MC tools for Colliders

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On behalf of local computing working group (LCWG)

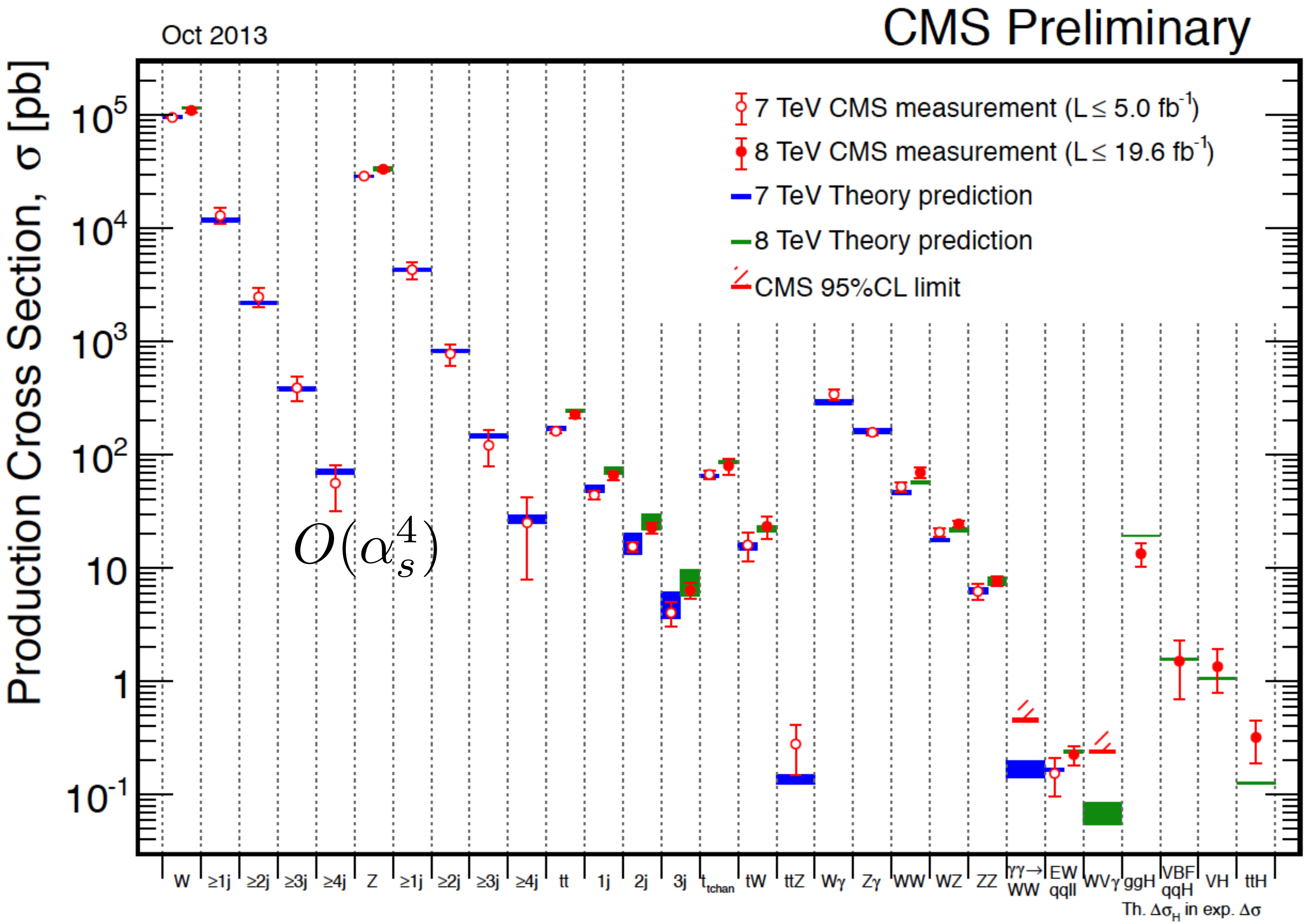
International Workshop for future high energy circular colliders
Beijing, 16-17/Dec. /2013

Outline

- 1. Introduction
- 2. Current MC Tools on the Market
- 3. Local Computing Working Group
- 4. Conclusion

