$\Lambda_b \to p\pi\mu\mu$ full run1+run2 branching fraction analysis

Piera Battista

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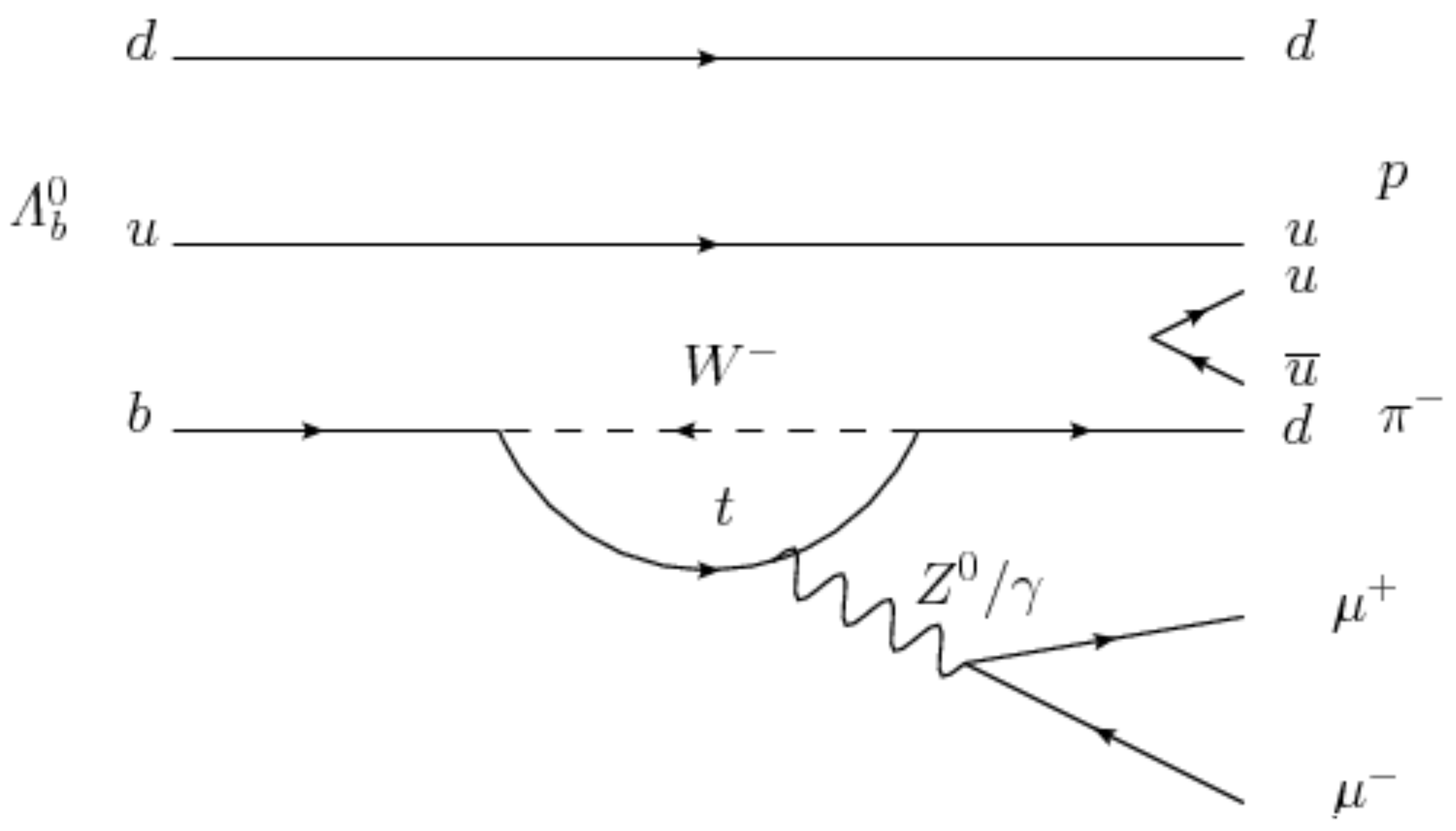
Why?

- $b \to d\ell^+\ell^-$ transitions are highly suppressed in the SM and a good probe for NP

- First observation and BF measurement of $\Lambda_b^0 \to p\pi^-\mu^+\mu^-$ with Run 1 data [1]

- Goals of this analysis:
  - Measure BF with full Run1+Run2 dataset [AP]
  - BF in bins of q^2 (if feasible), direct CP asymmetry
  - Look into hadronic $p\pi^-$ spectrum

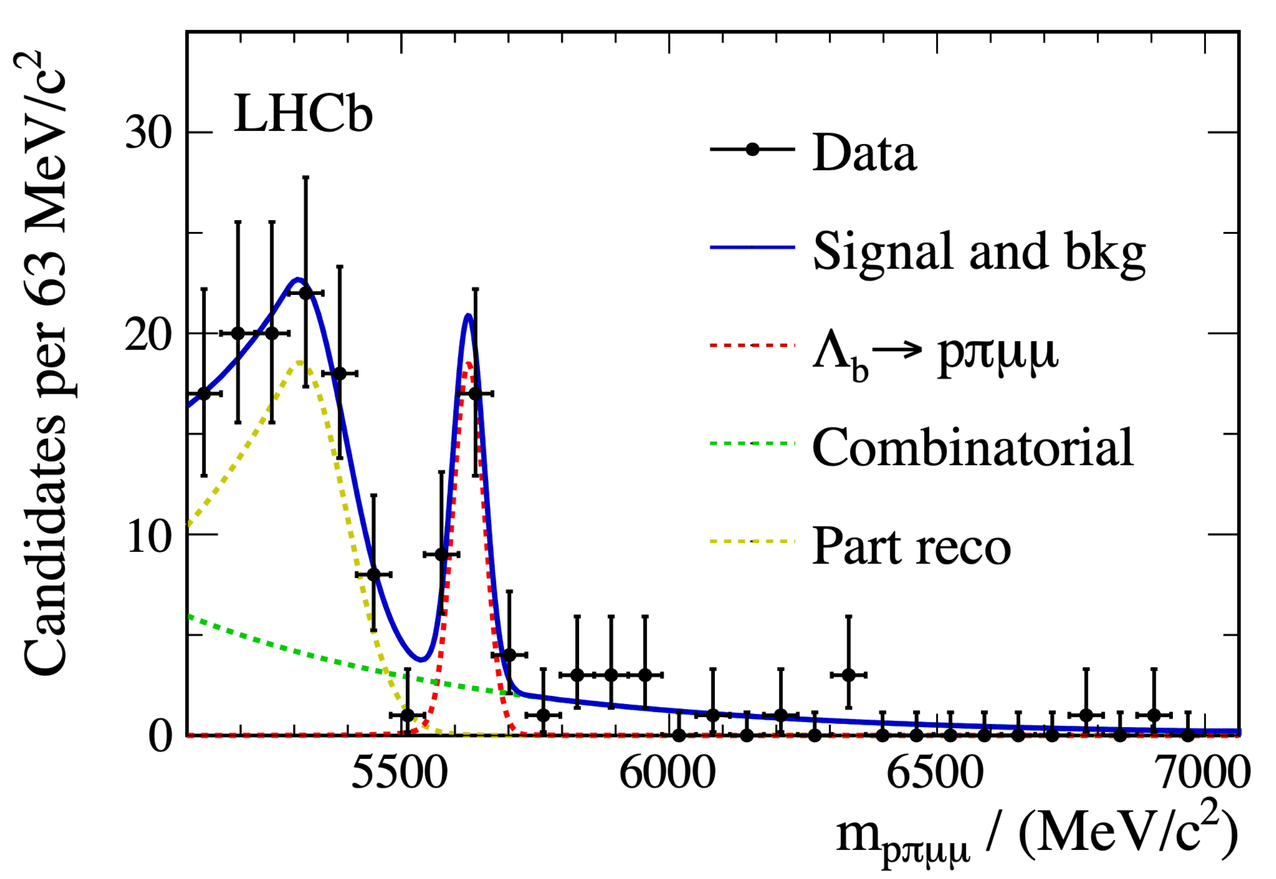


How?

- Can we improve with respect to run 1?

