Bhabha simulation for mono-photon DM analysis

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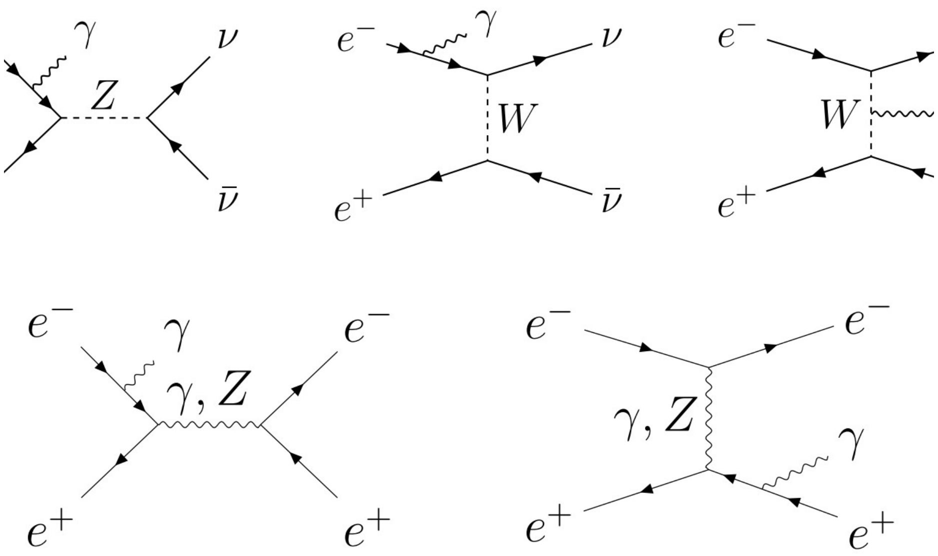
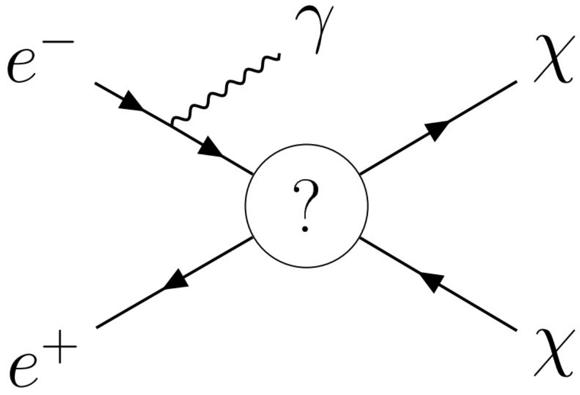
Some intro...

Feynman diagrams of main backgrounds:
$\nu\bar{\nu}$ and Bhabha with single photon



Pseudo-feynman diagram of our aim:
DM production with a single photon emission



Some intro...

- **$\nu\bar{\nu}$ background already tested and presented**
- **Bhabha background – issues with cross section calculations reported last time**
  - **σ calculations diverged without using cut on electrons (which, essentialy for the mono-photon analysis, should be avoided)**
  - **Even with electron cuts σ were Mandelstam-t cut dependent**
  - **Idea from whizard developers: to change precision**

σ calculation & whizard precision

- **whizard-2.8 with three different precision setups:**
  - **standard**
  - extended
  - quadruple
- **The same process:**

  e+e- →e+e- + nγ , n= 1,2,3

($E^{\gamma} > 30$ GeV and θ^{γ} cuts, more details later and in backups)

It	Integral[fb]	Error[fb]	Err[%]	Acc	Eff[%]	Chi2
40	4.1777472E+03	1.09E+02	2.60	18.37	NaN	5.81
50	4.2944615E+03	4.62E+02	10.75	23.97*	NaN	
51	2.4236897E+05	2.37E+05	97.89	218.18	NaN	
52	1.9850011E+03	1.65E+02	8.30	18.50*	NaN	
53	3.6407057E+03	3.66E+02	10.07	22.43	0.05	
54	3.2099567E+03	2.77E+02	8.64	19.24*	0.08	
55	4.6336602E+03	9.20E+02	19.84	44.21	0.03	
60	3.5495152E+03	8.07E+01	2.27	22.67	0.05	11.70
70	5.7381912E+03	1.57E+02	2.74	19.26	0.07	1.86

Common picture for outputs in standard setup: plenty of NaN's unable to simulate at all!

σ calculation & whizard precision

- **whizard-2.8 with three different precision setups:**
  - standard
  - **extended**
  - quadruple
- **The same process:**

  e+e- →e+e- + nγ , n= 1,2,3

(E$^{\gamma}$ > 30 GeV and θ$^{\gamma}$ cuts, more details later and in backups)

It	Integral[fb]	Error[fb]	Err[%]	Acc	Eff[%]	Chi2
40	8.1491474E+03	1.66E+02	2.03	14.35	0.12	1.29
60	8.0352710E+03	8.27E+01	1.03	10.26	0.17	1.49
61	8.2485813E+03	3.26E+02	3.95	8.79*	0.22	
62	8.4940982E+03	5.57E+02	6.56	14.58	0.11	
63	8.0649193E+03	3.79E+02	4.69	10.44*	0.20	
64	8.4724081E+03	4.49E+02	5.30	11.77	0.13	
65	8.4559385E+03	5.69E+02	6.73	14.95	0.11	
66	9.0275809E+03	6.39E+02	7.08	15.73	0.11	
67	8.2816015E+03	4.41E+02	5.32	11.83*	0.16	
68	8.9131300E+03	6.55E+02	7.34	16.31	0.12	
69	8.6937978E+03	5.12E+02	5.89	13.07*	0.13	
70	9.0863603E+03	8.53E+02	9.39	20.85	0.09	
70	8.4295340E+03	1.53E+02	1.81	12.75	0.09	0.41

