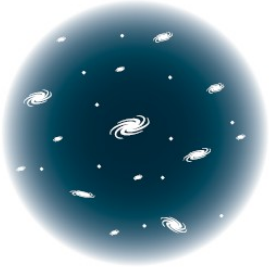
Searches for H→WW→ℓνℓν at DØ

Björn Penning

Outline

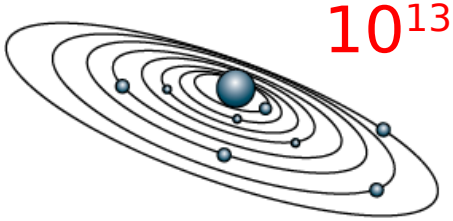
- Introduction
  - Objectives of Particle Physics
  - Fundamental Forces and Particles
  - The Higgs Boson
- Experimental Setup
  - The Tevatron
  - Particle Detection
  - On the Way to Analysis
- High Mass Higgs search at DØ
  - Experimental Signature and Backgrounds
  - Multivariate Methods
  - Systematical Uncertainties
  - Thinking out of the Box
- Conclusion

Objectives of Physics



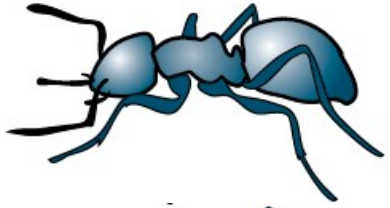
10^{26}m

10^{21}m



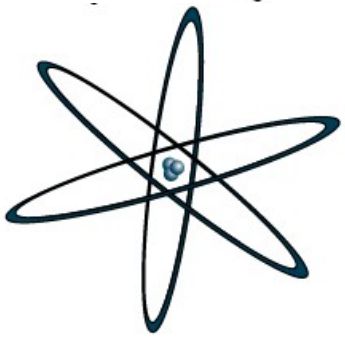
10^{13}m

10^{7}m

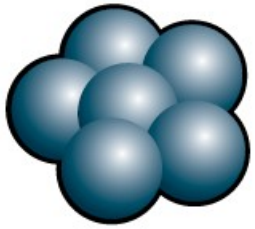


10^{-2}m

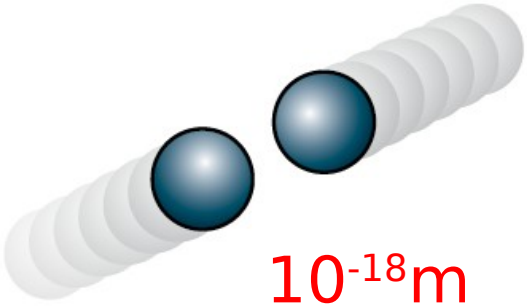
Finding universal laws valid over many order of magnitude.



10^{-10}m



10^{-15}m

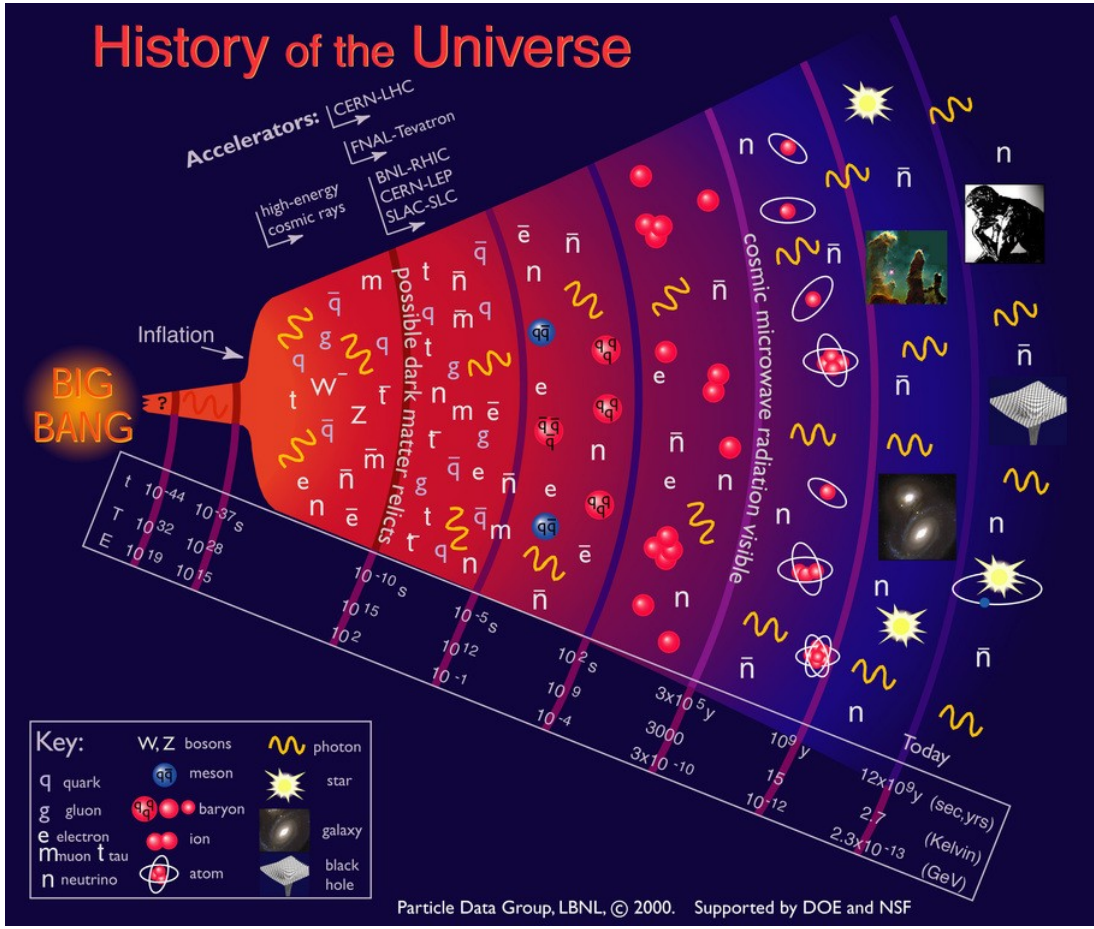


10^{-18}m

10^{-18} - 10^{-26}m

Big Bang in the Laboratory

- Collider experiments simulate the universe shortly after Big Bang



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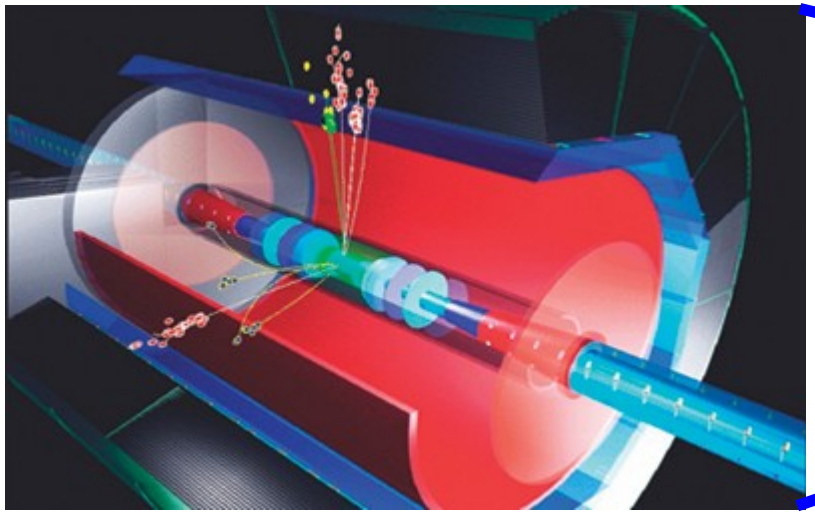
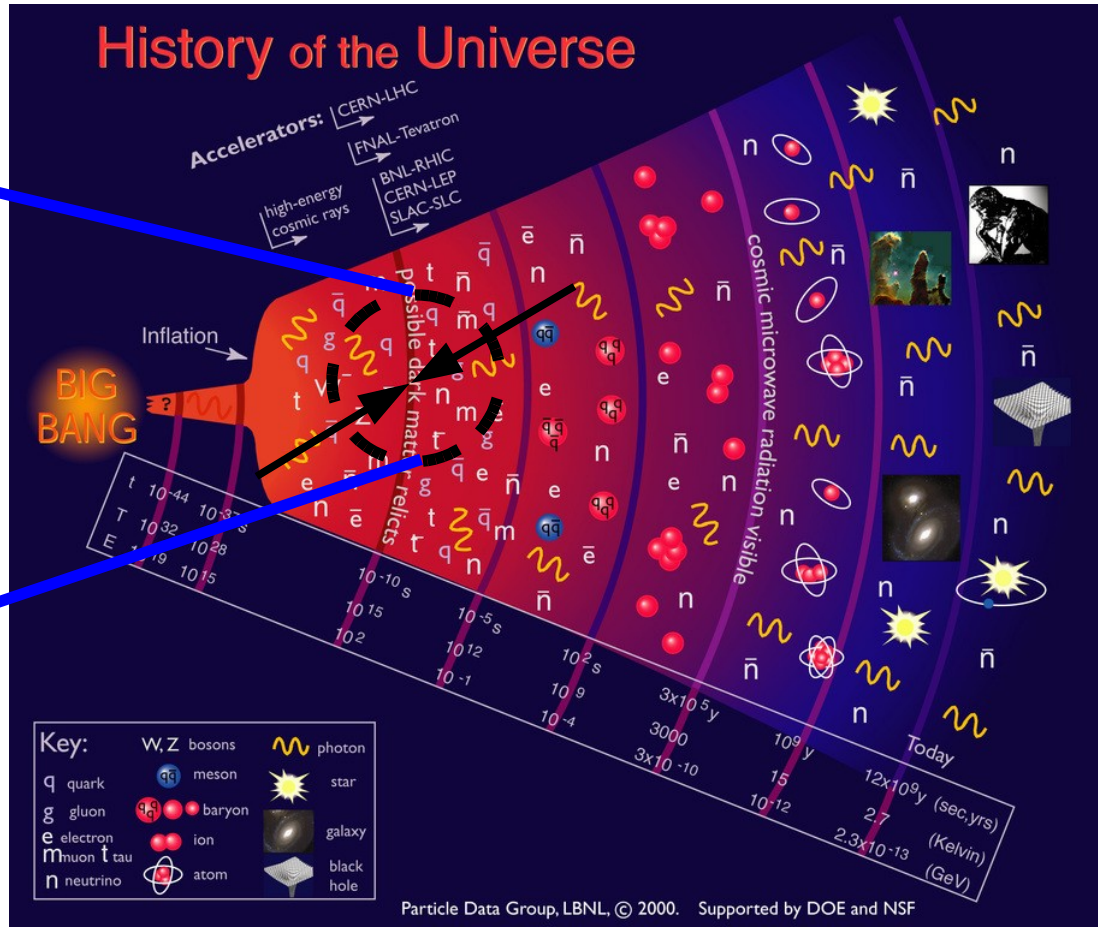
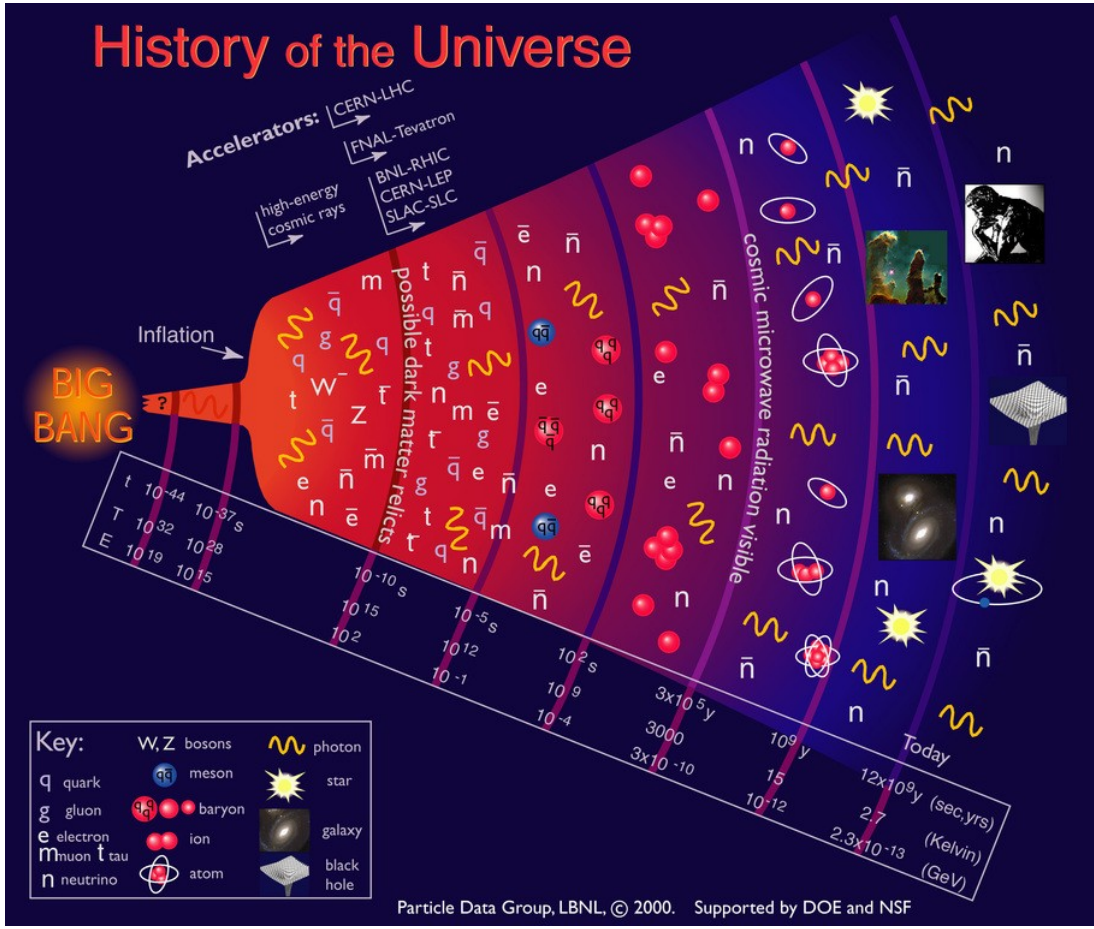




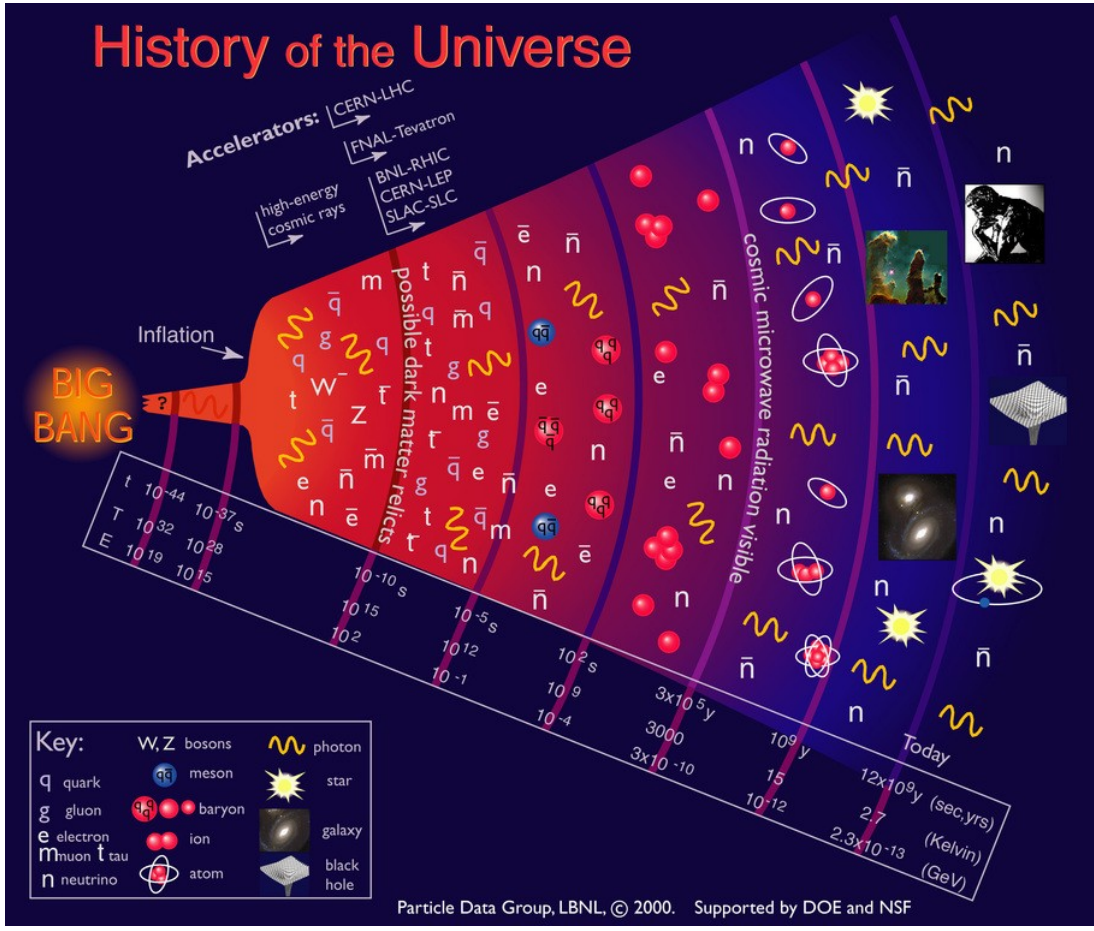
Big Bang in the Laboratory

- Collider experiments simulate the universe shortly after Big Bang
- Today we describe most phenomena using 3 fundamental forces + gravity and 38 elementary particles



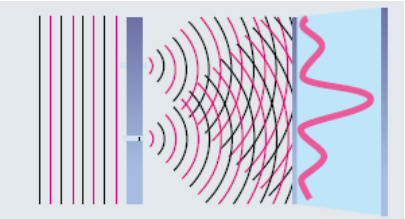
Big Bang in the Laboratory

- Collider experiments simulate the universe shortly after Big Bang
- Today we describe most phenomena using 3 fundamental forces + gravity and 38 elementary particles
- Open questions:
  - Origin of masses of fermions/bosons
  - Hierarchy problem
  - QM and GR to be unified
  - Dark Matter / Dark Energy
  - Matter/Antimatter asymmetry



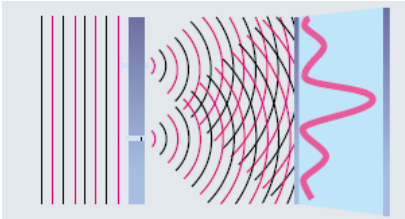
Fundamental Interactions

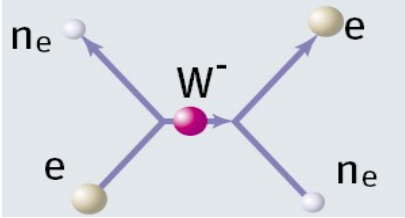
Interaction	Mediator	Range
electromagnetic	Photon γ	∞



Fundamental Interactions

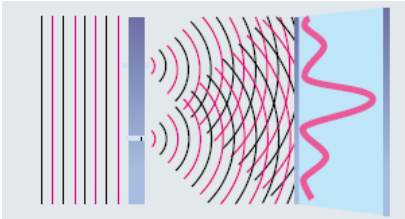
Interaction	Mediator	Range
electromagnetic	Photon γ	∞
weak	$W^{\pm}$, Z	10^{-18}

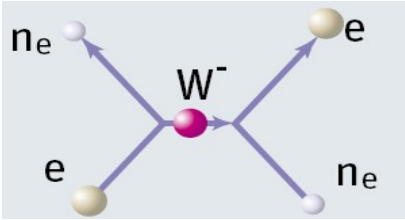


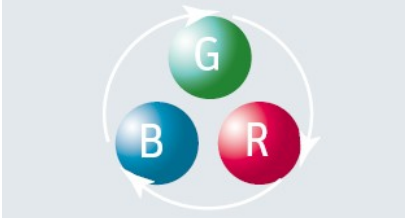


Fundamental Interactions

Interaction	Mediator	Range
electromagnetic	Photon γ	∞
weak	$W^{\pm}$, Z	10^{-18}
strong	8 gluons g	10^{-15}

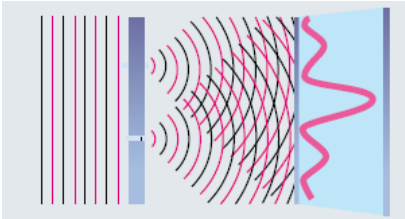


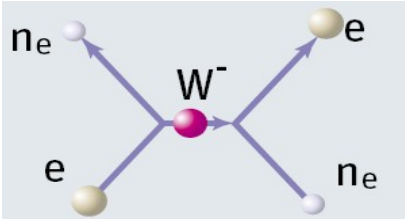


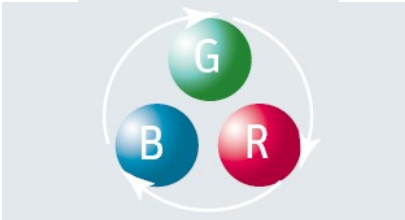


Fundamental Interactions

Interaction	Mediator	Range
electromagnetic	Photon γ	∞
weak	$W^{\pm}$, Z	10^{-18}
strong	8 gluons g	10^{-15}
gravitation	not included in existing models	

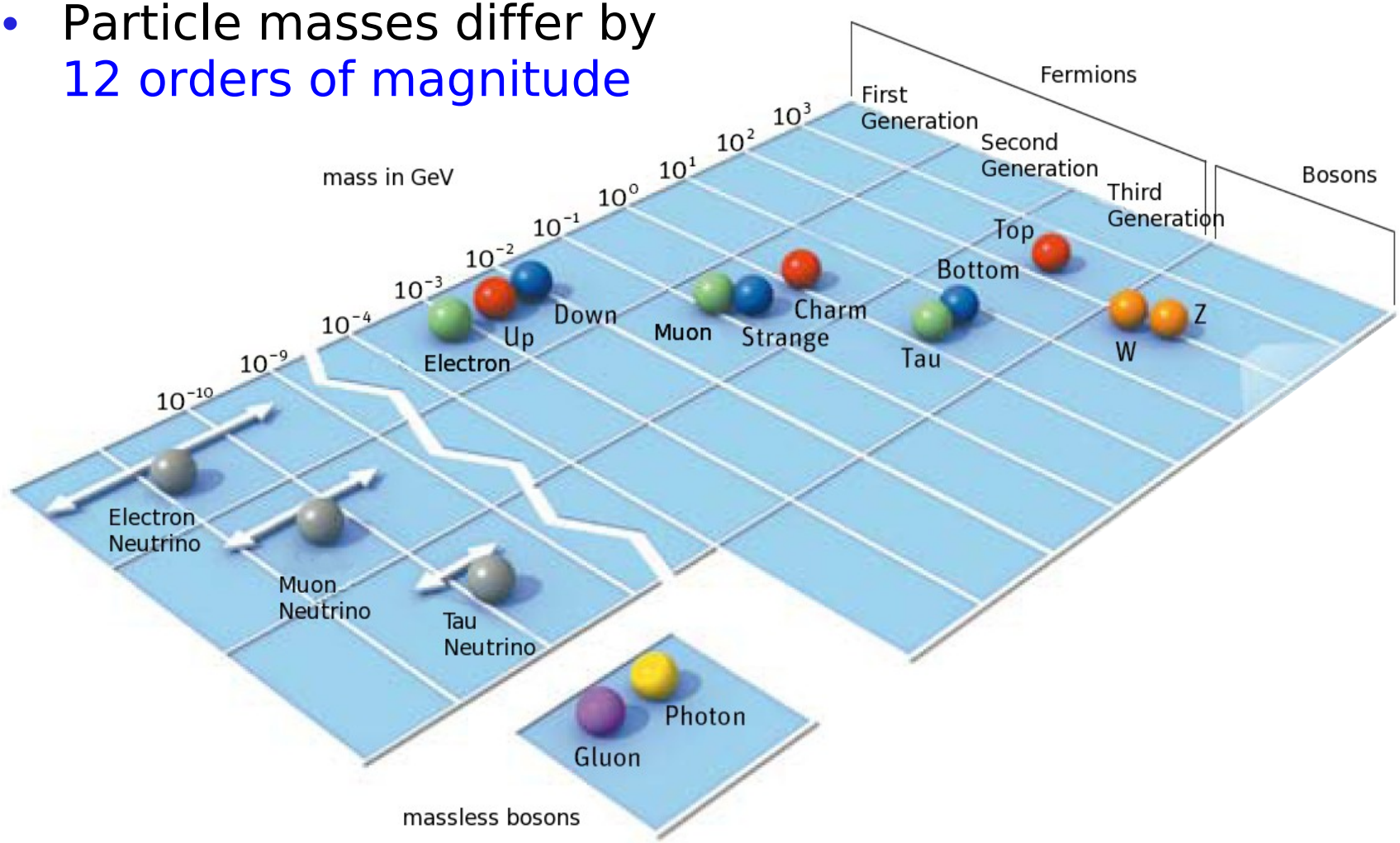






Elementary Particles

- Particle masses differ by 12 orders of magnitude



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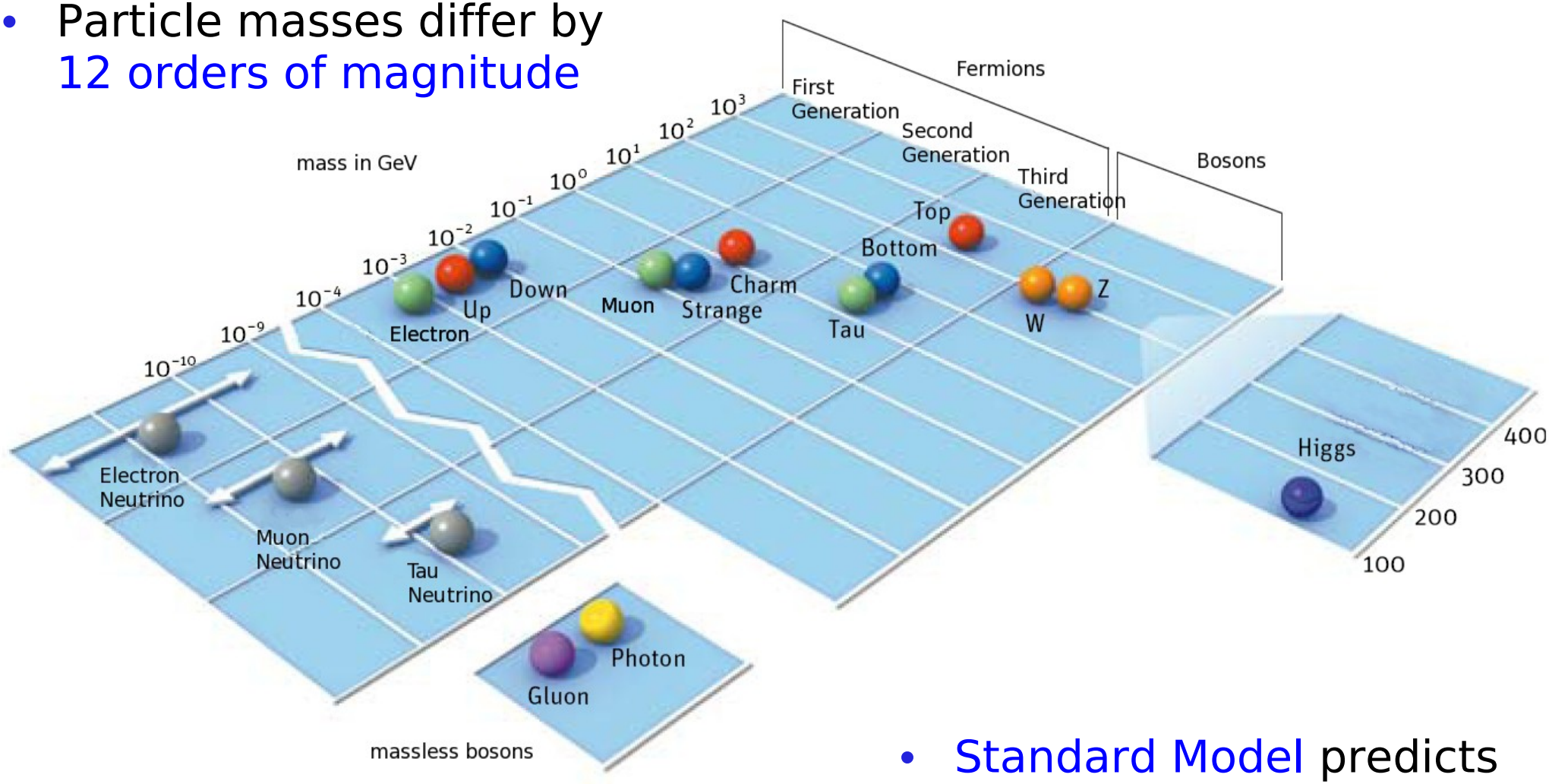

- Standard Model predicts Higgs boson

Elementary Particles

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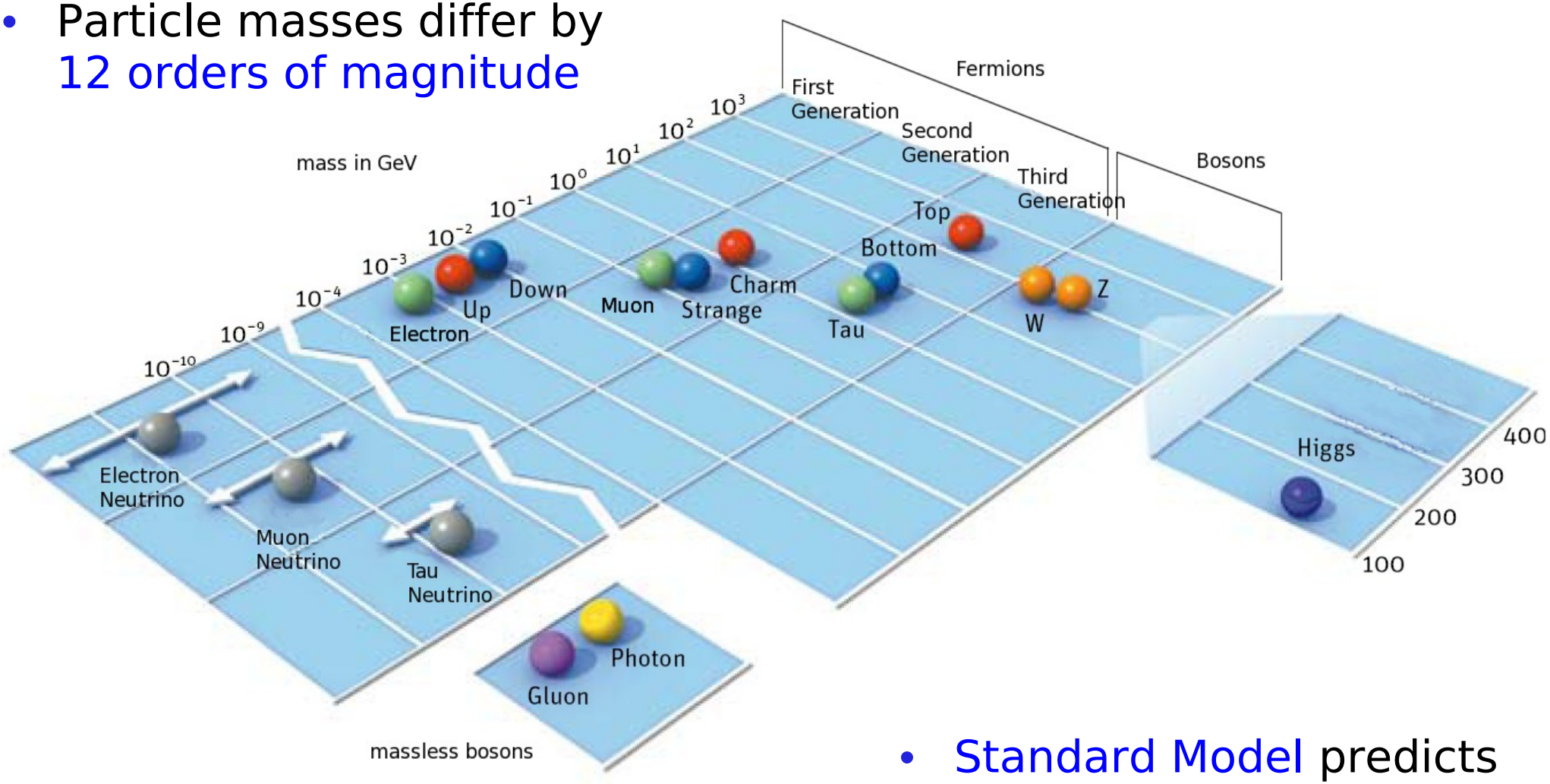


- Standard Model predicts Higgs boson

+ anti-particle for each particle
(identical mass, spin, opposite charge)

Generation of Masses

- Simplest proposed mechanism to generate fermion/boson masses → Universe filled by Higgs field

- Analogy: Higgs field = evenly distributed people

- Cluster of people makes it harder to move, to stop and to start again → Effectively increasing the mass

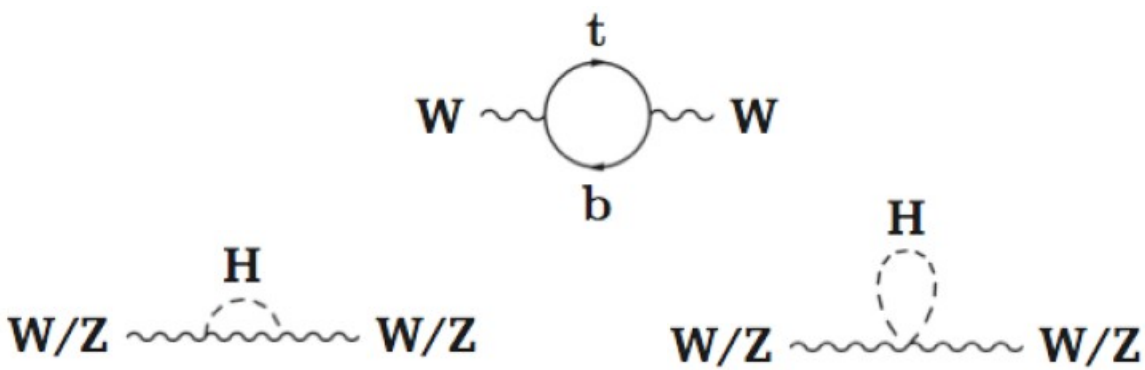
Generation of Masses

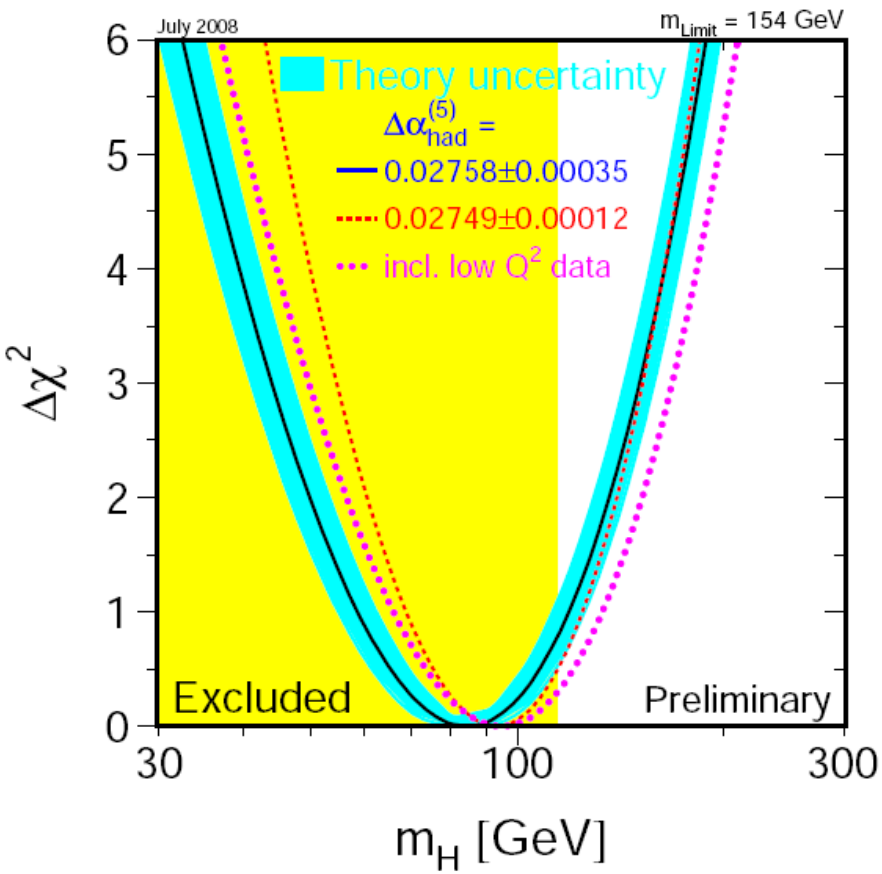
- Simplest proposed mechanism to generate fermion/boson masses → Universe filled by Higgs field

- Rumor passing the room may behave similar
  → the Higgs boson

Indirect Higgs Constraints

- Indirect constraints:
  - electroweak precision measurements: m_H<200 GeV
  - m_H, m_W and m_T are related via radiative corrections





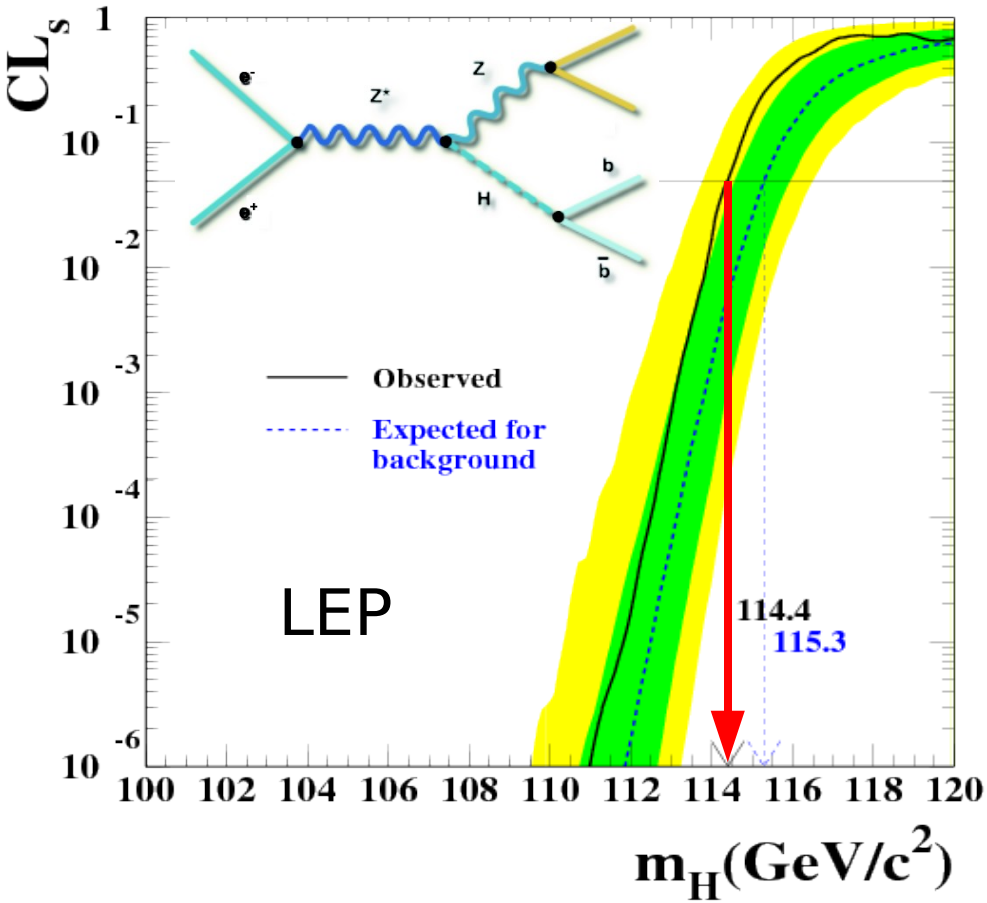
Electroweak Fits:

- $m_H = 84\ ^{+34}_{-26}$ GeV
- m_H< 154 GeV @95 C.L.

