The impact of the 2019 CMS muon endcap upgrade with GEMs on the search for the H-> ττ -> μμ final state

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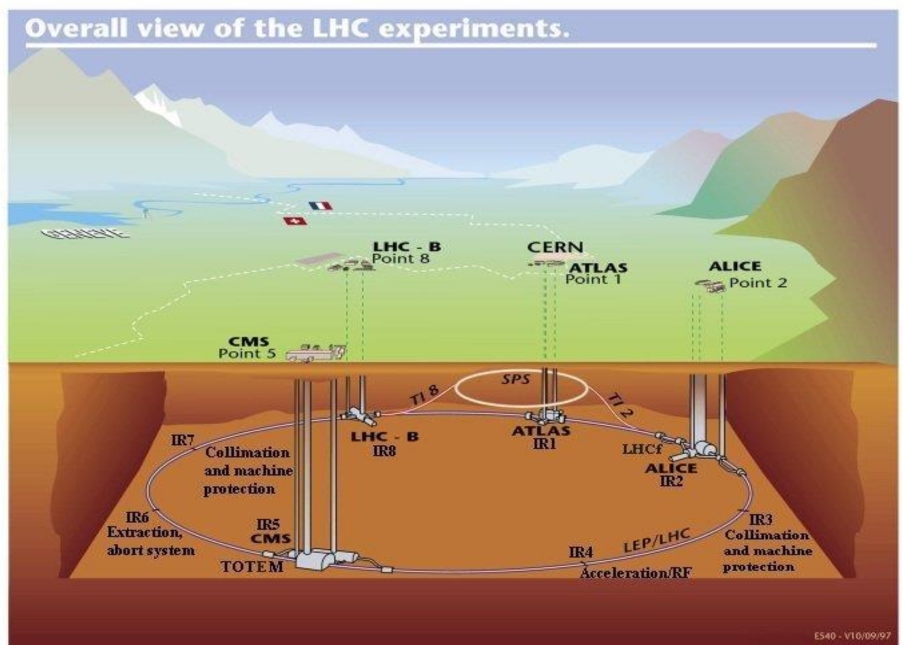
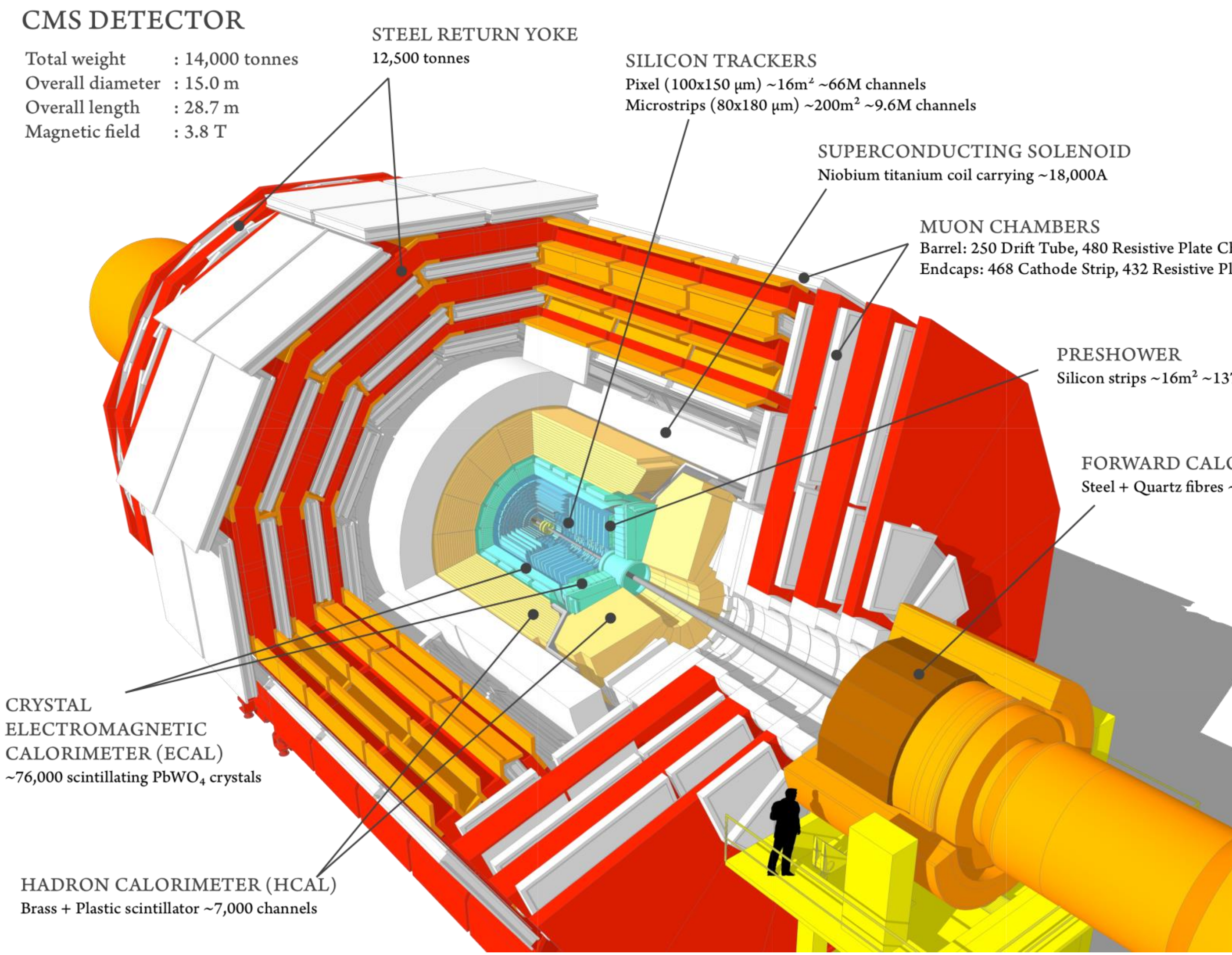
Large Hadron Collider (LHC)

- Large : 27 KMs in circumference
- Hadron: Accelerates protons and ions (Lead), which are hadrons
- Collider: Collides bunches of protons at 4 different interaction points!



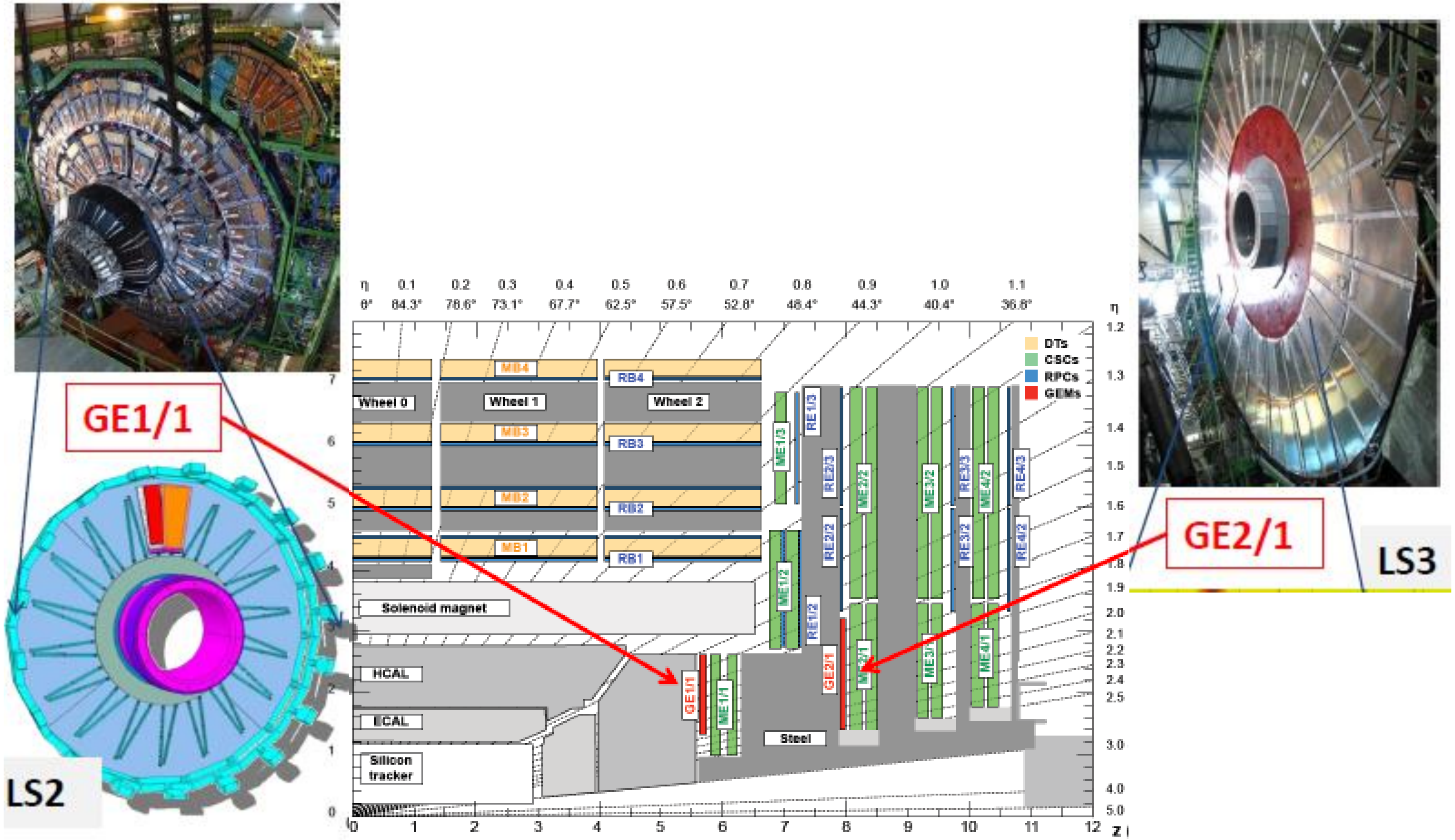
CMS

- Compact: Heaviest detector @ 14000 tons!
- Muon: Chambers to detect muons
- Solenoid: Built around a huge solenoid magnet
- One of the two General purpose detectors


CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

CMS GEM project

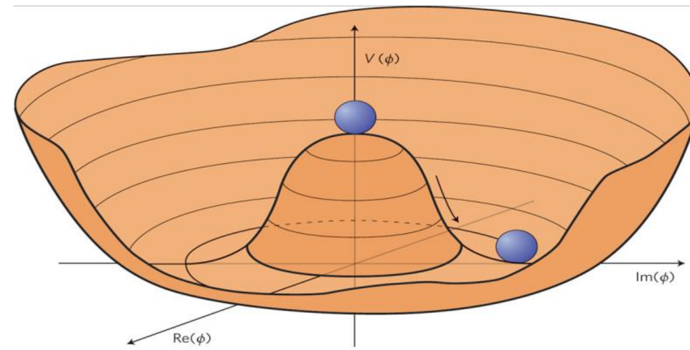
- Triple GEM detectors in $1.6 < |\eta| < 2.2$
- Redundancy in muon system for tracking and triggering
  - RPCs (Fast redundant detectors) end at 1.6, so only CSCs, no redundancy!
  - Must for High PU environment



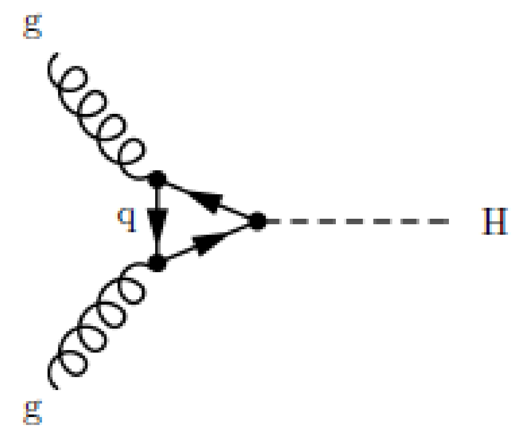
2019 Geometry deals with GE1/1

Higgs Boson

- Higgs mechanism- combination of spontaneous symmetry breaking and local gauge invariance (soft-condensed matter physics)



- Production mechanism studied for this analysis: gluon fusion to Higgs (VBF, ttH excluded)



- Decay channel studied:

  Higgs->ττ-> μμ

Monte-Carlo samples used for the analysis

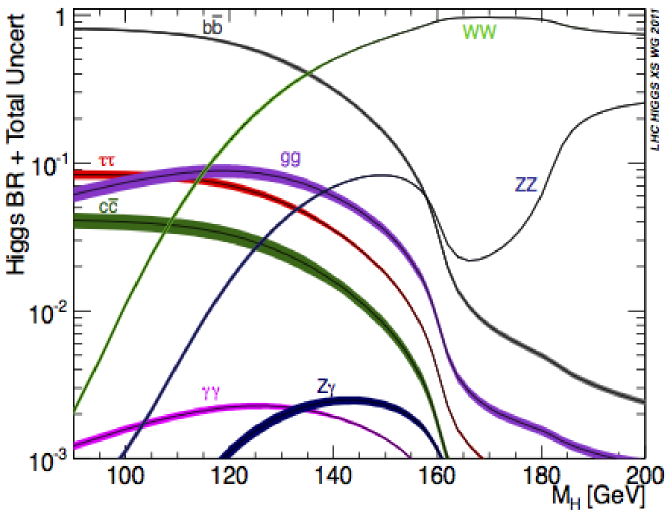
- Signal:
  - Official samples (200K) with GEM geometry
    - Left with only 2K dimuon events (Branching ratio of 3 % for tau to mu)
    - Soln: Private samples (Forced decay of Taus to Muons)
  - Private Samples (200K) with GEM geometry
    - 40 K events after all pre-selection cuts (discussed later)
- Background:
  - Drell Yan to Tau (irreducible!)
    - Official samples (990K) with GEM geometry
      - Left with 2K events after pre-selection cuts!
    - Private samples (close to 200K): forced decay
      - Left with 20k events
  - Drell Yan to Mu
    - Official samples (990K) with GEM geometry
      - Left with 30 K events after pre-selection cuts!