There are no NaNs anymore. Cross setion calculation stable

σ calculation & whizard precision

- **whizard-2.8 with three different precision setups:**
  - standard
  - extended
  - **quadruple**
- **The same process:**

  $e^+e^- \rightarrow e^+e^- + n\gamma$, n= 1,2,3

(E$^{\gamma}$ > 30 GeV and θ$^{\gamma}$ cuts, more details later and in backups)

It	Integral[fb]	Error[fb]	Err[%]	Acc	Eff[%]	Chi2
40	7.9102143E+03	1.25E+02	1.58	11.18	0.10	1.45
60	8.1195947E+03	8.52E+01	1.05	10.46	0.25	0.74
61	8.6351331E+03	3.67E+02	4.25	9.47	0.20	
62	8.6614269E+03	5.27E+02	6.08	13.53	0.14	
63	8.1442399E+03	2.95E+02	3.62	8.05*	0.28	
64	7.9980600E+03	2.89E+02	3.61	8.04*	0.24	
65	8.4393615E+03	4.40E+02	5.21	11.59	0.19	
66	8.0360783E+03	2.69E+02	3.35	7.45*	0.34	
67	8.6299178E+03	3.28E+02	3.80	8.44	0.28	
68	7.9667466E+03	2.61E+02	3.28	7.28*	0.39	
69	7.7173461E+03	2.12E+02	2.74	6.09*	0.40	
70	8.7570794E+03	2.99E+02	3.41	7.59	0.29	
70	8.1715578E+03	9.49E+01	1.16	8.17	0.29	1.61

Even smaller errors

σ calculation & whizard precision

- **Three different whizard-2.8 setups:**
  - **Tested with cuts on Energy or Pt of the hard photon (more details later)**
  - **Even though errors are smaller for the quadruple case, computing times are much longer. Therefore extended precision has been used for this studies**

E > 30 GeV	**σ [fb]**
Quadruple	9867.5 ± 126
Extended	9906.9 ± 161
Standard	6763.6 ± 167
Pt > 10 GeV	
Quadruple	9100.9 ± 86.4
Extended	9105.8 ± 88.7
Standard	6887.6 ± 146

Merging ISR and photons from ME (γ^{ME})

Merging ISR and photons from ME

- **Lets define q^+ and q^-**

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

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

- **Basic requirement: at least one γ^{ME} has**

  a) E > 30 GeV (1st option)

  b) Pt > 10 GeV (2nd option)

  and 7° < θ < 173° for both options

  and all γ^{ME} should have $E^{\gamma ME}$ > 1 GeV
- **Merging would be done for some q^{merge} : generated γ^{ME} should have q^+ and q^- above q^{merge},**
- **ISR photons passing γ^{ME} cuts are removed in selection**
- **Tests for $\nu\bar{\nu}$ background: total σ insensitive on q^{merge} changes. Is Bhabha background sensitive to q^{merge} value?**
  - **Note: $\nu\bar{\nu}$ test included a basic diagram without photons – not a case for Bhabha**

Merging ISR and photons from ME

Is Bhabha background sensitive to q^{merge} value?

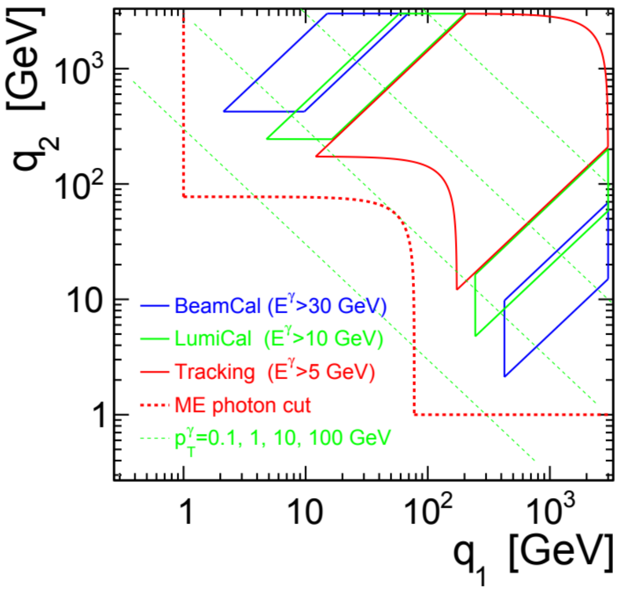
	Effic.	generated σ	error		corrected σ	
E30, q=1:	0.67	9865.2	+/- 138 fb	=>	6589.9 +/- 92.2	fb
E30, q=10:	0.78	8915.6	+/- 98.1 fb	=>	6973.3 +/- 76.7	fb
E30, q=50:	0.87	7762.5	+/- 80.7 fb	=>	6760.8 +/- 70.3	fb
Pt10, q=1:	0.66	9341.5	+/- 95.2 fb	=>	6158.4 +/- 62.8	fb
Pt10, q=10:	0.78	8546.5	+/- 66.2 fb	=>	6661.5 +/- 51.6	fb
Pt10, q= 50:	0.87	7846.7	+/- 69.3 fb	=>	6846.2 +/- 60.5	fb

Selection efficiency in whizard-2.8 'compensates' (a bit too much!) for the decrease in generated cross section

