MADGRAPH workshop
CERN Summer Students 2015

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Outline

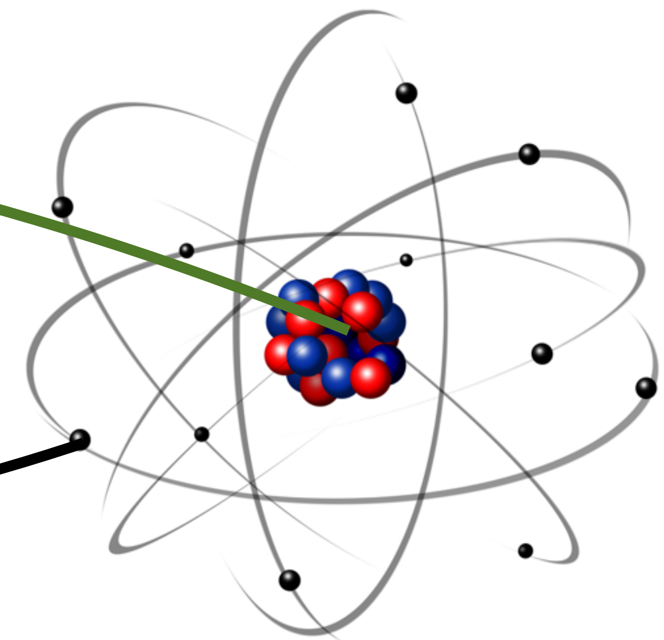
1. The Standard Model of particle physics (and beyond)
2. From the Standard Model to predictions at the LHC
3. Event simulations
4. Final challenge

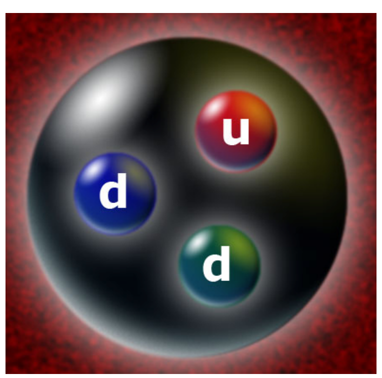
The Standard Model: matter (I)

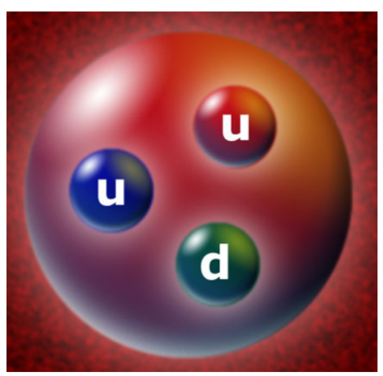
✦ At the atomic scale, matter is composed of atoms:

✤ A core: the nucleus, made of
- ★ Protons ( )
- ★ Neutrons ( )

✤ Peripheral electrons (•)



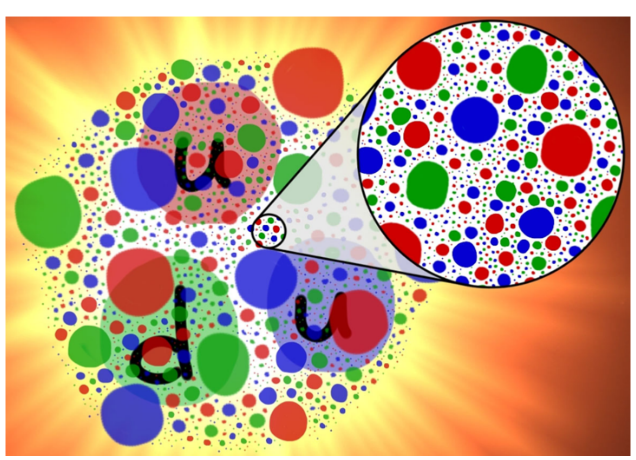




✦ Naively, protons and neutrons are composed objects:

✤ Proton: two up quarks and one down quark

✤ Neutron: one up quarks and two down quarks



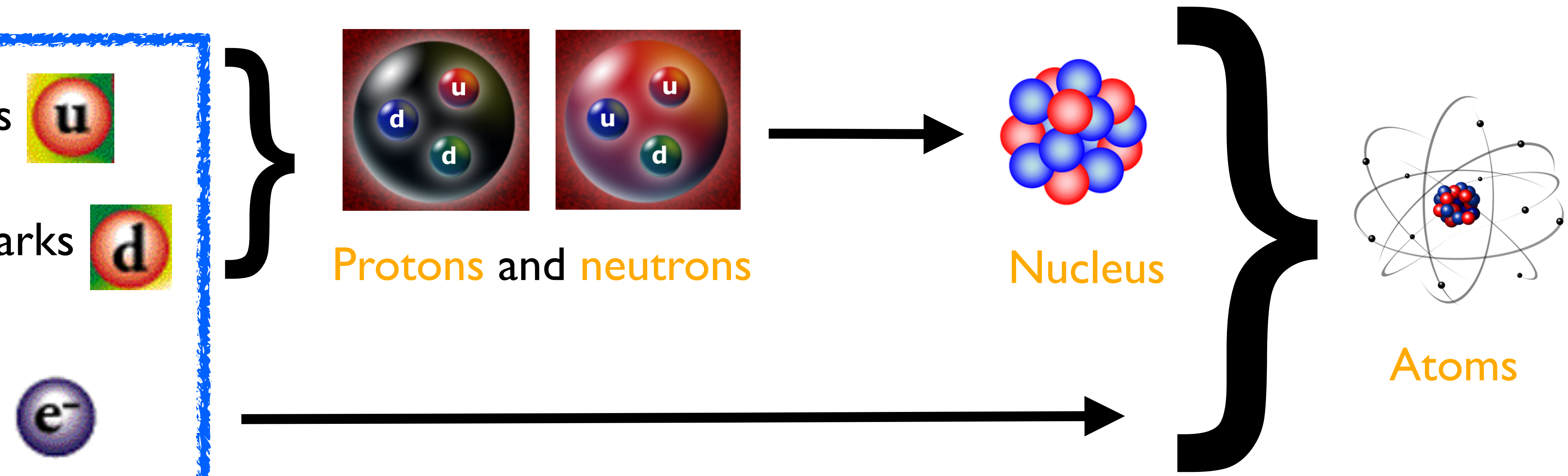
✦ In reality, they are dynamical objects:

✤ Made of many interacting quarks and gluons (see later)

The Standard Model: matter (2)

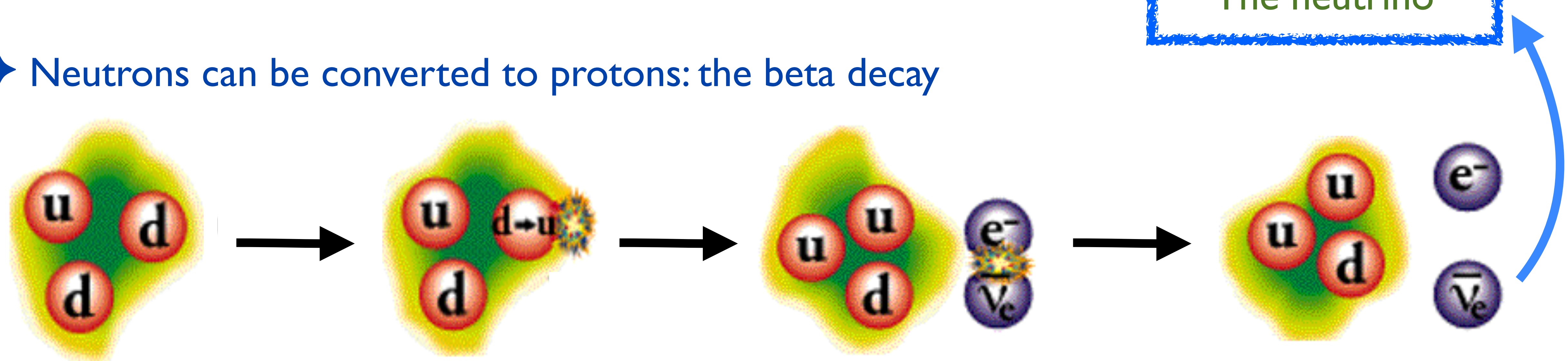
✦ Elementary matter constituents

- Up quarks
- Down quarks
- Electrons



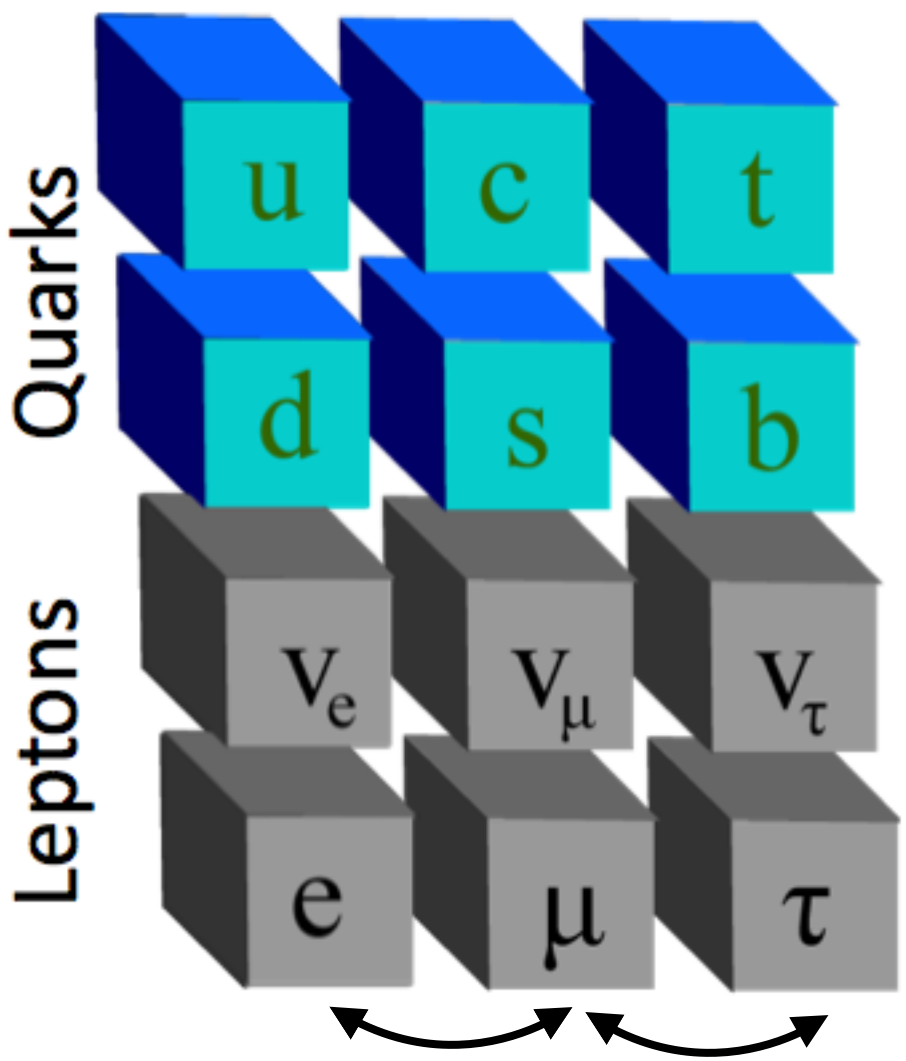
The neutrino

✦ Neutrons can be converted to protons: the beta decay



The Standard Model: matter (3)

