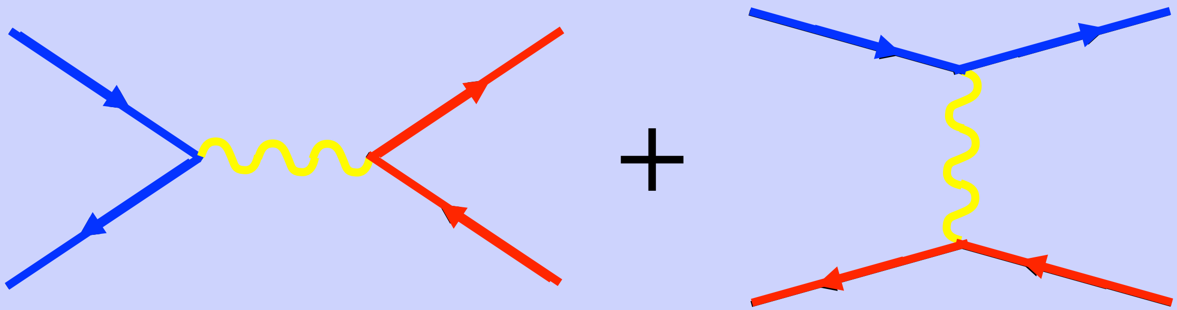
MadGraph + MadEvent



Automated Tree-Level Feynman Diagram and Event Generation

Fabio Maltoni
Center for Cosmology, Particle Physics and Phenomenology

Prizes

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- **1st question that me or Marco cannot answer**

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Prizes

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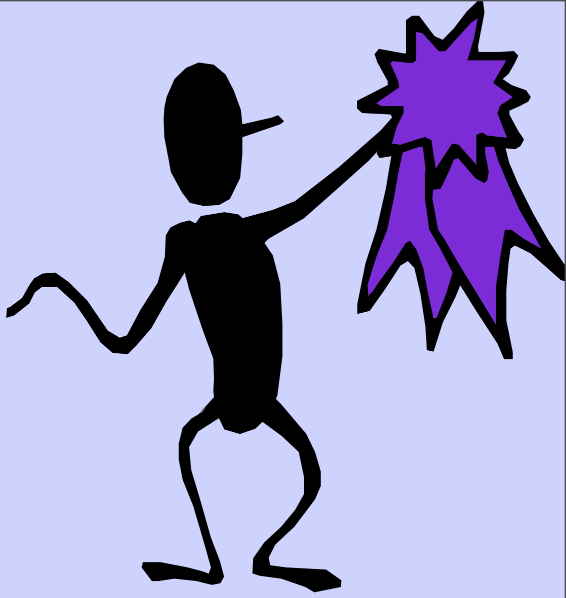
- Best (most complete) solution for the final challenge

Plan



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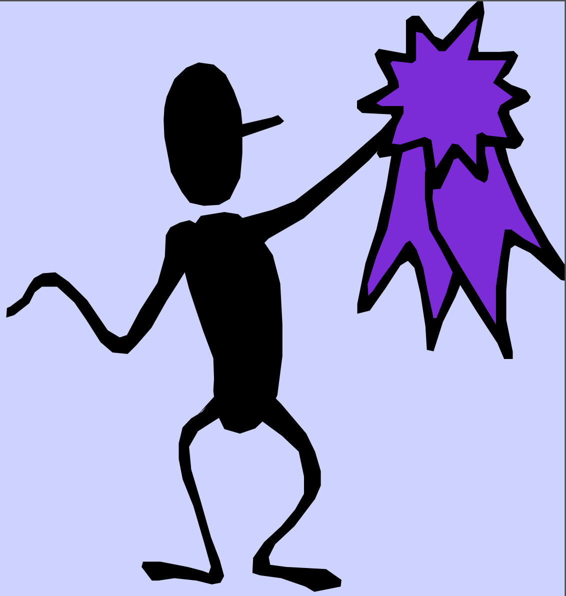

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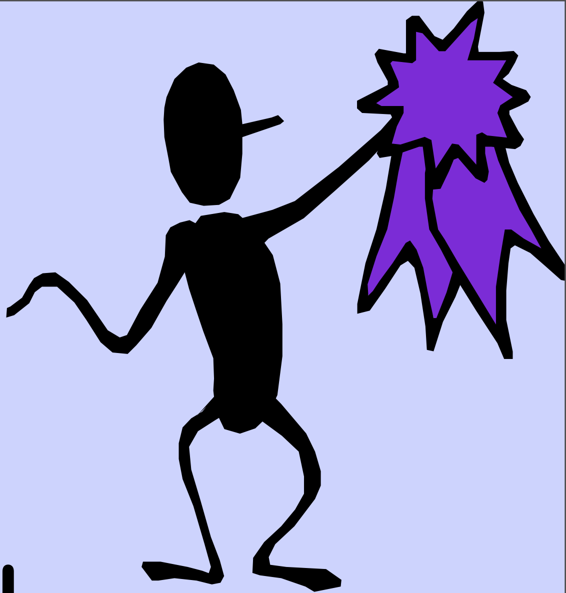
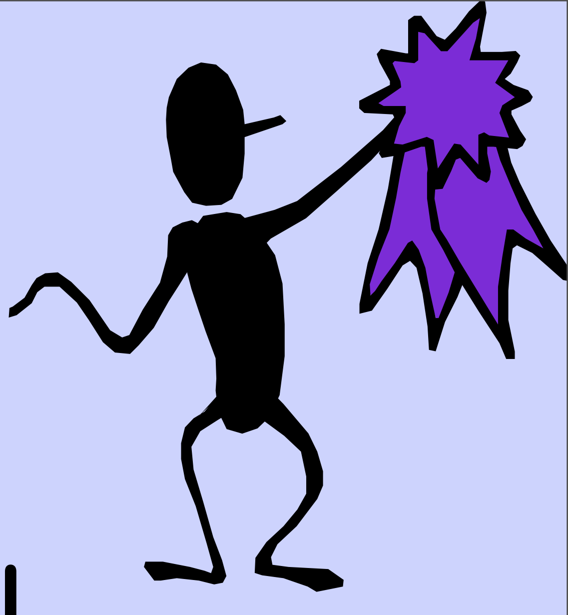


- **Overview of Standard Model**

Plan



- **Overview of Standard Model**
  - Introduction to Particle Physics

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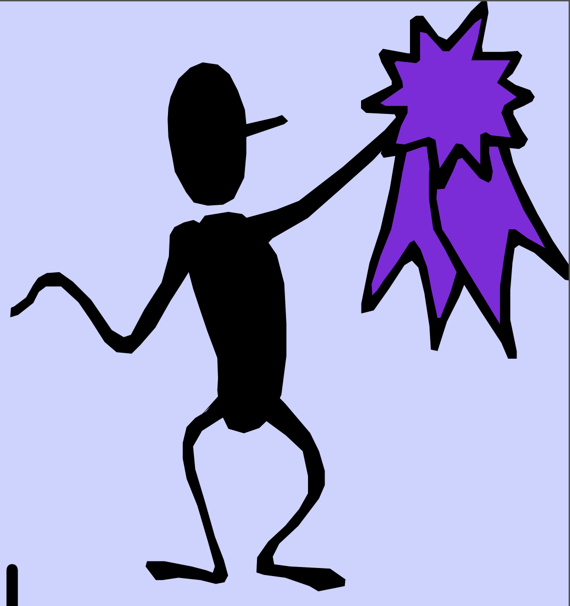
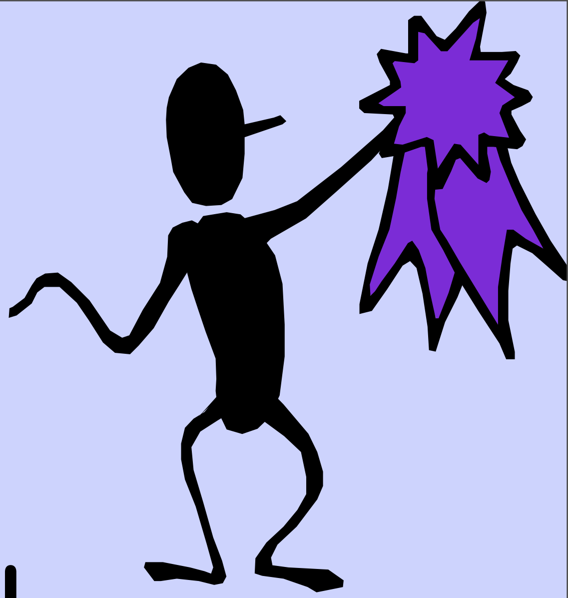


- **Overview of Standard Model**
  - Introduction to Particle Physics
  - The Standard Model

Plan



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  - Introduction to Particle Physics
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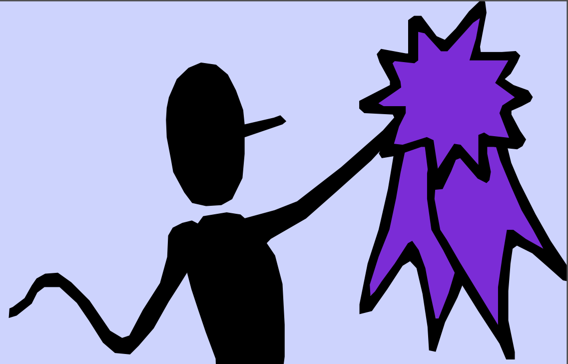
- **Parton level calculations**

Plan



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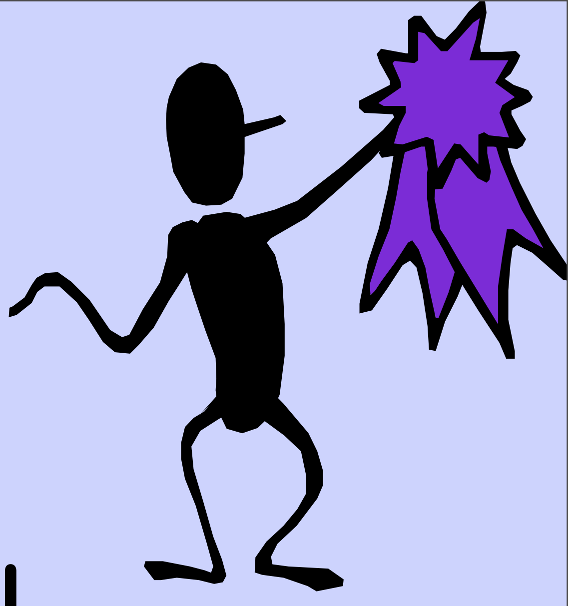

- Overview of Standard Model
  - Introduction to Particle Physics
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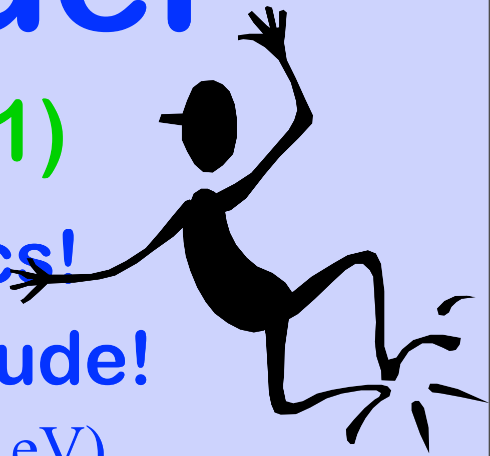
- Parton level calculations
- Full Event Simulations
- Identify 3 Newly Discovered Particles

Standard Model

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



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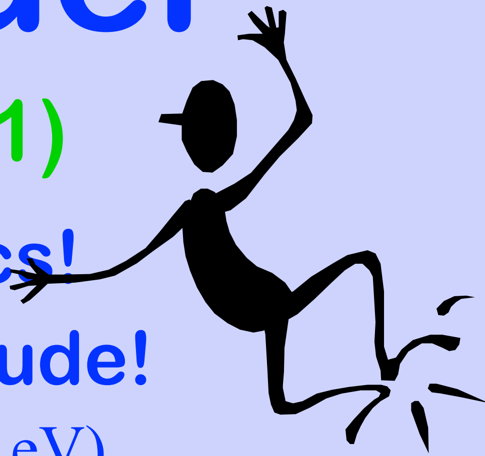

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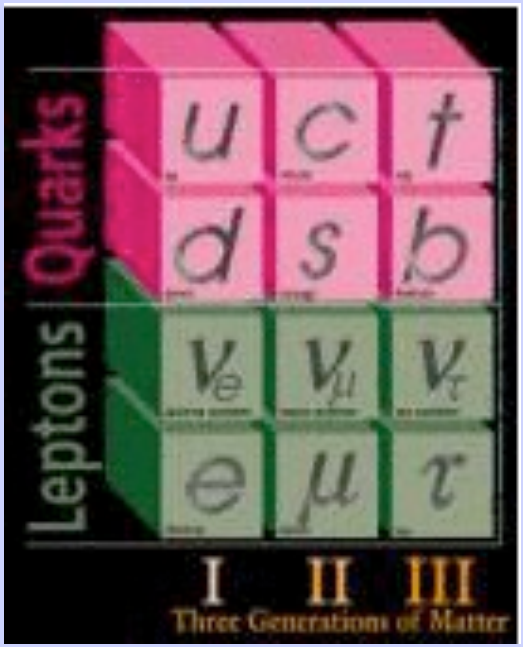