Physics process	COM energy (TeV)	Number of events	Pileup	GEMs used	Data Format	Private Official
Gluon fusion to Higgs, Higgs decaying to Tau	13	462681	Yes (PU40)	No	AODSIM	Official
Gluon fusion to Higgs, Tau decaying to muons	14	200000	No	No	RECOSIM	Private
Gluon fusion to Higgs Higgs decaying to Tau Tau decaying to muons	14	200000	No	No	RECOSIM	Private
Drell Yan to Tau	14	999772	Yes (PU50)	Yes	AODSIM	Official
Drell Yan to Mu	14	999772	Yes (PU50)	Yes	AODSIM	Official
Drell Yan to Tau, Tau decaying to muons	14	199700	No	Yes	RECOSIM	Private

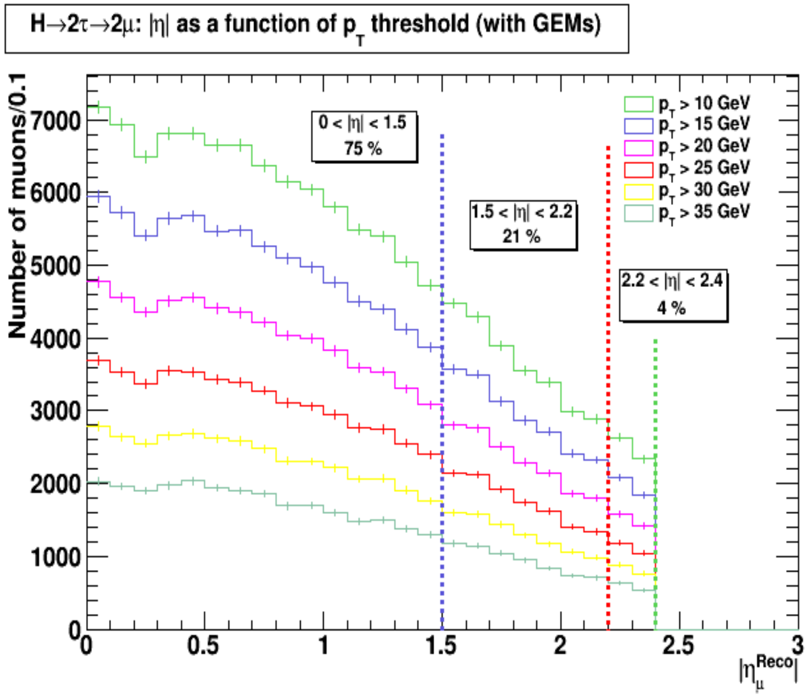
Motivation

- Significant signals for the decay of observed boson (125 GeV) in the γγ, ZZ and WW channels have been measured by CMS and ATLAS (July 4, 2012)
- Nature of interaction with fermions unclear (actively studied)
- Most promising channels H->b$\bar{b}$ (57%) and

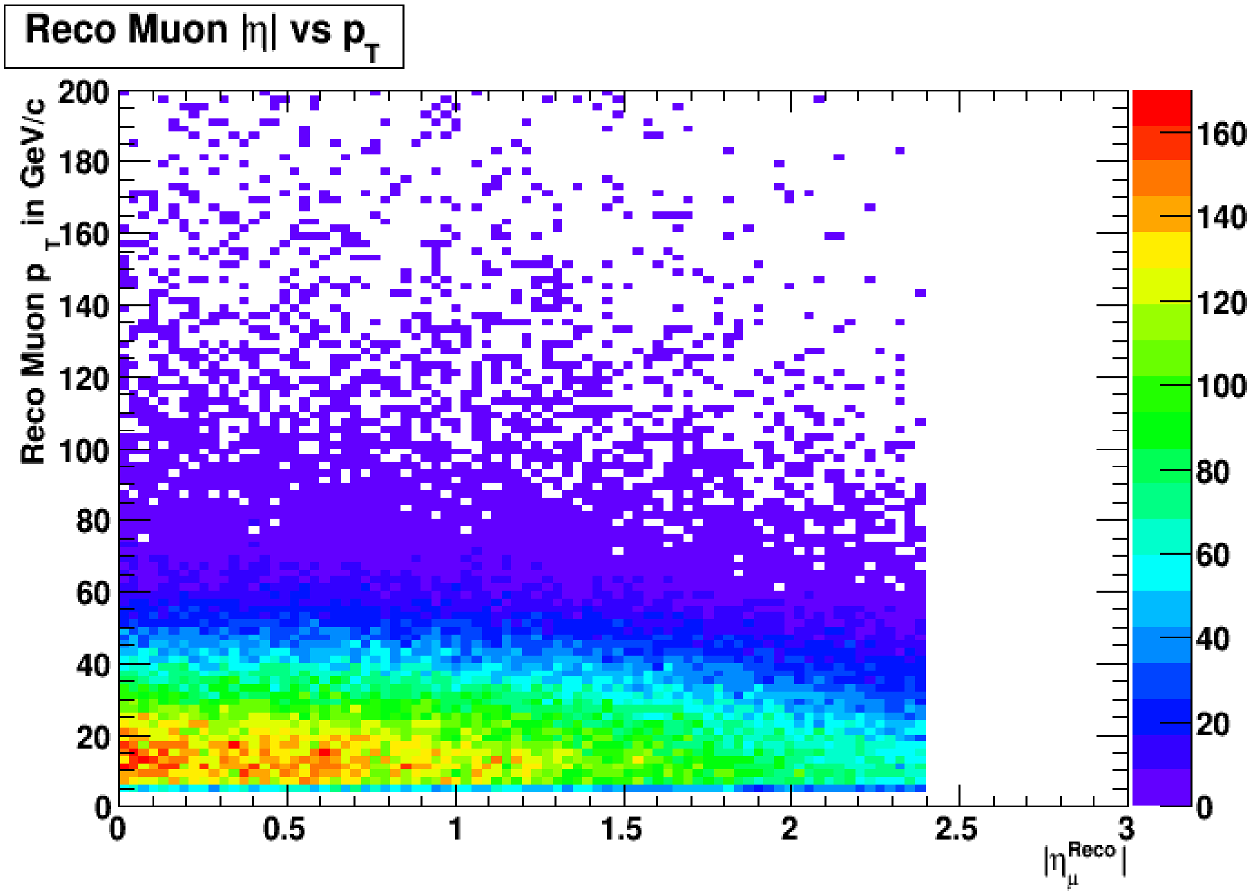
  H->τ τ (6%) (for a Higgs with m_H = 125 GeV)
- H->τ τ has Cleaner signature wrt b$\bar{b}$
- Challenging because of large backgrounds!
- Study involves dimuon final state



- Muons coming from τ decay have a soft p_T spectrum, need to keep high trigger and reconstruction efficiency
- 21 % of the muons in the high eta region: Good channel for probing possible benefits from GEM inclusion in muon reconstruction!
- Increase of pt threshold from 15 to 30 GeV would cause a 50 % event loss-> Importance of keeping trigger thresholds low in Run-2 and Run-3

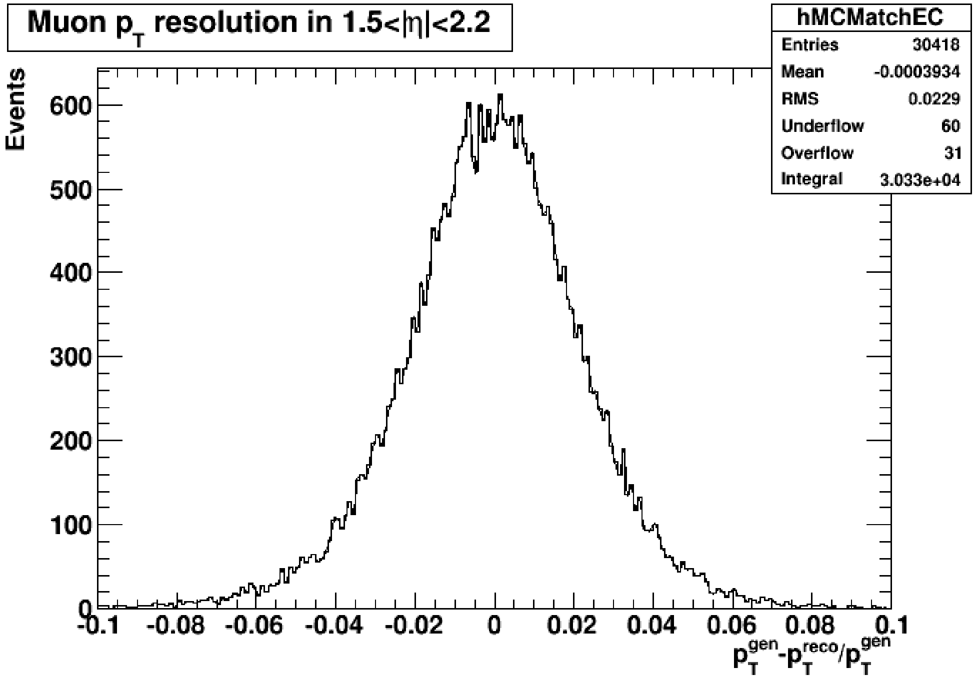


Kinematic phase space for gluon fusion H->tau tau->mu mu



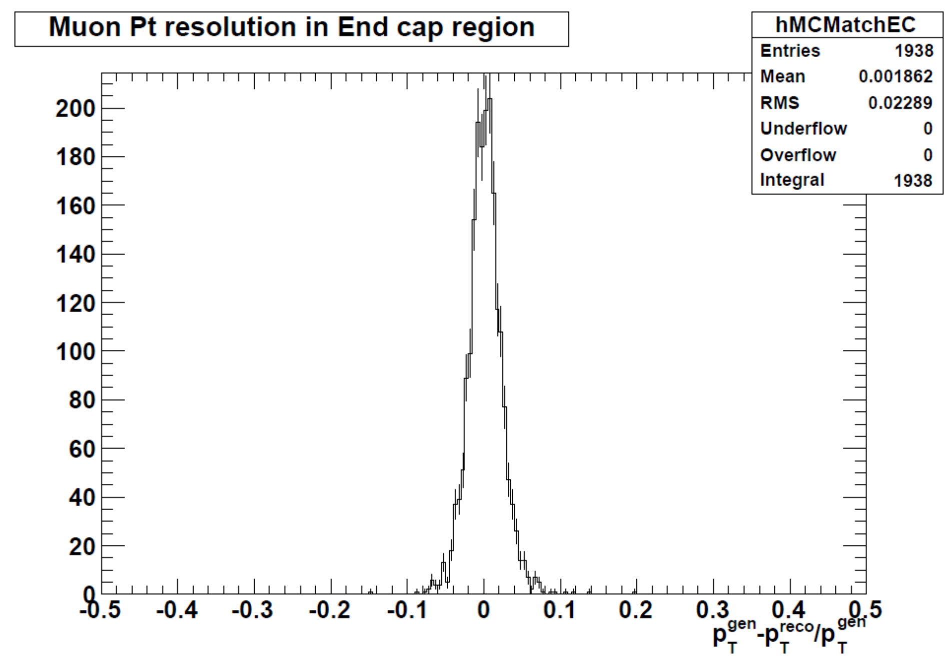
Reco Muon matched
With muon from tau
Decay at gen level
In DR < 0.1

Muon from signal events have quite soft pt spectrum in the whole detector acceptance



