MC Generators for Future Colliders in key4HEP

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Future Colliders Meeting
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work done with Alan Price (Cracovie)

- Introduction
- Setting up
- Comparing
- Summary/Outlook

Introduction

2020: ECFA recognizes the need for the experimental and theoretical communities involved in physics studies, experiment designs and detector technologies at **future Higgs *(added top and EW)* factories** to gather. ECFA supports **a series of workshops** with the aim to share challenges and expertise, to **explore synergies in their efforts** and to respond coherently to this priority in the European Strategy for Particle Physics (ESPP).

WG2: Physics Analysis Tools

- Patrizia Azzi
- Fulvio Piccinini
- Dirk Zerwas

SOFTWARE ECOSYSTEM

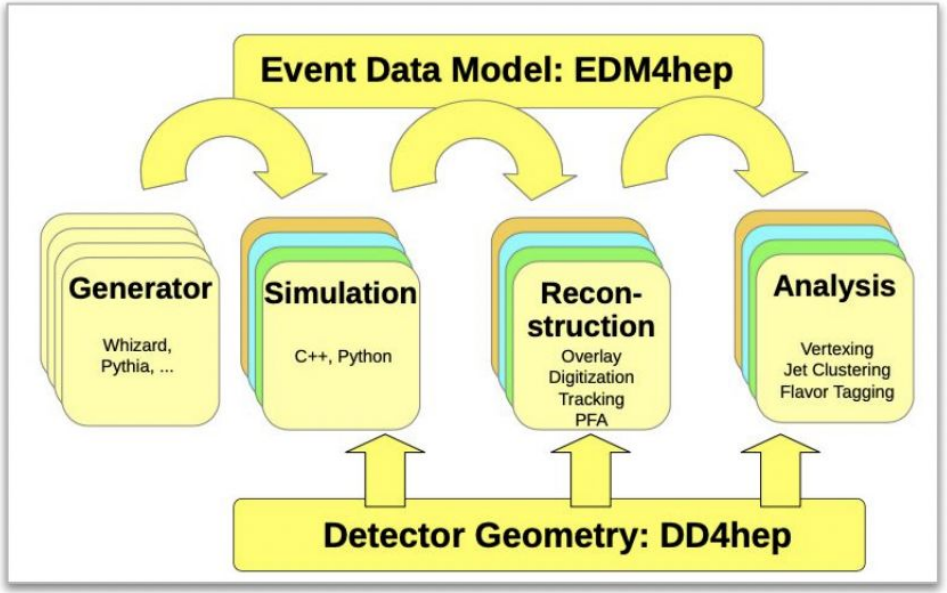
GENERATORS

SIMULATION

RECONSTRUCTION

key4HEP Ecosystem (Thomas, Frank et al):

- EDM4HEP
- Geometry DD4HEP
- Gaudi
- DIRAC
- ILCSOFT
- FCC
- CEPCSW
- ACTS….



Adopted by ECFA(well…), CEPC, C^3, FCC, ILC :

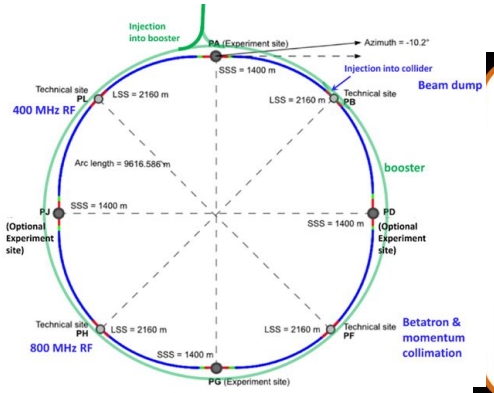
- Interoperability of algorithms
- comparisons and improvements

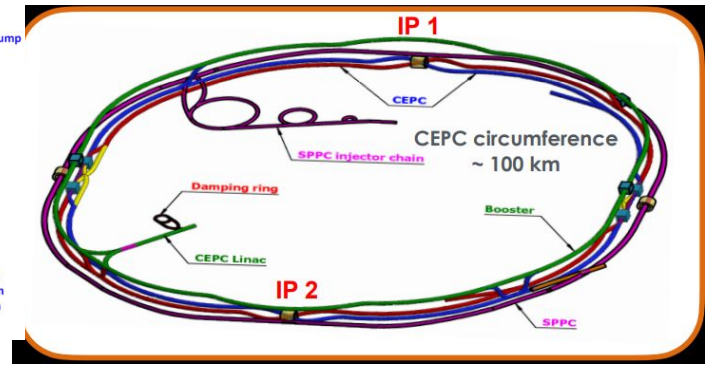
Machines

Circular:

- 90km (FCC), 100km (CEPC)
- √s=90-365GeV
- Tera-Z

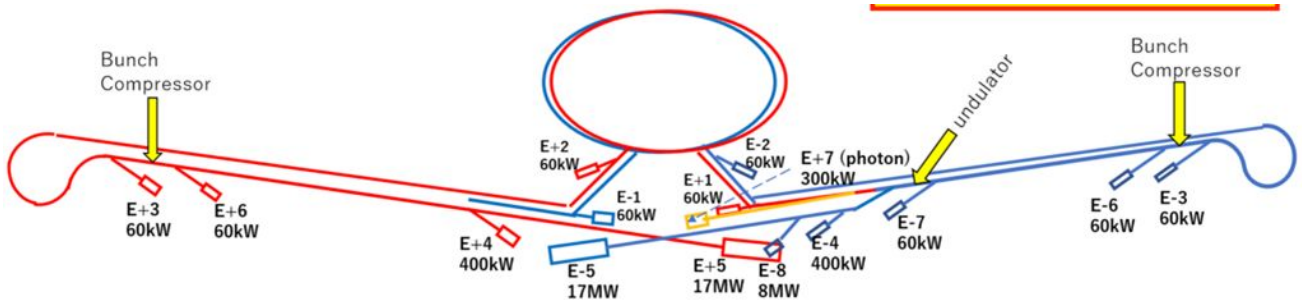
Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter x_x / x_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} cm^{-2}s^{-1}]	140	20	≥5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11





Linear

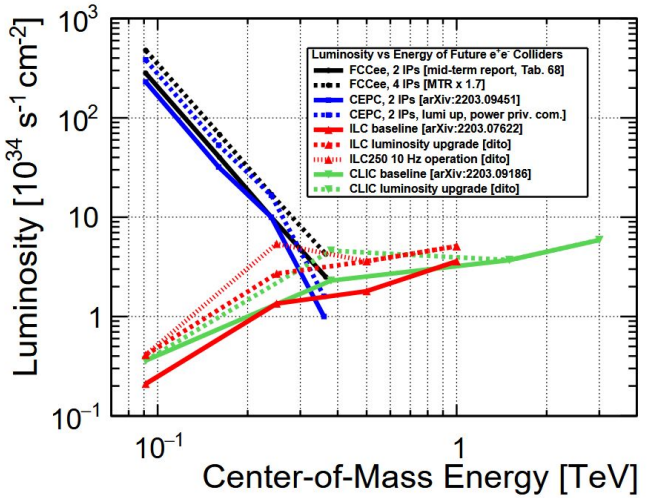
- 27 km
- √s=90-550GeV, 1.5TeV
- Giga-Z



Whatever CERN Council decides::

- 2nd gen Attobarn machines
- √s is √s (to first order)

Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade
Centre of mass energy	$\sqrt{s}$	GeV	250	250
Luminosity	$\mathcal{L}$	10^{34}cm^{-2}s^{-1}	1.35	2.7
Polarization for e^-/e^+	$P_-(P_+)$	%	80(30)	80(30)
Repetition frequency	$f_{\rm rep}$	Hz	5	5
Bunches per pulse	$n_{\rm bunch}$		1	1312	2625
Bunch population	N_e	10^{10}	2	2
Linac bunch interval	Δt_b	ns	554	366
Beam current in pulse	$I_{\rm pulse}$	mA	5.8	8.8
Beam pulse duration	$t_{\rm pulse}$	μs	727	961
Average beam power	$P_{\rm ave}$	MW	5.3	10.5
RMS bunch length	σ_z^*	mm	0.3	0.3
Norm. hor. emitt. at IP	$\gamma\epsilon_x$	μm	5	5
Norm. vert. emitt. at IP	$\gamma\epsilon_y$	nm	35	35
RMS hor. beam size at IP	σ_x^*	nm	516	516
RMS vert. beam size at IP	σ_y^*	nm	7.7	7.7
Luminosity in top 1%	$\mathcal{L}_{0.01}/\mathcal{L}$		73%	73%
Beamstrahlung energy loss	$\delta_{\rm BS}$		2.6%	2.6%
Site AC power	$P_{\rm site}$	MW	111	128
Site length	$L_{\rm site}$	km	20.5	20.5



Generators

LEP era generators:

- Pythia
- Herwig
- KKMC (2 fermions)
- Babayaga, BHLUMI (specialized)

LHC era generators (automation):

- Madgraph
- Sherpa

Modern e+e- era generators:

- Whizard
- CIRCE (specialized)

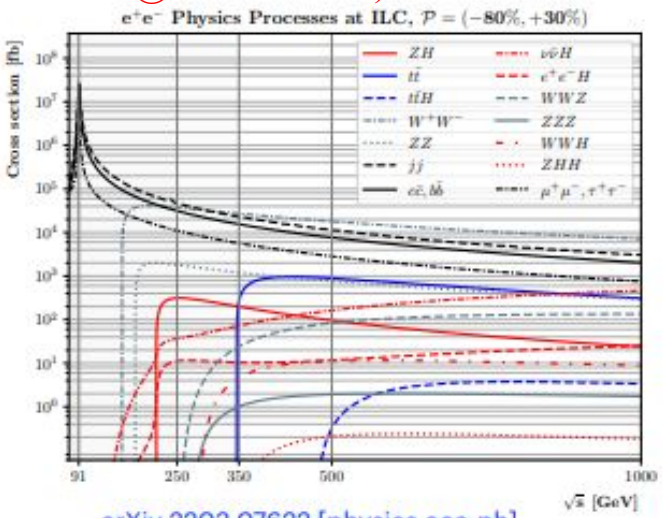
QED:

- ePDF, QED Parton Shower and Yennie-Frautchi-Suura resummation
- Some generators use ePDF (thought we got rid of this, but no….)

