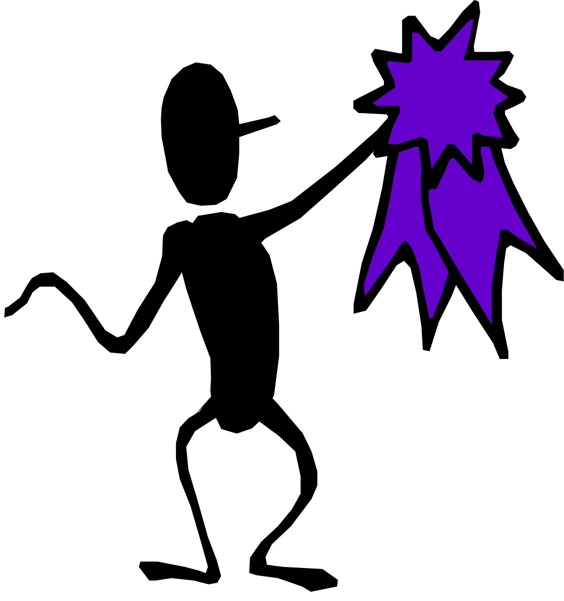
MadGraph5_aMC@NLO

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

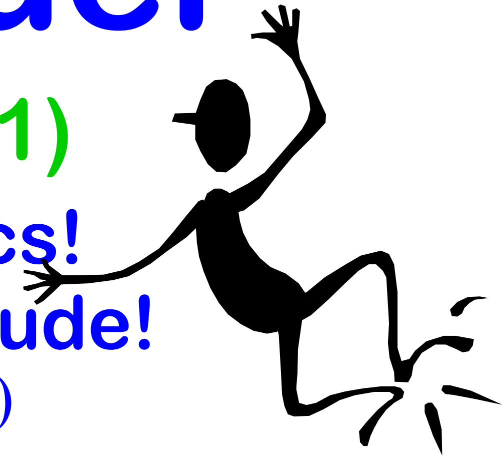
Valentin Hirschi and Olivier Mattelaer

Plan

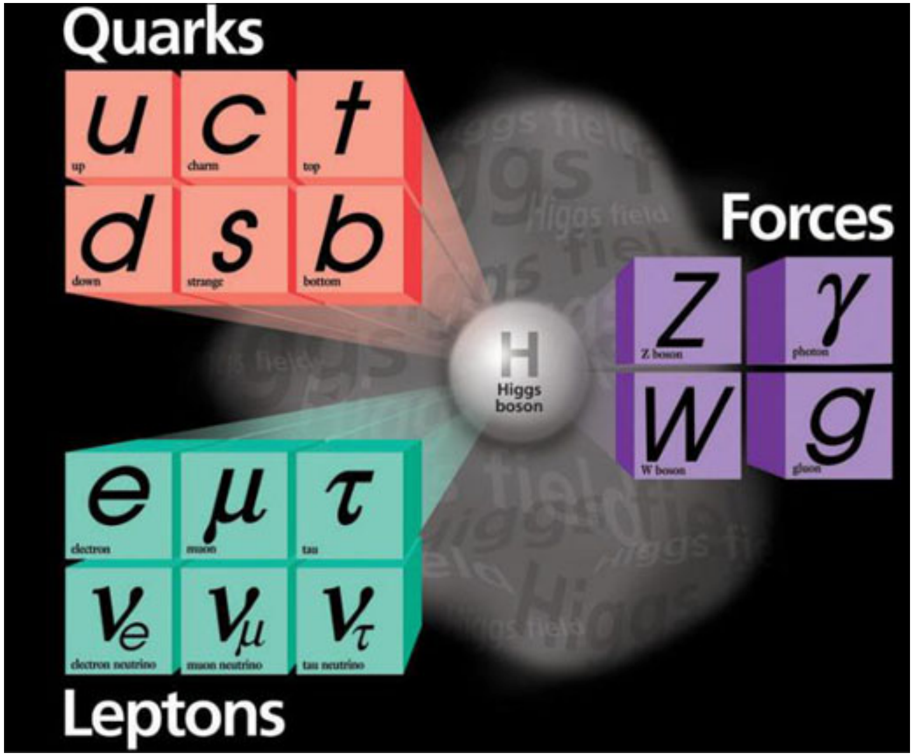


- Overview of Standard Model
  - Introduction to Particle Physics
  - The Standard Model
- Parton level calculations
- Full Event Simulations
- Identify 3 Newly Discovered Particles

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)

Standard Model

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

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

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

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

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

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

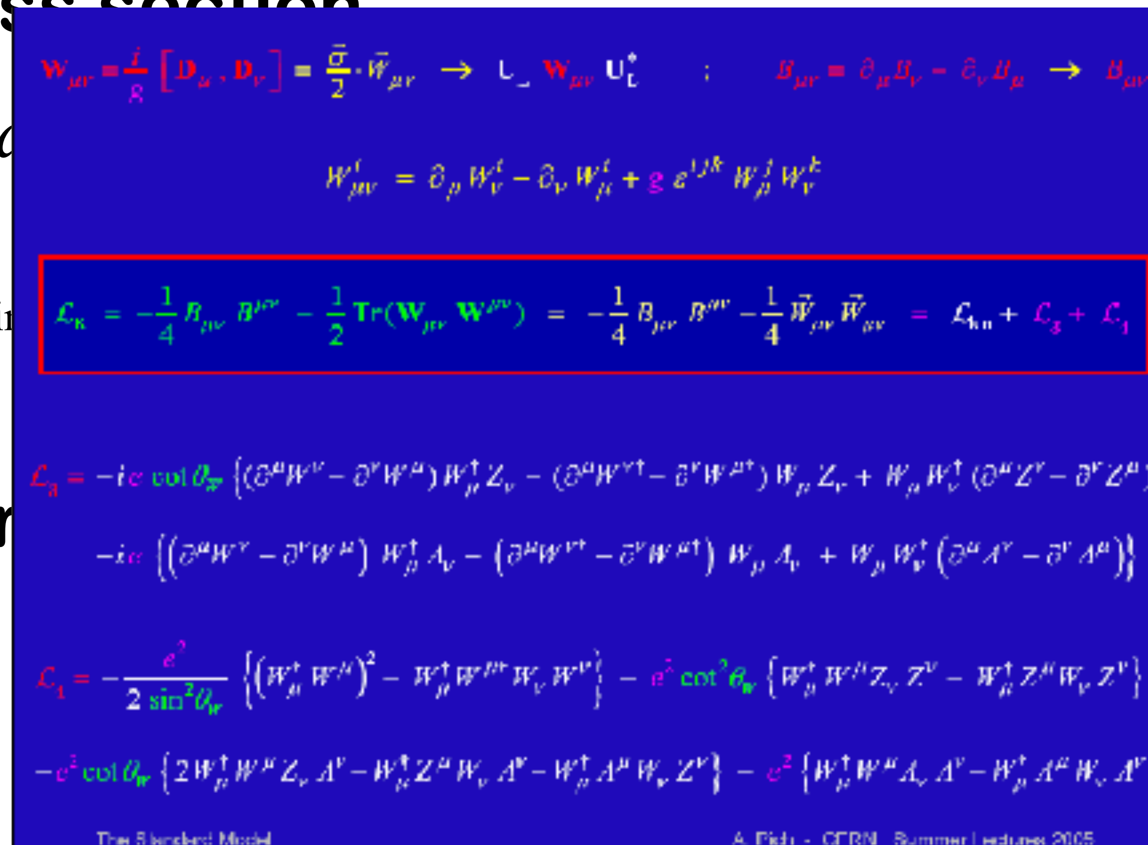
$$M \approx \left\langle \mu^+\mu^- \,|\, H_{\text{int}} \,|\, e^+e^- \right\rangle + \frac{1}{2}\left\langle \mu^+\mu^- \,|\, H_{\text{int}}^2 \,|\, e^+e^- \right\rangle + \ldots$$