✦ Elementary matter constituents: we have three families

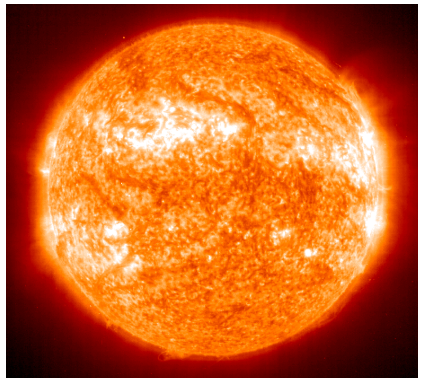


The only differences are the masses
All other properties are identical

- Three up-type quarks
  - ★ Up (u)
  - ★ Charm (c)
  - ★ Top (t)
- Three down-type quarks
  - ★ Down (d)
  - ★ Strange (s)
  - ★ Bottom (b)
- Three neutrinos
  - ★ Electron (ν_e)
  - ★ Muon (ν_μ)
  - ★ Tau (ν_τ)
- There charged leptons
  - ★ Electron (e)
  - ★ Muon (μ)
  - ★ Tau (τ)

The Standard Model: interactions

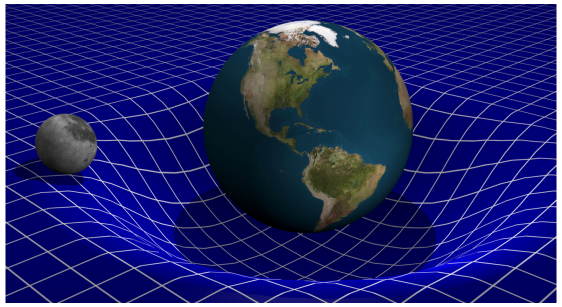
- Electromagnetism
  - Interactions between charged particles (quarks, charged leptons)
  - Mediated by massless photons γ



- Weak interactions
  - Interactions between all matter fields
  - Mediated by massive weak W-bosons and Z-bosons

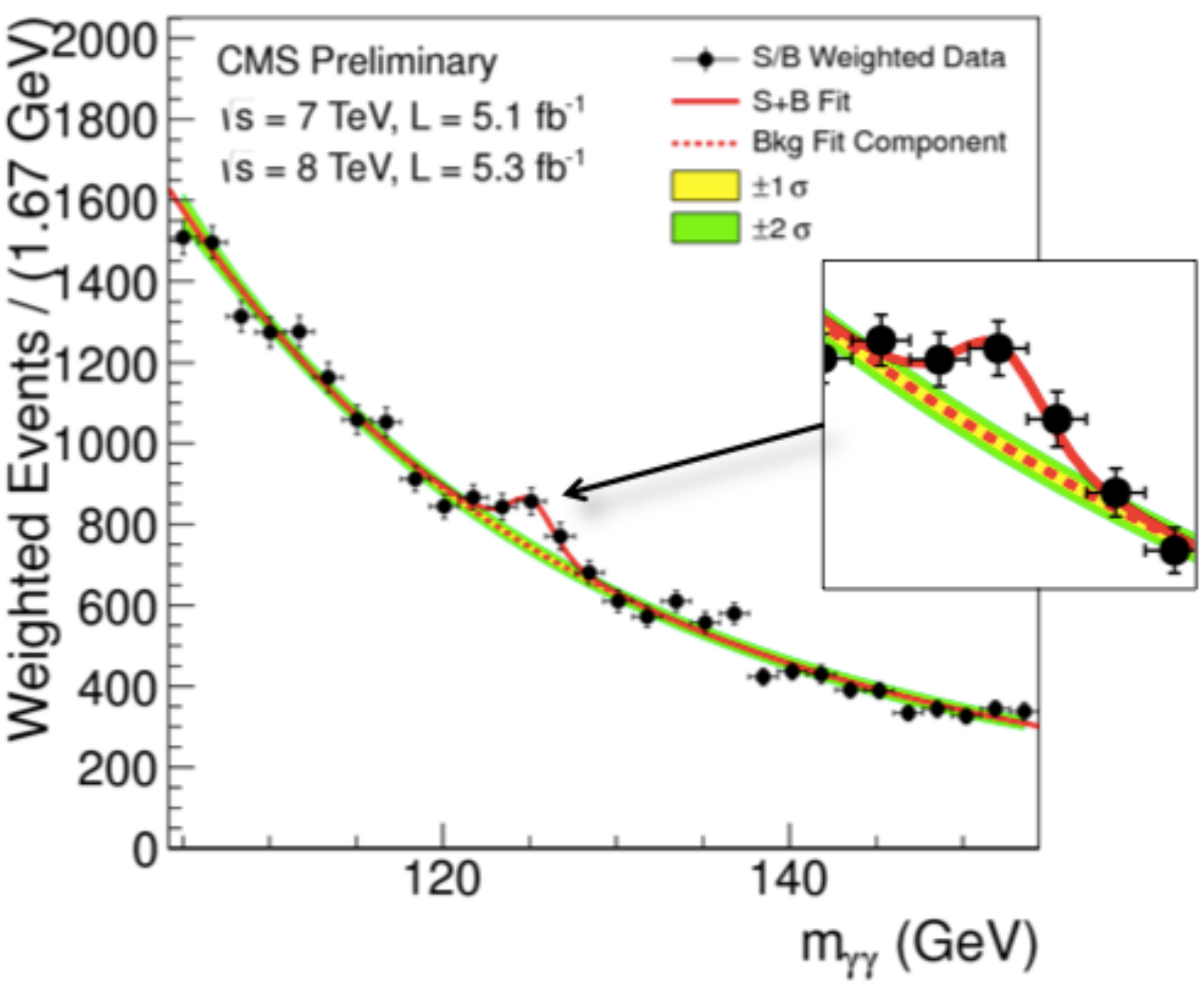
- Strong interactions
  - Interactions between colored particles (quarks)
  - Mediated by massless gluons g
  - Responsible for binding protons and neutrons within the nucleus

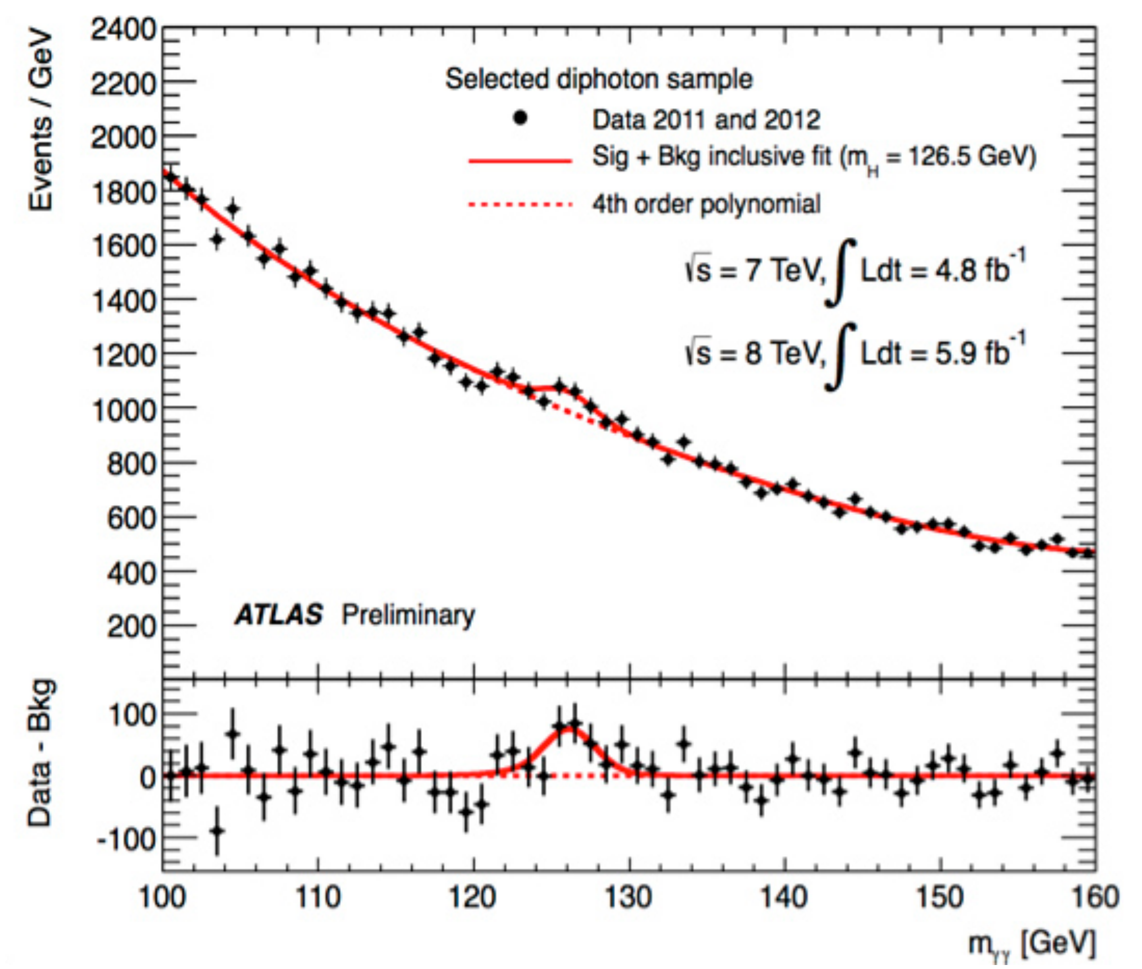
- Gravity
  - Not included in the Standard Model



