

# FeynRules

# MadGraph5\_aMC@NLO

Celine Degrande / Olivier Mattelaer  
IPPP/Durham

## FeynRules



- create a MC Model from a Lagrangian
- Mathematica code
- not in the virtual machine

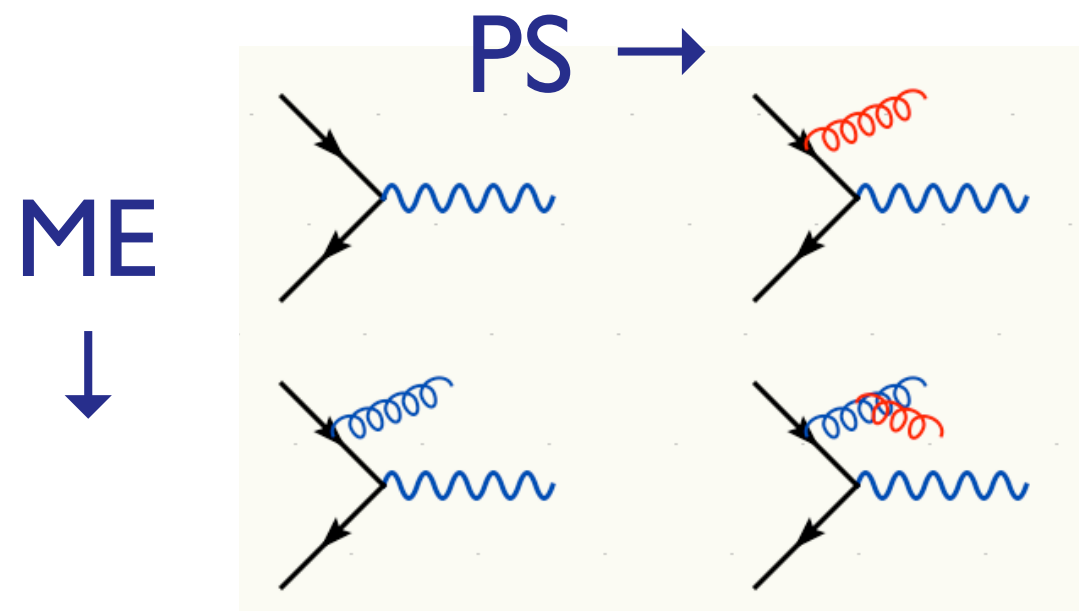
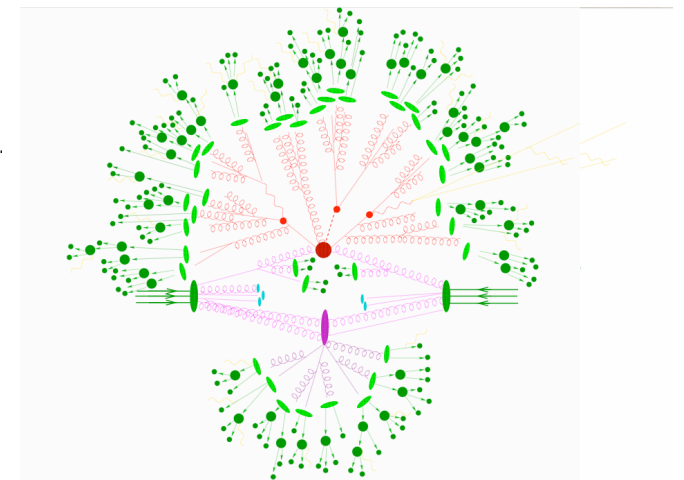
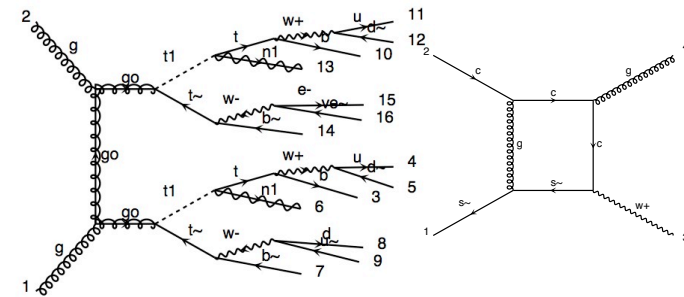
## MG5\_aMC



- generation of events for (close to) any model/process
- LO or NLO QCD precision
- in the virtual machine

# Type of generation

	Tree (B)SM	NLO (QCD) (SM)	NLO (QCD) (BSM)	NLO (EW) (SM)	Loop Induced (B)SM
<b>Fix Order</b>	✓	✓	✓	✓	✓
<b>+Parton Shower</b>	✓	✓	✓	✗	✓
<b>Merged Sample</b>	✓	✓	?	✗	✓



# List of package

- SysCalc (computation of systematics)
- MadWidth (computation of width in NWA)
- MadSpin (decay with full spin-correlation)
- Re-Weighting (change of the weight of an event)
- Shower / Detector Interface
- MadWeight (Matrix-Element Method)
- Interference
- MadAnalysis5
- Tau Decay
- MadDM
- GPU

# MG Tutorial

Olivier Mattelaer  
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## Learning MG5

- follow the built-in tutorial
- cards meaning
- meaning of QCD/QED
- details of syntax (\$/)
- script
- width computation
- decay chain

Detailed solution at the end of this PDF!

## BSM CASE

- generate the model
  - if you have mathematica
- check the model
- width computation
- signal generation
  - decay chain
- merging sample generation
- background/NLO

# Learning MG5\_aMC

- Ask Celine/Olivier
- Use the command “help” / “help XXX”
  - ➔ “help” tell you the next command that you need to do.
- Launchpad:
  - ➔ <https://answers.launchpad.net/madgraph5>
  - ➔ FAQ: <https://answers.launchpad.net/madgraph5/+faq>



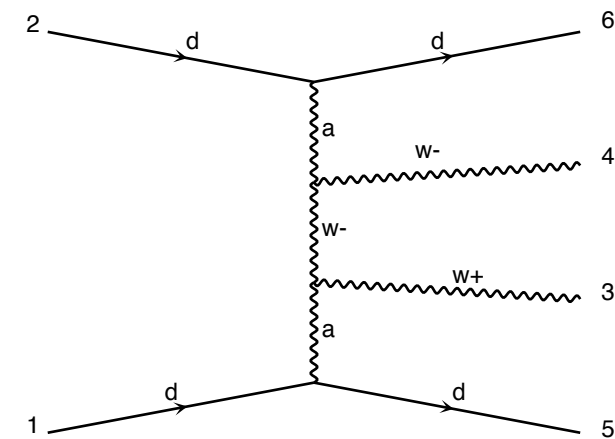
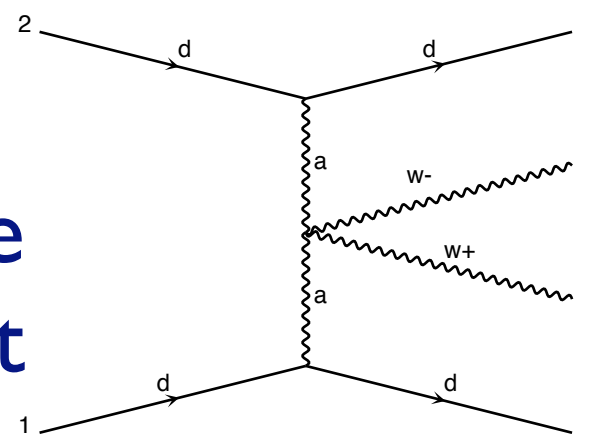
- Read the Cards and identify what they do
  - ➔ **param\_card**: model parameters
  - ➔ **run\_card**: beam/run parameters and cuts
    - ◆ <https://answers.launchpad.net/madgraph5/+faq/2014>

- How do you change
  - ➔ top mass
  - ➔ top width
  - ➔ W mass
  - ➔ beam energy
  - ➔ pt cut on the lepton

- Learn**
- What's the meaning of the order QED/QCD
  - What's the difference between
    - $p p \rightarrow t t^{\sim}$
    - $p p \rightarrow t t^{\sim} \text{ QED}=2$
    - $p p \rightarrow t t^{\sim} \text{ QED}=0$
    - $p p \rightarrow t t^{\sim} \text{ QCD}=0$
    - $p p \rightarrow t t^{\sim} \text{ QED}\leq 2$
    - $p p \rightarrow t t^{\sim} \text{ QCD}^2=2$
  - Compute the cross-section for each of those and check the diagram

## Check

- Generate VBF process
- check that you have the diagram that you want
- do not compute cross-section!!



- Generate the cross-section and the distribution (invariant mass) for

→  $p p \rightarrow e^+ e^-$

→  $p p \rightarrow z, z \rightarrow e^+ e^-$

→  $p p \rightarrow e^+ e^- \oplus z$

→  $p p \rightarrow e^+ e^- / z$

**Hint** :To plot automatically distributions:  
`mg5> install MadAnalysis`

- Use the invariant mass distribution to determine the meaning of each syntax.

# Exercise IV: Automation/Width

- Compute the cross-section for the top pair production for 3 different mass points.
  - ➔ Do **NOT** use the interactive interface
    - ✦ **hint:** you can edit the param\_card/run\_card via the “set” command [**After** the launch]
    - ✦ **hint:** All command [including answer to question] can be put in a file. (run ./bin/mg5 PATH\_TO\_FILE)
  - ➔ Remember to change the value of the width
    - ✦ “set width 6 Auto” works
    - ✦ cross-check that it indeed returns the correct width

## Examples

File:

```
import model EWDim6
generate p p > z z
output TUTO_DIM6
launch
set nevents 5000
set MZ 100
```

How to Run: `./bin/mg5_amc PATH`

- Generate  $p p \rightarrow t \bar{t} h$ , fully decayed (fully leptonic decay for the top)
  - ➔ Using the decay-chain formalism
  - ➔ Using MadSpin
- Compare cross-section
  - ➔ which one is the correct one?
  - ➔ Why are they different?
- Compare the shape.

# BSM Tutorial

- Check the model validity:

- ➔ check  $p p \rightarrow uv \, uv^{\sim}$
- ➔ check  $p p \rightarrow ev \, ev^{\sim}$
- ➔ check  $p p \rightarrow t \, t^{\sim} p_1 \, p_2$
- ➔ ...