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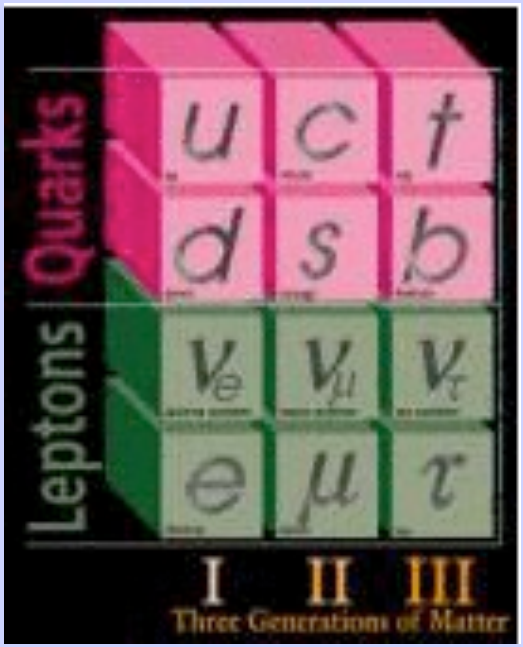

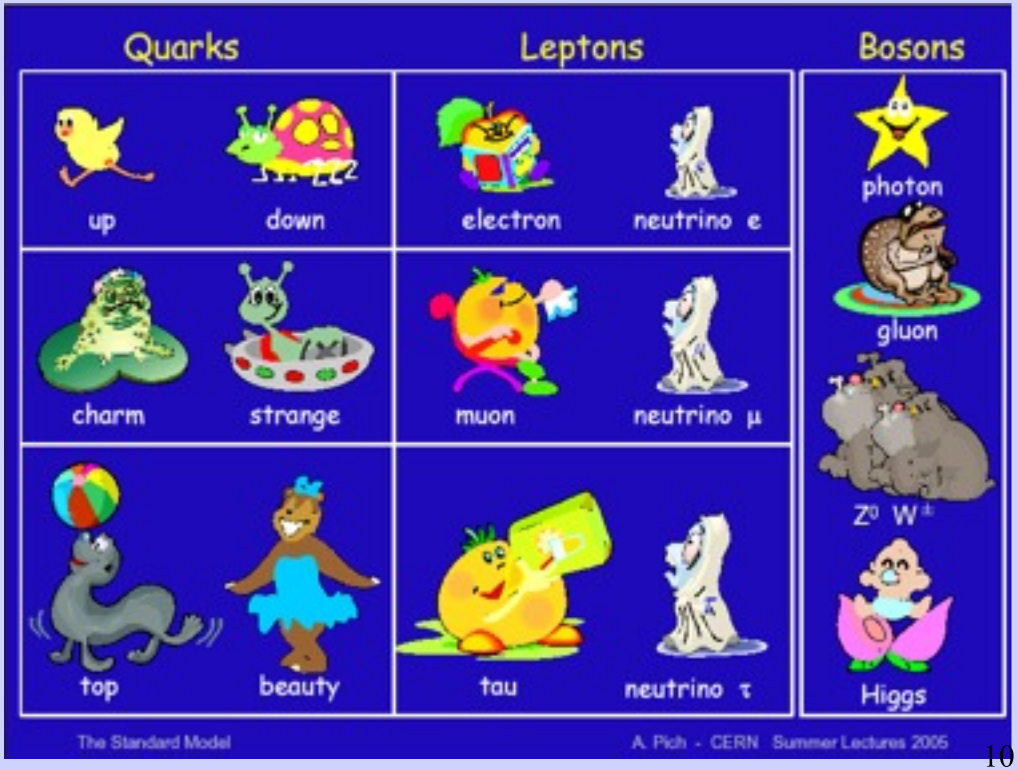

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Standard Model

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

$$= -\frac{1}{4}\left(\partial^{\mu}G^{\nu}_{a} - \partial^{\nu}G^{\mu}_{a}\right)\left(\partial_{\mu}G^{a}_{\nu} - \partial_{\nu}G^{a}_{\mu}\right) + \sum_{q}\bar{q}_{\alpha}\left[i\gamma^{\mu}\partial_{\mu} - m_{q}\right]q_{\alpha}$$

$$+ \frac{1}{2}\sum_{q} g_{s}\left[\bar{q}_{\alpha}\left(\lambda^{a}\right)_{\alpha\beta}\gamma^{\mu}q_{\beta}\right]G^{a}_{\mu}$$

$$- \frac{1}{2}g_{s}f_{abc}\left(\partial_{\mu}G^{a}_{\nu} - \partial_{\nu}G^{a}_{\mu}\right)G^{\mu}_{b}G^{\nu}_{c} - \frac{1}{4}g_{s}^{2}f_{abc}f_{ade}G^{\mu}_{b}G^{\nu}_{c}G^{d}_{\mu}G$$

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

$$- \frac{1}{2} g_s\, f_{abc}\,(\partial_\mu G^a_\nu - \partial_\nu G^a_\mu$$

$$\mathbf{W}_{\mu\nu} = \frac{i}{g}\left[\mathbf{D}_\mu, \mathbf{D}_\nu\right] = \frac{\vec{\sigma}}{2}\cdot\vec{W}_{\mu\nu} \rightarrow \mathbf{U}_L\,\mathbf{W}_{\mu\nu}\,\mathbf{U}_L^\dagger \quad ; \quad B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \rightarrow B_{\mu\nu}$$

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

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

$$\mathcal{L}_3 = -ie\cot\theta_W\left\{(\partial^\mu W^\nu - \partial^\nu W^\mu)\,W^\dagger_\mu Z_\nu - (\partial^\mu W^{\nu\dagger} - \partial^\nu W^{\mu\dagger})\,W_\mu Z_\nu + W_\mu W^\dagger_\nu\,(\partial^\mu Z^\nu - \partial^\nu Z^\mu)\right\}$$
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$$\mathcal{L}_4 = -\frac{e^2}{2\sin^2\theta_W}\left\{\left(W^\dagger_\mu W^\mu\right)^2 - W^\dagger_\mu W^{\mu\dagger} W_\nu W^\nu\right\} - e^2\cot^2\theta_W\left\{W^\dagger_\mu W^\mu Z_\nu Z^\nu - W^\dagger_\mu Z^\mu W_\nu Z^\nu\right\}$$
$$-e^2\cot\theta_W\left\{2W^\dagger_\mu W^\mu Z_\nu A^\nu - W^\dagger_\mu Z^\mu W_\nu A^\nu - W^\dagger_\mu A^\mu W_\nu Z^\nu\right\} - e^2\left\{W^\dagger_\mu W^\mu A_\nu A^\nu - W^\dagger_\mu A^\mu W_\nu A^\nu\right\}$$

Predictions from SM

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

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

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

- **Scattering cross section**

- **Feynman Diagrams**

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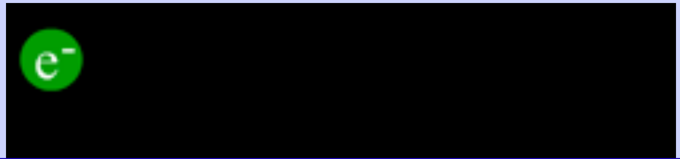

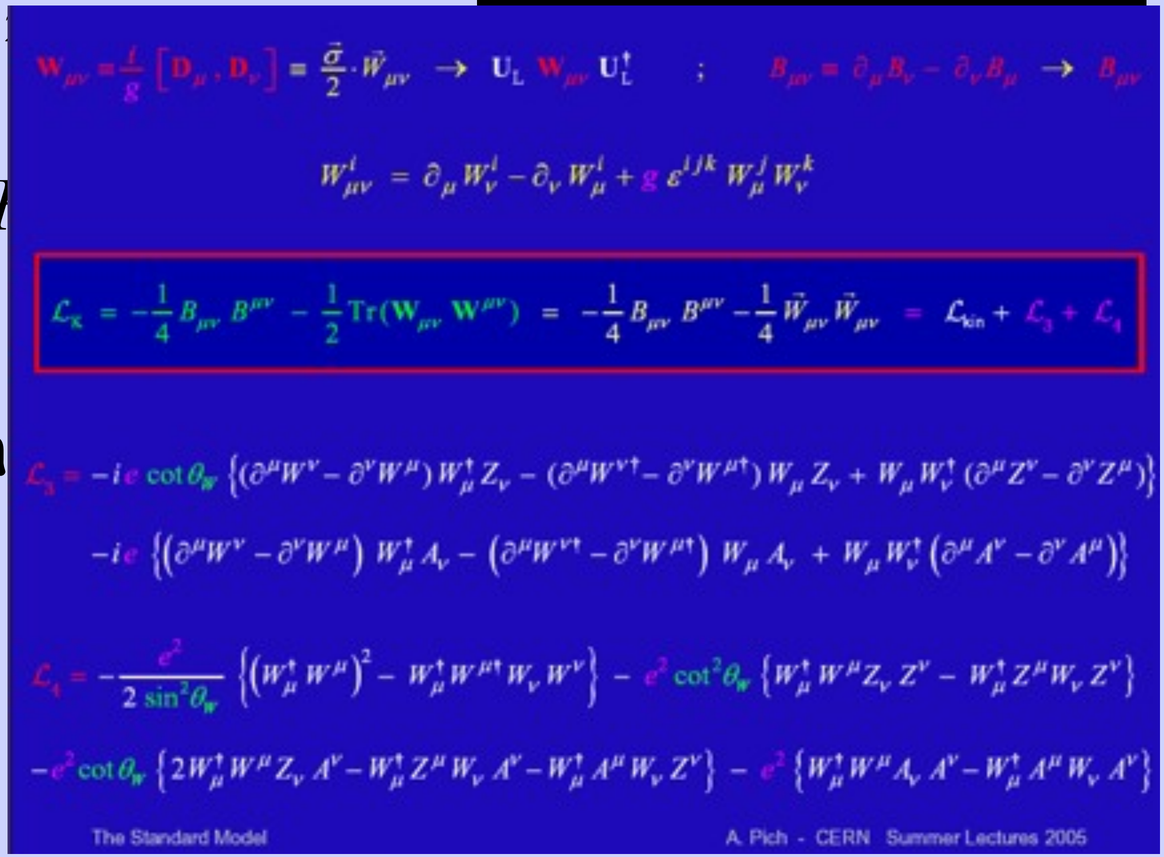

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The Standard Model A. Pich - CERN Summer Lectures 2005

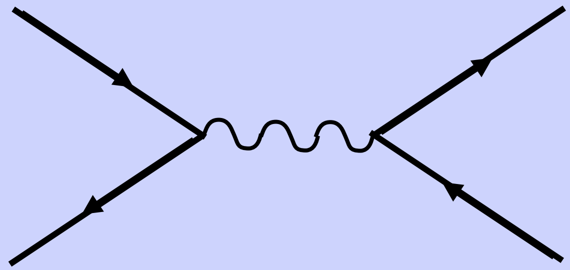
Example: $e^+e^- \rightarrow \mu^+\mu^-$

- **Scattering cross section**

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

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

- **Feynman Diagrams**



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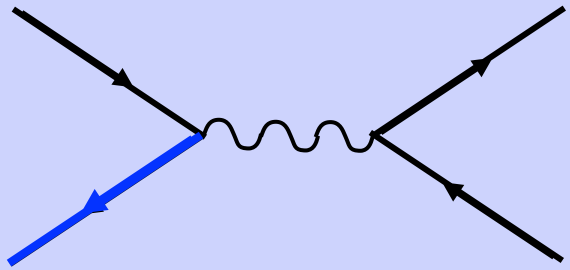

$$M \approx \overline{v}(e^+)$$

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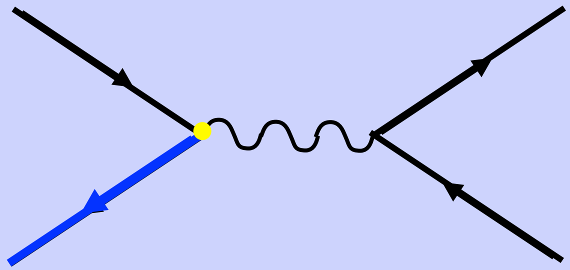

$$M \approx \bar{v}(e^+)\,(-iq\gamma^\mu)$$

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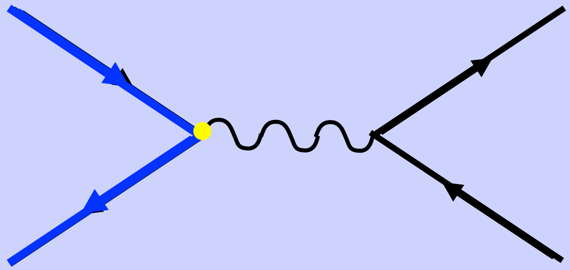

