COMPASS RHO0 ANALYSIS

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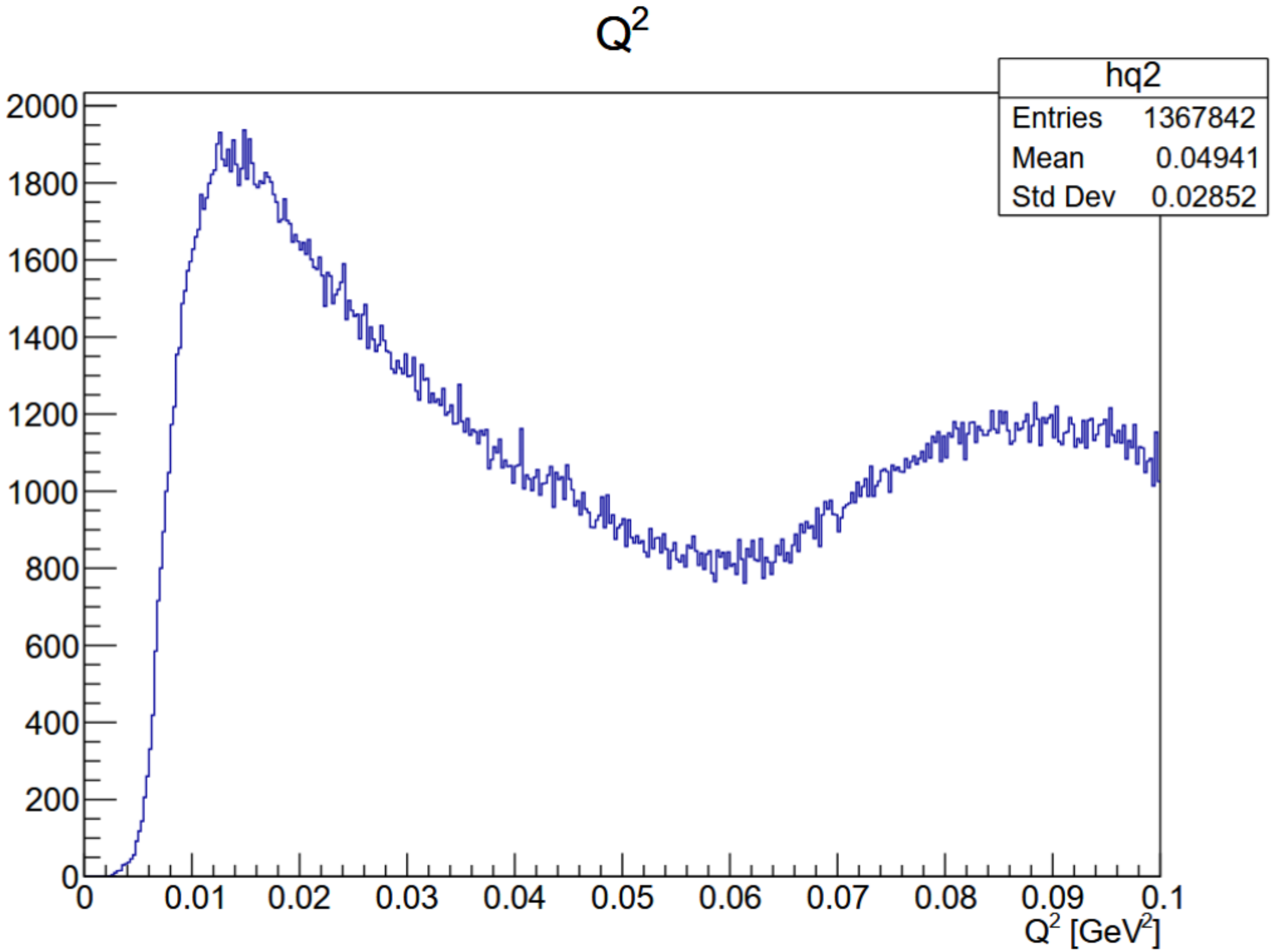
March 13th, 2025

COMPASS DATA AND MC

- Year 2016, and period 09
- COMPASS is using two different Monte Carlo for their 2012 analysis:
  - HepGEN – For the exclusive ρ0 reaction
  - LEPTO –For the SIDIS Background

Small Q2 events

1. Low Q2 physics
   - A group at COMPASS who looks at the low Q2 physics
   - quasi-real photoproduction
2. Bad reconstruction for small scattering angle
3. Acceptance with the scattered muon trigger
4. For DIS, the kinematic cut of Q2 > 0.8 GeV2 is typically used (Q2 >1 for this analysis)



Event Selection Muons

Coming from DVCS analysis of 2016 data
(J. V. Giarra, Deeply Virtual Compton Scattering at COMPASS, PhD thesis, 2022.)

Incoming muon track (μ):

- first measured before the target ($Z_{\text{tgt,min.}}$=-318.5 cm)
- track crosses the full target length
- momentum: $140\,\text{GeV/c} < p_\mu < 180\,\text{GeV/c}$
- momentum error: $\Delta p_\mu \leq 0.025 \cdot p_\mu$
- meantime: $-2\,\text{ns} < t_{\text{track}} < 2\,\text{ns}$
- hits in Beam Momentum Station (BMS): ≥ 3
- hits in Scintillation Fibre detectors (SCIFI): ≥ 2
- hits in Silicon strip detectors (SI): ≥ 3

Outgoing charged track (μ'):

- same charge as incoming muon
- rel. radiation length: $X/X_0 > 15$
- first measured before and last after SM1: $Z_{\text{first}} < 350\,\text{cm}$ and $Z_{\text{last}} > 350\,\text{cm}$
- track extrapolations are in the active hodoscope areas (PaHodoHelper::iMuPrim())

Vertex requirements:

- in target
  - $-318.5\,\text{cm} < Z_{\text{vtx}} < -78.5\,\text{cm}$
  - $R_{\text{vtx}} < 1.9\,\text{cm}$
  - $Y_{\text{vtx}} < 1.2\,\text{cm}$
- exactly one outgoing charged track

The common UCONN script and common to all of COMPASS

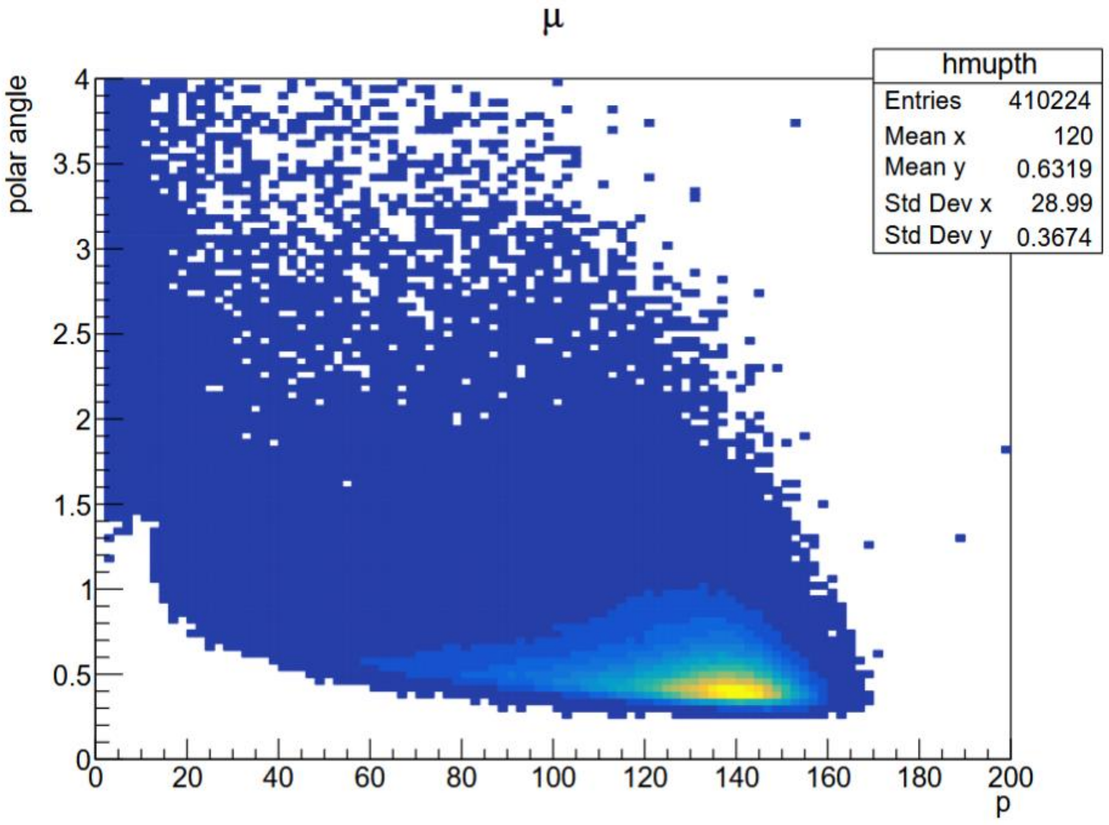
Event Selection Hadrons

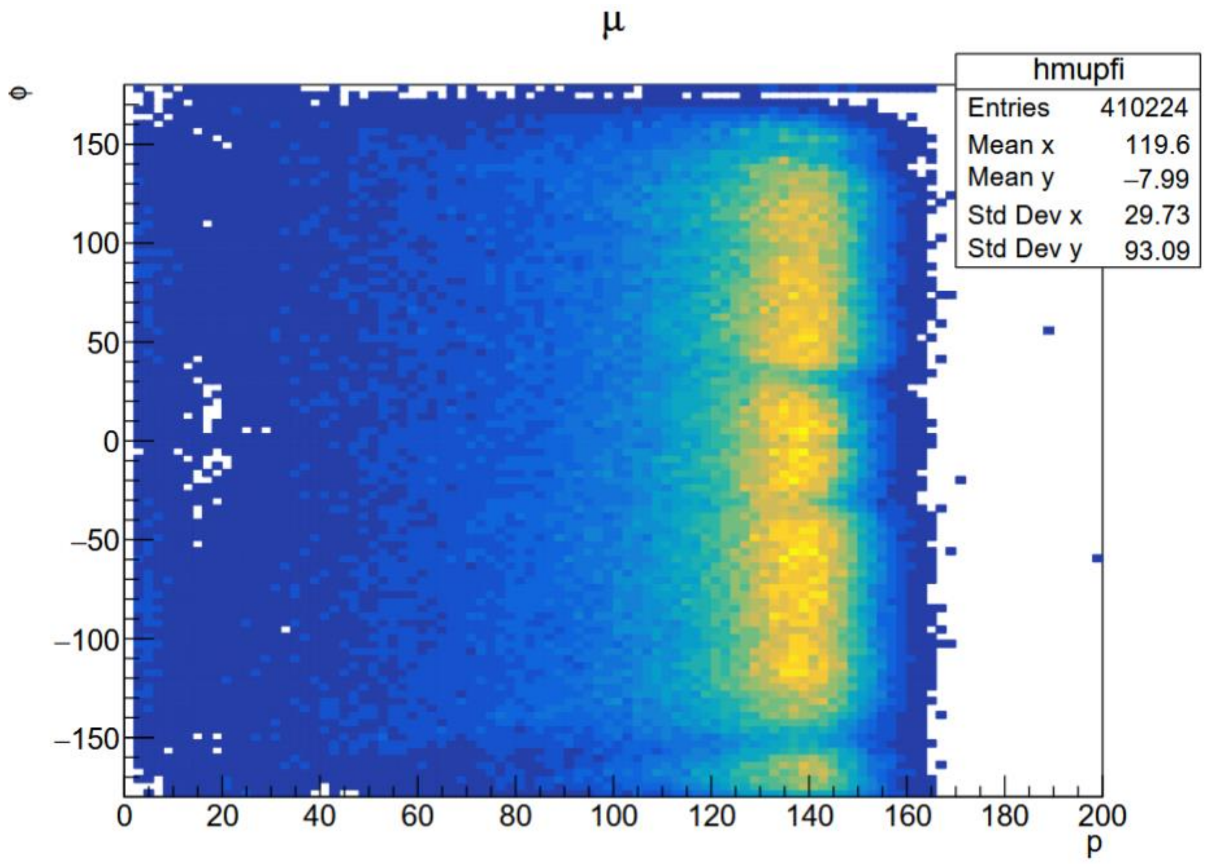
Coming from 2012 Rho analysis (W. Augustyniak, et al. ,Spin Density Matrix Elements for exclusive ρ0 meson production using the 2012 COMPASS data,internal note, 2021.)

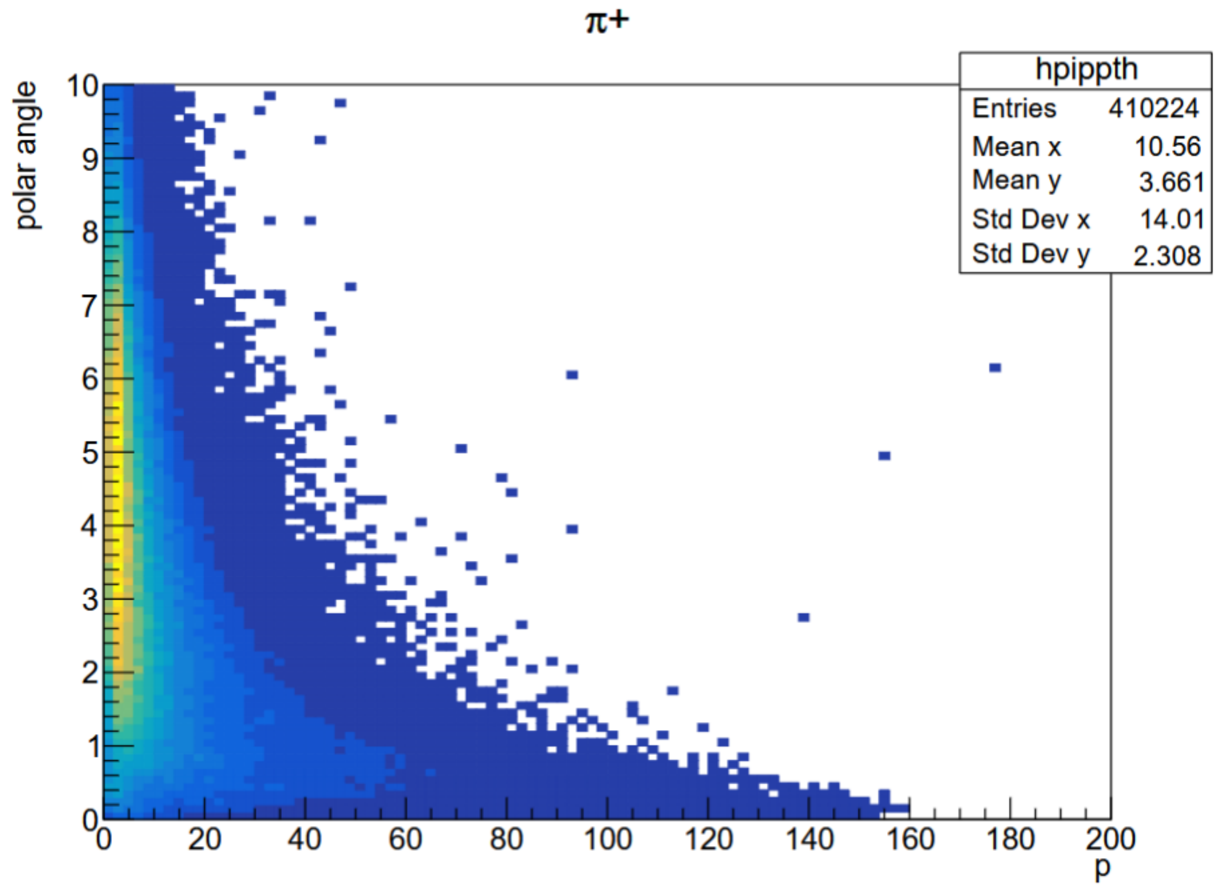
- Hadrons
  - Good fit quality of scattered hadron (π^+, π^- reconstruction, given by reduced χ^2 is required to be smaller than 10 (χ^2 <10).
    Track reconstruction quality χ^2 <10.
  - Penetration length of hadron track should be smaller than 10 radiation lengths.
  - Track starts before SM1, i.e. $Z_{first} < 350.0$ cm .

- Fit is on the track of the pions
- Also required both hadrons to have opposite charge
- Proton was identified using Missing Mass (2012 pre-CAMERA)

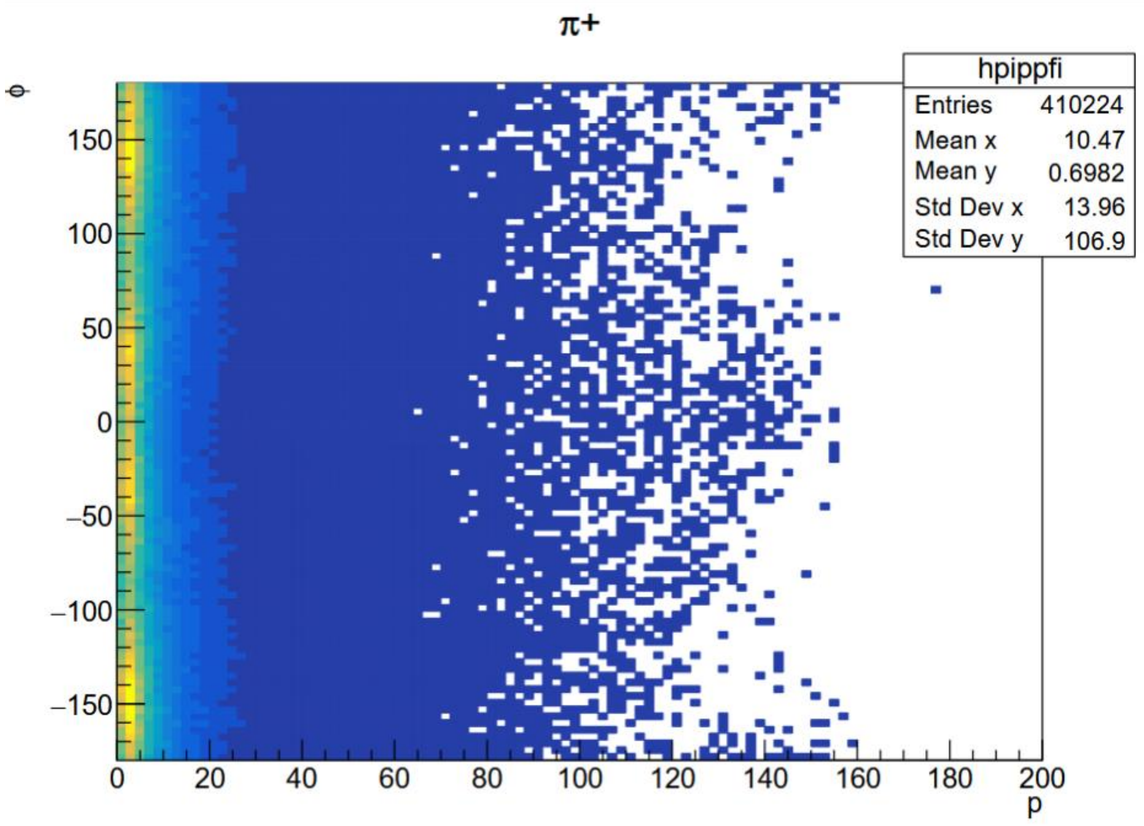
DATA PARTICLE KINEMATICS NO EXCLUSIVE CUTS (Q2 > 0.8 GEV2)


