Study of $B^+ \to K^+\tau^+\tau^-$ using hadronic tagging

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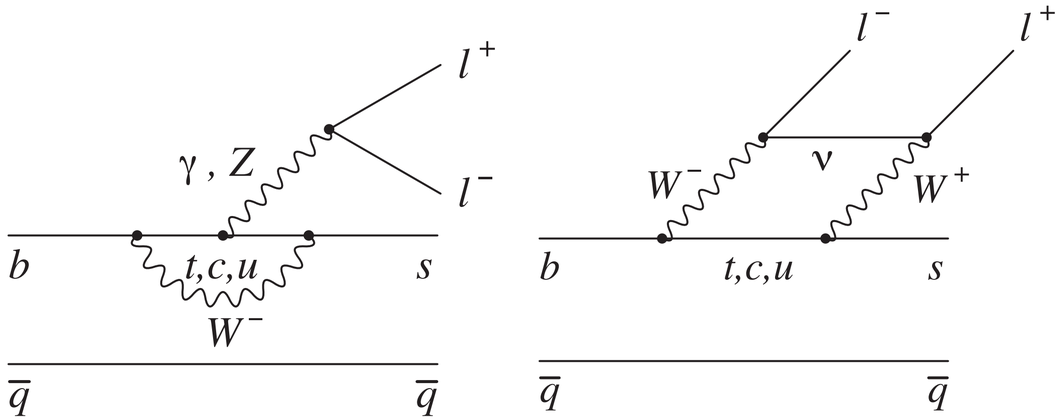
24 November 2022

Study of $B^+ \to K^+\tau^+\tau^-$

Motivation:

1. FCNC: highly suppressed in SM, $\mathcal{O}(10^{-7})$
2. 3^{rd} generation strongly couples to NP



Earlier searches:

1. Attempt in Belle (by Simon Wehle, 2016): Belle Note- 1394
   upper limit at $90\,\%$ confidence level, $\mathcal{B}(B^+ \to K^+\tau^+\tau^-) < 3.17 \times 10^{-4}$
2. BaBar (2017): arXiv:1605.09637
   upper limit at $90\,\%$ confidence level, $\mathcal{B}(B^+ \to K^+\tau^+\tau^-) < 2.25 \times 10^{-3}$

Initial step: Perform similar to Simon's study in Belle II

↳ modify Vidya's reconstruction script for Belle II

SignalMC generator

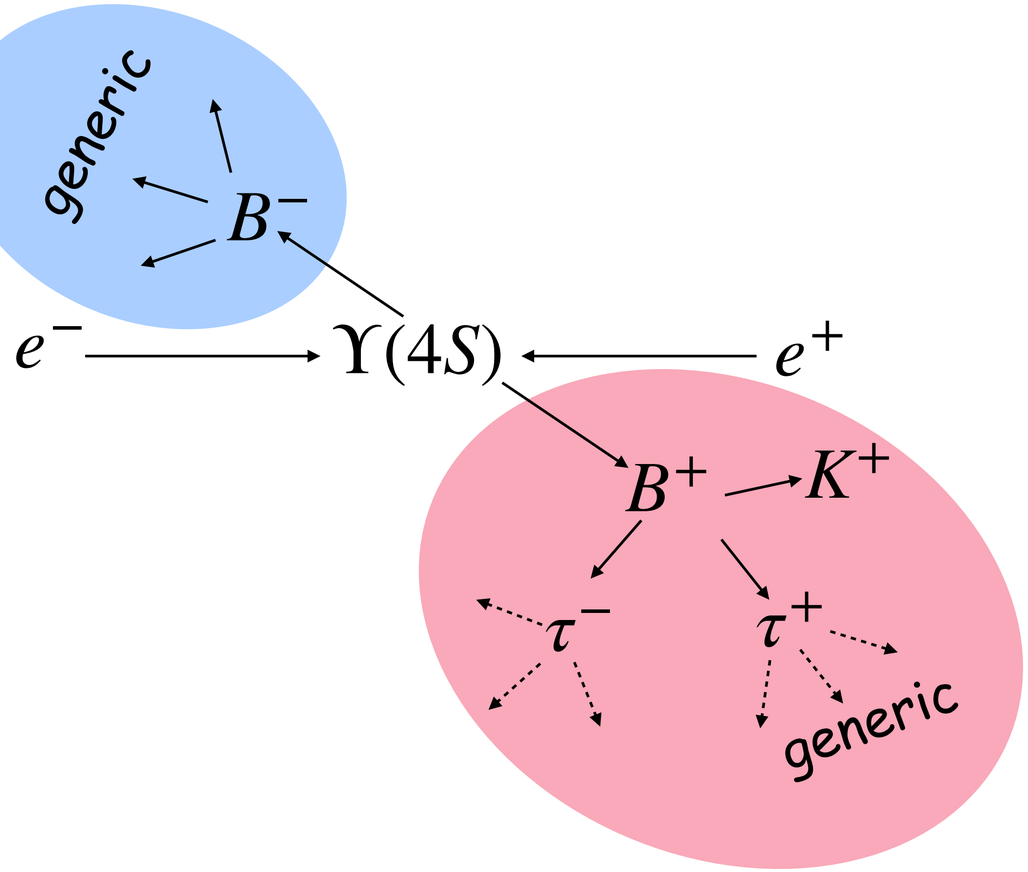
#simulated sample size: 50 million

generator model: BTOSLLBALL

release-06-00-10

globalTag: mc_production_MC15ri_a

bkg: early phase III (release-06-00-05), BGx1

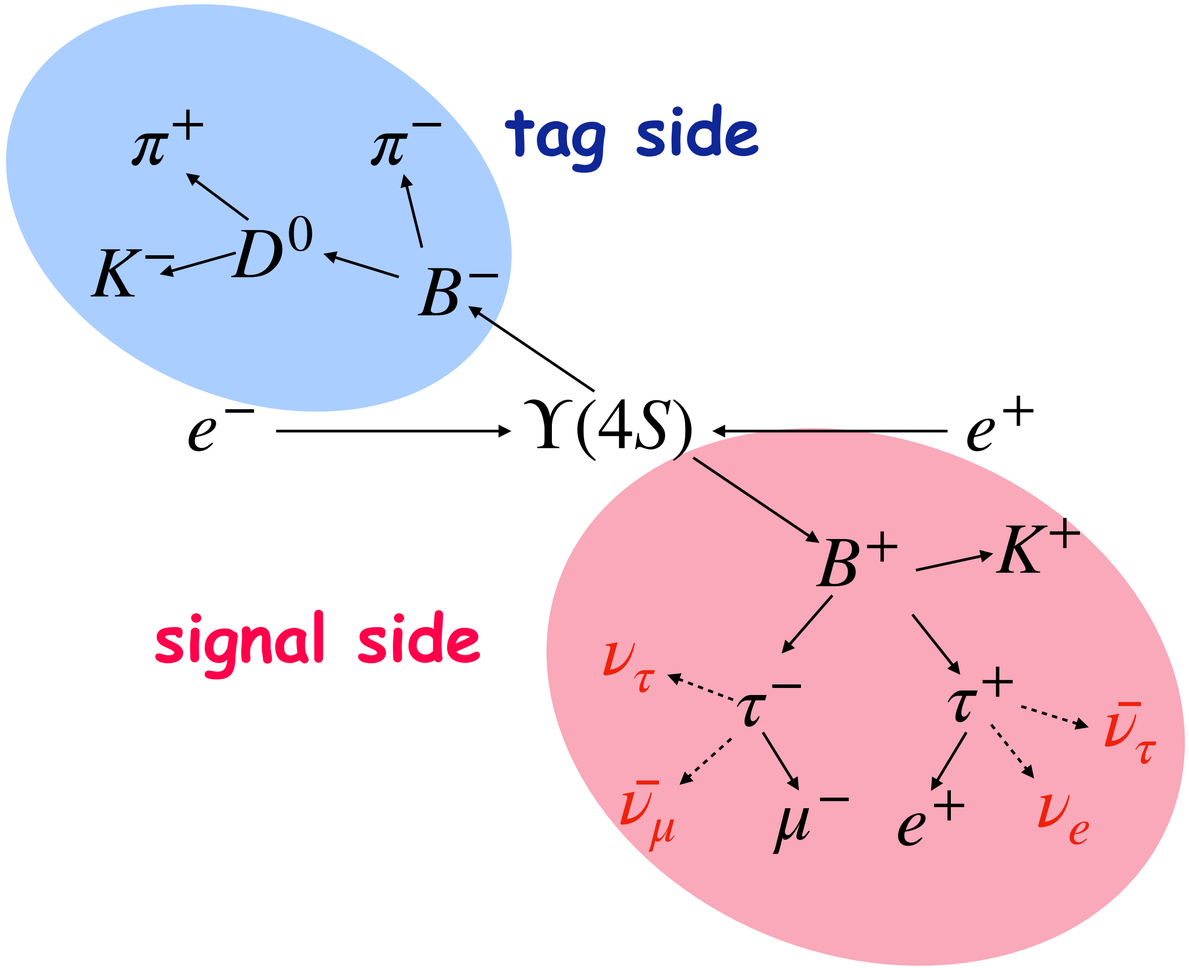


Future plan: only τ decays to $e^-\nu\nu$, $\mu^-\nu\nu$, $\pi^-\nu$

Reconstruction

Signal τ modes:

1. $\tau^- \to e^- \bar{\nu}_e \nu_\tau$
2. $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$
3. $\tau^- \to \pi^- \nu_\tau$



MC truth match

- Topoana package is used

Why is isSignalAcceptMissingNeutrino not used?

-> It shows 22 % less events (backup)

Sample and selections

SignalMC:

- Generated events: 50×10^6

GenericMC:

- Generated events: MC15rib ($400 fb^{-1}$)

Global tag:

- 'analysis_tools_light-2205-abys'

Charged tracks (e, μ, K, π) cuts:

- transverse distance from IP, $dr < 0.5$
- distance in beam direction from IP, $|dz| < 2$
- polar angle is with in CDC acceptance (thetaInCDCAcceptance)
- Kaon binary PID, $\mathscr{L}(K/\pi) > 0.6$
- Pion binary PID, $\mathscr{L}(\pi/K) > 0.6$
- Electron PID, $\mathscr{L}(e) > 0.9$
- Muon PID, $\mathscr{L}(\mu) > 0.9$

Sample and selections

Reconstruct FEI hadronic B_{tag}:

- weight file prefix - 'FEIv4_2022_MC15_light-2205-abys'
- most two probable B_{tag} candidates are accepted
- $M_{bc} > 5.27$
- $|\Delta E| < 0.1$
- FEI signal probability > 0.001
- ROE of B_{tag} has 3 charged tracks

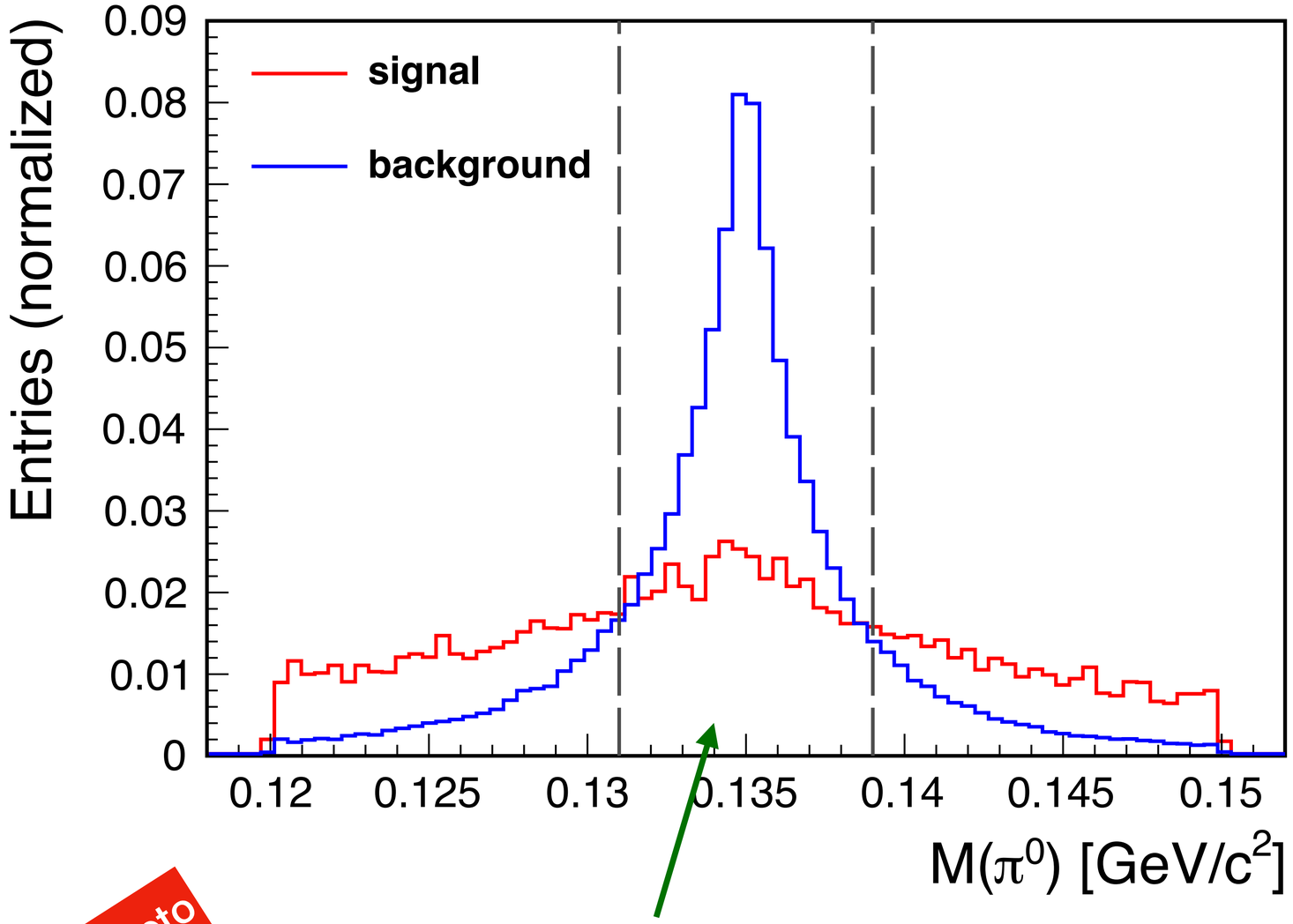
Continuum suppression:

- event sphericity > 0.2
- cosTBTO < 0.9

ROE mask:

- $dr < 0.5, |dz| < 2$, thetaInCDCAcceptance
- clusterNHits > 1.5
- $E > 0.080$ in forward
- $E > 0.030$ in barrel
- $E > 0.060$ in backward
- $|\text{cluster time}| < 200$
- minC2TDist > 20
- $\left|\frac{\text{cluster time}}{\text{clusterErrorTiming}}\right| < 2.0$

π^0 in ROE of $\Upsilon(4S)$



- π^0 is built from ROE photons
- Cut on photons: ROE mask
- Cut on π^0: $120 < \mathrm{M} < 150\,\mathrm{MeV/c^2}$
- No mass constraint
- Select one π^0 per event that has the nearest mass to the PDG mass

cut	Loss in signal	Loss in bkg
π^0 veto	12.09%	65.15%

π^0 veto

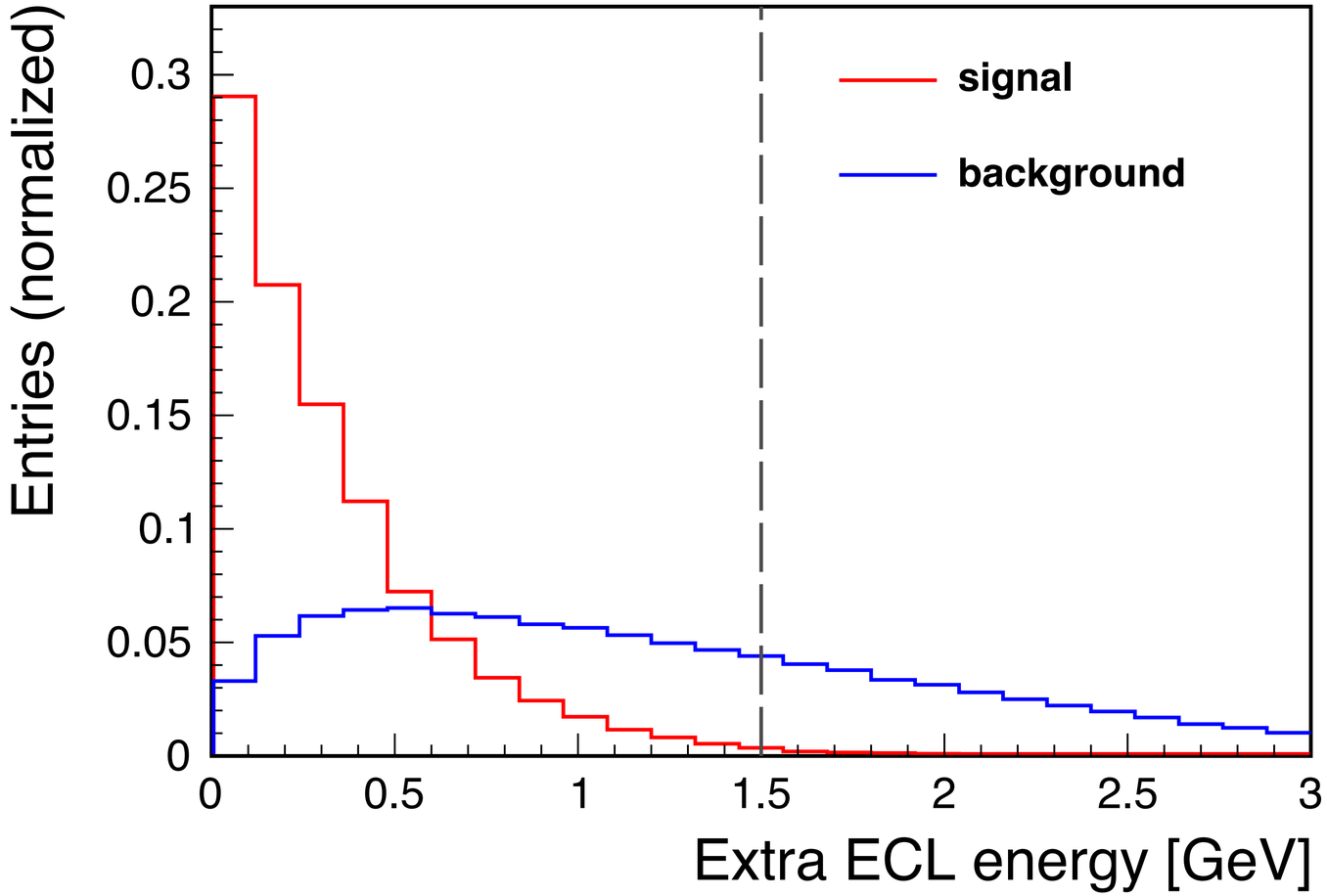
remove the events whose ROE π^0 mass peak around π^0 actual mass: $0.131 < \mathrm{M}(\pi^0) < 0.139\,\mathrm{GeV/c^2}$