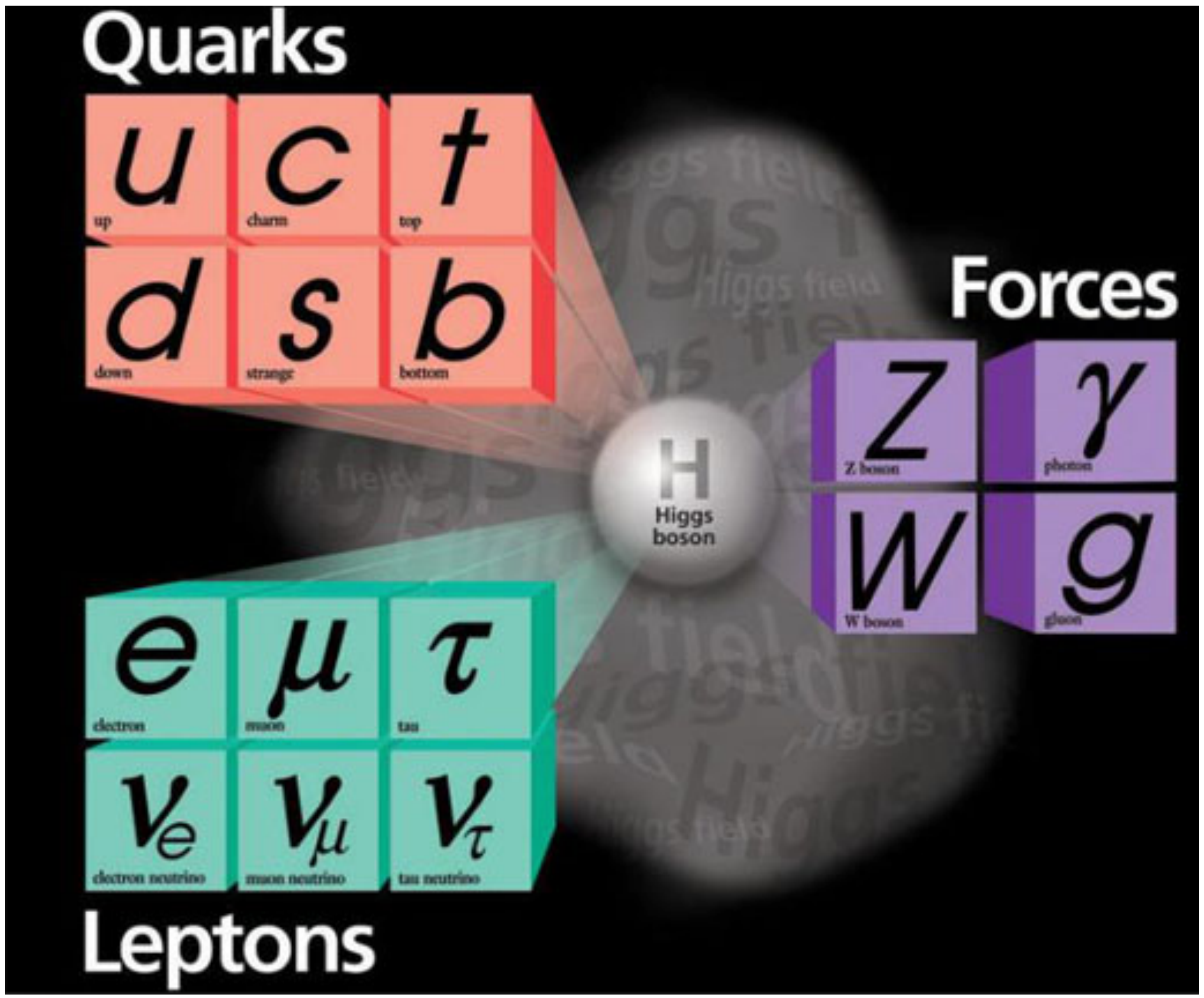
The last pieces: the Higgs boson

- The masses of the particles
  - Elegant mechanism to introduce them
  - Price to pay: a new particle, the so-called Higgs boson





The Standard Model: the full picture



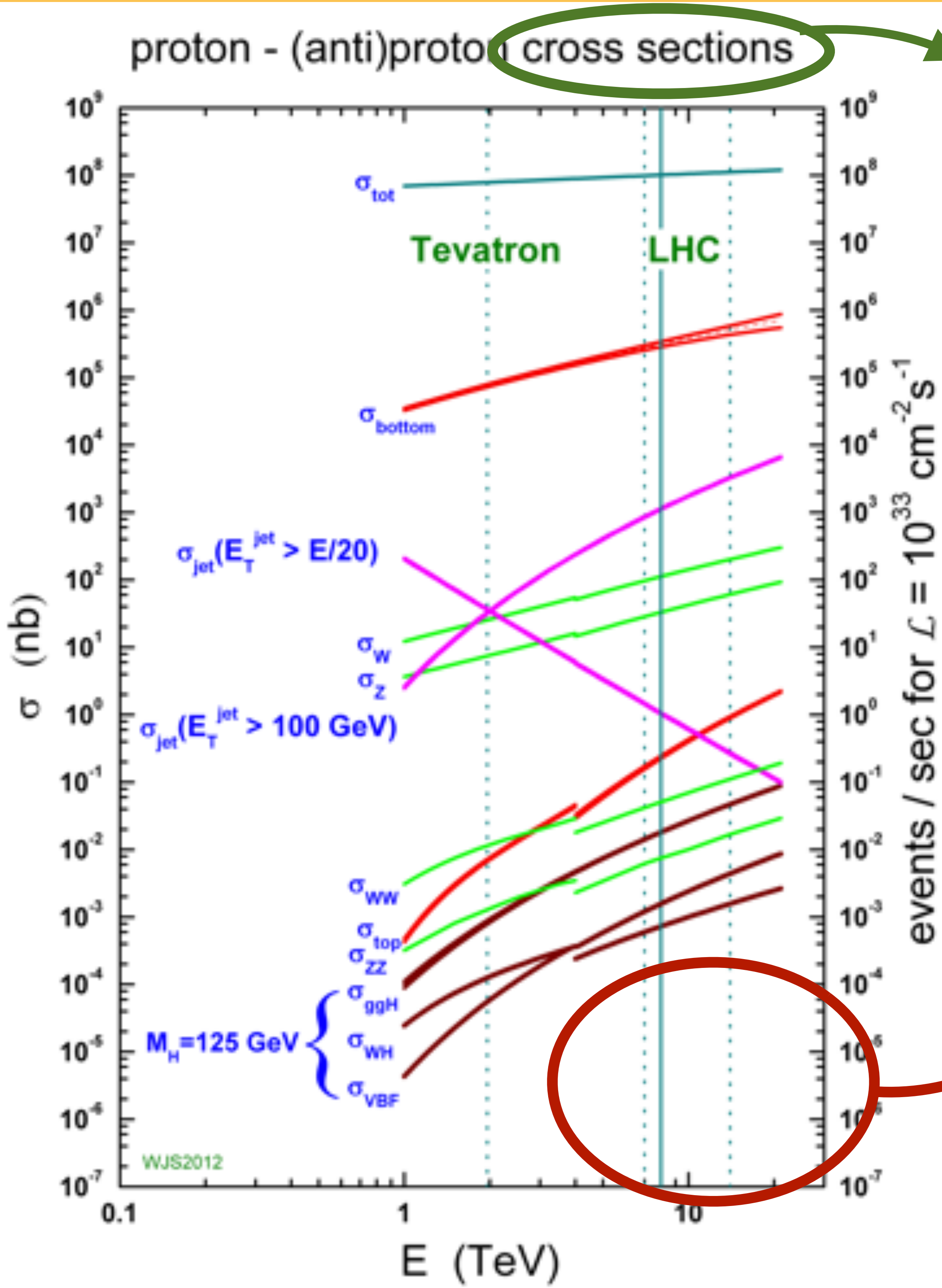
✦ All the particles have been observed:

- ✤ The last one: the Higgs (2012)
- ✤ The next-to-last one: the top quark (1995)

✦ Tested over 30 orders of magnitude:

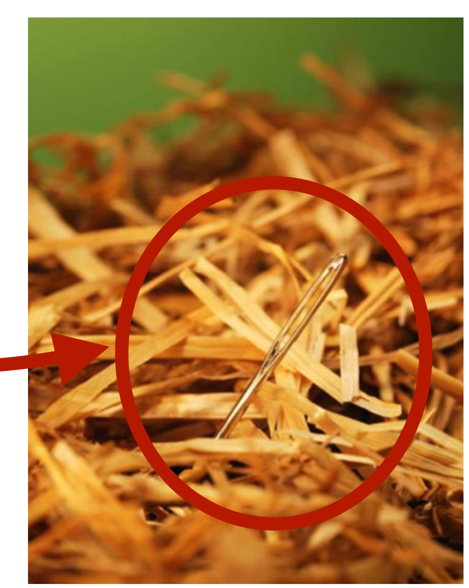
- ✤ from 10^{-18} eV (photon mass limit)
- ✤ to 10^{+13} eV (LHC energy)

Beyond the Standard Model: the challenge



= production rate: to be calculated

- ✦ This is where any new phenomenon would hide
  - ✤ Supersymmetry
  - ✤ Extra-dimensions
  - ✤ Grand-Unified Theories
  - ✤ *etc.*
- ✦ Cross sections = production rate
  - ✤ 1 possible new physics event (if any)
  - ✤ 1.000 Higgs events
  - ✤ 1.000.000.000.000 Standard Model events



Outline

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2. **From the Standard Model to predictions at the LHC**
3. Event simulations
4. Final challenge

Scattering theory

✦Cross sections can be calculated as

$$\sigma = \frac{1}{F}\int \mathrm{dPS}^{(n)}\overline{\left|M_{fi}\right|^2}$$

✤ We integrate over all final state configurations (momenta, *etc.*).
  ★The phase space (dPS) only depend on the final state particle momenta and masses
  ★ Purely kinematical

✤ We average over all initial state configurations
  ★ This is accounted for by the flux factor F
  ★ Purely kinematical

✤ The matrix element squared contains the physics model
  ★ Can be calculated from **Feynman diagrams**
  ★ Feynman diagrams can be drawn from the Lagrangian
  ★ The Lagrangian contains all the model information (particles, interactions)

- All the model information is included in the Lagrangian
  - Before electroweak symmetry breaking: very compact

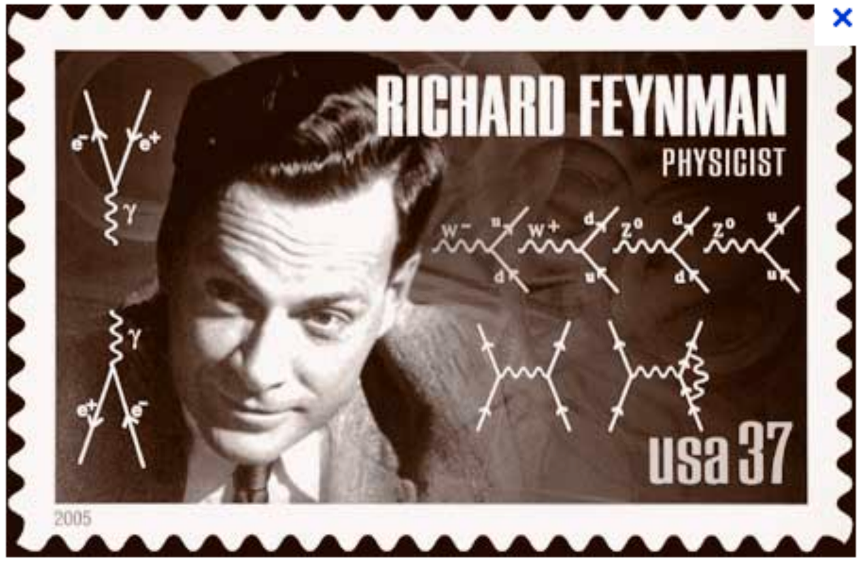
$$\begin{aligned}\mathcal{L} = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^i_{\mu\nu}W_i^{\mu\nu} - \frac{1}{4}G^a_{\mu\nu}G_a^{\mu\nu} \\ & + \sum_{f=1}^{3}\Big[\bar{L}_f\Big(i\gamma^\mu D_\mu\Big)L^f + \bar{e}_{Rf}\Big(i\gamma^\mu D_\mu\Big)e_R^f\Big] \\ & + \sum_{f=1}^{3}\Big[\bar{Q}_f\Big(i\gamma^\mu D_\mu\Big)Q^f + \bar{u}_{Rf}\Big(i\gamma^\mu D_\mu\Big)u_R^f + \bar{d}_{Rf}\Big(i\gamma^\mu D_\mu\Big)d_R^f\Big] \\ & + D_\mu\varphi^\dagger D^\mu\varphi - V(\varphi)\end{aligned}$$

