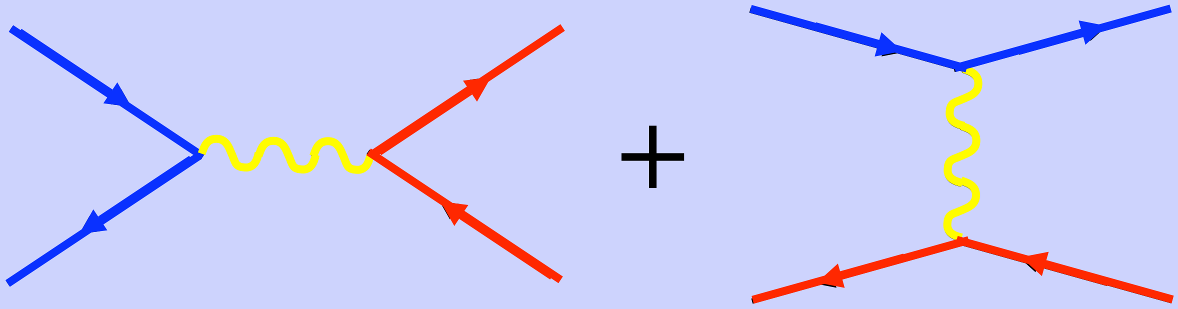
MadGraph + MadEvent

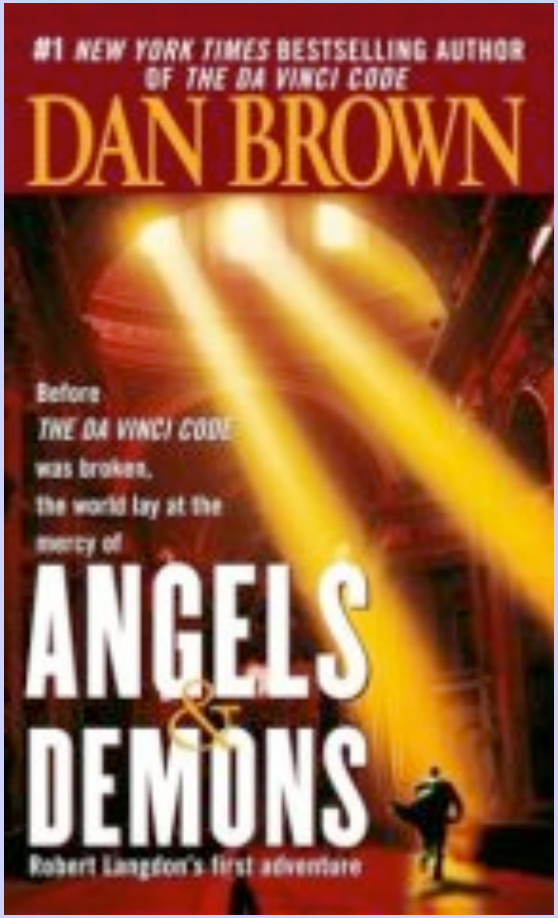


Automated Tree-Level Feynman Diagram and Event Generation

Olivier Mattelaer and Fabio Maltoni

Reading Assignment

Reading Assignment



Prizes

Prizes

Prizes

- 1st question that me or Olivier cannot answer

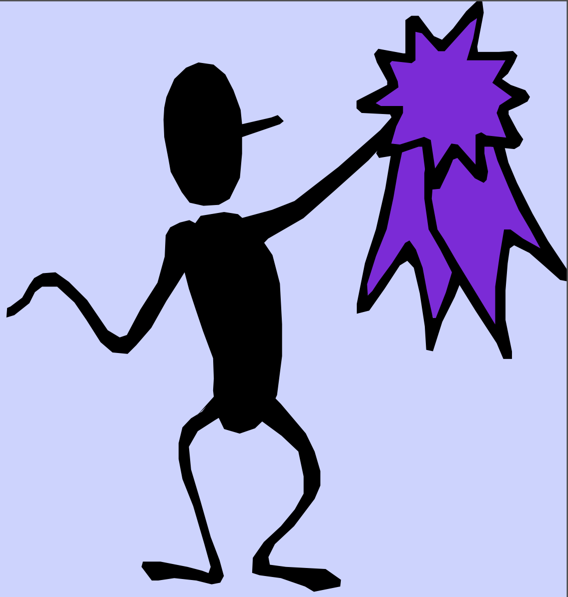
Prizes

- 1st question that me or Olivier cannot answer
- 1st question that neither me or Olivier can answer

Prizes

- 1st question that me or Olivier cannot answer
- 1st question that neither me or Olivier can answer
- Best solution for the final challenge

Plan



1. Overview of Standard Model
    1. Introduction to Particle Physics --- Close
    2. The Standard Model --- Murayama
    3. Parton level calculations
2. Full Event Simulations
3. Final challenge!

Standard Model

Standard Model

- Good News! $SU(3) \times SU_L(2) \times U(1)$

Standard Model

- Good News! $SU(3)xSU_L(2)xU(1)$
  - Most successful theory in physics!

Standard Model

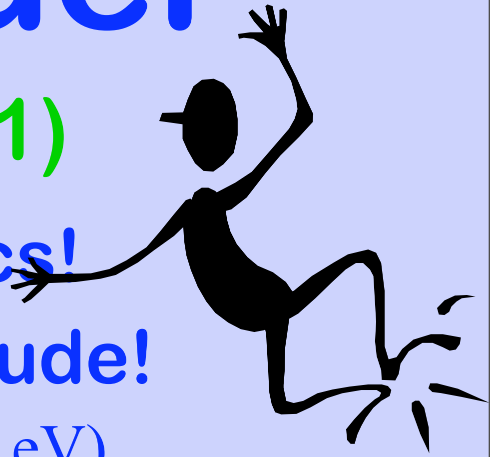
- Good News! $SU(3) \times SU_L(2) \times U(1)$
  - Most successful theory in physics!
  - Tested over 30 orders of magnitude!

Standard Model

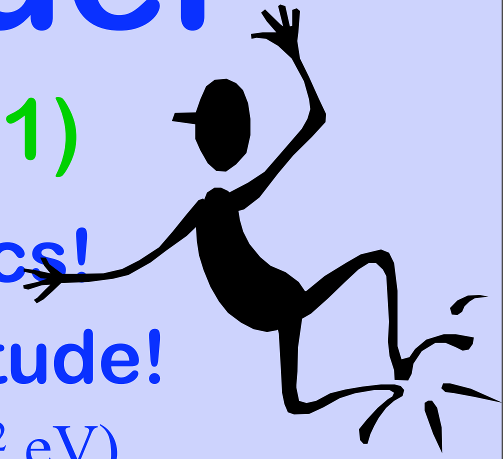
- Good News! $SU(3) \times SU_L(2) \times U(1)$
  - Most successful theory in physics!
  - Tested over 30 orders of magnitude!
    - (photon mass $< 10^{-18}$ eV , Tevatron $> 10^{12}$ eV)

Standard Model

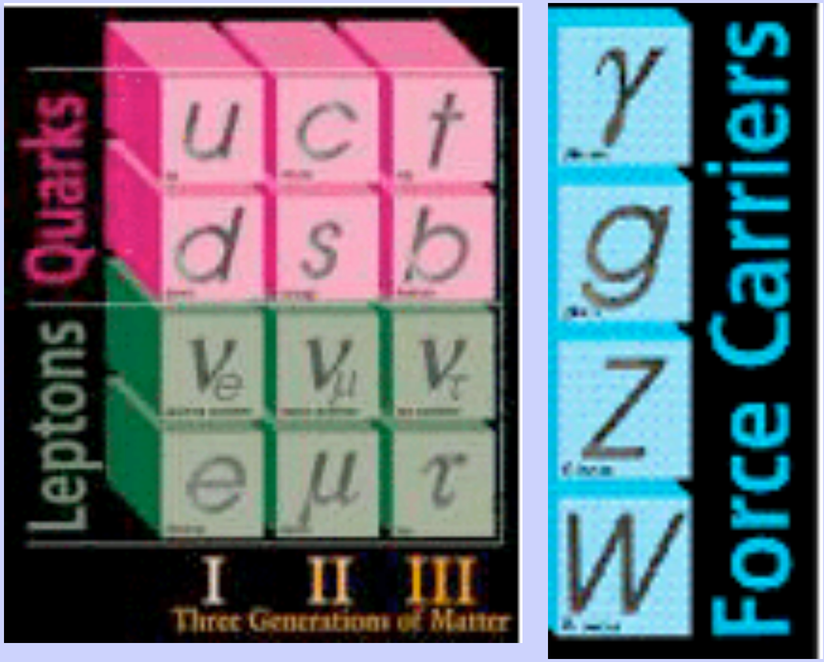
- Good News! $SU(3) \times SU_L(2) \times U(1)$
  - Most successful theory in physics!
  - Tested over 30 orders of magnitude!
    - (photon mass < 10^{-18} eV , Tevatron > 10^{12} eV)



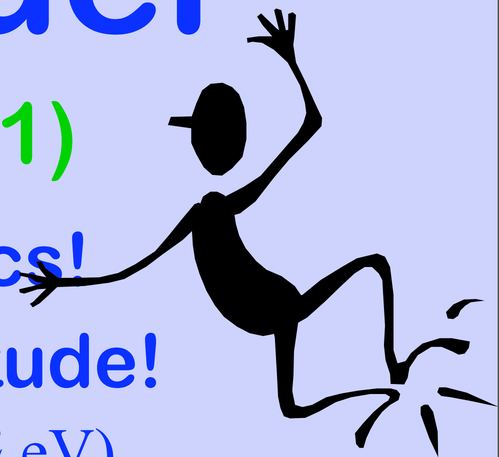
Standard Model



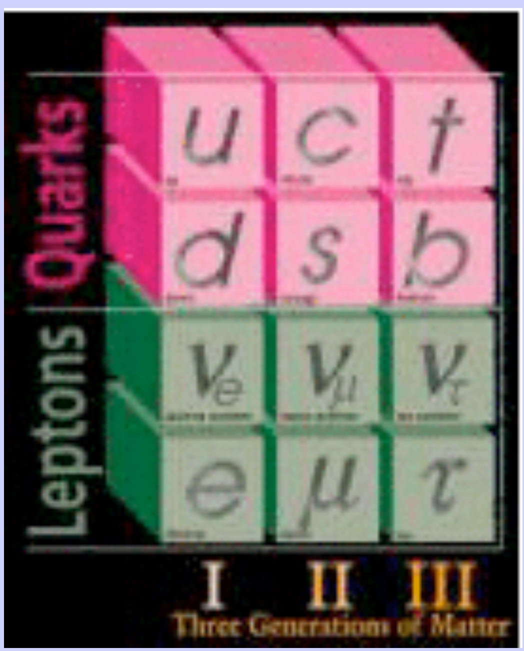
- Good News! SU(3)xSU$_L$(2)xU(1)
  - Most successful theory in physics!
  - Tested over 30 orders of magnitude!
    - (photon mass < 10^{-18} eV , Tevatron > 10^{12} eV)

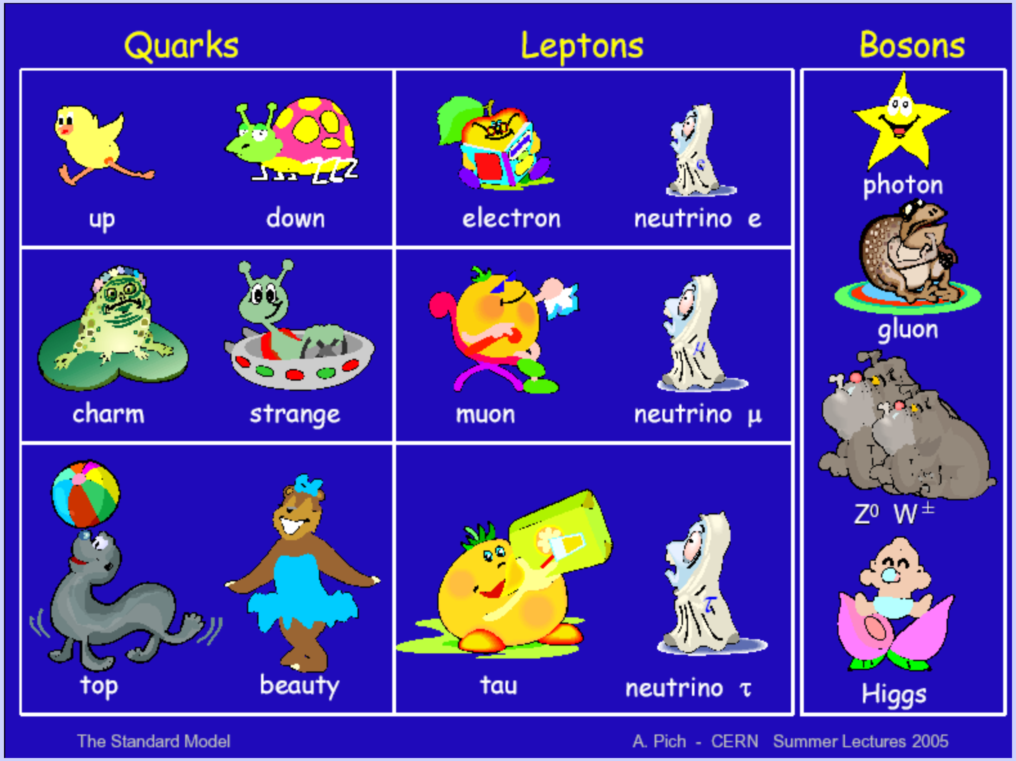


Standard Model



- 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 , Tevatron > 10^{12} eV)





