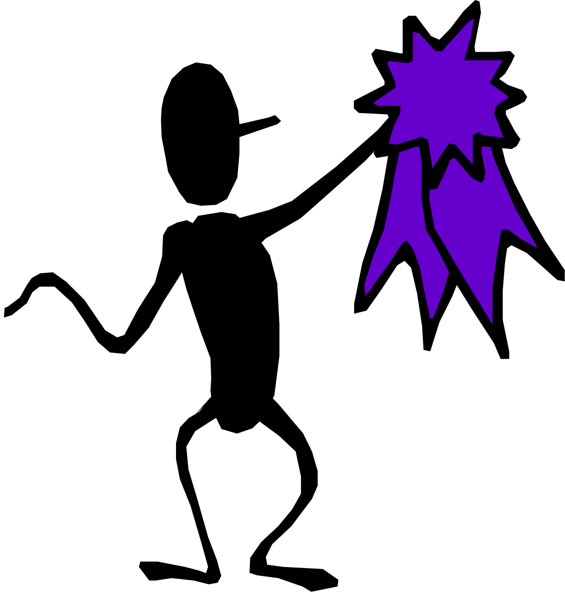
MadGraph5_aMC@NLO

Automated Tree-Level and one loop Feynman Diagram and Event Generation at LO and NLO

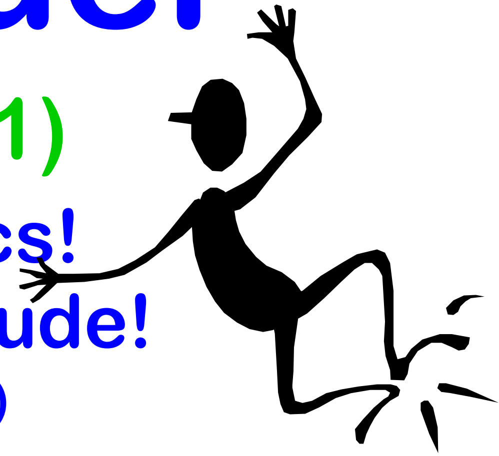
Olivier Mattelaer and Valentin Hirschi

Plan

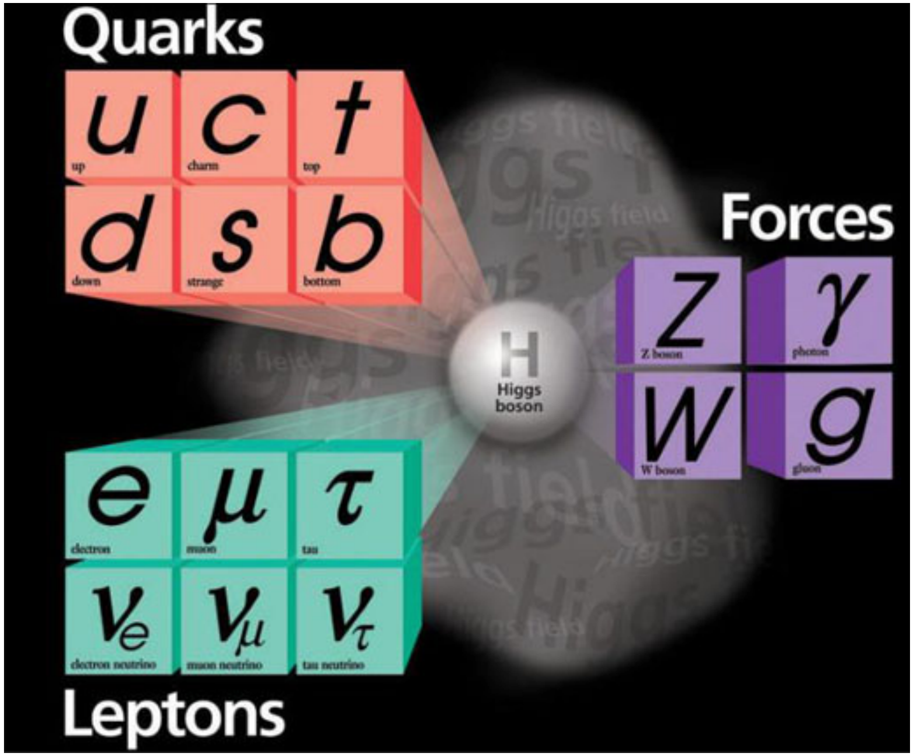


- Overview of Standard Model
  - Introduction to Particle Physics
  - The Standard Model
- Parton level calculations
- Full Event Simulations
- Identify 3 Newly Discovered Particles

Standard Model



- Good News! $SU(3)xSU_L(2)xU(1)$
  - Most successful theory in physics!
  - Tested over 30 orders of magnitude!
    - (photon mass < 10^{-18} eV , LHC > 10^{12} eV)



- All particles observed
  - Higgs (2012)
  - Top (1995)
- Gravity ?
  - GW (2015)

Standard Model

- **Bad News!**
  - We can't solve it!

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{2}\mathrm{Tr}\left(\mathbf{G}^{\mu\nu}\mathbf{G}_{\mu\nu}\right) + \bar{\mathbf{q}}\,[i\gamma^{\mu}\mathbf{D}_{\mu} - m_q]\,\mathbf{q}$$

$$= -\frac{1}{4}\left(\partial^{\mu}G_a^{\nu} - \partial^{\nu}G_a^{\mu}\right)\left(\partial_{\mu}G_{\nu}^{a} - \partial_{\nu}G_{\mu}^{a}\right) + \sum_q \bar{q}_{\alpha}\,[i\gamma^{\mu}\partial_{\mu} - m_q]\,q_{\alpha}$$

$$+ \frac{1}{2}\sum_q g_s\,[\bar{q}_{\alpha}\,(\lambda^a)_{\alpha\beta}\,\gamma^{\mu}q_{\beta}]\,G_{\mu}^{a}$$

$$- \frac{1}{2}g_s\,f_{abc}\,(\partial_{\mu}G_{\nu}^{a} - \partial_{\nu}G_{\mu}^{a})\,G_b^{\mu}G_c^{\nu} - \frac{1}{4}g_s^2\,f_{abc}\,f_{ade}\,G_b^{\mu}G_c^{\nu}G_{\mu}^{d}\,G$$

Predictions from SM

- **Cross Section:** $$\sigma = \frac{1}{2s}\int |M|^2 \, d\Phi$$

$$M = \left\langle \mu^+\mu^- \,|\, T\left(e^{-i\int H_I dt}\right) e^+e^- \right\rangle$$

  - Can't solve exactly because interactions change wave functions!

- **Perturbation Theory**
  - Start w/ Free Particle wave function
  - Assume interactions are small perturbation

$$M \approx \left\langle \mu^+\mu^- \,|\, H_{\text{int}} \,|\, e^+e^- \right\rangle + \frac{1}{2}\left\langle \mu^+\mu^- \,|\, H_{\text{int}}^2 \,|\, e^+e^- \right\rangle + \ldots$$

Example: $e^+e^- \rightarrow \mu^+\mu^-$

- **Scattering cross section**

$$\sigma = \frac{1}{2s}\int |M|^2 \; d\ldots$$

$$M \approx \langle \mu^+\mu^- \,|\, H_{in}\ldots$$

$$W_{\mu\nu} \equiv \frac{i}{g}\left[D_\mu , D_\nu\right] \equiv \frac{\vec{\sigma}}{2}\cdot\vec{W}_{\mu\nu} \;\rightarrow\; U_L\, W_{\mu\nu}\, U_L^\dagger \quad ; \quad B_{\mu\nu} \equiv \partial_\mu B_\nu - \partial_\nu B_\mu \;\rightarrow\; B_{\mu\nu}$$

$$W^i_{\mu\nu} = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu + g\,\varepsilon^{ijk}\, W^j_\mu W^k_\nu$$

$$\mathcal{L}_K = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{2}\mathrm{Tr}\left(W_{\mu\nu}W^{\mu\nu}\right) = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}\vec{W}_{\mu\nu}\vec{W}^{\mu\nu} = \mathcal{L}_{\text{kin}} + \mathcal{L}_3 + \mathcal{L}_4$$

$$\mathcal{L}_3 = -ie\cot\theta_W \left\{(\partial^\mu W^\nu - \partial^\nu W^\mu)W^\dagger_\mu Z_\nu - (\partial^\mu W^{\nu\dagger} - \partial^\nu W^{\mu\dagger})W_\mu Z_\nu + W_\mu W^\dagger_\nu(\partial^\mu Z^\nu - \partial^\nu Z^\mu)\right\}$$
$$-ie\left\{\left(\partial^\mu W^\nu - \partial^\nu W^\mu\right)W^\dagger_\mu A_\nu - \left(\partial^\mu W^{\nu\dagger} - \partial^\nu W^{\mu\dagger}\right)W_\mu A_\nu + W_\mu W^\dagger_\nu\left(\partial^\mu A^\nu - \partial^\nu A^\mu\right)\right\}$$

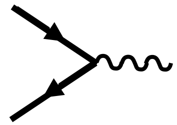
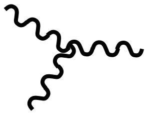
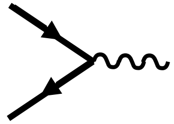
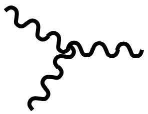
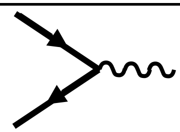
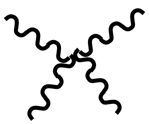
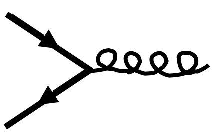
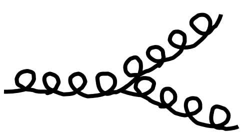
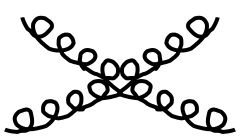
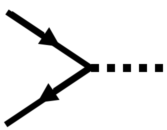
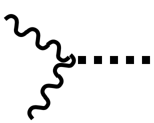
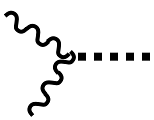
$$\mathcal{L}_4 = -\frac{e^2}{2\sin^2\theta_W}\left\{\left(W^\dagger_\mu W^\mu\right)^2 - W^\dagger_\mu W^{\mu\dagger}W_\nu W^\nu\right\} - e^2\cot^2\theta_W\left\{W^\dagger_\mu W^\mu Z_\nu Z^\nu - W^\dagger_\mu Z^\mu W_\nu Z^\nu\right\}$$
$$-e^2\cot\theta_W\left\{2W^\dagger_\mu W^\mu Z_\nu A^\nu - W^\dagger_\mu Z^\mu W_\nu A^\nu - W^\dagger_\mu A^\mu W_\nu Z^\nu\right\} - e^2\left\{W^\dagger_\mu W^\mu A_\nu A^\nu - W^\dagger_\mu A^\mu W_\nu A^\nu\right\}$$

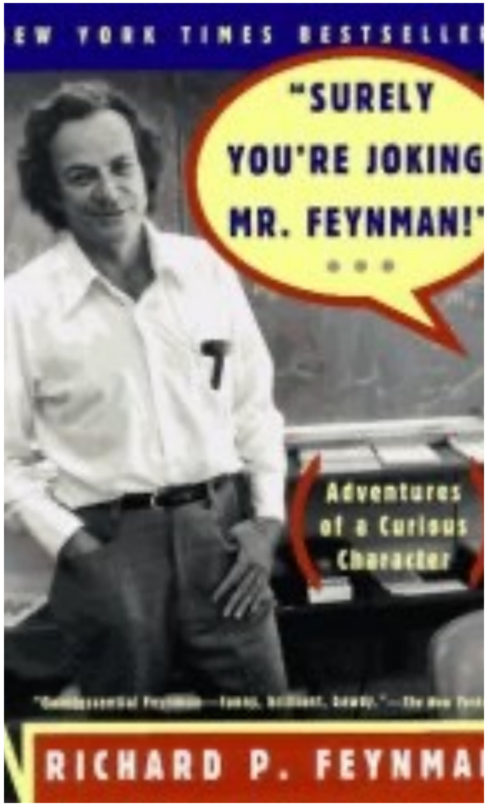
The Standard Model   A. Pich - CERN Summer Lectures 2005

- **Feynman Diagr**…

$$M \approx \overline{v}(e^+)\;(-iq\gamma^\mu)\;v(e^-)\;\frac{g_{\mu\nu}}{p^2}\;\overline{u}(\mu^+)(-iq\gamma^\nu)u(\mu^-)$$

Feynman Rules!

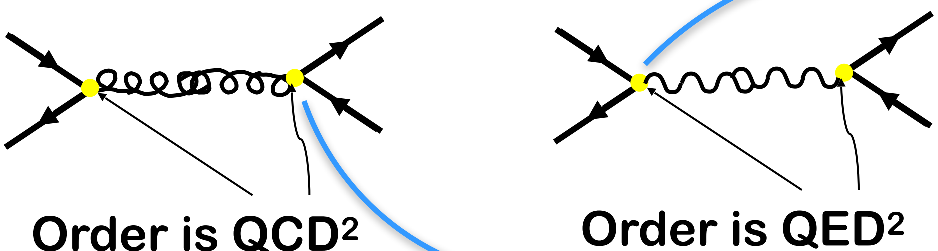
γ	QED	 $q\bar{q}\gamma$ $l^-l^+\gamma$	 $W^+W^-\gamma$	
Z	QED	 $q\bar{q}Z$ $l\bar{l}Z$	 W^+W^-Z	
W^{+-}	QED	 $q\bar{q}'W$ $l\nu W$		 $WWWW$
g	QCD	 $q\bar{q}g$	 ggg	 $gggg$
h	QED (m)	 $q\bar{q}h$ $l\bar{l}h$	 W^+W^-h	 ZZh

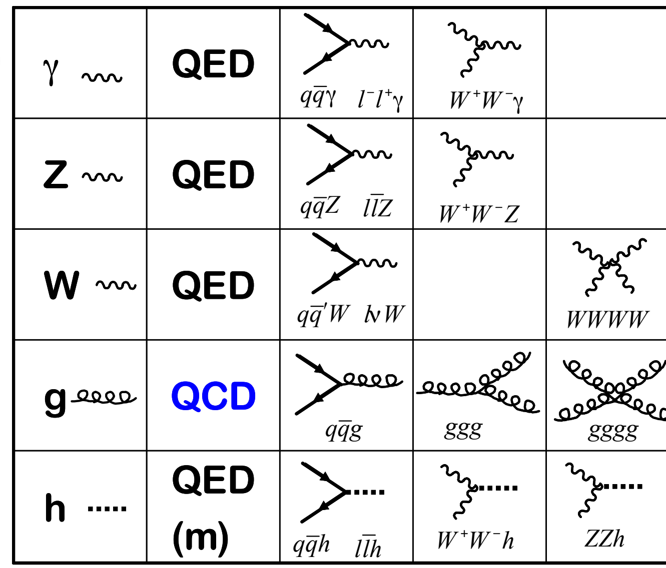


Partial list from SM

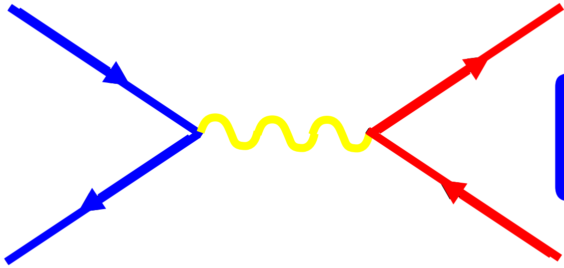
Feynman Rules!