Direct Higgs Searches

– LEPII limit @ 95% C.L.:

m_H>114.4 GeV



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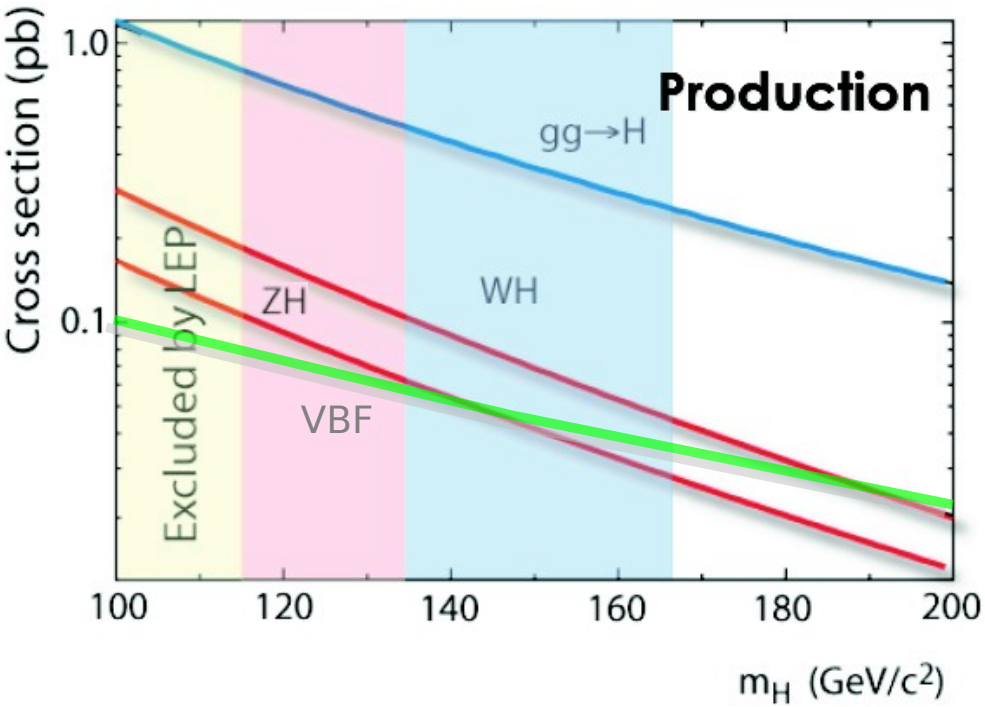
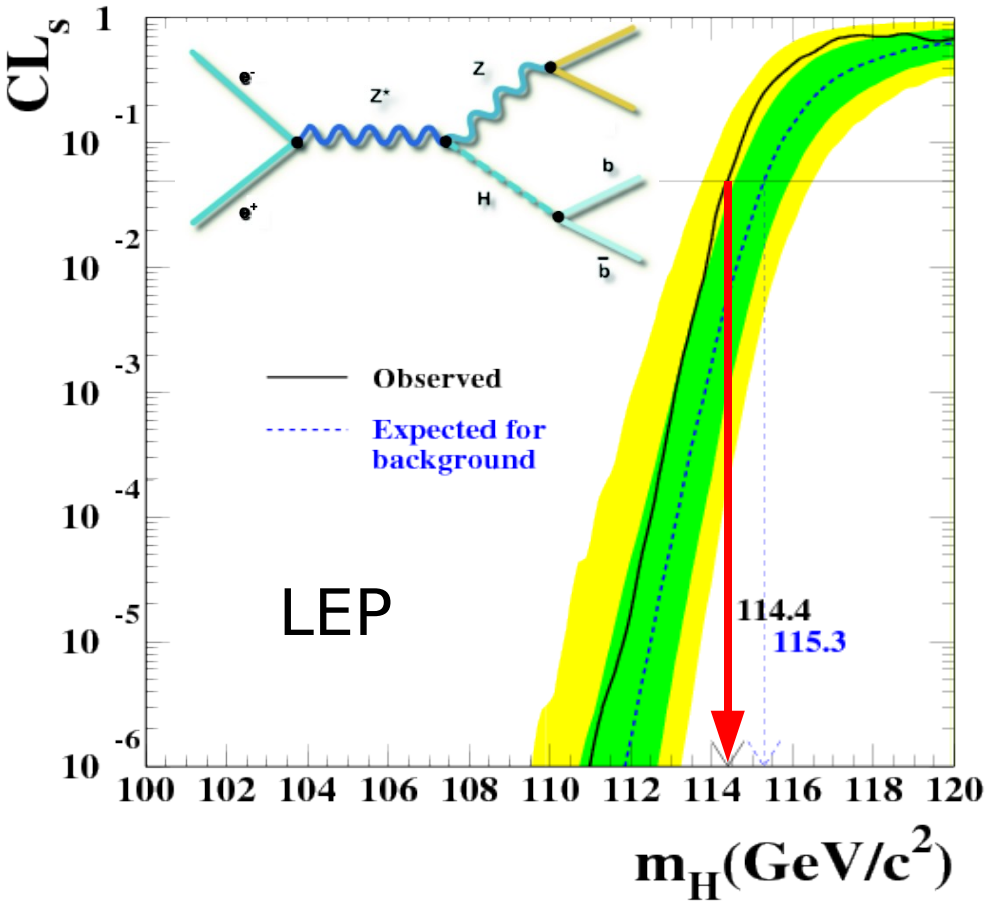




– Tevatron:
  - exp. 4000-400 Higgs events

Experimental Apparatus

The Tevatron Accelerator

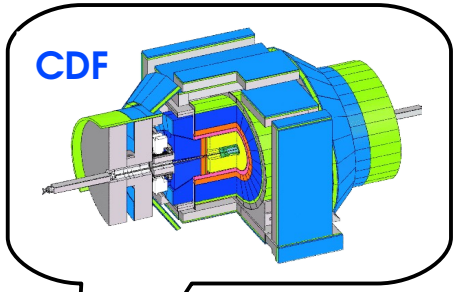
- So far Worlds highest energy collider

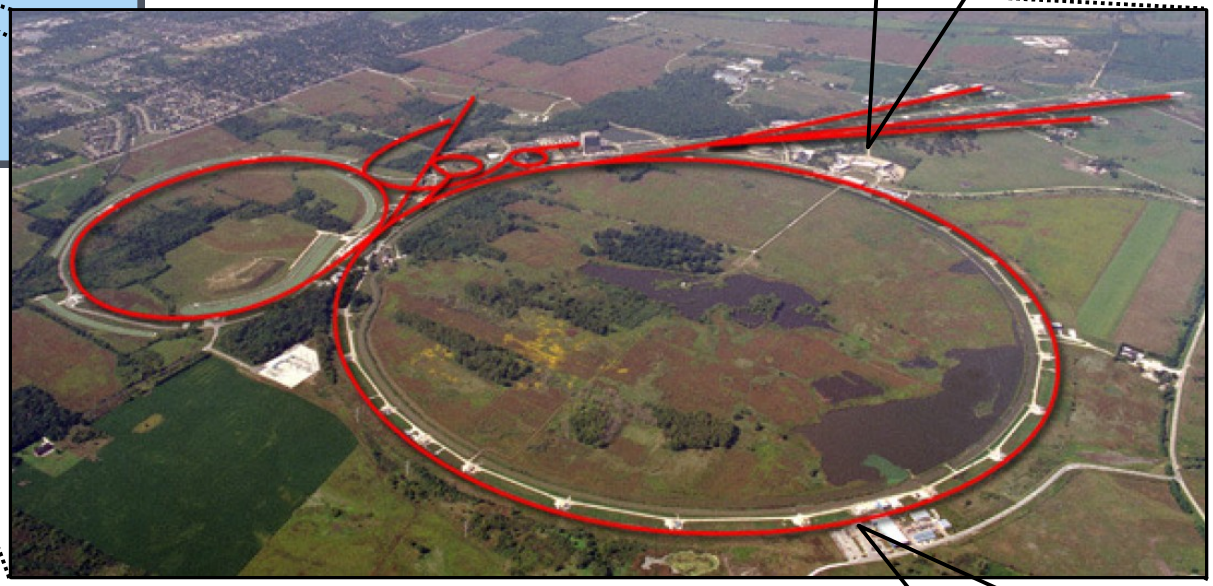
√s =1.96 TeV
Δt = 396 ns

Run I 1987 (92)-95 ← **Top quark discovery**
Run II 2001-1x: 40x larger dataset at increased energy ← **Higgs Evidence/ Discovery?**

The Tevatron Accelerator

- 2 Detectors
- Provides protons for ν experiment





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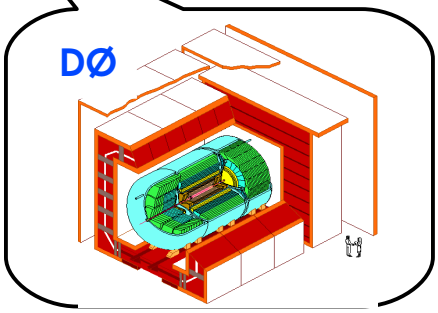
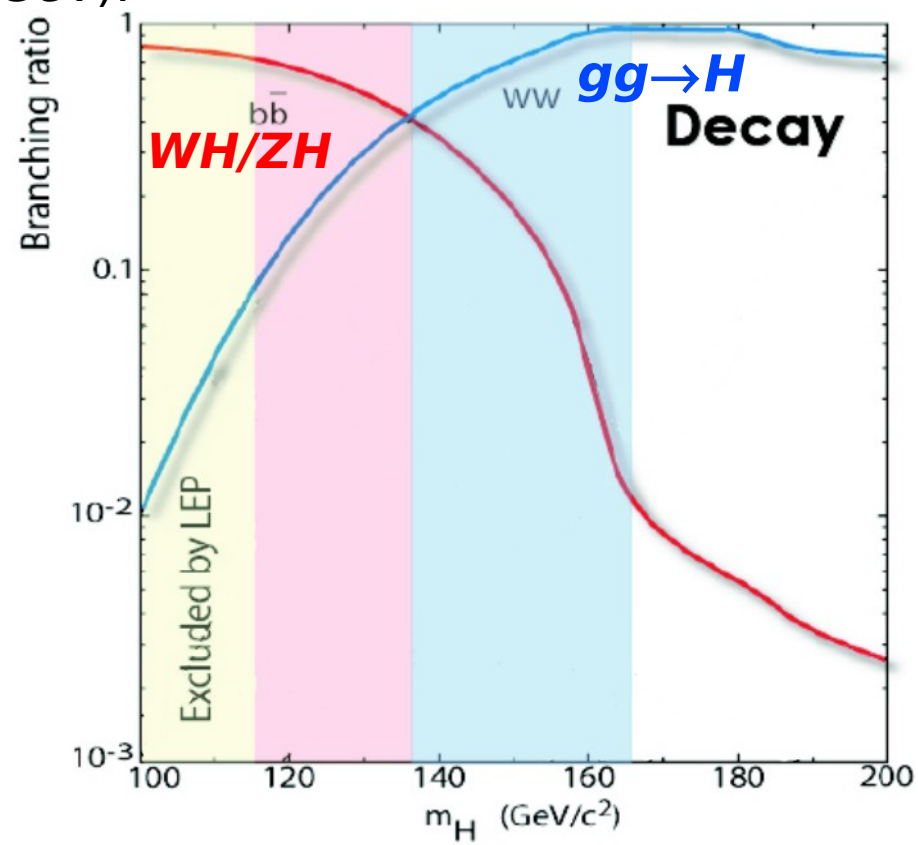


√s =1.96 TeV
Δt = 396 ns

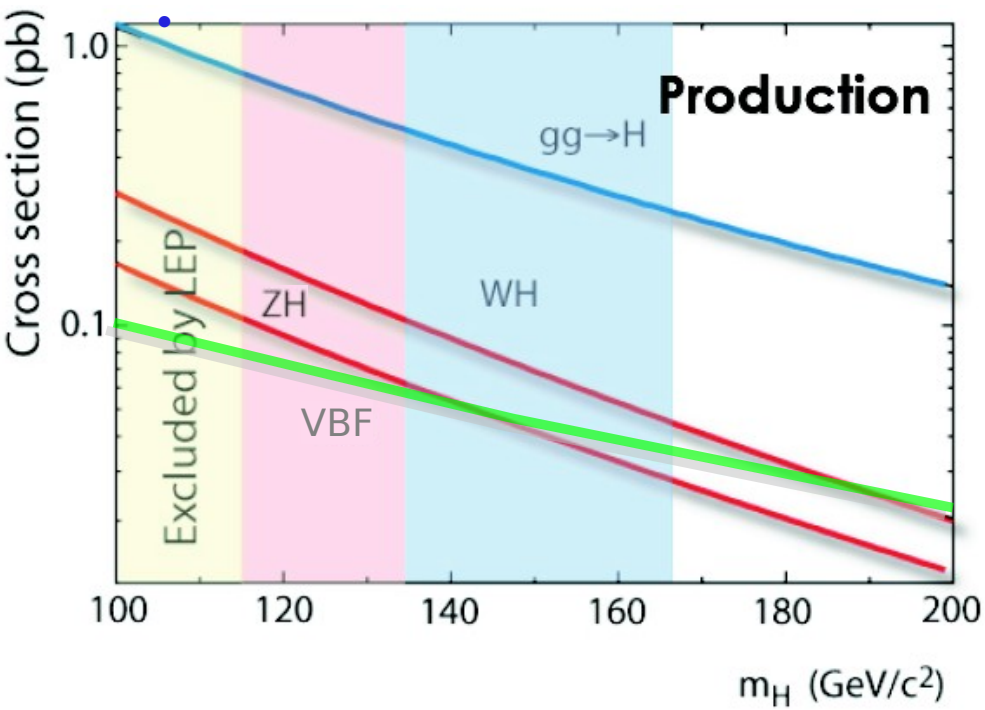
Run I 1987 (92)-95 ← **Top quark discovery**
Run II 2001-1x: 40x larger dataset at increased energy ← **Higgs Evidence/ Discovery?**

Higgs Production and Decay

- Cross Section Higgs production (80<m_H<200 GeV):
  - $\sigma(gg \to H) \approx 2 - 0.1\, pb$
  - $\sigma(q\bar{q} \to HW) \approx 0.6 - 0.02\, pb$



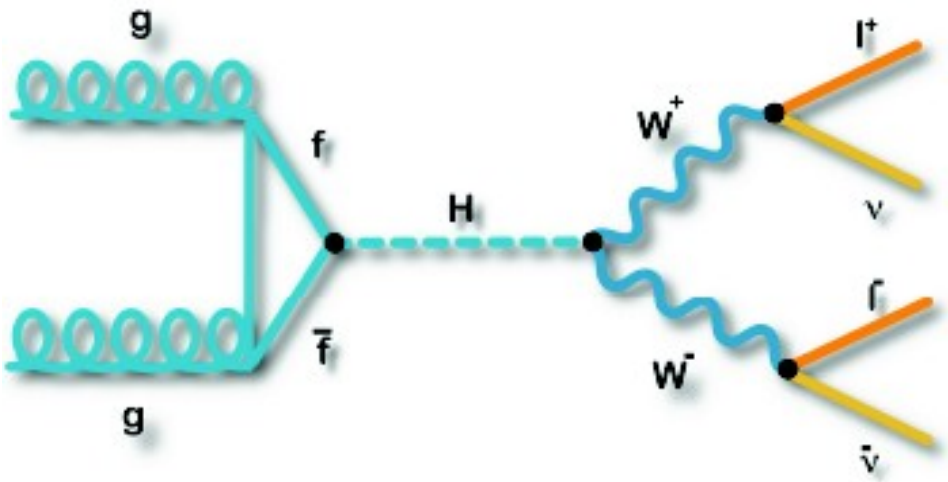
- Production Channels
  - $gg \to H \to WW \to \ell\nu\ell\nu$
  - associated WH/ZH production
  - $qq \to qq'H \to WW \to qq\ell\nu\ell\nu$

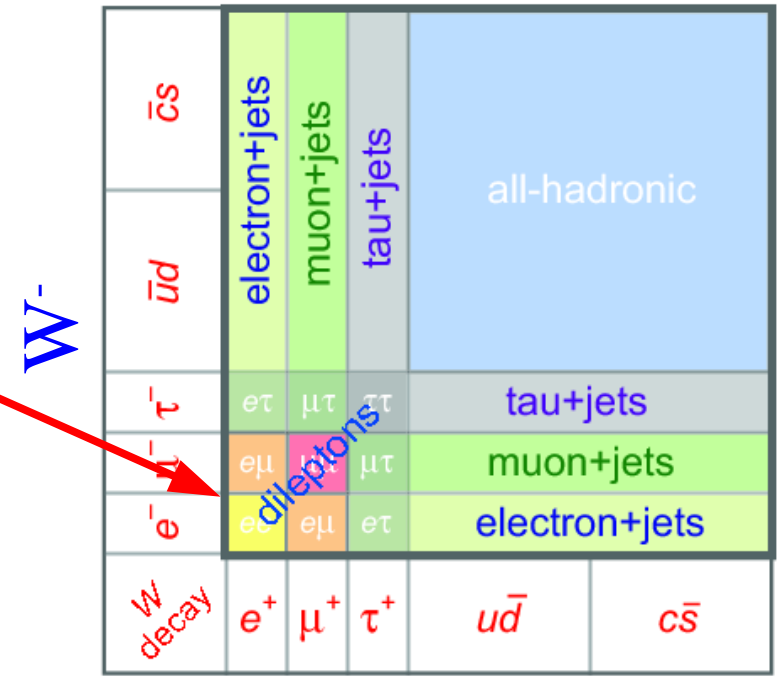


Main production via Gluon Fusion and Associated Production, dominant decay:

- m_H<135 GeV: $b\bar{b}$
- m_H>135 GeV: $WW \to \ell\nu\ell\nu$ decay

Search Strategy



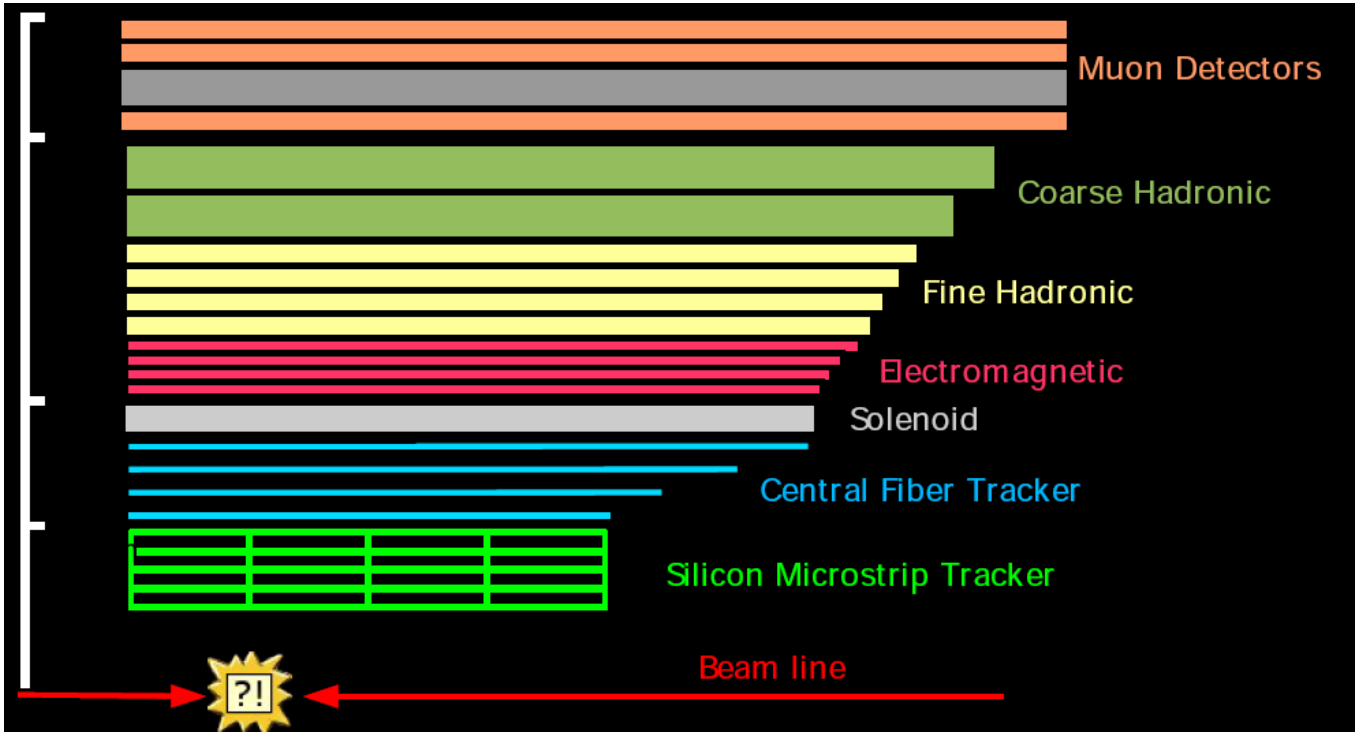


- Looking for Events with:
  - Two high p_T leptons
  - High missing transverse momentum (ν)
  - Oppositely charged leptons
- Major channels: $\mu\mu$, $e\mu$, ee, $\tau \rightarrow e/\mu$

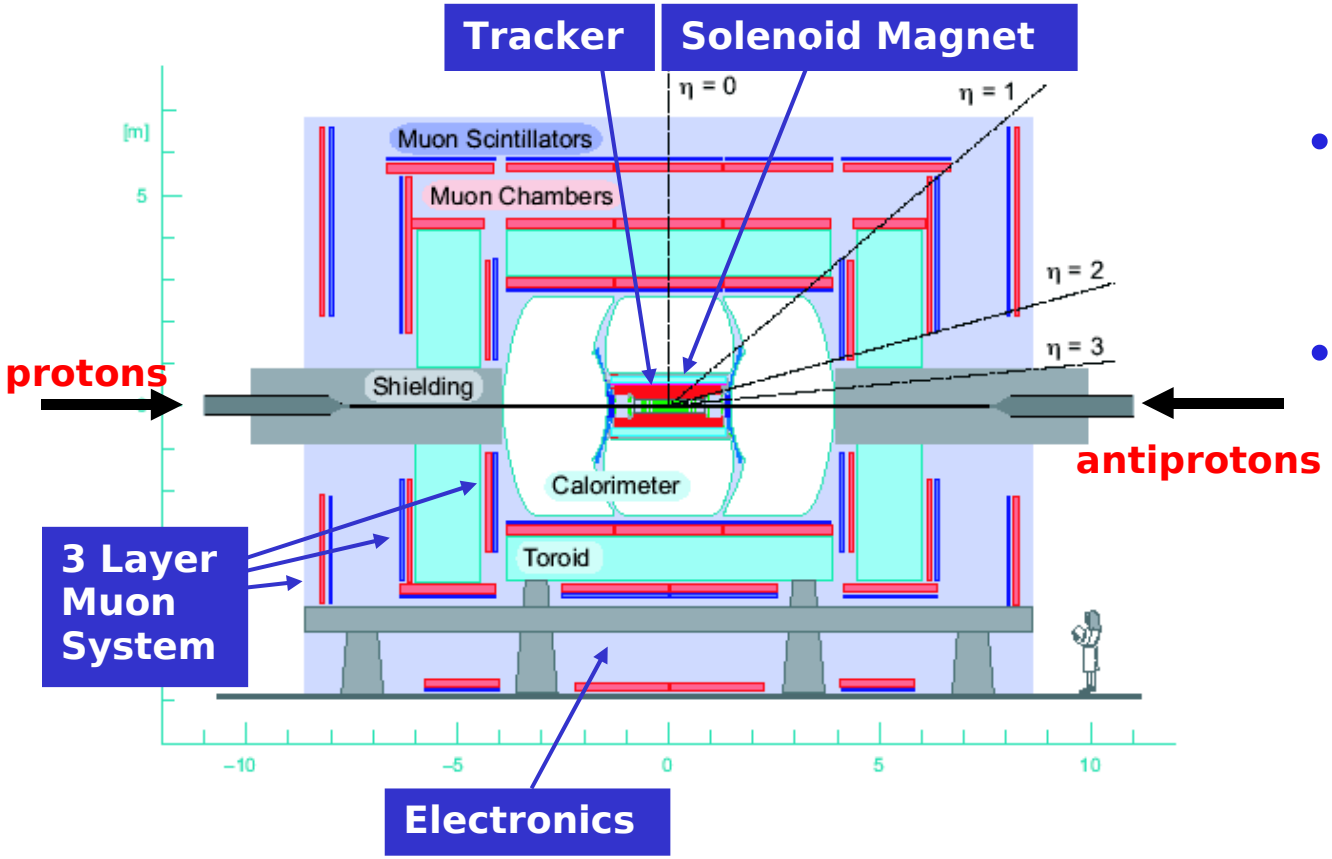
Principle of Particle Detection

- But how do we look...
  - Particles are detected by their interaction in matter
  - Various particles are able to penetrate various depths of matter

→ Layer structure of detectors

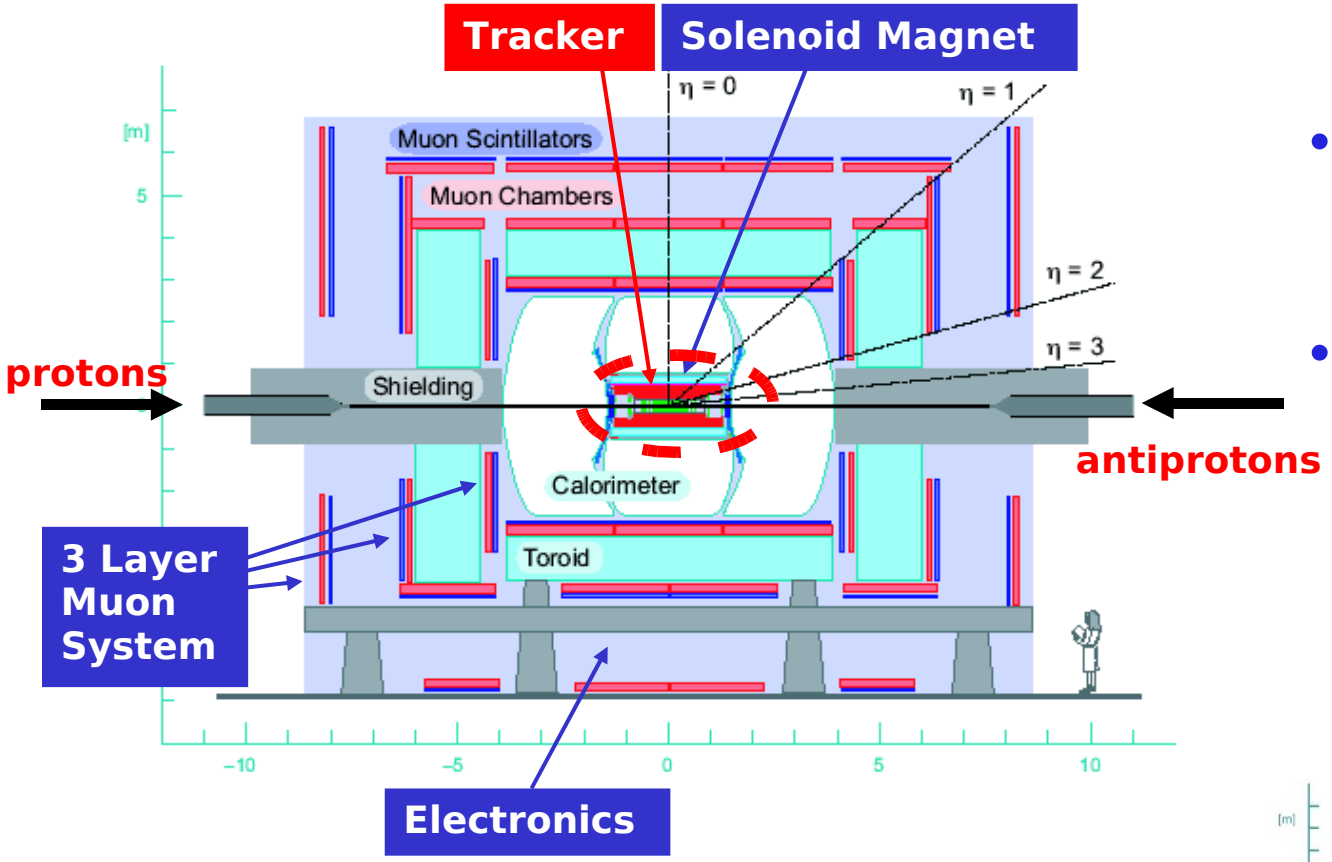


The DØ Experiment



- General high p_T physics detector
- Excellent coverage of:
  - Tracking
  - Muon
  - Calorimeter

