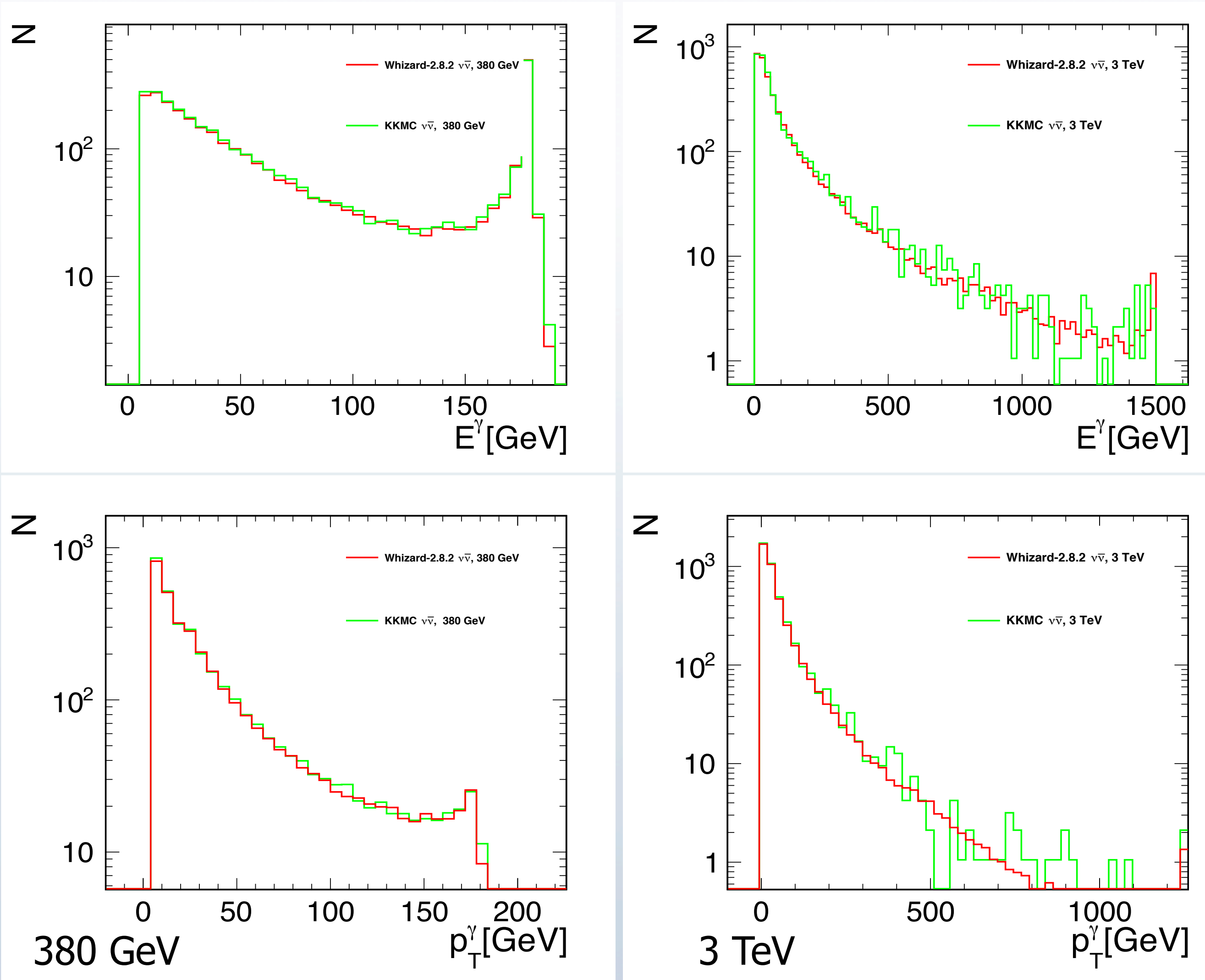


all photons

after hard photon selection

distributions normalised to # events expected for 1/fb

Comparison with *KK* MC: photon p_T



after hard photon selection

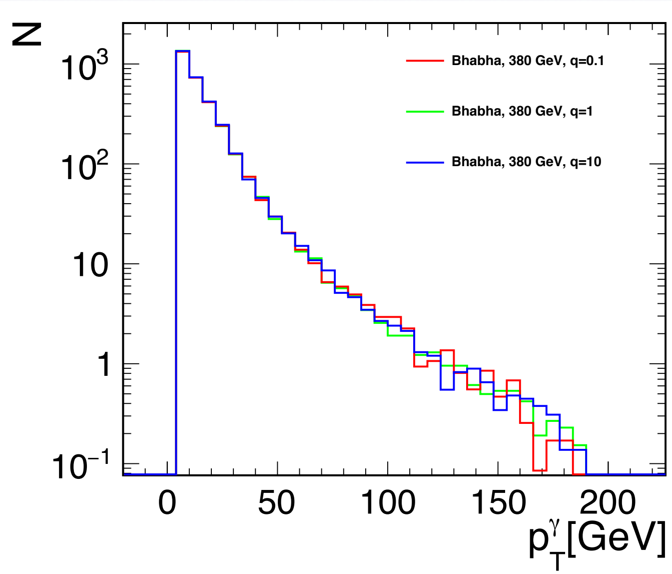
Merging: Bhabha sample

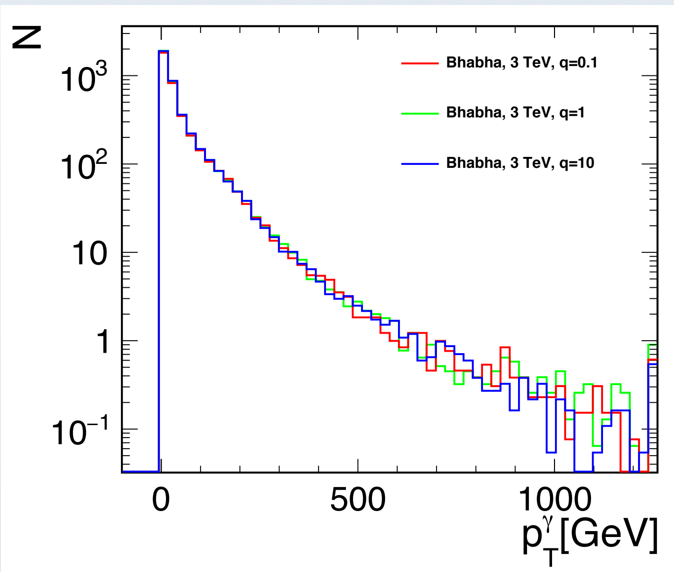
- leptons need not to be observed in the dectector
  - -> no constraints on scattering angle or q_min
- requirement of a hard photon removes most divergencies
  - -> at least one ME photon to be 'hard'
- collinear divergencies
  - -> angular separation between lepton and photon $\theta^{e\gamma}_{min} = 1^\circ$

$\sqrt{s}[GeV]$	Whizard-2.8 $\sigma(e^+e^- \to e^+e^- + N\gamma)$ [fb] $e^+e^- + \gamma_{ME}$	$e^+e^- + 2\gamma_{ME}$	$e^+e^- + 3\gamma_{ME}$	$\sigma(e^+e^- \to e^+e^- + N\gamma)$ [fb] after ISR rejection
240	236000	26100	1500	220000