- These are basic building blocks, combine to form "allowed" diagrams
  - e.g. u u~ -> t t~

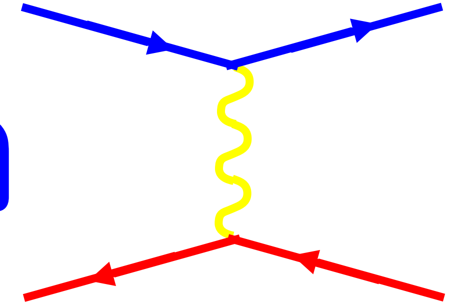




- Draw Feynman diagrams:
  - gg -> tt~
  - gg -> tt~h
  - gg -> h h
  - dd~ -> uu~Z
- Determine "order" for each diagram



MadGraph

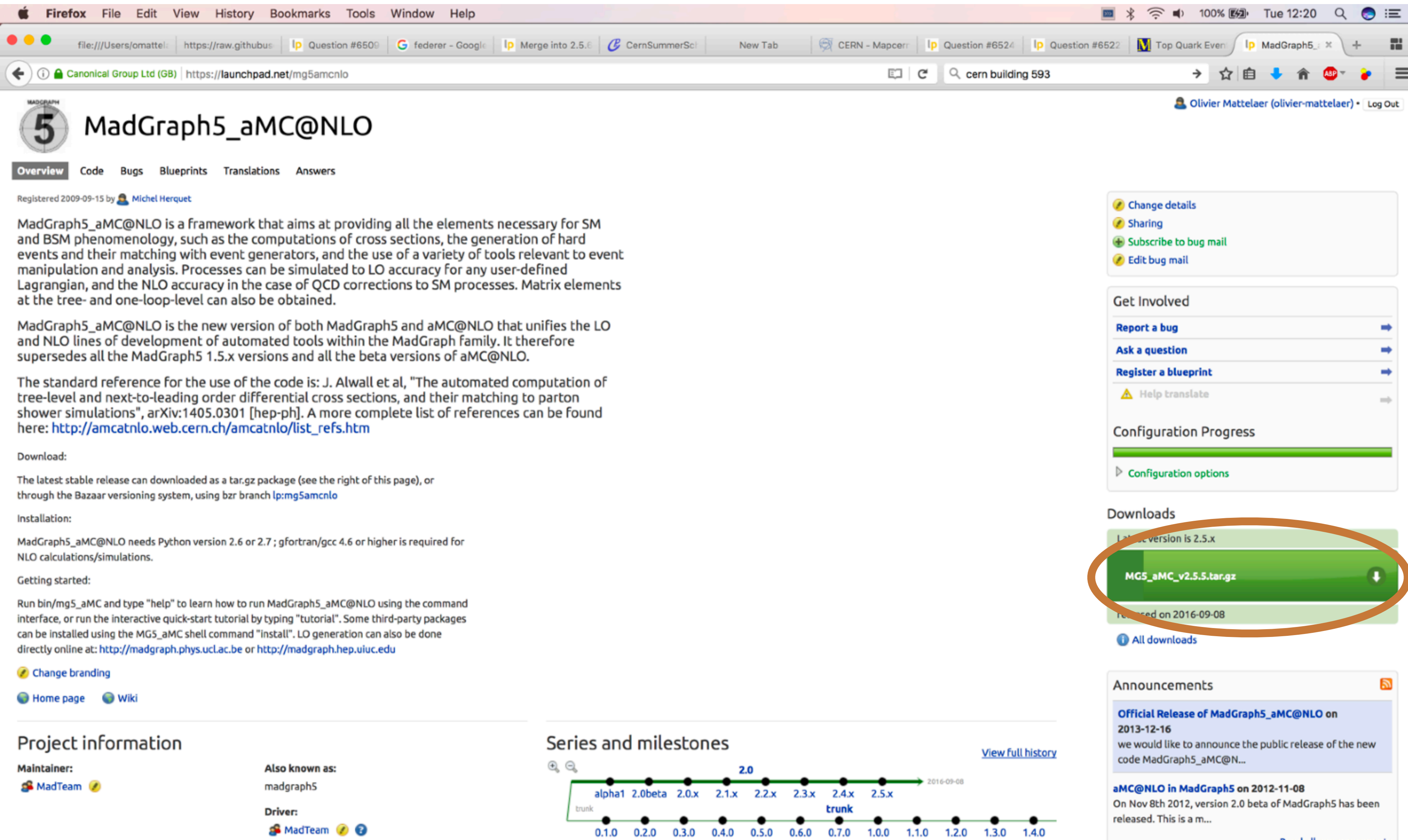


- User Requests:
  - g g > t t~ h QCD<=4
- MadGraph Returns
  - Feynman diagrams
  - Self-Contained Fort

```
 SUBROUTINE SMATRIX(P1,ANS)
C
C Generated by MadGraph II Version 3.83. Updated 06/13/05
C RETURNS AMPLITUDE SQUARED SUMMED/AVG OVER COLORS
C AND HELICITIES
C FOR THE POINT IN PHASE SPACE P(0:3,NEXTERNAL)
C
C FOR PROCESS : g g -> t t~ b b~
C
C Crossing   1 is g g -> t t~ b b~
      IMPLICIT NONE
C
C CONSTANTS
C
      Include "genps.inc"
      INTEGER             NCOMB,     NCROSS
      PARAMETER (          NCOMB=  64, NCROSS=  1)
      INTEGER    THEL
      PARAMETER (THEL=NCOMB*NCROSS)
C
C ARGUMENTS
C
      REAL*8 P1(0:3,NEXTERNAL),ANS(NCROSS)
C
```

install it on your laptop

https://launchpad.net/mg5amcnlo



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cern building 593

Olivier Mattelaer (olivier-mattelaer) • Log Out

MadGraph5_aMC@NLO

Overview Code Bugs Blueprints Translations Answers

Registered 2009-09-15 by Michel Herquet

MadGraph5_aMC@NLO is a framework that aims at providing all the elements necessary for SM and BSM phenomenology, such as the computations of cross sections, the generation of hard events and their matching with event generators, and the use of a variety of tools relevant to event manipulation and analysis. Processes can be simulated to LO accuracy for any user-defined Lagrangian, and the NLO accuracy in the case of QCD corrections to SM processes. Matrix elements at the tree- and one-loop-level can also be obtained.

MadGraph5_aMC@NLO is the new version of both MadGraph5 and aMC@NLO that unifies the LO and NLO lines of development of automated tools within the MadGraph family. It therefore supersedes all the MadGraph5 1.5.x versions and all the beta versions of aMC@NLO.

The standard reference for the use of the code is: J. Alwall et al, "The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations", arXiv:1405.0301 [hep-ph]. A more complete list of references can be found here: http://amcatnlo.web.cern.ch/amcatnlo/list_refs.htm

Download:

The latest stable release can downloaded as a tar.gz package (see the right of this page), or through the Bazaar versioning system, using bzr branch lp:mg5amcnlo

Installation:

MadGraph5_aMC@NLO needs Python version 2.6 or 2.7 ; gfortran/gcc 4.6 or higher is required for NLO calculations/simulations.

Getting started:

Run bin/mg5_aMC and type "help" to learn how to run MadGraph5_aMC@NLO using the command interface, or run the interactive quick-start tutorial by typing "tutorial". Some third-party packages can be installed using the MG5_aMC shell command "install". LO generation can also be done directly online at: http://madgraph.phys.ucl.ac.be or http://madgraph.hep.uiuc.edu

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Home page Wiki

Project information

Maintainer: MadTeam

Also known as: madgraph5

Driver: MadTeam

Series and milestones

View full history

2.0

alpha1 2.0beta 2.0.x 2.1.x 2.2.x 2.3.x 2.4.x 2.5.x

trunk

0.1.0 0.2.0 0.3.0 0.4.0 0.5.0 0.6.0 0.7.0 1.0.0 1.1.0 1.2.0 1.3.0 1.4.0

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Configuration options

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Latest version is 2.5.x

MG5_aMC_v2.5.5.tar.gz

released on 2016-09-08

All downloads

Announcements

Official Release of MadGraph5_aMC@NLO on 2013-12-16
we would like to announce the public release of the new code MadGraph5_aMC@N...

aMC@NLO in MadGraph5 on 2012-11-08
On Nov 8th 2012, version 2.0 beta of MadGraph5 has been released. This is a m...

./bin/mg5_aMC

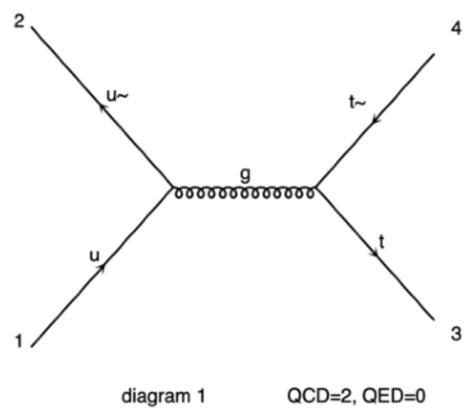
```
[version2]$ ./bin/mg5_aMC
Running MG5 in debug mode
('WARNING: loading of madgraph too slow!!!', 0.8461449146270752)
************************************************************
*                                                          *
*                     W E L C O M E  to                    *
*              M A D G R A P H 5 _ a M C @ N L O           *
*                                                          *
*                                                          *
*                 *                       *                *
*                   *        * *        *                  *
*                     * * * * 5 * * * *                    *
*                   *        * *        *                  *
*                 *                       *                *
*                                                          *
*         VERSION 2.9.10                2022-05-06         *
*         BZR version2                         304         *
*                                                          *
*    The MadGraph5_aMC@NLO Development Team - Find us at   *
*    https://server06.fynu.ucl.ac.be/projects/madgraph     *
*                            and                           *
*            http://amcatnlo.web.cern.ch/amcatnlo/         *
*                                                          *
*               Type 'help' for in-line help.              *
*           Type 'tutorial' to learn how MG5 works         *
*    Type 'tutorial aMCatNLO' to learn how aMC@NLO works   *
*    Type 'tutorial MadLoop' to learn how MadLoop works    *
```

Check on your laptop

Then type
generate u u~ > t t~

```
MG5_aMC>generate u u~ > t t~
INFO: Checking for minimal orders which gives processes.
INFO: Please specify coupling orders to bypass this step.
INFO: Trying coupling order WEIGHTED<=2: WEIGTHED IS QCD+2*QED
INFO: Trying process: u u~ > t t~ WEIGHTED<=2 @1
INFO: Process has 1 diagrams
1 processes with 1 diagrams generated in 0.004 s
Total: 1 processes with 1 diagrams
MG5_aMC>
```

Then type
display diagrams



Ex 1: Draw all the Feynman Diagrams:

g g > t t~ : **3** diagrams QCD=2

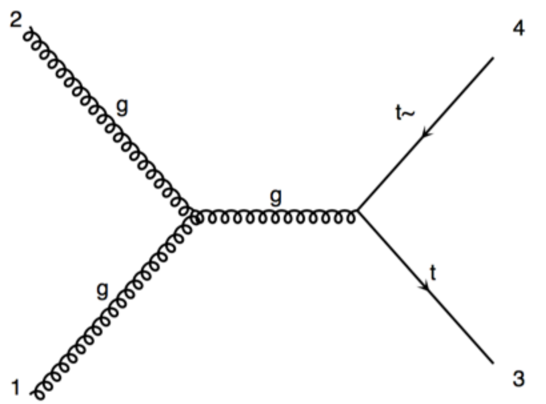


diagram 1 QCD=2, QED=0

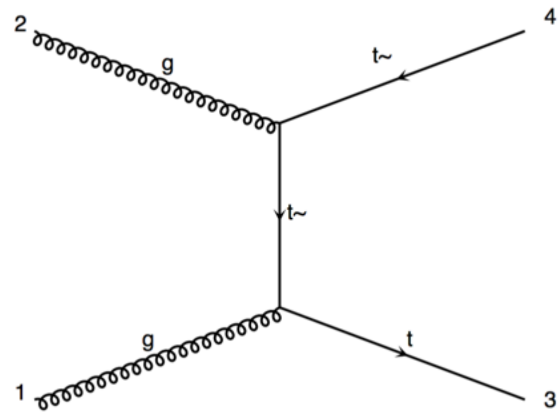


diagram 2 QCD=2, QED=0

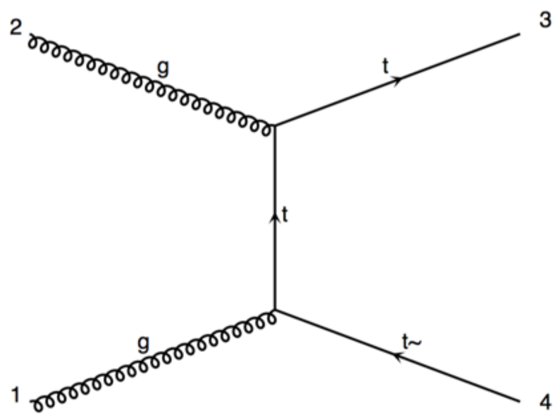


diagram 3 QCD=2, QED=0

Ex 1: Draw all the Feynman Diagrams:

g g > t t~ h: **8** diagrams QCD=2, QED=1

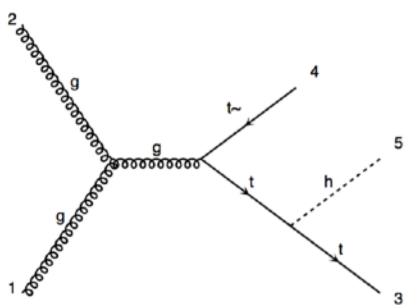


diagram 1 QCD=2, QED=1

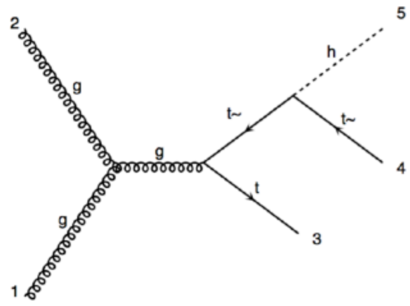


diagram 2 QCD=2, QED=1

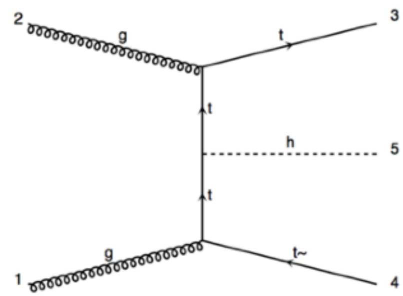


diagram 5 QCD=2, QED=1

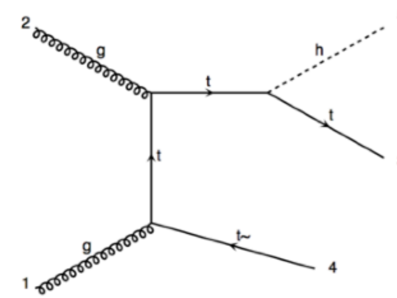


diagram 6 QCD=2, QED=1

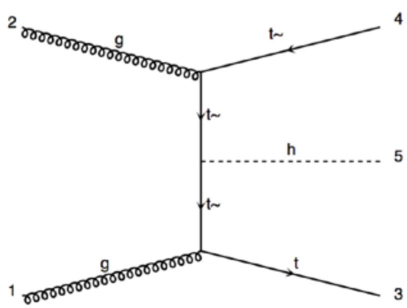


diagram 3 QCD=2, QED=1

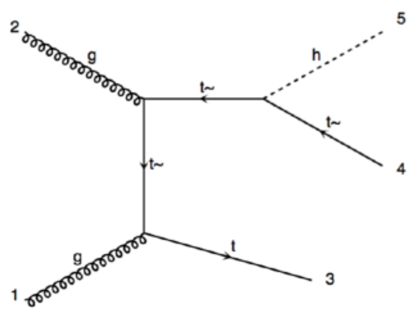


diagram 4 QCD=2, QED=1

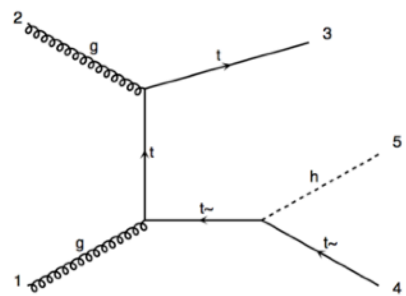


diagram 7 QCD=2, QED=1

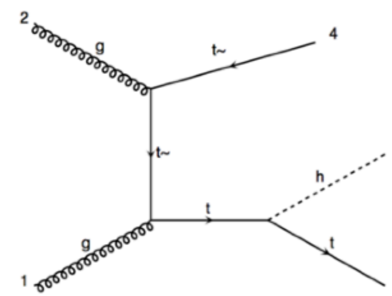


diagram 8 QCD=2, QED=1

Ex 1: Draw all the Feynman Diagrams:

g g > h h : **16** diagrams QCD=2, QED=2 *hint:* this process only occurs via <u>loops</u>

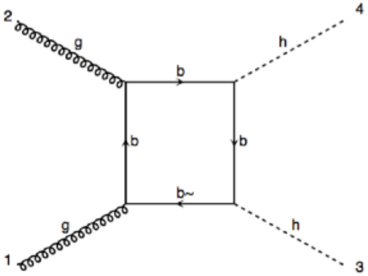


diagram 1 QCD=2, QED=2

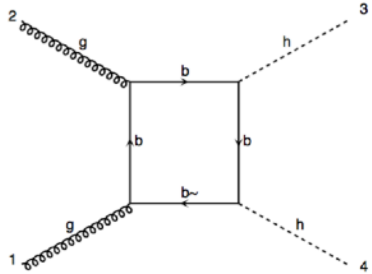


diagram 2 QCD=2, QED=2

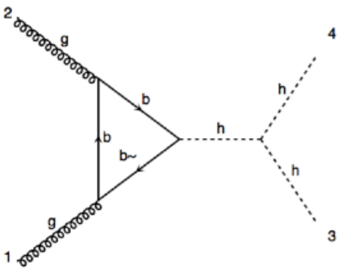


diagram 3 QCD=2, QED=2

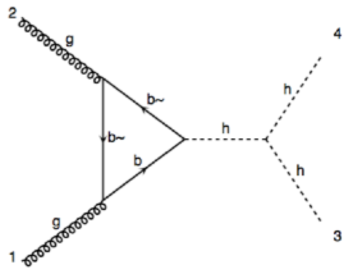


diagram 4 QCD=2, QED=2

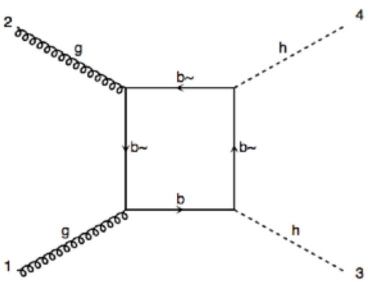


diagram 5 QCD=2, QED=2

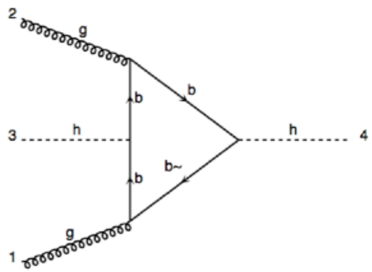


diagram 6 QCD=2, QED=2

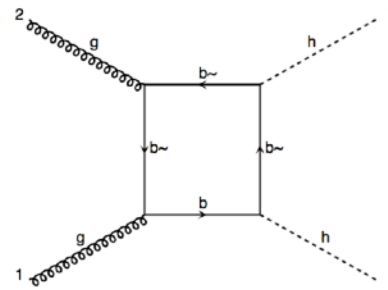


diagram 7 QCD=2, QED=2

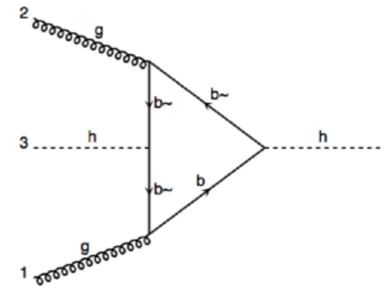


diagram 8 QCD=2, QED=2

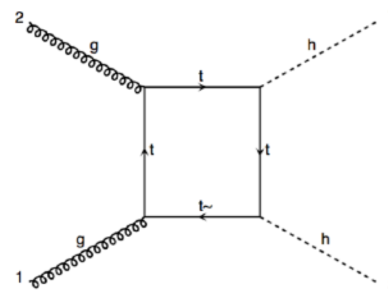


diagram 9 QCD=2, QED=2

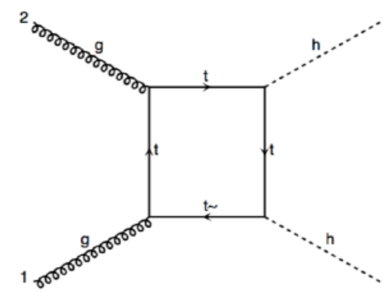


diagram 10 QCD=2, QED=2

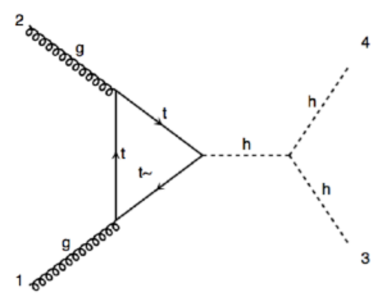


diagram 11 QCD=2, QED=2

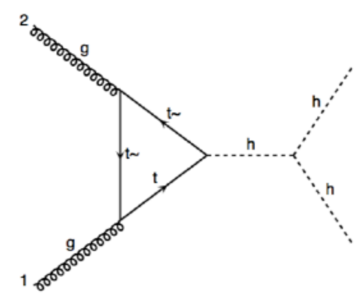


diagram 12 QCD=2, QED=2

Ex 1: Draw all the Feynman Diagrams:

d d~ > u u~ z : **4** diagrams QCD=2, QED=1 and...

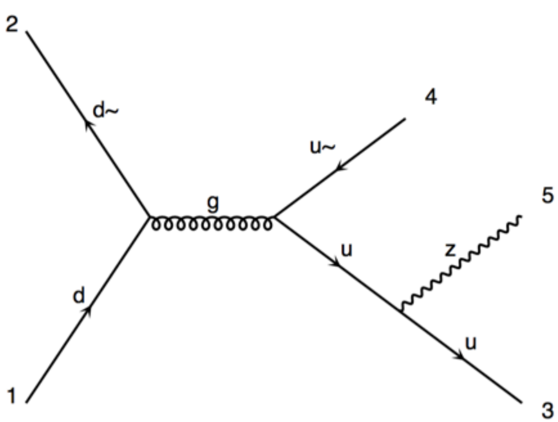


diagram 1 QCD=2, QED=1

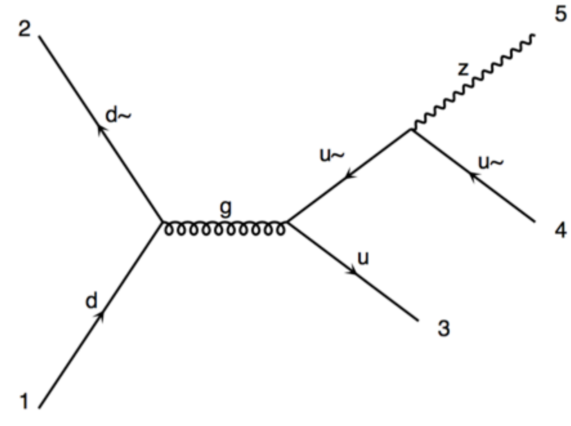


diagram 2 QCD=2, QED=1

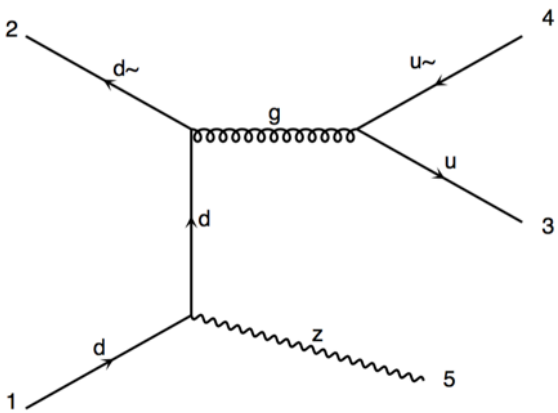


diagram 3 QCD=2, QED=1

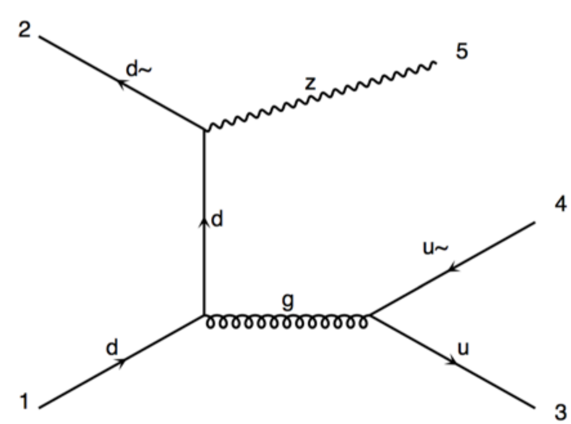
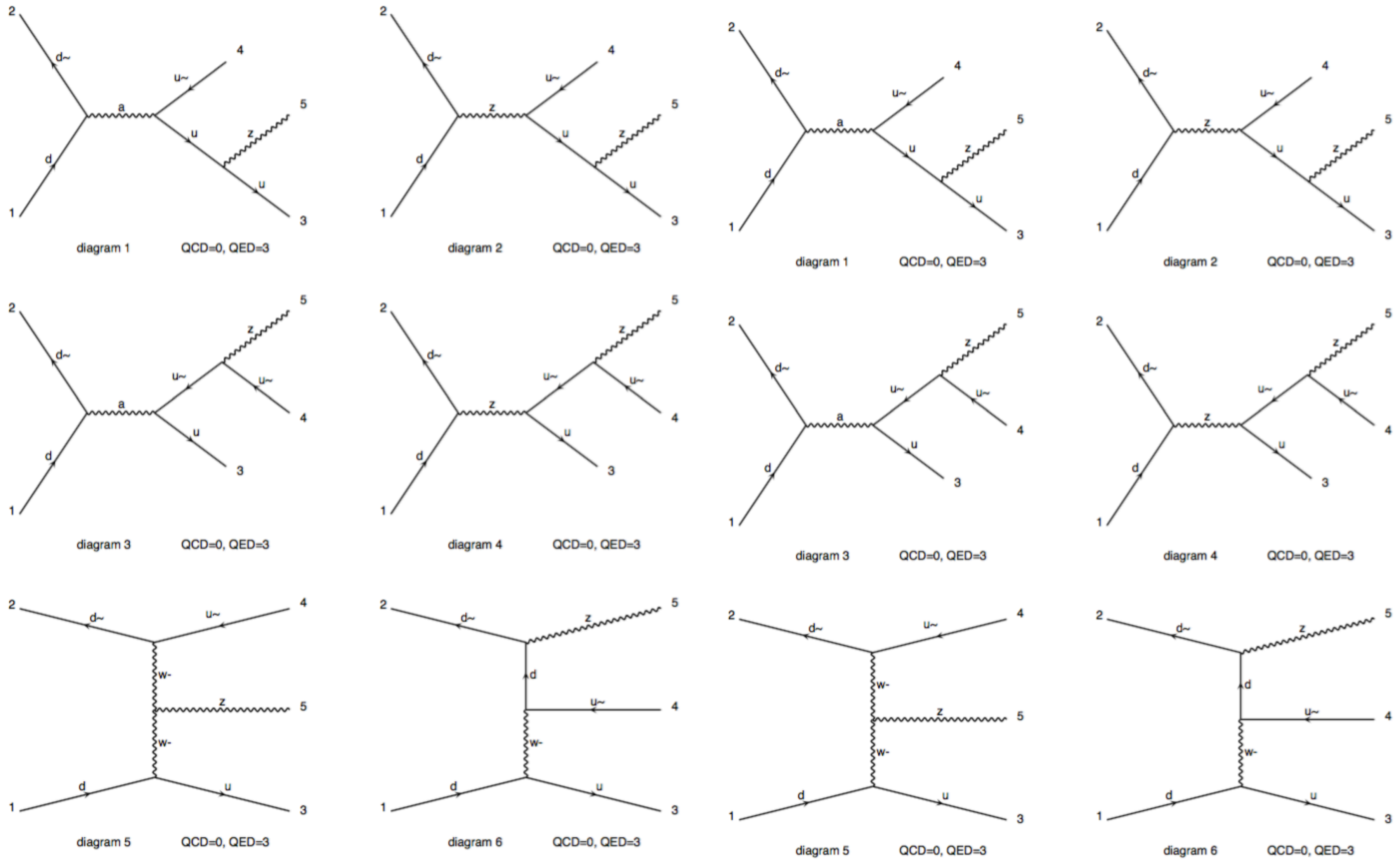