- This checks

- ➔ gauge invariance
- ➔ lorentz invariance
- ➔ that various way to compute the matrix element provides the same answer



- Check with MG the width computed with FR:

- ➔ generate uv > all all; output; launch
- ➔ generate ev > all all; output; launch
- ➔ generate p1 > all all; output; launch
- ➔ generate p2 > all all; output; launch

FR Number

0.2205 GeV

0.01490 GeV

0 GeV

0.06712 GeV

- Check with MadWidth

- ➔ compute\_widths uv ev p1 p2
- ➔ (or Auto in the param card)

- $M_{uv} = 400 \text{ GeV}$      $M_{ev} = 50 \text{ GeV}$      $\lambda=0.1$

- $m_1 = 1 \text{ GeV}$      $m_2 = 100 \text{ GeV}$      $m_{12} = 0.5 \text{ GeV}$

- Compute cross-section and distribution
  - ➔ uv pair production with decay in top and  $\Phi_1/\Phi_2$  (semi leptonic decay for the top)
- **Hint:** The width of the new physics particles has to be set correctly in the param\_card.
  - ➔ You can either use “Auto” arXiv:1402.1178
  - ➔ or use the value computed in exercise 1
- **Hint:** For sub-decay, you have to put parenthesis:
  - ➔ example:  

$$p\ p > t\ t^{\sim} w^+, (t > w^+ b, w^+ > e^+ \nu_e), (t^{\sim} > b^{\sim} w^-, w^- > j\ j), w^+ > l^+ \nu_l$$



- Use MadSpin!
  - ➔ Use Narrow Width Approximation to **factorize** production and decay
- instead of
  - ➔  $p p \rightarrow t \bar{t} w^+, (t \rightarrow w^+ b, w^+ \rightarrow e^+ \nu_e), (\bar{t} \rightarrow b \bar{\nu} w^-, w^- \rightarrow j \bar{j}), w^+ \rightarrow l^+ \nu_l$
- Do
  - ➔  $p p \rightarrow t \bar{t} w^+$

- At the question:

The following switches determine which programs are run:

1 Run the pythia shower/hadronization:	pythia=OFF
2 Run PGS as detector simulator:	pgs=OFF
3 Run Delphes as detector simulator:	delphes=NOT INSTALLED
4 Decay particles with the MadSpin module:	madspin=OFF
5 Add weight to events based on coupling parameters:	reweight=OFF

Either type the switch number (1 to 5) to change its default setting, or set any switch explicitly (e.g. type 'madspin=ON' at the prompt)

Type '0', 'auto', 'done' or just press enter when you are done.

[0, 1, 2, 4, 5, auto, done, pythia=ON, pythia=OFF, ... ][60s to answer]

- At the next question edit the madspin\_card and define the decay

- Generate at NLO precision
  - ➔  $p p \rightarrow u \bar{v} u \bar{v} \sim$  [QCD]
  - ➔ Compute the K-factor
    - ✦ you can run the LO run from the NLO generation which ensure that you have the same setup
    - ✦ you do not need to generate events
  - ➔ Compare some key distribution
- You need to specify the shower before showering the events (even if you ask MG to not shower them) Why?

# Exercise IV: generate multiple multiplicity sample for pythia8

- We will do MLM matching
  - ➔ in the run\_card.dat ickkw=1
  - ➔ the matching scale ( $Q_{\text{cut}}$ ) will be define in pythia
    - ◆ in madgraph we use xqcut which should be smaller than  $Q_{\text{cut}}$  (but at least 10-20 GeV)

# Solution Learning MG5\_aMC

- How do you change

- ➔ top mass
- ➔ top width
- ➔ W mass
- ➔ beam energy
- ➔ pt cut on the lepton



Param\_card

Run\_card

- top mass

```
#####
## INFORMATION FOR MASS
#####
Block mass
6 1.730000e+02 # MT
23 9.118800e+01 # MZ
25 1.200000e+02 # MH
## Dependent parameters, given by model restrictions.
## Those values should be edited following the
## analytical expression. MG5 ignores those values
## but they are important for interfacing the output of MG5
## to external program such as Pythia.
1 0.000000 # d : 0.0
2 0.000000 # u : 0.0
3 0.000000 # s : 0.0
4 0.000000 # c : 0.0
11 0.000000 # e- : 0.0
12 0.000000 # ve : 0.0
13 0.000000 # mu- : 0.0
14 0.000000 # vm : 0.0
16 0.000000 # vt : 0.0
21 0.000000 # g : 0.0
22 0.000000 # a : 0.0
24 80.419002 # w+ : cmath.sqrt(MZ__exp__2/2. + cmath.sqrt(MZ__exp__4/4. - (aEW*cmath.pi*MZ__exp__2)/(Gf*sqrt__2)))
```



- W mass

```
#####
## 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
## Dependent parameters, given by model restrictions.
## Those values should be edited following the
## analytical expression. MG5 ignores those values
## but they are important for interfacing the output of MG5
## to external program such as Pythia.
 1 0.000000 # d : 0.0
 2 0.000000 # u : 0.0
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 4 0.000000 # c : 0.0
11 0.000000 # e- : 0.0
12 0.000000 # ve : 0.0
13 0.000000 # mu- : 0.0
14 0.000000 # vm : 0.0
16 0.000000 # vt : 0.0
21 0.000000 # g : 0.0
22 0.000000 #
24 80.419002 # w+ : cmath.sqrt(MZ__exp__2/2. + cmath.sqrt(MZ__exp__4/4. - (aEW*cmath.pi*MZ__exp__2)/(Gf*sqrt__2)))
```

W Mass is an internal parameter!

**MG5 didn't use this value!**

So you need to change MZ or Gf or alpha\_EW

- What's the meaning of the order QED/QCD
- What's the difference between
  - ➔  $p p \rightarrow t \bar{t}$
  - ➔  $p p \rightarrow t \bar{t} \text{ QED}=2$
  - ➔  $p p \rightarrow t \bar{t} \text{ QED}=0$
  - ➔  $p p \rightarrow t \bar{t} \text{ QCD}^2=2$

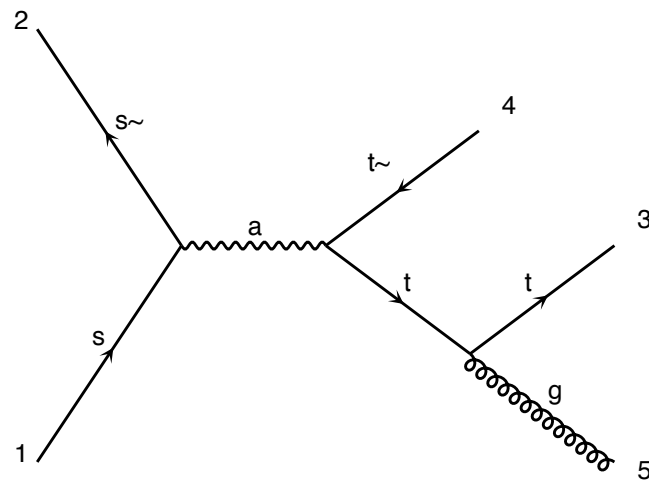
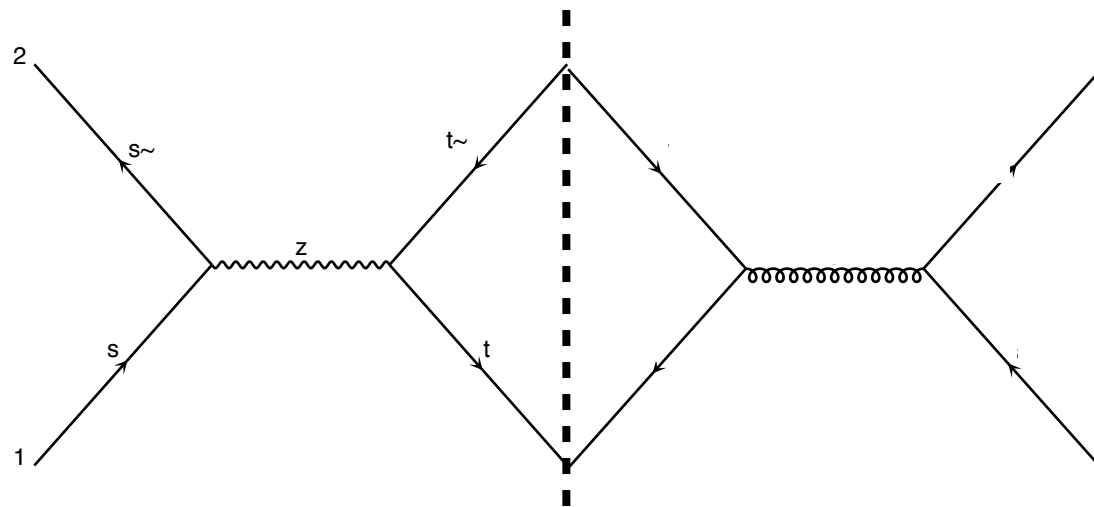


diagram 4

QCD=1, QED=2

QED/QCD are  
coupling restriction at  
the amplitude level



$\text{QED}^2/\text{QCD}^2$  are  
coupling restriction at  
the amplitude Square  
level

- $\text{QED} \leq 2$  is the SAME as  $\text{QED} = 2$
- $==$  means exactly equal to (only available for  $^2$ )

- If no order specify:
  - ➔ MG5 takes the **lowest order in QED!**
  - ➔  $p p \rightarrow t \bar{t}$  is equivalent to  $p p \rightarrow t \bar{t}$  **QED=0**
  - ➔ the default miss QED diagram. Carefull if they are important (like VBF)

$p p \rightarrow t \bar{t}$

**Cross section (pb)**

$555 \pm 0.84$

$p p \rightarrow t \bar{t}$  QED=2

**Cross section (pb)**

$555.8 \pm 0.91$

**No significant QED contribution**

$p p \rightarrow t \bar{t}$  QED<sup>2</sup>=2  
interference term

**Cross section (pb)**

$5.455e-17 \pm 4.7e-19 \pm \text{systematics}$

- What do you expect when doing:
  - ➔ generate  $p p > w^+ w^- j j$
- typical use of this process are for VBF search
  - ➔ interest in the QED only diagram

- In MG, the default syntax:
  - ➔ generate  $p p > w^+ w^- j j$
- is equivalent to
  - ➔ generate  $p p > w^+ w^- j j \text{ QED} \leq 2$
- **NO VBF diagram generated** (those are QED=4)