μ
hmupth
Entries 410224
Mean x 120
Mean y 0.6319
Std Dev x 28.99
Std Dev y 0.3674
polar angle
p

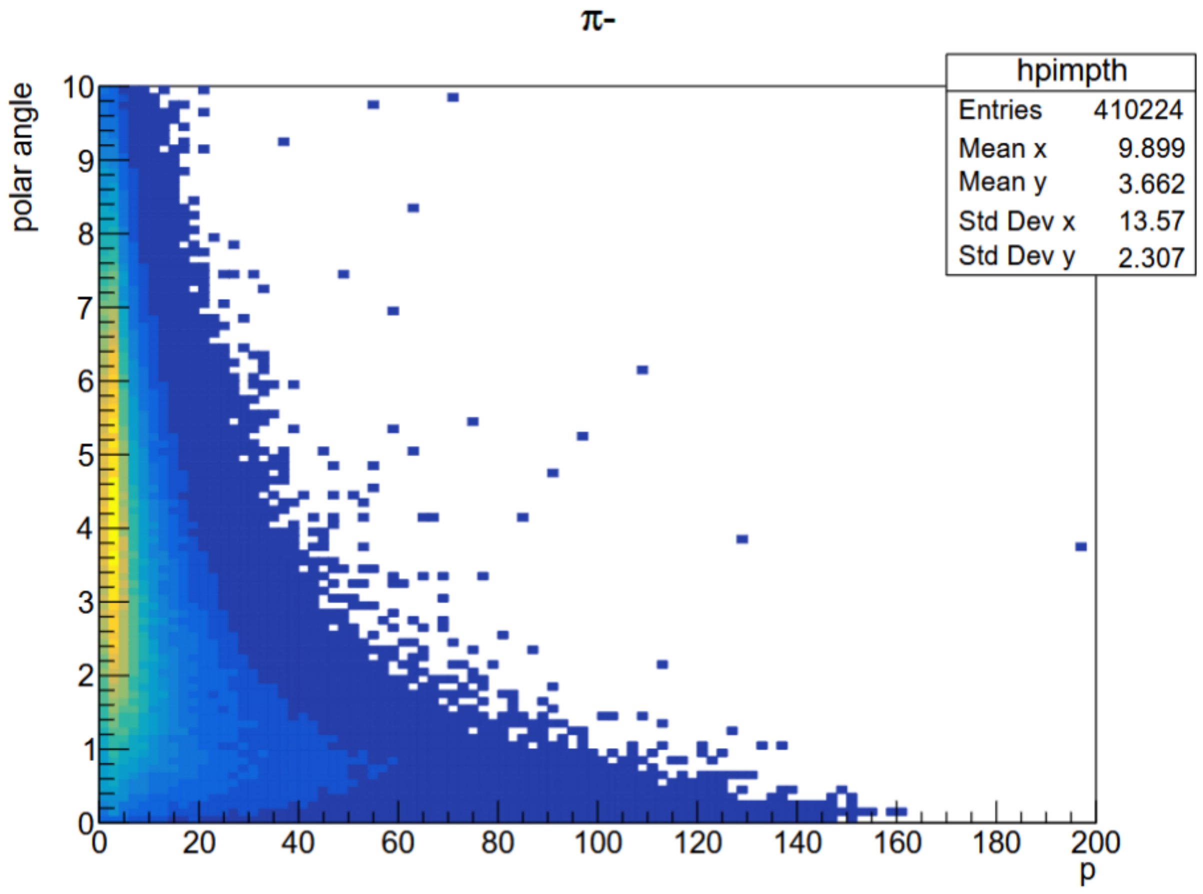

μ
hmupfi
Entries 410224
Mean x 119.6
Mean y −7.99
Std Dev x 29.73
Std Dev y 93.09
φ
p

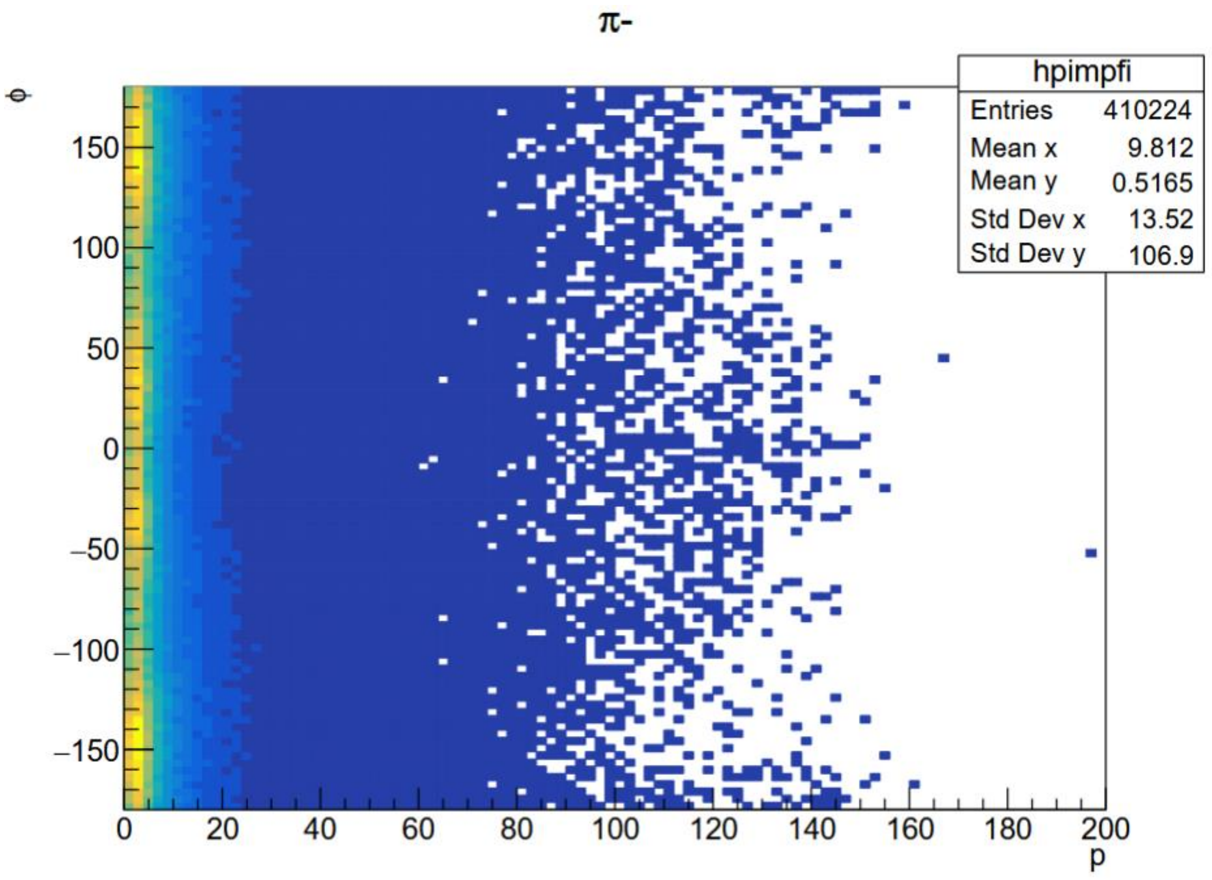


π+
hpippth
Entries 410224
Mean x 10.56
Mean y 3.661
Std Dev x 14.01
Std Dev y 2.308
polar angle
p



π+
hpippfi
Entries 410224
Mean x 10.47
Mean y 0.6982
Std Dev x 13.96
Std Dev y 106.9
φ
p


π-
hpimpth
Entries 410224
Mean x 9.899
Mean y 3.662
Std Dev x 13.57
Std Dev y 2.307
polar angle
p

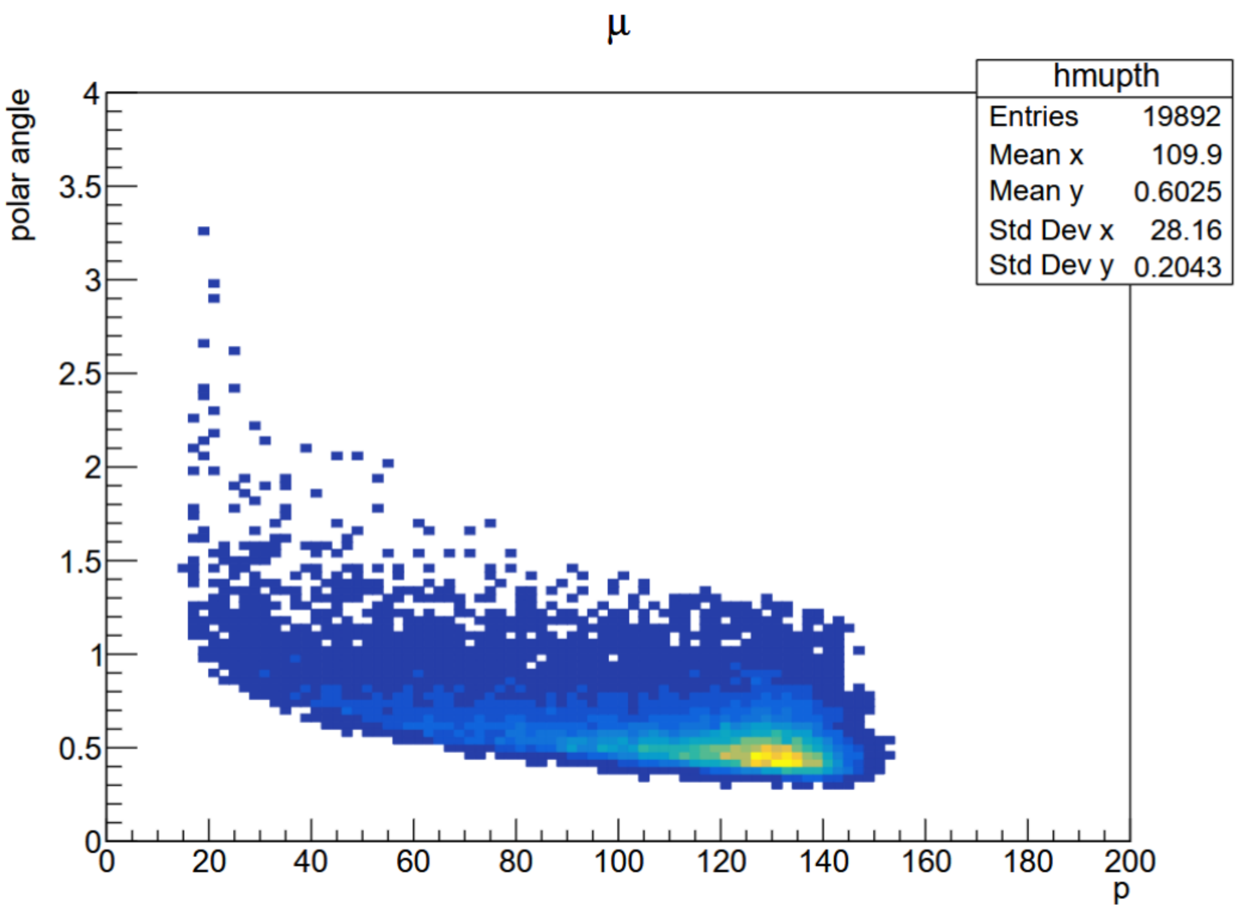

π-
hpimpfi
Entries 410224
Mean x 9.812
Mean y 0.5165
Std Dev x 13.52
Std Dev y 106.9
φ
p

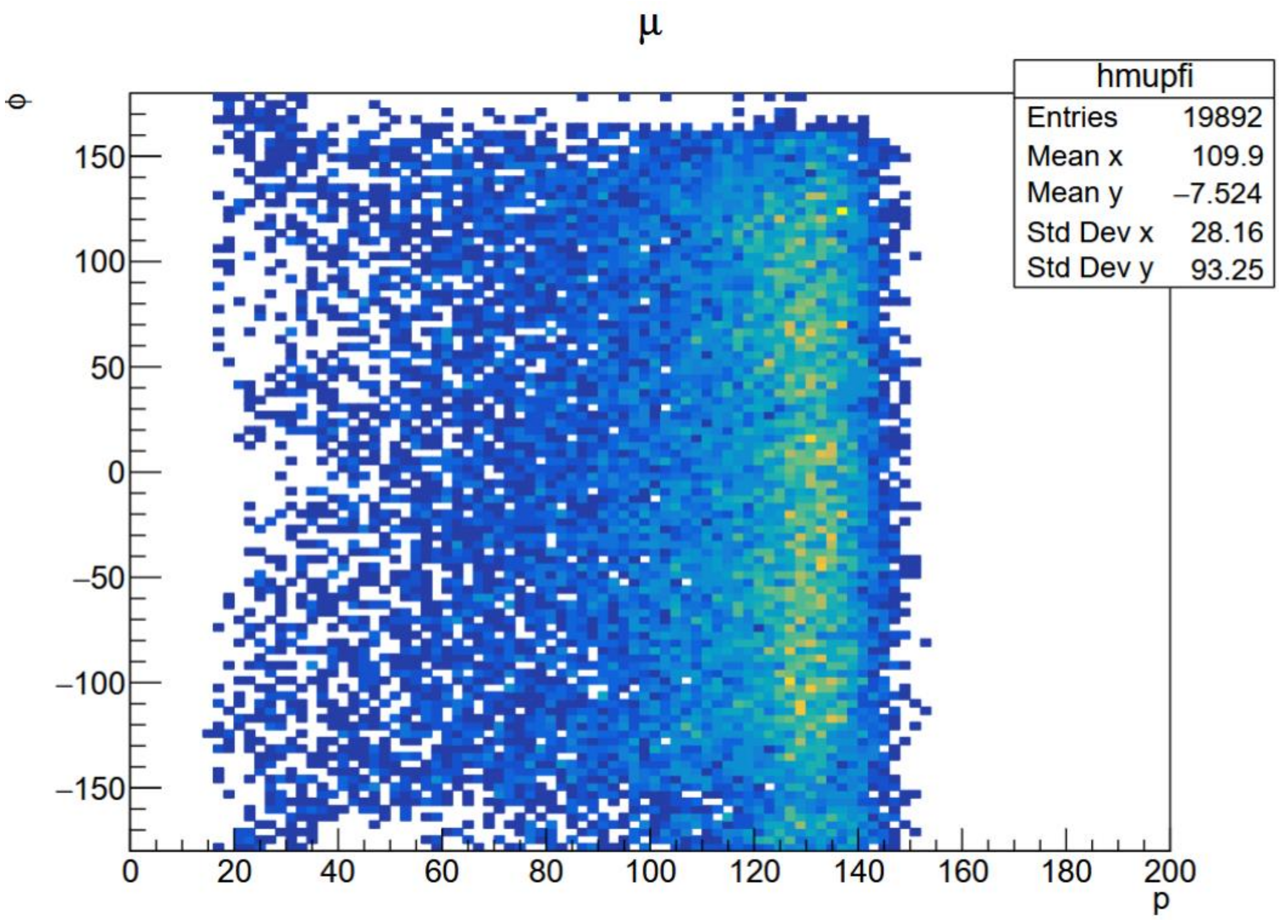
Coming from 2012 Rho analysis (W. Augustyniak, et al. ,Spin Density Matrix Elements for exclusive ρ0 meson production using the 2012 COMPASS data,internal note, 2021.)

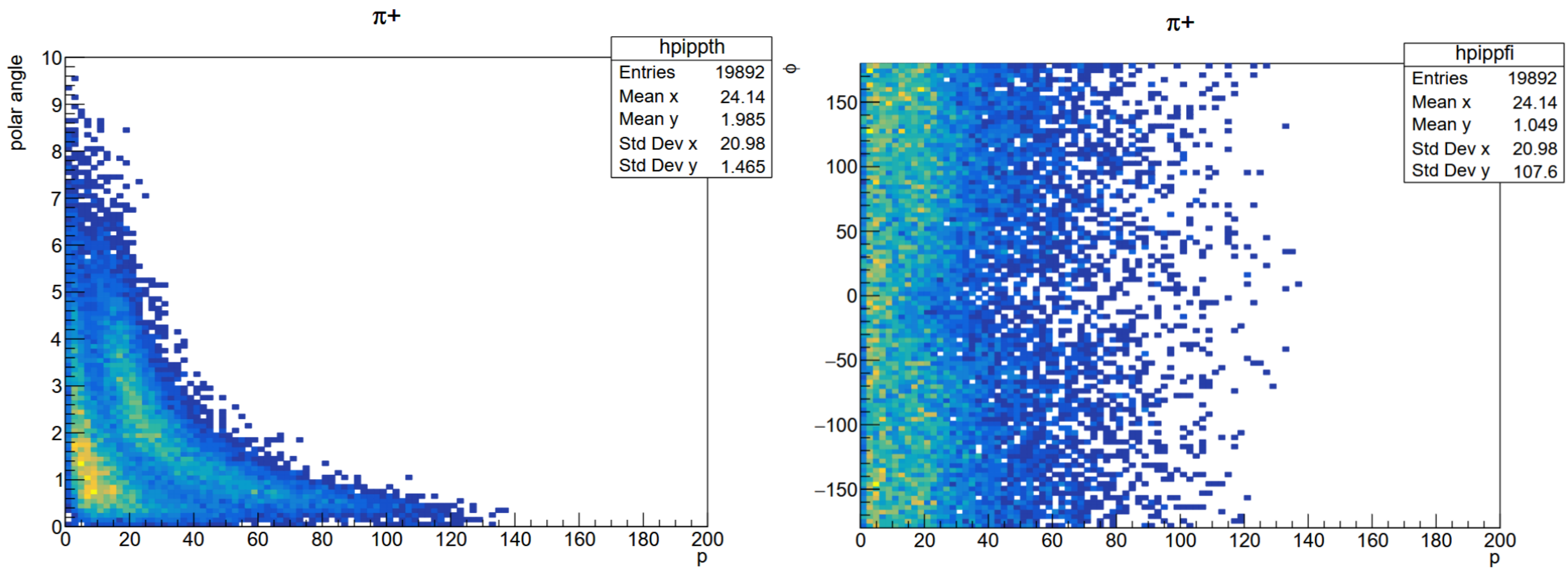
KINEMATIC CUTS

- $W > 5.0$ GeV to remove the kinematic region where the cross section for the semi-inclusive reactions changes rapidly due to a resonances production.
- $0.1 < y < 0.9$, lower cut suppresses events with a poorly reconstructed kinematics. The upper cut on y remove events with large radiative corrections.
- $1.0 < Q^2 < 10.0$ (GeV/c)^2, lower cut on virtuality Q^2 ensures hard processes regime and the upper one suppresses background due to the hadron production in DIS which hereafter is referred to as "SIDIS background".
- $\nu > 20$ Gev.
- squared transverse momentum of ρ^0 with respect to the virtual photon: $0.01 < p_T^2 < 0.5$ (GeV/c)^2.
- $0.5 < M_{\pi^+\pi^-} < 1.1$ GeV/c^2 invariant mass of two pions.
- $-2.5 < E_{miss} < 2.5$ GeV . $E_{miss} = \frac{M_X^2 - M_p^2}{2M_p}$, with M_p the proton mass and $M_X^2 = (p + q - p_{\pi^+} - p_{\pi^-})^2$ - the missing mass squared, where p, q, p_{π^+} and p_{π^-} are the four-momenta of target nucleon, virtual photon, and each of the two pions, respectively.
- momentum of ρ^0 $P_{\rho^0} > 15$ GeV/c. To reduce the semi-inclusive background contribution.

