# MadGraph 5: Advanced Topics

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University of Illinois at Urbana Champaign

Thanks to Celine Degrande to allow me to present part of her work

# Plan of the lectures

- Motivation For Dimension 6 Operators
- Example: forward-backward Asymmetry
- MG5 Generation

# What can we expect from the LHC?

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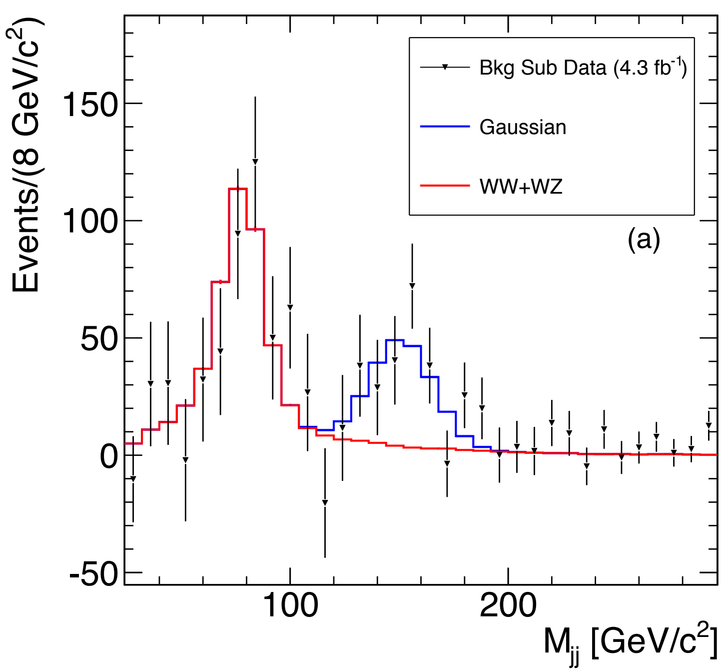
## A new peak



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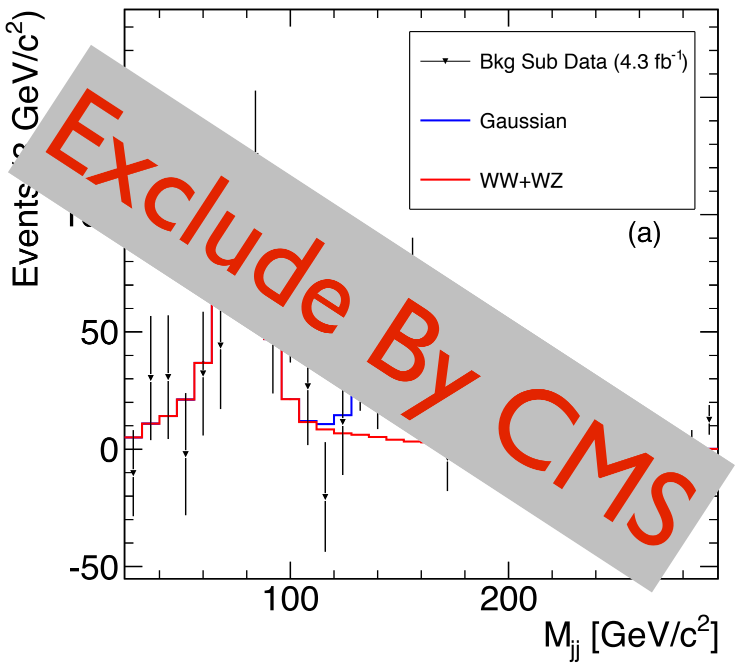

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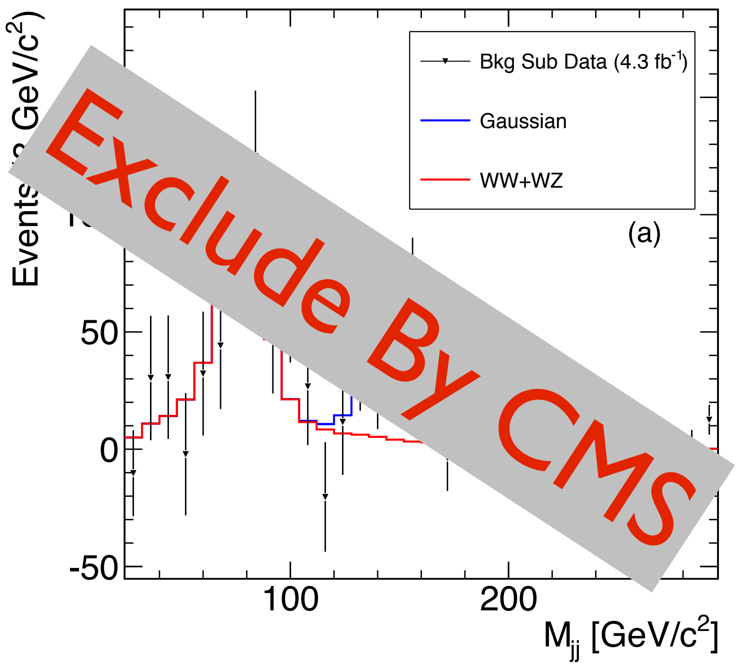


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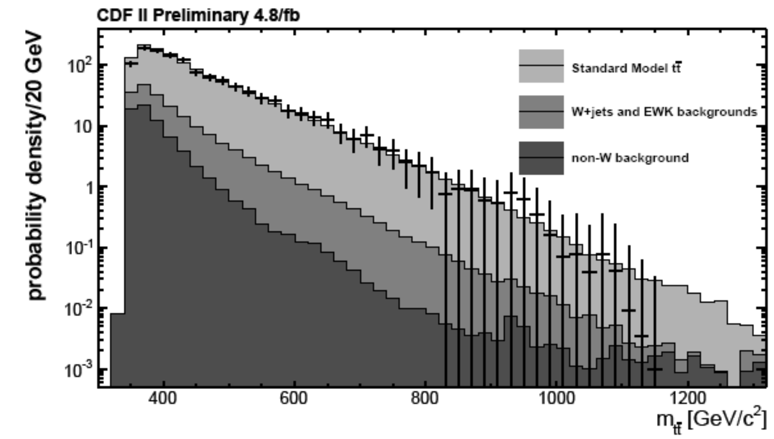

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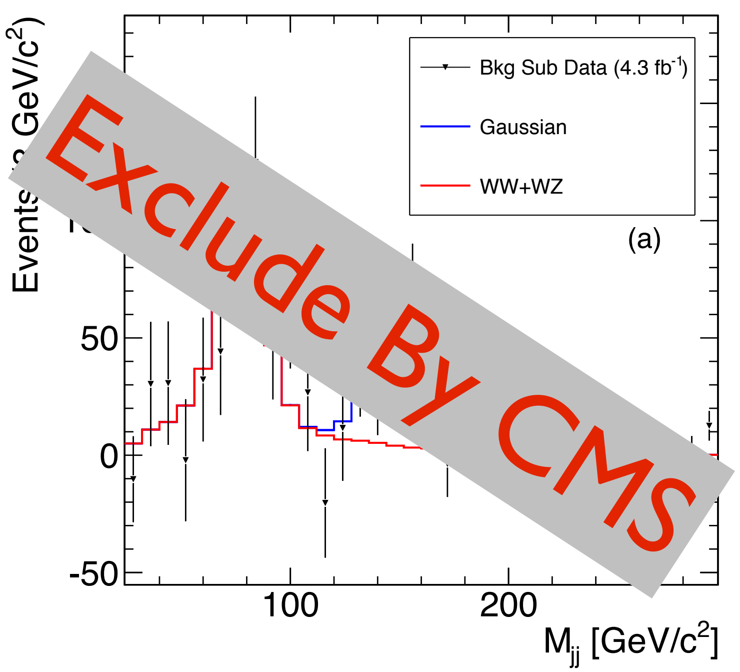
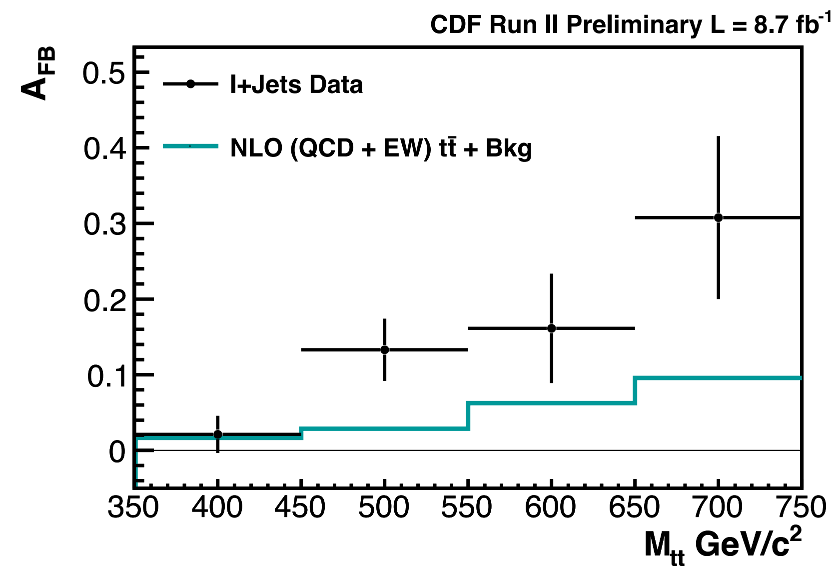



## Tension with SM

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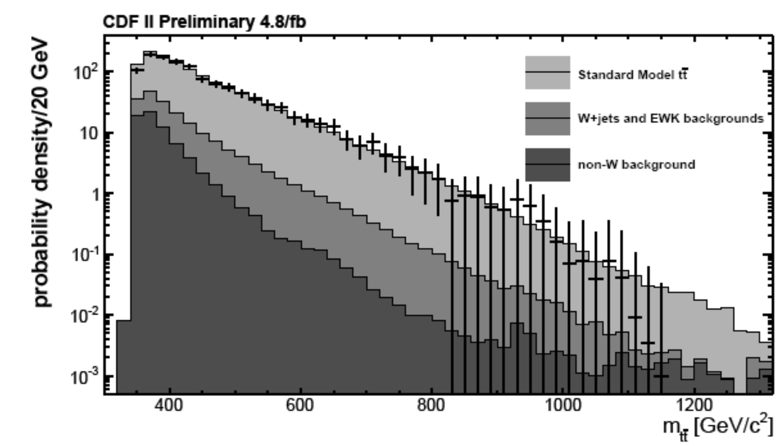

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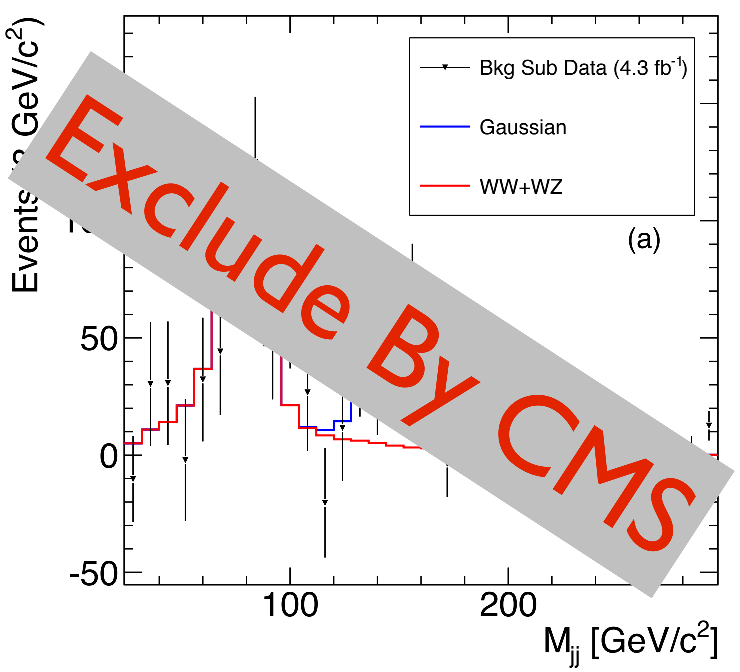


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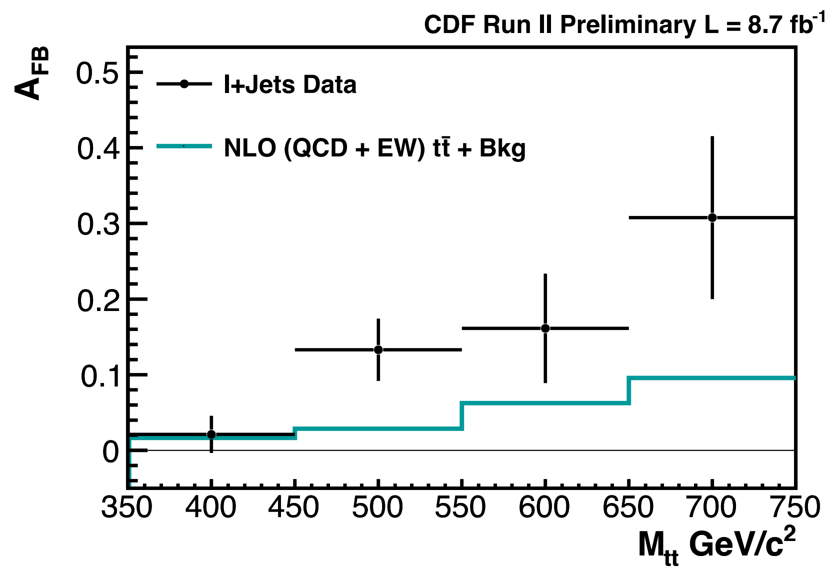


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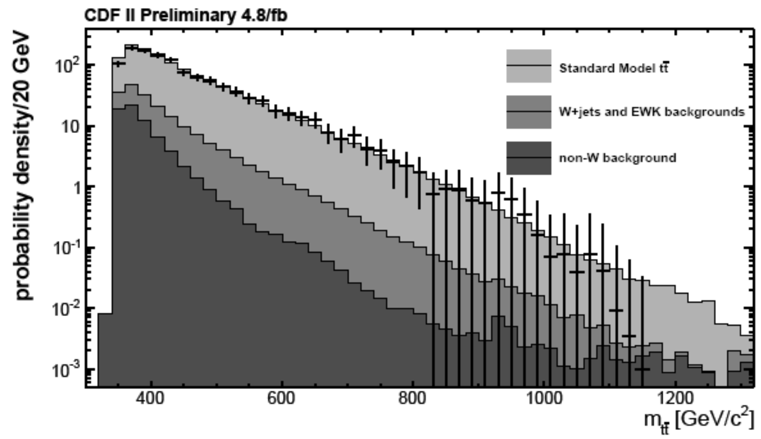