Standard Model

Standard Model

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

Standard Model

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

Standard Model

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

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

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

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

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

Standard Model

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

$$\mathcal{L}_{QCD} = -\frac{1}{2}\mathrm{Tr}\,(\mathbf{G}^{\mu\nu}\,\mathbf{G}$$

$$= -\frac{1}{4}\left(\partial^\mu G^\nu_a - \partial^\nu G^\mu_a\right)\left(\partial_\mu G\right.$$

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

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

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

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

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

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

$$-ie\left\{\left(\partial^\mu W^\nu - \partial^\nu W^\mu\right)W^\dagger_\mu A_\nu - \left(\partial^\mu W^{\nu\dagger} - \partial^\nu W^{\mu\dagger}\right)W_\mu A_\nu + W_\mu W^\dagger_\nu\left(\partial^\mu A^\nu - \partial^\nu A^\mu\right)\right\}$$

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

$$-e^2\cot\theta_W\left\{2W^\dagger_\mu W^\mu Z_\nu A^\nu - W^\dagger_\mu Z^\mu W_\nu A^\nu - W^\dagger_\mu A^\mu W_\nu Z^\nu\right\} - e^2\left\{W^\dagger_\mu W^\mu A_\nu A^\nu - W^\dagger_\mu A^\mu W_\nu A^\nu\right\}$$

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

Predictions from SM

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

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

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

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

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

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

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

- **Scattering cross section**

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

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

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

- **Scattering c**

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

$$M \approx \langle \mu^+\mu^- |$$

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

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

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

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

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

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

- **Scattering cross section**

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

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

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

- **Scattering cross section**

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

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

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

- **Scattering cross section**

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

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

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

- **Scattering cross section**

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

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

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

- **Scattering cross section**

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

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

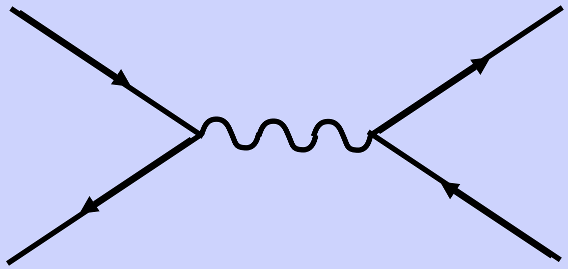
Example: $e^+e^- \rightarrow \mu^+\mu^-$

- **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**



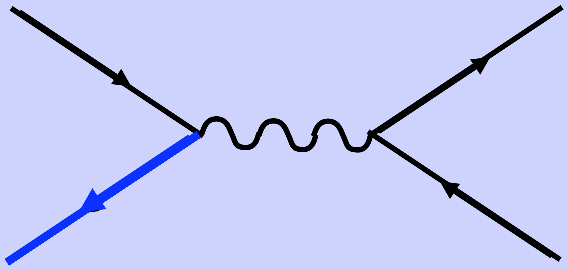
Example: $e^+e^- \to \mu^+\mu^-$

- **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**



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

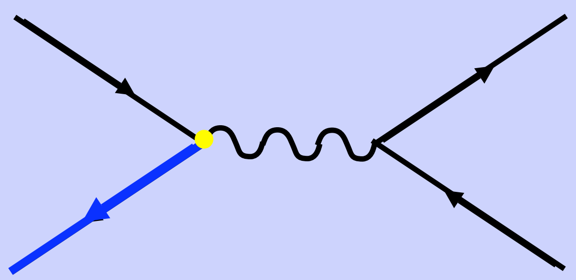
Example: $e^+e^- \rightarrow \mu^+\mu^-$

- **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**



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

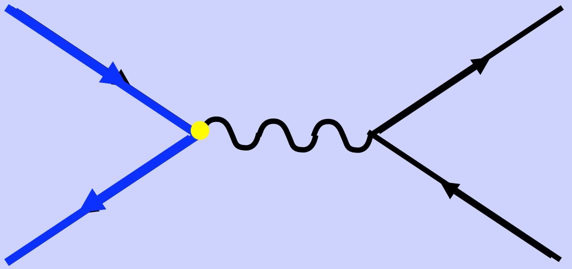
Example: $e^+e^- \rightarrow \mu^+\mu^-$

- **Scattering cross section**

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

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

- **Feynman Diagrams**



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

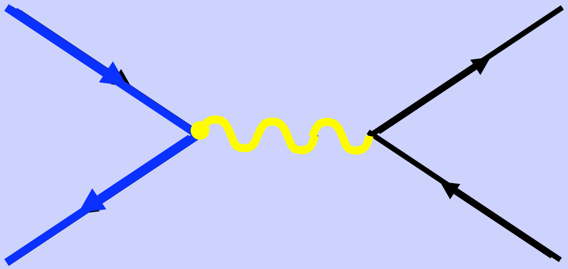
Example: $e^+e^- \rightarrow \mu^+\mu^-$

- **Scattering cross section**

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

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

- **Feynman Diagrams**



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

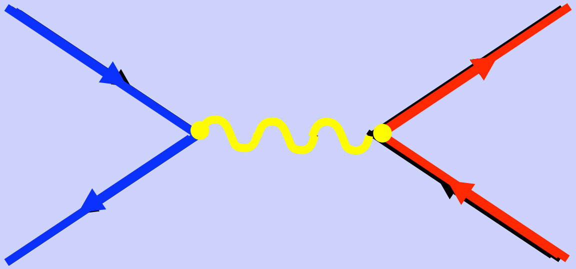
Example: $e^+e^- \rightarrow \mu^+\mu^-$

- **Scattering cross section**

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

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

- **Feynman Diagrams**



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

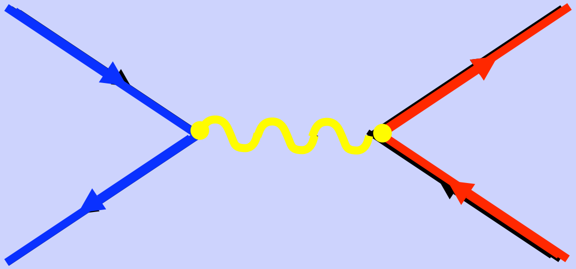
Example: $e^+e^- \rightarrow \mu^+\mu^-$

- **Scattering cross section**

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

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

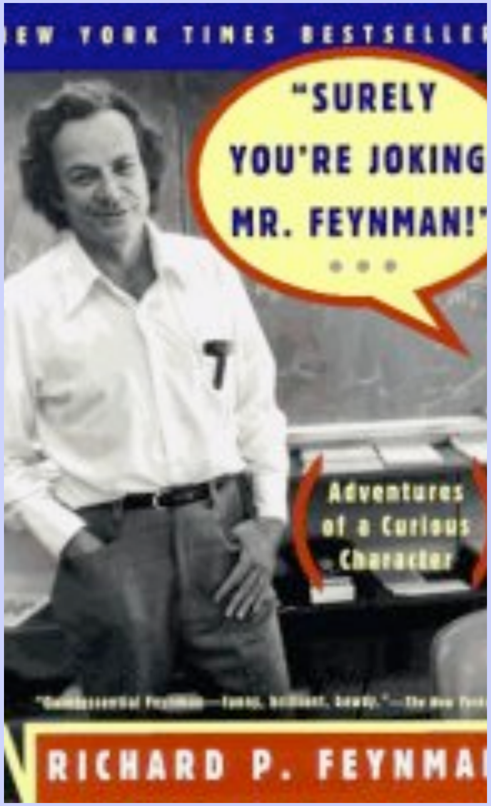
- **Feynman Diagrams**



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

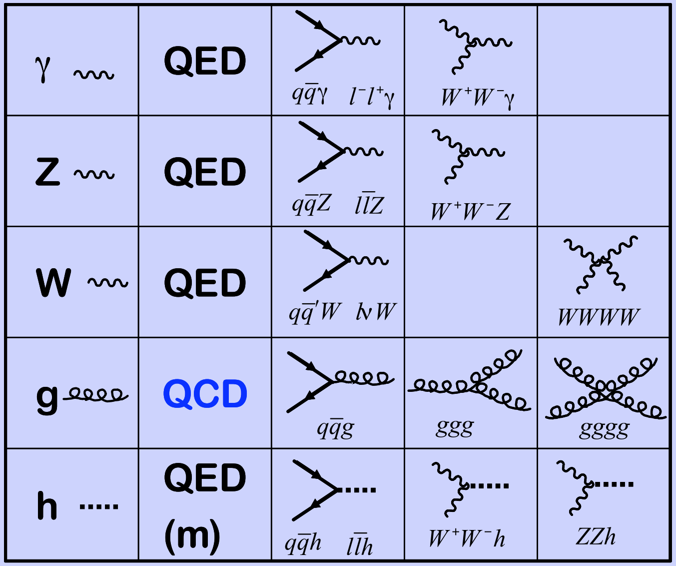
Feynman Rules!

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



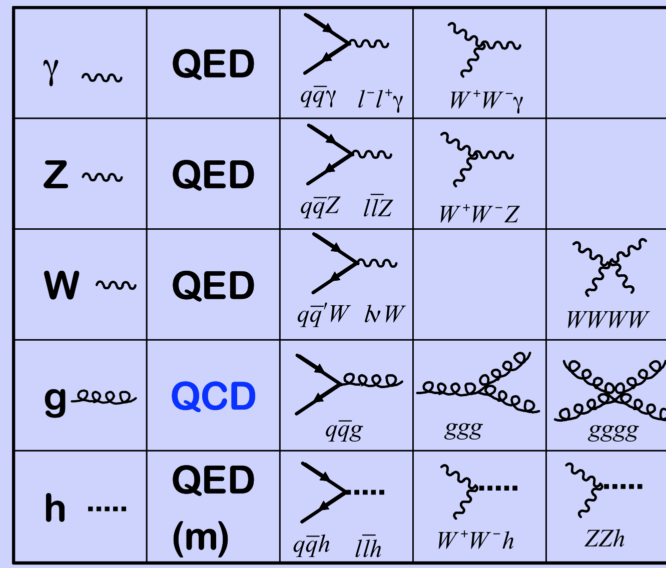
Partial list from SM

Feynman Rules!



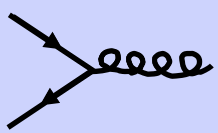
Feynman Rules!

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



Feynman Rules!

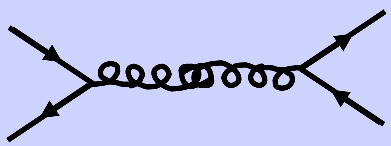
- These are basic building blocks, combine to form "allowed" diagrams
  - e.g. u u~ > t t~



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

Feynman Rules!

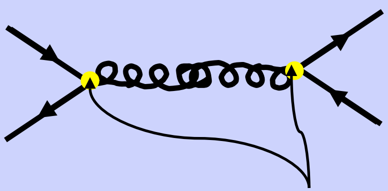
- These are basic building blocks, combine to form “allowed” diagrams
  - e.g. u u~ > t t~



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

Feynman Rules!

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

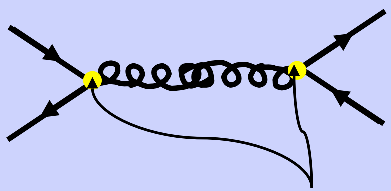


Order is QCD^2

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

Feynman Rules!

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



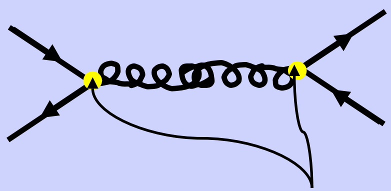
Order is QCD^2

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

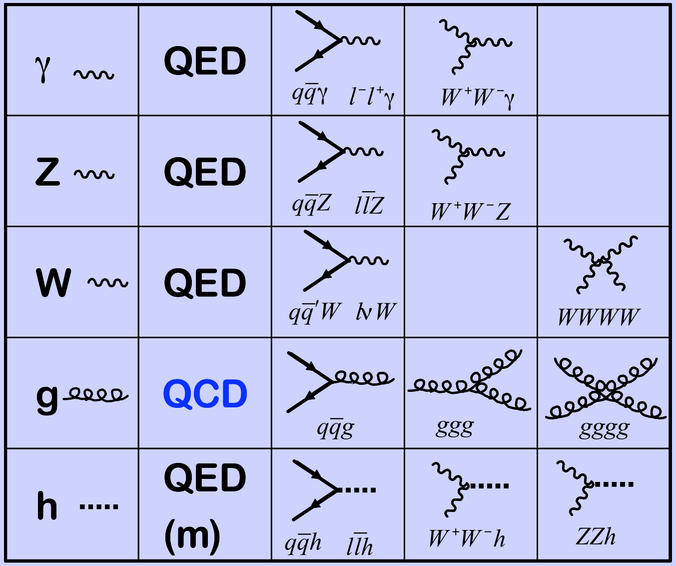
- Draw Feynman diagrams:
  - gg > tt~
  - gg > tt~h

Feynman Rules!