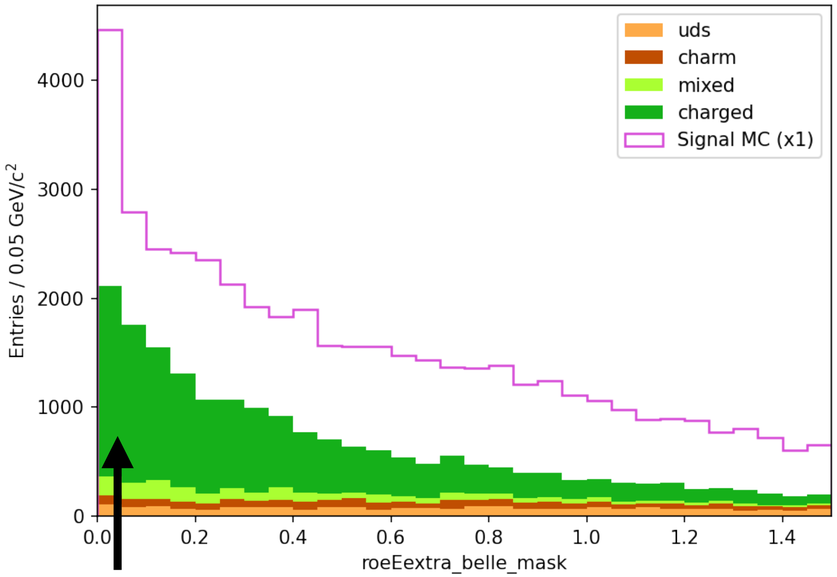
* backup:about NAN value of π^0 mass

Extra ECL energy (E_{ECL})

signal=> signalMC

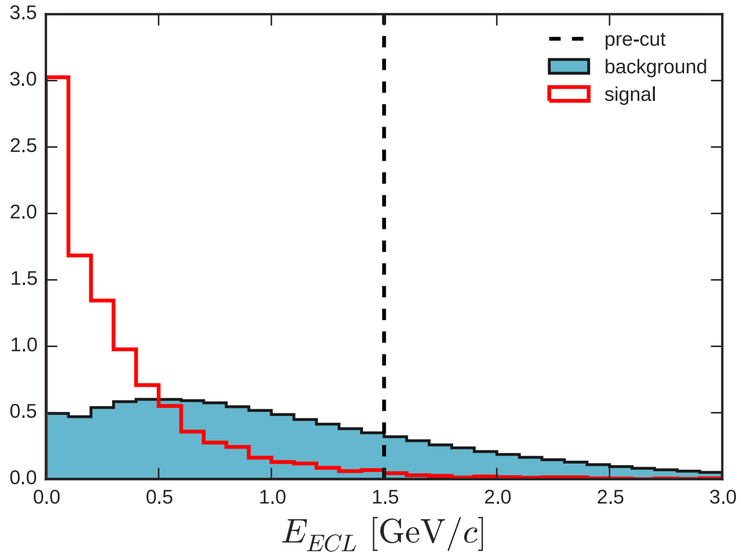
background=> genericMC (MC15rib, $400\,fb^{-1}$)





Vidya

background plot don't match



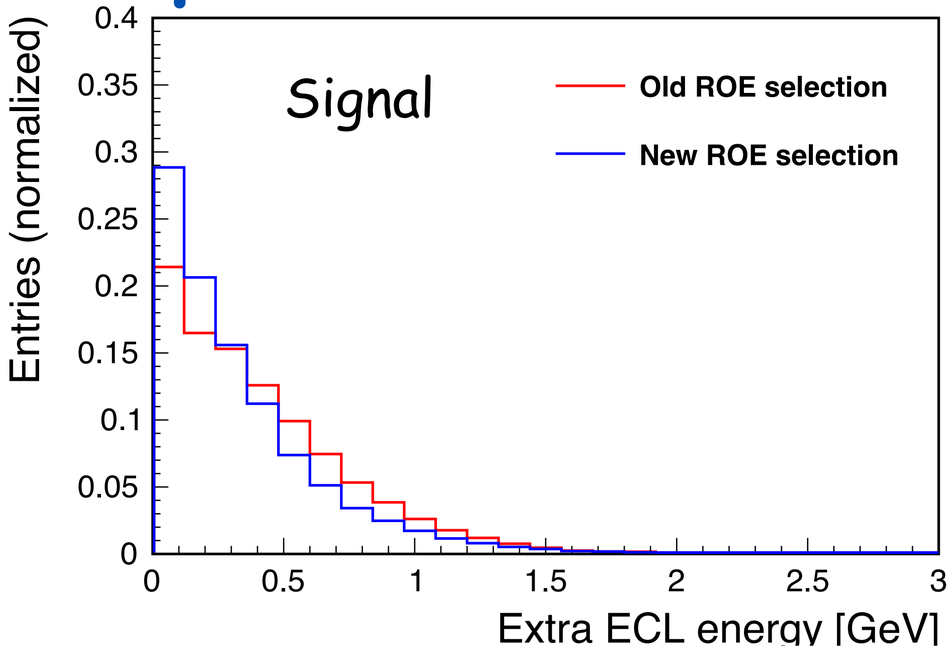
Simon

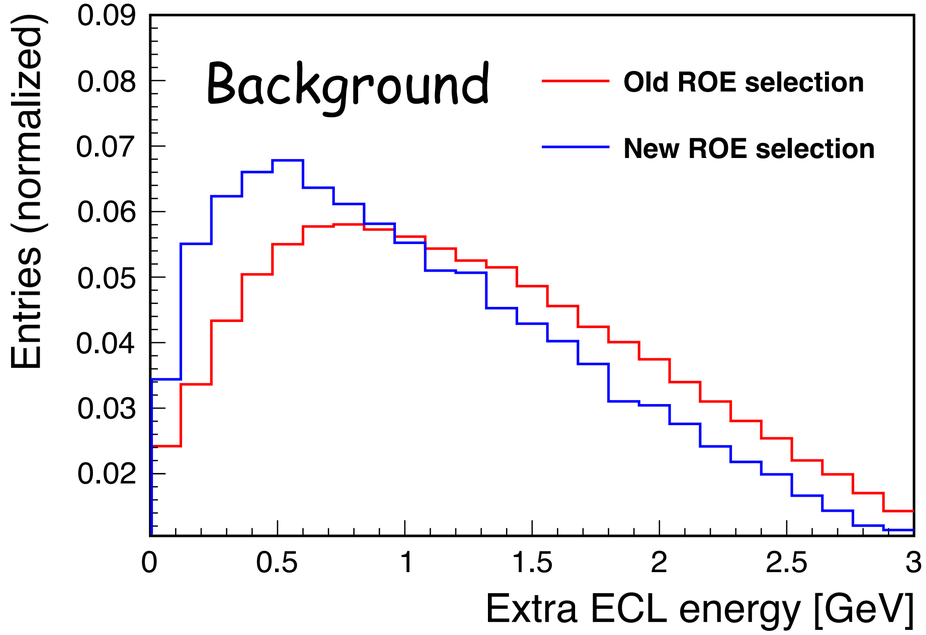
cut	Loss in signal	Loss in bkg
$E_{\mathrm{ECL}} < 1.5$	0.91%	33.07%

Comparison btw ROE selections

signal=> signalMC

background=> genericMC (MC15rib, $400\,fb^{-1}$)





Old ROE selection

- $E > 0.06$
- $|\text{cluster time}| < 20$

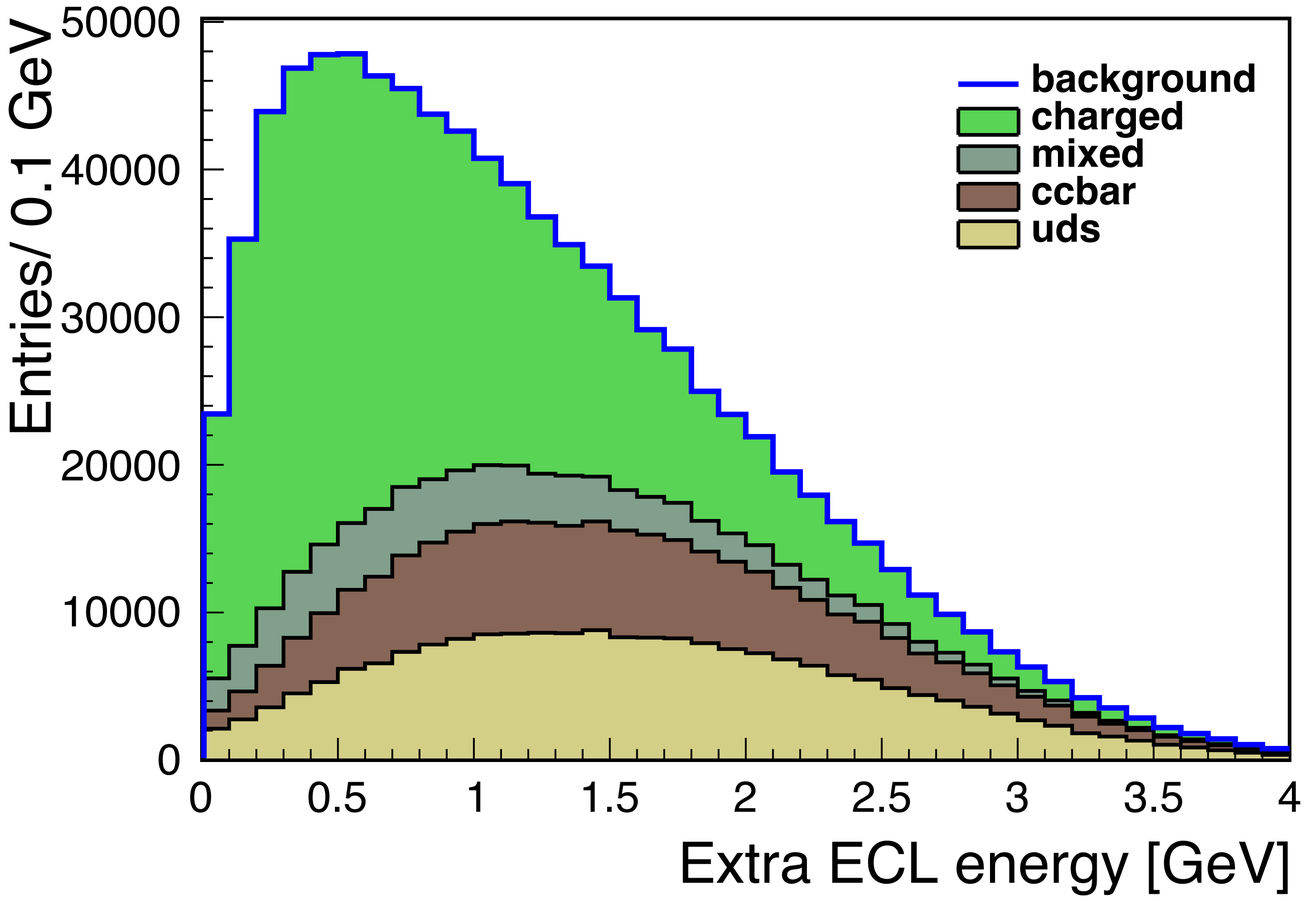
New ROE selection

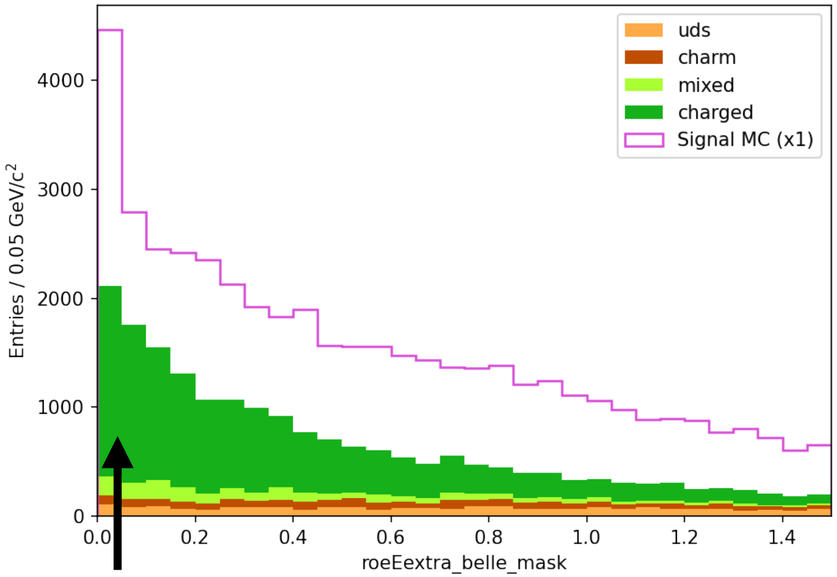
- clusterNHits > 1.5
- $E > 0.080$ in forward
- $E > 0.030$ in barrel
- $E > 0.060$ in backward
- $|\text{cluster time}| < 200$
- minC2TDist > 20
- $\left|\frac{\text{cluster time}}{\text{clusterErrorTiming}}\right| < 2.0$

Extra ECL energy (E_{ECL})

signal=> signalMC

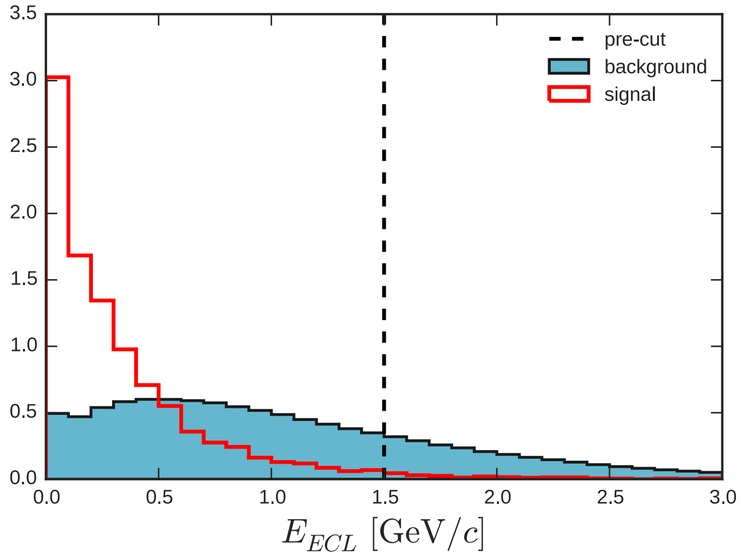
background=> genericMC (MC15rib, $400\,fb^{-1}$)





Vidya

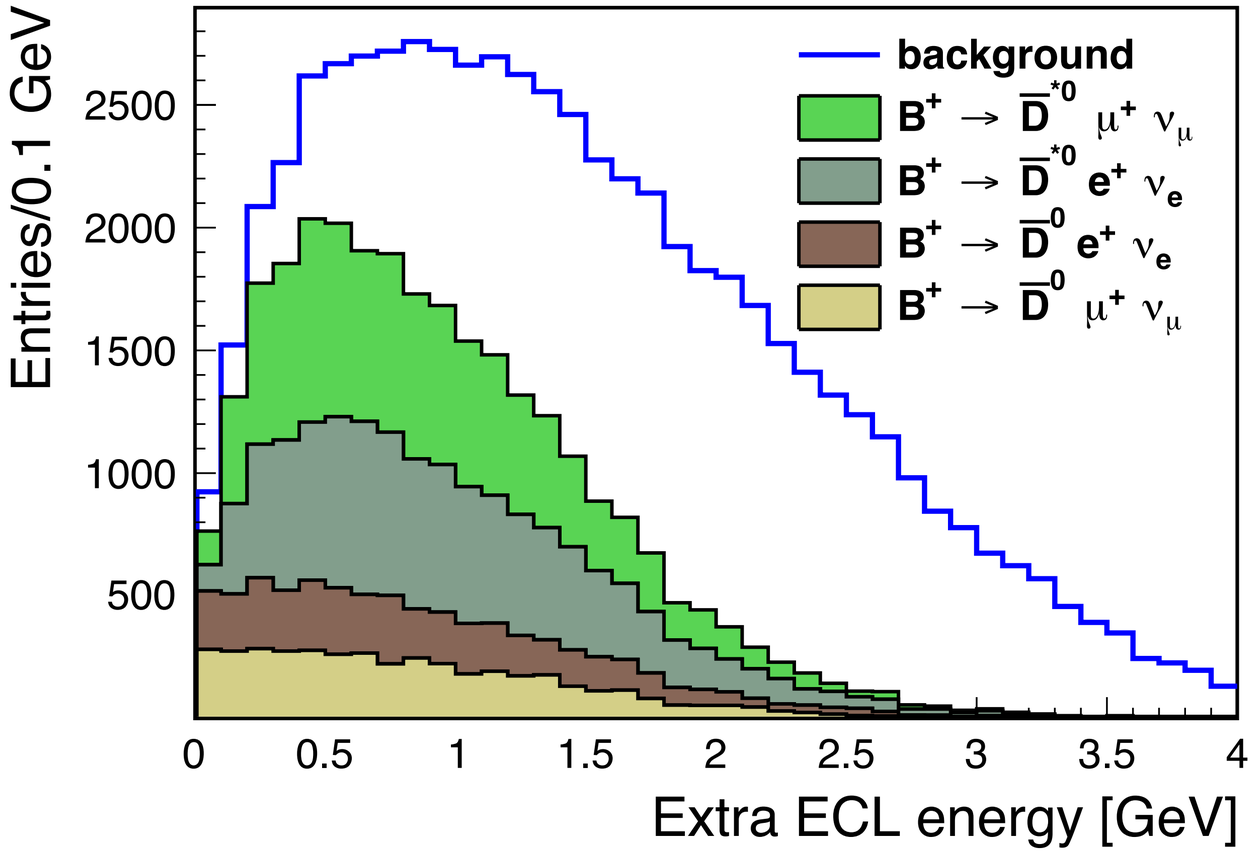
background plot don't match



Simon

Charged mode

background=> generic charged MC (MC15rib, $400\,fb^{-1}$)



rowNo	decay branch of B^+	iDcyBrP	nCase	nCcCase	nAllCase	nCCase
1	$B^+ \to \mu^+\nu_\mu\bar{D}^{*0}$	21	93018	94246	187264	187264
2	$B^+ \to e^+\nu_e\bar{D}^{*0}$	4	89973	90344	180317	367581
3	$B^+ \to \rho^+\bar{D}^0$	59	84825	84628	169453	537034
4	$B^+ \to \bar{D}^{*0}a_1^+$	3	81276	81101	162377	699411
5	$B^+ \to \pi^0\pi^+\pi^+D^{*-}$	16	50887	52375	103262	802673
6	$B^+ \to \pi^0\pi^+\pi^+\pi^-\bar{D}^{*0}$	20	49553	49043	98596	901269
7	$B^+ \to \rho^+\bar{D}^{*0}$	14	47935	47970	95905	997174
8	$B^+ \to \pi^+\bar{D}^0$	15	42432	42146	84578	1081752
9	$B^+ \to \mu^+\nu_\mu\bar{D}^0$	10			77916	1159668
10	$B^+ \to \pi^+\pi^+\pi^-\bar{D}^0$	11				1234534
11	$B^+ \to e^+\nu_e\bar{D}^0$	2				
12	$B^+ \to \pi^+\bar{D}^{*0}$	43				
13	$B^+ \to \rho^0\pi^+\bar{D}^0$	106				
14	$B^+ \to \bar{D}^0a_1^+$	27	26448			
15	$B^+ \to \bar{D}^{*0}D_s^{*+}$	103	23343	23287		
16	$B^+ \to \bar{D}^{*0}D_{s0}^{*+}$	31	21142	21111	42253	1581261
17	$B^+ \to \tau^+\nu_\tau\bar{D}^{*0}$	137	20953	21085	42038	1623299
18	$B^+ \to \bar{D}^0D_s^+$	12	19178	19241	38419	1661718
19	$B^+ \to \pi^0\rho^+\bar{D}^0$	115	19030	18710	37740	1699458
20	$B^+ \to \pi^+\omega\bar{D}^0$	47	15309	15330	30639	1730097
21	$B^+ \to \rho^+\bar{D}_2^{*0}$	56	14679	14887	29566	1759663
22	$B^+ \to \bar{D}^{*0}D_s^+$	63	14555	14556	29111	1788774
23	$B^+ \to \bar{D}^{*0}D_{s1}^{\prime+}$	70	14327	14226	28553	1817327
24	$B^+ \to \bar{D}^0D_s^{*+}$	9	14221	14329	28550	1845877
25	$B^+ \to \bar{D}^0\bar{p}\Delta^{++}$	66	12789	12658	25447	1871324
26	$B^+ \to \pi^+\omega\bar{D}^{*0}$	50	12312	12230	24542	1895866
27	$B^+ \to K^+D^{*0}\bar{D}^{*0}$	104	11806	11869	23675	1919541
28	$B^+ \to \pi^+\pi^+\pi^-\bar{D}^{*0}$	32	10098	10134	20232	1939773
29	$B^+ \to \bar{D}^0D_{s0}^{*+}$	173	9992	10158	20150	1959923
30	$B^+ \to \tau^+\nu_\tau\bar{D}^0$	122	10022	10109	20131	1980054
31	$B^+ \to \pi^0\pi^0\pi^+\bar{D}^0$	222	10117	9870	19987	2000041
32	$B^+ \to \pi^+\pi^-\rho^+\bar{D}^0$	65	9461	9221	18682	2018723
33	$B^+ \to \mu^+\nu_\mu\bar{D}_1^0$	48	9108	8961	18069	2036792

