Software Tools in High Energy Physics

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Outline

Lecture 1

Motivation and introduction to collider physics, getting started with Madgraph

Lecture 2

Showering and hadronizing with Pythia, detector simulations with Delphes, analyses in ROOT

Lecture 3

Beyond the standard model in Madgraph, implementing new models in FeynRules

Resources

Much of this material has been adapted (or in some cases directly taken) from a number of very good resources online. Below I list some of the main resources I used in writing these lectures.

- Event Generation with Madgraph5, *Johan Alwall*, [1, 2, 3]
- The Madgraph/Madevent Generator, *Fabio Maltoni*, [Slides]
- Madgraph and CalcHEP, *Matt Buckley*, [Slides]

Additionally there are a number of arxiv reviews focussing on getting started with HEP computations. Some of these include

- Computer tools in particle physics, *Avelino Vicente*, *1507.06349*
- Introduction to SARAH and related tools, *Florian Staub*, *1509.07061*

Broad Motivation

The standard model is incomplete

- Dark matter
- Neutrino masses
- Baryon asymmetry
- Hierarchy problem

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Many proposed models occur at the weak scale

- Low energy supersymmetry
- Composite Higgs
- Little Higgs
- Twin Higgs
- Extra dimensions

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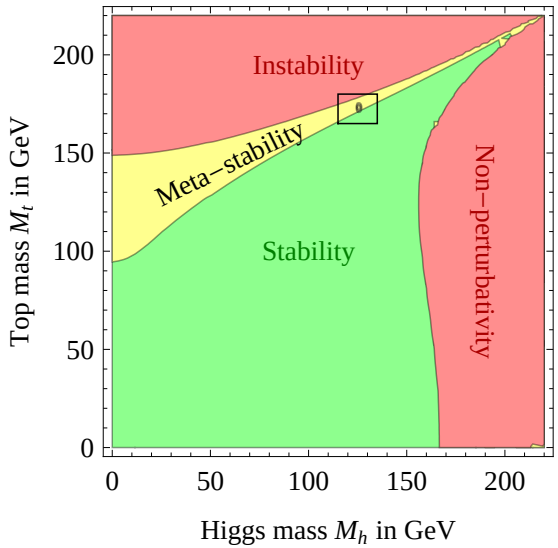
and the LHC is running!

Colliders: Measurements

- Identify an observable
- Calculate within the standard model
- Measure at an experiment

Can use to identify deviations from standard model predictions



Example: Higgs mass and top mass to determine stability of our vacuum.

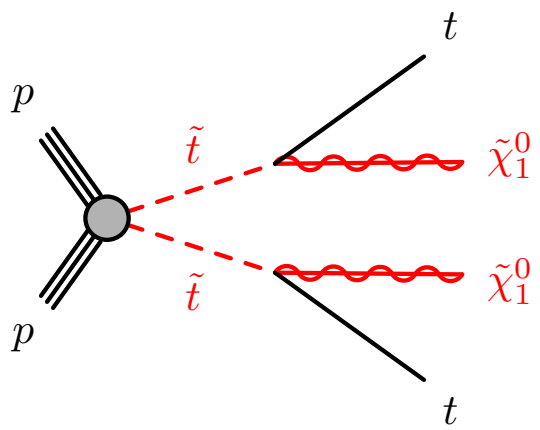
(Degrassi et al., 1205.6497)

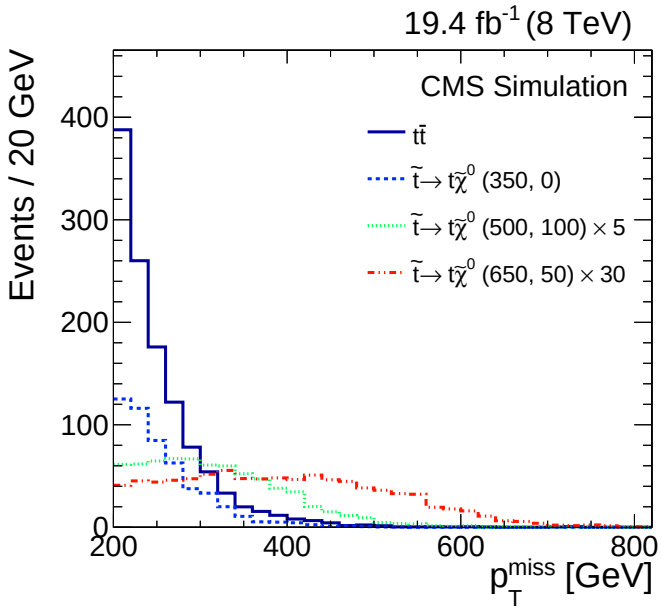
(CMS, 1503.08037)
(ATLAS, 1506.08616)

Colliders: Searches

- Identify a new physics model
- Choose a signature of that model
- Select cuts to isolate the signature

Directly constrain parameters of a new physics model





Example: Stop pair production

Motivation

(CMS, 1503.08037)
(ATLAS, 1506.08616)

Colliders: Searches

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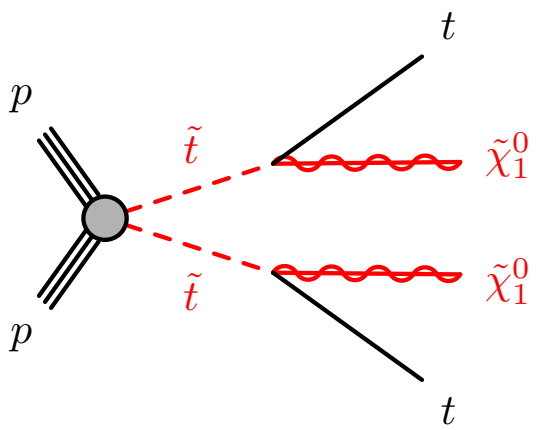
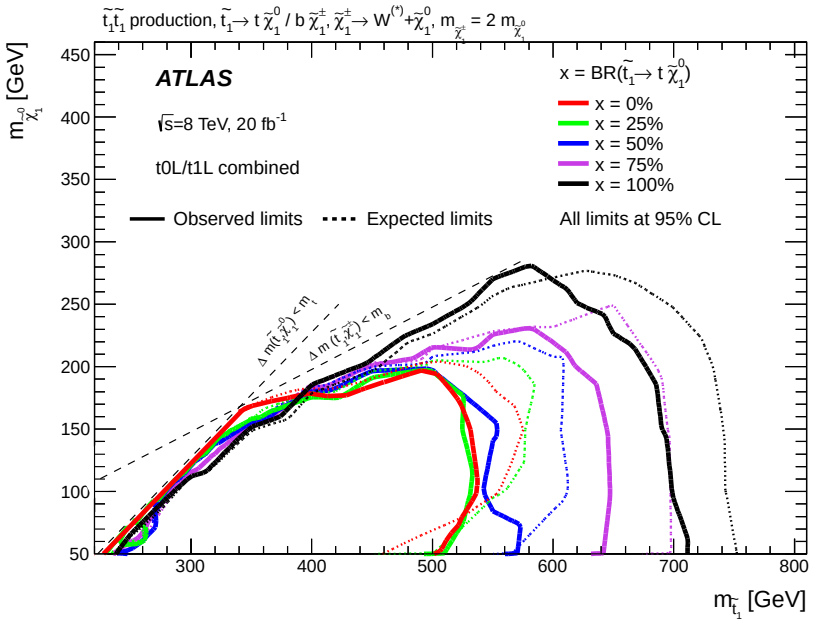




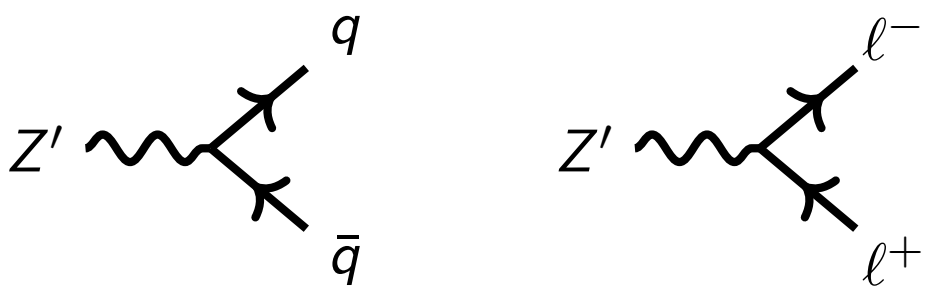
Example: Stop pair production

Cross-Sections

- Why are cross-sections important?
- Need to compute rates to look for new physics
- *Example:* Add a Z' to the standard model

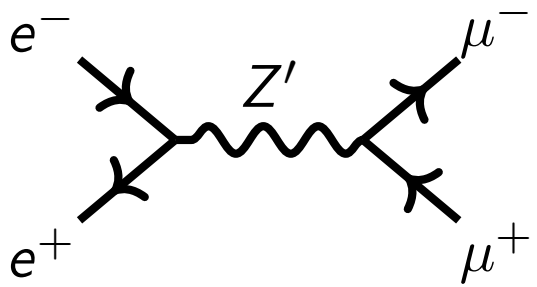
$$\mathcal{L}_{Z'} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \frac{1}{2} m^2_{Z'} Z'_{\mu} Z'^{\mu} + \sum_{f \in \text{fermions}} g_{Z'} Z'_{\mu} \bar{f} \gamma^{\mu} f .$$

- Interacts with leptons and quarks with coupling $g_{Z'}$



Cross-Sections

- *Example*: At an electron-positron collider, can produce via

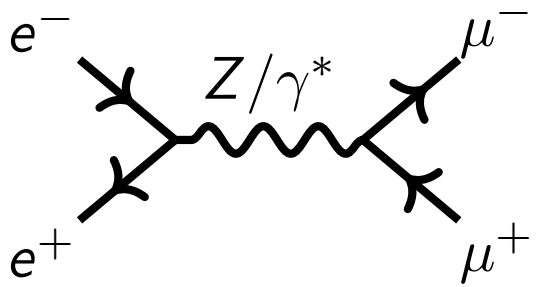


- Possible final state are muon pairs
- **Signal** cross-section would approximately be

$$\sigma_{Z'} = \frac{g_{Z'}^4}{12\pi} \frac{m_{Z'}^2}{(E_{cm}^2 - m_{Z'}^2)^2 + (m_{Z'}\Gamma)^2}$$

Cross-Sections

- To evaluate reach requires standard model background calculation



- **Background** cross-section is approximately (ignoring the Z and interference terms)

$$\sigma_\gamma = \frac{4\pi\alpha^2}{3E_{cm}^2}$$

Cross-Sections

- Number of events predicted is

$$N = \sigma \times \mathcal{L}$$

$N =$ number of events, $\sigma =$ cross-section, $\mathcal{L} =$ integrated luminosity