250	224000	24900	1400	209000
380	140000	18400	1200	128000
500	100000	14600	1100	89800
1000	39800	7700	700	34400
1500	23000	5300	500	19400
3000	8800	2700	300	7200

at least one ME photon is hard

Merging: Bhabha sample





at least one ME photon 'hard'

$\sqrt{s}[GeV]$	$q_{min}[GeV]$	Whizard-2.8 $\sigma(e^+e^- \to e^+e^- + N\gamma)$ [fb] $e^+e^- + \gamma_{ME}$	$e^+e^- + 2\gamma_{ME}$	$e^+e^- + 3\gamma_{ME}$	$\sigma(e^+e^- \to e^+e^- + N\gamma))$ [fb] after ISR rejection
380	q_{min}=0.1	141000	29500	3200	123000
	q_{min}=0.5	140000	21700	1500	126000
	q_{min}=1	140000	18400	1200	128000
	q_{min}=5	141000	10000	400	131000
	q_{min}=10	140000	5100	170	145000
	q_{min}=50	11200	160	2	11000
3000	q_{min}=0.1	8900	3700	420	6400
	q_{min}=0.5	9000	3000	230	7000
	q_{min}=1	8800	2700	300	7200
	q_{min}=5	8900	2000	140	7600
	q_{min}=10	8900	1300	90	7500
	q_{min}=50	7000	300	10	6100