numbers are incorrect

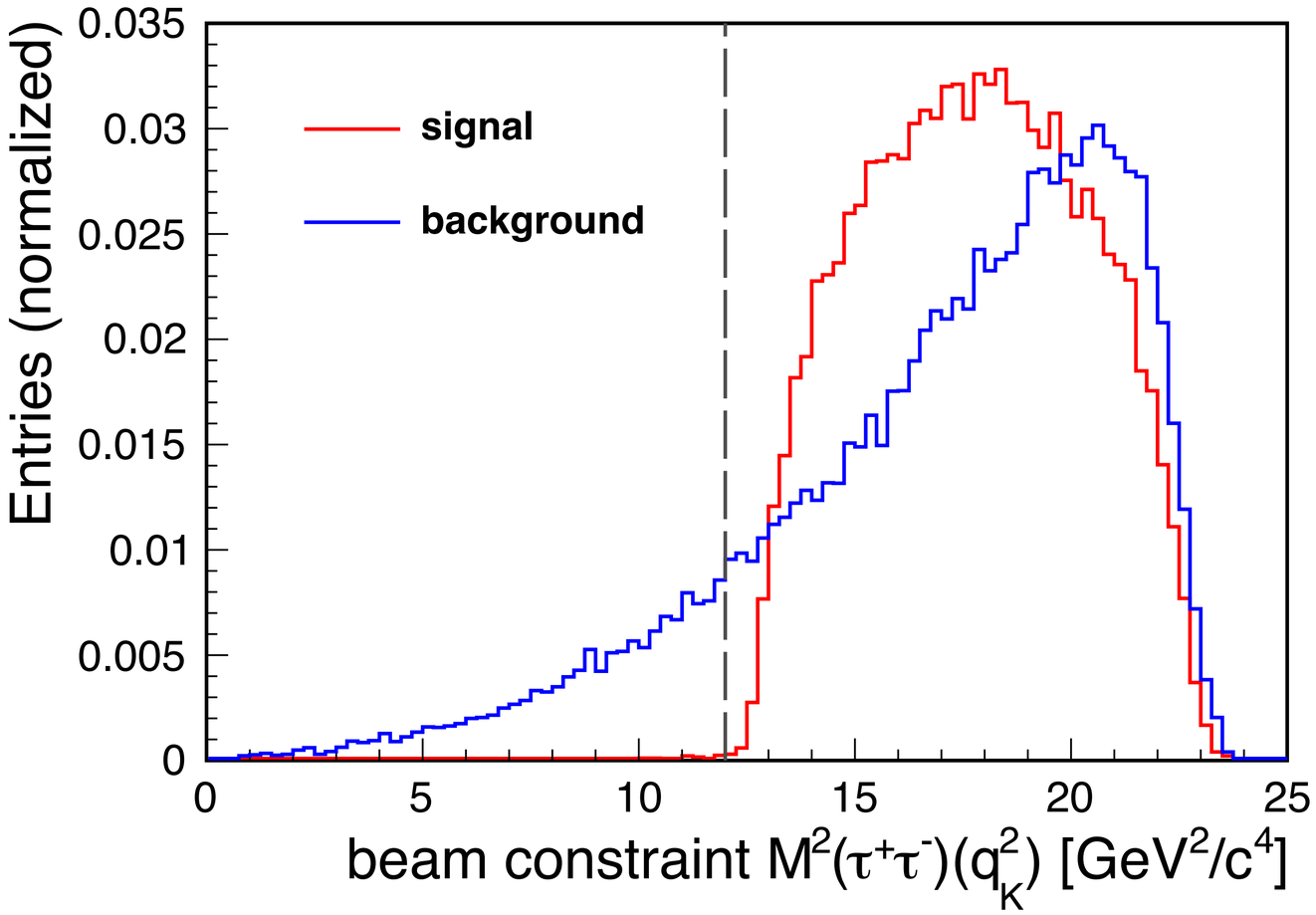
*Decay modes can be in tag or signal sides

q_K^2

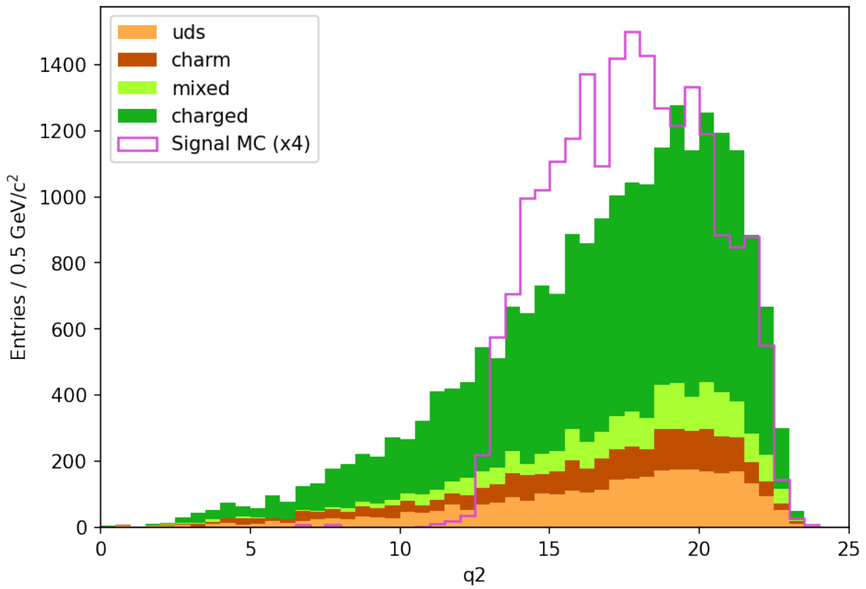
$$q_K^2 \equiv (p_{\Upsilon(4S)} - p_{B_{tag}} - p_K)^2$$

signal=> signalMC

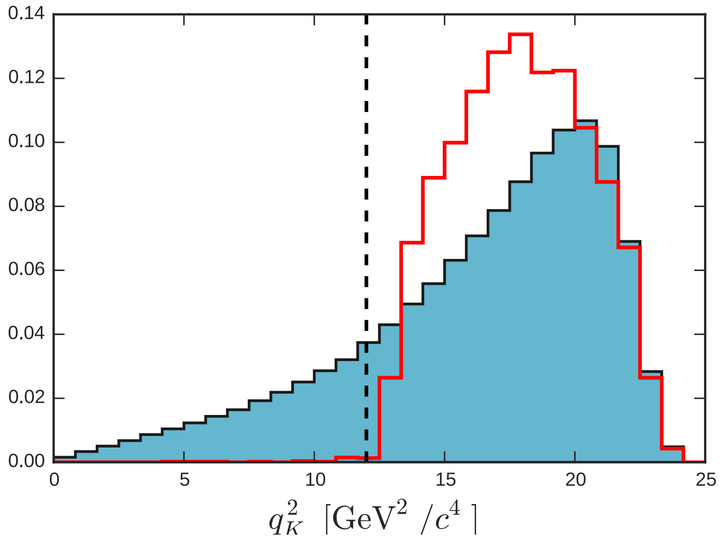
background=> genericMC (MC15rib, $400\,fb^{-1}$)



Vidya



Simon

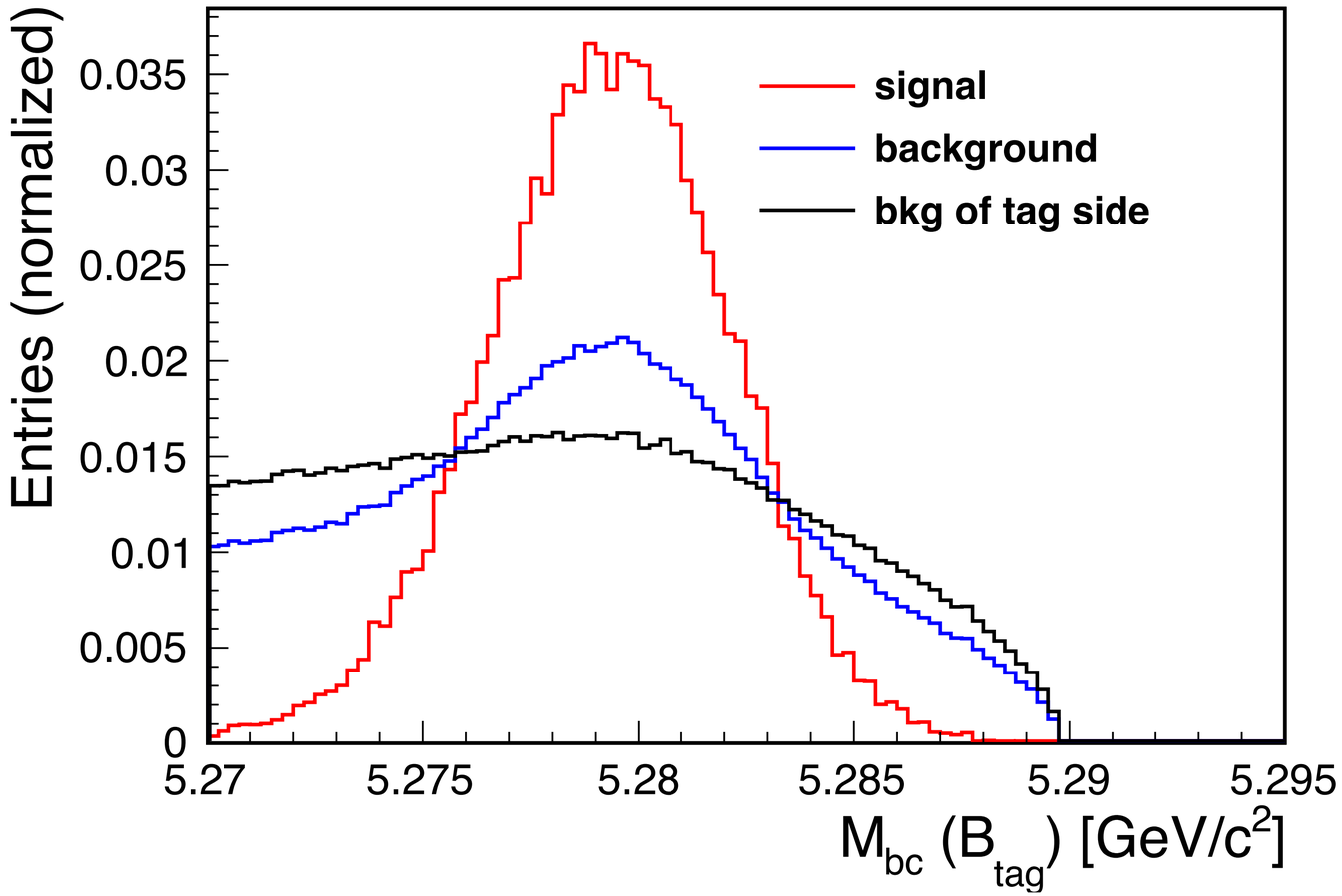


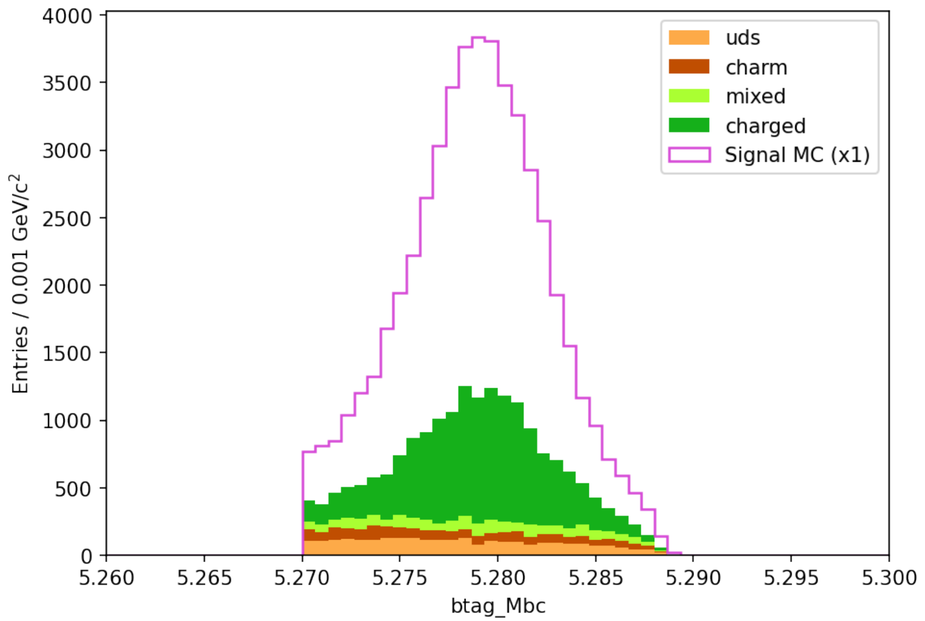
cut	Loss in signal	Loss in bkg
$q_K^2 > 12$	0.14%	13.29%

Tag side M_{bc}

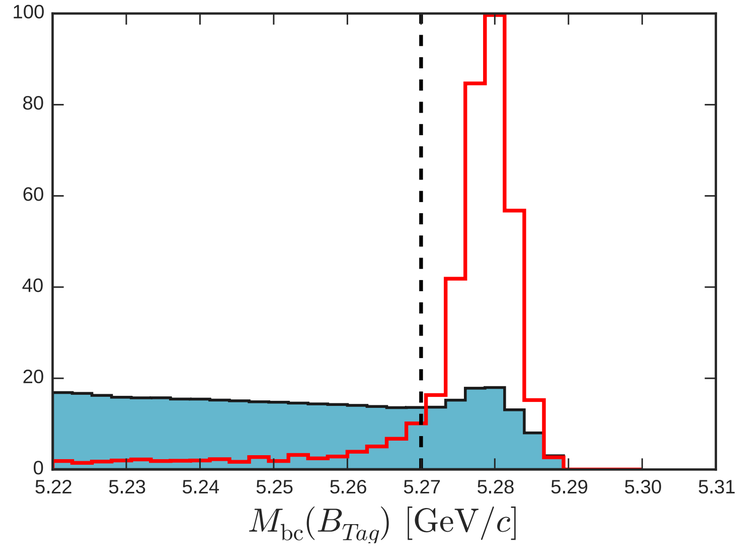
signal=> signalMC

background=> genericMC (MC15rib, $400\,fb^{-1}$)





Vidya



Simon

Signal efficiency

with some additional cuts same as Vidya's,

- $q_K^2 > 12$
- $E_{\mathrm{ECL}} < 0.2$
- $p(l_1) < 1.5$
- $M(K^+\tau^-) < 1.8$ or $\mathrm{M}(\mathrm{K}^+\tau^-) > 1.9$

Truth-match:

signal efficiency $= 2.783 \times 10^{-4}$

Signal + self-cross feed:

Efficiency $= 5.00 \times 10^{-4}$

Efficiency $= 6.96 \times 10^{-4}$ Vidya's

BDT input variables

Simon's list

$\mathcal{NB}(B_{tag})$: The NeuroBayes output of the B_{tag} candidate.

$M_{K^+\tau^-}$: Invariant mass of the K^+ and charged daughter of the τ^-.

$\hat{p}_{\tau^+}$: The momentum of the positively charged τ in the rest frame of the signal B candidate.

decay channel : Decay hash value corresponding to the six possibilities for the mass hypotheses of the charged children of the τ pair ($ee, e\mu, e\pi, \mu\mu, \mu\pi$ and $\pi\pi$).

$\mathcal{NB}(\tau^+ \times \tau^-)$: The product of the NeuroBayes outputs of the children of both τ.

ΔE^{tag} : The beam constrained energy of the B_{tag} candidate.

q^2 : The constrained invariant mass of the τ pair, defined as

$$q^2 \equiv (\vec{p}_{(\Upsilon(4S))} - \vec{p}_{B_{tag}} - \vec{p}_{K^+})^2, \tag{2.1}$$

where $\vec{p}_{(\Upsilon(4S))}$ is the momentum of the $\Upsilon(4S)$, $\vec{p}_{tag}$ the momentum of the B_{tag} and $\vec{p}_K$ the momentum of the $K^\pm$.

$M_{\tau^+\tau^-}$: The reconstructed invariant mass of the τ pair.

M_{bc}^{tag} : The beam constrained mass of the B_{tag} candidate.

$\theta_{\tau^-}^{hel}$: The pseudo helicity angle of the τ^-.

$\sigma(d_{B_{tag}})$: The significance of the distance to the B_{tag} candidate, derived from the error of the vertex fit.

χ^2 : χ^2 value of the vertex fit of the candidate.

d_{IP} : Distance of the candidate to the interaction point.

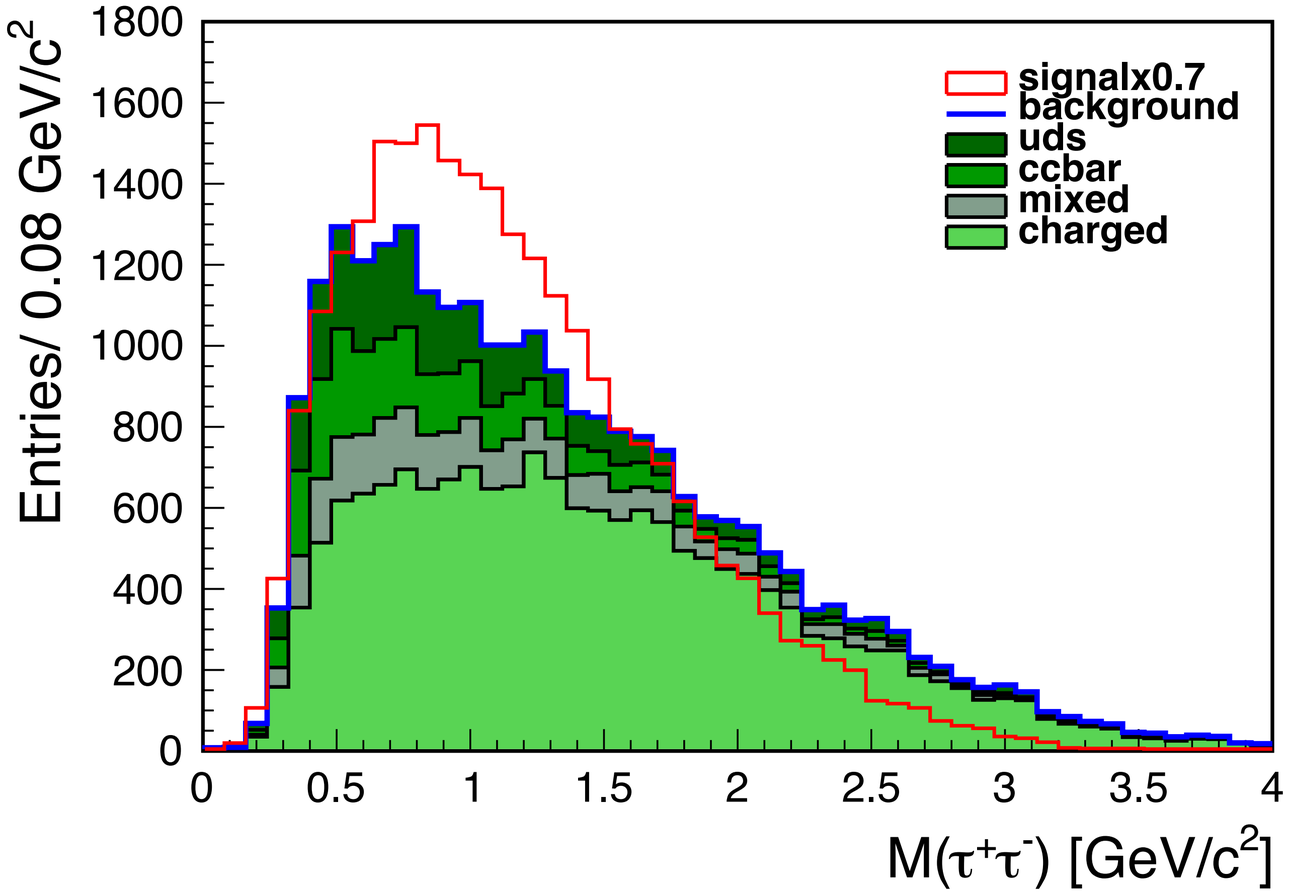
Q : Defined as the reconstructed mass of the B candidate subtracted by the reconstructed mass of the children: $Q \equiv M_B - M_{K^+} - M_{\tau^+} - M_{\tau^-}$.