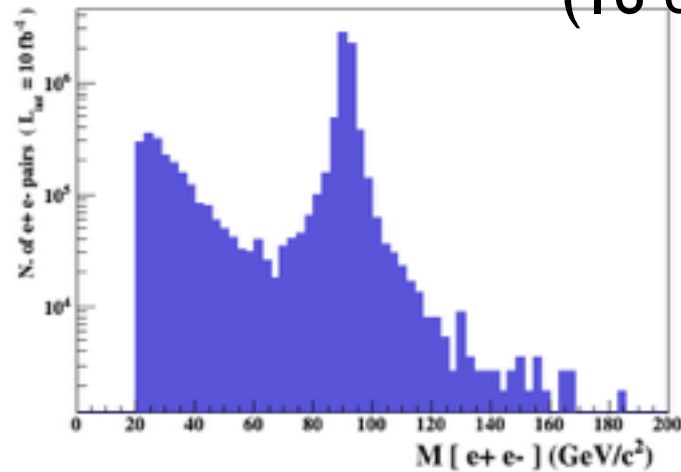
- So you **need to** generate
  - ➔ generate  $p p > w^+ w^- j j \text{ QED} \leq 4$ 
    - ➔ signal + QCD
  - ➔ generate  $p p > w^+ w^- j j \text{ QCD} = 0$ 
    - ➔ signal only

## Exercise IV: Syntax

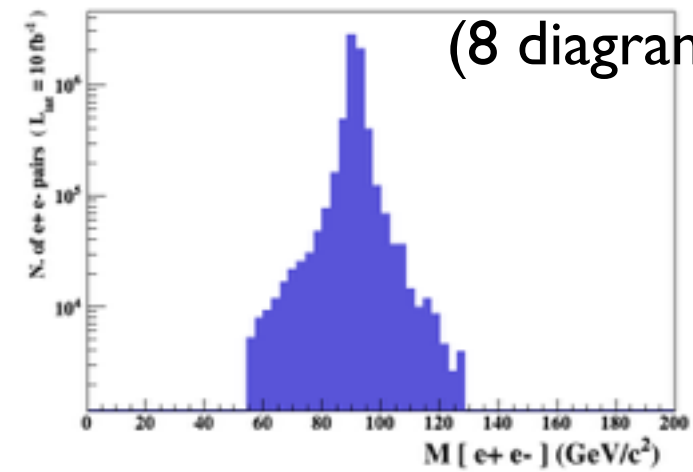
- Generate the cross-section and the distribution (invariant mass) for
  - ➔  $p p \rightarrow e^+ e^-$
  - ➔  $p p \rightarrow z, z \rightarrow e^+ e^-$
  - ➔  $p p \rightarrow e^+ e^- \text{ } \$ z$
  - ➔  $p p \rightarrow e^+ e^- / z$

**Hint** :To have automatic distributions:  
`mg5> install MadAnalysis`

$p p \rightarrow e^+ e^-$   
(16 diagrams)

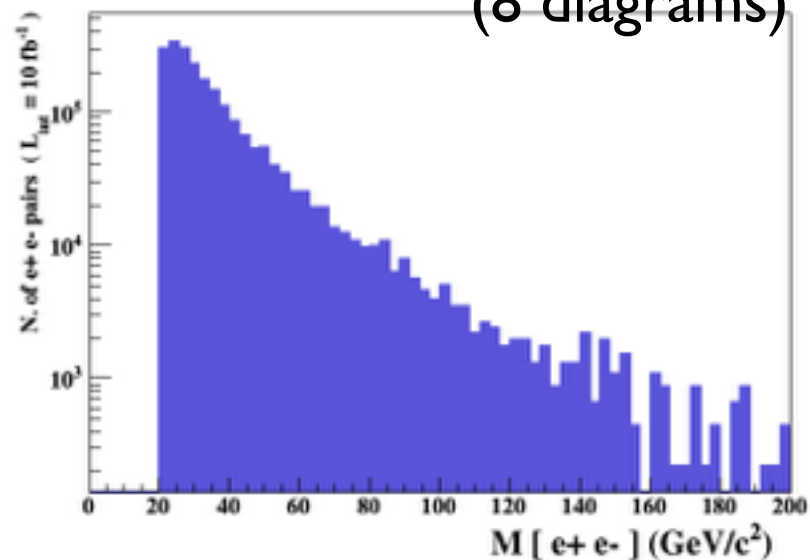


$p p \rightarrow z, z \rightarrow e^+ e^-$   
(8 diagrams)



$p p \rightarrow e^+ e^- / z$

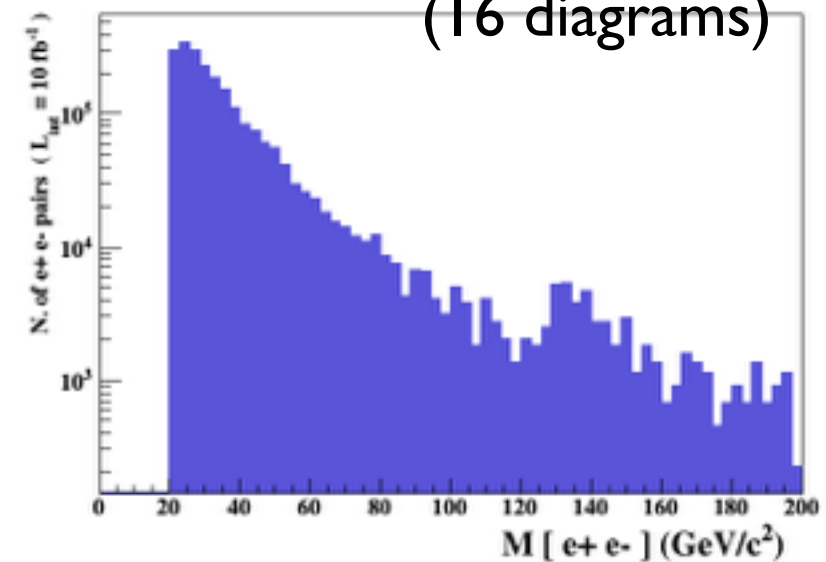
(8 diagrams)



No Z

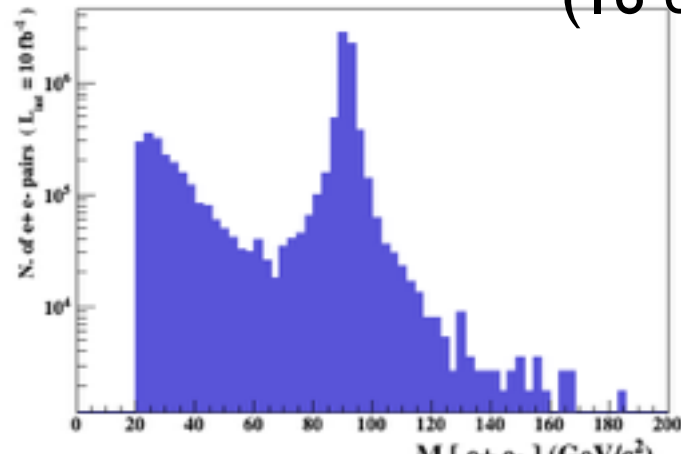
$p p \rightarrow e^+ e^- + z$

(16 diagrams)



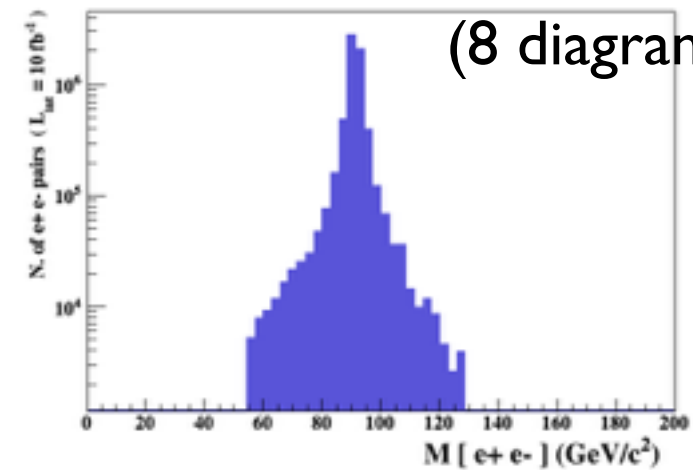
Z- onshell veto

$p p \rightarrow e^+ e^-$   
(16 diagrams)



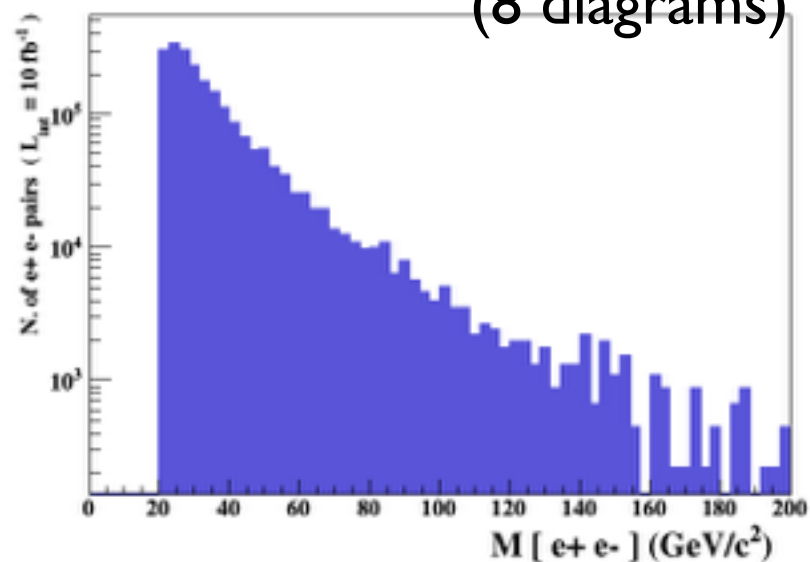
Correct Distribution

$p p \rightarrow z, z \rightarrow e^+ e^-$   
(8 diagrams)



$p p \rightarrow e^+ e^- / z$

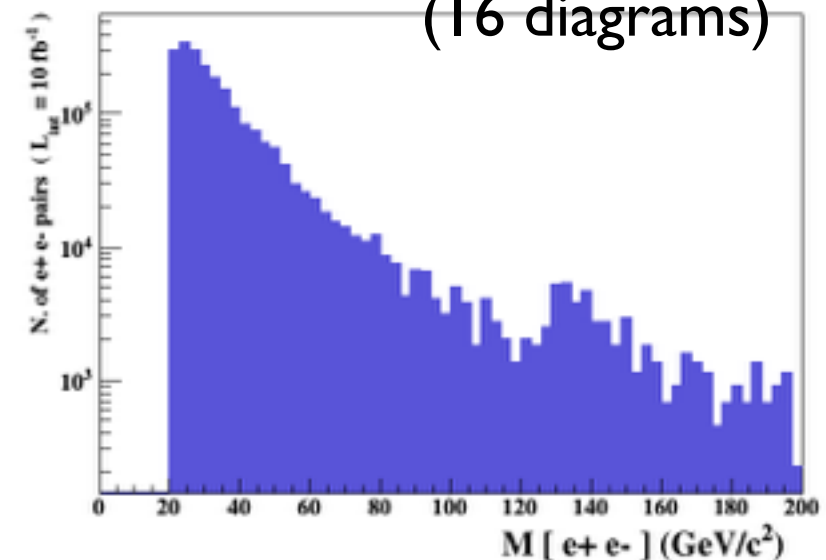
(8 diagrams)