- Note that LHC has 20 fb^{-1} at 8 TeV, which means for $N_{\text{min}} \simeq 10$, signals of $\simeq 0.5$ fb could be tested. (In practice much less because of backgrounds)
- Statistical significance is about

$$\text{significance} = \frac{N_S}{\sqrt{N_B}}$$

N_S: number of signal events

N_B: number of background events

Cross-Sections

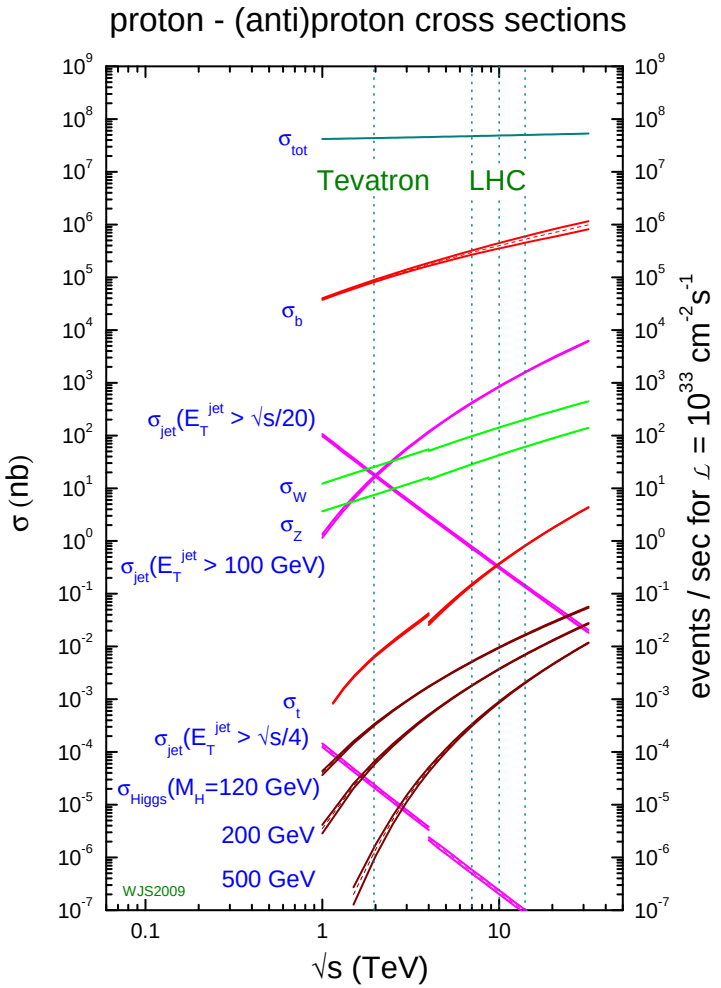
- To set limits
  - Run the experiment and count events
  - Set limits on $g_{Z'}$ and $m_{Z'}$ (or make discovery)
- Our calculation thus far has been analytic*
  - This is a simple example
  - We will show that using numerical approaches is inevitable

* See *1503:07209*, for an example of the limits that can be set with the above analytic calculation

Numerical approaches

1. proton-proton collisions

   - For e^+e^- collisions the cross-section goes like $1/E_{cm}^2$
   - Why do pp cross-sections increase with E_{cm}?

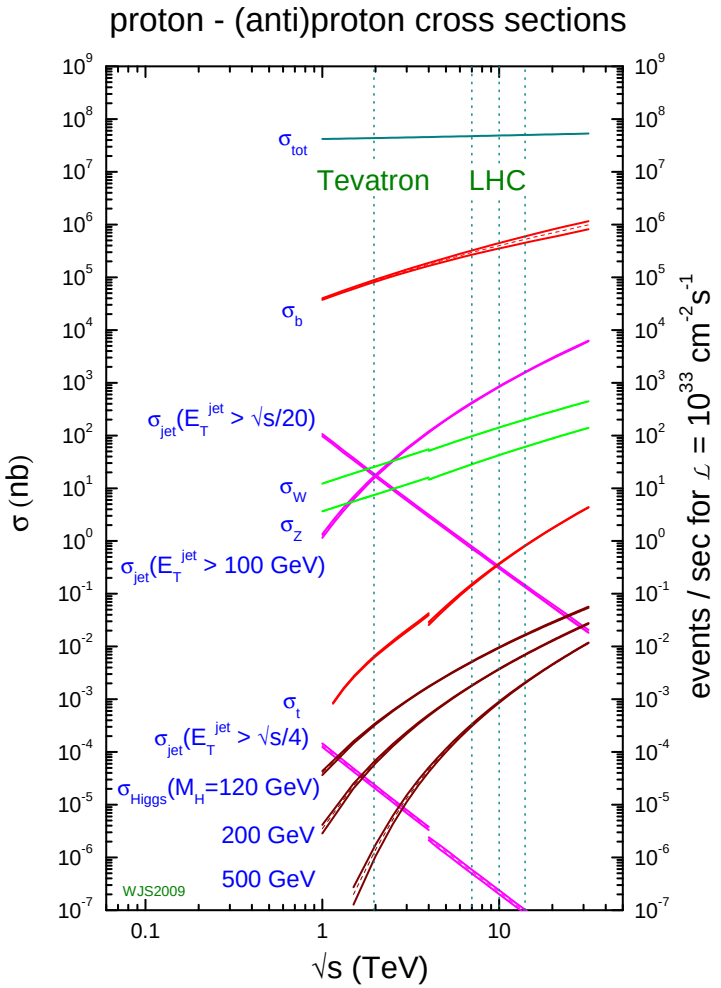


(1305.6131)

Numerical approaches

1. proton-proton collisions

- For e^+e^- collisions the cross-section goes like $1/E_{cm}^2$
- Why do pp cross-sections increase with E_{cm}?
- Parton distribution functions (PDFs)



(1305.6131)

Numerical approaches

1. proton-proton collisions

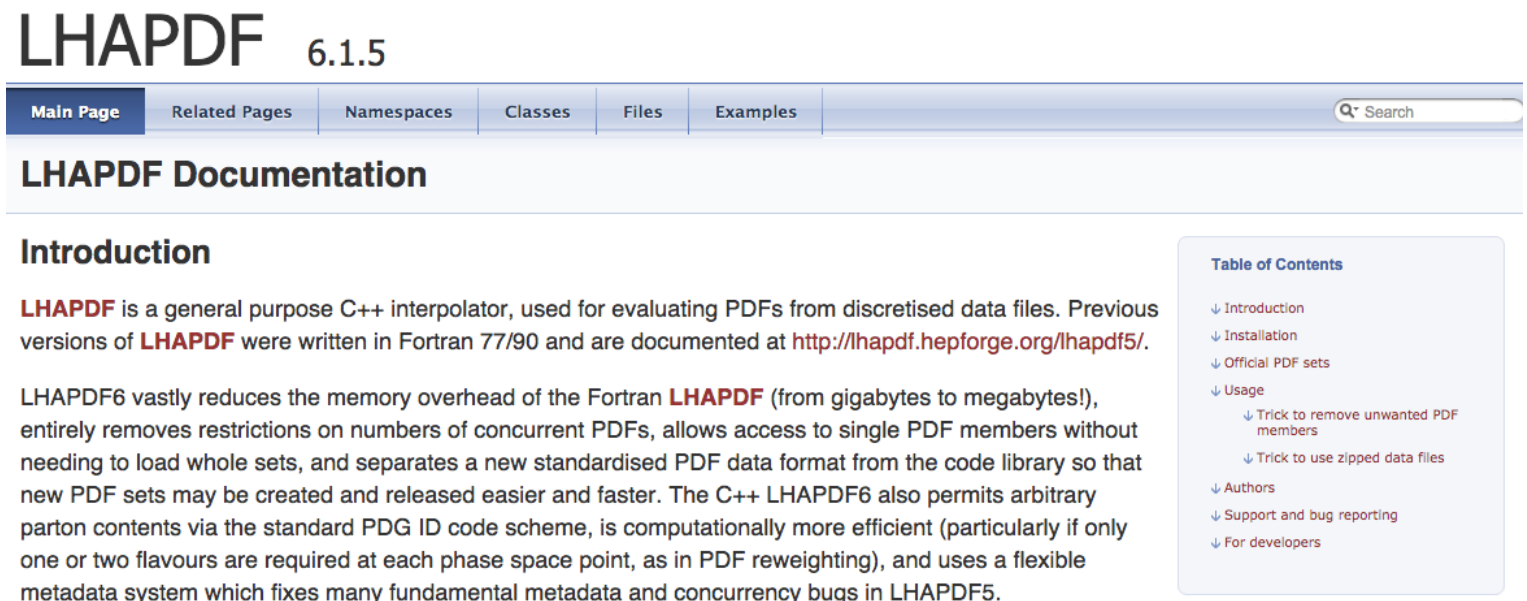
   - Master formula (for hadron collisions)

$$\sigma_{pp\to X}(s) = \sum_{a,b\in \text{partons}} \int dx_1 dx_2 f_a(x_1) f_b(x_2) \hat{\sigma}_{ab\to X}(x_1 x_2 s)$$

$$\begin{aligned} x &= \text{ parton momentum fraction of proton} \\ f_a(x) &= \text{ PDF for } a \text{ inside proton} \\ \hat{\sigma} &= \text{ parton cross-section} \end{aligned}$$

Numerical approaches

1. proton-proton collisions
   - PDFs are measured and are provided in "grids"
   - The program LHAPDF (`https://lhapdf.hepforge.org/`) allows you to download the grids and interpolates between grid points



Numerical approaches

1. proton-proton collisions *(aside)*

   - It is convenient to parameterize PDF effects in *parton luminosity*

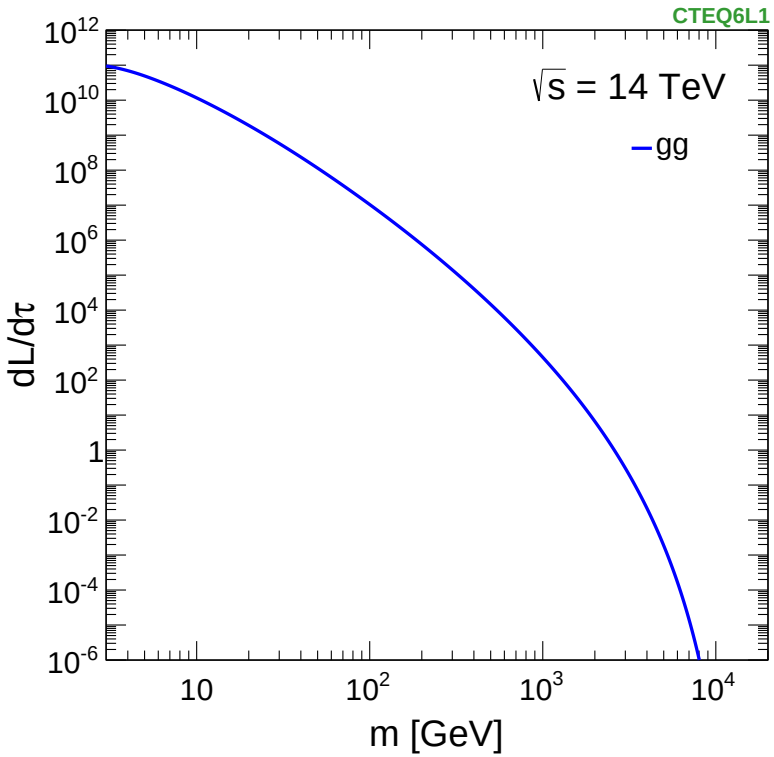
$$\sigma_{pp\to X}(s) = \sum_{a,b\in \text{partons}} \int d\tau \frac{dL_{ab}}{d\tau} \hat{\sigma}_{ab\to X}(\tau s)$$

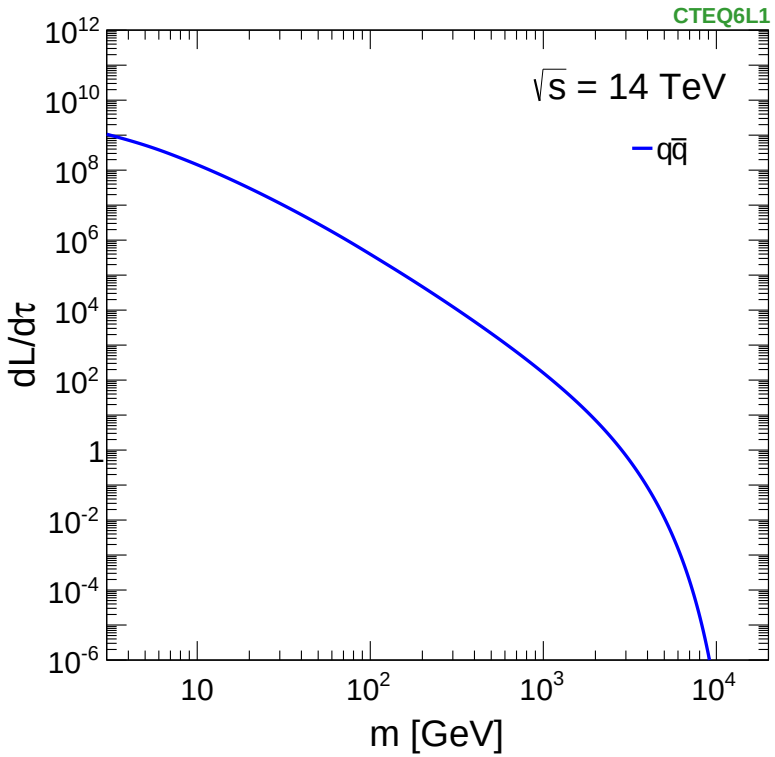
$$dL_{ab}/d\tau = \text{parton luminosity}$$