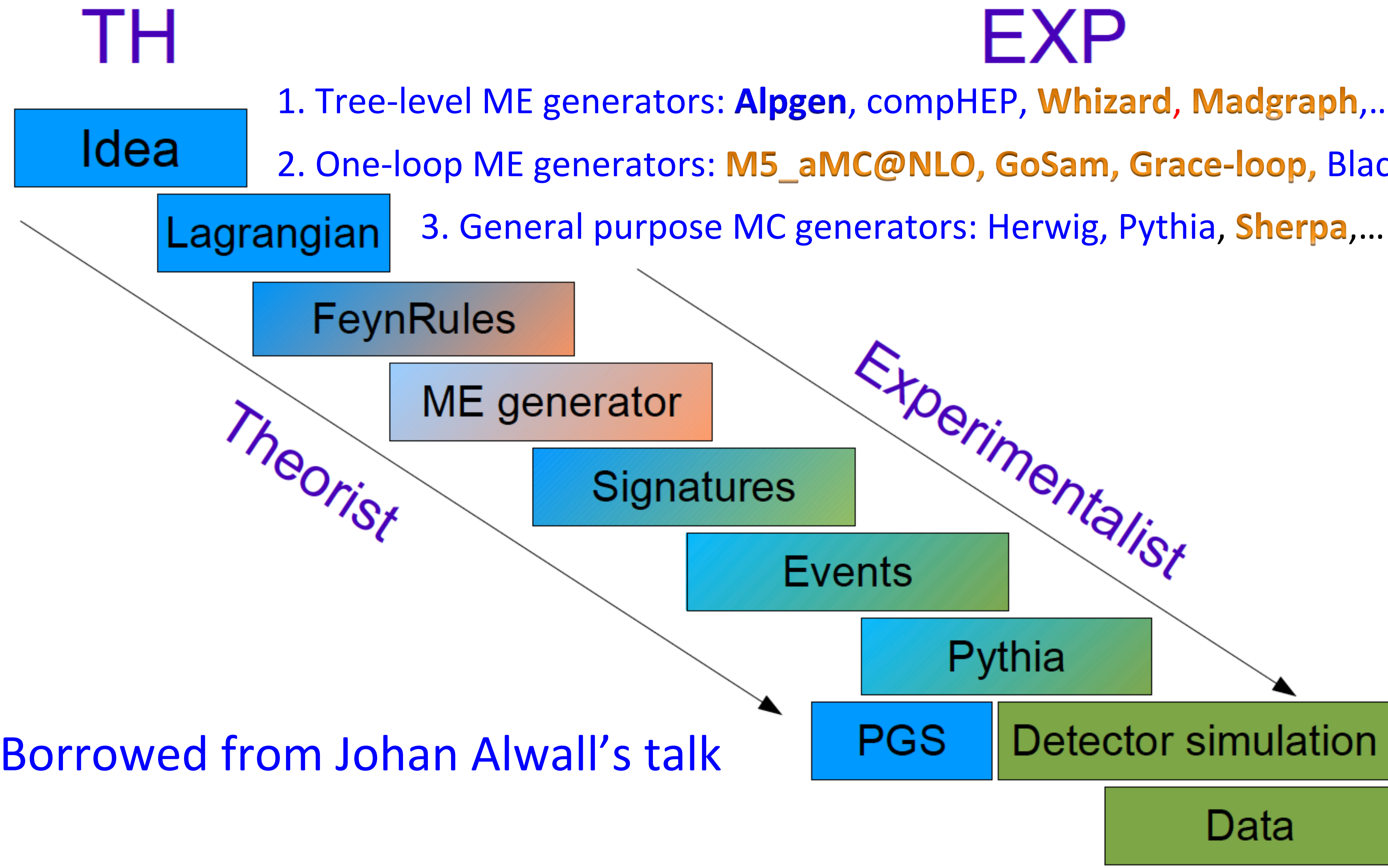
1. Introduction

- The importance of MC tools for high energy physics can never be overestimated.
- MC tools integrate both theoretical and experimental knowledge and provide powerful means to explore new physics.
- Higgs Factories and future CEPC/SPPC are high precision/discovery machines, the task for MC tool development is to incorporate the latest experimental results and to provide compatible theoretical predictions.
- In order to match with LHC experimental needs, the new frontier of MC tools' development to increase theoretical precisions has already emerged.



LHC data and future runs need high precision theoretical predictions (especially QCD processes).

1. Tree-level ME generators: **Alpgen**, compHEP, **Whizard**, **Madgraph**,…
2. One-loop ME generators: **M5_aMC@NLO, GoSam, Grace-loop,** Blackhat,…
3. General purpose MC generators: Herwig, Pythia, **Sherpa**,…



Borrowed from Johan Alwall's talk

MC tools bridge theory and experiment and promote the communication and collaboration.

2. MC on the Market (1)

Some specialized and time-honored MC tools:

- ALPGEN: M.L.M, et.al. hep-ph/0206293 MLM ME-PS matching@LO
  a generator for hard multiparton processes in Hadronic Collisions.
  Powerful to generate tree-level SM background.

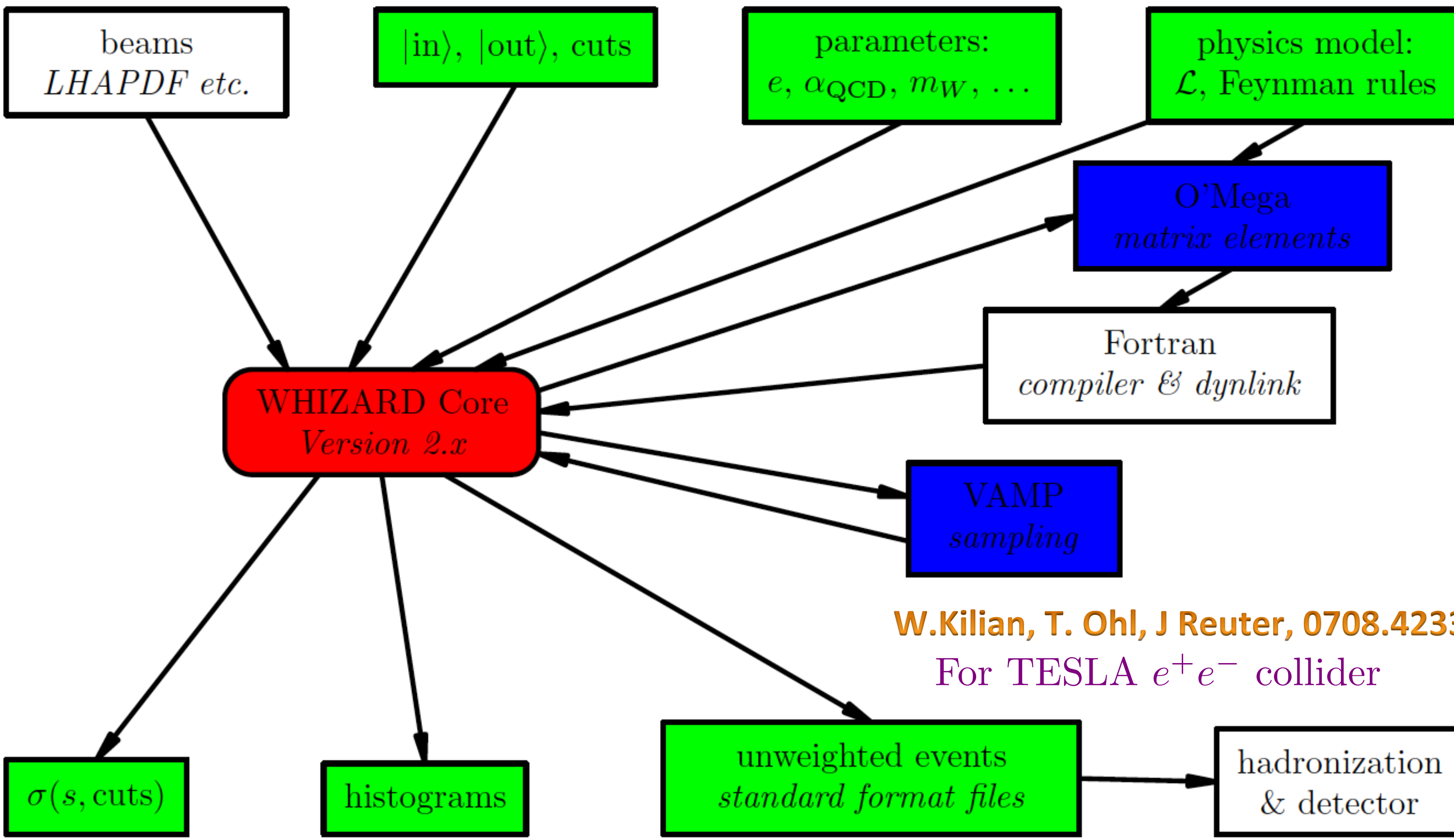
- MCFM: J.Campbell,K.Ellis,C.Williams, hep-ph/9810489
  NLO QCD $2 \to 2$, $2 \to 3$ processes, Some Gluon induced processes included, e.g. $gg \to W^+W^-$
  Parton level only, no showering, not an event generator

- POWHEG: Nason, JHEP0411:040,2004; Hamilton and Nason, JHEP1006(2010)
  NLO PS matching, Competitor of MC@NLO, Exponential of non-singular parts, universal interface to any parton shower
  No negative weight events

These specialized MC tools are useful to explore the physics potentials of future hadron colliders like SPPC.