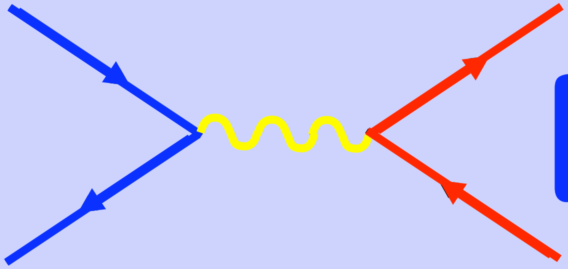
- These are basic building blocks, combine to form “allowed” diagrams
  - e.g. u u~ > t t~



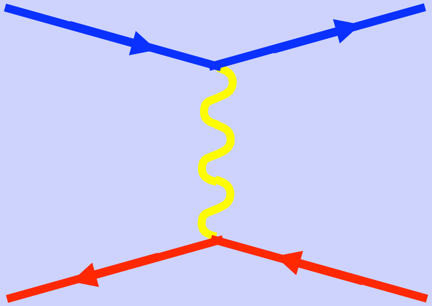
Order is QCD^2

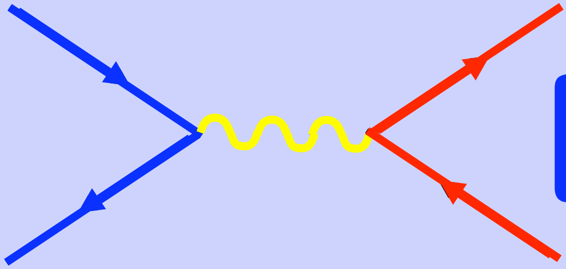


- Draw Feynman diagrams:
  - gg > tt~
  - gg > tt~h
- Determine “order” for each diagram

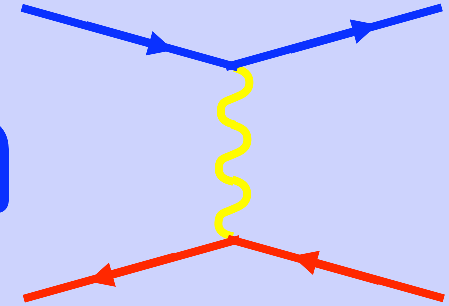


MadGraph

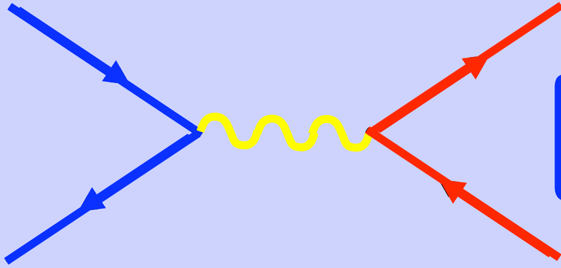




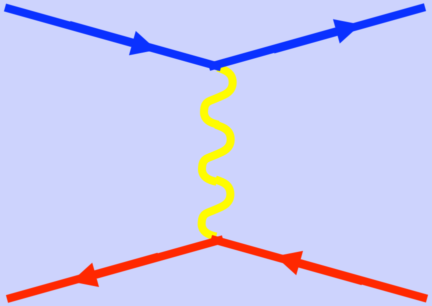
MadGraph



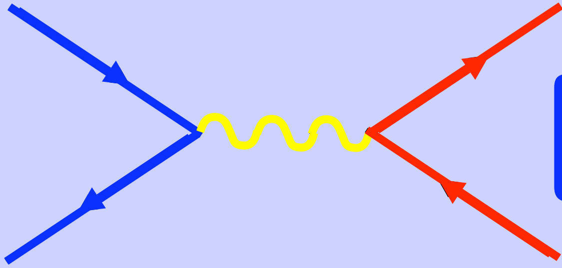
- **User Requests:**



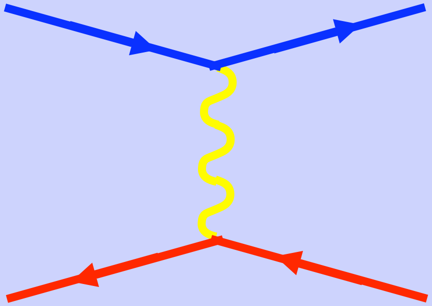
MadGraph



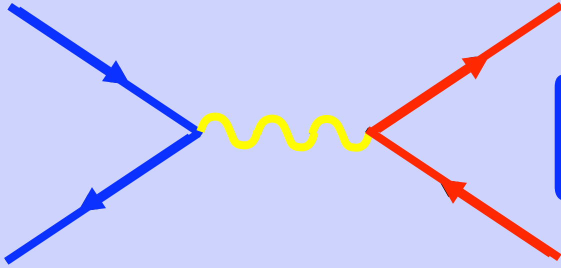
- **User Requests:**
  - gg -> tt~bb~



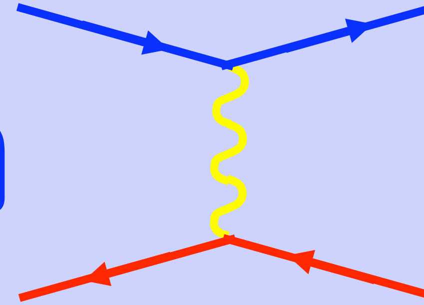
MadGraph



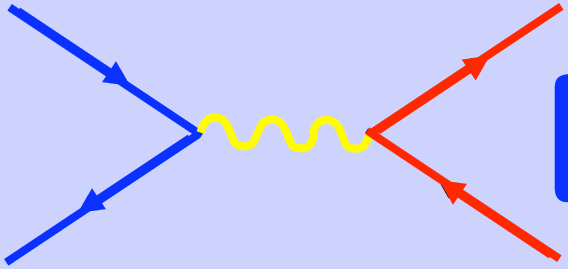
- **User Requests:**
  - **gg -> tt~bb~**
  - **QCD Order = 4**



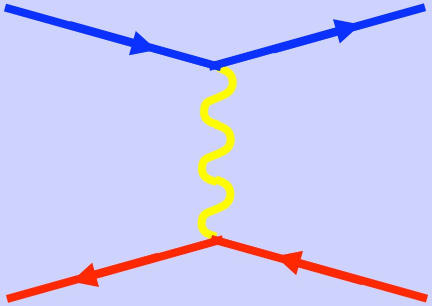
MadGraph



- User Requests:
  - gg -> tt~bb~
  - QCD Order = 4
  - QED Order =0

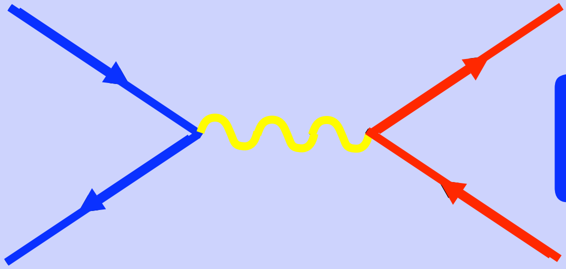


MadGraph

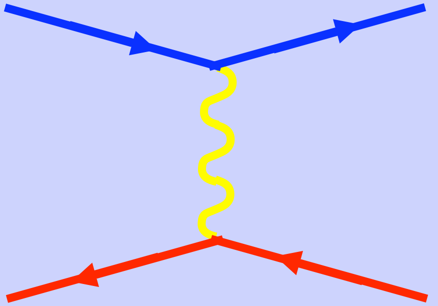


- **User Requests:**
  - gg -> tt~bb~
  - QCD Order = 4
  - QED Order =0

- **MadGraph Returns:**

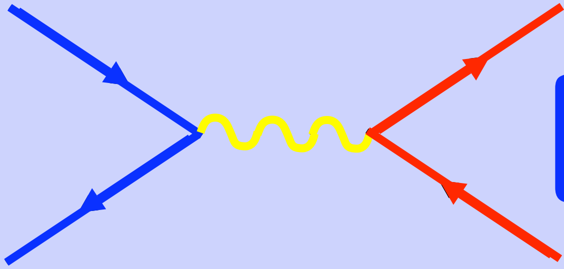


MadGraph

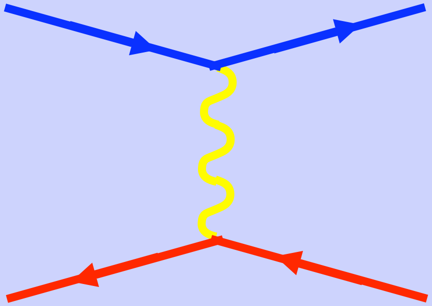


- **User Requests:**
  - gg -> tt~bb~
  - QCD Order = 4
  - QED Order =0

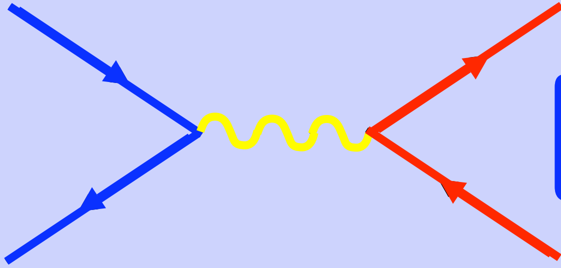
- **MadGraph Returns:**
  - Feynman diagrams



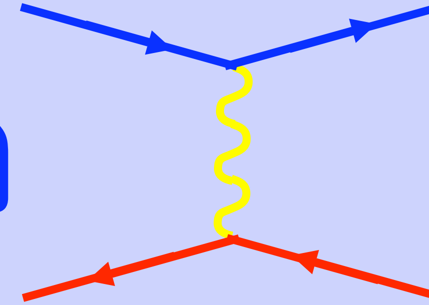
MadGraph



- **User Requests:**
  - gg -> tt~bb~
  - QCD Order = 4
  - QED Order =0
- **MadGraph Returns:**
  - Feynman diagrams
  - Self-Contained Fortran Code for |M|^2



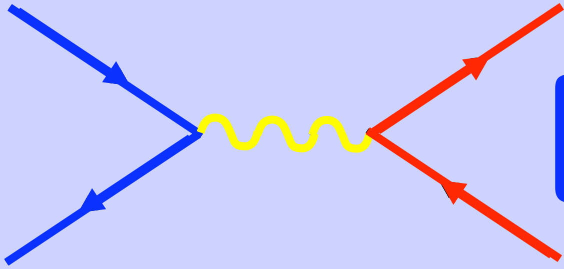
MadGraph



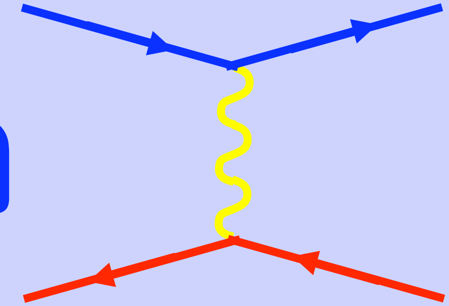
- **User Requests:**
  - gg -> tt~bb~
  - QCD Order = 4
  - QED Order =0

```
 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|^2



MadGraph



- **User Requests:**
  - gg -> tt~bb~
  - QCD Order = 4
  - QED Order =0

```
 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|^2

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

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

Feynman Rules!

- **Draw Feynman diagrams + determine order (QED, QCD):**
  - **gg -> tt~**

  - **gg -> tt~h**

  - **gg -> tt~bb~ (QCD only)**

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

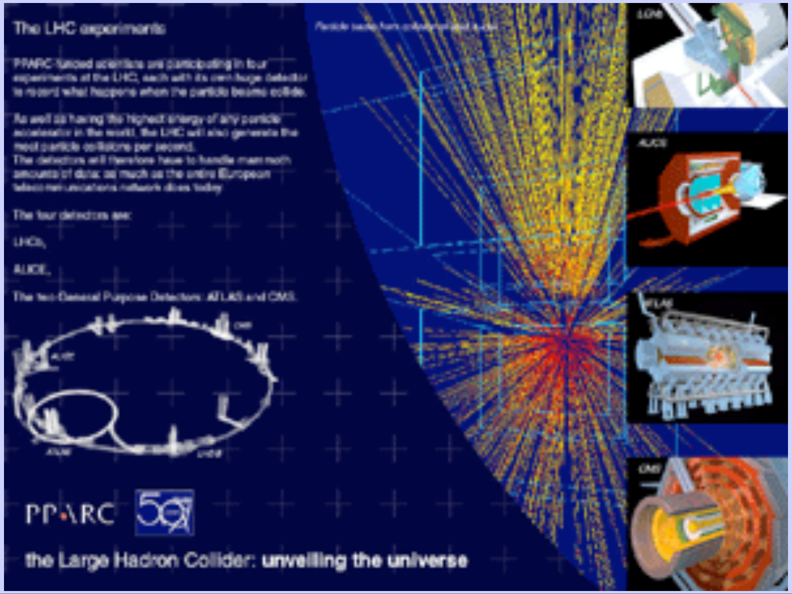
Check at http://madgraph.hep.uiuc.edu/

Status

Status

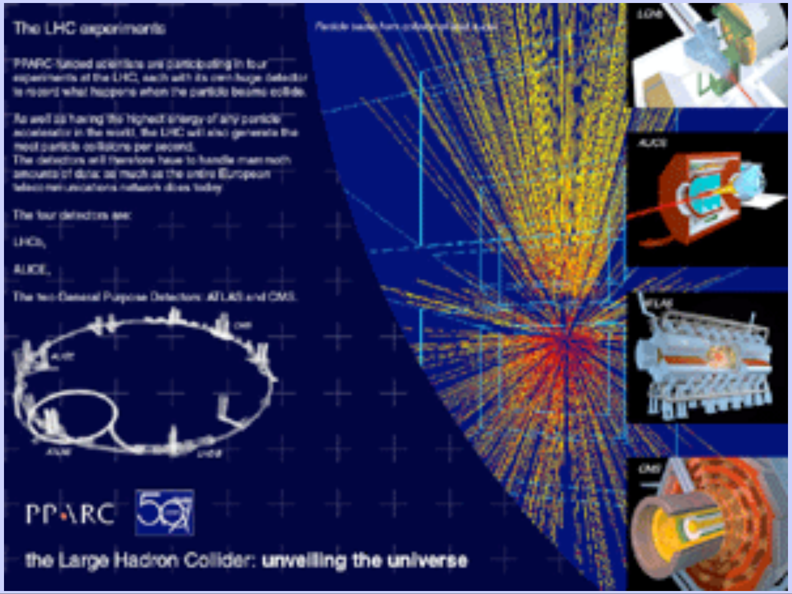
- Good News
  - MadGraph generates all tree-level diagrams
  - MadGraph generates fortran code to calculate $\Sigma|M|^2$
- Bad News
  - Madgraph generates fortran code….
  - Hadron colliders are tough!
- Good News
  - There's a cool animation next!

