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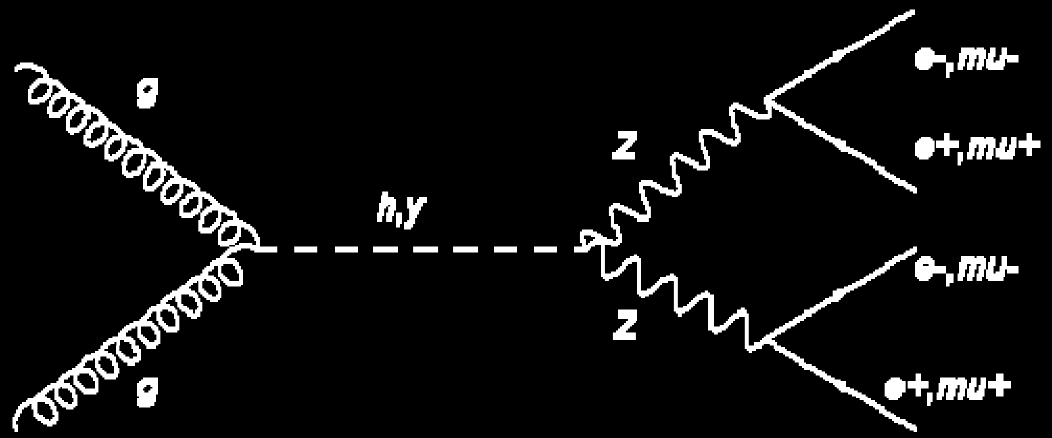
DIBOSON SIGNATURES OF HIGH MASS NEUTRAL RESONANCES AT THE LHC

BSM High Mass Resonances

- Many proposed theories for physics beyond the standard model include new heavy particles with some coupling to two Z bosons
- Different theories predict such new particles with different spins, for example a spin-2 graviton, a spin-1 boson arising from a new U(1) gauge group, or a spin-0 Higgs-like particle
- Given such a new particle X, we consider the process whereby an X resonance in the LHC decays through two Zs, and then into two negatively charged and two positively charged leptons (namely e, mu)

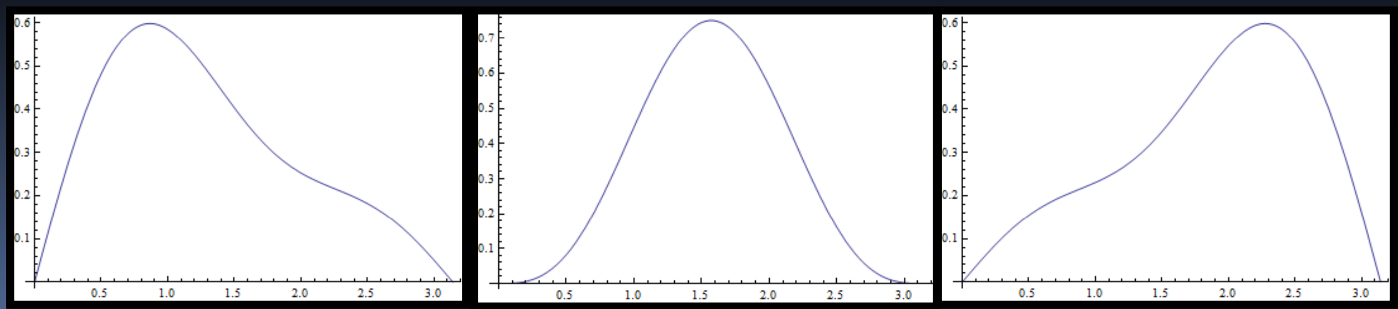
Bivariate Angular Distributions



- Deriving observables from the bivariate distribution of the angles of the negatively charged leptons in their respective Z rest frames, we can probe the spin of the resonance

Polarization States of the Z

- As a massive spin-1 particle, the Z boson has three polarization states, which we can characterize as right handed, left handed, and longitudinal
- Each of these states gives a distinct probability distribution for the lepton angles

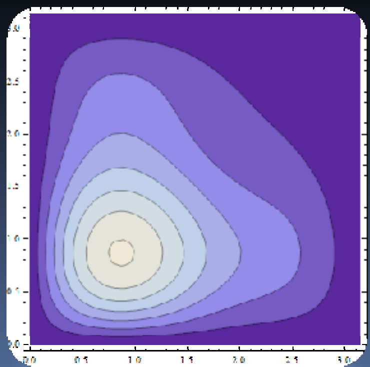


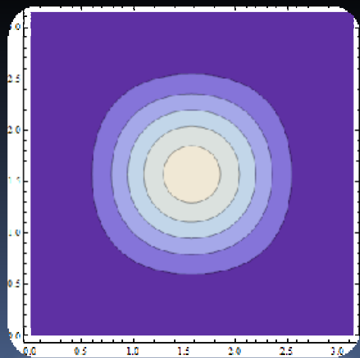
Bivariate Distributions of ZZ

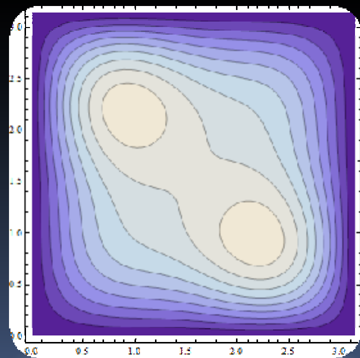
- Given two Z bosons we have the relation:

$$\frac{d^2 N_{ij}}{d\theta_1 d\theta_2} = \frac{1}{2}\left(\frac{dN_i}{d\theta_1}\frac{dN_j}{d\theta_2} + \frac{dN_i}{d\theta_2}\frac{dN_j}{d\theta_1}\right)$$

- Thus we can generate the bivariate distributions of leptons if the state of each Z in the ZZ pair is known