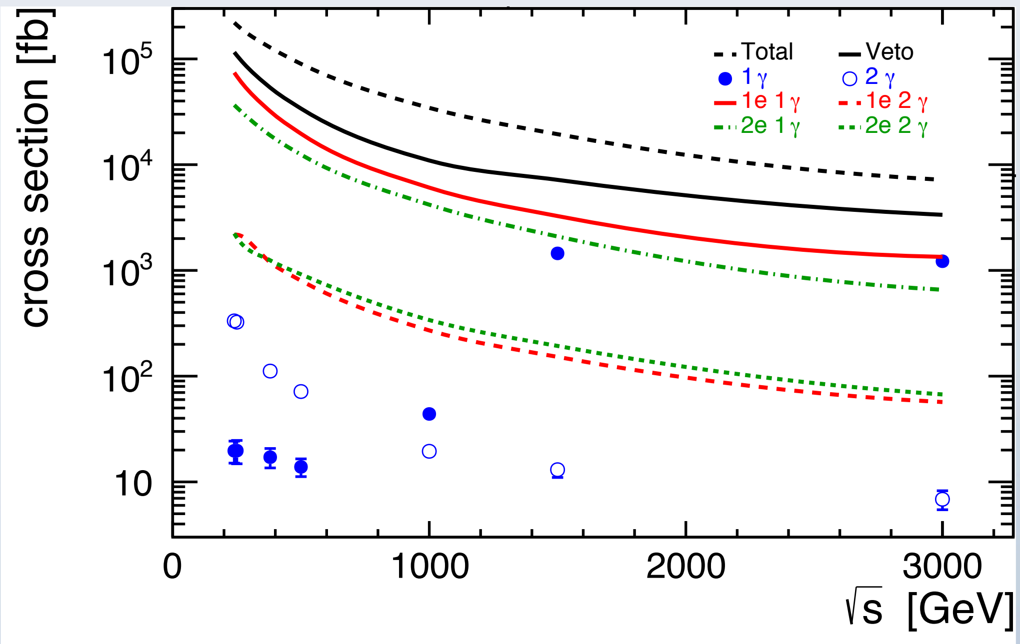
again contributions of multi-photon events strongly depend on q_min,
while total cross section after ISR rejection is weakly dependent on q_min

Neutrino vs Bhabha

neutrino pair production with hard photon is dominated by events with only a single photon visible in the detector

for Bhabha the p_T of hard photon has to be balanced either by scattered lepton or by emission of additional photons

applying a veto on energy deposits in BeamCal and LumiCal ~half of the events can be identified and rejected



important to understand performance of the detector and its modeling to suppress Bhabha background