2. MC on the Market (2)

Whizard:W, Higgs, Z and Respective Decays



W.Kilian, T. Ohl, J Reuter, 0708.4233

For TESLA e^+e^- collider

2. MC on the Market (2)

Whizard:W, Higgs, Z and Respective Decays

Basic facts:

- Helicity amplitudes with complete avoidance of redundancies
- Iterative adaptive multi-channel phase space (viable for $2 \to 10$)
- **Unweighted events** (formats: binary, HEPEVT, ATHENA, LHA, STDHEP)
- Graphical analysis tool

Able to handle multi-particle scattering processes efficiently.

Both longitudinal and transverse polarizations of beam have been realized in the package.

New physics models can be implemented by FeynRules

Whizard 2 is a tree-level ME generator
[sufficient for Detector Design at the early stage of CEPC]

2. MC on the Market (3)

A few cornerstones of Madgraph: From K. Hagiwara

- In 1992, H. Murayama, I. Watanabe, and K. Hagiwara, HELAS
- In 1994, T.Stelzer and W. F. Long, Madgraph was released.
- In 2002, F. Maltoni and Tim Stelzer, MadEvent was released.
- In 2007, J. Alwall, et. al., Madgraph4 was released.
- In 2011, J. Alwall, et.al., Madgraph5 was released.
- Now, the transition to NLO is ongoing

Both Hua-Sheng Shao and Qiang Li have being involved into its development and contributed.

Remarkable features of Madgraph5:
automation and user-friendly, multiparticle processes, speedy, general interface to new physics, precision for jet description (link to pythia provided, MLM ME-PS matching)

2. MC on the Market (3)

Features of Madgraph5[1106.0522]_aMC@NLO:

- UFO (The Universal FeynRules Output) at NLO.
- ALOHA (Automatic Libraries Of Helicity Amplitudes for Feynman diagram computations) at NLO.
- MadGraph 5 framework to generate tree-like structure.
- MadEvent framework to perform phase-space integration and events generation.
- MadLoop 5 framework to calculate virtual (CC+R1+R2+UV) contributions, which uses OPP/CutTools to reduce loop integrals.
- MadFKS 5 framework to calculate real/subtraction contributions and generate hard events and counter-term events.
- MC@NLO to do matching with Parton-Shower programs and finally use Parton-Shower programs to do showering and hadronizing.
- MadSpin to calculate the spin correlations in decays.

Transition to NLO is ongoing. Provided by Hua-Sheng Shao (PKU/CERN)

2. MC on the Market (3)

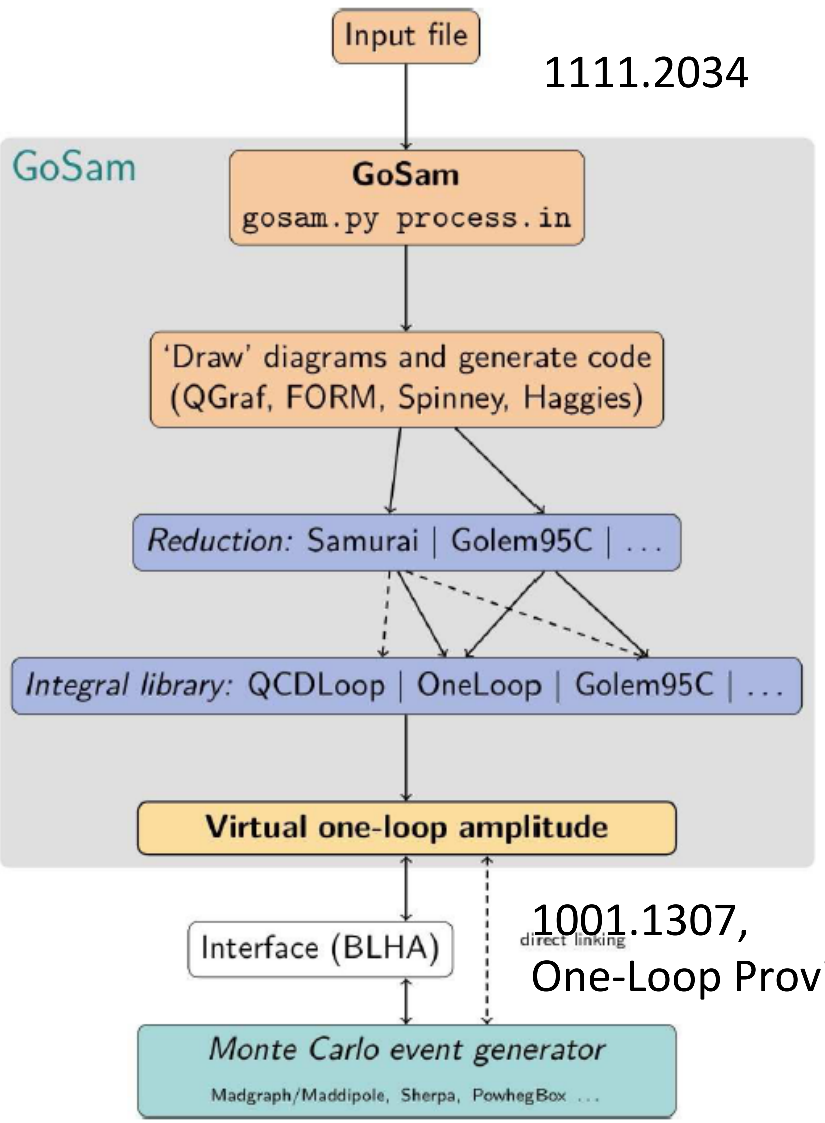
What can Madgraph5_aMC@NLO do?