Hadron Colliders



Hadron Colliders

- **Initial State: Protons**
  - Made of quarks/gluons in bound state
  - Strongly interacting P.T. won't work
- **Final State: Hadrons**
  - Made of quarks/gluons in bound state
  - Strongly interacting P.T. won't work



Parton Distribution Functions
(Measured)

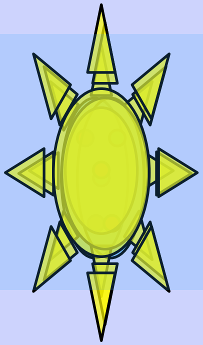
Evolution
+Splitting

Hard
Scattering

Showering
Fragmentation

Hadronization

Parton Distribution Functions
(Measured)

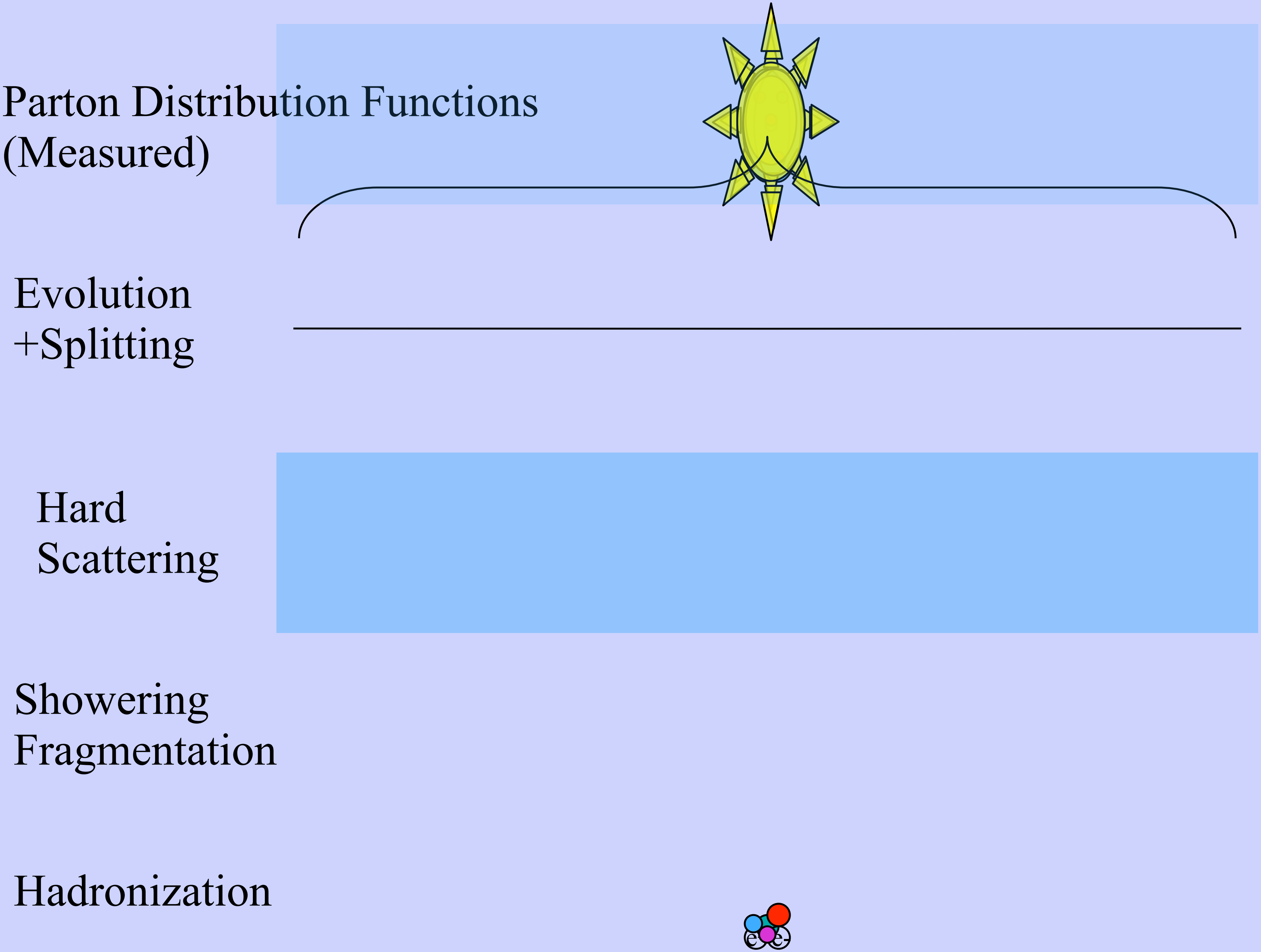


Evolution
+Splitting

Hard
Scattering

Showering
Fragmentation

Hadronization


Parton Distribution Functions
(Measured)
Evolution
+Splitting
Hard
Scattering
Showering
Fragmentation
Hadronization

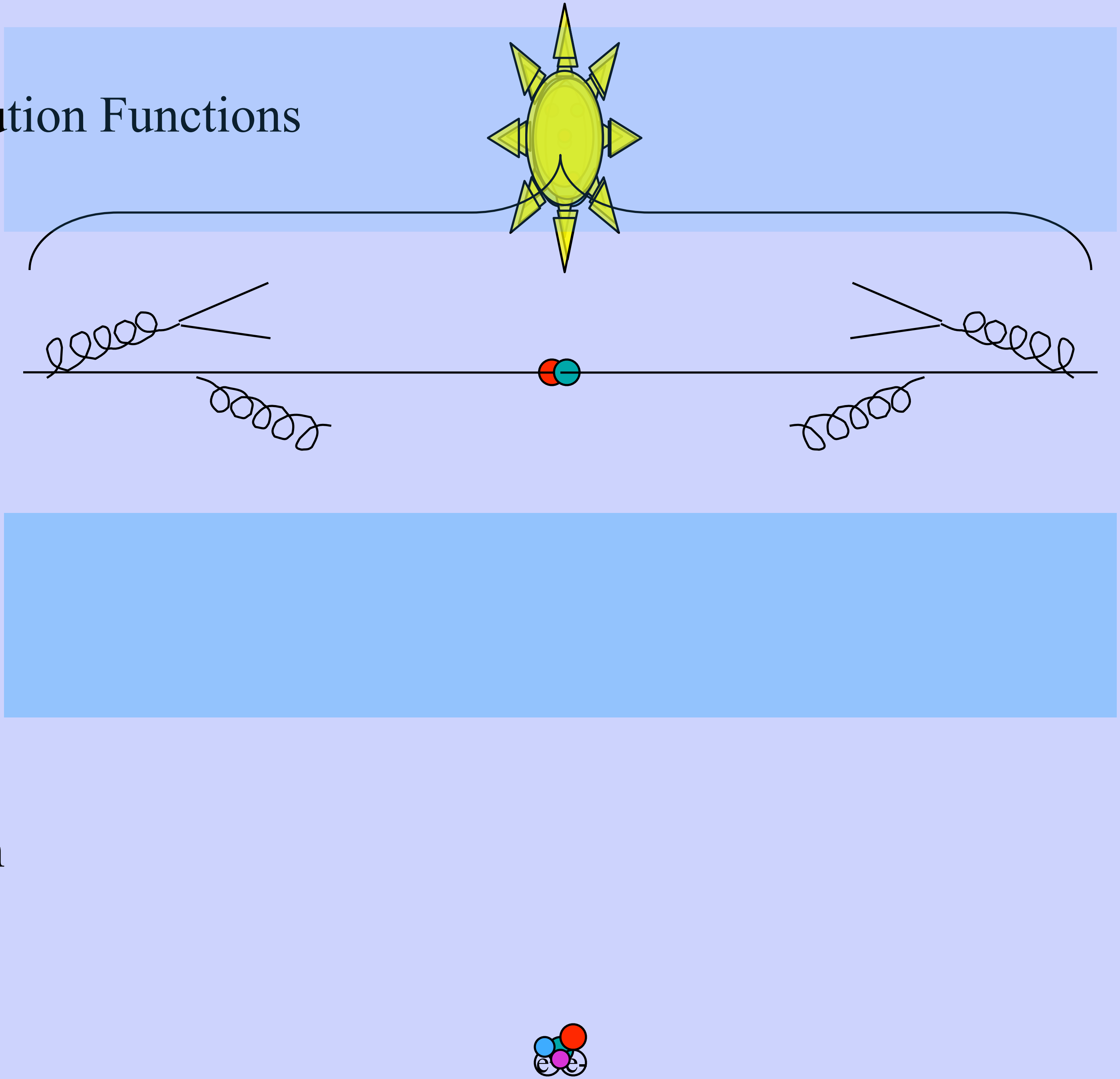
Parton Distribution Functions
(Measured)

Evolution
+Splitting

Hard
Scattering

Showering
Fragmentation

Hadronization



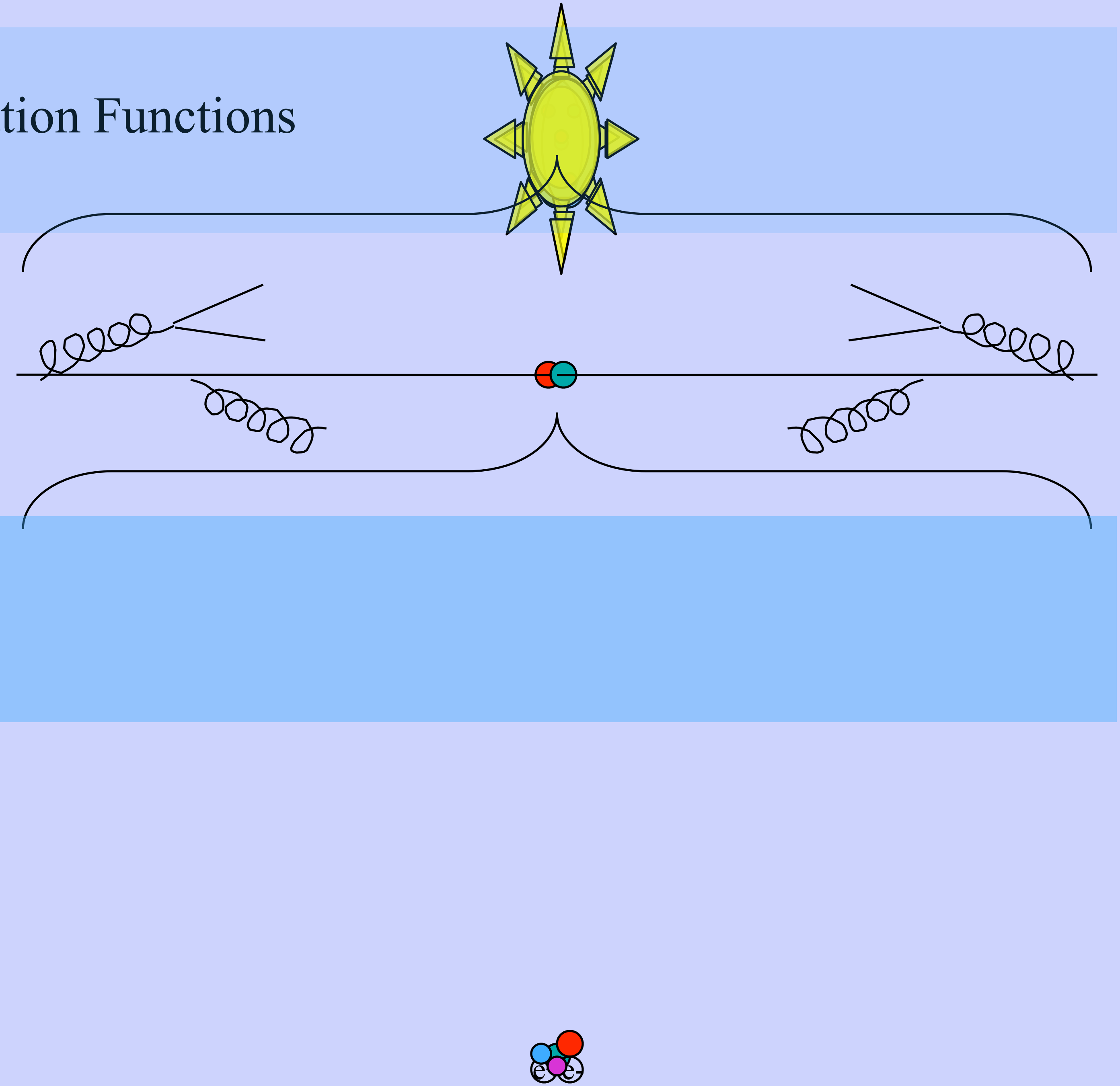
Parton Distribution Functions (Measured)