<u>Run 1 selection</u>

- Very tight PID cuts
  - Proton PID
  - all misID



Reproduced by CCNU

<u>Now: Run1+Run2</u>

- Loosen all PID cuts
  - Study a new selection
- Use simultaneous fit:
  - Fit $\Lambda_b \rightarrow pK\mu\mu$ and $\Lambda_b \rightarrow p\pi\mu\mu$
  - Constrain midID of pK reconstructed as $p\pi$ using the $\Lambda_b \rightarrow pK\mu\mu$ yield (more later)

Studied by Barcelona and us

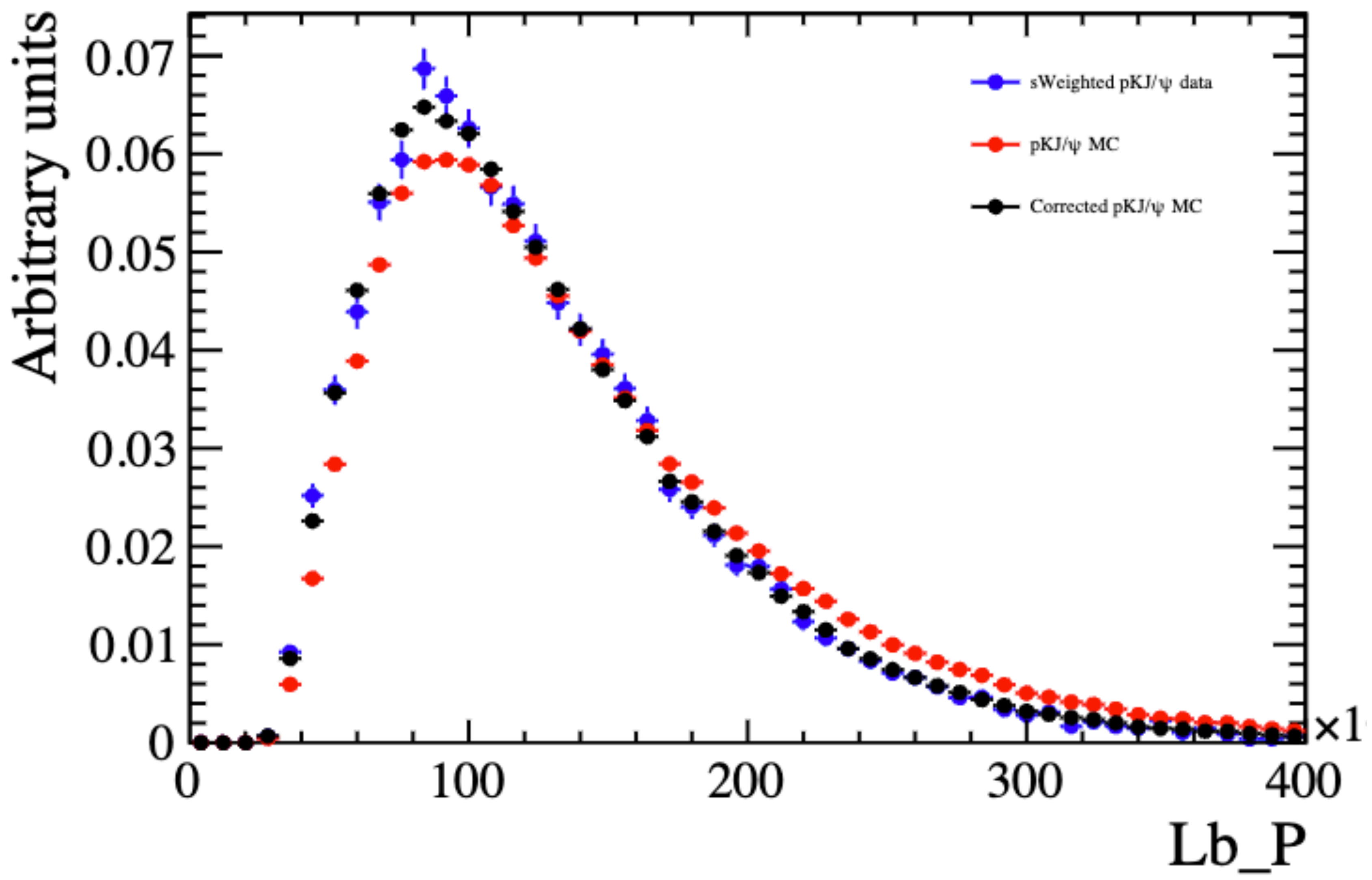
MC corrections

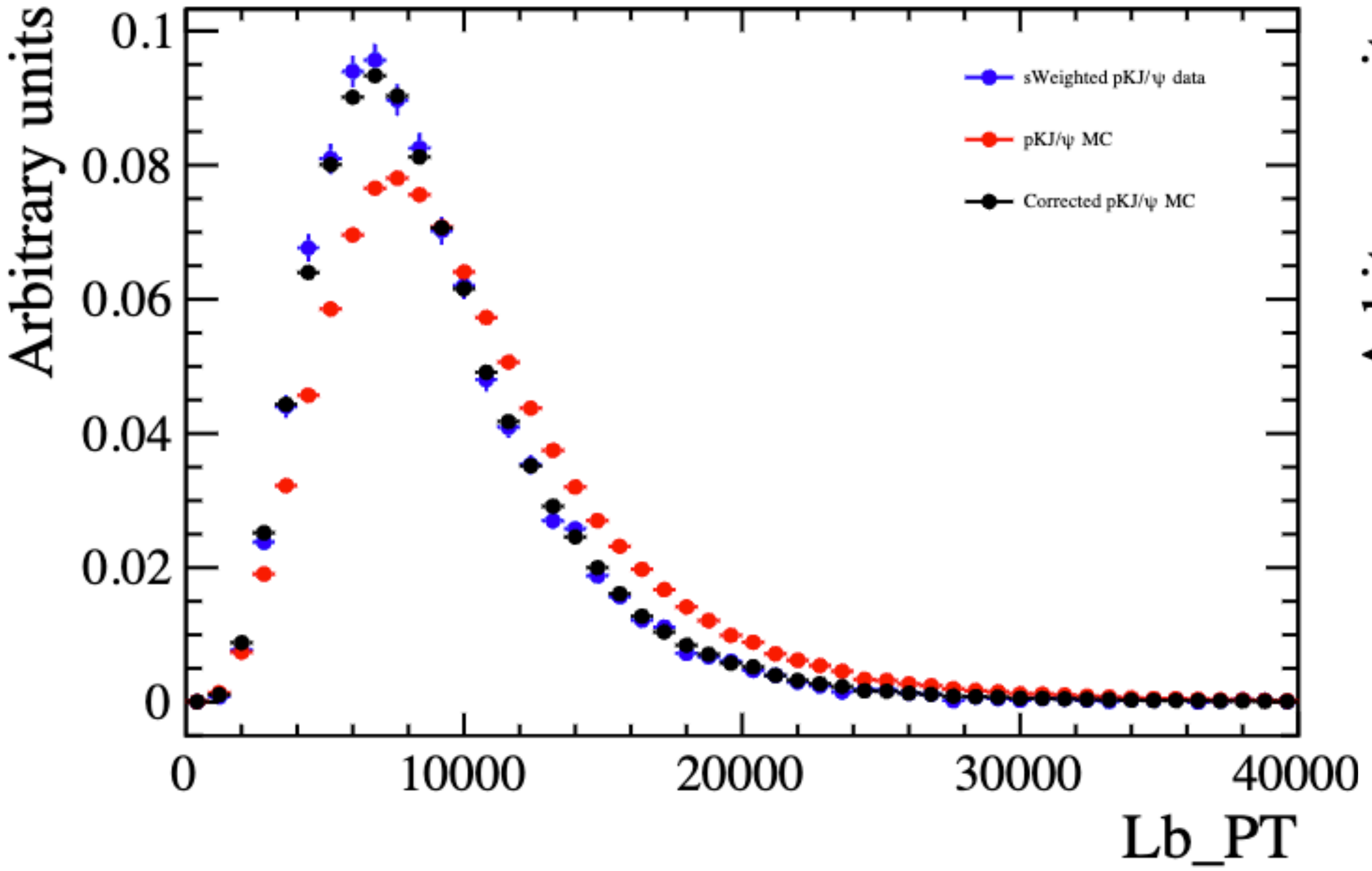
- Kinematics
  - Correction of generated shape of p^{Λ_b}, $p_T^{\Lambda_b}$, τ^{Λ_b}, nTracks
- PID corrections: PIDcorr
- q^2: theoretical calculation of $\Lambda_b \to \Lambda^0 \mu\mu$ q^2
- $m(p\pi)$: 1D correction
- $m(pK)$: pentaquark angular analysis