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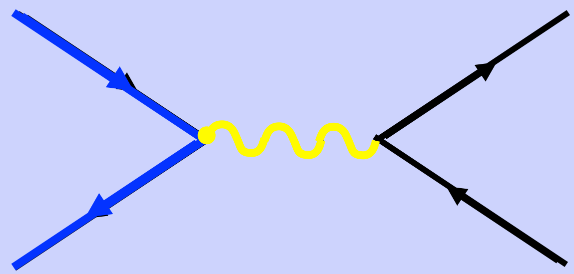

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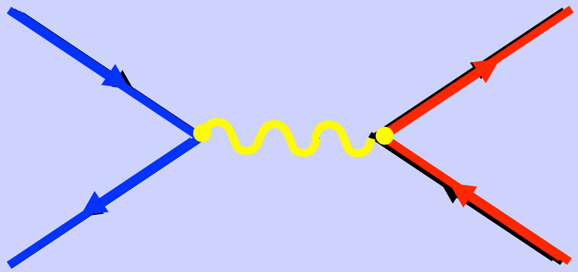

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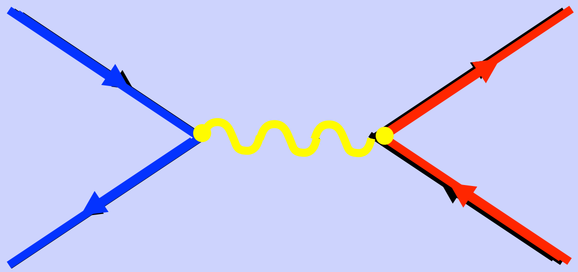

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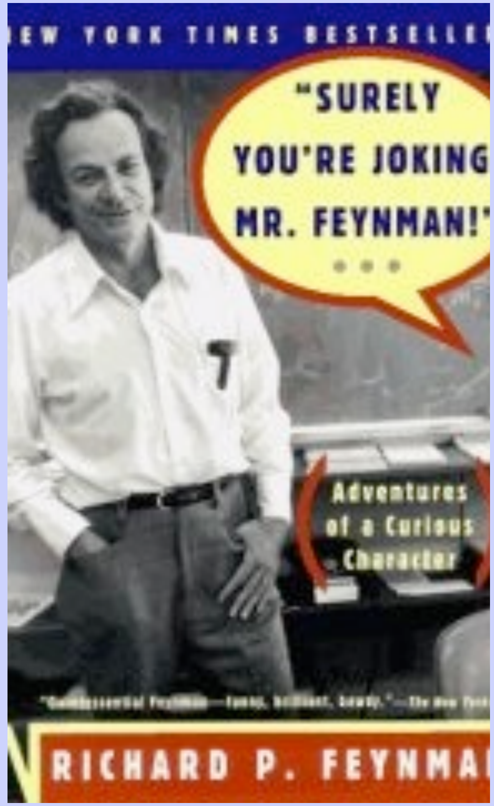
Feynman Rules!

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!

γ	QED	$q\bar{q}\gamma$ $l^-l^+\gamma$	$W^+W^-\gamma$	
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Feynman Rules!

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

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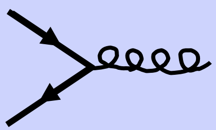

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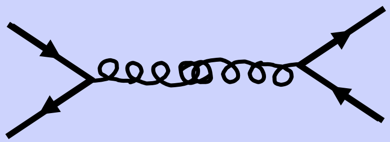

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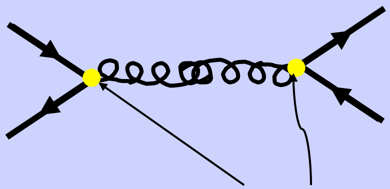

Order is QCD^2

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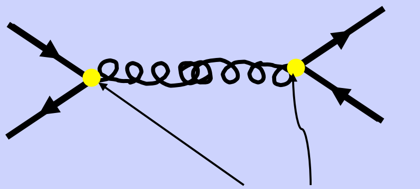
W	QED	$q\bar{q}'W$ $l\nu W$		$WWWW$
g	QCD	$q\bar{q}g$	ggg	$gggg$
h	QED (m)	$q\bar{q}h$ $l\bar{l}h$	W^+W^-h	ZZh

Feynman Rules!

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



Order is QCD^2

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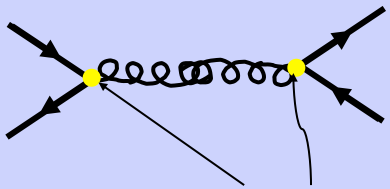

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- Draw Feynman diagrams:
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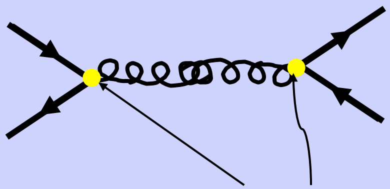

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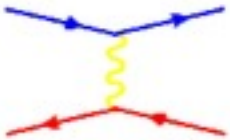
- Draw Feynman diagrams:
  - g g > t t~
  - g g > t t~ h
- Determine “order” for each diagram

High Energy Physics
Illinois

This material is based upon work supported by the National Science Foundation under Grant No. 0426272.
Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation

MadGraph Version 4

UCL UIUC Fermi
by the MG/ME Development team



Generate Process | Register | Tools | My Database | Cluster Status | Downloads (needs registration) | Wiki/Docs | Admin

---

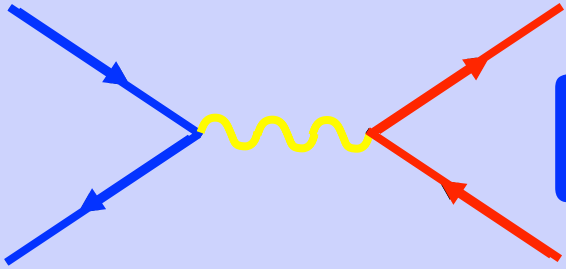
Generate Code On-Line

To improve our web services we now request that you register. Registration is quick and free. You may register for a password by clicking here

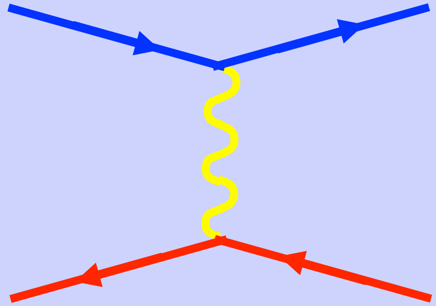
Code can be generated either by:

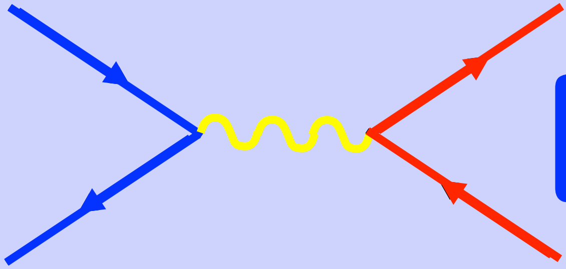
I. Fill the form:

Model: SM — Model descriptions
Input Process: — Examples
Max QCD Order: 99
Max QED Order: 99
p and j definitions: p=j=d u s c d~ u~ s~ c~ g
sum over leptons: l+ = e+, mu+ ; l- = e-, mu- ; vl = ve, vm ; vl~ = ve~, vm~
Submit



MadGraph





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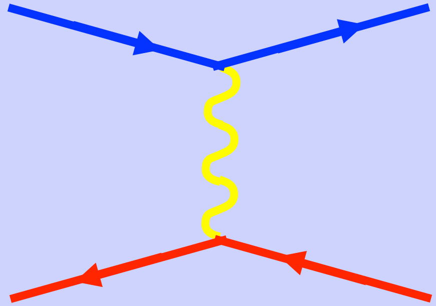

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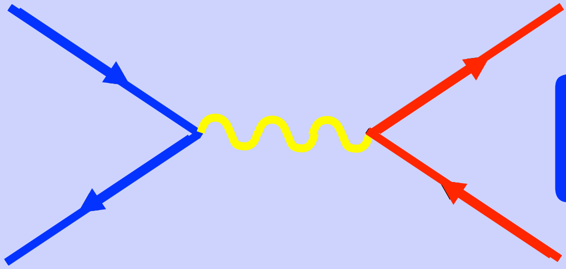

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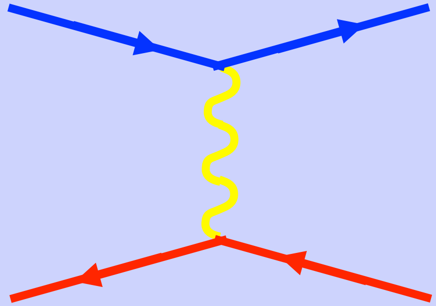

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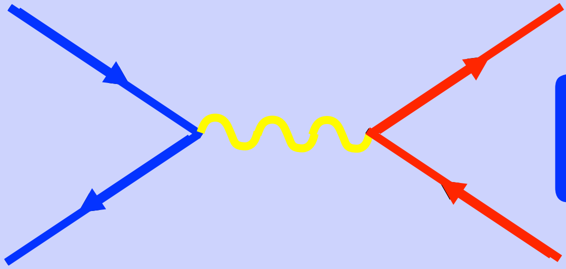

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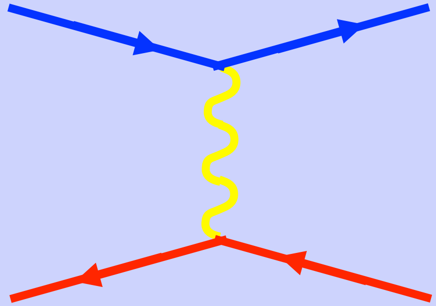
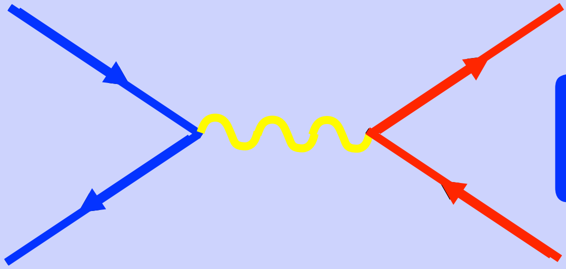


- **User Requests:**
  - **g g > t t~ b b~**
  - **QCD Order = 4**



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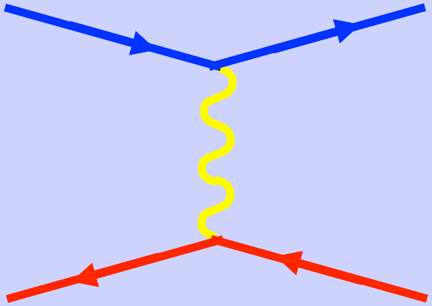

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  - g g > t t~ b b~
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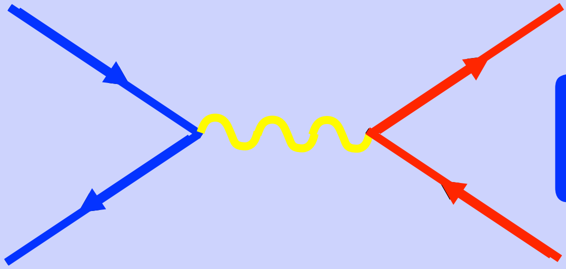

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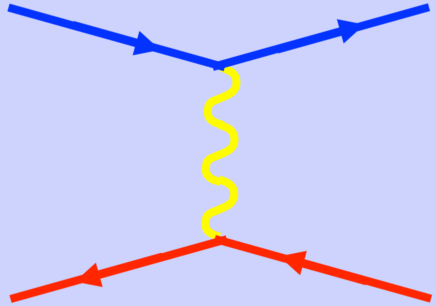

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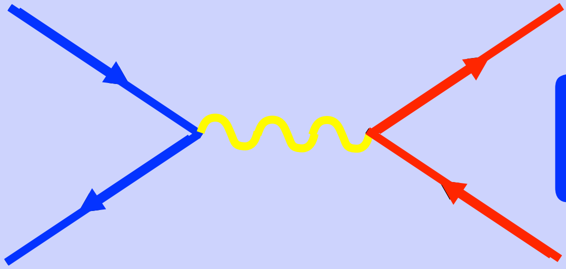

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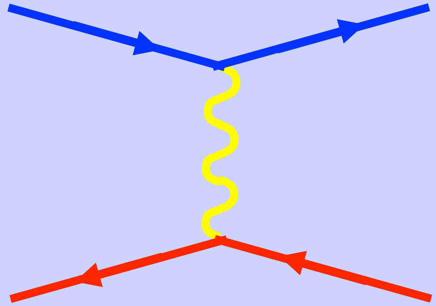

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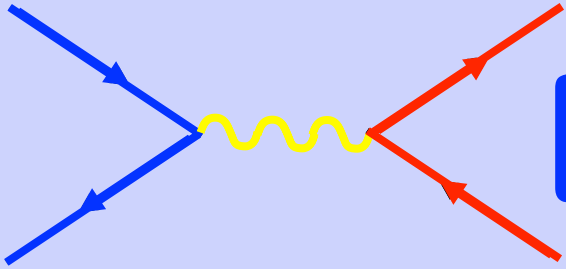