No Z

$p p \rightarrow e^+ e^- \& z$

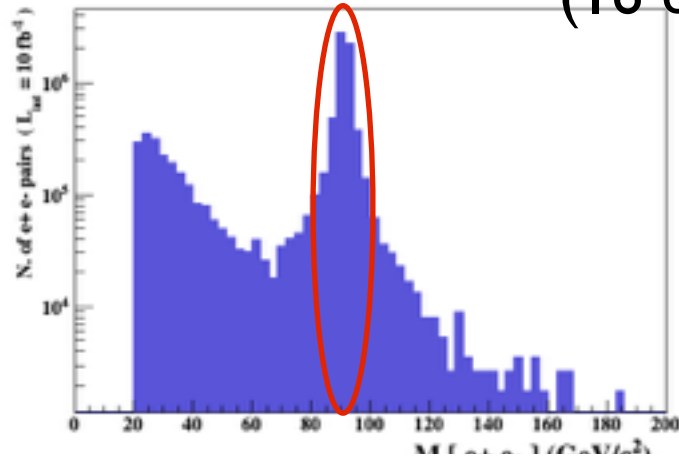
(16 diagrams)



Z- onshell veto



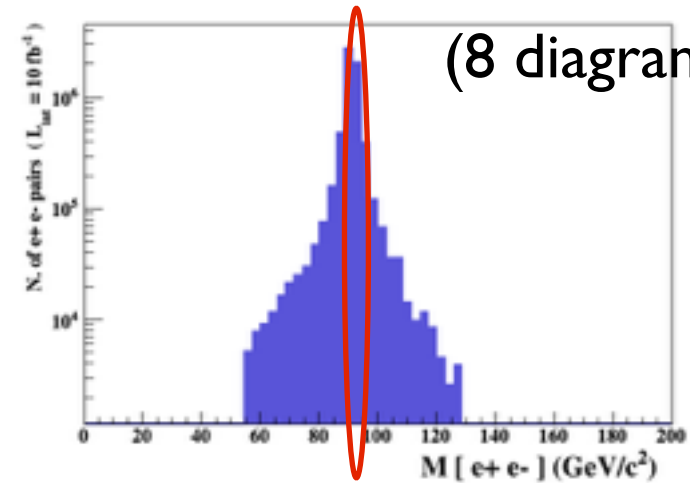
$p p \rightarrow e^+ e^-$   
(16 diagrams)



Correct Distribution

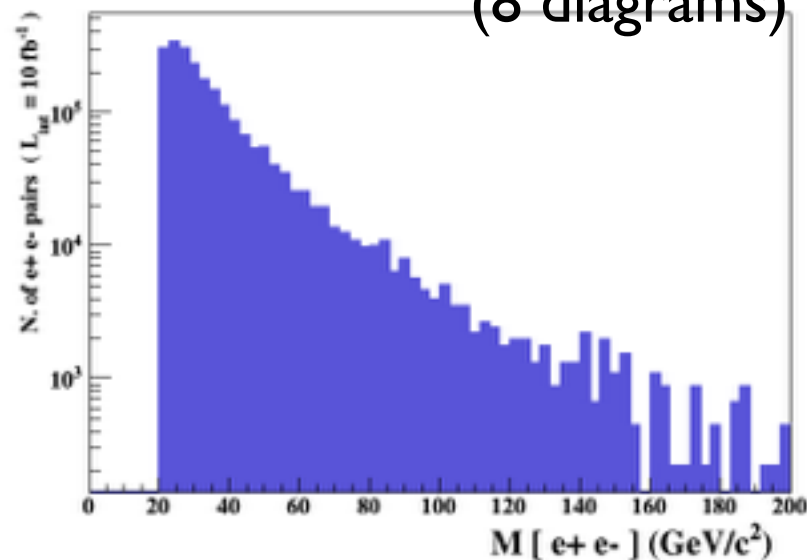
Z Peak

$p p \rightarrow z, z \rightarrow e^+ e^-$   
(8 diagrams)



$p p \rightarrow e^+ e^- / z$

(8 diagrams)

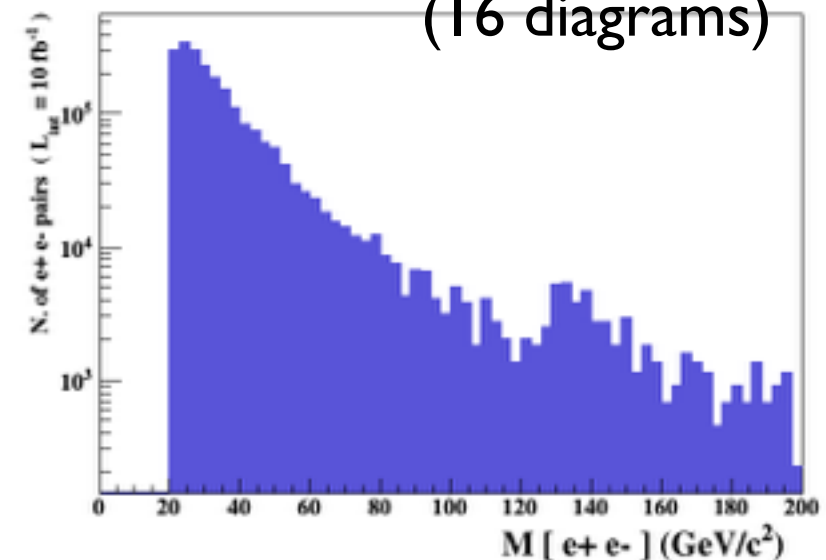


No Z

NO Z Peak

$p p \rightarrow e^+ e^- \cancel{z}$

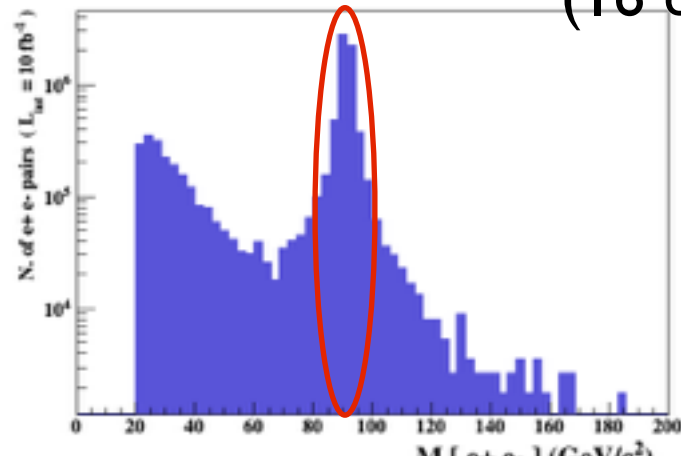
(16 diagrams)



Z- onshell veto

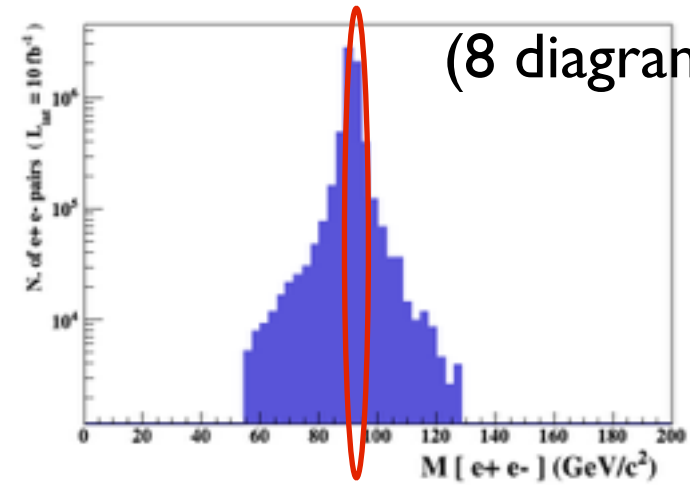
$p p \rightarrow e^+ e^-$   
(16 diagrams)

**Z Peak**



**Correct Distribution**

$p p \rightarrow z, z \rightarrow e^+ e^-$   
(8 diagrams)

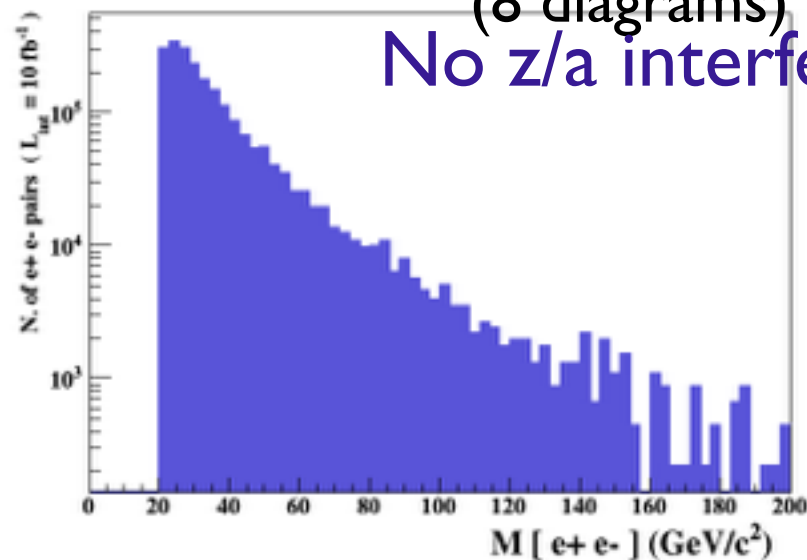


$p p \rightarrow e^+ e^- / z$

$p p \rightarrow e^+ e^- \text{ } \$ z$

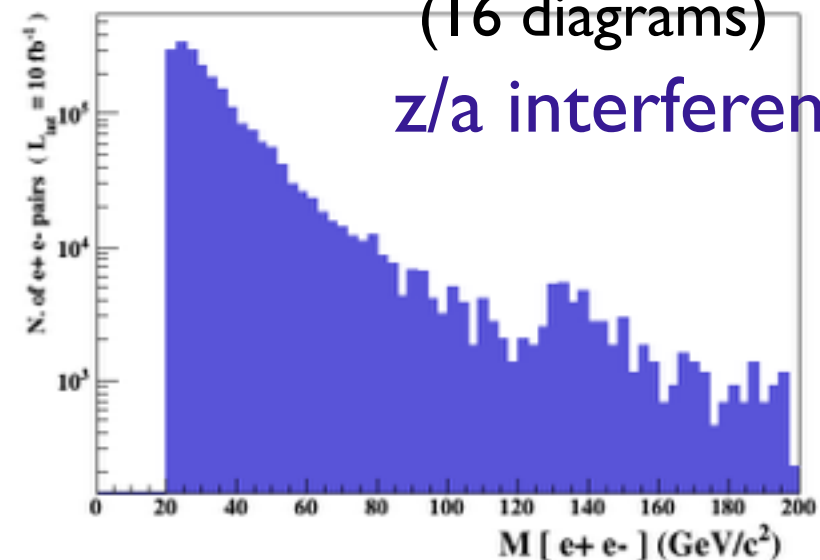
(8 diagrams)  
No  $z/\alpha$  interference