  - After electroweak symmetry breaking: quite large

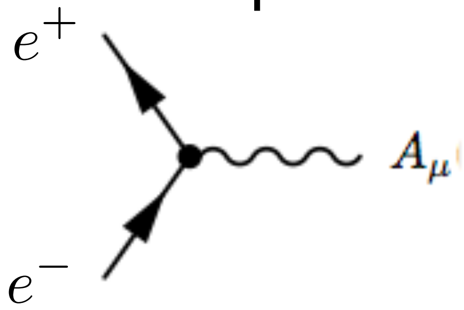
    Example: electroweak boson interactions with the Higgs boson:

$$\begin{aligned}D_\mu\varphi^\dagger\ D^\mu\varphi = & \frac{1}{2}\partial_\mu h\partial^\mu h + \frac{e^2v^2}{4\sin^2\theta_w}W^+_\mu W^{-\mu} + \frac{e^2v^2}{8\sin^2\theta_w\cos^2\theta_w}Z_\mu Z^\mu \\ & + \frac{e^2v}{2\sin^2\theta_w}W^+_\mu W^{-\mu}h + \frac{e^2v}{4\sin^2\theta_w\cos^2\theta_w}Z_\mu Z^\mu h \\ & + \frac{e^2}{4\sin^2\theta_w}W^+_\mu W^{-\mu}hh + \frac{e^2}{8\sin^2\theta_w\cos^2\theta_w}Z_\mu Z^\mu hh\ .\end{aligned}$$

Feynman diagrams and Feynman rules (I)

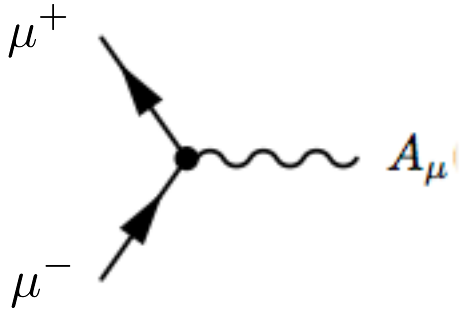


- Diagrammatic representation of the Lagrangian
  - Electron-positron-photon (q = -1)



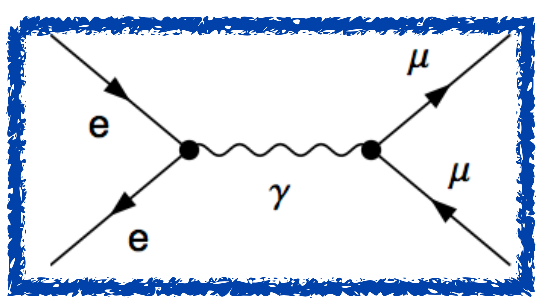
$ieq\gamma^\mu$ → From the Lagrangian

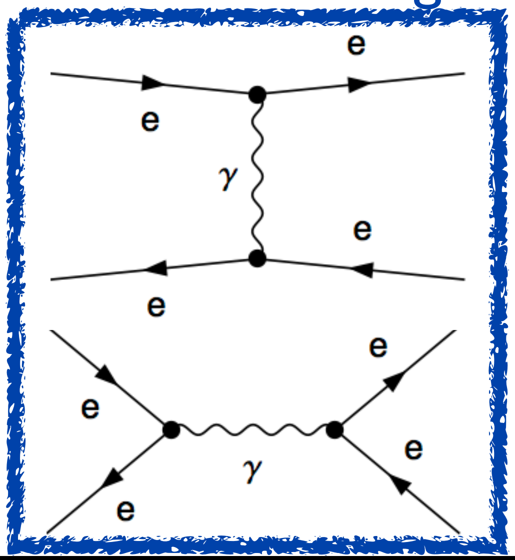
  - Muon-antimuon-photon (q = -1)

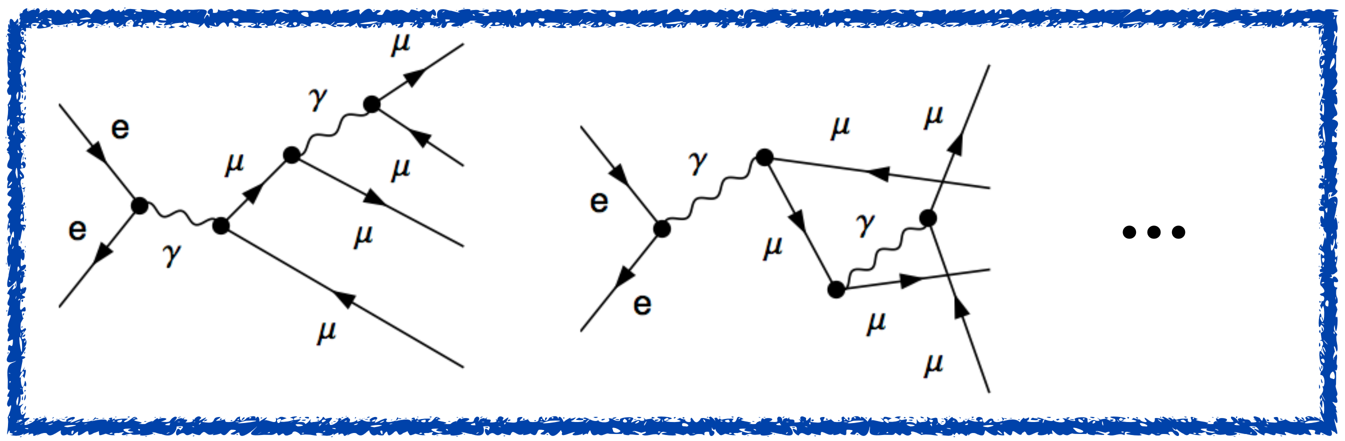


$ieq\gamma^\mu$

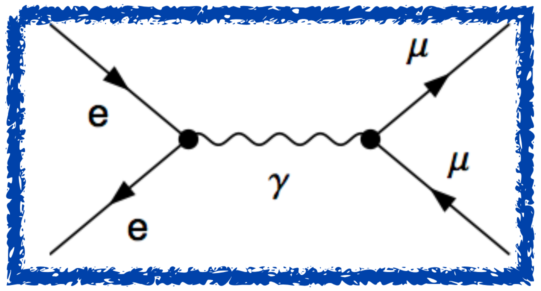
- The Feymman rules are the building blocks to construct Feynman diagrams