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

- **Scattering cross section**

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

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

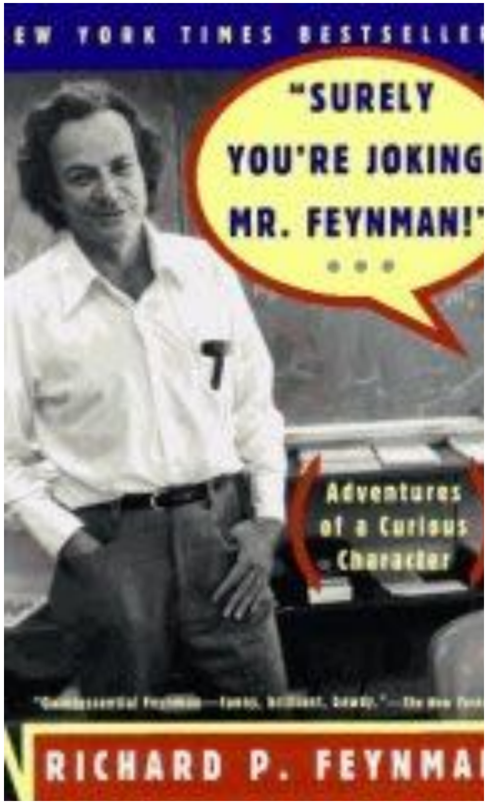


- **Feynman Diagr**

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

Feynman Rules!

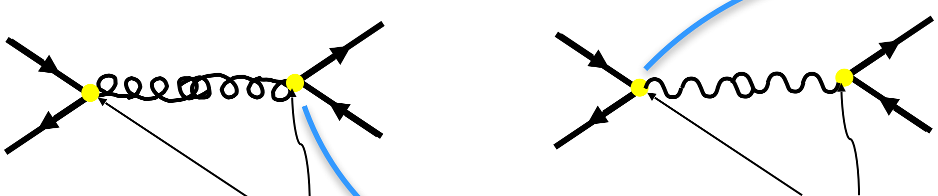
γ	QED	$q\bar{q}\gamma$ $l^-l^+\gamma$	$W^+W^-\gamma$	
Z	QED	$q\bar{q}Z$ $l\bar{l}Z$	W^+W^-Z	
W^{+-}	QED	$q\bar{q}'W$ $l\nu W$		$WWWW$
g	QCD	$q\bar{q}g$	ggg	$gggg$
h	QED (m)	$q\bar{q}h$ $l\bar{l}h$	W^+W^-h	ZZh



Partial list from SM

Feynman Rules!

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

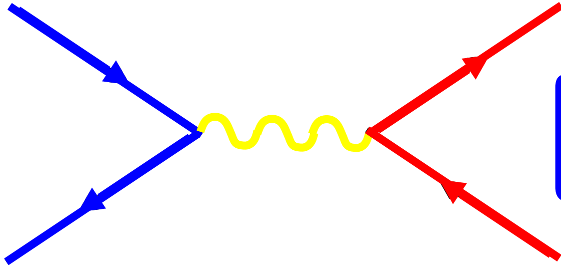


Order is QCD^2

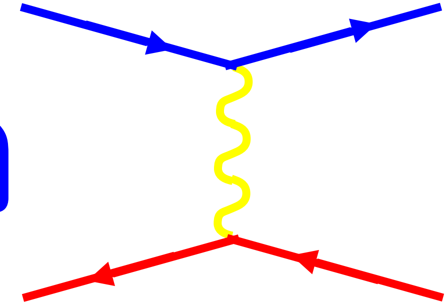
Order is QED^2

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

- 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

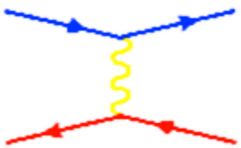
```
 SUBROUTINE SMATRIX(P1,ANS)
C
C Generated by MadGraph II Version 3.83. Updated 06/13/05
C RETURNS AMPLITUDE SQUARED SUMMED/AVG OVER COLORS
C AND HELICITIES
C FOR THE POINT IN PHASE SPACE P(0:3,NEXTERNAL)
C
C FOR PROCESS : g g -> t t~ b b~
C
C Crossing   1 is g g -> t t~ b b~
      IMPLICIT NONE
C
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
```

Check your answer

High Energy Physics Illinois

The MadGraph5_aMC@NLO homepage

UCL UIUC Launchpad
by the MG/ME Development team



Generate Process | Register | Tools | My Database | Cluster Status | Downloads (needs account) | Wiki | Answers | Bug reports

---

Generate processes online using MadGraph5_aMC@NLO

To improve our web services we request that you register. Registration is quick and free. You may register for a password by clicking here.
Please note the correct reference for MadGraph5_aMC@NLO, arXiv:1405.0301 [hep-ph].

Code can be generated either by (only LO process can be generated online):

I. Fill the form:

Model: SM — Model descriptions

Input Process: — Examples/format

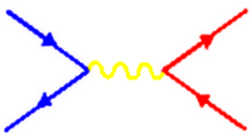
Example: p p > w+ j j QED=3, w+ > l+ vl

p and j definitions: p=j=d u s c d~ u~ s~ c~ g

Register

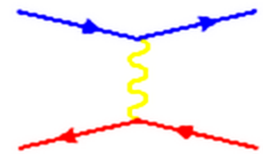
High Energy Physics Illinois

I 1867



The MadGraph5_aMC@NLO homepage

UCL UIUC Launchpad
by the MG/ME Development team



Generate Process | Register | Tools | My Database | Cluster Status | Downloads (needs account) | Wiki | Answers | Bug reports

---

MadGraph5_aMC Registration

Please complete the form below. Your username and password will be sent to the e-mail address you enter.

