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MG5aMC for ee collider

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Plan

- Lepton-lepton collision: Old result
  - LO (since 2002)
  - LO BSM (since 2011)
  - NLO in QCD (since 2014)
- More-reliable ee collider [2108.10261]
- Z and W PDf (Effective Boson Approximation) [2111.02442]

What it is MG5aMC?

- This is a Framework of tools
  - ➡ Event generation LO
  - ➡ Event generation NLO
  - ➡ MadSpin
  - ➡ MadDM
  - ➡ MadWeight
  - ➡ Width

- This is a matrix element provider
  - tree-level and one loop
  - example: Pythia8 and matchbox mode
  - Your own format (PLUGIN mode)

Event Generation

Theoretical precision

- FLO: fixed order tree-level/loop induced
- LO+PS: hard events showered
- LO merged: MLM/CKKW(L)
- fNLO: fixed order QCD and/or EW NLO
- NLO+PS: hard events showered (MC@NLO QCD only)
- NLO merged: FxFx/ UNLOPs

LO and NLO for lepton

Process		Syntax	Cross section (pb)			
Heavy quarks and jets			LO 1 TeV		NLO 1 TeV	
i.1	$e^+e^- \to jj$	`e+ e- > j j`	$6.223 \pm 0.005 \cdot 10^{-1}$	$^{+0.0\%}_{-0.0\%}$	$6.389 \pm 0.013 \cdot 10^{-1}$	$^{+0.2\%}_{-0.2\%}$
i.2	$e^+e^- \to jjj$	`e+ e- > j j j`	$3.401 \pm 0.002 \cdot 10^{-1}$	$^{+9.6\%}_{-8.0\%}$	$3.166 \pm 0.019 \cdot 10^{-1}$	$^{+0.2\%}_{-2.1\%}$
i.3	$e^+e^- \to jjjj$	`e+ e- > j j j j`	$1.047 \pm 0.001 \cdot 10^{-1}$	$^{+20.0\%}_{-15.3\%}$	$1.090 \pm 0.006 \cdot 10^{-1}$	$^{+0.0\%}_{-2.8\%}$
i.4	$e^+e^- \to jjjjj$	`e+ e- > j j j j j`	$2.211 \pm 0.006 \cdot 10^{-2}$	$^{+31.4\%}_{-22.0\%}$	$2.771 \pm 0.021 \cdot 10^{-2}$	$^{+4.4\%}_{-8.6\%}$
i.5	$e^+e^- \to t\bar{t}$	`e+ e- > t t~`	$1.662 \pm 0.002 \cdot 10^{-1}$	$^{+0.0\%}_{-0.0\%}$	$1.745 \pm 0.006 \cdot 10^{-1}$	$^{+0.4\%}_{-0.4\%}$
i.6	$e^+e^- \to t\bar{t}j$	`e+ e- > t t~ j`	$4.813 \pm 0.005 \cdot 10^{-2}$	$^{+9.3\%}_{-7.8\%}$	$5.276 \pm 0.022 \cdot 10^{-2}$	$^{+1.3\%}_{-2.1\%}$