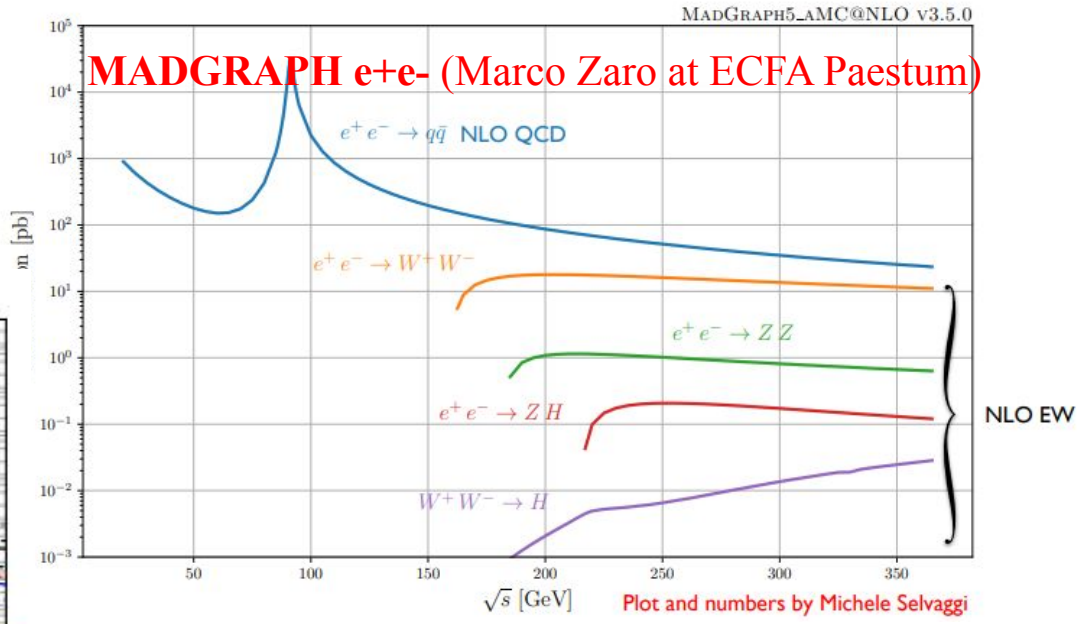
Beamstrahlung:

- high density of bunches leads to strong fields
- machine dependent (Guinea Pig)
- Input to Generators (MADGRAPH, CIRCE+Whizard)

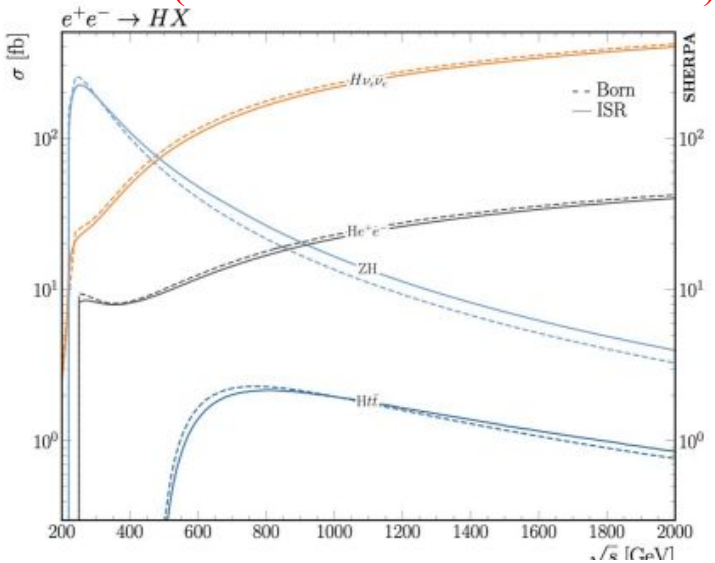
Whizard e+e- (Juergen Reuter@LCWS2024)



MADGRAPH e+e- (Marco Zaro at ECFA Paestum)



SHERPA e+e- (Daniel Reichelt at ECFA Paris)



All is good….individually….standalone

Generators: Configuration

Attobarn data with N^nLO under control:

- many generators claim the same precision (differing approaches)
- needs high precision in generation
- first step: cross section
- second step: differential distributions
- Technical Benchmarks