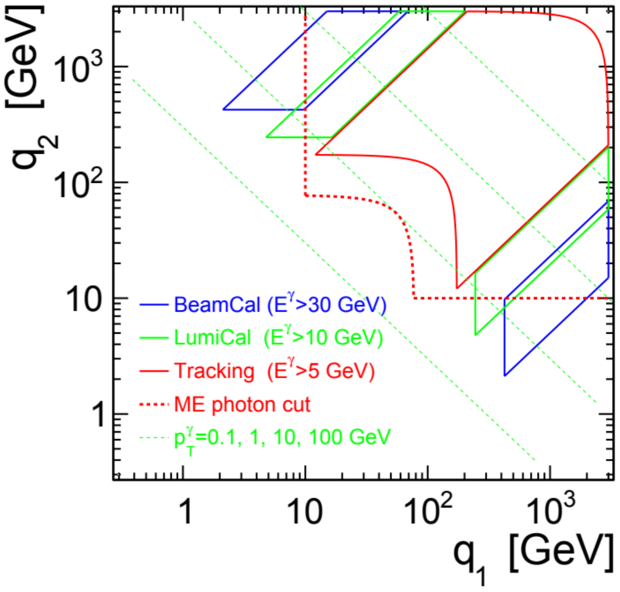
Ok. But, is there a preference for some q^{merge} value?

Merging ISR and photons from ME

Using CLICdet design and plots by Filip Zarnecki (thank you!) one can see that $q^{merge} \sim 1$ GeV are prefered: no ISR photons reach the BeamCal



$q^{merge} = 1$ GeV



$q^{merge} = 10$ GeV

γ^{ME} : where and what to cut on?
Energy vs Pt in $\nu\bar{\nu}$ and Bhabha

Energy vs Pt for $\nu\bar{\nu}$ and Bhabha

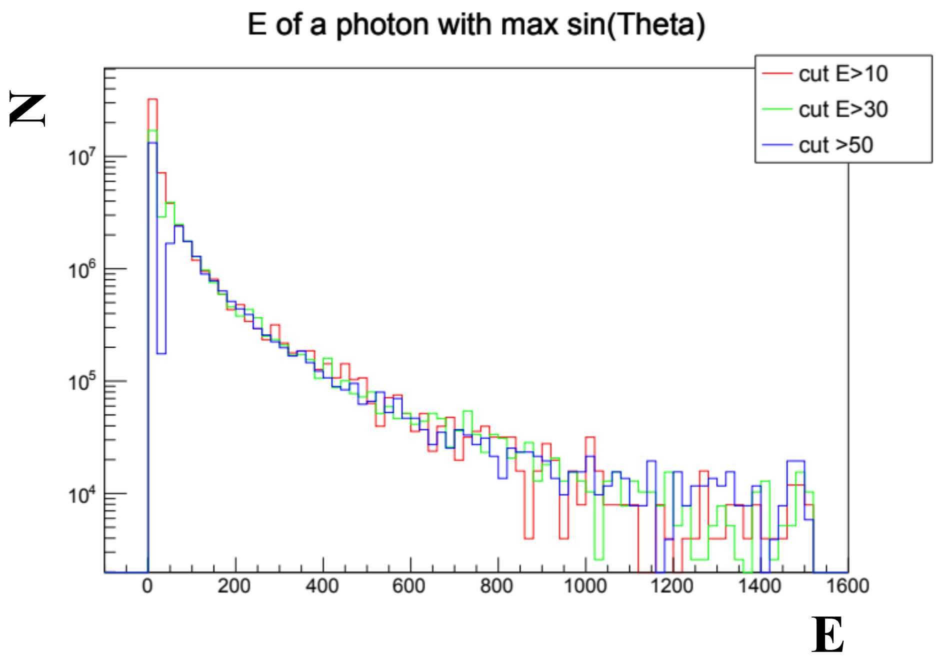
- With a **q^{merge}** set to 1 GeV, scans were done for **E_{cut}= 10, 30, 50 GeV** and **Pt_{cut}= 5, 10 GeV**

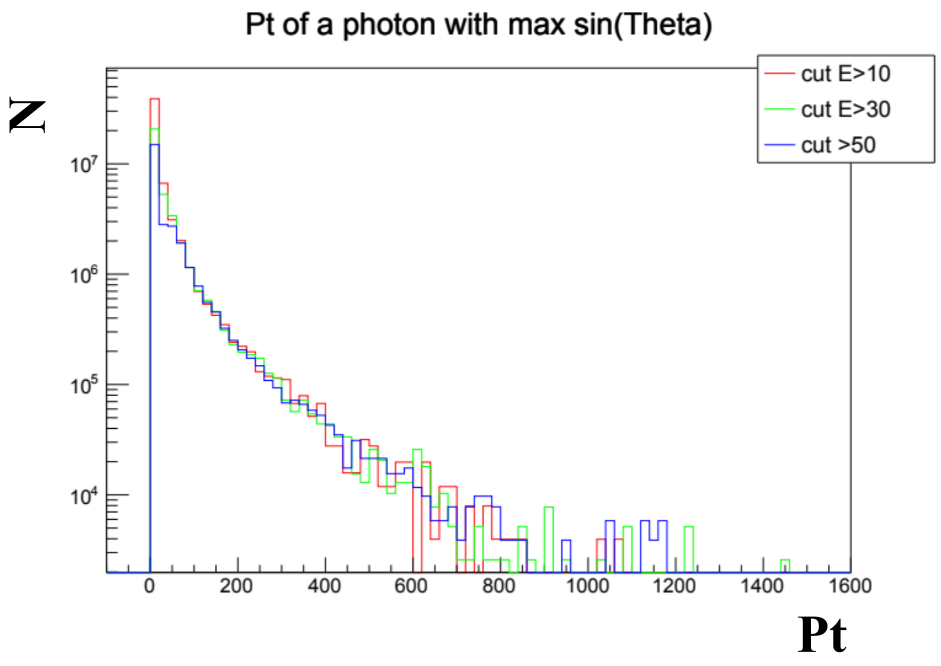
- **Considering best integration-step stability and ratios of total $\sigma_{\nu\bar{\nu}}$ / σ_{Bhabha} :**