i.7*	$e^+e^- \to t\bar{t}jj$	`e+ e- > t t~ j j`	$8.614 \pm 0.009 \cdot 10^{-3}$	$^{+19.4\%}_{-15.0\%}$	$1.094 \pm 0.005 \cdot 10^{-2}$	$^{+5.0\%}_{-6.3\%}$
i.8*	$e^+e^- \to t\bar{t}jjj$	`e+ e- > t t~ j j j`	$1.044 \pm 0.002 \cdot 10^{-3}$	$^{+30.5\%}_{-21.6\%}$	$1.546 \pm 0.010 \cdot 10^{-3}$	$^{+10.6\%}_{-11.6\%}$
i.9*	$e^+e^- \to t\bar{t}t\bar{t}$	`e+ e- > t t~ t t~`	$6.456 \pm 0.016 \cdot 10^{-7}$	$^{+19.1\%}_{-14.8\%}$	$1.221 \pm 0.005 \cdot 10^{-6}$	$^{+13.2\%}_{-11.2\%}$
i.10*	$e^+e^- \to t\bar{t}t\bar{t}j$	`e+ e- > t t~ t t~ j`	$2.719 \pm 0.005 \cdot 10^{-8}$	$^{+29.9\%}_{-21.3\%}$	$5.338 \pm 0.027 \cdot 10^{-8}$	$^{+18.3\%}_{-15.4\%}$
i.11	$e^+e^- \to b\bar{b}$ (4f)	`e+ e- > b b~`	$9.198 \pm 0.004 \cdot 10^{-2}$	$^{+0.0\%}_{-0.0\%}$	$9.282 \pm 0.031 \cdot 10^{-2}$	$^{+0.0\%}_{-0.0\%}$
i.12	$e^+e^- \to b\bar{b}j$ (4f)	`e+ e- > b b~ j`	$5.029 \pm 0.003 \cdot 10^{-2}$	$^{+9.5\%}_{-8.0\%}$	$4.826 \pm 0.026 \cdot 10^{-2}$	$^{+0.5\%}_{-2.5\%}$
i.13*	$e^+e^- \to b\bar{b}jj$ (4f)	`e+ e- > b b~ j j`	$1.621 \pm 0.001 \cdot 10^{-2}$	$^{+20.0\%}_{-15.3\%}$	$1.817 \pm 0.009 \cdot 10^{-2}$	$^{+0.0\%}_{-3.1\%}$
i.14*	$e^+e^- \to b\bar{b}jjj$ (4f)	`e+ e- > b b~ j j j`	$3.641 \pm 0.009 \cdot 10^{-3}$	$^{+31.4\%}_{-22.1\%}$	$4.936 \pm 0.038 \cdot 10^{-3}$	$^{+4.8\%}_{-8.9\%}$
i.15*	$e^+e^- \to b\bar{b}b\bar{b}$ (4f)	`e+ e- > b b~ b b~`	$1.644 \pm 0.003 \cdot 10^{-4}$	$^{+19.9\%}_{-15.3\%}$	$3.601 \pm 0.017 \cdot 10^{-4}$	$^{+15.2\%}_{-12.5\%}$
i.16*	$e^+e^- \to b\bar{b}b\bar{b}j$ (4f)	`e+ e- > b b~ b b~ j`	$7.660 \pm 0.022 \cdot 10^{-5}$	$^{+31.3\%}_{-22.0\%}$	$1.537 \pm 0.011 \cdot 10^{-4}$	$^{+17.9\%}_{-15.3\%}$
i.17*	$e^+e^- \to t\bar{t}b\bar{b}$ (4f)	`e+ e- > t t~ b b~`	$1.819 \pm 0.003 \cdot 10^{-4}$	$^{+19.5\%}_{-15.0\%}$	$2.923 \pm 0.011 \cdot 10^{-4}$	$^{+9.2\%}_{-8.9\%}$
i.18*	$e^+e^- \to t\bar{t}b\bar{b}j$ (4f)	`e+ e- > t t~ b b~ j`	$4.045 \pm 0.011 \cdot 10^{-5}$	$^{+30.5\%}_{-21.6\%}$	$7.049 \pm 0.052 \cdot 10^{-5}$	$^{+13.7\%}_{-13.1\%}$