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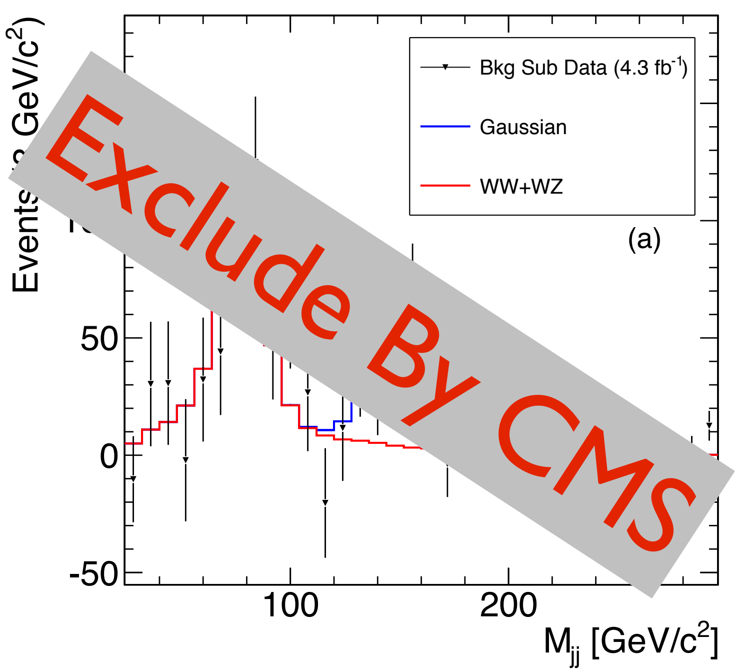


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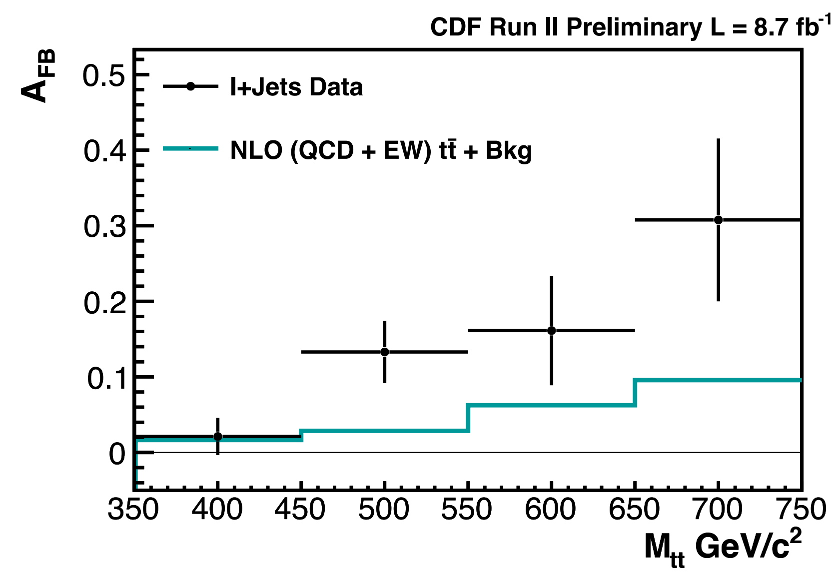
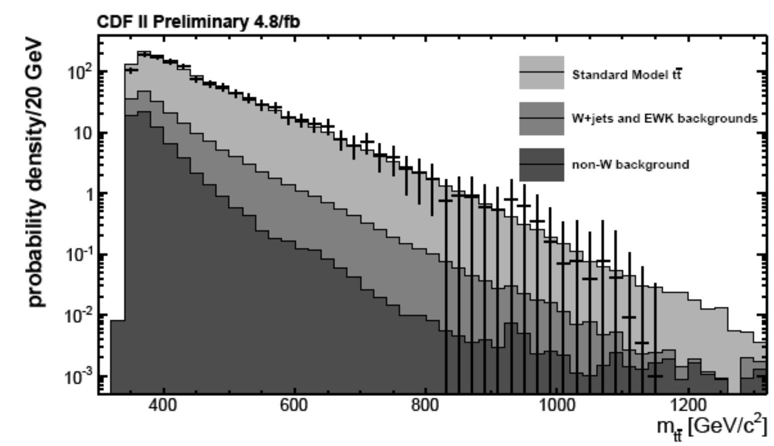



☞ New model

OR

☞ Model independent

## Nothing






Friday, October 5, 12

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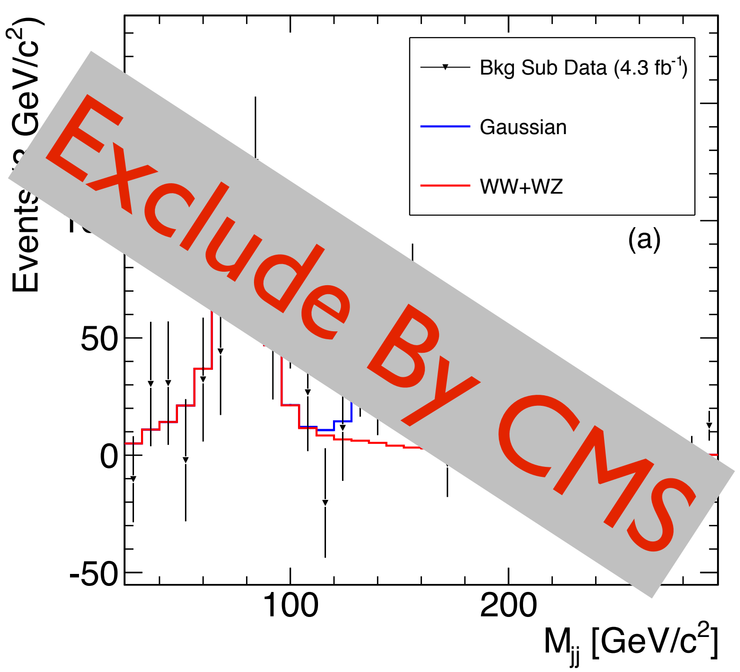


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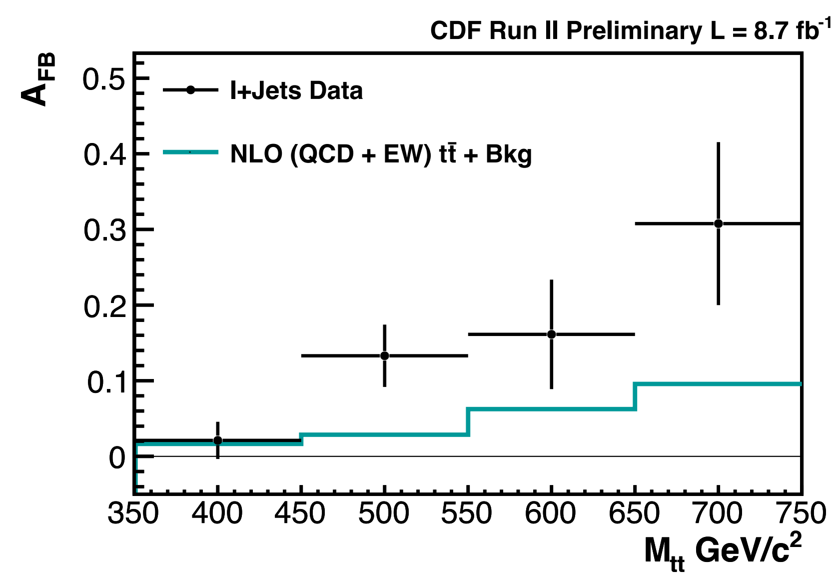


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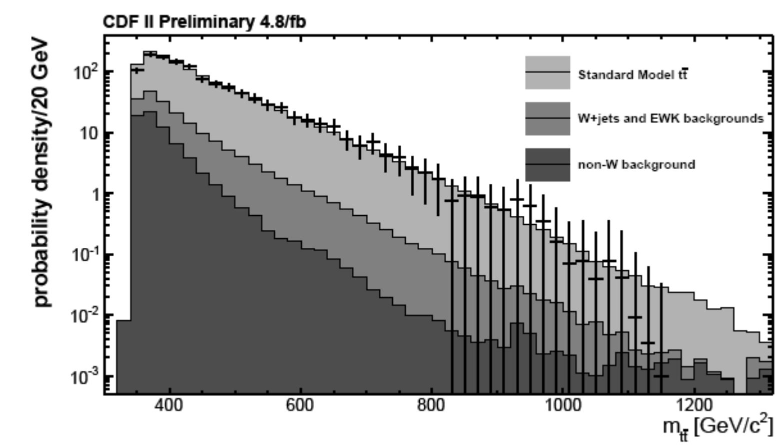


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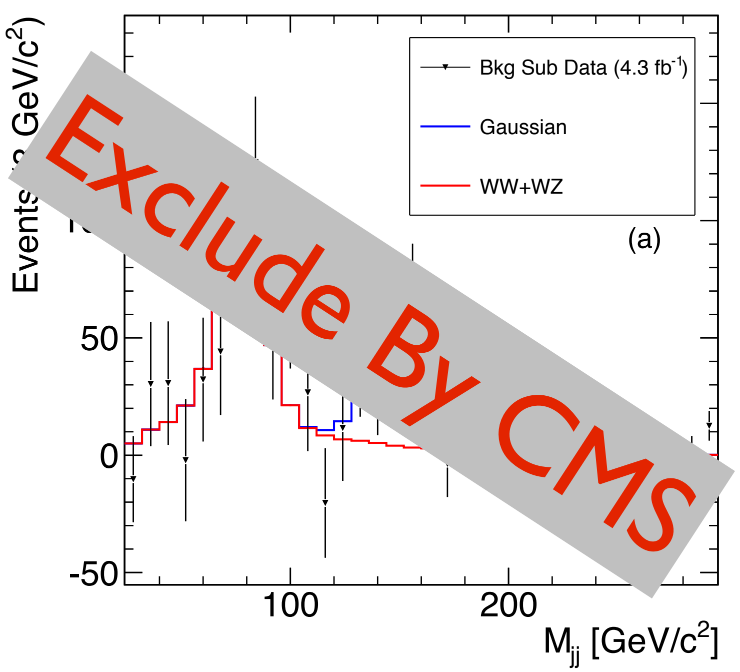
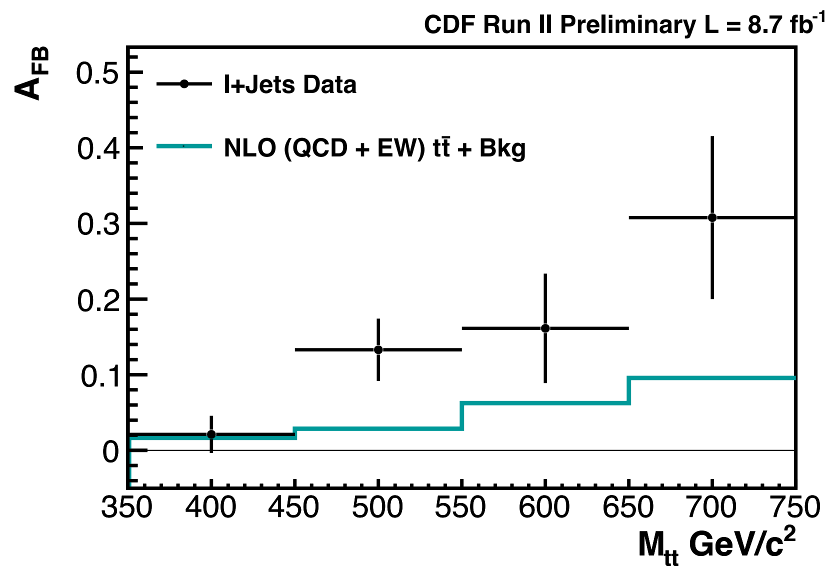
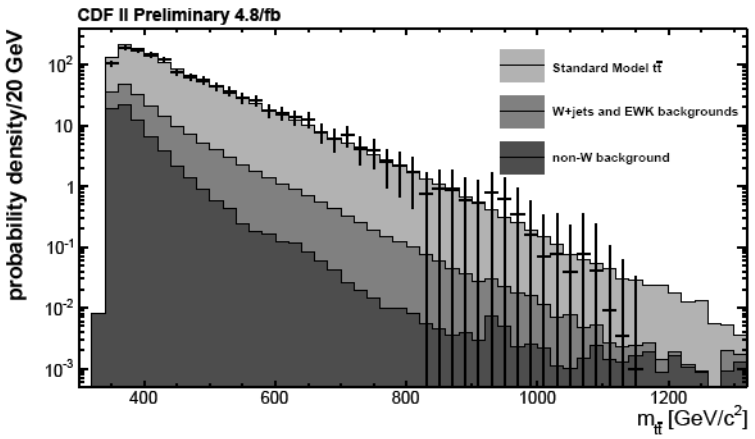
| A new peak | Tension with SM | Nothing |
|---|---|---|
|  |  |  |
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- New Physics at (too?) High Energy

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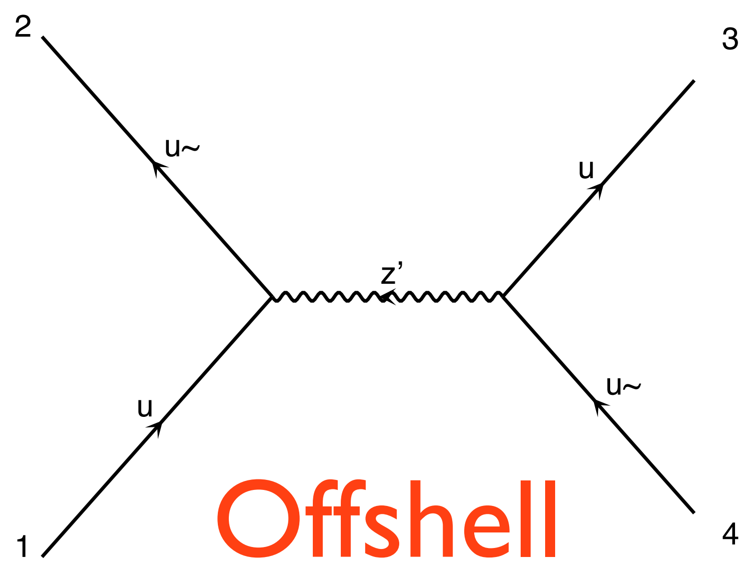