Without GEM

With GEM

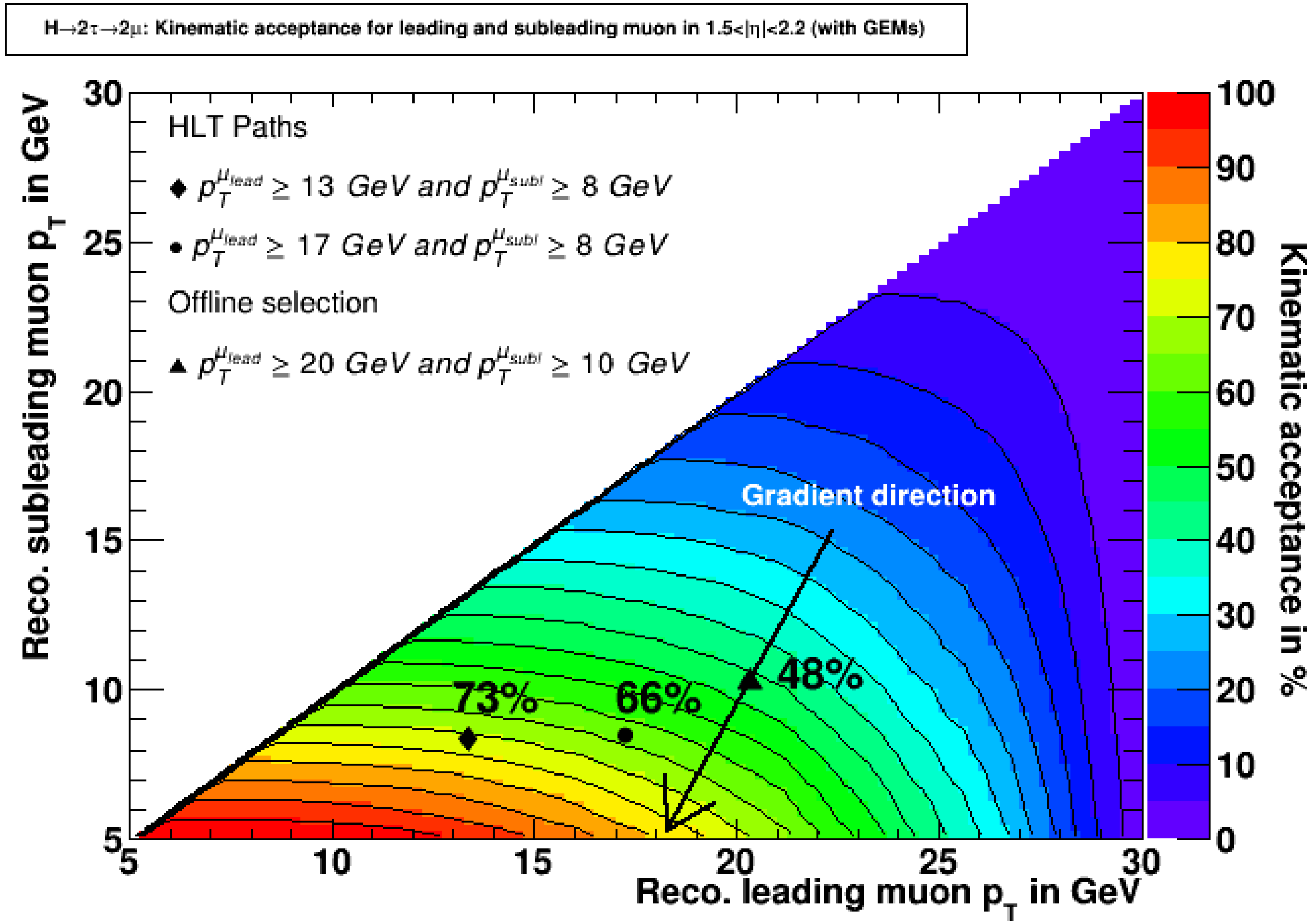


Mean Values:
w GEMs: -0.0003934
w/o GEMs:0.001862

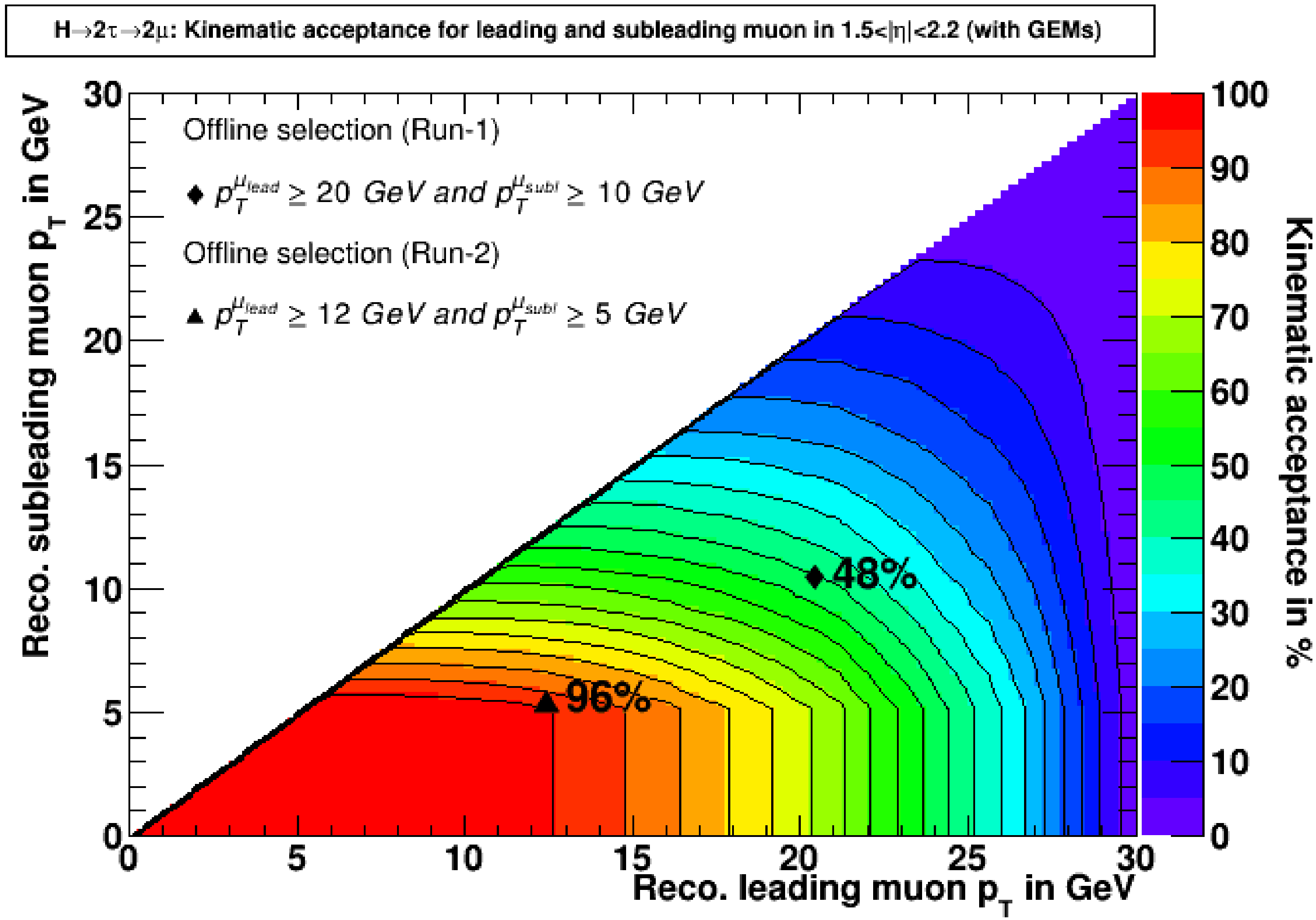
- The improvement probably due to tracker upgrade and not end-cap upgrade
- Would be interesting to see the corresponding plots from the emu (or ee) channel
- With improvement in pT resolution, it would be insightful to look at the effect of lowering dimuon pT thresholds: **Acceptance plots**

Acceptance plots

- novel way of determining the correct dimuon p_T trigger thresholds for the 2019 CMS run with the GEMs.
- Calculated by counting the number of events which have leading and sub-leading muon p_T greater than the pair, and dividing it by the total number of (accepted) events.
- Only cuts used:
  - Dimuon event
  - $|Eta| < 2.4$
  - Global muon



The acceptance for dimuons in this channel can be improved over what we had in Run 1 by using the GE1/1 to lower trigger thresholds!



A clear improvement is seen with the Run-2 offline selection

Towards a full-fledged analysis

- Pre-selection cuts:
  - the global muon must have at least one good hit in muon stations
  - the muon track must have more than 5 hits in the inner tracker and atleast one pixel hit
  - χ^2/ndof < 10 of the global muon track fit
  - Impact parameter in transverse plane $|d_0| < 0.04$ cm wrt primary vertex
  - longitudinal impact parameter w.r.t. primary vertex $|d_z| < 0.1$ cm

Multivariate Analysis

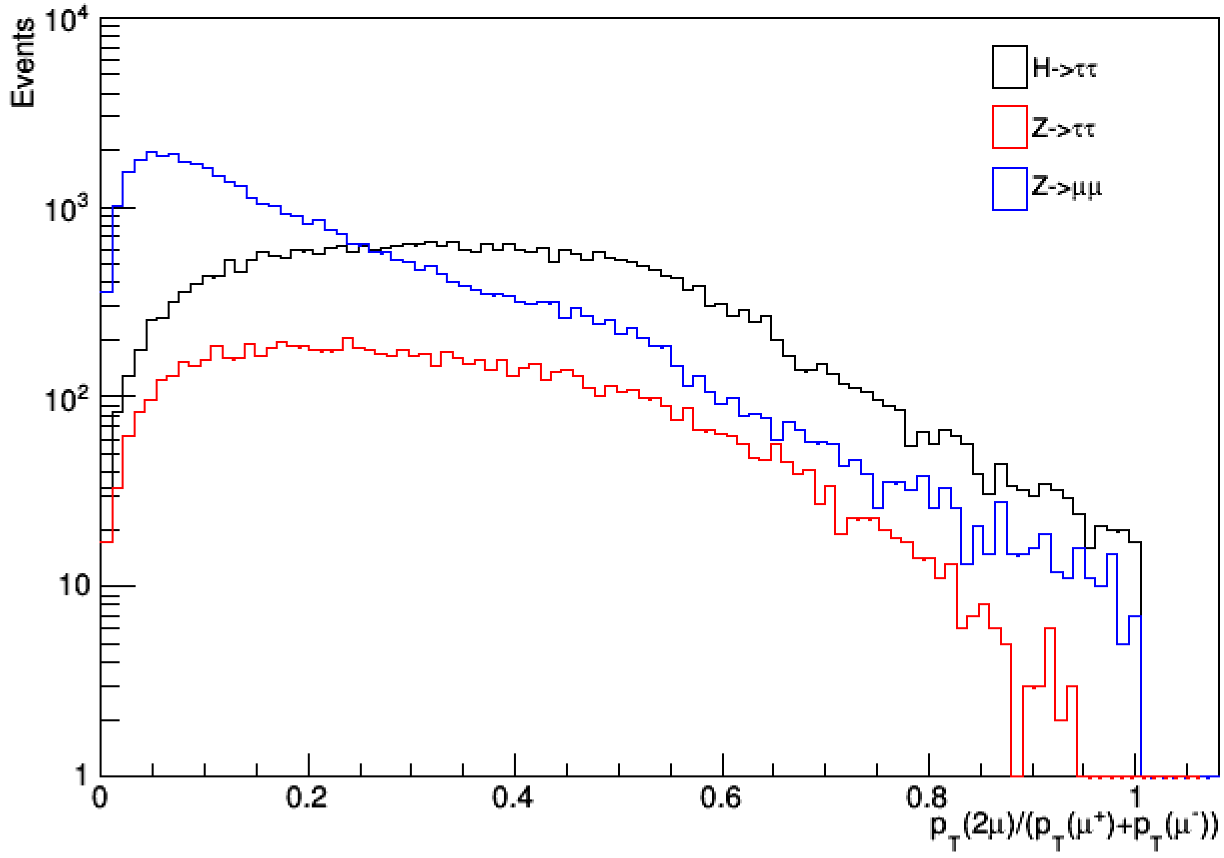
- Low signal and high background cross-section!
- No single horizontal cut can differentiate the signal from the background
- Hence, the need to use Multivariate techniques
- Boosted Decision trees-out of the box method for weak classifiers!

Boosted Decision Trees

- **Software**:TMVA (Toolkit for Multivariate Analysis)interfaced with root
- Boost type: Adaptive boost
- Booked as:
  - factory->BookMethod(TMVA::Types::kBDT, "BDT","!H:!V:NTrees=950:MinNodeSize=3.5%:MaxDepth=3:BoostType=AdaBoost:AdaBoostBeta=0.1:UseBaggedBoost:BaggedSampleFraction=0.5:SeparationType=GiniIndex:nCuts=20:DoBoostMonitor");
- Can be fine tuned extensively!

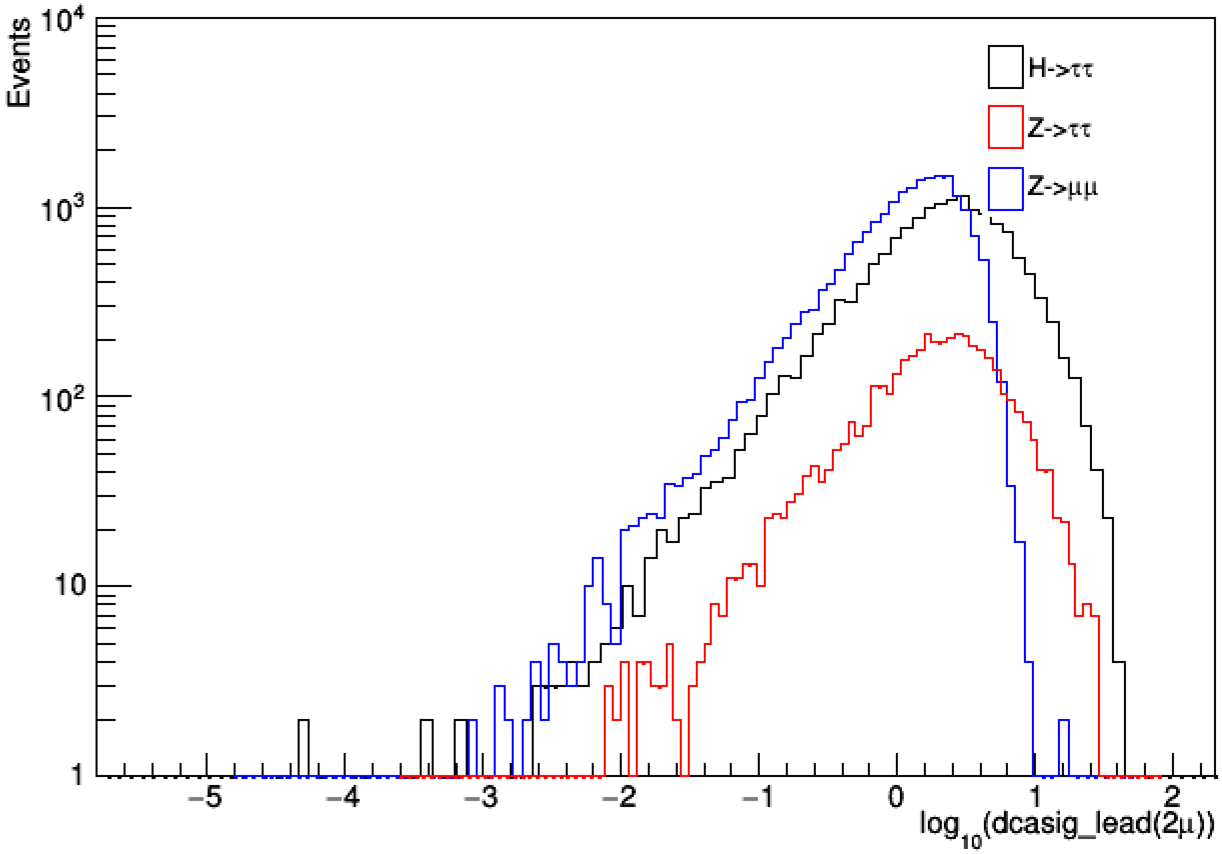
Discriminants

- The ratio of the transverse momentum of the dimuon system to the scalar sum of the positive and negative muon momenta, pT (2μ)/
- Σ pT (μ)
- The muon distance of closest approach (DCA) significance, DCASig(2μ) of dxy and dz for both the leading and the subleading muon
- The pseudorapidity of the dimuon system, η(2μ).
- MET
- The angle ω^* between three-momentum of the positively charged muon and production plane of the dimuon system, assuming that the two muons originate directly from the Z boson decay.
- The azimuthal angle between direction of the positively charged muon three-momentum and the missing transverse energy, $\Delta\Phi(\mu^+;\mathrm{MET})$