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LO and NLO for lepton

Process		Syntax	Cross section (pb)			
Top quarks +bosons			LO 1 TeV		NLO 1 TeV	
j.1	$e^+e^- \to t\bar{t}H$	`e+ e- > t t~ h`	$2.018 \pm 0.003 \cdot 10^{-3}$	$^{+0.0\%}_{-0.0\%}$	$1.911 \pm 0.006 \cdot 10^{-3}$	$^{+0.4\%}_{-0.5\%}$
j.2*	$e^+e^- \to t\bar{t}Hj$	`e+ e- > t t~ h j`	$2.533 \pm 0.003 \cdot 10^{-4}$	$^{+9.2\%}_{-7.8\%}$	$2.658 \pm 0.009 \cdot 10^{-4}$	$^{+0.5\%}_{-1.5\%}$
j.3*	$e^+e^- \to t\bar{t}Hjj$	`e+ e- > t t~ h j j`	$2.663 \pm 0.004 \cdot 10^{-5}$	$^{+19.3\%}_{-14.9\%}$	$3.278 \pm 0.017 \cdot 10^{-5}$	$^{+4.0\%}_{-5.7\%}$
j.4*	$e^+e^- \to t\bar{t}\gamma$	`e+ e- > t t~ a`	$1.270 \pm 0.002 \cdot 10^{-2}$	$^{+0.0\%}_{-0.0\%}$	$1.335 \pm 0.004 \cdot 10^{-2}$	$^{+0.5\%}_{-0.4\%}$
j.5*	$e^+e^- \to t\bar{t}\gamma j$	`e+ e- > t t~ a j`	$2.355 \pm 0.002 \cdot 10^{-3}$	$^{+9.3\%}_{-7.9\%}$	$2.617 \pm 0.010 \cdot 10^{-3}$	$^{+1.6\%}_{-2.4\%}$
j.6*	$e^+e^- \to t\bar{t}\gamma jj$	`e+ e- > t t~ a j j`	$3.103 \pm 0.005 \cdot 10^{-4}$	$^{+19.5\%}_{-15.0\%}$	$4.002 \pm 0.021 \cdot 10^{-4}$	$^{+5.4\%}_{-6.6\%}$
j.7*	$e^+e^- \to t\bar{t}Z$	`e+ e- > t t~ z`	$4.642 \pm 0.006 \cdot 10^{-3}$	$^{+0.0\%}_{-0.0\%}$	$4.949 \pm 0.014 \cdot 10^{-3}$	$^{+0.6\%}_{-0.5\%}$
j.8*	$e^+e^- \to t\bar{t}Zj$	`e+ e- > t t~ z j`	$6.059 \pm 0.006 \cdot 10^{-4}$	$^{+9.3\%}_{-7.8\%}$	$6.940 \pm 0.028 \cdot 10^{-4}$	$^{+2.0\%}_{-2.6\%}$
j.9*	$e^+e^- \to t\bar{t}Zjj$	`e+ e- > t t~ z j j`	$6.351 \pm 0.028 \cdot 10^{-5}$	$^{+19.4\%}_{-15.0\%}$	$8.439 \pm 0.051 \cdot 10^{-5}$	$^{+5.8\%}_{-6.8\%}$
j.10*	$e^+e^- \to t\bar{t}W^\pm jj$	`e+ e- > t t~ wpm j j`	$2.400 \pm 0.004 \cdot 10^{-7}$	$^{+19.3\%}_{-14.9\%}$	$3.723 \pm 0.012 \cdot 10^{-7}$	$^{+9.6\%}_{-9.1\%}$
j.11*	$e^+e^- \to t\bar{t}HZ$	`e+ e- > t t~ h z`	$3.600 \pm 0.006 \cdot 10^{-5}$	$^{+0.0\%}_{-0.0\%}$	$3.579 \pm 0.013 \cdot 10^{-5}$	$^{+0.1\%}_{-0.0\%}$
j.12*	$e^+e^- \to t\bar{t}\gamma Z$	`e+ e- > t t~ a z`	$2.212 \pm 0.003 \cdot 10^{-4}$	$^{+0.0\%}_{-0.0\%}$	$2.364 \pm 0.006 \cdot 10^{-4}$	$^{+0.6\%}_{-0.5\%}$
j.13*	$e^+e^- \to t\bar{t}\gamma H$	`e+ e- > t t~ a h`	$9.756 \pm 0.016 \cdot 10^{-5}$	$^{+0.0\%}_{-0.0\%}$	$9.423 \pm 0.032 \cdot 10^{-5}$	$^{+0.3\%}_{-0.4\%}$
j.14*	$e^+e^- \to t\bar{t}\gamma\gamma$	`e+ e- > t t~ a a`	$3.650 \pm 0.008 \cdot 10^{-4}$	$^{+0.0\%}_{-0.0\%}$	$3.833 \pm 0.013 \cdot 10^{-4}$	$^{+0.4\%}_{-0.4\%}$
j.15*	$e^+e^- \to t\bar{t}ZZ$	`e+ e- > t t~ z z`	$3.788 \pm 0.004 \cdot 10^{-5}$	$^{+0.0\%}_{-0.0\%}$	$4.007 \pm 0.013 \cdot 10^{-5}$	$^{+0.5\%}_{-0.5\%}$
j.16*	$e^+e^- \to t\bar{t}HH$	`e+ e- > t t~ h h`	$1.358 \pm 0.001 \cdot 10^{-5}$	$^{+0.0\%}_{-0.0\%}$	$1.206 \pm 0.003 \cdot 10^{-5}$	$^{+0.9\%}_{-1.1\%}$
j.17*	$e^+e^- \to t\bar{t}W^+W^-$	`e+ e- > t t~ w+ w-`	$1.372 \pm 0.003 \cdot 10^{-4}$	$^{+0.0\%}_{-0.0\%}$	$1.540 \pm 0.006 \cdot 10^{-4}$	$^{+1.0\%}_{-0.9\%}$