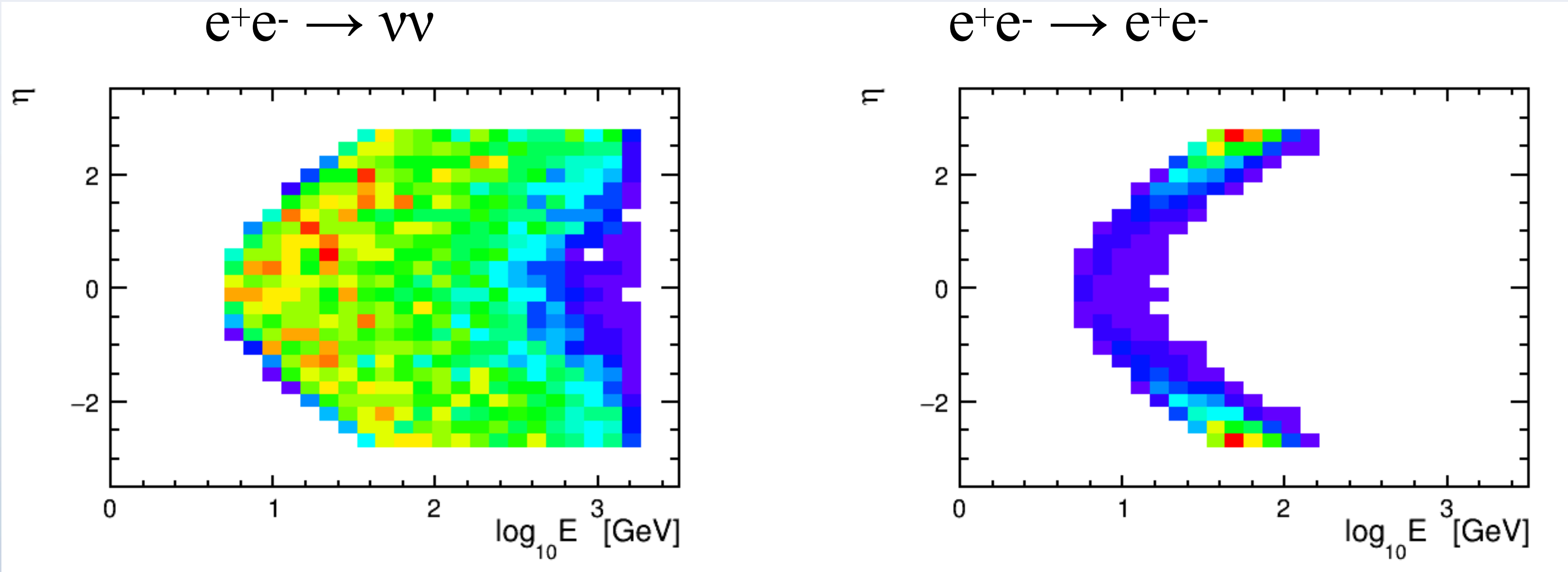
Prospects for future use

JK, W. Kotlarski, K. Mękała, P. Sopicki, A.F. Zarnecki, in progress

Proposed procedure should be useful for simulation of BSM mono-photons in Whizard

example: dark matter searches

experimental-like approach using 2-D distributions



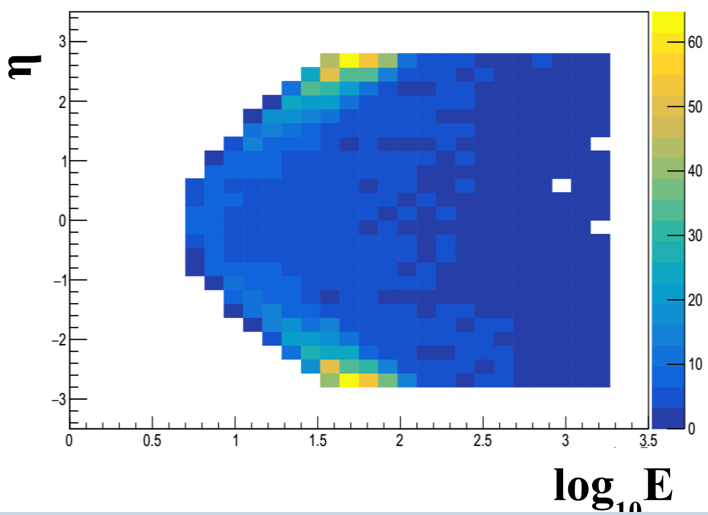
SM background at 3 TeV CLIC (generator level cuts only)

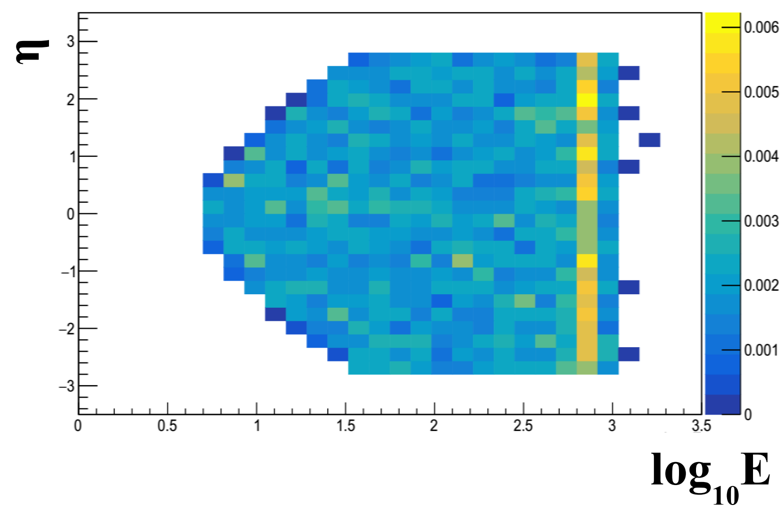
Prospects for future use

example: dark matter coupled to the SM particles via a mediator

- Main backgrounds vs signal @ 3TeV CLIC

$e^+e^- \longrightarrow \nu\bar{\nu}$ + $e^+e^- \longrightarrow e^+e^-$ M_{DM}=50GeV M_{med}=2TeV Γ_{med}=50GeV