diagram 4 QCD=2, QED=1

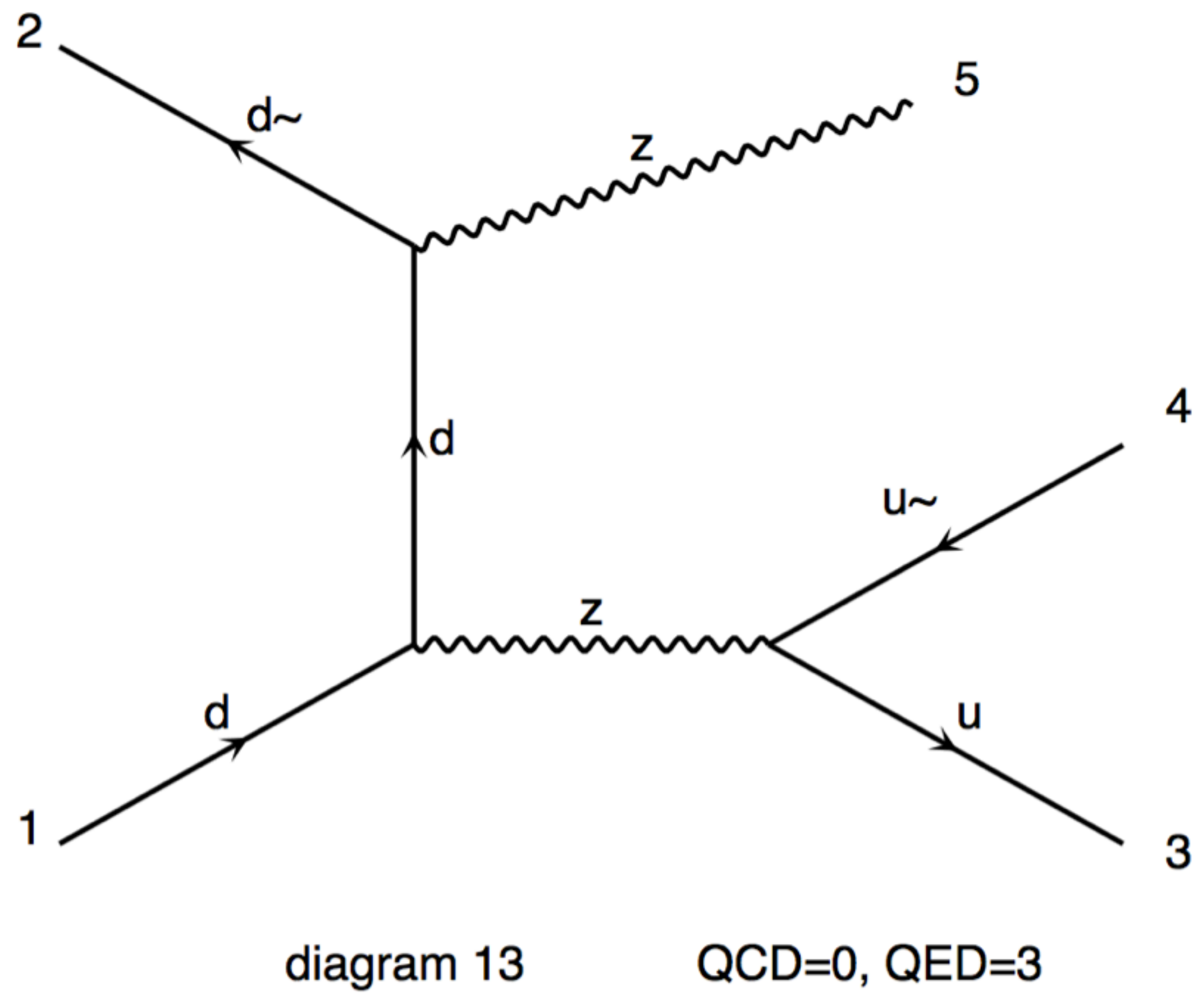
Ex 1: Draw all the Feynman Diagrams:

d d~ > u u~ z : ... **13** diagrams QCD=0, QED=3



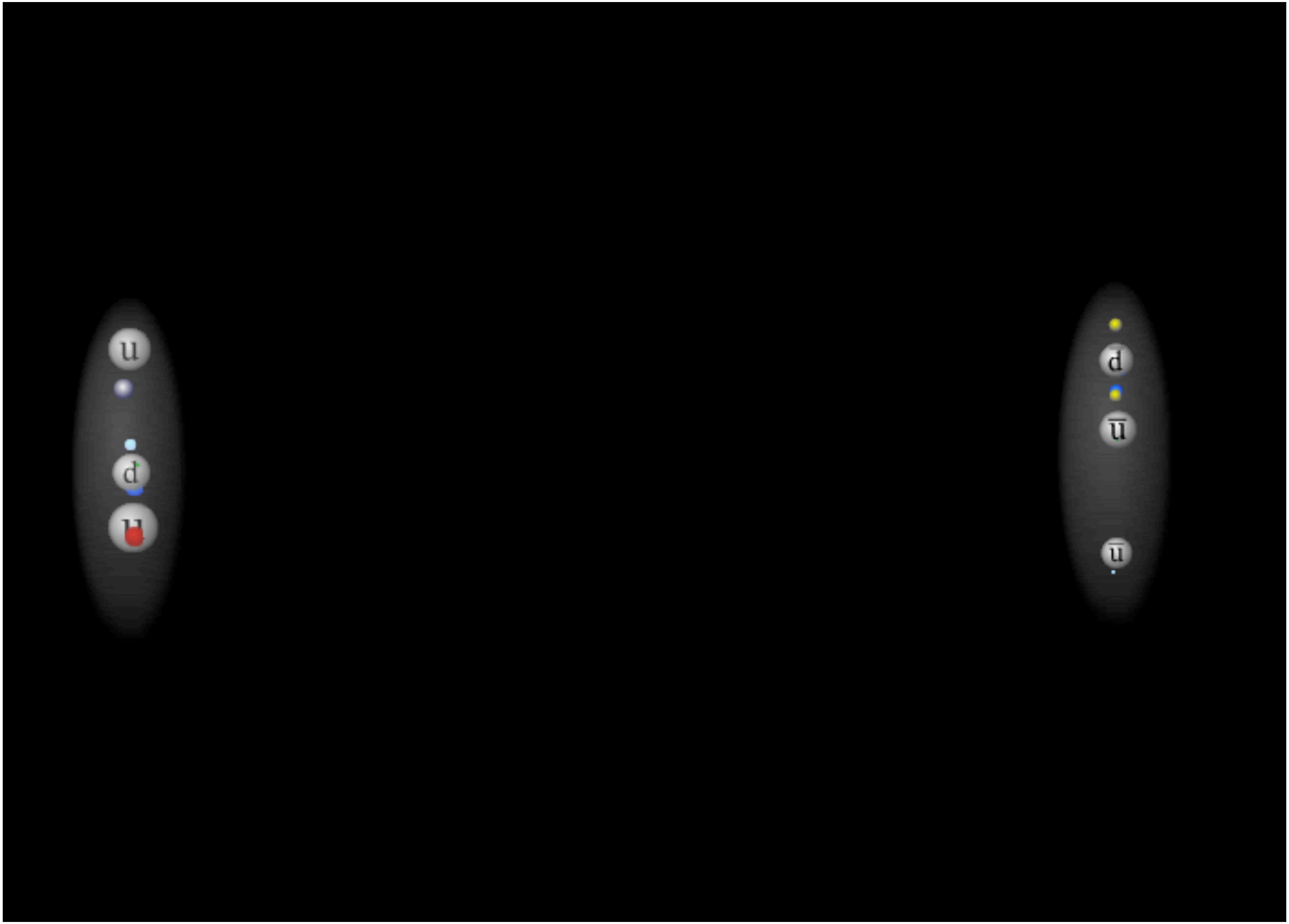
Ex 1: Draw all the Feynman Diagrams:

d d~ > u u~ z : ... **13** diagrams QCD=0, QED=3



Status

- Good News
  - MadGraph generates all tree-level and one loop diagrams
  - MadGraph generates fortran/C++/ Python code to calculate $\Sigma|M|^2$
    - Also tensorflow, cuda, kokkos, sycl, alpaka
- Bad News
  - Madgraph generates code….
  - Hadron colliders are tough!
- Good News
  - There's a cool animation next!


u
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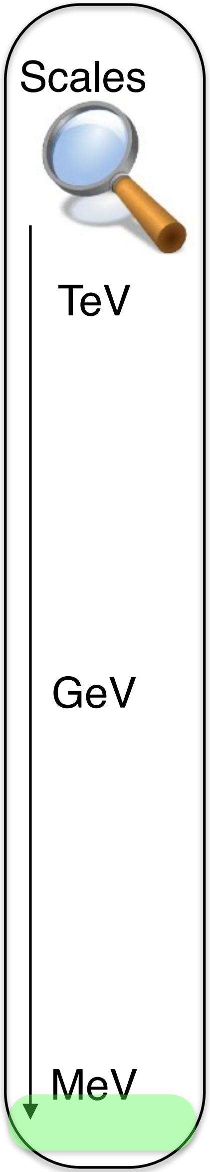
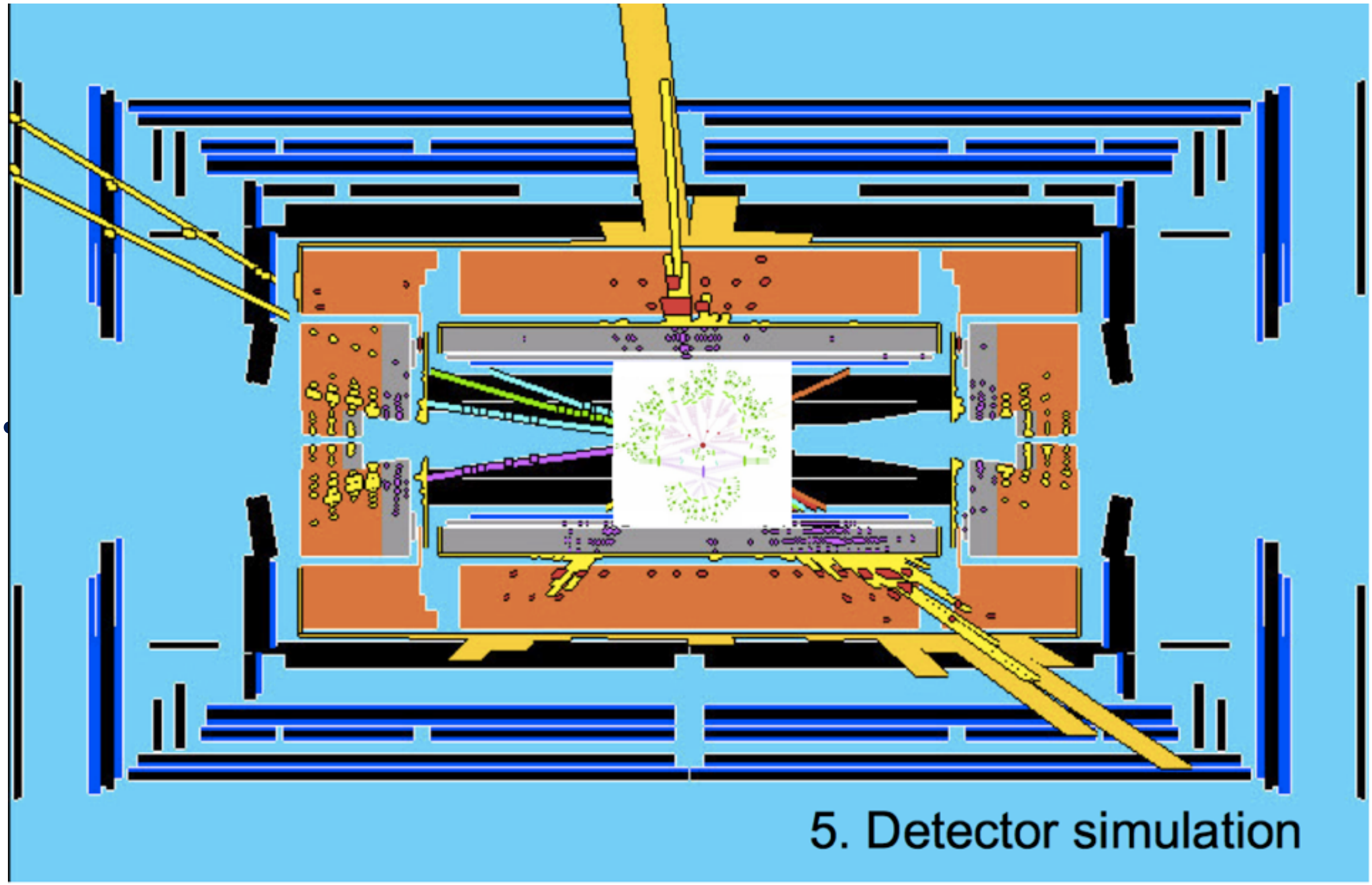
What are the MC for?