   - It characterizes luminosity of parton collisions as a function of $\tau = x_1 x_2$
   - Evolves very slowly with respect to s

Numerical approaches

1. proton-proton collisions *(aside)*
   - Parton luminosity falls very quickly with m (where $\tau = m^2/s$)

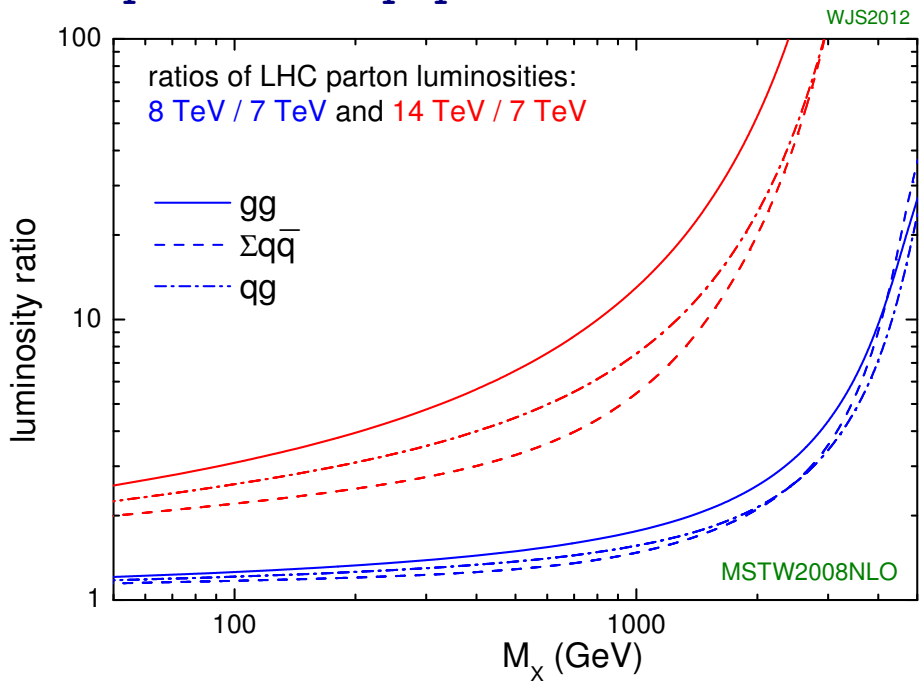




Numerical approaches

1. proton-proton collisions *(aside)*

   - Ratios are convenient to characterize increase in mass reach at different colliders
   - Sample plots at `http://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html`



Numerical approaches

2. phase space cuts

   - Returning to the Z' search, we don't directly measure the inclusive cross-section
   - *e.g.* detectors miss low energy muons

$$\int_{\text{detector}} \frac{d^2\sigma}{dE_{\mu^+} dE_{\mu^-}}$$

   - Even without the detector, signal enhanced (with respect to the background) with phase space cuts
   - *e.g.* cut on muon p_T, missing energy, etc.

Numerical approaches

2. phase space cuts

- We need to compute highly differential cross-sections
- To arrive at previous cross-section ($e^+e^- \to \mu^+\mu^-$)

$$\sigma_\gamma = \frac{4\pi\alpha^2}{3E_{cm}^2}$$

- We integrated $A + B \to 1 + 2$

$$d\sigma = \frac{1}{2E_A 2E_B |v_A - v_B|} \int \frac{d^3p_1}{(2\pi)^3 2E_1} \int \frac{d^3p_2}{(2\pi)^3 2E_2} |\mathcal{M}|^2 \times (2\pi)^4 \delta^{(4)}(p_A + p_B - p_1 - p_2)$$

Numerical approaches

2. phase space cuts

- General formula is (in total, we have $3n-4$ integrals) $A+B \to \{f\}$

$$d\sigma = \frac{1}{2E_A 2E_B |v_A - v_B|} \left(\prod_f \int \frac{d^3 p_f}{(2\pi)^3 2E_f} \right) |\mathcal{M}|^2 \times (2\pi)^4 \delta^{(4)}(p_A + p_B - \sum_f p_f)$$

- Above two-body, integration by hand becomes difficult

Numerical approaches

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3. repetitive

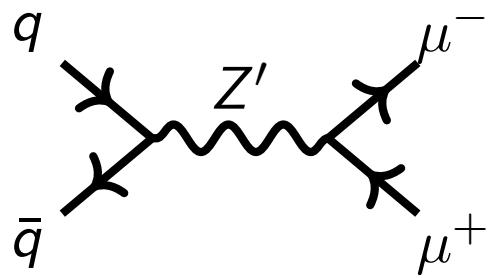
   - Computers are useful for repetitive tasks with well-defined rules

Calculation outline

- Determine relevant subprocesses

```
p p > Z' > mu+ mu-
```

- Compute matrix element



- Perform phase space integration

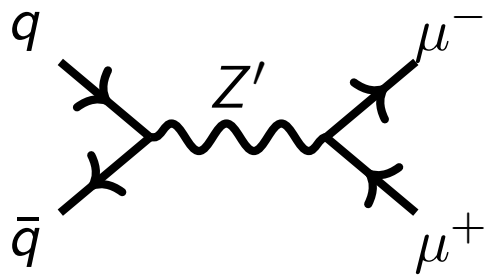
$$\sigma \sim \int d\Phi_n |\mathcal{M}|^2$$

Calculation outline

- Determine relevant subprocesses (Easy)

```
p p > Z' > mu+ mu-
```

- Compute matrix element (Hard)

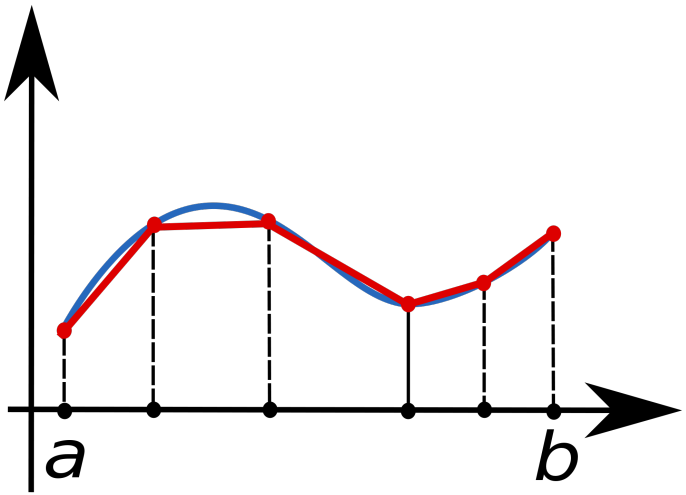


- Perform phase space integration (Very Hard)

$$\sigma \sim \int d\Phi_n |\mathcal{M}|^2$$

Numerical integration *(partially aside)*

- *Example:* in 1-dimension, can use Trapezoid method



$$I = \int f(x)dx$$

$$I_n = \frac{1}{n}\sum_{i=1}^{n} f(x_i)\Delta x_i$$

- Error converges as (for n points)

$$\mathcal{O}\left(\frac{1}{n^2}\right)$$

Numerical integration *(partially aside)*

- But in d-dimensions, integration becomes inefficient

$$I = \int f(x_1, \ldots, x_d) dx_1 \cdots dx_d$$

$$I_n = \frac{1}{n^d} \sum_{i_1=1}^{n} \cdots \sum_{i_d=1}^{n} f(x_{i_1}, \ldots, x_{i_d}) \Delta x_{i_1} \cdots \Delta x_{i_d}$$

- Error converges as

$$\mathcal{O}\left(\frac{1}{n^2}\right) = \mathcal{O}\left(\frac{1}{N^{2/d}}\right)$$

(n points per dimension, N points total)

Numerical integration *(partially aside)*

- Can use Monte Carlo methods

$$I_n = \frac{1}{N} \sum_{i_1=1}^{n} \cdots \sum_{i_d=1}^{n} f(x_{i_1}, \ldots, x_{i_d}) \Delta x_{i_1} \cdots \Delta x_{i_d}$$

- Generate random numbers $(x_{i_1}, \ldots, x_{i_d})$, evaluate f, and average
- Monte Carlo method converges (independent of d) as

$$\mathcal{O}\left(\frac{1}{N^{1/2}}\right)$$

- Often method of choice for high dimensional integrals

Monte Carlo

- Advantages:
  - Since generated $(x_{i_1}, \ldots, x_{i_d})$, can compute distribution for any observable
  - Can combine results (from independent integrations)

- Disadvantages:
  - Convergence is not that fast
  - Inefficient for non-flat functions (*e.g.* Lorentz peaks)

Monte Carlo

- Weighted vs. unweighted events
  - Generate point $(x_{i_1}, \ldots, x_{i_d})$ is an *event*.
  - **Weighted**: generation distributed by

$$\int f(x_1, \ldots, x_n) dx_1 \cdots dx_n$$

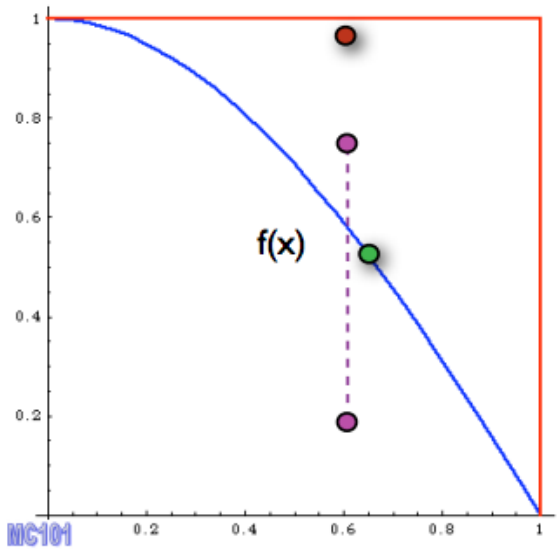
  - **Unweighted**: generation distributed by

$$\int f(x_1, \ldots, x_n) dx_1 \cdots dx_n$$

generate according to this PDF

Monte Carlo *(partially aside)*

- Acceptance/rejection method
  - Converts weighted events to unweighted events
  - Efficiency given by fraction of events accepted



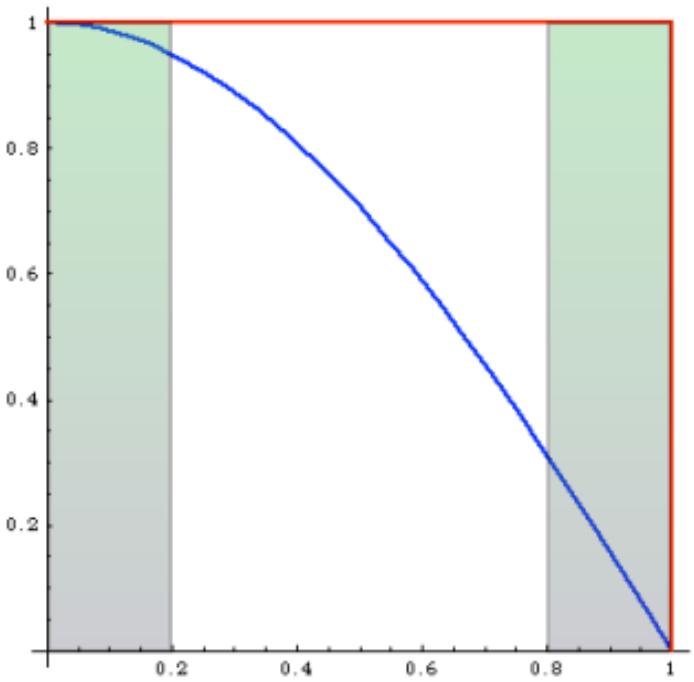
1. pick x
2. calculate f(x)
3. pick 0<y<fmax
4. Compare:
   if f(x)>y accept event,

   else reject it.