Momentum Measurement



- General high p_T physics detector
- Excellent coverage of:
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  - Muon
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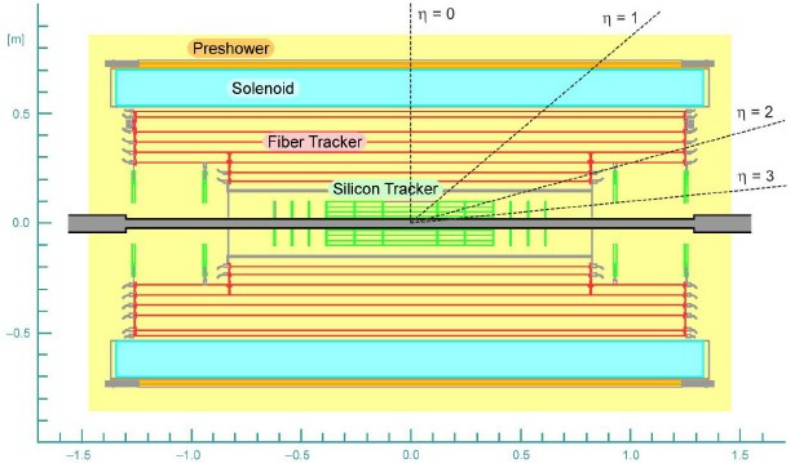
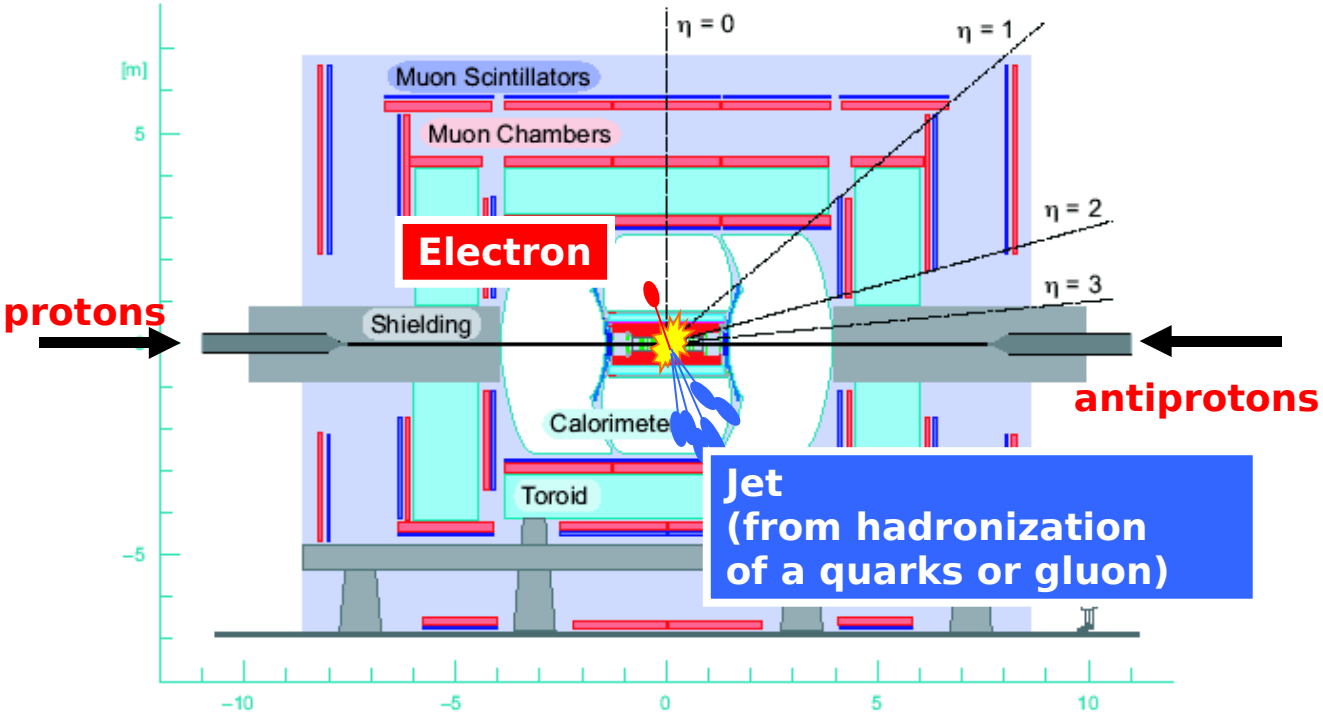
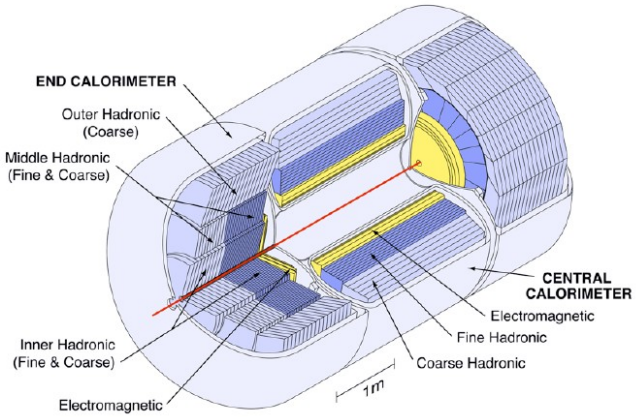
- Tracking:
  - Coverage: $\eta<3$
  - Tracks of charged particles Vertex-Identification



Electron/Jet Measurement

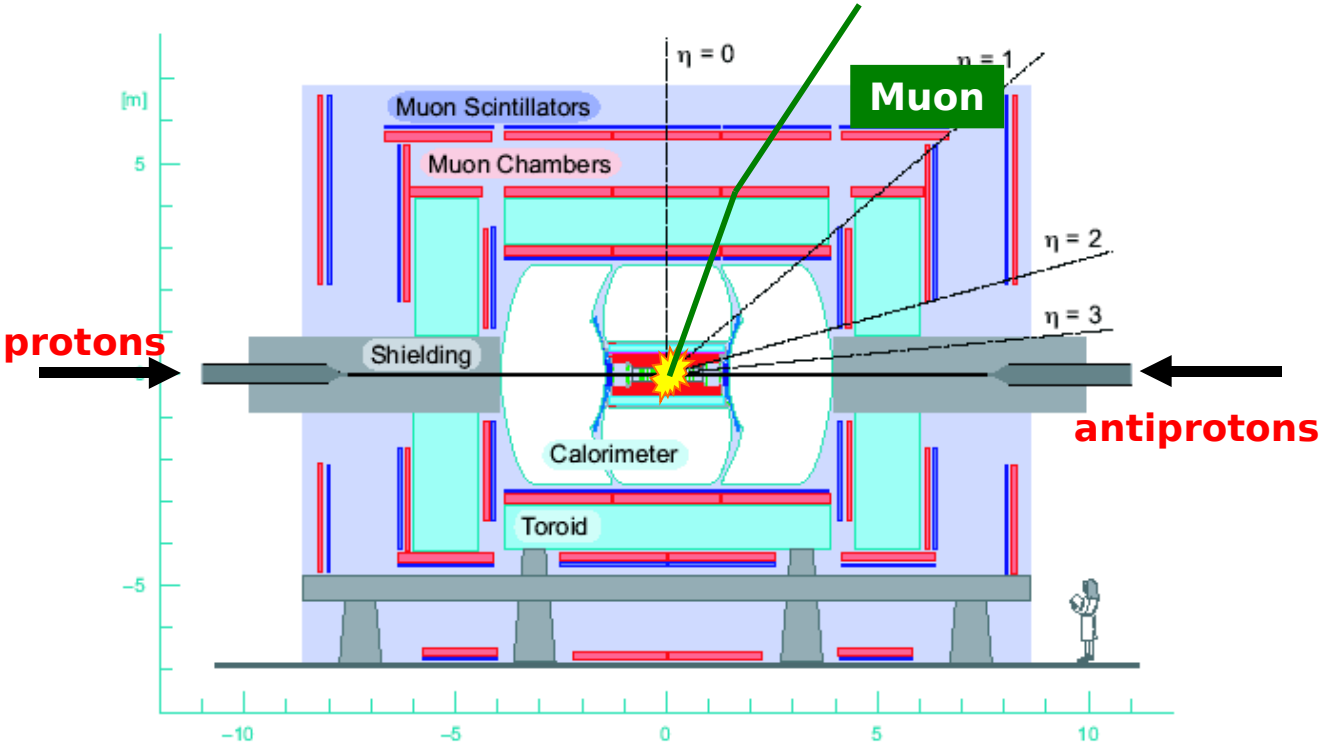




Calorimeter:

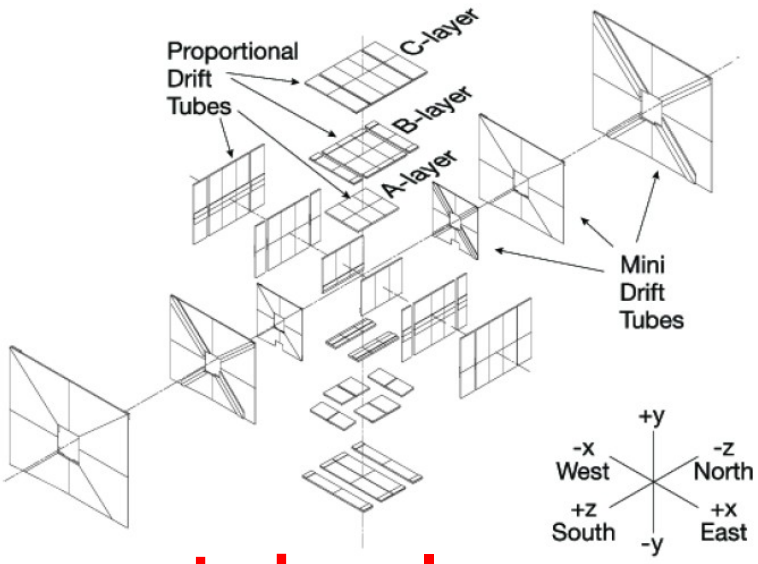
- Liquid Argon/Uranium
- Coverage: $\eta<4.2$
- Reconstruction of electrons, jets and taus

Muon Measurement



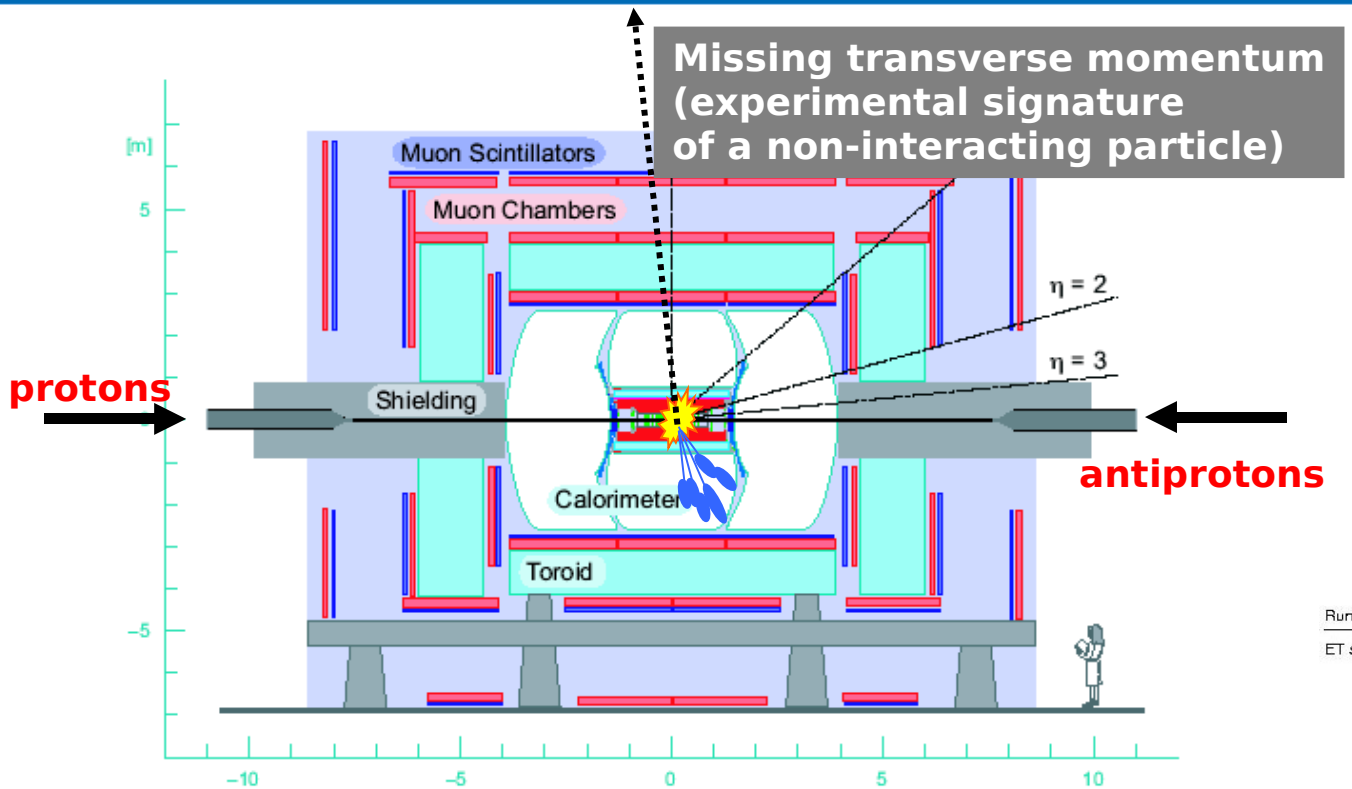
Muon Chambers:

- Muon-Reconstruction
- Coverage: $\eta<2$

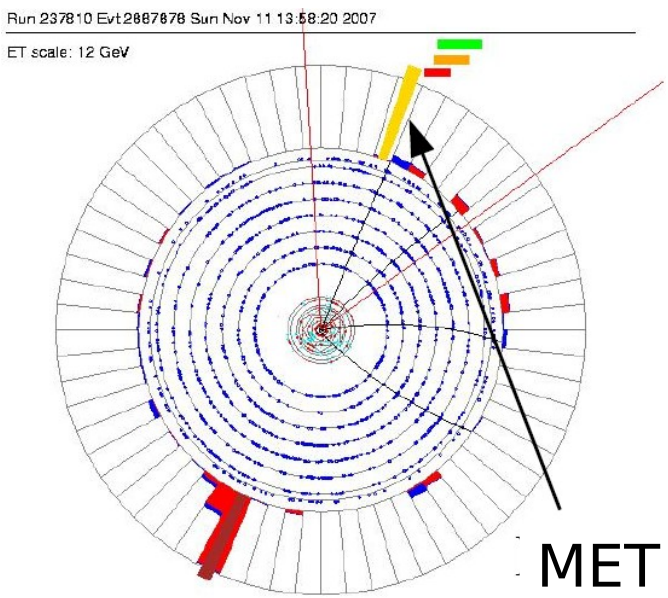


All sub-detectors used in presented analyses

Neutrino Measurement



- ν escape detector



- Imbalance in transverse plane

On the way to analysis

Participated in all steps from data taking to higher level analysis

Data Taking

↓

Calibration

↓

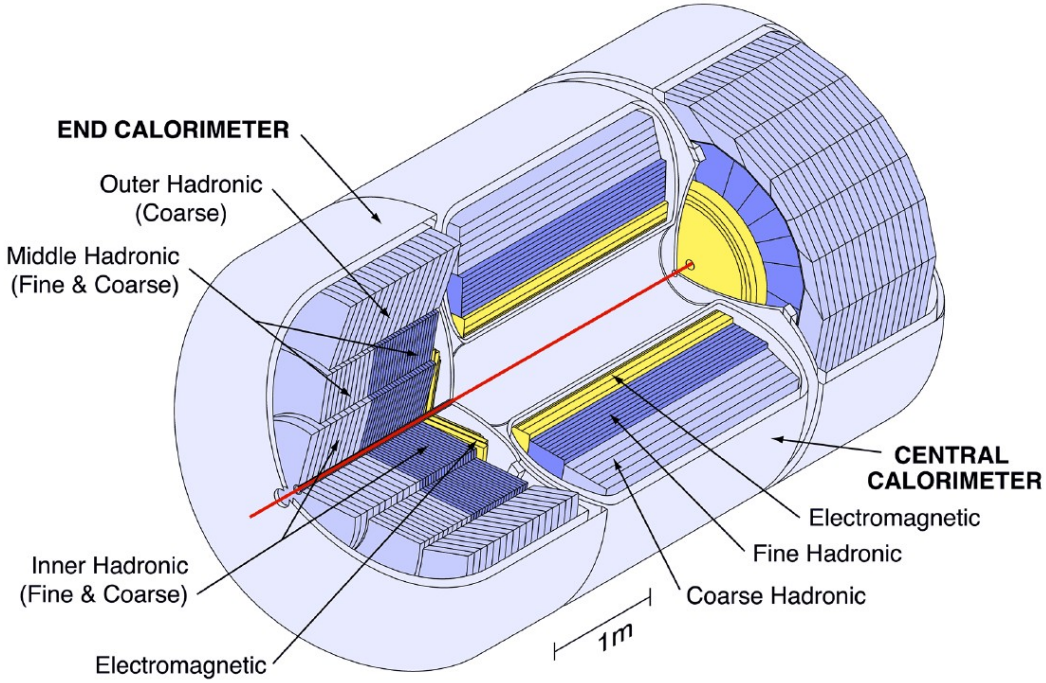
Particle-ID

↓

Analysis

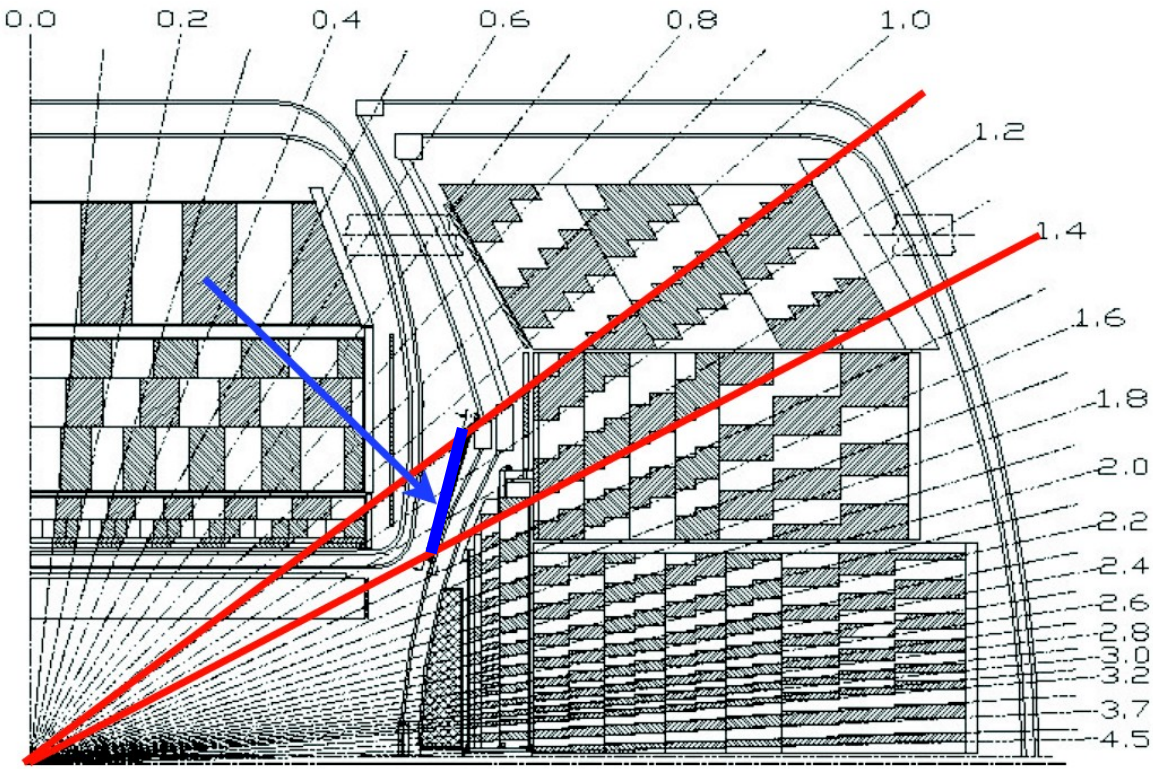
Data Taking

- 2 ½ years as Calorimeter Expert
- Detect/prevent hardware failures
- Training of shifters
- online/offline assessment of problems



Calibration

- Participated in calorimeter calibration
- Leading role in re-commissioning of the Inter-Cryostat-Detector (ICD)

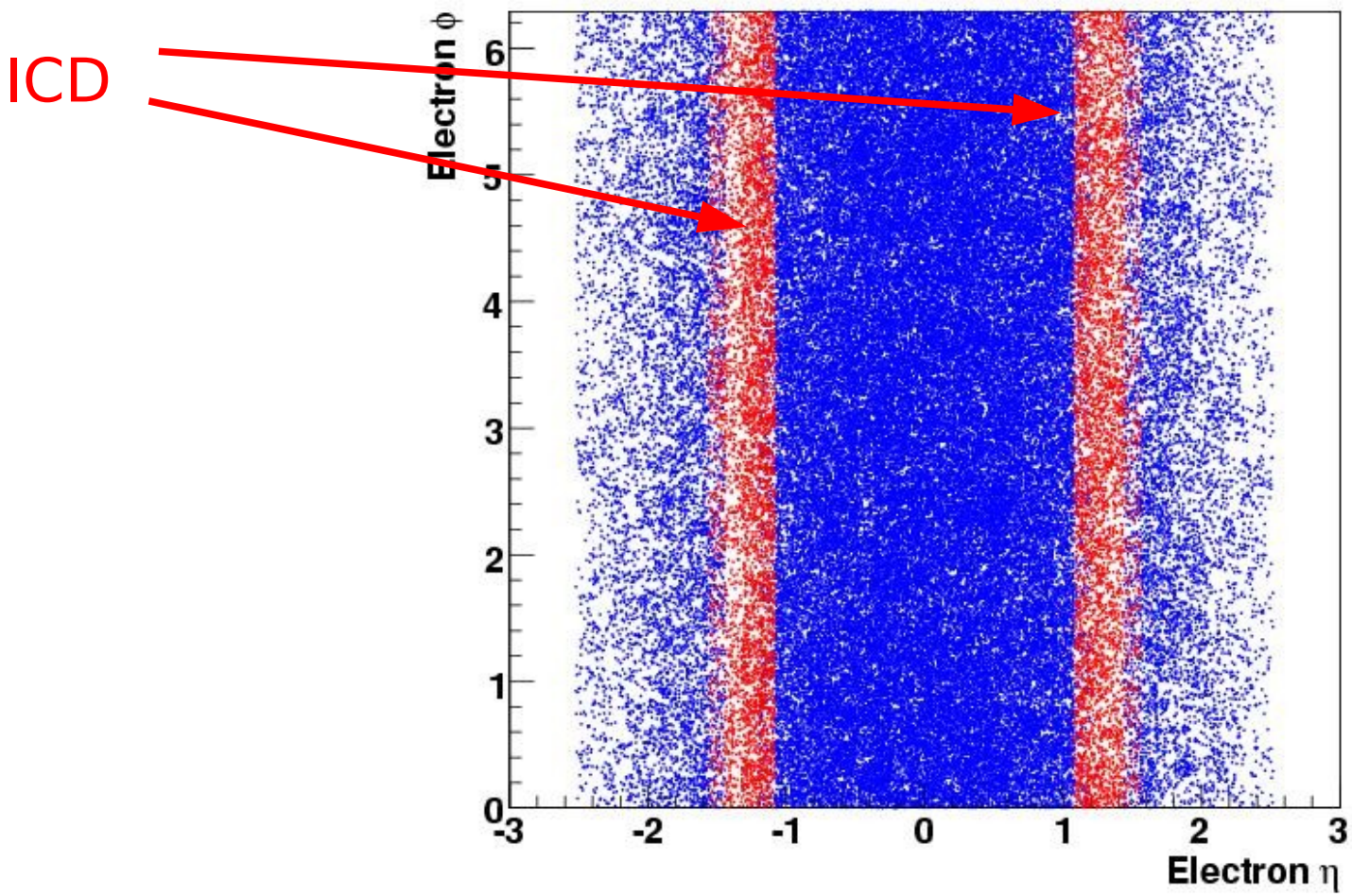


- Scintillator sampling

Energy flow method → assuming azimuthal symmetry

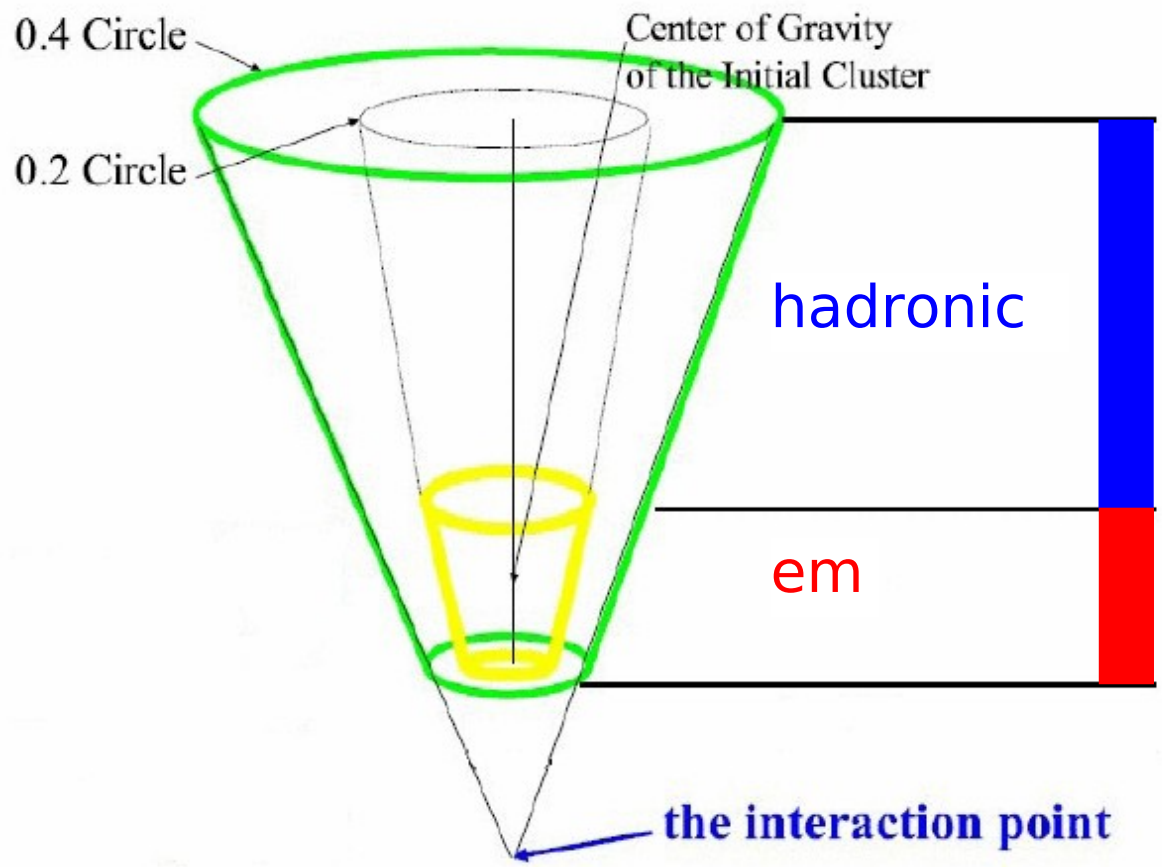
Calibration

- Calibration lead to more uniform calorimeter response



gaining about 20% in signal efficiency

Electron-ID



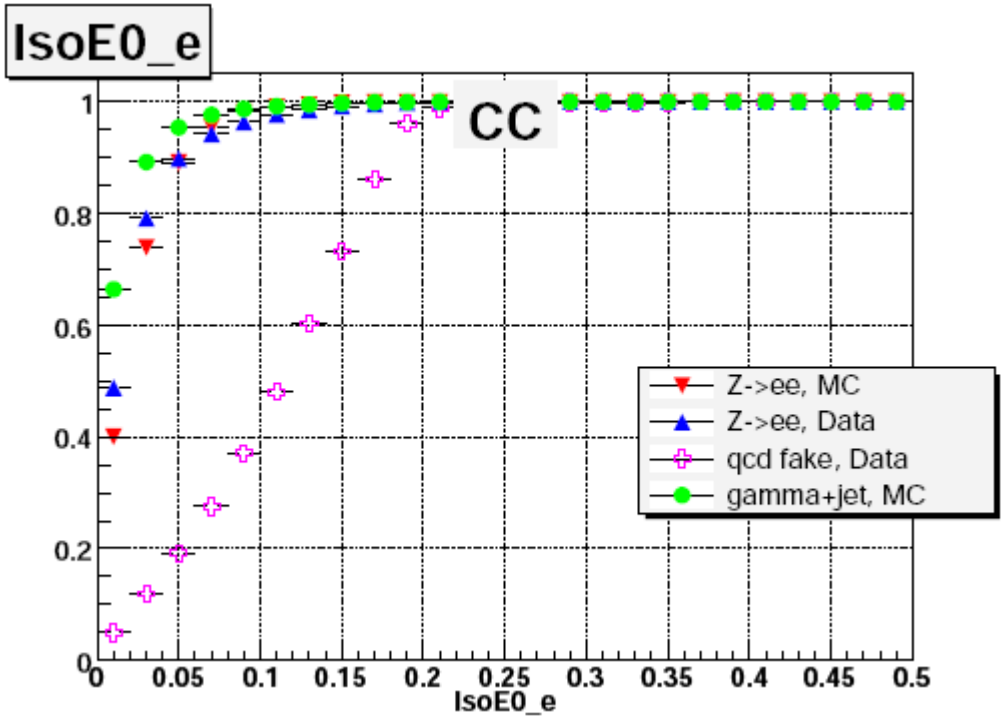
EM-Fraction: (■)/(■+■)>0.9

Isolation: <0.2

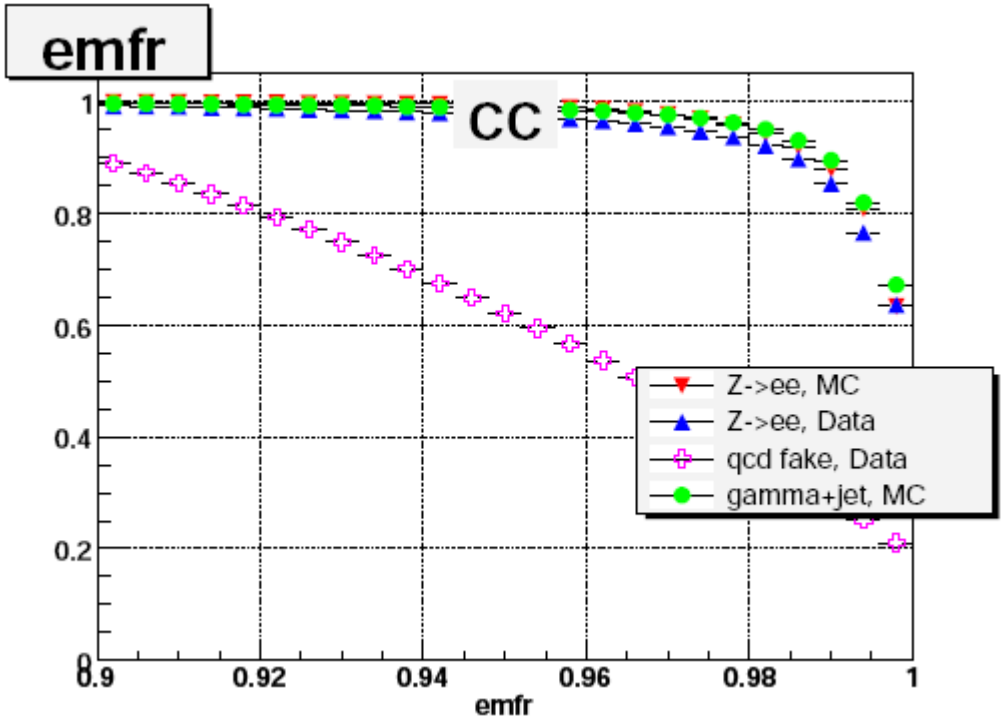
- Challenges in Run IIb
  - Higher luminosity
  - Low track eff. in forward region
  - Degrading tracking eff.
- Electron Identification based on
  - Isolation in cal/tracker
  - EM fraction
  - Lateral/longitudinal Shower shapes
  - Multivariate methods
  - Track qualities
- Separate for central/endcap

Electron-ID

Isolation



EM-Fraction

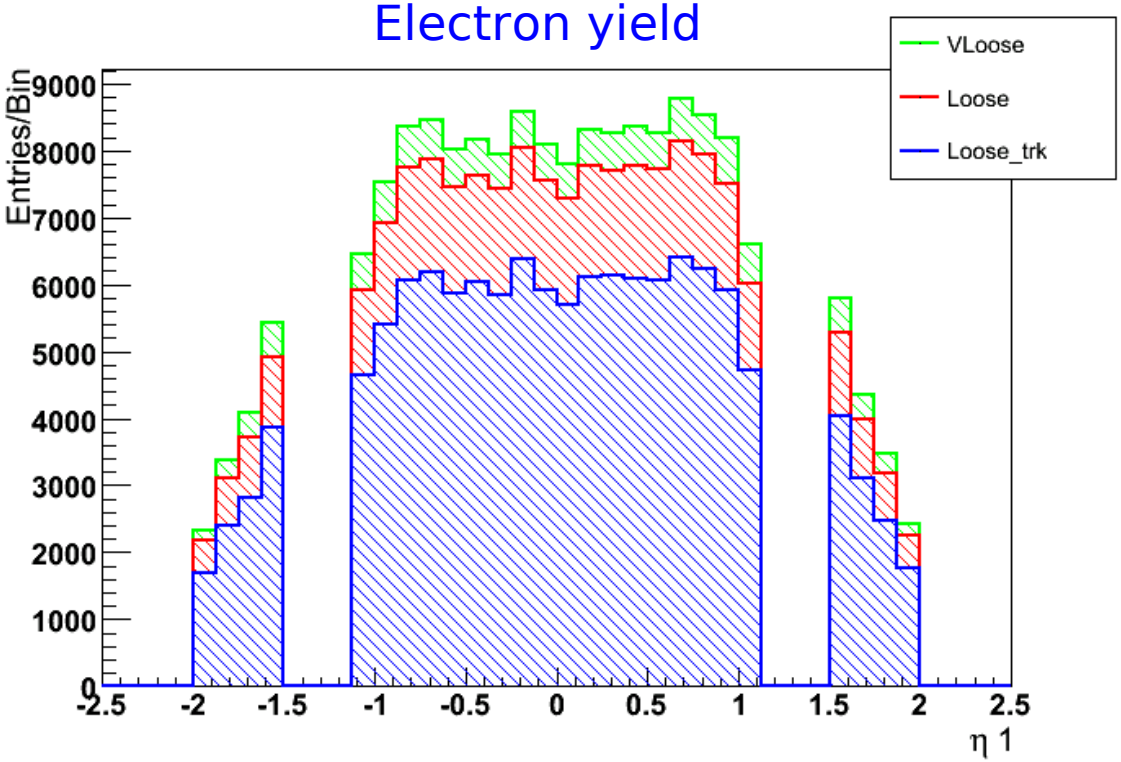


Particle-ID

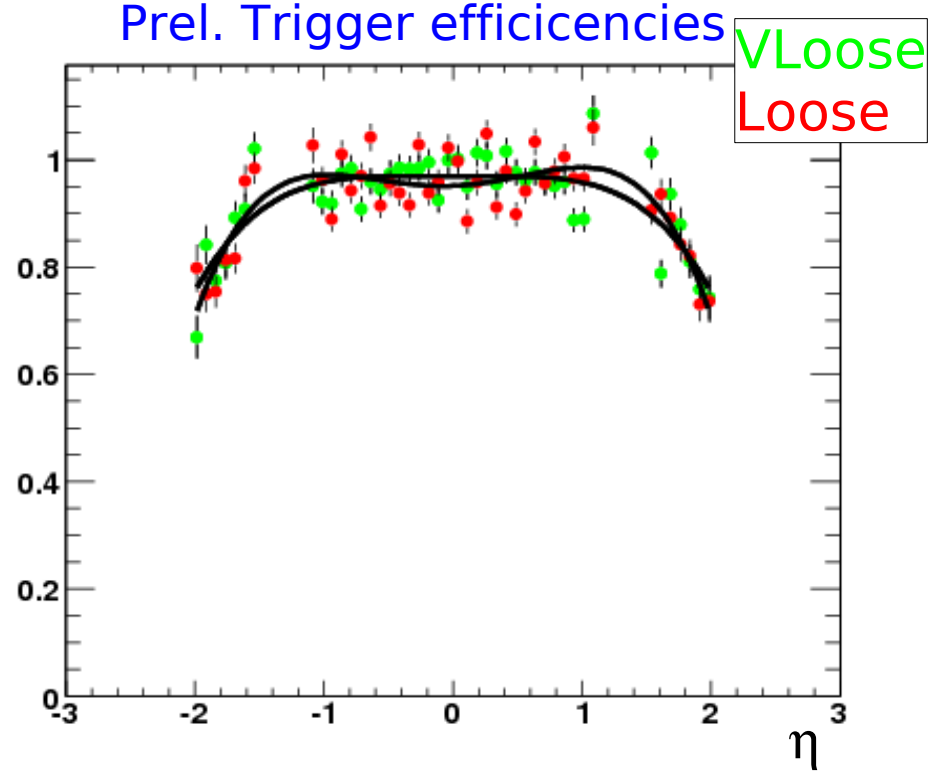
- Co-developed new Electron-ID algorithm