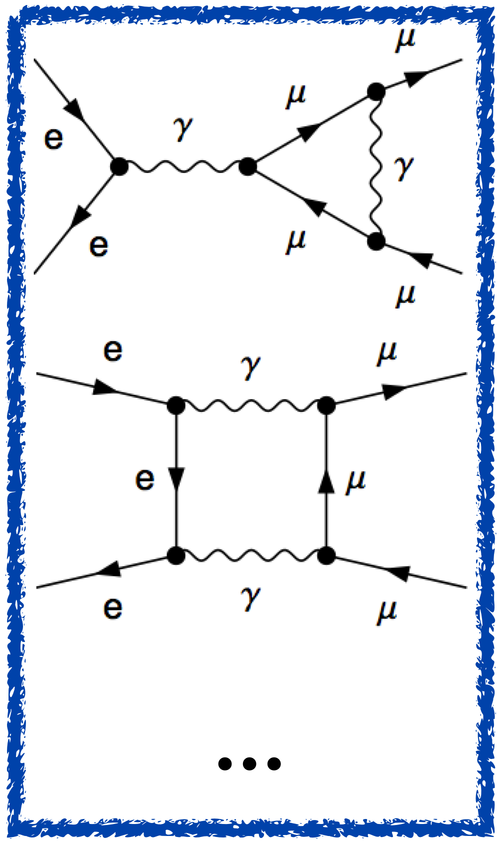




Feynman diagram loops



two interactions

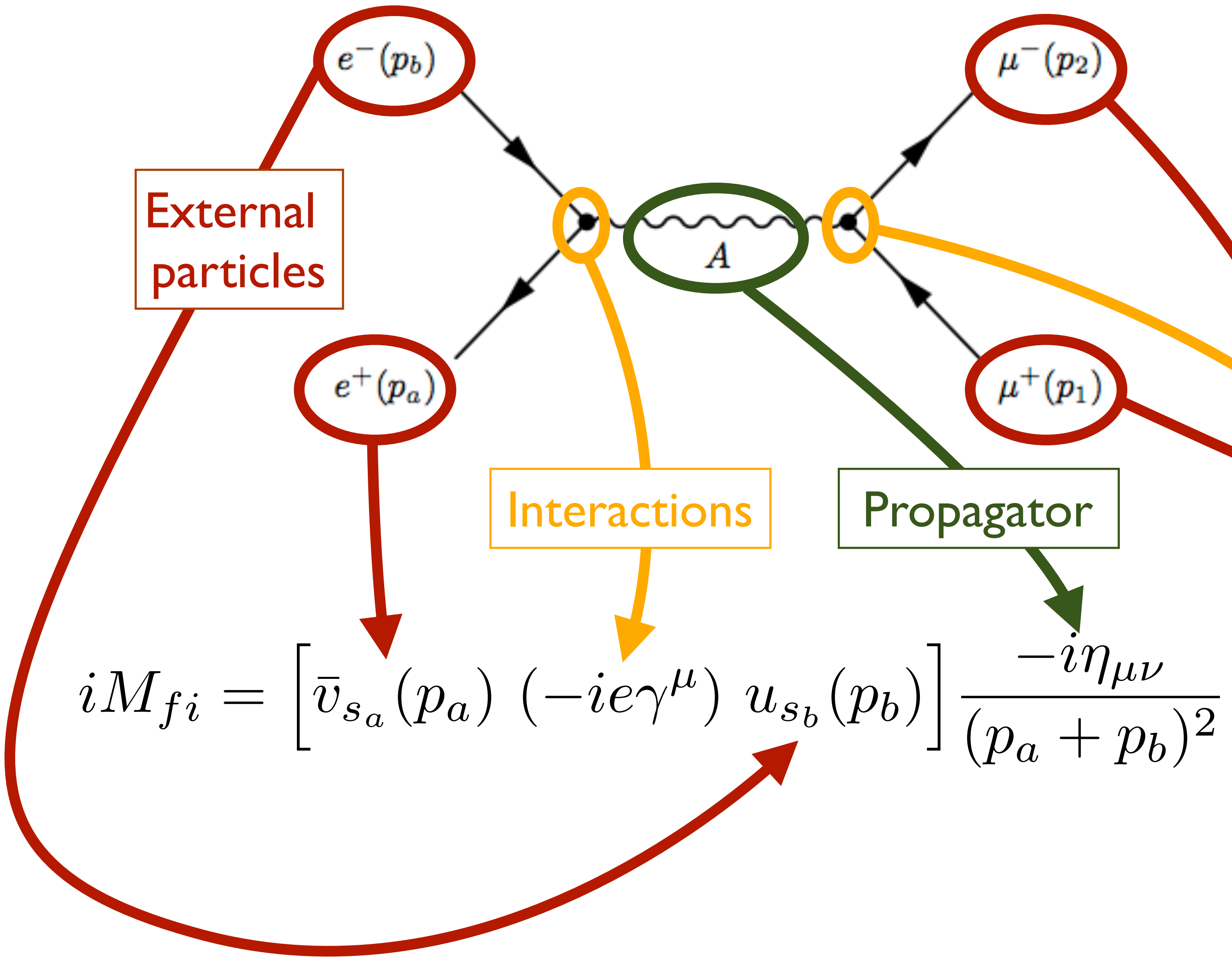


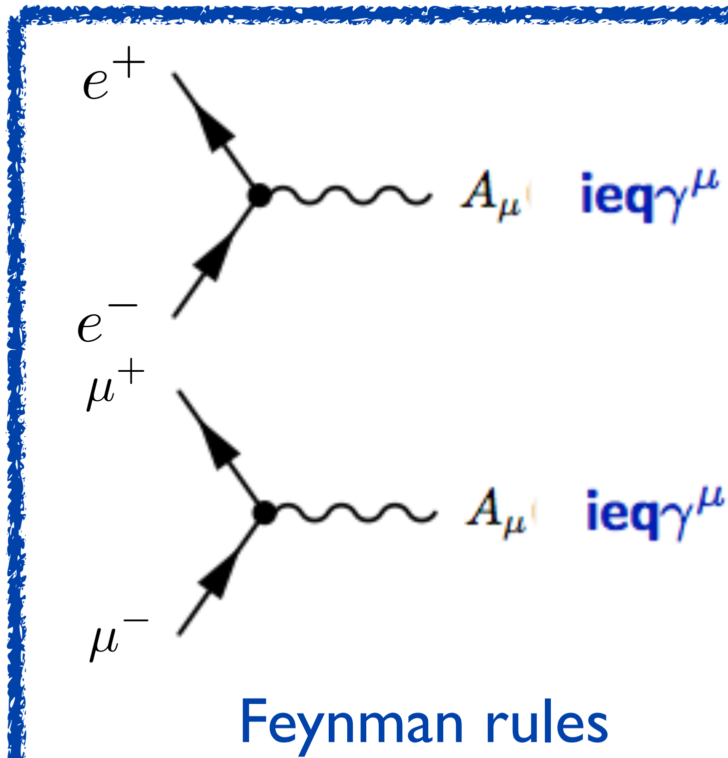
four interactions

Loops exist, but their contribution can usually be neglected

Feynman diagrams and Feynman rules (2)

✦ From Feynman diagrams to M_{fi} :





$$iM_{fi} = \left[\bar{v}_{s_a}(p_a)\;(-ie\gamma^\mu)\;u_{s_b}(p_b)\right]\frac{-i\eta_{\mu\nu}}{(p_a+p_b)^2}\left[\bar{u}_{s_2}(p_2)\;(-ie\gamma^\nu)\;v_{s_1}(p_1)\right]$$

✤ We construct all possible diagrams with the set of rules at our disposal
✤ We can then calculate the squared matrix element and get the cross section

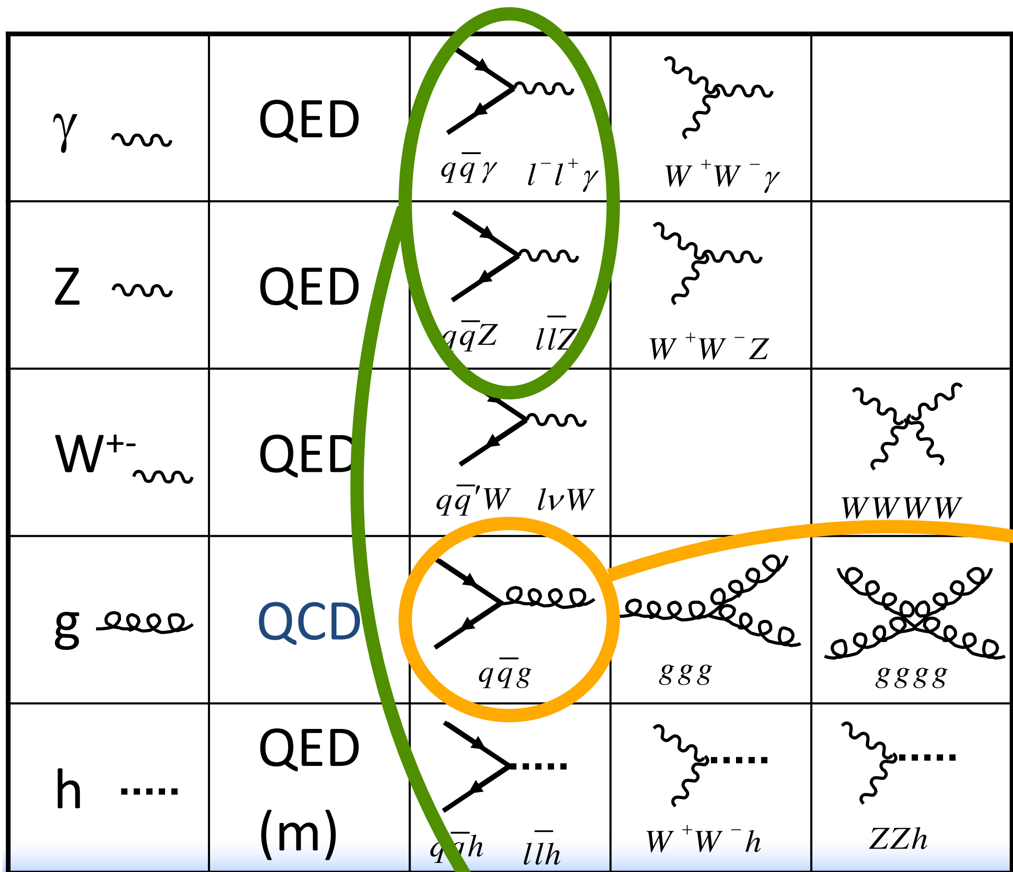
Feynman rules for the Standard Model

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

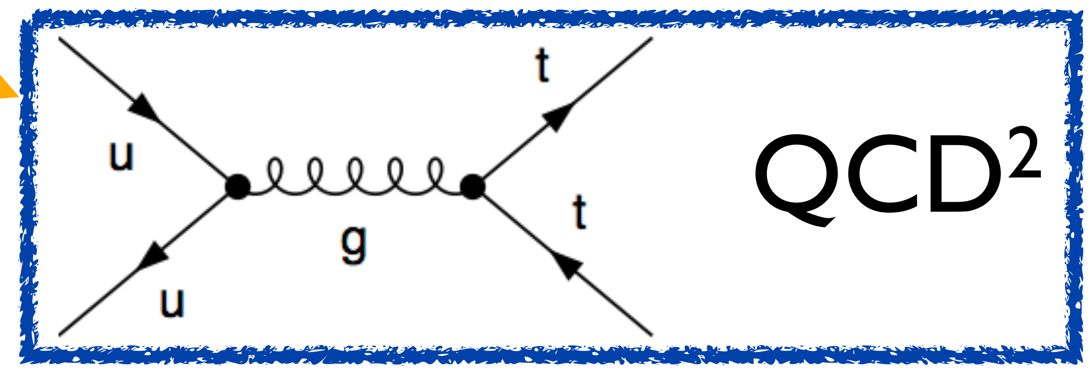
Almost all the building blocks necessary to draw any Standard Model diagrams

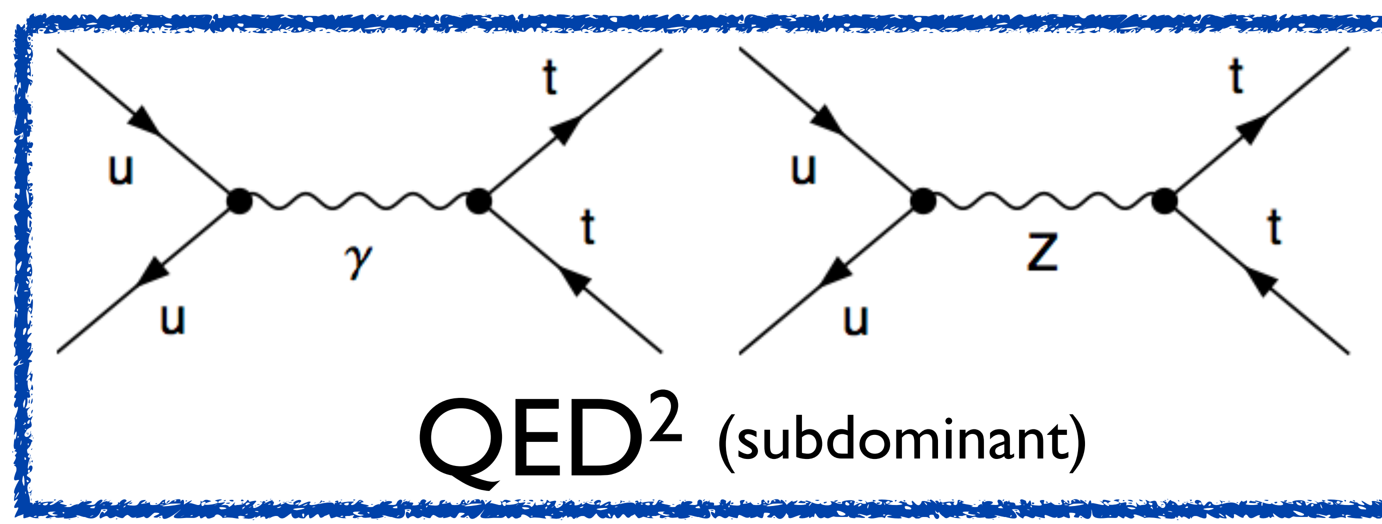
QCD coupling stronger than QED coupling → dominant diagrams

Drawing Feynman diagrams (I)



- We can now combine building blocks to draw diagrams
  - This ensures to focus only on the allowed diagrams
  - We must only consider the dominant diagrams
- Process 0. $u\bar{u} \to t\bar{t}$