First Name Benjamin

Family Name Fuks

Name of your institution SummerCERN17

Your e-mail address benjamin.fuks@iphc.c

The letter sequence you can read on the following image: fgvqfn

fgvqfn captchas.net

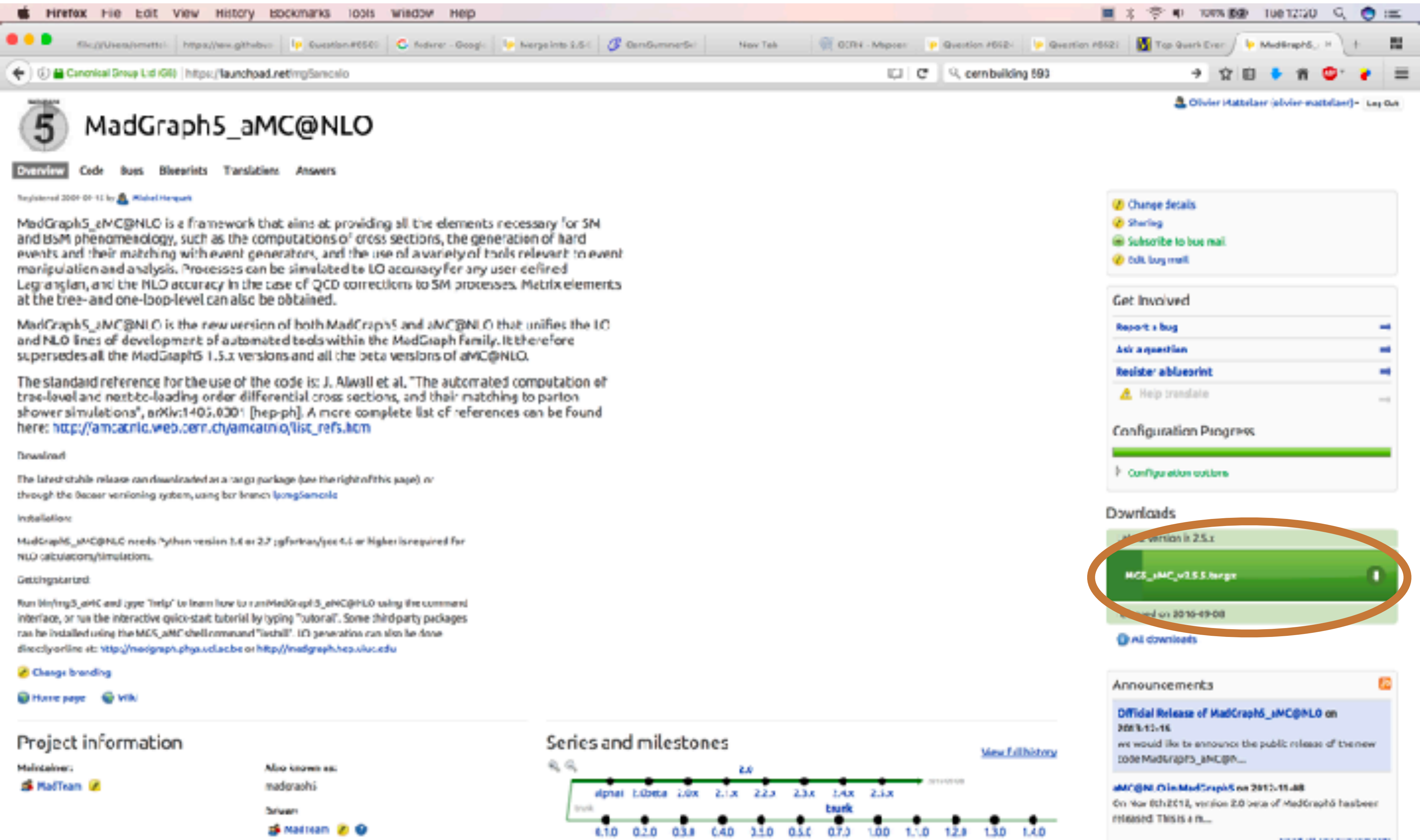
SUBMIT

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

SummerCERN17

OR install it on your laptop

https://launchpad.net/mg5amcnlo



Status

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

High Energy Physics
Illinois

The MadGraph5_aMC@NLO homepage

UCL UIUC Launchpad
by the MG/ME Development team

Generate Process | Register | Tools | My Database | Cluster Status | Downloads (needs account) | Wiki | Answers | Bug reports

---

General

- News
- Community
- MC Links
- Twiki Groups

Documents

- References
- Update notes
- Manual and Help (FAQ's)

Communication

- Talks
- Lectures and Tutorials
- Collaboration meetings
- MadGraph Schools

Software

Physics applications

Events library

MadGraph

Wiki | Timeline | Roadmap | View Tickets | New Ticket | Search | Admin

wiki: MGTutorial

Lectures on the MadGraph framework

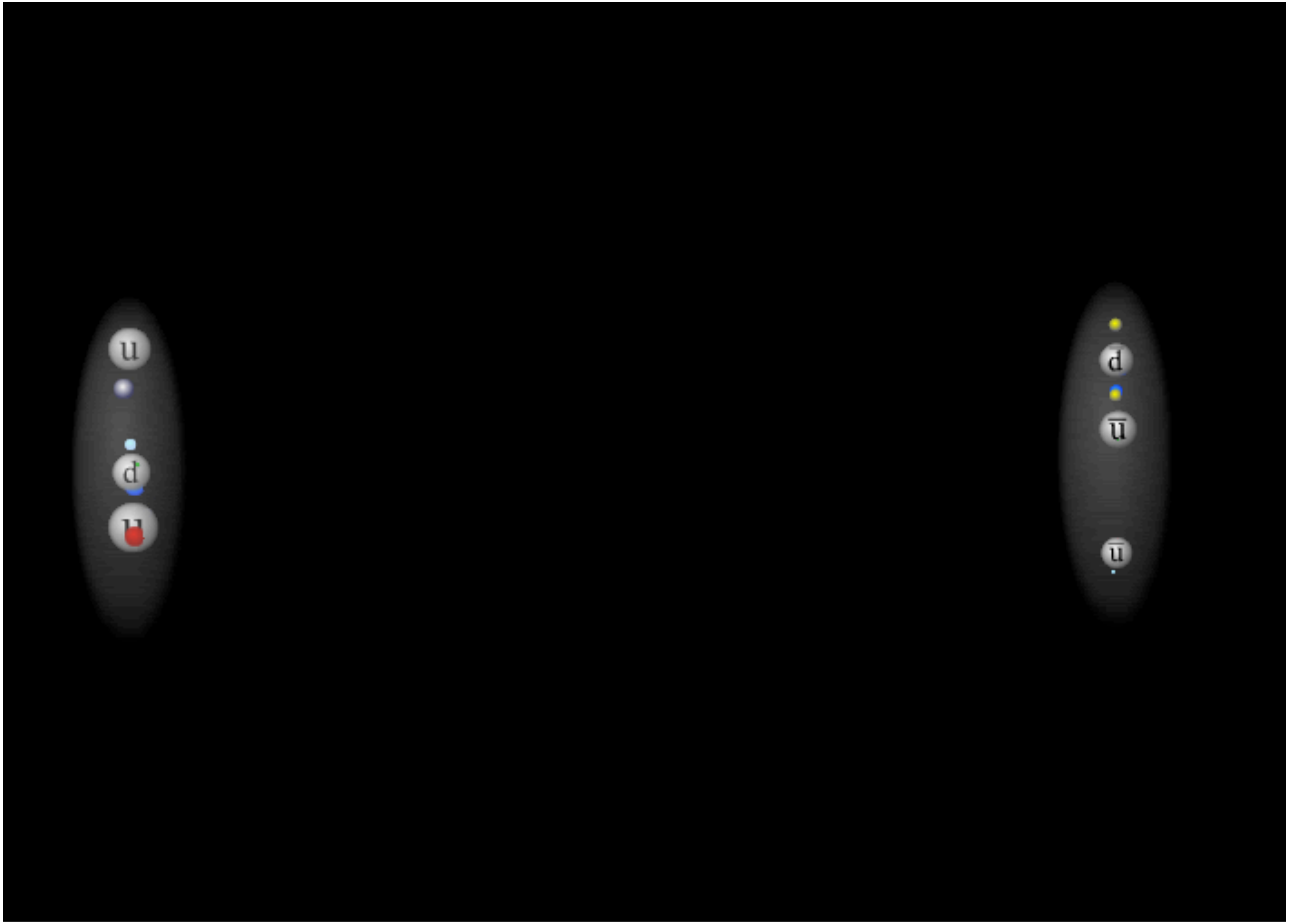
- 2017 Cern Summer School, by Valentin Hirschi and Olivier Mattelaer.
- 2017 MCNET2017, by O. Mattelaer, V. Hirschi, E. Vryonidou
- 2017 [illegible], by O. Mattelaer, B. Fuks, L. Moore
- 2016 MC4BSM16, by O.Mattelaer.