  → 6% efficiency gain

Electron yield



Prel. Trigger efficicencies



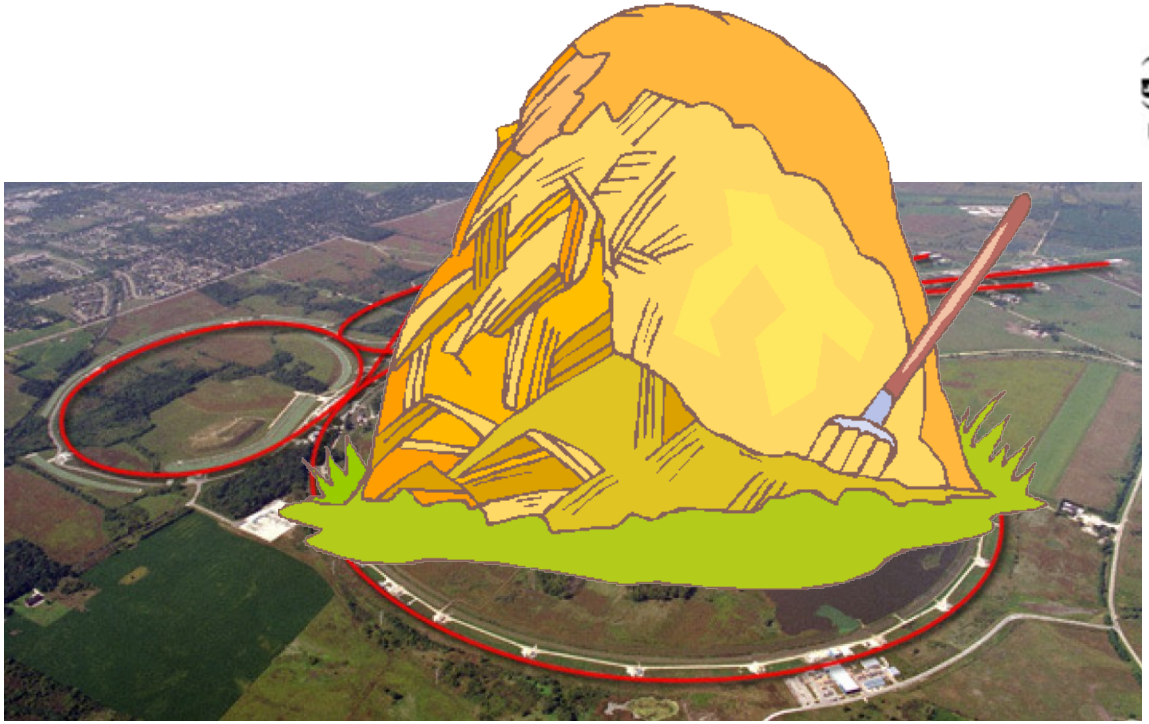
First to apply new methods in analysis

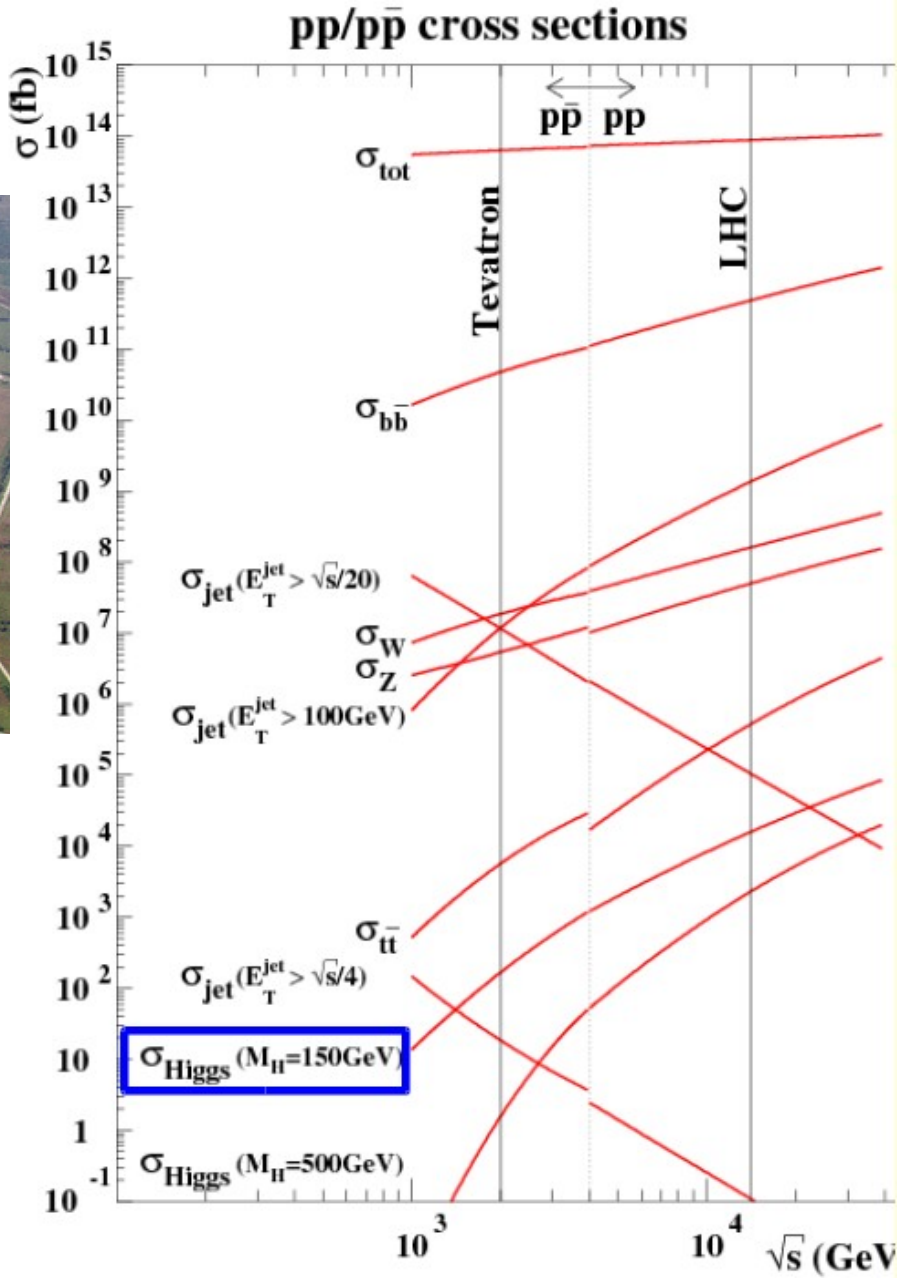
High mass Higgs search at DØ

H→WW→eνeν

- If not mentioned otherwise plots shown in the following will be from the H→WW→eνeν channel
- Responsible analyzer for this particular sub-channel
- However, each method and tool for all H→WW analysis channels at DØ was developed by me and passed on

A stretched analogy… revisited





- Comparing $\sigma_{tot}/\sigma_{Higgs}$ with the density of a haystack

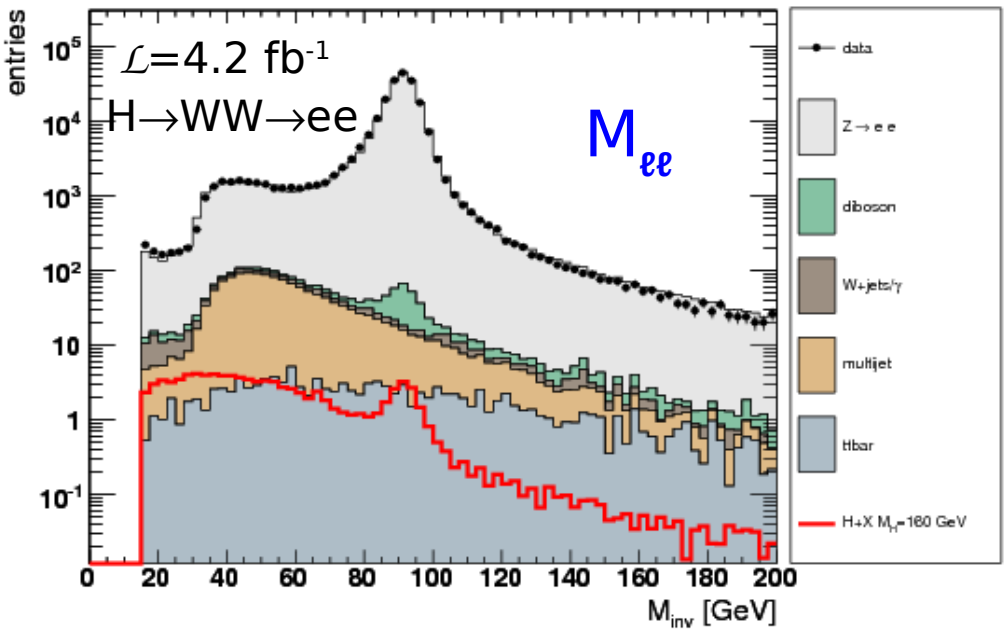
  → $r_{haystack}$=620m

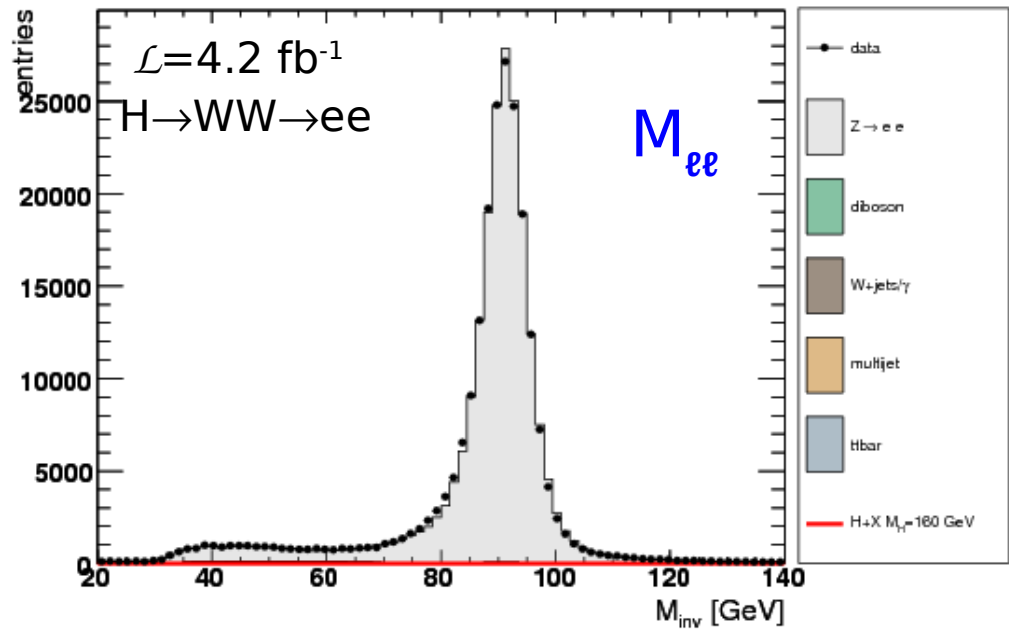
Data/MC Comparison

- Preselection requirements:

  lepton p_T >15 GeV, M> 15 GeV, opposite charge

- using dedicated set of lepton, di-lepton and E_T^{miss} trigger
  S:B ~ 1:20000





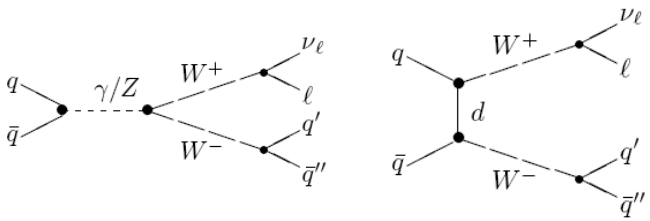
Very good agreement

Background Contributions

- **Di-Boson (WW, WZ, ZZ):**
- **Electroweak (W+jets/γ):**
- **Double-Top production:**
- **Drell-Yan (Z/γ):**
- **Multijet:**

Background Contributions

- **Di-Boson (WW, WZ, ZZ):**
  - Two leptons
  - Very signal like, high E_T^{miss} from W decays
  - Almost identical to Signal



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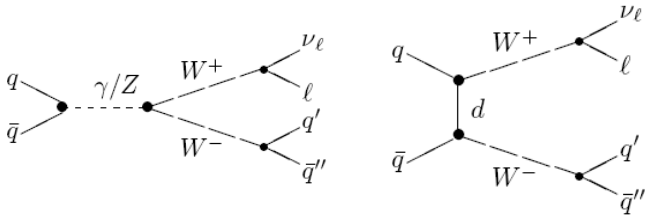

- **Electroweak (W+jets/γ):**
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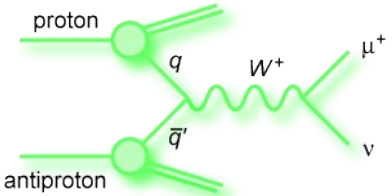

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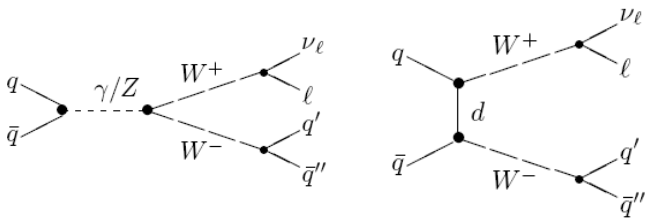

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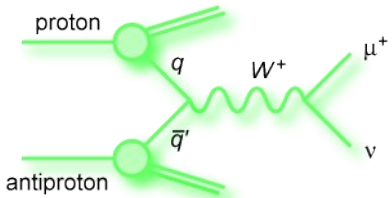

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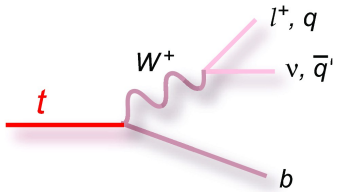

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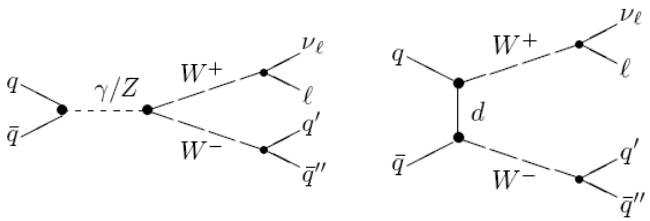

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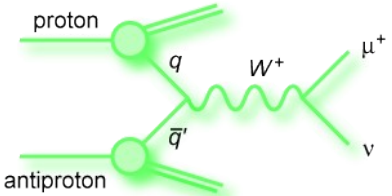

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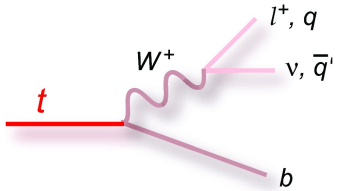
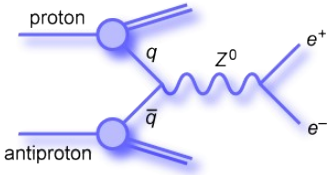


- **Drell-Yan (Z/γ):**
  - Two real leptons,
  - E_T^{miss} from mismeasurements



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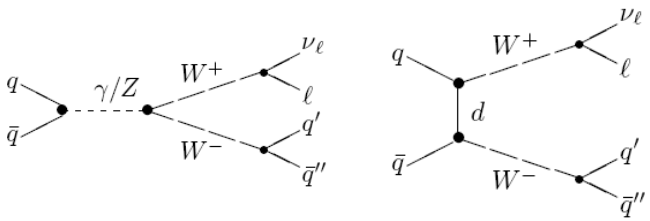

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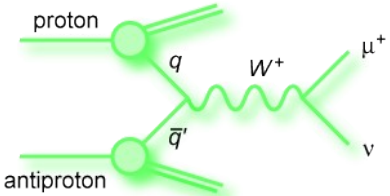

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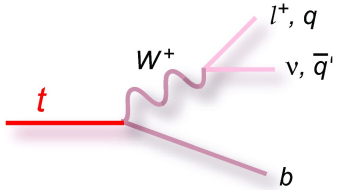

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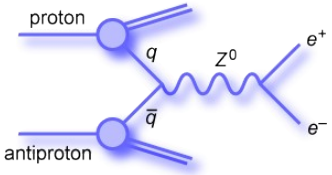
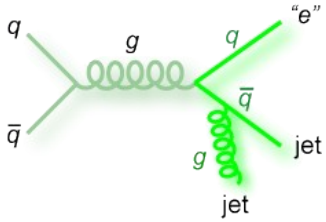
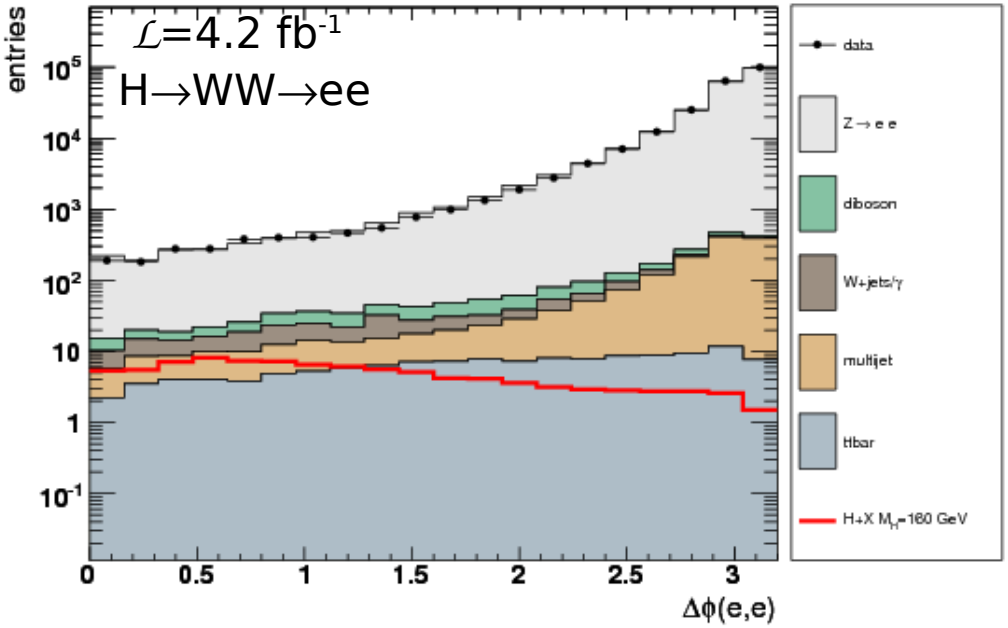


- **Multijet:**
  - Jets or low p_T leptons faking signal
  - Estimated from Data



Selection Requirements

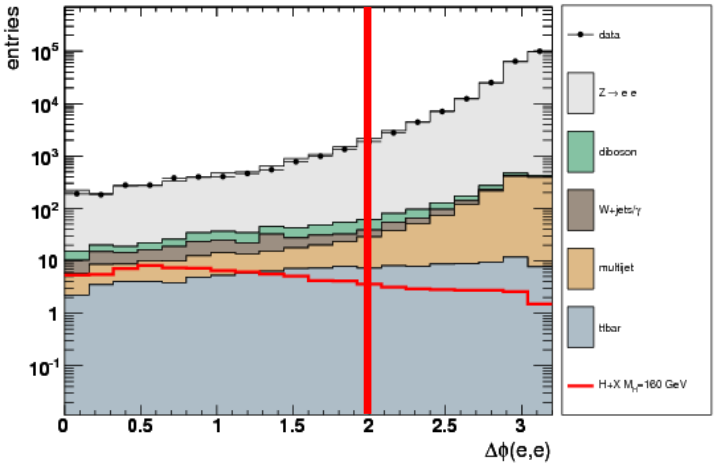
further background suppression:

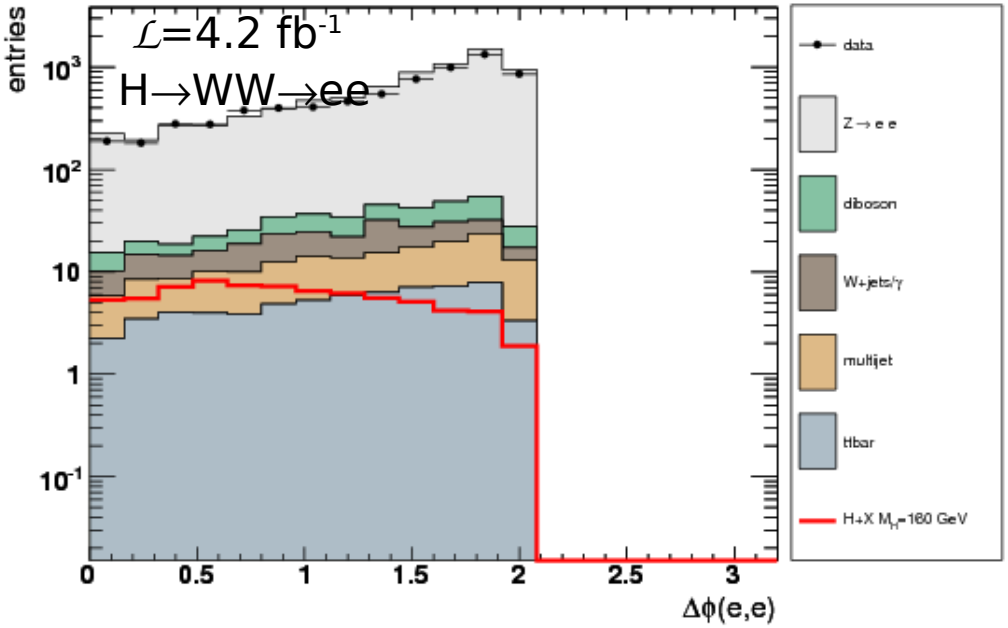


Selection Requirements

further background suppression:

- $\Delta\phi(\ell,\ell)<2$

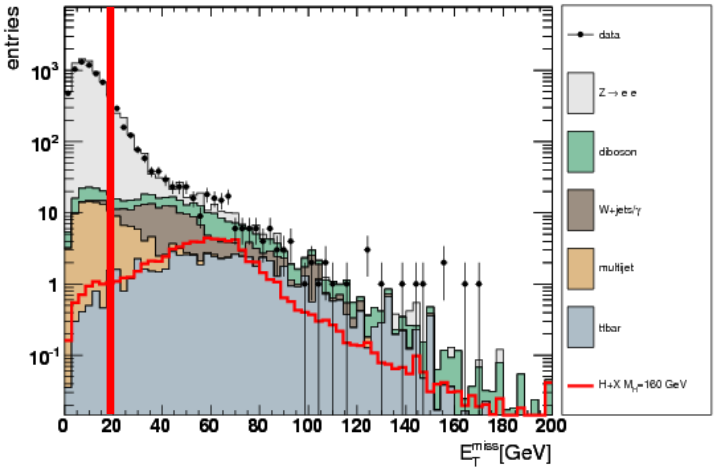


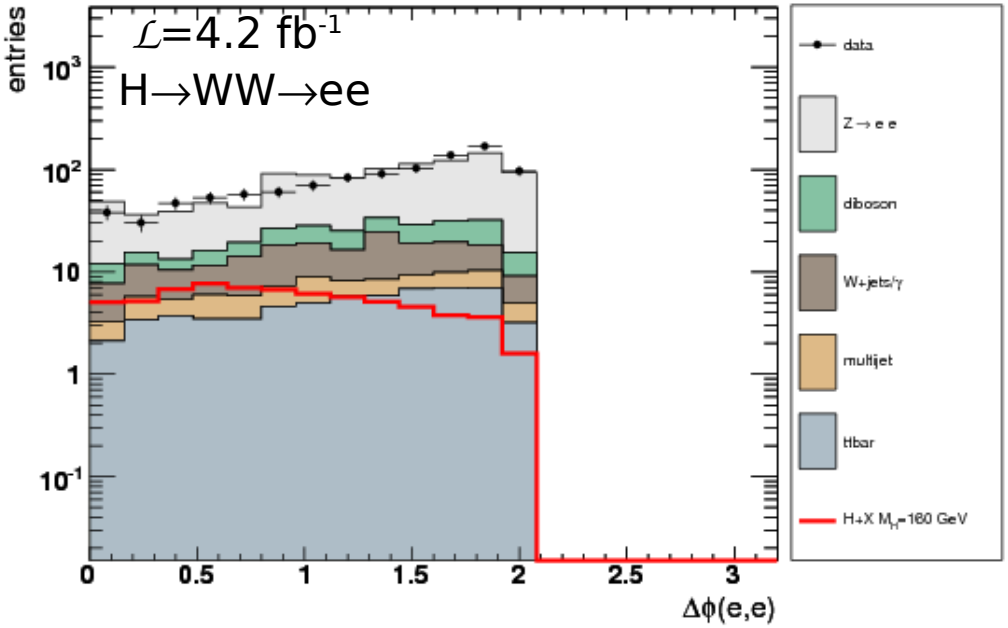


Selection Requirements

further background suppression:

- $\Delta\phi(\ell,\ell)<2$
- $E_T^{miss}>20$ GeV





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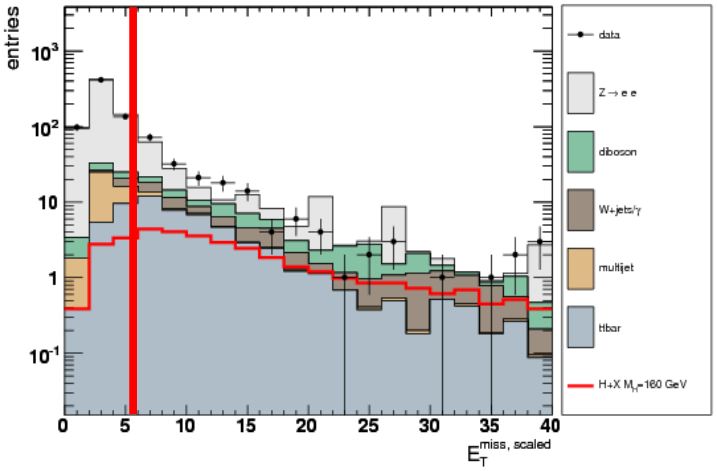
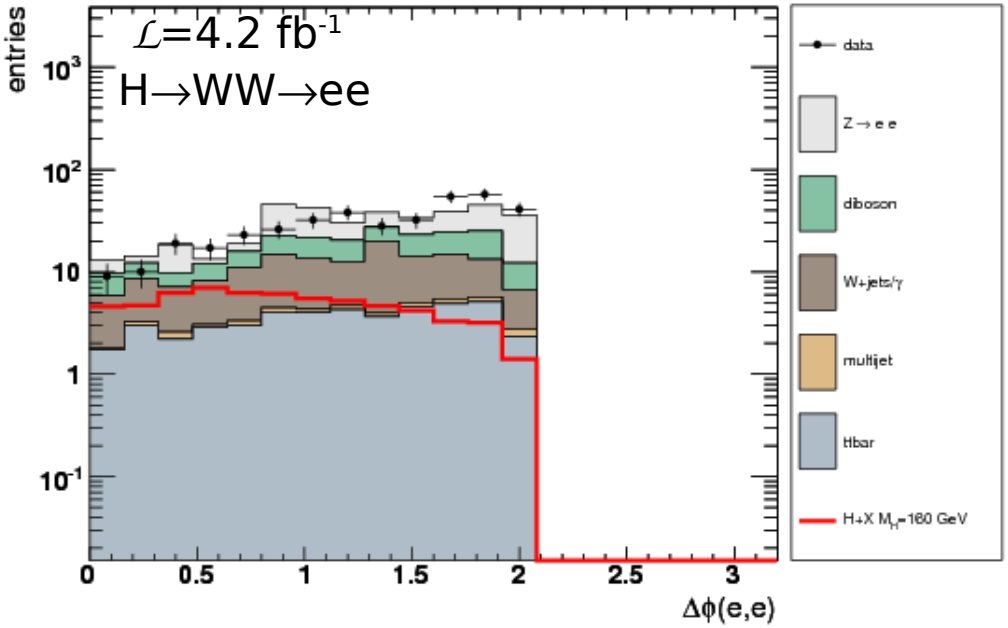
- $E_T^{miss,\ scal}>6$ GeV





Selection Requirements

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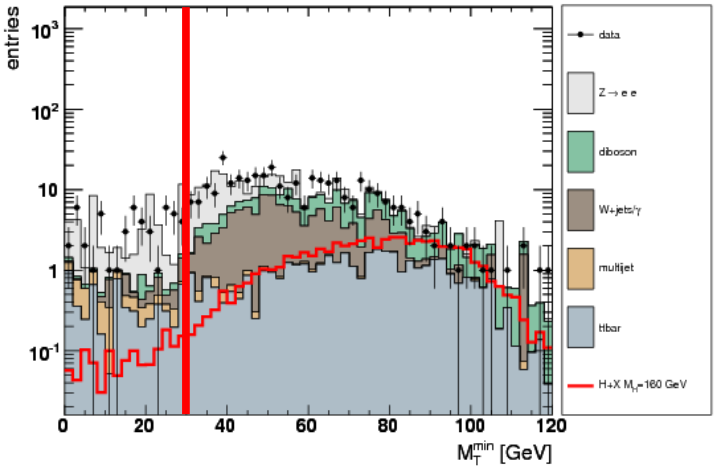
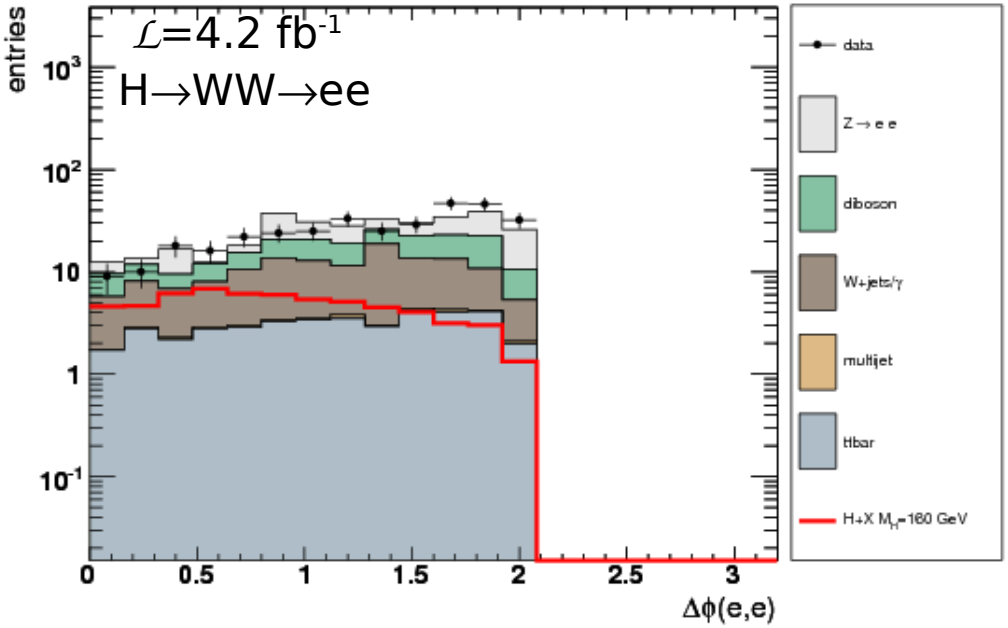
- $E_T^{miss,\ scal}>6$ GeV
- $M_T^{min}(\ell,E_T^{miss})>30$ GeV





Event Yield

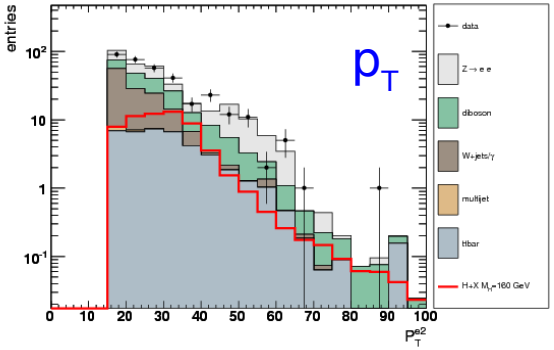
- S/B ration after applying the cuts: ~ 1:50

	ee pre-selection	ee final
$Z \to ee$	218695 ± 704	108 ± 14
$Z \to \mu\mu$	–	–
$Z \to \tau\tau$	1135 ± 16	1.4 ± 0.5
$t\bar{t}$	131.4 ± 1.4	39.9 ± 0.8
W+jets	241 ± 5	98 ± 3
WW	172.2 ± 2.6	66.8 ± 1.6
WZ	112.5 ± 0.2	9.68 ± 0.05
ZZ	98.2 ± 0.2	7.68 ± 0.07
Multijet	1351 ± 55	$1.7^{+2.0}_{-1.7}$
Signal ($M_H = 165$ GeV)	9.45 ± 0.01	6.13 ± 0.01
Total Background	221937 ± 707	332 ± 15
Data	221530	336

- Further background suppression: Multivariate Techniques
- Artificial Neural Network (NN)

Artificial Neural Networks

Kinematic Variables



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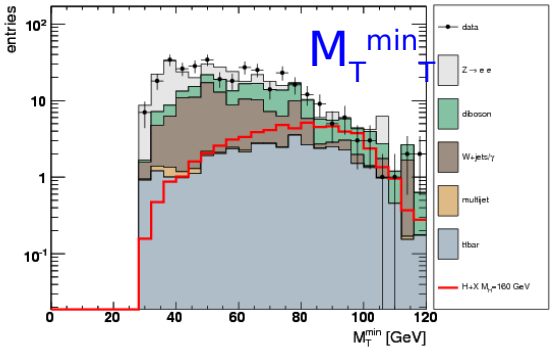
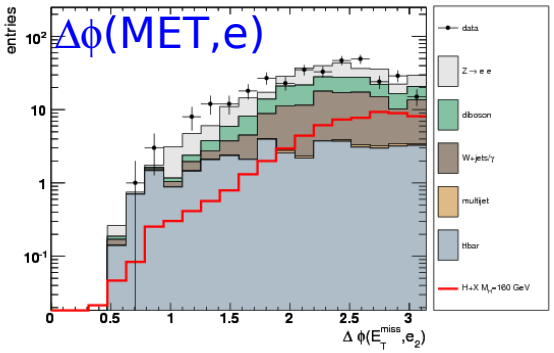


Angular Variables



Artificial Neural Networks

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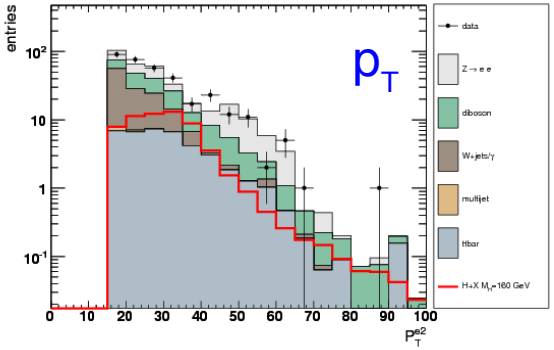

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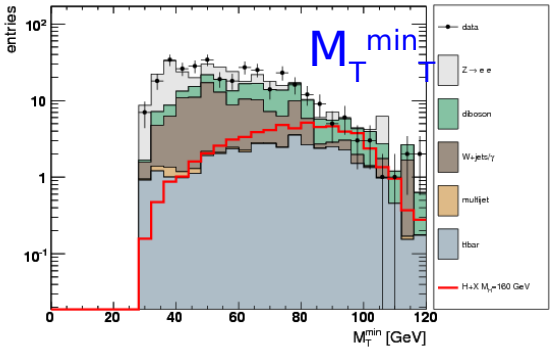