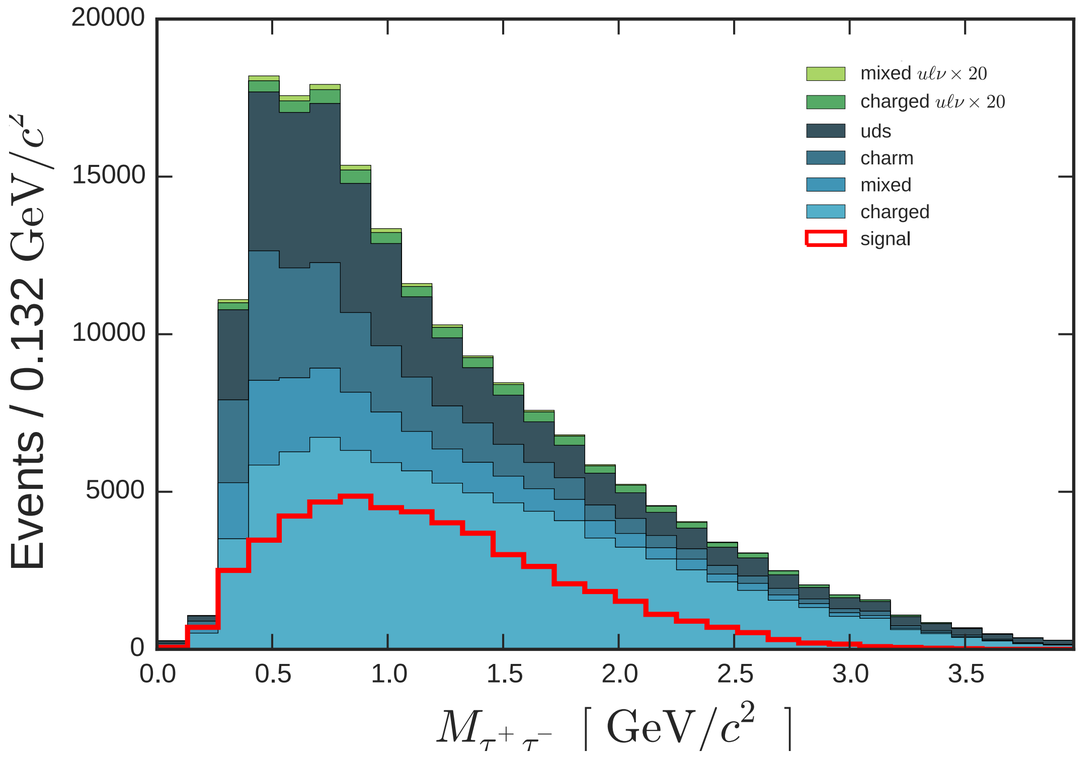
let's look at their distribution after pre-selections

Tau pair mass $M(\tau^+\tau^-)$

signal=> signalMC

background=> genericMC (MC15rib,$400\,fb^{-1}$)





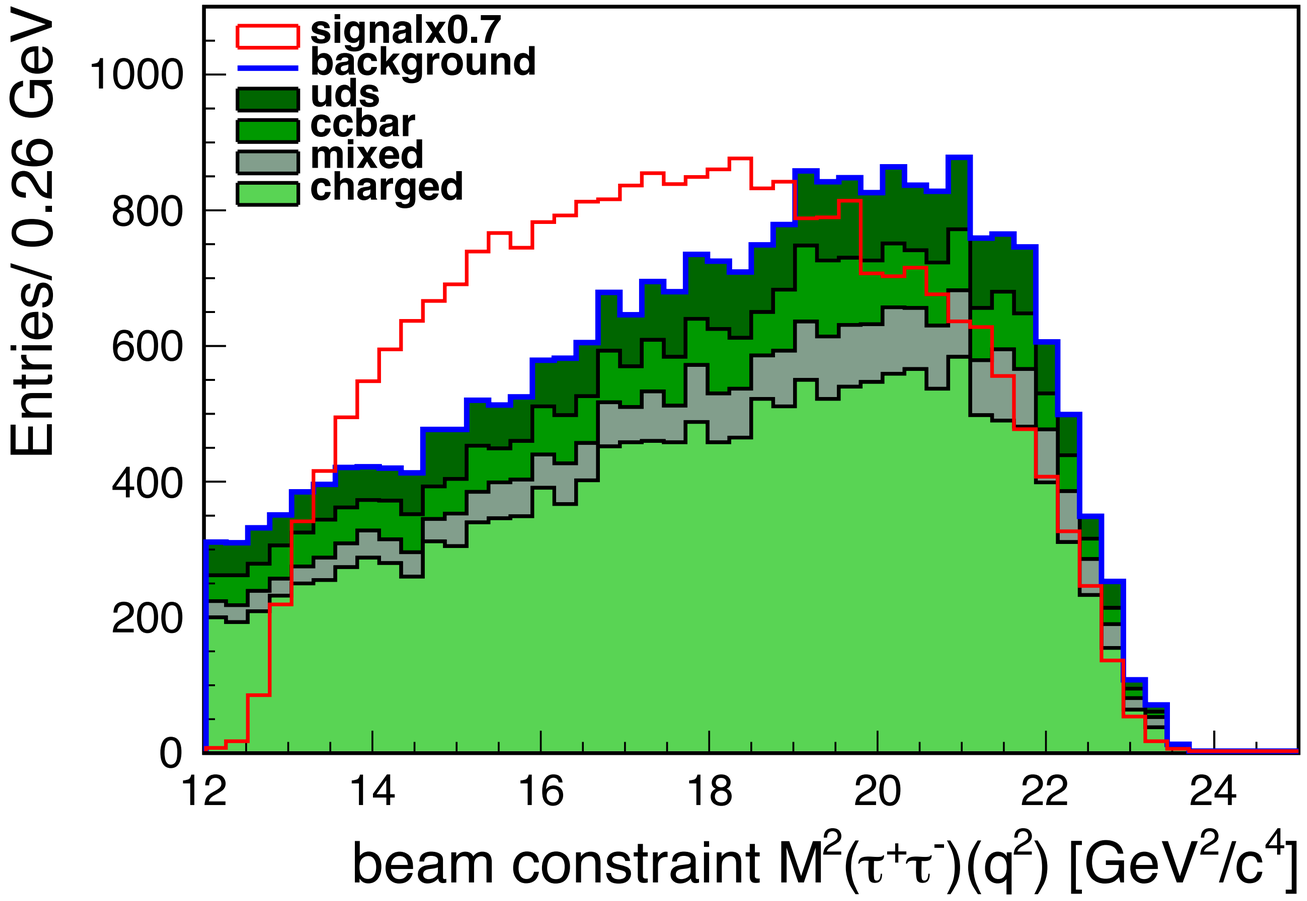
Simon

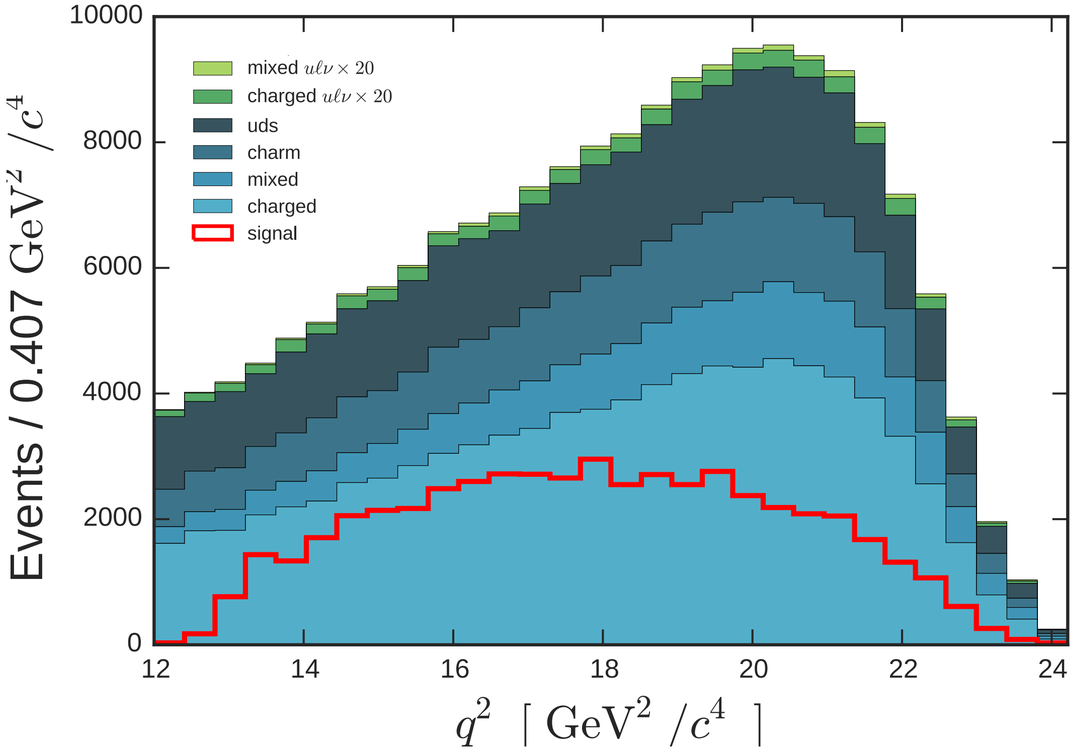
q^2

$$q^2 \equiv (p_{\Upsilon(4S)} - p_{B_{tag}} - p_K)^2$$

signal=> signalMC

background=> genericMC (MC15rib, $400\,fb^{-1}$)



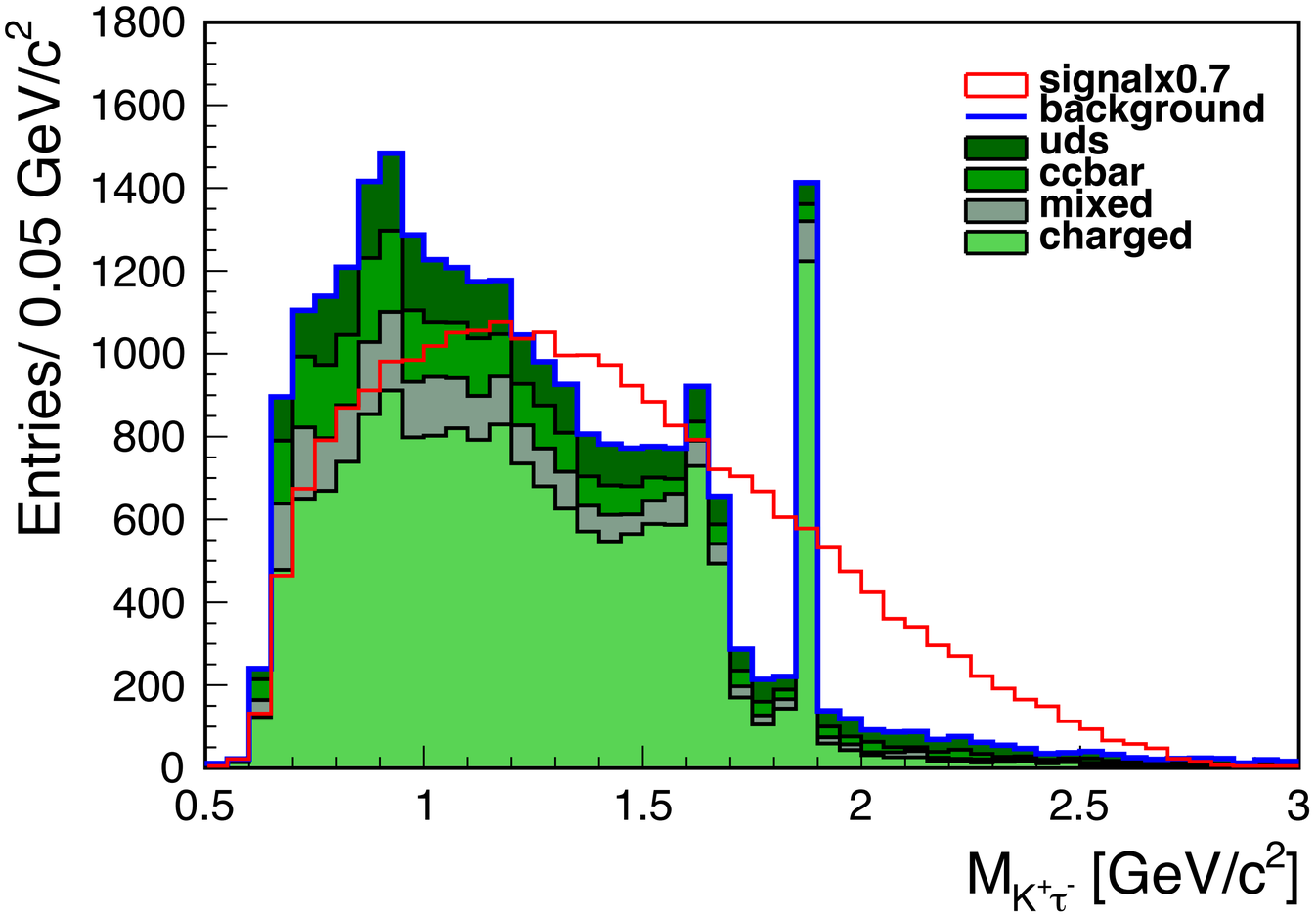


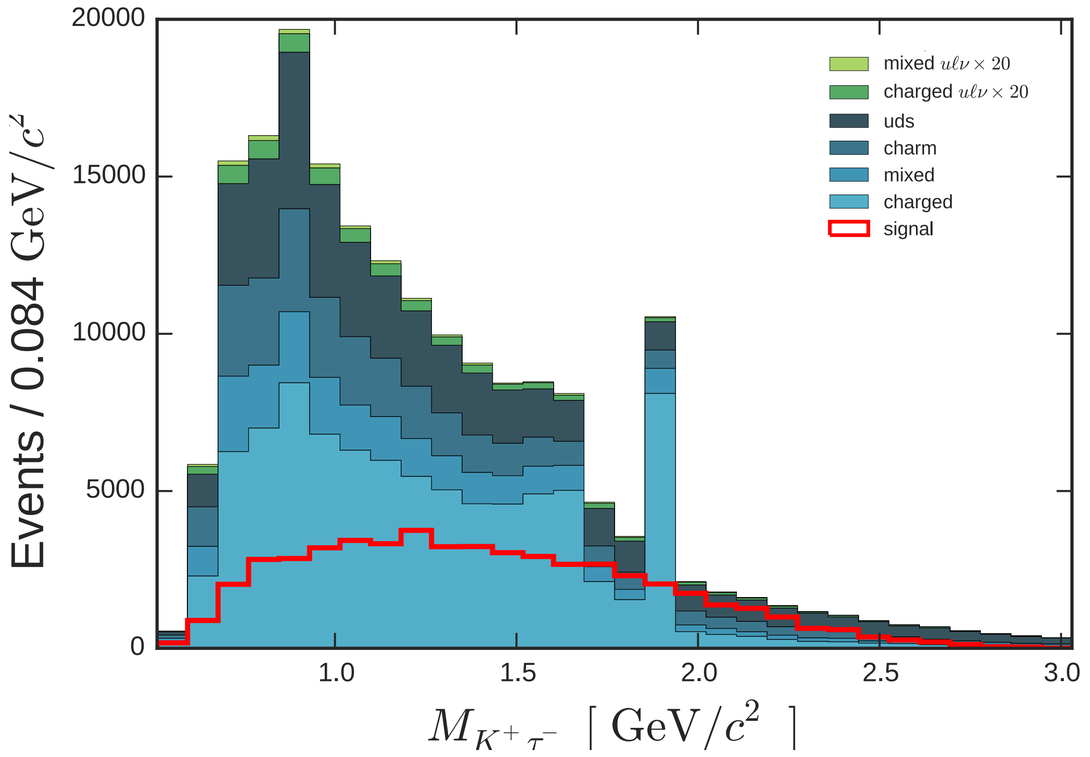
Simon

$M(K^+\tau^-)$

signal=> signalMC

background=> genericMC (MC15rib, $400\,fb^{-1}$)





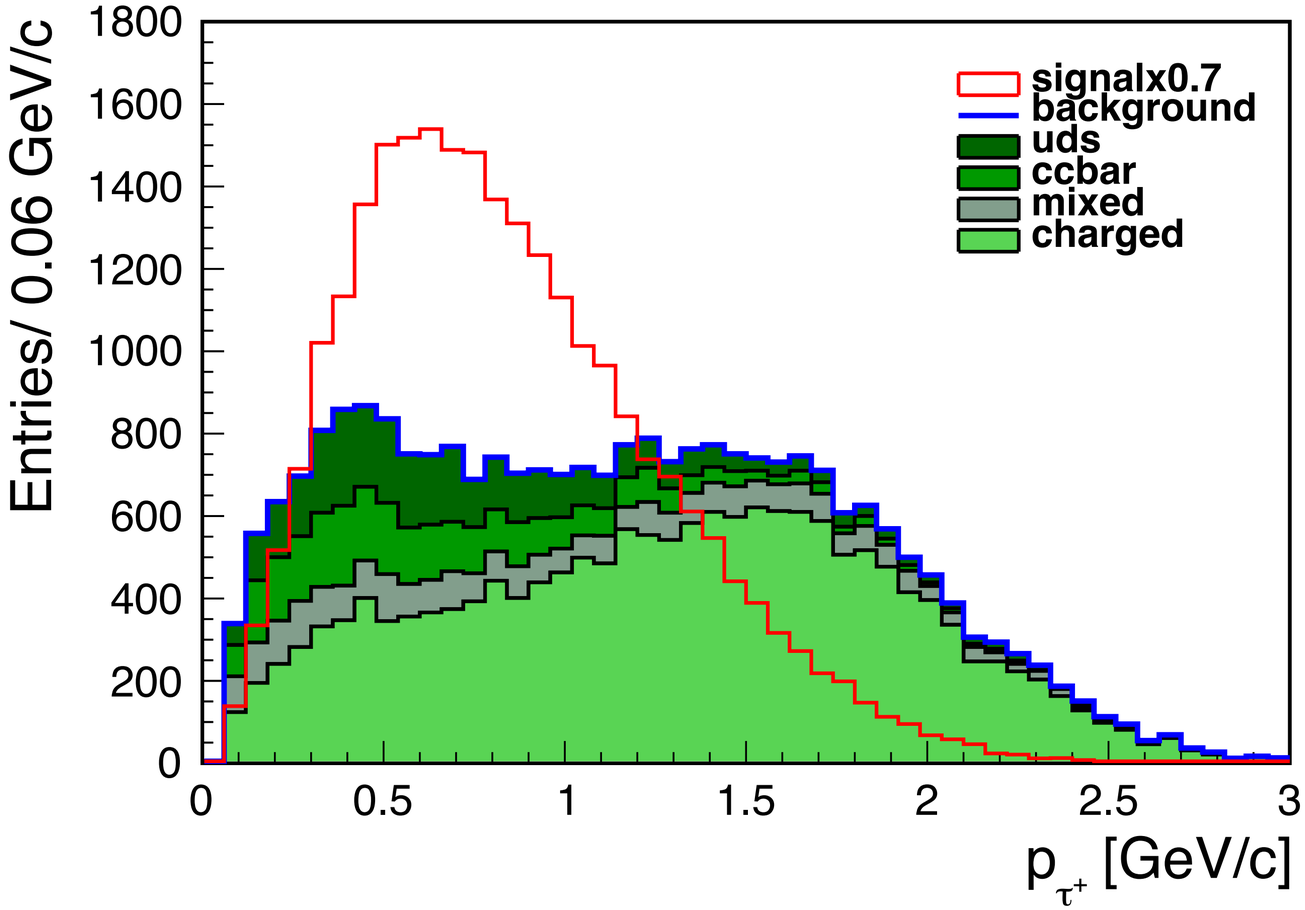
Simon

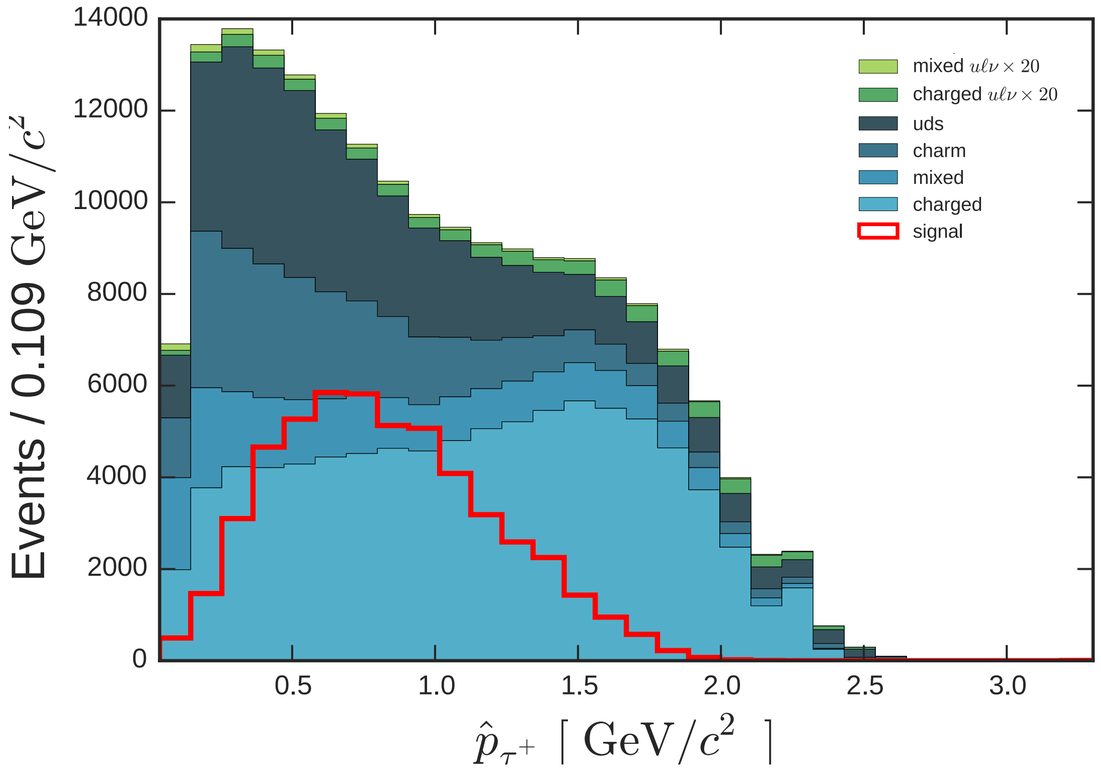
D and D^* peak at $1.8 \sim 1.9\,\mathrm{GeV/c^2}$ ⟶ remove that part