MadGraph

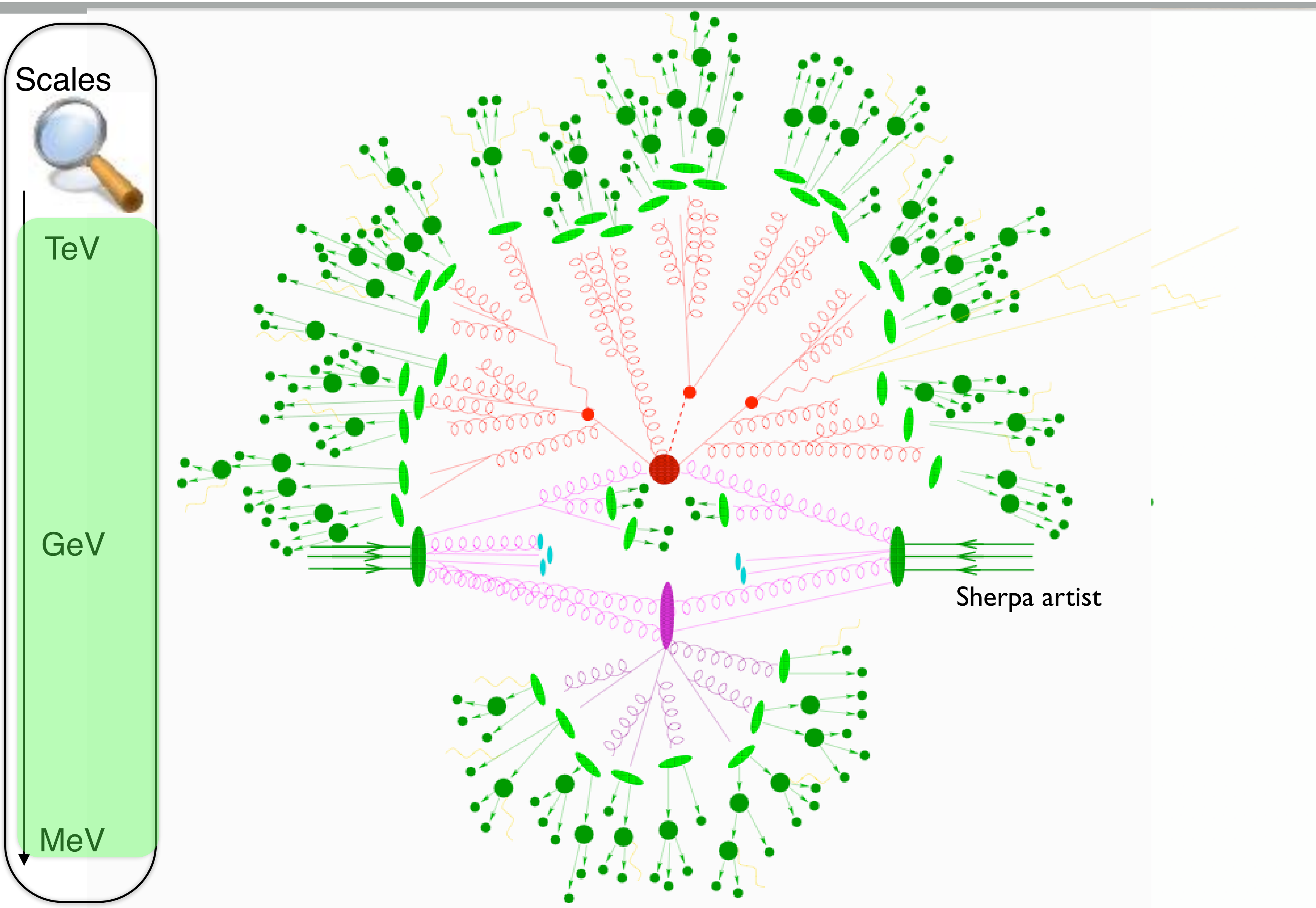
2017 CERN Summer student workshop

Animations

- Interactive Flash version Note you may want to zoom in!
- Fast movie (.avi) of collision
- Guided movie (.mov) of collision


u
d
u
d
ū
ū

What are the MC for?



What are the MC for?