E > 10 GeV :	0.137+/-0.003
E > 30 GeV :	0.189 +/- 0.003
E > 50 GeV :	0.215 +/- 0.002
Pt > 5 GeV :	0.221 +/- 0.002
Pt > 10 GeV :	0.291 +/- 0.002

For generation purposes the setup with Pt > 5 GeV seems to be the best solution: allows for further DM-signal cuts optimisations.

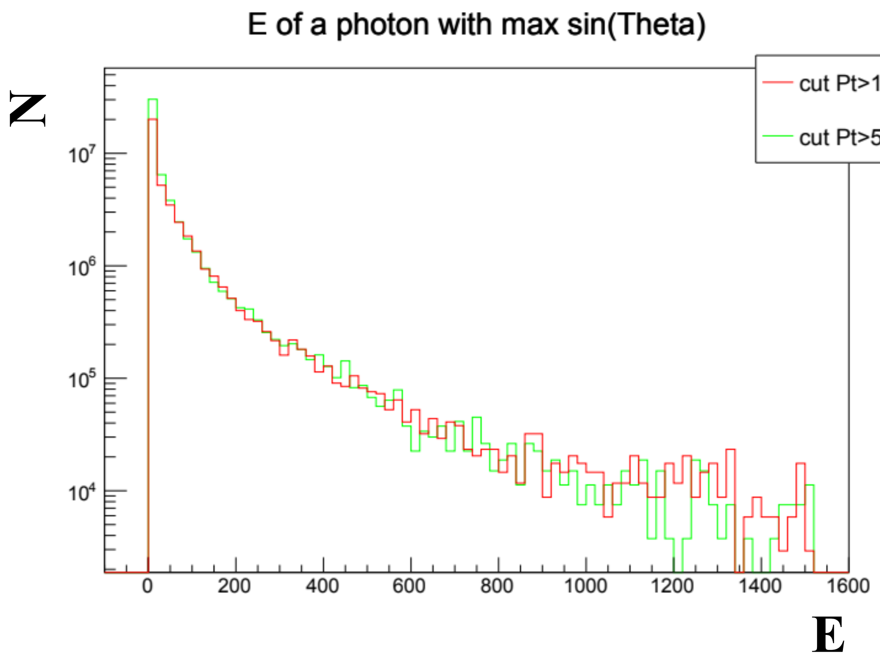
$\nu\bar{\nu}$ sample with cuts on Energy