Offshell

$$M_{Z'} \gg \sqrt{\hat{S}}$$

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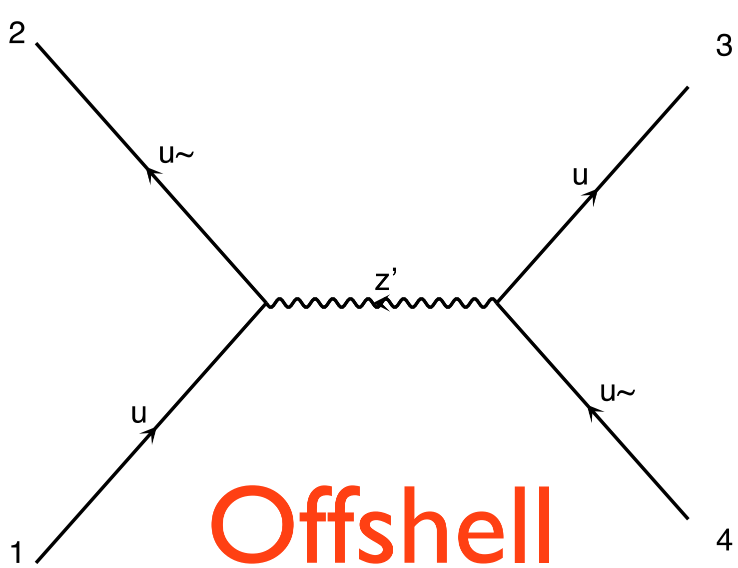


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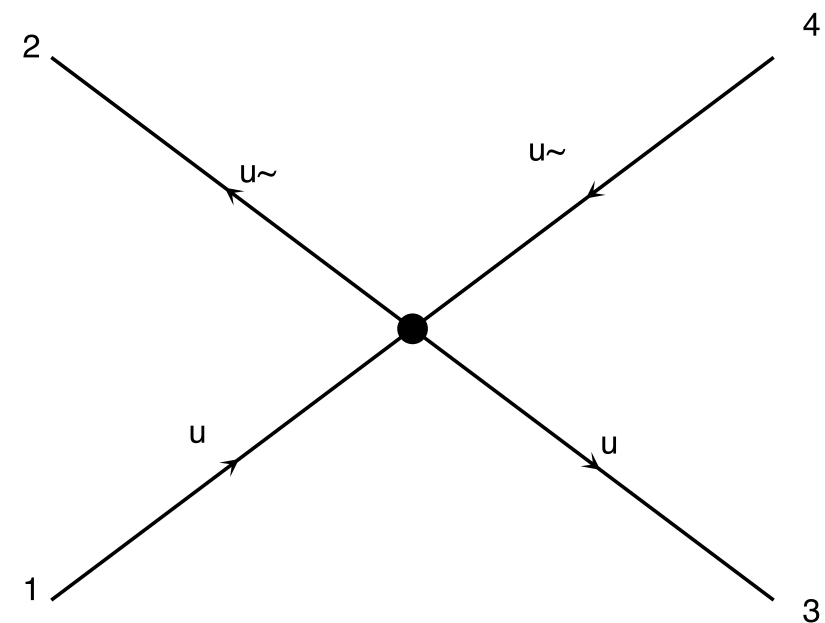


Effective Vertex

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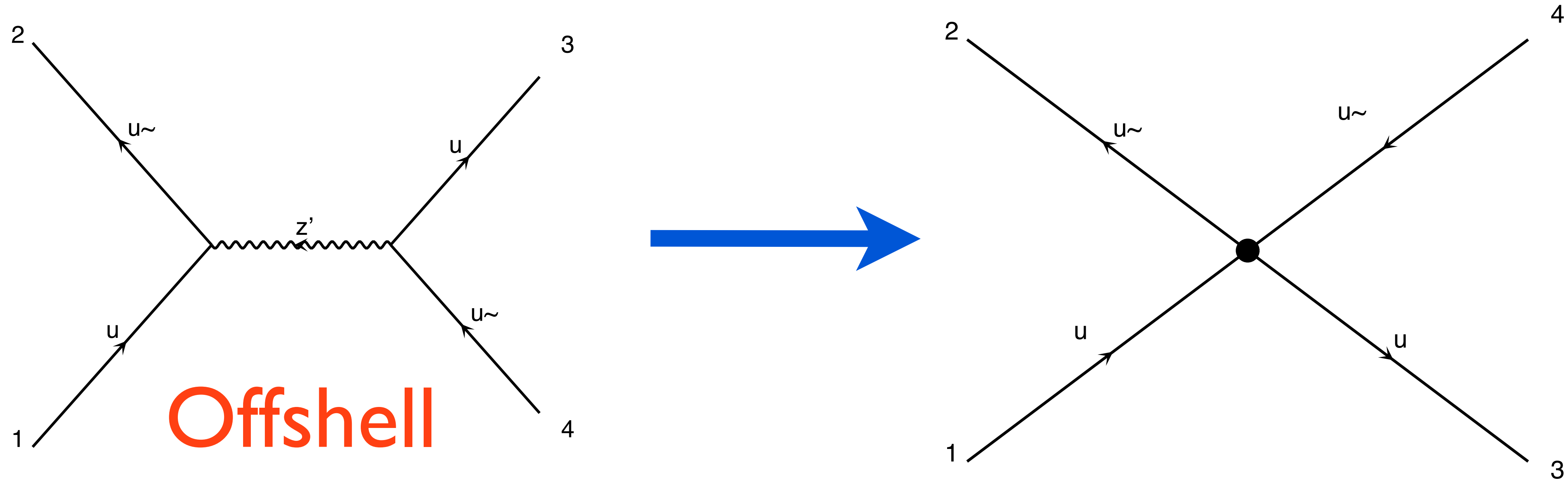


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☞ Additional terms in the Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \dots$$

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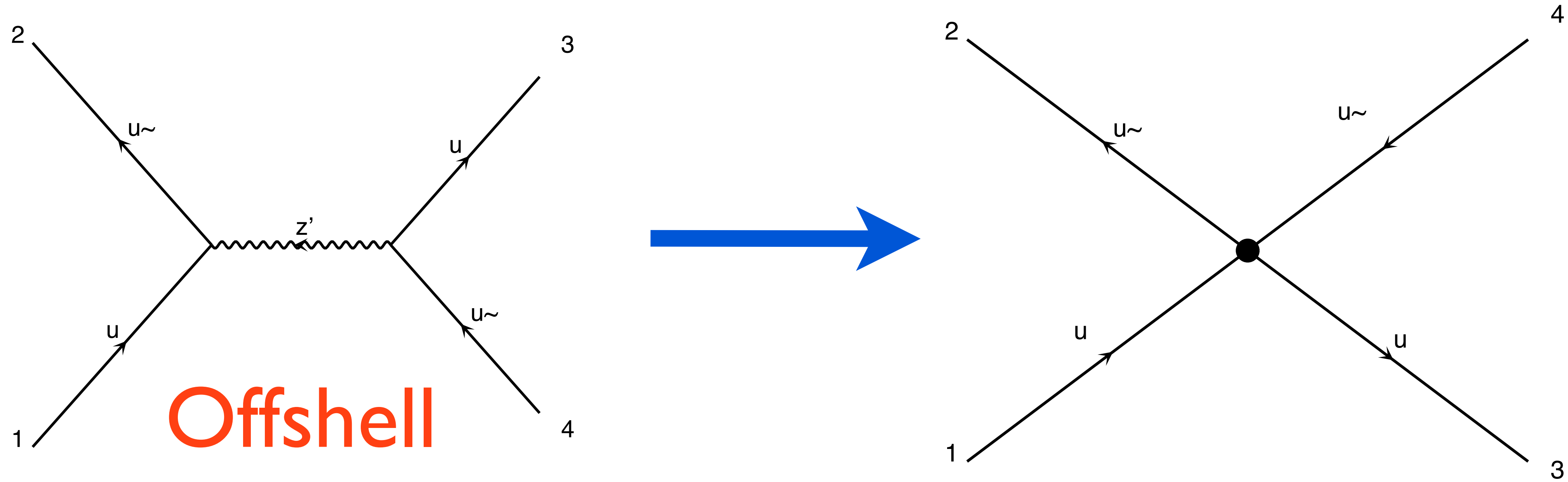


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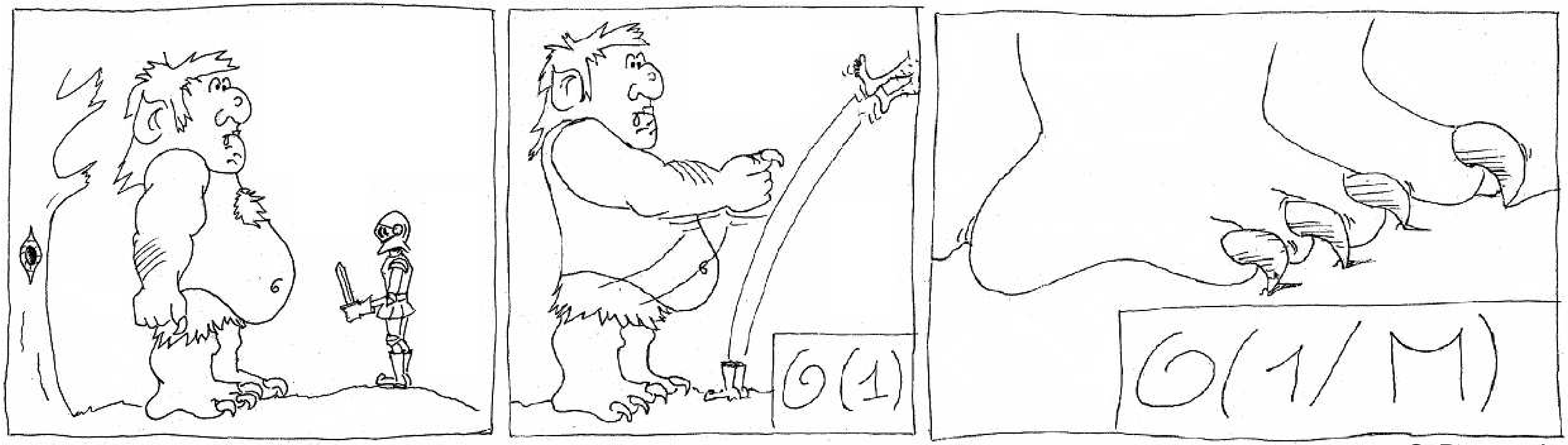
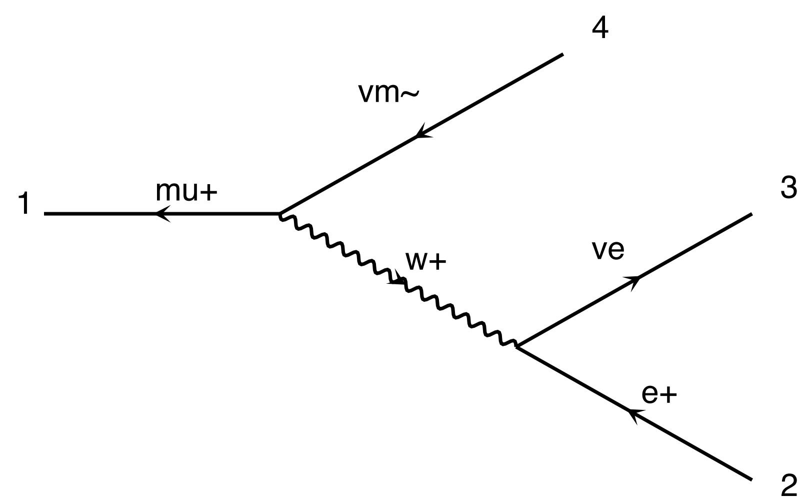



C. Degrande

# A Famous Example: Fermi Theory

- The muon decay can (and was) be described by a Dimension 6 operator



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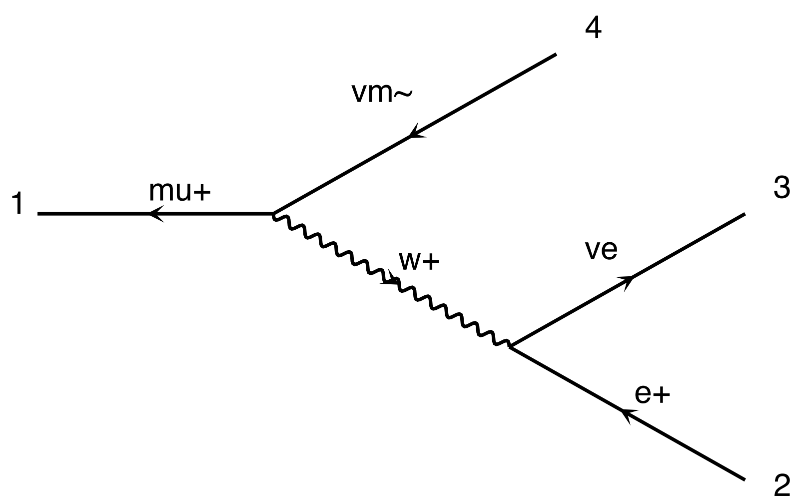


$$\frac{G_F}{\sqrt{2}}\left(\bar{\nu}_l\gamma_\mu(1-\gamma_5)l\right)\left(\bar{l}\gamma^\mu(1-\gamma_5)\nu_l\right)$$

Dimension 6: $$\frac{G_F}{\sqrt{2}}=\frac{c_F}{\Lambda_F^2}$$

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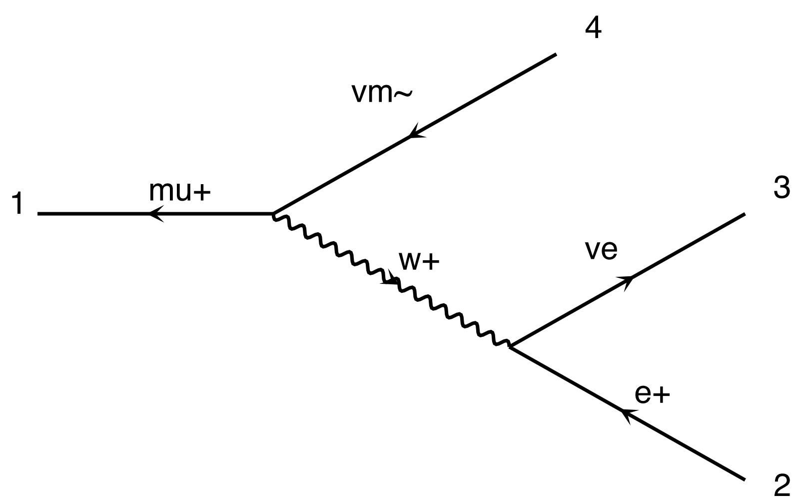