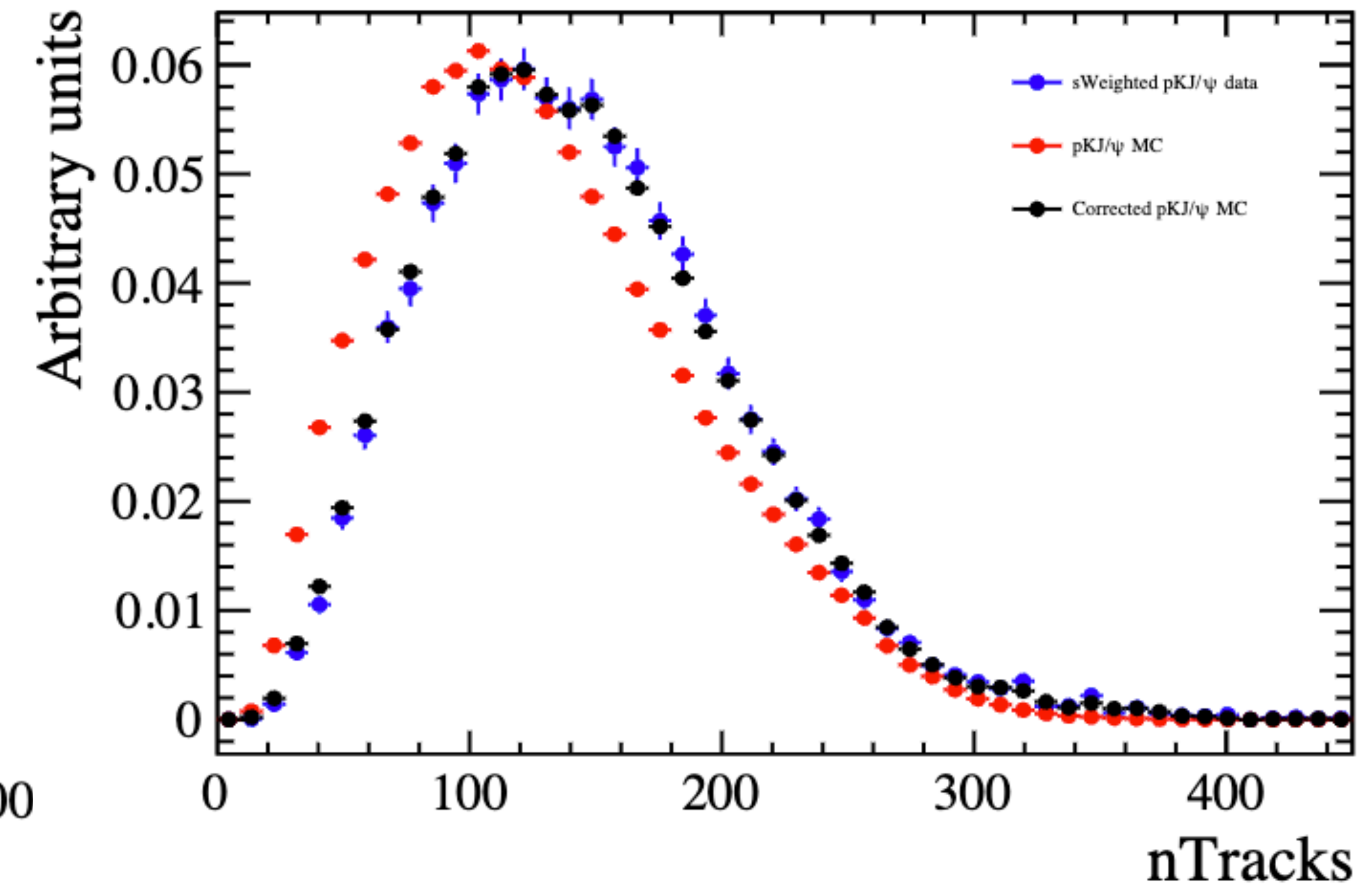
Kinematic corrections

- Corrected p^{Λ_b}, $p_T^{\Lambda_b}$, τ^{Λ_b}, nTracks from the $\Lambda_b \to pKJ/\psi$ MC and sWeigthed data

- Same weights are applied to the $\Lambda_b \to p\pi J/\psi$ and $\Lambda_b \to p\pi\mu\mu$ MC