Scales

TeV

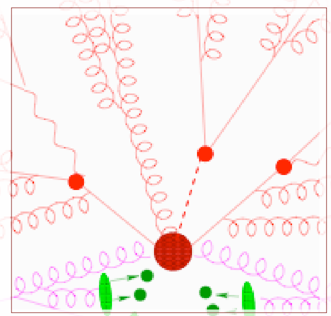
GeV

MeV

1. High-Q^2 Scattering

2. Parton Shower

☞ where BSM physics lies



☞ process dependent

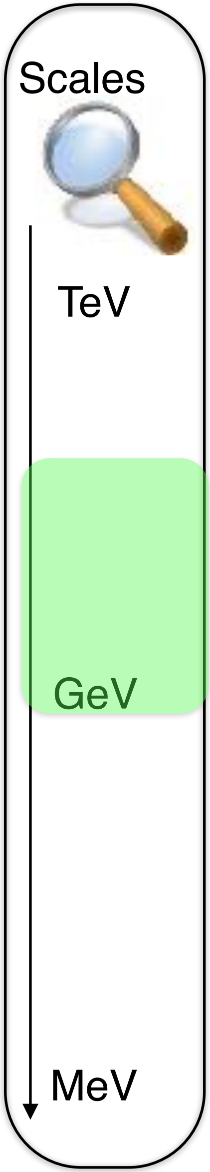
☞ first principles description

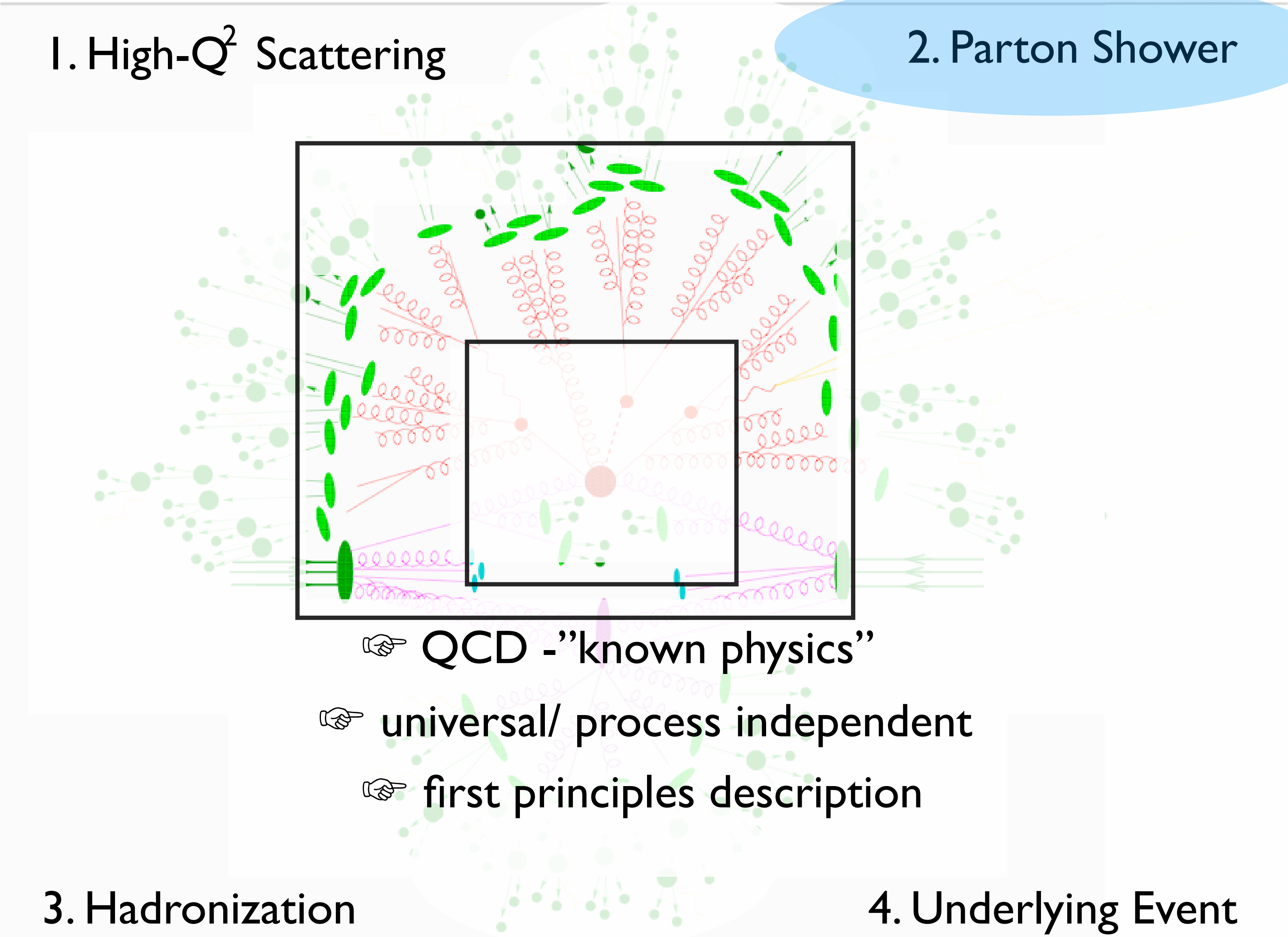
☞ it can be systematically improved

3. Hadronization

4. Underlying Event

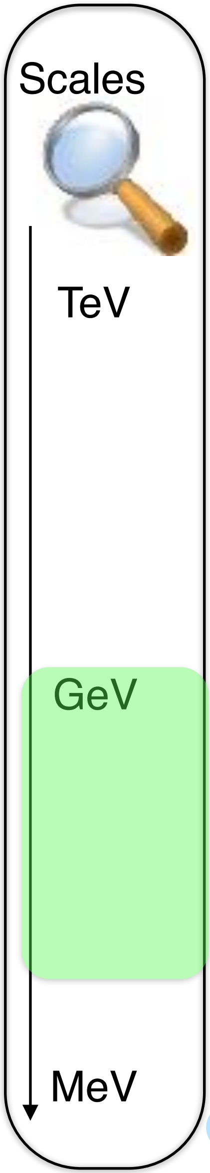
What are the MC for?





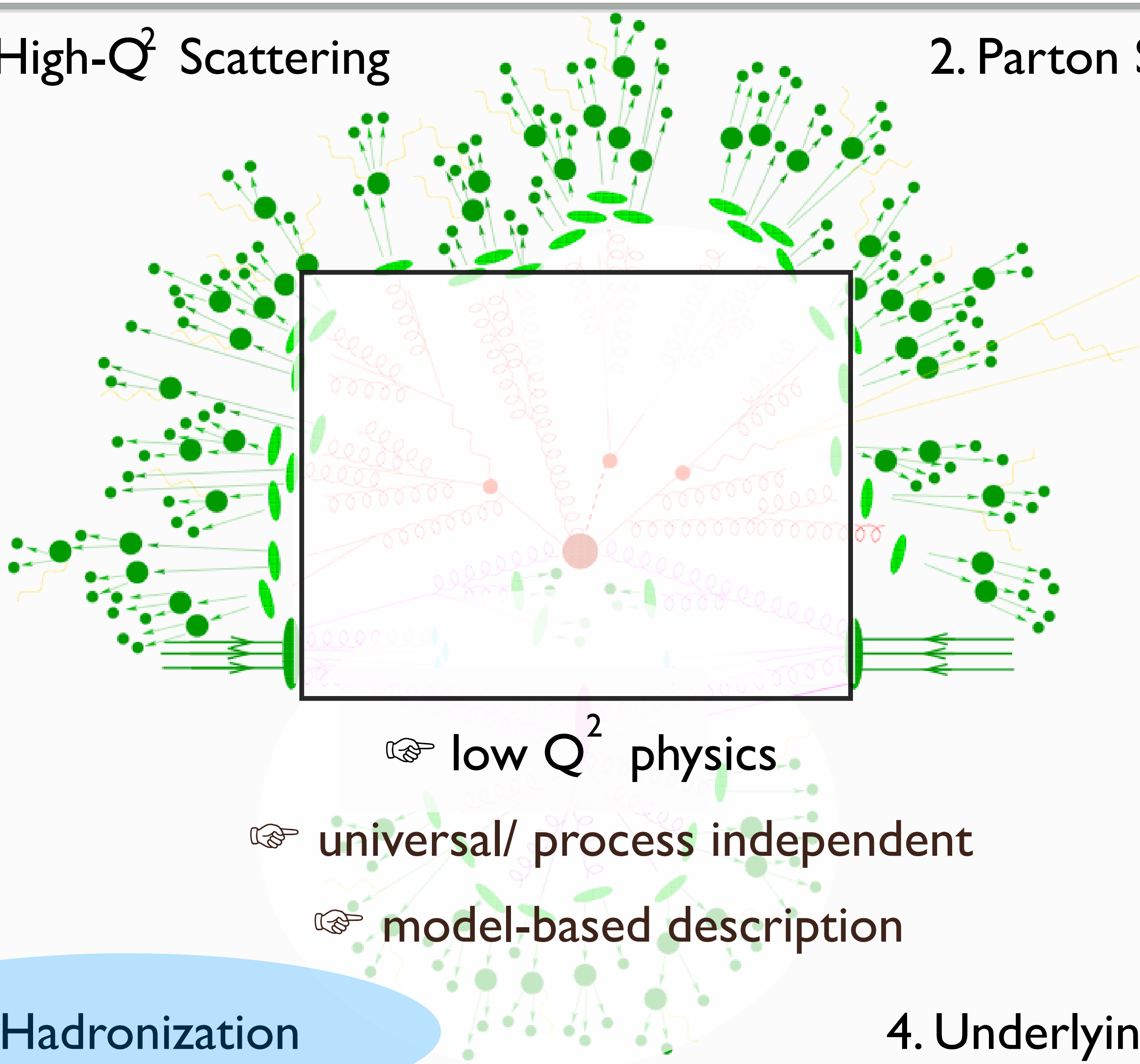
- ☞ QCD -”known physics”
- ☞ universal/ process independent
- ☞ first principles description

What are the MC for?