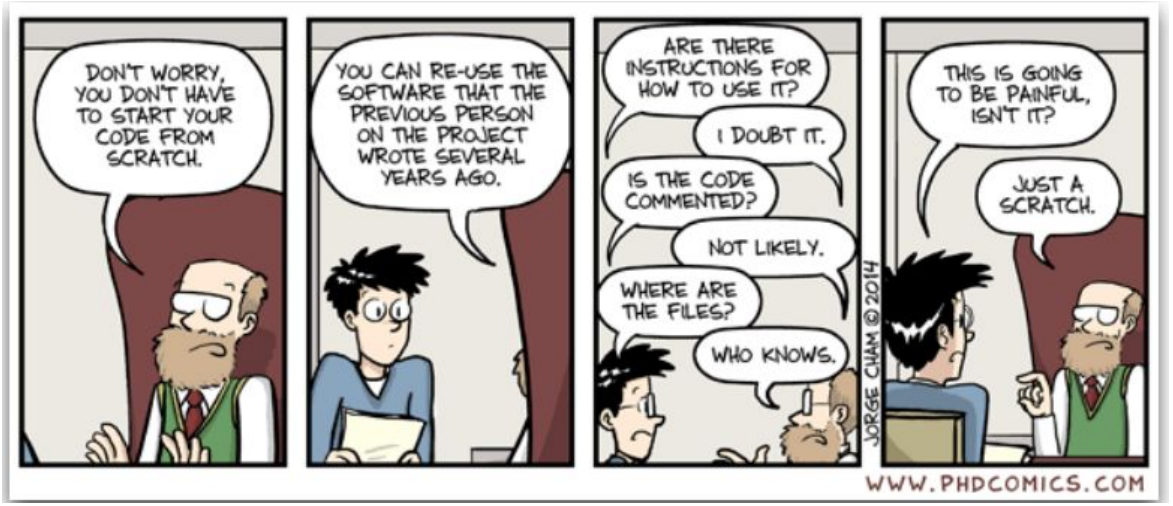
k4GeneratorsConfig in key4HEP:

- define process
- define generators
- generates datacards for the generators
  - dynamic and template based
- generates event generation script in key4HEP environment (run anywhere, well…..)

In practice:

- python
- dynamic loading of generators by name
- OO usage 2+1 levels deep

```
Generators:
  - Sherpa
  - Whizard
  - Madgraph
  - KKMC
  - Pythia

OutputFormat: hepmc3
OutDir: Run-Cards
Events: 10000
EventMode: unweighted

SqrtS: 91.2
Model: SM
ISRMode: 0

Processes:
  Muon:
     Final: [13, -13]
     Order: [2,0]

  Tau:
     Final: [15, -15]
     Order: [2,0]

Sherpa:
  Run:
    EW_SCHEME: 3


ParticleData:
  23:
    mass: 91.1876
    width: 2.4952
```



behind the scenes:

- converter HEPMC/LHE to EDM4HEP
- Pythia main with PhaseSpace cuts
- MADGRAPH LHE to HepMC via Pythia (turned out to be useful for others…)

Generators: EDM

edm4HEP:

- provided by key4HEP
- contains MCTruth, Simulation and Reconstruction
- convince ALL MC groups to write edm4HEP unlikely
- provide a converter compatible with HepMC Writers

HepMC:

- Problem with LHE reader
- color flows, but iflow1, iflow2 seem to persist
- best effort standard, not a standard (2 versus 3)
- quick reaction/update by HepMC team

HepMC to edm4HEP:

- aim for lossless conversion
- key4HEP provides flexible structures
  - but not sustainable
- quick reaction/update of MC EDM by key4HEP team

HepMC and edm4HEP

- meta data
- philosophical differences:
  - provide detailed MCTruth/provide order-safe MCTruth
  - LHC inspired/e+e- inspired: $\sqrt{s}$….
- useful discussions between key4HEP (Thomas, Frank) and HepMC (Andy and Chris) teams

Generators: Technical Features

Goal:

- detect
- correct
- follow up

key4HEP

- Whizard in key4HEP works on CENTOS, ALMA, UBUNTU
- Whizard does not work on ALMA in CI
- traced to incomplete setup on all OS but UBUNTU
- bugfix (SPACK) provided by Thomas

KKMC:

- cross section not provided
- will be provided in the next version (imminent since 2024, but now it really is)

Babayaga

- cross section not provided
- update by author, included in key4HEP and tested (solved)

The MODEL:

- **SUPER-SPLIT SUPERSYMMETRY arXiv hep-th/0503249 Fox et al**

MADGRAPH:

- σ(ddbar) > σ(bbar)
- LHC inspired implicit pT cut (bQuark)
- reset all cuts
- update of MADGRAPH setup in key4HEP