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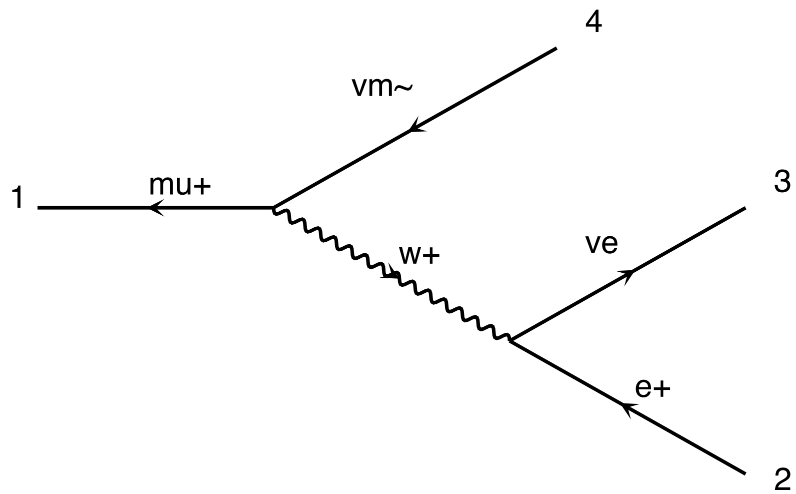


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Dimension 8

$$\frac{1}{p^2-M_W^2} = -\frac{1}{M_W^2} - \frac{p^2}{M_W^4} + \dots$$

# Effective Field Theory

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

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| Type | Name | Dimension |
|---|---|---|
| Bosons | $H\,, G\,, W\,,\ B$ | 1 |
| Fermion | $L, Q, l_R, u_R, d_R$ | 3/2 |
| Covariant derivative | $D^\mu$ | 1 |
| Strength tensor | $F^{\mu\nu}$ | 2 |

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The number of possible Operators are huge

- 59 Dimension 6 Operators If
  - ☞ Preserve the SM gauge symmetries
  - ☞ Preserve B-L accidental symmetries
  - ☞ We consider only one flavor

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- Only One Dimension 5 Operator:

$$\mathcal{O} = LHLH$$

Give a mass to the neutrino

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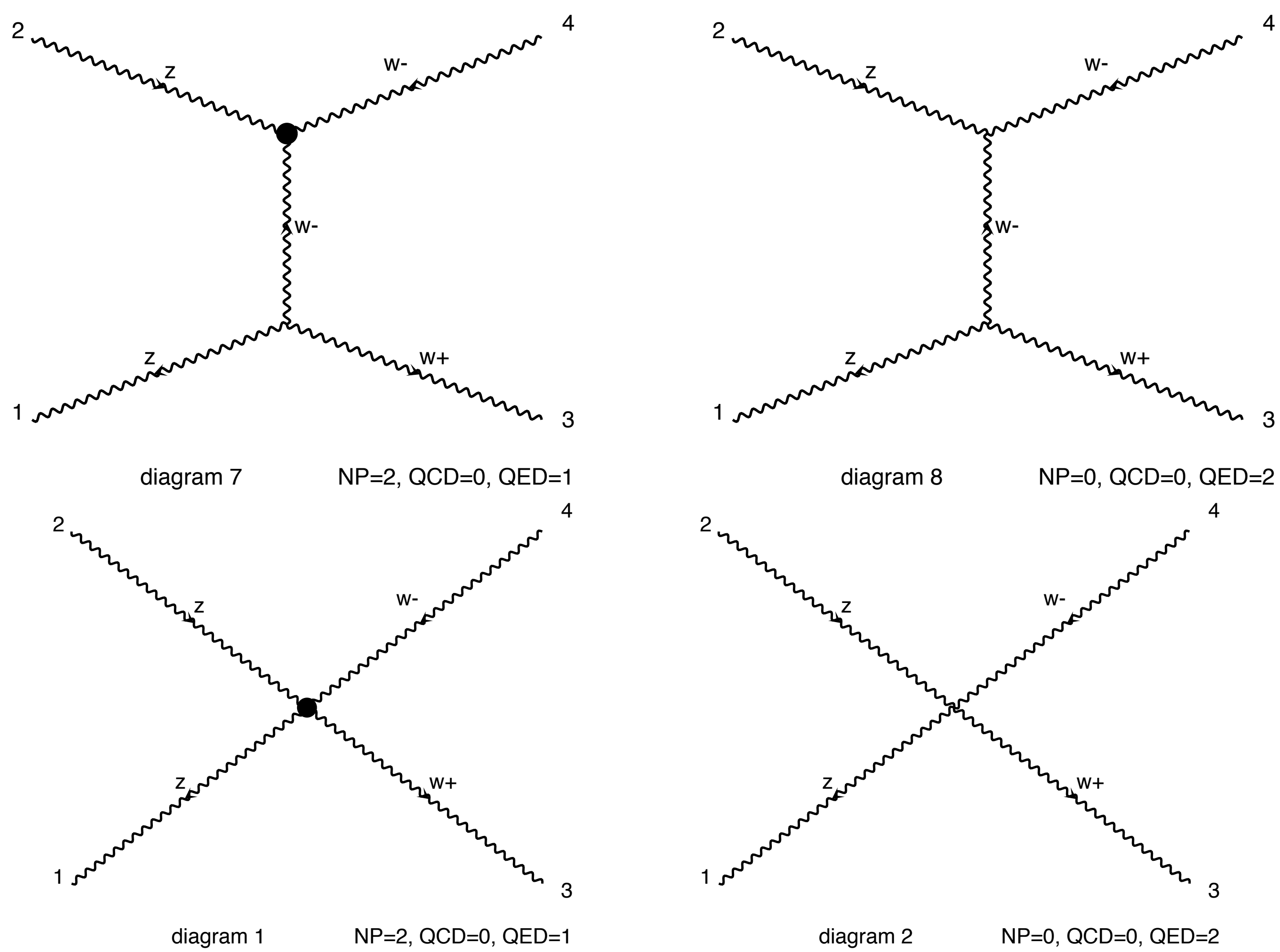


No Additional couplings

# Effective Field Theory

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- Only few Operators for one process and different effects
- Unitary Satisfied at low Energy
- More than one vertex in an operator
- Description valid at NLO (Loop and radiation)

# Forward-Backward Asymmetry

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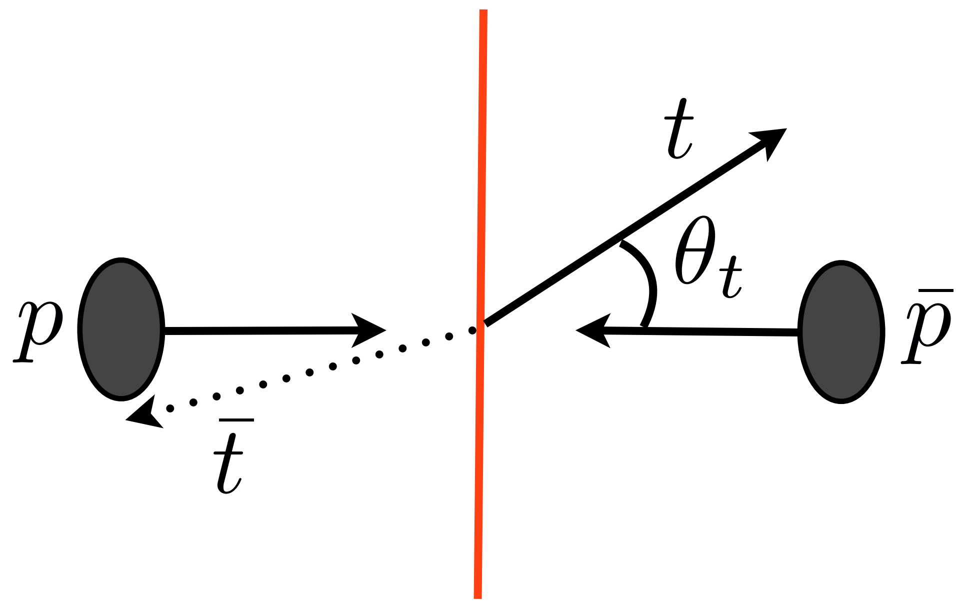


$$A_{FB} \equiv \frac{\sigma\left(\cos\theta_t > 0\right) - \sigma\left(\cos\theta_t < 0\right)}{\sigma\left(\cos\theta_t > 0\right) + \sigma\left(\cos\theta_t < 0\right)}$$

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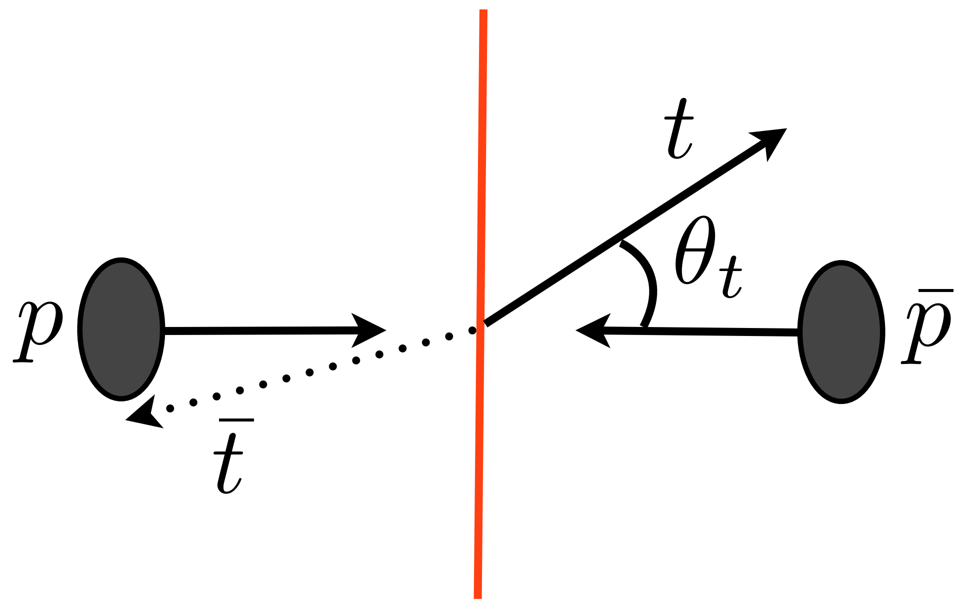


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$$A_{FB}^{SM} = 0.066 \pm 0.007$$

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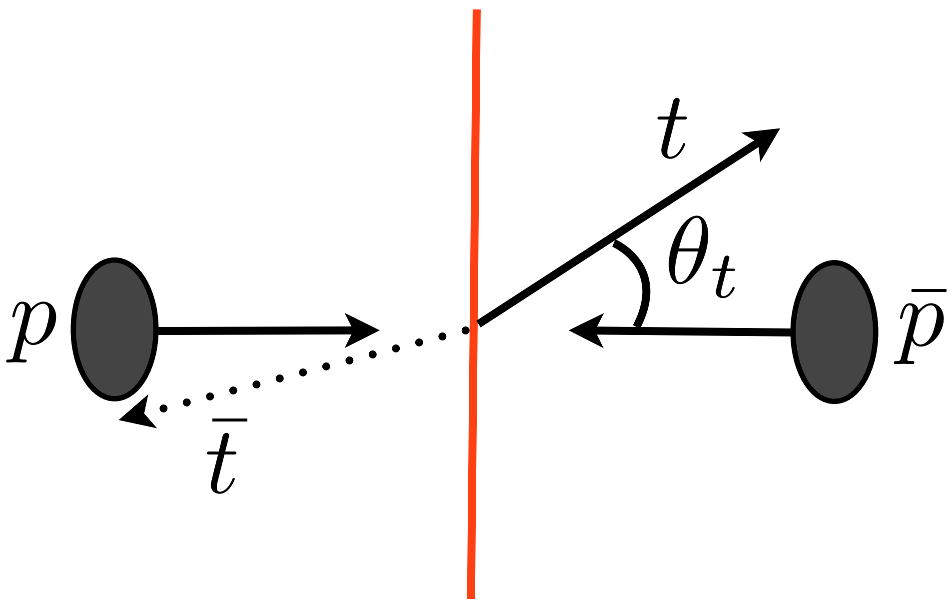


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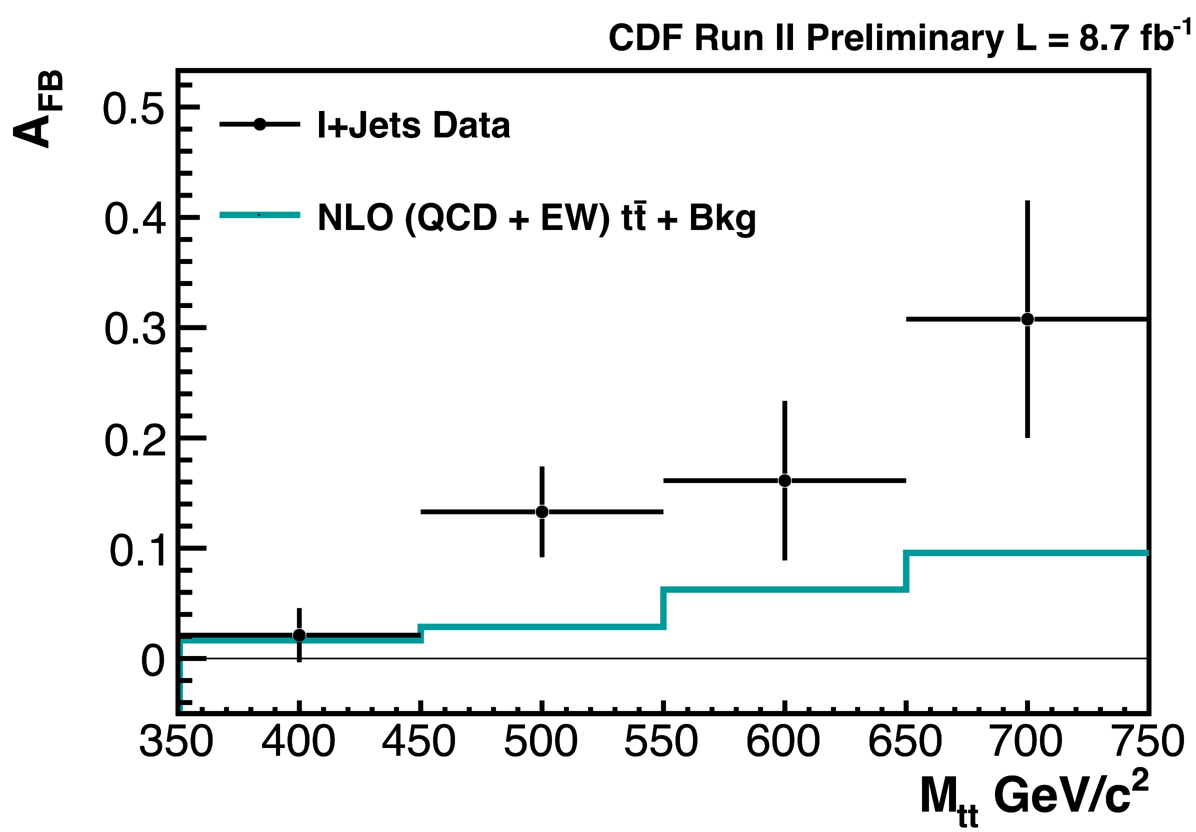