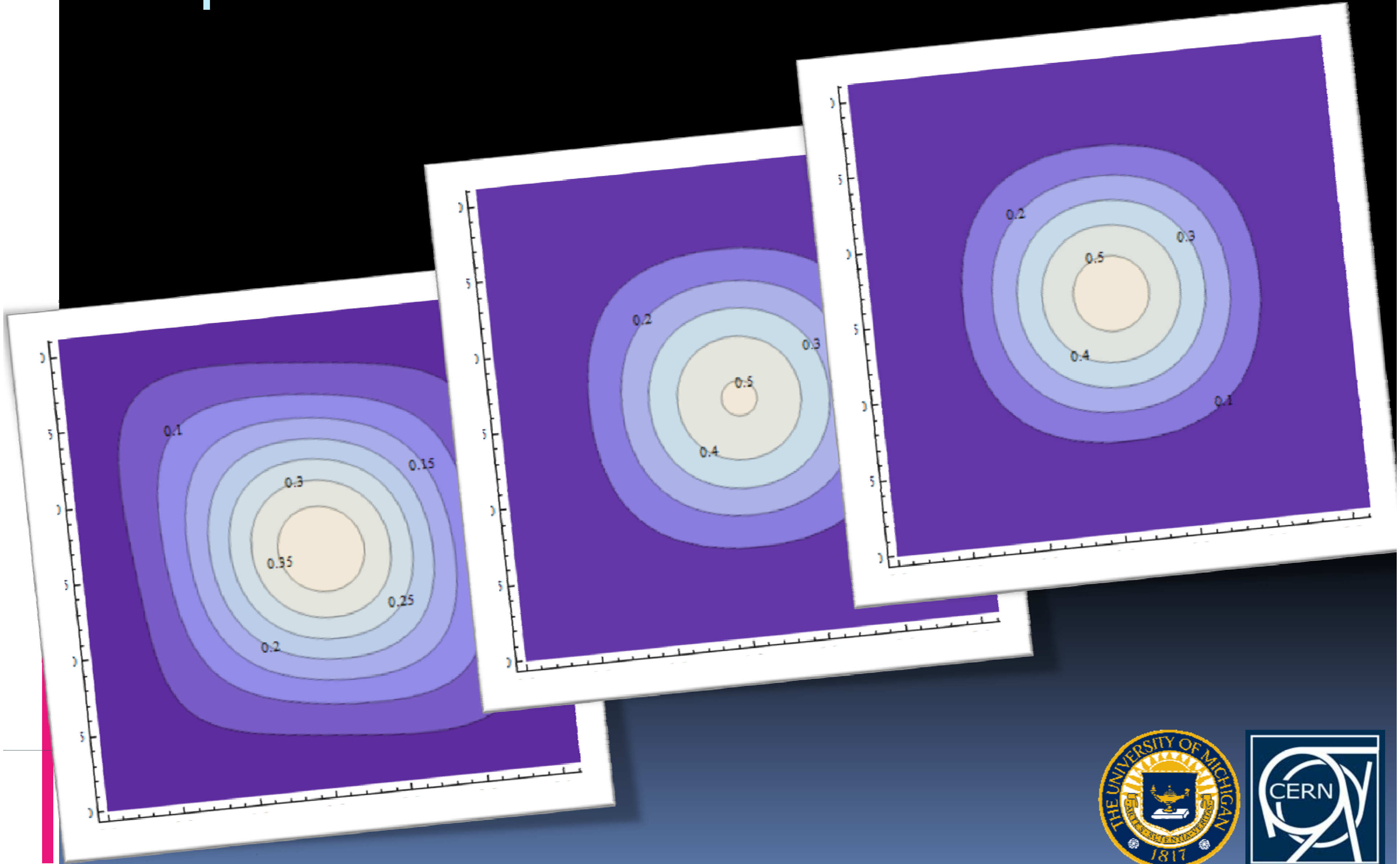


Bivariate distributions for the decay of a new particle

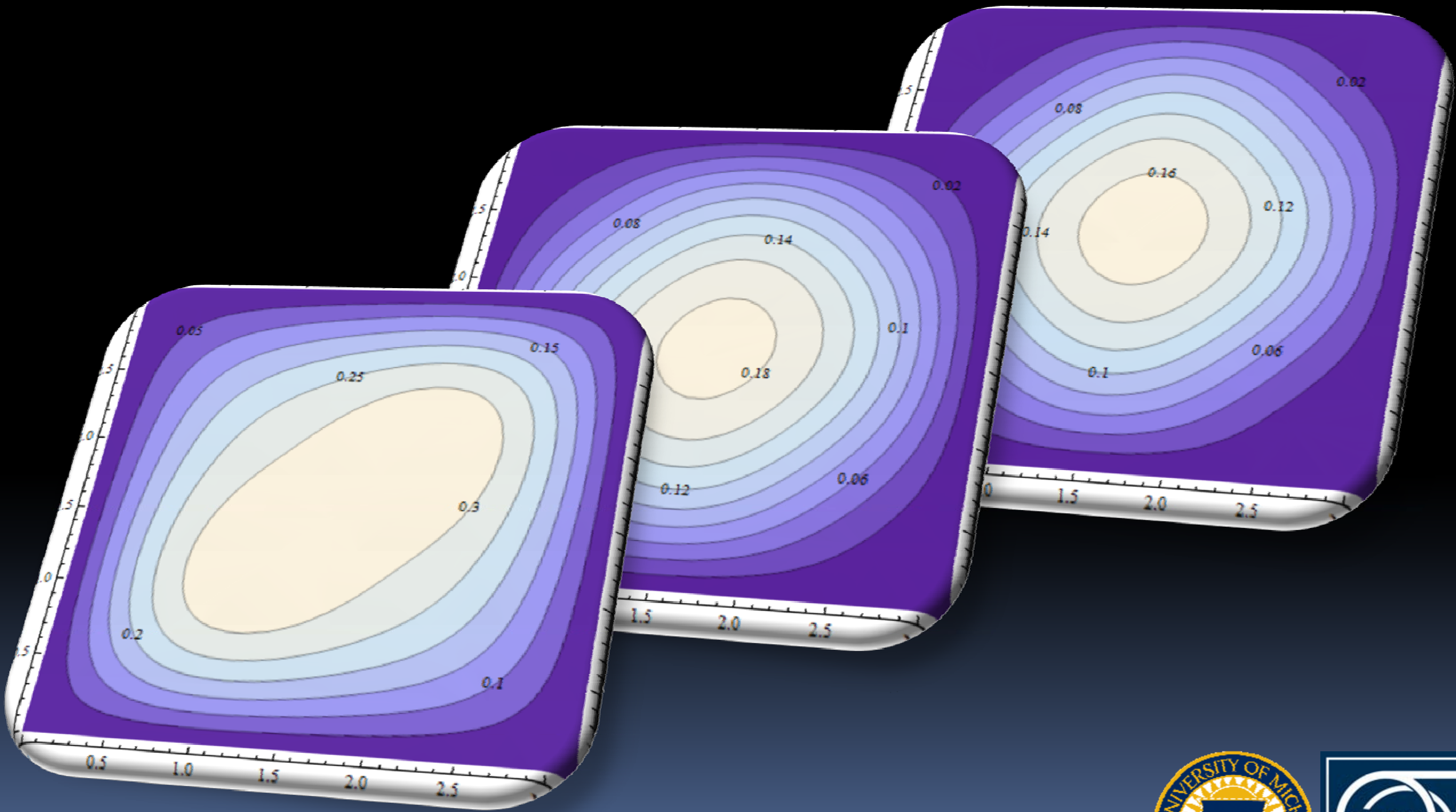
- To derive the bivariate distributions for new particles we calculate the relative decay widths into each possible pair of ZZ states (for our analytic calculations we assume that the Zs are on shell)
- For example, for the SM Higgs coupling we have

$$\Gamma_{h\rightarrow ZZ} = \Sigma_{i,j}\Gamma_{h\rightarrow Z_i Z_j} = (-1)^2 + (-1)^2 + (1 + \frac{1}{2}((\frac{M_h}{M_z})^2 - 4))$$