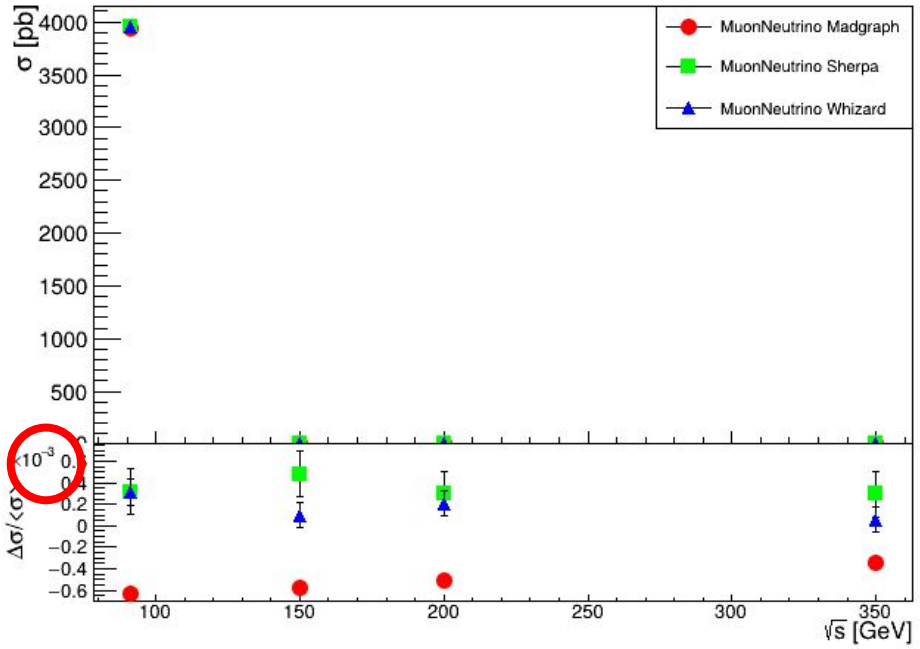
k4GeneratorsConfig

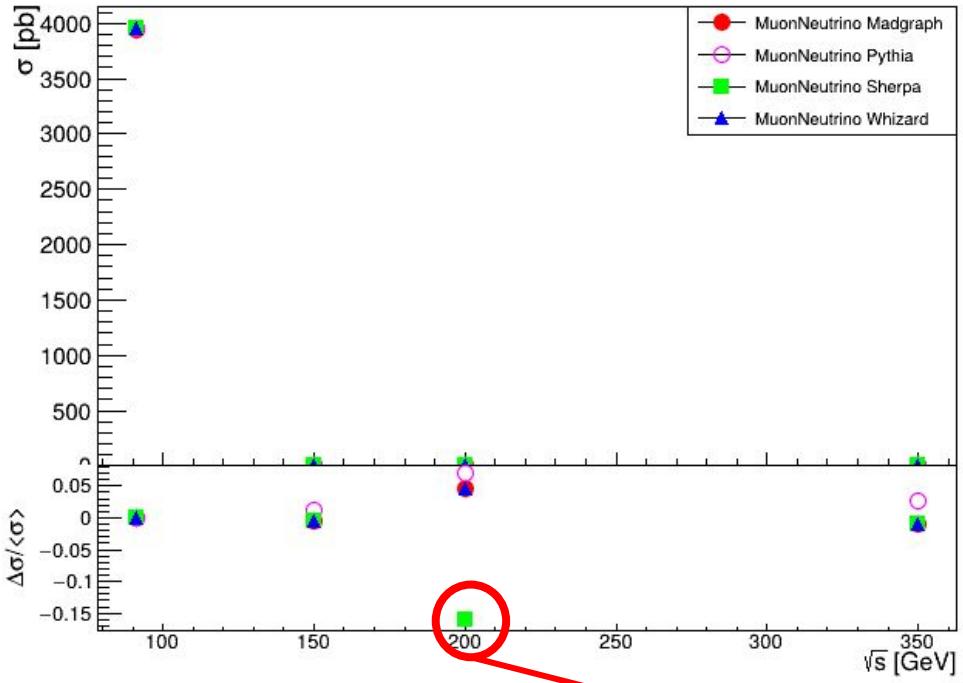
- consistent initialization of parameters (de facto SLHA)
- overconstrained input (eg EW scheme)
- database
- generator specific process configuration additions

Generators: Fermion Pairs

BottomUp:

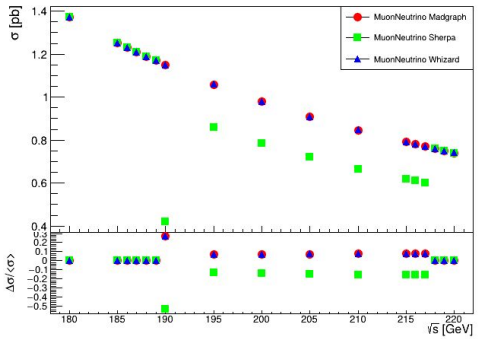
- fermion pairs
- LO
- no ISR
- MuonNeutrino: 1 diagram only, no interference





Processing:

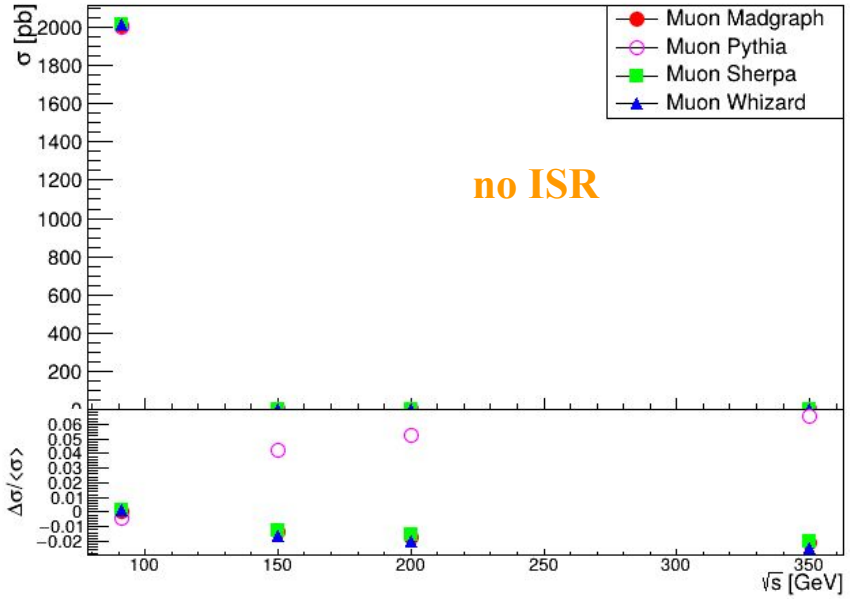
- 3% agreement Madgraph/Pythia/Sherpa/Whizard
- Drop of -15% for Sherpa@200GeV (in all fermion pairs)
- Alan and Daniel investigated: fix in Sherpa 3.0.X
- Fixed confirmed in key4HEP on tuesday
- Madgraph/Sherpa/Whizard agreement: <0.1%
- Sherpa/Whizard agreement: ~0.01%