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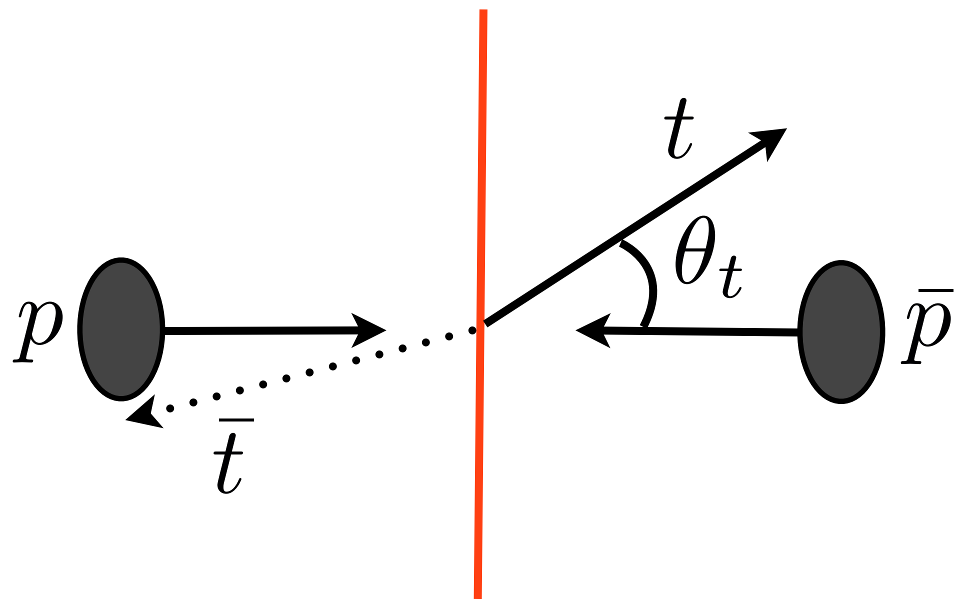


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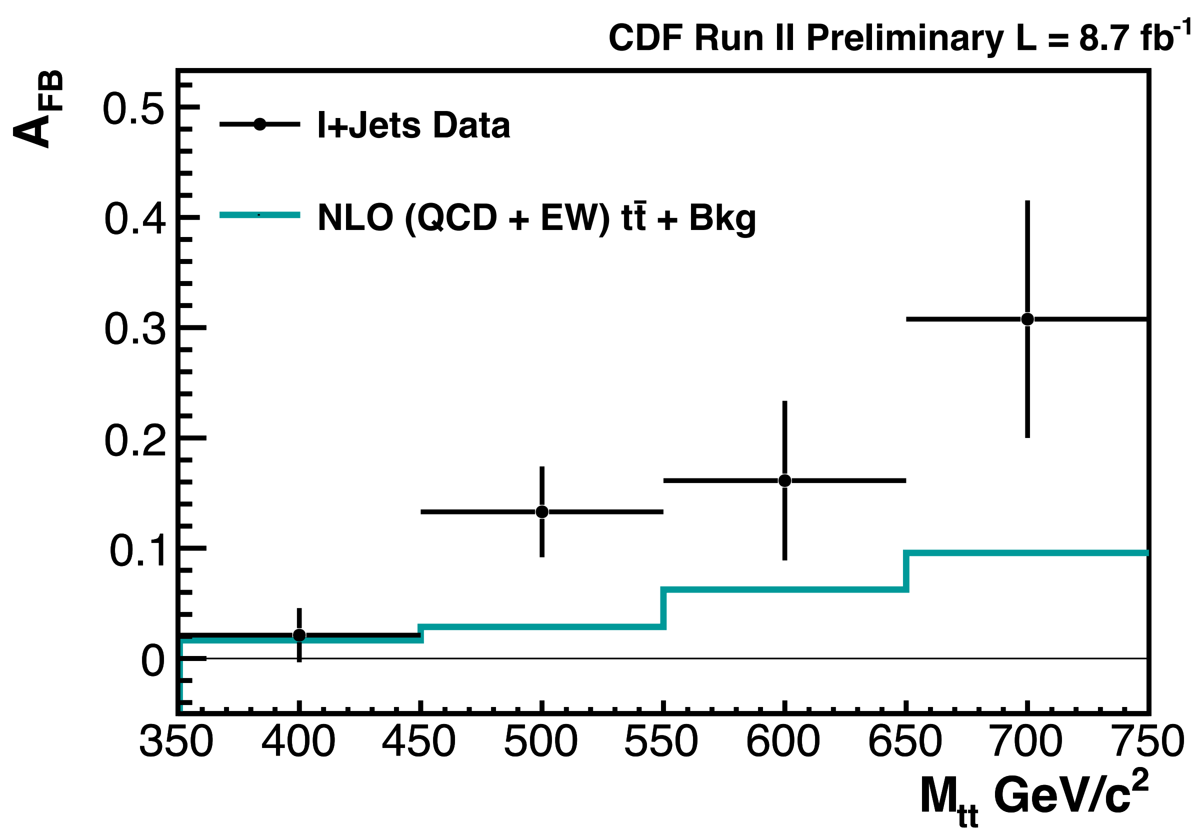


$$A_{FB}^{obs} = 0.162 \pm 0.047$$

$$A_{FB}^{SM} = 0.066 \pm 0.007$$

2 Sigma

# Dimension 6 operators

$$\mathcal{O}_{hg} = \left[\left(H\bar{Q}_L\right)\sigma^{\mu\nu}T^A t_R\right] G^A_{\mu\nu}$$

$$\mathcal{O}_{Rv} = \left[\bar{t}_R\gamma^\mu T^A t_R\right]\sum_q \left[\bar{q}\gamma_\mu T^A q\right]$$

$$\mathcal{O}_{Ra} = \left[\bar{t}_R\gamma^\mu T^A t_R\right]\sum_q \left[\bar{q}\gamma_\mu\gamma_5 T^A q\right]$$

$$\Bigg\} \; t_R \to Q_L$$

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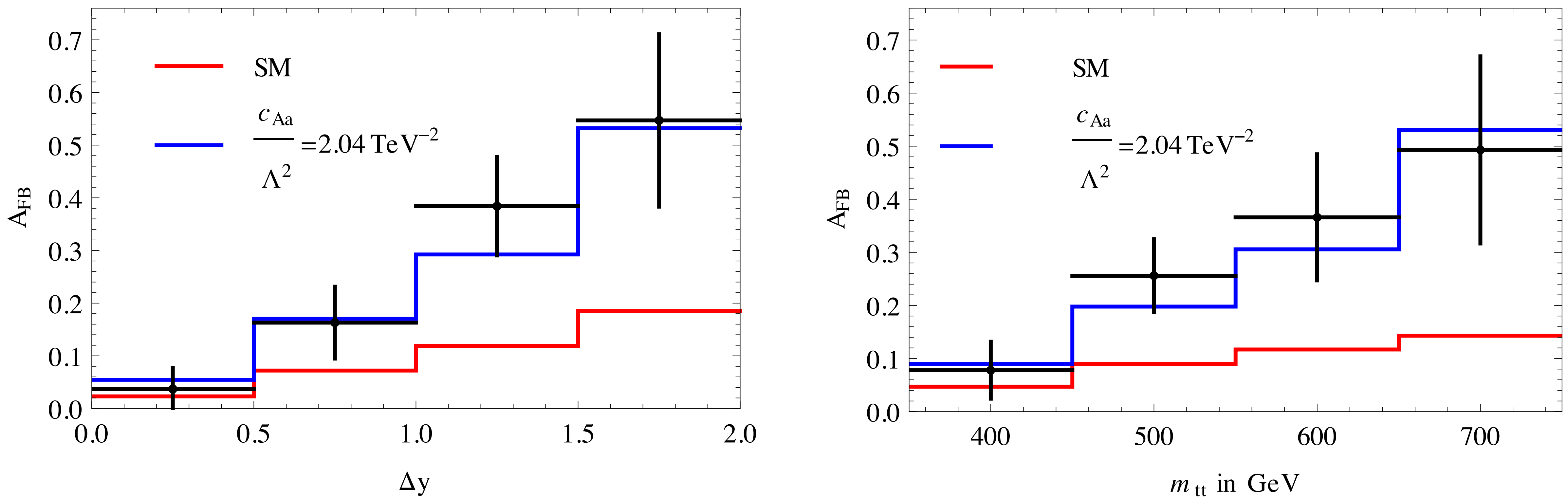
**Best Fit:** $$\frac{c_{Aa}}{\Lambda^2} = 2.04\,TeV^{-2}$$

# Forward-Backward Asymmetry

## Does it fit the distributions?




## Provides a correct description

# Generation

# FR Implementation

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}]$$

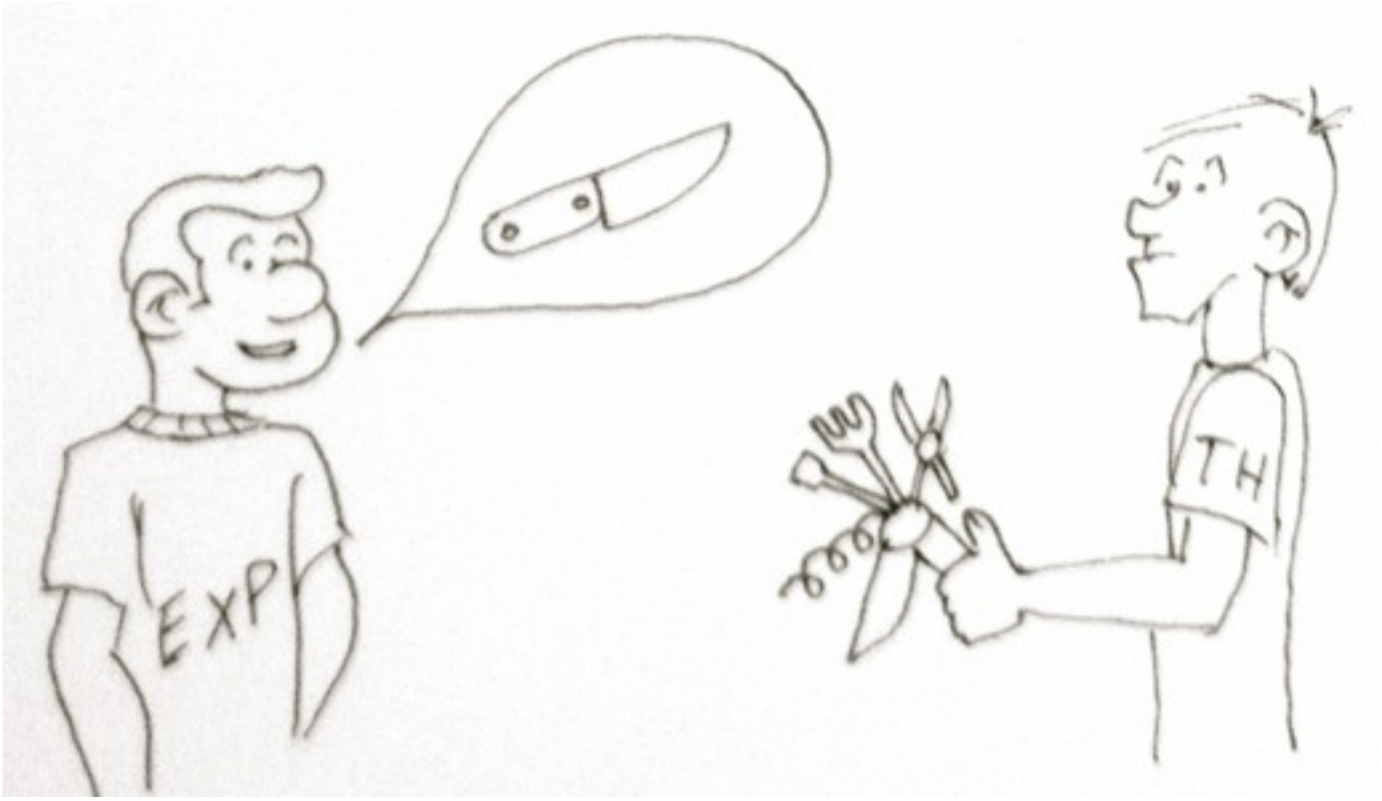
```
M$InteractionOrderHierarchy = {
{NP,1}
}

M$InteractionOrderLimit = {
{NP,2}
}

CWWWL2== {
      ParameterType -> External,
      ParameterName -> CWWWL2,
      BlockName -> DIM6,
        InteractionOrder -> {{QED,-3},{ NP, 2}},
      Value -> 1,
        TeX -> Subscript[C,WWW]/\[CapitalLambda]^2,
      Description -> "coefficient of OWWW in TeV-2"},

  LWWW := ExpandIndices[CWWWL2*10^(-6) gw^3/4 Module[{mu, nu, rho, L, J, K},
  Eps[L, J, K] FS[Wi, mu, nu, L] FS[Wi, nu, rho, J] FS[Wi, rho,
  mu,K]],FlavorExpand->SU2W] ;
```

# Make an efficient generation




- When studying Operators, we want to study those one (or two) at the time.
- Theoretician wants to provide a single model

→ How to have an efficient generation?

# Model too generic

## Solution 1:

- Assign a specific order to each operator

generate p p > w+ w- NP2=0 NP3=0 NP4=0 NP5=0 NP6=0

☞ Not beautiful

# Model too generic

## Solution I:

- Assign a specific order to each operator

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## Solution II:

- Set the associated coupling value to zero and keep the diagram

generate p p > w+ w-

☞ Not efficient and not 100% safe

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## Solution III:

- Restrict the model to what you need!

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What is this doing ?