$p(\tau^+)$

signal=> signalMC

background=> genericMC (MC15rib,$400\,fb^{-1}$)



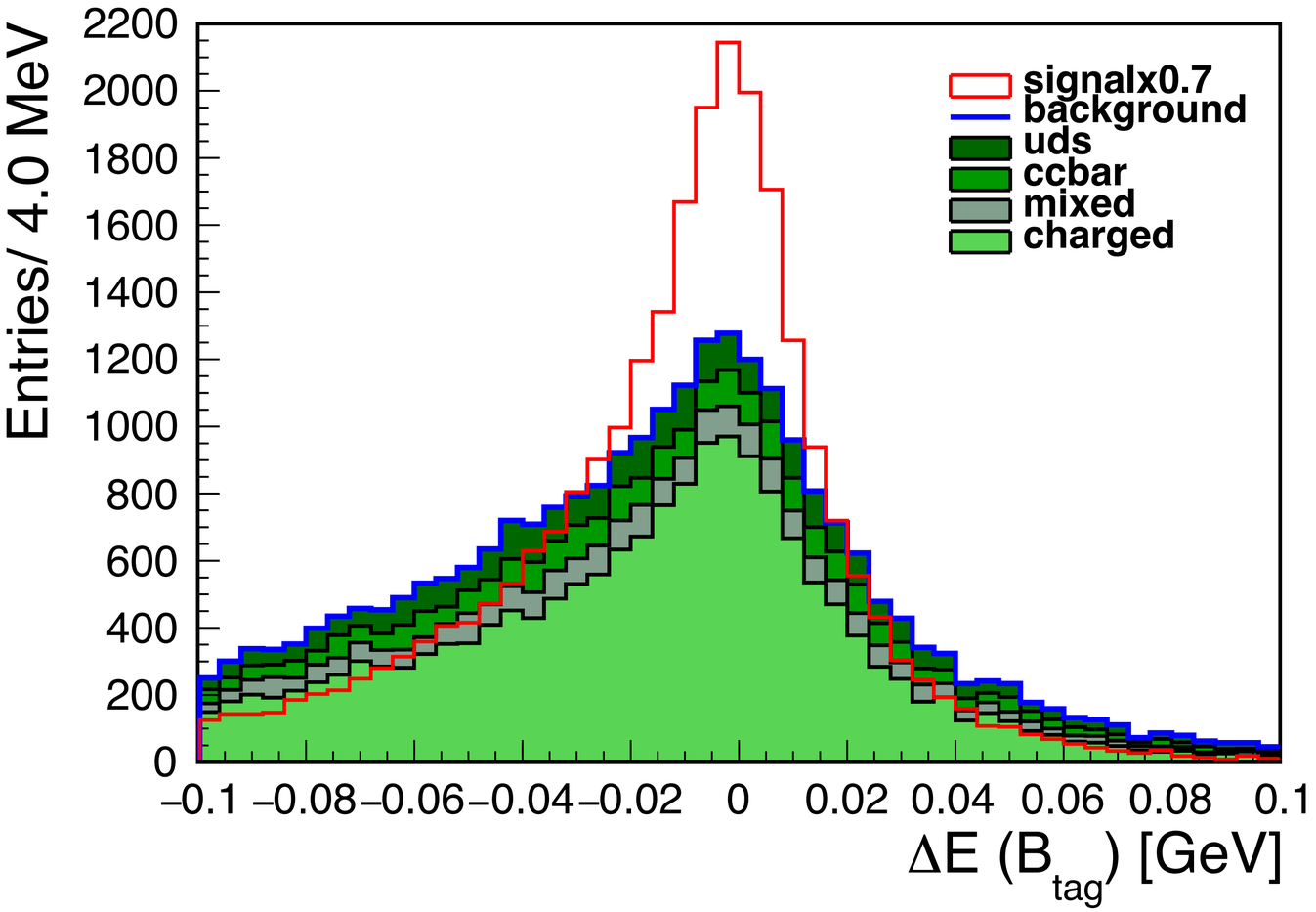


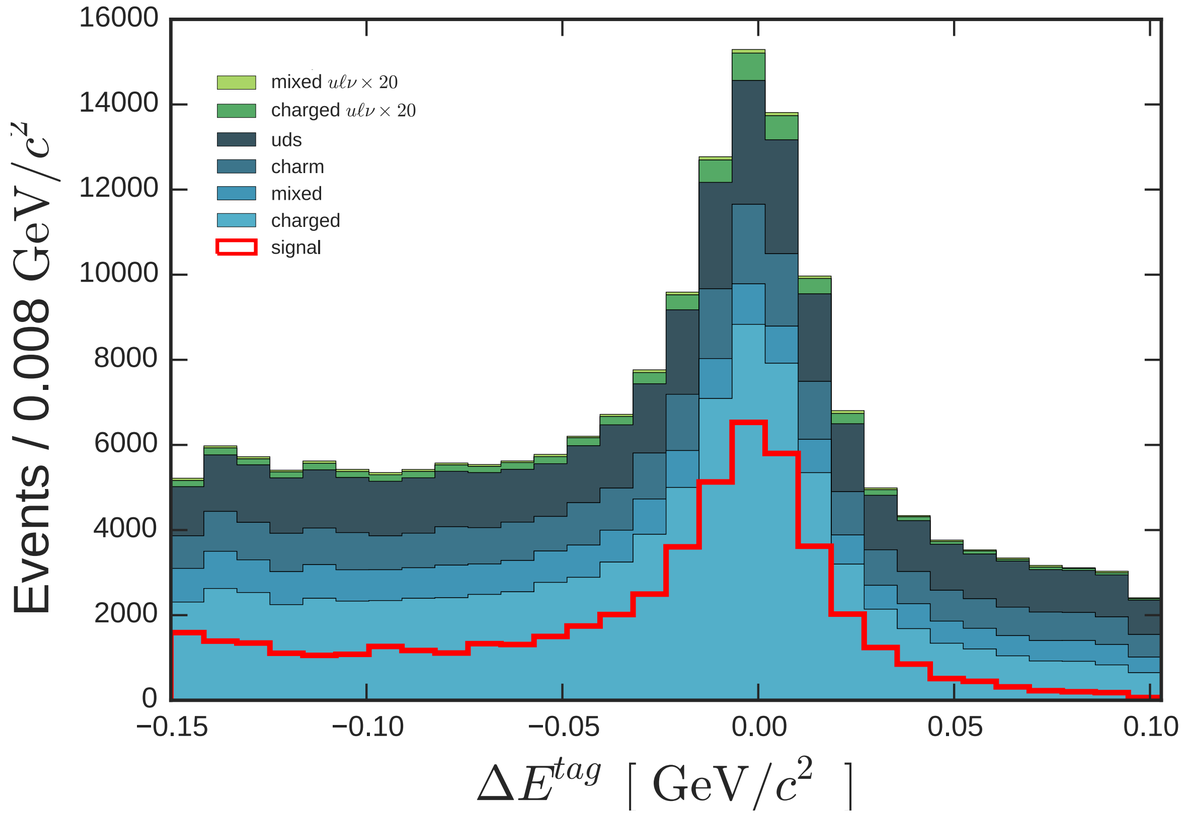
Simon

$\Delta E\,(B_{\mathrm{tag}})$

signal=> signalMC

background=> genericMC (MC15rib,$400\,fb^{-1}$)



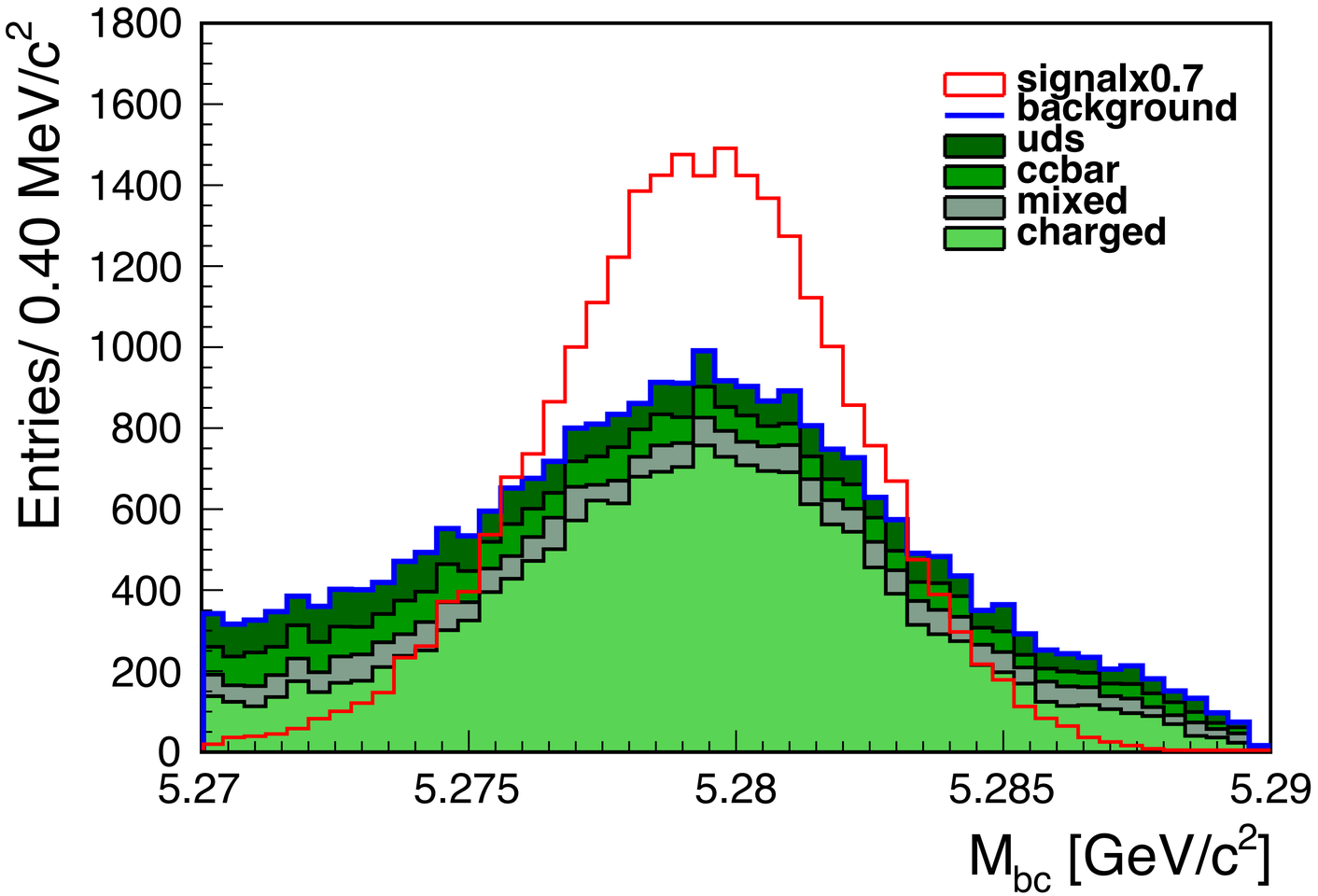


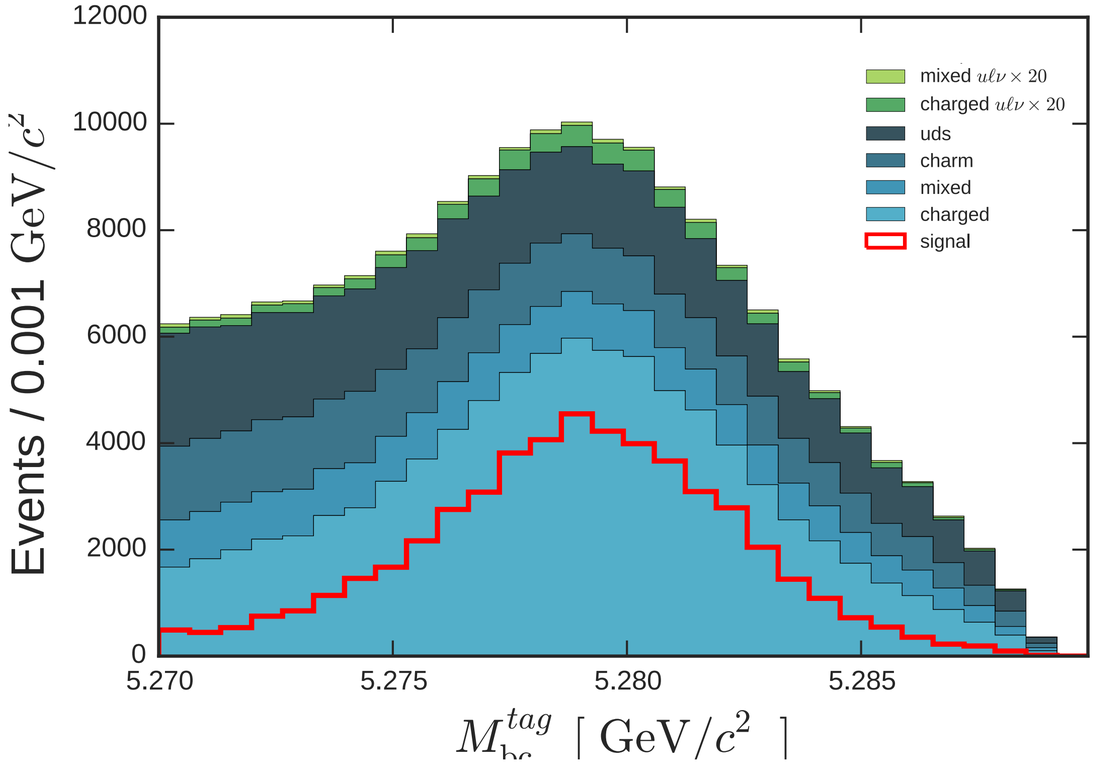
Simon

$M_{\mathrm{bc}}\,(B_{\mathrm{tag}})$

signal=> signalMC

background=> genericMC (MC15rib,$400\,fb^{-1}$)





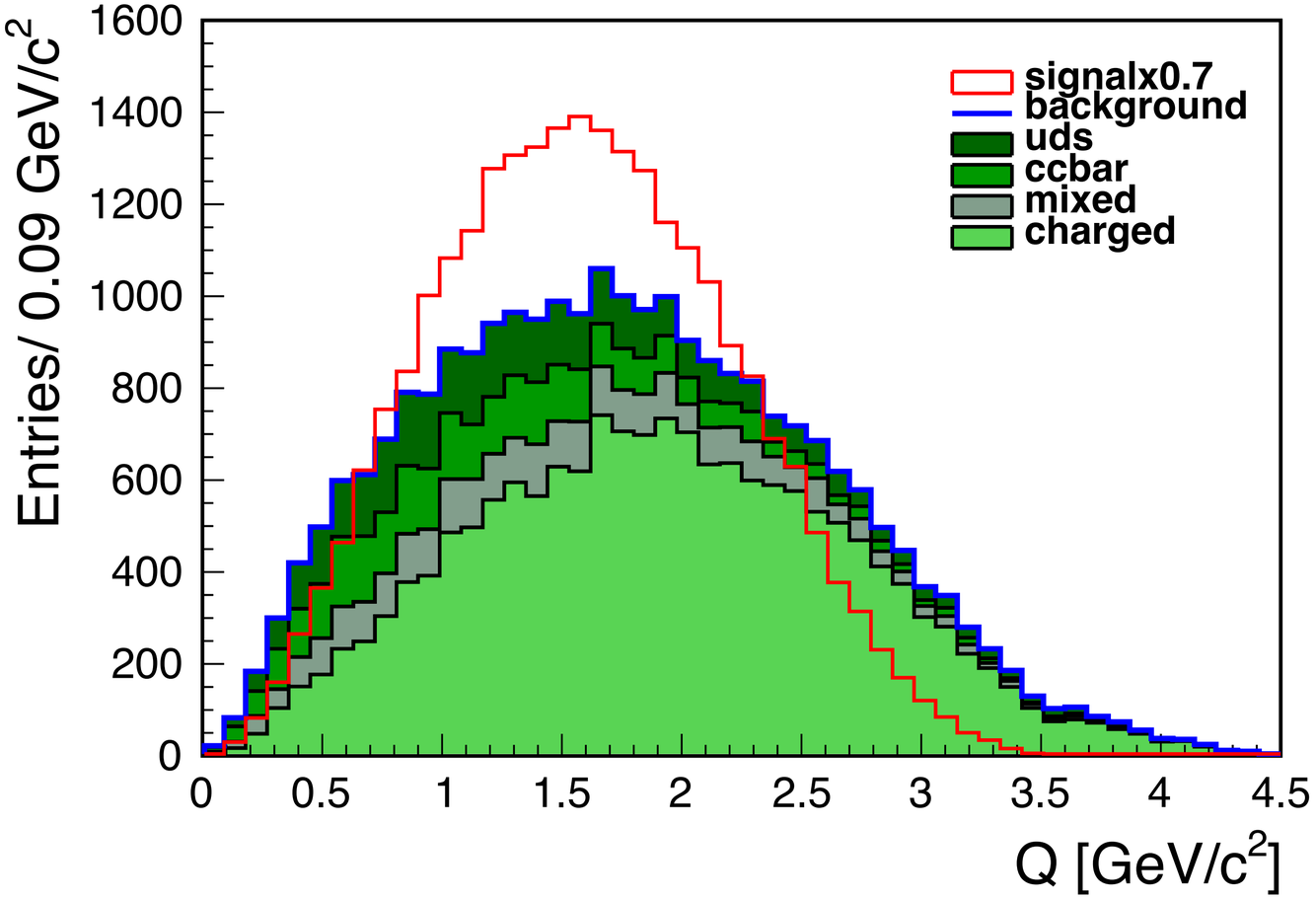
Simon

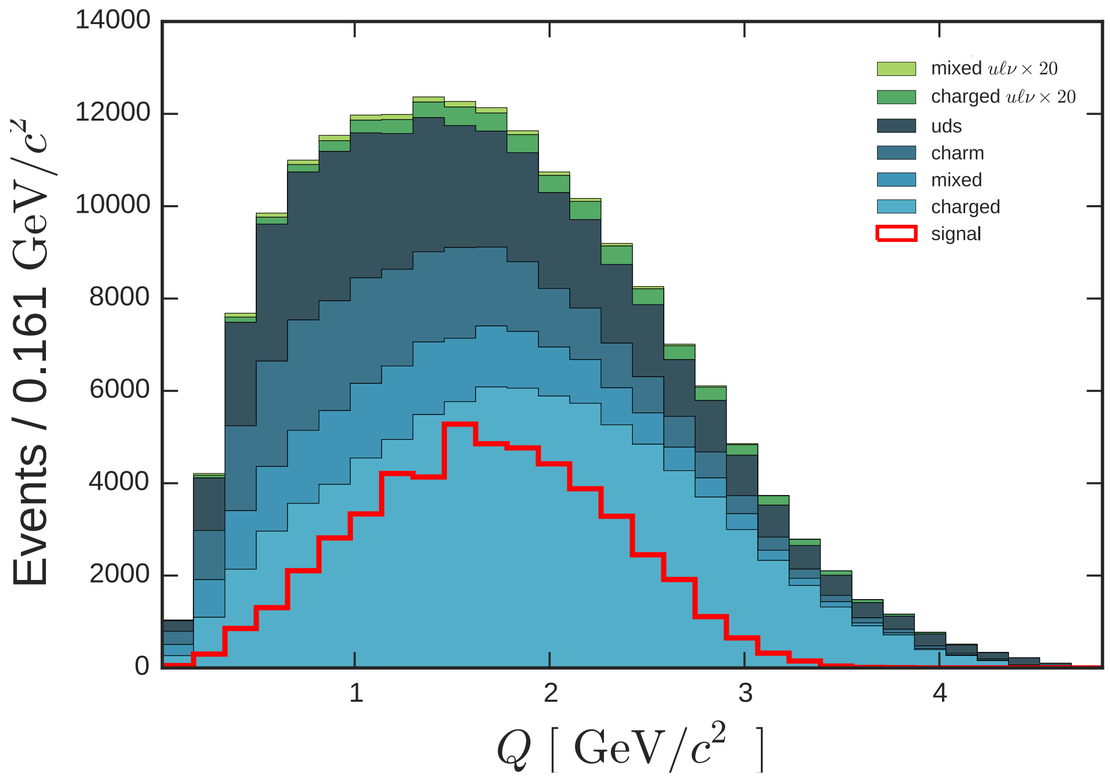
Q

$$Q \equiv M_{B^+_{\text{sig}}} - M_{K^+} - M_{\tau^+} - M_{\tau^-}$$

signal=> signalMC

background=> genericMC (MC15rib, $400\,fb^{-1}$)