- In principle, QCD corrections in Standard Model can be done,especially
  - Fixed-ordered LO and NLO corrections.
  - Unweighted events generated by matching with parton shower programs (like HY6,HY++,PY6,PY8 etc) with MC@NLO method.
  - FxFx merging can be applied to resolve the double-counting in multi-jet process.
  - MadSpin can be ultilitied to take account spin correlation in.
- EW virtual corrections (i.e. in MadLoop) in Standard Model was done.
- QCD corrections in SUSY models can be done recently.
- Many interfaces are done or are working on like GoSam, Sherpa, MadGloem.

Provided by Hua-Sheng Shao (PKU/CERN)

2. MC on the Market (3)

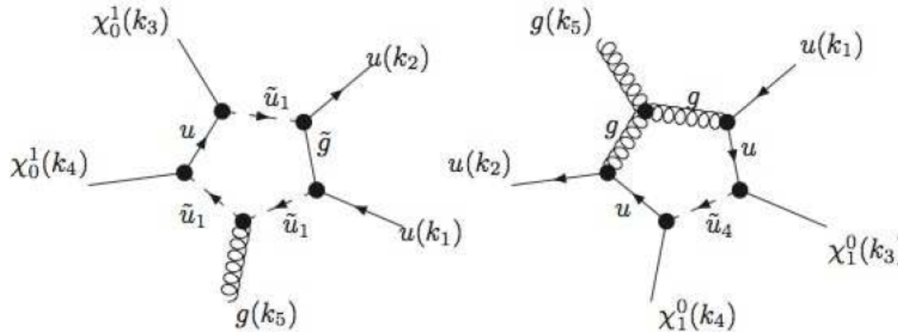
GoSam: a one-loop level VME calculator for NP



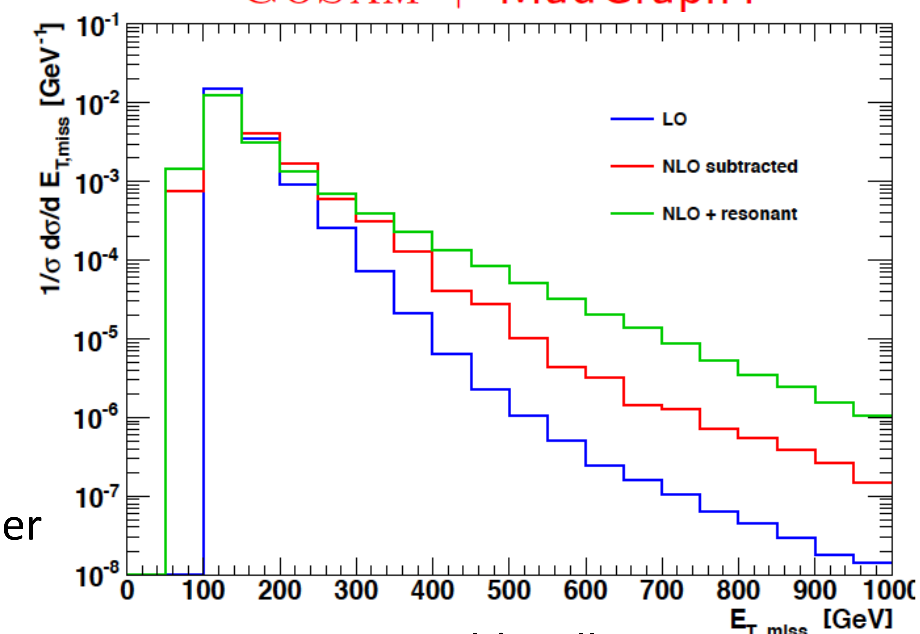
1111.2034

1001.1307,
One-Loop Provider

$\tilde{\chi}_1^0\,\tilde{\chi}_1^0 + \text{jet}$ (p19MSSM)



GoSam + MadGraph4



From G. Heinrich's talk@ACAT2013

2. MC on the Market (4)

GRACE-Loop is a generic automated program for calculating High Energy Physics processes [3].

G. Belanger, F. Boudjema, J. Fujimoto, T.Ishikawa, T. Kaneko, K. Kato, Y. Shimizu

- *All Feynman diagrams for a given process at fixed order of perturbation theory.*
- *A FORM or REDUCE code.*
- *A Fortran code generated for amplitude calculations.*
- *Kinematic library.*
- *The multi-dimensional integration by BASES.*
- *Event generation by SPRING.*

For GRACE system, please visit website:

Grace at tree level was released in 1993. Designed for e^+e^- colliders

http://minami-home.kek.jp/

[3] **Phys. Rept. 430 (2006) 117**

2. MC on the Market (4)

The GRACE-Loop system has also been used to calculate

- $2 \to 3$-body processes such as $e^+e^- \to ZHH$, $e^+e^- \to t\bar{t}H$, $e^+e^- \to \nu\bar{\nu}H$, etc.
- $2 \to 4$-body process as $e^+e^- \to \nu_\mu\bar{\nu}_\mu HH$.

Recently the processes:

- $e^+e^- \to t\bar{t}\gamma$ (Eur. Phys. J. C **73**, 2400 (2013)).
- $e^+e^- \to e^+e^-\gamma$ at ILC in preparation.
- $pp \to W^+W^- + 1$jet at LHC in progress.

More works may be needed to handle massless gauge bosons.

From P.H. Khiem's talk@LCWS13-Tokyo

2. MC on the Market (5)

Herwig (CERN, DESY, Durham, Karlsruhe, Manchester)

- Originated in studies of coherent QCD evolution
- Front-runner in matching of NLO QCD ME and PS
- Original framework for cluster fragmentation

Pythia (CERN, DESY, FNAL, Lund)

- Originated in hadronization studies → Lund string
- Leading in development of models for non-perturbative physics
- Extensive PS development and earliest ME+PS matching

Sherpa (CERN, Dresden, Durham, Göttingen, SLAC)

- Started with matching of LO ME and PS
- First automated framework for NLO calculations
- First automated merging of ME and PS at NLO

0311263,
JHEP02(2009)007

Herwig/Herwig++,Pythia6/Pythia8,ISAJET,Sherpa:
General Purpose MC event generator