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Loop-induced process

Process		Syntax	Cross section (pb)	$\Delta_{\hat{\mu}}$	Δ_{PDF}	Ref.
Selected $2 \to 4$			$\sqrt{s} = 13$ TeV			
†d.1	$pp \to Hjjj$	`p p > h j j j QED=1 [QCD]`	2.519 ± 0.005	$^{+75.1\%}_{-39.8\%}$	$^{+0.6\%}_{-0.6\%}$	[62]
⋆d.2	$pp \to HHjj$	`p p > h h j j QED=1 [QCD]`	$1.085 \pm 0.002 \cdot 10^{-2}$	$^{+62.1\%}_{-35.8\%}$	$^{+1.2\%}_{-1.3\%}$	[63]
†d.3	$pp \to HHHj$	`p p > h h h j [QCD]`	$4.981 \pm 0.008 \cdot 10^{-5}$	$^{+46.3\%}_{-29.6\%}$	$^{+1.4\%}_{-1.4\%}$	[–]
†d.3	$pp \to HHHH$	`p p > h h h h [QCD]`	$1.080 \pm 0.003 \cdot 10^{-7}$	$^{+33.3\%}_{-23.4\%}$	$^{+1.7\%}_{-1.7\%}$	[–]
d.4	$gg \to e^+e^-\mu^+\mu^-$	`g g > e+ e- mu+ mu- [QCD]`	$2.022 \pm 0.003 \cdot 10^{-3}$	$^{+26.4\%}_{-19.4\%}$	$^{+0.7\%}_{-1.1\%}$	[64]
†d.5	$pp \to HZ\gamma j$	`g g > h z a g [QCD]`	$4.950 \pm 0.008 \cdot 10^{-6}$	$^{+45.8\%}_{-29.3\%}$	$^{+1.2\%}_{-1.3\%}$	[–]
Non-hadronic processes			$\sqrt{s} = 500$ GeV, no PDF			
⋆e.1	$e^+e^- \to ggg$	`e+ e- > g g g [QED]`	$2.526 \pm 0.004 \cdot 10^{-6}$	$^{+31.2\%}_{-22.0\%}$		[65]
†e.2	$e^+e^- \to HH$	`e+ e- > h h [QED]`	$1.567 \pm 0.003 \cdot 10^{-5}$			[–]
†e.3	$e^+e^- \to HHgg$	`e+ e- > h h g g [QED]`	$6.629 \pm 0.010 \cdot 10^{-11}$	$^{+19.2\%}_{-14.8\%}$		[–]
⋆e.4	$\gamma\gamma \to HH$	`a a > h h [QED]`	$3.198 \pm 0.005 \cdot 10^{-4}$			[66]
Miscellaneous			$\sqrt{s} = 13$ TeV			
†f.1	$pp \to tt$	`p p > t t [QED]`	$4.045 \pm 0.007 \cdot 10^{-15}$	$^{+0.2\%}_{-0.8\%}$	$^{+0.9\%}_{-1.0\%}$	[–]

Hirschi, OM 1507.00020

BSM Features

- Full support of UFO model
  - LO and NLO model
  - Customise propagator and Form-Factor
  - No limitation on Lorentz structure
- MadSpin: Decays with full spin-correlation and off-shell effects
- Automatic width computation: Automatic check of relevance of 3 body decay
- BSM re-weighting: LO and NLO

Beam for e+ e-

Old status

- beam polarisation is supported
  - Thanks to helicity amplitude
- photon initial state can be generated within the Improved Weizsäcker-Williams formula (elastic photon) Phys.Rep. 15C (1975) 181

lacking support for

- Beamstrahlung
- ISR
- Collinear Z/W emission

How important are they?