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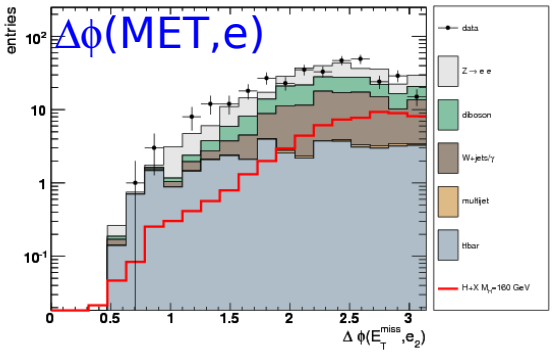
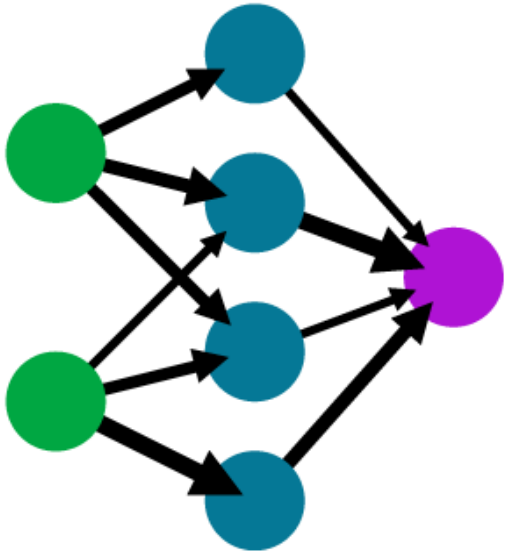


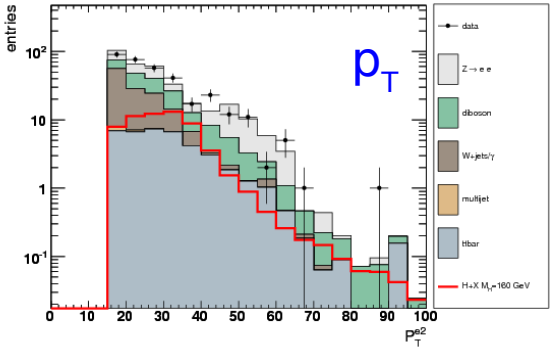
Multivariate Method



13 variables

Artificial Neural Networks

Kinematic Variables



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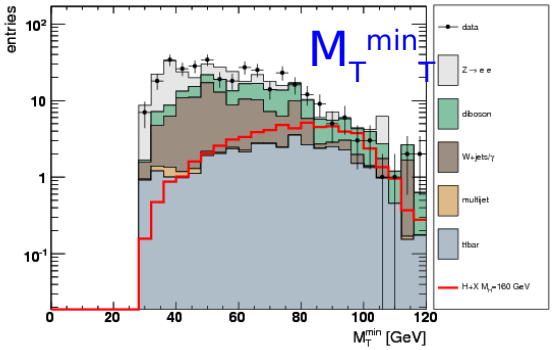

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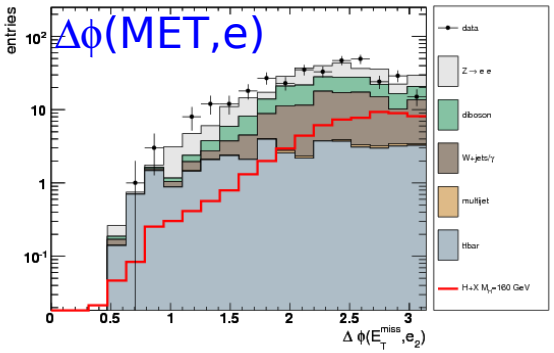

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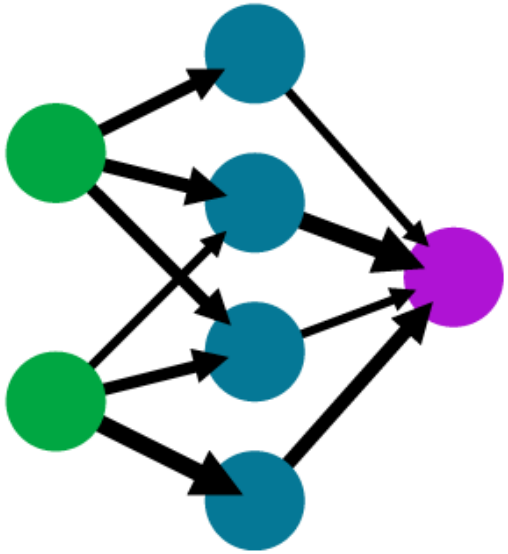
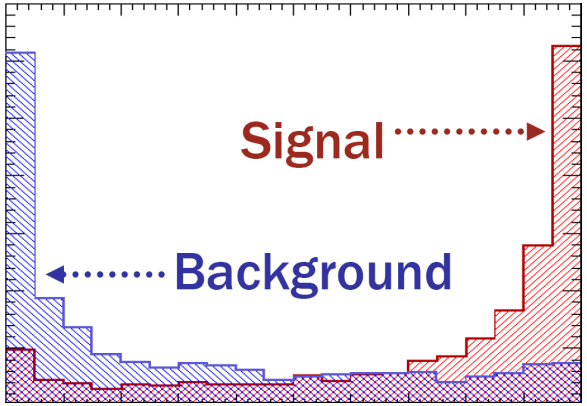


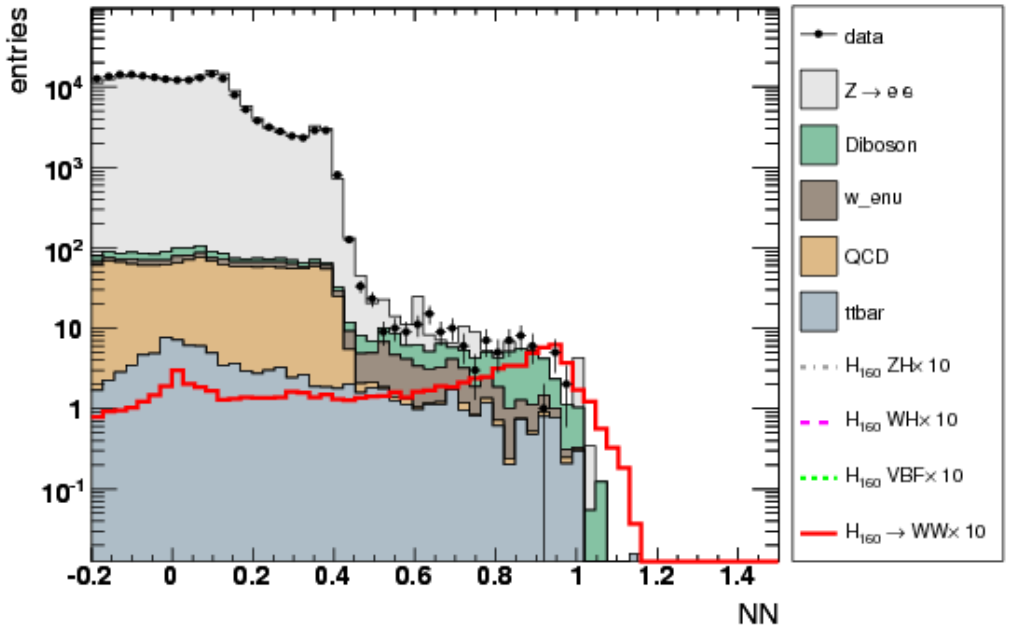
13 variables



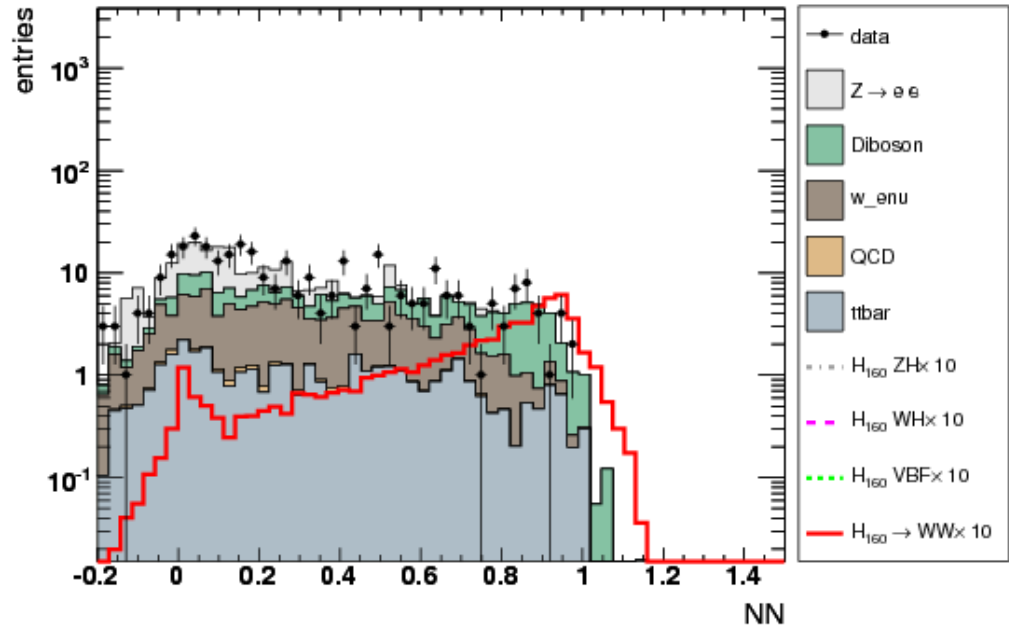
NN ouput

Artificial Neural Networks

pre-selection

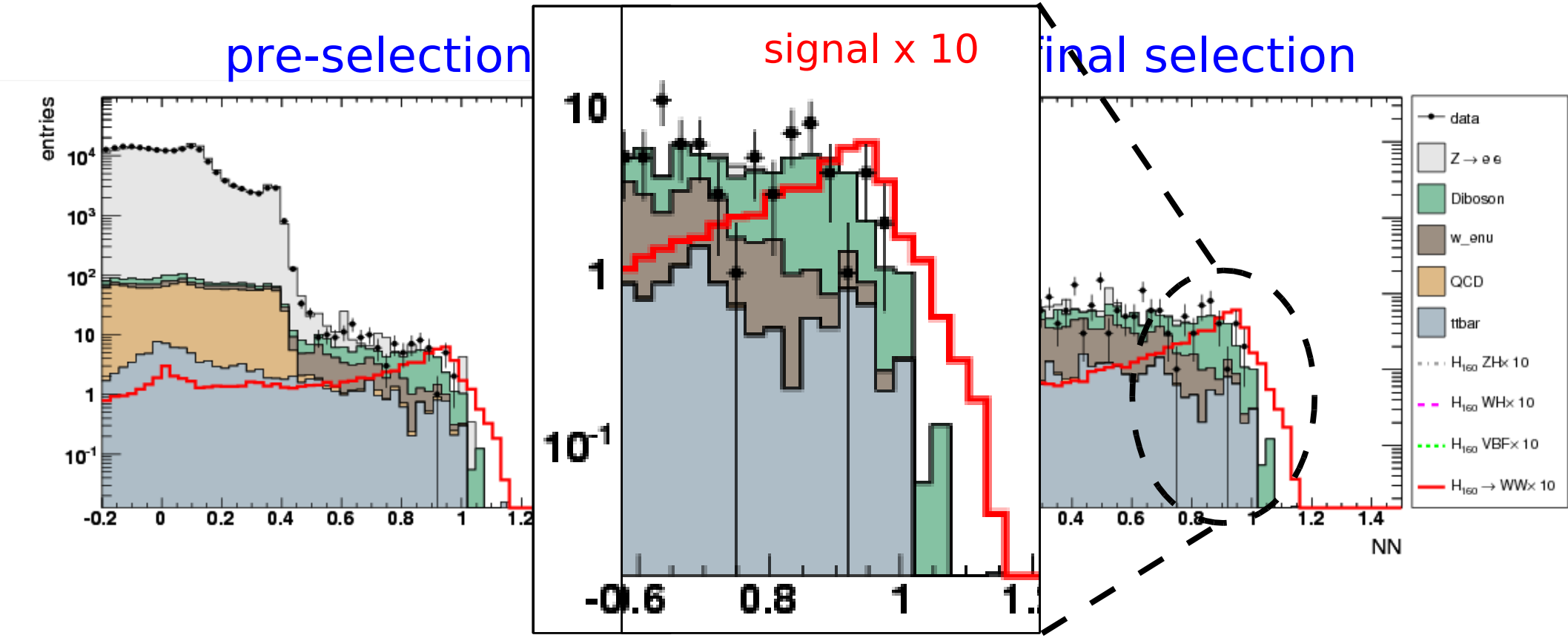


final selection



- Separate NN trained for each Higgs mass analyzed
- Good description on various cut stages

Artificial Neural Networks



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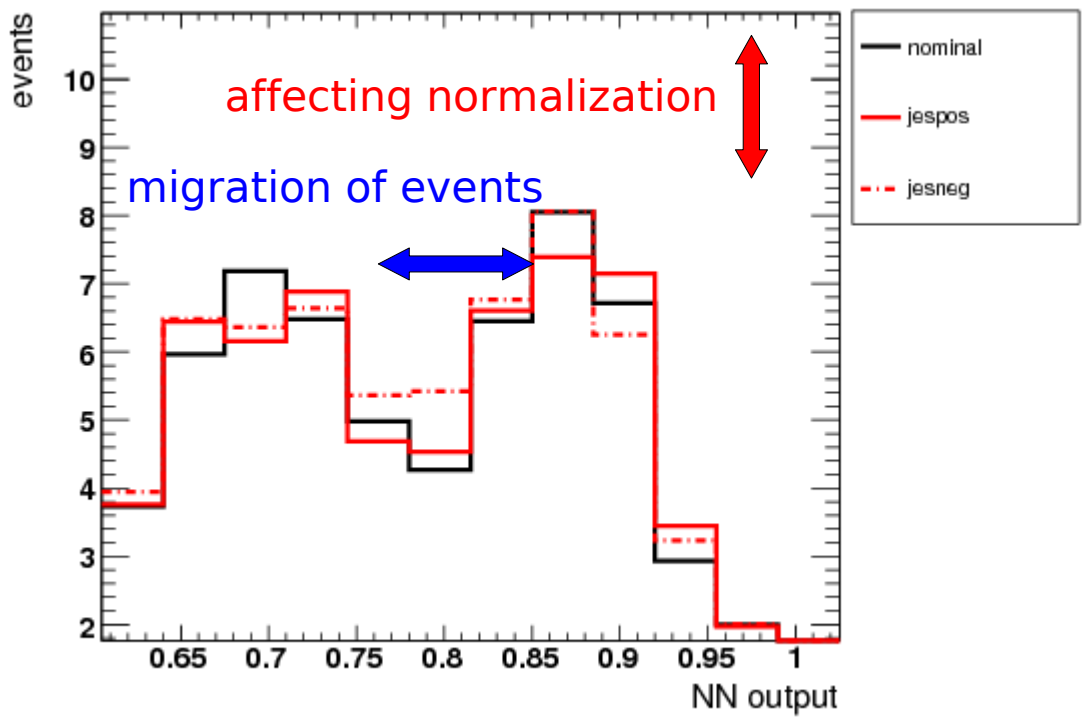
Uncertainties

Two types of uncertainties:

- Statistical Variations
- Systematic Variations:
  - Arise from uncertainties associated with the nature of the
    - measurement apparatus and methods
    - assumptions by the experimentalist
    - type of model used
  - Evaluation of systematic uncertainties not always trivial

Systematical Uncertainties

- Two types of systematics have been studied:
  - *Rate Systematics:*
    related to overall normalization and efficiencies of the contributing physical processes.
  - *Shape Systematics*:
    uncertainties which impact the multivariate classification of events



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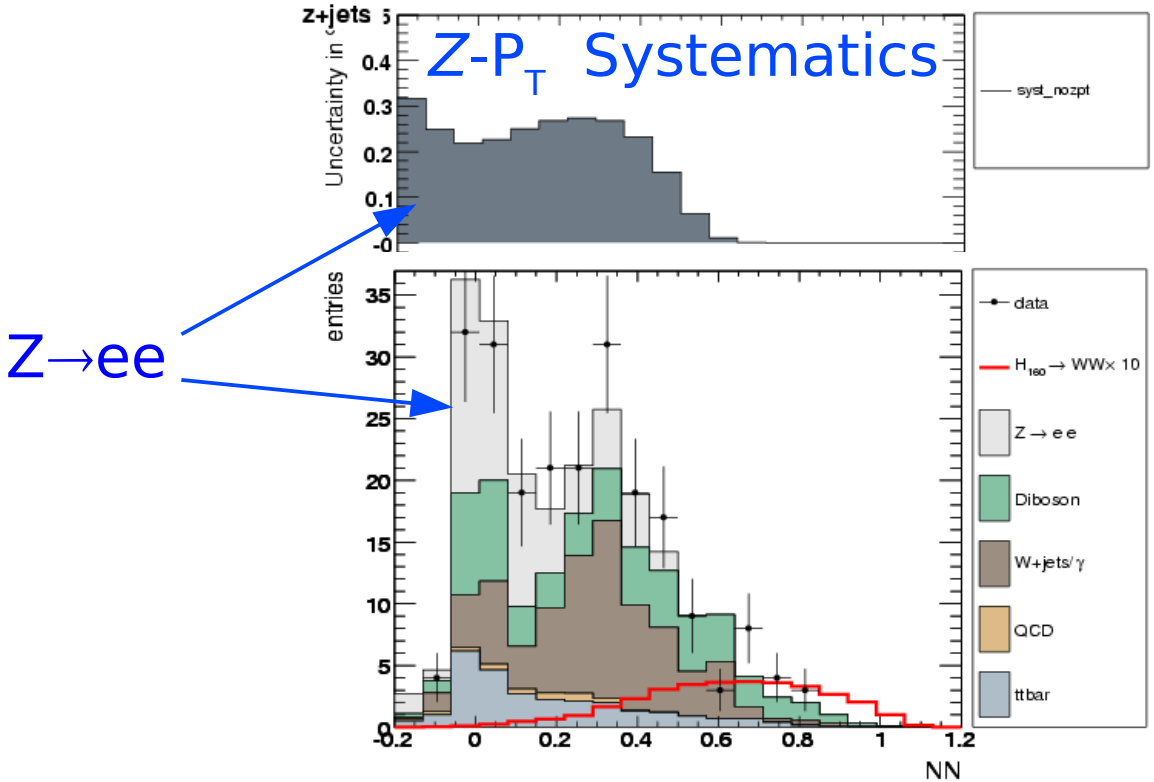
  - *Shape Systematics*:
    uncertainties which impact the multivariate classification of events



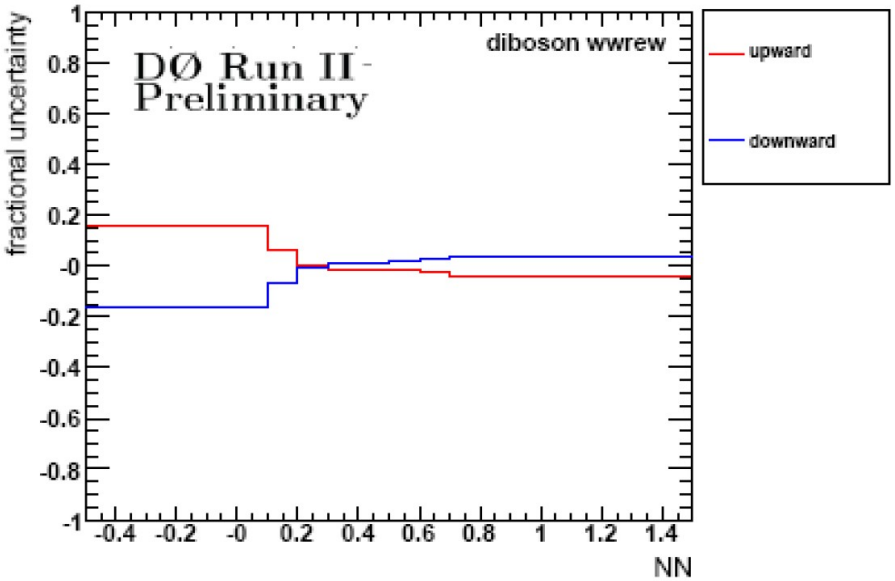
Systematical Uncertainties

- Two types of systematics have been studied:
  - *Rate Systematics:*
    related to overall normalization and efficiencies of the contributing physical processes.
  - *Shape Systematics*:
    uncertainties which impact the multivariate classification of events

Flat systematics:
- Lepton efficiencies (2-8%)
- Lepton momentum scale (2%)
- Theoretical cross-sections (7-10%)
- Jet→lepton fake rate (10%)
- QCD normalization (30%)

Shape systematics (on NN output):
- Jet efficiency (6%)
- Jet energy scale (7%)
- Jet energy resolution (3%)
- Di-boson p_T (5%)

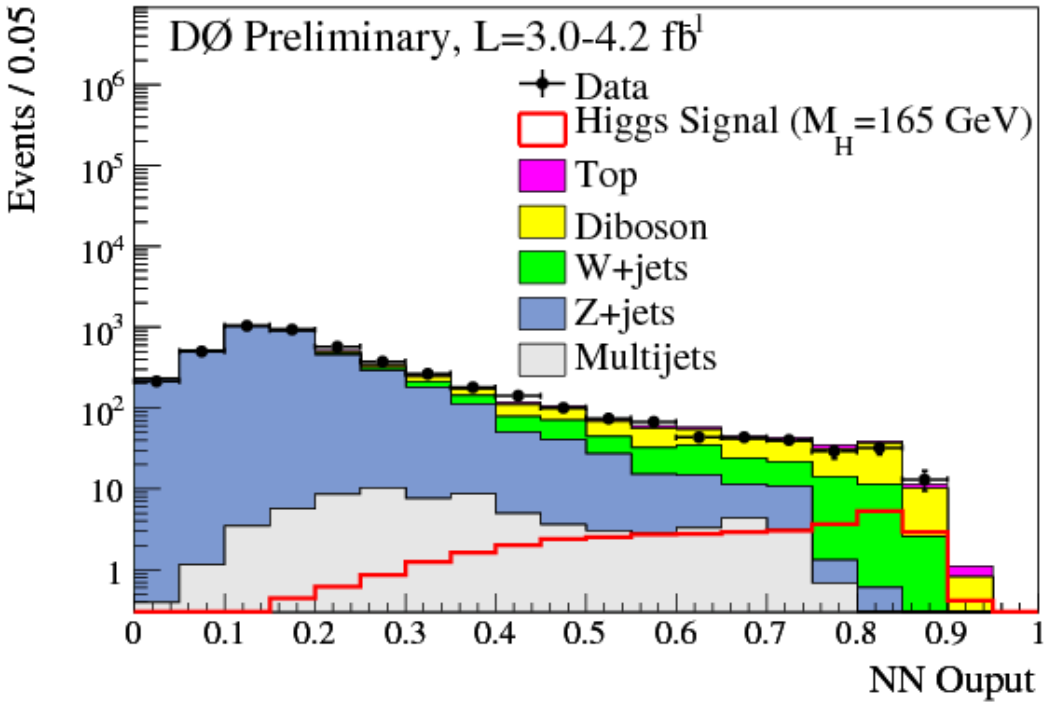
Signal: 10%, Bkgd: 13%

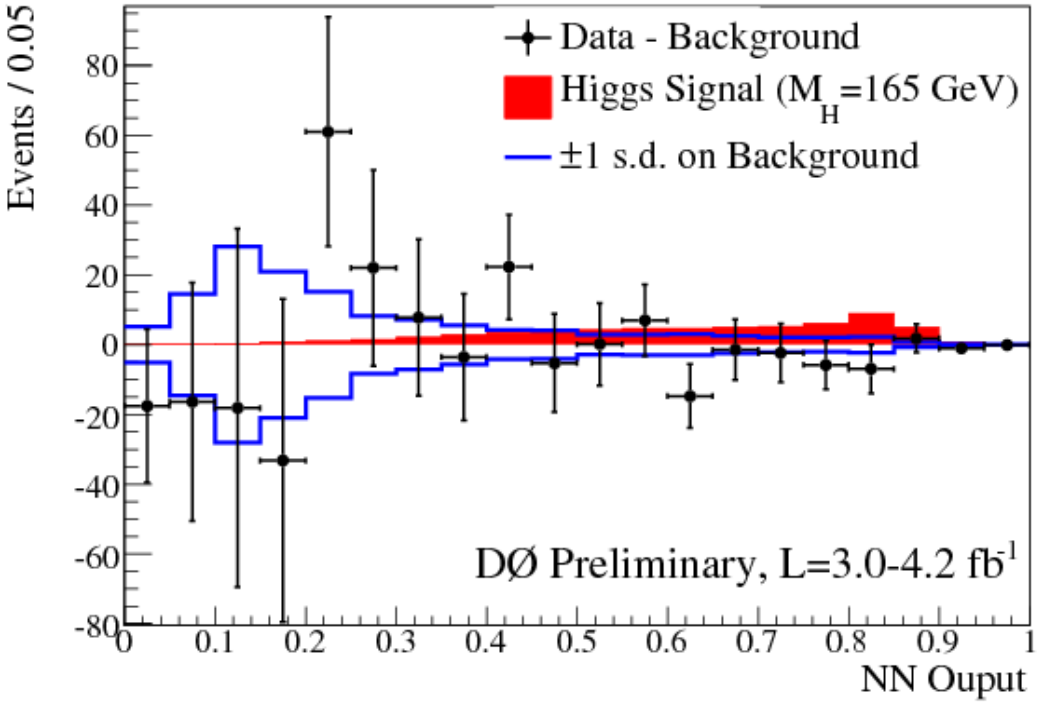


Change of NN when p_T(WW) changes

Results – Combined Output

NN output classifier for full dataset
and all channels

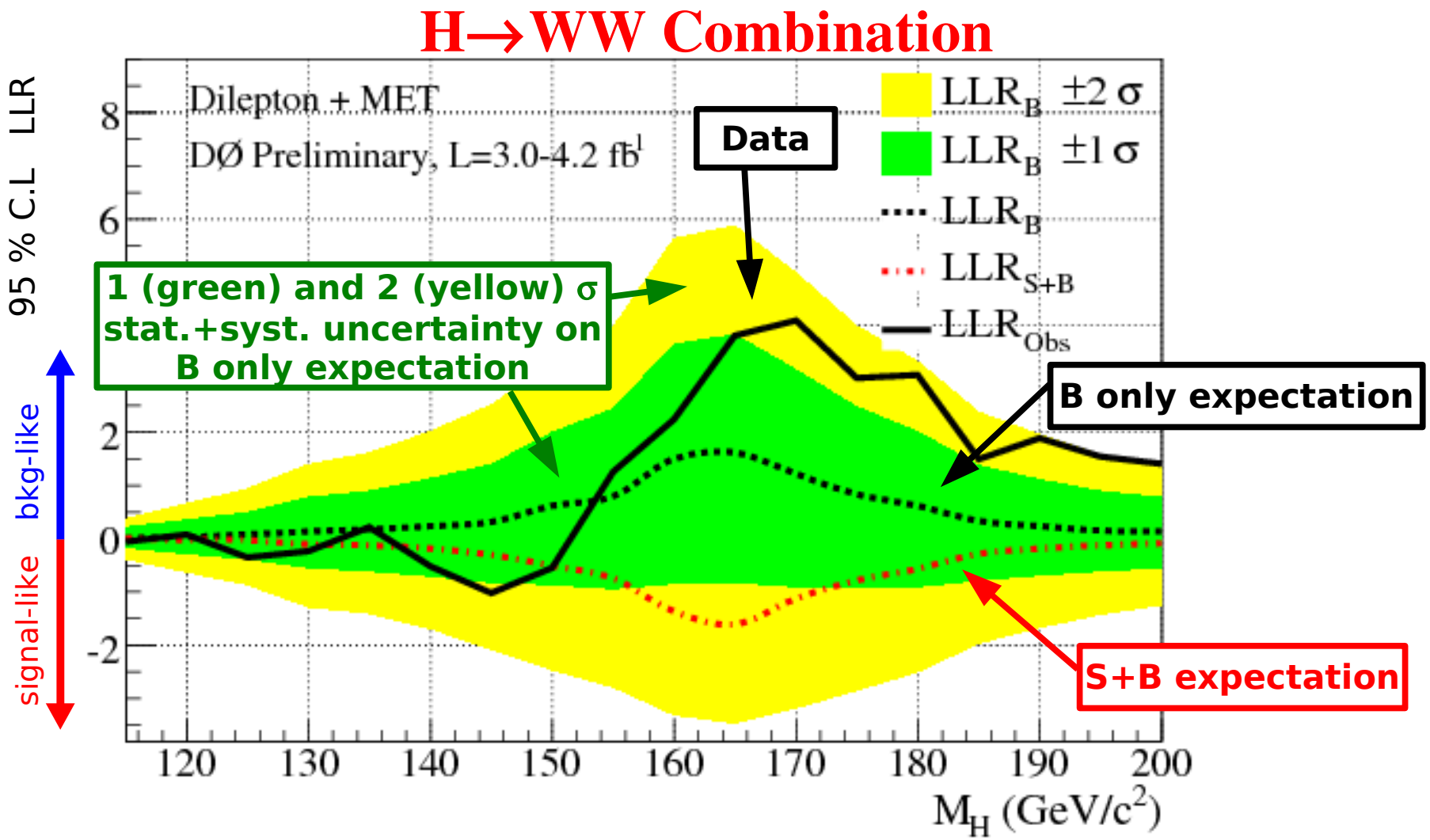




Large backgrounds, but under control

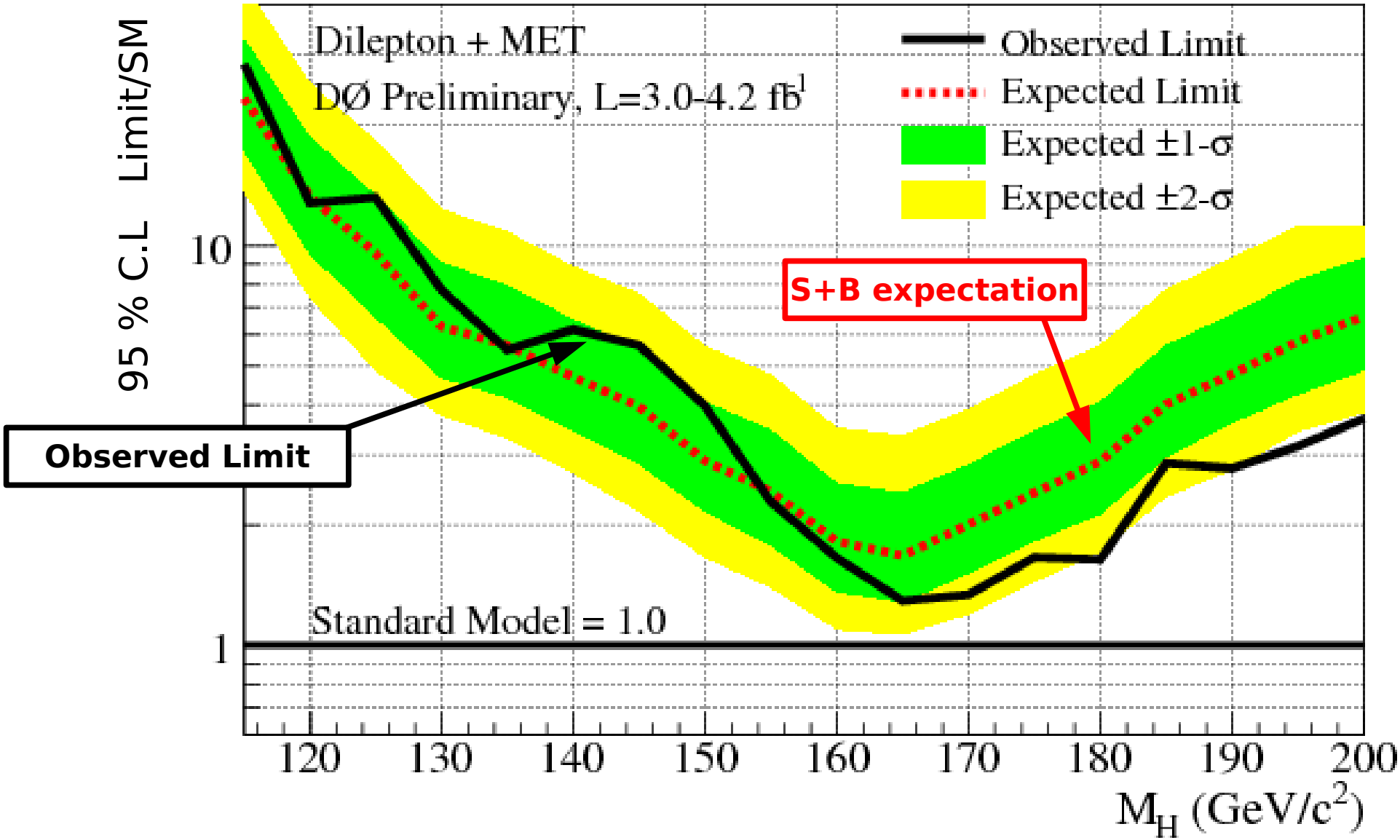
Results – Log Likelihood Ratio

- Log-likelihood-ratio: statistical test between two hypotheses
- Using CLs method similar to LEPII