**NO Z Peak**



**No Z**

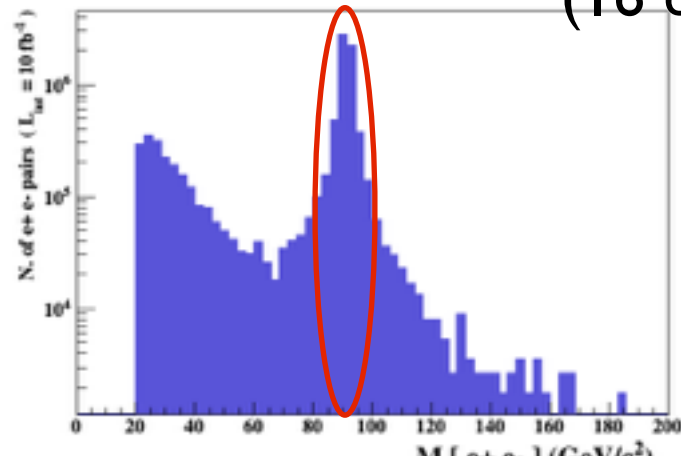
(16 diagrams)  
 $z/\alpha$  interference



**Z- onshell veto**

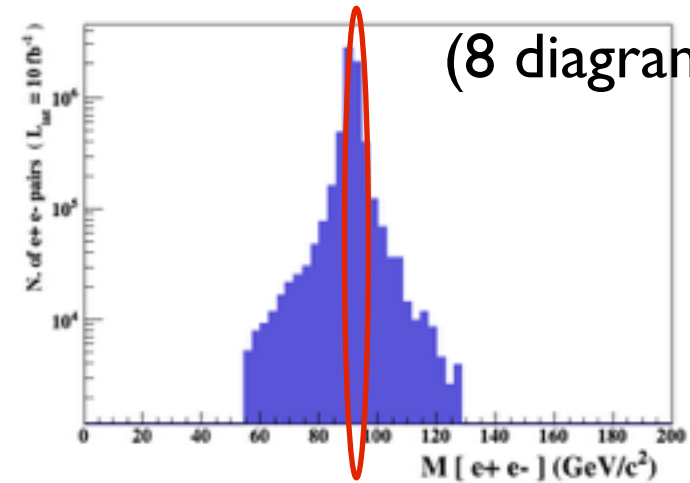
$p p \rightarrow e^+ e^-$   
(16 diagrams)

**Z Peak**



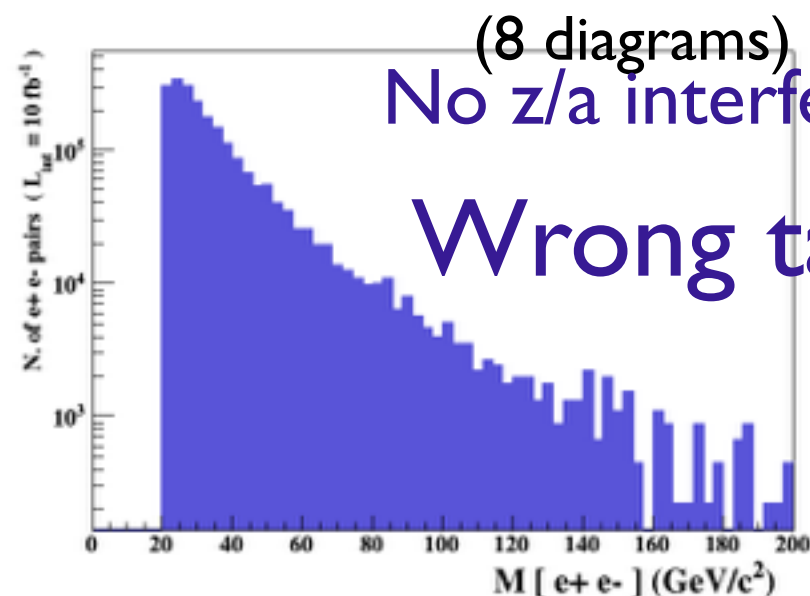
**Correct Distribution**

$p p \rightarrow z, z \rightarrow e^+ e^-$   
(8 diagrams)



$p p \rightarrow e^+ e^- / z$

$p p \rightarrow e^+ e^- \text{ } z$

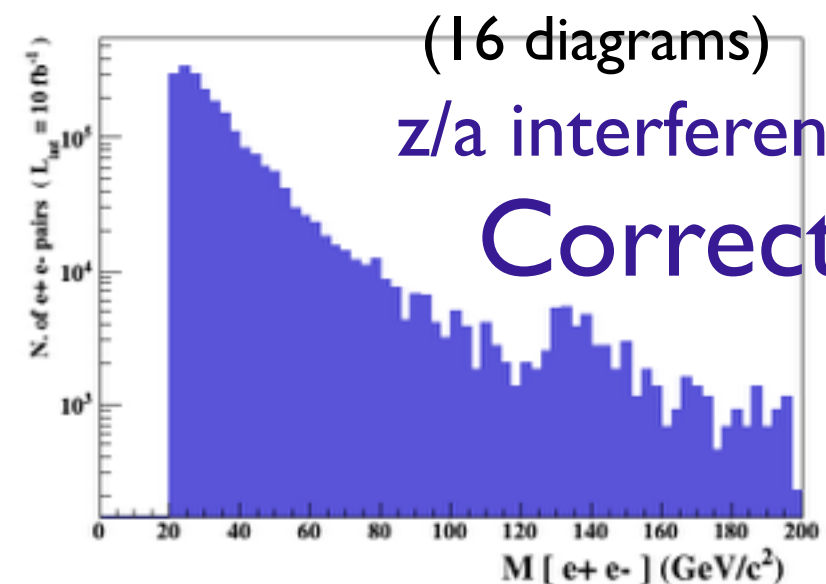


**NO Z Peak**

No z/a interference

**Wrong tail**

**No Z**



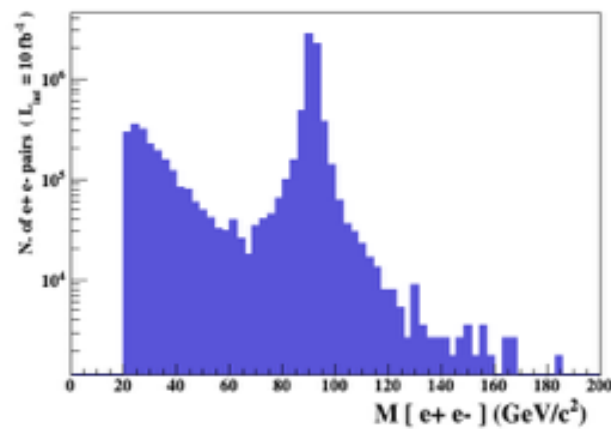
**Correct tail**

**Z- onshell veto**

$p p \rightarrow e^+ e^-$

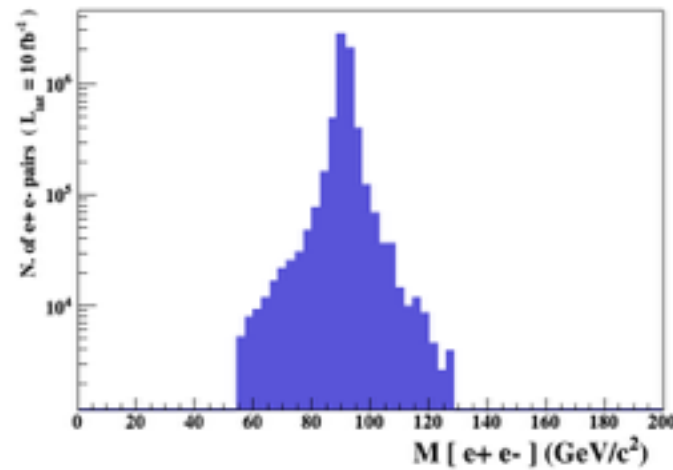
$p p \rightarrow Z, Z \rightarrow e^+ e^-$

$p p \rightarrow e^+ e^- \$ Z$



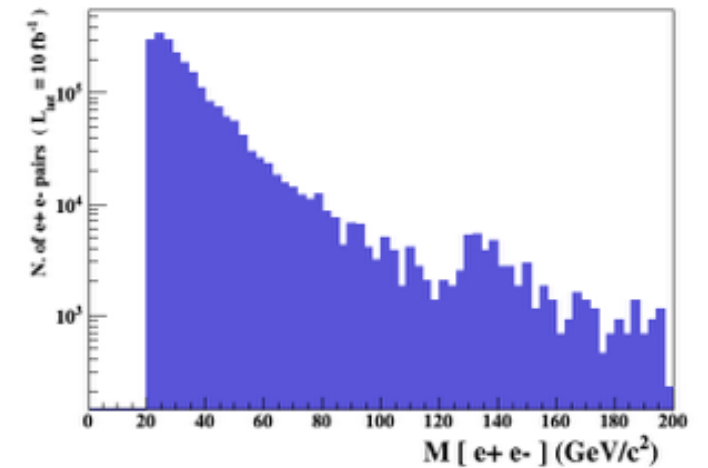
(16 diagrams)

=



(8 diagrams)