$\sqrt{s}$[GeV]	Pol.	Process	σ[pb] CEPC	σ[pb] MG5
250	none	$e^+e^- \to \mu^+\mu^-, \tau^+\tau^-$	4.40	3.50
250	none	$e^+e^- \to q\bar{q}$	50.2	11.3
250	none	$e^+e^- \to ZZ$	1.03	1.10
250	none	$e^+e^- \to WW$	15.4	16.5
250	none	$e^+e^- \to Zh$	0.212	0.240
$\sqrt{s}$[GeV]	Pol.	Process	σ[pb] ILC	σ[pb] MG5
250	(+, −)	$e^+e^- \to Zh$	0.319	0.356
250	(−, +)	$e^+e^- \to Zh$	0.206	0.240
350	(+, −)	$e^+e^- \to t\bar{t}$	0.286	0.378
350	(−, +)	$e^+e^- \to t\bar{t}$	0.137	0.166
500	(+, −)	$e^+e^- \to t\bar{t}$	1.08	0.921
500	(−, +)	$e^+e^- \to t\bar{t}$	0.470	0.436

C.T. Potter 1702.04827

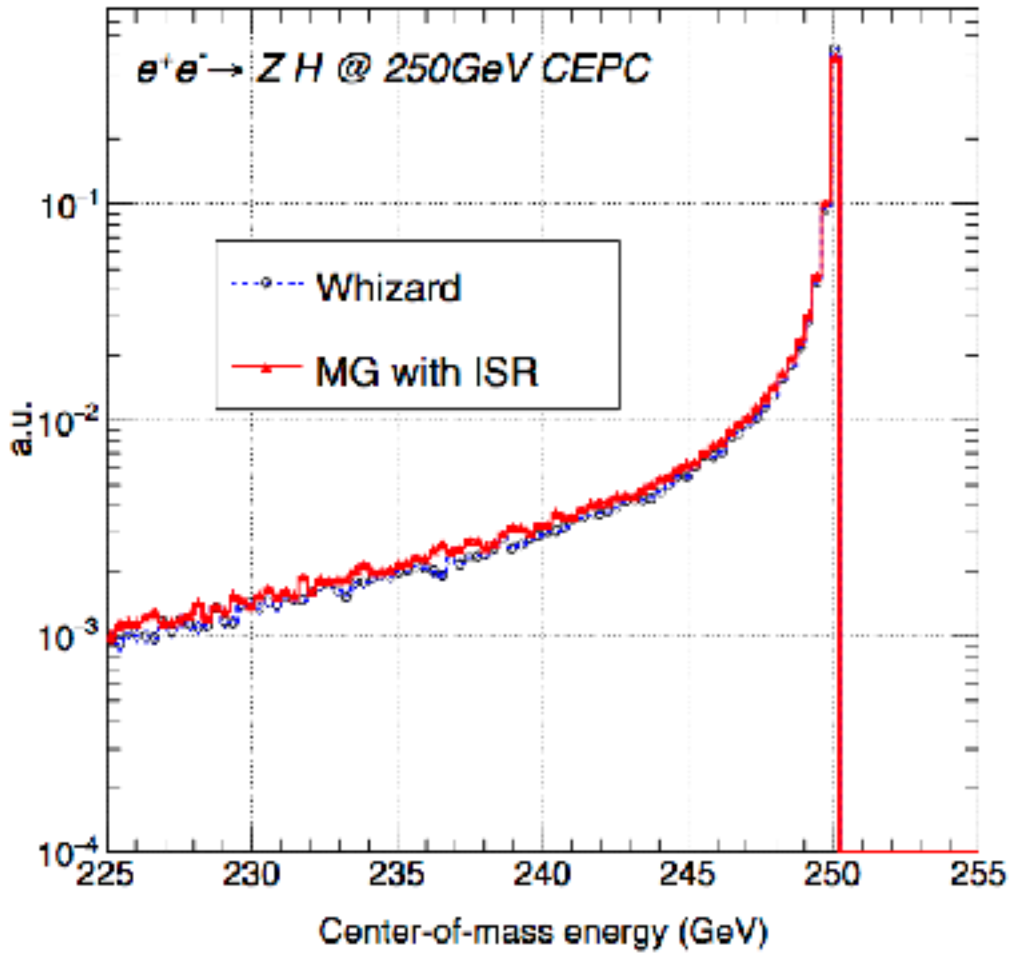
6 Conclusion

We have described the production of fast simulation background samples for new physics studies at a future e^+e^- collider like the ILC or CEPC. Events are generated for a variety of run scenarios with approximately five times the integrated luminosity envisaged by the most optimistic run scenario for each $\sqrt{s}$. The events are generated with MG5_aMC@NLO with detector simulation performed by Delphes using the DSiD detector card. Finally, the samples are compared to the ILC background samples made for the DBD study and CEPC background samples.