From S. Hoeche

2. MC on the Market (5)

Special features of Sherpa

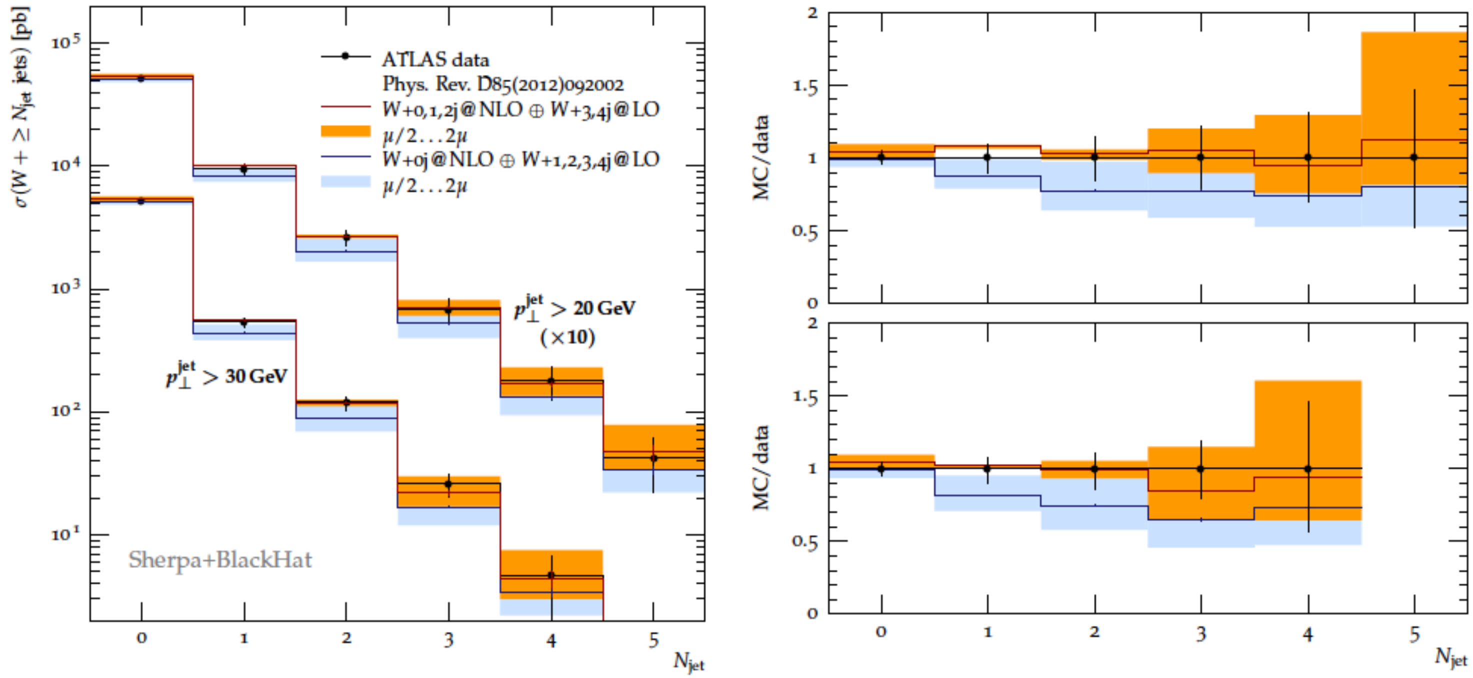
- Two matrix-element generators
  Amegic++ Kuhn,Krauss & Comix Gleisberg,Höche
- Complete framework for NLO calculations Gleisberg,Krauss
- Independent parton shower (no interface to Pythia or Herwig) based on Catani-Seymour dipole subtraction Schumann,Krauss
- Independent implementation of MC@NLO method (S-MC@NLO) based on CS dipole subtraction Höche,Krauss,Schönherr,Siegert
- ME+PS merging at LO & NLO Höche,Krauss,Schönherr,Siegert
- Complete hadron & τ decay package Krauss,Siegert
- Photon emission generator Krauss,Schönherr
- Minimum bias simulation Krauss,Zapp

From S. Hoeche

Interface to NP is provided; CKKW ME-PS matching/merging @NLO is realized.

2. MC on the Market (5)

Höche, Krauss, Schönherr, Siegert



- MEPS@NLO with W+0,1&2 jet at NLO plus W+3&4 jet at LO compared to W+0 jet at NLO plus up to W+4 jets at LO
- Better agreement with experimental data
- Largely reduced scale uncertainty

From S. Hoeche

Merging/Matching@NLO is necessary for the LHC runs and high precision MC event generators are inevitable for SPPC.

3. The LCWG

Affiliations	**Core Members**
CMS, Zhejiang University	Bo Feng
Hangzhou University	Qingjun Xu
He-Bei University	Taifu Feng
Hua-Zhong Normal University	XingQiang Li
IHEP,CAS	J.X. Wang, Bing Gong, Zhao Li
Peking University	Qiang Li, Hua-Sheng Shao
UCAS	Q.S. Yan
USTC	Lei Guo, Renyou Zhang
Shan-Dong University	**Zongguo Si**

3. The LCWG

- Amplitude of Matrix Element

  (B. Feng/J.X. Wang/B. Gong)

- General MC generators [**FDC@LOOP,aMC,Sophie…**]

  (J.X. Wang/B. Gong/H.S. Shao/Z.Li)

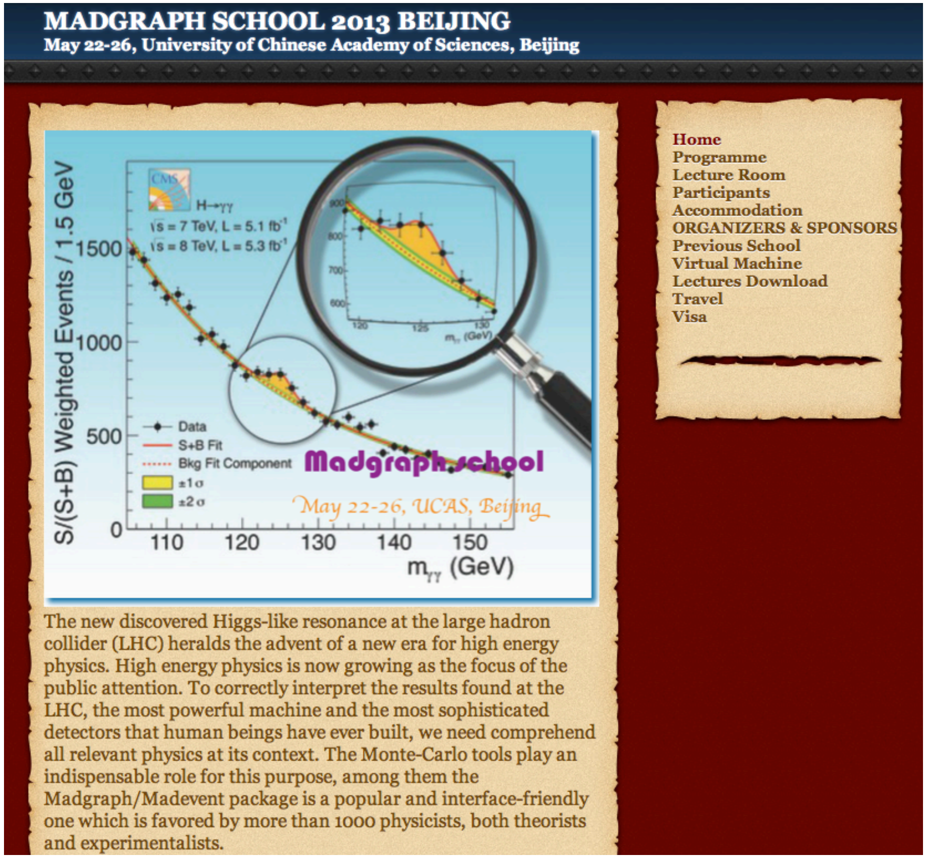
- Application, toolkit development and feasibility study:

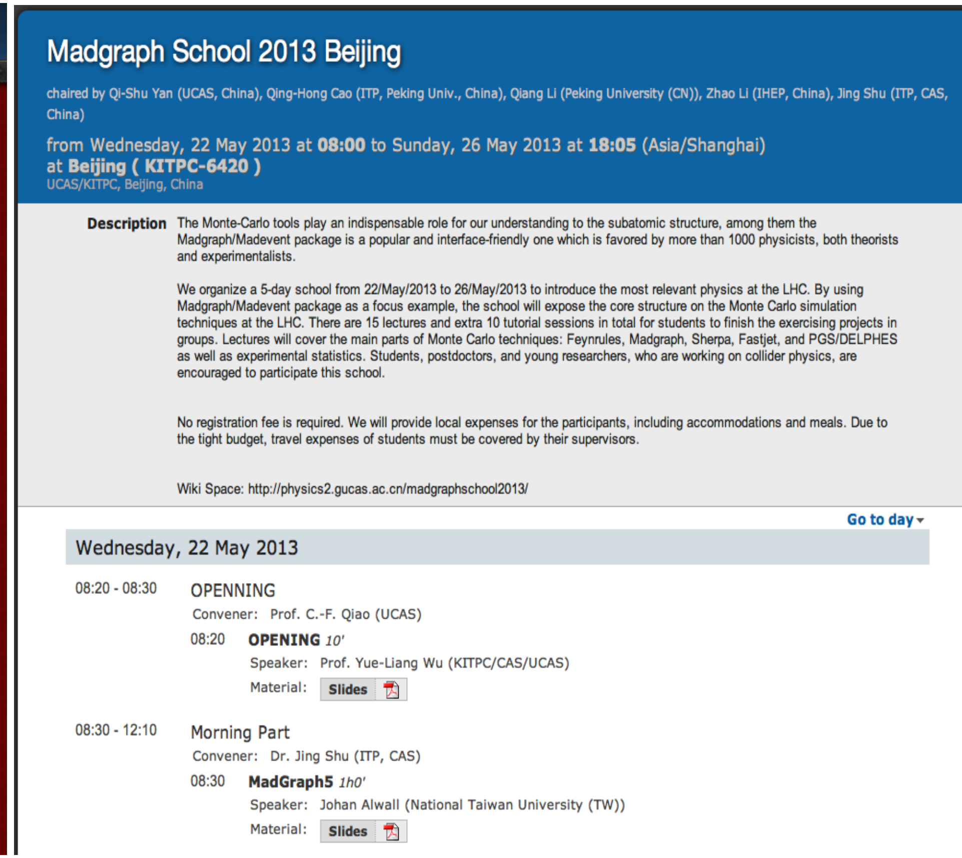
  (Q. Li/Q.S. Yan/H.S. Shao/L. Guo/R.Y.Zhang/Q.J. Xu)

- W/Z/Higgs/top decay up to high loop

  (X.Q. Li/Z.G. Si/T.F. Feng)

Activity of Local computing working group
International conference ACAT2013
Beijing, May16-21, 2013





Activity of Local computing working group

International School: Madgraphschool 2013

Beijing, May22-25, 2013

Activity of Local computing working group
Domestic computing mini-Workshop
Beijing, Nov. 27-30, 2013

4.1 Matrix Element Computation

Tree-level Amplitudes:

- Feynman Diagram approach + squared Matrix (**CompHEP**)
- Feynman Diagram + Helicity Amplitude approach (**Madgraph,** …)
- No Feynman Diagram Amplitude approach (**Alpgen, Whizard,** …)

One Loop Amplitudes:

- A well used method is the reduction to master integral

  Passarino, Veltman, 1979; **Grace-Loop/Gosam**

- OPP method

  Ossola, Papadopoulos, Pittau, 2006; **GoSam/aMC@NLO**

From Bo Feng(CMS, ZJU)

4.1 Matrix Element Computation

Higher (2) Loop Amplitude Frontier:

- The reduction at the integrand level has been understood using computational algebraic geometry@2 loop

  Mastroliia, Ossola, 2011; Mastroila, Mirabella, Peraro, 2012; Mastrolia, Mirabella, Ossola, Peraro, 2012
  Zhang, 2012; Badger, Frellesvig, Zhang, 2012

- The master integral is classified by denominator (topology) and numerator (algebraic geometry)@2-loop

  Feng, Huang, 2012

New opportunity for high precision MC generator development

From Bo Feng(CMS, ZJU)

4.1 Other exciting progresses

- Wilson loop method

  Alday, Maldacena; Drummond, Henn, Korchemsky, Sokatchev; etc

- Loop-level recursion relation

  Bern, Dixon, Kosower, etc; Arkani-Hamed, Cachazo, Caron-Huot etc; Boels; etc

- Symbol Goncharov, Spradlin, Vergu, Volovich; etc
- Grassmanian and Twistor

  Witten; Arkani-Hamed, Cachazo etc; Mason, Skinner; more

Breakthrough in these methods will lead to a new revolution for industry of MC generator development

From Bo Feng(CMS, ZJU)

4.2 A general purpose generator: FDC

FDC@Loop started its one-loop upgrade in 2002 and commenced work from 2007. **FDC1.0 was released in 1993**

- The amplitude can be obtained analytically.
- The one-loop results has been demonstrated to work for low energy physics processes (quarkonium production at HC)
- In principle, there is no difficulty to apply FDC@Loop for high energy processes, *though the matching/merging at NLO need to be complished.*

for CEPC

for SPPC

From J.X. Wang & B.Gong (IHEP,CAS)

4.3. An Automation@NNLO tool: Sophie

Sophie: A ME Generator Created By Zhao Li (IHEP,CAS)

Ambitions:

Under development

- High precision: Fixed order calculation
  for LO, NLO, NNLO, etc.