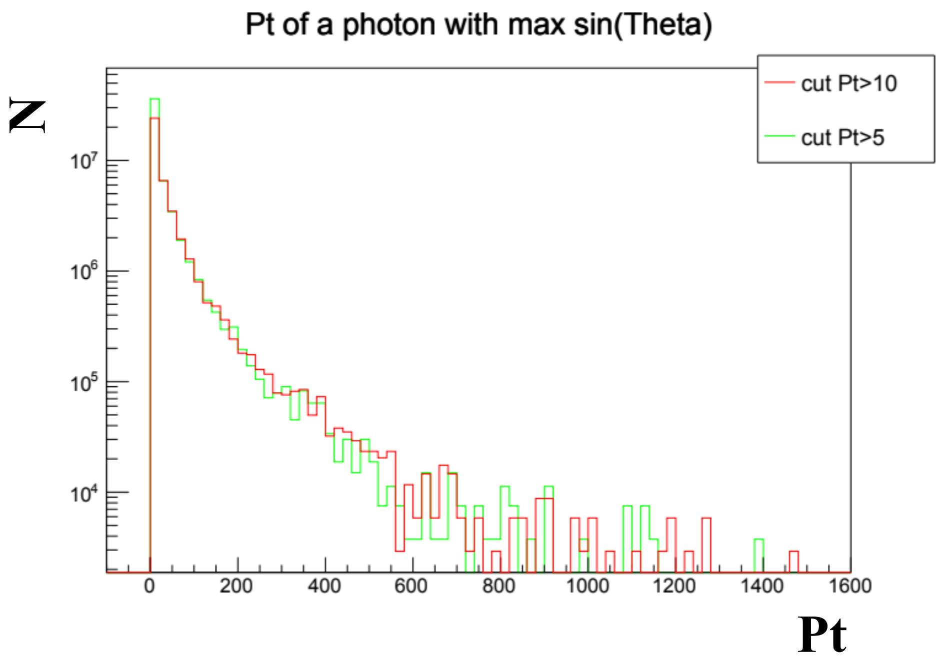




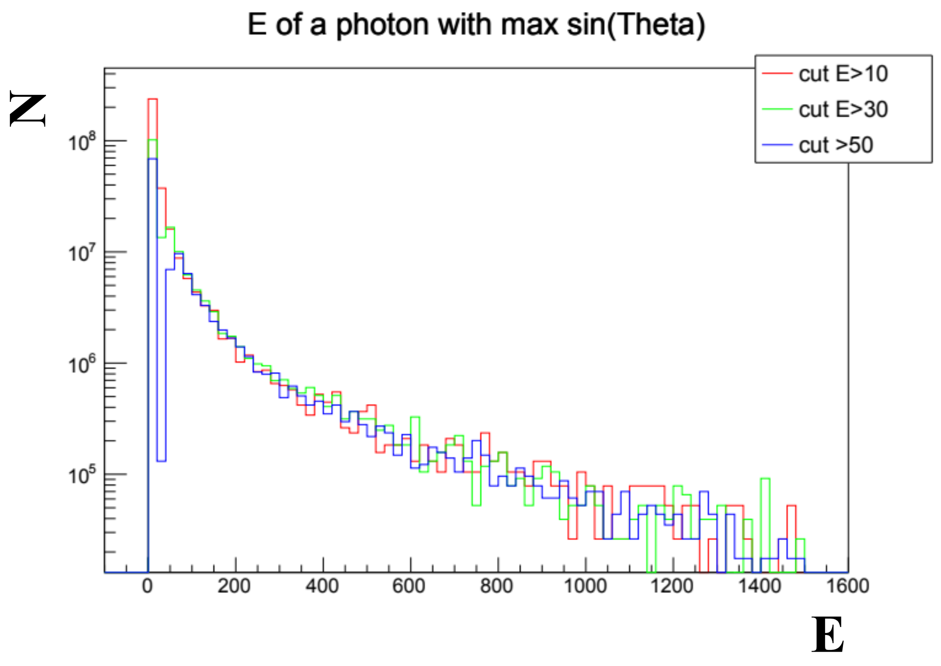
Distributions of photons with maximal $\sin(\theta_\gamma)$