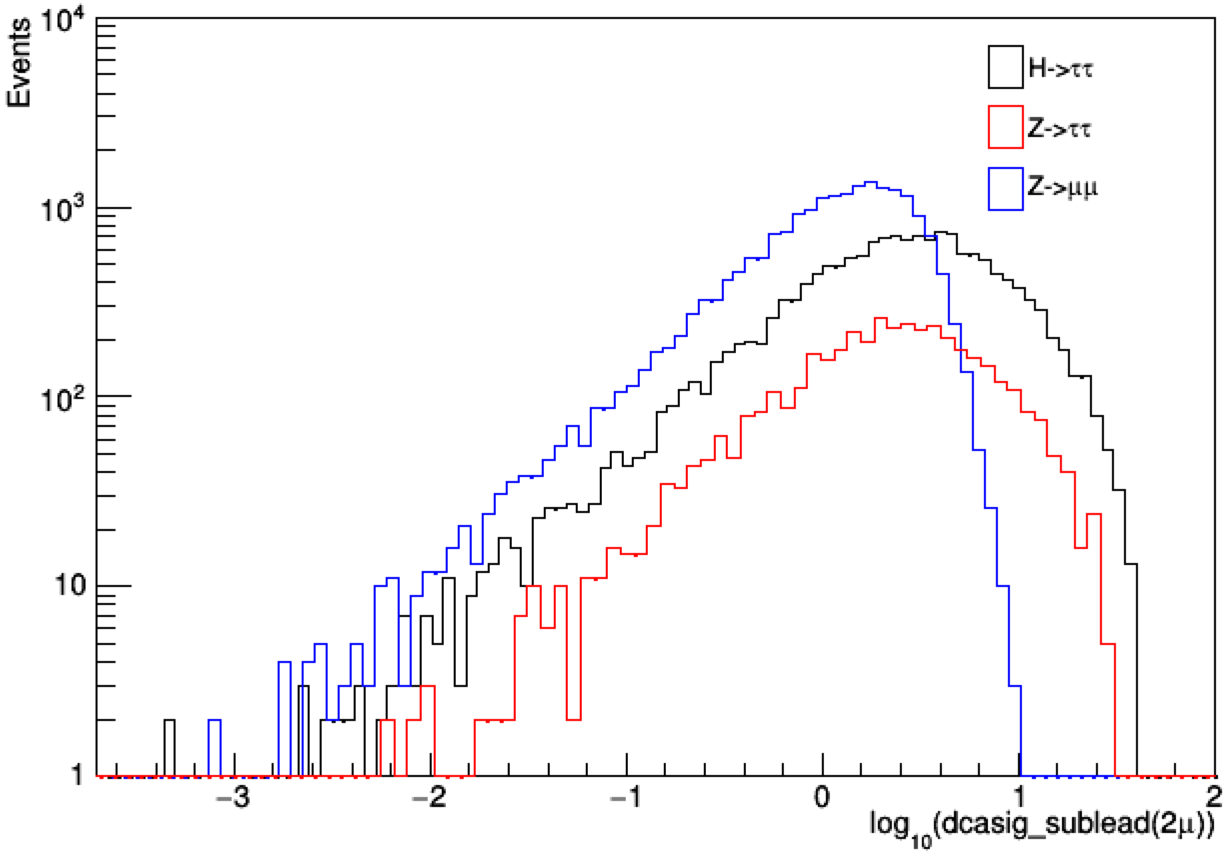
Events
10^4
10^3
10^2
10
1
0
0.2
0.4
0.6
0.8
1
p_T(2μ)/(p_T(μ⁺)+p_T(μ⁻))
H->ττ
Z->ττ
Z->μμ

d_{xy}



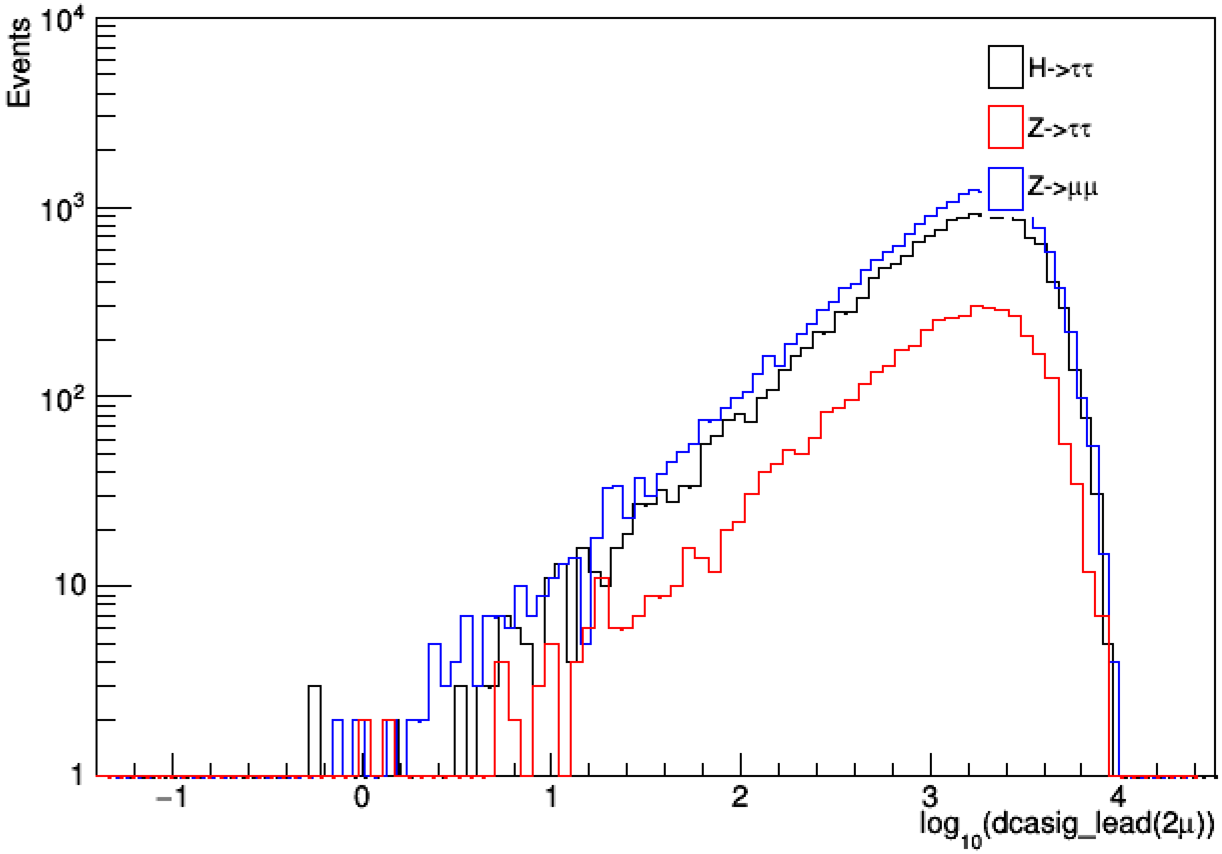
Events
10^4
10^3
10^2
10
1
H->ττ
Z->ττ
Z->μμ
−5
−4
−3
−2
−1
0
1
2
log10(dcasig_lead(2μ))

d_{xy}

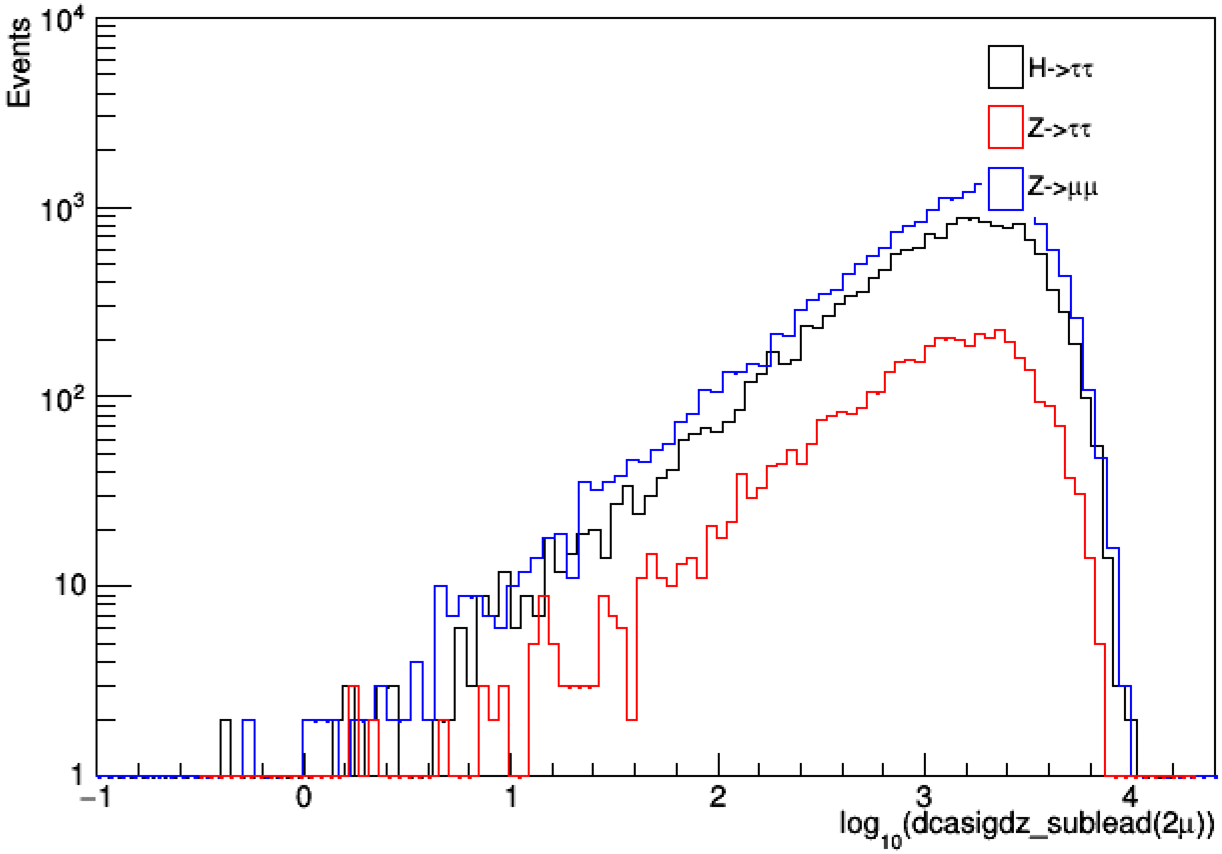


Events
10⁴
10³
10²
10
1
H->ττ
Z->ττ
Z->μμ
−3
−2
−1
0
1
2
log10(dcasig_sublead(2μ))

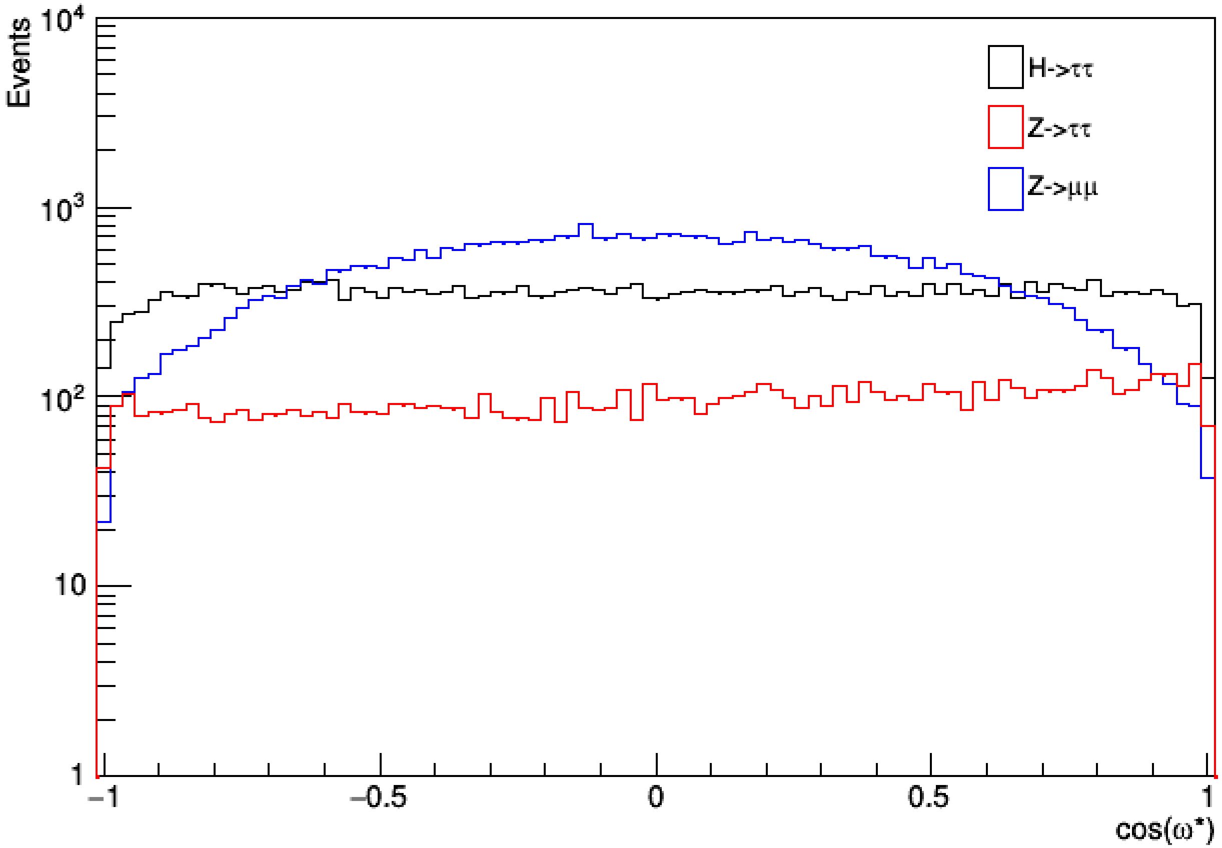
d_z



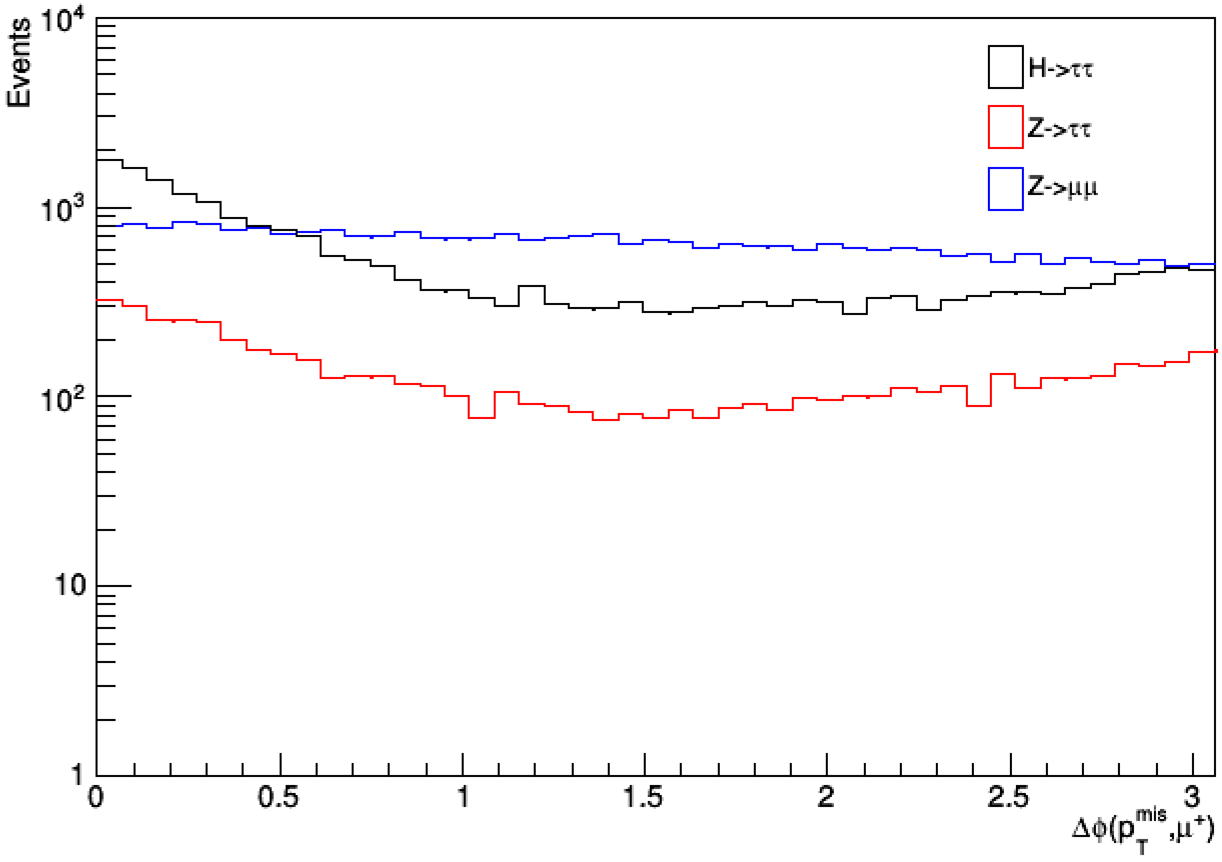
Events
10^4
10^3
10^2
10
1
−1
0
1
2
3
4
log$_{10}$(dcasig_lead(2μ))
H->ττ
Z->ττ
Z->μμ