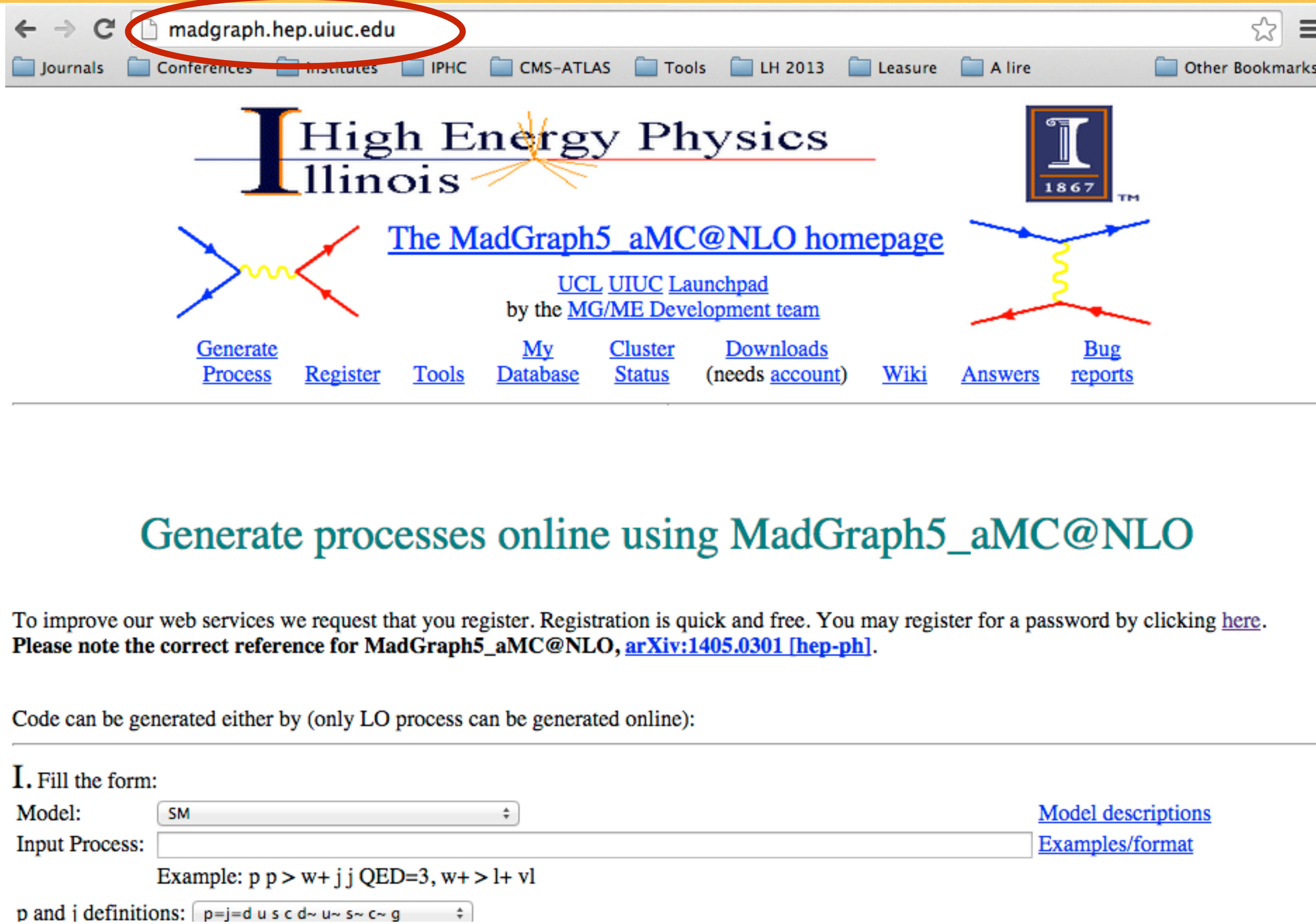


Drawing Feynman diagrams (2)

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

- Find out the dominant diagrams for
  - Process 1. $gg \to t\bar{t}$
  - Process 2. $gg \to t\bar{t}h$
  - Process 3. $u\bar{u} \to t\bar{t}\ b\bar{b}$
- What is the QCD/QED order?
  (keep only the dominant diagrams)

Check your answer!



madgraph.hep.uiuc.edu

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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:

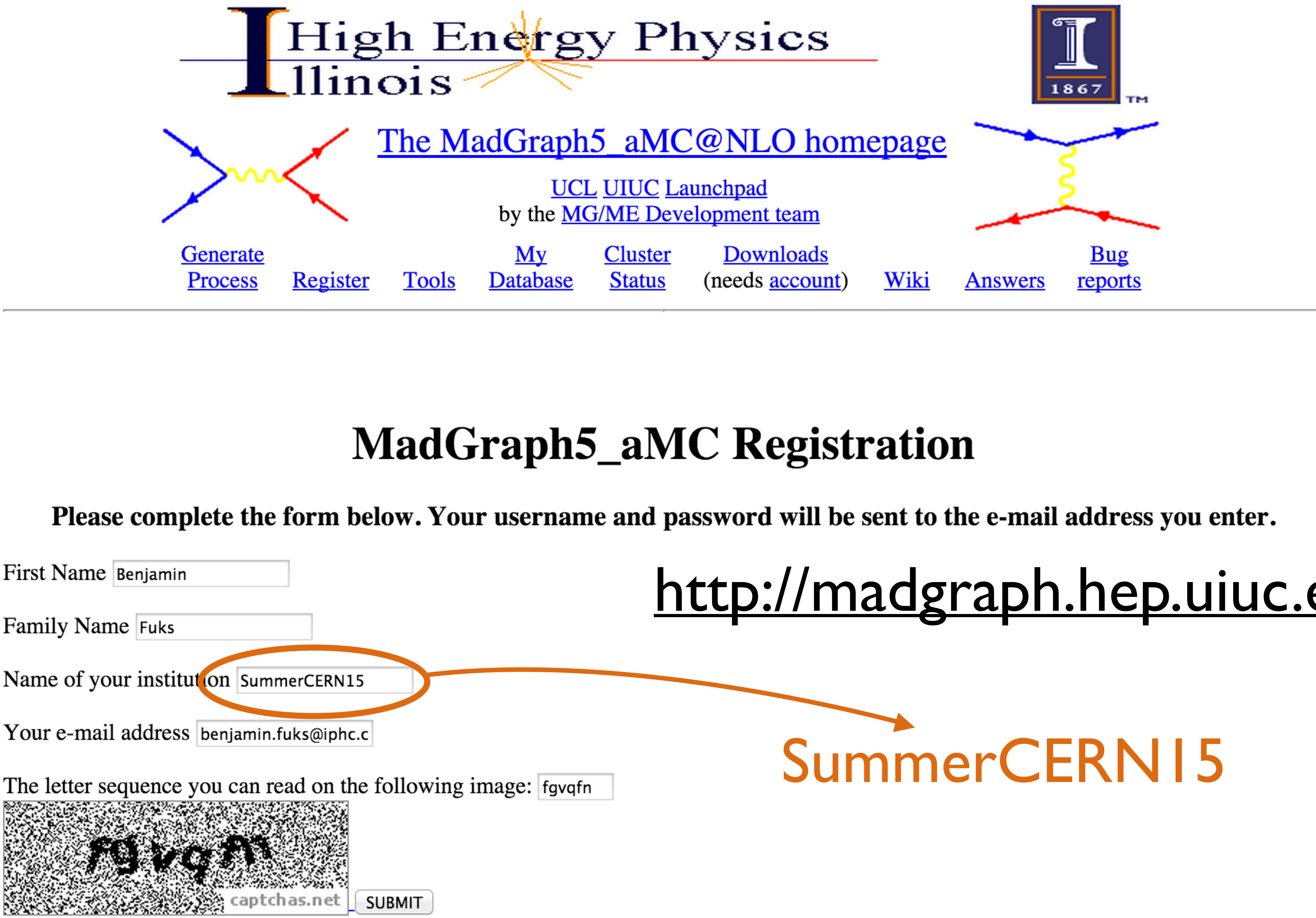
Model: SM — Model descriptions

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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UCL UIUC Launchpad
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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: SummerCERN15

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

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

captchas.net

SUBMIT

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

SummerCERN15

Web process syntax

Initial state

```
u u~ > b b~ t t~
```

Final state

```
u u~ > b b~ t t~ QED=2
```

Minimal coupling order

```
u u~ > h > b b~ t t~
```

Required intermediate particles

Excluded particles

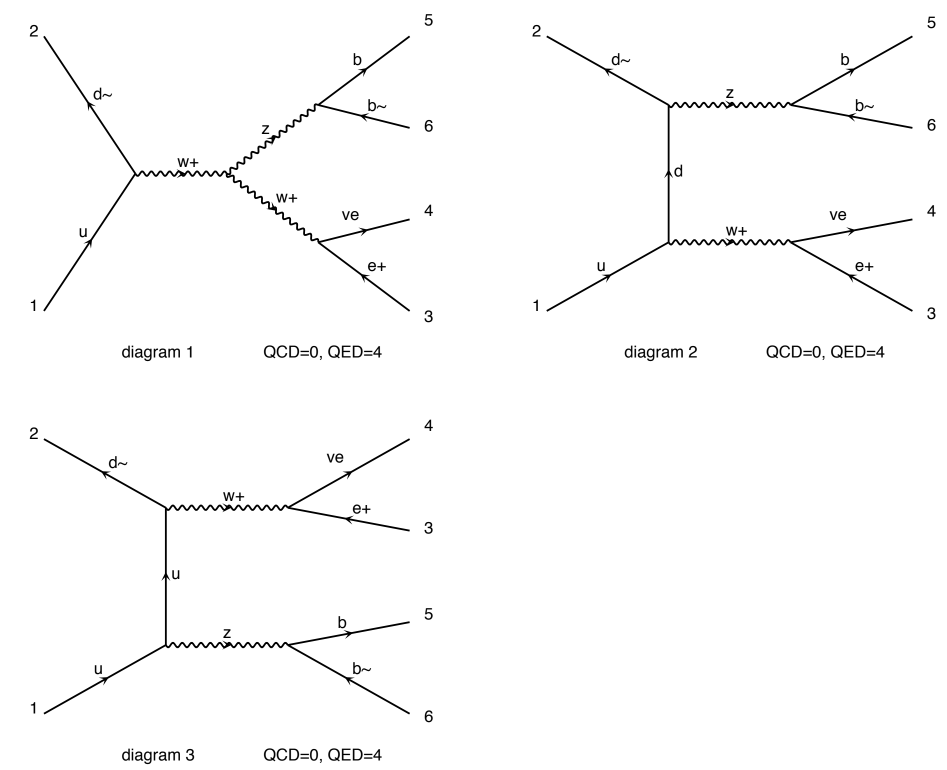
```
u u~ > b b~ t t~ / z a
```

```
u u~ > b b~ t t~, t~ > w- b~
```