Evolution +Splitting

Hard Scattering

Showering Fragmentation

Hadronization



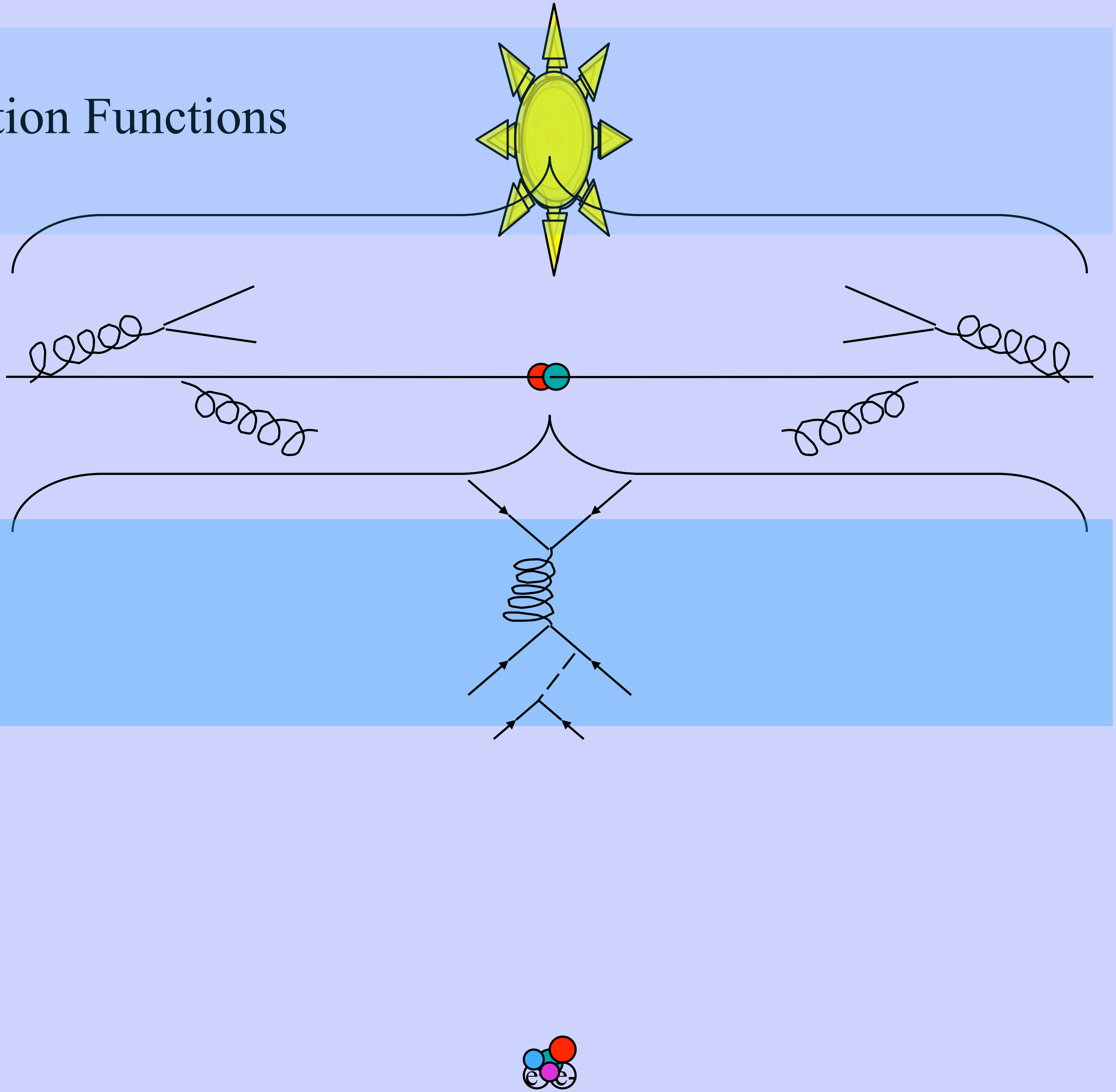
Parton Distribution Functions
(Measured)

Evolution
+Splitting

Hard
Scattering

Showering
Fragmentation

Hadronization



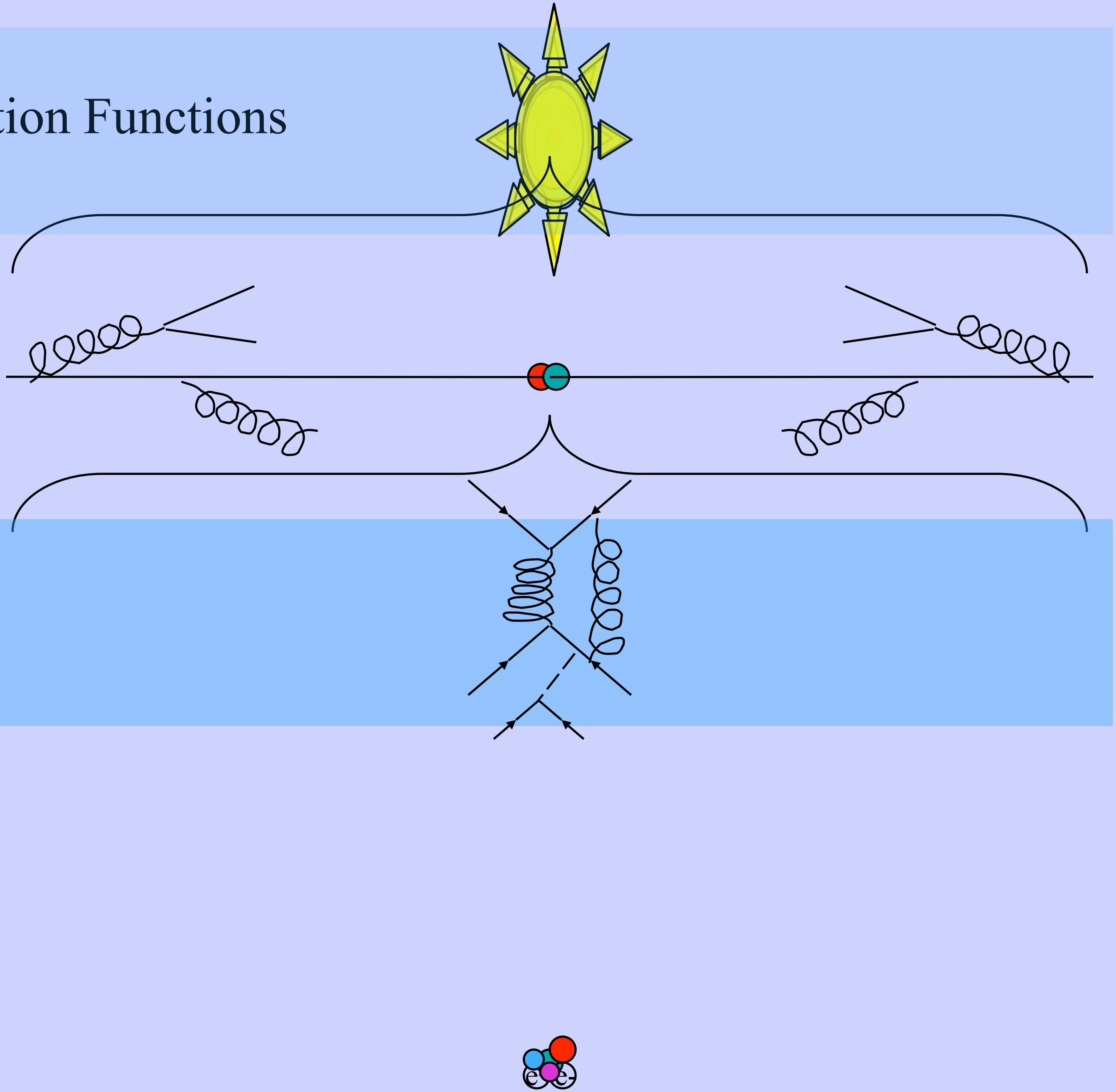
Parton Distribution Functions
(Measured)

Evolution
+Splitting

Hard
Scattering

Showering
Fragmentation

Hadronization



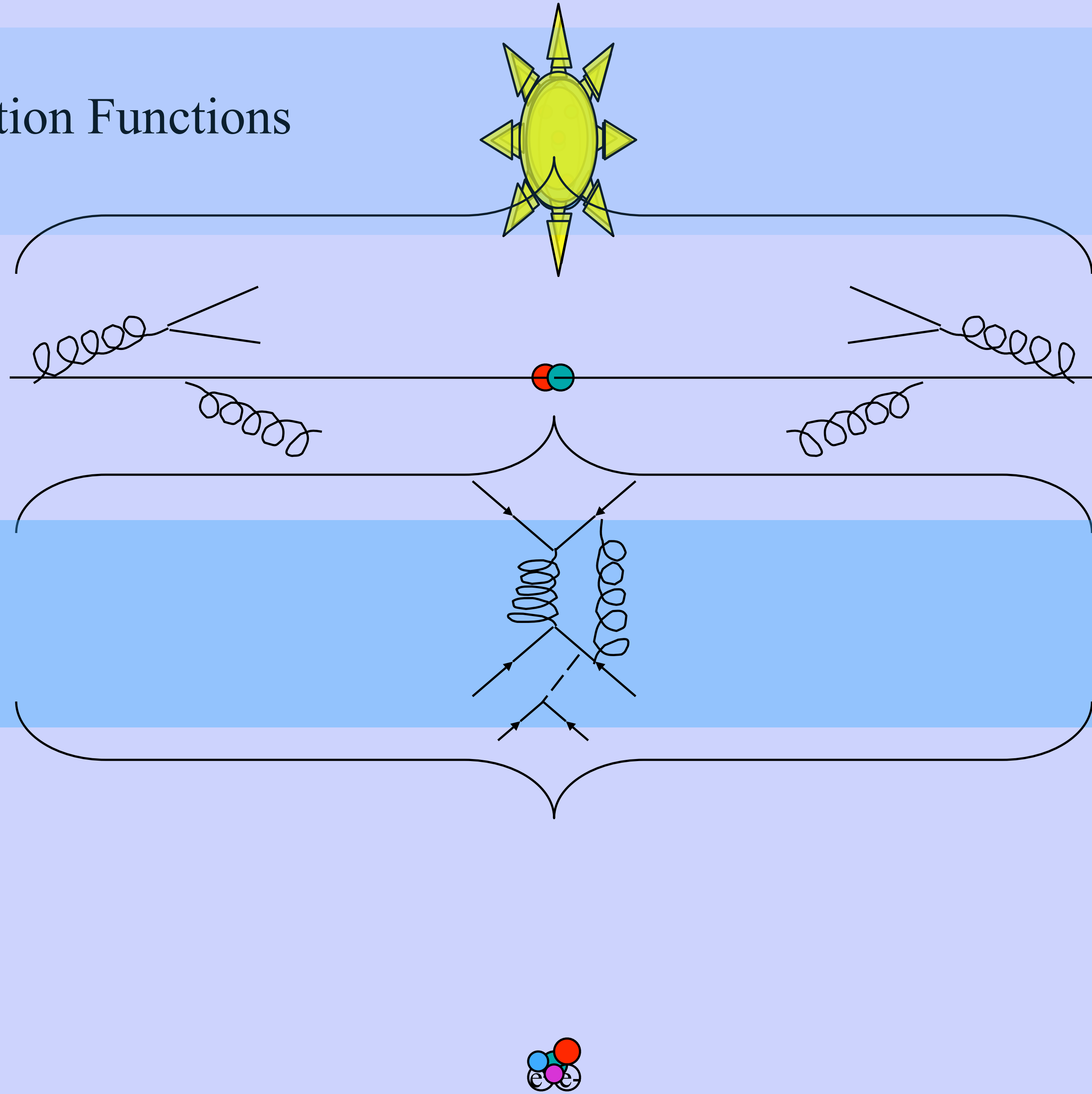
Parton Distribution Functions
(Measured)