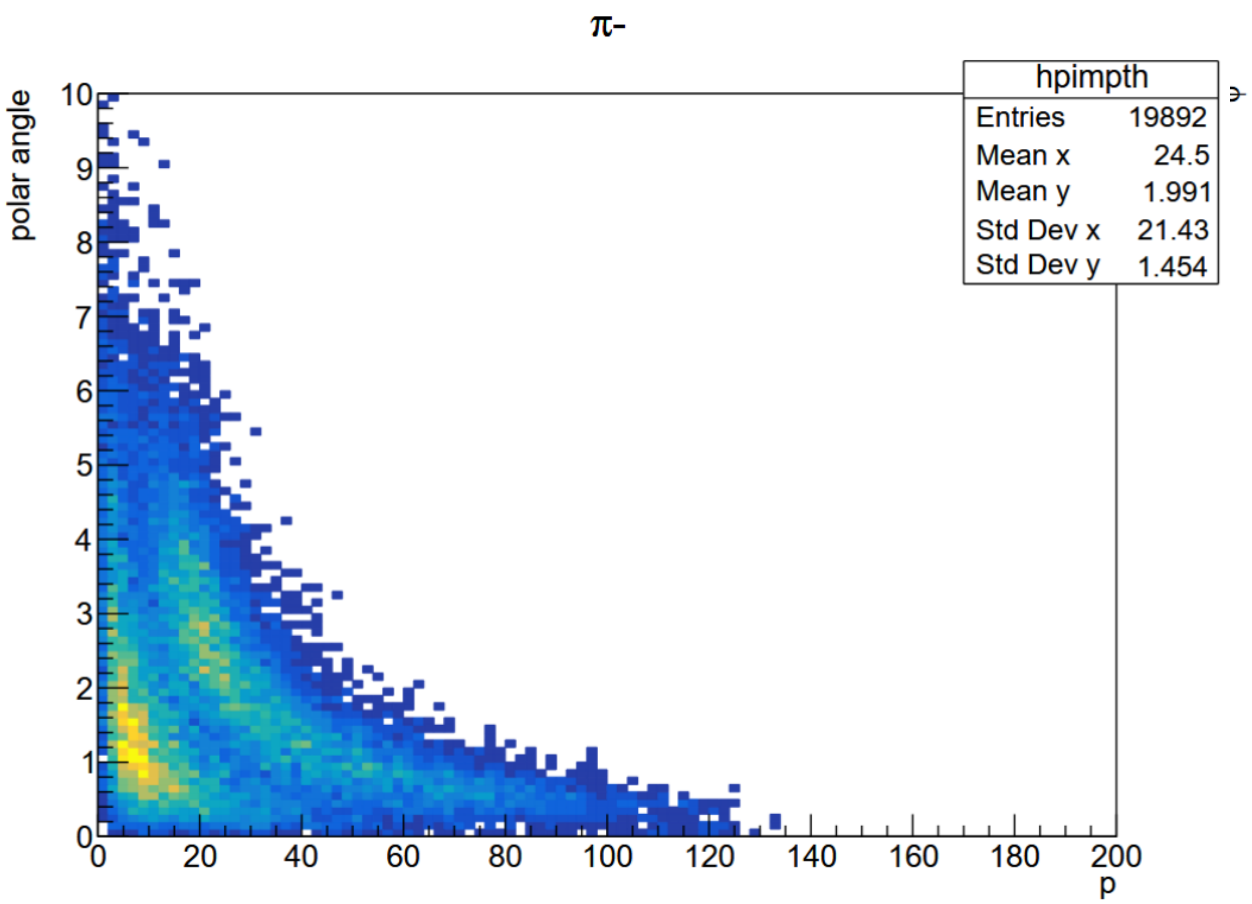
DATA PARTICLE KINEMATICS WITH CUTS

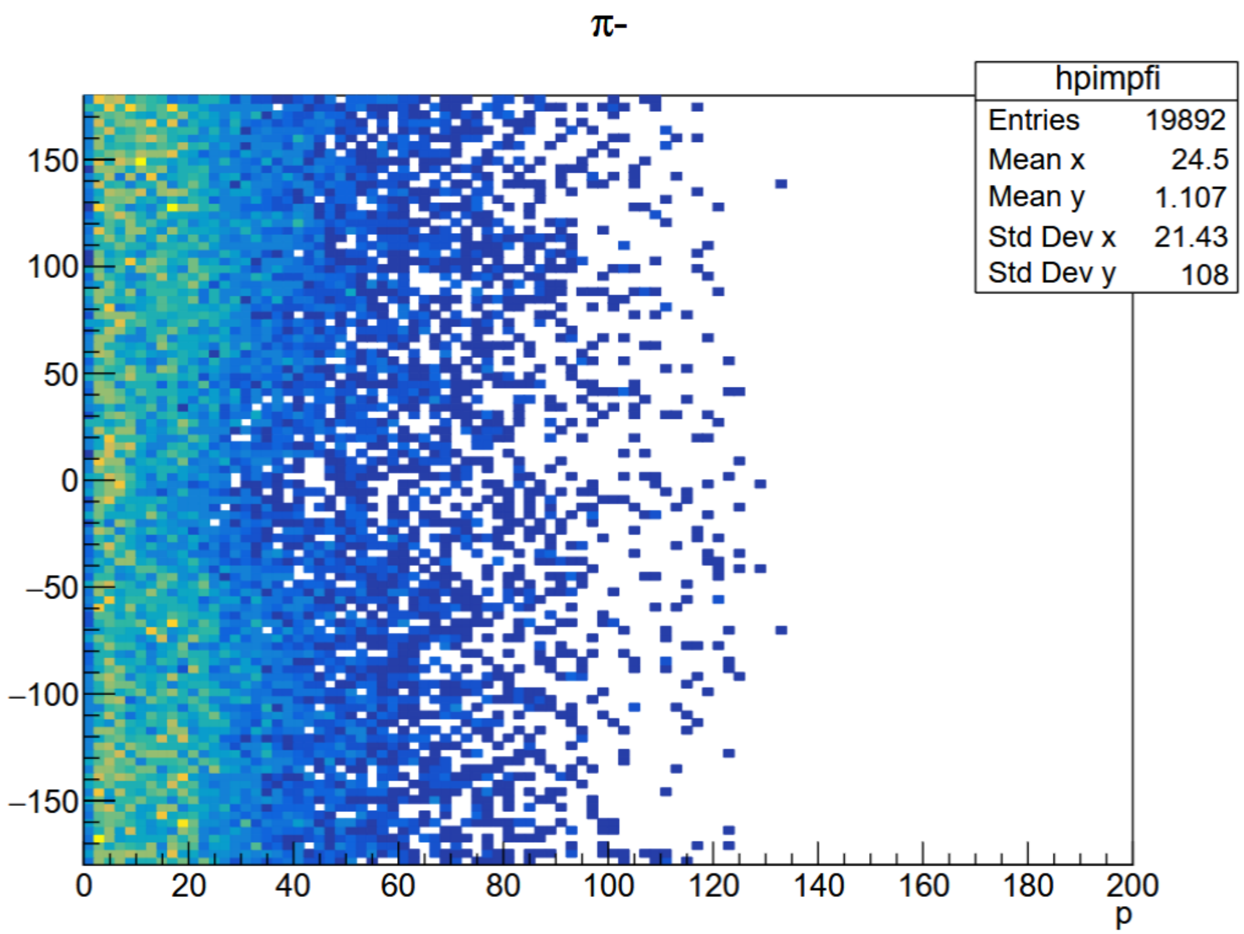

μ
hmupth
Entries 19892
Mean x 109.9
Mean y 0.6025
Std Dev x 28.16
Std Dev y 0.2043
polar angle
0
0.5
1
1.5
2
2.5
3
3.5
4
0
20
40
60
80
100
120
140
160
180
200
p


μ
hmupfi
Entries 19892
Mean x 109.9
Mean y −7.524
Std Dev x 28.16
Std Dev y 93.25
ϕ
150
100
50
0
−50
−100
−150
0
20
40
60
80
100
120
140
160
180
200
p



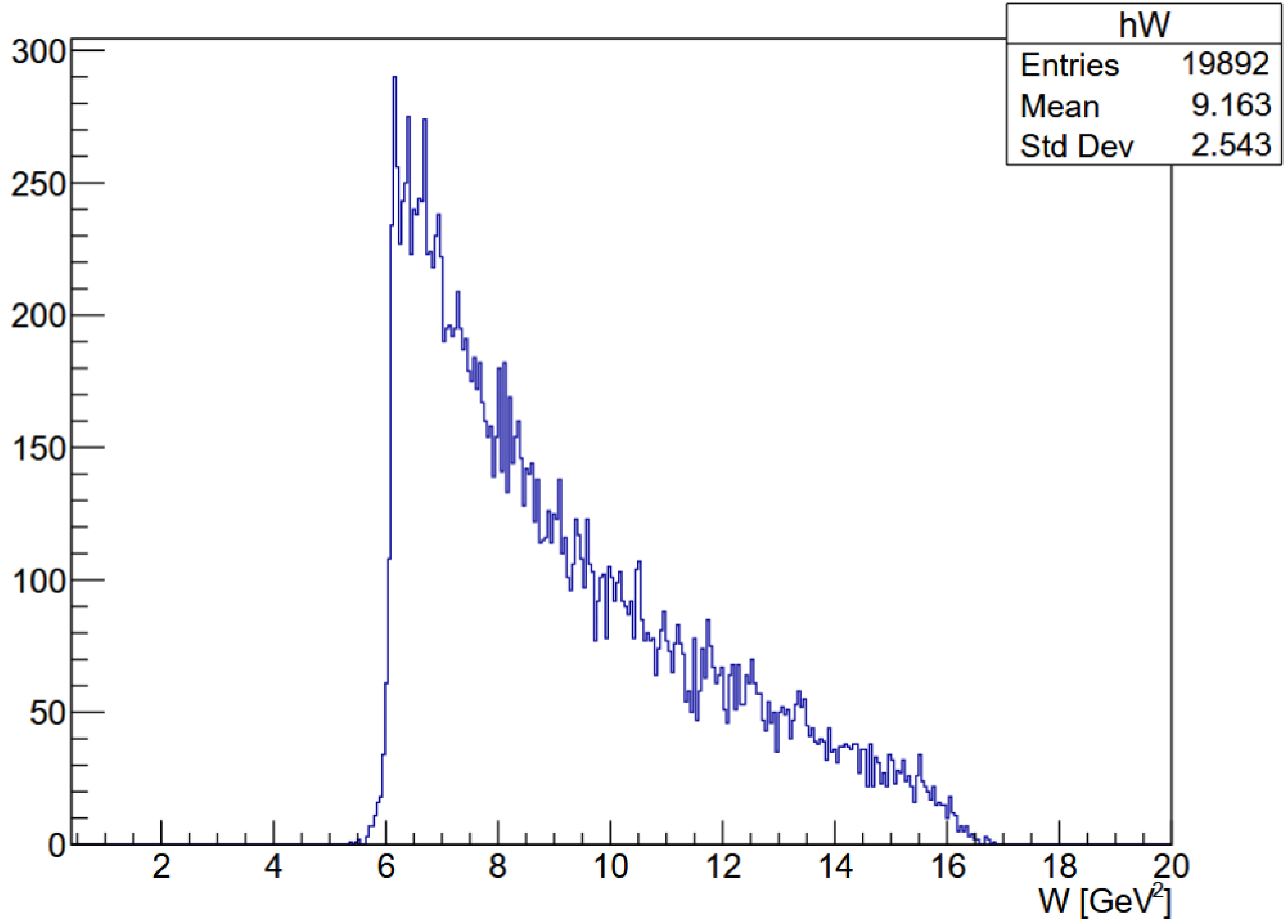
π+
polar angle
hpippth
Entries 19892
Mean x 24.14
Mean y 1.985
Std Dev x 20.98
Std Dev y 1.465
p
π+
ϕ
hpippfi
Entries 19892
Mean x 24.14
Mean y 1.049
Std Dev x 20.98
Std Dev y 107.6
p


π-
hpimpth
Entries 19892
Mean x 24.5
Mean y 1.991
Std Dev x 21.43
Std Dev y 1.454
polar angle
p
0
1
2
3
4
5
6
7
8
9
10
0
20
40
60
80
100
120
140
160
180
200

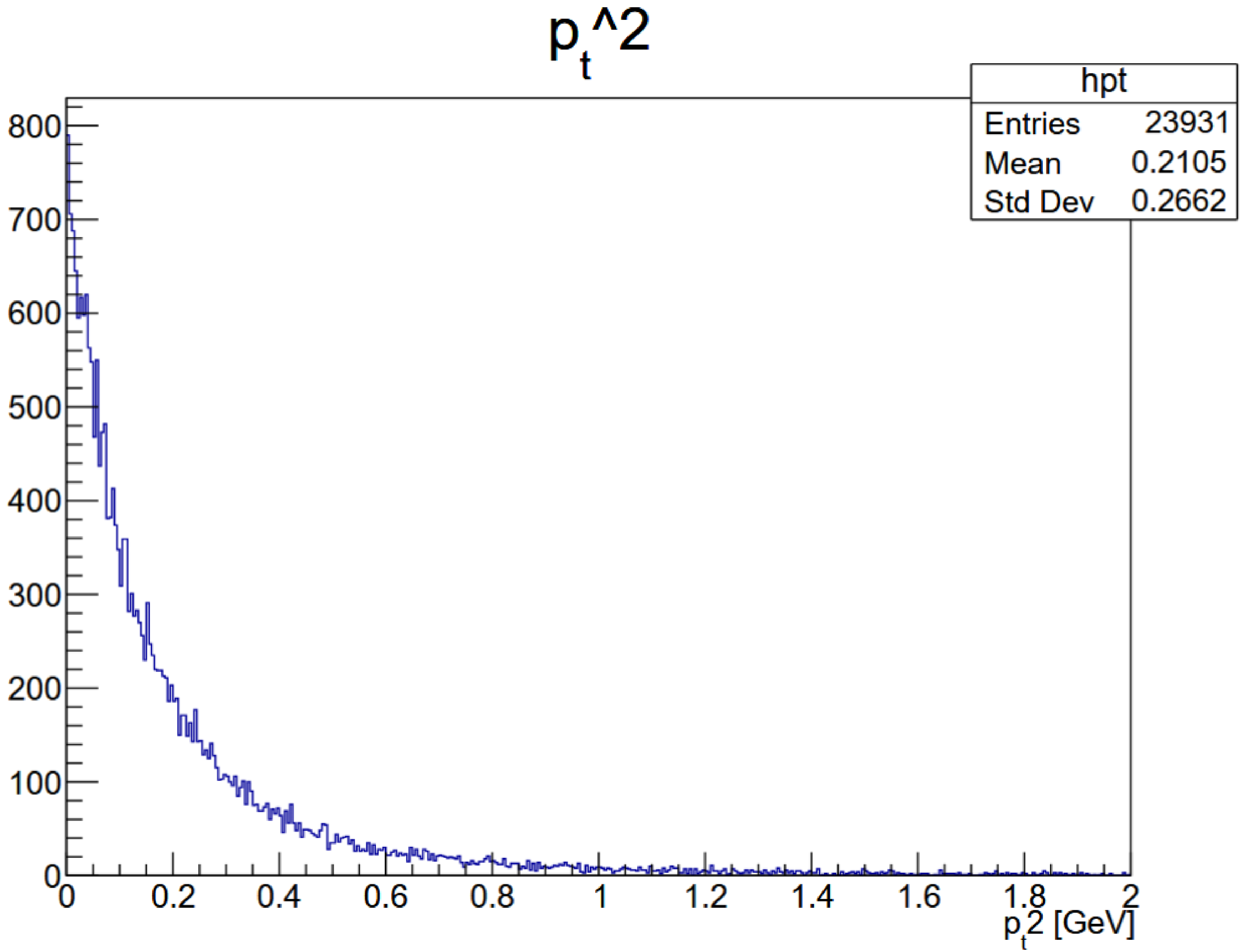

π-
hpimpfi
Entries 19892
Mean x 24.5
Mean y 1.107
Std Dev x 21.43
Std Dev y 108
p
150
100
50
0
−50
−100
−150
0
20
40
60
80
100
120
140
160
180
200