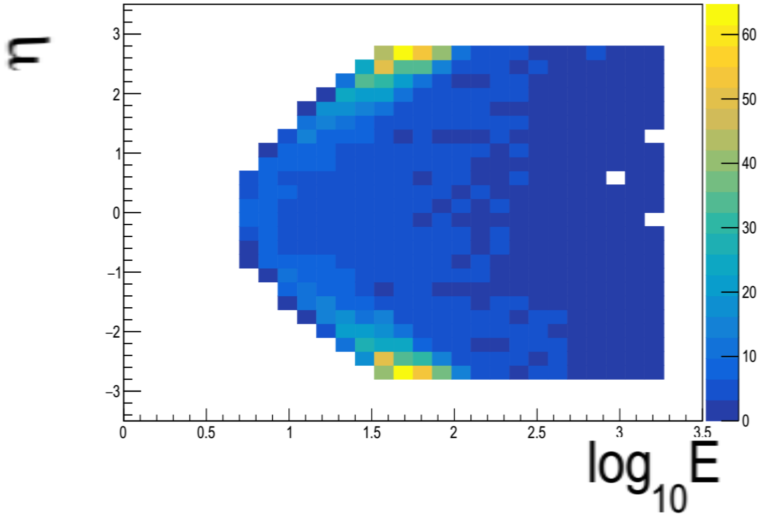


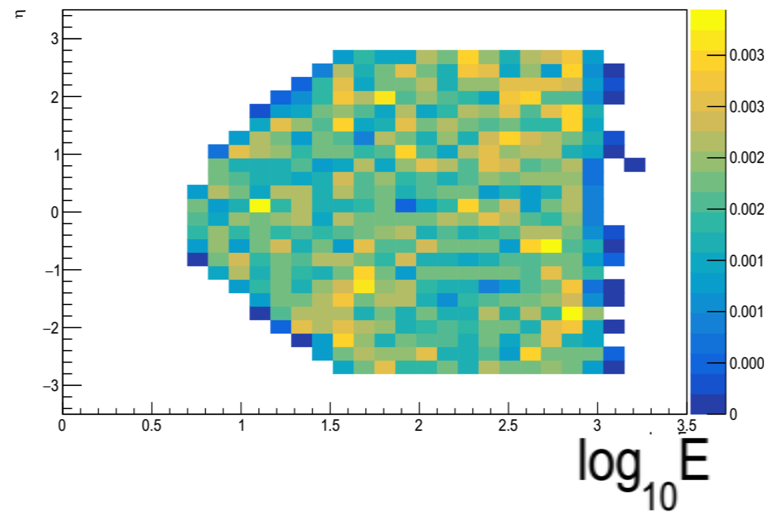
Prospects for future use

example: dark matter coupled to the SM particles via a mediator

- Main backgrounds vs signal @ 3TeV CLIC

  $e^+e^- \to \nu\bar{\nu}$ + $e^+e^- \to e^+e^-$ M_{DM}=50GeV M_{med}=2TeV Γ_{med}=500GeV



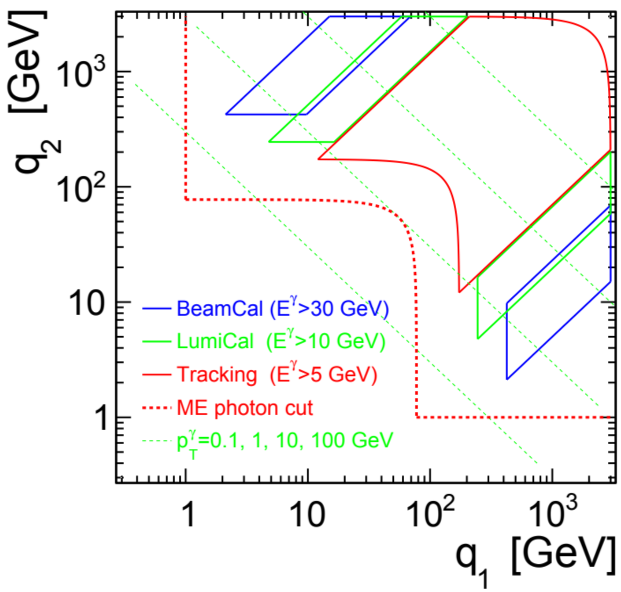


Summary

- Proposed merging procedure allows to treat two main SM backgrounds for mono-photon events on equal footing
- Reliable simulation of the mono-photons in Whizard demonstrated
- The same procedure can be applied for polarised beams
- Results checked against *KK* MC generator for neutrino pairs
- Background from Bhabha strongly depends on detector performance and electron veto efficiency