Evolution
+Splitting

Hard
Scattering

Showering
Fragmentation

Hadronization



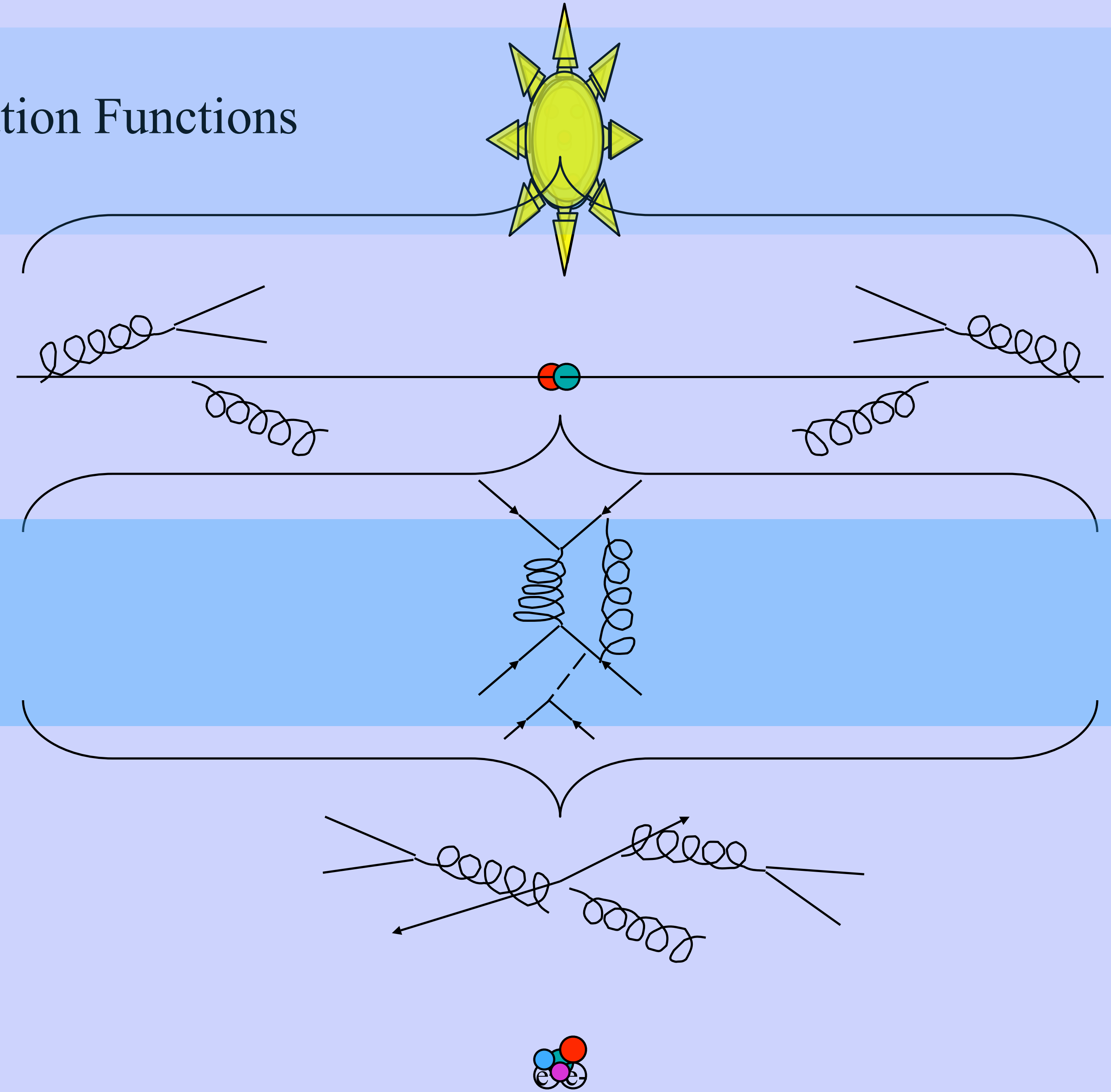
Parton Distribution Functions (Measured)

Evolution +Splitting

Hard Scattering

Showering Fragmentation

Hadronization



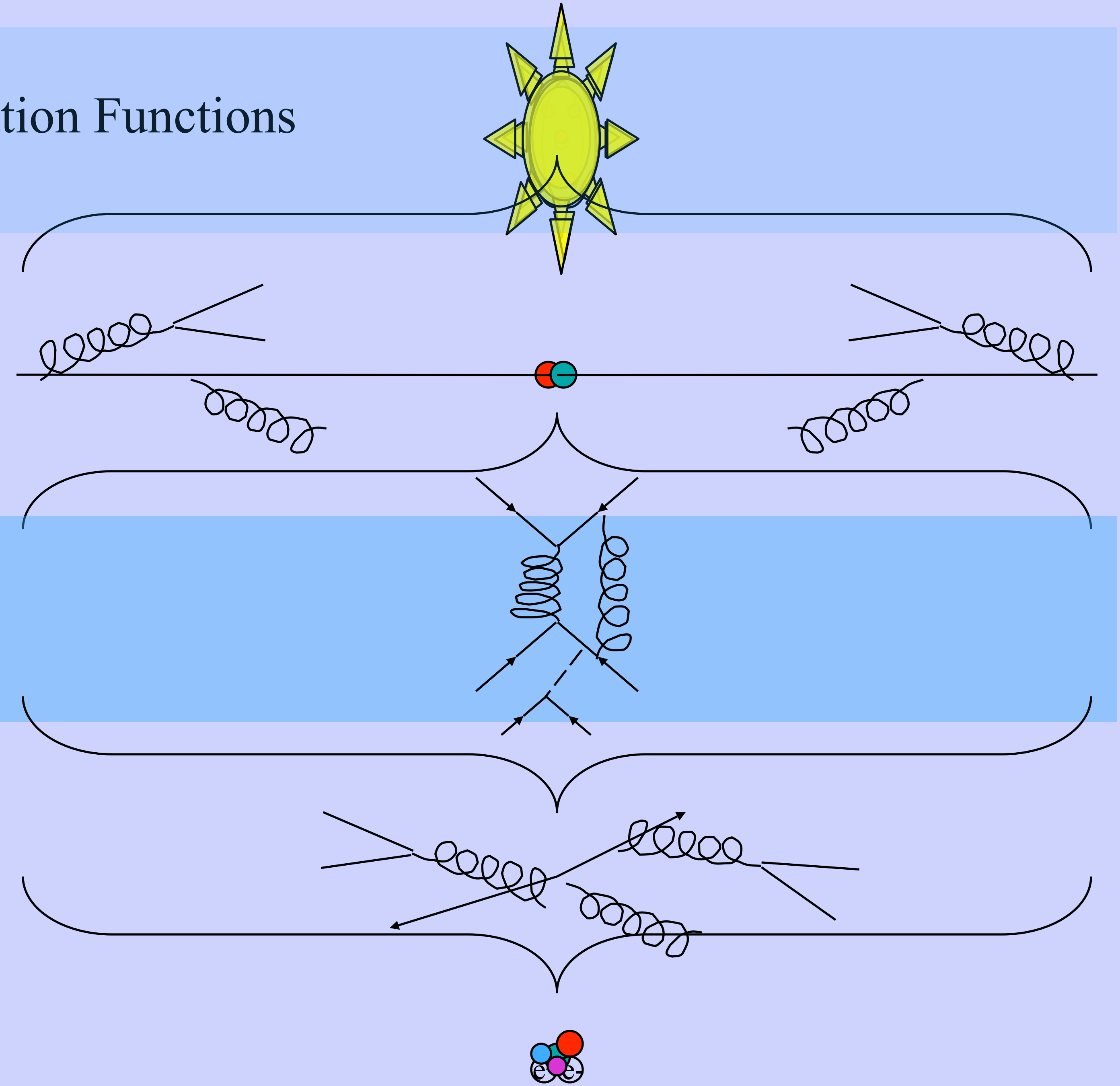
Parton Distribution Functions (Measured)

Evolution +Splitting

Hard Scattering

Showering Fragmentation

Hadronization



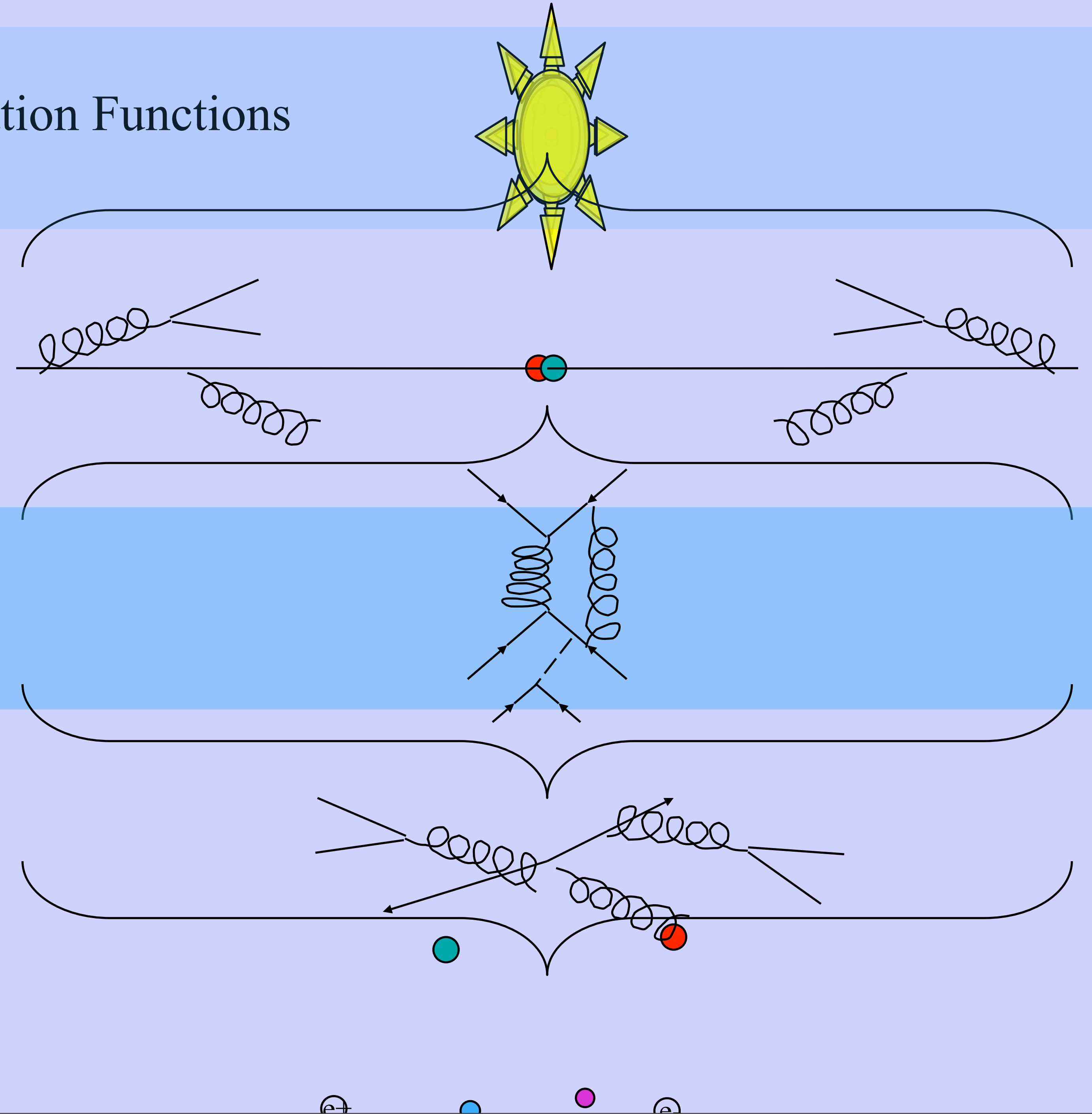
Parton Distribution Functions (Measured)