(Slide from Johan Alwall)

Monte Carlo *(partially aside)*

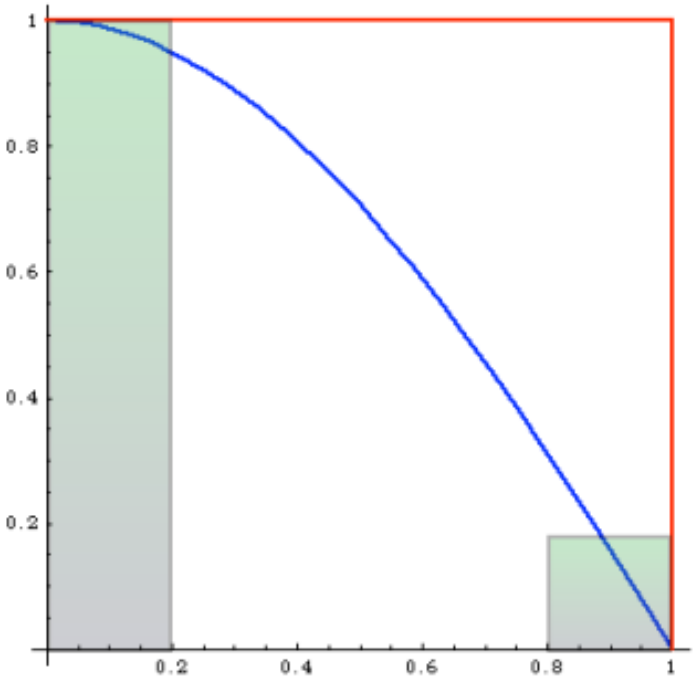
- Weighted events



- Same number of events in regions of phase space with very different probabilities
- Can be useful to populate tails

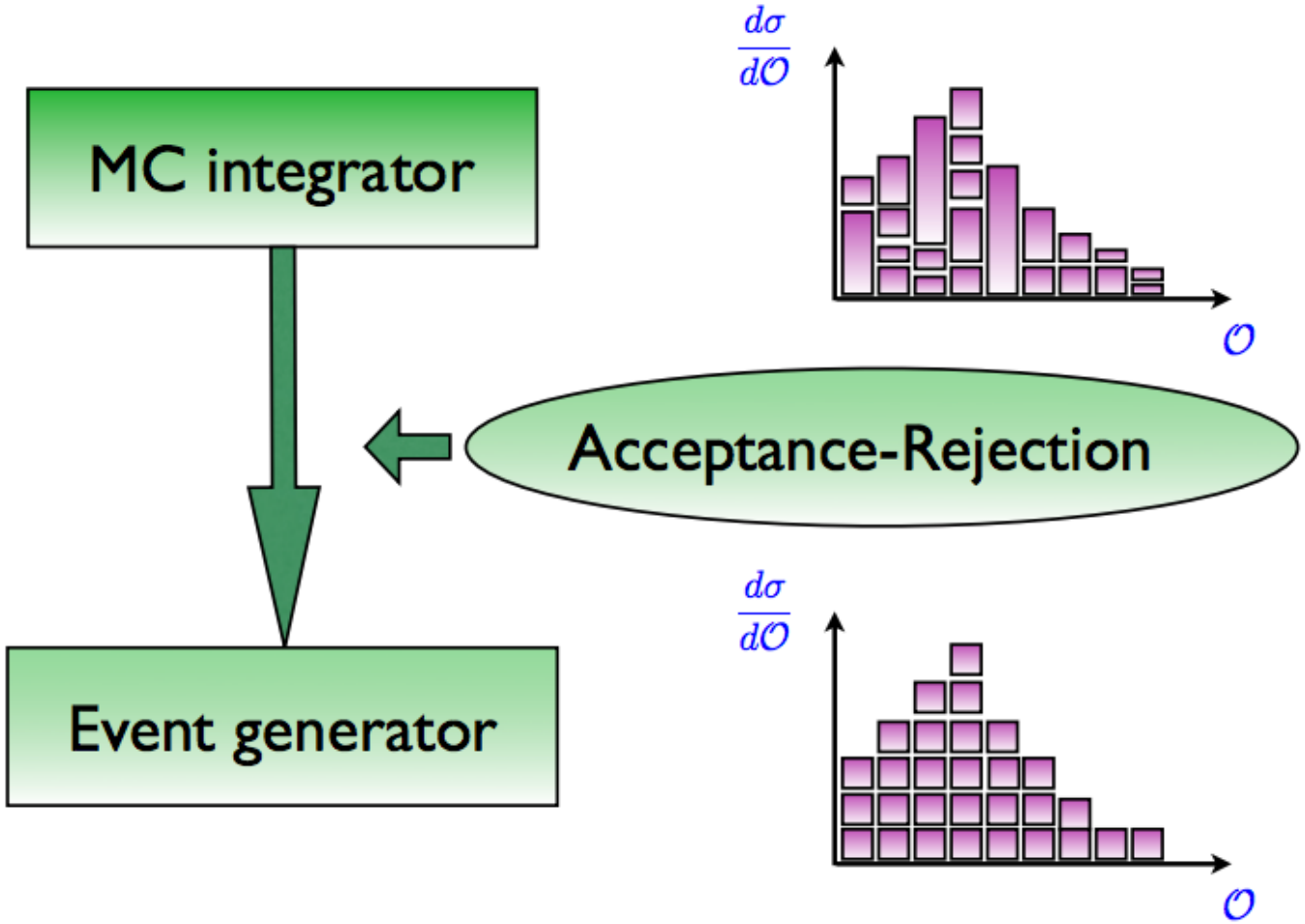
Monte Carlo *(partially aside)*

- Unweighted events



- Number of events proportional to probability of phase space
- Events distributed as in nature
- Can be interfaced simply with other shower/hadronization programs, detector simulations, etc.
- Provided by Madgraph

Monte Carlo Event Generator



Madgraph

"General purpose matrix-element based event generator"

Madgraph

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- Specify a physics process $pp \to e^- \bar{\nu}_e$

Madgraph

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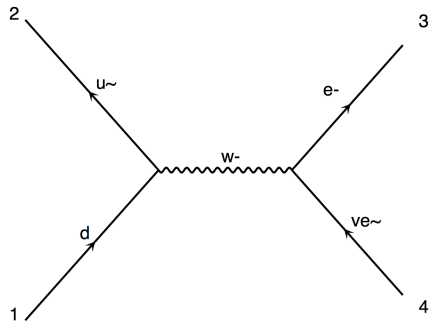
- Specify a physics process $pp \to e^- \bar{\nu}_e$
- Draws Feynman diagrams



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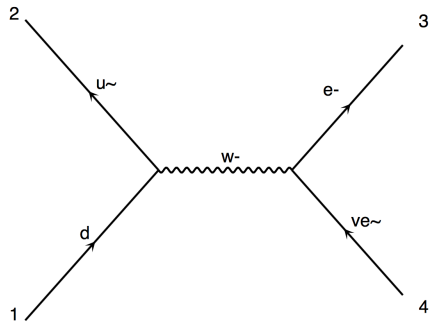

- Computes cross-sections

```
# Integrated weight (pb) :  0.49047E-01
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Madgraph

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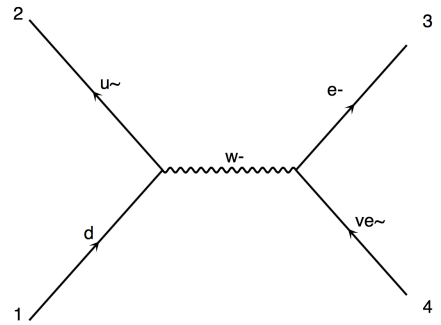

- Computes cross-sections