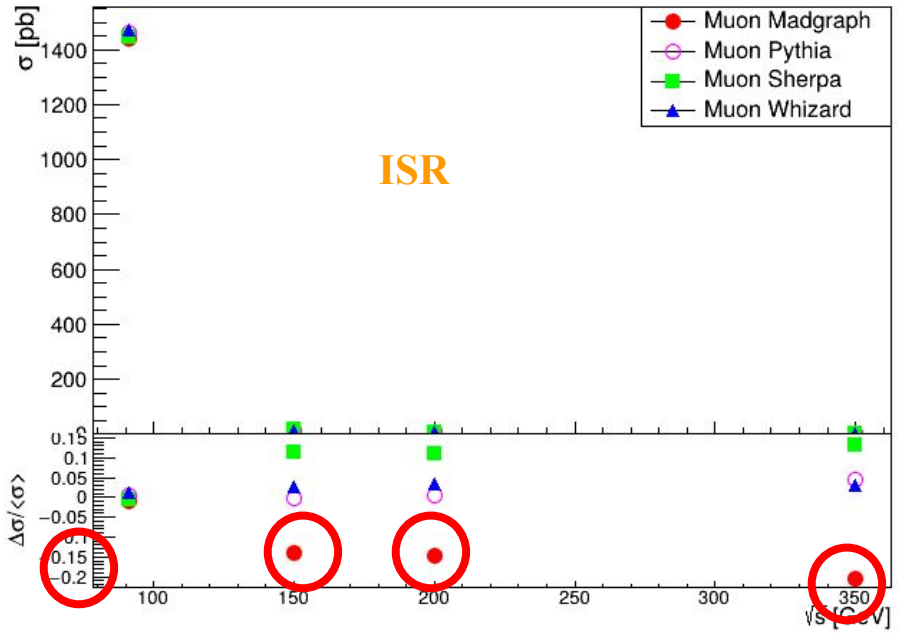


Generators: Fermion Pairs

BottomUp:

- Muons: 2 diagram, interference
- LO
- ISR:
  - YFS eg Sherpa, KKMC
  - PDF eg Pythia, Madgraph