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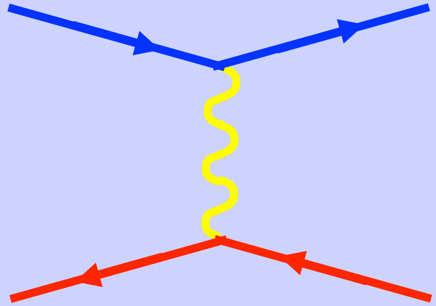

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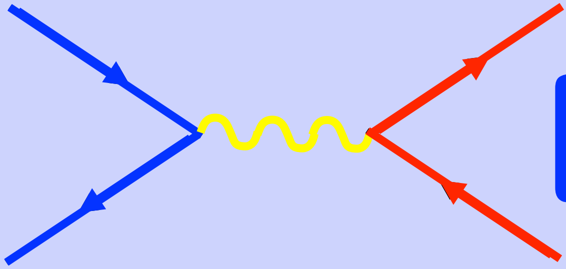

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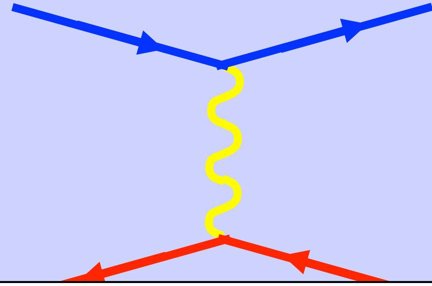