1. High-Q^2 Scattering

2. Parton Shower

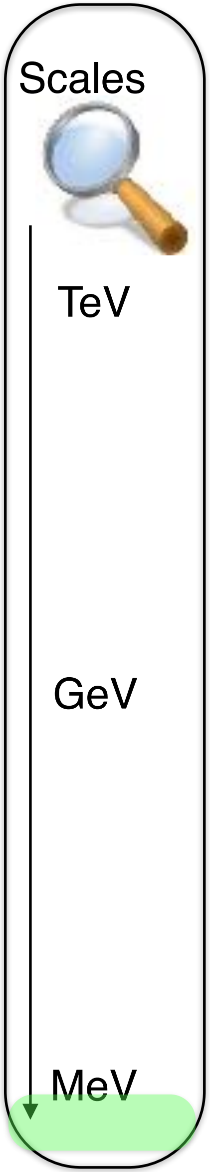


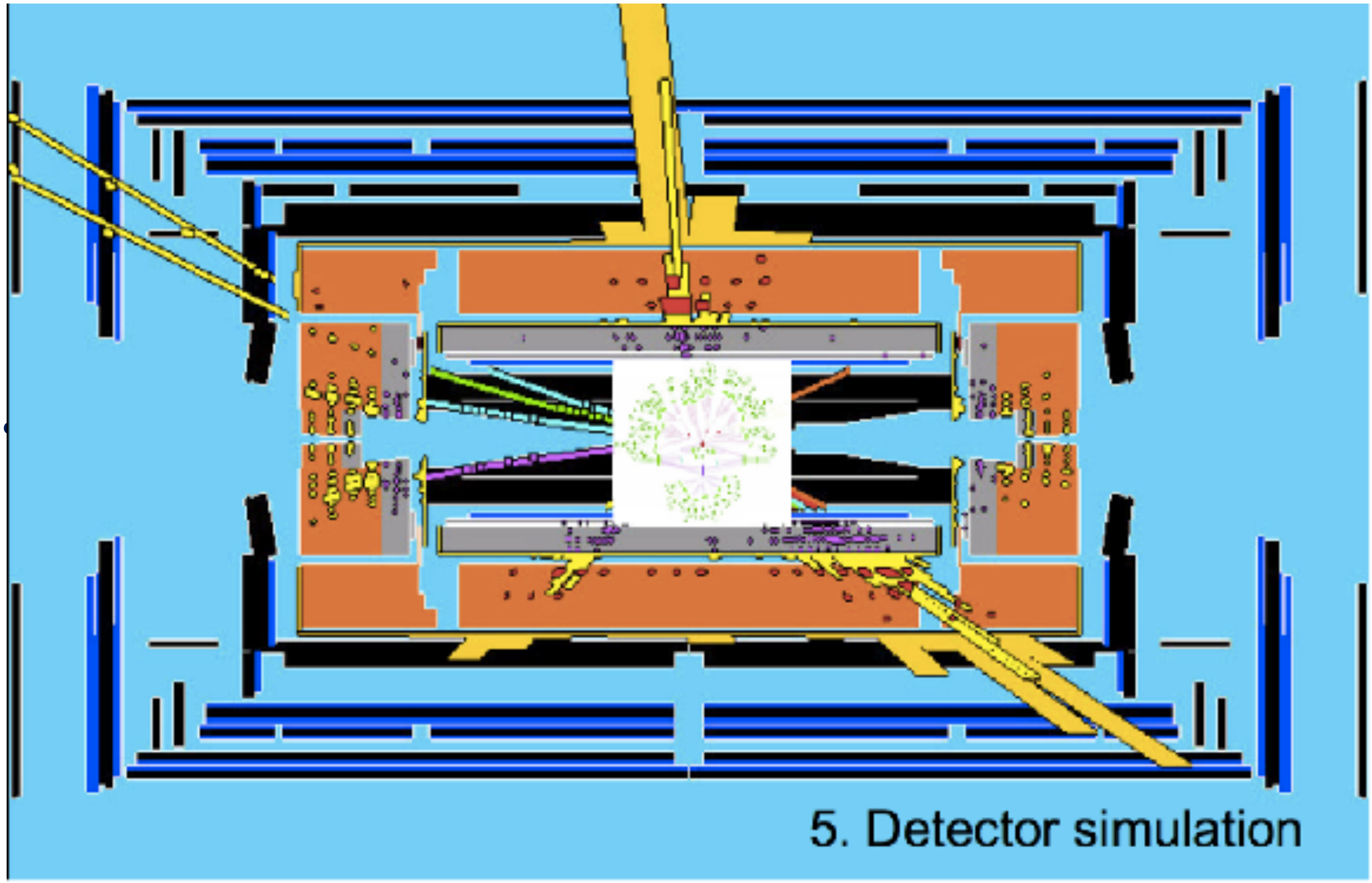
- low Q^2 physics
- universal/ process independent
- model-based description

3. Hadronization

4. Underlying Event

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

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

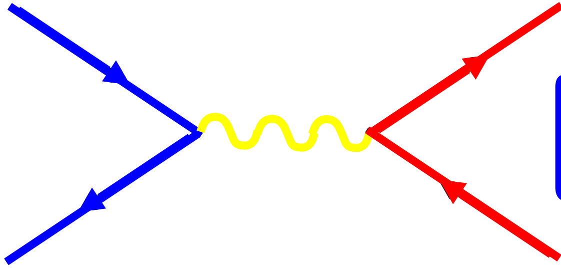
- Many parton level sub processes contribute to same hadron level event (e.g. pp > $e^+ \nu$ j j j)

Exercise

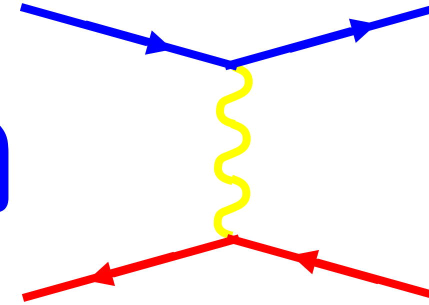
- List processes for signal pp > t t~ h with Higgs decaying to b b~
  - e.g. uu~ > tt~ h

- List process for background pp > tt~bb~
  - e.g. uu~ > tt~bb~

- List process for reducible background pp>tt~jj
  - e.g. uu~ > tt~gg



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

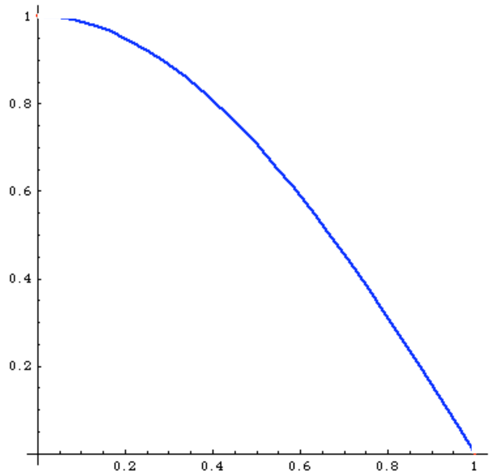
- Good News
  - Automatically determine sub processes and Feynman diagrams
  - Automatically create function needed to integrate

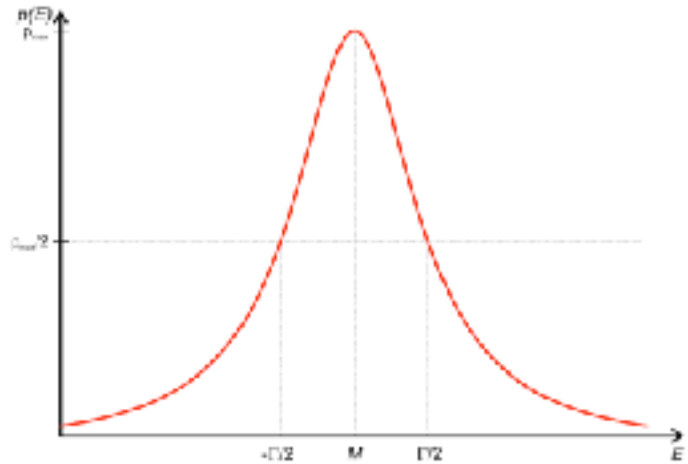
$$\sigma = \frac{1}{2s}\int f(x_1)f(x_2)\,|M|^2\, d^3P_1 \ldots d^3P_n \delta^4(P - p_1 - p_2 \ldots - p_n)$$

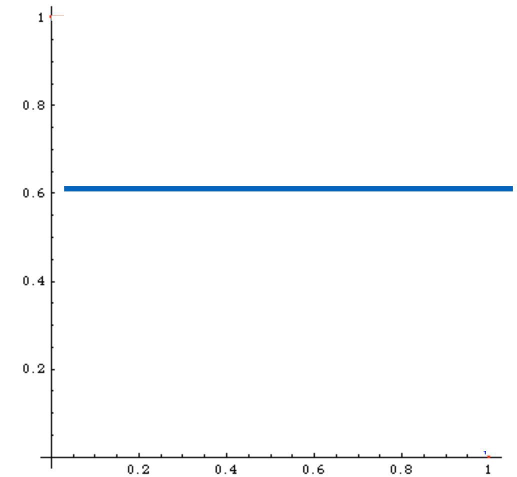
- Bad News
  - Hard to integrate!
  - 3N-4+2 dimensions