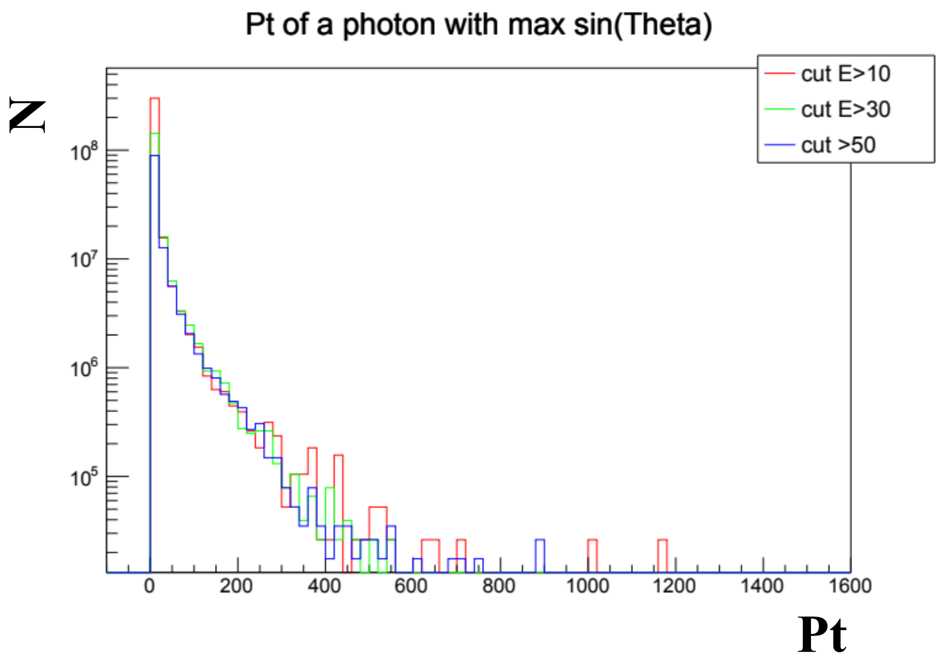
$\nu\bar{\nu}$ sample with cuts on Pt



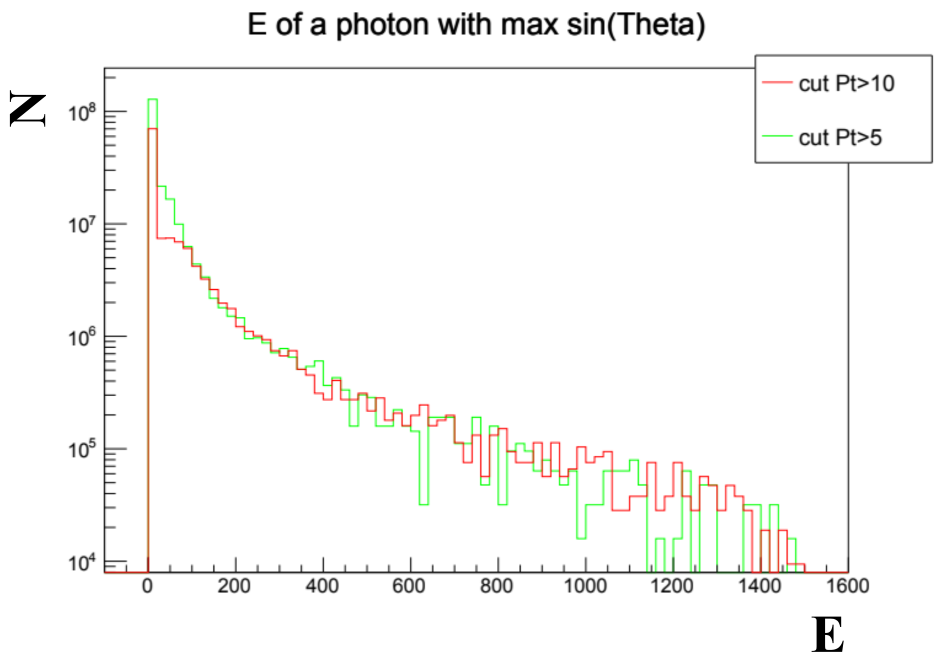


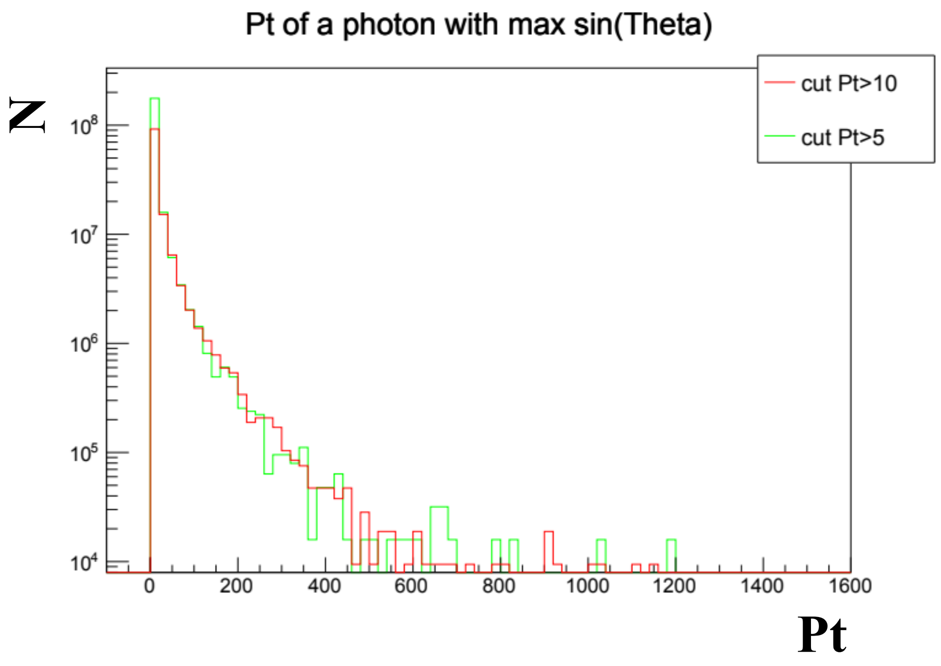
Bhabha sample with cuts on Energy



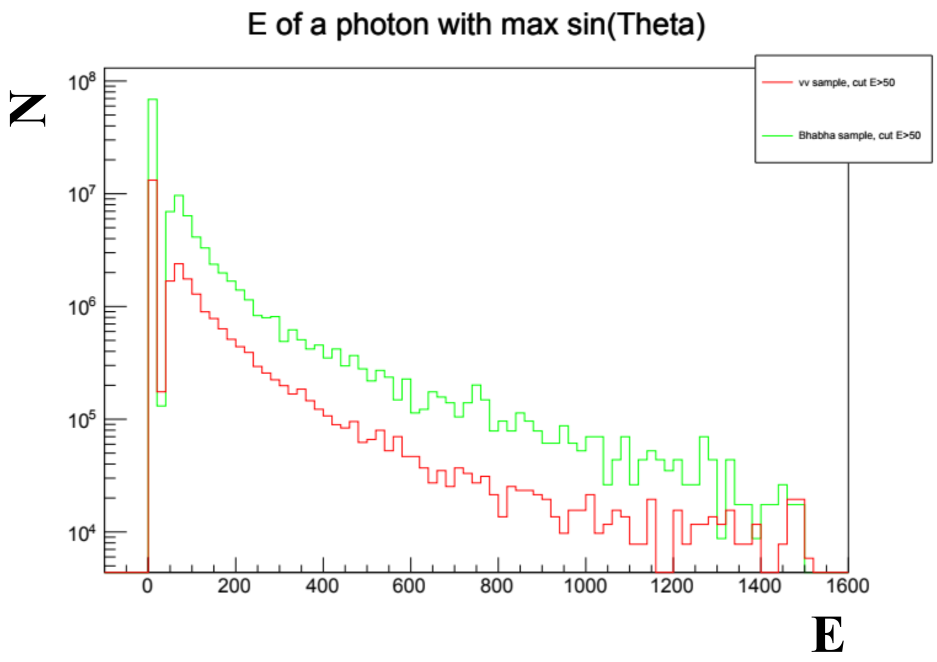


Bhabha sample with cuts on Pt



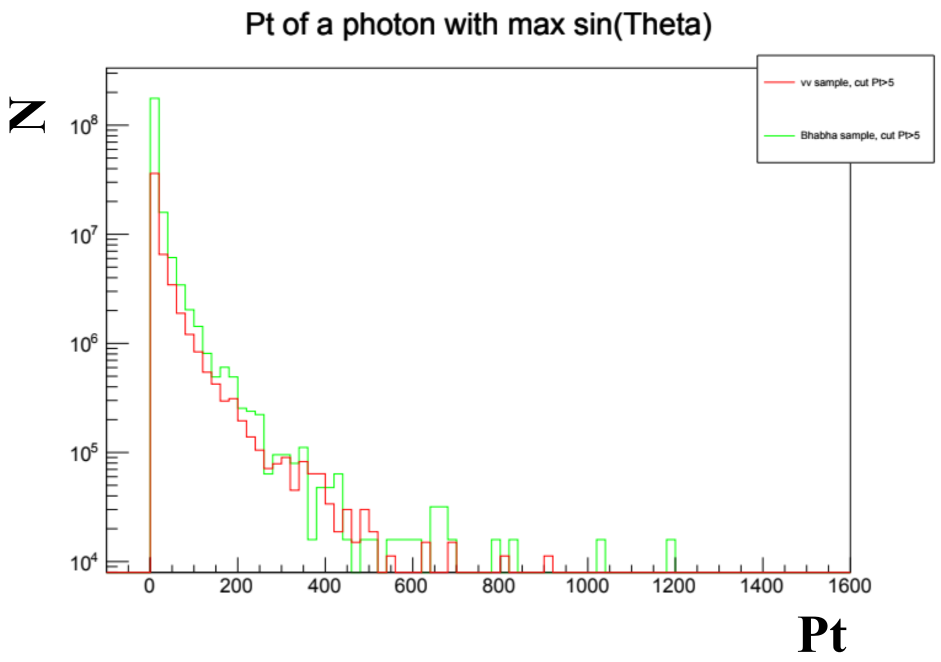