```
# Integrated weight (pb) :  0.49047E-01
```

- Generates unweighted events

`unweighted_events.lhe`

Madgraph

Very widely used *(in both experimental and theoretical communities)*

MadGraph 5 : Going Beyond
Johan Alwall (Fermilab), Michel Herquet (NIKHEF, Amsterdam), Fabio Maltoni, Olivier Mattelaer (Louvain U., CP3), Tim Stelzer (Illinois U., Urbana). Jun 2011. 37 pp.
Published in **JHEP 1106 (2011) 128**
FERMILAB-PUB-11-448-T
DOI: 10.1007/JHEP06(2011)128
e-Print: **arXiv:1106.0522 [hep-ph]** | PDF

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server ; ADS Abstract Service; Fermilab Library Server (fulltext available)

Detailed record - Cited by 1828 records 1000+

MadGraph/MadEvent v4: The New Web Generation
Johan Alwall (SLAC), Pavel Demin, Simon de Visscher, Rikkert Frederix, Michel Herquet, Fabio Maltoni (Louvain U., CP3), Tilman Plehn (Edinburgh U.), David L. Rainwater (Rochester U.), Tim Stelzer (Illinois U., Urbana). Jun 2007. 38 pp.
Published in **JHEP 0709 (2007) 028**
SLAC-PUB-12603, CP3-07-17
DOI: 10.1088/1126-6708/2007/09/028
e-Print: **arXiv:0706.2334 [hep-ph]** | PDF

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CERN Document Server ; ADS Abstract Service; JHEP Electronic Journal Server; SLAC Document Server

Detailed record - Cited by 1446 records 1000+

MadEvent: Automatic event generation with MadGraph
Fabio Maltoni, Tim Stelzer (Illinois U., Urbana). Aug 2002. 12 pp.
Published in **JHEP 0302 (2003) 027**
DOI: 10.1088/1126-6708/2003/02/027
e-Print: hep-ph/0208156 | PDF

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CERN Document Server ; ADS Abstract Service; JHEP Electronic Journal Server

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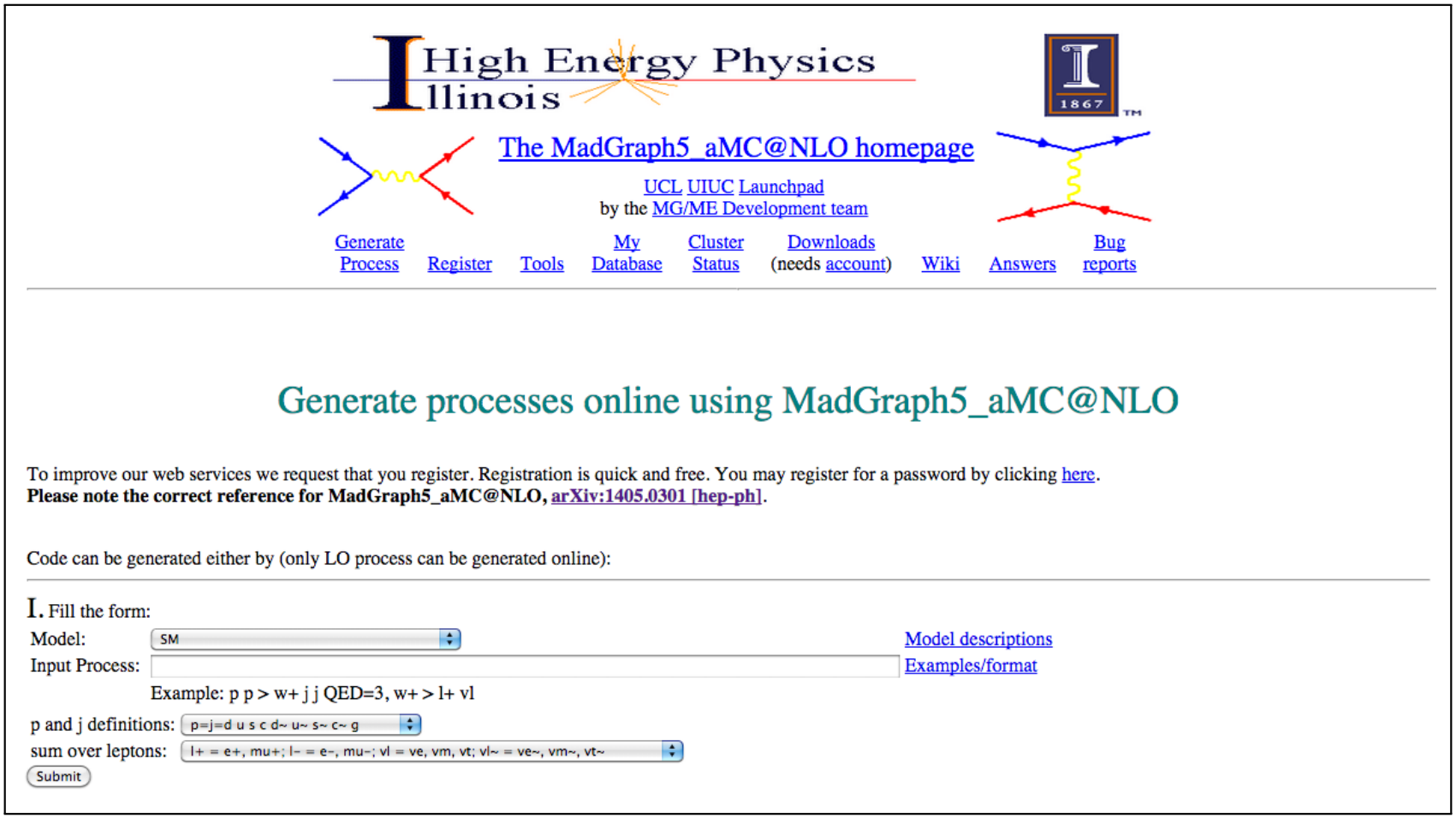
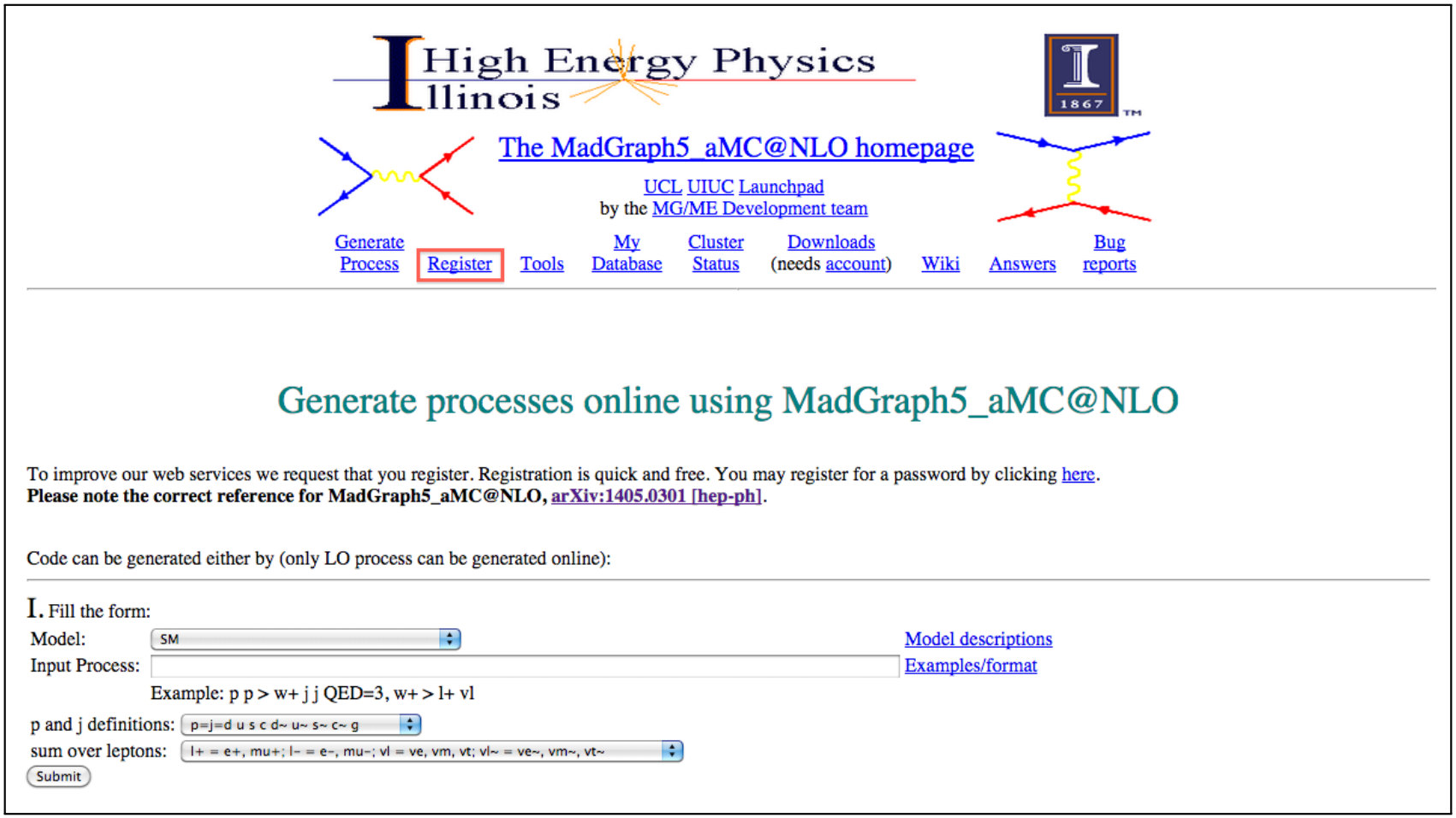
Getting started

`http://madgraph.hep.uiuc.edu/`



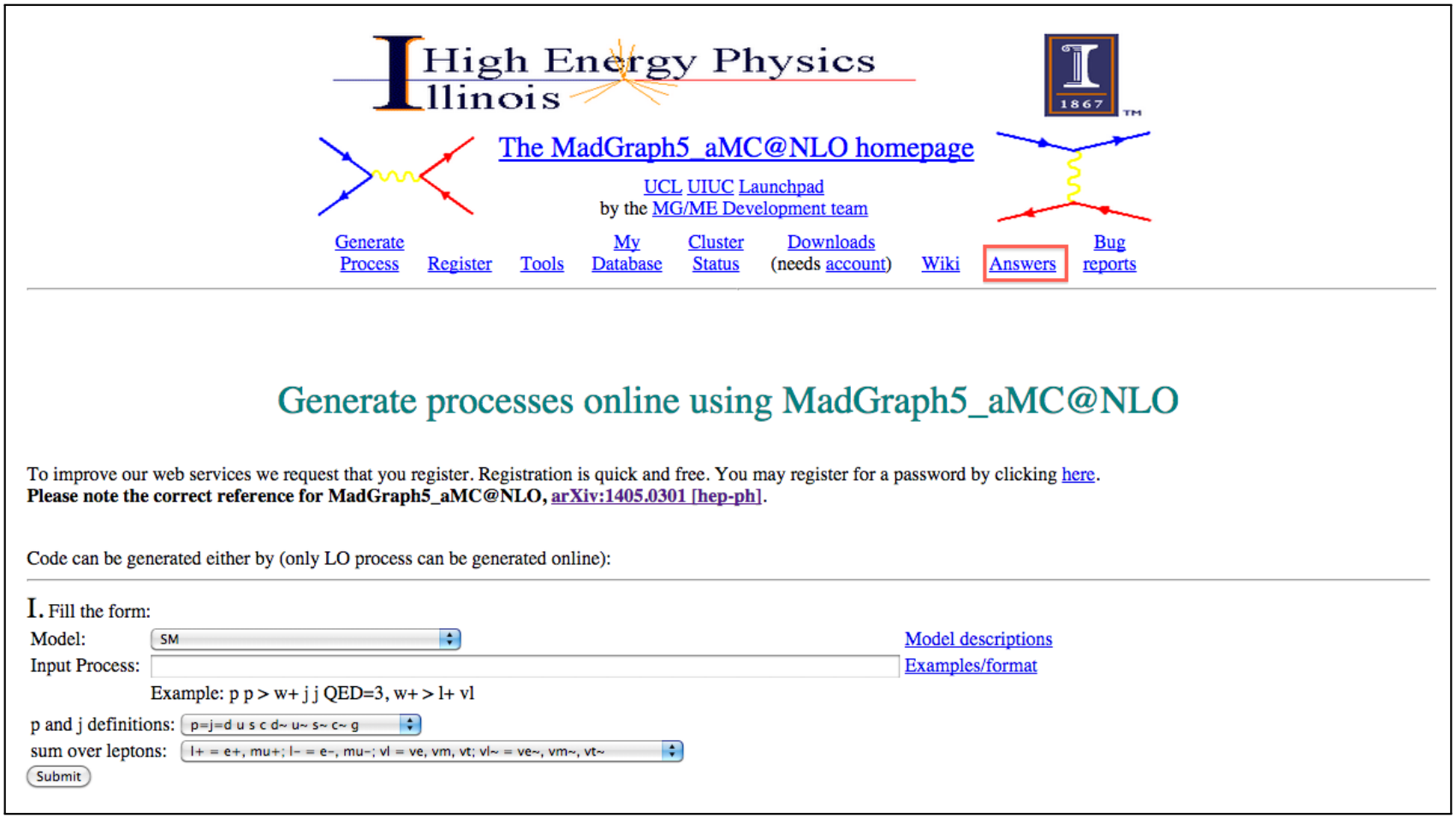
Getting started

→ Register for access to online resources



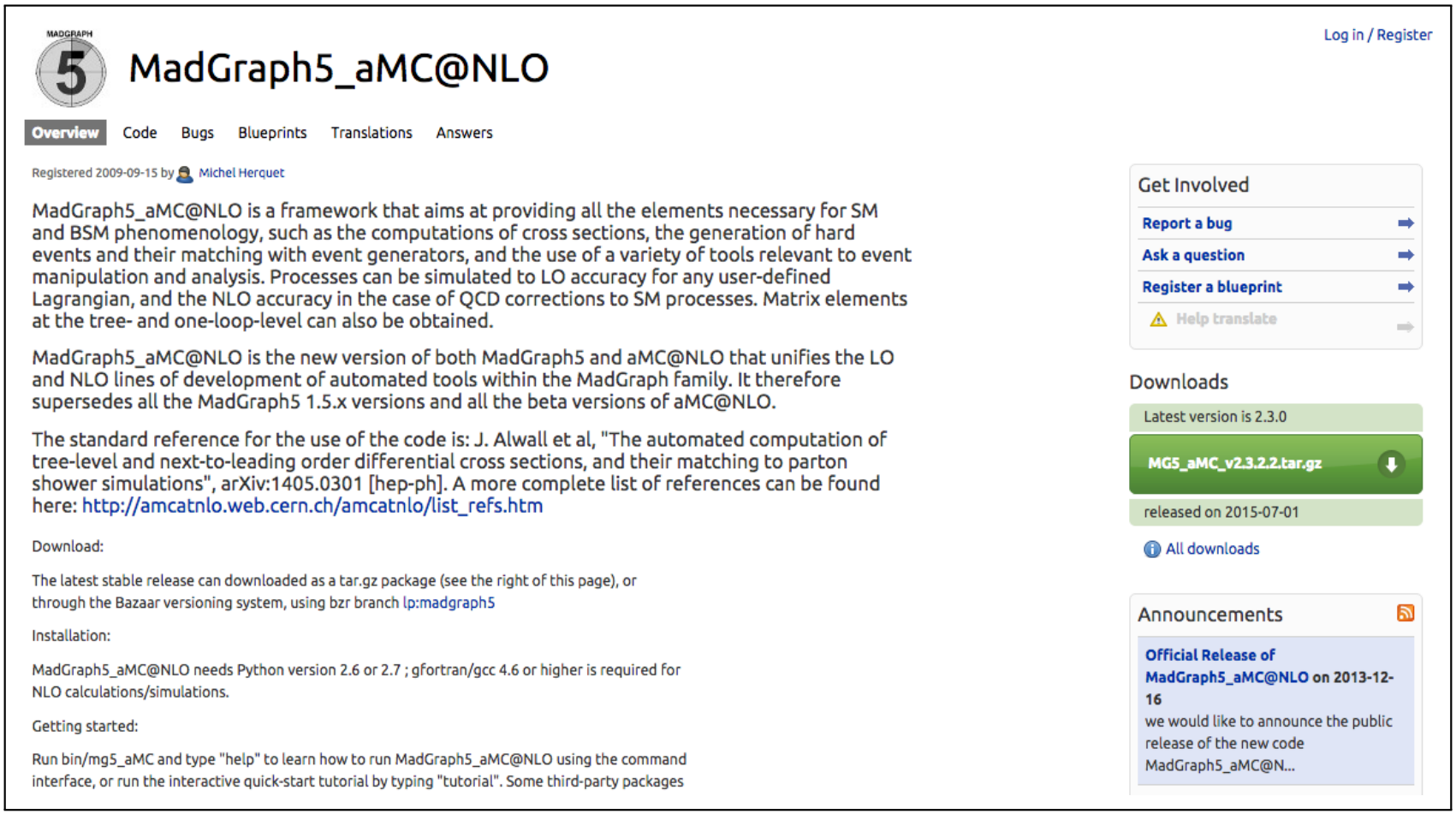