Specific decay chain

MADGRAPH so far

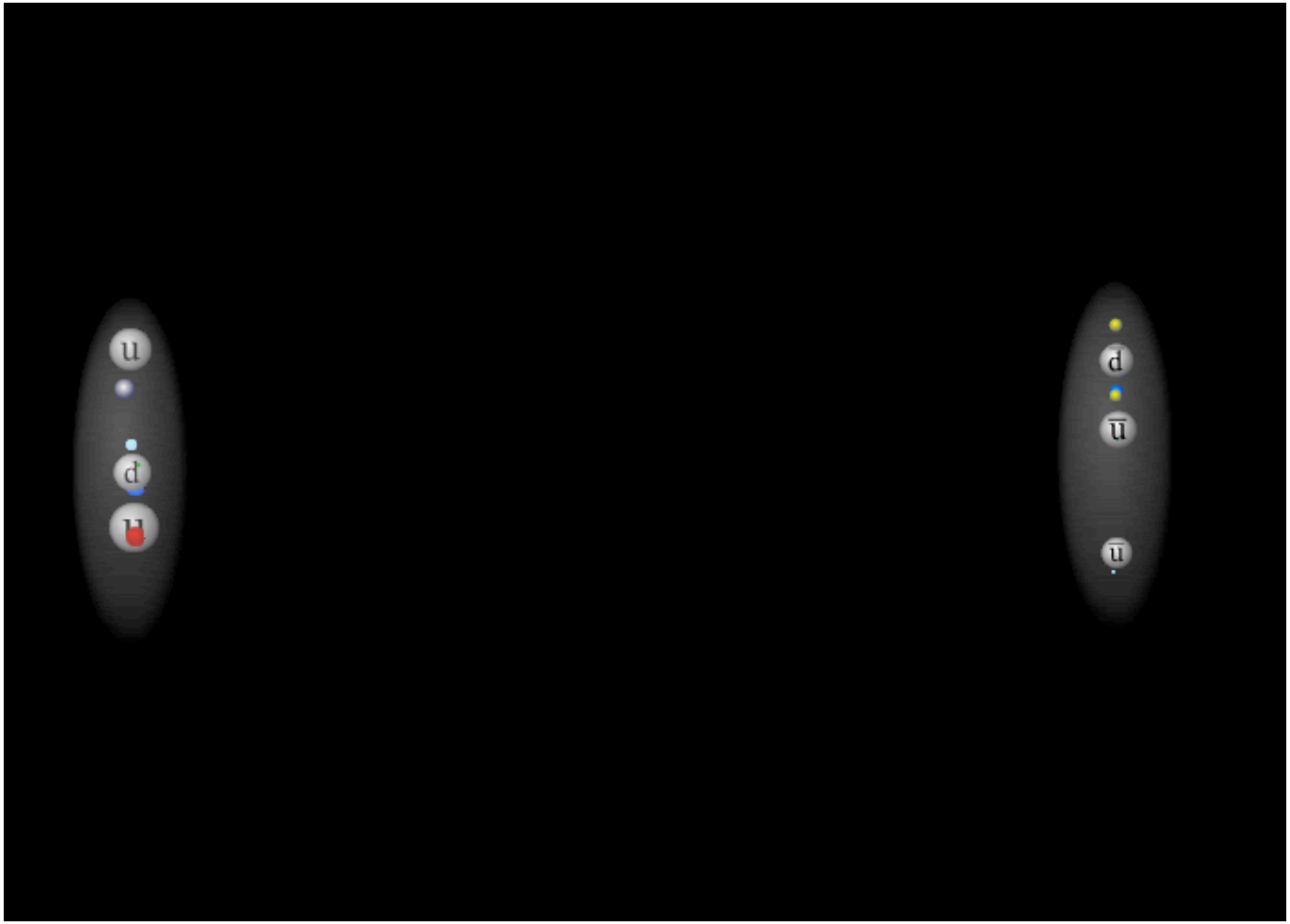
- User requests a process
  - g g > t t~ b b~
  - u d~ > w+ z, w+ > e+ ve, z > b b~
  - etc.




```
 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
```

- MADGRAPH returns:
  - Feynman diagrams
  - Self-contained Fortran code for $|M_{fi}|^2$
- Still needed:
  - What to do with a Fortran code?
  - How to deal with hadron colliders?

Video of a hadron collision



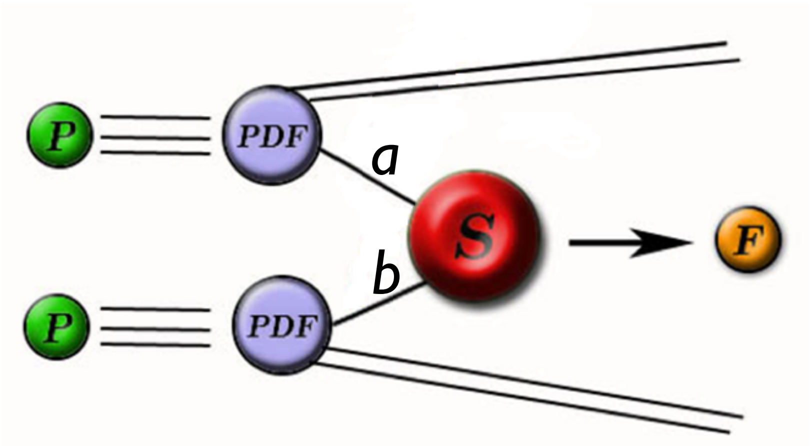
Hadron colliders (1)

✦The master formula for hadron colliders

$$\sigma = \frac{1}{F} \sum_{ab} \int \mathrm{dPS}^{(n)} \mathrm{d}x_a\ \mathrm{d}x_b\ f_{a/p}(x_a)\ f_{b/p}(x_b) \overline{|M_{fi}|^2}$$

✤ We sum over all proton constituents (*a* and *b* here)

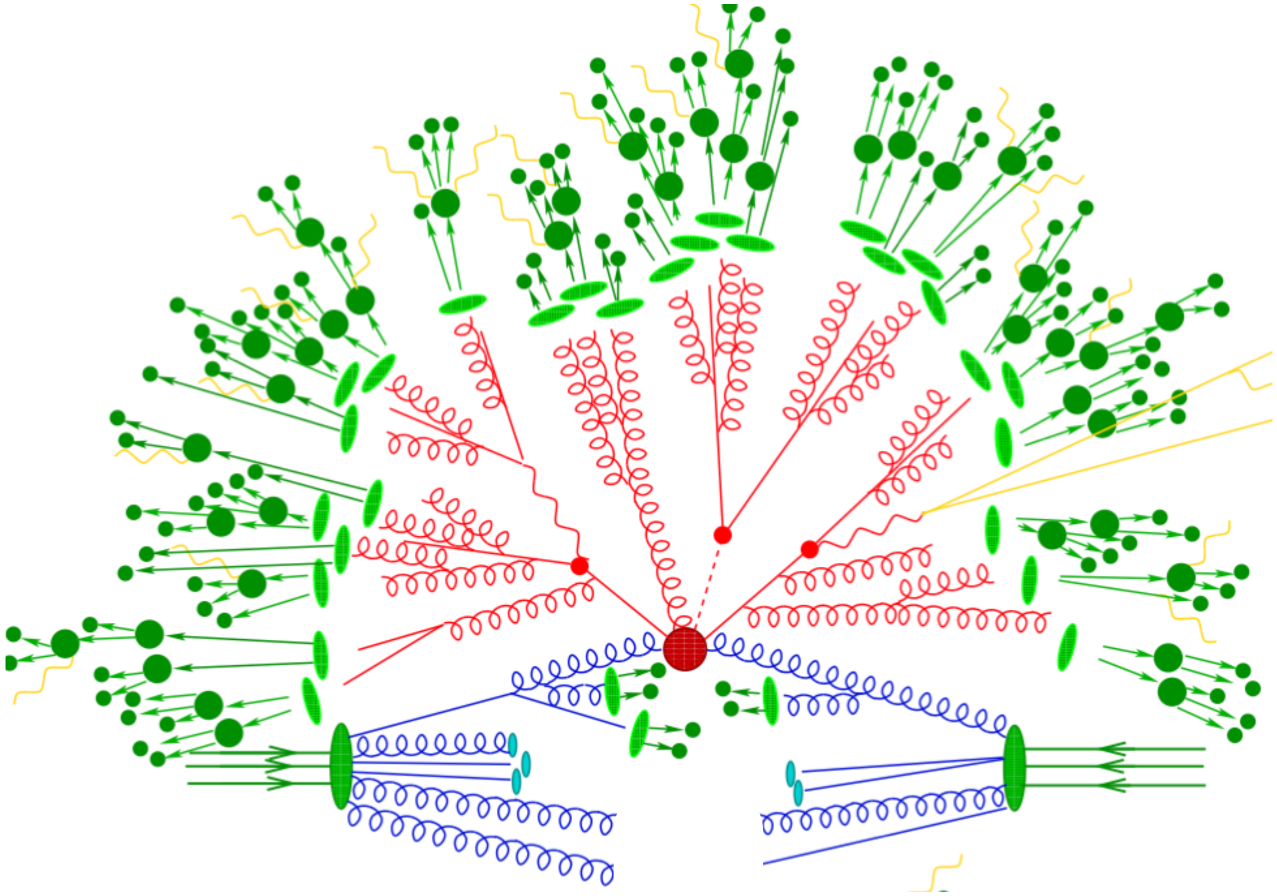
✤ We include the parton densities (the *f*-function)



They represent the probability of having a parton *a* inside the proton carrying a fraction x_a of the proton momentum

Hadron colliders (2)

- This is not the end of the story...
  - At high energies, initial and final state quarks and gluons radiate other quark and gluons
  - The radiated partons radiate themselves
  - And so on...
  - Radiated partons hadronize
  - We observe hadrons in detectors



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1. The Standard Model of particle physics (and beyond)
2. From the Standard Model to predictions at the LHC
3. **Event simulations**
4. Final challenge

MadGraph so far (2)

- User requests a process (including hadron collider processes)
  - `p p > t t~ b b~`
  - `p p > w+ z, w+ > e+ ve, z > b b~`
  - etc.

- MadGraph returns
  - All sub processes and Feynman diagrams
  - A function that needs to be integrated:

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

- Bad news
  - Integration is hard!
  - Large number of integrals to do: 3n - 4 + 2

Monte Carlo integration

✦ Integrals can be approximated by sums!

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

✦ Advantages

- Works also for large number of dimensions
- Can apply complicated cuts (integration limits)
- It's the only option...
- Allows for event generation

✦ Limitations

- Only works if $f(x) \approx 1$
- Error scales like $1/\sqrt{N}$

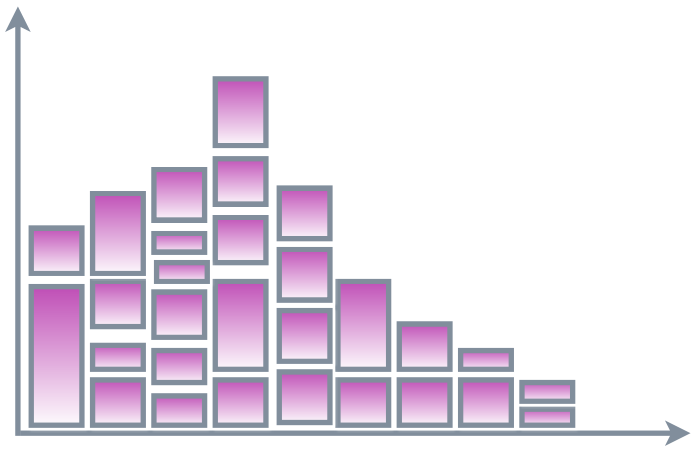
Integration *vs.* event simulation

✦ Remember that we have 3n-4+2 dimensions...