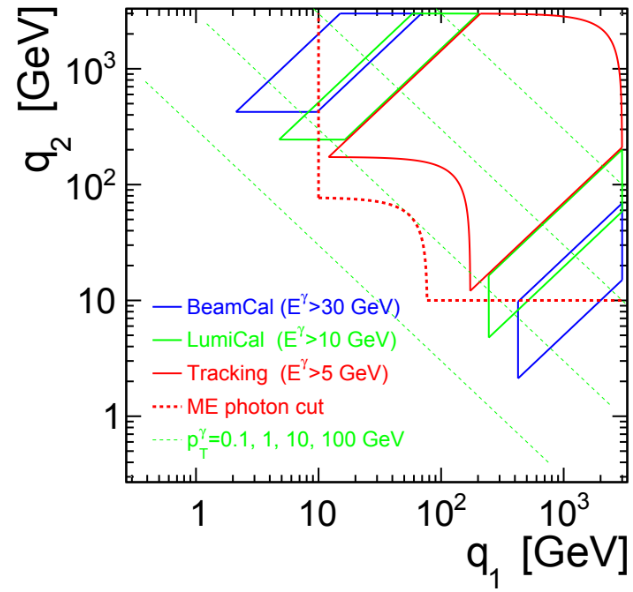
- Our procedure should be useful for simulating BSM mono-photon events in Whizard additional slides

CLIC detector design -> q_min = 1 GeV preferred since no ISR photons reach Beam Cal