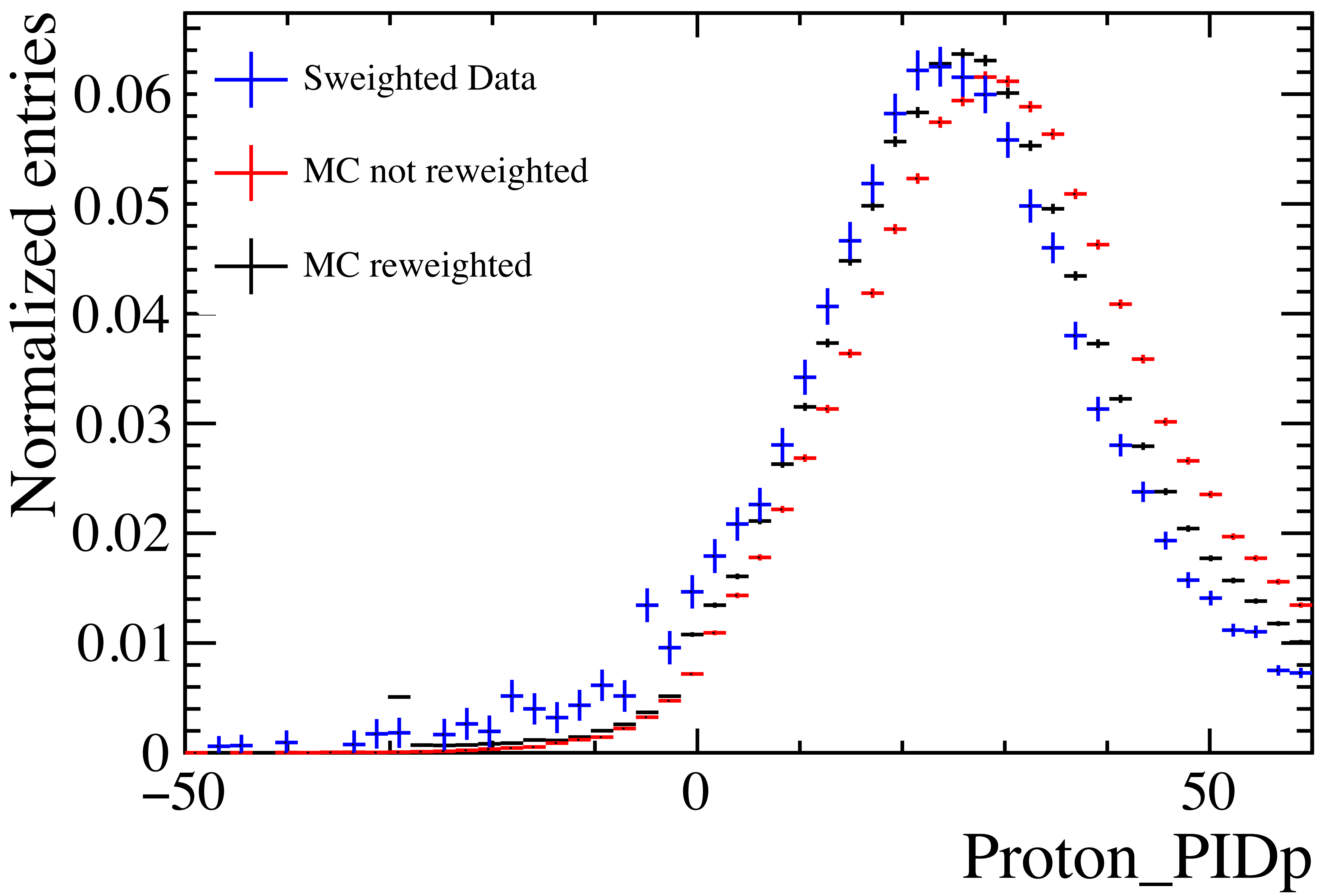


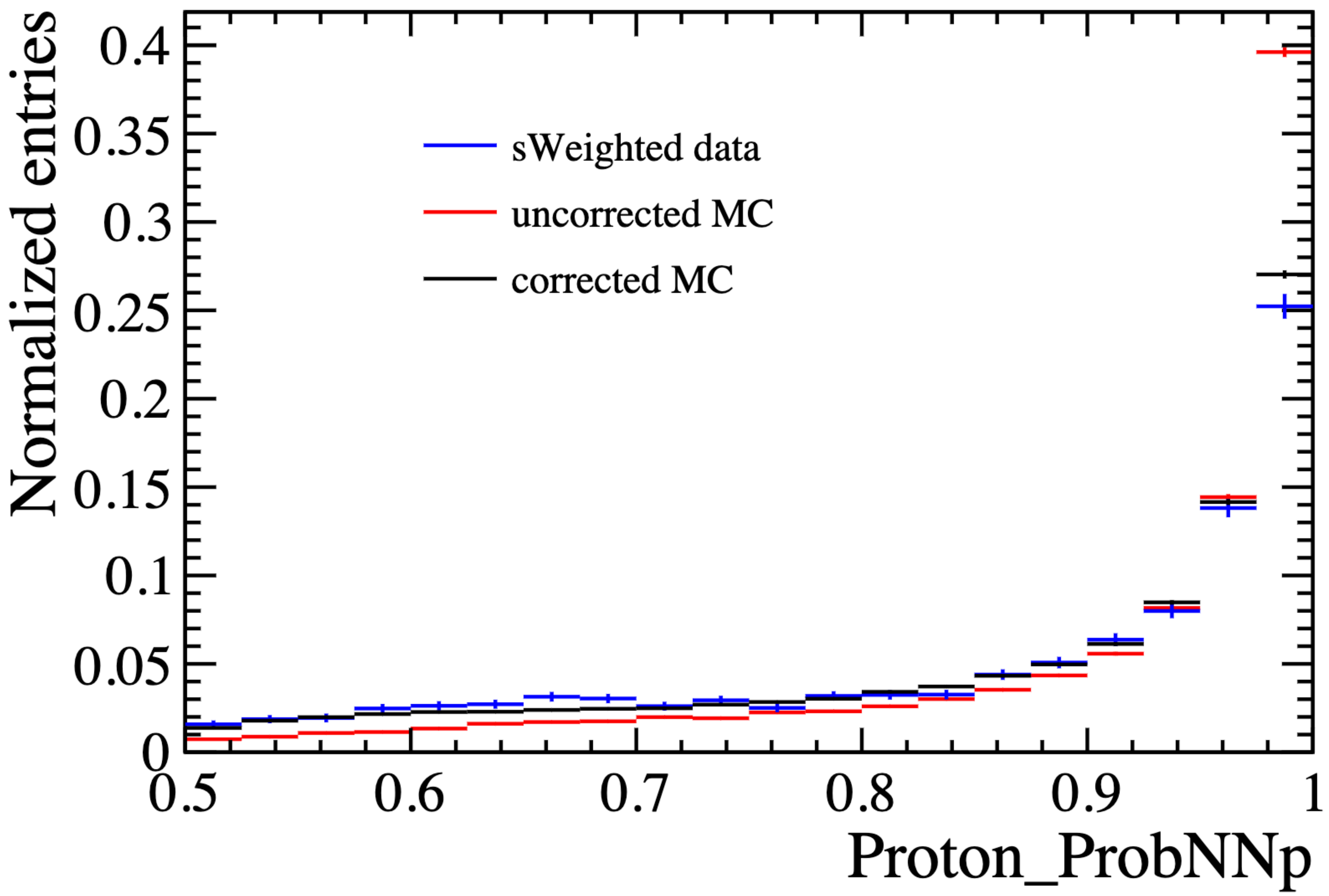




MC corrections - PID

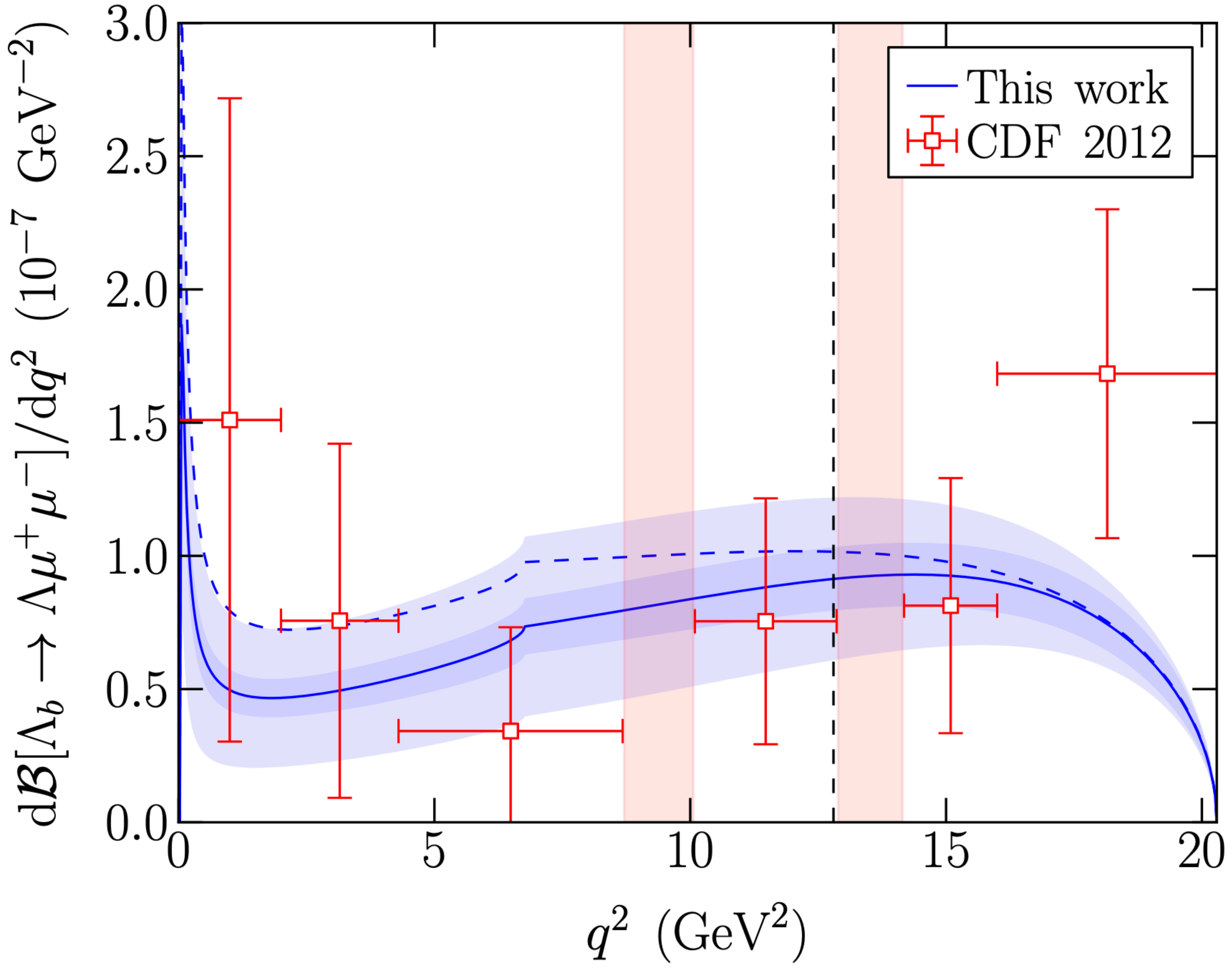
- PID correction computed with PIDcorr package
  - Full transformation of the PID variables, retain correlation between variables