Integration

$$I = \int_0^1 dx \cos \frac{\pi}{2} x \qquad \int \frac{dq^2}{(q^2 - M^2 + iM\Gamma)^2} \qquad \int dx\, C$$







	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

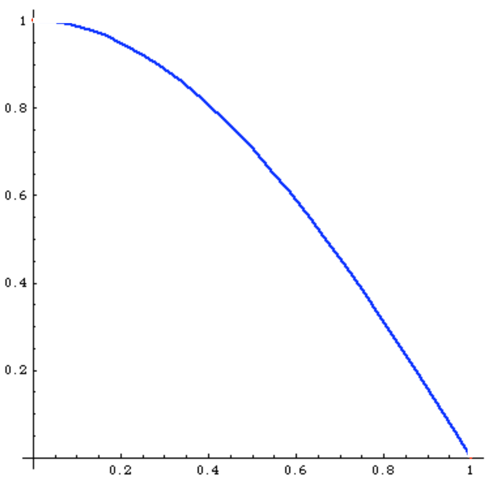
- MonteCarlo $1/\sqrt{N}$
- Trapezium $1/N^2$
- Simpson $1/N^4$

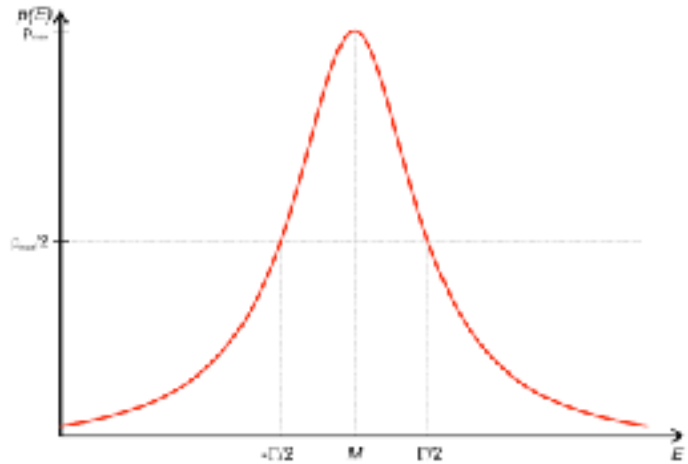
Integration

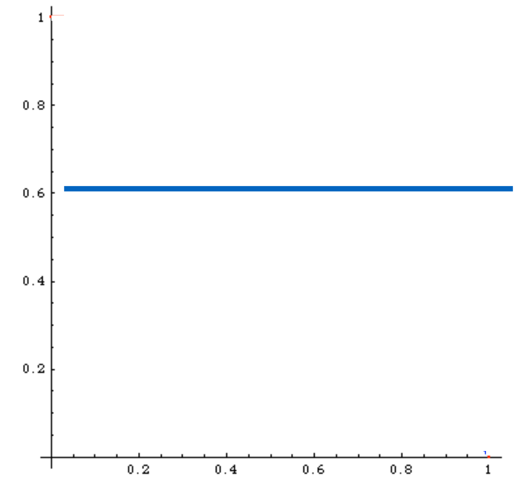
$$I = \int_0^1 dx \cos\frac{\pi}{2}x$$

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

$$\int dx\, C$$







Method of evaluation

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

More Dimension

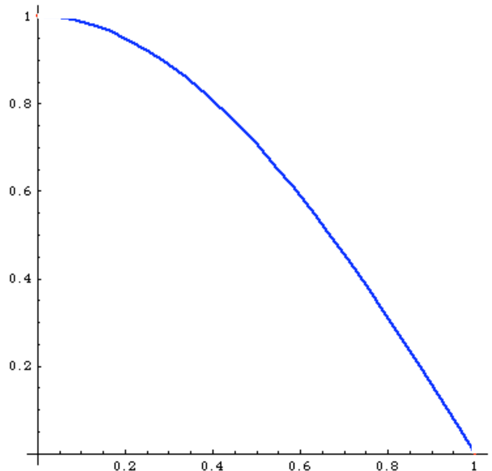
$1/\sqrt{N}$

$1/N^{2/d}$

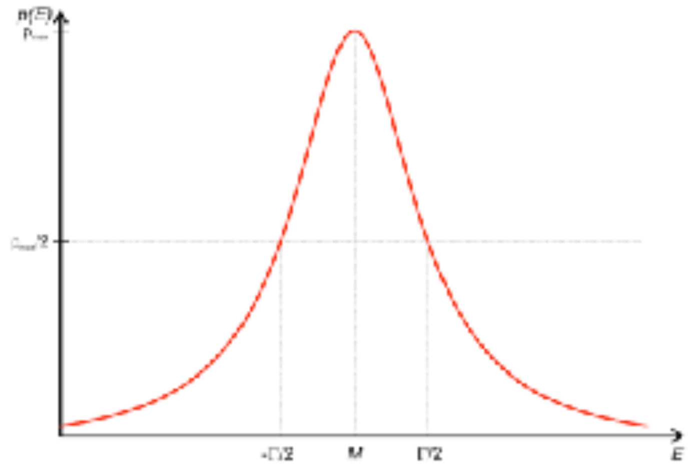
$1/N^{4/d}$

Integration

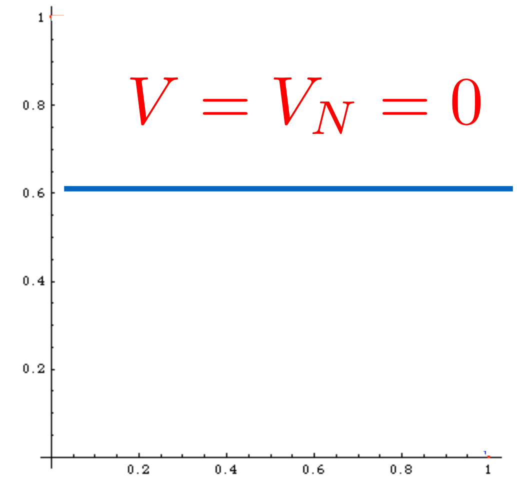
$$I = \int_0^1 dx \cos\frac{\pi}{2}x$$



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



$$\int dx\, C$$



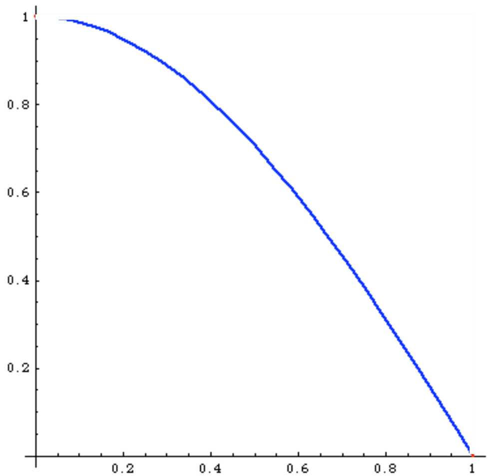
$$I = \int_{x_1}^{x_2} f(x)dx \quad \Rightarrow \quad I_N = (x_2 - x_1)\frac{1}{N}\sum_{i=1}^{N} f(x)$$

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

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

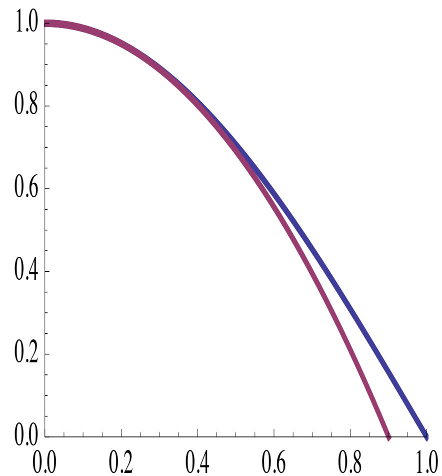
Can be minimized!