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```
 SUBROUTINE SMATRIX(P1,ANS)
C
C Generated by MadGraph II Version 3.83. Updated 06/13/05
C RETURNS AMPLITUDE SQUARED SUMMED/AVG OVER COLORS
C AND HELICITIES
C FOR THE POINT IN PHASE SPACE P(0:3,NEXTERNAL)
C
C FOR PROCESS : g g -> t t~ b b~
C
C Crossing   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
```

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- Good News
  - MadGraph generates all tree-level diagrams
  - MadGraph generates fortran code to calculate $\Sigma|M|^2$

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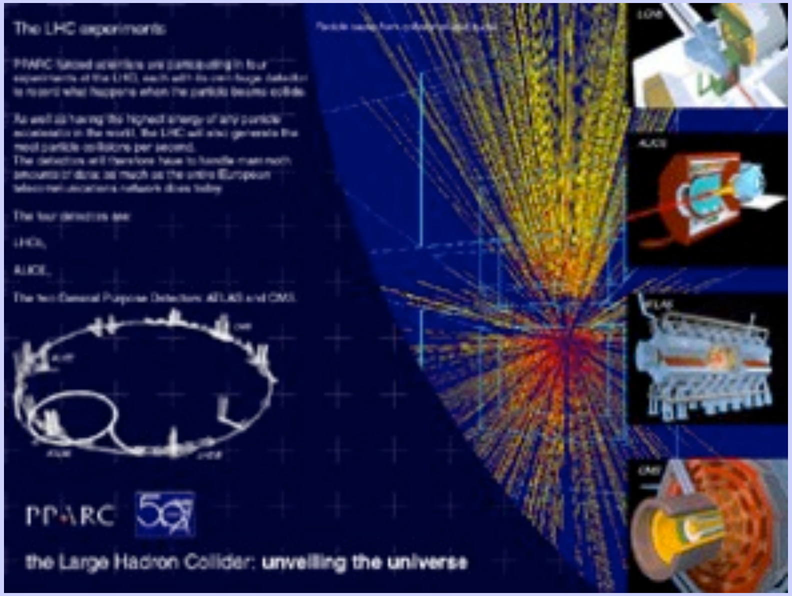
- Good News
  - There’s a cool animation next!

Hadron Colliders



Hadron Colliders

- **Initial State: Protons**
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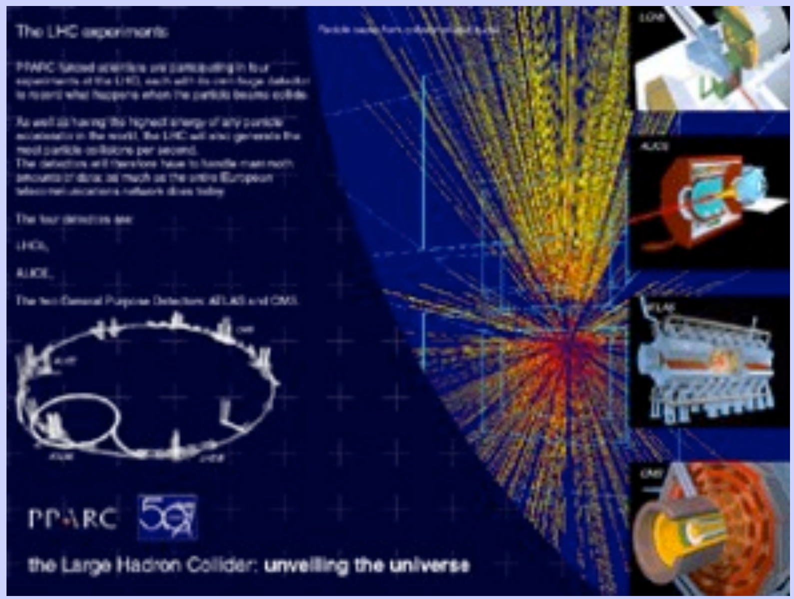
  - Strongly interacting P.T. won't work



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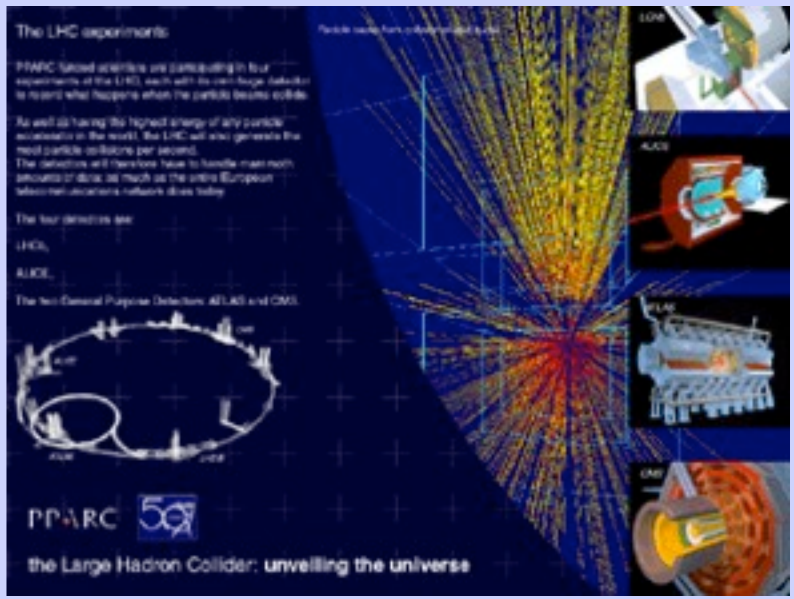


Let's watch an animation

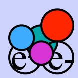
Parton Distribution Functions
(Measured)

Evolution
+Splitting

Hard
Scattering

Showering
Fragmentation

Hadronization



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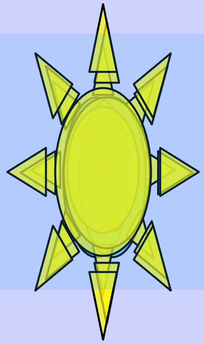

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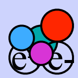

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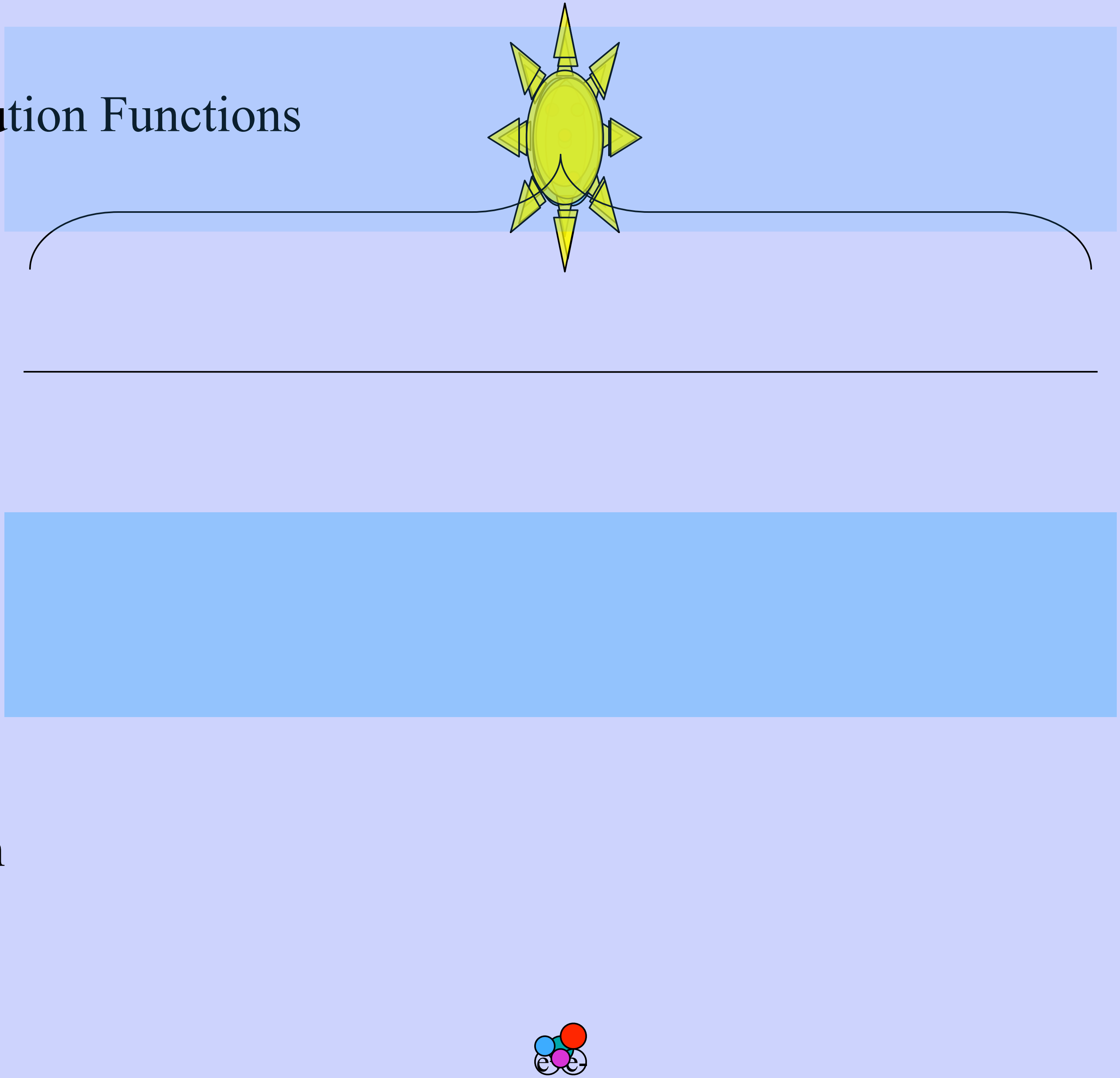

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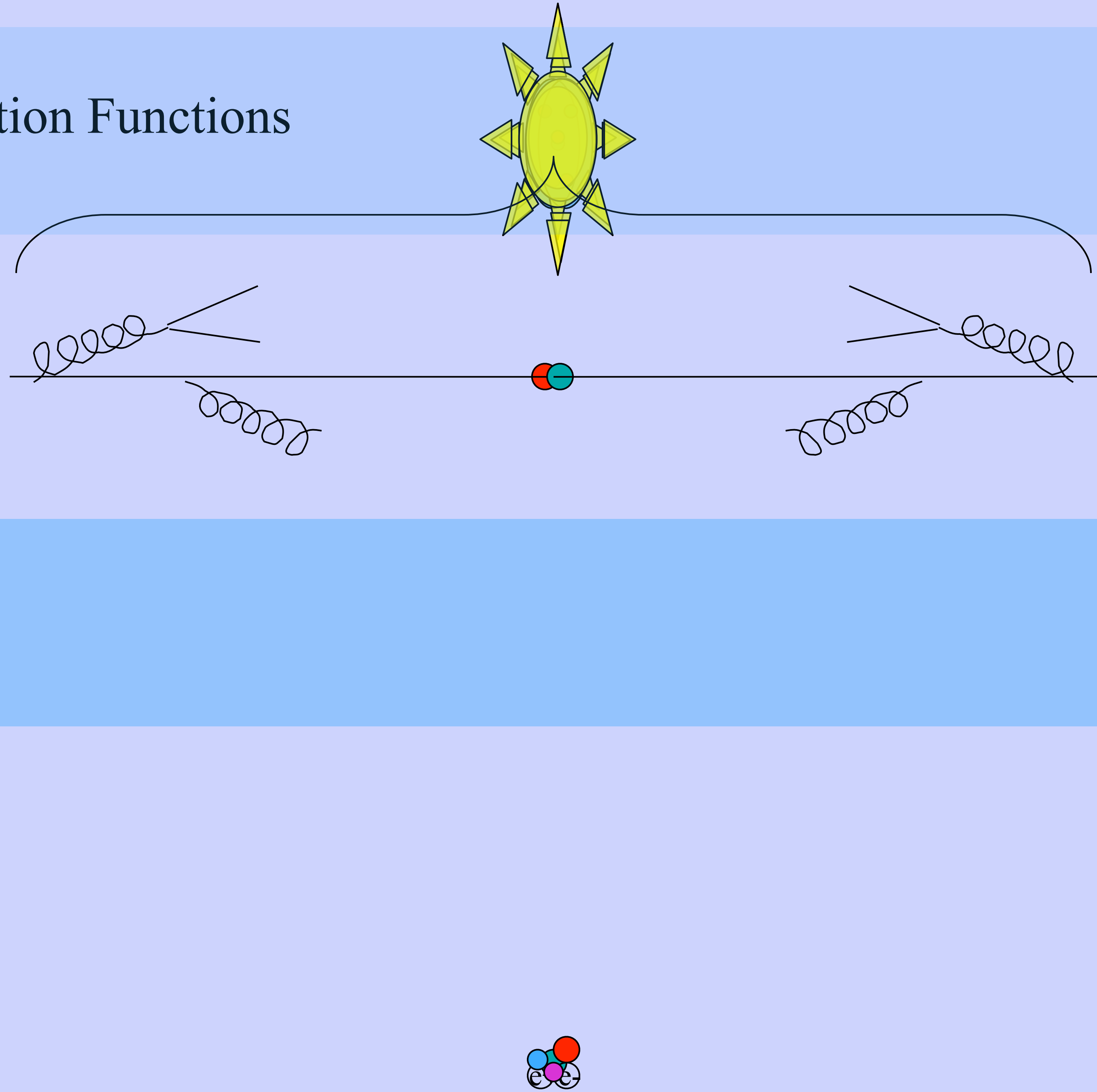

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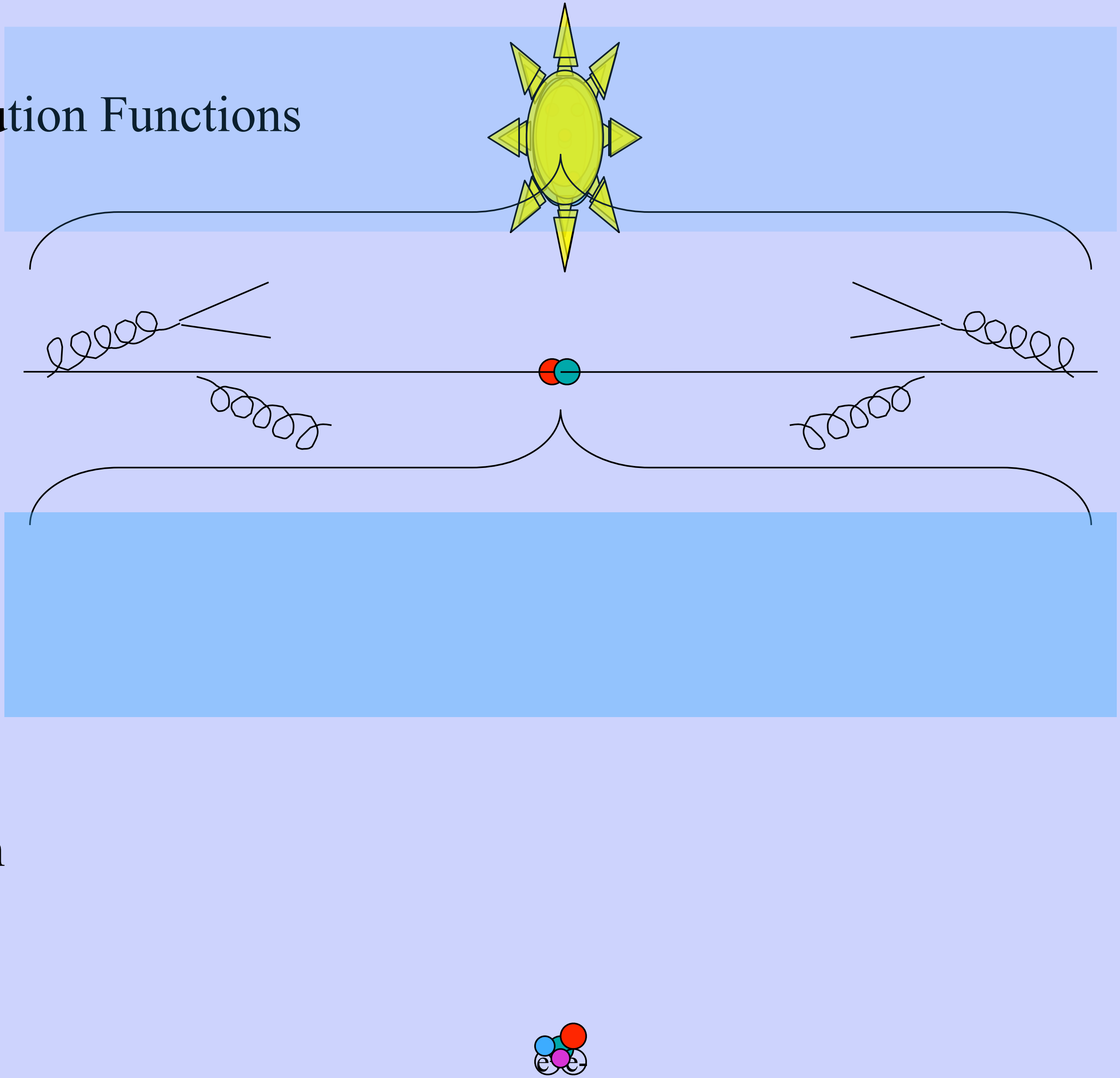

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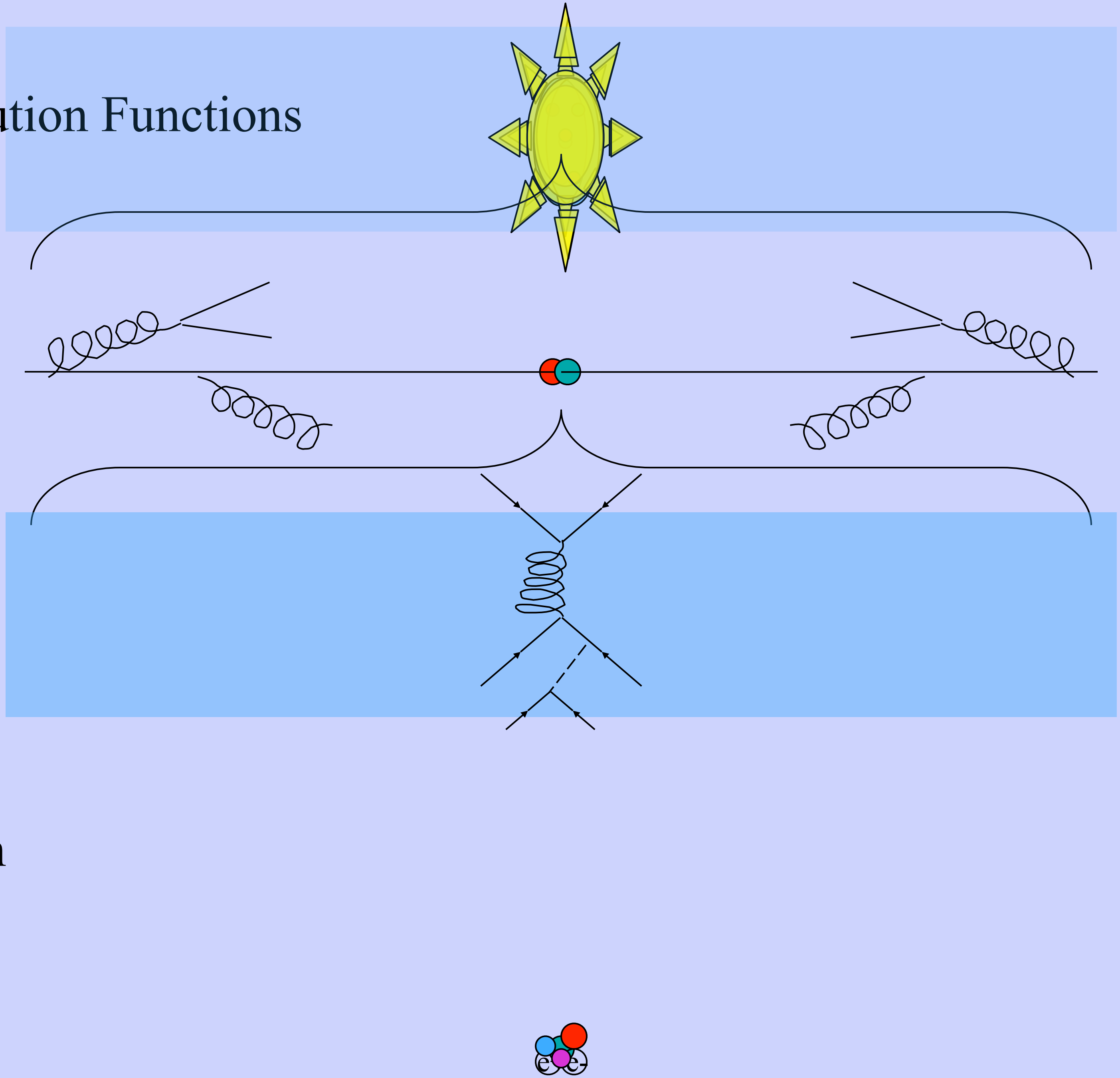

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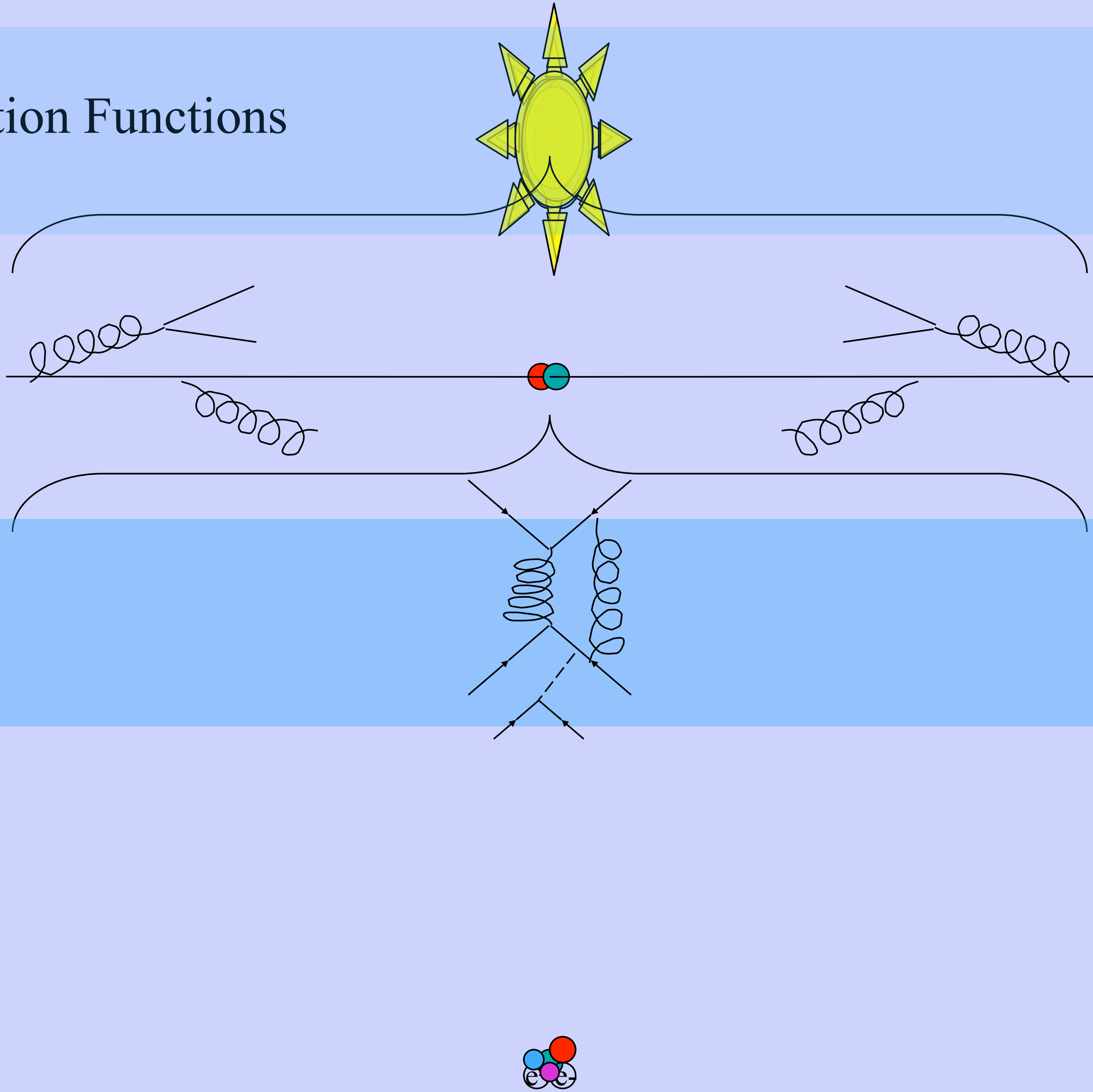

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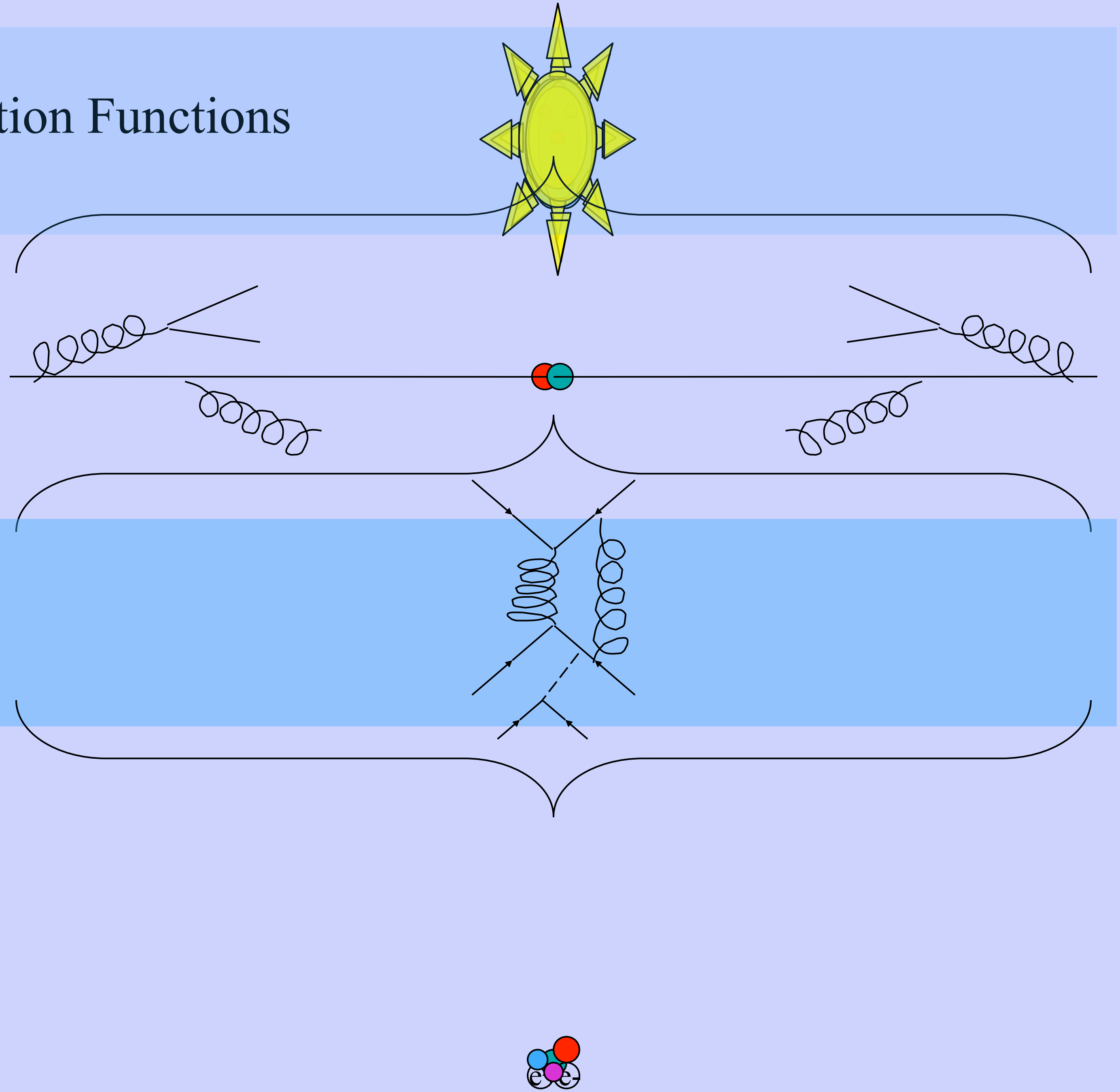

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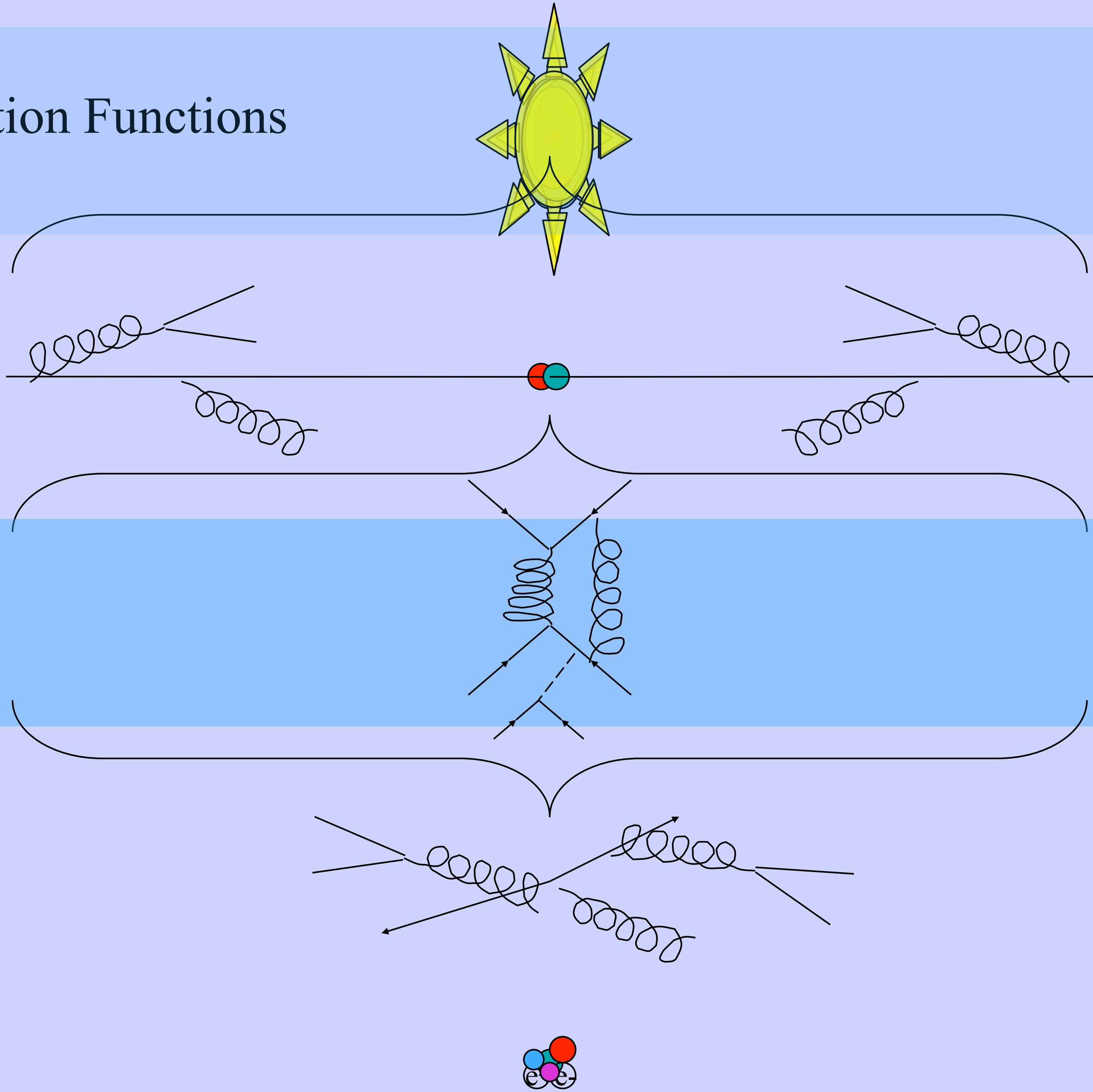

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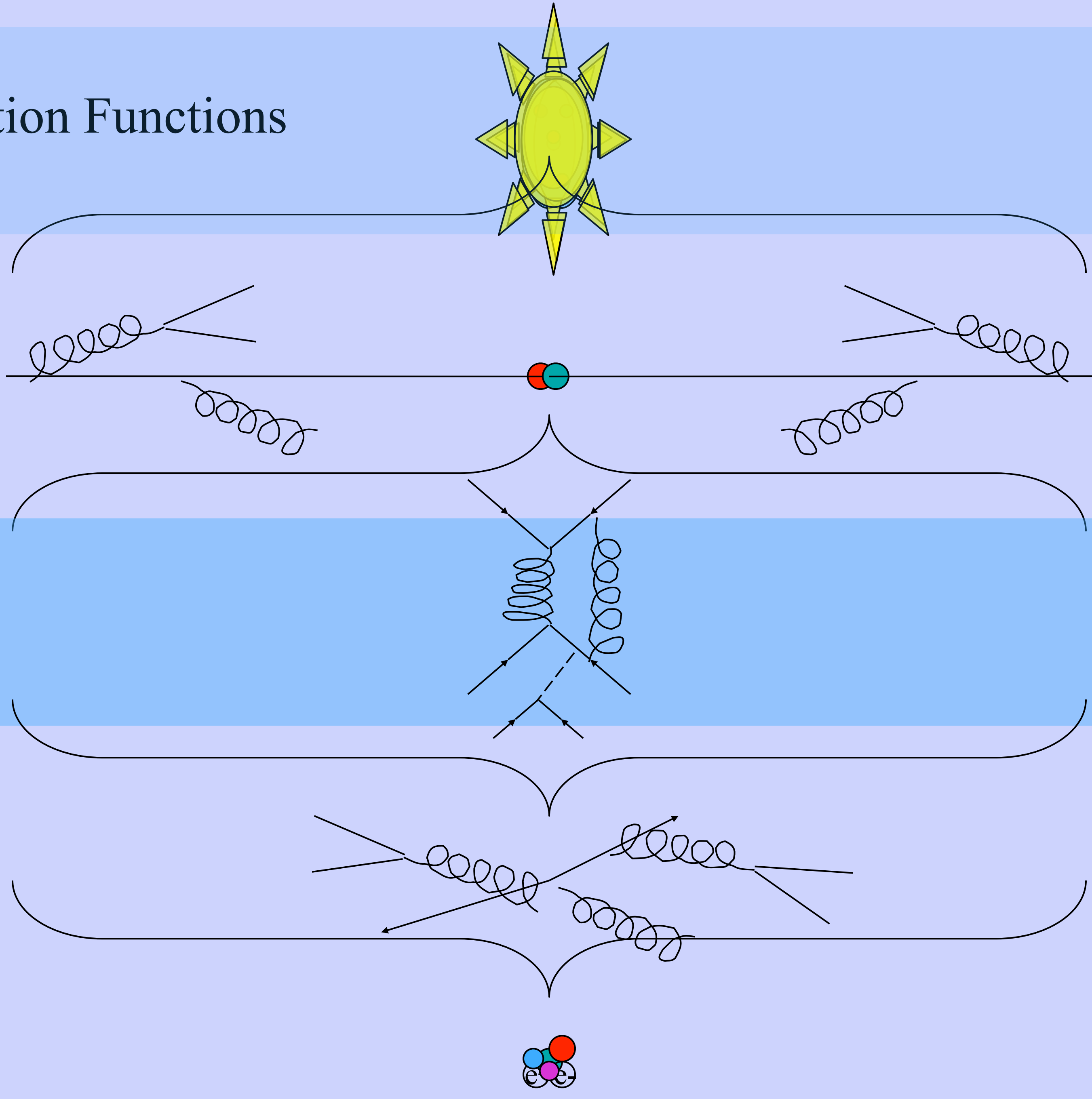

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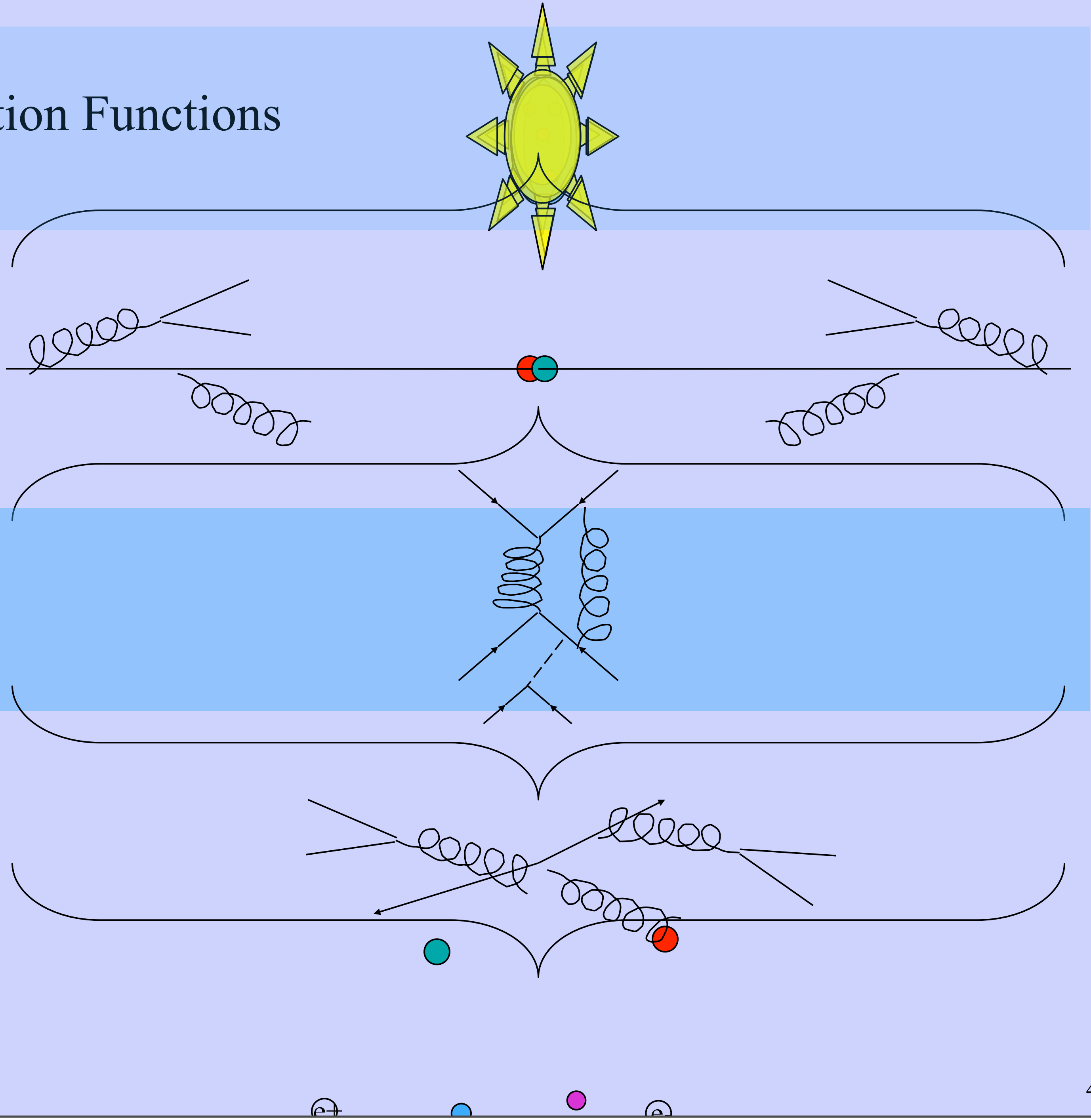