Evolution +Splitting

Hard Scattering

Showering Fragmentation

Hadronization



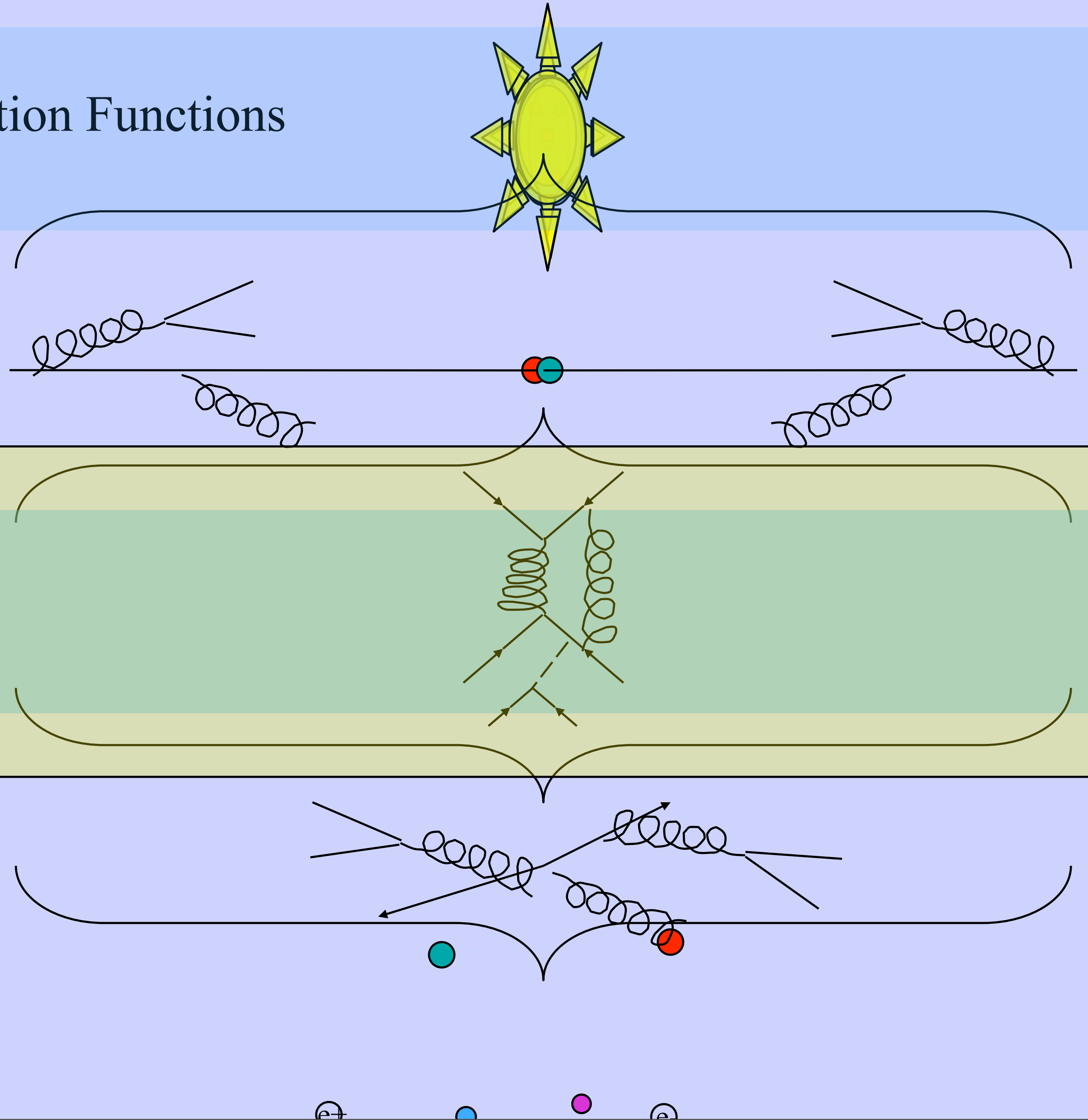
Parton Distribution Functions
(Measured)

Evolution
+Splitting

Hard
Scattering

Showering
Fragmentation

Hadronization



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

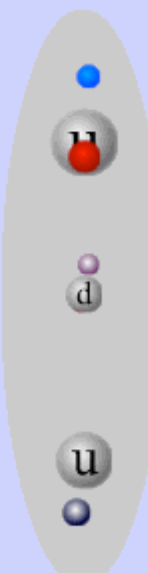
- Deep Inelastic Scattering Results
  - Short time scales “sea” partons
  - u and d. but also u~ d~ s, c and g with varying amounts of momentum

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

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**

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

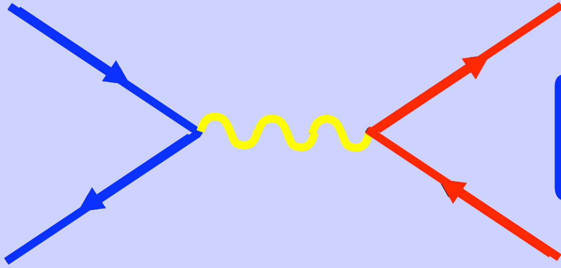
Hadron Colliders

Hadron Colliders

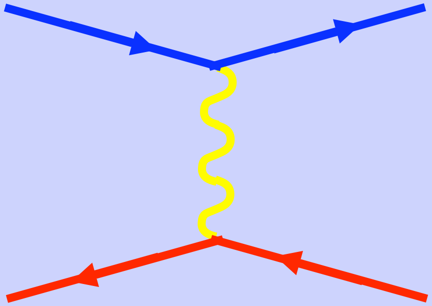
- Initial State: Protons
  - Made of quarks/gluons in bound state
  - Approximately free at very short times
  - Measure distributions in experiments and use
- Final State: Hadrons
  - Made of quarks/gluons in bound state
  - Combine into jets and evolve back to partons
  - Measure hadronization in experiments and use
- Many parton level sub processes contribute to same hadron level event (e.g. $pp > e^+ \nu\, j\, j\, j$)

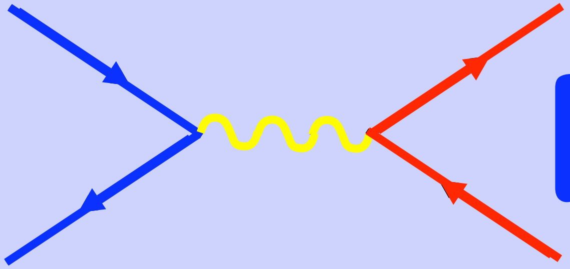
Exercise

- List processes for signal pp > h > tt~bb~
  - e.g. uu~ > h > tt~ bb~
- 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

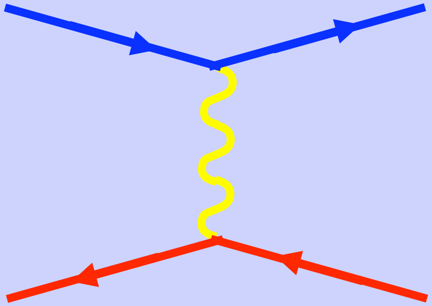


MadGraph

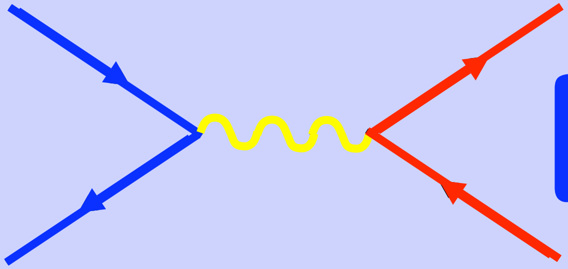




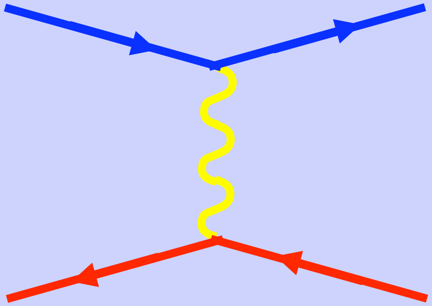
MadGraph



- **User Requests:**
  - pp -> bb~tt~
  - QCD Order = 4
  - QED Order =0

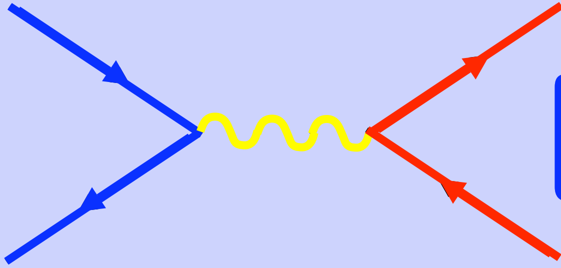


MadGraph

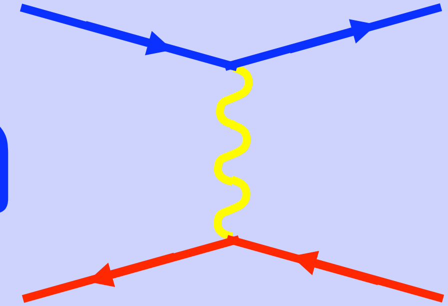


- User Requests:
  - pp -> bb~tt~
  - QCD Order = 4
  - QED Order =0

- MadGraph Returns:
  - Feynman diagrams
  - Fortran Code for |M|^2
  - Summed over all sub processes w/ pdf