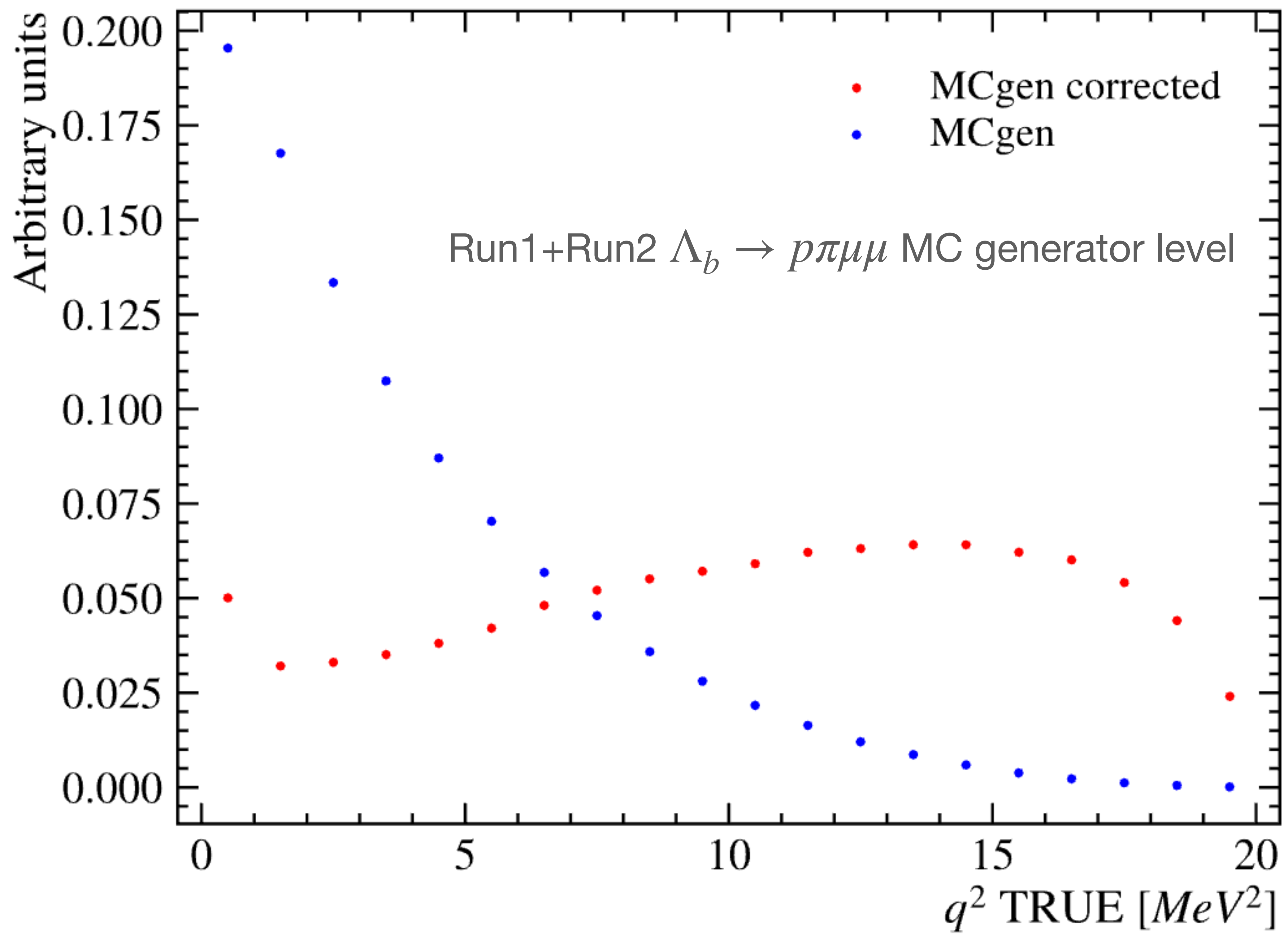


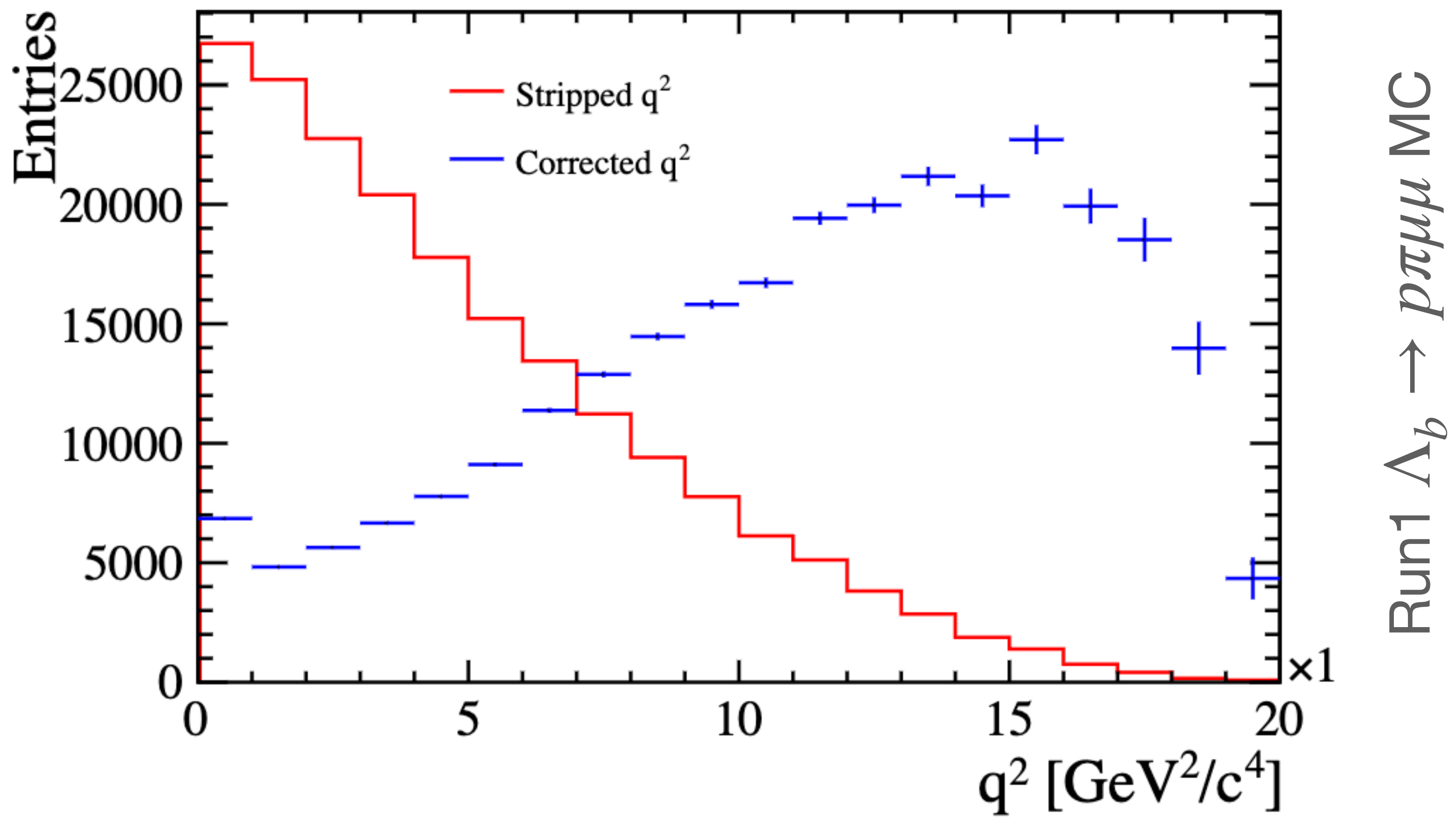


q^2 corrections

- Using the calculations from theoretical paper of branching fraction of $\Lambda_b \to \Lambda^0 \mu\mu$