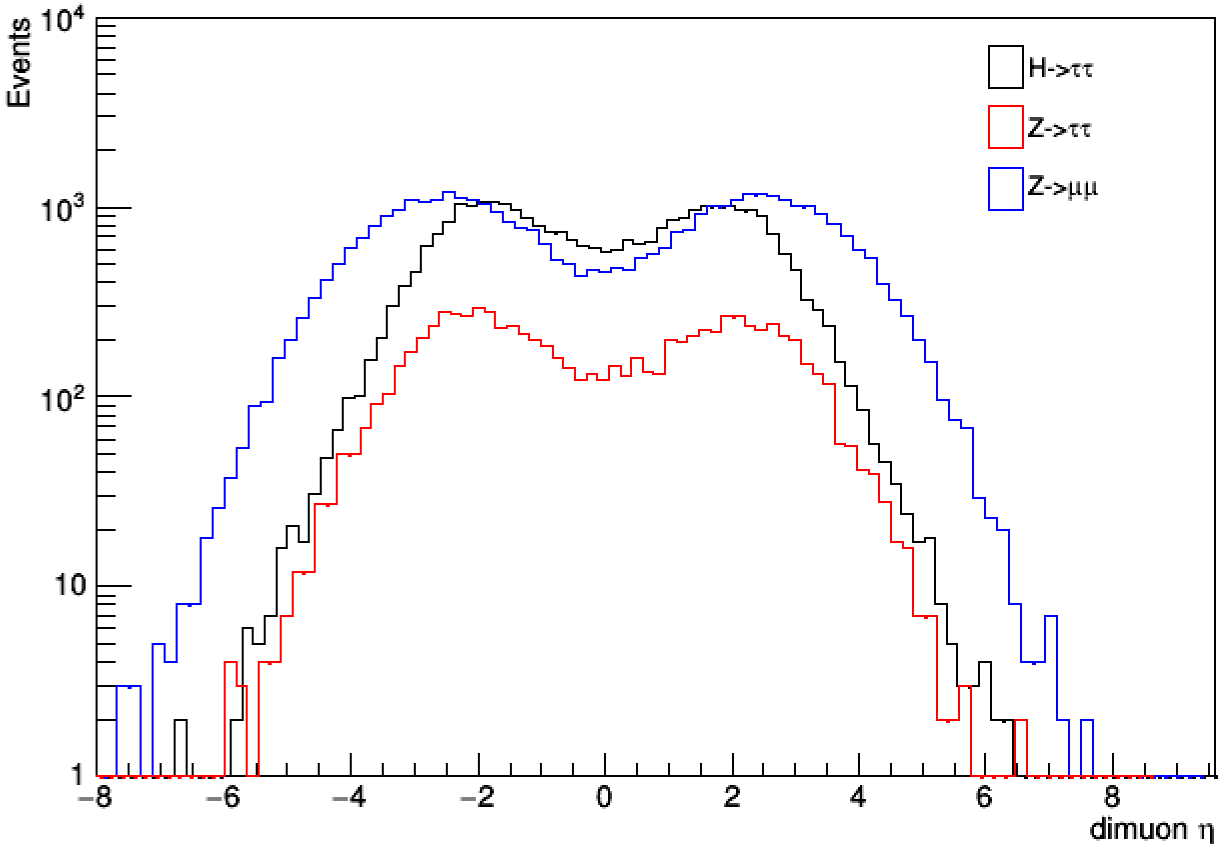
Events
10^4
10^3
10^2
10
1
−1
0
1
2
3
4
log10(dcasigdz_sublead(2μ))
H->ττ
Z->ττ
Z->μμ

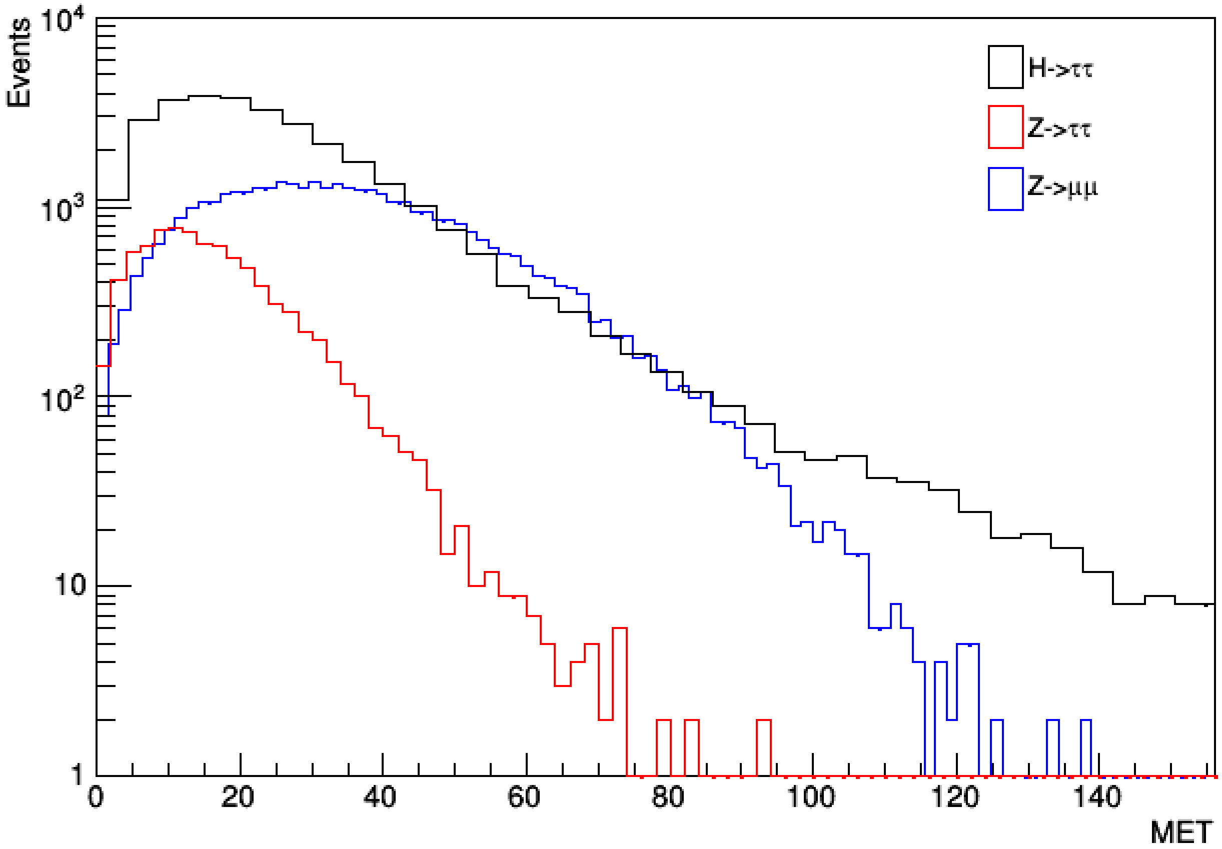


Events
H->ττ
Z->ττ
Z->μμ
10^4
10^3
10^2
10
1
−1
−0.5
0
0.5
1
cos(ω*)



Events
10^4
10^3
10^2
10
1
0
0.5
1
1.5
2
2.5
3
$\Delta\phi(p_T^{mis},\mu^+)$
H->ττ
Z->ττ
Z->μμ


Events
dimuon η
H->ττ
Z->ττ
Z->μμ
10^4
10^3
10^2
10
1
−8
−6
−4
−2
0
2
4
6
8

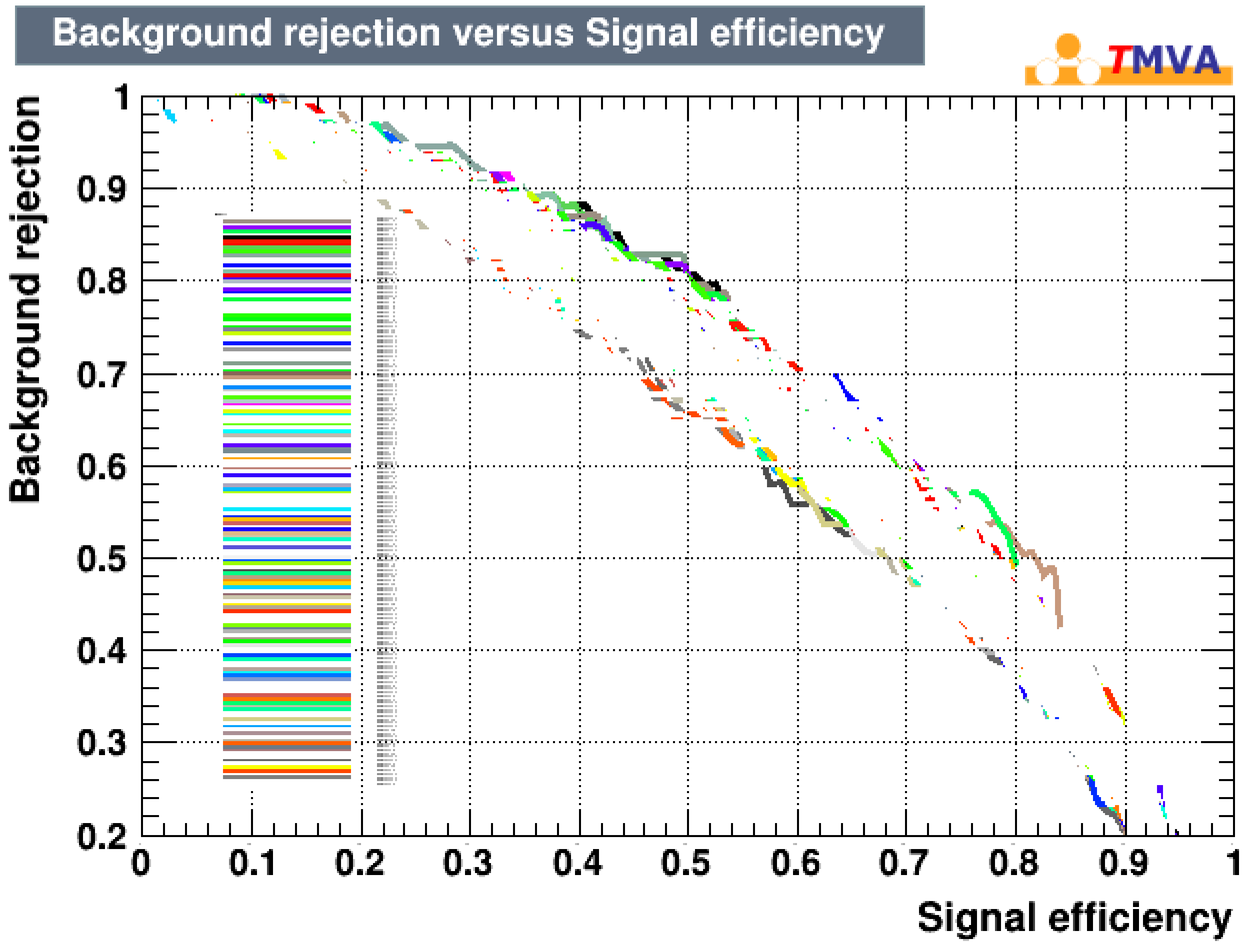


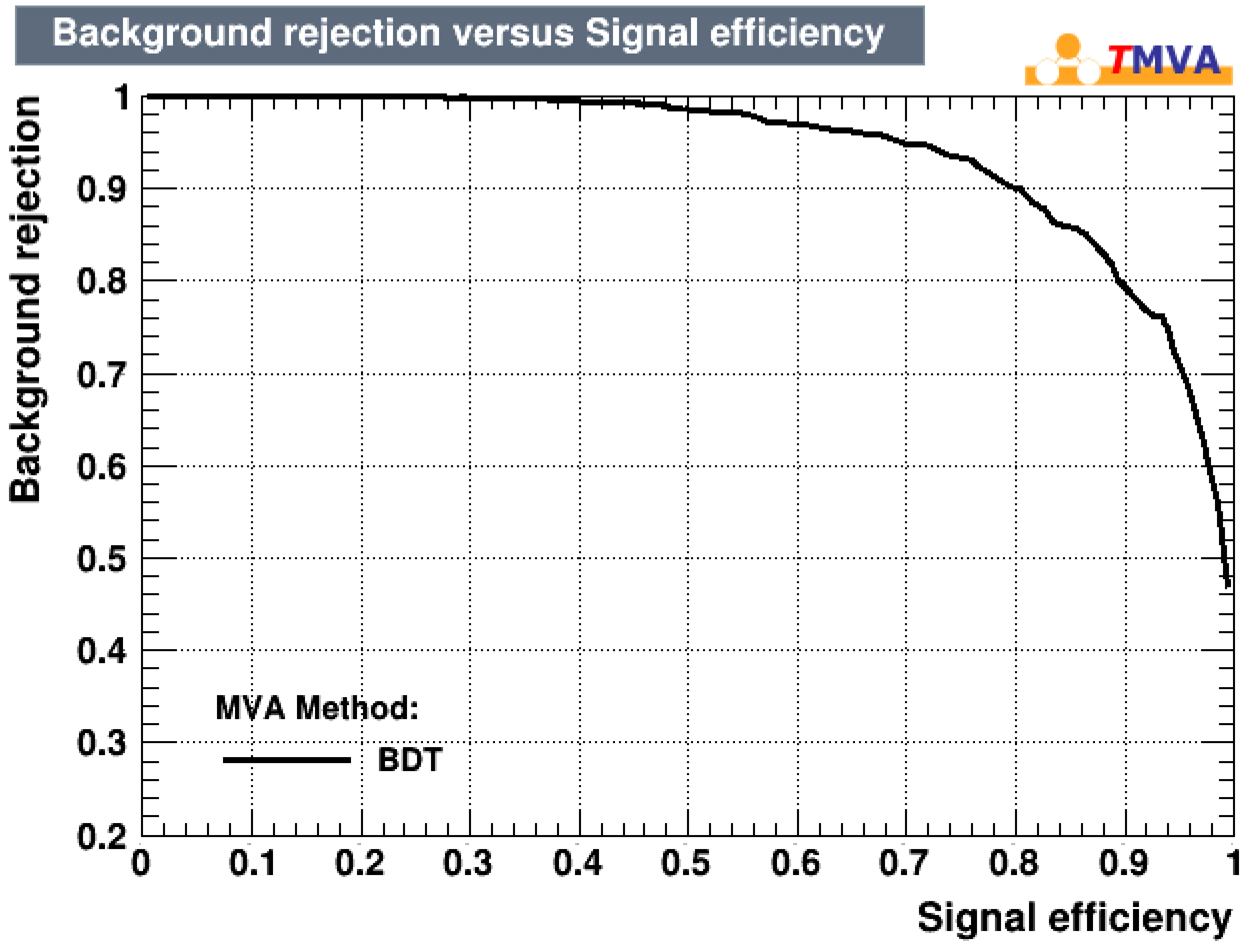
Events
10^4
10^3
10^2
10
1
0
20
40
60
80
100
120
140
MET
H->ττ
Z->ττ
Z->μμ