Getting started

→ Download links *and* Questions/Answers page



Getting started

`https://launchpad.net/mg5amcnlo`



MADGRAPH 5 MadGraph5_aMC@NLO

Log in / Register

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:madgraph5

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

Get Involved

Report a bug

Ask a question

Register a blueprint

Help translate

Downloads

Latest version is 2.3.0

MG5_aMC_v2.3.2.2.tar.gz

released on 2015-07-01

All downloads

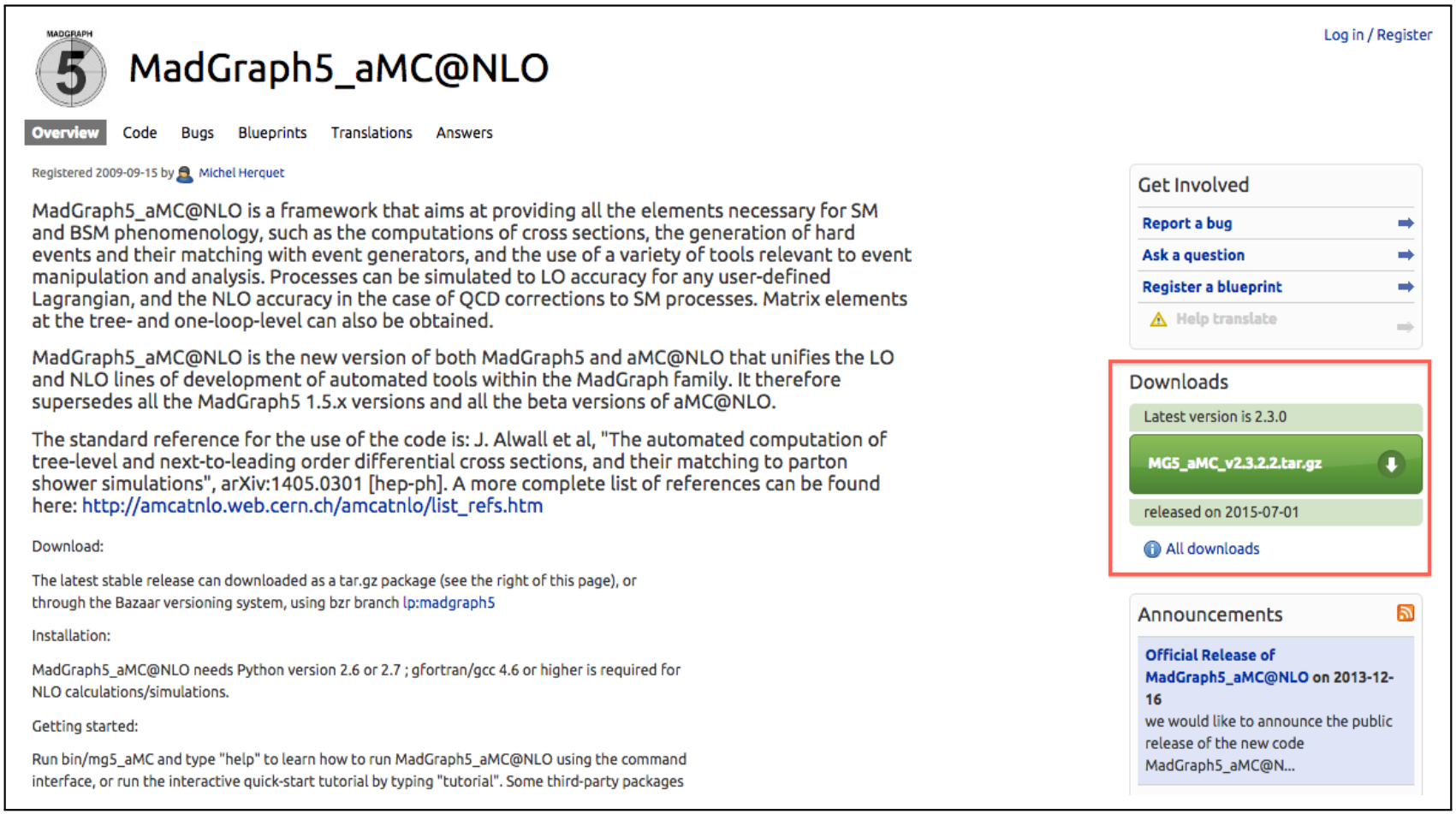
Announcements

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...

Getting started

→ Download current and past versions

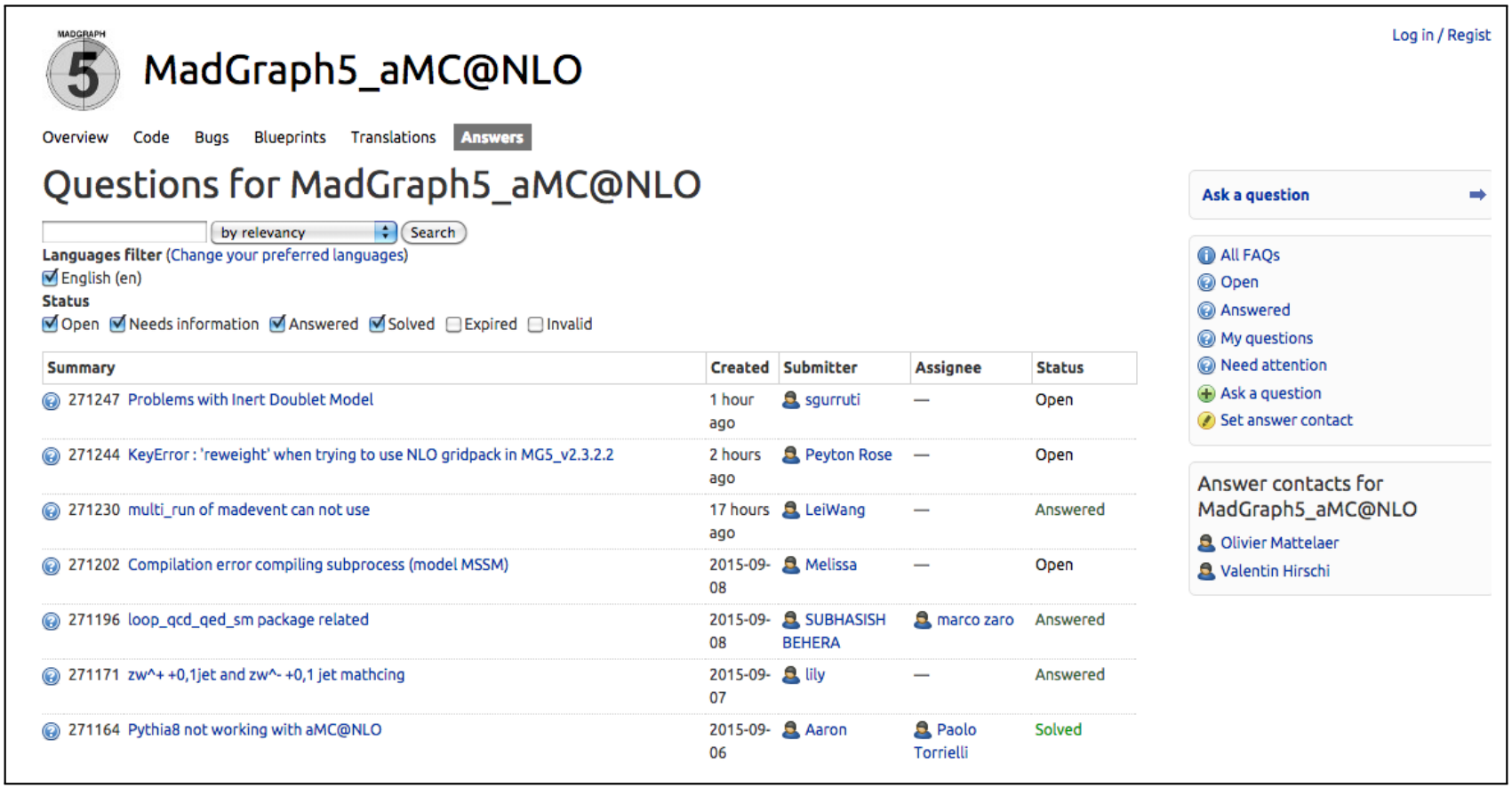


Getting started

→ Authors will help with (technical) questions.

Getting started

→ Many common problems are already addressed



MadGraph5_aMC@NLO

Log in / Regist

Overview Code Bugs Blueprints Translations **Answers**

Questions for MadGraph5_aMC@NLO

by relevancy Search

Languages filter (Change your preferred languages)

English (en)

Status

Open Needs information Answered Solved Expired Invalid

Summary	Created	Submitter	Assignee	Status
271247 Problems with Inert Doublet Model	1 hour ago	sgurruti	—	Open
271244 KeyError : 'reweight' when trying to use NLO gridpack in MG5_v2.3.2.2	2 hours ago	Peyton Rose	—	Open
271230 multi_run of madevent can not use	17 hours ago	LeiWang	—	Answered
271202 Compilation error compiling subprocess (model MSSM)	2015-09-08	Melissa	—	Open
271196 loop_qcd_qed_sm package related	2015-09-08	SUBHASISH BEHERA	marco zaro	Answered
271171 zw^+ +0,1jet and zw^- +0,1 jet mathcing	2015-09-07	lily	—	Answered
271164 Pythia8 not working with aMC@NLO	2015-09-06	Aaron	Paolo Torrielli	Solved

Ask a question

All FAQs
Open
Answered
My questions
Need attention
Ask a question
Set answer contact

Answer contacts for MadGraph5_aMC@NLO

Olivier Mattelaer
Valentin Hirschi

Getting started

- After downloading ($\sim$ 20 MB) and unzipping ($\sim$ 120 MB)