Protons

- **Simple Model**
  - 3 “Valence” quarks u u d
  - 2/3 chance of getting up quark
  - 1/3 chance of getting down quark
  - Guess each carries 1/3 of momentum

- **Deep Inelastic Scattering Results**
  - Short time scales “sea” partons
  - u and d. but also u~ d~ s, c and g with varying amounts of momentum

- **Need to multiple matrix element by probability f(x) of finding parton i with fraction of momentum x**

$$\sigma = \frac{1}{2s}\sum \int f_u(x_1) f_{\bar{u}}(x_2) \,|\, M \,|^2 \, d\Phi dx_1 dx_2$$

- **Many parton level sub processes contribute to same hadron level event (e.g. pp > $e^+ \nu$ j j j)**

Exercise

- List processes for signal p p > t t~ h with Higgs decaying to b b~
  - e.g. uu~ > tt~ h
- List process for background p p > t t~ b b~
  - e.g. uu~ > tt~bb~
- List process for reducible background p p > t t~ j j
  - e.g. uu~ > tt~gg

Check on your laptop

Then type
generate p p > t t~

```
MG5_aMC>generate p p > t t~
INFO: Checking for minimal orders which gives processes.
INFO: Please specify coupling orders to bypass this step.
INFO: Trying coupling order WEIGHTED<=2: WEIGTHED IS QCD+2*QED
INFO: Trying process: g g > t t~ WEIGHTED<=2 @1
INFO: Process has 3 diagrams
INFO: Trying process: u u~ > t t~ WEIGHTED<=2 @1
INFO: Process has 1 diagrams
INFO: Trying process: u c~ > t t~ WEIGHTED<=2 @1
INFO: Trying process: c u~ > t t~ WEIGHTED<=2 @1
INFO: Trying process: c c~ > t t~ WEIGHTED<=2 @1
INFO: Process has 1 diagrams
INFO: Trying process: d d~ > t t~ WEIGHTED<=2 @1
INFO: Process has 1 diagrams
INFO: Trying process: d s~ > t t~ WEIGHTED<=2 @1
INFO: Trying process: s d~ > t t~ WEIGHTED<=2 @1
INFO: Trying process: s s~ > t t~ WEIGHTED<=2 @1
INFO: Process has 1 diagrams
INFO: Process u~ u > t t~ added to mirror process u u~ > t t~
INFO: Process c~ c > t t~ added to mirror process c c~ > t t~
INFO: Process d~ d > t t~ added to mirror process d d~ > t t~
INFO: Process s~ s > t t~ added to mirror process s s~ > t t~
5 processes with 7 diagrams generated in 0.026 s
Total: 5 processes with 7 diagrams
```

Then type
output test1
open info.html

SubProcesses and Feynman diagrams

Directory	# Diagrams	# Subprocesses	FEYNMAN DIAGRAMS	SUBPROCESS
P1_qq_ttx	1	8	html	u u~ > t t~ , c c~ > t t~ , d d~ > t t~ , s s~ > t t~ , u~ u > t t~ , c~ c > t t~ , d~ d > t t~ , s~ s > t t~
P1_gg_ttx	3	1	html	g g > t t~

11 diagrams (4 independent).

Ex 2: List subprocesses generated for these processes:

p p > h > t t~ b b~ :

Directory	# Diagrams	# Subprocesses	FEYNMAN DIAGRAMS	SUBPROCESS
P1_gg_ttxbbx	16	1	html postscript	g g > t t~ b b~
P1_qq_ttxbbx	4	8	html postscript	u u~ > t t~ b b~ , c c~ > t t~ b b~ , d d~ > t t~ b b~ , s s~ > t t~ b b~ , u~ u > t t~ b b~ , c~ c > t t~ b b~ , d~ d > t t~ b b~ , s~ s > t t~ b b~

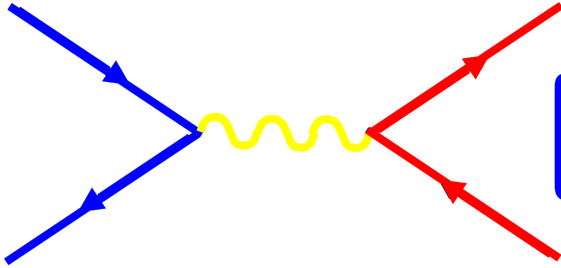
p p > t t~ b b~ :

Directory	# Diagrams	# Subprocesses	FEYNMAN DIAGRAMS	SUBPROCESS
P1_gg_ttxbbx	36	1	html postscript	g g > t t~ b b~
P1_qq_ttxbbx	7	8	html postscript	u u~ > t t~ b b~ , c c~ > t t~ b b~ , d d~ > t t~ b b~ , s s~ > t t~ b b~ , u~ u > t t~ b b~ , c~ c > t t~ b b~ , d~ d > t t~ b b~ , s~ s > t t~ b b~

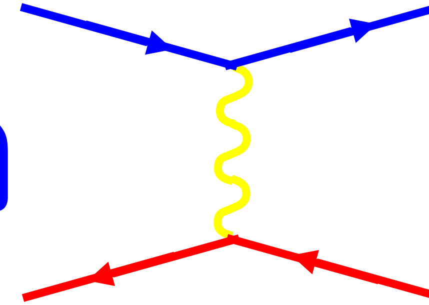
Ex 2: List subprocesses generated for these processes:

p p > t t~ j j :

Directory	# Diagrams	# Subprocesses	FEYNMAN DIAGRAMS	SUBPROCESS
P1_gg_ttxgg	123	1	html postscript	g g > t t~ g g
P1_gg_ttxqq	36	4	html postscript	g g > t t~ u u~ , g g > t t~ c c~ , g g > t t~ d d~ , g g > t t~ s s~
P1_gq_ttxgq	36	8	html postscript	g u > t t~ g u , g c > t t~ g c , g d > t t~ g d , g s > t t~ g s , u g > t t~ g u , c g > t t~ g c , d g > t t~ g d , s g > t t~ g s
	36	8	html postscript	g u~ > t t~ g u~ , g c~ > t t~ g c~ , g d~ > t t~ g d~ , g s~ > t t~ g s~ , u~ g > t t~ g u~ , c~ g > t t~ g c~ , d~ g > t t~ g d~ , s~ g > t t~ g s~
P1_qq_ttxgg	36	8	html postscript	u u~ > t t~ g g , c c~ > t t~ g g , d d~ > t t~ g g , s s~ > t t~ g g , u~ u > t t~ g g , c~ c > t t~ g g , d~ d > t t~ g g , s~ s > t t~ g g
P1_qq_ttxqq	14	4	html postscript	u u > t t~ u u , c c > t t~ c c , d d > t t~ d d , s s > t t~ s s
	14	8	html postscript	u u~ > t t~ u u~ , c c~ > t t~ c c~ , d d~ > t t~ d d~ , s s~ > t t~ s s~ , u~ u > t t~ u u~ , c~ c > t t~ c c~ , d~ d > t t~ d d~ , s~ s > t t~ s s~
	14	4	html postscript	u~ u~ > t t~ u~ u~ , c~ c~ > t t~ c~ c~ , d~ d~ > t t~ d~ d~ , s~ s~ > t t~ s~ s~
	7	12	html postscript	u c > t t~ u c , u d > t t~ u d , u s > t t~ u s , c d > t t~ c d , c s > t t~ c s , d s > t t~ d s , c u > t t~ u c , d u > t t~ u d , s u > t t~ u s , d c > t t~ c d , s c > t t~ c s , s d > t t~ d s
	7	24	html postscript	u u~ > t t~ c c~ , u u~ > t t~ d d~ , u u~ > t t~ s s~ , c c~ > t t~ u u~ , c c~ > t t~ d d~ , c c~ > t t~ s s~ , d d~ > t t~ u u~ , d d~ > t t~ c c~ , d d~ > t t~ s s~ , s s~ > t t~ u u~ , s s~ > t t~ c c~ , s s~ > t t~ d d~ , u~ u > t t~ c c~ , u~ u > t t~ d d~ , u~ u > t t~ s s~ , c~ c > t t~ u u~ , c~ c > t t~ d d~ , c~ c > t t~ s s~ , d~ d > t t~ u u~ , d~ d > t t~ c c~ , d~ d > t t~ s s~ , s~ s > t t~ u u~ , s~ s > t t~ c c~ , s~ s > t t~ d d~
	7	24	html postscript	u c~ > t t~ u c~ , u d~ > t t~ u d~ , u s~ > t t~ u s~ , c u~ > t t~ c u~ , c d~ > t t~ c d~ , c s~ > t t~ c s~ , d u~ > t t~ d u~ , d c~ > t t~ d c~ , d s~ > t t~ d s~ , s u~ > t t~ s u~ , s c~ > t t~ s c~ , s d~ > t t~ s d~ , c~ u > t t~ u c~ , d~ u > t t~ u d~ , s~ u > t t~ u s~ , u~ c > t t~ c u~ , d~ c > t t~ c d~ , s~ c > t t~ c s~ , u~ d > t t~ d u~ , c~ d > t t~ d c~ , s~ d > t t~ d s~ , u~ s > t t~ s u~ , c~ s > t t~ s c~ , d~ s > t t~ s d~
	7	12	html postscript	u~ c~ > t t~ u~ c~ , u~ d~ > t t~ u~ d~ , u~ s~ > t t~ u~ s~ , c~ d~ > t t~ c~ d~ , c~ s~ > t t~ c~ s~ , d~ s~ > t t~ d~ s~ , c~ u~ > t t~ u~ c~ , d~ u~ > t t~ u~ d~ , s~ u~ > t t~ u~ s~ , d~ c~ > t t~ c~ d~ , s~ c~ > t t~ c~ s~ , s~ d~ > t t~ d~ s~



MadGraph



- **User Requests:**
  - pp -> bb~tt~ QCD<=4
- **MadGraph Returns:**
  - Feynman diagrams
  - Fortran Code for |M|^2
  - Summed over all sub processes w/ pdf

```
 DOUBLE PRECISION FUNCTION DSIG(PP,WGT)
C ****************************************************
C Generated by MadGraph II Version 3.83. Updated
06/13/05
C    RETURNS DIFFERENTIAL CROSS SECTION
C    Input:
C         pp    4 momentum of external particles
C         wgt   weight from Monte Carlo
C    Output:
C         Amplitude squared and summed
C ****************************************************

       ------------------------------------

       IPROC=IPROC+1      ! u u~ -> t t~ b b~
       PD(IPROC)=PD(IPROC-1) + u1 * ub2
       IPROC=IPROC+1      ! d d~ -> t t~ b b~
       PD(IPROC)=PD(IPROC-1) + d1 * db2
       IPROC=IPROC+1      ! s s~ -> t t~ b b~
       PD(IPROC)=PD(IPROC-1) + s1 * sb2
       IPROC=IPROC+1      ! c c~ -> t t~ b b~
       PD(IPROC)=PD(IPROC-1) + c1 * cb2
       CALL SMATRIX(PP,DSIGUU)

       dsig = pd(iproc)*conv*dsiguu
```

Hadronic Collision Cross Sections

- Good News
  - Automatically determine sub processes and Feynman diagrams
  - Automatically create function needed to integrate

$$\sigma = \frac{1}{2s}\int f(x_1) f(x_2) \, | M |^2 \, d^3P_1 \ldots d^3P_n \delta^4(P - p_1 - p_2 \ldots - p_n)$$

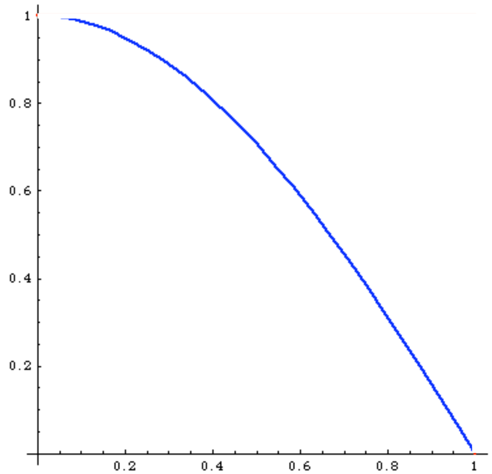
- Bad News
  - Hard to integrate!
  - 3N-4+2 dimensions

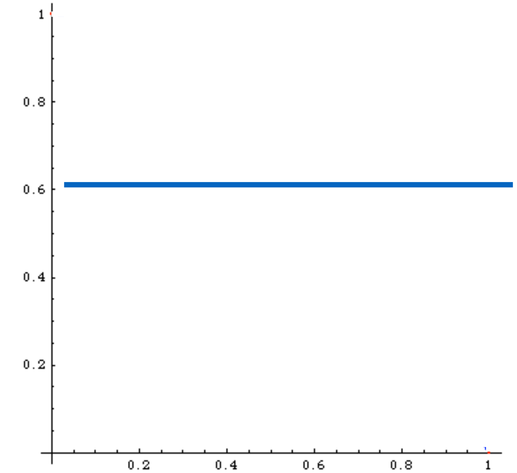
Integration

$$I = \int_0^1 dx \cos \frac{\pi}{2} x$$

$$\int \frac{dq^2}{(q^2 - M^2 + iM\Gamma)^2}$$

$$\int dx\, C$$





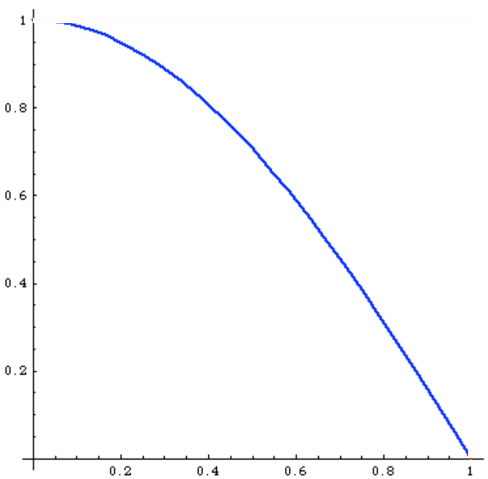
	simpson	MC
3	0,638	0,3
5	0,6367	0,8
20	0,63662	0,6
100	0,636619	0,65
1000	0,636619	0,636

Method of evaluation

- MonteCarlo $1/\sqrt{N}$
- Trapezium $1/N^2$
- Simpson $1/N^4$

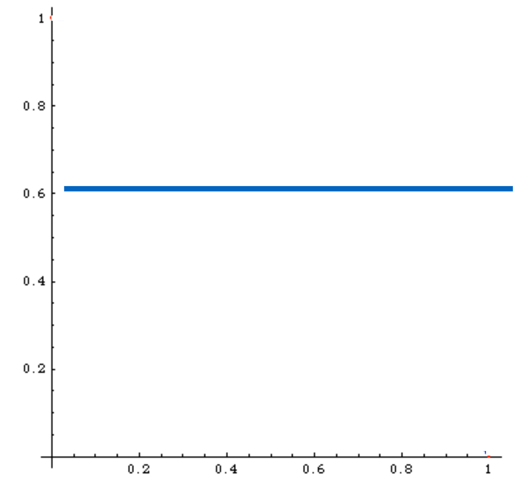
Integration

$$I = \int_0^1 dx \cos\frac{\pi}{2}x$$



$$\int \frac{dq^2}{(q^2 - M^2 + iM\Gamma)^2}$$

$$\int dx\, C$$



Method of evaluation

- MonteCarlo $1/\sqrt{N}$
- Trapezium $1/N^2$
- Simpson $1/N^4$

More Dimension →

$1/\sqrt{N}$

$1/N^{2/d}$

$1/N^{4/d}$

Monte Carlo Integration

$$\int_a^b f(x)dx \approx \frac{b-a}{N} \sum_{i=1,N} f(x_i)$$

- Advantages
  - Large numbers of dimensions
  - Complicated cuts
  - ONLY OPTION
  - Event generation
  -