DATA EXCLUSIVE KINEMATICS WITH CUTS

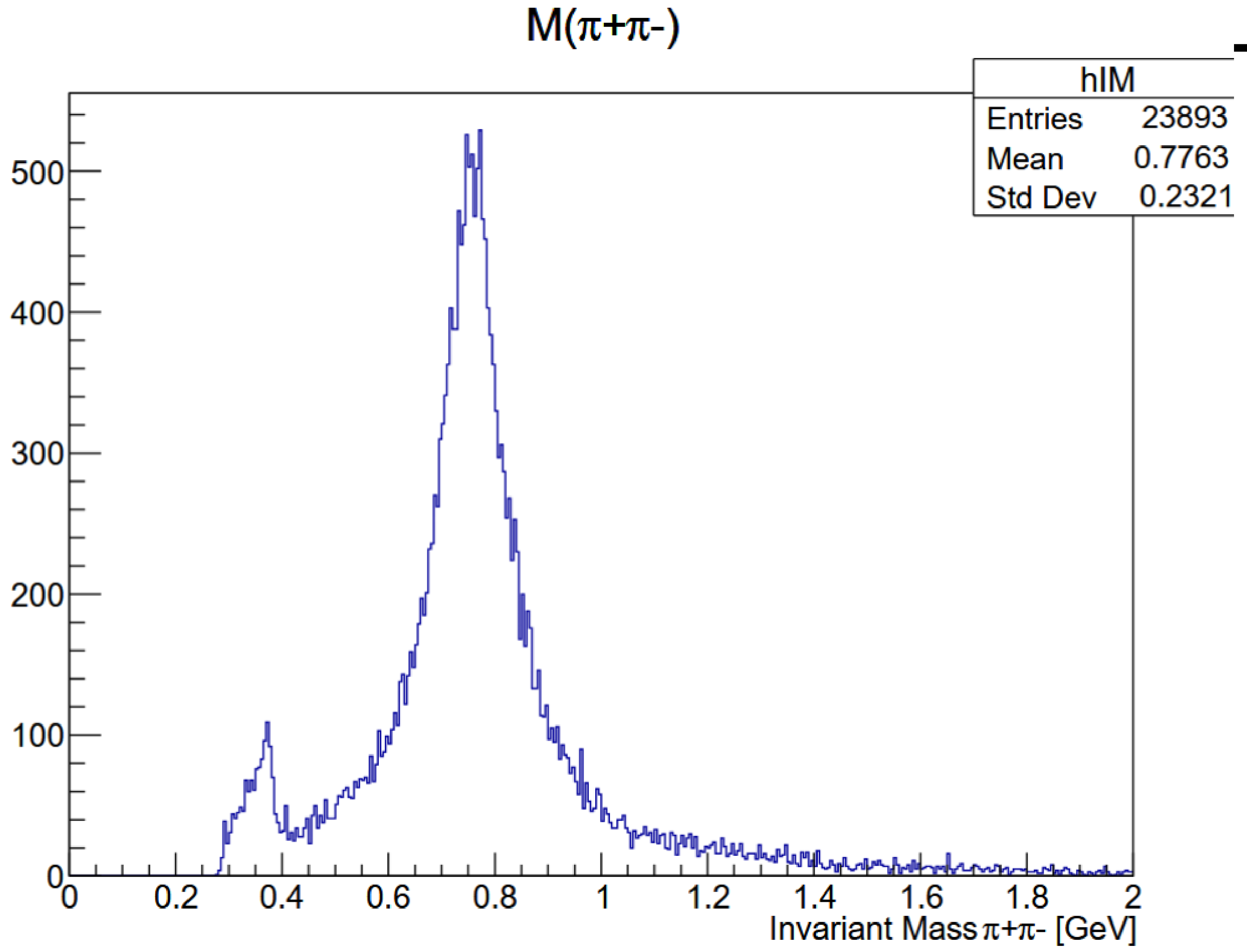
W



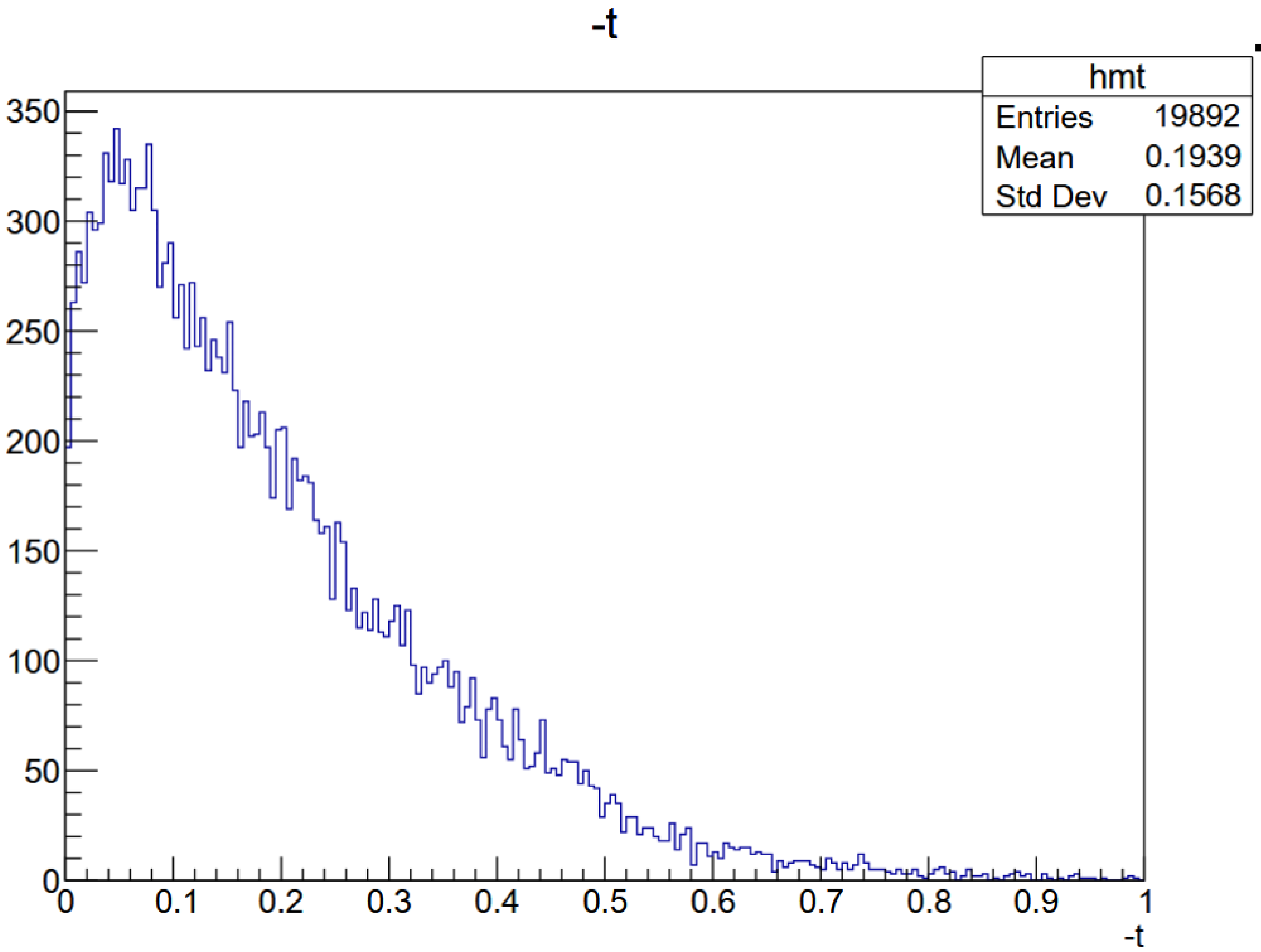
Cuts:y,Q2,nu,Pt2, Invariant Mass
Missing Energy, Momentum of rho0



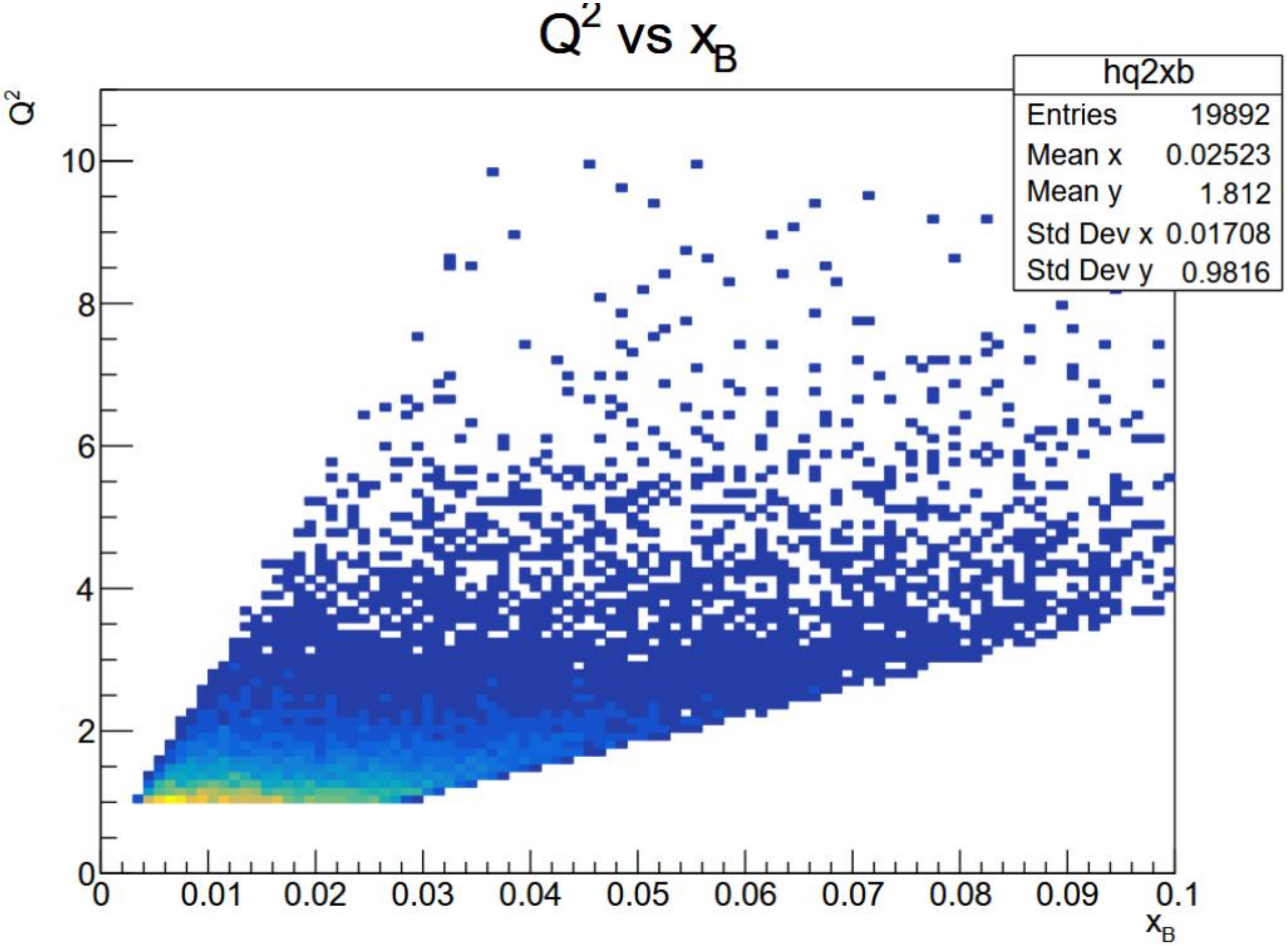
Cuts:W,y,Q2,nu, Invariant Mass
Missing Energy, Momentum of rho0



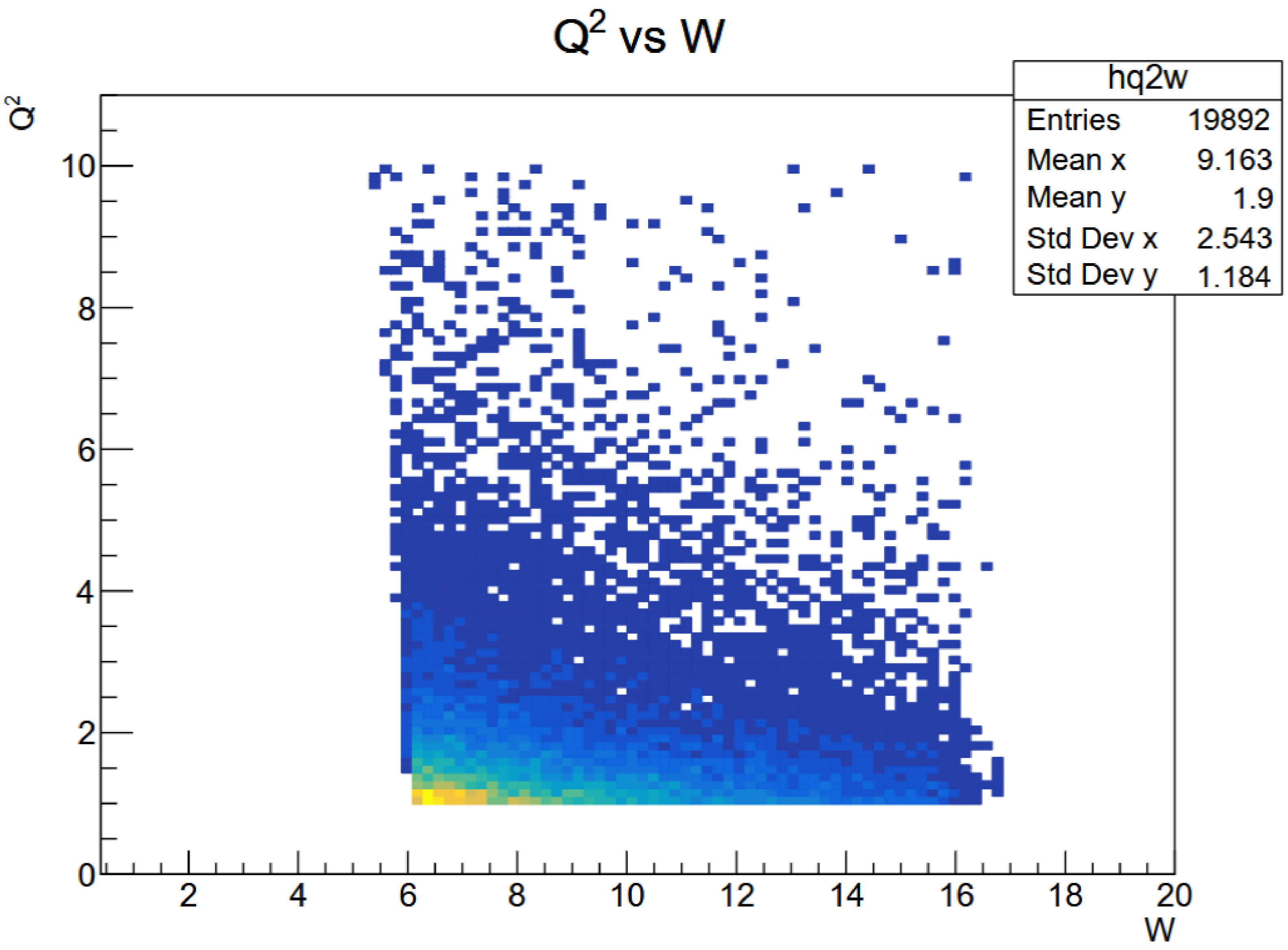
Cuts:W,y,Q2,nu,Pt2, Missing Energy, Momentum of rho0



Cuts:W,y,Q2,nu,Pt2, Invariant Mass
Missing Energy, Momentum of rho0

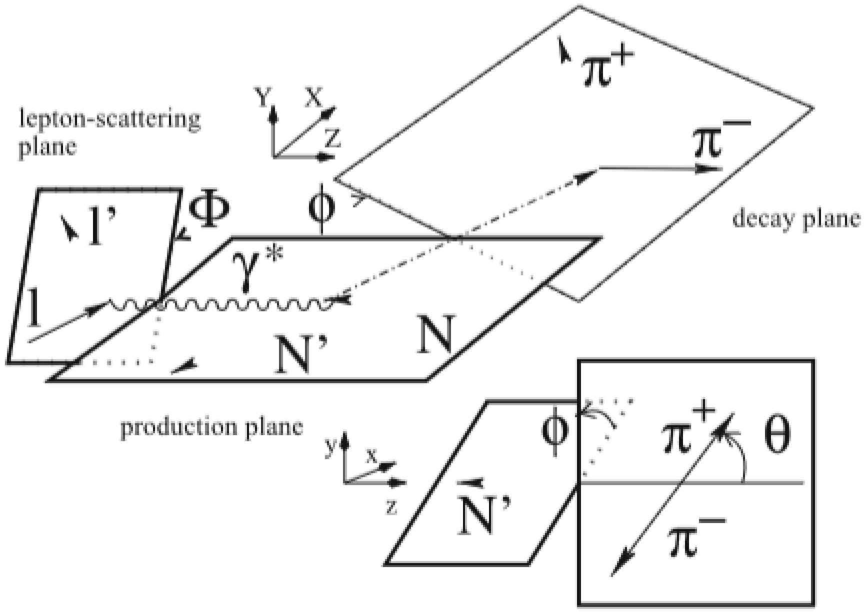


Cuts:W,y,Q2,nu,Pt2, Invariant Mass
Missing Energy, Momentum of rho0



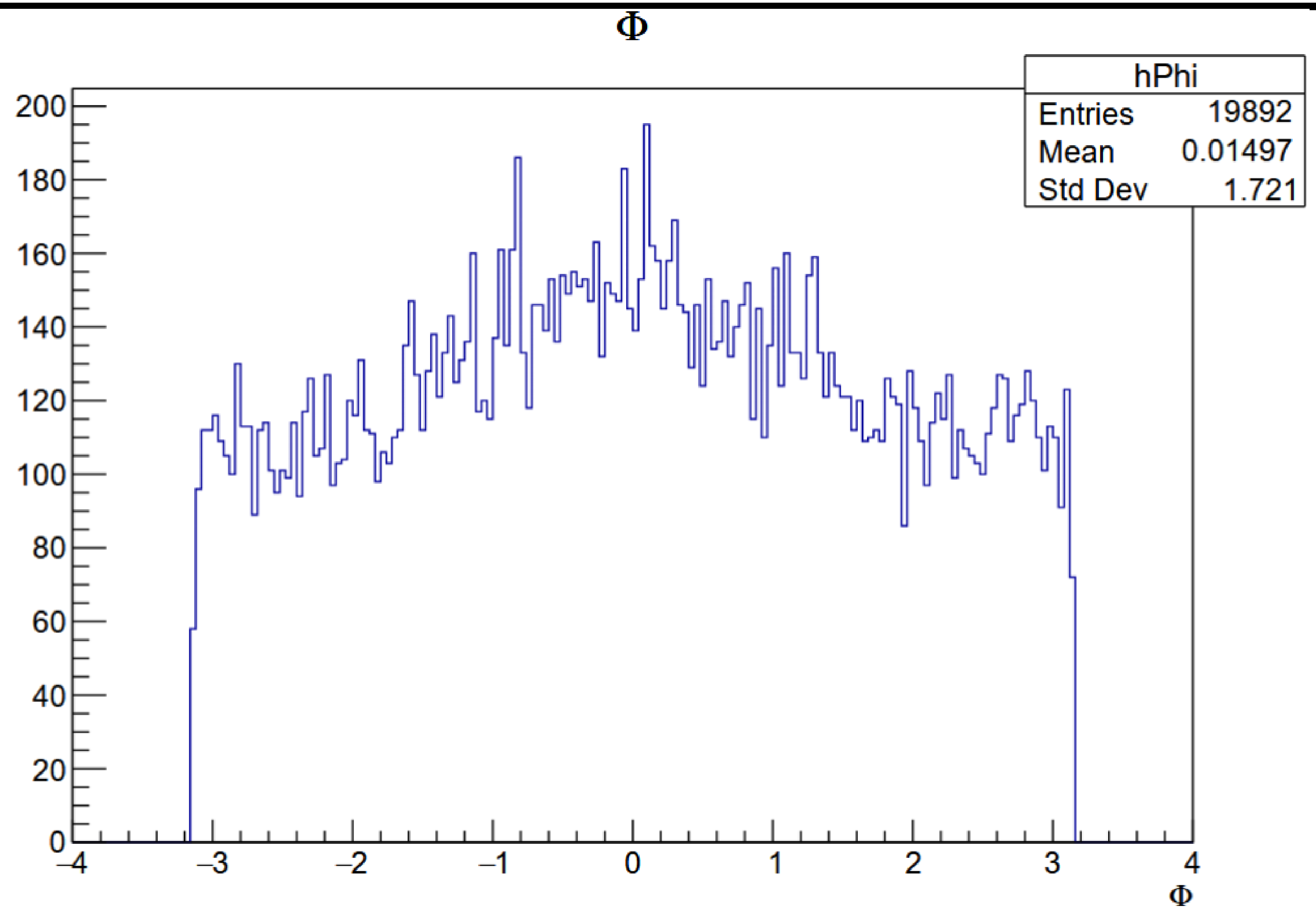
Cuts:W,y,Q2,nu,Pt2, Invariant Mass
Missing Energy, Momentum of rho0