- Remove all interaction with zero coupling
- Optimize Model
- Simplify Param_card

# Model too generic

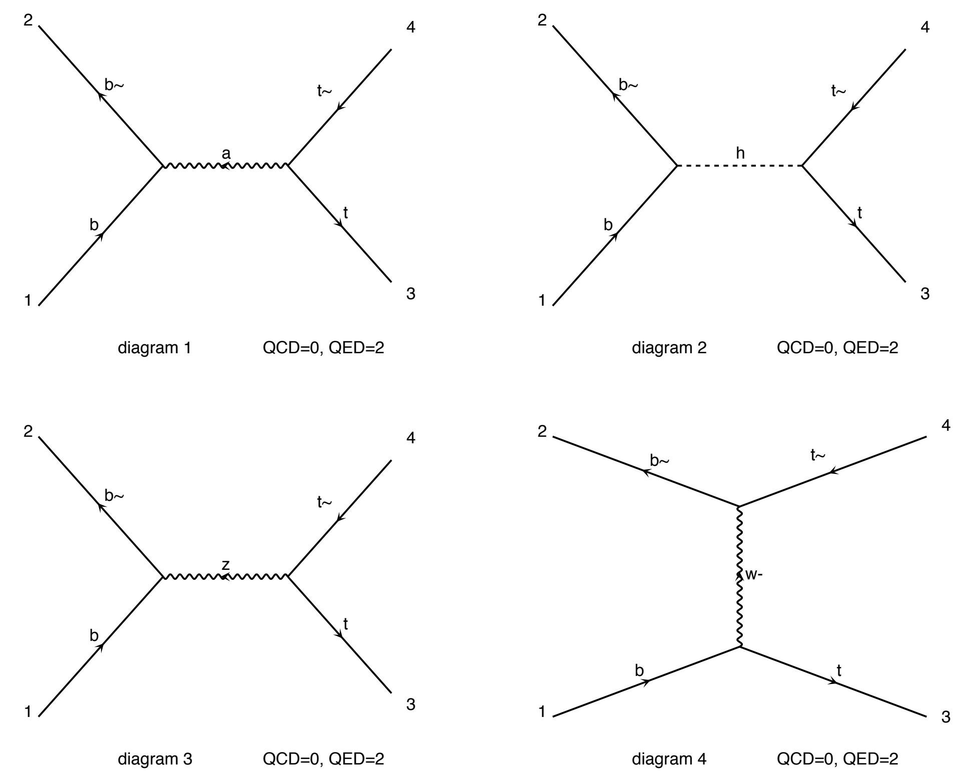
## Solution III:

Examples: sm-ckm sm-lepton_masses sm-no_b_mass sm-no_masses sm-no_tau_mass sm-zeromass_ckm

# Example

## b b~ > t t~ QCD=0

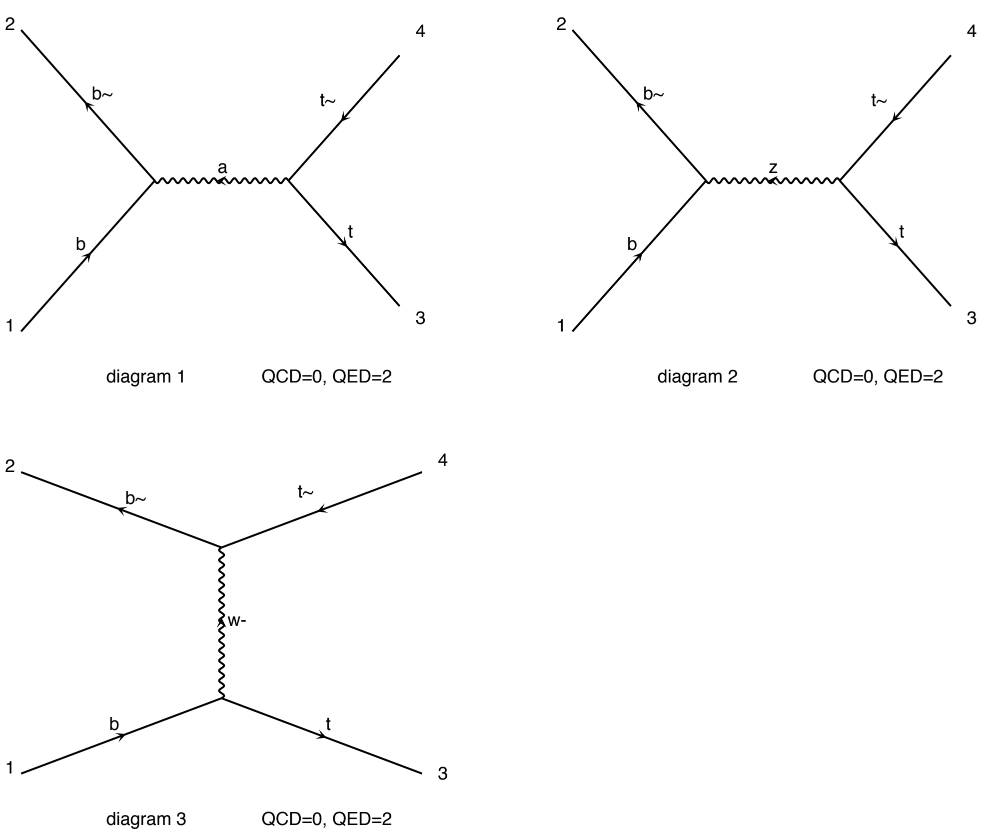
SM



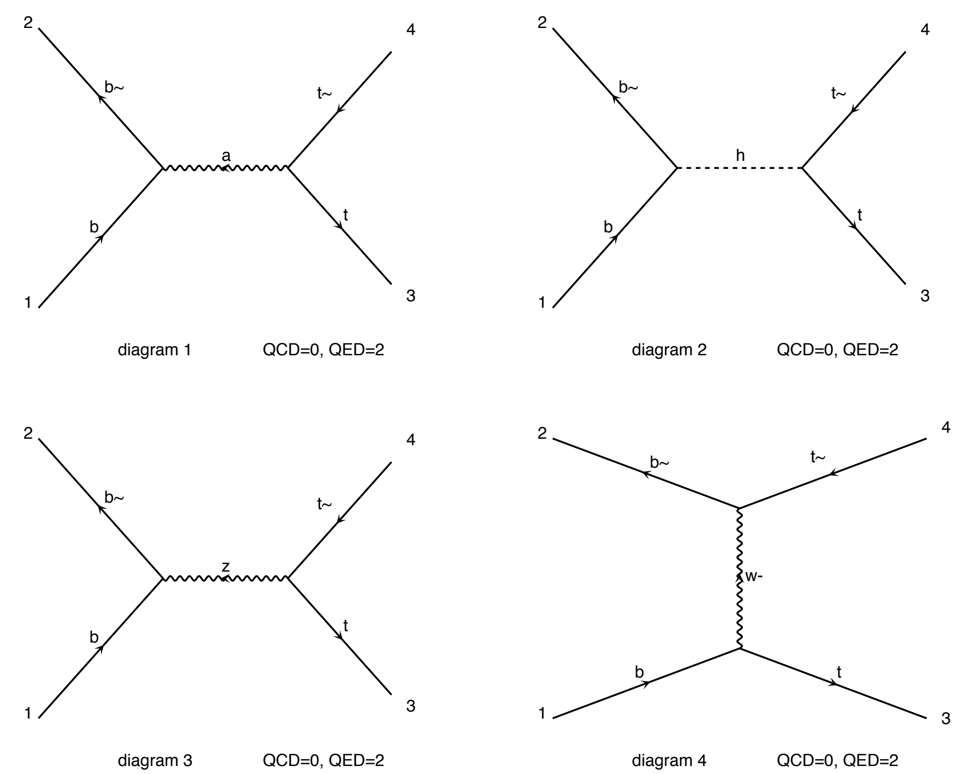
# Example

## b b~ > t t~ QCD=0

SM-no_b_mass




SM



# Example

## b b~ > t t~ QCD=0

SM-no_b_mass

SM

restriction card:

```
####################################
## INFORMATION FOR MASS
####################################
Block MASS
    4 0.000000e+00 # MC
    5 0.000000e+00 # MB
    6 1.730000e+02 # MT
   11 0.000000e+00 # Me
   13 0.000000e+00 # MM
   15 1.777000e+00 # MTA
   23 9.118800e+01 # MZ
   25 1.200000e+02 # MH
```

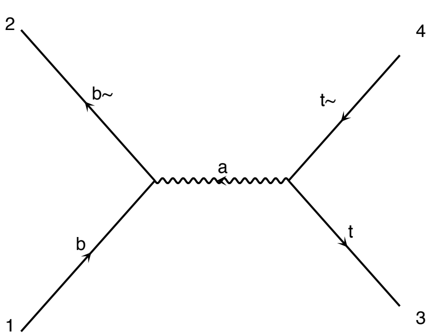
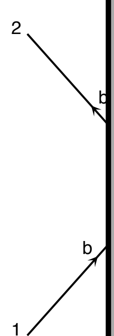



diagram 1 QCD=0, QED=2



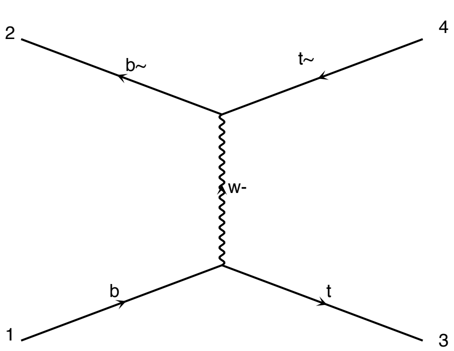




diagram 3 QCD=0, QED=2

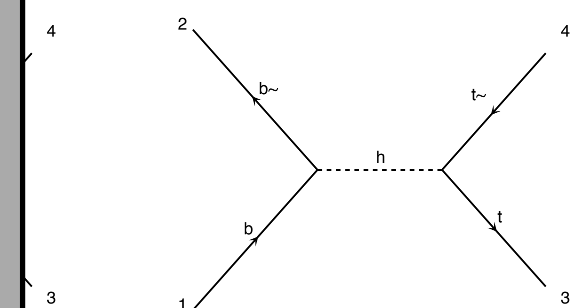



diagram 2 QCD=0, QED=2

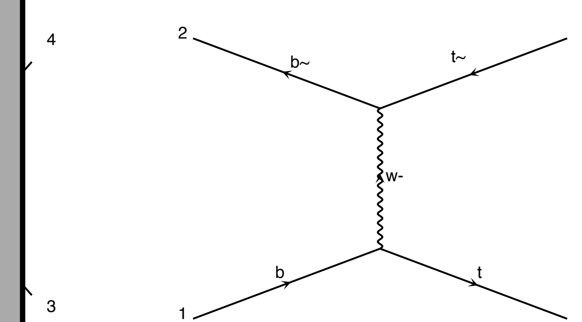



diagram 4 QCD=0, QED=2

# Example

## b b~ > t t~ QCD=0

SM-no_b_mass

SM

restriction card:

```
####################################
## INFORMATION FOR MASS
####################################
Block MASS
    4 0.000000e+00 # MC
    5 0.000000e+00 # MB
    6 1.730000e+02 # MT
   11 0.000000e+00 # Me
   13 0.000000e+00 # MM
   15 1.777000e+00 # MTA
   23 9.118800e+01 # MZ
   25 1.200000e+02 # MH
```

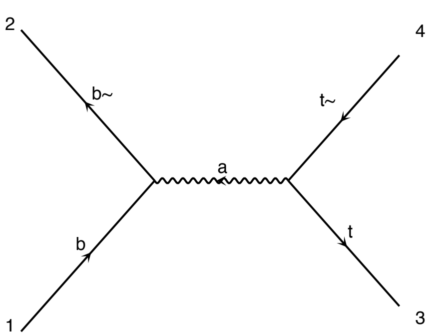



diagram 1 QCD=0, QED=2

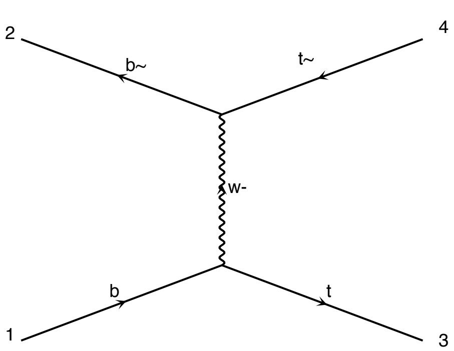



diagram 3 QCD=0, QED=2

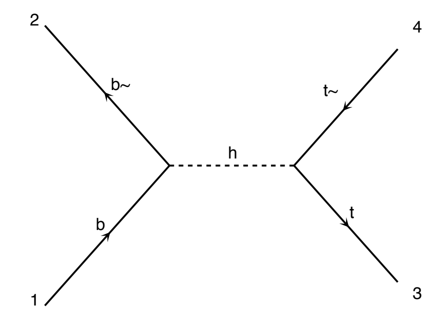



diagram 2 QCD=0, QED=2

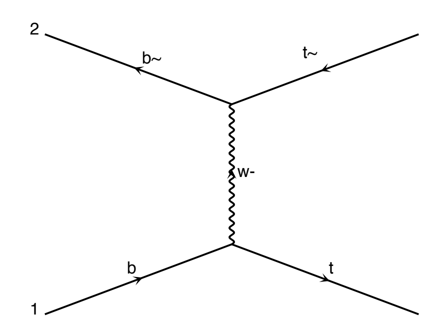
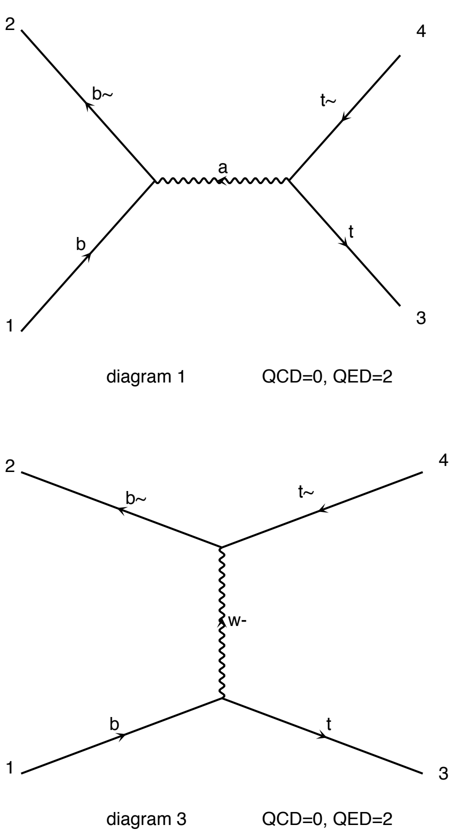