Fine-tuning BDT parameters

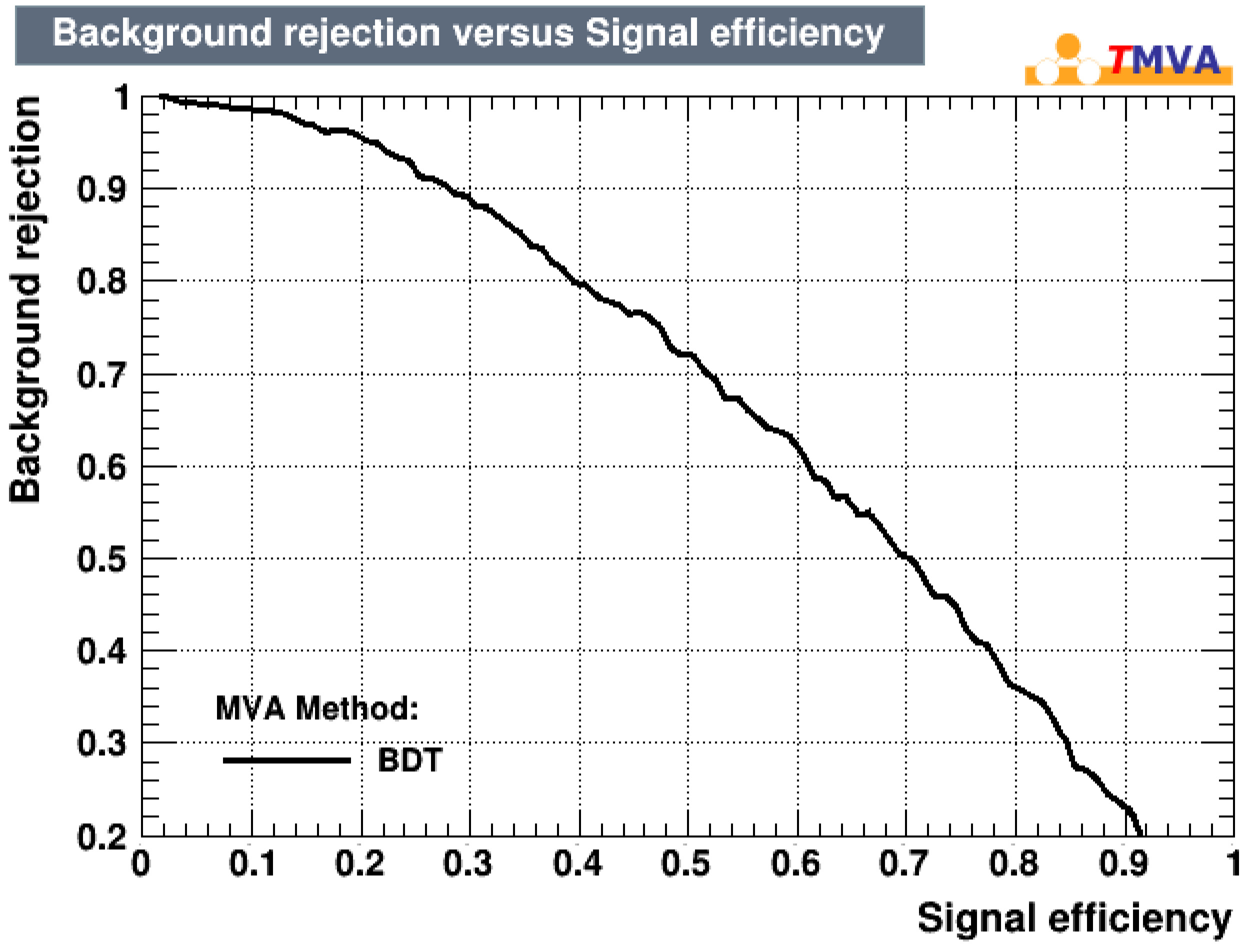
- Separation power of BDTs can be enhanced by fine tuning the parameters (provided at the time of booking)
  - Number of trees (no effect!)
  - Tree Depth
  - Learning rate
  - Minimum number of events in leaf-node
  - Bagging
- A very useful parameter to optimize could be nCuts (however might make it time-consuming!)

Optimization seems to be a must!





Background rejection versus Signal efficiency
TMVA
Background rejection
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Signal efficiency
MVA Method:
BDT



Can be optimized further!

Signal	Background	ROC Integral value
Z$\to \tau\tau$	Z$\to \mu\mu$	0.939
H$\to \tau\tau$	Z$\to \tau\tau$	0.706

Great for Drell yan, but not for signals!

Conclusion

- Kinematic variables were studied
- Acceptance plots were used to quantify the improvement in dimuon trigger thresholds
- Decision trees were optimised and used to separate the signal from the background.

Acknowledgements

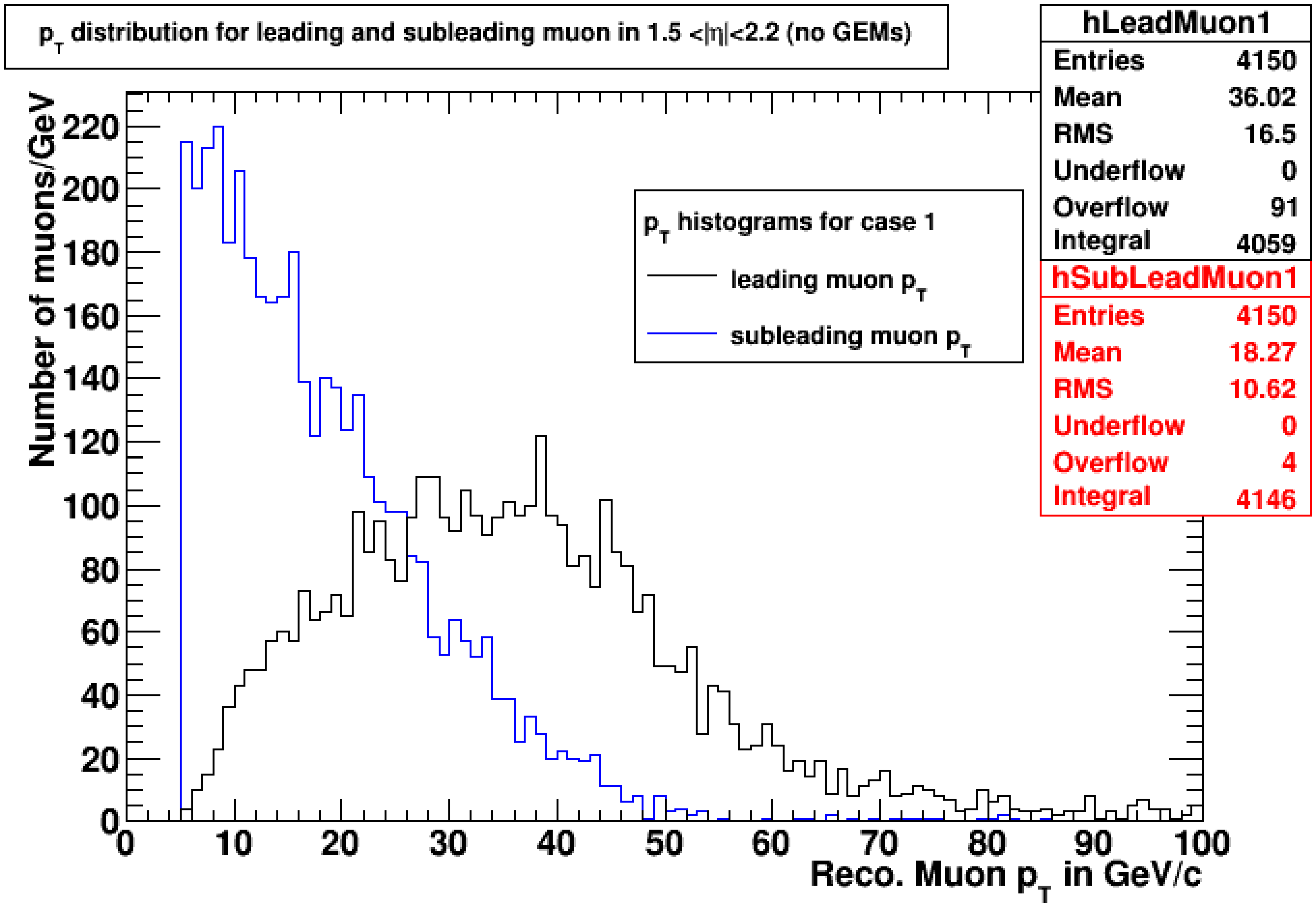
- Dr. Hohlmann: Thesis advisor
- Dr. Yumiceva (also helped in creating PAT tuples) and Dr. Welters: thesis committee
- Kerstin and Paolo: useful discussions on the upgrade physics topics
- Rosamaria: Bari skimmer
- Vallary: useful discussions on the MVAs (BDTs)

Backup!

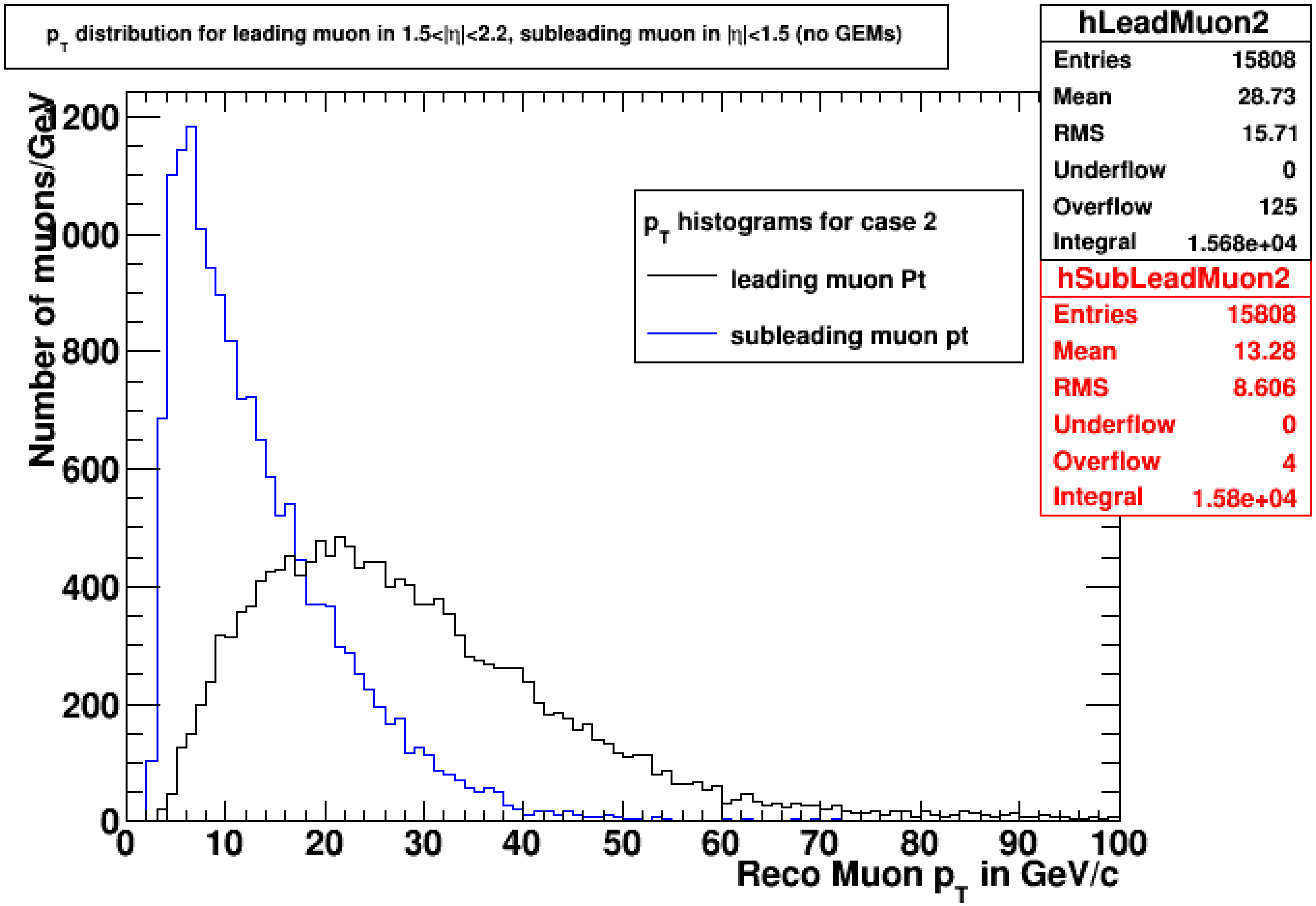
Cross-sections

- https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt1314TeV
- Drell Yan to Tau: 6025 pb
- Drell Yan to Tau (less than 50 GeV): 18610 pb