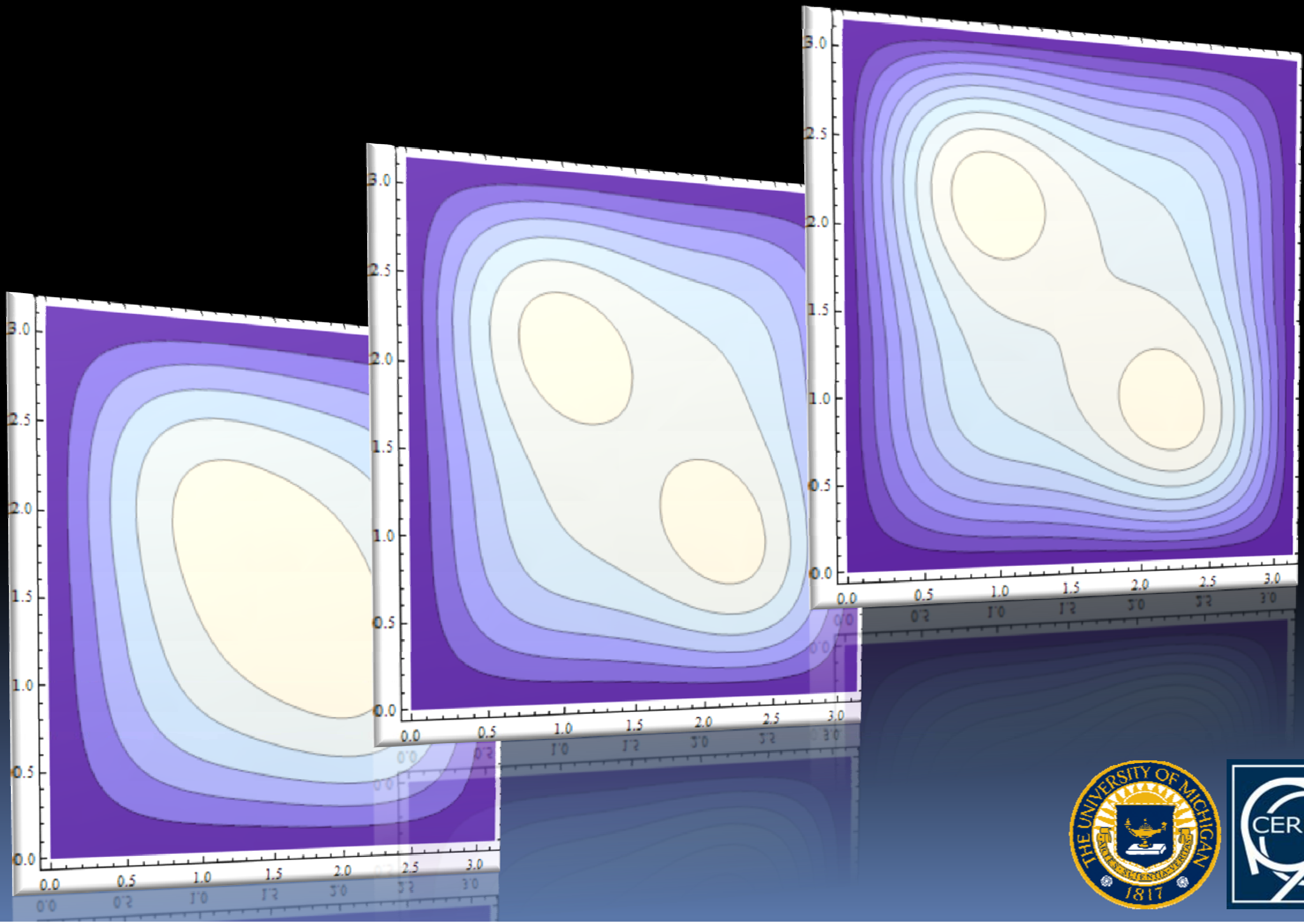
Spin-0 Distribution



Spin-1 Distribution



Spin-2 Distribution

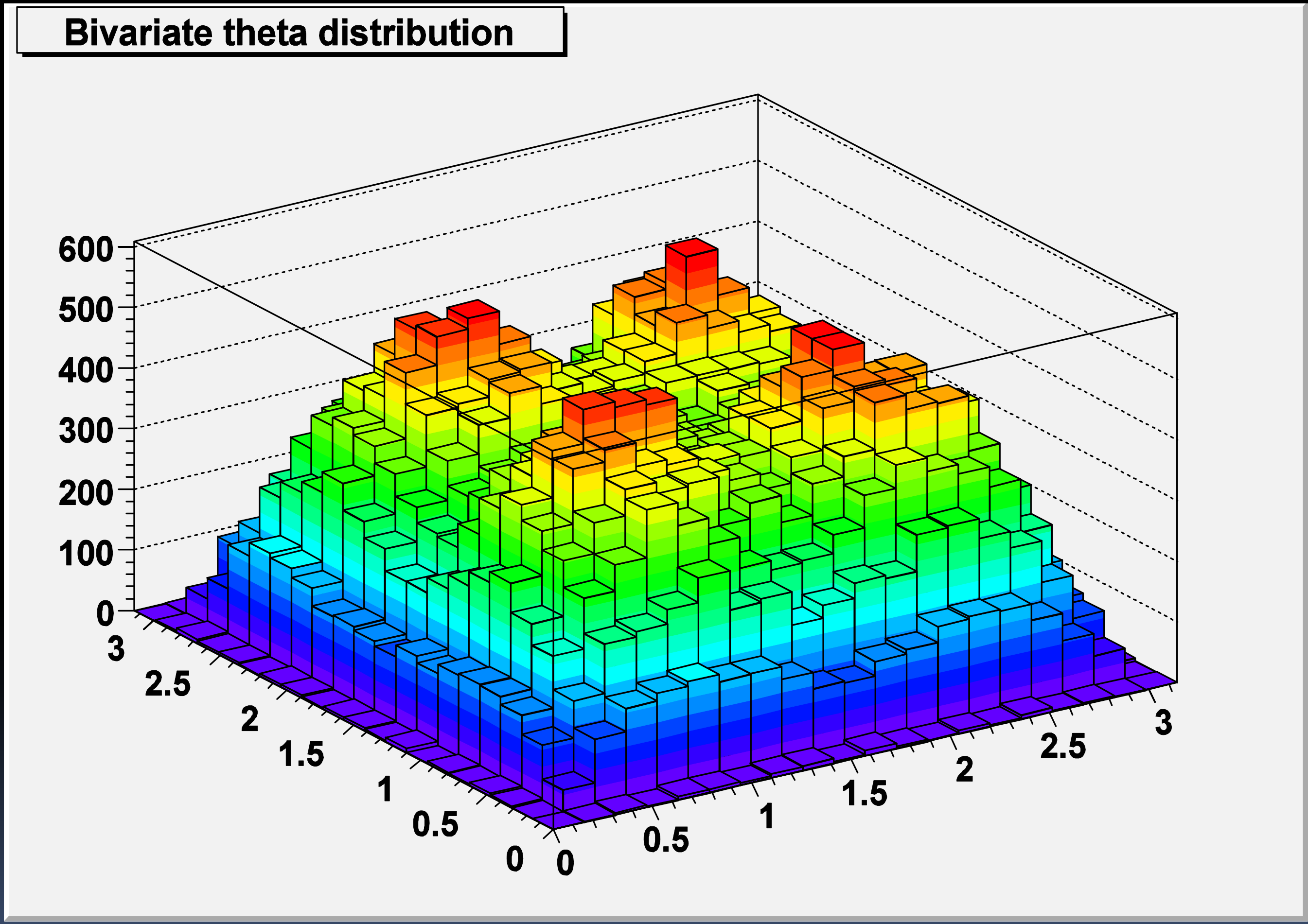


Monte Carlo Event Generation

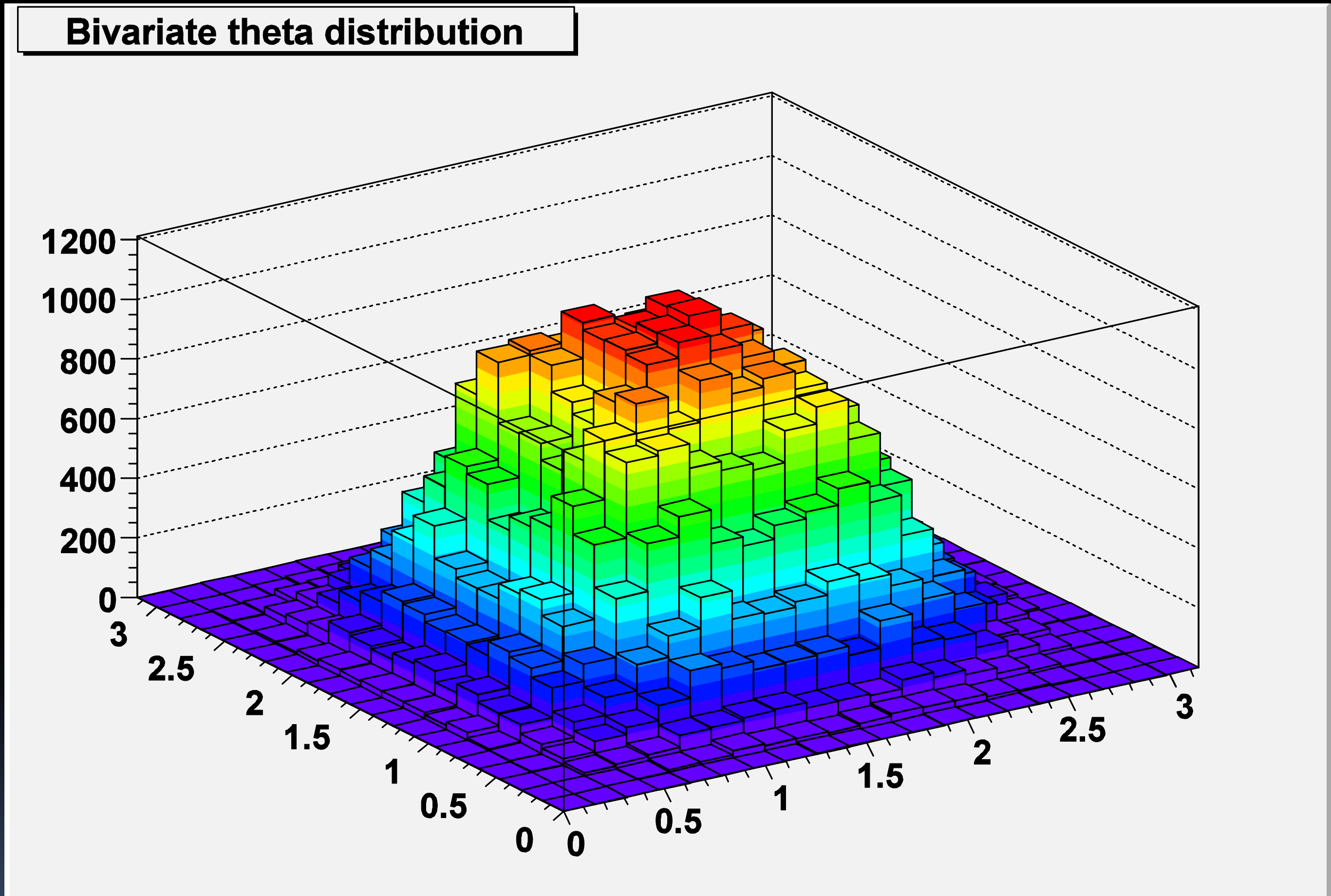
- To take account of the background and the corresponding experimental cuts to deal with it we use a Monte Carlo simulator to get a better sense of what experiments will see
- We record events for 250, 500, and 1,000 GeV resonances for spin-0, spin-1, and spin-2
- We require that the invariant mass of the lepton pairs reconstruct that of the Z to within 5 GeV, and use the following windows for the 4-lepton invariant masses