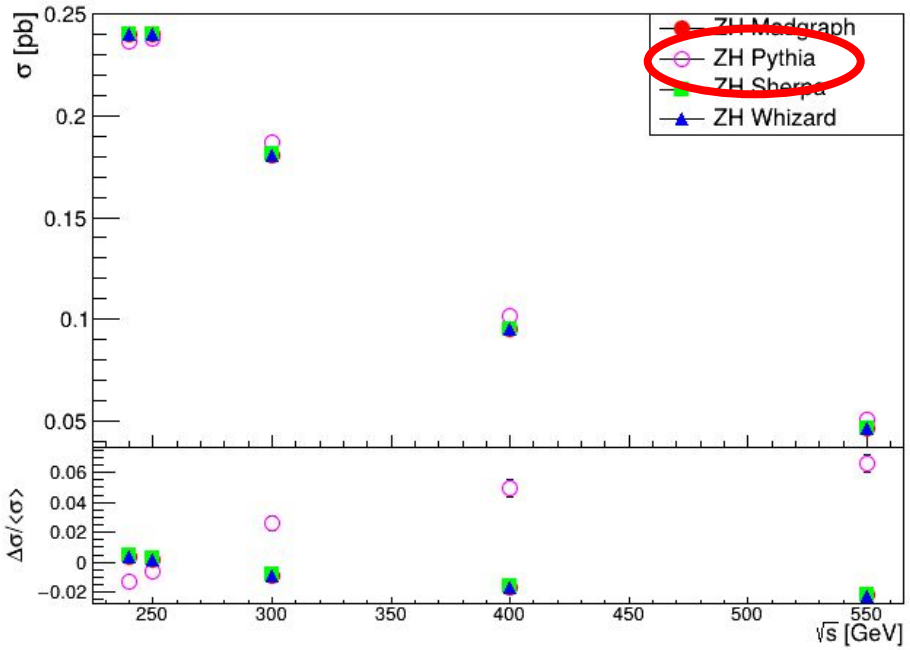


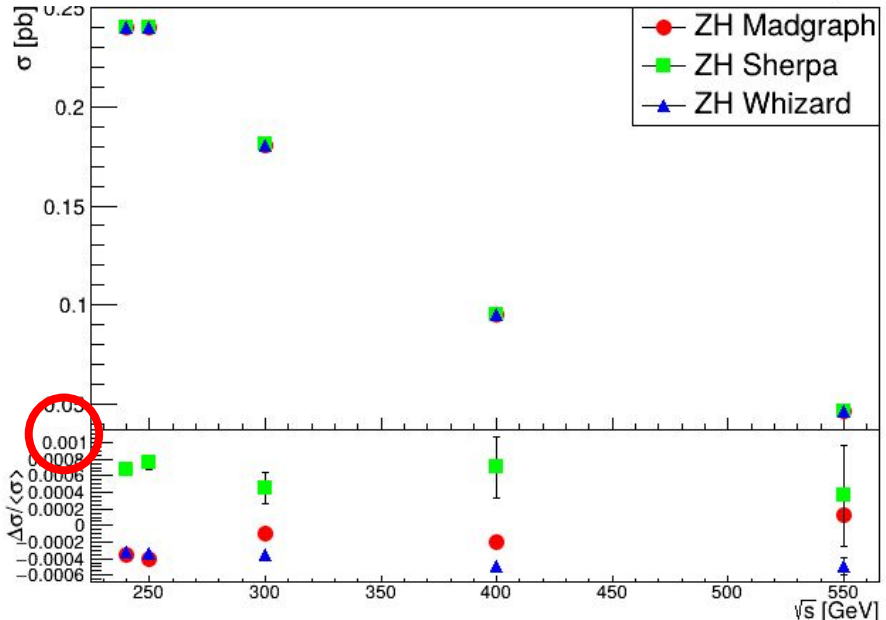


Processing:

- no ISR
  - Pythia versus Madgraph, Sherpa, Whizard
    - kind of understood: sin2theta is intelligently set by Pythia
- ISR
  - Reasonable agreement Pythia/Sherpa/Whizard (also at 200GeV)
  - Madgraph off up to 20%
    - SM ok-ish, SM-FULL
    - x=1 effect: 10^-6 precision in ISR
    - shat = x1*x2*s (imprecise in 3 terms)
    - boost with massive initial state particles
    - expect adhoc correction in 3.5.9