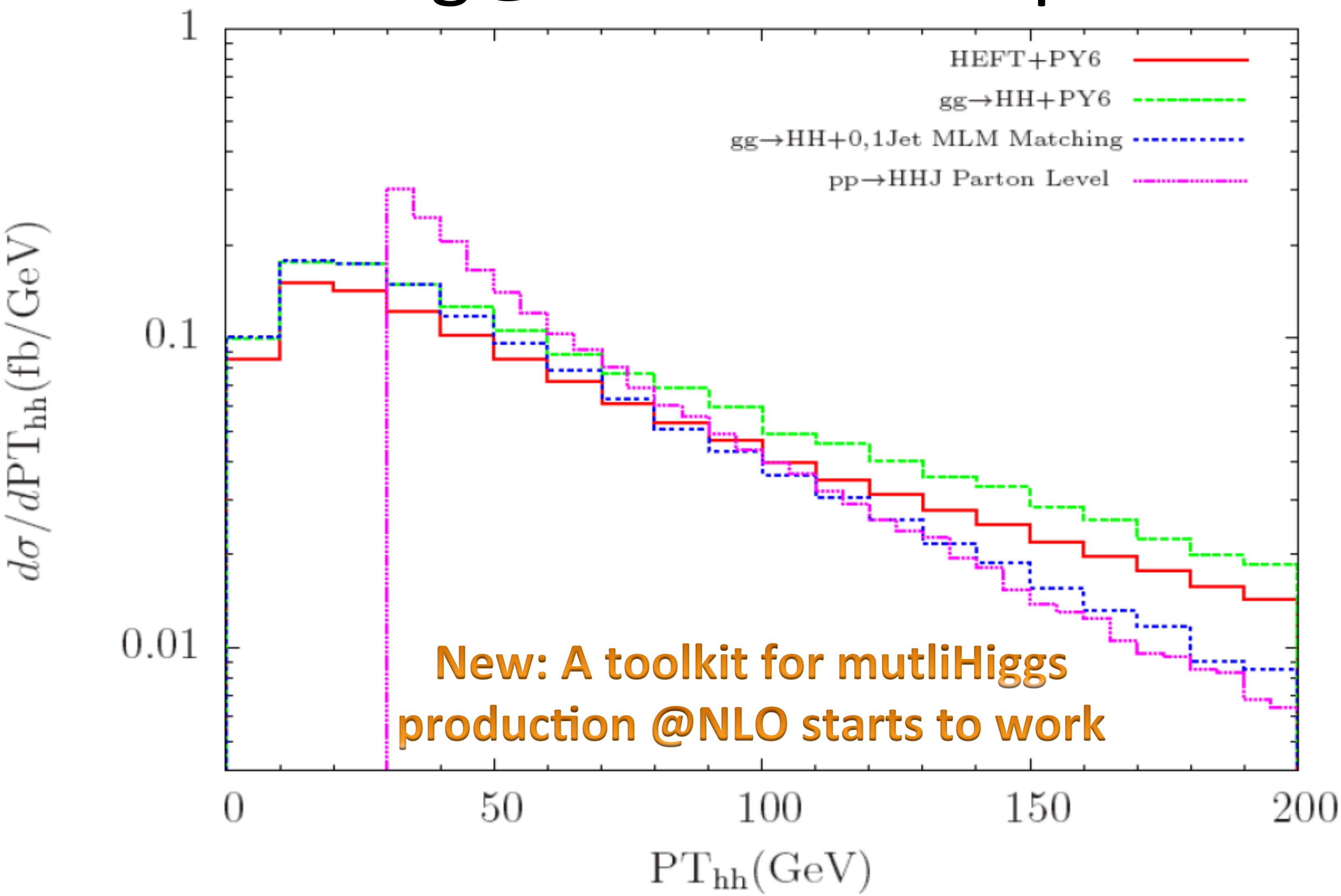
- Fast: LO (seconds), NLO (minutes), NNLO (hours),...
  Fully utilizing the computing potential of GPU
  to handle loop integrals

- Efficient:
  Fully utilizing the analytic method for
  helicity amplitudes of spinors

- Flexible for New Physics:
  Using the UFO model files

From Z. Li (IHEP,CAS)

4.4 Matching@LO at one-loop



Matched predictions for Higgs pair production (LHC 14TeV) @LO

Qiang Li(PKU), Qi-Shu Yan(UCAS), Xiao-Ran Zhao(UCAS), 1312.3830

4.4 Feasibility @ HC

signal: $pp \to hh \to \mathrm{w\ w\ w^*\ w^*} \to 2j3l + MET$

	Before	Cut 1	Cut 2	Cut 3	Cut 4
signal	71.3634	9.22015	6.59398	4.78135	3.24831
ttw	12771.3	759.15	427.045	89.3584	23.8853
zw	867414	114.272	59.6232	13.4169	3.98163
www	3634.44	148.685	90.5845	13.1526	2.73745
hw	2956.61	99.7478	55.1647	19.1807	6.51472
$\frac{S}{\sqrt{B}}$	0.07578	0.27527	0.26220	0.411347	0.53316

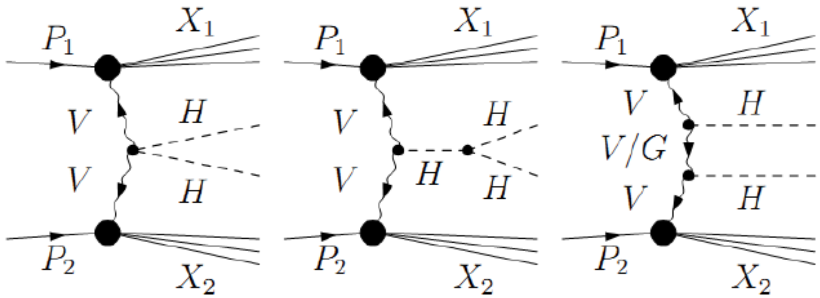
>5.0 for 100 TeV

- Cut 1:enlarge Z reconstruct cut: m(e^+, e^-) and m(μ^+, μ^-) are not in [50,120]
- Cut 2:New W reconstruct method: iterate all jets, to find two jets that make mass(h1)+mass(h2) smallest.
- Cut 3:h1 and h2 mass cut
- Cut 4:TMVA