250 GeV	500 GeV	1 TeV
7.5 GeV	10 GeV	20 GeV

Events at 1 TeV: The Graviton



Events at 1 TeV: The Scalar

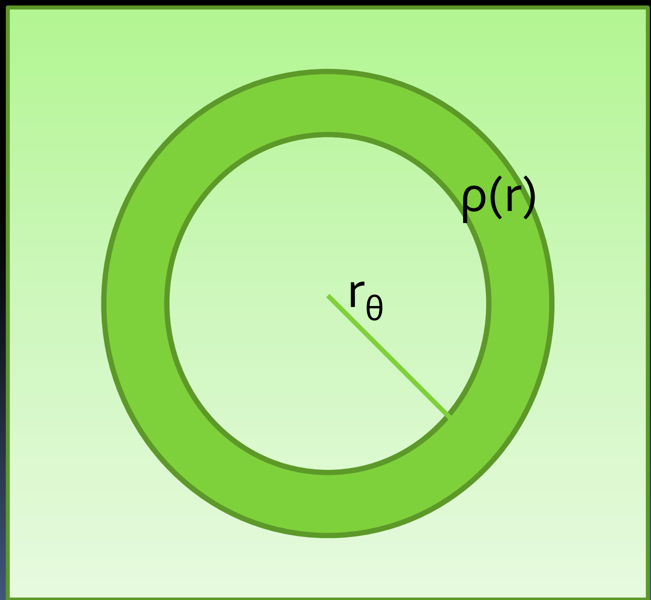


Constructing an Observable

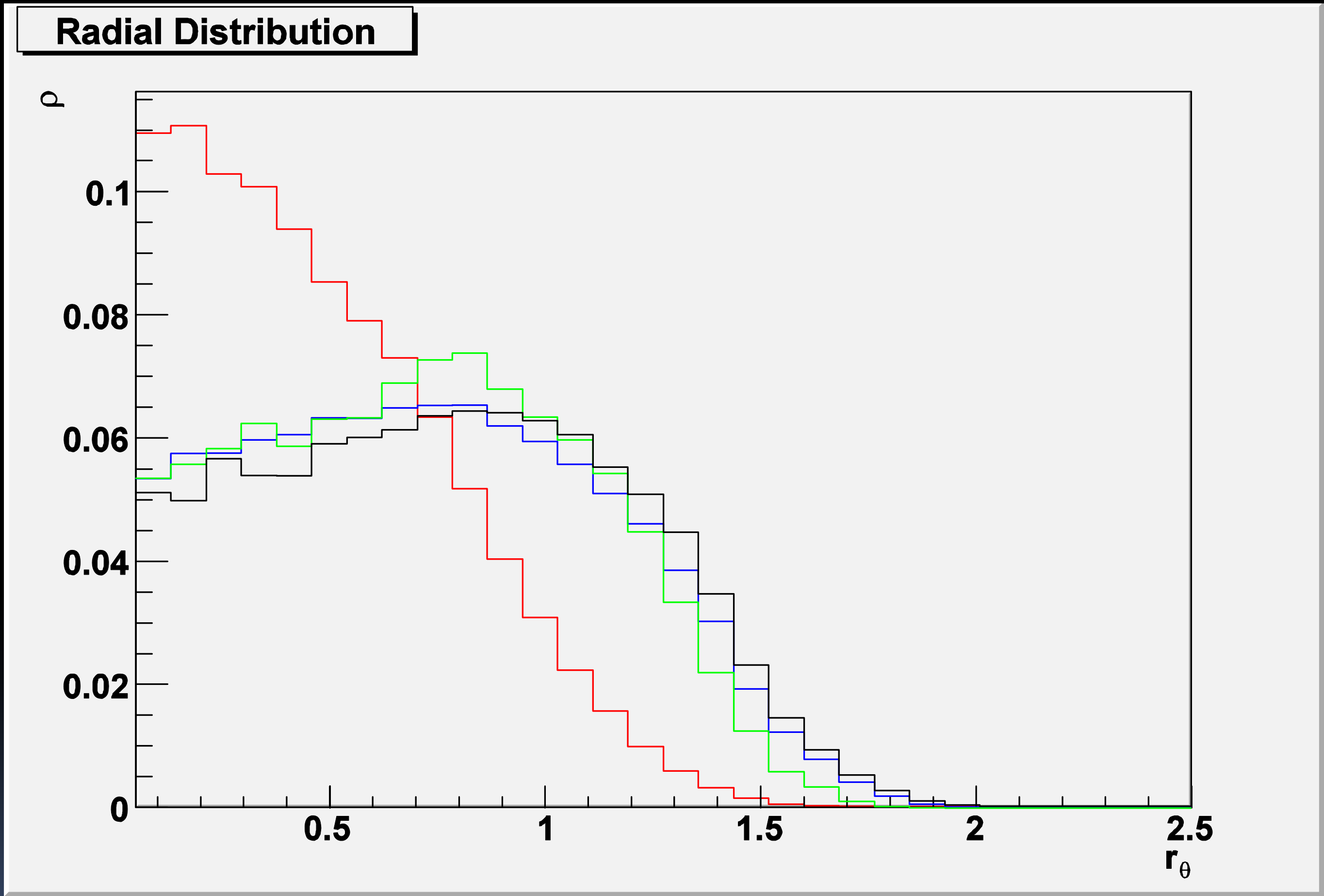
- Because contour plots are by design effective for continuous distributions and not for the discrete approximations resulting from a finite number of events, we must find some more useful characterization of the angular distributions
- The reality of event production means that some finer aspects of the angular distributions, such as even the existence of the transverse ZZ modes in the Higgs decay, cannot be probed
- However, some features of the angular distributions are markedly different for particles of different spin
- For example, our spin-1 vertex has no decay modes into two longitudinally polarized Zs

Constructing an Observable

- One way these differences can be seen is by observing the radial density distribution of the bivariate plots