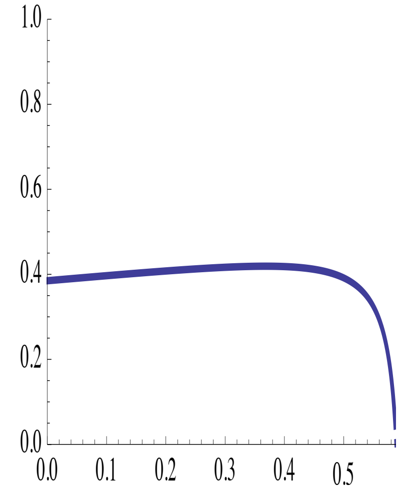
Importance Sampling



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

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





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

$$\simeq 1$$

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

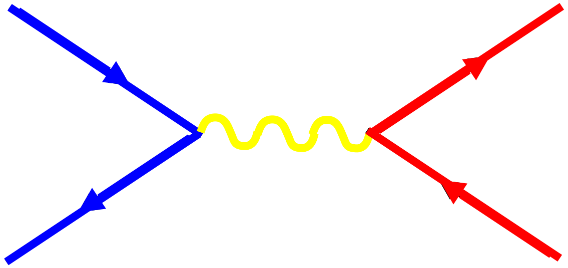
100 times faster

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

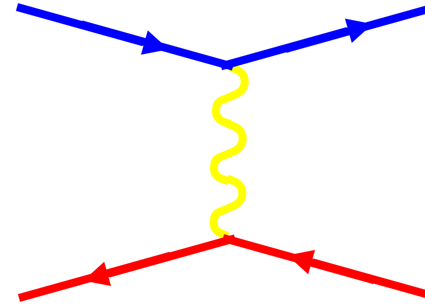
Single Diagram Enhanced
MadEvent

$$\sigma = \int |a_1 + a_2|^2 \, \mathrm{d}(PS) = \int \frac{|a_1 + a_1|^2}{|a_1|^2 + |a_1|^2} |a_1|^2 \, \mathrm{d}(PS) + \int \frac{|a_1 + a_1|^2}{|a_1|^2 + |a_1|^2} |a_2|^2 \, \mathrm{d}(PS)$$

- **Key Idea**
  - Any single diagram is “easy” to integrate
  - Divide integration into pieces, based on diagrams
- **Get N independent integrals**
  - Errors add in quadrature so no extra cost
  - No need to calculate “weight” function from other channels.
  - Can optimize # of points for each one independently
  - Parallel in nature

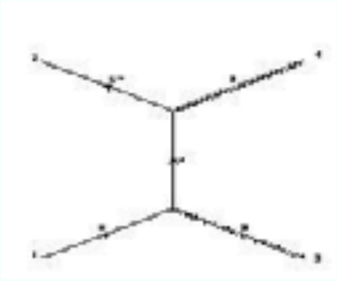


MadEvent



- User Requests:
  - Model (HiggsHeft)
  - pp -> a a
  - Cuts + Parameters
- MadEvent Returns:
  - Feynman diagrams
  - Complete package for event generation
  - Events/Plots on line!

Created: Tue Jul 25 03:21:21 CDT 2017

Process: p p > a a **Model: sm**	

Links	Status
Process Information	**Generation Complete**
Code Download	**Available**
On-line Event Generation	Available (access restricted)
Results and Event Database	No runs available

Notes:

pp > a a

- Generate SubProcesses+Diagrams
  - Use HiggsEFT model

- Generate Parton Level Plots

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?

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 wiki page to get the plots and determine which sample is which model:**
- **https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/CernSummerSchool17**

Advice

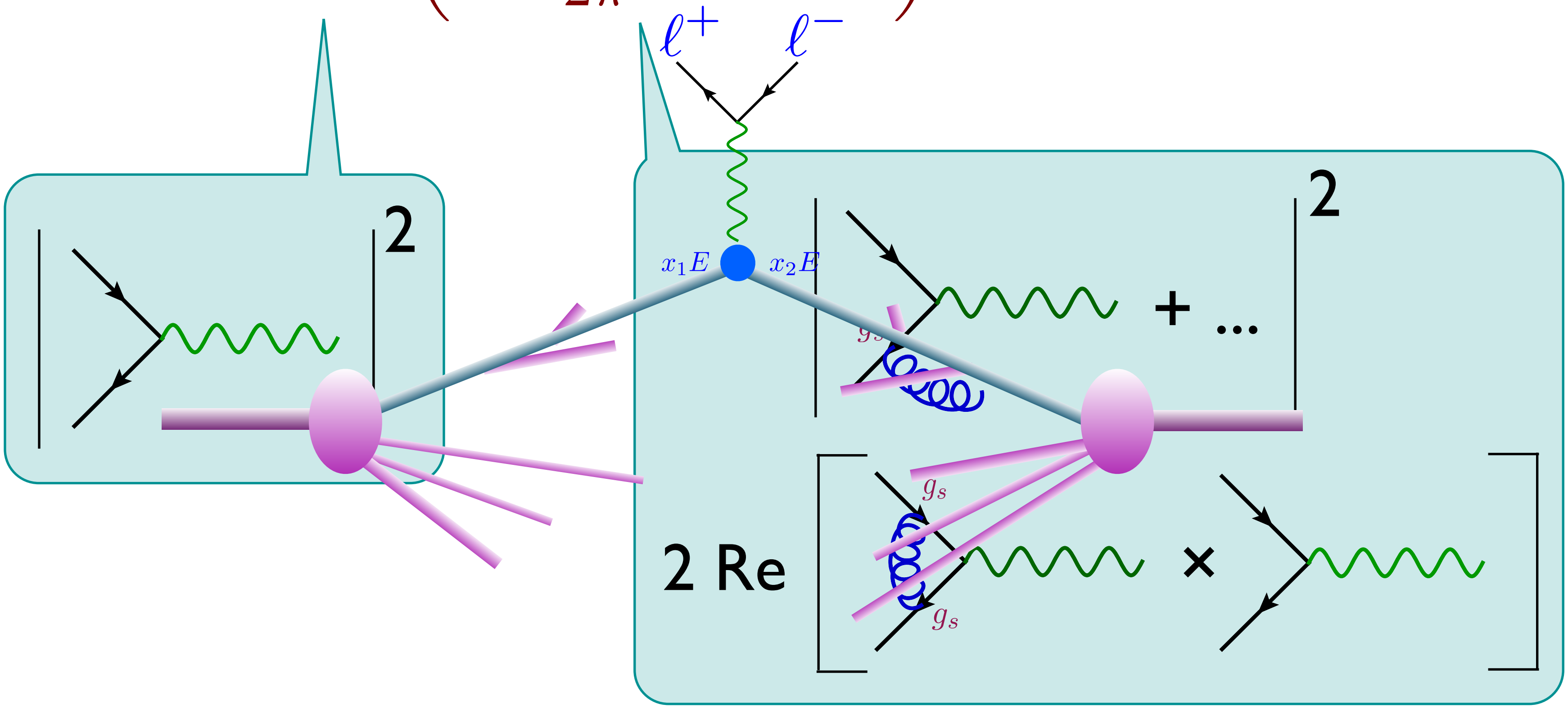
- A person who can efficiently calculate cross sections can be useful to a collaboration
- A person who can efficiently calculate the CORRECT cross section is ESSENTIAL to a collaboration

NLO predictions

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

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

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



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!