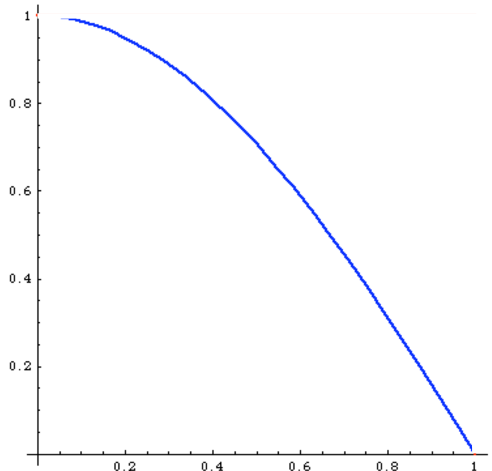
- Limitations
  - Only works for function f(x) ≈ 1
  - Error scales as 1/sqrt(N)

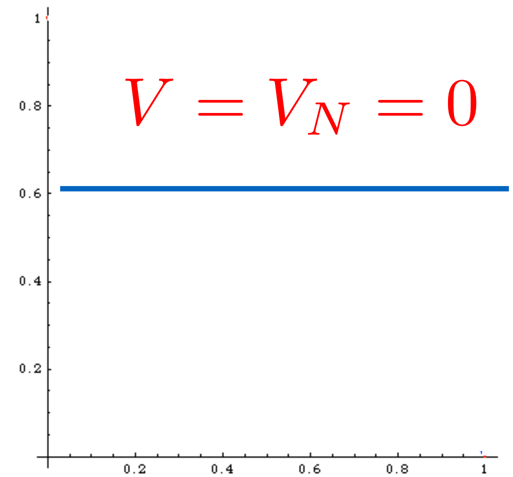
Integration

$$I = \int_0^1 dx \cos\frac{\pi}{2}x$$

$$\int \frac{dq^2}{(q^2 - M^2 + iM\Gamma)^2}$$

$$\int dx\, C$$





$$V = V_N = 0$$

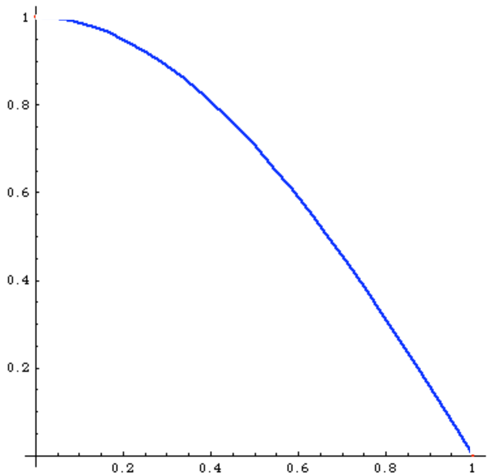
$$I = \int_{x_1}^{x_2} f(x)dx \quad\Rightarrow\quad I_N = (x_2 - x_1)\frac{1}{N}\sum_{i=1}^{N} f(x)$$

$$V = (x_2 - x_1)\int_{x_1}^{x_2} [f(x)]^2 dx - I^2 \quad\Rightarrow\quad V_N = (x_2 - x_1)^2 \frac{1}{N}\sum_{i=1}^{N}[f(x)]^2 - I_N^2$$

$$I = I_N \pm \sqrt{V_N / N}$$

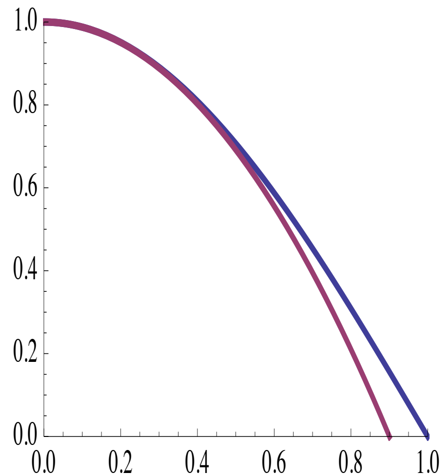
Can be minimized!

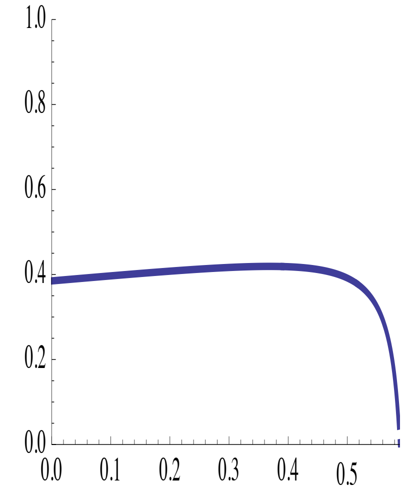
Importance Sampling



$$I = \int_0^1 dx \cos\frac{\pi}{2}x$$

$$I_N = 0.637 \pm 0.307/\sqrt{N}$$





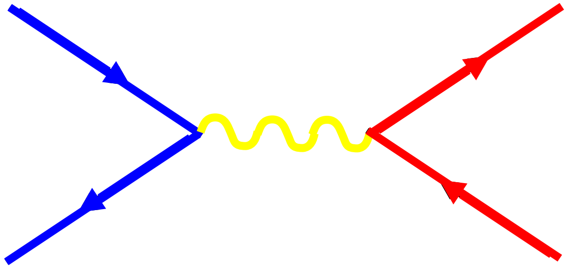
$$I = \int_0^1 dx(1-cx^2)\frac{\cos\left(\frac{\pi}{2}x\right)}{(1-cx^2)} = \int_{\xi_1}^{\xi_2} d\xi \frac{\cos\frac{\pi}{2}x[\xi]}{1-x[\xi]^2 c}$$

$$\rightarrow \simeq 1$$

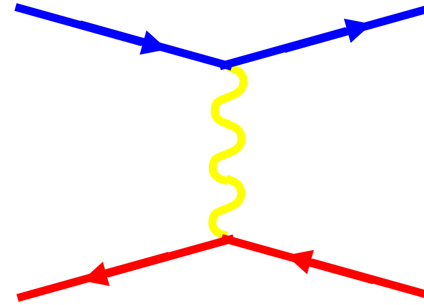
$$I_N = 0.637 \pm 0.031/\sqrt{N}$$

100 times faster

The Phase-Space parametrization is important to have an efficient computation!



MadEvent



- **User Requests:**
  - Model (heft)
  - pp -> a a
  - Cuts + Parameters
- **MadEvent Returns:**
  - Feynman diagrams
  - Complete package for event generation
  - Events/Plots on your laptop (or cluster or online)!

Check on your laptop

```
import model heft
generate p p > a a
output mydir2
launch
```

Results in the heft for p p > a a

Available Results

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 6500.0 x 6500.0 GeV	tag_1	149.1 ± 0.44 ± systematics	10000	parton madevent	LHE MA5_report_analysis1	remove run / launch detector simulation

Main Page

Issue? -> go online for this step

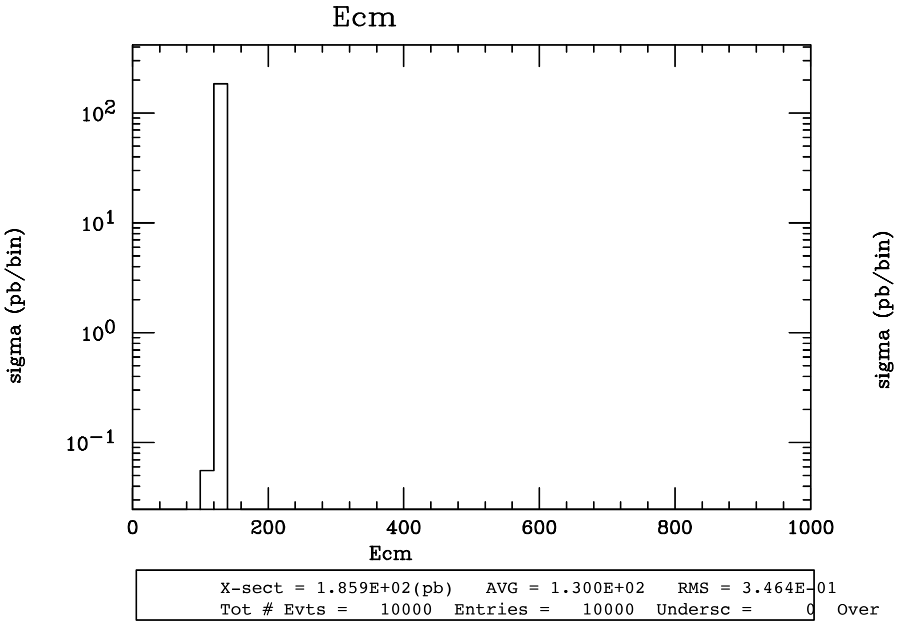
pp > a a

- Generate SubProcesses+Diagrams
  - Use HiggsEFT model

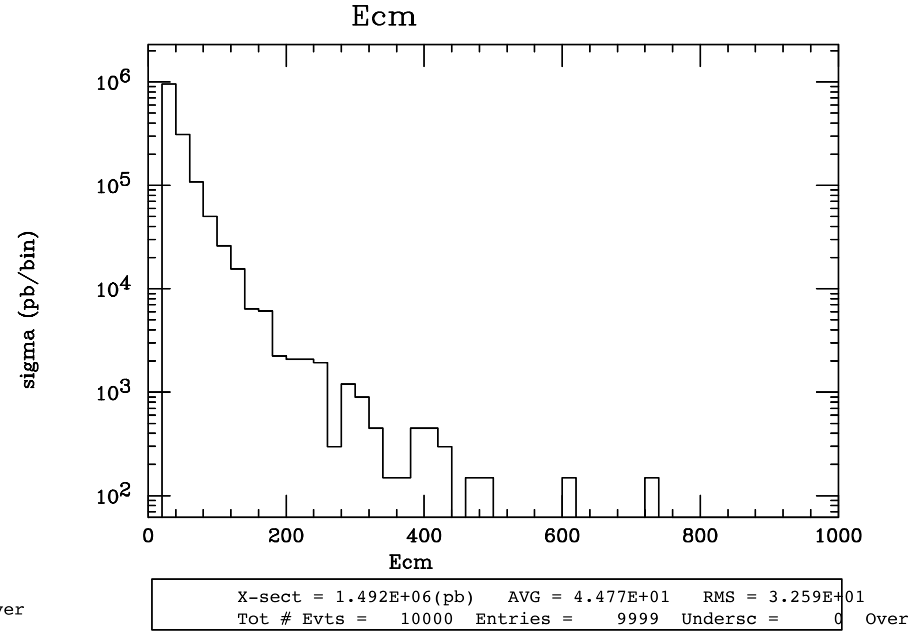
- Generate Parton Level Plots

Ex 3: Study observables, you need to generate events here!

p p > h > a a



p p > a a



- Pseudo-rapidity 'eta' and rapidity 'y' are different for massive particles only.
  Pseudo-rapidity more handy their differences is Longitudinal Lorentz boost invariant

- The quantity HT is loosely called Transverse energy:

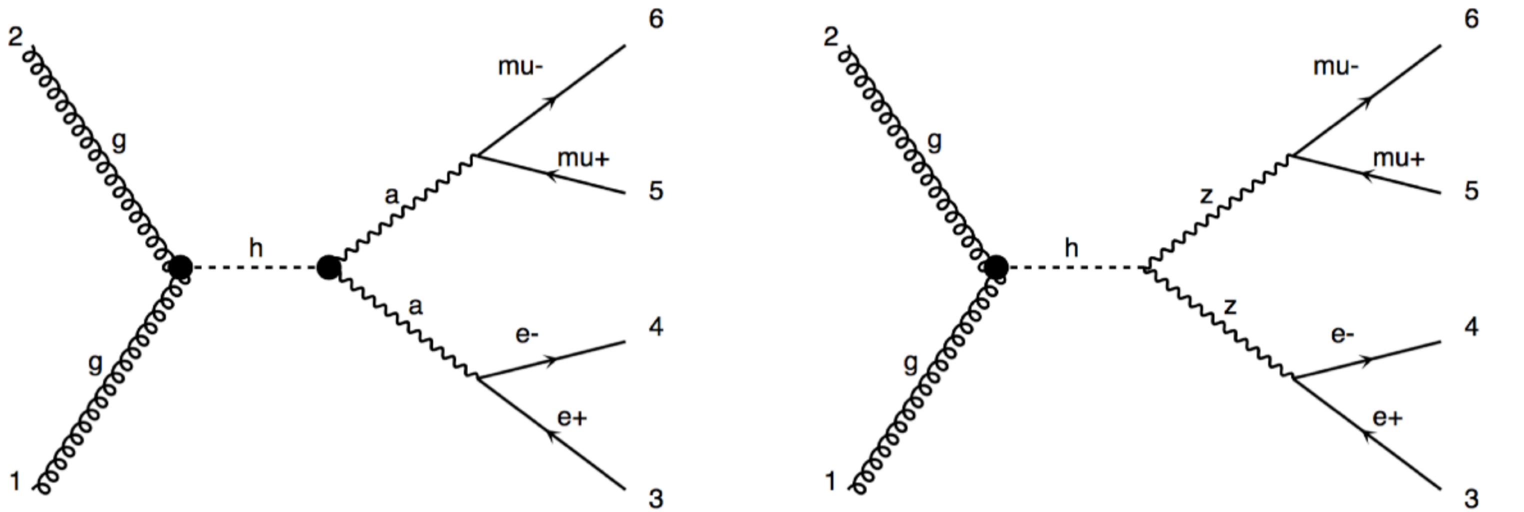
$$H_T = \sum_{i=1}^{N_{\text{particles}}} \sqrt{P_{T,i}^2 - m_i^2}$$

Exercise

- Generate parton level plot for the Higgs production to four lepton
  - e.g. g g > h > e+ e- mu+ mu- (use HiggsEFT)
- List process for background and generate the associate partonic plot
- What is a strategy to observe the Higgs?