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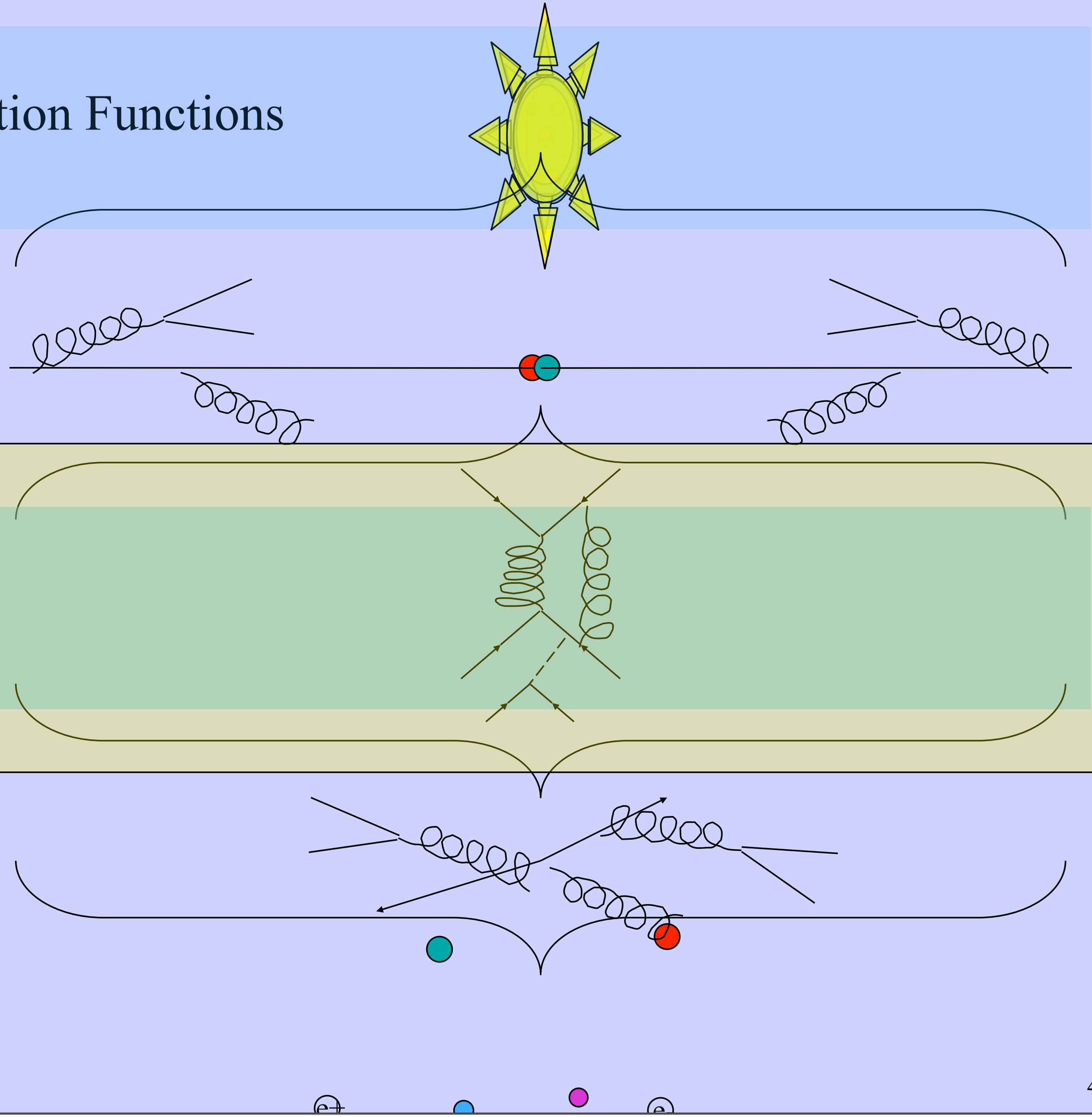
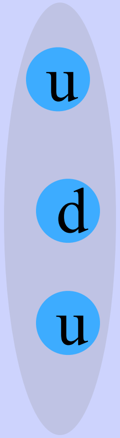
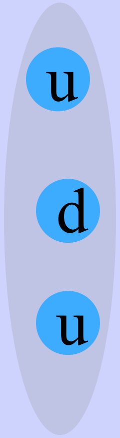


Protons



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



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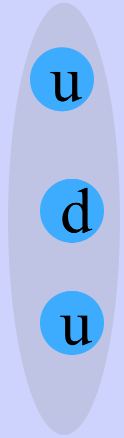

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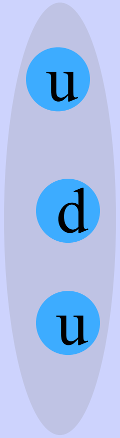

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$$\sigma = \frac{1}{2s}\sum \int f_u(x_1) f_{\bar{u}}(x_2) |M|^2 \, d\Phi dx_1 dx_2$$

Hadron Colliders

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- **Initial State: Protons**
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  - Approximately free at very short times
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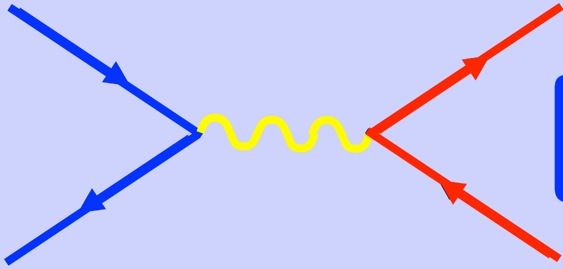
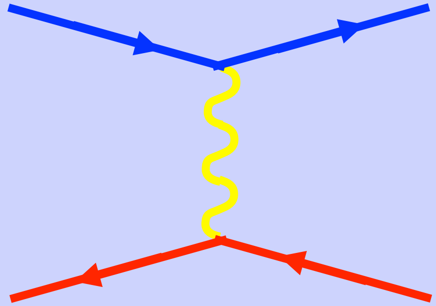
  - Measure hadronization in experiments and use
- **Many parton level sub processes contribute to same hadron level event (e.g. pp > $e^+ \nu$ j j j)**

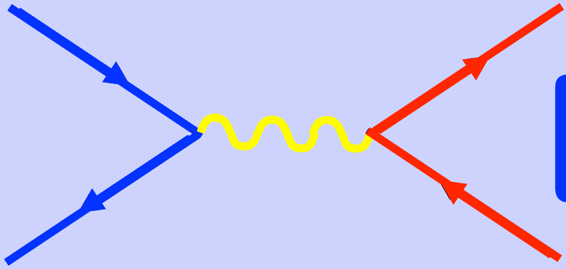
Exercise

- List processes for signal p p > h > t t~ b b~
  - e.g. u u~ > h > t t~ b b~
- List process for background p p > t t~ b b~
  - e.g. u u~ > t t~ b b~
- List process for reducible background pp>ttjj
  - e.g. u u~ > t t~ g g

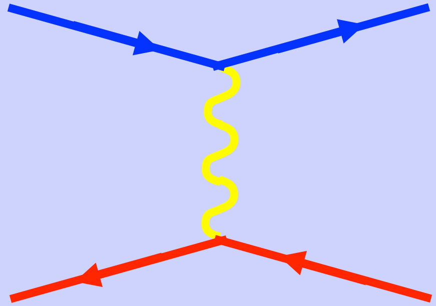


MadGraph





MadGraph



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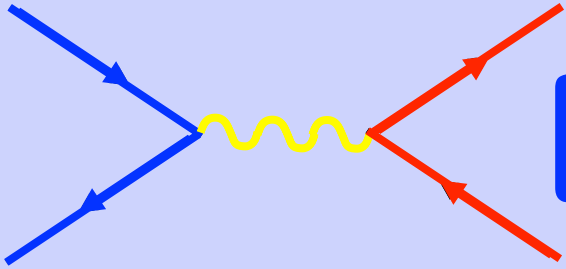

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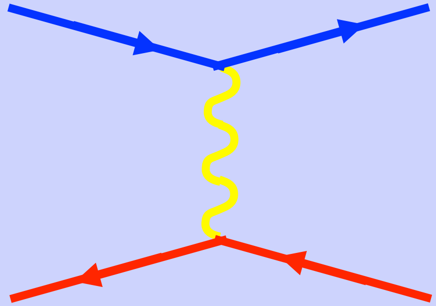

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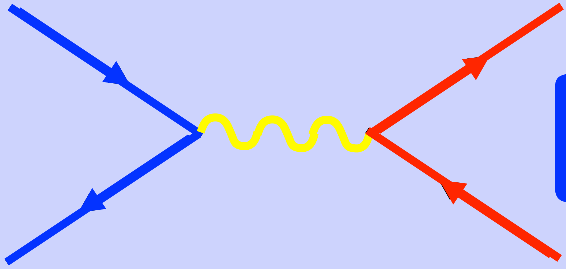

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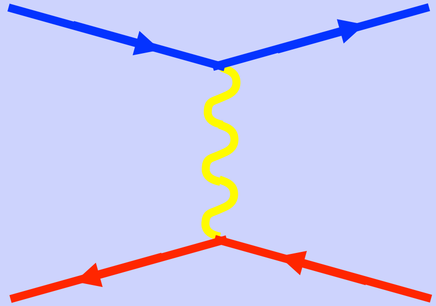

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```
 DOUBLE PRECISION FUNCTION DSIG(PP,WGT)
C ****************************************************
C Generated by MadGraph II Version 3.83. Updated 06/13/05
C     RETURNS DIFFERENTIAL CROSS SECTION
C     Input:
C           pp    4 momentum of external 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
```