Simon

Control channel

$B^+ \to J/\psi K^+$ using hadronic FEI

Sample and selections

GenericMC:

- Generated events: MC15rib ($400\,fb^{-1}$)

Data:

- Proc 13 + Moriond2023_prompt (exp 20-26)
  Luminosity = $364.35\,fb^{-1}$

Global tag:

- analysis_tools_light-2205-abys
- data_beam_conditions_proc13prompt (data)

Charged tracks (e, μ, K, π) cuts:

- transverse distance from IP, $dr < 0.5$
- distance in beam direction from IP, $|dz| < 2$
- polar angle is with in CDC acceptance (thetaInCDCAcceptance)
- Kaon binary PID, $\mathscr{L}(K/\pi) > 0.6$
- Electron PID, $\mathscr{L}(e) > 0.9$
- Muon PID, $\mathscr{L}(\mu) > 0.9$

J/ψ mass window cut:

- $2.90 < M(l^+l^-) < 3.15\,\mathrm{GeV/c^2}$

Only difference compare to signal sample reconstruction

Sample and selections

Reconstruct FEI hadronic B_{tag}:

- weight file prefix - 'FEIv4_2022_MC15_light-2205-abys'
- Two most probable B_{tag} candidates are accepted
- $M_{bc} > 5.27$
- $|\Delta E| < 0.1$
- FEI signal probability > 0.001
- ROE of B_{tag} has 3 charged tracks

Continuum suppression:

- event sphericity > 0.2
- cosTBTO < 0.9

ROE mask:

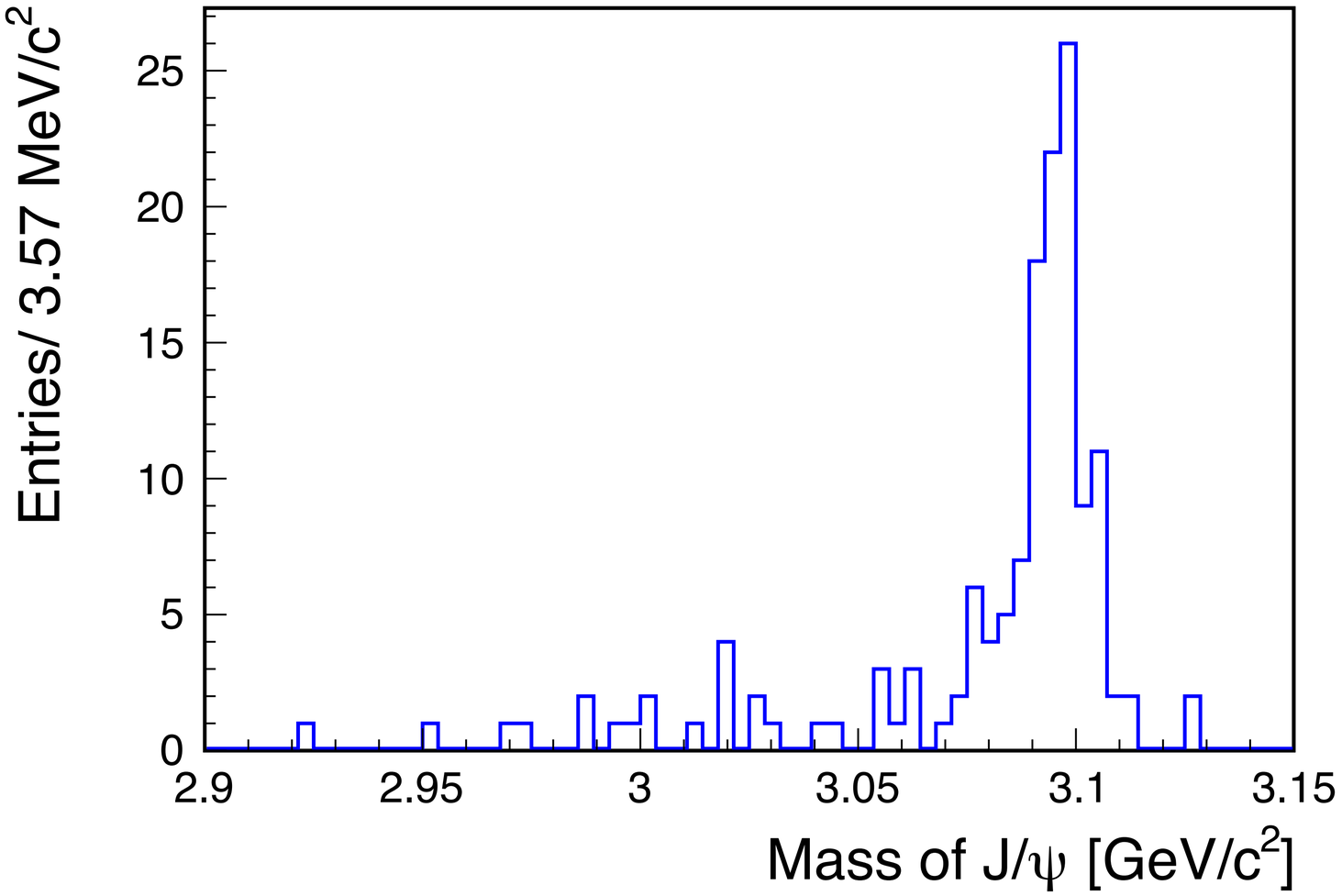
- $dr < 0.5, |dz| < 2$, thetaInCDCAcceptance
- clusterNHits > 1.5
- $E > 0.080$ in forward
- $E > 0.030$ in barrel
- $E > 0.060$ in backward
- $|\text{cluster time}| < 200$
- minC2TDist > 20
- $\left|\frac{\text{cluster time}}{\text{clusterErrorTiming}}\right| < 2.0$

π^0 veto:

- Cut on ROE π^0: $120 < \mathrm{M} < 150\,\mathrm{MeV/c^2}$
- Select one π^0 per event that has the nearest mass to the PDG mass

Control signal

MC



Truth match signal events after:

1. π^0 veto
2. Particle ID cuts
3. Extra ECL cut ($< 1.5\,\mathrm{Gev}$)

No. of events in $364.35\,fb^{-1}$: 131

only $J/\psi \to \mu^+\mu^-$ mode: 77

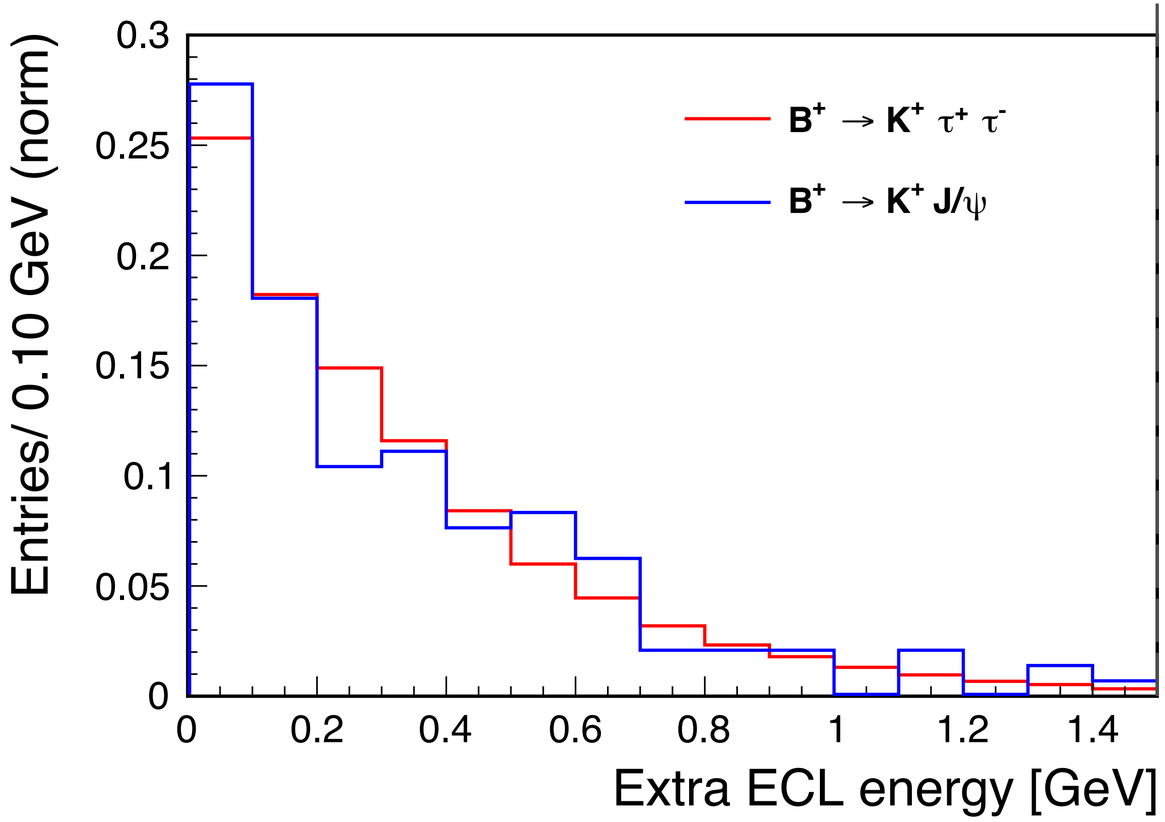
only $J/\psi \to e^+e^-$ mode: 53

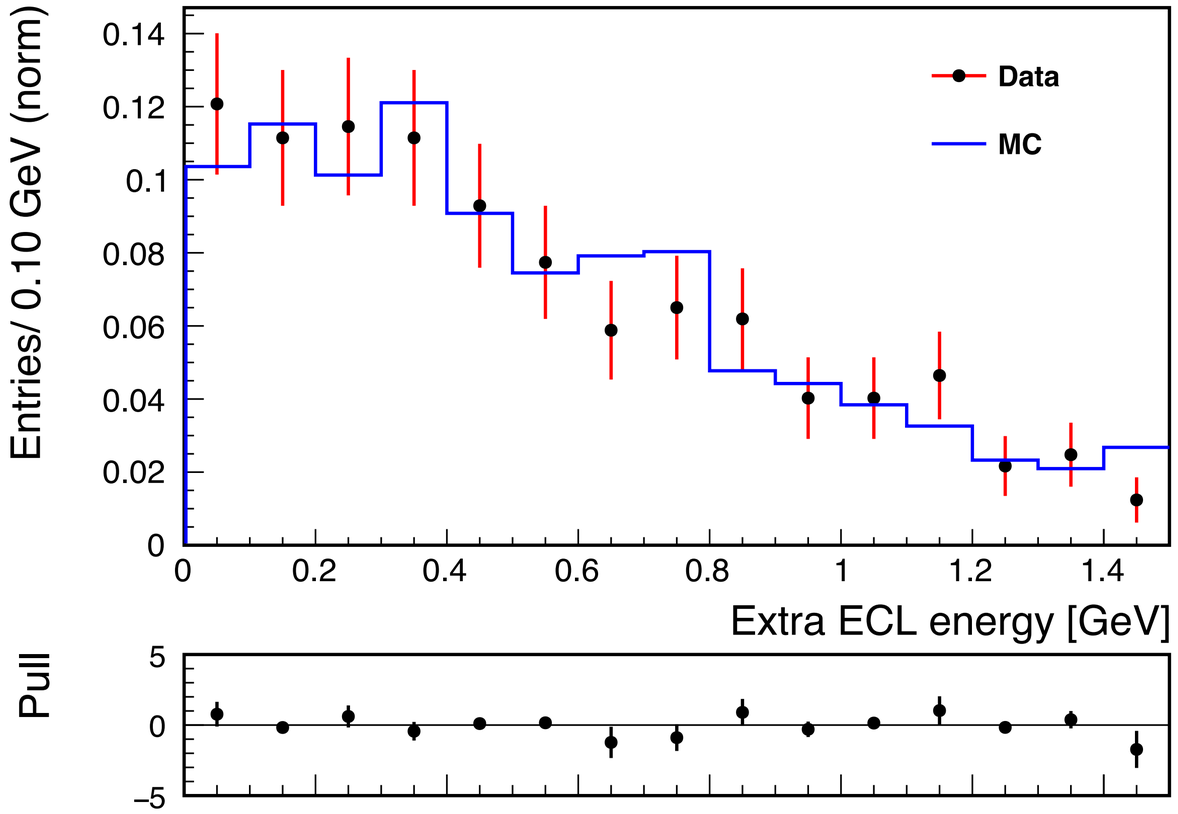
Truth match flag: Signal side (topoana) and tag side (btag_isSignal=1)

Extra ECL energy (E_{ECL})

Pre-selection cut:

Extra ECL $< 1.5\,\mathrm{GeV}$

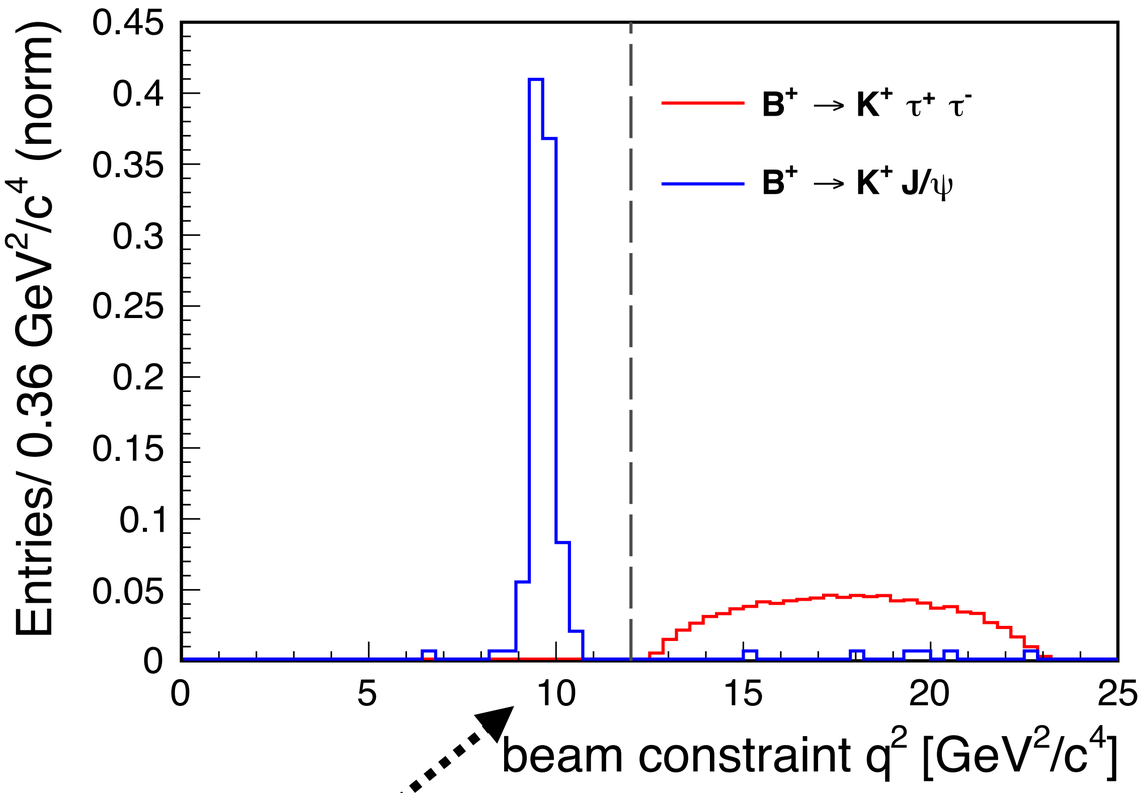


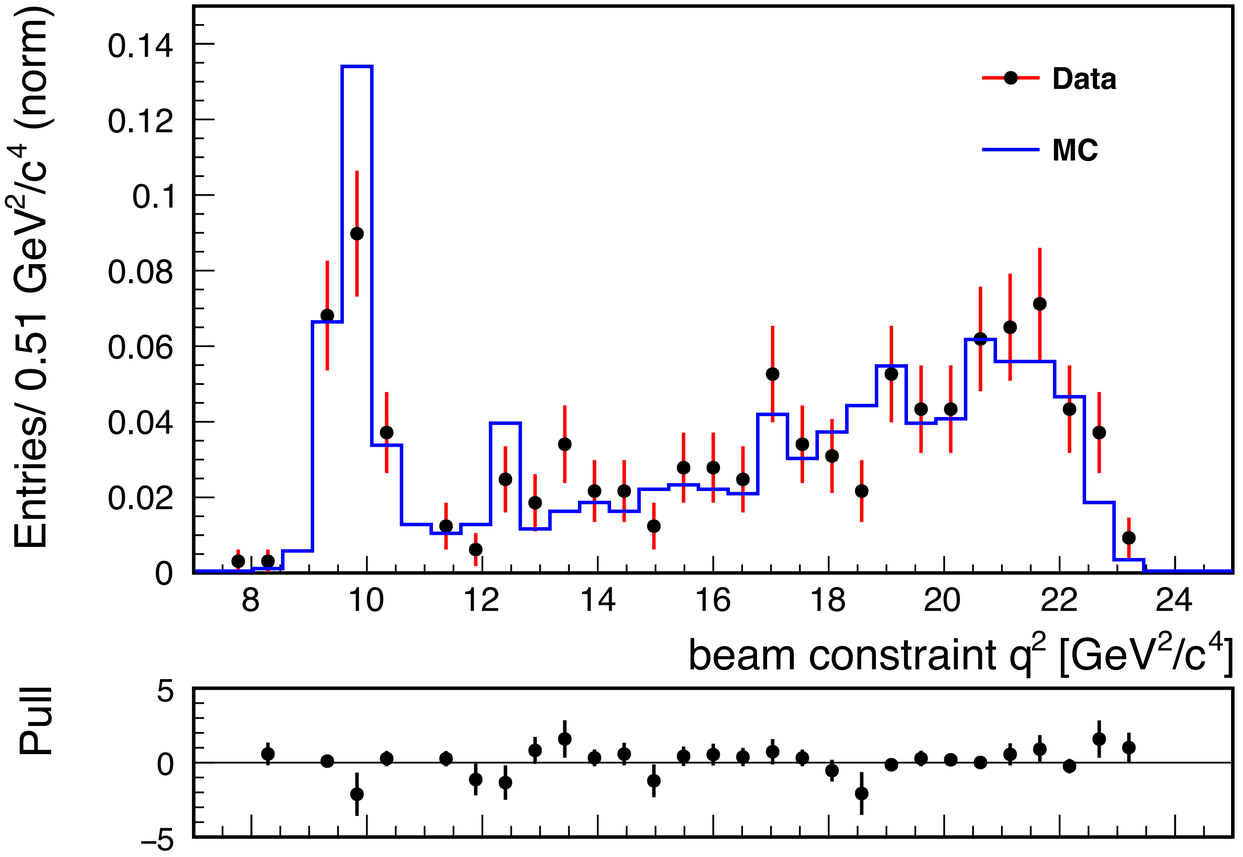


$$\mathrm{Pull} = \frac{\mathrm{data} - \mathrm{MC}}{\sqrt{\sigma^2_{data} + \sigma^2_{MC}}}$$