Ex 3: Study observables, you need to generate events here!

p p > h > e+ e- mu+ mu-



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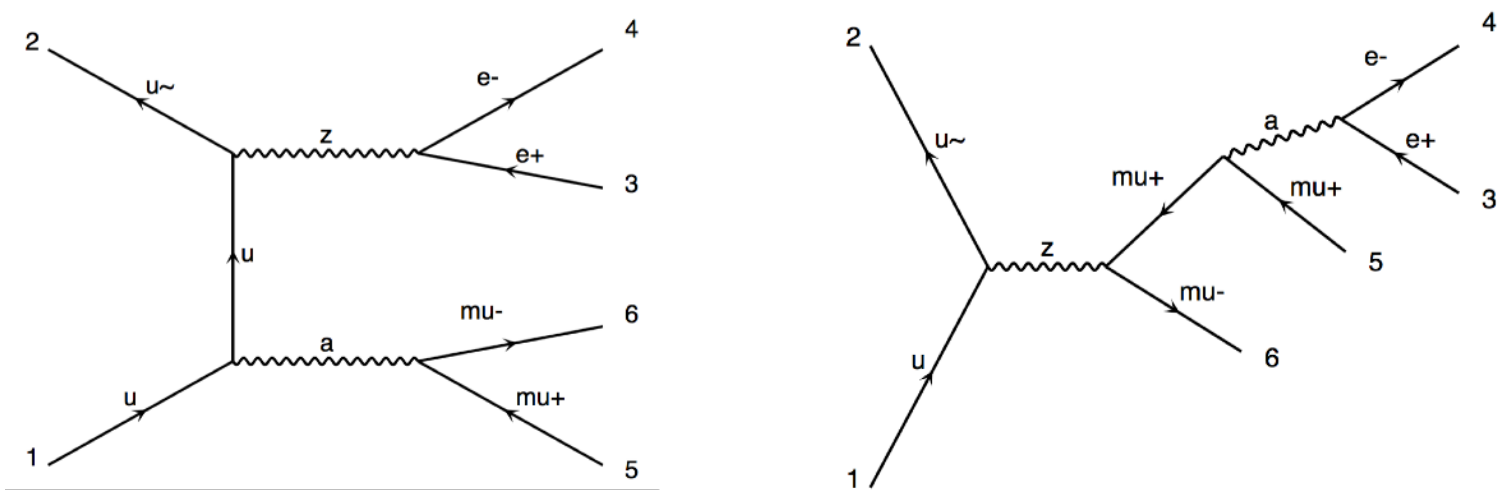

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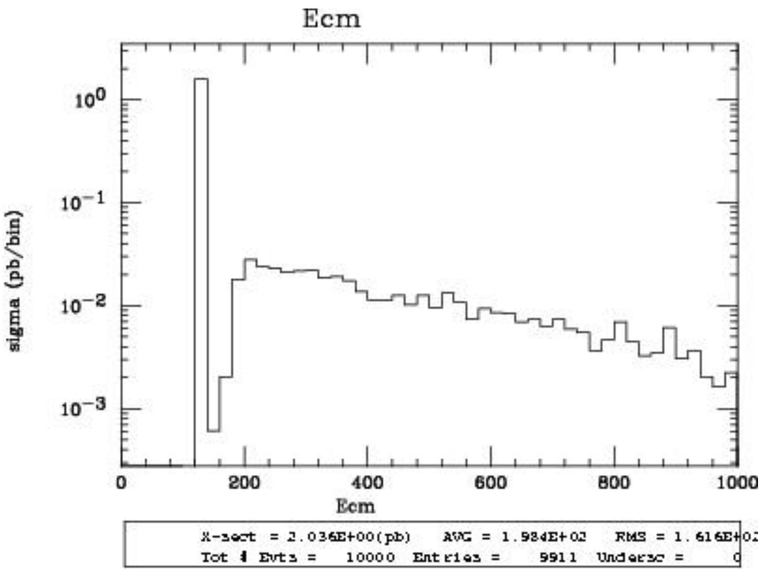

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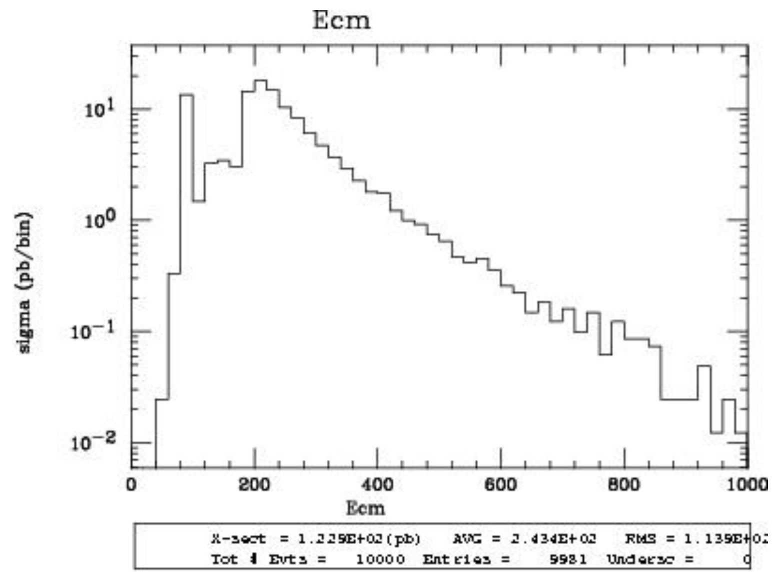

- What is the first peak on each plot
- Why is there a second peak on each plot and why is it so asymmetric?
- Why the first plot does not have contribution before 125 GeV?
- Why the b

Ex 3: Study observables, you need to generate events here!

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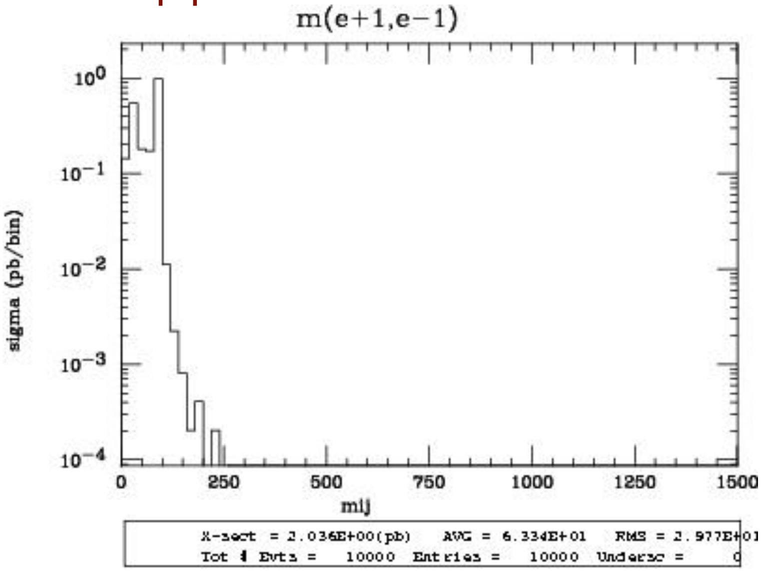

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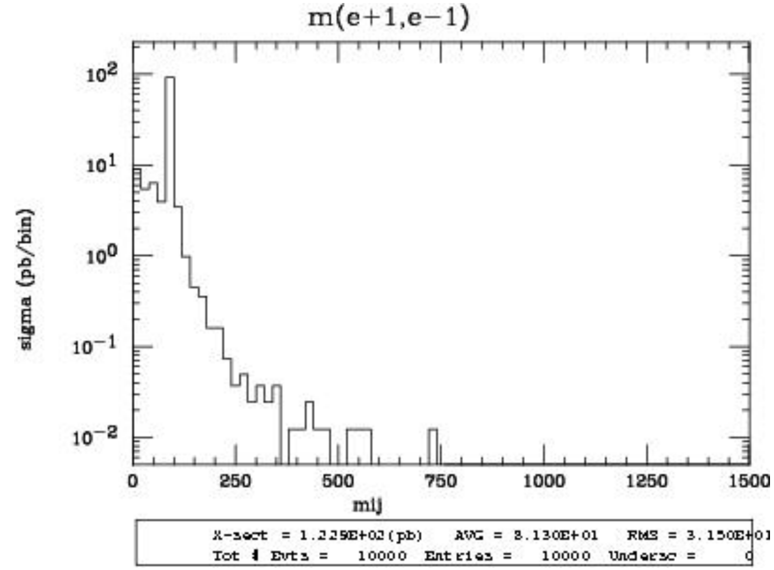

- Why do we have two peaks for the signal?
- Why the background increase at low invariant mass?

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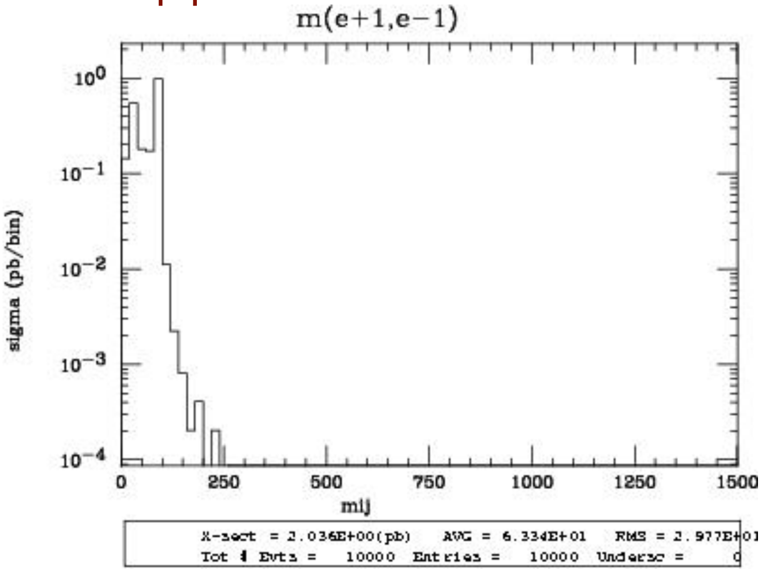

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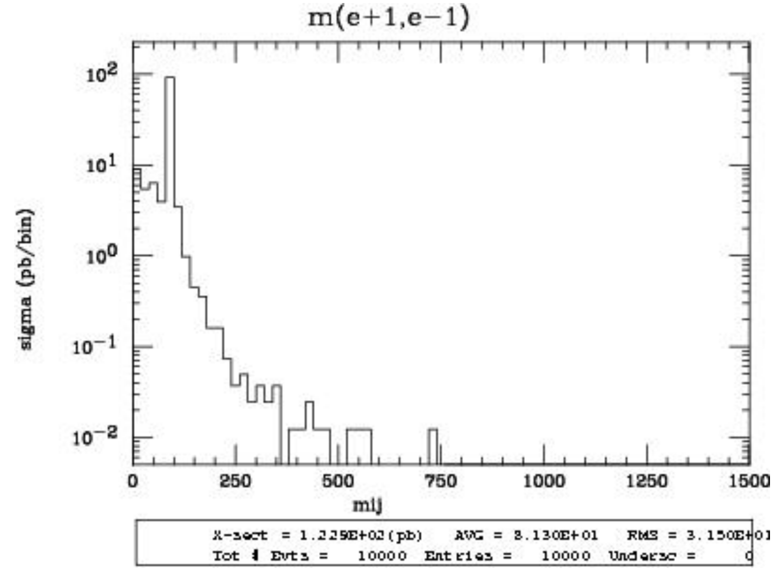

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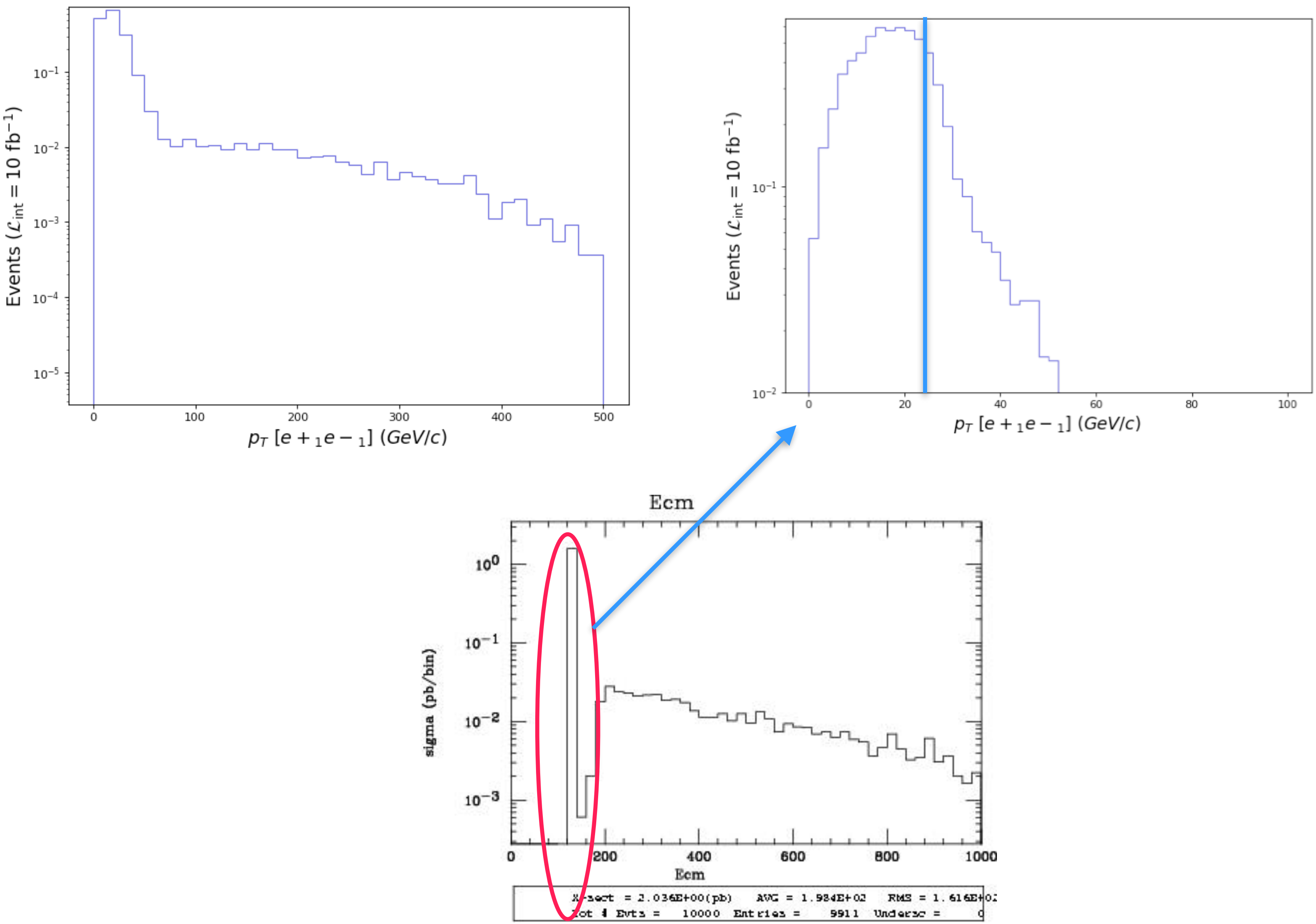
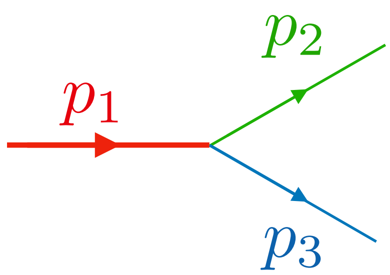