+



(16 diagrams)

Onshell cut: BW\_cut

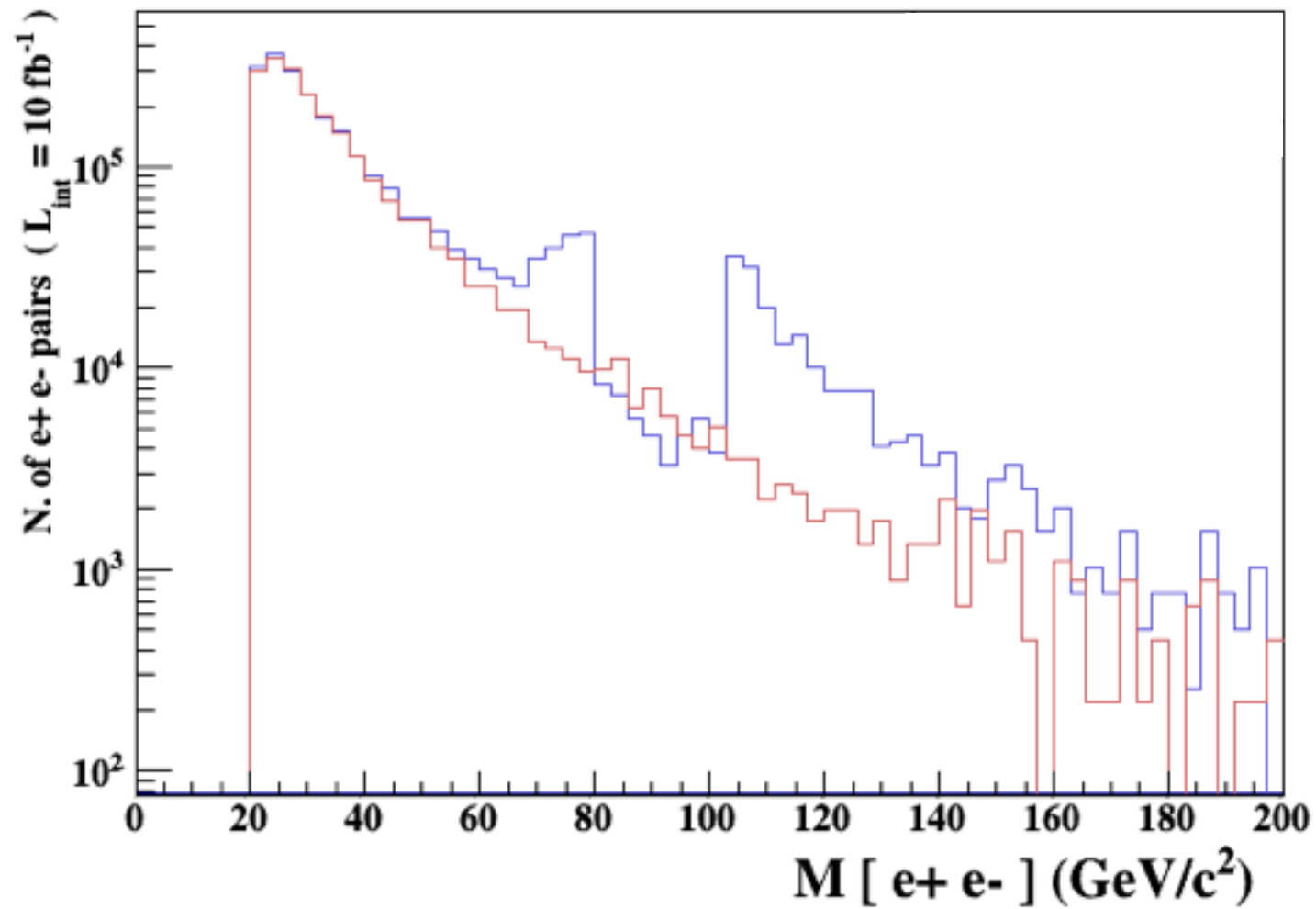
$$|M^* - M| < BW_{cut} * \Gamma$$

- The Physical distribution is (very close to) exact sum of the two other one.
- The “\$” forbids the Z to be onshell but the photon invariant mass can be at MZ (i.e. on shell subtraction).
- The “/” is to be avoid if possible since this leads to violation of gauge invariance.

- NEXT SLIDE is generated with `bw_cut = 5`
- This is **TOO SMALL** to have a physical meaning (15 the default value used in previous plot is better)
- This was done to **illustrate** more in detail how the “\$” syntax works.

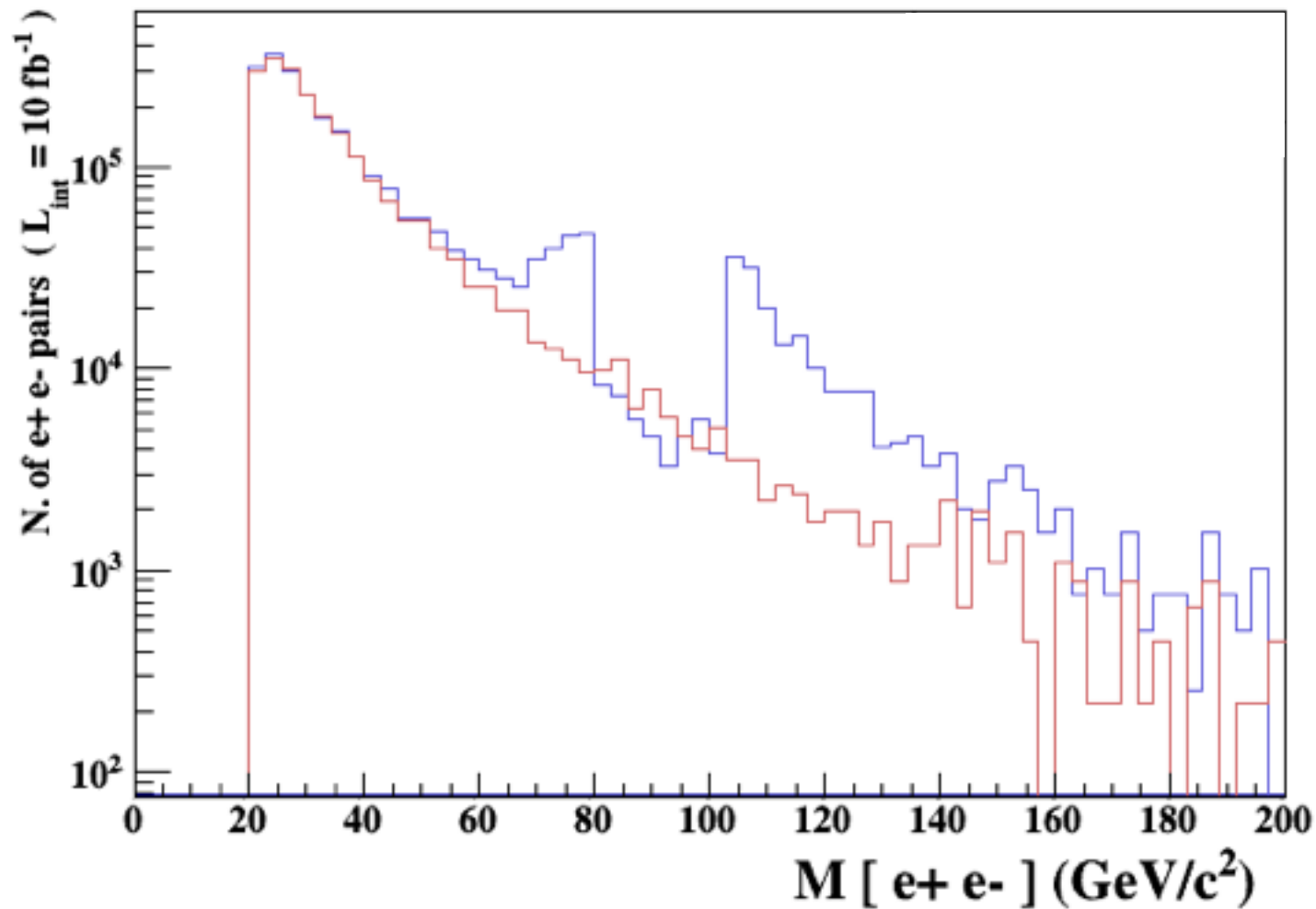
$p p \rightarrow e^+ e^- / Z$   
(red curve)

(blue curve)



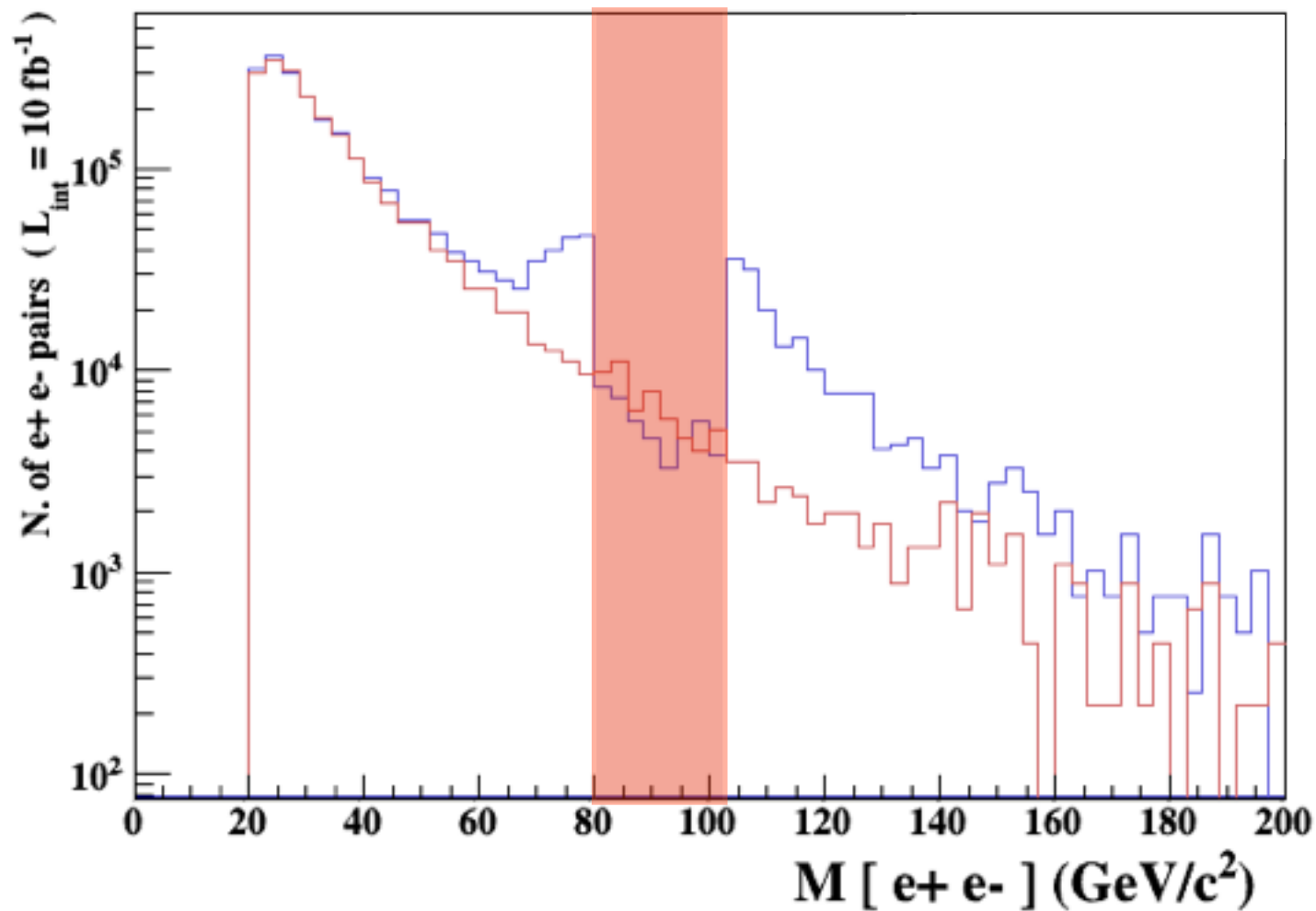
$p p \rightarrow e^+ e^- / Z$   
(red curve)