```
INSTALL
LICENSE
README
UpdateNotes.txt
VERSION
doc.tgz
```

- Version/update notes
- Brief notes on simple uses

Getting started

`HELAS`
`MadSpin`
`Template`
`aloha`
`doc`
`madgraph`
`mg5decay`
`tests`
`vendor`

- Code for modules
- Unlikely to need to modify

`proc_card.dat`
`bin`
`input`
`models`

- Specifies physics process
- Contains main executables
- Contains configuation settings
- Contains new physics models

Getting started

- Start with interactive mode:

```
> ./bin/mg5
Loading default model:  sm
...
Defined multiparticle p = g u c d s u~ c~ d~ s~
...
MG5_aMC>
```

Getting started

- Start with interactive mode:

```
> ./bin/mg5
Loading default model:  sm
...
Defined multiparticle p = g u c d s u~ c~ d~ s~
...
MG5_aMC> generate p p > e+ e-
```

Getting started

- Start with interactive mode:

```
> ./bin/mg5
Loading default model:  sm
...
Defined multiparticle p = g u c d s u~ c~ d~ s~
...
MG5_aMC> generate p p > e+ e-
...
4 processes with 8 diagrams generated in 0.313 s
Total:  4 processes with 8 diagrams
```

Getting started

- Start with interactive mode:

```
> ./bin/mg5
Loading default model:  sm
...
Defined multiparticle p = g u c d s u~ c~ d~ s~
...
MG5_aMC> generate p p > e+ e-
...
4 processes with 8 diagrams generated in 0.313 s
Total:  4 processes with 8 diagrams
MG5_aMC> add process p p > mu+ mu-
```

Getting started

- Start with interactive mode:

```
> ./bin/mg5
Loading default model:  sm
...
Defined multiparticle p = g u c d s u~ c~ d~ s~
...
MG5_aMC> generate p p > e+ e-
...
4 processes with 8 diagrams generated in 0.313 s
Total:  4 processes with 8 diagrams
MG5_aMC> add process p p > mu+ mu-
...
4 processes with 8 diagrams generated in 0.088 s
Total:  8 processes with 16 diagrams
```

Getting started

- Start with interactive mode:

```
MG5_aMC> output MyDileptonProcess
```

Getting started

- Start with interactive mode:

```
MG5_aMC> output MyDileptonProcess

Output to directory /MG5_aMC_v2_3_2_2/MyDileptonProcess done.
Type ‘‘launch’’ to generate events from this process, or see

/MG5_aMC_v2_3_2_2/MyDileptonProcess/README

Run ‘‘open index.html’’ to see more information about this process.
```

Getting started

- Start with interactive mode:

```
MG5_aMC> output MyDileptonProcess

Output to directory /MG5_aMC_v2_3_2_2/MyDileptonProcess done.
Type ‘‘launch’’ to generate events from this process, or see

/MG5_aMC_v2_3_2_2/MyDileptonProcess/README

Run ‘‘open index.html’’ to see more information about this process.
```

- Have created a *process*
- Subfolder `MyDileptonProcess` created (contains files needed for process)

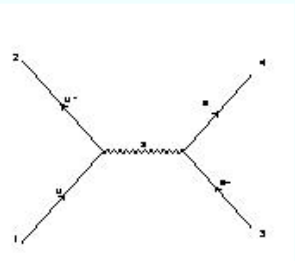
Getting started

```
MG5_aMC> open index.html
```

MadEvent Card for p p > e+ e-

Created: Unknown

Process: p p > e+ e-
Model: sm



Links	Status
Process Information	Generation Complete
Code Download	Available
On-line Event Generation	Only available from the web
Results and Event Database	No runs available

Notes:

Getting started

- Shows Feynman diagrams for the process

SubProcesses and Feynman diagrams

Directory	# Diagrams	# Subprocesses	FEYNMAN DIAGRAMS	SUBPROCESS
P0_qq_ll	2	8	html postscript	u u~ > e+ e- , c c~ > e+ e- , u u~ > mu+ mu- , c c~ > mu+ mu- , u~ u > e+ e- , c~ c > e+ e- , u~ u > mu+ mu- , c~ c > mu+ mu-
	2	8	html postscript	d d~ > e+ e- , s s~ > e+ e- , d d~ > mu+ mu- , s s~ > mu+ mu- , d~ d > e+ e- , s~ s > e+ e- , d~ d > mu+ mu- , s~ s > mu+ mu-

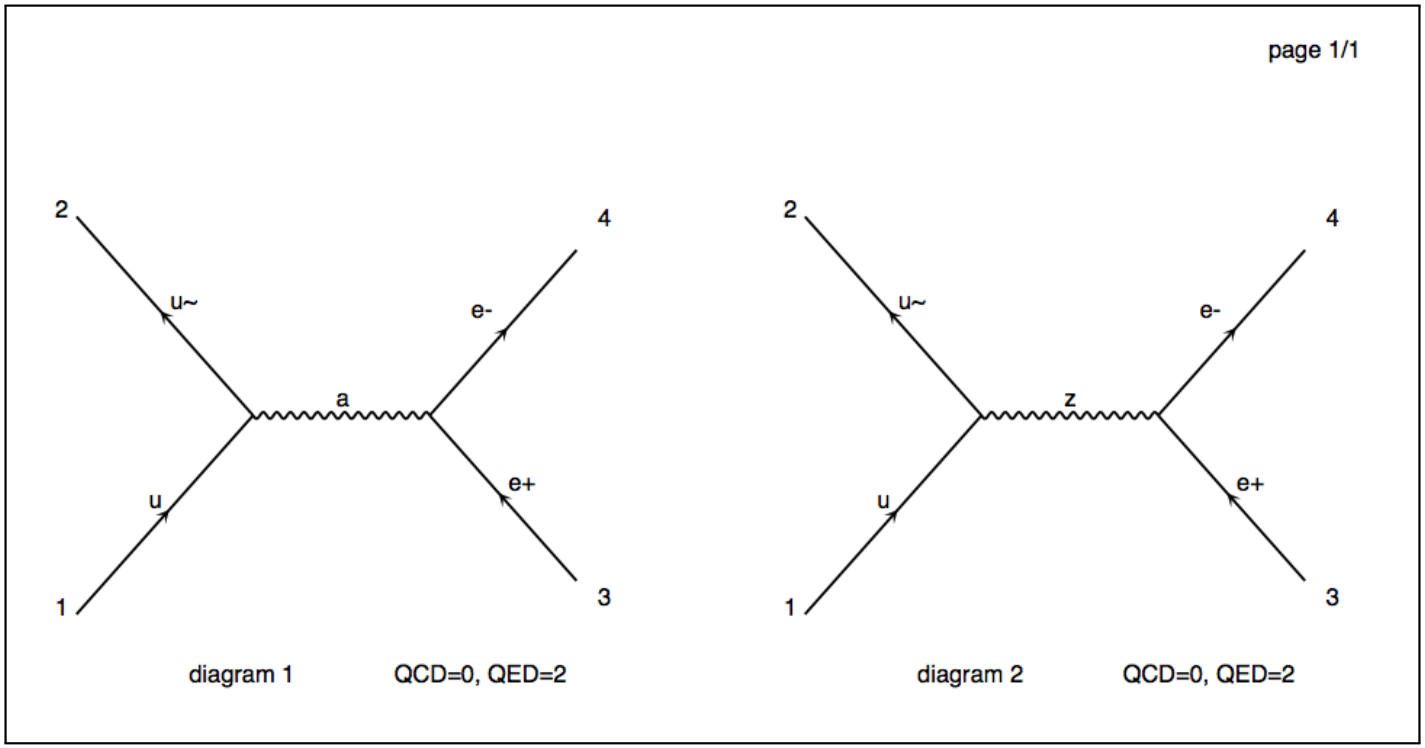
32 diagrams (4 independent).

proc_card_mg5.dat Input file used for code generation.

Back to Process main page

Getting started

- `QCD=0, QED=2` tracks the order of the diagram (more on this later)



Getting started

- Code for this process stored in `MyDileptonProcess` folder
- Let's generate some events

```
MG5_aMC> launch MyDileptonProcess
```

Getting started

- Code for this process stored in `MyDileptonProcess` folder
- Let's generate some events

```
MG5_aMC> launch MyDileptonProcess
generate_events run_01
The following switches determine which programs are run:
1 Run the pythia shower/hadronization:  pythia=NOT INSTALLED
...
Type '0', 'auto', 'done' or just press enter when you are done.
[0, 4, 5, auto, done, madspin=ON, madspin=OFF, madspin, parton]...
> (Just press return)
```

(It is asking which other programs to run, we will cover this later)

Getting started

- Code for this process stored in `MyDileptonProcess` folder
- Let's generate some events