ANGLES FOR SDME



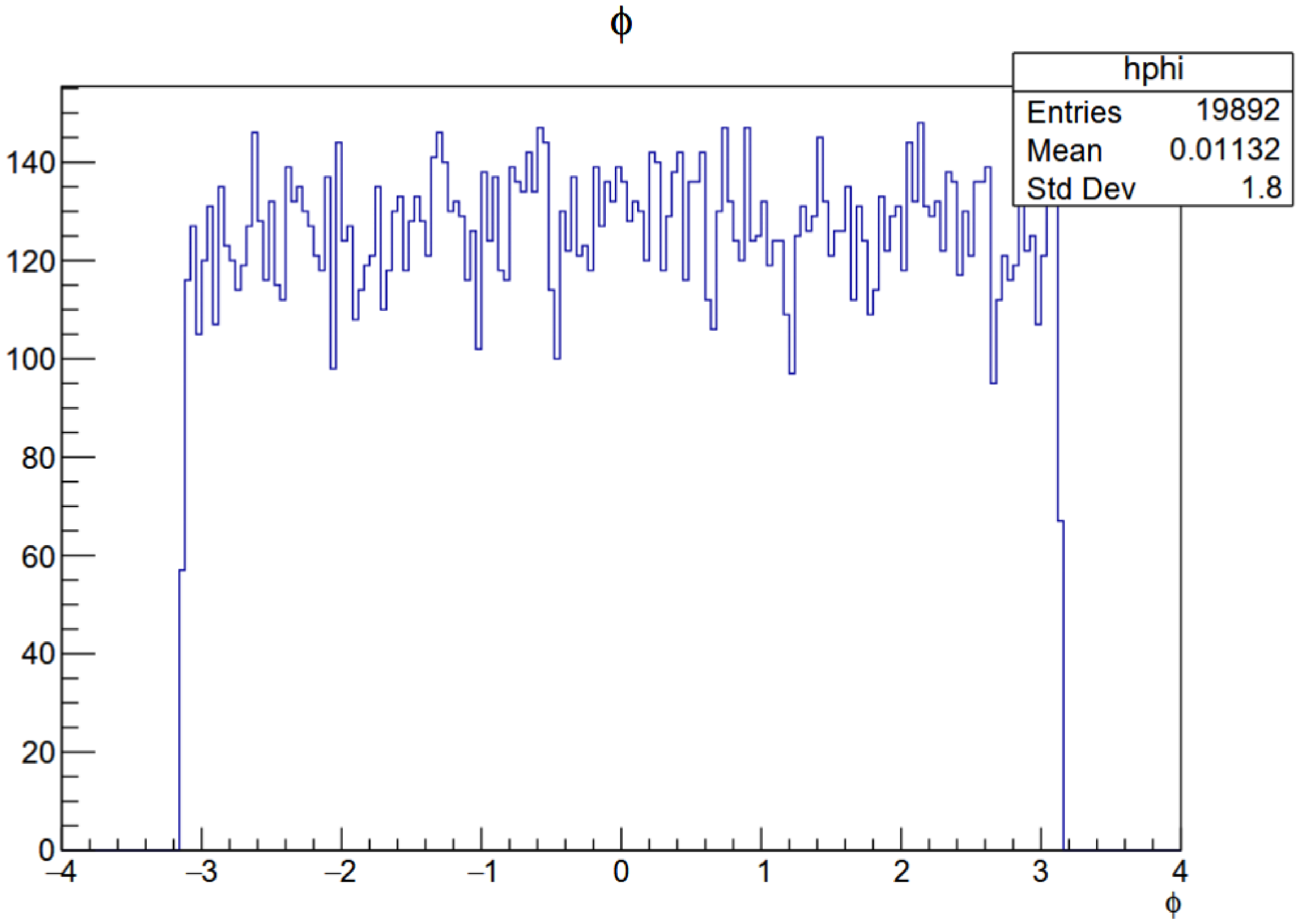
W. Augustyniak, et al. ,Spin Density Matrix Elements for exclusive ρ0 meson production using the 2012 COMPASS data,internal note, 2021.

All Exclusive Cuts



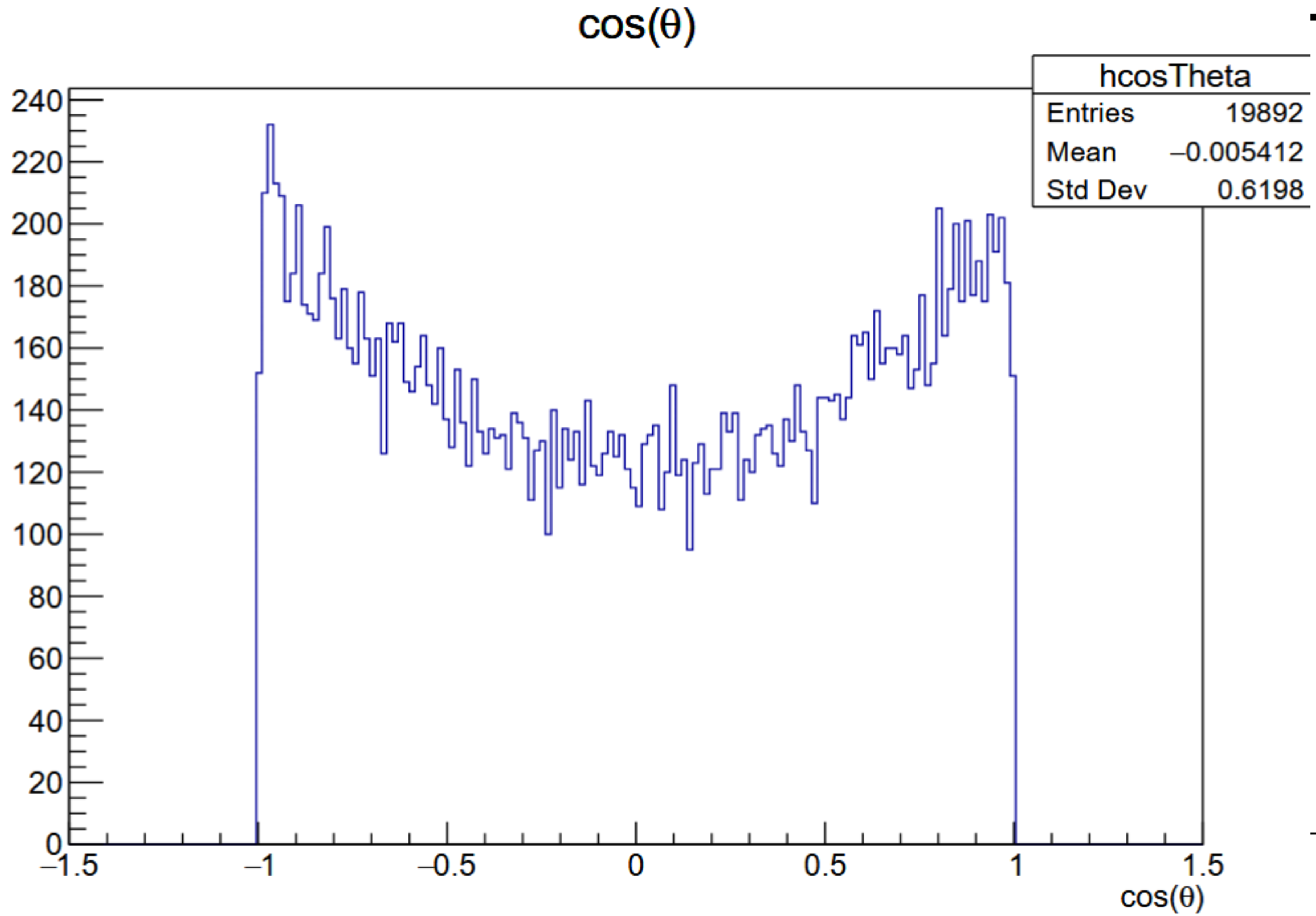
Angle between the lepton scattering plane and rho production plane (phi trento)

All Exclusive Cuts



Angle between the rho production plane and the rho decay plane

All Exclusive Cuts



The polar angle of the pi+ in the vector meson decay frame

SDME CODE

```python
import ROOT.Math as rm
import numpy as np
#log sum function (the one we are minimizing)
class logsum(object):
    def __init__(self, cosTheta, phi, Phi, eps, n_Data, cosTheta_sim, phi_sim, Phi_sim, eps_sim, n_sim):
        self.cosTheta = cosTheta
        self.phi = phi
        self.Phi = Phi
        self.eps = eps
        self.n_Data = n_Data

        self.cosTheta_sim = cosTheta_sim
        self.phi_sim = phi_sim
        self.Phi_sim = Phi_sim
        self.eps_sim = eps_sim
        self.n_sim = n_sim

    def __call__(self, x):
        N = 0.0
        for i in range(self.n_Data):
            cT = self.cosTheta[i]
            ph = self.phi[i]
            Ph = self.Phi[i]

            sin2Theta = 2 * cT * rm.sqrt(1 - cT * cT)
            sinTheta2 = (1 - cT * cT)

            N_u = (1/2 * (1 - x[0]) + 1/2 * (3 * x[0] - 1) * cT * cT
                   - rm.sqrt(2) * x[1] * sin2Theta * rm.cos(ph)
                   - x[2] * sinTheta2 * rm.cos(2 * ph))
            N_u += (-self.eps[i] * rm.cos(2 * Ph) * (x[3] * sinTheta2 + x[4] * cT * cT
                    - rm.sqrt(2) * x[5] * sin2Theta * rm.cos(ph)
                    - x[6] * sinTheta2 * rm.cos(2 * ph)))
            N_u += (-self.eps[i] * rm.sin(2 * Ph) * (rm.sqrt(2) * x[7] * sin2Theta * rm.sin(ph)
                    + x[8] * sinTheta2 * rm.sin(2 * ph)))
            N_u += (rm.sqrt(2 * self.eps[i] * (1 + self.eps[1])) * rm.cos(Ph) * (x[9] * sinTheta2
                    + x[10] * cT * cT - rm.sqrt(2) * x[11] * sin2Theta * rm.cos(ph)
                    - x[12] * sinTheta2 * rm.cos(2 * ph)))
            N_u += (rm.sqrt(2 * self.eps[i] * (1 + self.eps[1])) * rm.sin(Ph) * (rm.sqrt(2) * x[13] * sin2Theta * rm.sin(ph)
                    + x[14] * sinTheta2 * rm.sin(2 * ph)))

            N_p = (rm.sqrt(1 - self.eps[i] * self.eps[i]) * (rm.sqrt(2) * x[15] * sin2Theta * rm.sin(ph)
                    + x[16] * sinTheta2 * rm.sin(2 * ph)))
            N_p += (rm.sqrt(2 * self.eps[i] * (1 + self.eps[1])) * rm.cos(Ph) * (rm.sqrt(2) * x[17] * sin2Theta * rm.sin(ph)
                    + x[18] * sinTheta2 * rm.sin(2 * ph)))
            N_p += (rm.sqrt(2 * self.eps[i] * (1 + self.eps[1])) * rm.sin(Ph) * (x[19] * sinTheta2
                    + x[20] * cT * cT - rm.sqrt(2) * x[21] * sin2Theta * rm.cos(ph)
                    - x[22] * sinTheta2 * rm.cos(2 * ph)))

            N += 3 / (8 * rm.pi * rm.pi) * (N_u + Pb * N_p)

        NF = 0.0
        for i in range(self.n_sim):
            cT = self.cosTheta_sim[i]
            ph = self.phi_sim[i]
            Ph = self.Phi_sim[i]

            sin2Theta = 2 * cT * rm.sqrt(1 - cT * cT)
            sinTheta2 = (1 - cT * cT)

            N_u = (1/2 * (1 - x[0]) + 1/2 * (3 * x[0] - 1) * cT * cT
                   - rm.sqrt(2) * x[1] * sin2Theta * rm.cos(ph)
                   - x[2] * sinTheta2 * rm.cos(2 * ph))
            N_u += (-self.eps_sim[i] * rm.cos(2 * Ph) * (x[3] * sinTheta2 + x[4] * cT * cT
                    - rm.sqrt(2) * x[5] * sin2Theta * rm.cos(ph)
                    - x[6] * sinTheta2 * rm.cos(2 * ph)))
            N_u += (-self.eps_sim[i] * rm.sin(2 * Ph) * (rm.sqrt(2) * x[7] * sin2Theta * rm.sin(ph)
                    + x[8] * sinTheta2 * rm.sin(2 * ph)))
            N_u += (rm.sqrt(2 * self.eps_sim[i] * (1 + self.eps_sim[1])) * rm.cos(Ph) * (x[9] * sinTheta2
                    + x[10] * cT * cT - rm.sqrt(2) * x[11] * sin2Theta * rm.cos(ph)
                    - x[12] * sinTheta2 * rm.cos(2 * ph)))
            N_u += (rm.sqrt(2 * self.eps_sim[i] * (1 + self.eps_sim[1])) * rm.sin(Ph) * (rm.sqrt(2) * x[13] * sin2Theta * rm.sin(ph)
                    + x[14] * sinTheta2 * rm.sin(2 * ph)))

            N_p = (rm.sqrt(1 - self.eps_sim[i] * self.eps_sim[i]) * (rm.sqrt(2) * x[15] * sin2Theta * rm.sin(ph)
                    + x[16] * sinTheta2 * rm.sin(2 * ph)))
            N_p += (rm.sqrt(2 * self.eps_sim[i] * (1 + self.eps_sim[1])) * rm.cos(Ph) * (rm.sqrt(2) * x[17] * sin2Theta * rm.sin(ph)
                    + x[18] * sinTheta2 * rm.sin(2 * ph)))
            N_p += (rm.sqrt(2 * self.eps_sim[i] * (1 + self.eps_sim[1])) * rm.sin(Ph) * (x[19] * sinTheta2
                    + x[20] * cT * cT - rm.sqrt(2) * x[21] * sin2Theta * rm.cos(ph)
                    - x[22] * sinTheta2 * rm.cos(2 * ph)))

            NF += 3 / (8 * rm.pi * rm.pi) * (N_u + Pb * N_p)

        tot = ROOT.TMath.Log(N) - ROOT.TMath.Log(NF)
        return -tot
```

- The code for extracting the SDMEs using maximum likelihood method (MLM) has been written
  - Extracts all 23 SDMEs
  - Based on the python code used for sig_LT'/sig_0 extraction
  - Minuit2 minimizer used
    - "Minimize" as minimizer

SDME EXTRACTION

```
Minuit2Minimizer: Minimize with max-calls 1000000000 convergence for edm < 1e-05 strategy 1
Minuit2Minimizer : Valid minimum - status = 5
FVAL  = 6576.50353652266949
Edm   = 4.79283608001424e-06
Nfcn  = 6167
r0400     = 0.410402    +/-  0.00157315     (limited)
Rer0410   = 0.0474622   +/-  9.30313e-05
r041-1    = -0.00684965 +/-  0.000285276    (limited)
r111      = -0.0353175  +/-  0.000303622
r100      = -0.0339607  +/-  0.000529229    (limited)
Rer110    = -0.0453918  +/-  0.00134616
r11-1     = 0.191225    +/-  0.000263597    (limited)
IMr210    = 0.0530152   +/-  9.61016e-05
IMr21-1   = -0.187034   +/-  0.000359324    (limited)
r511      = -0.00155803 +/-  6.3797e-05
r500      = 0.105656    +/-  0.000540968    (limited)
Rer510    = 0.199261    +/-  0.000189833
r51-1     = 0.00669897  +/-  0.00058654     (limited)
IMr610    = -0.196338   +/-  0.000231288
IMr61-1   = 0.00400155  +/-  0.000259956    (limited)
IMr310    = 0.000981204 +/-  0.00132292
IMr31-1   = 0.00825558  +/-  6.10577e-05    (limited)
IMr710    = 0.04883     +/-  0.000132237
IMr71-1   = -0.00292473 +/-  0.000558384    (limited)
r811      = 0.019578    +/-  0.00117429
r800      = 0.00665597  +/-  0.000671774    (limited)
r810      = 0.0323718   +/-  0.000634082
r81-1     = -0.0206489  +/-  0.00234235     (limited)
```

COMPASS 2012

SDME	
r^{04}_{00}	$0.4698 \pm 0.0035 \pm 0.0220$
r^{1}_{1-1}	$0.2457 \pm 0.0037 \pm 0.0064$
$\mathrm{Im}\, r^{2}_{1-1}$	$-0.2459 \pm 0.0038 \pm 0.0049$
$\mathrm{Re}\, r^{5}_{10}$	$0.1769 \pm 0.0015 \pm 0.0041$
$\mathrm{Im}\, r^{6}_{10}$	$-0.1662 \pm 0.0014 \pm 0.0040$
$\mathrm{Im}\, r^{7}_{10}$	$0.0453 \pm 0.0096 \pm 0.0156$
$\mathrm{Re}\, r^{8}_{10}$	$0.0362 \pm 0.0095 \pm 0.0121$
$\mathrm{Re}\, r^{04}_{10}$	$0.0454 \pm 0.0021 \pm 0.0058$
$\mathrm{Re}\, r^{1}_{10}$	$-0.0539 \pm 0.0029 \pm 0.0040$
$\mathrm{Im}\, r^{2}_{10}$	$0.0532 \pm 0.0028 \pm 0.0043$
r^{5}_{00}	$0.1456 \pm 0.0033 \pm 0.0129$
r^{1}_{00}	$-0.0376 \pm 0.0062 \pm 0.0114$
$\mathrm{Im}\, r^{3}_{10}$	$0.0067 \pm 0.0067 \pm 0.0045$
r^{8}_{00}	$0.0019 \pm 0.0194 \pm 0.0253$
r^{5}_{11}	$0.0027 \pm 0.0016 \pm 0.0025$
r^{5}_{1-1}	$0.0050 \pm 0.0020 \pm 0.0025$
$\mathrm{Im}\, r^{6}_{1-1}$	$-0.0028 \pm 0.0020 \pm 0.0019$
$\mathrm{Im}\, r^{7}_{1-1}$	$-0.0045 \pm 0.0134 \pm 0.0224$
r^{8}_{11}	$0.0203 \pm 0.0101 \pm 0.0305$
r^{8}_{1-1}	$-0.0300 \pm 0.0128 \pm 0.0091$
r^{04}_{1-1}	$-0.0120 \pm 0.0027 \pm 0.0032$
r^{1}_{11}	$-0.0162 \pm 0.0032 \pm 0.0037$
$\mathrm{Im}\, r^{3}_{1-1}$	$0.0163 \pm 0.0085 \pm 0.0043$