✦ Every phase-space point computed this way can be seen as an event (=collision) in an experiment

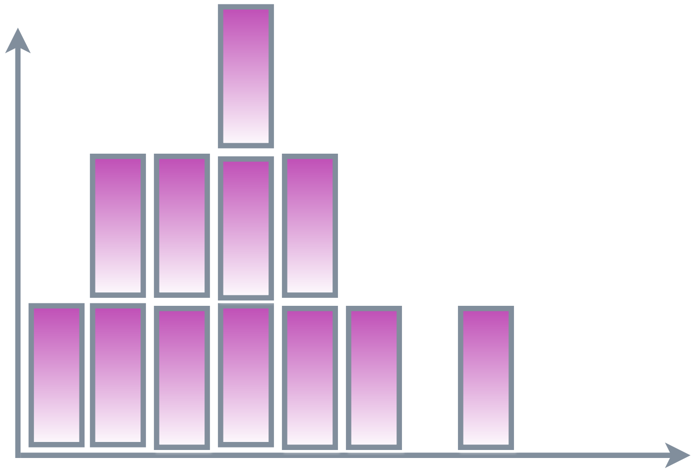
✦ However the events still carry the weight of the matrix elements

- ✤ Events with large weights where the cross section is large
- ✤ Events with small weights where the cross section is small



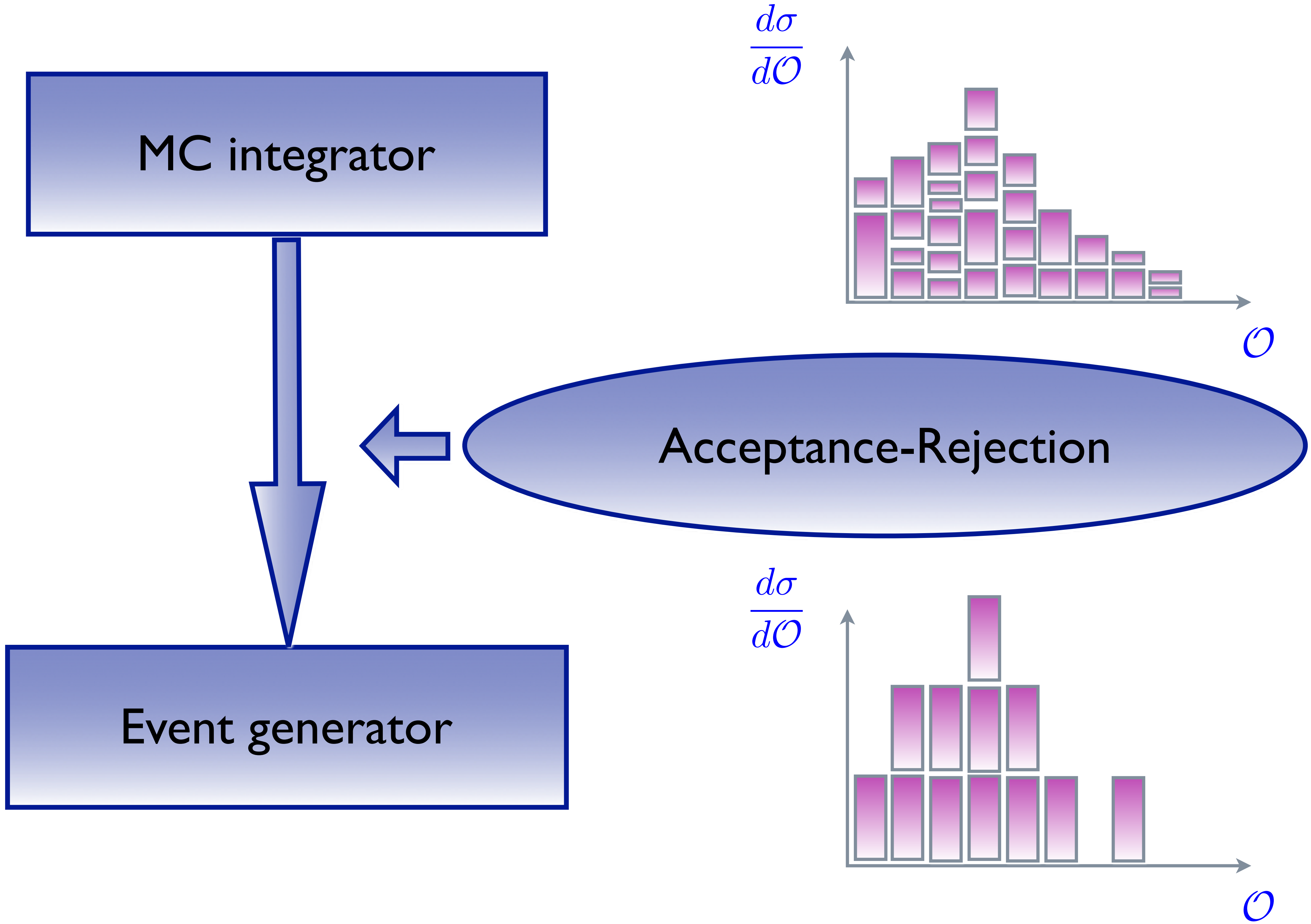
✦ In nature, events do not carry a weight (only a probability to occur)

- ✤ More events where the cross section is large
- ✤ Less events where the cross section is small



✦ Need to go from "weighted events" to "unweighted events"

Unweighted events



MADGRAPH so far (3)

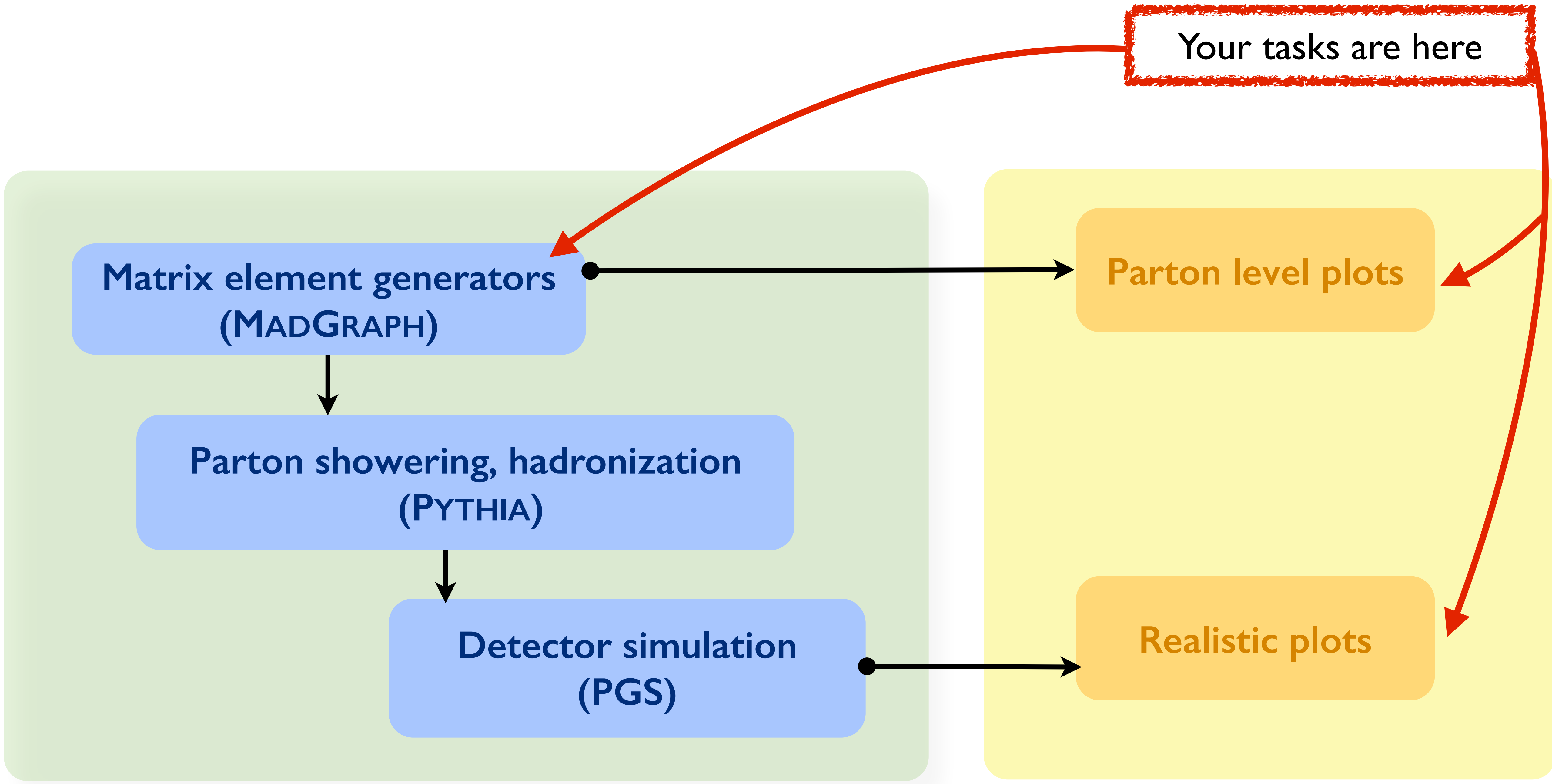
✦ User requests a process (including hadron collider processes) and cuts and parameters

- `p p > t t~ b b~`
- with $p_T(b) > 20$ GeV, $m_{top} = 172.5$ GeV, etc.

✦ MADGRAPH returns:

- All sub processes and Feynman diagrams
- A complete package for event generation
- Events & Plots on-line!

Your job!



Let the fun begin!

p p > a a

- Generate subprocesses and diagrams

- Generate events and Parton Level plots

Outline

1. The Standard Model of particle physics (and beyond)
2. From the Standard Model to predictions at the LHC
3. Event simulations
4. **Final challenge**

Exercise 1: find the Higgs in p p > mu+ mu- e+ e-

- Generate subprocesses and diagrams
  - Use HiggsEFT model to get the $gg \to H$ interaction

- Generate parton level plots

- Generate detector level plots

Exercise 2: find the Higgs in p p > t t~ b b~ / w+ w- z a QED=2

- Generate subprocesses and diagrams
- Generate parton level plots
  - Cut with m_bb > 80 GeV
- Generate detector level plots

Get ready

- Wiki with these exercises
  - MadGraph → Wiki → Lectures&Tutorials → CERN Summer School 2015

2015 CERN Summer student workshop

Exercises

Discover the Higgs boson at the LHC:

- Find predictions for Higgs boson production at the LHC here.
- Find the Higgs boson branching ratio table here.
- Choose a channel and investigate both the signal and background:
  1. The 4 lepton final state: $pp \to H \to ZZ \to e^+e^-\mu^+\mu^-$
     - Signal Plots: Parton Level Detector Level
     - Background Plots: Parton Level Detector Level
  2. Top associated production $pp \to t\bar{t}H$ with $H \to b\bar{b}$
     - Signal + Background Plots: Parton Level Detector Level

Final Challenge: mapping events and models

The Challenge

Three "black boxes" are given, in the form of event files in the LHC Olympics (LHCO) format and a series of selected figures.

- Box A : Events, parton level figures, detector level figures
- Box B : Events, parton level figures, detector level figures
- Box C : Events, parton level figures, detector level figures

These Black boxes are associated with signal events only. It is asked to pair up the boxes above with the three following new physics models and answer the related questions:

- Model 1 - Extra neutral gauge boson (Z'): what is its mass and does it have Standard Model couplings to fermions?
- Model 2 - Heavy scalar (heavy Higgs boson): what is its mass and is it a Standard Model Higgs boson?
- Model 3 - Extra charged gauge boson (W'): what its mass and does it have Standard Model couplings to fermions?

Conclusion

- ✦ Standard model is successful
- ✦ With the Higgs boson the final missing link in the model has been found
  - ✤ The discovery opens many questions
- ✦ There are good motivations to study new physics

- ✦ 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