adding  $p p \rightarrow e^+ e^- \gamma Z$   
(blue curve)



$p p \rightarrow e^+ e^- / Z$   
(red curve)

adding  $p p \rightarrow e^+ e^- \text{ } \$ Z$   
(blue curve)



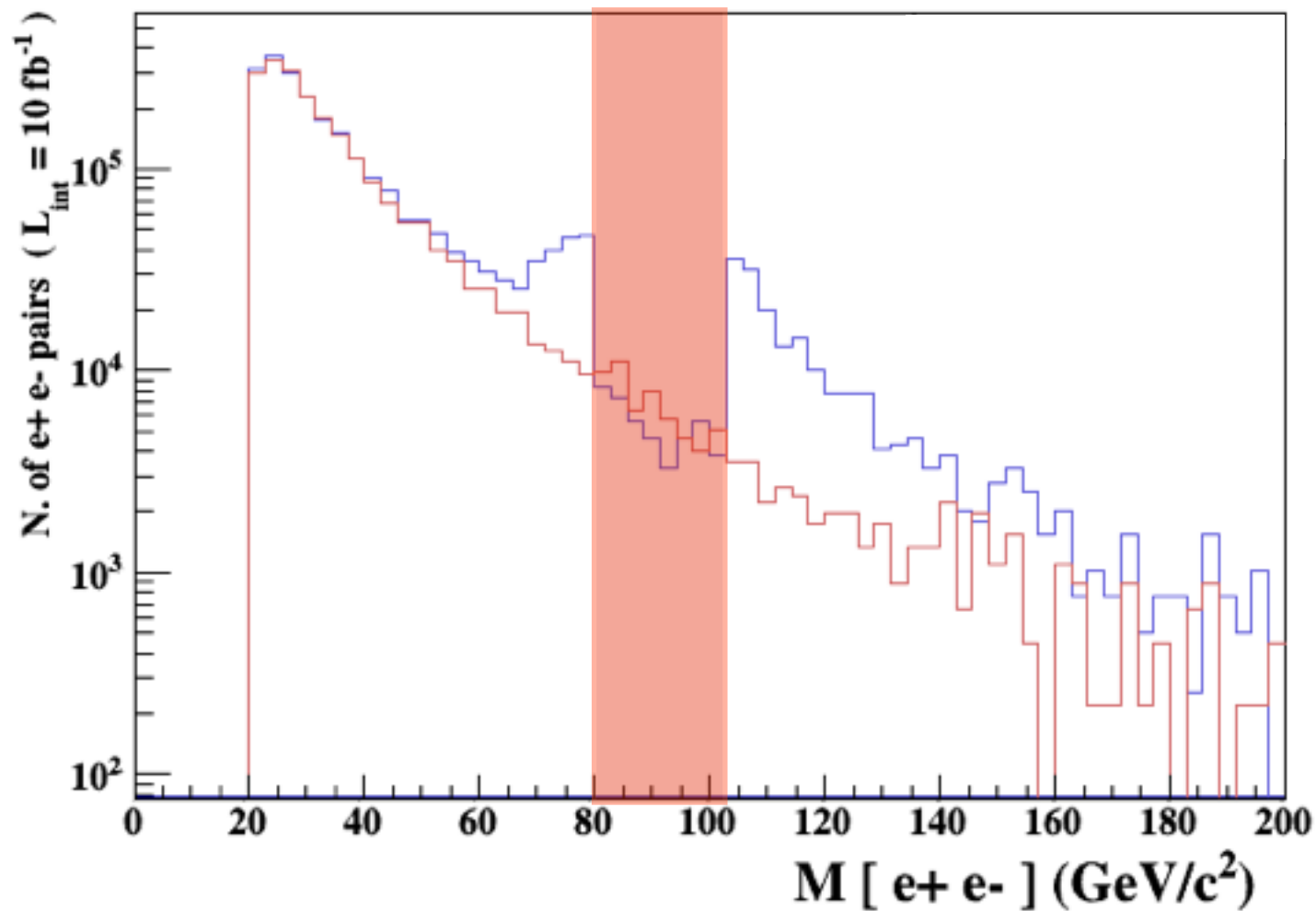
- Z onshell veto

5 times width area



$p p \rightarrow e^+ e^- / Z$   
(red curve)

adding  $p p \rightarrow e^+ e^- \gamma Z$   
(blue curve)

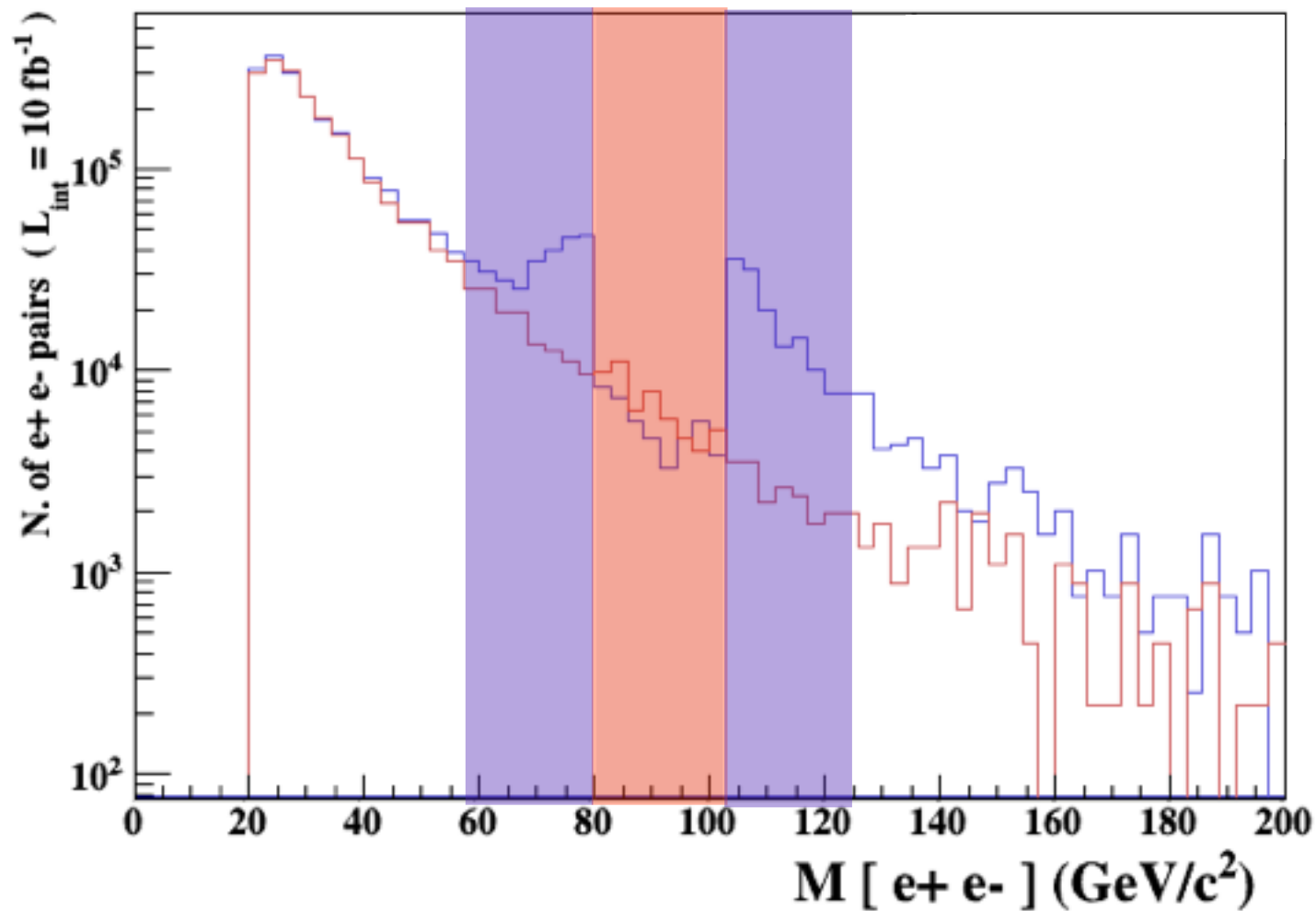


- Z onshell veto
- In veto area only photon contribution

5 times width area

$p p \rightarrow e^+ e^- / Z$   
(red curve)

adding  $p p \rightarrow e^+ e^- \gamma Z$   
(blue curve)