MadGraph



- **User Requests:**
  - pp -> bb~tt~
  - QCD Order = 4
  - QED Order =0

```
  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
  - Summed over all sub processes w/ pdf

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

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

Monte Carlo Integration

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

- **Advantages**

Monte Carlo Integration

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

- **Advantages**
  - Large numbers of dimensions

Monte Carlo Integration

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

- **Advantages**
  - Large numbers of dimensions
  - Complicated cuts

Monte Carlo Integration

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

- **Advantages**
  - Large numbers of dimensions
  - Complicated cuts
  - ONLY OPTION

Monte Carlo Integration

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

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

Monte Carlo Integration

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

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

Monte Carlo Integration

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

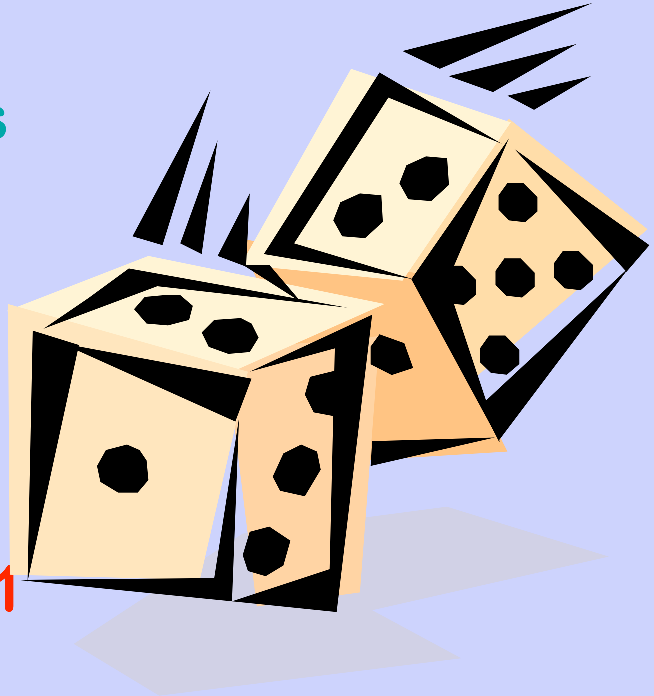
- **Advantages**
  - Large numbers of dimensions
  - Complicated cuts
  - ONLY OPTION
  - Event generation

- **Limitations**

Monte Carlo Integration

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

- Advantages
  - Large numbers of dimensions
  - Complicated cuts
  - ONLY OPTION
  - Event generation
- Limitations
  - Only works for function f(x) ≈ 1

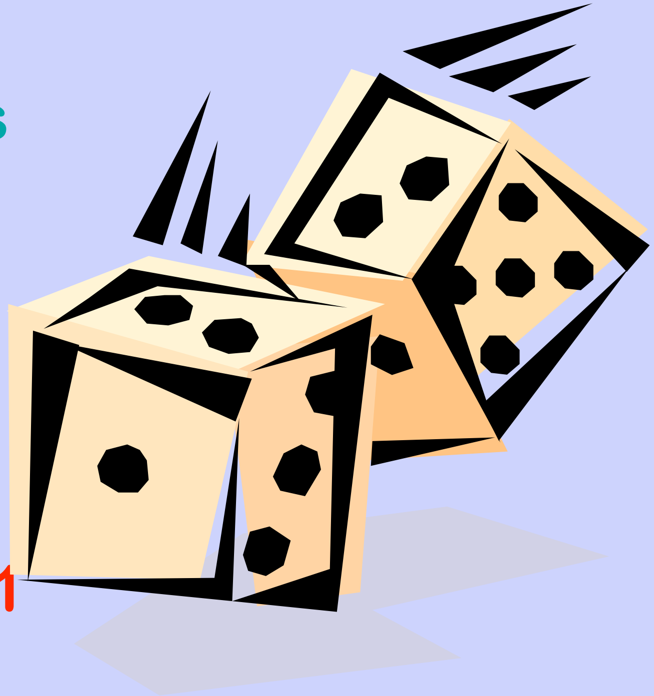


Monte Carlo Integration

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

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

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



Adaptive M.C. (VEGAS)

Adaptive M.C. (VEGAS)

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

Adaptive M.C. (VEGAS)

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

- **Advantages** $\int \frac{1}{(x^2+a)} \frac{1}{(y^2+b)} dxdy$

Adaptive M.C. (VEGAS)

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

- **Advantages** $\int \frac{1}{(x^2+a)} \frac{1}{(y^2+b)} dxdy$
  - Grid adjusts to numerically flatten peaks

Adaptive M.C. (VEGAS)

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

- **Advantages** $\int \frac{1}{(x^2 + a)} \frac{1}{(y^2 + b)} dxdy$
  - Grid adjusts to numerically flatten peaks
  - Flexible

Adaptive M.C. (VEGAS)

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

- **Advantages** $\int \frac{1}{(x^2+a)} \frac{1}{(y^2+b)} dxdy$
  - Grid adjusts to numerically flatten peaks
  - Flexible

Adaptive M.C. (VEGAS)

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

- **Advantages** $\int \frac{1}{(x^2+a)} \frac{1}{(y^2+b)} dxdy$
  - Grid adjusts to numerically flatten peaks
  - Flexible

- **Limitations**

Adaptive M.C. (VEGAS)

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

- **Advantages** $\int \frac{1}{(x^2+a)} \frac{1}{(y^2+b)} dxdy$
  - Grid adjusts to numerically flatten peaks
  - Flexible
- **Limitations**
  - Adjusting grid takes time

Adaptive M.C. (VEGAS)

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

- **Advantages** $\int \frac{1}{(x^2 + a)} \frac{1}{(y^2 + b)} dxdy$
  - Grid adjusts to numerically flatten peaks
  - Flexible
- **Limitations**
  - Adjusting grid takes time
  - Peaks must lie on integration variable

Adaptive M.C. (VEGAS)

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

- **Advantages** $\int \frac{1}{(x^2 + a)} \frac{1}{(y^2 + b)} dxdy$
  - Grid adjusts to numerically flatten peaks
  - Flexible

- **Limitations** $\int \frac{1}{((x - y)^2 + a)} dxdy$
  - Adjusting grid takes time
  - Peaks must lie on integration variable

Single Diagram Enhanced

MadEvent

Single Diagram Enhanced

MadEvent

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

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**

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

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

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**

Single Diagram Enhanced

MadEvent

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

- **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

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.

Single Diagram Enhanced

MadEvent

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

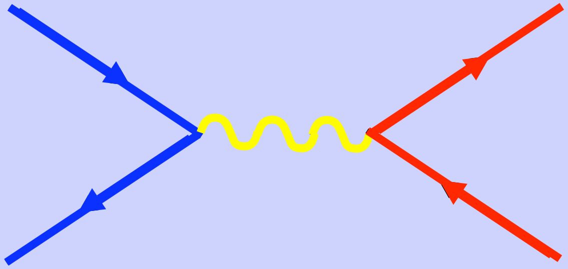
- **Key Idea**
  - Any single diagram is “easy” to integrate
  - Divide integration into pieces, based on diagrams
- **Get N independent integrals**
  - Errors add in quadrature so no extra cost
  - No need to calculate “weight” function from other channels.
  - Can optimize # of points for each one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

Single Diagram Enhanced

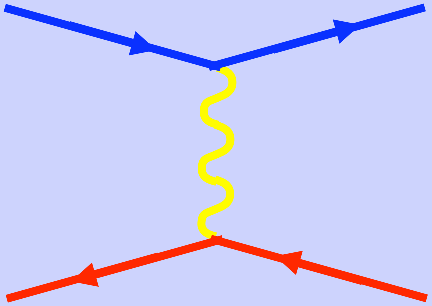
MadEvent

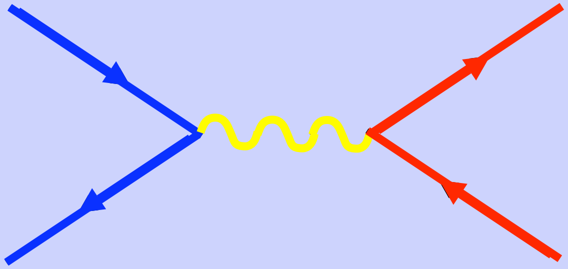
$$\sigma = \int |a_1 + a_2|^2 \, \mathrm{d}(PS) = \int \frac{|a_1 + a_1|^2}{|a_1|^2 + |a_1|^2} |a_1|^2 \, \mathrm{d}(PS) + \int \frac{|a_1 + a_1|^2}{|a_1|^2 + |a_1|^2} |a_2|^2 \, \mathrm{d}(PS)$$

- **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

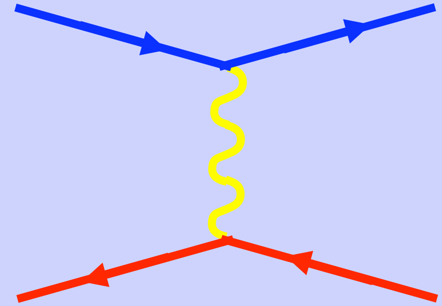


MadEvent

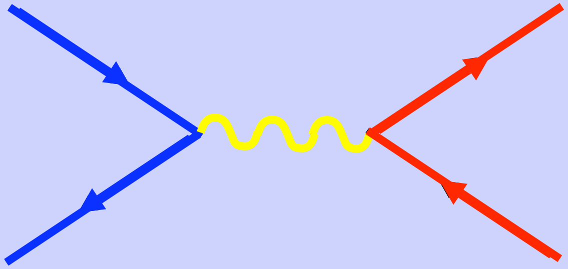




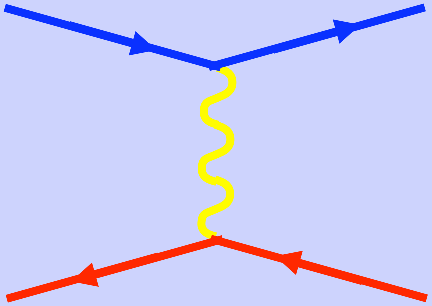
MadEvent



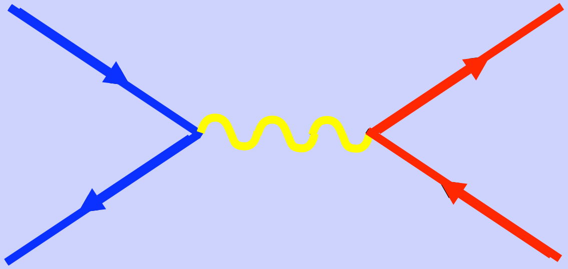
- **User Requests:**



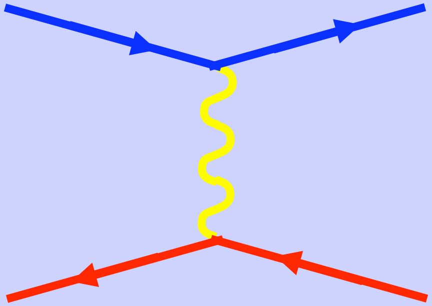
MadEvent



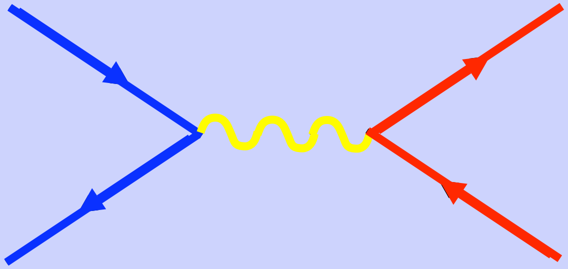
- **User Requests:**
  - pp -> bb~tt~



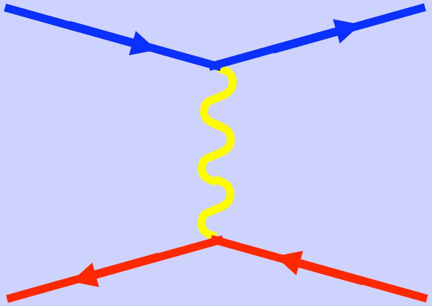
MadEvent



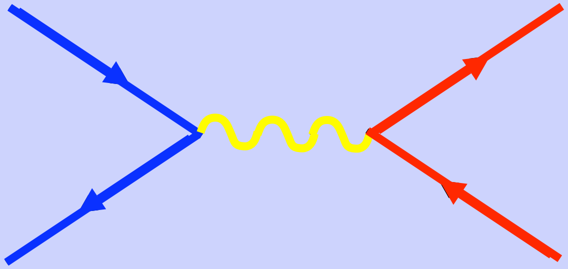
- **User Requests:**
  - **pp -> bb~tt~**
  - **QCD Order = 4**



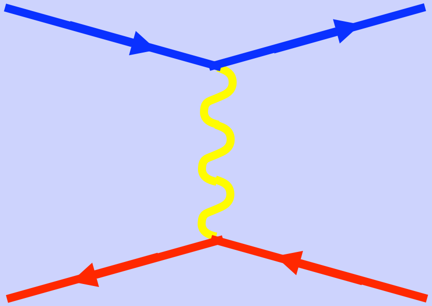
MadEvent



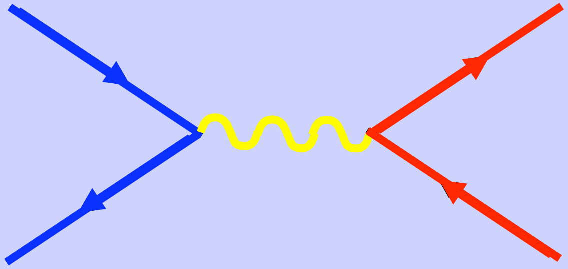
- **User Requests:**
  - **pp -> bb~tt~**
  - **QCD Order = 4**
  - **QED Order =0**



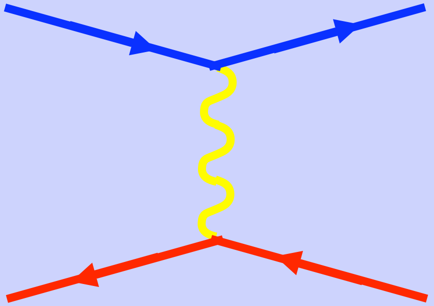
MadEvent



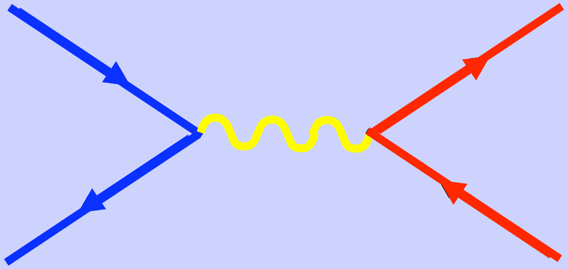
- **User Requests:**
  - **pp -> bb~tt~**
  - **QCD Order = 4**
  - **QED Order =0**
  - **Cuts + Parameters**



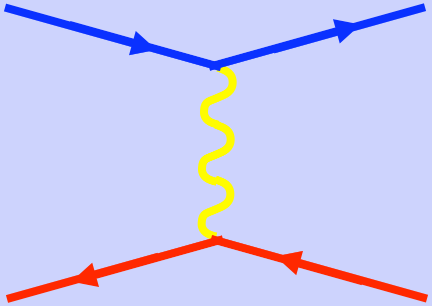
MadEvent



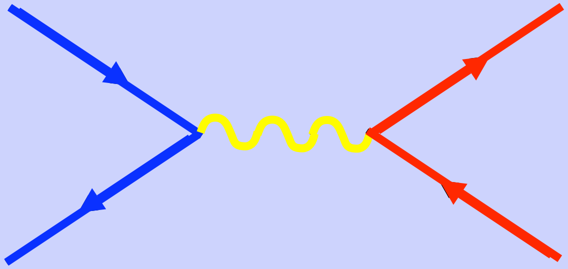
- User Requests:
  - pp -> bb~tt~
  - QCD Order = 4
  - QED Order =0
  - Cuts + Parameters
- MadEvent Returns:



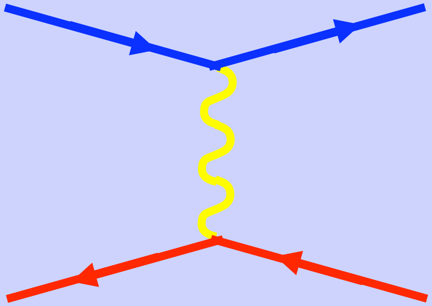
MadEvent



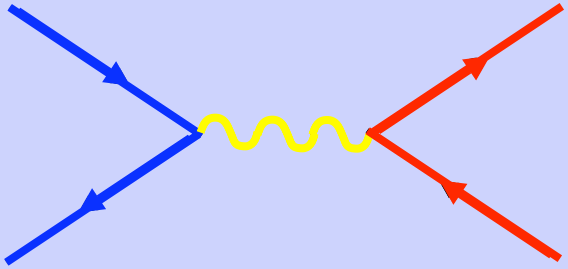
- User Requests:
  - pp -> bb~tt~
  - QCD Order = 4
  - QED Order =0
  - Cuts + Parameters
- MadEvent Returns:
  - Feynman diagrams



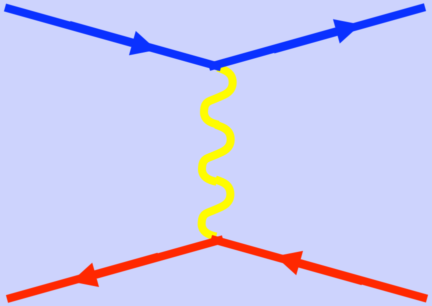
MadEvent



- **User Requests:**
  - pp -> bb~tt~
  - QCD Order = 4
  - QED Order =0
  - Cuts + Parameters
- **MadEvent Returns:**
  - Feynman diagrams
  - Complete package for event generation



MadEvent



- **User Requests:**
  - pp -> bb~tt~
  - QCD Order = 4
  - QED Order =0
  - Cuts + Parameters

- **MadEvent Returns:**
  - Feynman diagrams
  - Complete package for event generation
  - 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

pp > mu+mu- e+e- /a

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

Kinematics at LHC

- plots
- invariant mass
- rapidity
- Et

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 hints that there might be 3 new particles at the LHC (Z', H, W+'). Your job is to find them in the three given data sets and determine their mass.

Advice

Advice

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

Advice

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

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!