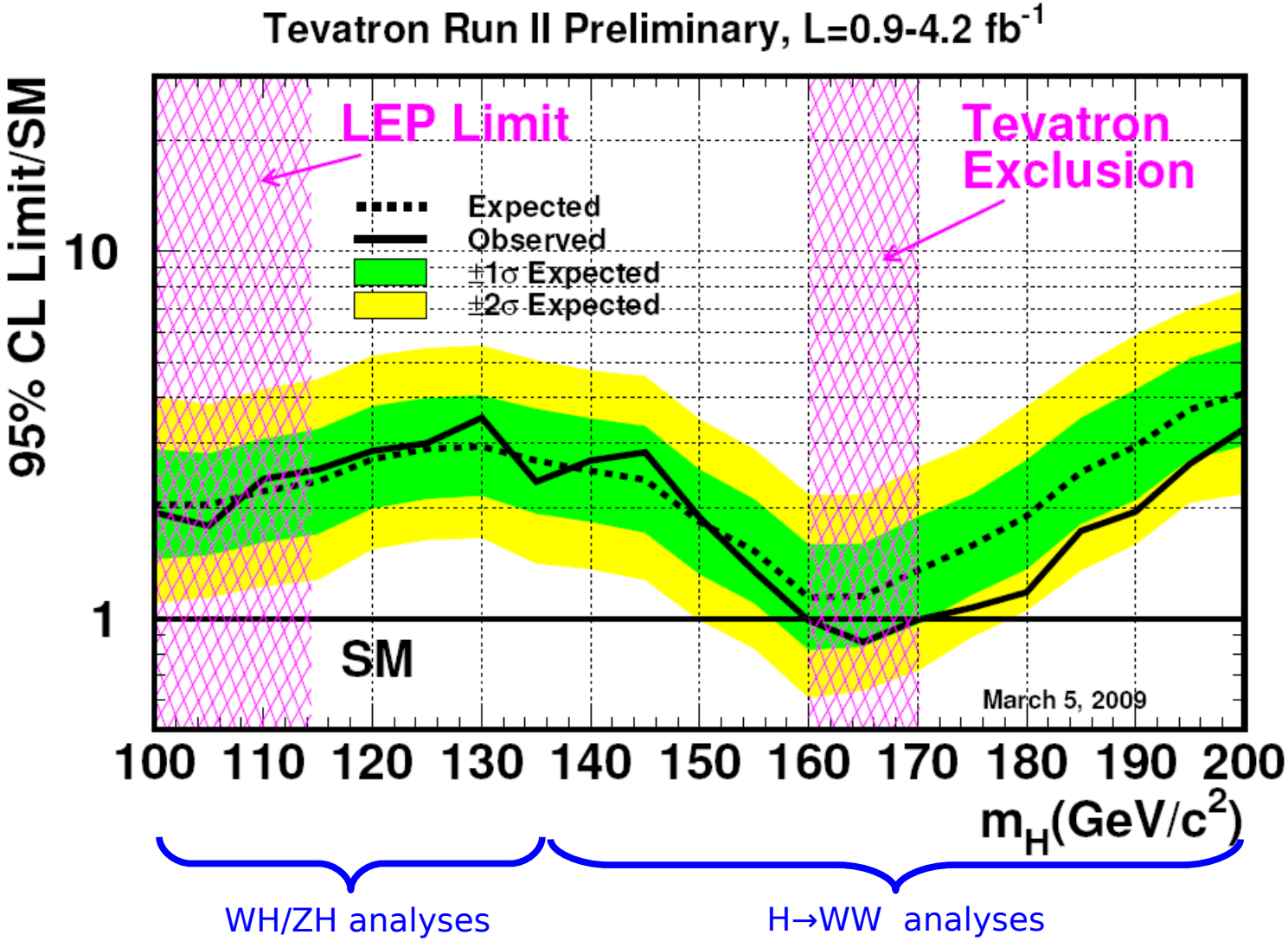
Results - Limit

H→WW Combination



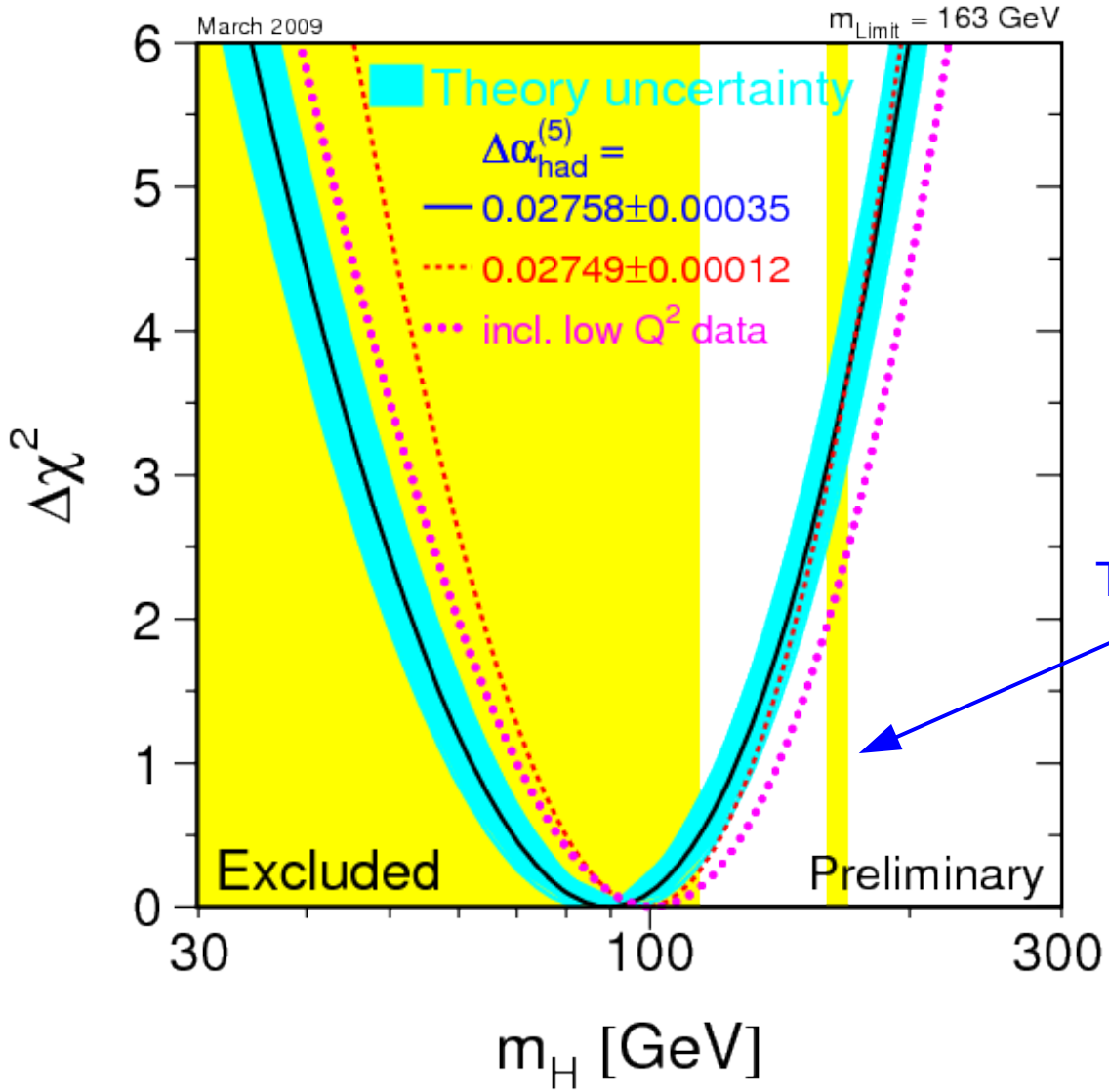
Combination & Exclusion

- In order two achieve maximal sensitivity CDF and DØ combined



- Excluding significant region, rapidly adding more Data

Combination & Exclusion



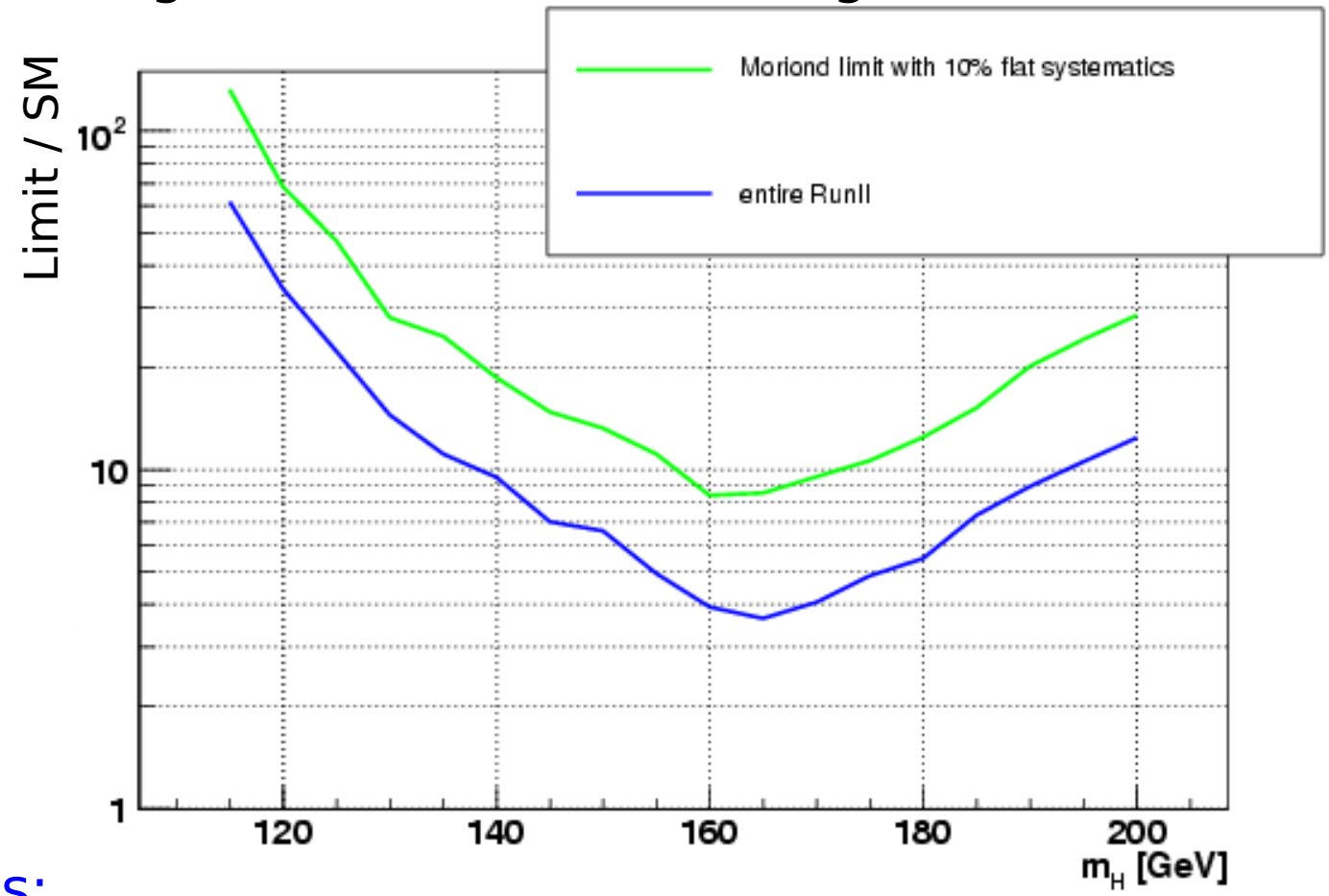
Tevatron Exclusion

m_t, m_W updated

Thinking out of the Box

Thinking out of the box

- Constantly revisit and improve tools, reconstruction and methods with increasing detector understanding



Examples:

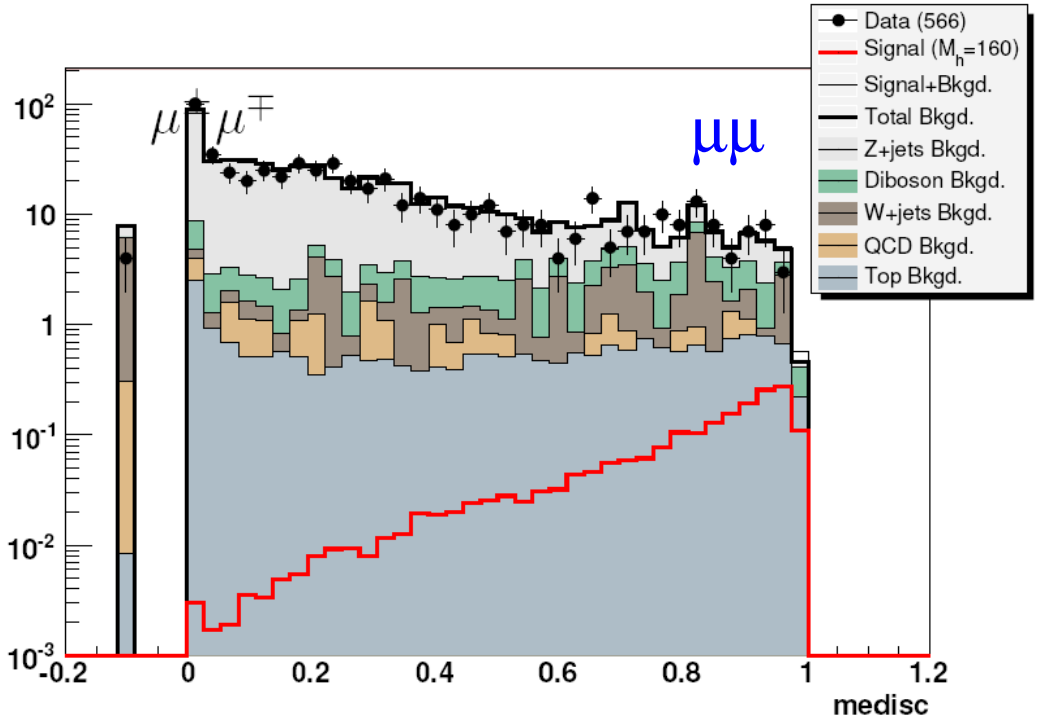
lumi from 1.2 to 2.8 fb^{-1} → expect improvement of sqrt(2.3)=1.52

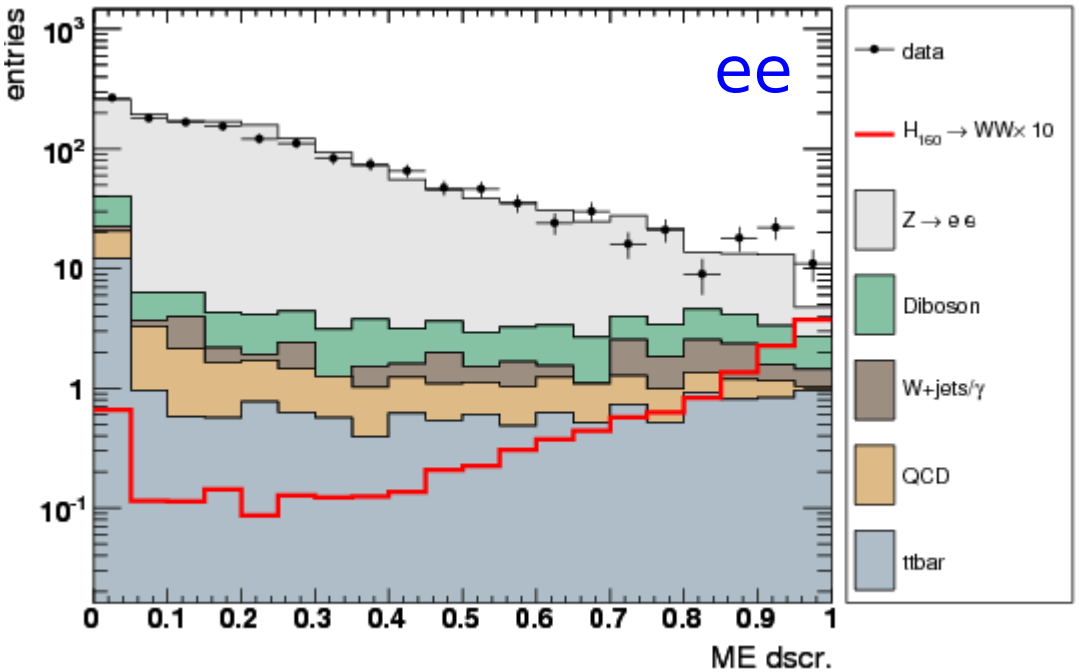
→ achieved 2!

Matrix Element Method

- Use Matrix Element Methods as input to the NN

$$D(\vec{x}) = \frac{P_{\text{Signal}}(\vec{x})}{P_{\text{Signal}}(\vec{x}) + P_{\text{Background}}(\vec{x})}$$

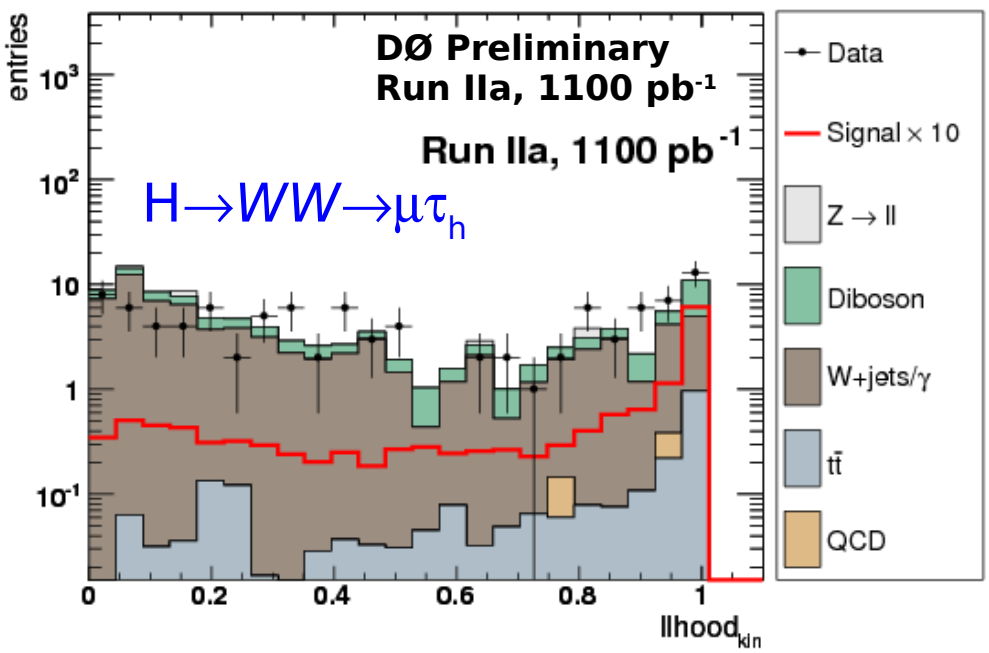


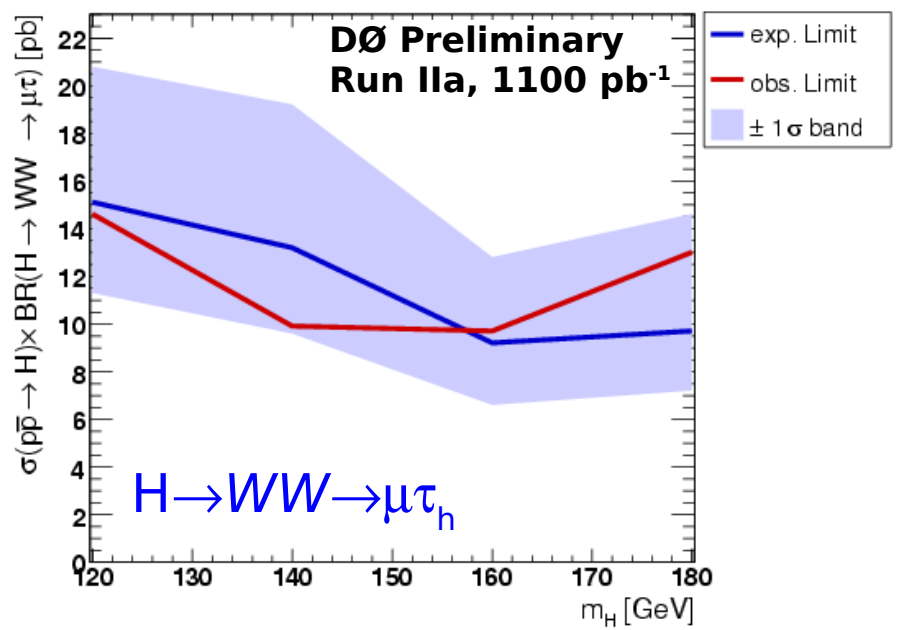


- ~3-5% improvement
- Very CPU intensive→ not applied in all updates of analysis

Tau Final States

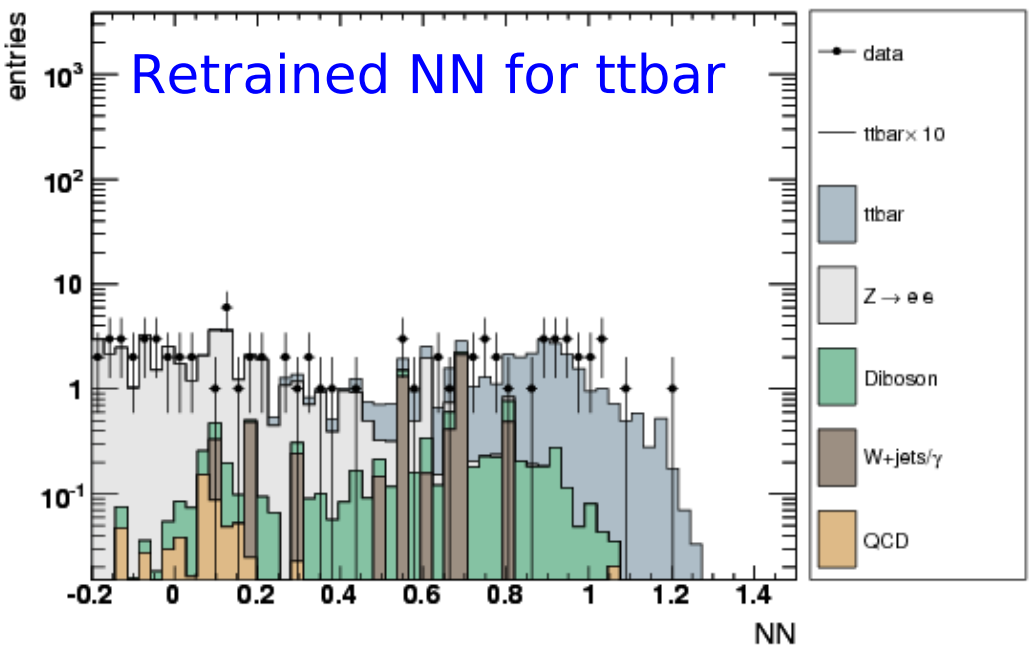
- Using likelihood technique to maximize separation power between signal and background
- Retaining event neglected by eμ analysis
  - 2 separate Likelihoods/τ type (5 & 6 input variables)
- First SM Higgs search in $\mu+\tau_{had}$ final state
- Supervising grad. student for update, will be presented Summer 2009





Understanding the SM

- Performing cross checks of our understanding
- Looking for deviations in $2\ell+E_T^{miss}$
- Not as powerful as dedicated search, but good performance



Cut	Data	Sum MC	$t\bar{t}$
0	6908.00 ± 83.11	6619.59 ± 19.94	53.21 ± 0.13
1	852.00 ± 29.19	889.37 ± 9.04	48.35 ± 0.13
2	224.00 ± 14.97	214.70 ± 4.57	35.54 ± 0.11
3	82.00 ± 9.06	84.33 ± 1.78	27.74 ± 0.09
4	19.00 ± 4.36	20.08 ± 0.39	18.28 ± 0.08

fall 2008: σ(ttbar)=9.35 ± 2.39 (2.17 stat+ 0.99 syst) pb

σ(ttbar)= 7pb

Conclusions

This experience lead to

- Public result for each conference period the last 2 ½ years
- Often biggest data set
- Sensitivity of each result improved better than just scaling with luminosity
- Developed all methods, framework and code for the H→WW searches: ntuple-maker, very fast framework, multivariate methods, systematics studies

Conclusions

- Exciting times in particles physics ahead

Conclusions

- Exciting times in particles physics ahead

Experience in Calorimetry and Particle Identification

Experience in Higgs Physics at Hadron Colliders

Experience with guiding students and supervision

Most important: Curiosity

Conclusions

- Exciting times in particles physics ahead

Experience in Calorimetry and Particle Identification

Experience in Higgs Physics at Hadron Colliders

Experience with guiding students and supervision

Most important: Curiosity

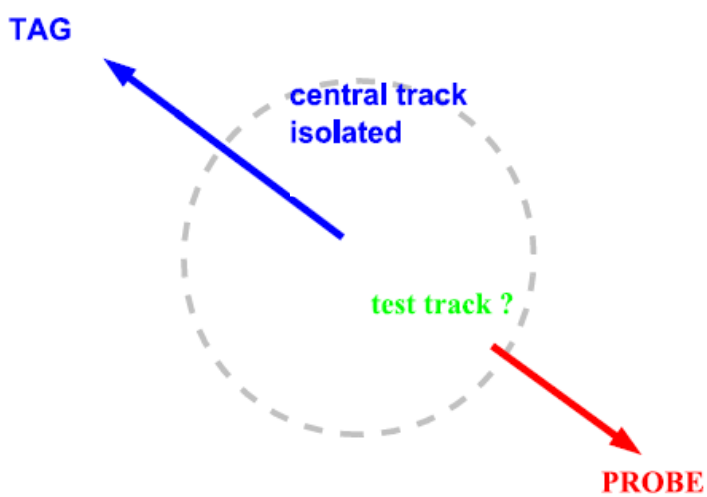
- I would like to continue at the Tevatron to discover the Higgs or make a strong statement on the mass range
- Later I want to bring my experience to the LHC in the search for new Physics

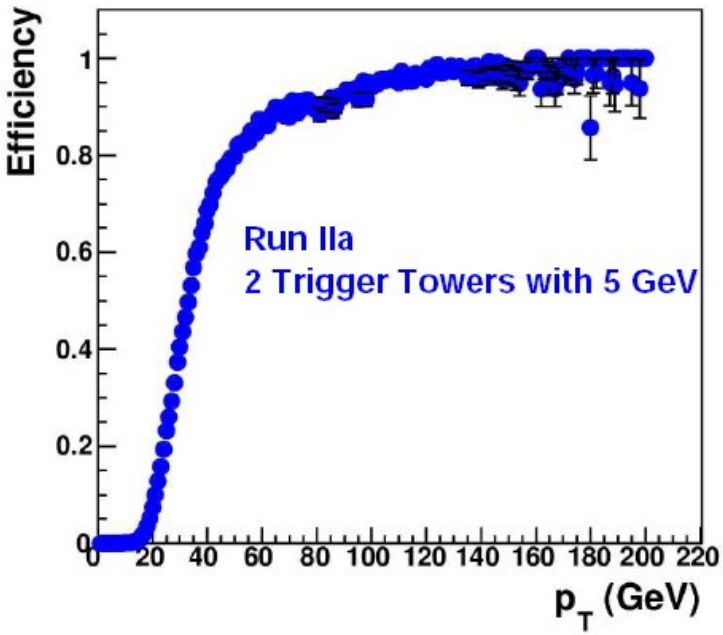
Backup Slides

The Triggering System

- High rate of collisions requires doesn't allow to store the information for each occurring interaction
  →3 Level trigger system allows fast decision to write 50 evt/sec

- MC needs to be corrected for the trigger efficiency (prescales, turn-ons) → Tag-And-Probe Method





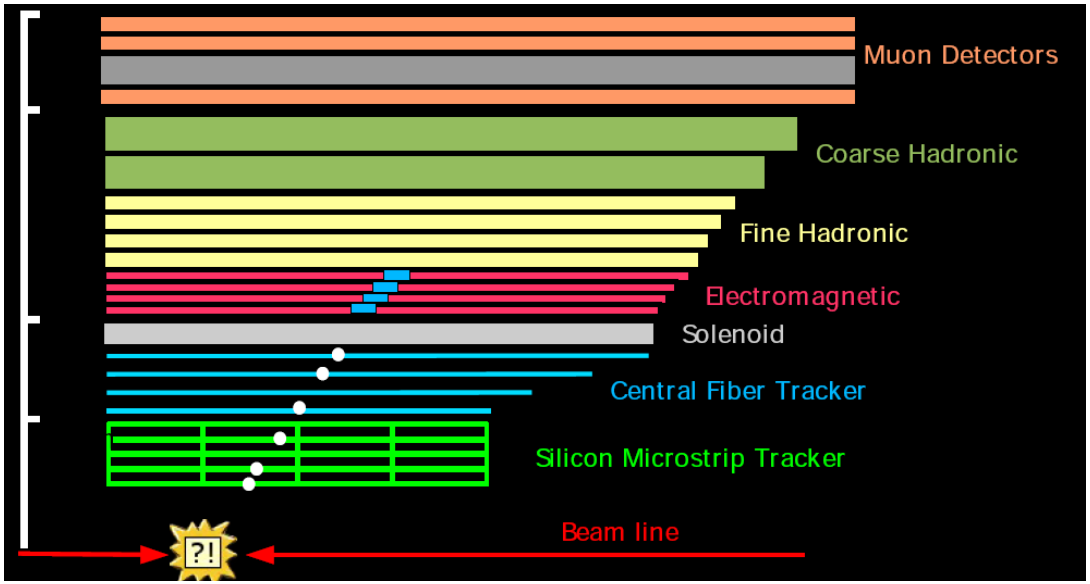
- Trigger corrections parametrized in p_T, η, vtx-z, n_{jet}...

Principle of Particle Detection

- Theory tells us what we are looking for
- But how do we look..
  - Particles are detected by their interaction in matter
  - Various particles are able to penetrate various depths

→ Layer structure of detectors

Detection: Electrons



Principle of Particle Detection

- Theory tells us what we are looking for
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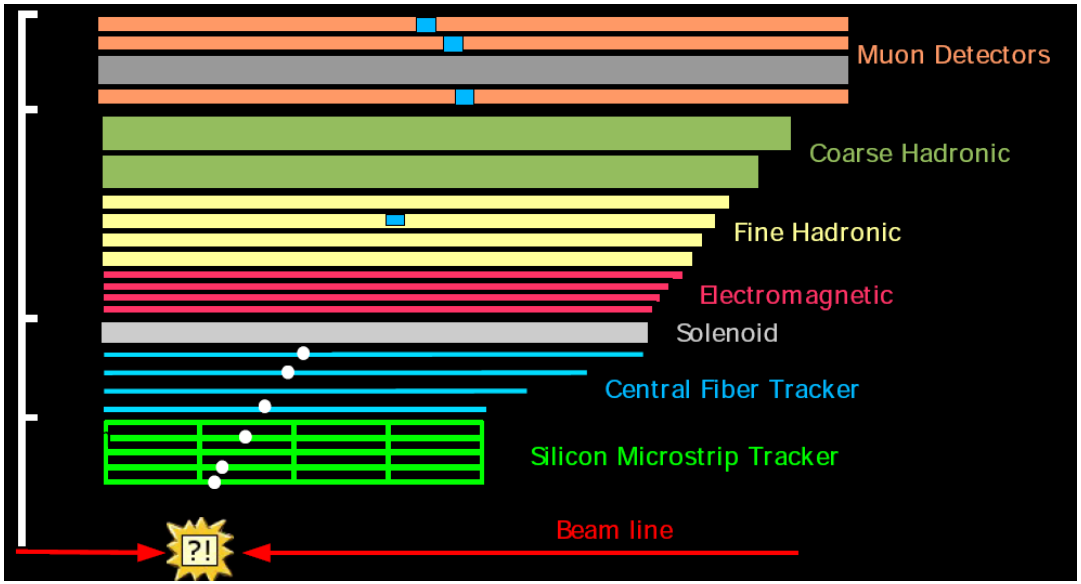
  - Various particles are able to penetrate various depths

→ Layer structure of detectors

Detection: Muons

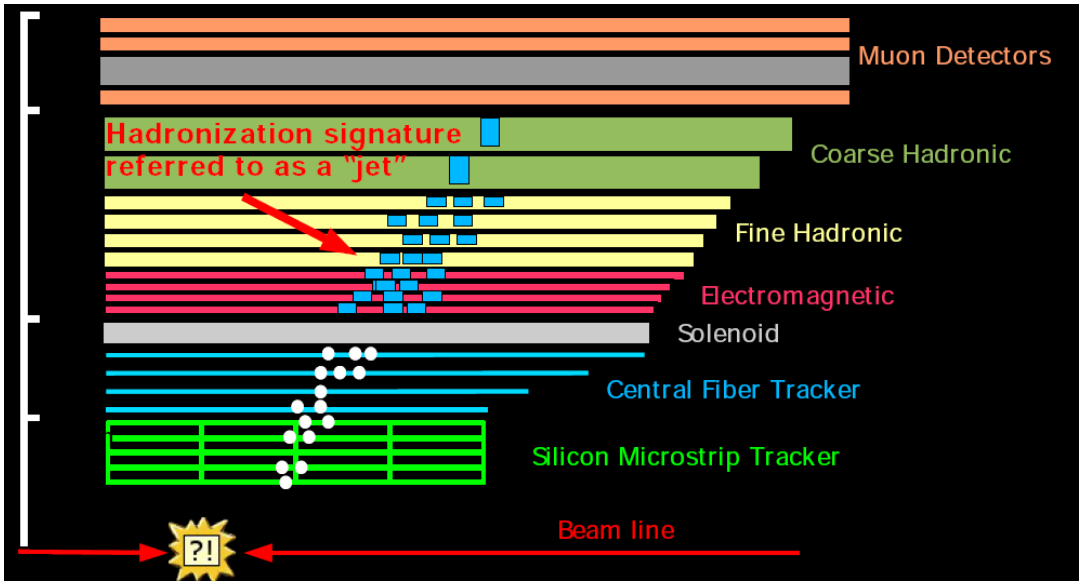


Principle of Particle Detection

- Theory tells us what we are looking for
- But how do we look..
  - Particles are detected by their interaction in matter
  - Various particles are able to penetrate various depths

→ Layer structure of detectors

Detection: Quarks & Gluons

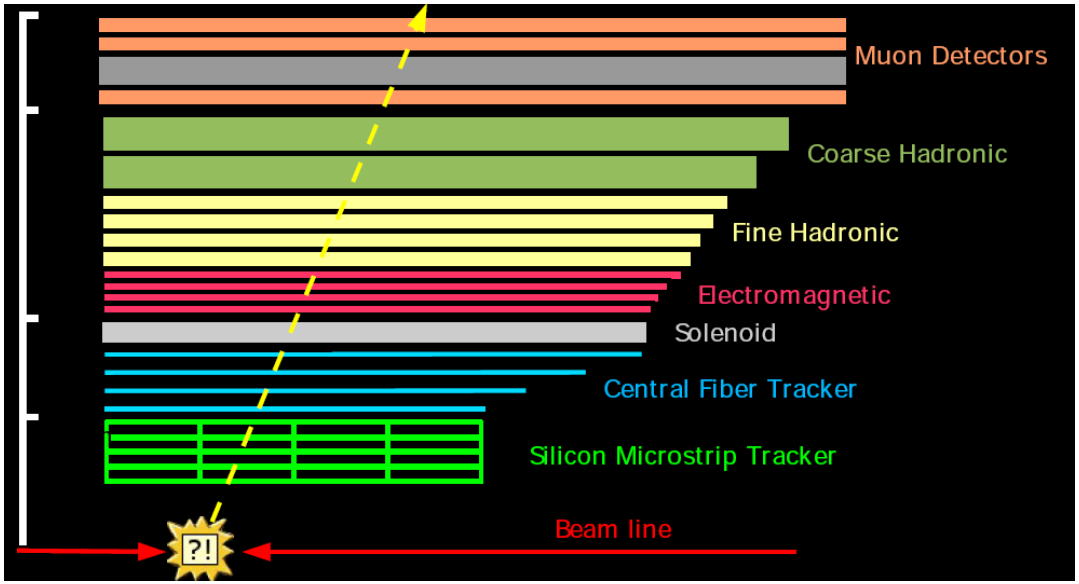


Principle of Particle Detection

- Theory tells us what we are looking for
- But how do we look..
  - Particles are detected by their interaction in matter
  - Various particles are able to penetrate various depths