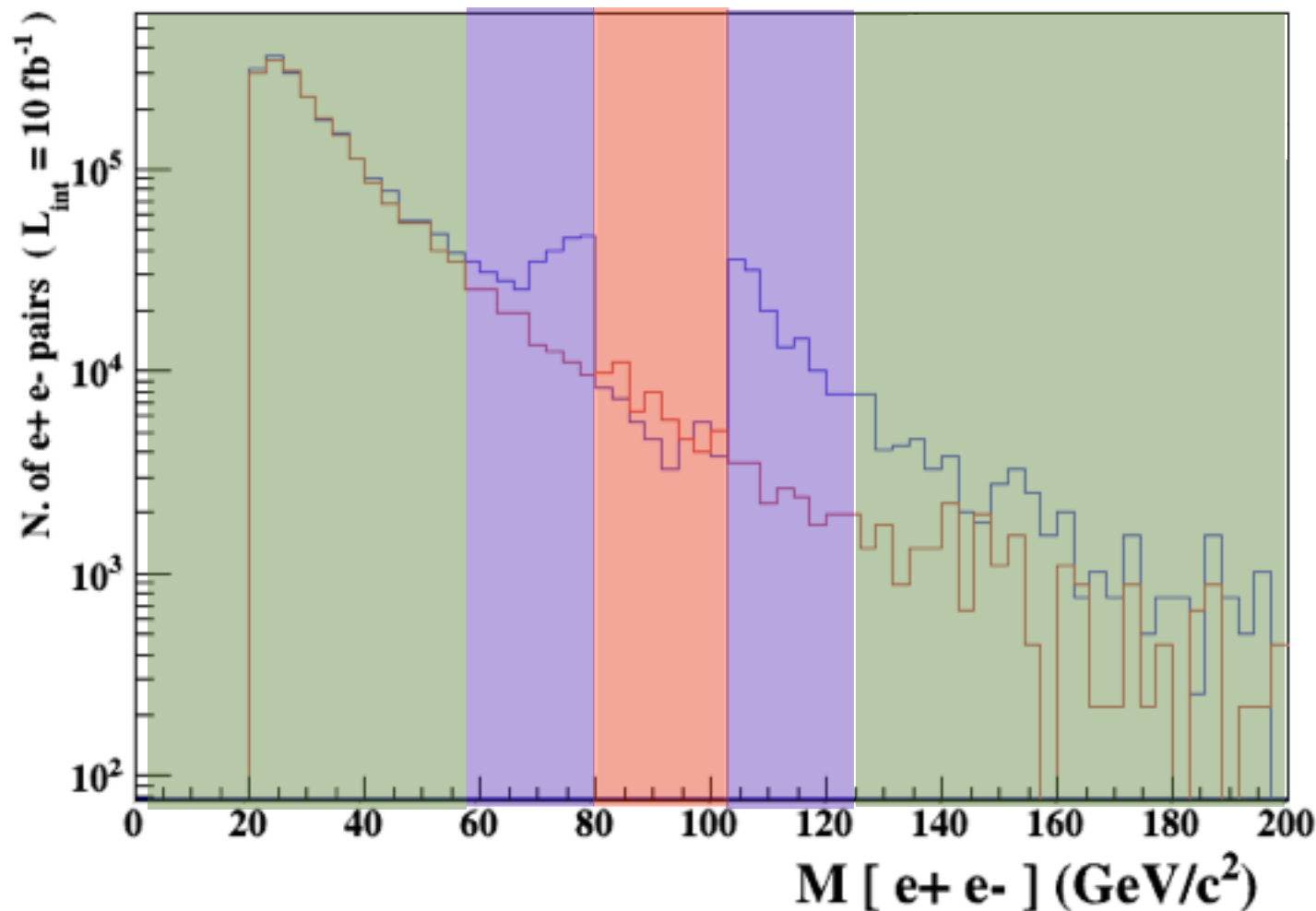
- Z onshell veto
- In veto area only photon contribution
- area sensitive to z-peak

5 times width area

15 times width area

$p p \rightarrow e^+ e^- / Z$   
(red curve)

adding  $p p \rightarrow e^+ e^- \gamma Z$   
(blue curve)



- Z onshell veto
- In veto area only photon contribution
- area sensitive to z-peak
- very off-shell Z, the difference between the curve is due to interference which are need to be KEPT in simulation.

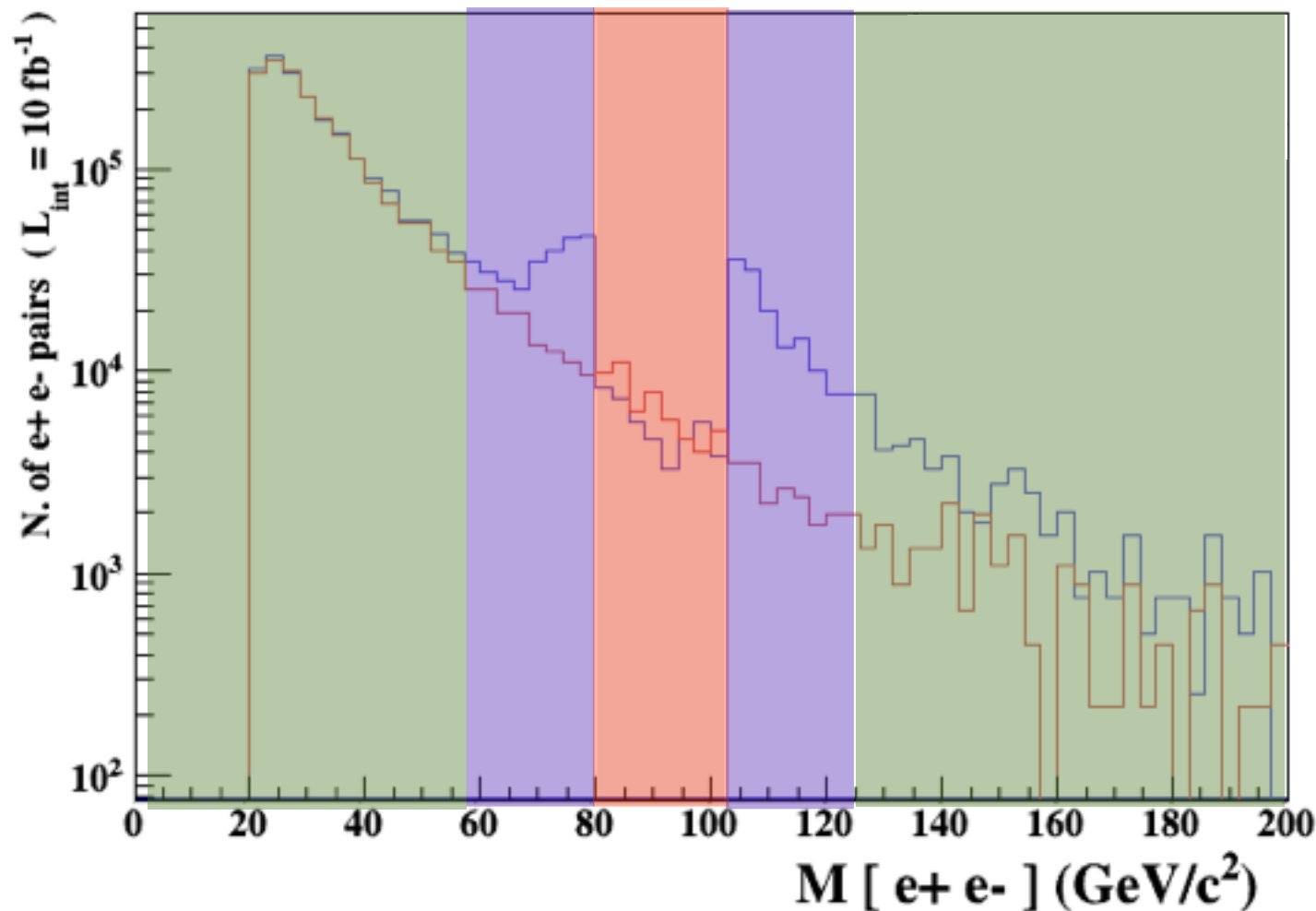
5 times width area

15 times width area

>15 times width area

$p p \rightarrow e^+ e^- / Z$   
(red curve)

adding  $p p \rightarrow e^+ e^- \$ Z$   
(blue curve)



- Z onshell veto
- In veto area only photon contribution
- area sensitive to z-peak
- very off-shell Z, the difference between the curve is due to interference which are need to be KEPT in simulation.

5 times width area

15 times width area

>15 times width area

The “\$” can be use to split the sample in BG/SG area

- Syntax Like

→  $p p \rightarrow z \rightarrow e^+ e^-$

(ask one S-channel  $z$ )

→  $p p \rightarrow e^+ e^- / z$

(forbids any  $z$ )

→  $p p \rightarrow e^+ e^- \$\$ z$

(forbids any  $z$  in s-channel)

- ARE NOT GAUGE INVARIANT !
- forgets diagram interference.
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(forbids any  $z$  in s-channel)

- ARE NOT GAUGE INVARIANT !
- forgets diagram interference.
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# Avoid Those as much as possible!

check physical meaning and gauge/Lorentz invariance if you do.

- Syntax like
  - $p p \rightarrow z, z \rightarrow e^+ e^-$  (on-shell  $z$  decaying)
  - $p p \rightarrow e^+ e^- \ \$ \ z$  (forbids s-channel  $z$  to be on-shell)
- Are linked to cut  $|M^* - M| < BW_{cut} * \Gamma$
- Are more safer to use
- **Prefer** those syntax to the previous slides one



- Look at the cross-section for the previous process for 3 different mass points.
  - ➔ **hint:** you can edit the param\_card/run\_card via the “set” command [After the launch]
  - ➔ **hint:** All command [including answer to question] can be put in a file.

- File content:

```
import model sm
generate p p > t t~
output
launch
set mt 160
set wt Auto
done
launch
set mt 165
set wt Auto
launch
set mt 170
set wt Auto
launch
set mt 175
set wt Auto
launch
set mt 180
set wt Auto
launch
set mt 185
set wt Auto
```

- Run it by:
  - `./bin/mg5 PATH`
    - (smarter than `./bin/mg5 < PATH`)
- If an answer to a question is not present: **Default is taken** automatically

## MadSpin

- generate  $p p \rightarrow t \bar{t} h$

MadSpin Card

```

→ decay t > w+ b, w+ > e+ ve
→ decay t~ > w- b~, w- > e- ve~
→ decay h > b b~
    
```

2m18.214s

0.004707

## MadGraph

- generate  $p p \rightarrow t \bar{t} h, (t \rightarrow w^+ b, w^+ \rightarrow e^+ \nu_e), (t \rightarrow w^- \bar{b}, w^- \rightarrow e^- \bar{\nu}_e), h \rightarrow b \bar{b}$

9m30.806s

0.003014

Different here because of cut (not cut should be applied since 2.3.0)