Systematic uncertainties associated with the MG5_aMC@NLO samples have been estimated. These samples lack a detailed simulation of initial state radiation and beamstrahlung. The $2f$ background from radiative return events is absent, and both pileup from bunch-bunch interactions and a realistic beam energy distribution are absent. Nevertheless, these shortcomings can be ameliorated.

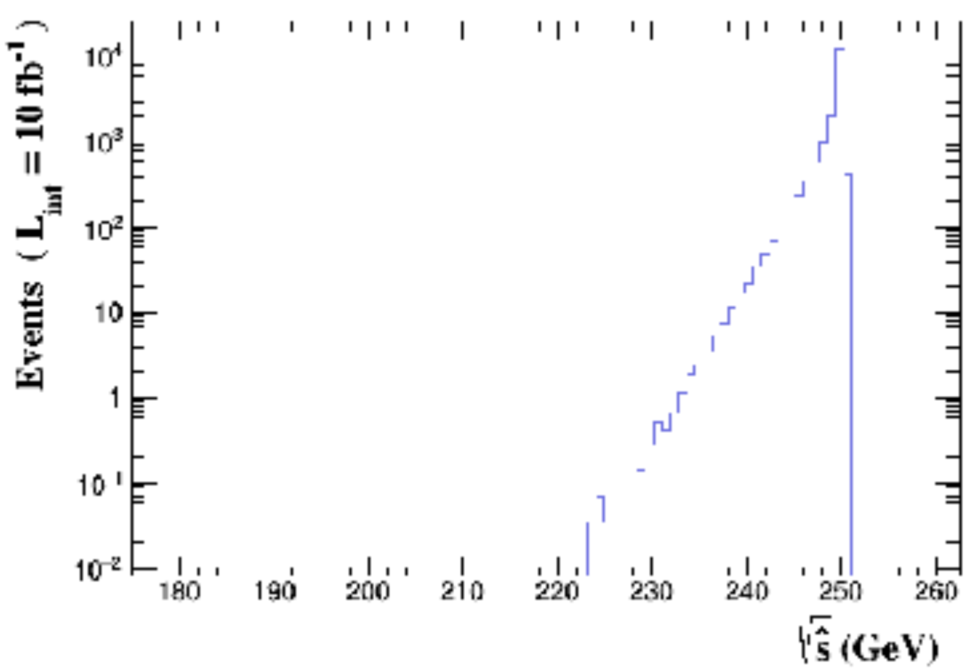
“Solution” in 2017

- MGISR PLUGIN



C. Chen et al 1705.04886

- Beamstralung branch



Using a beam profile input
-> not able to handle resonance/…
-> never published (2017)

Not possible to combine both and only LO

Solution in 2021

$$d\Sigma_{e^+e^-}(P_{e^+}, P_{e^-}) = \sum_{kl=e^+e^-\gamma} \int dy_+ dy_- \, \mathcal{B}_{kl}(y_+, y_-) \, d\sigma_{kl}(y_+ P_{e^+}, y_- P_{e^-})$$

- $d\Sigma_{e^+e^-}$: the collider-level cross section
- $d\sigma_{kl}$: the particle-level cross section
- $\mathcal{B}_{kl}(y_+, y_-)$: describes beam dynamics (including beamstrahlung)
- e^+, e^- on the lhs: the beams
- e^+, e^-, γ on the rhs: the particles

2108.10261

EE PDF (version 3.2.x)

- We provide library for the B
  - ➡ ISR only
  - ➡ FCC (beamstralung + isr)
  - ➡ cepc (beamstralung + isr)
  - ➡ llc (beamstralung + isr)
- And method to fit your own from guinapig.