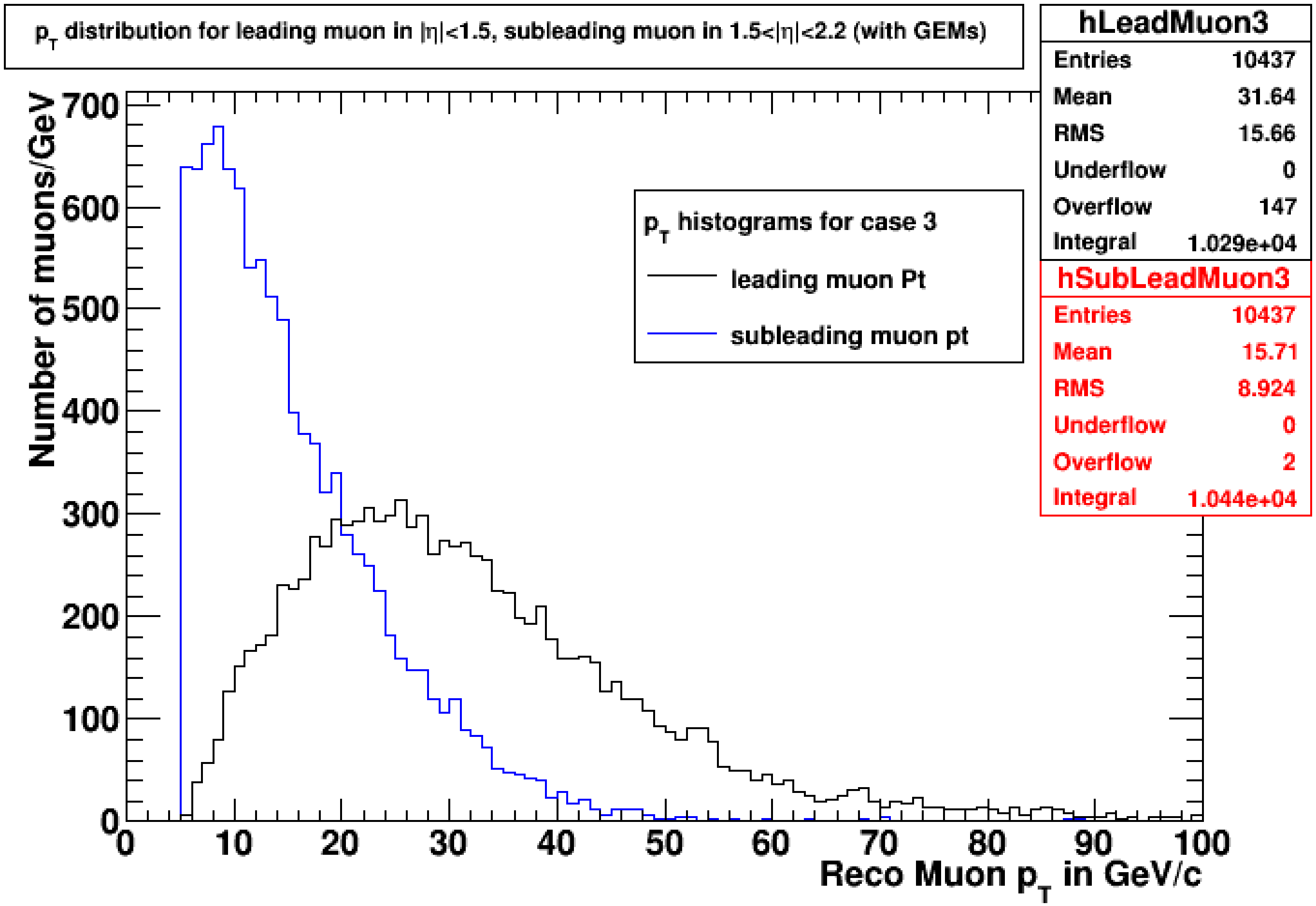
m_H (GeV)	Cross Section (pb)
125.0	49.47
125.5	49.13
126.0	48.80



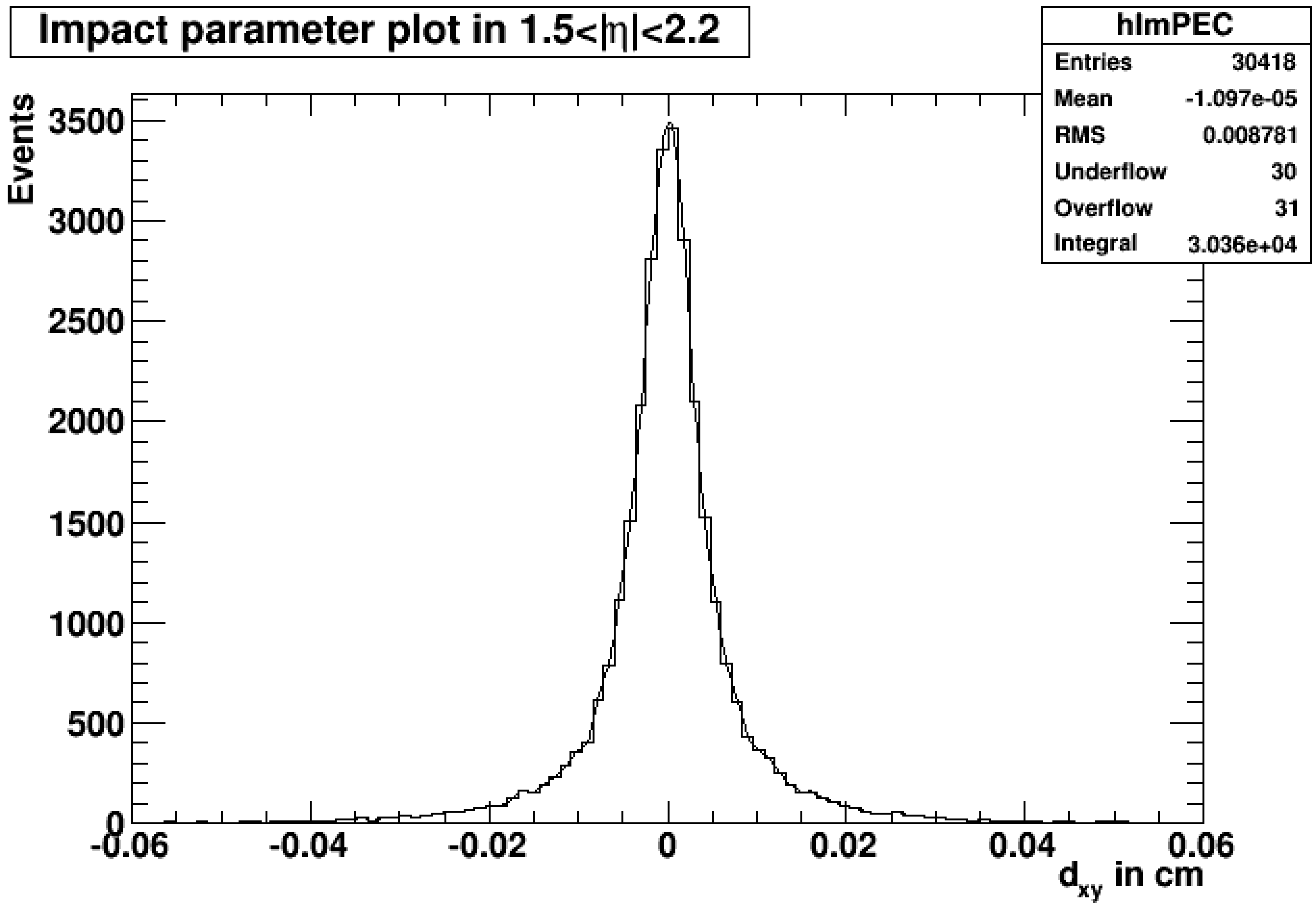
p_T distribution for leading and subleading muon in $1.5 < |\eta| < 2.2$ (no GEMs)
hLeadMuon1
Entries 4150
Mean 36.02
RMS 16.5
Underflow 0
Overflow 91
Integral 4059
hSubLeadMuon1
Entries 4150
Mean 18.27
RMS 10.62
Underflow 0
Overflow 4
Integral 4146
p_T histograms for case 1
leading muon p_T
subleading muon p_T
Number of muons/GeV
Reco. Muon p_T in GeV/c
0
20
40
60
80
100
120
140
160
180
200
220
0
10
20
30
40
50
60
70
80
90
100



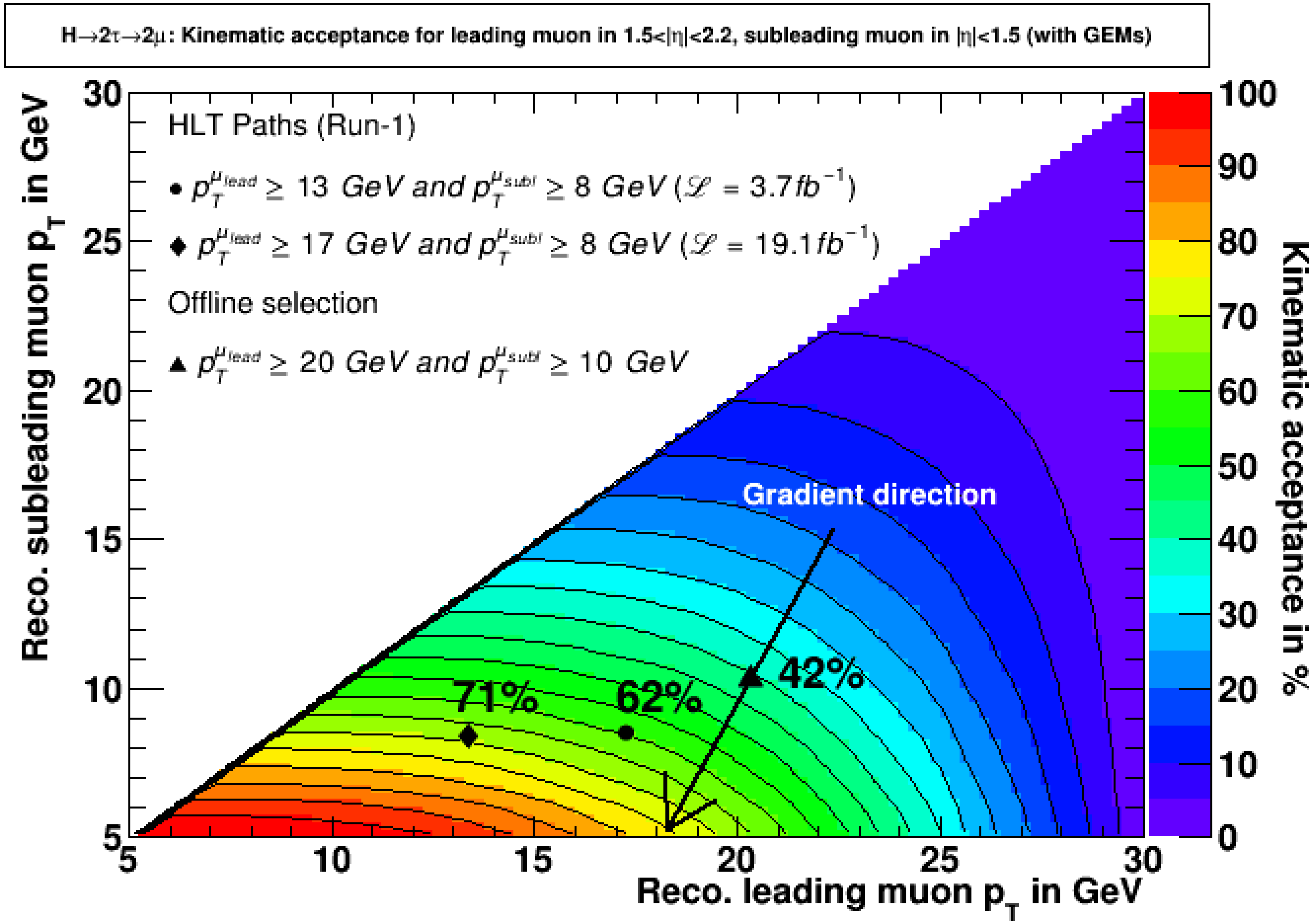
p_T distribution for leading muon in 1.5<|η|<2.2, subleading muon in |η|<1.5 (no GEMs)
hLeadMuon2
Entries 15808
Mean 28.73
RMS 15.71
Underflow 0
Overflow 125
Integral 1.568e+04
hSubLeadMuon2
Entries 15808
Mean 13.28
RMS 8.606
Underflow 0
Overflow 4
Integral 1.58e+04
p_T histograms for case 2
leading muon Pt
subleading muon pt
Number of muons/GeV
0
200
400
600
800
1000
1200
0
10
20
30
40
50
60
70
80
90
100
Reco Muon p_T in GeV/c