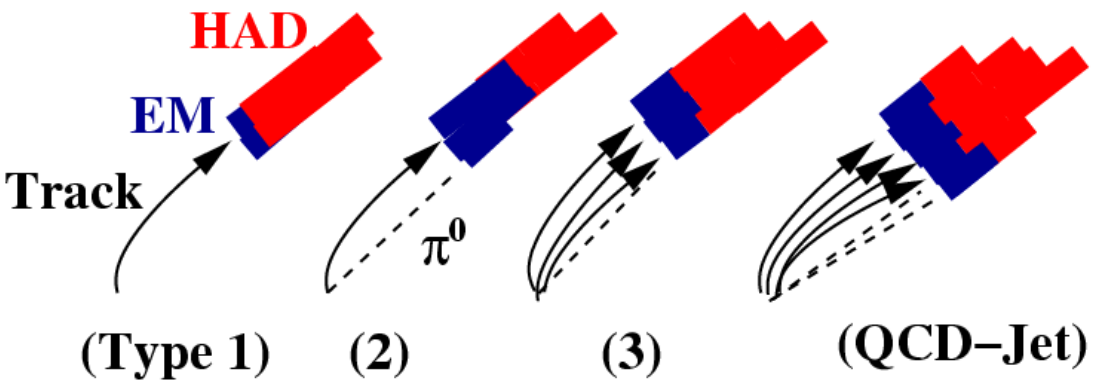
→ Layer structure of detectors

Detection: Neutrinos

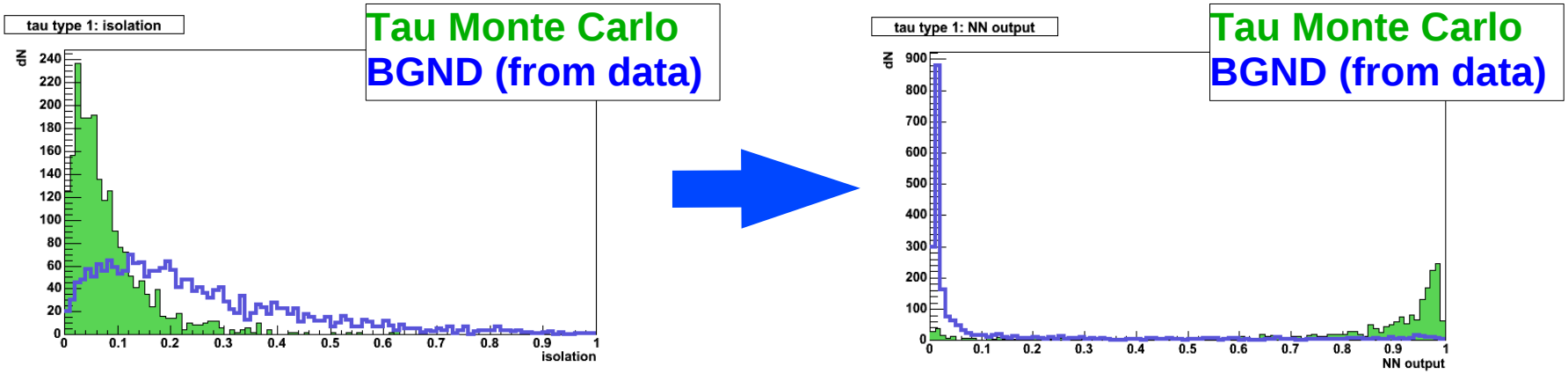


τ Identification at DØ

- Tau = narrow isolated jet with low track and π^0 multiplicity
- Taus decay inside detector:
  - $BR(\tau \to e/\mu + \nu\ \nu)$ ~17%
  - $BR(\tau \to \text{hadrons} + \nu)$ ~65%



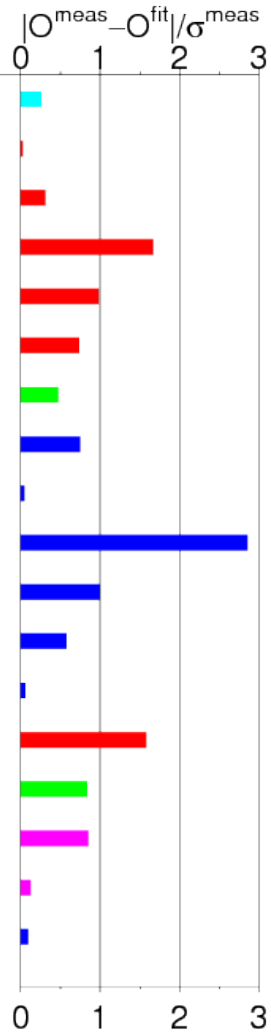
- Final states with τ initially neglected in sensitivity studies
- DØ uses one Neural Network per tau type to discriminate taus from jets



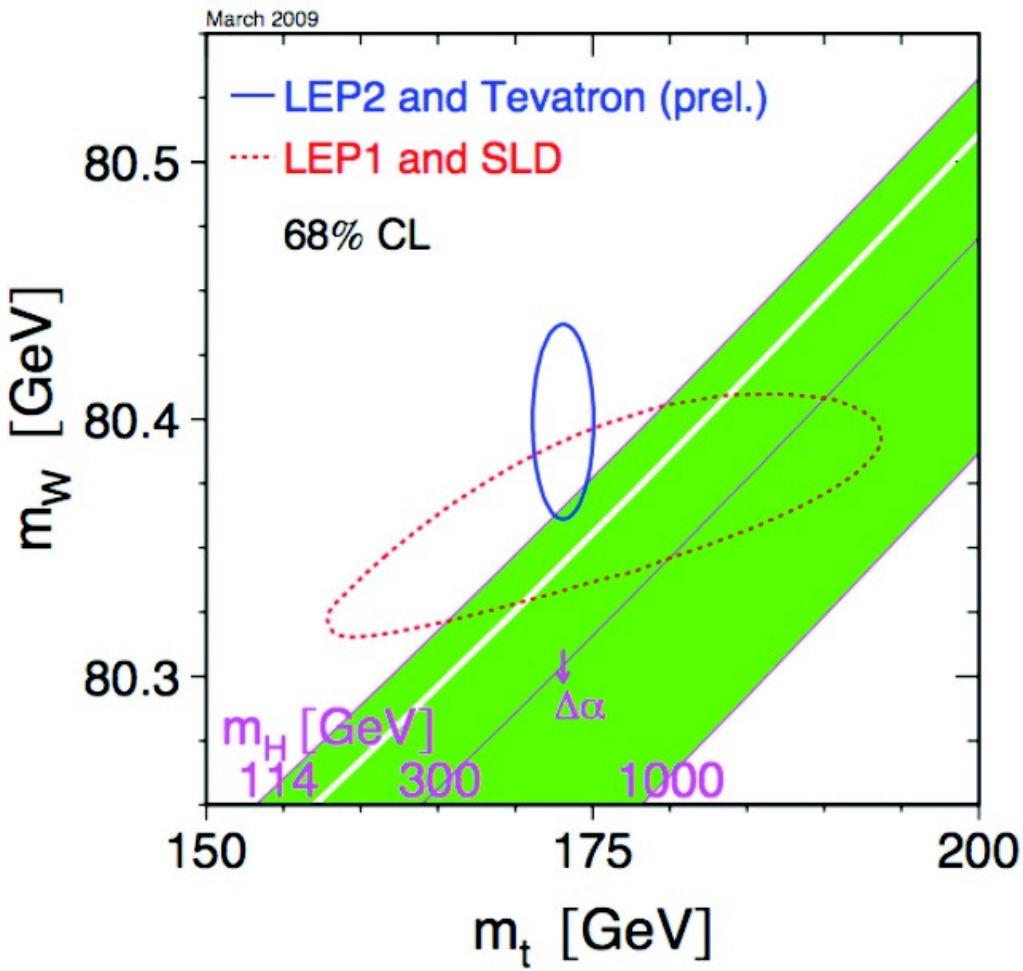
- Electrons picked up not selected by default EM-ID → recover efficiency

Electroweak Fits

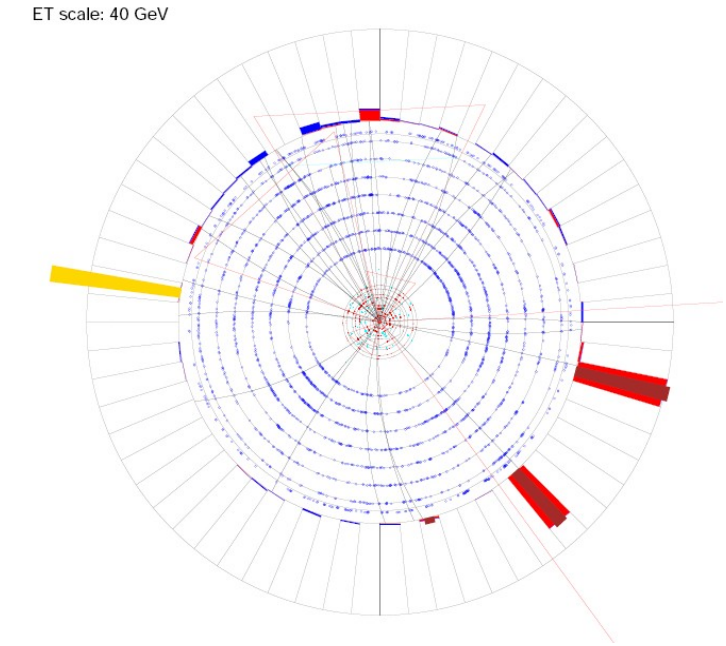
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.025	80.378
Γ_W [GeV]	2.098 ± 0.048	2.092
m_t [GeV]	173.1 ± 1.3	173.2

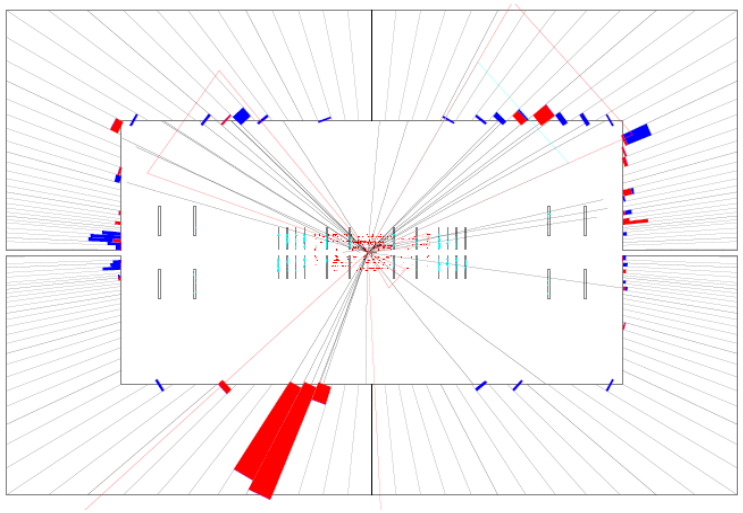


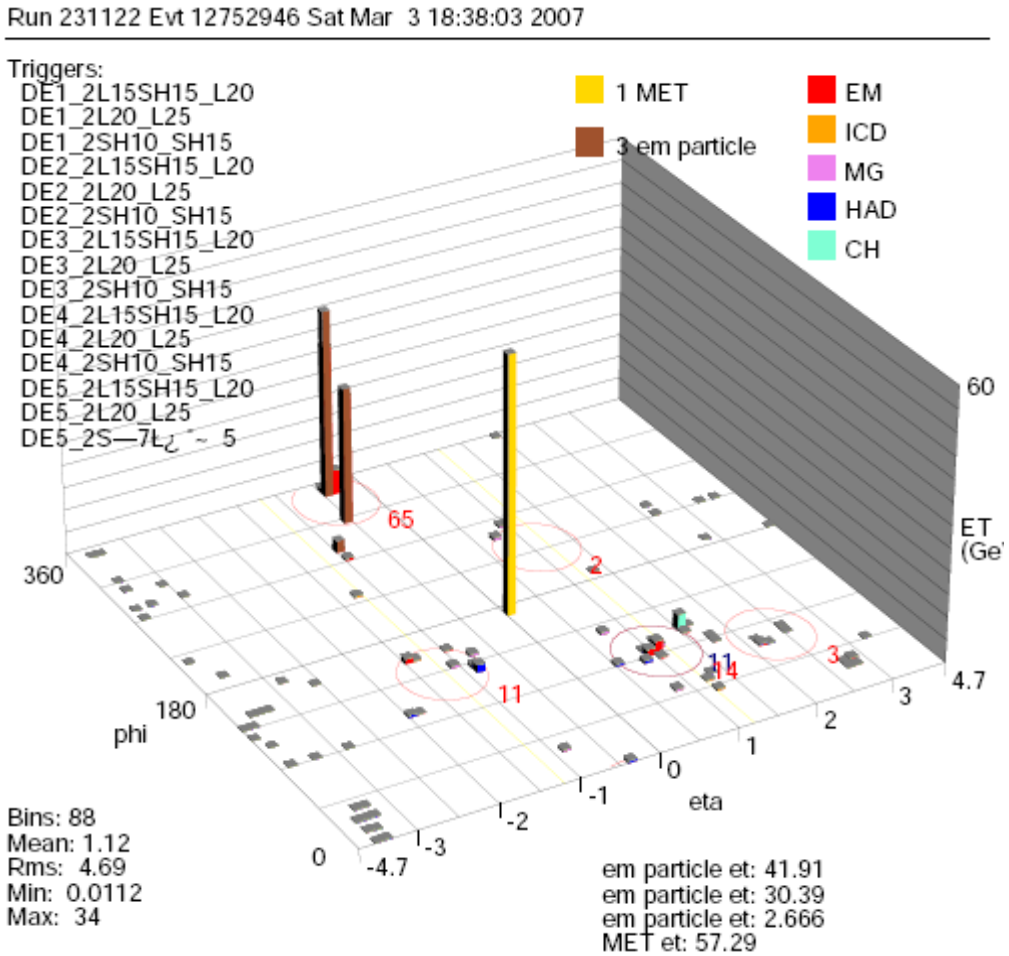
March 2009



Candidate Events

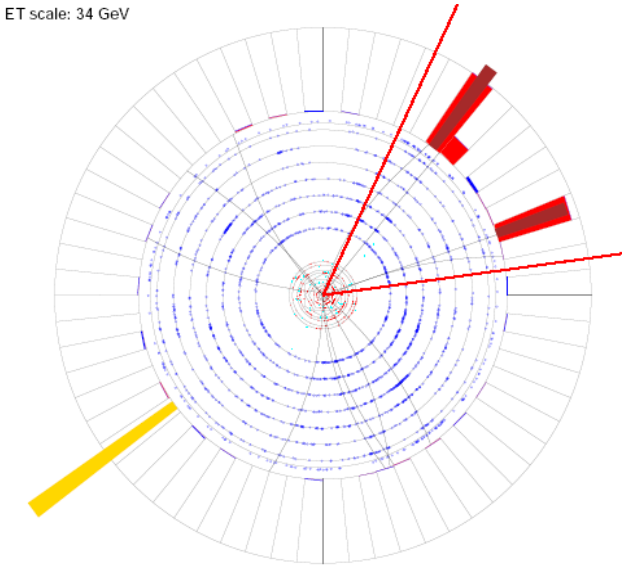


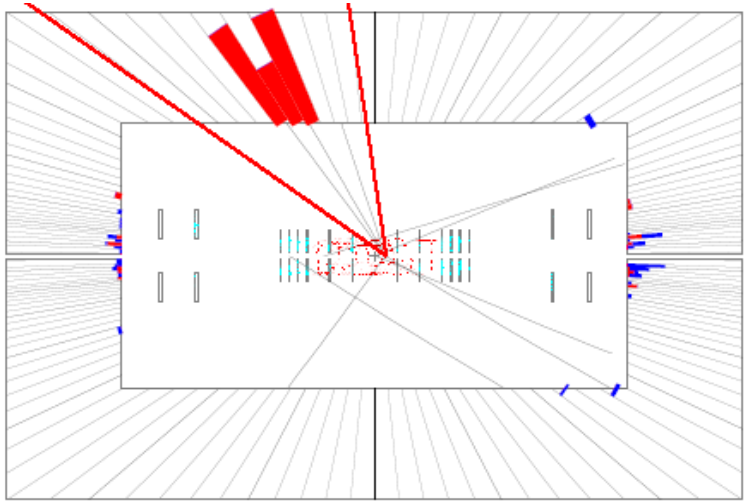


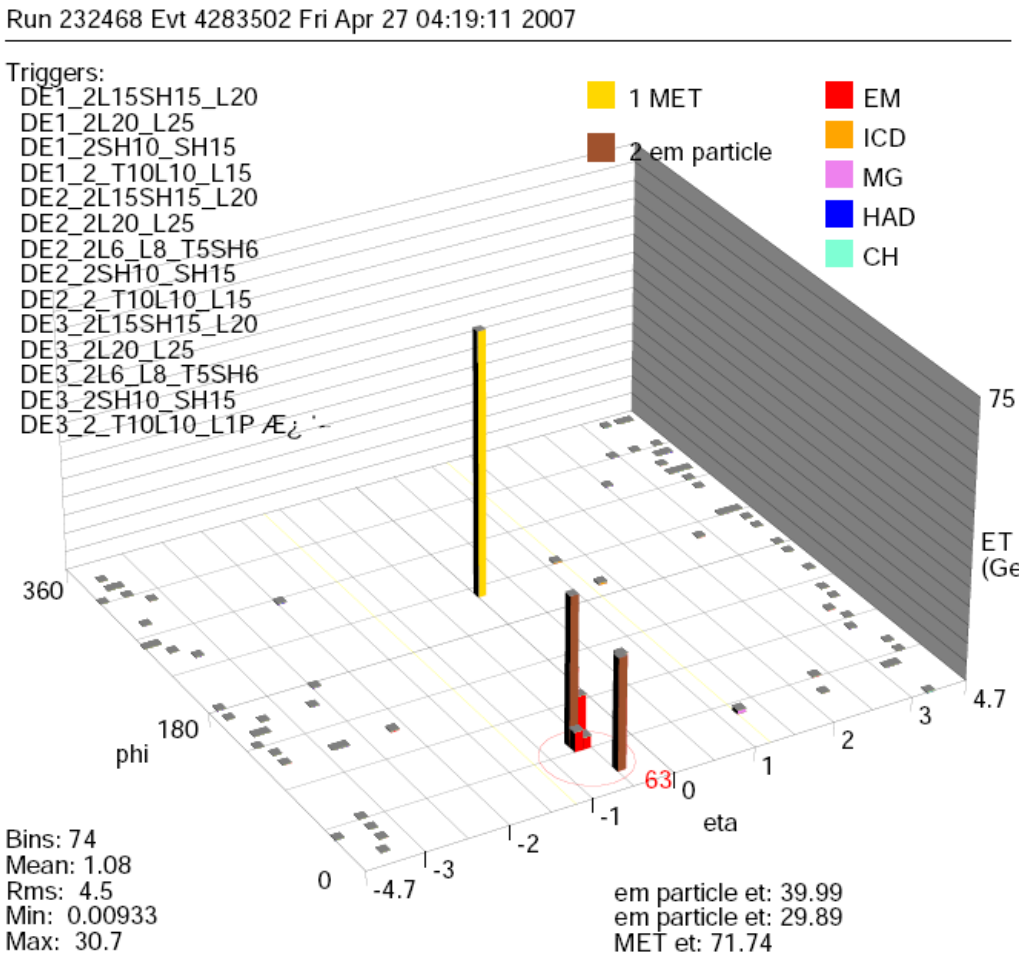


- Candiates selected for mH=160 with very high NN output

Candidate Events

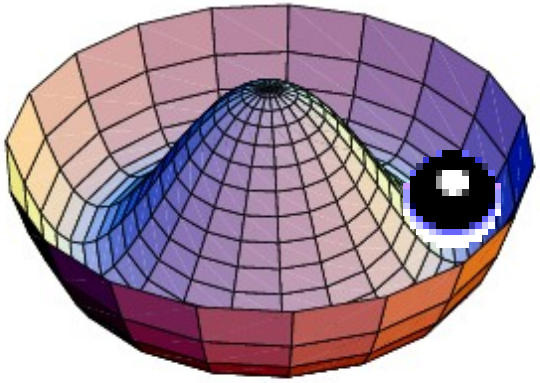






The Higgs Mechanism

- Simplest proposed mechanism to generate fermion/boson masses:
  - Higgs Mechanism → Self-interacting scalar field $V(\phi)$

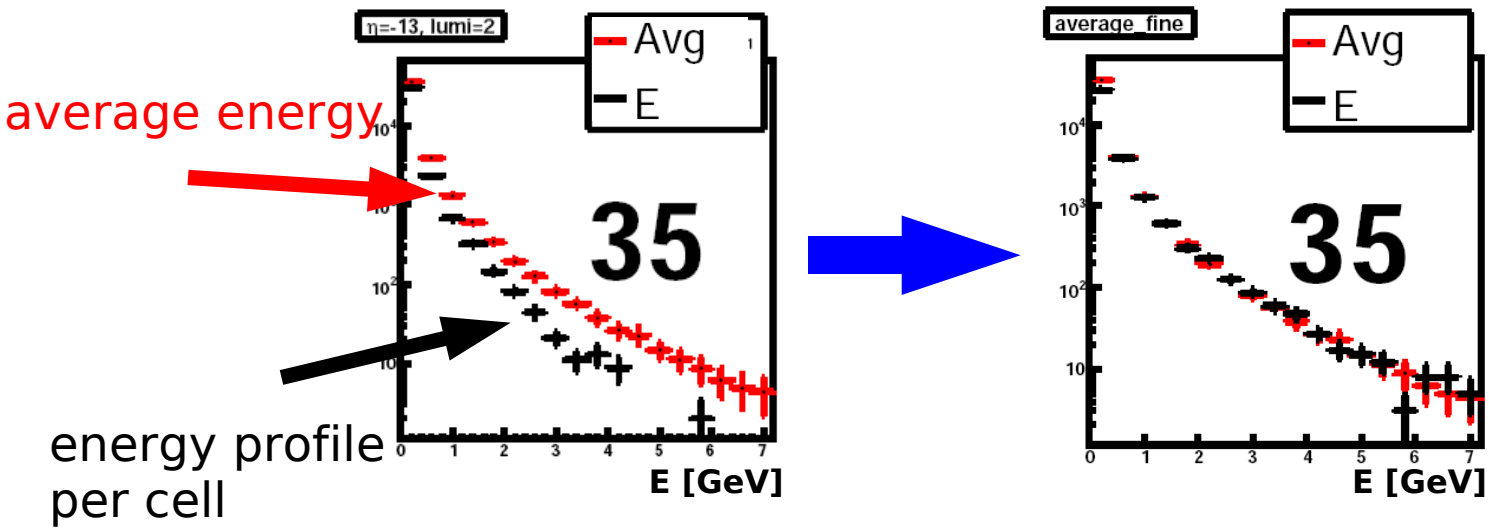


  - broken symmetry→ $W^{\pm}$, Z acquire mass
  - Spin 0 boson appears → Higgs boson
  - Mass not predicted by theory

- Regulates WW scattering cross-section which otherwise diverges at the TeV scale

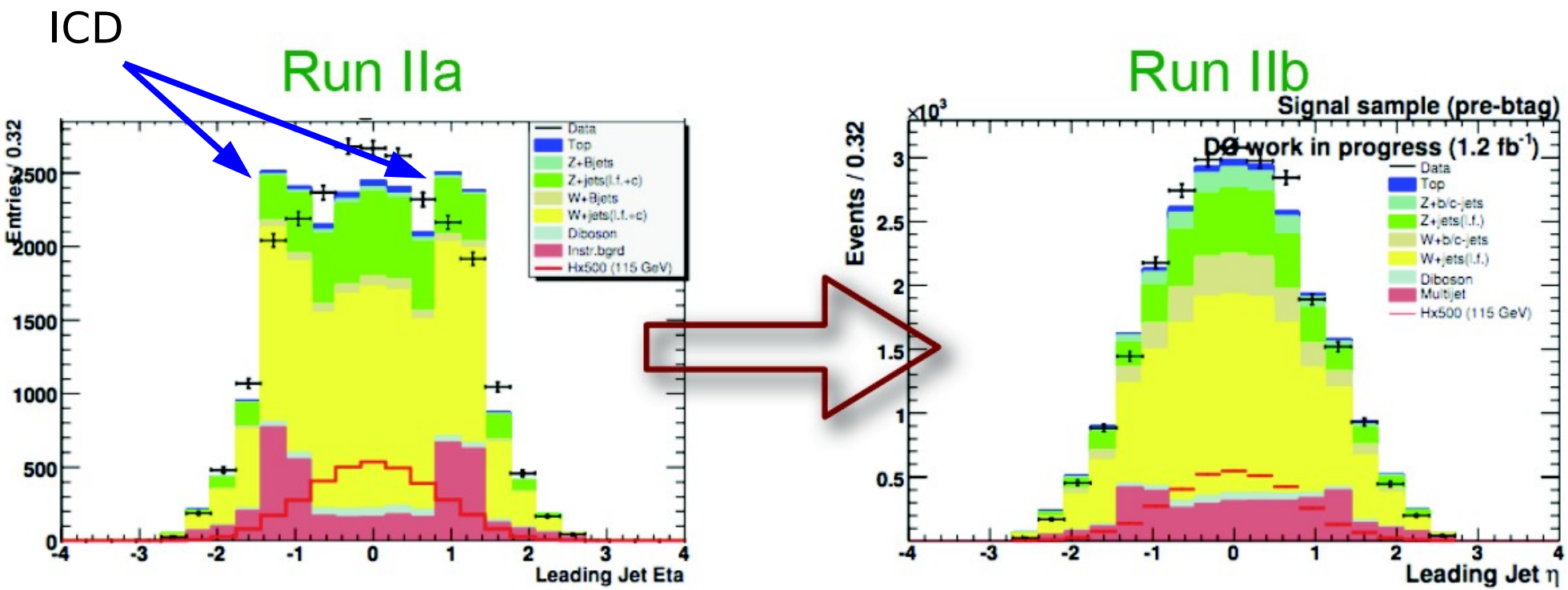
Calibration

- Participated in calorimeter calibration
- Leading role in re-commissioning of the ICD detector



Energy flow method → assuming azimuthal symmetry

Effect of Calorimter Calibration

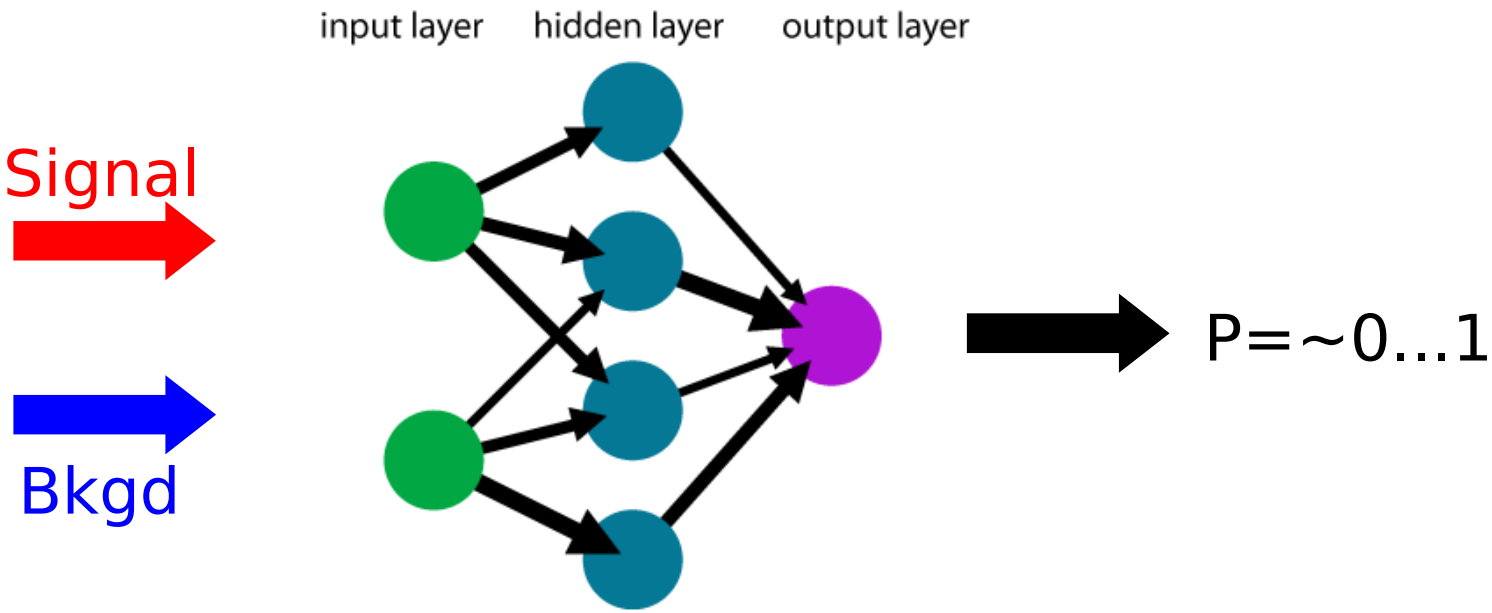


Before calibration

After calibration

Artificial Neural Networks

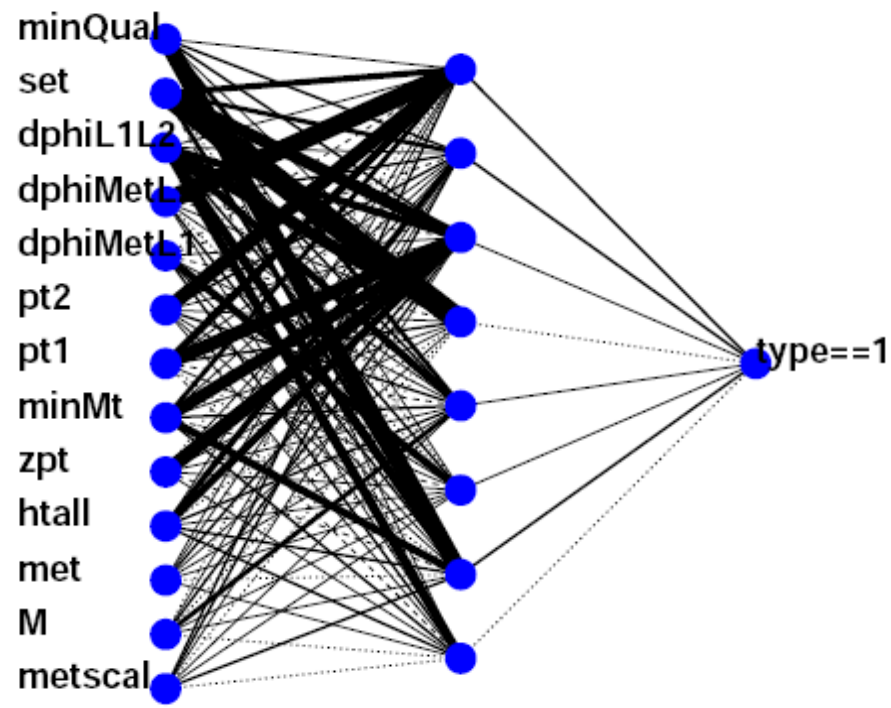
- Artificial Neural Networks are computational tools for pattern recognition



- Exploits information of correlations and shape

Input Variables for NN

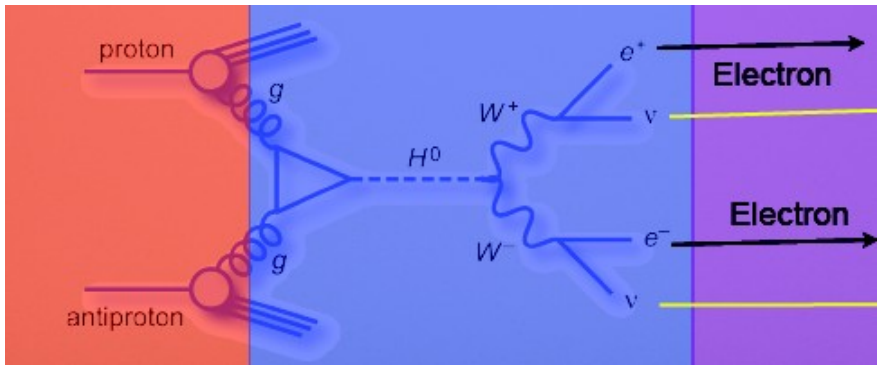
NN Analysis Variables	
Object kinematics	
p_T of leading electron	$p_T(e1)$
p_T of trailing electron	$p_T(e2)$
sum of the transverse momenta of the leptons:	$\vec{p}_T(e1) + \vec{p}_T(e2)$
sum of the momenta of all jets:	$H_T = \sum_i \mathrm{jet}_i$
minimal quality of one of the two leptons:	$\mathcal{Q}_{min}(e_1, e_2)$
Event Kinematics	
invariant mass of both leptons	$M_{\mathrm{inv}}(e1, e2)$
minimal transverse mass of one lepton and $\not{E}_{\mathrm{T}}$	M_T^{min}
missing transverse energy	$\not{E}_{\mathrm{T}}$
scalar transverse energy	E_T^{scalar}
Topological Variables	
angle between selected electrons	$\Delta\phi(e1, e1)$
angle between leading electron and $\not{E}_{\mathrm{T}}$	$\Delta\phi(\not{E}_{\mathrm{T}}, e1)$
angle between trailing electron and $\not{E}_{\mathrm{T}}$	$\Delta\phi(\not{E}_{\mathrm{T}}, e2)$



Matrix Element Method

- probability density proportional to differential cross-sections of parton level process convoluted with squared matrix element and transfer function of measurement

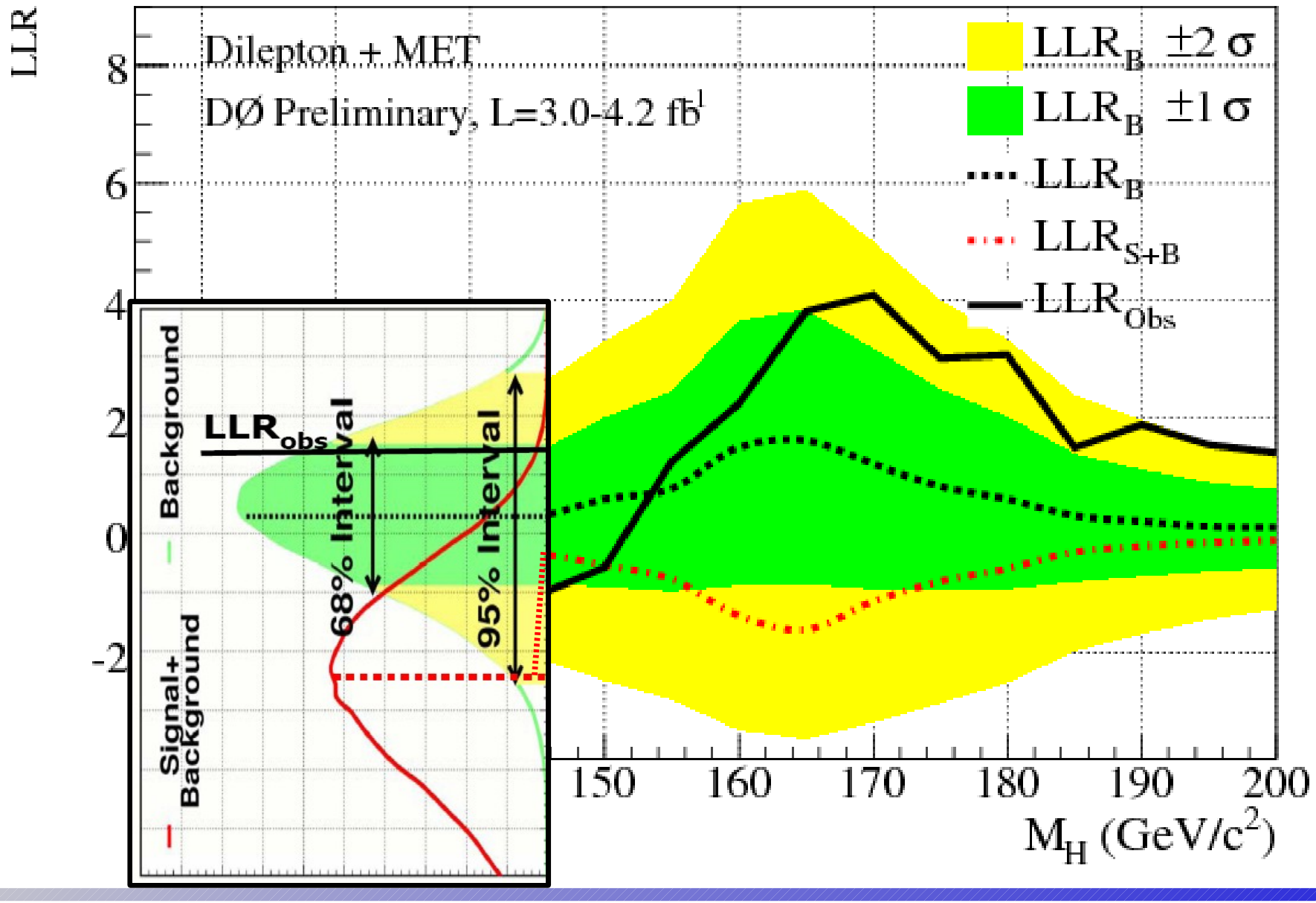
$$\underbrace{\frac{d\sigma}{d\vec{x}}}_{\text{Detector level differential cross section}} \propto \int \underbrace{\frac{f(q_1)}{q_1}\frac{f(q_2)}{q_2}dq_1 dq_2}_{\text{CTEQ6 LO Parton distribution functions}} \times \underbrace{|\mathcal{M}(\vec{y})|^2 d\Phi(\vec{y})}_{\text{Leading order matrix elements from MCFM times phase space factor}} \times \underbrace{W(\vec{y}|\vec{x})}_{\text{Probability density for parton event } \mathbf{y} \text{ given measured event } \mathbf{x}}$$