$q^{min} = 1$ GeV

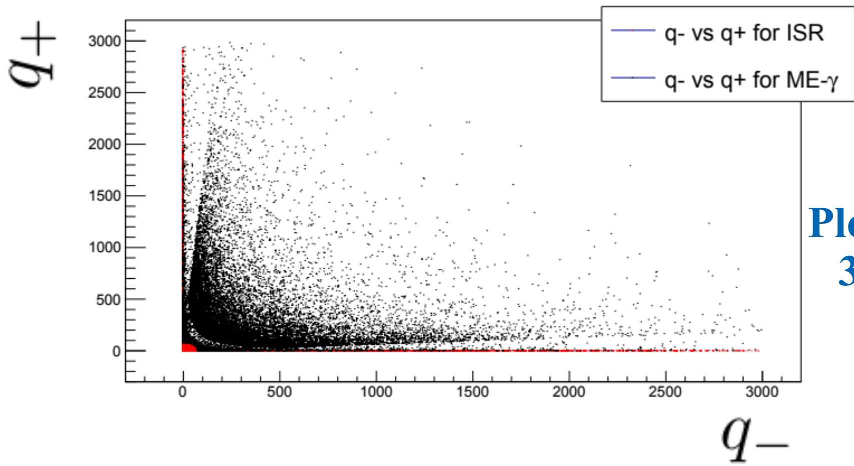
Plots for 3 TeV case



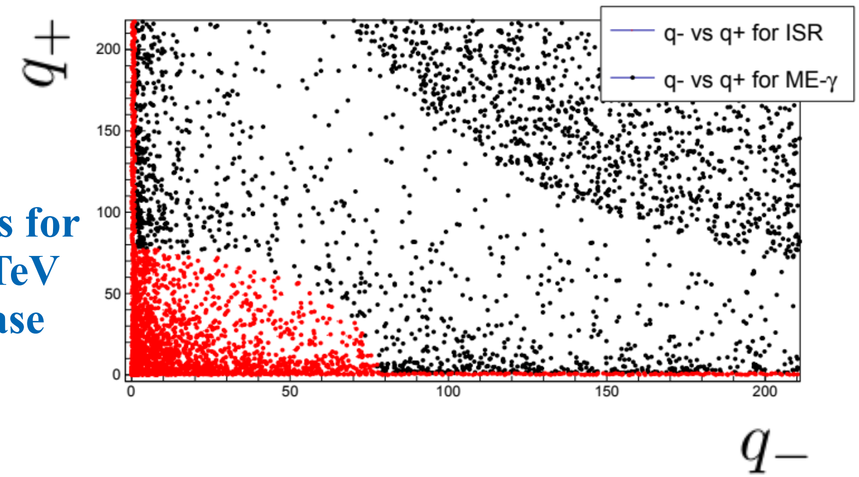
$q^{min} = 10$ GeV

Merging ISR and ME photons in WHIZARD

Neutrino sample

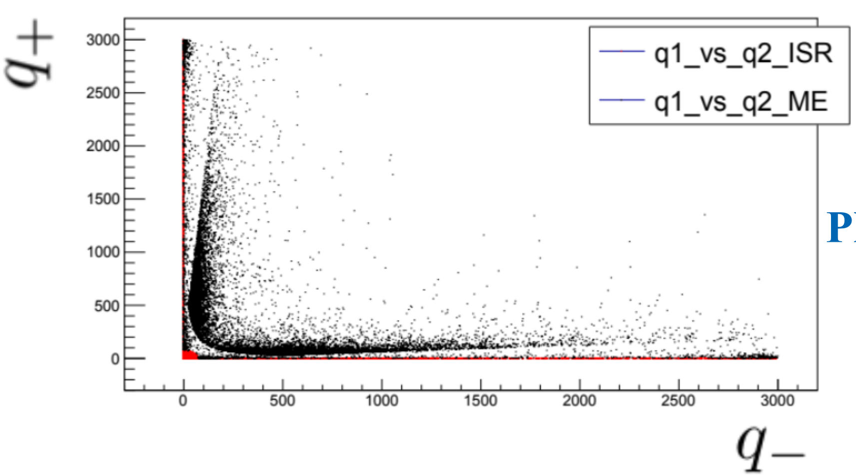


Zoom

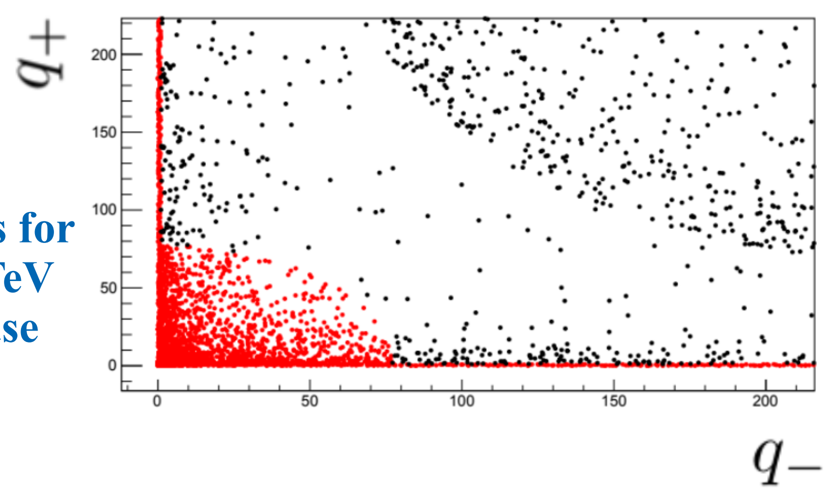


Plots for 3 TeV case

Bhabha sample



Zoom



Plots for 3 TeV case

p_t>5 GeV

red points – ISR photons, black points – ME photons

Example of generating neutrino events

Sindarin file for Whizard

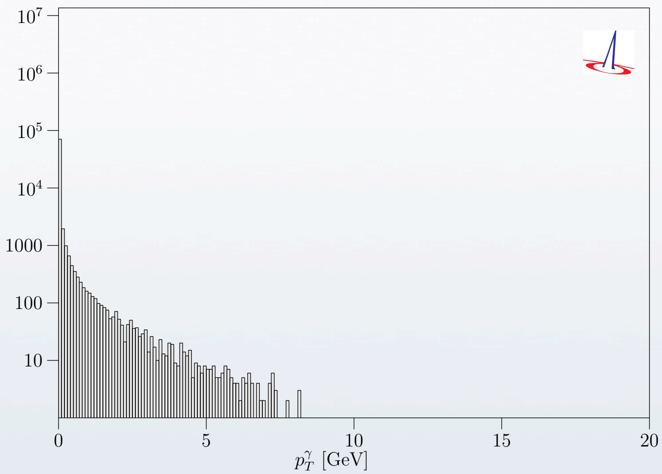
```
# model        = SM_CKM
model        = SM
sqrts = 3000 GeV
n_events = 100000
checkpoint = 1000
mH = 12 TeV
alphas = 0 # to remove overlap with higher multiplicities
show (model)
alias nu = n1:n2:n3
alias NU = N1:N2:N3
process eevv   = e1, E1 =>  (nu, NU)
process eevv1a = e1, E1 =>  (nu, NU, A)
process eevv2a = e1, E1 =>  (nu, NU, A, A)
process eevv3a = e1, E1 =>  (nu, NU, A, A, A )
process eevv4a = e1, E1 =>  (nu, NU, A, A, A, A )
cuts = let subevt @meA = select if Index > 2 [A]
       in all 2*sqrt(1500*E)*sin(Theta/2.) > 10 GeV [@meA]
       and all 2*sqrt(1500*E)*cos(Theta/2.) > 10 GeV [@meA]
compile
beams = e1, E1  => isr
?isr_handler       = true
$isr_handler_mode = "recoil"
?keep_beams = true
?keep_remnants = true
isr_mass = me
integrate (eevv,eevv1a,eevv2a) {relative_error_goal=0.01
                iterations = 20:20000:"gw", 5:50000:""}
integrate (eevv3a,eevv4a) {relative_error_goal=0.05
                iterations = 10:20000:"", 10:20000:"w",
                 10:20000:"gw", 5:50000:""}
$sample = "sm_eevv_selection"
?write_raw = false
sample_format = mokka
```

```
$extension_stdhep = "stdhep"
$extension_mokka = "mokka"
?unweighted = true