- **MadGraph Returns:**
  - Feynman diagrams
  - Fortran Code for |M|^2
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Hadronic Collision Cross Sections

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

Monte Carlo Integration

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

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Thursday 14 July 2011

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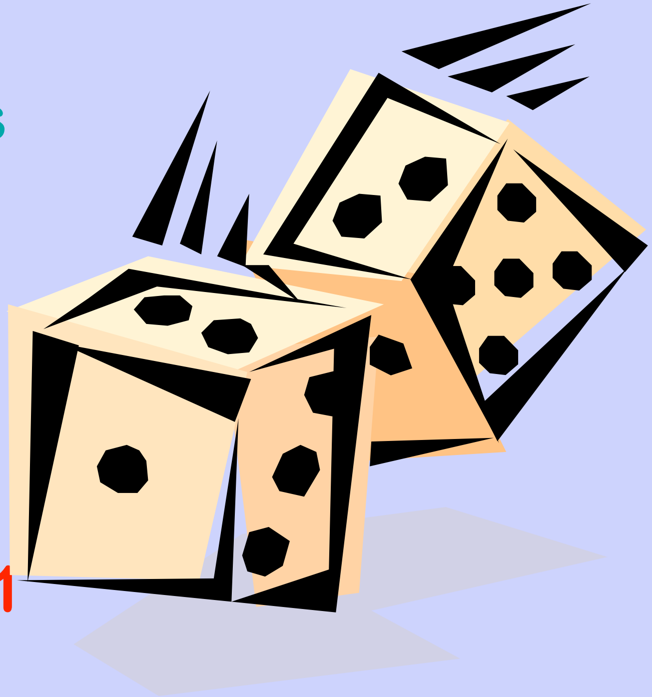