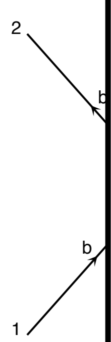

diagram 4 QCD=0, QED=2

# Example

## b b~ > t t~ QCD=0

**SM-no_b_mass** | **SM**

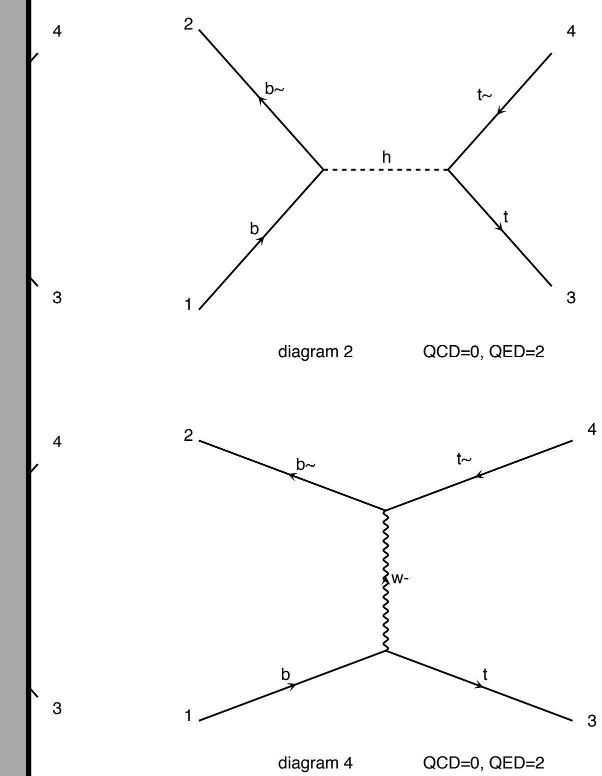



### restriction card:

```
####################################
## INFORMATION FOR MASS
####################################
Block MASS
```

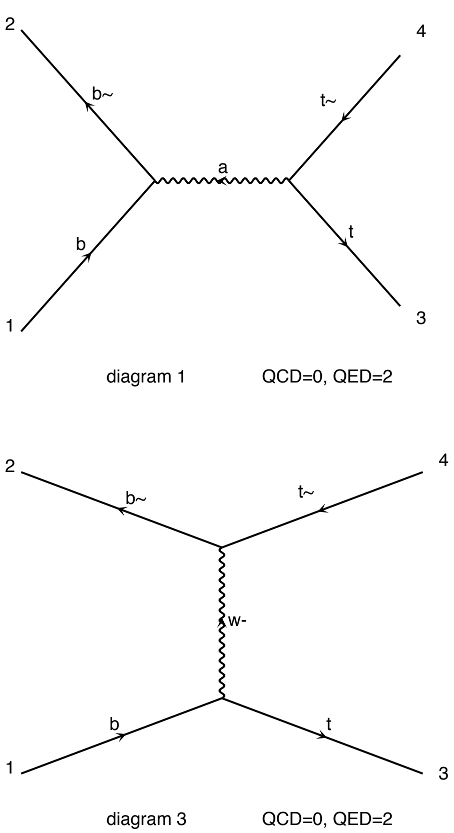
```
####################################
## INFORMATION FOR YUKAWA
####################################
Block YUKAWA
    4 0.000000e+00 # ymc
    5 0.000000e+00 # ymb
    6 1.645000e+02 # ymt
   11 0.000000e+00 # yme
   13 0.000000e+00 # ymm
   15 1.777000e+00 # ymtau
```

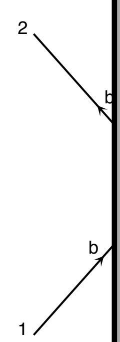


# Example

## b b~ > t t~ QCD=0

SM-no_b_mass | SM

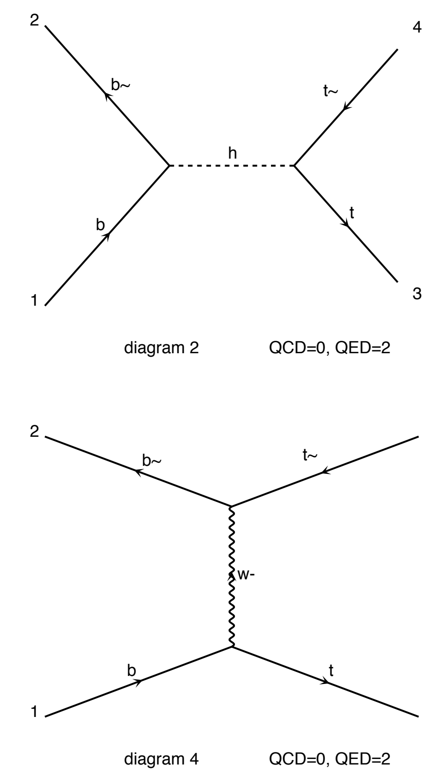


restriction card:

```
##################################
## INFORMATION FOR MASS
##################################
Block MASS
      4
      5
      6
     11
     13
     15
     23
     25
```

```
##################################
## INFORMATION FOR YUKAWA
##################################
Block YUKAWA
    4 0.000000e+00 # ymc
    5 0.000000e+00 # ymb
    6 1.645000e+02 # ymt
   11 0.000000e+00 # yme
   13 0.000000e+00 # ymm
   15 1.777000e+00 # ymtau
```



# Example

## b b~ > t t~ QCD=0

**SM-no_b_mass**

Param_card:

```
###################################
## INFORMATION FOR MASS
###################################
Block mass
    6 1.730000e+02 # MT
   15 1.777000e+00 # MTA
   23 9.118800e+01 # MZ
   25 1.200000e+02 # MH
##  Not dependent paramater.
## Those values should be edited fo
## analytical expression. MG5 ignor
## but they are important for inter
## to external program such as Pyth
  12 0.000000 # ve : 0.0
  14 0.000000 # vm : 0.0
  16 0.000000 # vt : 0.0
  2 0.000000 # u : 0.0
  4 0.000000 # c : 0.0
  1 0.000000 # d : 0.0
  3 0.000000 # s : 0.0
  5 0.000000 # b : 0.0
```

**SM**

Param_card:

```
###################################
## INFORMATION FOR MASS
###################################
Block mass
    5 4.700000e+00 # MB
    6 1.730000e+02 # MT
   15 1.777000e+00 # MTA
   23 9.118800e+01 # MZ
   25 1.200000e+02 # MH
##  Not dependent paramater.
## Those values should be edited fo
## analytical expression. MG5 ignor
## but they are important for inter
## to external program such as Pyth
  12 0.000000 # ve : 0.0
  14 0.000000 # vm : 0.0
  16 0.000000 # vt : 0.0
  2 0.000000 # u : 0.0
  4 0.000000 # c : 0.0
  1 0.000000 # d : 0.0
  3 0.000000 # s : 0.0
```

# Example

## b b~ > t t~ QCD=0

### SM-no_b_mass

Param_card:

```
####################################
## INFORMATION FOR MASS
####################################
Block mass
    6 1.730000e+02 # MT
   15 1.777000e+00 # MTA
   23 9.118800e+01 # MZ
   25 1.200000e+02 # MH
##  Not dependent paramater.
## Those values should be edited fo
## analytical expression. MG5 ignor
## but they are important for inter
## to external program such as Pyth
  12 0.000000 # ve : 0.0
  14 0.000000 # vm : 0.0
  16 0.000000 # vt : 0.0
  2 0.000000 # u : 0.0
  4 0.000000 # c : 0.0
  1 0.000000 # d : 0.0
  3 0.000000 # s : 0.0
  5 0.000000 # b : 0.0
```

### SM

Param_card:

```
####################################
## INFORMATION FOR MASS
####################################
Block mass
    5 4.700000e+00 # MB
    6 1.730000e+02 # MT
   15 1.777000e+00 # MTA
   23 9.118800e+01 # MZ
   25 1.200000e+02 # MH
##  Not dependent paramater.
## Those values should be edited fo
## analytical expression. MG5 ignor
## but they are important for inter
## to external program such as Pyth
  12 0.000000 # ve : 0.0
  14 0.000000 # vm : 0.0
  16 0.000000 # vt : 0.0
  2 0.000000 # u : 0.0
  4 0.000000 # c : 0.0
  1 0.000000 # d : 0.0
  3 0.000000 # s : 0.0
```

# Model too generic

## Solution III:

Examples: sm-ckm sm-lepton_masses sm-no_b_mass sm-no_masses sm-no_tau_mass sm-zeromass_ckm

- **Advantages**
  - ☞ Easy to implement for the final user
  - ☞ Quite optimal

# Model too generic

## Solution III:

**Examples:** sm-ckm sm-lepton_masses sm-no_b_mass sm-no_masses sm-no_tau_mass sm-zeromass_ckm

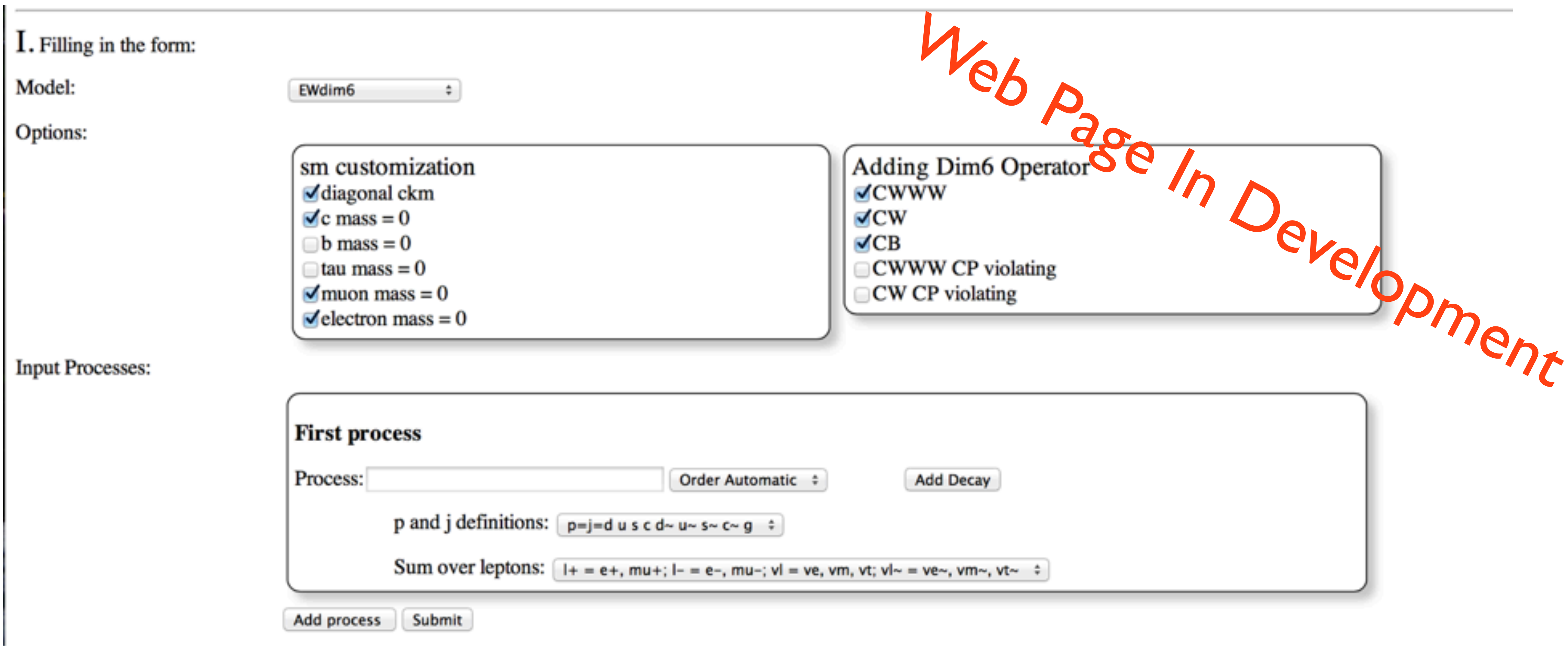
- **Advantages**
  - ☞ Easy to implement for the final user
  - ☞ Quite optimal

- **Drawbacks**
  - ☞ Potential accidental removal
  - ☞ The number of restriction card to cover all cases

# Model Too Generic

## Solution IV:

- Create your restriction card on the flight:



# Model Too Generic

## Solution IV:

- Create your restriction card on the flight:

```
mg5>customize_model
INFO: load particles
INFO: load vertices
sm customization:
    1: diagonal ckm [True]
    2: c mass = 0 [True]
    3: b mass = 0 [False]
    4: tau mass = 0 [False]
    5: muon mass = 0 [True]
    6: electron mass = 0 [True]
Adding Dim6 Operator:
    7: CWWW [True]
    8: CW [True]
    9: CB [True]
    10: CWWW CP violating [False]
    11: CW CP violating [False]
Enter a number to change it's status or press enter to validate [0, 1, 2, 3, 4, 5, 6, 7, 8, ... ][60s to answer]
```

Available Now!

This require some work of the model builder

- Require an additional file in UFO: build_restrict.py

```
import models.build_restriction_lib as build_restrict_lib
all_categories = []


first_category = build_restrict_lib.Category('sm customization')
all_categories.append(first_category)

first_category.add_options(name='diagonal ckm', # name
                           default=True,         # default
                           inverted_display=False,
                           rules=[('CKMBLOCK',[1], 0.0)],
                           )
```

initialisation

create category

options and insert value in the card

→ Not automatic ! But easy to write !

→ Allow a lot of freedom

MadGraph is here to help you!