$\nu\bar{\nu}$/Bhabha comparison



Red – neutrino sample, E>30 GeV

Black – Bhabha sample, E>30 GeV



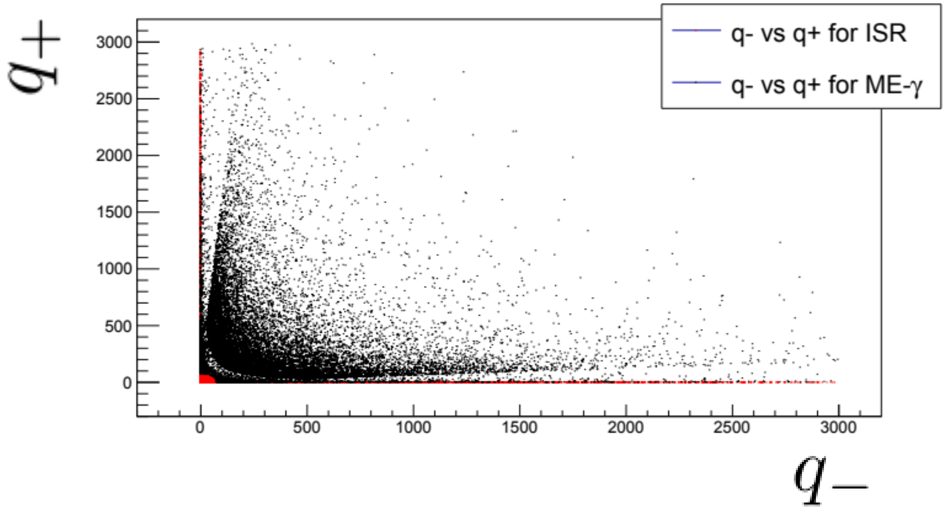
Red – neutrino sample, Pt>5 GeV

Black – Bhabha sample, Pt>5 GeV

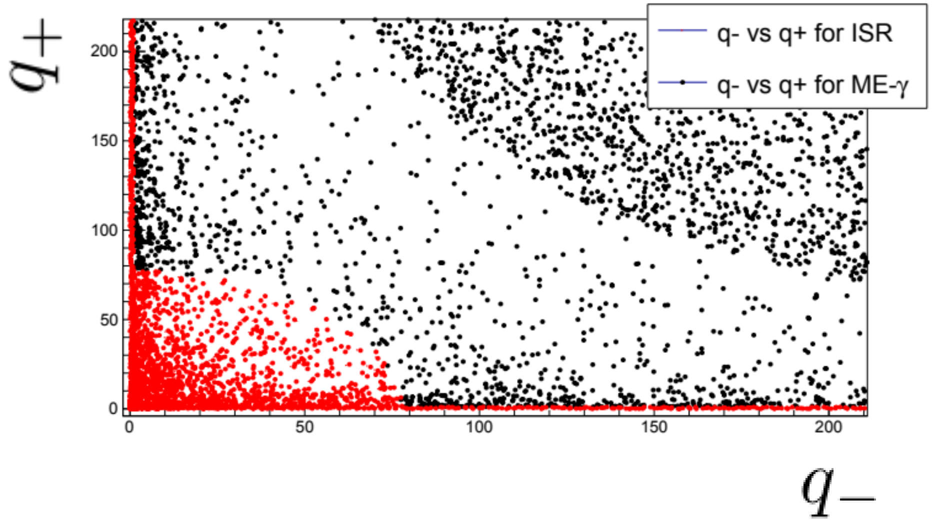
Merging ISR and γ^{ME} for sample with Pt > 5 GeV cut