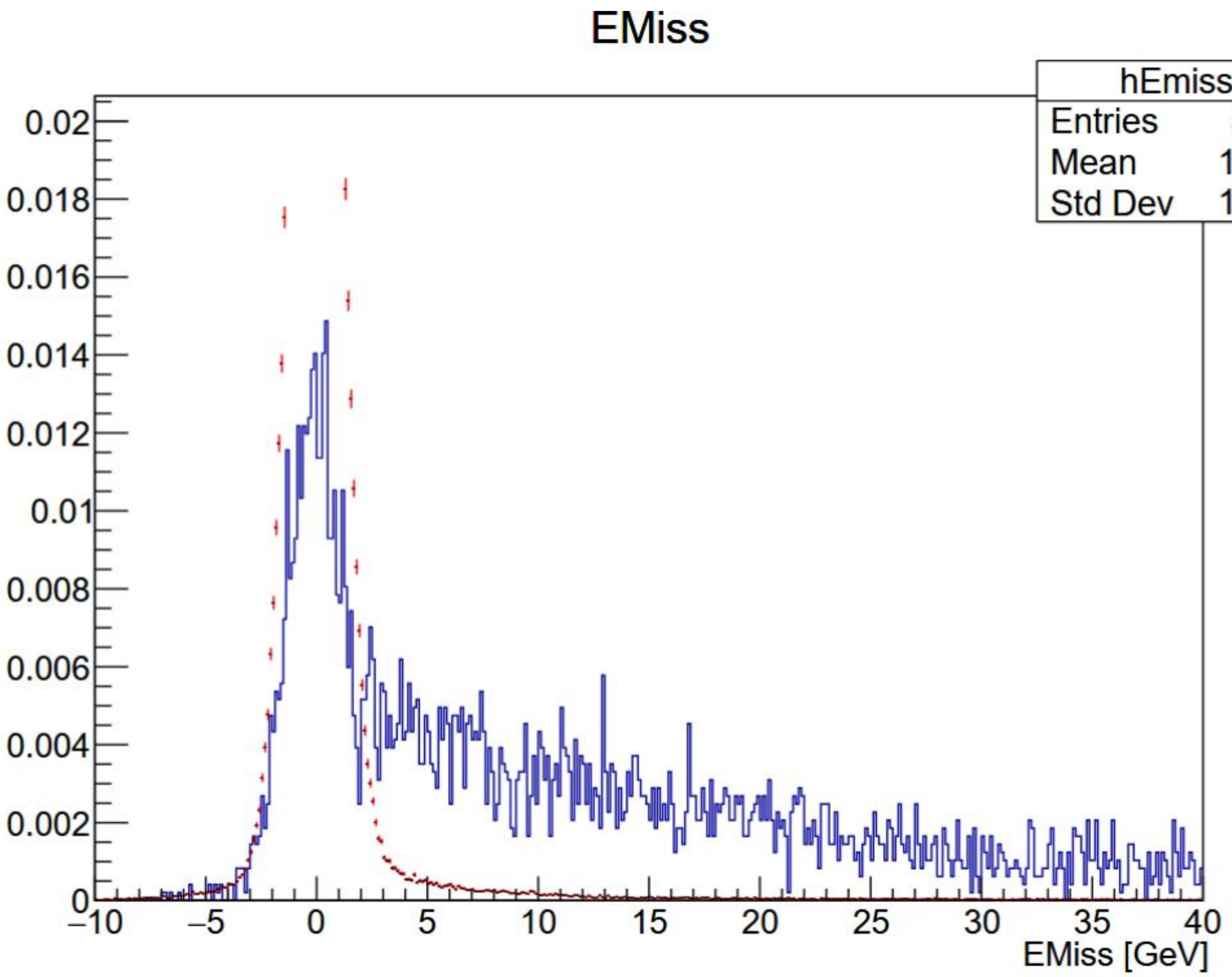
NEXT STEPS

- Run all the data and MC files
- Fix script of SDME
    - Unbinned extraction
- Improve script so I can use background correction extraction

BACKUP SLIDES

(OLD) DATA VS MONTE CARLO

Cuts on W,y,Q2,Pt2, Invariant Mass and Momentum of rho0

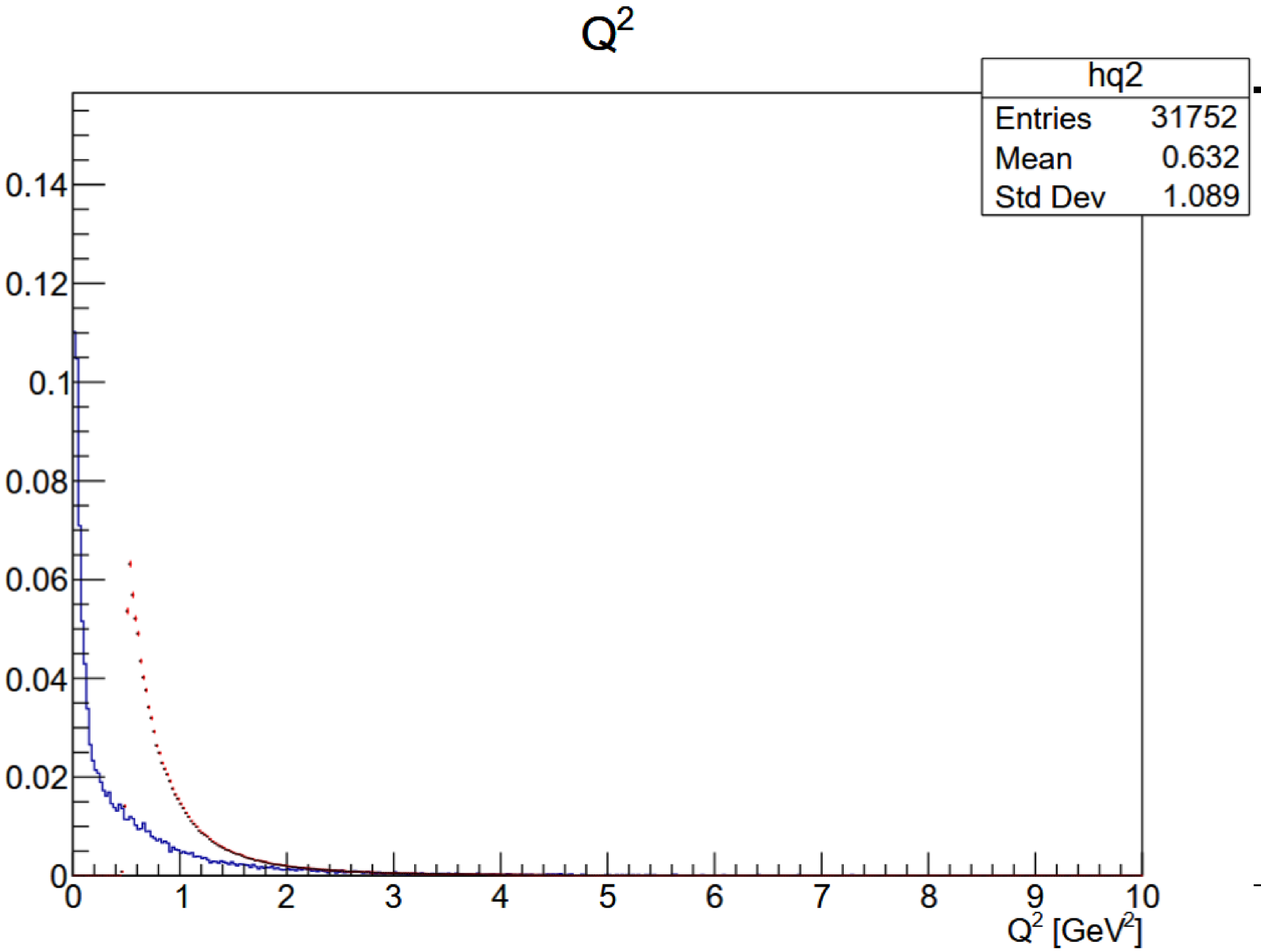


Data

HepGen

Q2_Min=
7.890324923209846e-06

Cuts on W,y,Pt2, Invariant Mass and Momentum of rho0



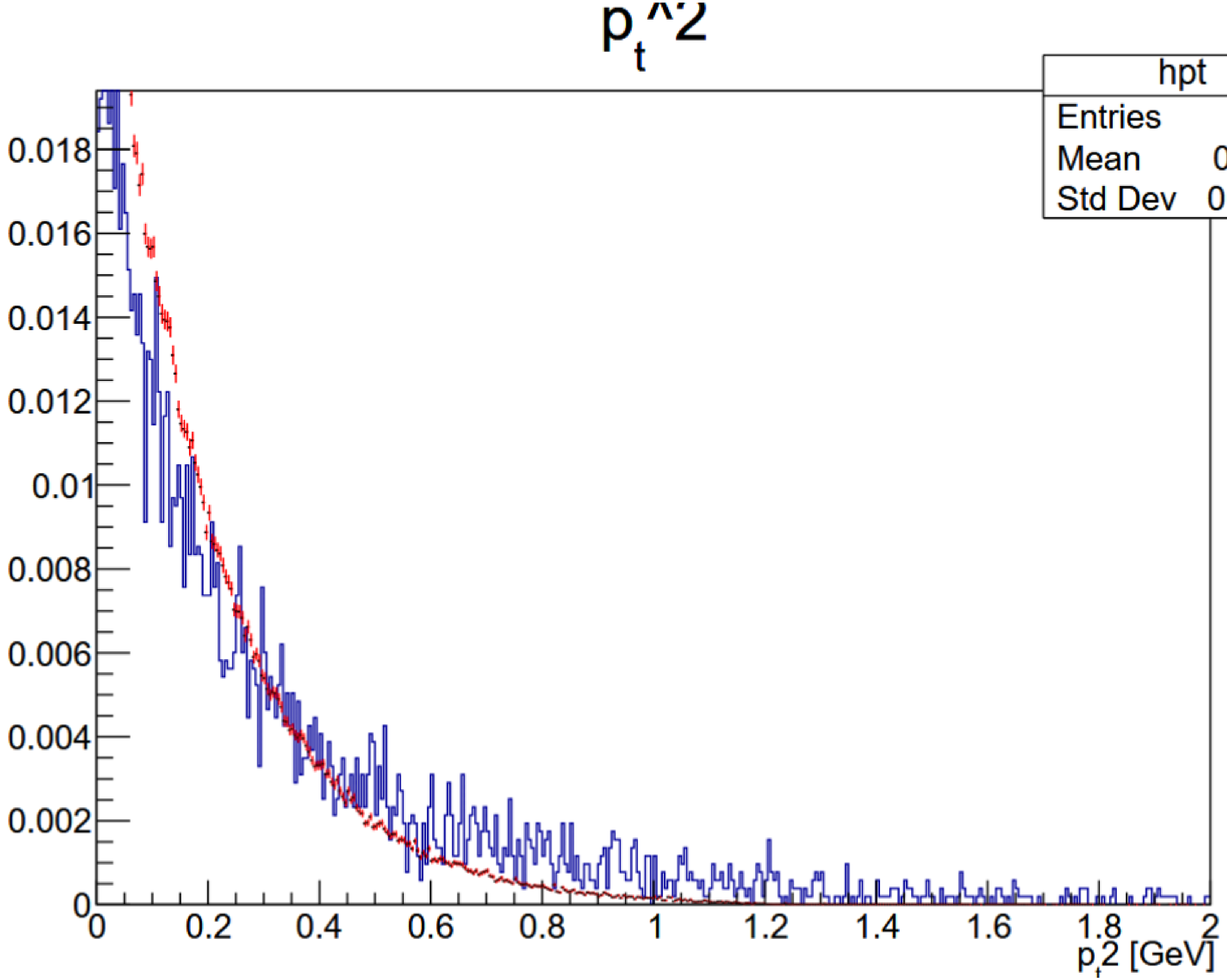
Cut not included:

1.0 < Q2 < 10.0

Data

HepGen

Cuts on W,y,Q2, Invariant Mass and Momentum of rho0



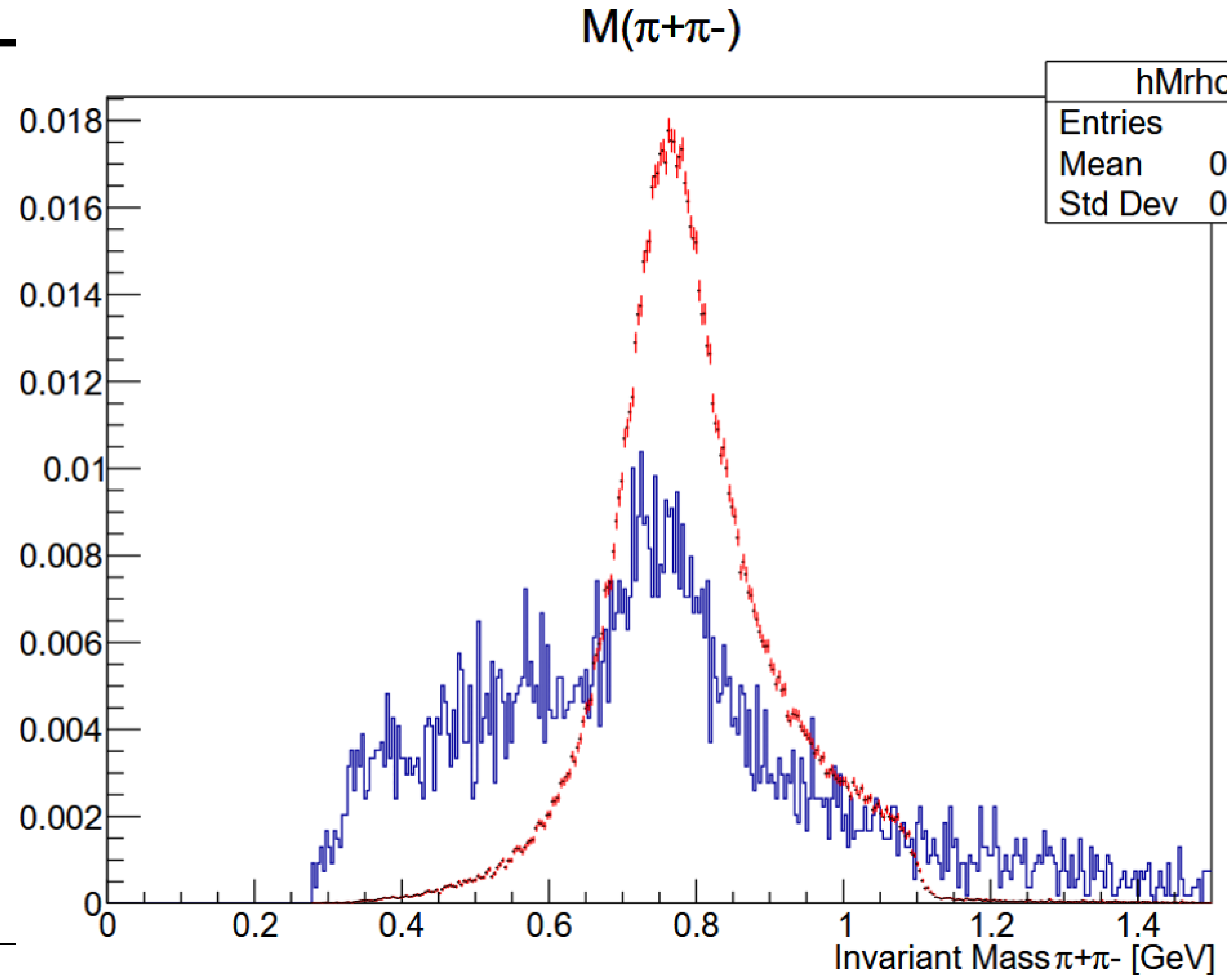
Cut not included:

0.01 < pT2< 0.5

Data

HepGen

Cuts on W,y,Q2,Pt2, and Momentum of rho0

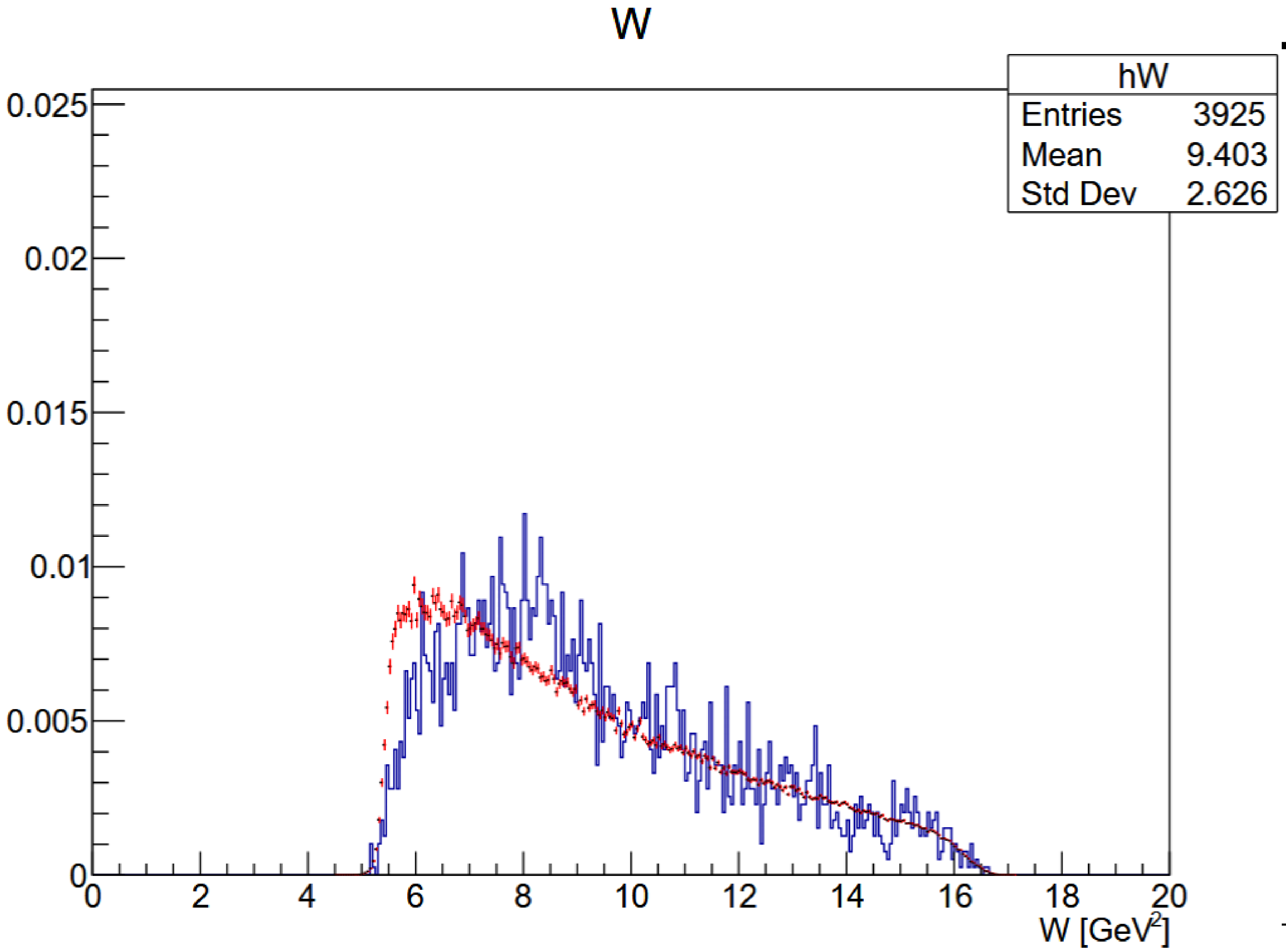


Cut not included:
$0.5 < M\pi+\pi- < 1.1$

Data

HepGen

Cuts on y,Q2,Pt2, Invariant Mass and Momentum of rho0



Cut not included:
W > 5.0 GeV

Data

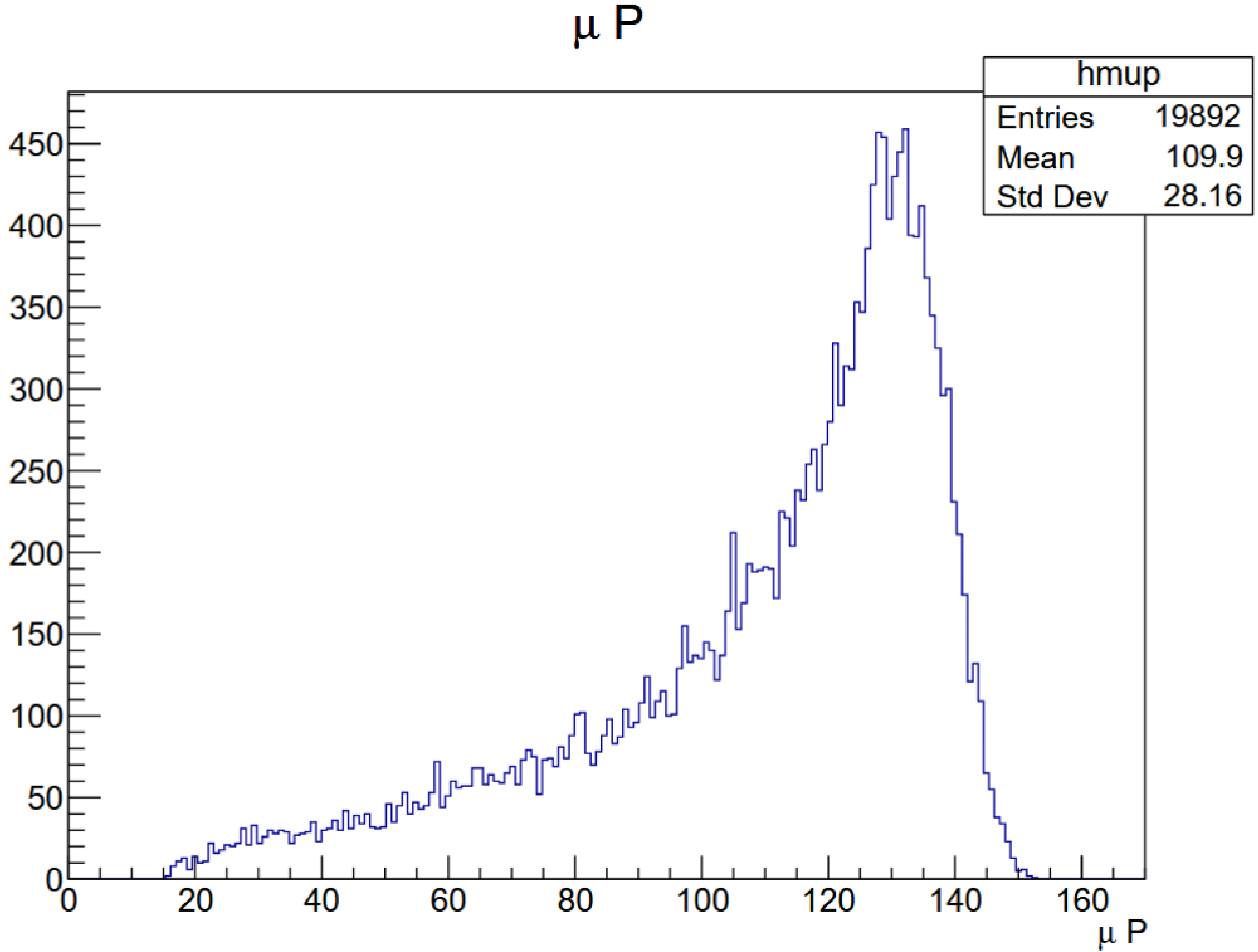
HepGen

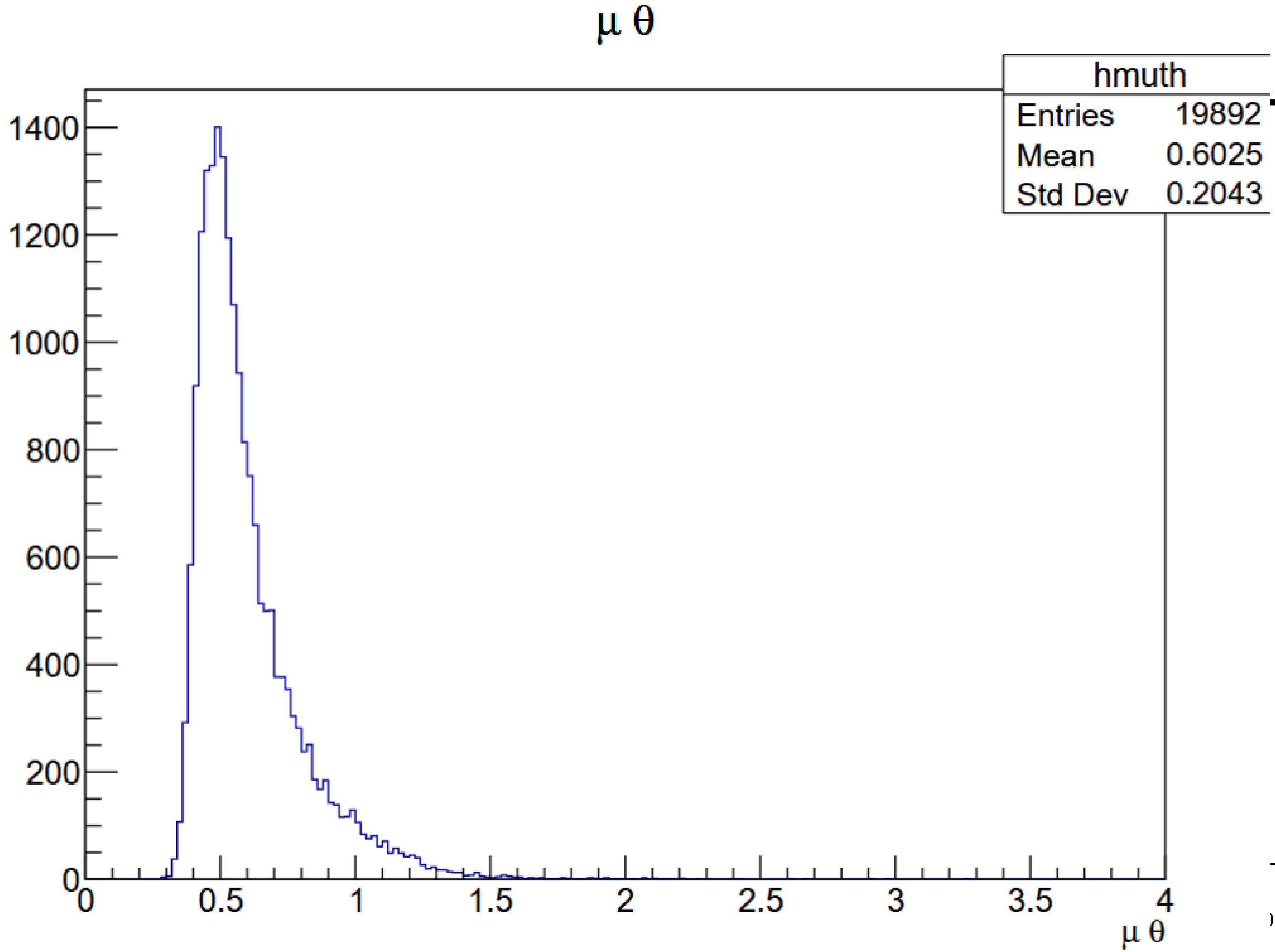
KINEMATIC CUTS

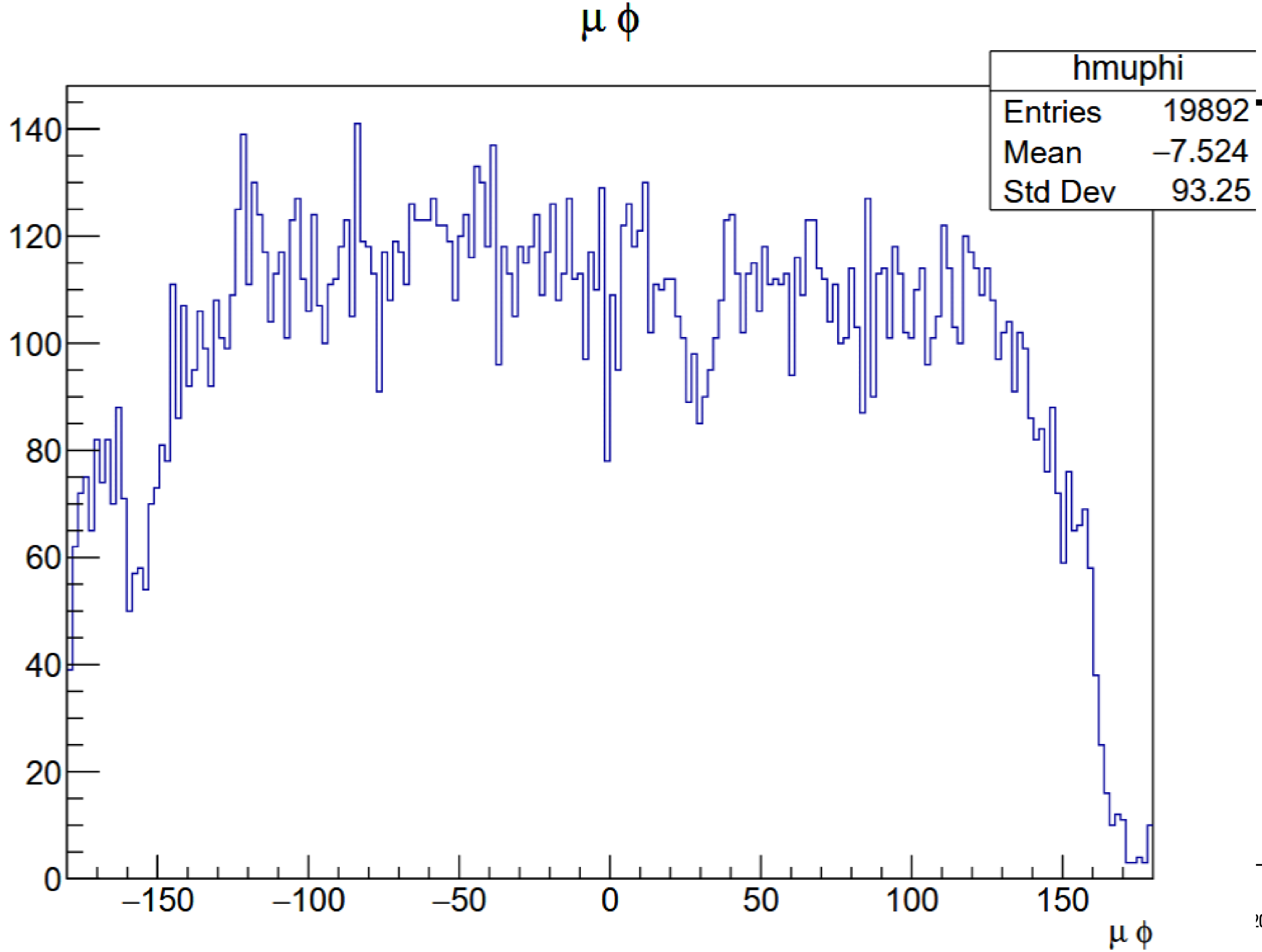
- $W > 5.0$ GeV
- $0.1 < y < 0.9$
- $1.0 < Q2 < 10.0$
- $0.01 < pT2 < 0.5$
- $0.5 < M\pi+\pi- < 1.1$
- P_{ρ0} > 15

Each plot is shown without the cut on the variable

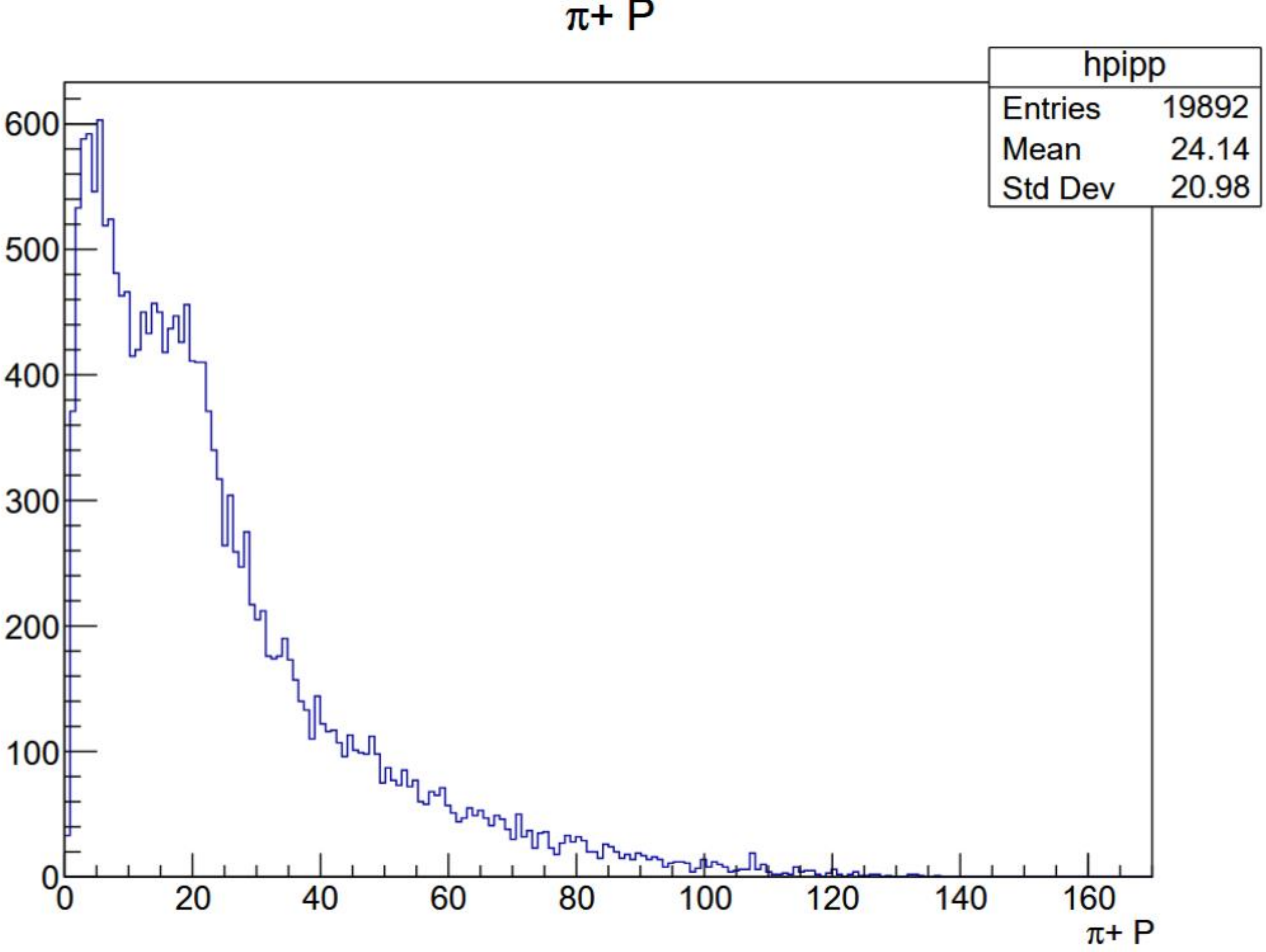
DATA 1D PARTICLE KINEMATICS WITH CUTS

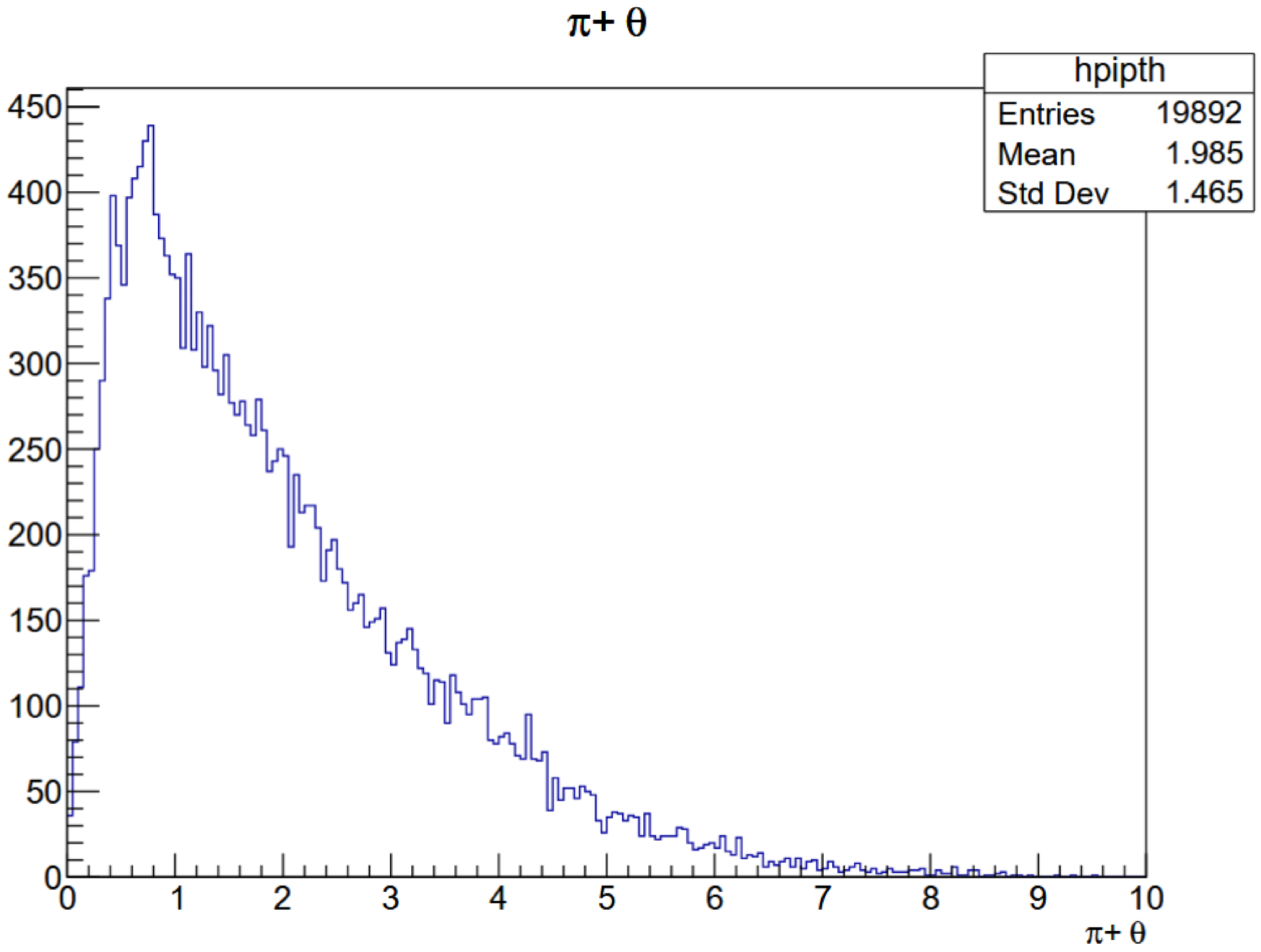

μ P
hmup
Entries 19892
Mean 109.9
Std Dev 28.16
0
50
100
150
200
250
300
350
400
450
0
20
40
60
80
100
120
140
160
μ P


μ θ
hmuth
Entries 19892
Mean 0.6025
Std Dev 0.2043
0
200
400
600
800
1000
1200
1400
0
0.5
1
1.5
2
2.5
3
3.5
4
μ θ