- Discrimination using probability density:

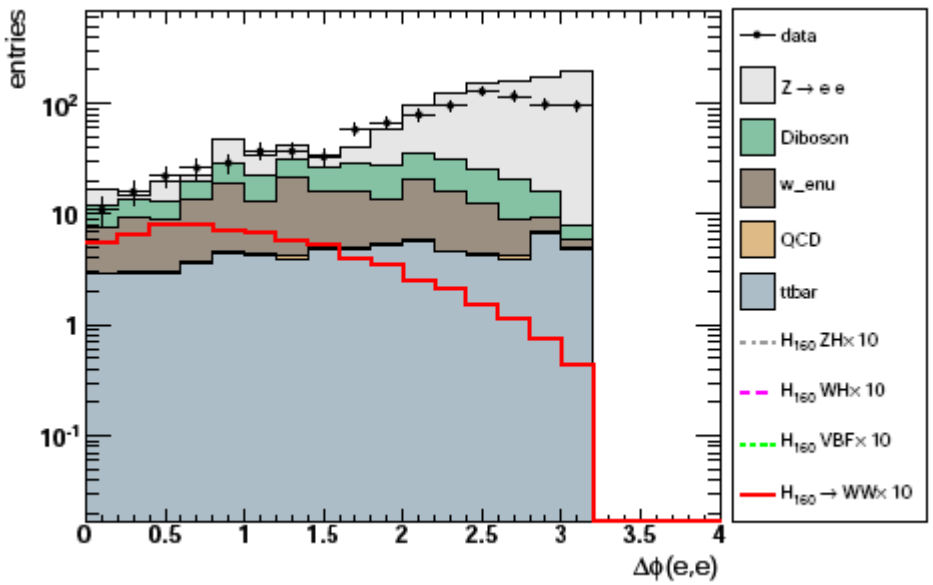
$$D(\vec{x}) = \frac{P_{\text{Signal}}(\vec{x})}{P_{\text{Signal}}(\vec{x}) + P_{\text{Background}}(\vec{x})}$$

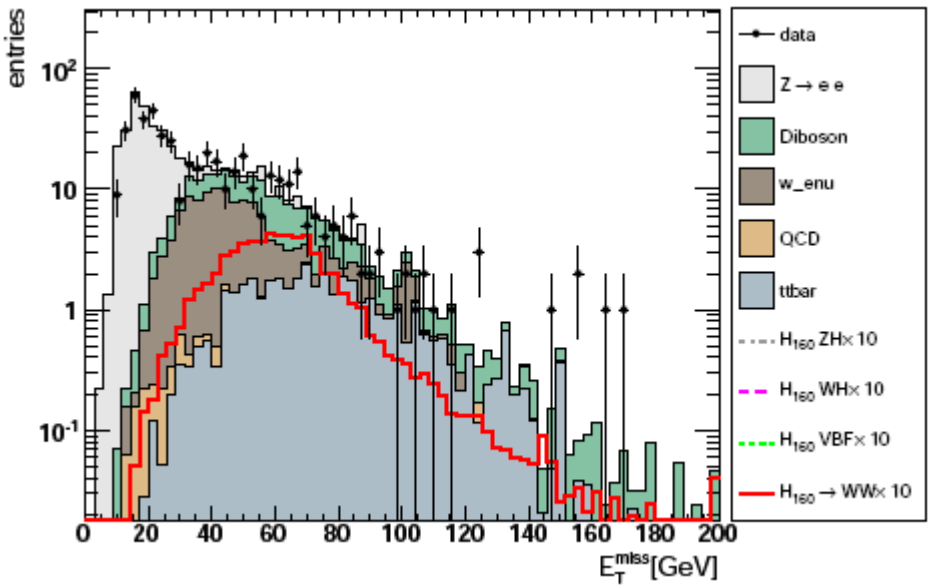
Results – Log Likelihood Ratio

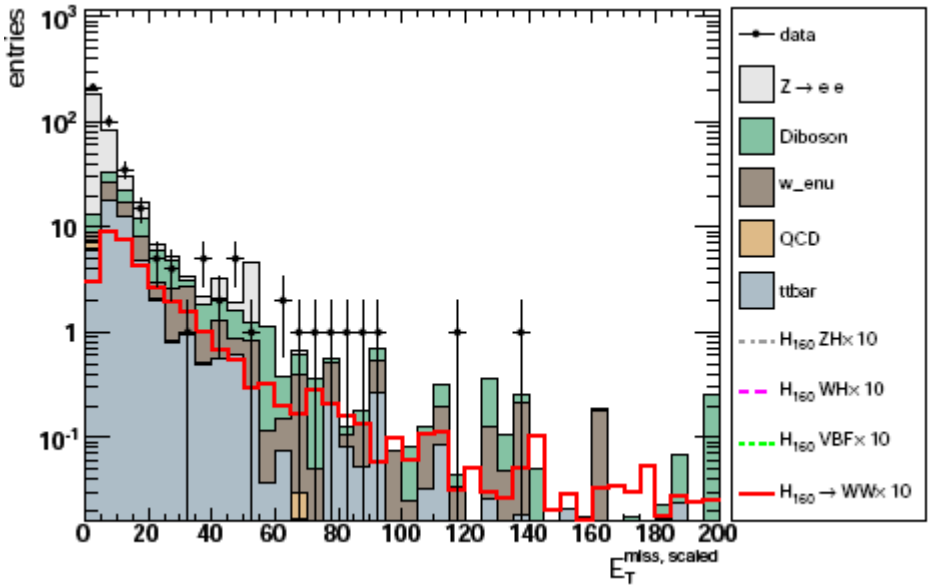


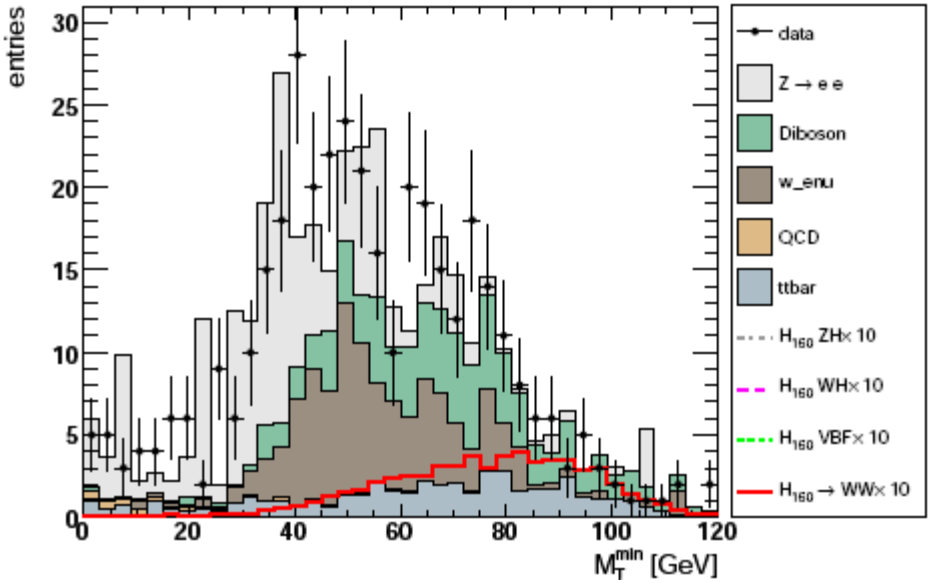
Marginal Distributions for the Cuts

Physics Department
University of Freiburg

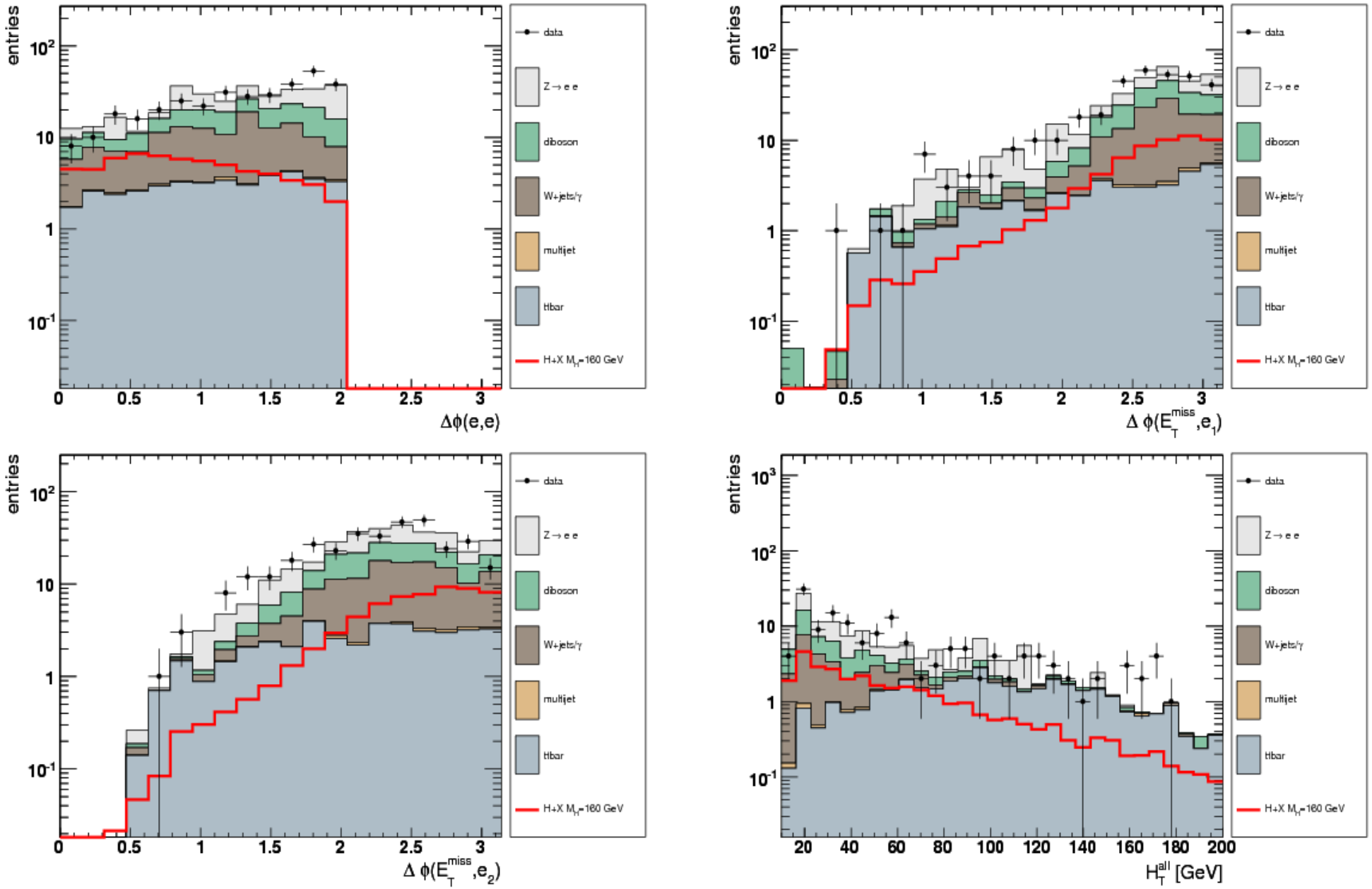




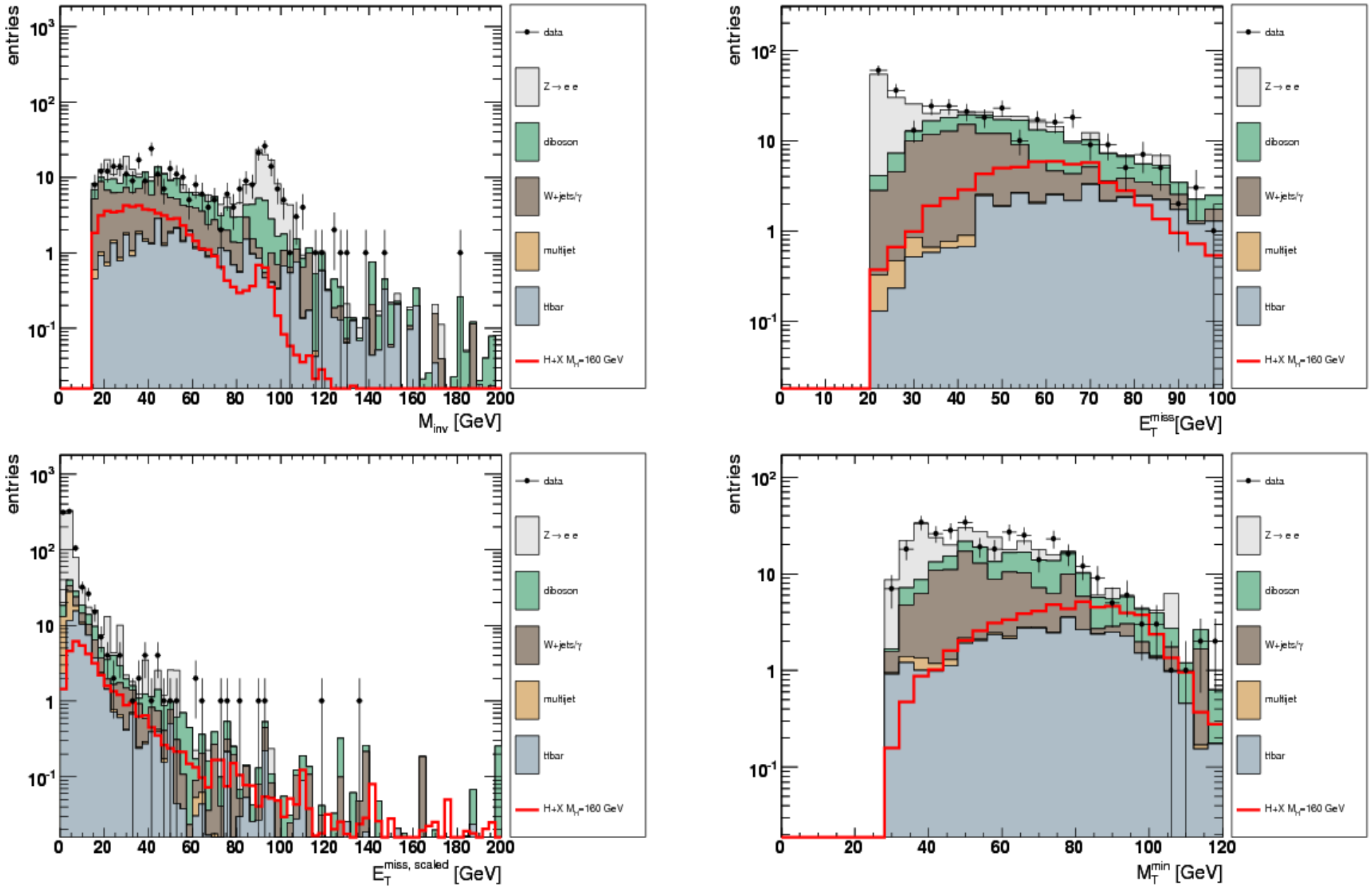




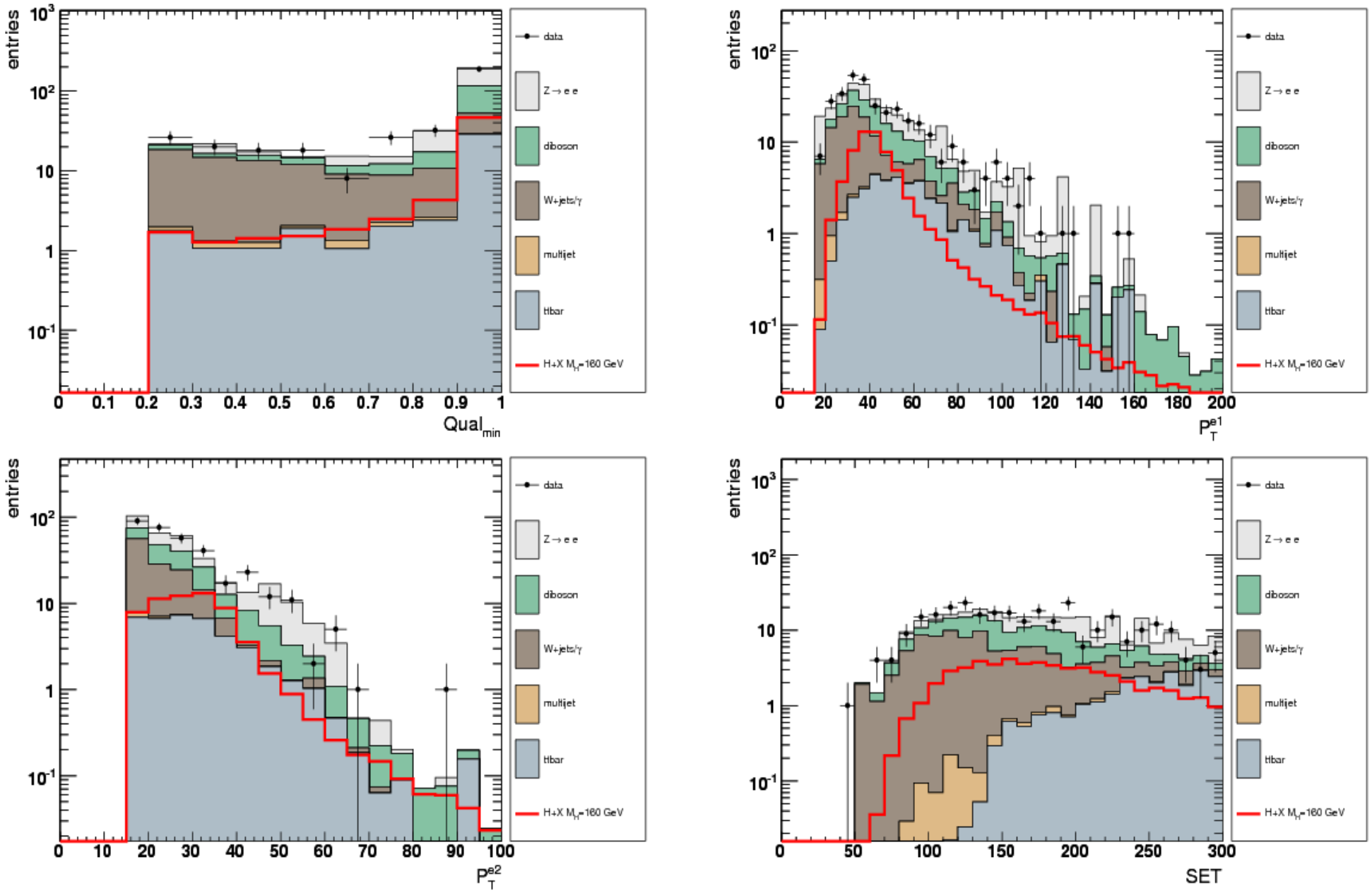
NN input distributions I - log



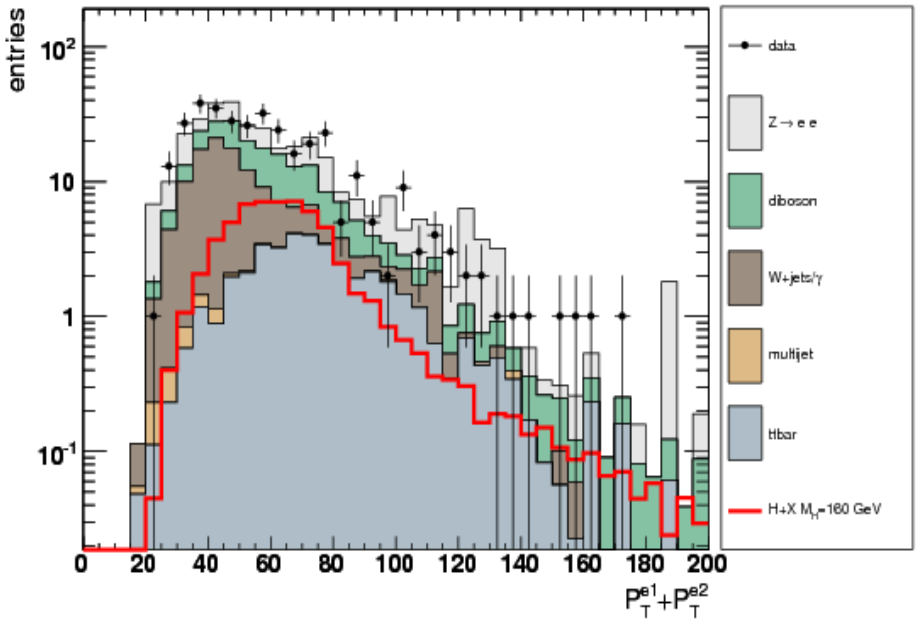
NN input distributions II - log



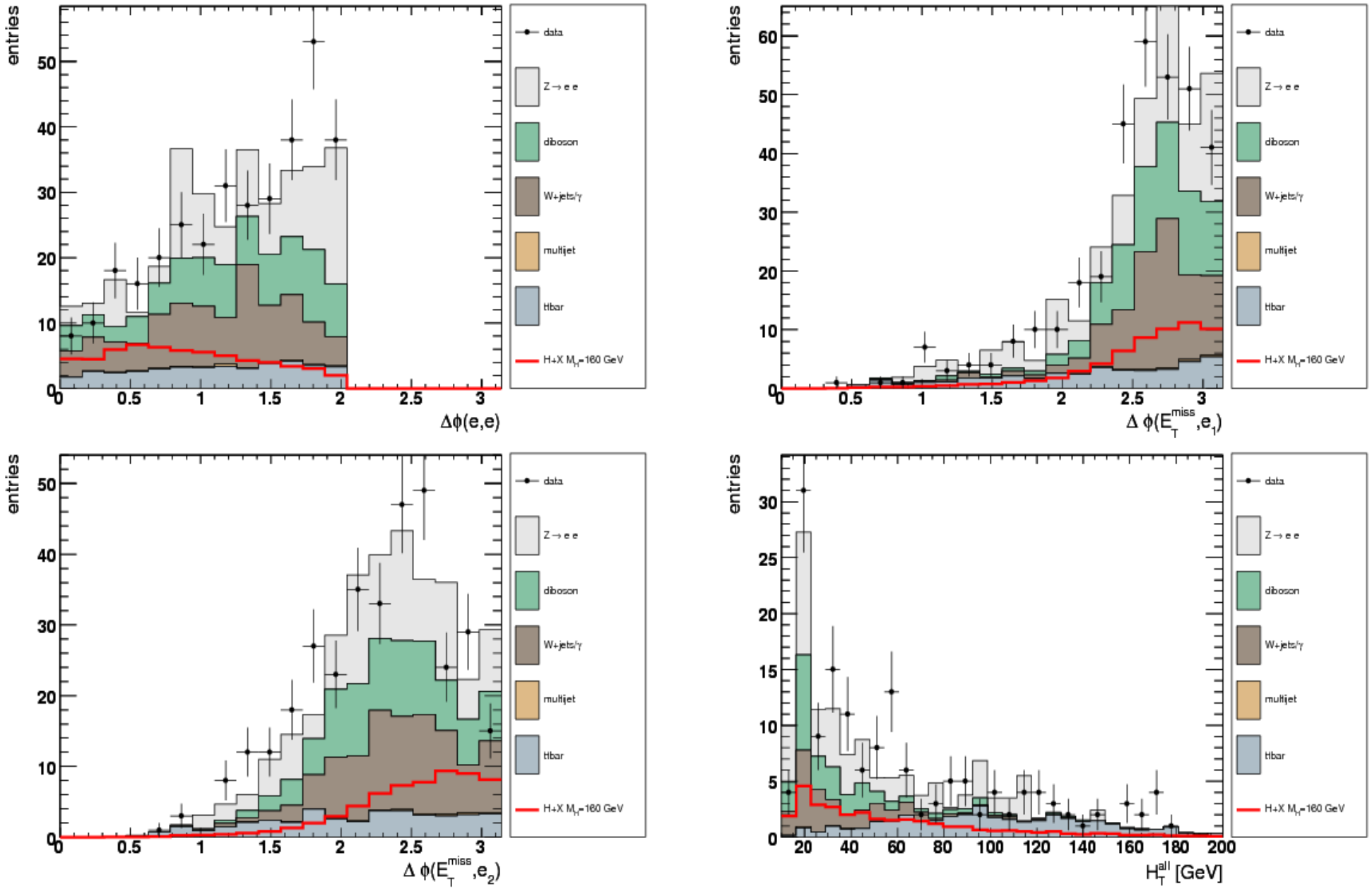
NN input distributions III - log



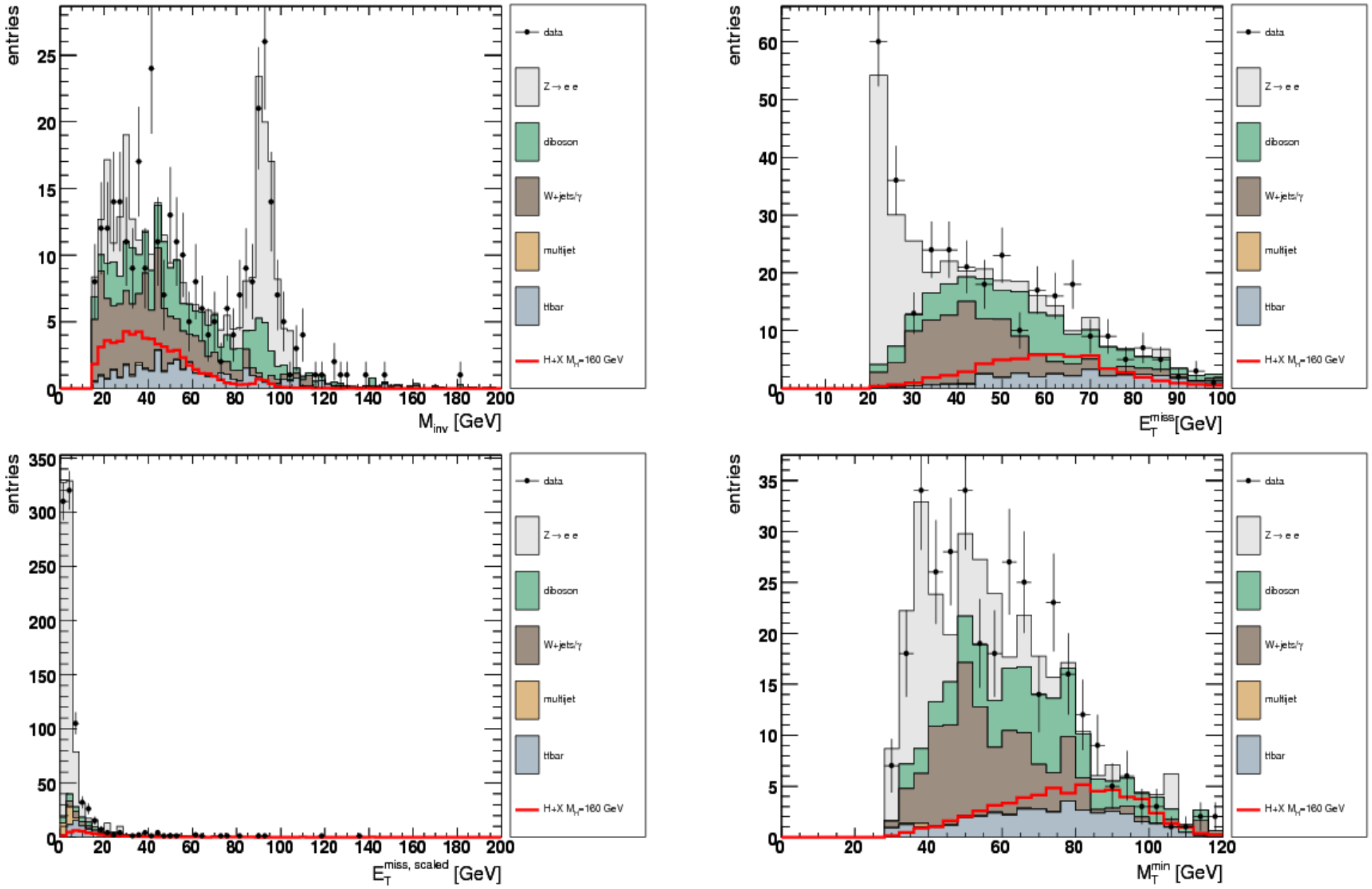
NN input distributions V - lin



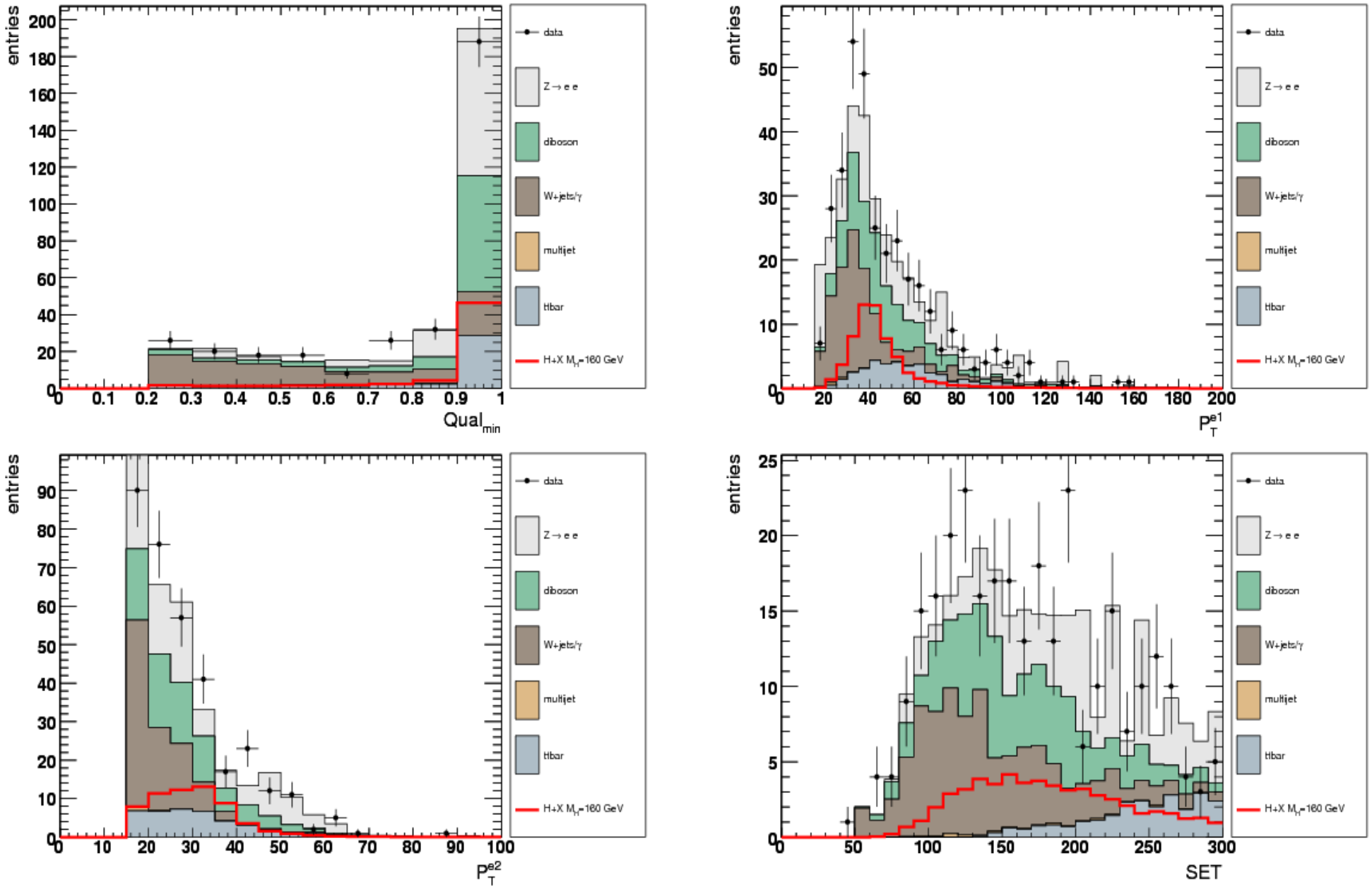
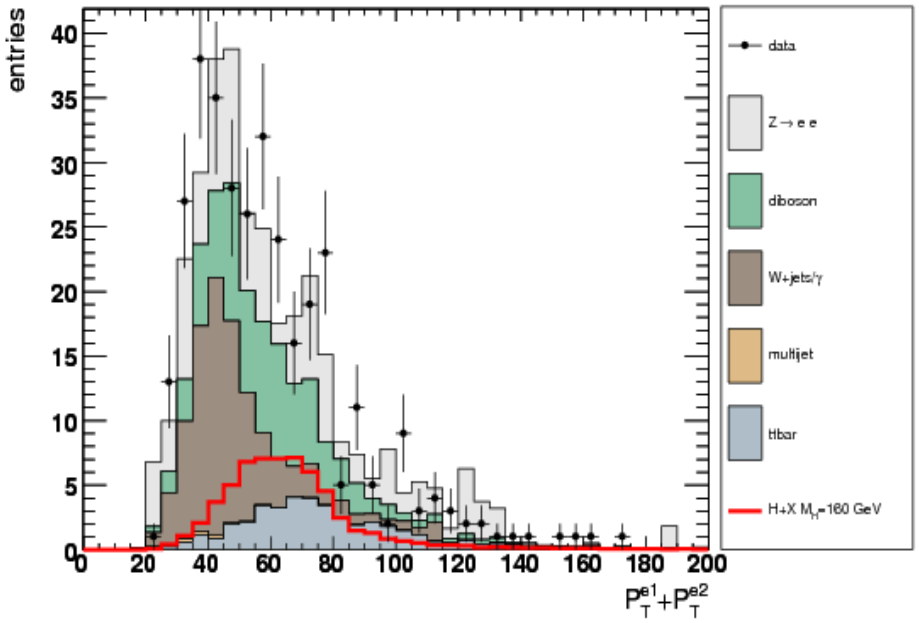
NN input distributions I - lin



NN input distributions II - lin



NN input distributions III - lin



NN input distributions V - lin