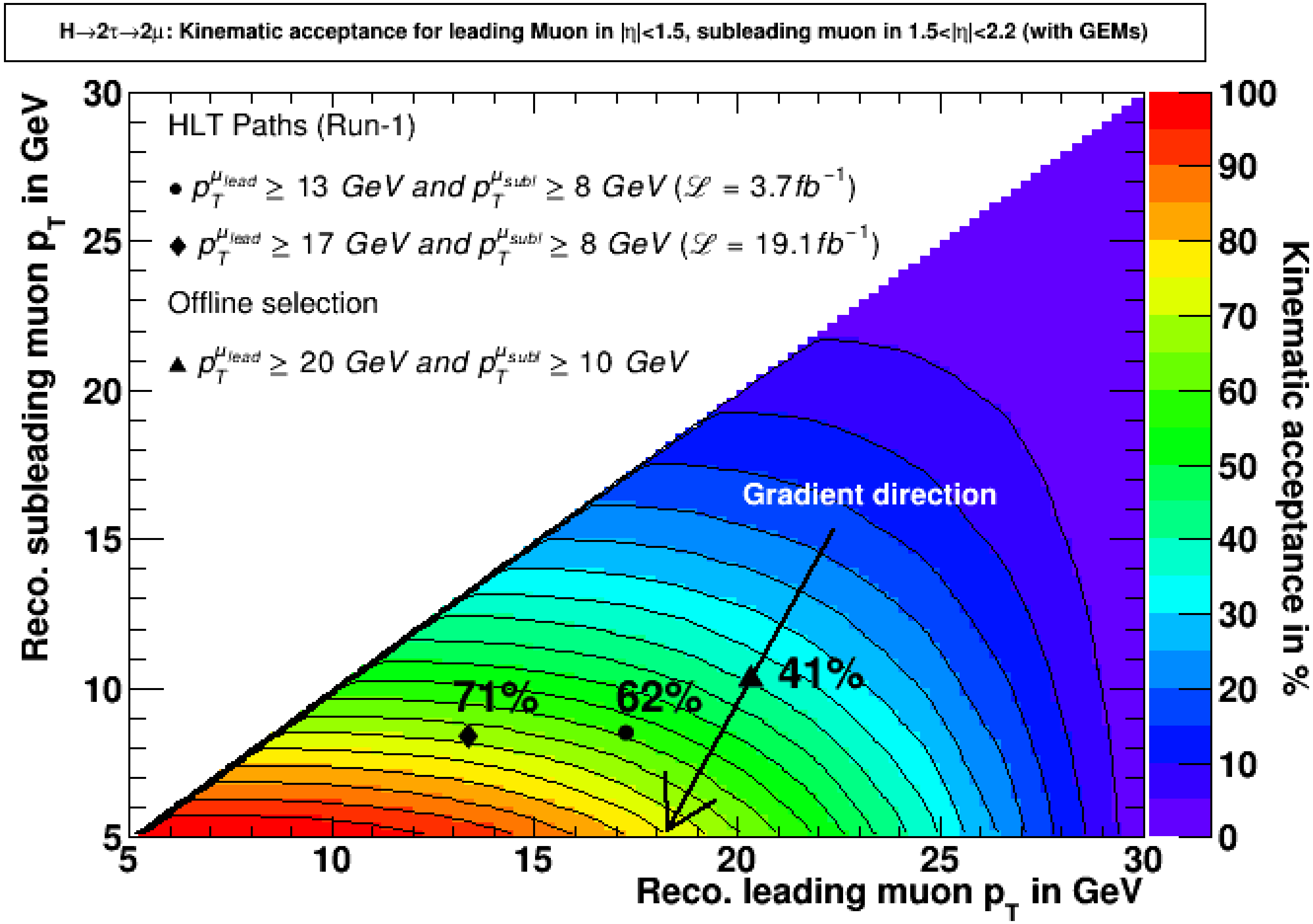


p_T distribution for leading muon in |η|<1.5, subleading muon in 1.5<|η|<2.2 (with GEMs)
hLeadMuon3
Entries 10437
Mean 31.64
RMS 15.66
Underflow 0
Overflow 147
Integral 1.029e+04
hSubLeadMuon3
Entries 10437
Mean 15.71
RMS 8.924
Underflow 0
Overflow 2
Integral 1.044e+04
p_T histograms for case 3
leading muon Pt
subleading muon pt
Number of muons/GeV
Reco Muon p_T in GeV/c
0
100
200
300
400
500
600
700
10
20
30
40
50
60
70
80
90
100

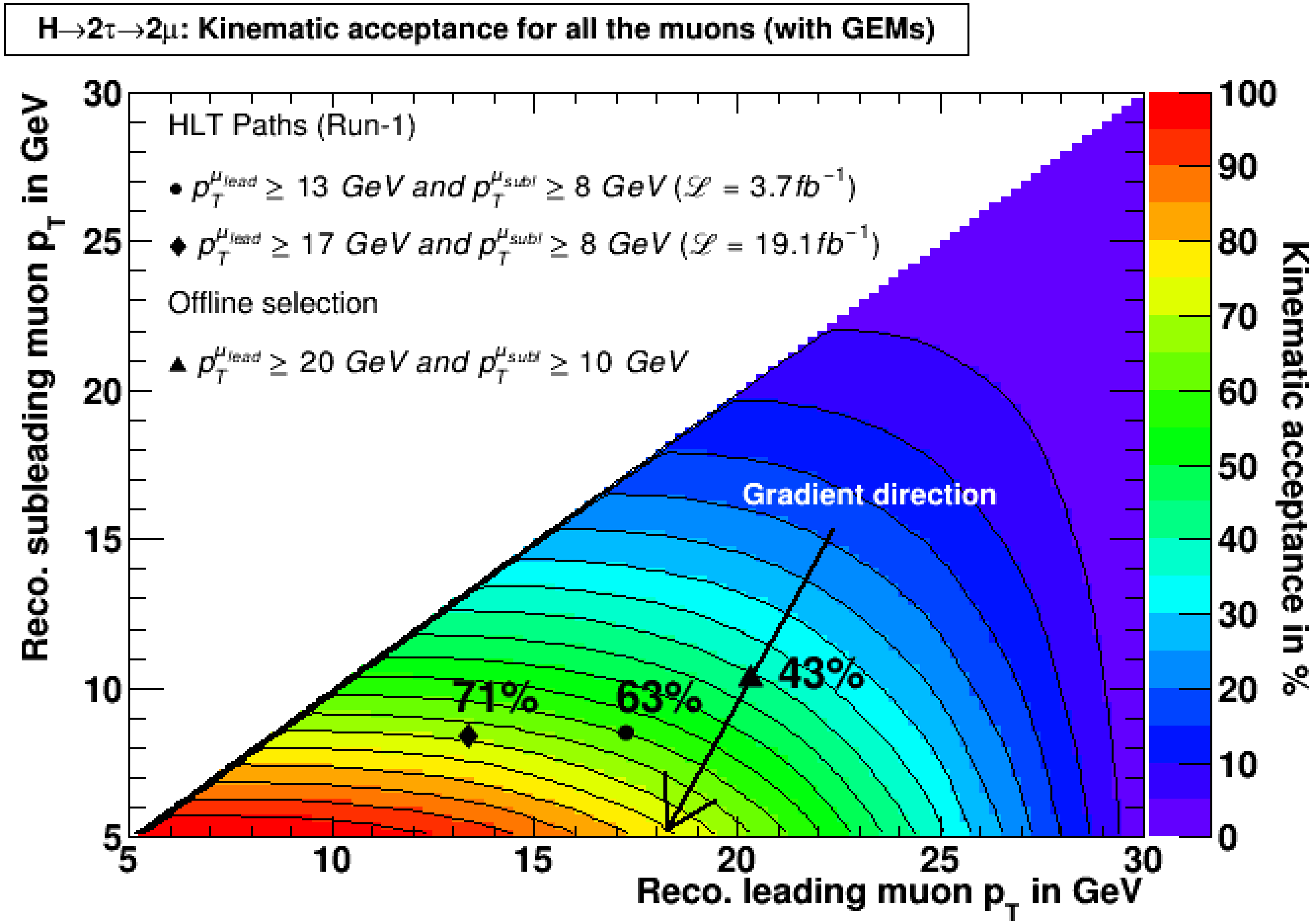


Impact parameter plot in 1.5<|η|<2.2
hImPEC
Entries 30418
Mean -1.097e-05
RMS 0.008781
Underflow 30
Overflow 31
Integral 3.036e+04
Events
3500
3000
2500
2000
1500
1000
500
0
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
d_xy in cm

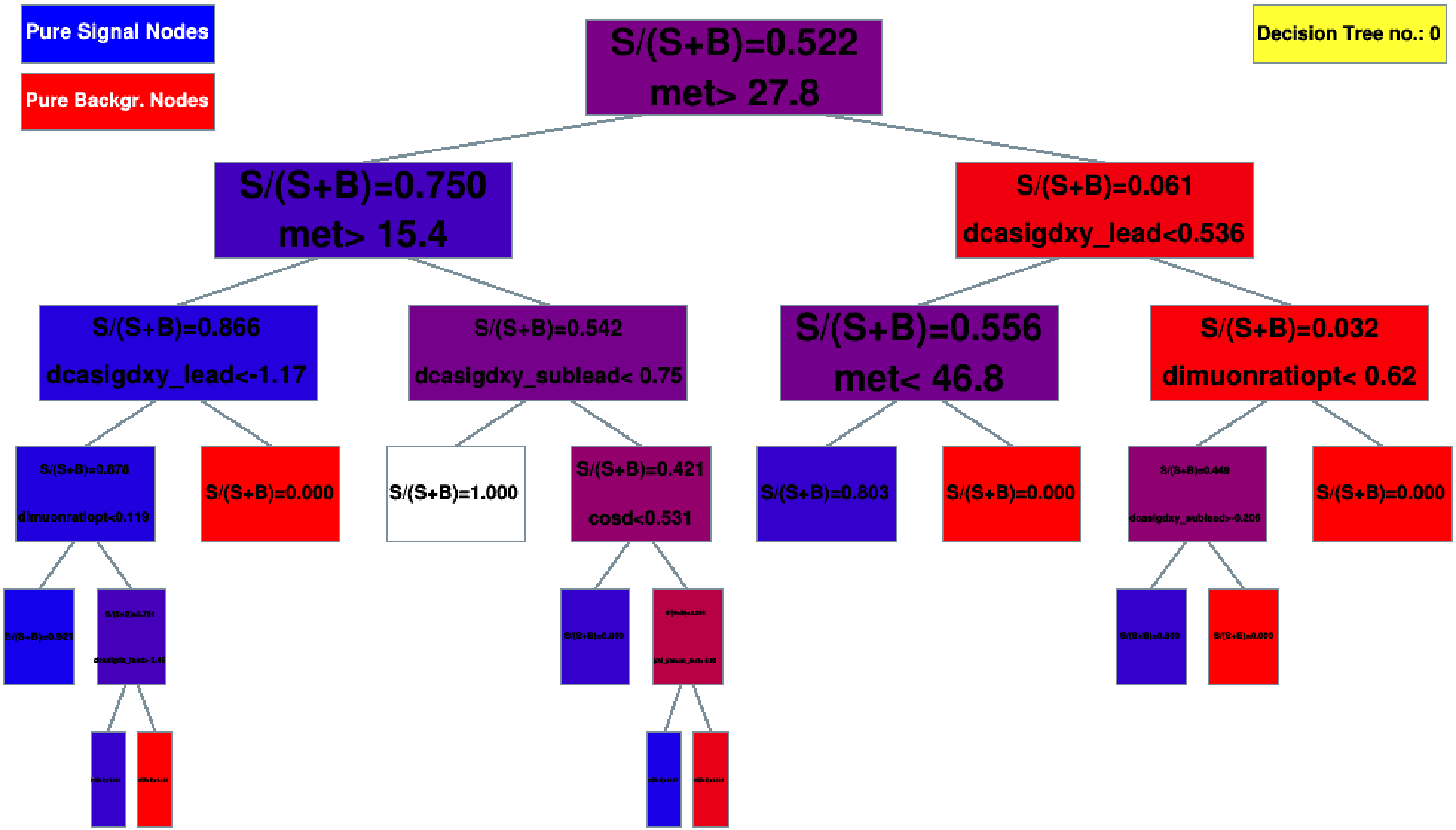

H→2τ→2μ: Kinematic acceptance for leading muon in 1.5<|η|<2.2, subleading muon in |η|<1.5 (with GEMs)
HLT Paths (Run-1)
• $p_T^{\mu_{lead}} \geq 13$ GeV and $p_T^{\mu_{subl}} \geq 8$ GeV ($\mathscr{L}$ = 3.7 fb^{-1})
♦ $p_T^{\mu_{lead}} \geq 17$ GeV and $p_T^{\mu_{subl}} \geq 8$ GeV ($\mathscr{L}$ = 19.1 fb^{-1})
Offline selection
▲ $p_T^{\mu_{lead}} \geq 20$ GeV and $p_T^{\mu_{subl}} \geq 10$ GeV
Gradient direction
71%
62%
42%
Reco. subleading muon p_T in GeV
Reco. leading muon p_T in GeV
Kinematic acceptance in %
5
10
15
20
25
30
0
10
20
30
40
50
60
70
80
90
100



H→2τ→2μ: Kinematic acceptance for leading Muon in |η|<1.5, subleading muon in 1.5<|η|<2.2 (with GEMs)
HLT Paths (Run-1)
● $p_T^{\mu_{lead}} \geq 13$ GeV and $p_T^{\mu_{subl}} \geq 8$ GeV ($\mathscr{L} = 3.7 fb^{-1}$)
◆ $p_T^{\mu_{lead}} \geq 17$ GeV and $p_T^{\mu_{subl}} \geq 8$ GeV ($\mathscr{L} = 19.1 fb^{-1}$)
Offline selection
▲ $p_T^{\mu_{lead}} \geq 20$ GeV and $p_T^{\mu_{subl}} \geq 10$ GeV
Gradient direction
71%
62%
41%
Reco. subleading muon p_T in GeV
Reco. leading muon p_T in GeV
Kinematic acceptance in %



H→2τ→2μ: Kinematic acceptance for all the muons (with GEMs)
HLT Paths (Run-1)
● $p_T^{\mu_{lead}} \geq 13$ GeV and $p_T^{\mu_{subl}} \geq 8$ GeV ($\mathscr{L}$ = 3.7 fb^{-1})
◆ $p_T^{\mu_{lead}} \geq 17$ GeV and $p_T^{\mu_{subl}} \geq 8$ GeV ($\mathscr{L}$ = 19.1 fb^{-1})
Offline selection
▲ $p_T^{\mu_{lead}} \geq 20$ GeV and $p_T^{\mu_{subl}} \geq 10$ GeV
Gradient direction
71%
63%
43%
Reco. subleading muon p_T in GeV
Reco. leading muon p_T in GeV
Kinematic acceptance in %



Pure Signal Nodes
Pure Backgr. Nodes
Decision Tree no.: 0
S/(S+B)=0.522
met> 27.8
S/(S+B)=0.750
met> 15.4
S/(S+B)=0.061
dcasigdxy_lead<0.536
S/(S+B)=0.866
dcasigdxy_lead<-1.17
S/(S+B)=0.542
dcasigdxy_sublead< 0.75
S/(S+B)=0.556
met< 46.8
S/(S+B)=0.032
dimuonratiopt< 0.62
S/(S+B)=0.878
dimuonratiopt<0.119
S/(S+B)=0.000
S/(S+B)=1.000
S/(S+B)=0.421
cosd<0.531
S/(S+B)=0.803
S/(S+B)=0.000
S/(S+B)=0.449
dcasigdxy_sublead>-0.205
S/(S+B)=0.000
S/(S+B)=0.921

Cluster (highlights)!

- Significant efforts were made to fix the cluster (not in a very healthy state back in 2014)! – system admin for 2 years
- Upgraded the cluster from CENT OS 5 to 6 (almost a semester)
- Fixed CERN SAM CE and SE tests
- Fixed Phedex (took a year!)
- Installed NAS-2 (new storage unit) with Curtis
- Figured out NAS-1 (main storage unit) issues, (convinced LSI support team! ☺)