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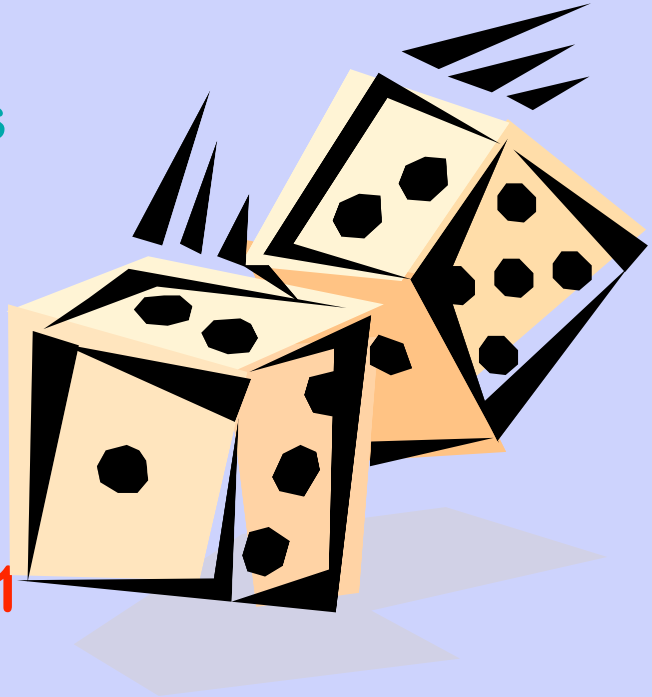

- **Limitations**
  - Only works for function f(x) ≈ 1
  - Error scales as 1/sqrt(N)

Adaptive M.C. (VEGAS)

4:10

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$$\sigma = \int |a_1 + a_2|^2 \, \mathrm{d}(PS) = \sum_{i=1,N} \frac{|a_1(p_i) + a_2(p_i)|^2}{g_i} \frac{V}{N}$$

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Single Diagram Enhanced

MadEvent

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MadEvent

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

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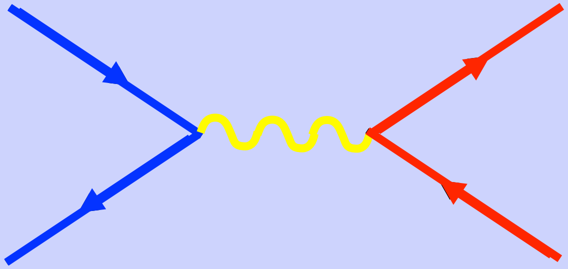
  - No need to calculate “weight” function from other channels.
  - Can optimize # of points for each one independently
  - Parallel in nature



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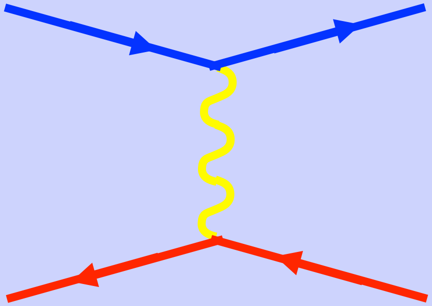

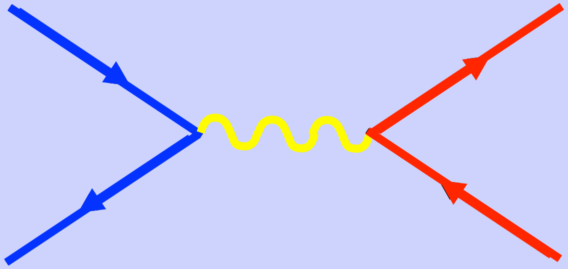

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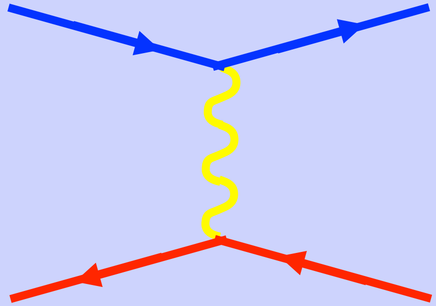

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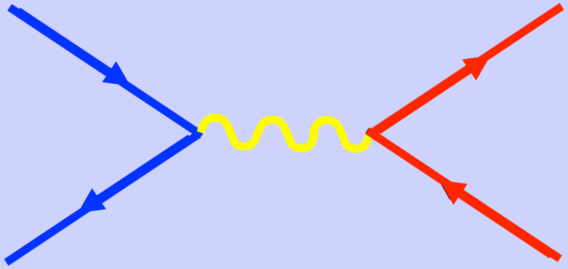

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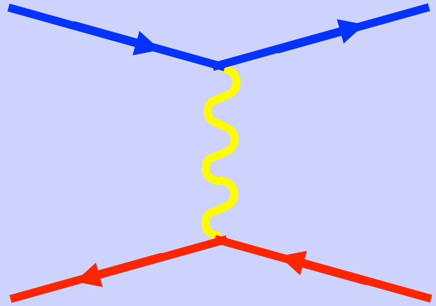

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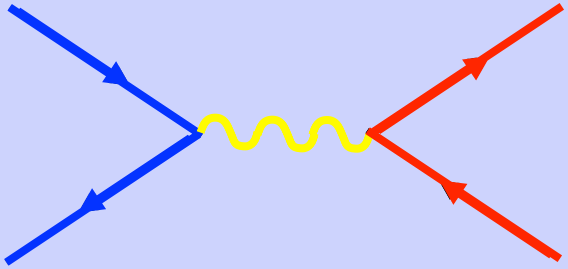

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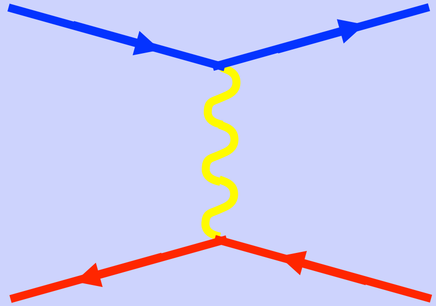

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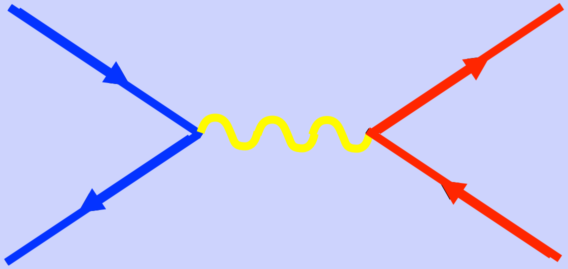

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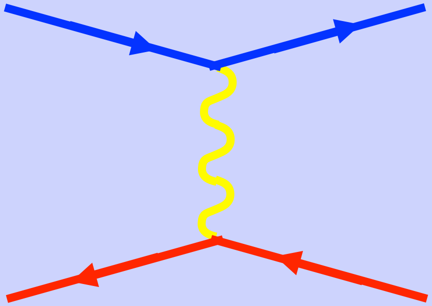

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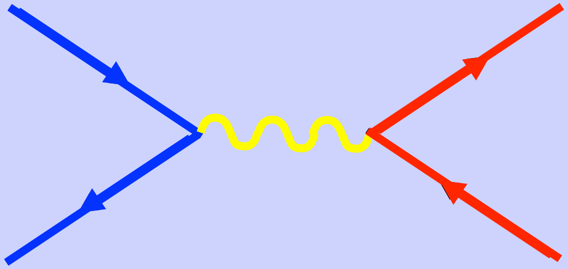

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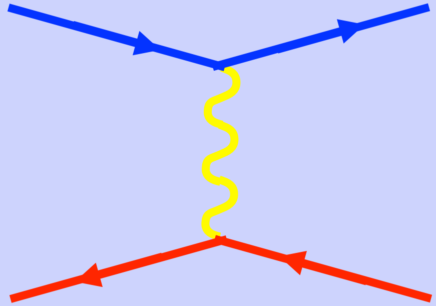

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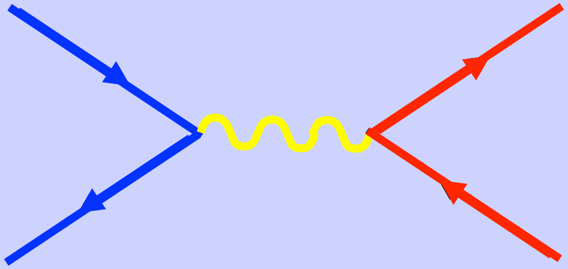
  - Cuts + Parameters



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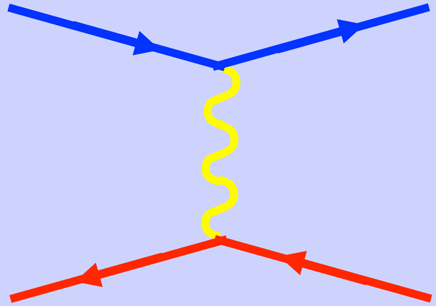

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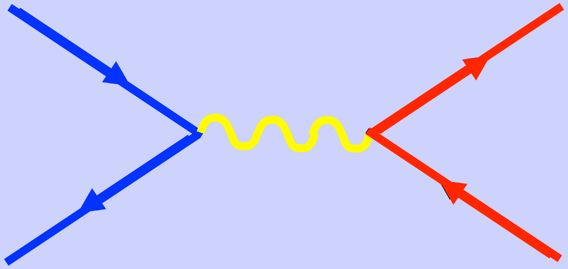

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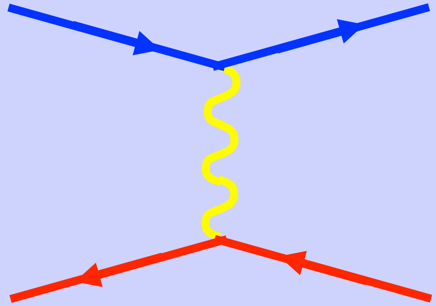

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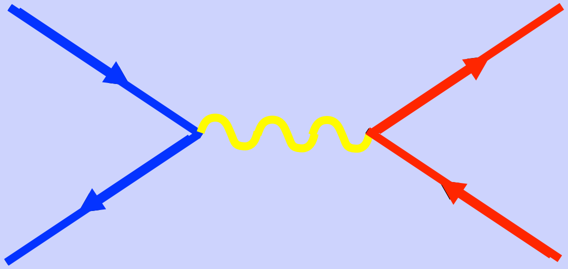

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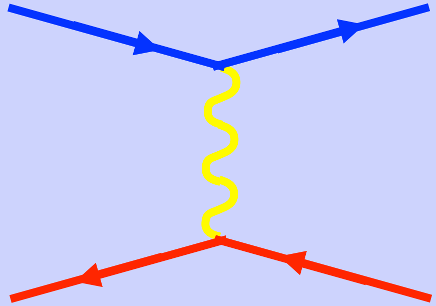

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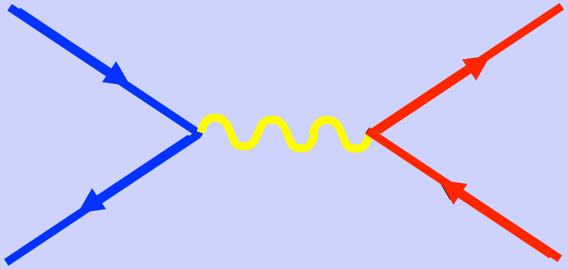

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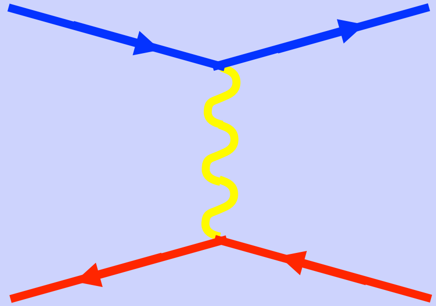

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  - Events/Plots on line!

pp > aa

- **Generate SubProcesses+Diagrams**

- **Generate Parton Level Plots**

Radiation, Hadronization + Detectors

- Detectors far from hard interaction
- Pythia---HERWIG
  - Radiation---Hadronization ++
- Detector Simulators (PGS)
  - Particle ID, Jets, b-tagging etc

p p > mu+ mu- e+ e- /a

- Generate SubProcesses+Diagrams
  - Use HEFT for model to get gg>h
- Generate Parton Level Plots
- Generate Detector Level Plots

4:30

pp > tt~bb~ /aZW+W-

- Generate SubProcesses+Diagrams
- Generate Parton Level Plots
  - Cut w/ m_bb > 80 GeV
- Generate Detector Level Plots

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.

Advice

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- **A person who can efficiently calculate cross sections can be useful to a collaboration**

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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

Conclusions

- Standard Model is Amazing (good news)

- S.M. is tough to Solve (good news!)
  - Factorization allows use of Perturbation Theory
  - Feynman Diagrams help
  - MadGraph/MadEvent can help too

- Good Luck!