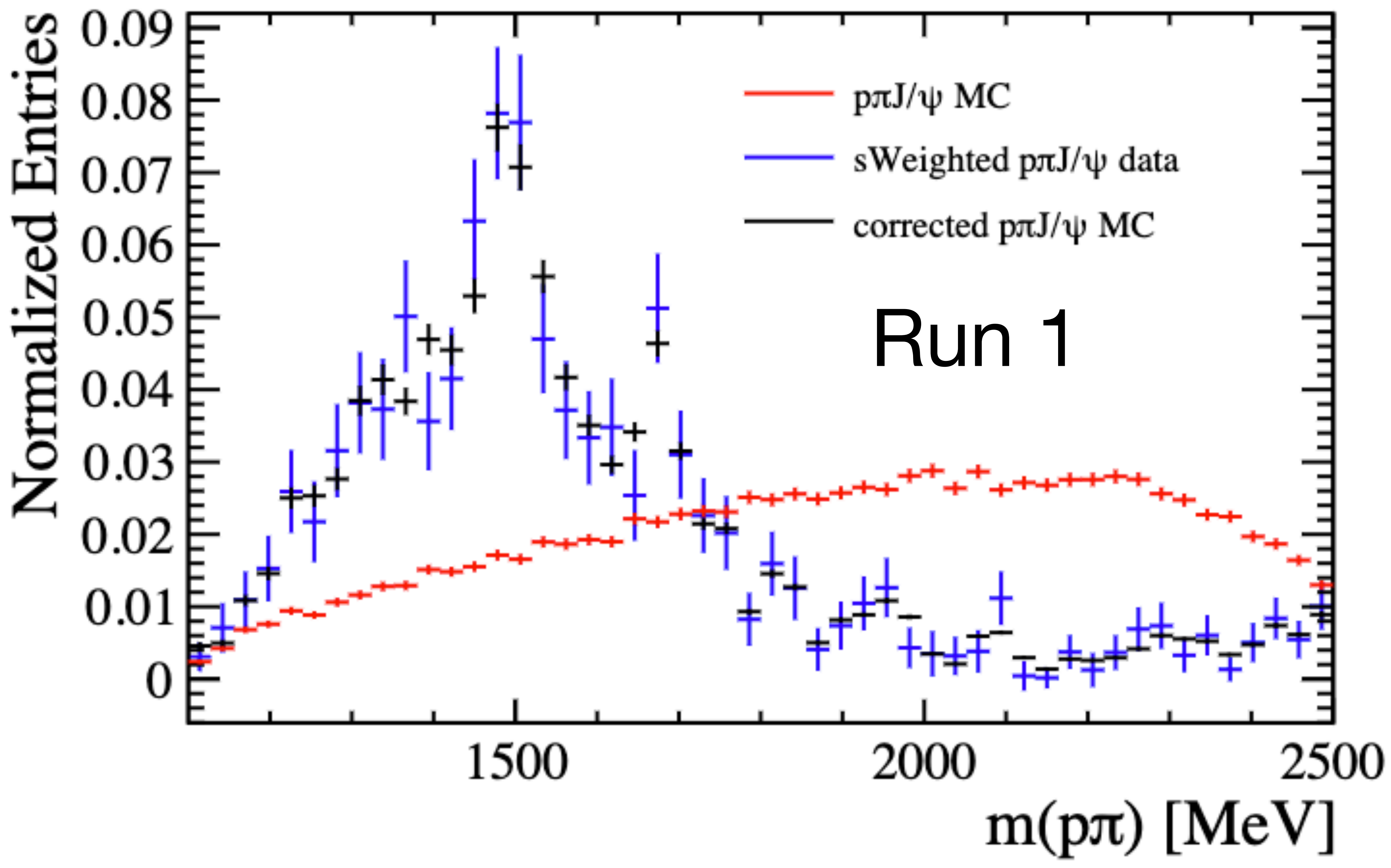


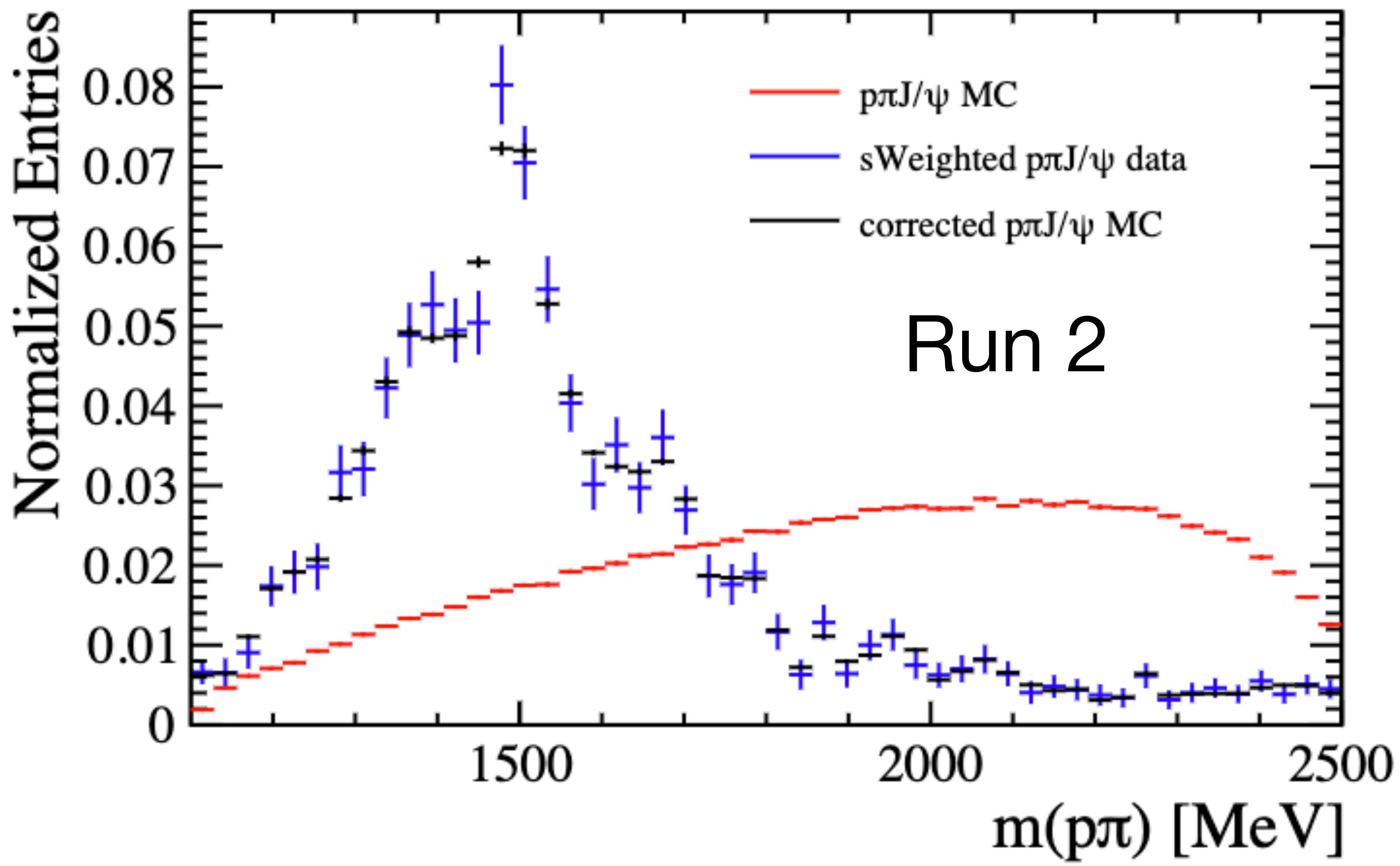




m($p\pi$) corrections

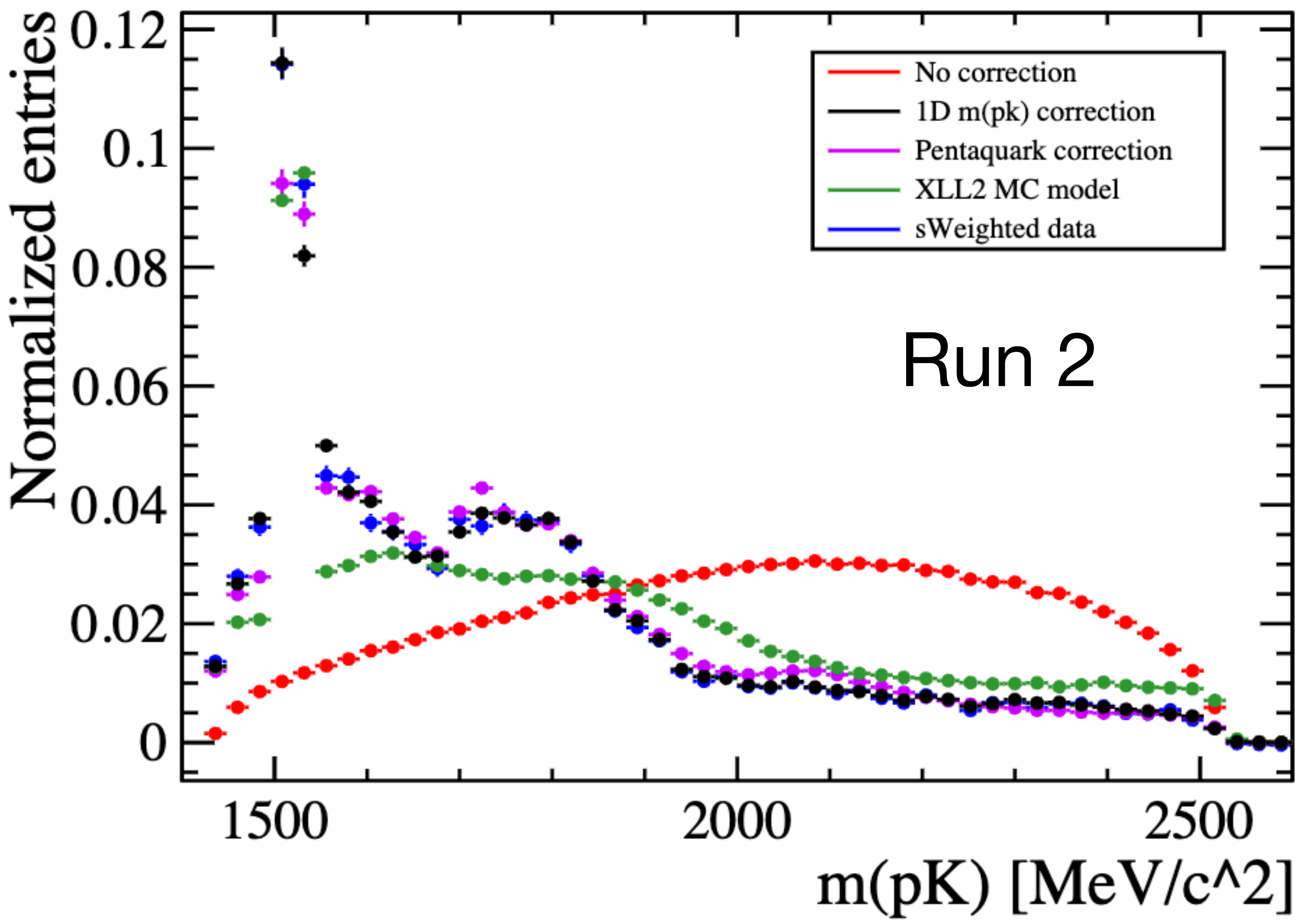
- SWeight $\Lambda_b \rightarrow p\pi J/\psi$ data and perform a 1D correction