```
MG5_aMC> launch MyDileptonProcess
...
Do you want to edit a card (press enter to bypass editing)?
1 / param :  param_card.dat
2 / run :  run_card.dat
[0, done, 1, param, 2, run, enter path][60s to answer]
> (Just press return)
```

(It is asking about run settings, we will cover this soon)

Getting started

- Page automatically opens which reports status of running
- *Currently Running*: in progress
- *Available Results*: stored results

Results in the sm for p p > e+ e- , p p > mu+ mu-

Currently Running

Run Name	Tag Name	Cards	Results	Status/Jobs		
				Queued	Running	Done
run_01	tag_1	param_card run_card plot_card	No results yet	compile directory		

Available Results

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 6500.0 x 6500.0 GeV	tag_1	0 ± 0	No events yet		banner only	remove run / re-run from the banner

Main Page

Getting started

- Page automatically opens which reports status of running
- *Currently Running*: in progress
- *Available Results*: stored results

Results in the sm for p p > e+ e- , p p > mu+ mu-

Currently Running

Run Name	Tag Name	Cards	Results	Status/Jobs		
				Queued	Running	Done
run_01	tag_1	param_card run_card plot_card	No results yet	Refine results to 10000		

Available Results

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 6500.0 x 6500.0 GeV	tag_1	0 ± 0	No events yet		banner only	remove run / re-run from the banner

Main Page

Getting started

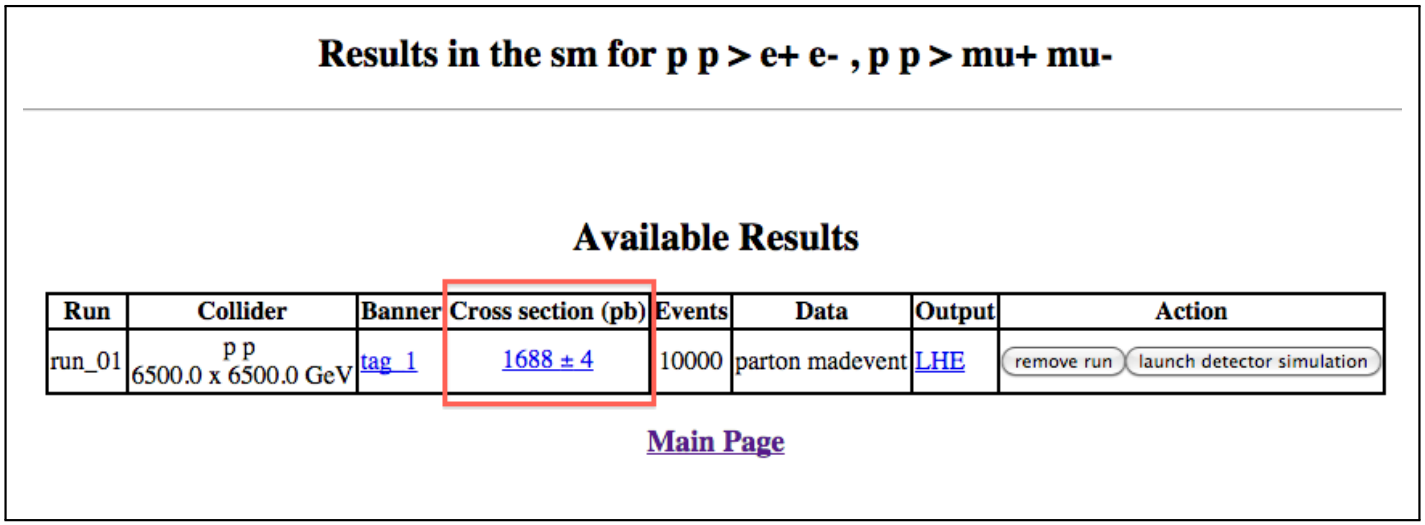
Results in the sm for p p > e+ e- , p p > mu+ mu-

Available Results

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 6500.0 x 6500.0 GeV	tag_1	1688 ± 4	10000	parton madevent	LHE	remove run / launch detector simulation

Main Page

Getting started



Results in the sm for p p > e+ e- , p p > mu+ mu-

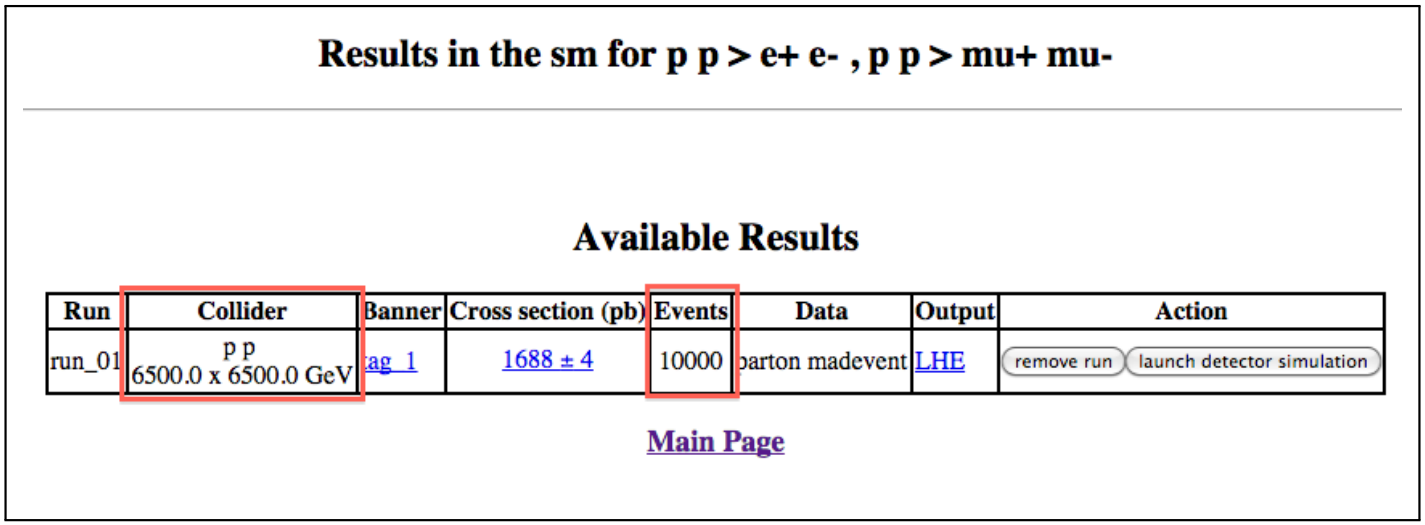
Available Results

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 6500.0 x 6500.0 GeV	tag_1	1688 ± 4	10000	parton madevent	LHE	remove run / launch detector simulation

Main Page

- Run output:
  - Reports computed cross-section (1688 ± 4 pb)

Getting started



Results in the sm for p p > e+ e- , p p > mu+ mu-

Available Results

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 6500.0 x 6500.0 GeV	ag_1	1688 ± 4	10000	parton madevent	LHE	remove run / launch detector simulation

Main Page

- Run settings:
  - Center of mass energy (13 TeV)
  - Colliding beams (pp)
  - Number of events (10000)

Selecting run settings

- Madgraph settings are all controlled via *cards*
- Stored in `ProcessDirectory/Cards`
- Relevant cards are:
  - `proc_card.dat`: Record of the process we chose
  - `run_card.dat`: Specifies the run settings
  - `param_card.dat`: Changes model parameters
  - `pythia_card.dat`: Specify shower/hadronization settings
  - `delphes_card.dat`: Detector simulation parameters

Selecting run settings

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  - `pythia_card.dat`: Specify shower/hadronization settings
  - `delphes_card.dat`: Detector simulation parameters

Lecture 2

Process settings

```
> cat proc_card_mg5.dat
import model sm
define p = g u c d s u~ c~ d~ s~
define j = g u c d s u~ c~ d~ s~
define l+ = e+ mu+
define l- = e- mu-
define vl = ve vm vt
define vl~ = ve~ vm~ vt~
generate p p > e+ e-
add process p p > mu+ mu-
output MyDileptonProcess
```

Process settings – Syntax

- Specify first process by `generate`
- Specify additional processes by `add process`
- `define p = ...` defines what can be inside the proton
- `define l+ = e+ mu-...` defines a "lepton"
- Can use the shorthand to simplify our example to:

```
generate p p > l+ l-
```

- Particles all have text names (`http://madgraph.hep.uiuc.edu/sm_particles.html`)

Process settings – Syntax

- Additional syntax found at

  `http://madgraph.hep.uiuc.edu/EXAMPLES/example.html`

Process settings – Syntax

- Additional syntax found at
  `http://madgraph.hep.uiuc.edu/EXAMPLES/example.html`

- *Example:* Can choose decays by listing with a comma

```
generate p p > w+ w- , w+ > l+ vl , w- > j j
```

- *Example:* Can exclude particles from diagrams with a slash

```
generate p p > w+ w- / z
```

Run settings

- Specify collider settings and phase space cuts.

```
10000 = nevents !  Number of unweighted events requested
0 = iseed !  rnd seed (0=assigned automatically=default)

1 = lpp1 !  beam 1 type

1 = lpp2 !  beam 2 type
20 = ptj !  minimum pt for the jets
0 = ptb !  minimum pt for the b
10 = pta !  minimum pt for the photons
10 = ptl !  minimum pt for the charged leptons
```

Run settings

- Take note of phase space cuts:
  1. Can change the value of the cross-section

Run settings

- Take note of phase space cuts:

  1. Can change the value of the cross-section

Available Results

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 6500.0 x 6500.0 GeV	tag_1	2325 ± 7	10000	parton madevent	LHE	remove run / launch detector simulation
run_02	p p 6500.0 x 6500.0 GeV	tag_1	568.7 ± 2.2	10000	parton madevent	LHE	remove run / launch detector simulation
run_03	p p 6500.0 x 6500.0 GeV	tag_1	104.5 ± 0.28	10000	parton madevent	LHE	remove run / launch detector simulation
run_04	p p 6500.0 x 6500.0 GeV	tag_1	9.823 ± 0.029	10000	parton madevent	LHE	remove run / launch detector simulation

Main Page

- Varied value of `misset` in each run

Run settings

- Take note of phase space cuts:

  2 For practical use, often need cuts (stricter than the default)

Example: search for a jet and missing energy

```
p p > z j , z > vl vl~
```

Available Results

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 6500.0 x 6500.0 GeV	tag_1	2325 ± 7	10000	parton madevent	LHE	remove run / launch detector simulation

Main Page

$$\mathcal{L} = \frac{N}{\sigma} = \frac{10000}{2325\ \text{pb}} = 4\ \text{pb}^{-1}$$

Run settings

- Take note of phase space cuts:
  2. For practical use, often need cuts (stricter than the default)

$$\mathcal{L} = \frac{N}{\sigma} = \frac{10000}{2325 \text{ pb}} = 4 \text{ pb}^{-1}$$

  - Would need $(20 \text{ fb}^{-1}/4 \text{ pb}^{-1}) \times 10000 = 5 \times 10^8$ events

Run settings

- Take note of phase space cuts:
  2. For practical use, often need cuts (stricter than the default)

$$\mathcal{L} = \frac{N}{\sigma} = \frac{10000}{2325 \text{ pb}} = 4 \text{ pb}^{-1}$$

  - Would need $(20 \text{ fb}^{-1}/4 \text{ pb}^{-1}) \times 10000 = 5 \times 10^8$ events
  - Using `misset` cut is convenient here

$$\mathcal{L} = \frac{N}{\sigma} \simeq \frac{10000}{10 \text{ pb}} = 1 \text{ fb}^{-1}$$

  - Only about 200k events needed

Run settings

- Take note of phase space cuts:

  3 Cut off singular parts of phase space

  Example: Z and 2 jets

  ```
  p p > z j j
  ```

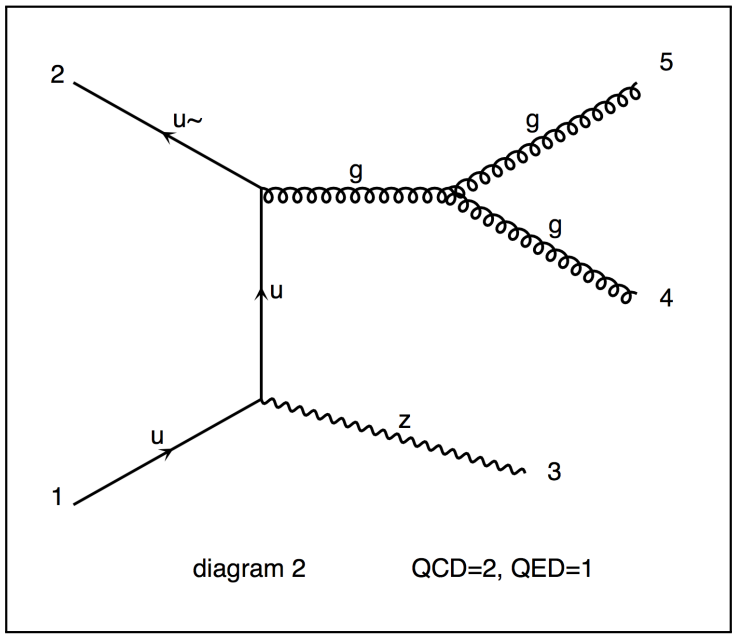
- Default run settings are

  ```
  20.0 = ptj !  minimum pt for the jets
  0.4 = drjj !  min distance between jets
  ```

- What happens if these are both set to 0?

Run settings

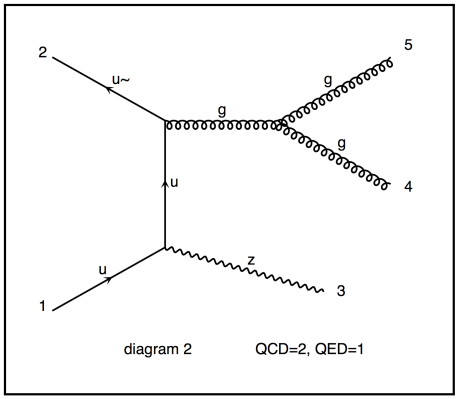
- The cross-section diverges
  - A sign of this is that there are less events generated than were specified in the run card
  - The generation can also take a very long time



Madgraph

- The splitting function of $g \to gg$

$$P_{g \to gg} \propto \frac{1-z}{z} + \frac{z}{1-z} + z(1-z)$$



- z is energy fraction carried by one outgoing gluon
- Has soft divergence for $z \to 0$
- `ptj` cut regulates the soft divergence
- `drjj` cut regulates the collinear divergence
  (or `mmjj`, the invariant mass of pairs of jets also does this)

Lecture 1 Summary

- Accurately generating Monte Carlo events is an indispensible tool for studying new physics
- Madgraph is a general purpose matrix-element based event generator
- Compute matrix element and integrates multibody phase space
- Processes specified in `proc_card.dat`
- Phase space cuts specified in `run_card.dat`