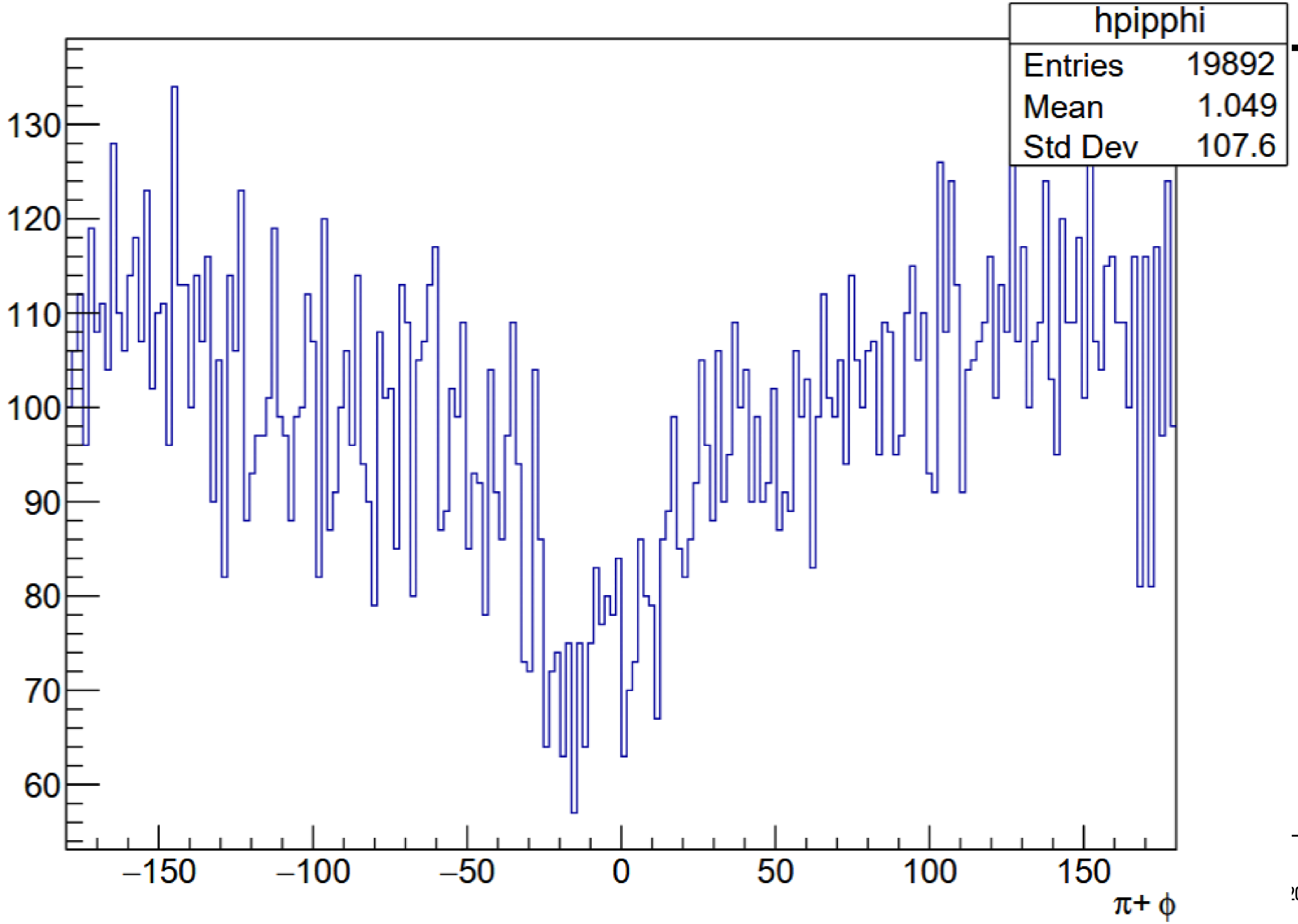


μ φ
hmuphi
Entries 19892
Mean −7.524
Std Dev 93.25
140
120
100
80
60
40
20
0
−150
−100
−50
0
50
100
150
μ φ

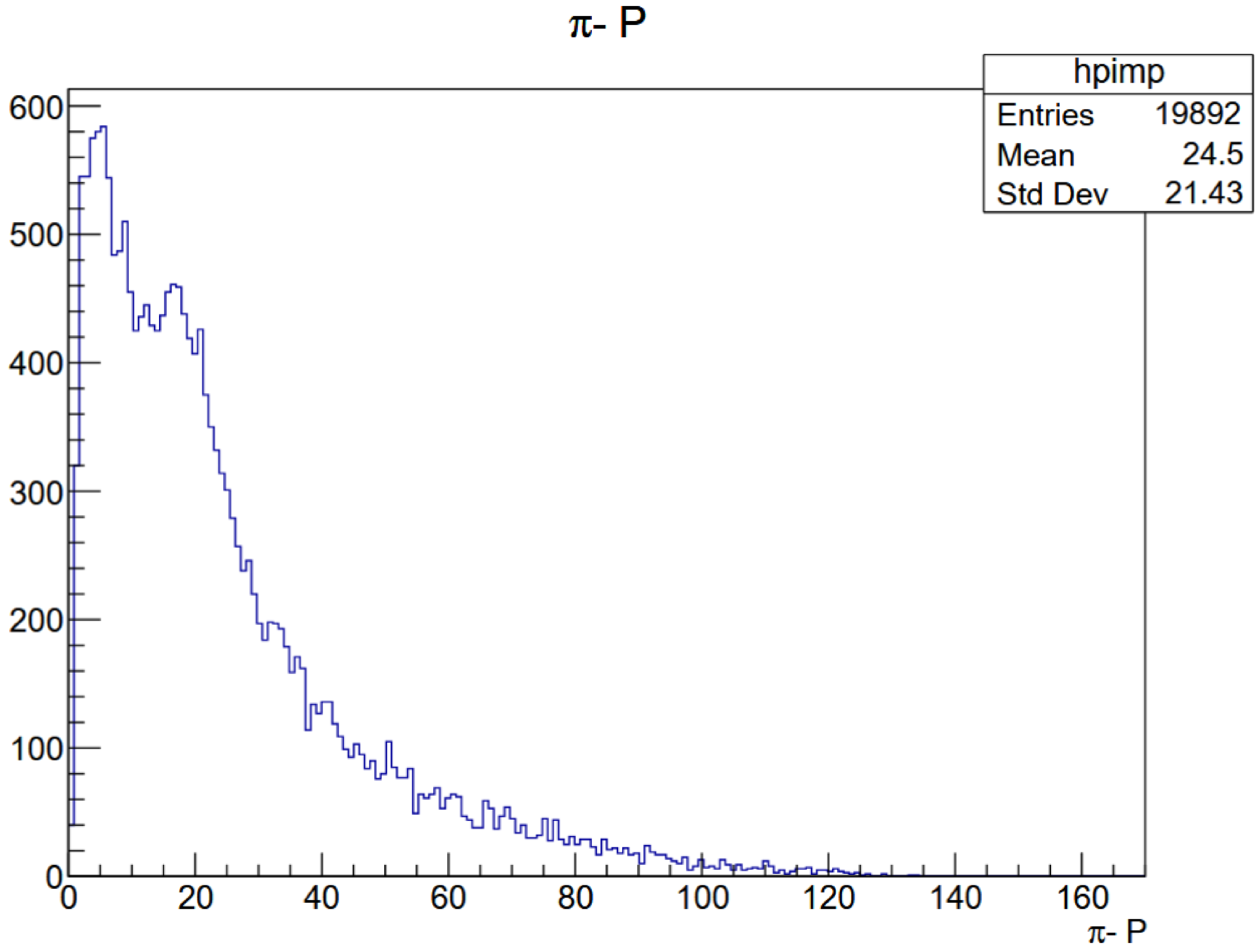

π+ P
hpipp
Entries 19892
Mean 24.14
Std Dev 20.98
0
100
200
300
400
500
600
0
20
40
60
80
100
120
140
160
π+ P

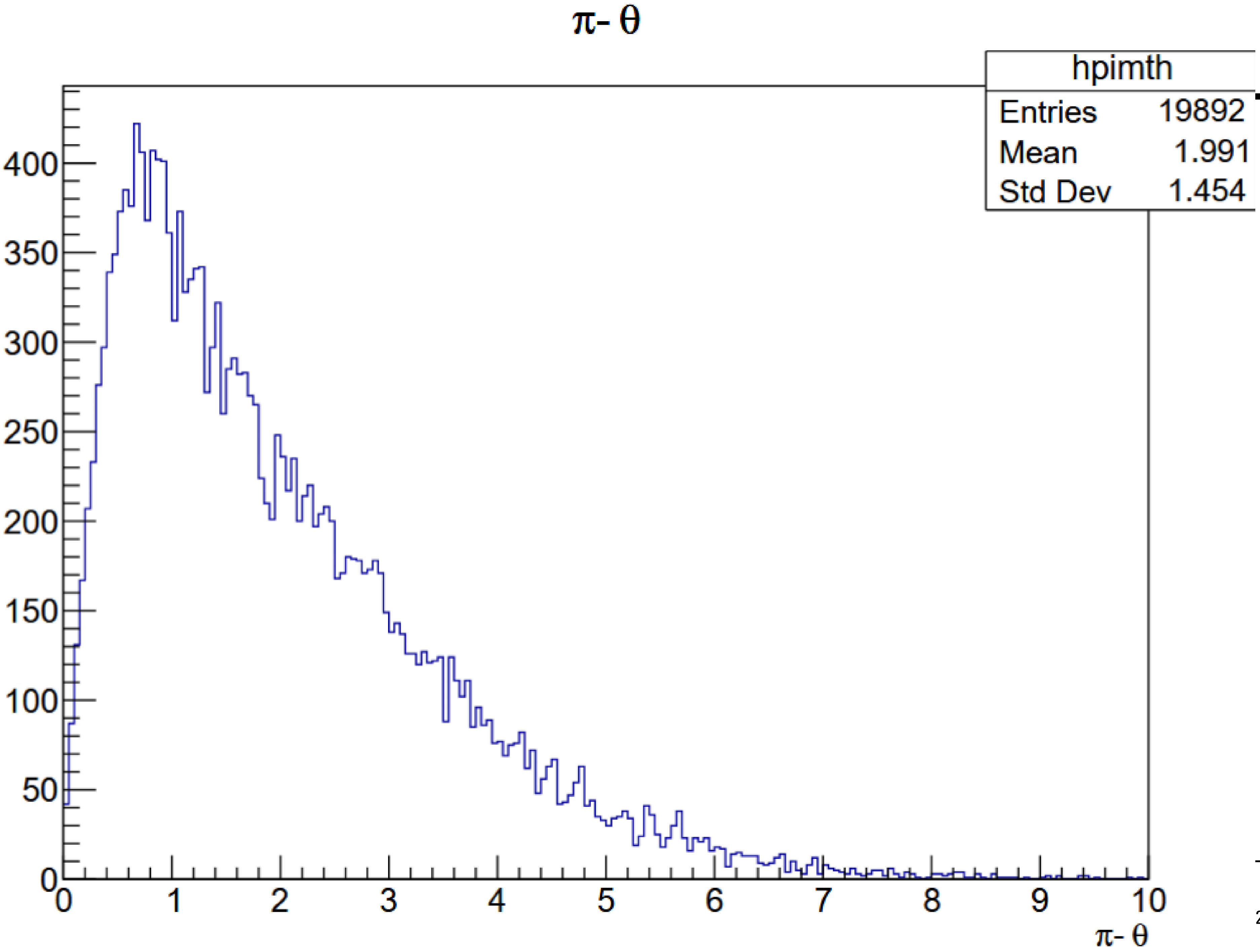

π+ θ
hpipth
Entries 19892
Mean 1.985
Std Dev 1.465
0
50
100
150
200
250
300
350
400
450
0
1
2
3
4
5
6
7
8
9
10
π+ θ

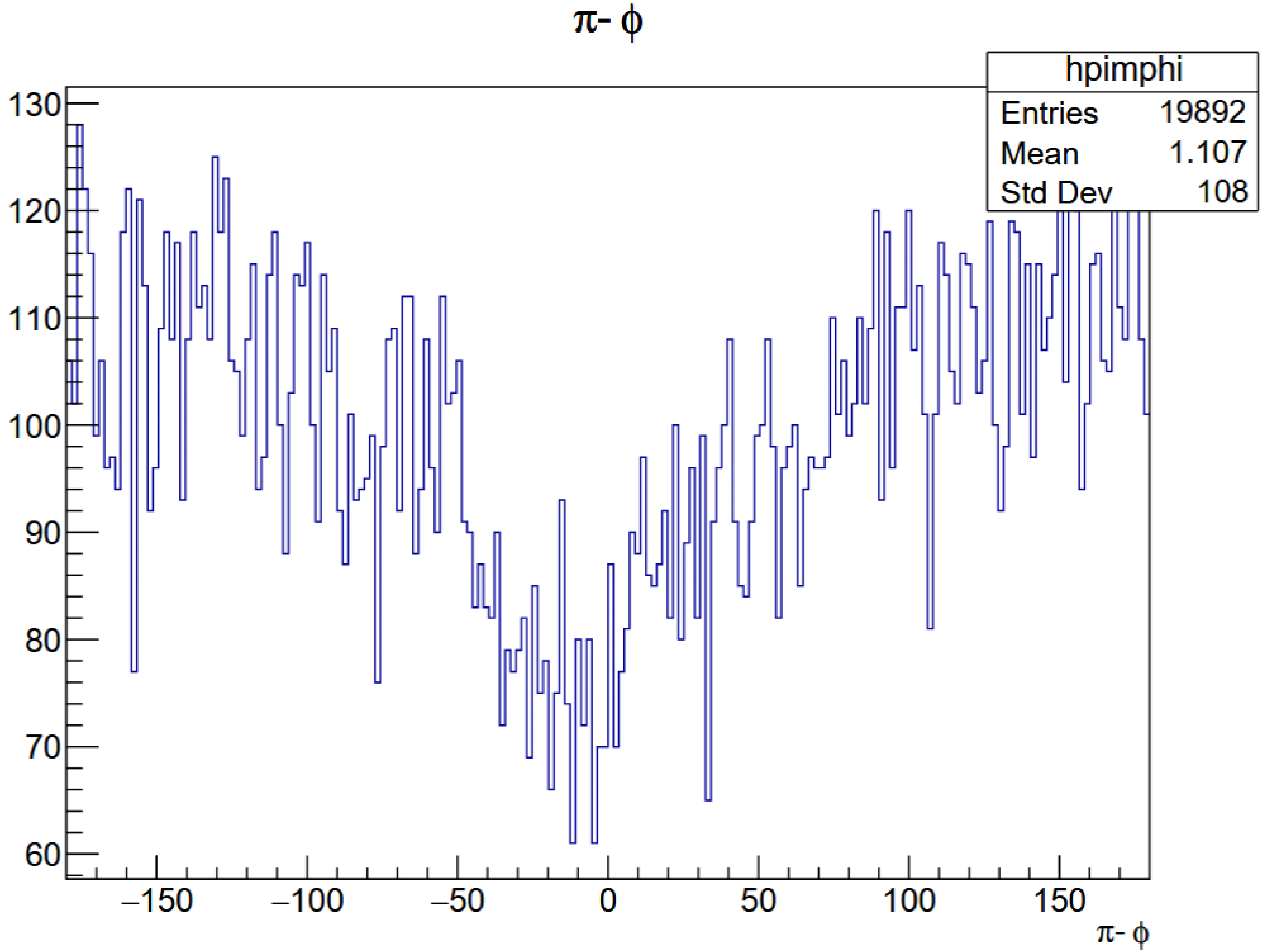
π+ φ

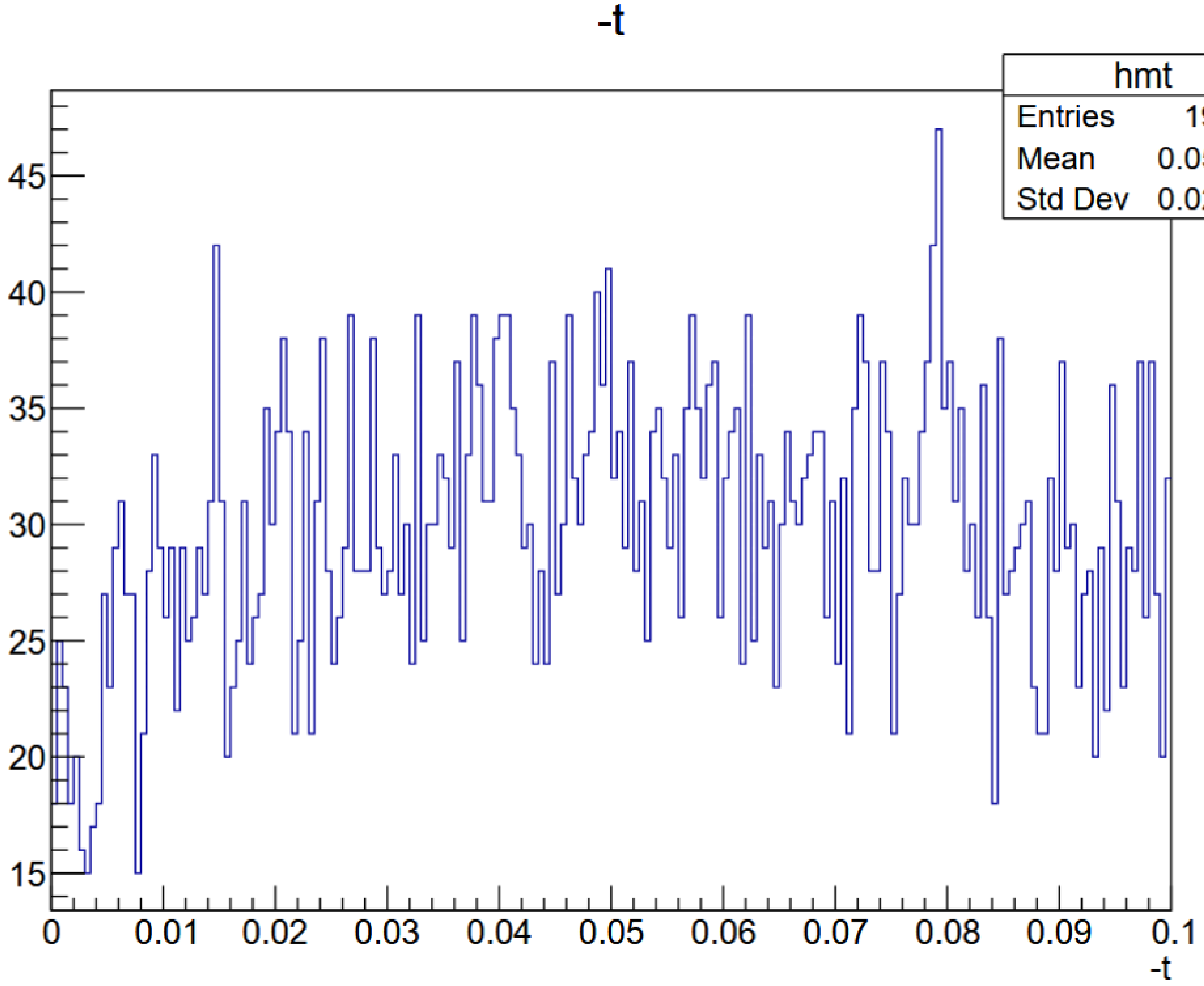


hpipphi
Entries 19892
Mean 1.049
Std Dev 107.6
130
120
110
100
90
80
70
60
−150
−100
−50
0
50
100
150
π+ φ


π- P
hpimp
Entries 19892
Mean 24.5
Std Dev 21.43
600
500
400
300
200
100
0
0
20
40
60
80
100
120
140
160
π- P


π- θ
hpimth
Entries 19892
Mean 1.991
Std Dev 1.454
0
50
100
150
200
250
300
350
400
0 1 2 3 4 5 6 7 8 9 10
π- θ


π- φ
hpimphi
Entries 19892
Mean 1.107
Std Dev 108
130
120
110
100
90
80
70
60
−150
−100
−50
0
50
100
150
π- φ


-t
hmt
Entries 19892
Mean 0.05118
Std Dev 0.02774
15
20
25
30
35
40
45
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
-t