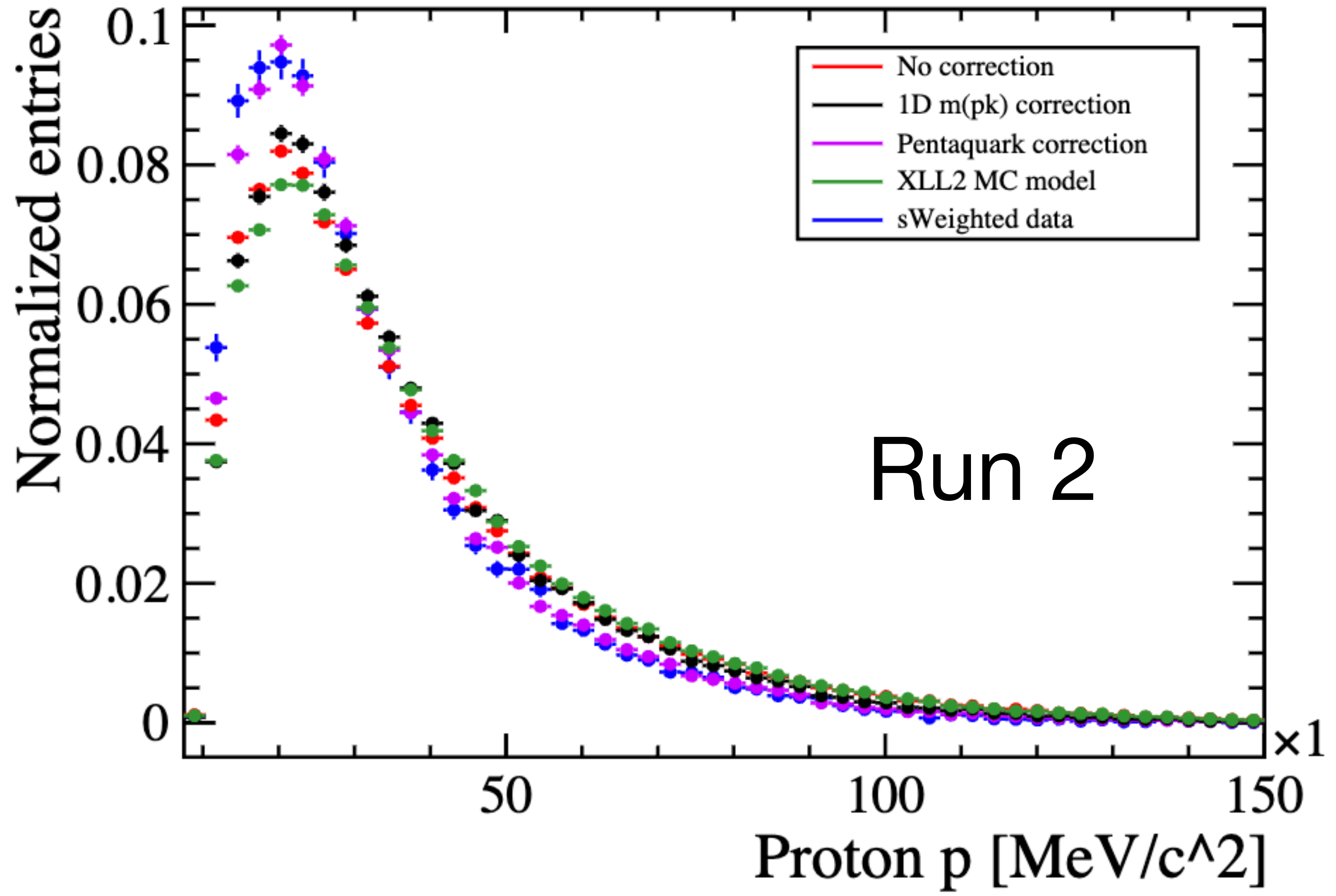


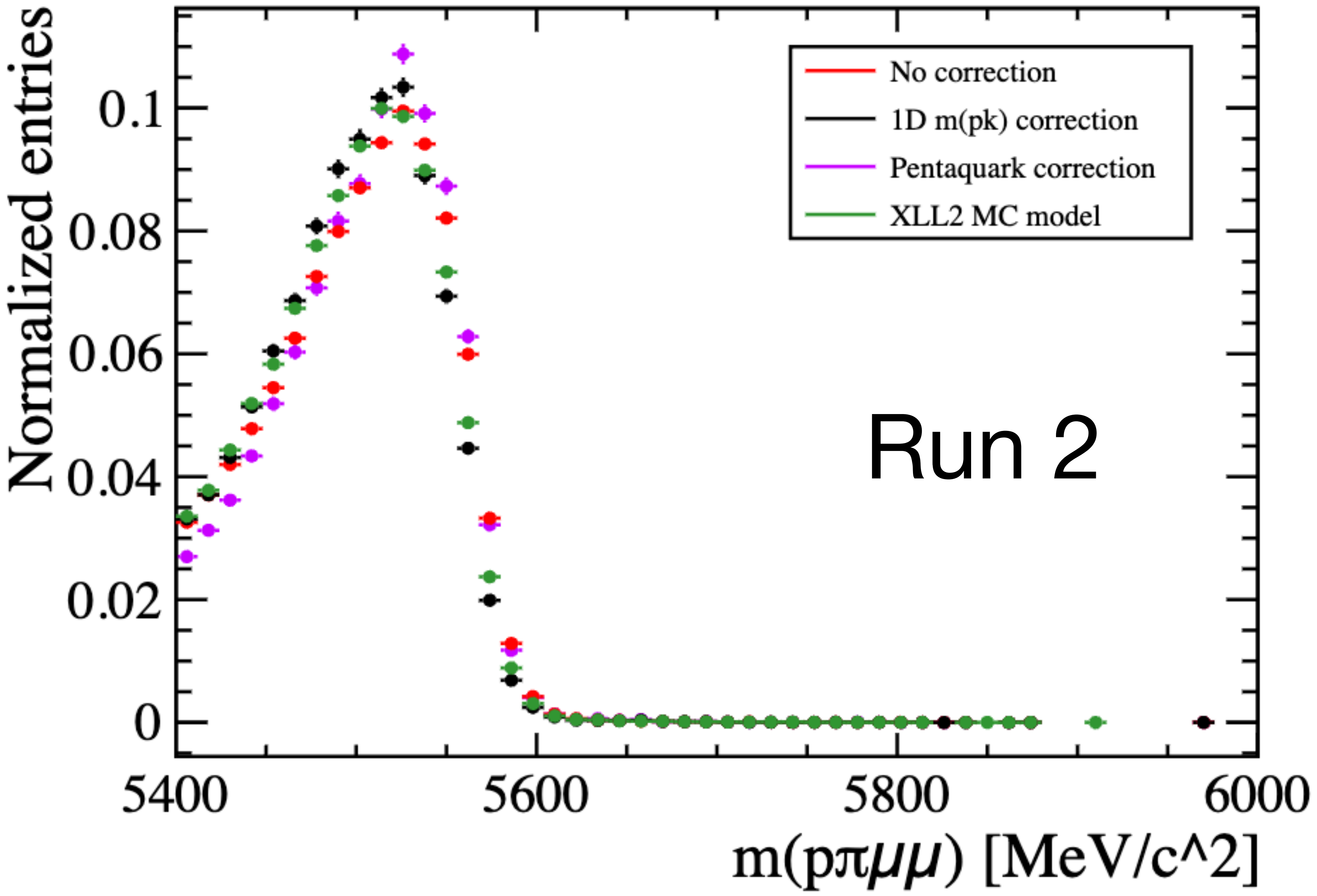


m(pK)

- Using pentaquark amplitude analysis
  $J/\psi \rightarrow pKJ/\psi$







Backgrounds

- Combinatorial: BDT and Proton PID cut
- MisID:
  - $\Lambda_b \to pK\mu\mu$
  - $B^0 \to K^*(\to K\pi)\mu\mu$
  - $B^0 \to K^*(\to K\pi)\mu\mu$ double misID, $B_s \to \phi(\to KK)\mu\mu$, $B_{(s)} \to \pi\pi\mu\mu$

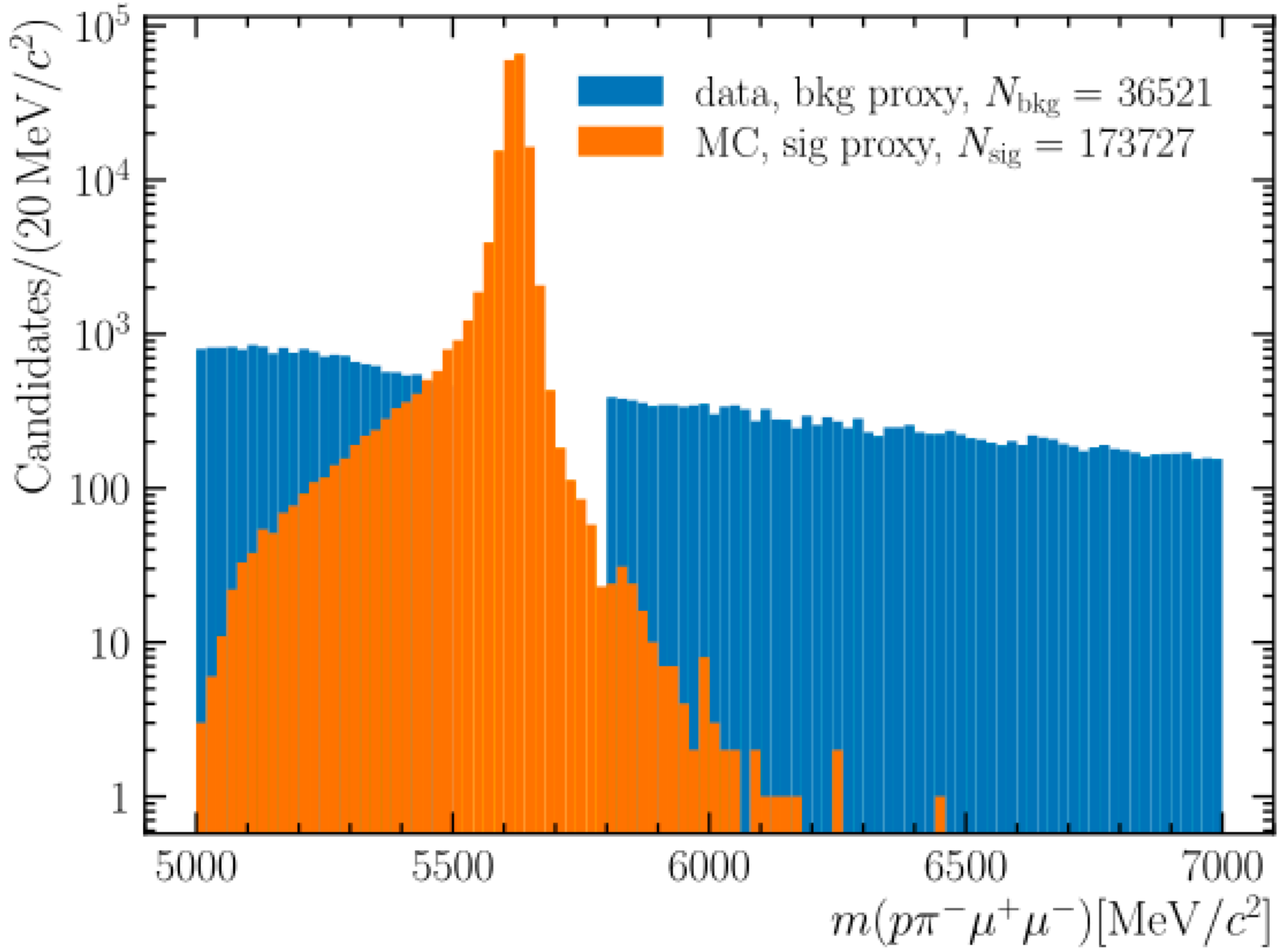
Contamination in mass range 5400-6000 MeV in 2016

Decay	Only preselection	Contamination with vetos
$B^0 \to K^*(\to K\pi)J/\psi$ single	36 %	20 %
$B^0 \to K^*(\to K\pi)J/\psi$ double	1.3%	0.6 %
$B_s \to KKJ/\psi$	1%	0.5%
$B_s \to \phi(\to KK)J/\psi$	0.8 %	0.04%
$B^0_{(s)} \to \pi\pi J/\psi$	3.3%	2%

- Clone tracks: cut on opening angle — IN BACKUP
- Semileptonic: e.g. $\Lambda_b \to \Lambda_c(\to p\pi\pi)\mu\nu$ — IN BACKUP
- $\Lambda_b \to \Lambda(\to p\pi)\mu\mu$ background — IN BACKUP