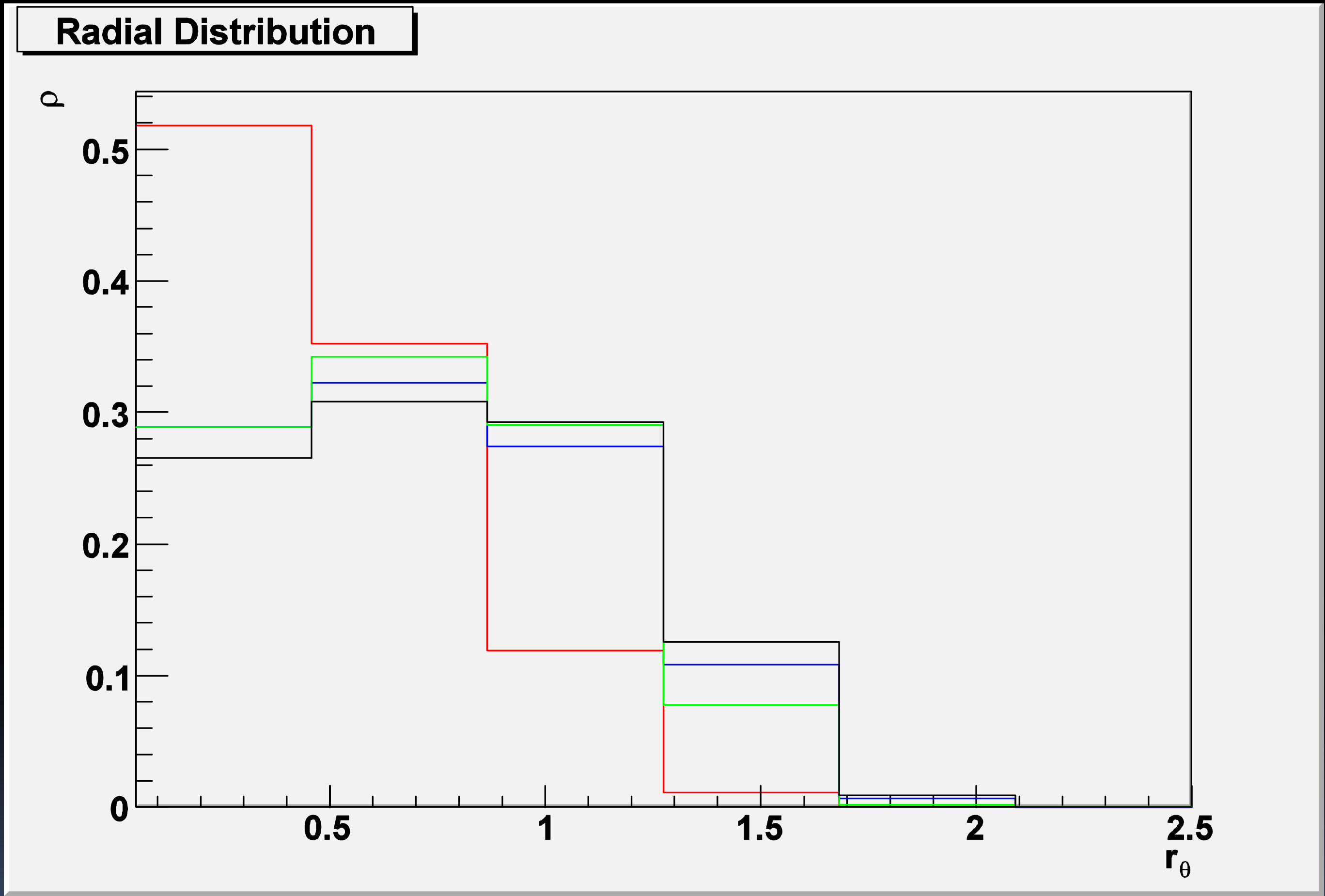


Events at 1 TeV



Red	Green	Blue	Black
Scalar	Vector	Tensor	Background

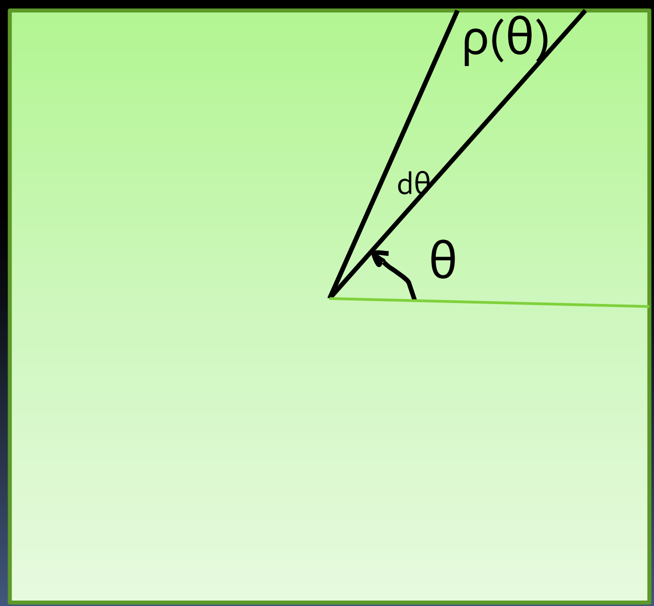
Events at 1 TeV



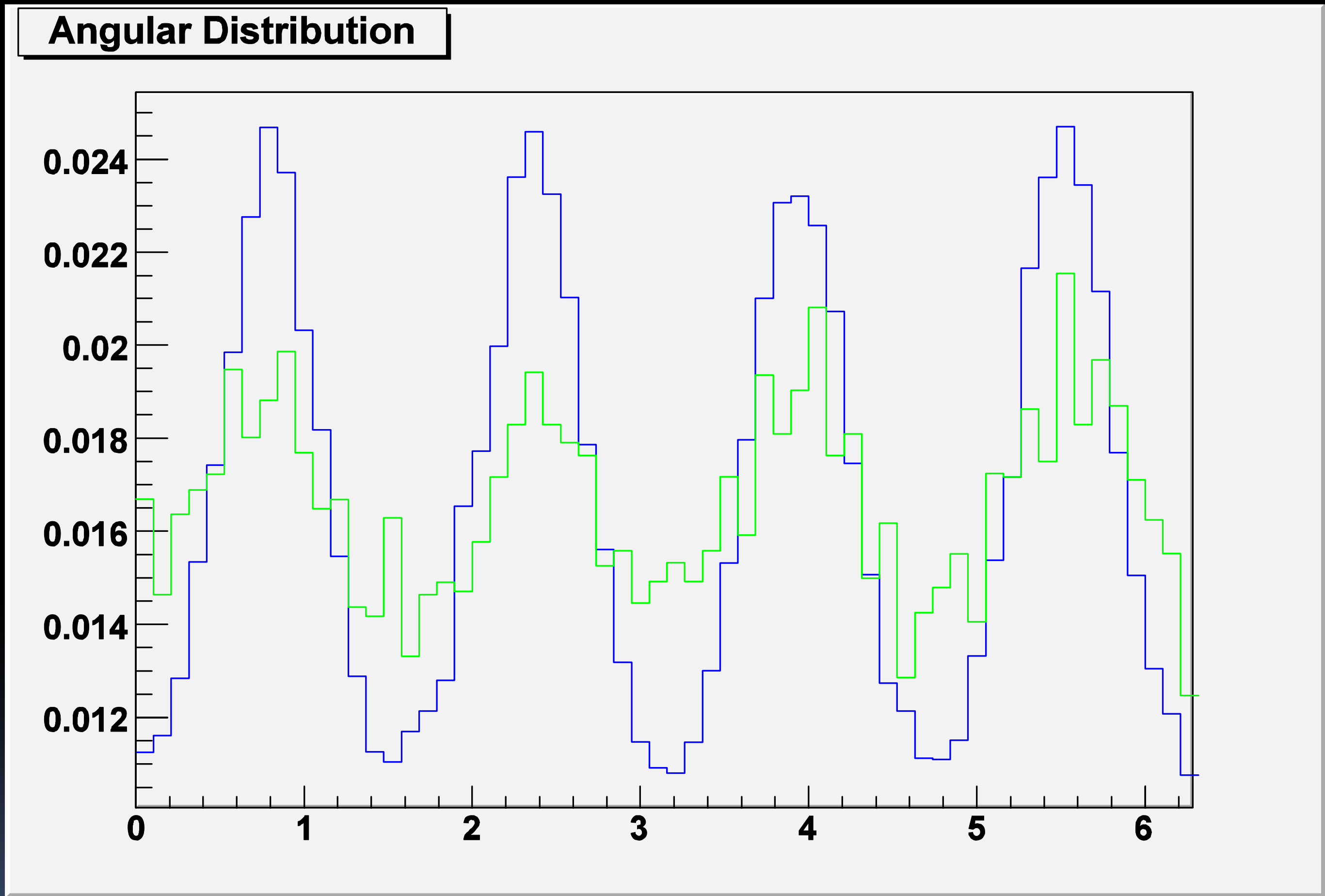
Red	Green	Blue	Black
Scalar	Vector	Tensor	Background