Events ($\mathcal{L}_{\rm int} = 10\ {\rm fb}^{-1}$)
p_T [e + 1 e − 1] (GeV/c)
Events ($\mathcal{L}_{\rm int} = 10\ {\rm fb}^{-1}$)
p_T [e + 1 e − 1] (GeV/c)
Ecm
sigma (pb/bin)
Ecm
X-sect = 2.036E+00(pb) AVG = 1.984E+02
Tot # Evts = 10000 Entries = 9911

A bit of kinematics...



$$p_1 = p_2 + p_3$$

$$\vec{p_1} = \vec{0} \qquad \vec{p_2} = -\vec{p_3}$$

$$p_i^2 = m_i^2$$

$$E_1 = m_1 \qquad E_2 = \sqrt{|\vec{p_2}|^2 + m_2^2} \qquad E_3 = \sqrt{|\vec{p_2}|^2 + m_3^2}$$

$$p_1^2 = (p_2 + p_3)^2 \qquad m_1^2 = m_2^2 + m_3^2 + 2E_2E_3 - 2|\vec{p_2}||\vec{p_3}|\cos(\theta_{23})$$

$$m_1^2 - m_2^2 - m_3^2 = +2\sqrt{|\vec{p_2}|^2 + m_2^2}\sqrt{|\vec{p_2}|^2 + m_3^2} + 2|\vec{p_2}|^2$$

$$p_t^{(\max)}(\vec{p_2}) = |\vec{p_2}| = E_2 = \frac{\sqrt{m_1{}^4 + (m_2{}^2 - m_3{}^2) - 2m_1{}^2(m_2{}^2 + m_3{}^2)}}{2m_1}$$

$$p_t^{(\max)}(\vec{p_2}) = p_t^{(\max)}(\vec{p_3}) \overbrace{=}^{m_3=m_2} \frac{1}{2}\sqrt{m_1{}^2 - 4m_2{}^2} \overbrace{=}^{m_3=0} \frac{m_1{}^2 - m_2{}^2}{2m_1}$$

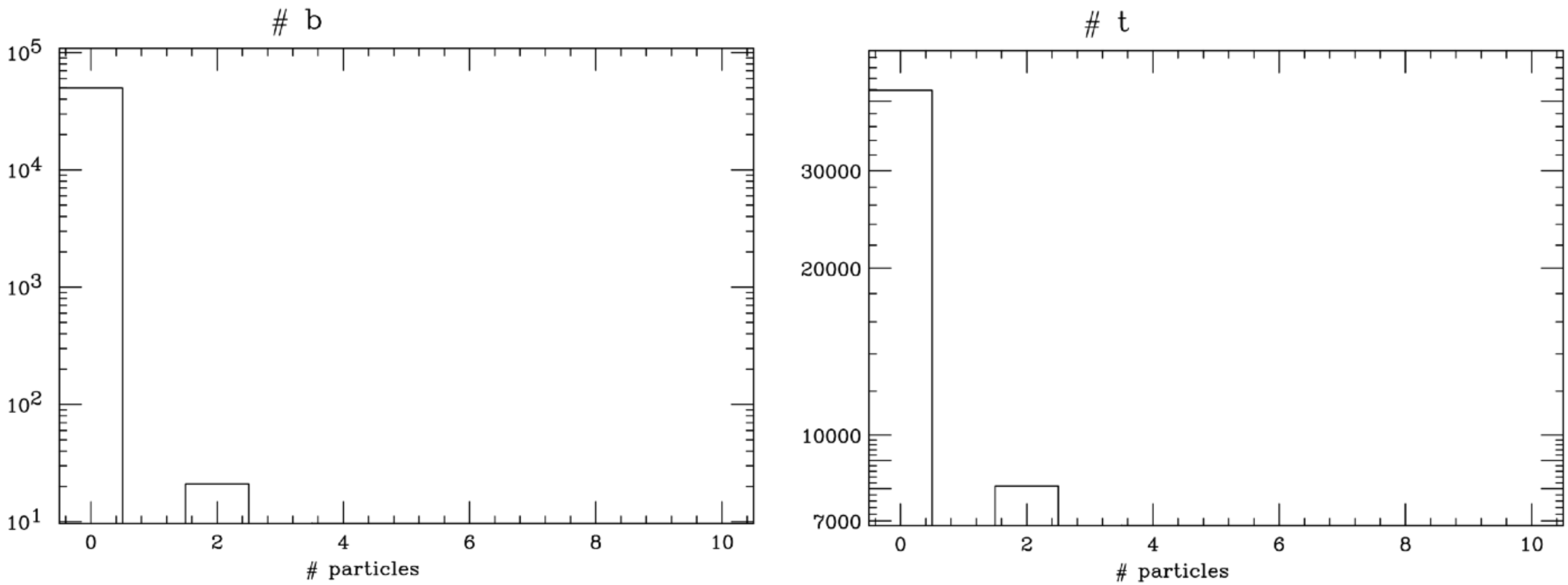
Final Project

- **Good News….we have discovered 3 new particles at the LHC (Z', H, W+') Your job is to determine their mass using the plots provided.**

- **Go to the indico page to get the plots and determine which sample is which model:**

- **Try to understand those plot (why a peak, a shoulder, …)**
  - **We have example of question in the following slides**

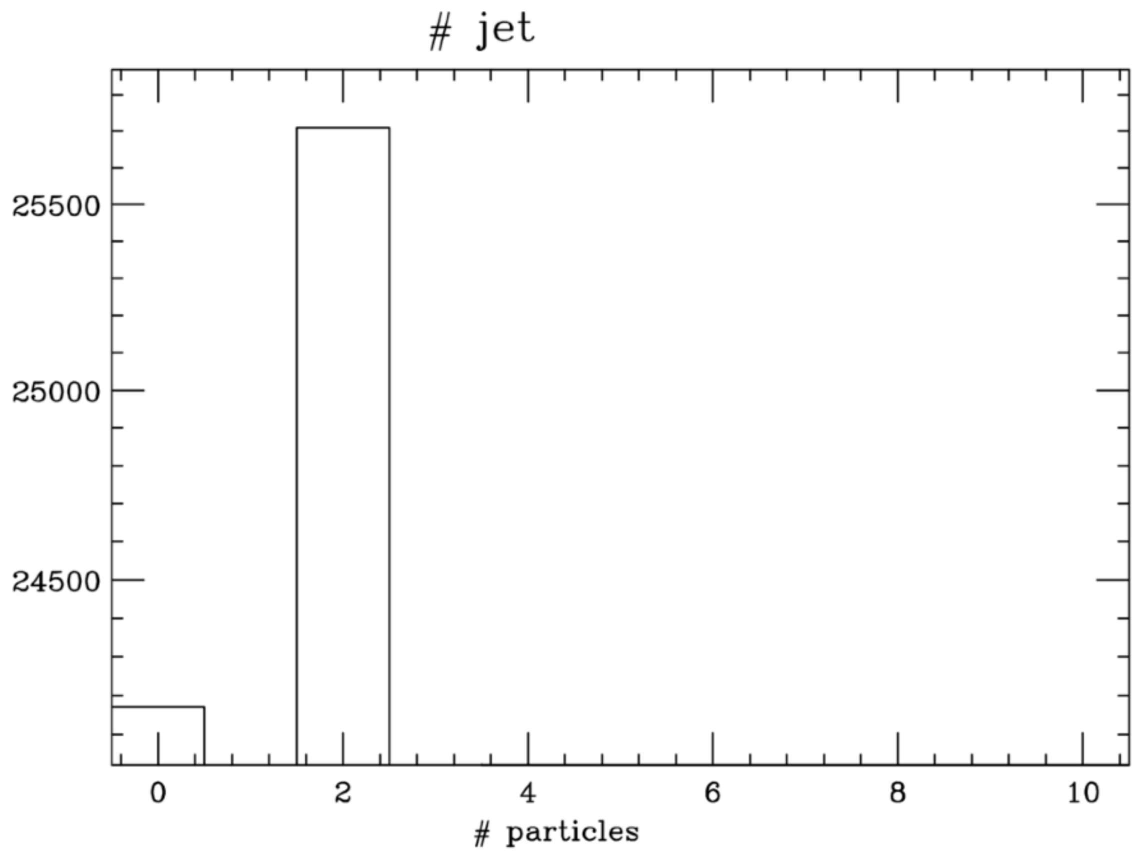
Sample A) A heavy scalar Higgs with SM-like couplings!



Decays preferentially to top-quarks!

- Why is the number of b's, W's, Z's always 0 or 2 at parton level, but more at detector level?
- Why does the pt(b1) look so erratic at parton level but not any longer at detector level?
- What is the X mass and its decay modes, including their relative strengths?
- How stable this X is ? What is its Γ/m ratio ? Does it look the same for all decay modes?
- Can you also guess the X mass from the shape of the Pt spectrum of its decay products (incl. top)?

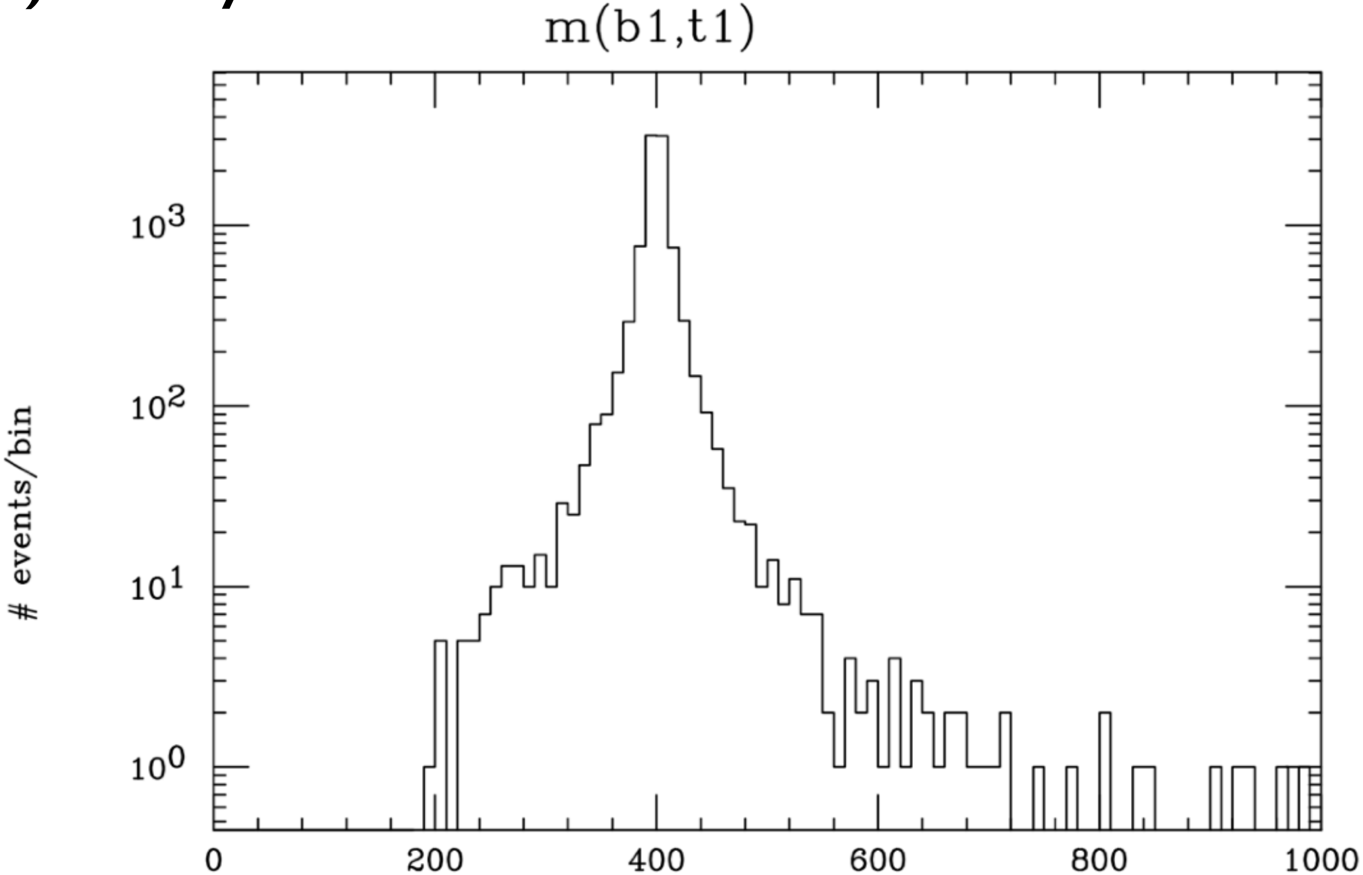
Sample B) A heavy Z'



Decays to jets!

- Why are the invariant mass spectra always slightly left-right asymmetrical?
- Why is missing ET zero at parton level and not at detector level
- Why does the 0th bin of the HT observable have such a large weight?
- How would you go about disentangling with certainty the Scalar (H) case vs Vector (Z') case?

Sample C) A heavy W' !



Features a resonance in a charged combination !

- Why is there already missing ET at the parton-level in this case?
- Observe how the invariant mass peak in m(j1, j2) gets 'washed out' when looking at detector plots.
- Can one deduce the mass of the resonance from the missing ET plot? How stable is this estimation when comparing it to the corresponding detector level plot?
- Why don't you find the m(b1, t1) plot at the detector level?

Conclusions

- Standard Model is Amazing (good news)
- S.M. is tough to Solve (good news!)
  - Factorization allows use of Perturbation Theory
  - Feynman Diagrams help
  - MG5aMC can help too
- LHC requires NLO (at least for the SM)
  - MG5aMC can help here too !!
- Good Luck!

Advice

- A person who can efficiently calculate cross sections can be useful to a collaboration
- A person who can efficiently calculate the CORRECT cross section is ESSENTIAL to a collaboration

NLO predictions

- **As an example, consider Drell-Yan Z/γ* production**

$$M \approx \langle \mu^+\mu^- \,|\, H_{\text{int}} \,|\, e^+e^- \rangle + \frac{1}{2}\langle \mu^+\mu^- \,|\, H_{\text{int}}^2 \,|\, e^+e^- \rangle + \ldots$$

$$\hat{\sigma} = \sigma^{\text{Born}}\left(1 + \frac{\alpha_s}{2\pi}\sigma^{(1)} + \ldots\right)$$