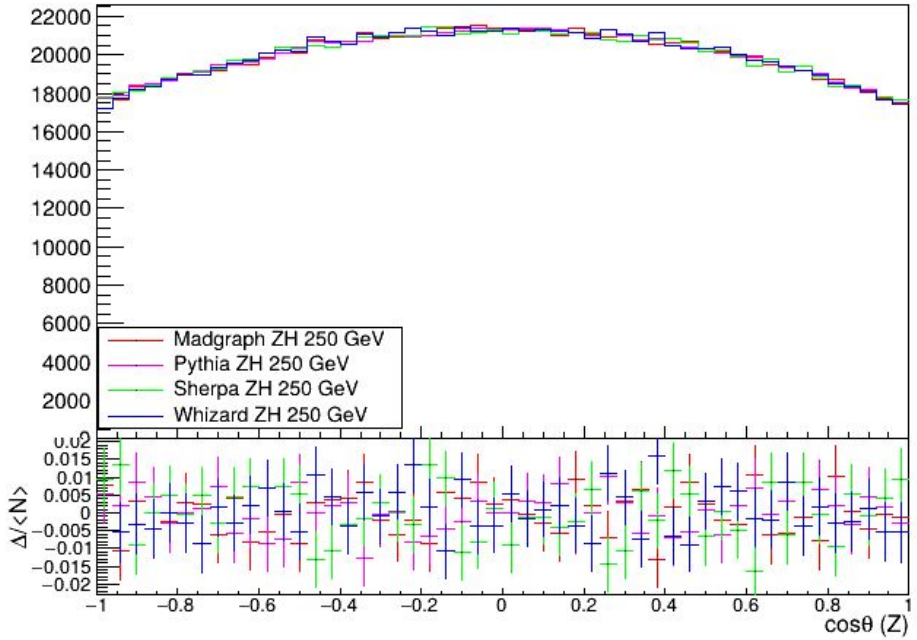
Generators: ZH



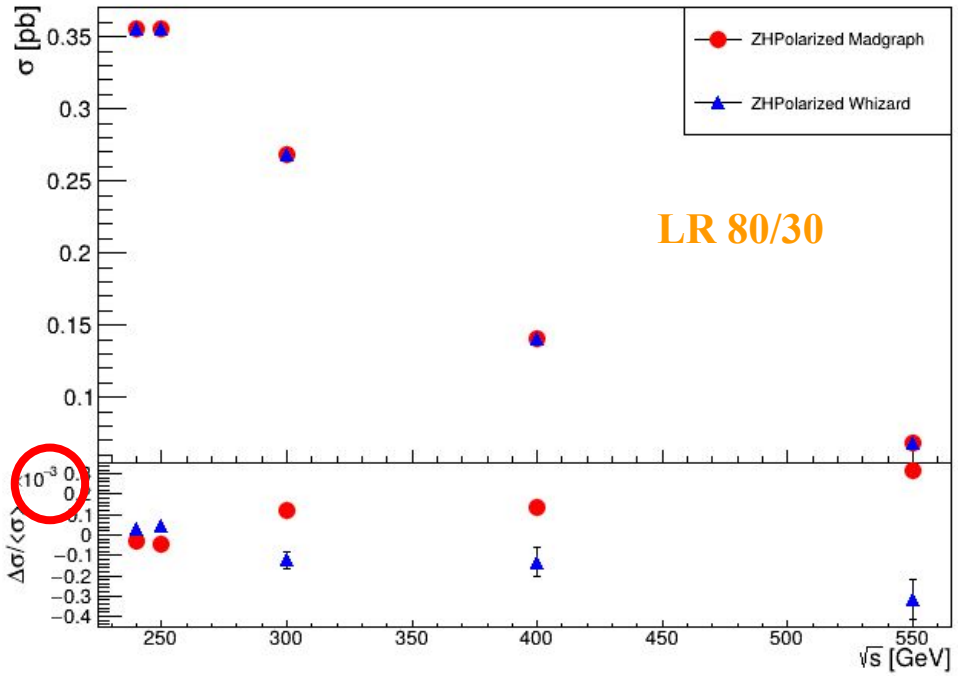


ZH LO noISR:

- several percent agreement level
- differential distribution (costheta) roughly ok
- Sherpa versus Madgraph/Whizard
  - globally: permil level agreement
  - locally: 0.01 % level
  - Sherpa being checked by Alan



Generators: Polarization

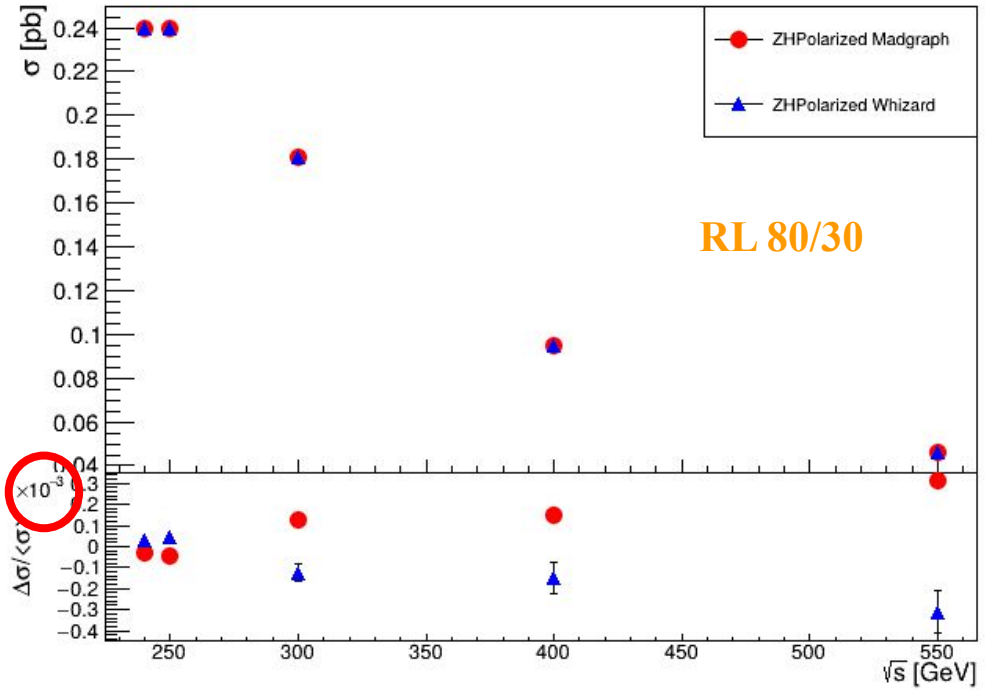


ZH Polarized LO noISR:

- Gudi's and Whizard's eminent domain
- Sherpa in principle available, but not released
- Madgraph can do!

Classical setting:

- 80/30 -1/1 e-/e+
- 80/30 1/-1 e-/e+



Results:

- Excellent agreement for both settings
- permil level

Generators: Time

Generators Running efficiency

- CI low stat only
- overhead significant

UBUNTU

```
10/14 Test #12: Run_Sherpa ........................   Passed  519.10 sec
11/14 Test #11: Run_Pythia ........................   Passed  805.32 sec
12/14 Test #10: Run_Madgraph ......................   Passed  921.24 sec
13/14 Test #13: Run_Whizard .......................   Passed  973.16 sec
```

ALMA

```
10/14 Test #12: Run_Sherpa ........................   Passed  521.62 sec
11/14 Test #11: Run_Pythia ........................   Passed  816.74 sec
12/14 Test #10: Run_Madgraph ......................   Passed 1015.55 sec
13/14 Test #13: Run_Whizard .......................   Passed 1045.10 sec
```

Overall:

- MADGRAPH and Whizard similar
- Pythia (my surprise) similar to Madgraph/Whizard
- Sherpa is 2x faster than Madgraph/Whizard
- Slightly better performance on alma (probably insignificant)

Summary/Outlook

Summary:

- **Exciting prospects for electron-positron Higgs/Top/EW factories :)**
- **MonteCarlo Generators: heritage and modern, lots of “new”comers in addition to Whizard**
- **key4HEP Eco-system robust, flexible and reactive**
- **MonteCarlo author teams do a great job:**
  - **10^-3 reached for some comparisons**
  - **the devil is in the details….**

Outlook:

- Preparing a draft of a paper (CPC)

Thank you:

- **ECFA chair Karl Jakobs for the support**
- **WG coordinators for collaboration**