Constructing another observable

- We can also plot the distribution as a function of the angle from an axis

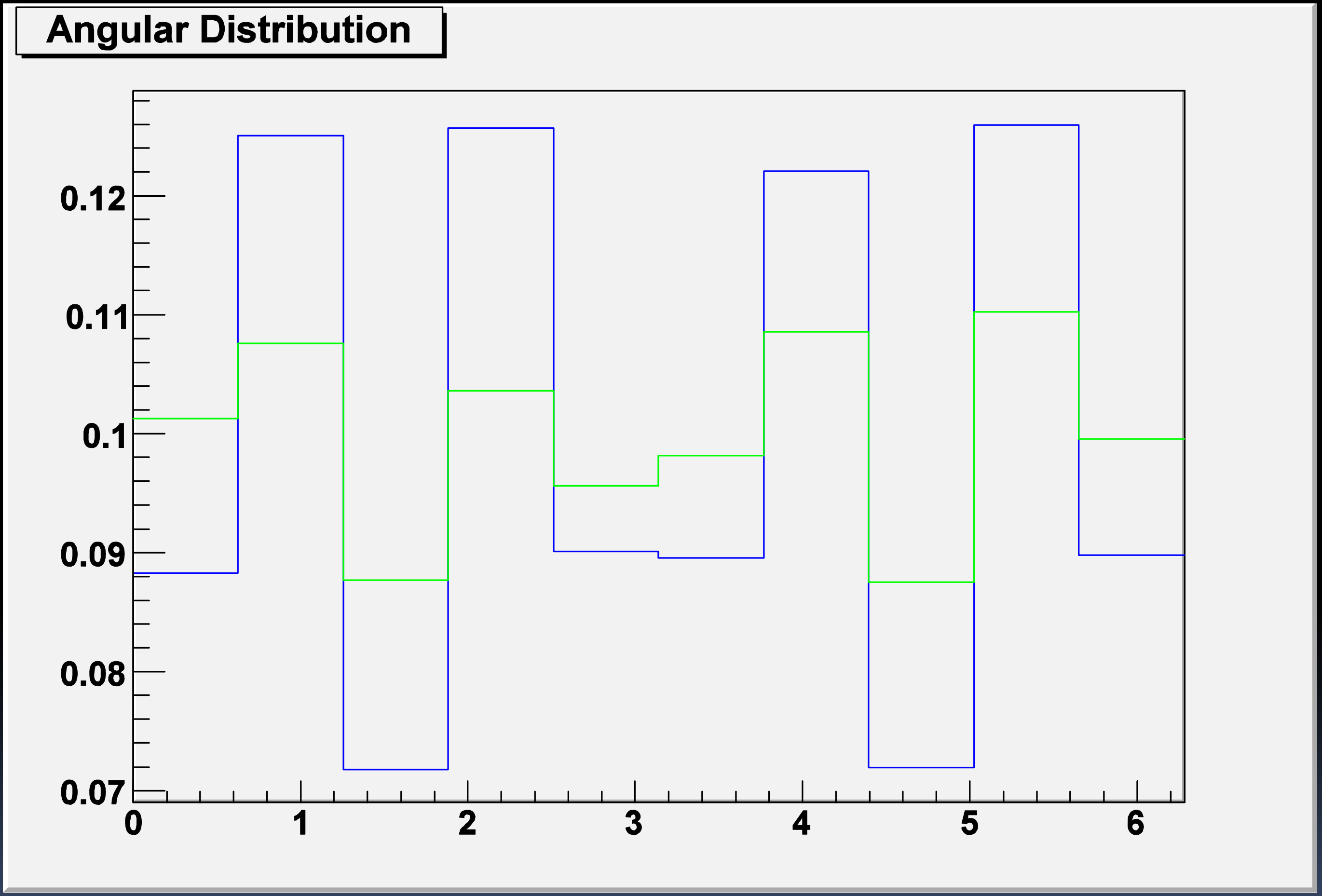


Events at 1 TeV



Green	Blue
Vector	Tensor

Events at 1 TeV



Green	Blue
Vector	Tensor

Acknowledgements

- James Wells
- Rikkert Frederix from the Madgraph development team
- Jean Krisch, Myron Campbell, Homer Neal and Jeremy Herr

Backup Slides

HELAS and new vertices

```
     &  + v1(3)*v2(2)*p1(3)*q(0)*q(0)*vmass**-2
     &  + v1(3)*v2(2)*p2(0)*q(0)*q(3)*vmass**-2
     &  - v1(3)*v2(2)*p2(3)*q(0)*q(0)*vmass**-2
     &  + v1(3)*v2(4)*p1(0)*q(0)*q(1)*vmass**-2
     &  - v1(3)*v2(4)*p1(1)*q(0)*q(0)*vmass**-2
     &  - v1(3)*v2(4)*p2(0)*q(0)*q(1)*vmass**-2
     &  + v1(3)*v2(4)*p2(1)*q(0)*q(0)*vmass**-2
     &  - v1(4)*v2(1)*p1(1)*q(0)*q(2)*vmass**-2
     &  + v1(4)*v2(1)*p1(2)*q(0)*q(1)*vmass**-2
     &  + v1(4)*v2(1)*p2(1)*q(0)*q(2)*vmass**-2
     &  - v1(4)*v2(1)*p2(2)*q(0)*q(1)*vmass**-2
     &  + v1(4)*v2(2)*p1(0)*q(0)*q(2)*vmass**-2
     &  - v1(4)*v2(2)*p1(2)*q(0)*q(0)*vmass**-2
     &  - v1(4)*v2(2)*p2(0)*q(0)*q(2)*vmass**-2
     &  + v1(4)*v2(2)*p2(2)*q(0)*q(0)*vmass**-2
     &  - v1(4)*v2(3)*p1(0)*q(0)*q(1)*vmass**-2
     &  + v1(4)*v2(3)*p1(1)*q(0)*q(0)*vmass**-2
     &  + v1(4)*v2(3)*p2(0)*q(0)*q(1)*vmass**-2
     &  - v1(4)*v2(3)*p2(1)*q(0)*q(0)*vmass**-2

      jvv(2) = - wp(1)*v1(3)*p1(3)
     &  + wp(1)*v1(3)*p2(3)
     &  + wp(1)*v1(4)*p1(2)
     &  - wp(1)*v1(4)*p2(2)
     &  + wp(3)*v1(1)*p1(3)
     &  - wp(3)*v1(1)*p2(3)
     &  - wp(3)*v1(4)*p1(0)
     &  + wp(3)*v1(4)*p2(0)
     &  - wp(4)*v1(1)*p1(2)
     &  + wp(4)*v1(1)*p2(2)
     &  + wp(4)*v1(3)*p1(0)
     &  - wp(4)*v1(3)*p2(0)
     &  + v1(1)*v2(2)*p1(2)*q(1)*q(3)*vmass**-2
     &  - v1(1)*v2(2)*p1(3)*q(1)*q(2)*vmass**-2
     &  - v1(1)*v2(2)*p2(2)*q(1)*q(3)*vmass**-2
     &  + v1(1)*v2(2)*p2(3)*q(1)*q(2)*vmass**-2
     &  - v1(1)*v2(3)*p1(1)*q(1)*q(3)*vmass**-2
     &  + v1(1)*v2(3)*p1(3)*q(1)*q(1)*vmass**-2
     &  + v1(1)*v2(3)*p2(1)*q(1)*q(3)*vmass**-2
```