selection = all 2*sqrt(1500.*E)*sin(Theta/2.) < 10 GeV [extract index 1 [A]]
        and
          all 2*sqrt(1500.*E)*cos(Theta/2.) < 10 GeV [extract index 2 [A]]
histogram isr_pt (0 GeV, 20 GeV, 0.1 GeV)  {
                 $title = "ISR photon transverse momentum"
                 $x_label = "$p_{T}^{\gamma}$ [GeV]"
                                     ?y_log = true
                                     y_min = 1}
histogram isr_q1 (-5, 5, 0.05)  {
                 $title = "ISR photon momentum transfer"
                 $x_label = "$log_{10} |q|/GeV$"}

histogram photon_pt (0 GeV, 20 GeV, 0.1 GeV)  {
                 $title = "ME photon transverse momentum"
                 $x_label = "$p_{T}^{\gamma}$ [GeV]"
                                     ?y_log = true
                                     y_min = 1}
histogram photon_q1 (-5, 5, 0.05)  {
                 $title = "ME photon momentum transfer"
                 $x_label = "$log_{10} |q|/GeV$”
analysis =  record isr_pt ( eval Pt [extract index 1 [A]]);
            record isr_q1 ( eval log10(2*sqrt(1500.*E)*sin(Theta/2.))
                    [extract index 1 [A]]);
            record photon_pt ( eval Pt  [extract index 1 [sort by -Pt [A]]]);
            record photon_q1 ( eval log10(2*sqrt(1500.*E)*sin(Theta/2.))
                    [extract index 1 [sort by -Pt [A]]])
simulate (eevv,eevv1a,eevv2a,eevv3a,eevv4a)
compile_analysis
```

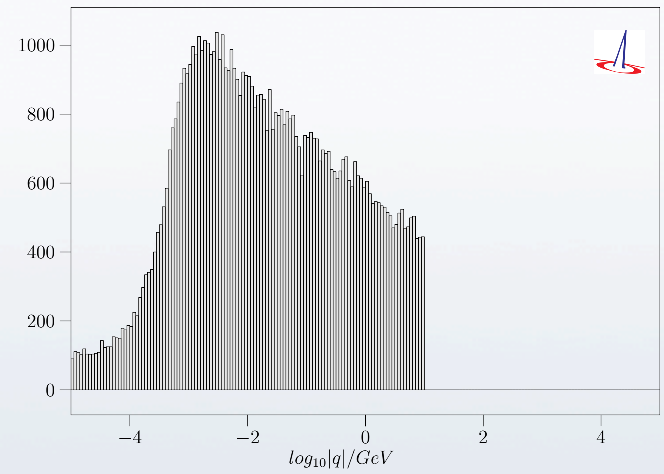
Example of generating neutrino events

output from Whizard

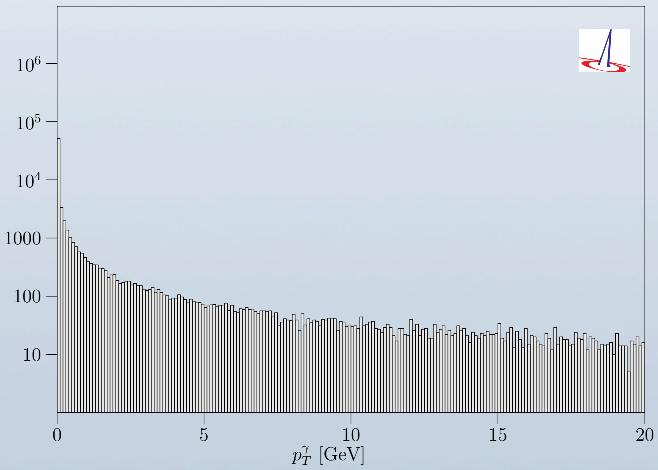
1 ISR photon transverse momentum



2 ISR photon momentum transfer



3 ME photon transverse momentum



4 ME photon momentum transfer