Beam constraint q^2

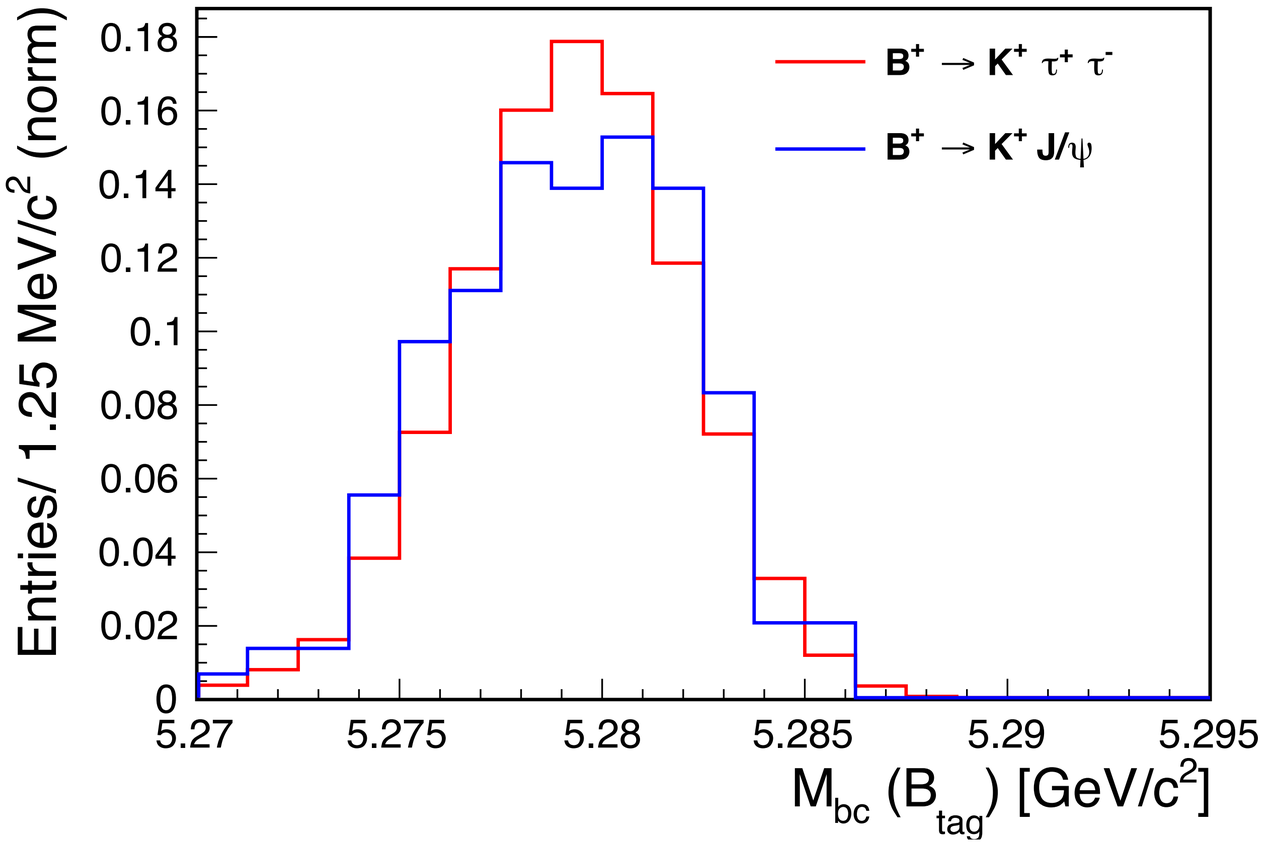
$$q^2 \equiv (p_{\Upsilon(4S)} - p_{B_{tag}} - p_K)^2$$

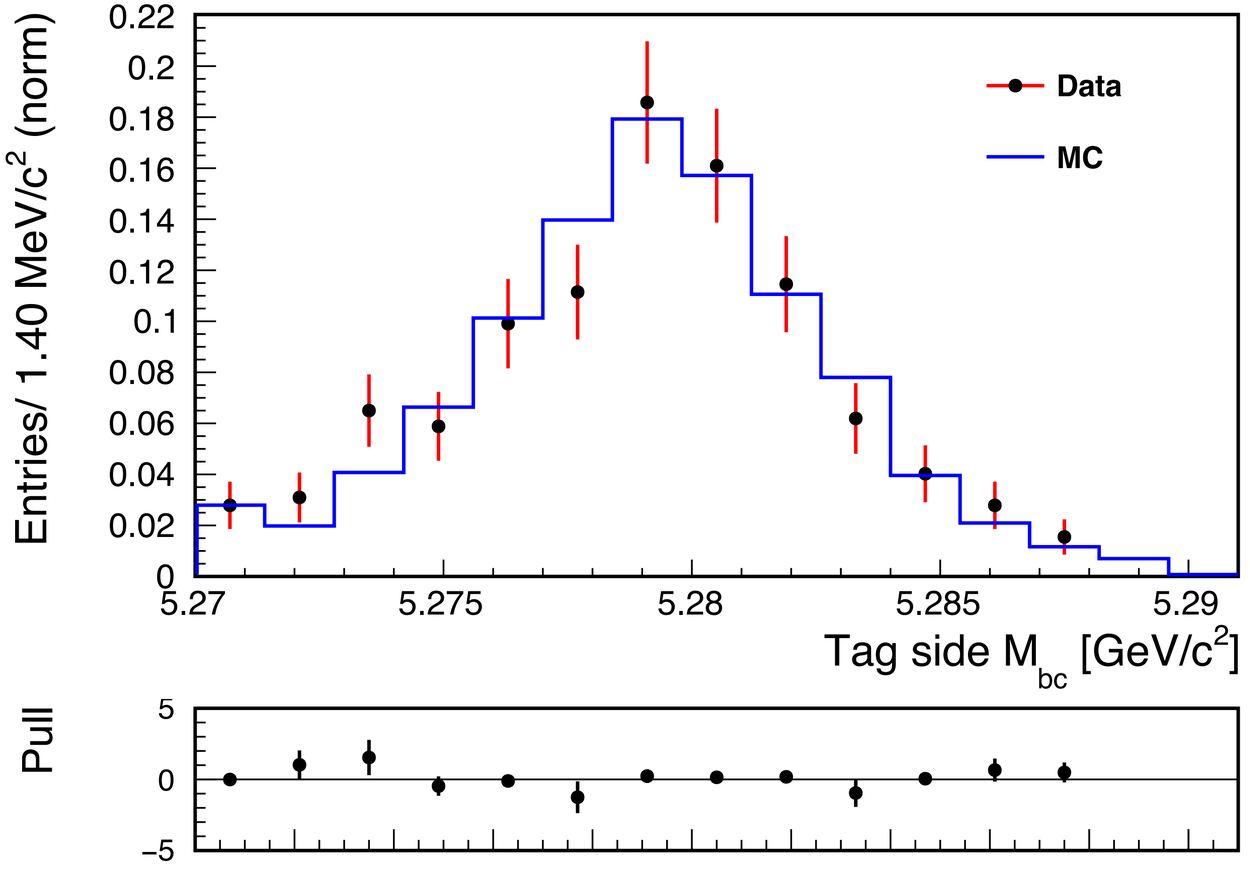




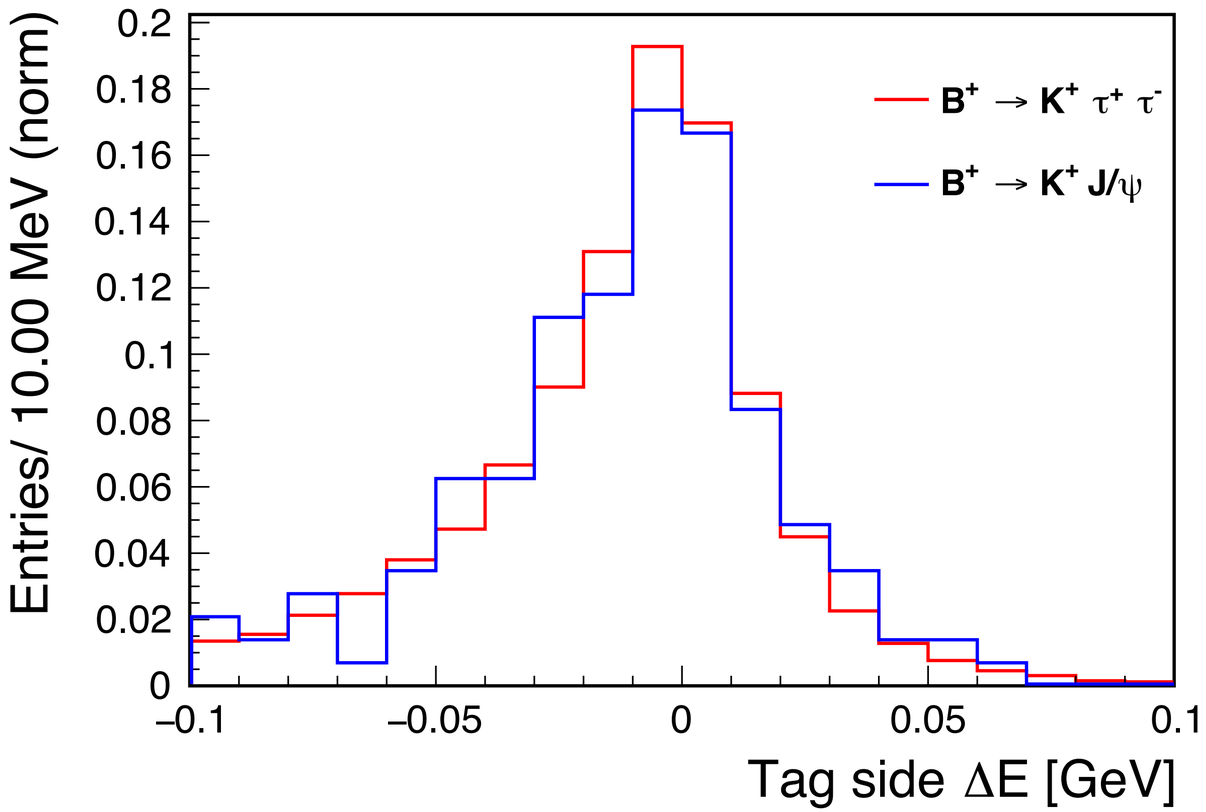
pre-selection cut we used before: $q^2 > 12\,\mathrm{GeV}^2/c^4$

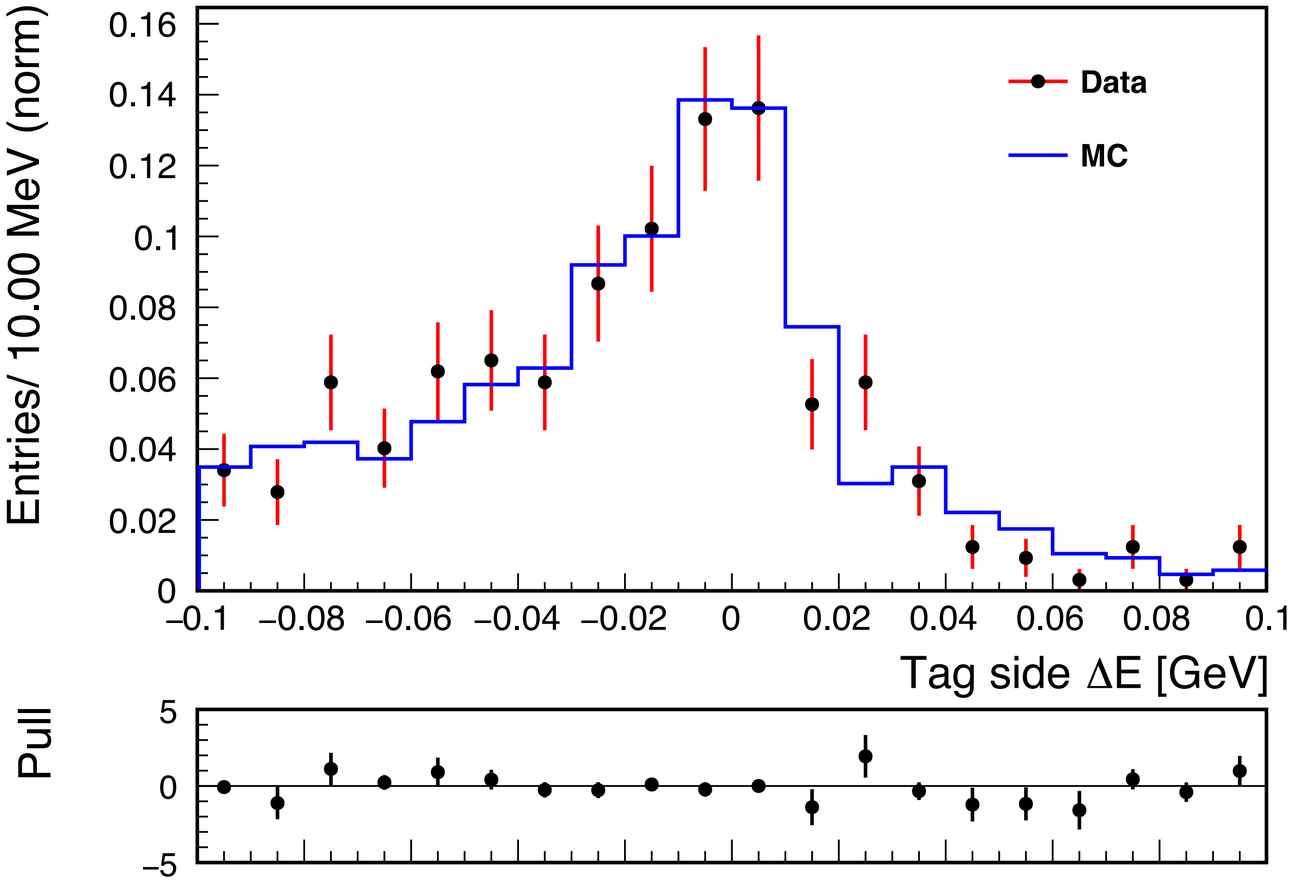
$M_{\mathrm{bc}}\,(B_{\mathrm{tag}})$





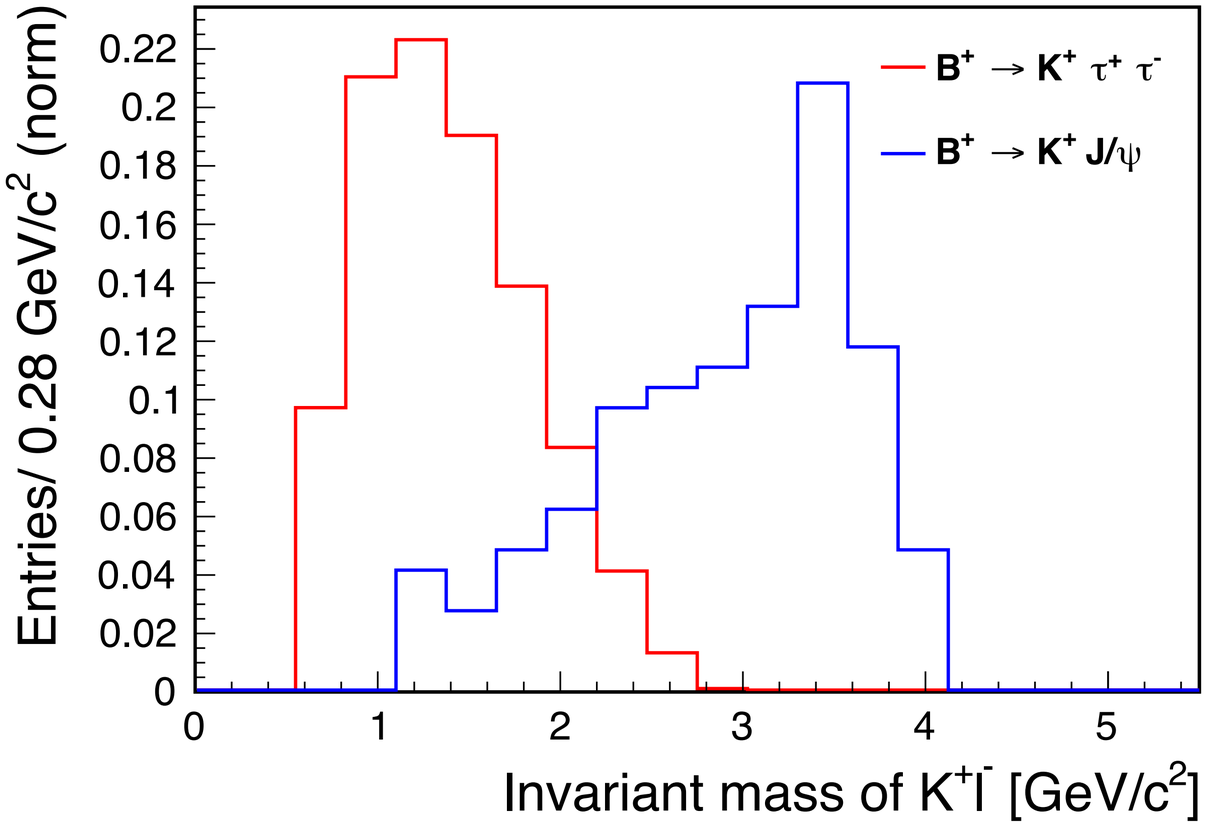
Tag side ΔE

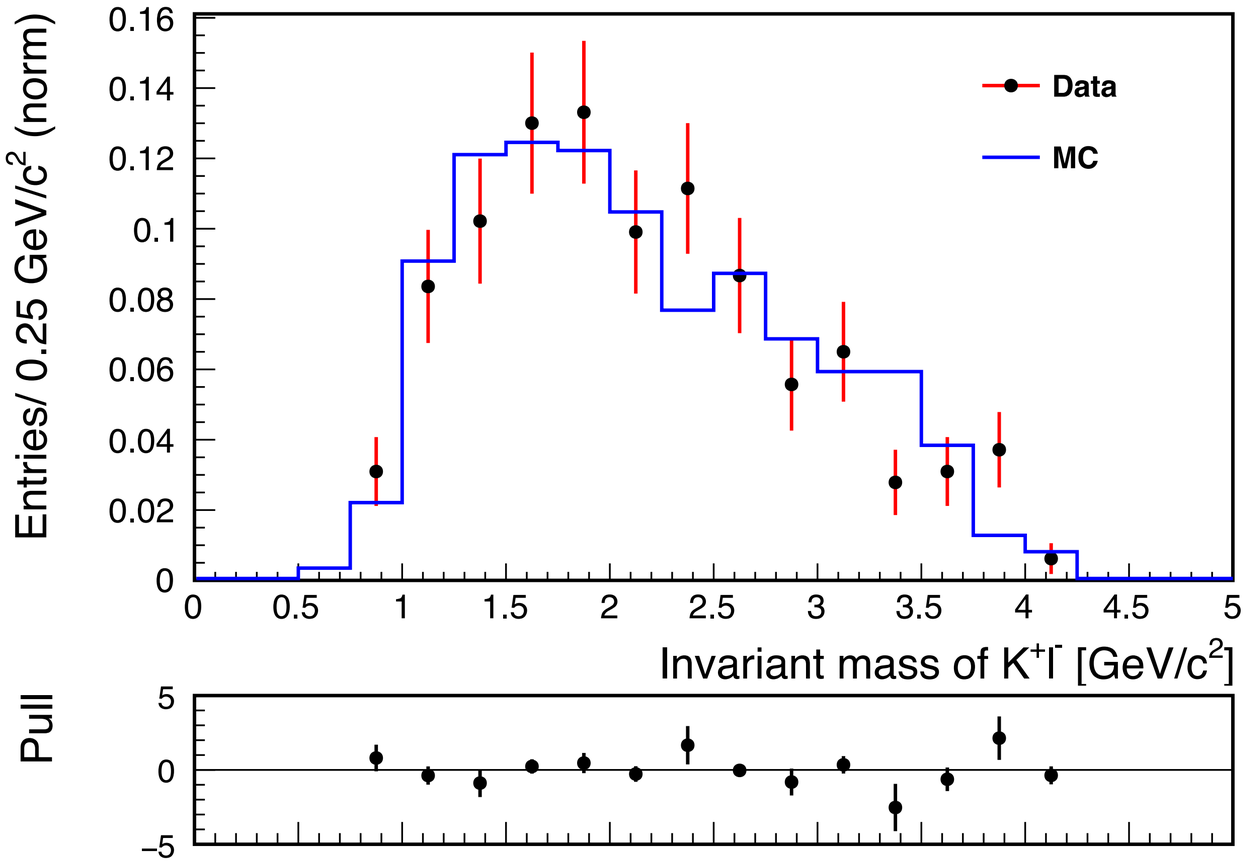




Invariant mass (K^+l^-)