FORM

```
[J] =
    - k1.k2*e1plus.e2zero*e3plus.e3plus + 2*k1.k2*e1plus.e3plus*
   e2zero.e3plus + k1.e2zero*k2.e1plus*e3plus.e3plus - 2*k1.e2zero*
   k2.e3plus*e1plus.e3plus - 2*k1.e3plus*k2.e1plus*e2zero.e3plus + 2*
   k1.e3plus*k2.e3plus*e1plus.e2zero - e1plus.e2zero*e3plus.e3plus*Mz^2 + 2
   *e1plus.e3plus*e2zero.e3plus*Mz^2;

[K] =
    - k1.k2*e1zero.e2plus*e3plus.e3plus + 2*k1.k2*e1zero.e3plus*
   e2plus.e3plus + k1.e2plus*k2.e1zero*e3plus.e3plus - 2*k1.e2plus*
   k2.e3plus*e1zero.e3plus - 2*k1.e3plus*k2.e1zero*e2plus.e3plus + 2*
   k1.e3plus*k2.e3plus*e1zero.e2plus - e1zero.e2plus*e3plus.e3plus*Mz^2 + 2
   *e1zero.e3plus*e2plus.e3plus*Mz^2;

[L] =
    - k1.k2*e1minus.e2zero*e3plus.e3plus + 2*k1.k2*e1minus.e3plus*
   e2zero.e3plus + k1.e2zero*k2.e1minus*e3plus.e3plus - 2*k1.e2zero*
   k2.e3plus*e1minus.e3plus - 2*k1.e3plus*k2.e1minus*e2zero.e3plus + 2*
   k1.e3plus*k2.e3plus*e1minus.e2zero - e1minus.e2zero*e3plus.e3plus*Mz^2
    + 2*e1minus.e3plus*e2zero.e3plus*Mz^2;

[M] =
    - k1.k2*e1zero.e2minus*e3plus.e3plus + 2*k1.k2*e1zero.e3plus*
   e2minus.e3plus + k1.e2minus*k2.e1zero*e3plus.e3plus - 2*k1.e2minus*
   k2.e3plus*e1zero.e3plus - 2*k1.e3plus*k2.e1zero*e2minus.e3plus + 2*
   k1.e3plus*k2.e3plus*e1zero.e2minus - e1zero.e2minus*e3plus.e3plus*Mz^2
    + 2*e1zero.e3plus*e2minus.e3plus*Mz^2;


 repeat;

 id k1.k1 = Mz^2;
 id k2.k2 = Mz^2;
 id k3.k3 = Mh^2;

 id e2plus = e1minus;
 id e2minus = e1plus;

 id e3zero.k3 = 0;
 id e3plus.k3 = 0;
 id e3minus.k3 = 0;

 id  k3 = k1+k2;

 id e1zero.k1 = 0;
 id e1plus.k1 = 0;
 id e1minus.k1 = 0;
```

Madgraph

```
# 2. The charcter after the @ is used as an identifier for the class *
#    of processes. It can be a single or a digit.                     *
# 3. The number of lines for the max couplings depends on how many    *
#    different classes of couplings are present in the model          *
#    In the SM these are just two: QED (which include EW) and QCD      *
# 4. Write "end_coup" after  the couplings list,                       *
#    to tell MG that the couplings input is over.                      *
# 5. Write "done" after the proc list to                               *
#    to tell MG that the proc input is over.                           *
# 6. Some model names available at present are:                        *
#    sm      =  Standard Model                                         *
#    sm_ckm =  Standard Model with Cabibbo matrix                      *
#    mssm    =  Minimal Supersymmetric Standard Model                  *
#    2hdm    =  Generic Two Higgs Doublet model                        *
#    heft    =  Higgs EFT (+Standard Model)                            *
#    usrmod =  User Model                                              *
# 7. Don't leave spaces between the particles name in the              *
#    definition of the multiparticles.                                 *
#**********************************************************************
#**********************************************************************
# Process(es) requested : mg2 input                                    *
#**********************************************************************
# Begin PROCESS # This is TAG. Do not modify this line

e+e->mu+mu-    @0        # First Process
QCD=4               # Max QCD couplings
QED=5                # Max QED couplings
end_coup             # End the couplings input

done                 # this tells MG there are no more procs

# End PROCESS  # This is TAG. Do not modify this line
#**********************************************************************
# Model information                                                    *
#**********************************************************************
# Begin MODEL  # This is TAG. Do not modify this line
crazy
# End   MODEL  # This is TAG. Do not modify this line
#**********************************************************************
# Start multiparticle definitions                                      *
#**********************************************************************
# Begin MULTIPARTICLES # This is TAG. Do not modify this line
P uu~dd~ss~cc~g
J uu~dd~ss~cc~g
L+ e+mu+
L- e-mu-
```

```
u d w+ GWF QED
c s w+ GWF QED
t b w+ GWF QED

# FFV (ll'W)
ve   e-  w+ GWF QED
vm   mu- w+ GWF QED
vt   ta- w+ GWF QED
e-   ve  w- GWF QED
mu-  vm  w- GWF QED
ta-  vt  w- GWF QED

# FFS (Yukawa)
ta- ta- h GHTAU QED
b   b   h GHBOT QED
t   t   h GHTOP QED


#
# Boson 3-,4-pt
#

#   VVV
w- w+ a  GWWA  QED
w- w+ z  GWWZ  QED

#   VVS
w- w+ h  GWWH  QED
z  z  h  GZZH  QED


#   SSS
h  h  h  GHHH  QED

#   VVVV
w- a  w+ a  GWWA  GWWA  QED QED
w- z  w+ a  GWWZ  GWWA  QED QED
w- z  w+ z  GWWZ  GWWZ  QED QED
w- w+ w- w+ GWWZ  GWWA  QED QED

#   VVSS
w- w+ h  h  GWWHH GWWHH QED QED
z  z  h  h  GZZHH GZZHH QED QED


#   USRVertex
u u x GUUX QED
z a x GZAX QED E
```