# Conclusion

- We have the tools to make analysis
  ☞ Effective Lagrangians available (FR/MG)
- Dimension 6 operators are simple and powerful
  ☞ automatic gauge invariance
  ☞ unitarity
  ☞ guidance for experimentalist
- Dimension 6 operators can explain the data

# Order Restriction

- You can have up to ONE dimension six operator by diagram

$$\mathcal{M} = \mathcal{M}_{SM} + \frac{1}{\Lambda^2}\mathcal{M}_{one} + \frac{1}{\Lambda^4}\mathcal{M}_{two}$$

Equivalent to dimension 8 operator

# Order Restriction

- You can have up to ONE dimension six operator by diagram

```
NP = CouplingOrder(name = 'NP',
                   expansion_order = 2,
                   hierarchy = 1)

QCD = CouplingOrder(name = 'QCD',
                    expansion_order = 99,
                    hierarchy = 1)

QED = CouplingOrder(name = 'QED',
                    expansion_order = 99,
                    hierarchy = 2)
```

# Order Restriction

- You can have up to ONE dimension six operator by diagram

UFO File: coupling_order

```
NP = CouplingOrder(name = 'NP',
                   expansion_order = 2,
                   hierarchy = 1)

QCD = CouplingOrder(name = 'QCD',
                    expansion_order = 99,
                    hierarchy = 1)

QED = CouplingOrder(name = 'QED',
                    expansion_order = 99,
                    hierarchy = 2)
```

Maximal order allowed

# Three Gauge Couplings
## Comparison with Anomalous Coupling

# SM Processes

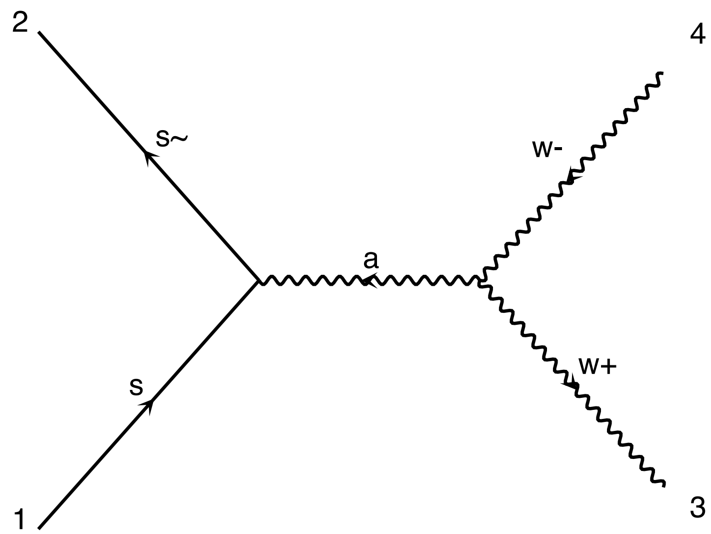



diagram 1 QCD=0, QED=2

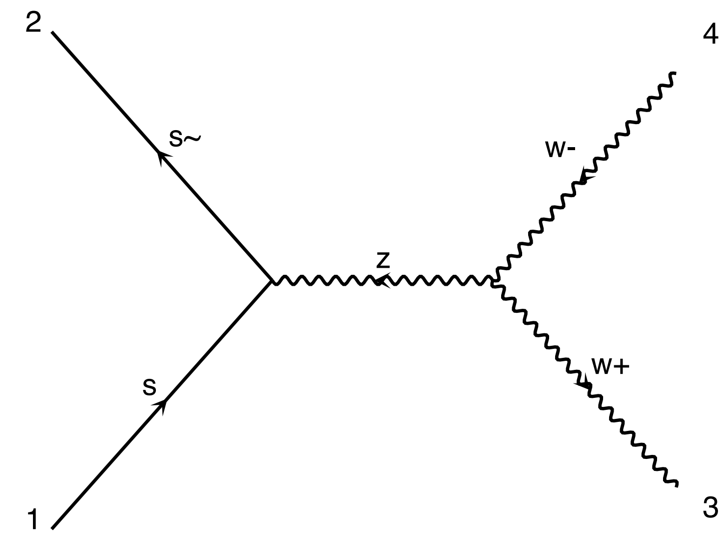



diagram 2 QCD=0, QED=2

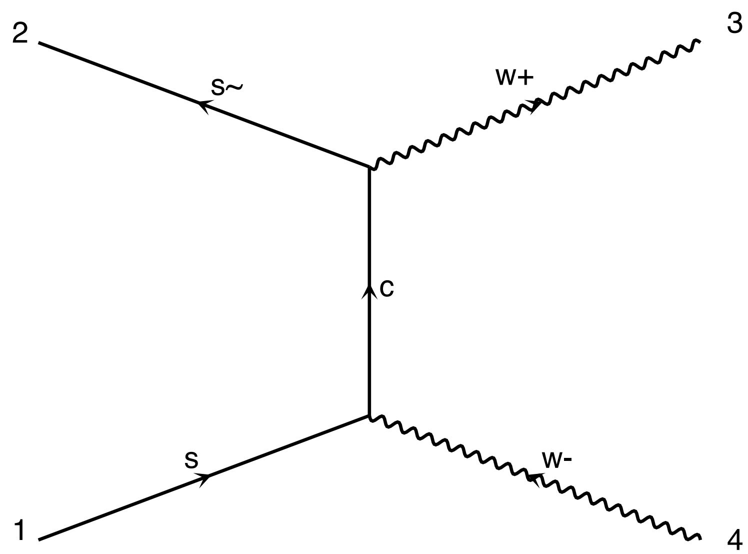



diagram 3 QCD=0, QED=2

# Operator Affecting those processes

- We don't consider Operator with quark
  ☞ Not the best processes to study those

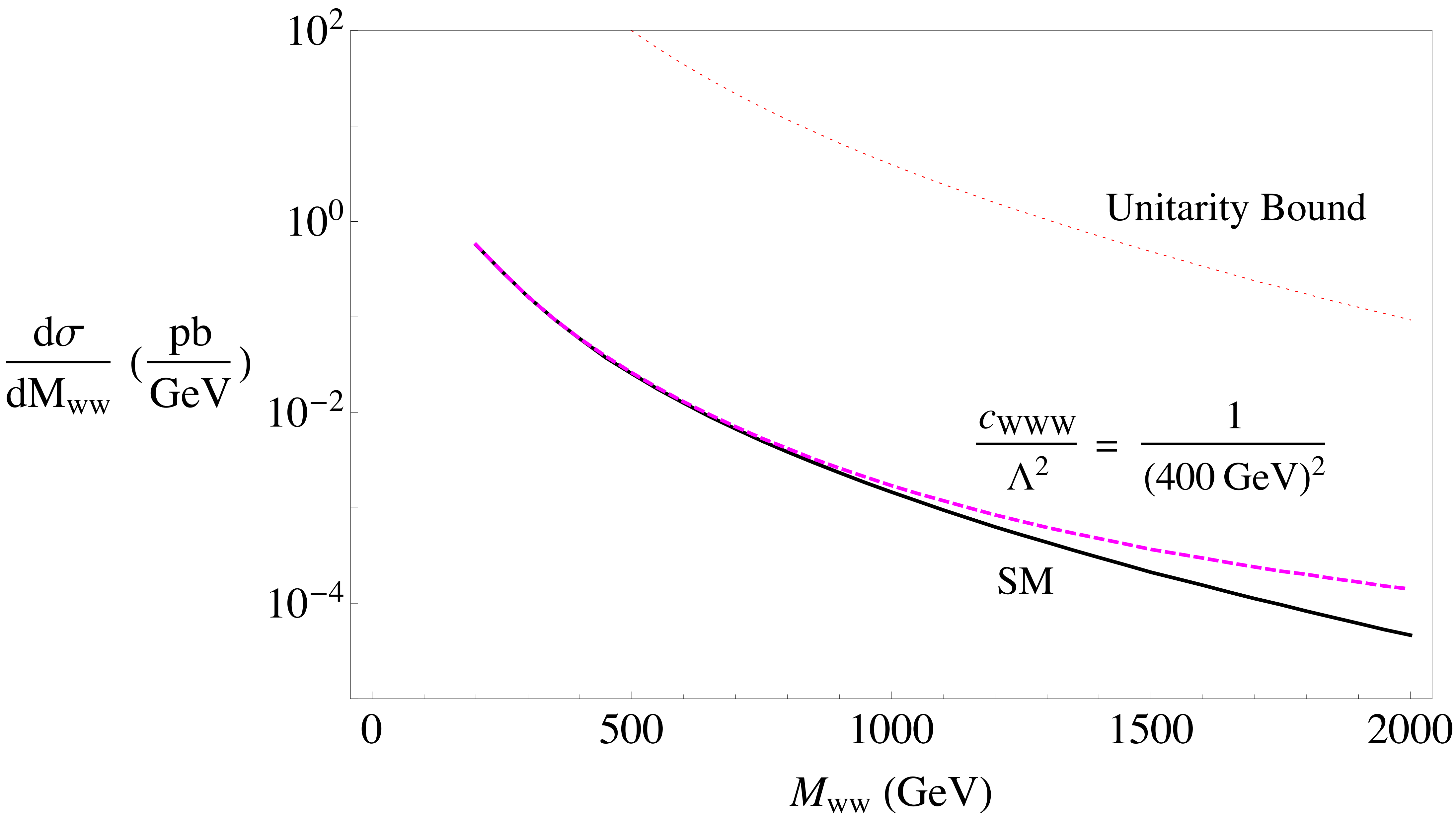
## Conserving CP

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_\rho^\mu]$$
$$\mathcal{O}_W = (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)$$
$$\mathcal{O}_B = (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)$$

## Not Conserving CP

$$\mathcal{O}_{\tilde{W}WW} = \mathrm{Tr}[\tilde{W}_{\mu\nu}W^{\nu\rho}W_\rho^\mu]$$
$$\mathcal{O}_{\tilde{W}} = (D_\mu\Phi)^\dagger \tilde{W}^{\mu\nu}(D_\nu\Phi)$$

# Unitarity


$10^2$
$10^0$
$10^{-2}$
$10^{-4}$
$\frac{d\sigma}{dM_{ww}} \left(\frac{pb}{GeV}\right)$
Unitarity Bound
$\frac{c_{WWW}}{\Lambda^2} = \frac{1}{(400\ GeV)^2}$
SM
0
500
1000
1500
2000
$M_{ww}$ (GeV)

# Comparison with Anomalous Coupling

$$\mathcal{L} = ig_{WWV}\Big(g_1^V(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2}W^{\nu+}_\mu W^{-\rho}_\nu V^\mu_\rho$$
$$+ig_4^V W^+_\mu W^-_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu) - ig_5^V\epsilon^{\mu\nu\rho\sigma}(W^+_\mu \partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu)V_\sigma$$
$$+\tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{m_W^2}W^{\nu+}_\mu W^{-\rho}_\nu \tilde{V}^\mu_\rho\Big)$$

- This is not Gauge Invariant
- No New Physics scale
- No Suppression : Dimension 4 and 6 but also 8 or more if extra derivatives are added
- Breaking unitarity
- Not valid loop description

# Link between the two

$$
\begin{aligned}
g_1^Z &= 1 + c_W \frac{m_Z^2}{2\Lambda^2} \\
\kappa_\gamma &= 1 + (c_W + c_B)\frac{m_W^2}{2\Lambda^2} \\
\kappa_Z &= 1 + (c_W - c_B \tan^2\theta_W)\frac{m_W^2}{2\Lambda^2} \\
\lambda_\gamma &= \lambda_Z = c_{WWW}\frac{3g^2 m_W^2}{2\Lambda^2} \\
g_4^V &= g_5^V = 0 \\
\tilde{\kappa}_\gamma &= c_{\tilde{W}}\frac{m_W^2}{2\Lambda^2} \\
\tilde{\kappa}_Z &= -c_{\tilde{W}} \tan^2\theta_W \frac{m_W^2}{2\Lambda^2} \\
\tilde{\lambda}_\gamma &= \tilde{\lambda}_Z = c_{\tilde{W}WW}\frac{3g^2 m_W^2}{2\Lambda^2}
\end{aligned}
$$

- Gauge Invariance
- New Scale Suppression

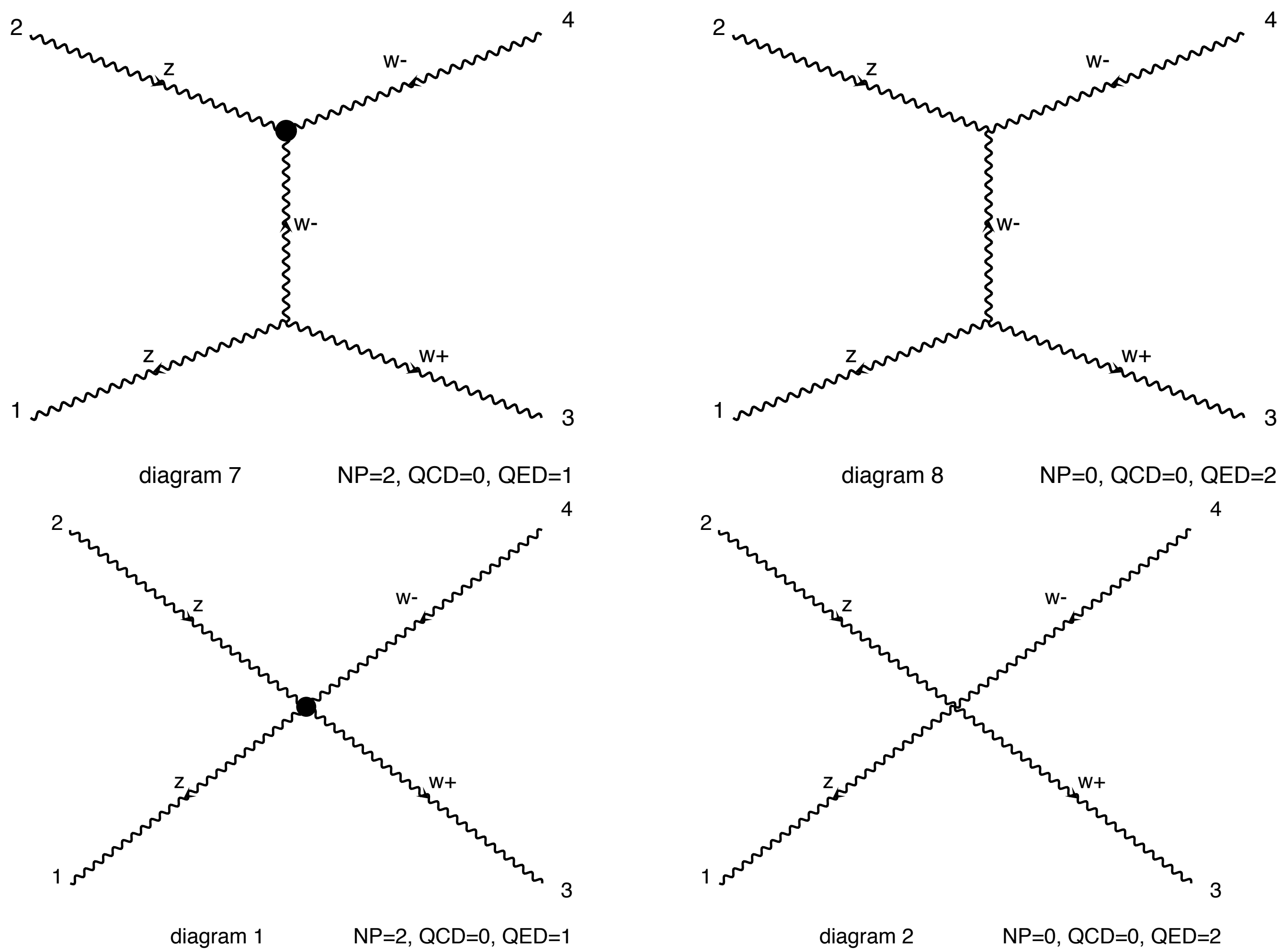
$$\Delta g_1^Z = \Delta\kappa_Z + \tan^2\theta_W \Delta\kappa_\gamma$$

$$0 = \tilde{\kappa}_Z + \tan^2\theta_W \tilde{\kappa}_\gamma$$

☞ Provide Guidance

# High multiplicity

- Automatic gauge invariance.
  - z z > w+ w-




No Additional couplings

7 other diagrams