Higgs pair signal search @LHC 14TeV Ongoing works:

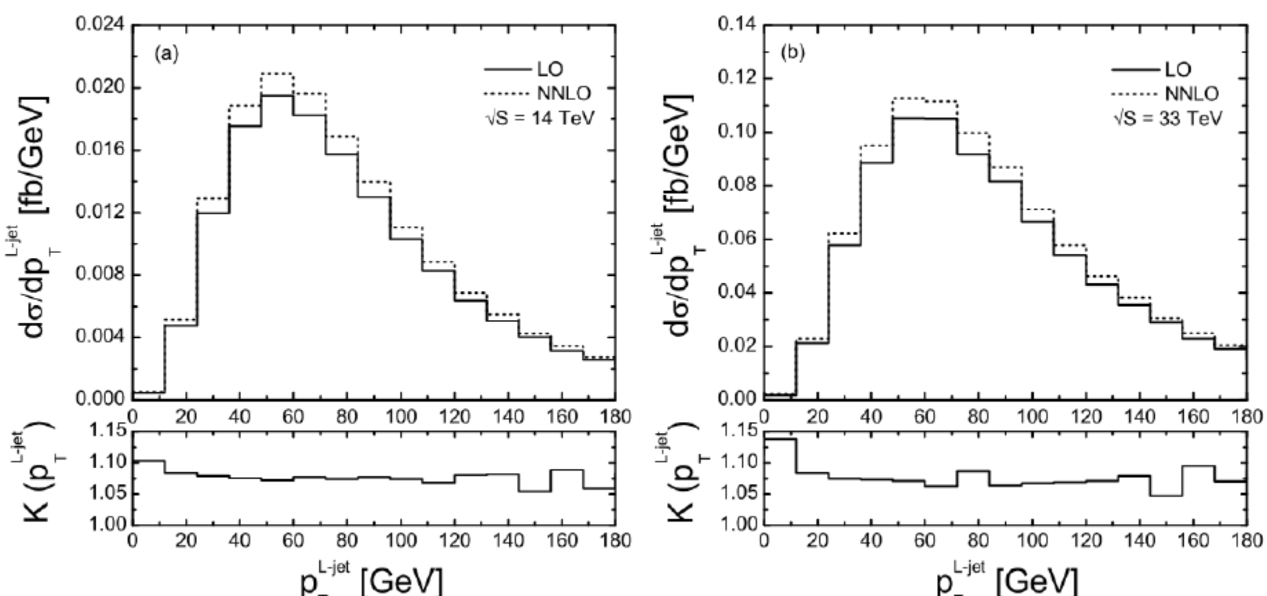
Qiang Li(PKU), Qi-Shu Yan(UCAS), Xiao-Ran Zhao(UCAS)

4.5 Infrared subtractions



VBF@NNLO

$\sqrt{S}$	LO [fb]	NLO [fb]	NNLO [fb]
$14\ TeV$	$1.858^{+0.378}_{-0.270}$	$1.975^{+0}_{-0.077}$	$1.987^{+0.044}_{-0}$
$26\ TeV$	$7.063^{+0.779}_{-0.663}$	$7.538^{+0.067}_{-0.330}$	$7.570^{+0.192}_{-0}$
$33\ TeV$	$11.235^{+0.878}_{-0.831}$	$11.995^{+0.198}_{-0.554}$	$12.040^{+0.361}_{-0.059}$



Physics study, provided by Lei Guo(USTC Group)

5. Conclusion

- The high precision MC generators (both ME generators [Grace@loop/aMC@NLO] and general purpose event generators [Sherpa +GoSam]) are growing into their maturity.
- The demand for high precision MC generators will be strong for the future colliders.
- New theoretical breakthrough for amplitude computation can greatly benefit MC generator development.

High precision general purpose event generators for LHC future runs and future colliders CEPC/SPPC are necessary.

5. Conclusion

- Future collider projects will offer opportunities for our high energy community and our next generations and the LCWG can contribute.
- The LCWG is necessary and urgent in order to build a strong local HEP community.
- The LCWG faces the challenge but the morale is high.
- The mission for high precision MC generators can be accomplished and **the LCWG should involve**.

Backup

B. Connection to theories

1. Precision measurements: SM is the main background for discovery and should be understood with top priority.
2. Discovery: Evidences of new physics might be found via loop processes for LHC/CEPC/SPPC.
3. For high precision MC event generator development, we need a convenient interface with BSM @high order (UFO might be an option, similar to aMC@NLO)

An accurate MC Event generator for Linear Collider

for Both SM and NP

1. e+e− → Z (→ l+l−) NLO EWK + QED Shower
2. e+e− → ZA, ZZ, ZH, NLO EWK + QED Shower
3. e+e− → bbar, ttbar NLO EWK + QED Shower
   e+e− → bbar, ttbar NLO QCD + QCD Shower
4. e+e− → Z, ZA, ZAA matching, comparing with 1,2
   urgently needed for $ZH \to ZAA$
5. e+e− → Z NNLO EWK, Z→ l+l− NNLO EWK
6. e+e− → Z → f+f− NNLO QCD
7. AA → HH, ZZ NLO (2 loop)

Whizard, Grace@Loop, FDC@Loop, Sophie are at our disposals.

8. New physics: e.g. effective anomalous operators
9. $e^+e^- \to VVV(W^+W^-Z/\gamma, ZZ\gamma, \cdots)$

A more pragmatic wishlist provided by Qiang Li (PKU)

High Precision MC tools for SPPC

- High precision PDF
- High precision event generators [high loop and multiparticle processes, high order matching, …]
- **M5_aMC@NLO, Sherpa, Sophie could be our options …**

B. Connection to Experiments

A tentative experiment wishlist for CEPC/SPPC:

1) To understand the theoretical error bars in Higgs branching ratio @CEPC.

2) To understand the predictions of SM beyond tree/1-loop level @CEPC.

3) To what extent we can rule out/discover new physics @CEPC.

4) Using LHC/CEPC and other experimental data, to form a no-lose search for new physics @SPPC.

High precision MC tools are needed for physics analysis of CEPC/SPPC.

Provided by Manqi Ruan(IHEP,CAS)