q^{merge} = 1 GeV

Neutrino sample



Zoom



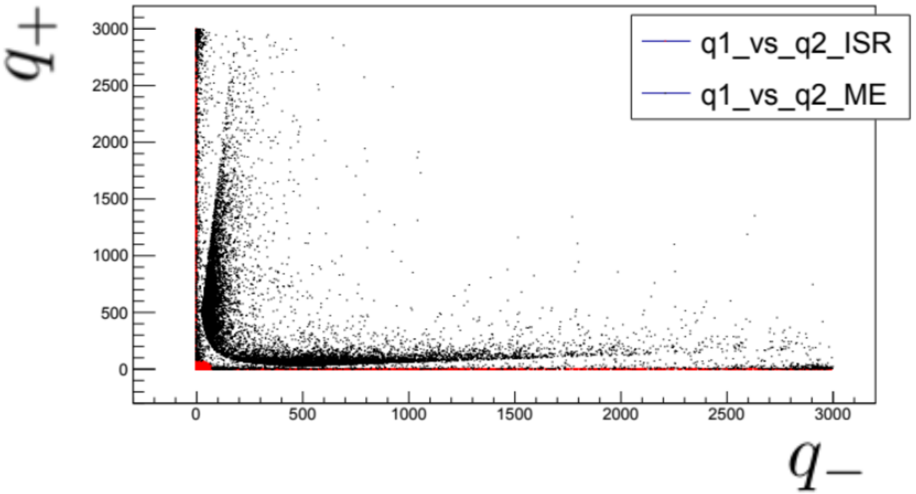
Red – γ ISR

Black - γ^{ME}

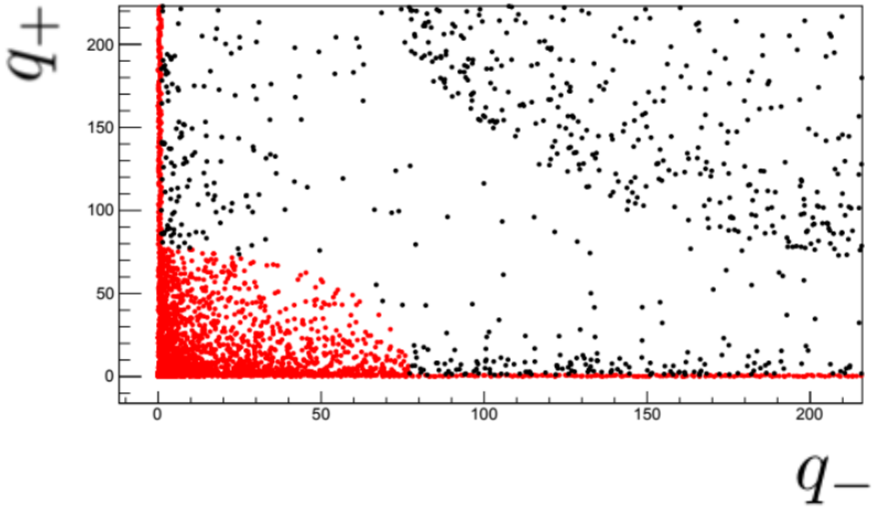
Merging ISR and γ^{ME} for sample with $Pt > 5$ GeV cut

$q^{merge} = 1$ GeV

Bhabha sample



Zoom



Red – γ ISR

Black - γ^{ME}

Conclusions & Outlook

- **Moving to the extended precision with whizard-2.8 solved the problem of the unstable cross sections calculations**
- **Merging procedure for Bhabha background a bit more complicated than for $\nu\bar{\nu}$ case**
- **Sample with a cut on Pt of γ^{ME} has:**
  - **Better σ calculation stability**
  - **Smaller discrepancies between final σ for subprocesses calculated with extended and quadruple precision**
  - **Better ratios of $\sigma_{\nu\bar{\nu}}$ / σ_{Bhabha}**

- **Now all main backgrounds are tested and 'established' - next step is to compare it to some DM models**

Backups

σ calculation & whizard precision

E > 30 GeV **σ(1 photon + 2 photons 3 photons = total) [fb]**

Quadruple 8171.6 (± 94.9) + 1643.8 (± 82.7) + 52.1(± 4.9) = 9867.5 (± 126)

Extended 8429.5 (± 153) + 1419.4 (± 50.6) + 57.9 (± 3.8) = 9906.9 (± 161)

Standard 6763.6 (± 167)

Pt > 10 GeV

Quadruple 7521.2 (± 73.1) + 1515.5 (± 45.9) + 64.2 (± 4.0) = 9100.6 (± 86.4)

Extended 7506.5 (± 64.7) + 1548.4 (± 60.6) + 50.8 (± 3.3) = 9105.8 (± 88.7)

Standard 6887.6 (± 146)

Current whizard-2.8 setup

```
cuts =
    let subevt @meA = select if Index > 2 [A]
    in
      any E > E_gamma_cut and  Theta > Th_low_cut and  Theta < Th_hgh_cut
[@meA]
     and
       all  sqrt(2.*sqrts*E)*sin(Theta/2.) > isr_q_cutoff [@meA]
     and
       all  sqrt(2.*sqrts*E)*cos(Theta/2.) > isr_q_cutoff [@meA]
     and
       all  E > isr_e_cutoff [@meA]
     and
        all Theta > angle_separation  [@meA,e1]
     and
        all Theta > angle_separation  [@meA,E1]

selection =
     let subevt @isrA = select if Index < 3 [A]
    in
      all ( sqrt(2.*sqrts*E)*sin(Theta/2.) < isr_q_cutoff
        or  sqrt(2.*sqrts*E)*cos(Theta/2.) < isr_q_cutoff
          or  E < isr_e_cutoff ) [@isrA]
```

Paramteres:

```
real E_gamma_cut = 10 GeV
real Th_low_cut = 7 degree
real Th_hgh_cut = 173 degree
real isr_q_cutoff = 1 GeV
real isr_e_cutoff = 1 GeV
real angle_separation = 1 degree
```

Previous whizard-2.7 setup

- Controling Bhabha σ singularities
  - e- or e+ too soft or too collinear to each other
  - ME-photon singularity and the collinear singularity with the beam
  - collinear singularity between final state leptons and photon
  - **singularity of the final state leptons to the beam axis**
    - Can be done with Mandelstam-t cut or pt/theta of the final state lepton
    - Presented approach inherited from whizard 1 analyses

```
cuts =
   all M > 4 GeV [e1,E1]
  and
  let subevt @meA = select if Index > 2 [A]
    in
      all Pt > 10 [@meA]
  and
   all M > 4 GeV [@meA,e1:E1]
  and
     all M < -4 [incoming e1, e1]
  and
   all M < -4 [incoming E1, E1]
```

Lets call this a ‘standard’ set of cuts