EE PDF

Advantages

- Treated as normal PDF (importance sampling,...)
- NLO (in QCD) compatible

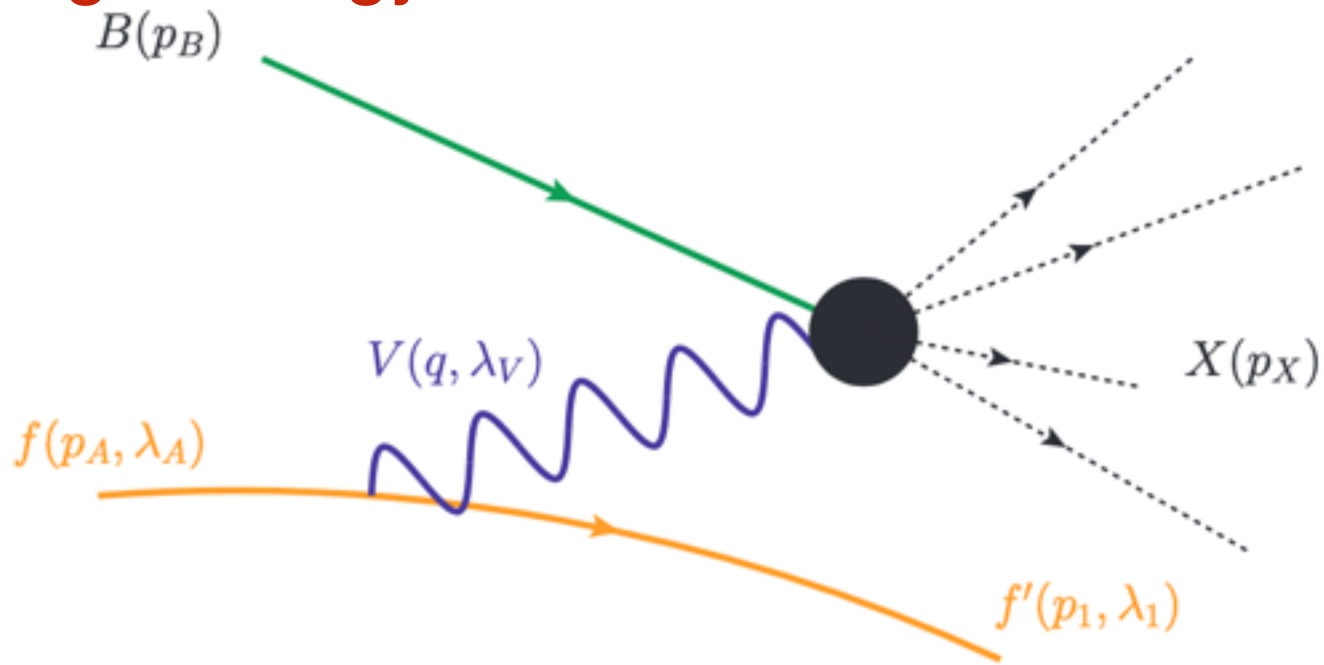
Issue

- Discussion in progress to be sure that guinapig does not include ISR
- Need to implement interface to Parton-Shower

EWA (version 3.3.x)

2111.02442

High Energy Collision



- Collinear W/Z
- Quasi on-shell

- Dedicated PDF for such process
  - fully polarised PDF
  - Study of their validity
    - Requires at least 1 TeV

Conclusion

- MadGraph5_aMC@NLO is ready for lepton collider
  - ➡ Electron - electron
  - ➡ Muon - Muon
- Both at LO and NLO
- We have recently improved the support of lepton beam
  - ➡ ISR
  - ➡ Beamstrahlung
  - ➡ Collinear PDF (EWA)