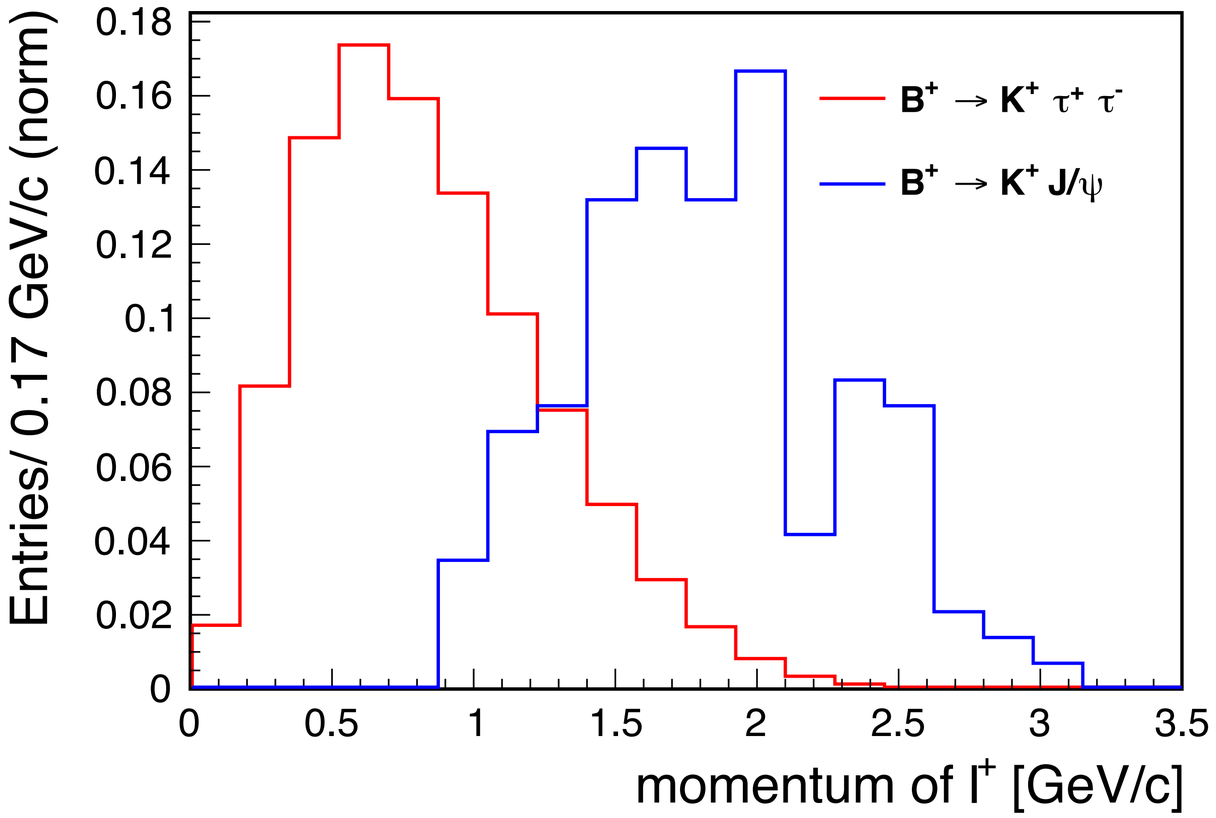
Kaon and opposite charged lepton

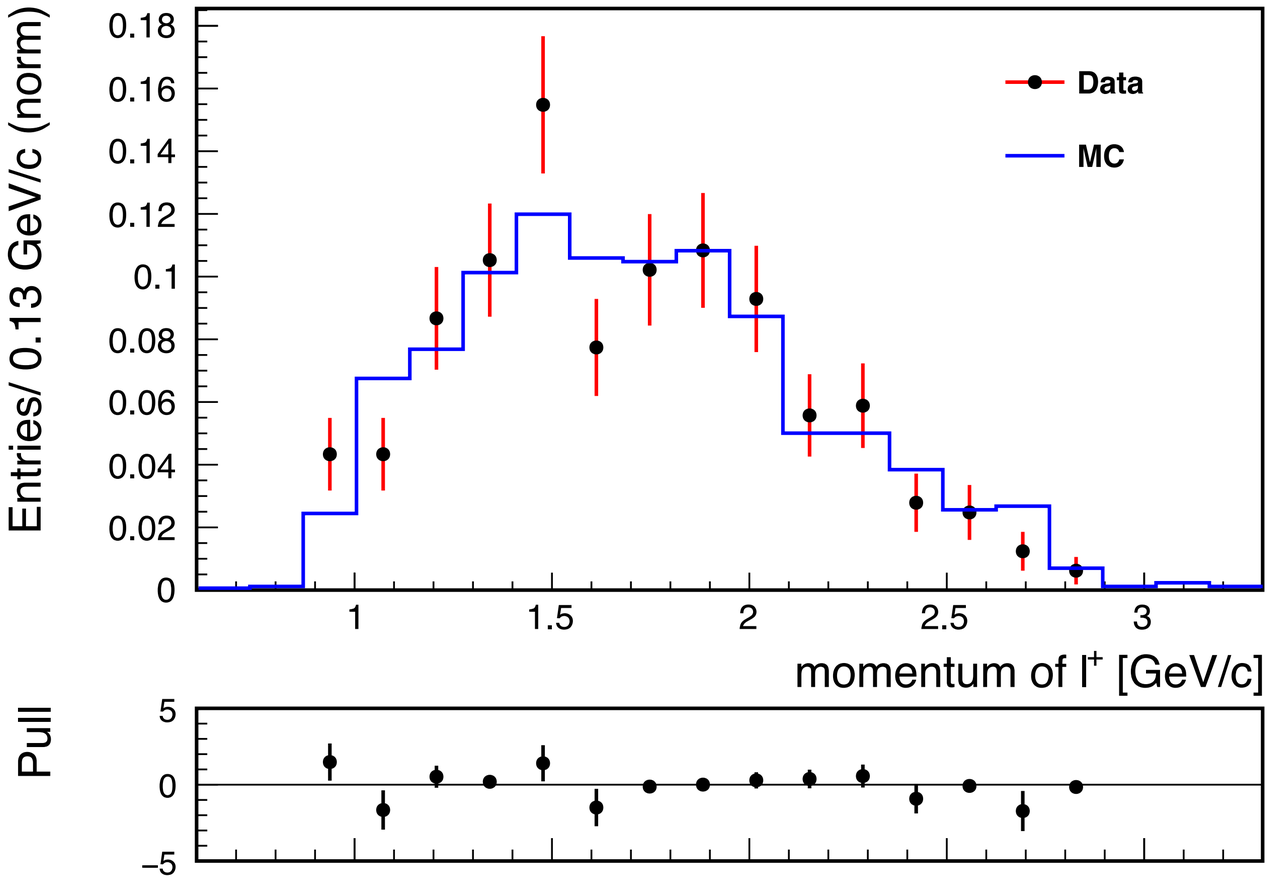




Momentum (l^+)

same charged (w.r.t Kaon) lepton





Backup

Test of truth match flag

22 % difference

signalMC

```
# reconstruct signal side B-mesons
ma.reconstructDecay(decayString='B+:ch0 -> K+:sel e+:sel e-:sel',
                    cut='',
                    dmID=0,
                    path=main)
ma.reconstructDecay(decayString='B+:ch1 -> K+:sel e+:sel mu-:sel',
                    cut='',
                    dmID=1,
                    path=main)
ma.reconstructDecay(decayString='B+:ch2 -> K+:sel mu+:sel e-:sel',
                    cut='',
                    dmID=2,
                    path=main)
```

events selected using topoana -> 4849

isSignalAcceptMissingNeutrino -> 3779

```
# reconstruct signal side B-mesons
ma.reconstructDecay(decayString='tau+:ch0 -> e+:sel',
                    cut='',
                    dmID=0,
                    path=main)

ma.reconstructDecay(decayString='tau+:ch1 -> mu+:sel',
                    cut='',
                    dmID=1,
                    path=main)
```

events selected using topoana -> 4849

isSignalAcceptMissingNeutrino -> 3779

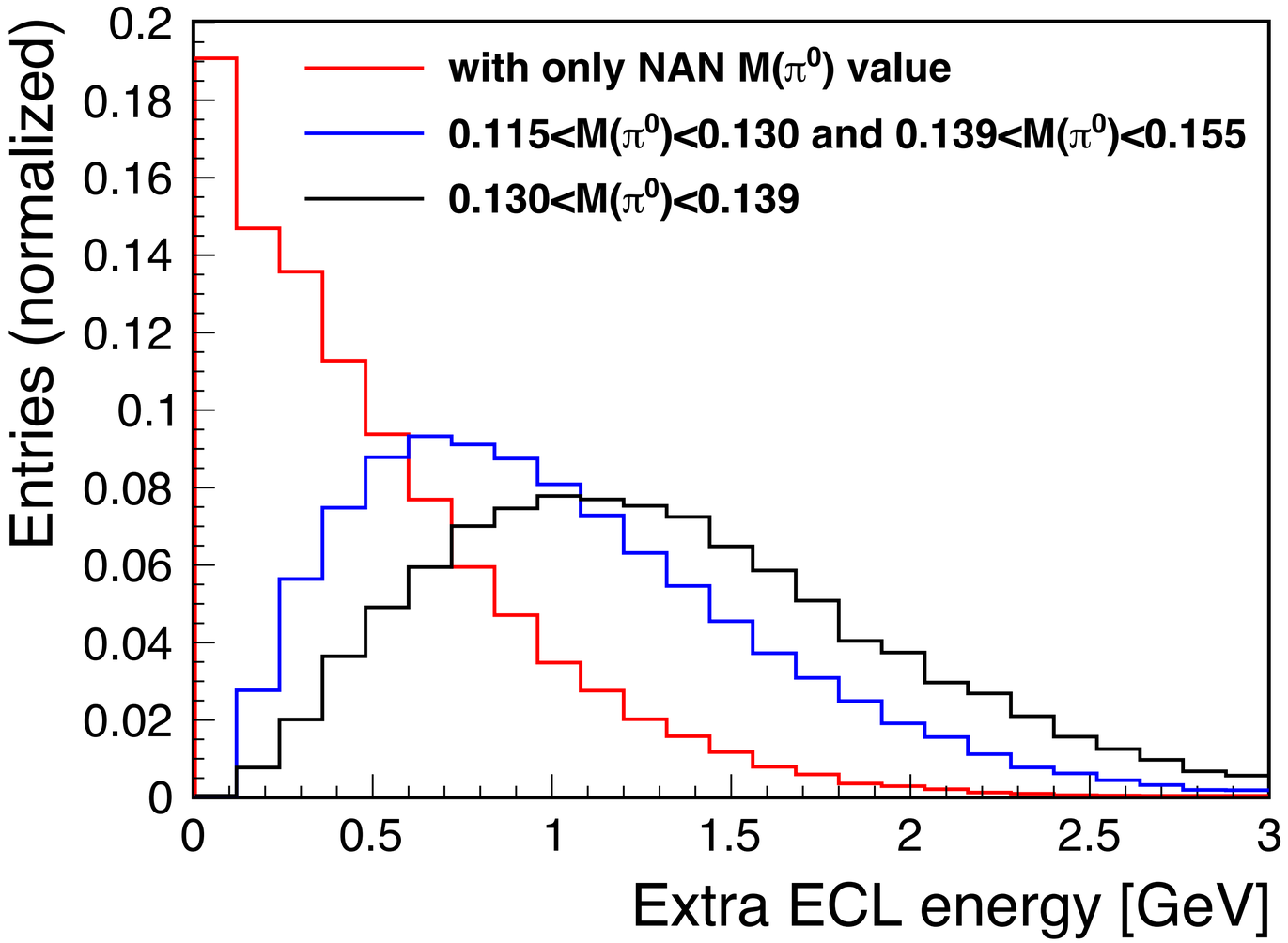
```
# reconstruct signal side B-mesons
ma.reconstructDecay(decayString='tau+:ch0 =direct=> e+:sel ?nu',
                    cut='',
                    dmID=0,
                    path=main)

ma.reconstructDecay(decayString='tau+:ch1 =direct=> mu+:sel ?nu',
                    cut='',
                    dmID=1,
                    path=main)

ma.reconstructDecay(decayString='tau+:ch2 =direct=> pi+:sel ?nu',
                    cut='',
```

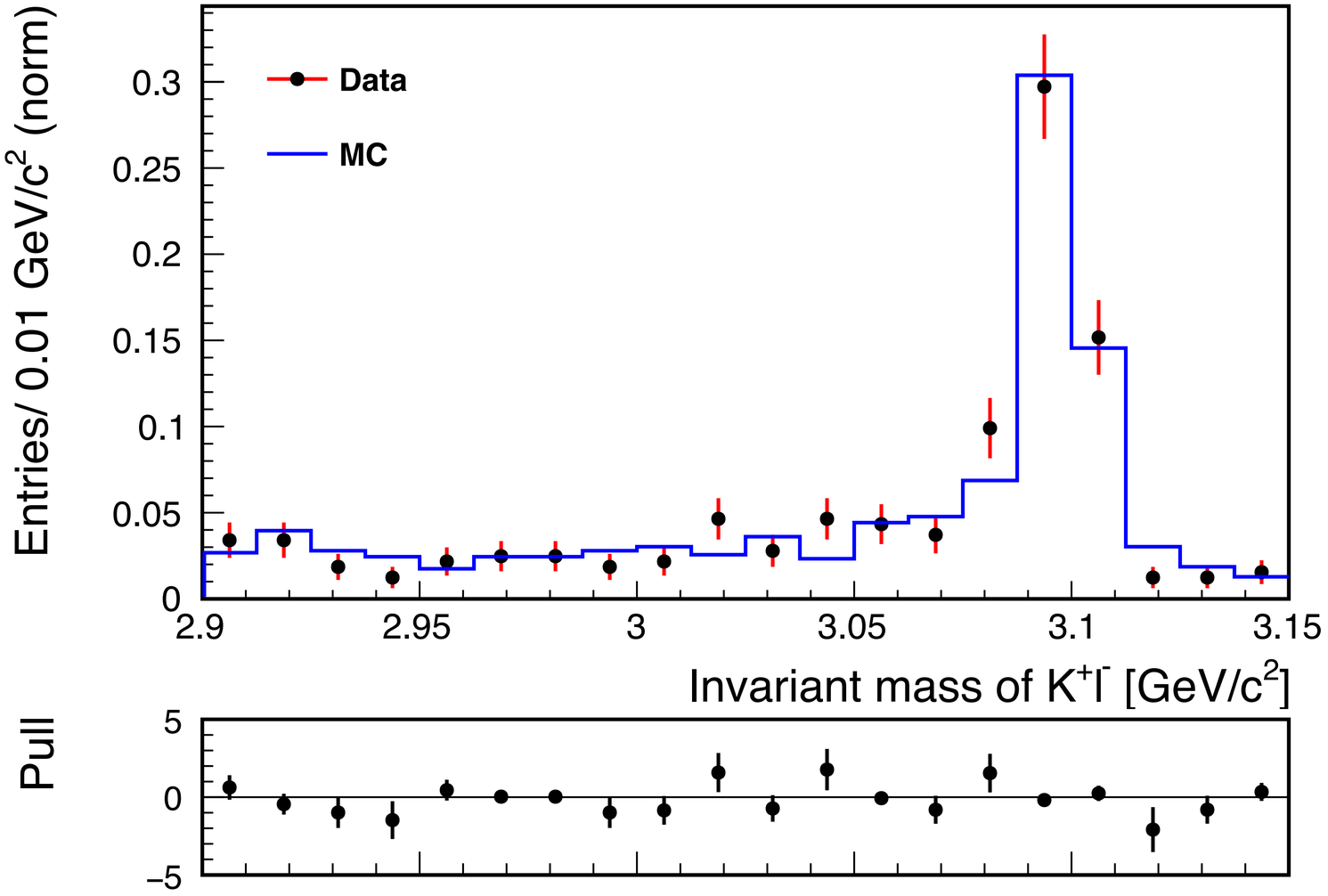
events selected using topoana -> 4849

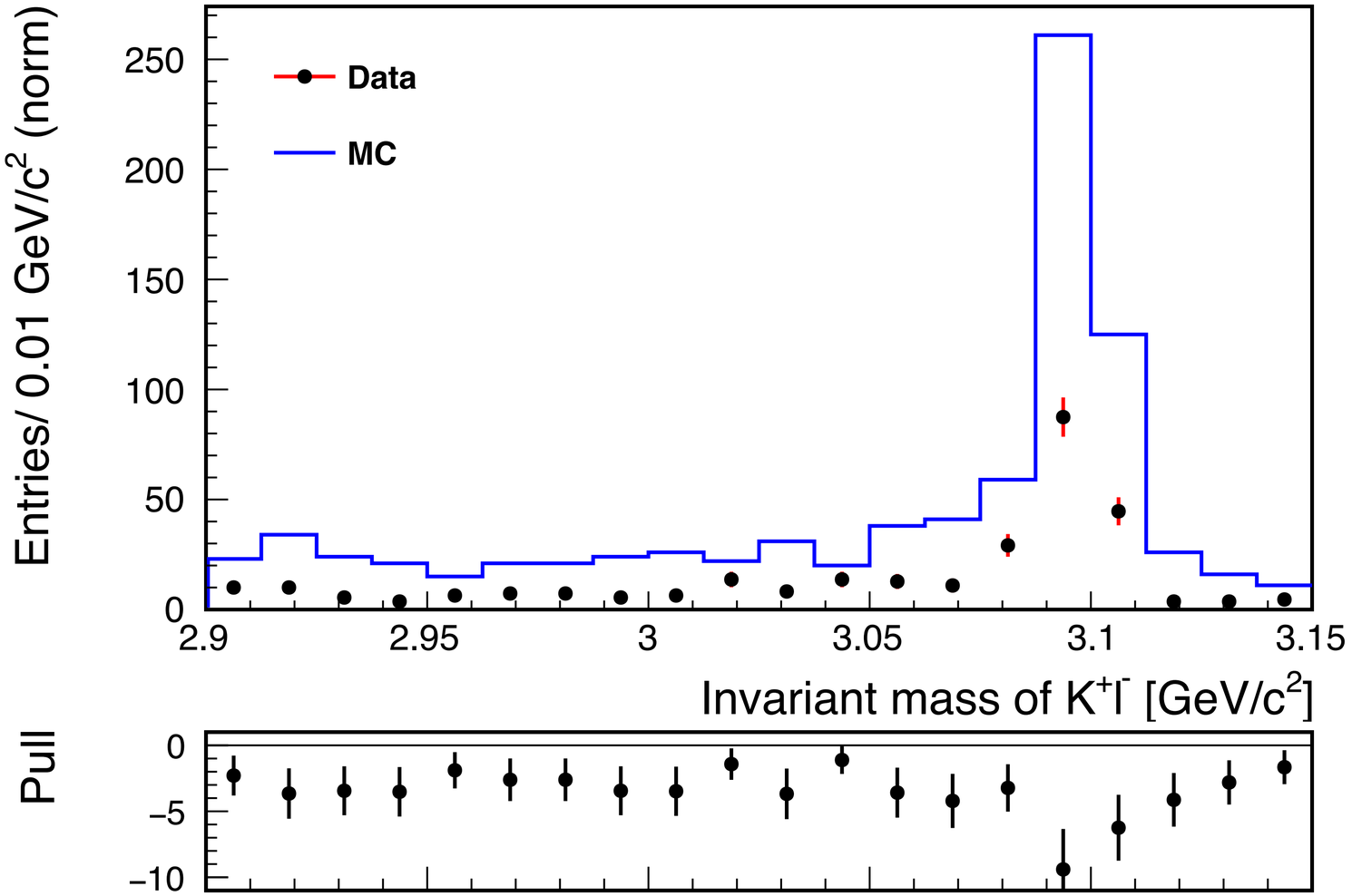
isSignal -> 3779

isSignalAcceptMissingNeutrino -> 3779

About NAN π^0 mass value




Data
MC
Entries/ 0.01 GeV/c^2 (norm)
0.3
0.25
0.2
0.15
0.1
0.05
0
2.9
2.95
3
3.05
3.1
3.15
Invariant mass of K$^+$l$^-$ [GeV/c^2]
Pull
5
0
−5



GenericMC:

- Scaled to luminosity of $364.35\,fb^{-1}$

#MC = 782

#data = 323