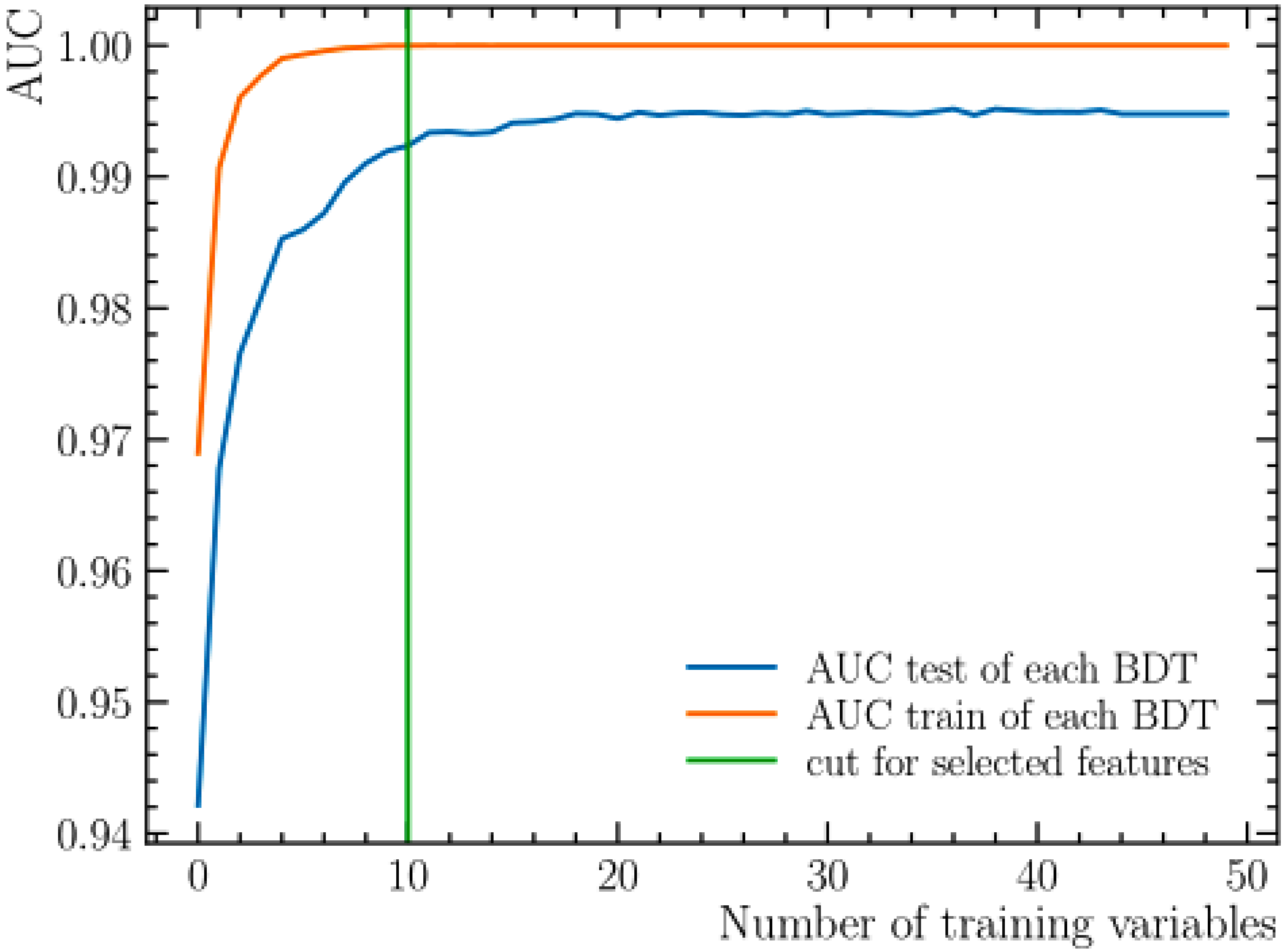
BDT

- xgboost library used to train the BDT
- Using truth-matched $\Lambda_b^0 \to p\pi^-\mu^+\mu^-$ as **signal** and upper mass sideband $(5.8 - 7\,\mathrm{GeV}/c^2)$ and lower mass sideband $(4.8 - 5.5\,\mathrm{GeV}/c^2)$ as **background** proxy
- Undersampling the signal sample when input data is very unbalanced
- Training separately for Run1, Run2a (15+16) Run2b (17+18)



BDT

- Iterate BDT training over different number of training variables
- Start with a long list of training variables and remove variable with the lowest feature importance in each iteration
- Decide on number of training variables where AUC of the test samples drops below 99.5% of the starting value



$$\chi^2_{\mathrm{IP}}(\mu^+), \chi^2_{\mathrm{IP}}(\mu^-), \vartheta_{\mathrm{DIRA}}(\Lambda_b^0), \chi^2_{\mathrm{vtx}}(\Lambda_b^0), \eta(\Lambda_b^0), \chi^2_{\mathrm{FD}}(\Lambda_b^0), p_{\mathrm{T}}(\Lambda_b^0), \chi^2_{\mathrm{IP}}(\pi^-), \mathrm{IP}(\pi^-), \chi^2_{\mathrm{IP}}(p)$$

2D optimisation

- Cutting on the Proton PID also reduces combinatorial background

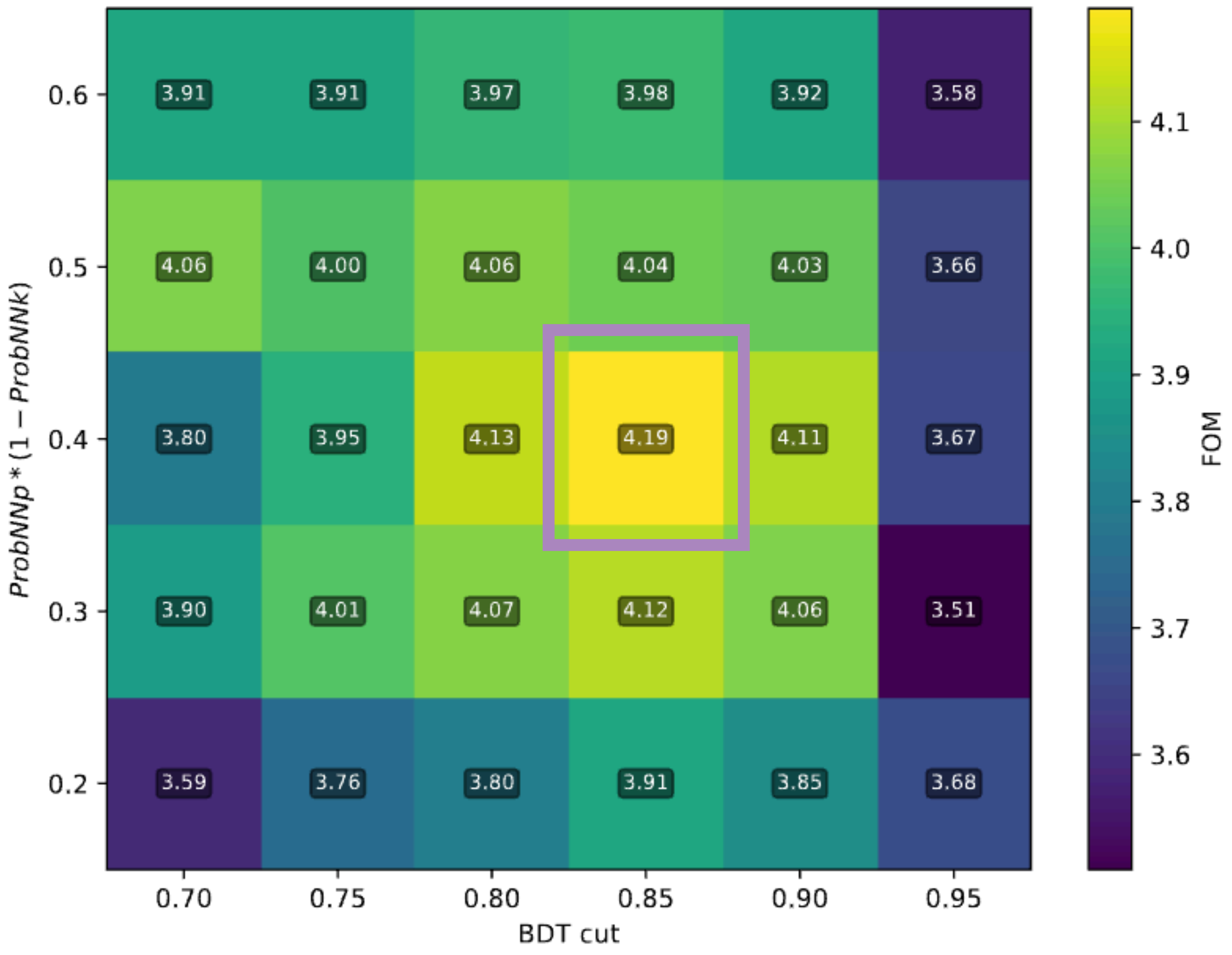
- 2D optimisation: BDT vs Proton PID

  - S: number of signal in the J/Ψ data scaled by efficiency ratios and branching fractions

  - B: fitting exponential background in rare mode in mass range (5720, 6000) MeV and integrating background under signal peak

$$FOM = \frac{S}{\sqrt{S+B}}$$

Run1



Backgrounds

- Combinatorial: BDT and Proton PID cut
- MisID:
  - $\Lambda_b \to pK\mu\mu$
  - $B^0 \to K^*(\to K\pi)\mu\mu$

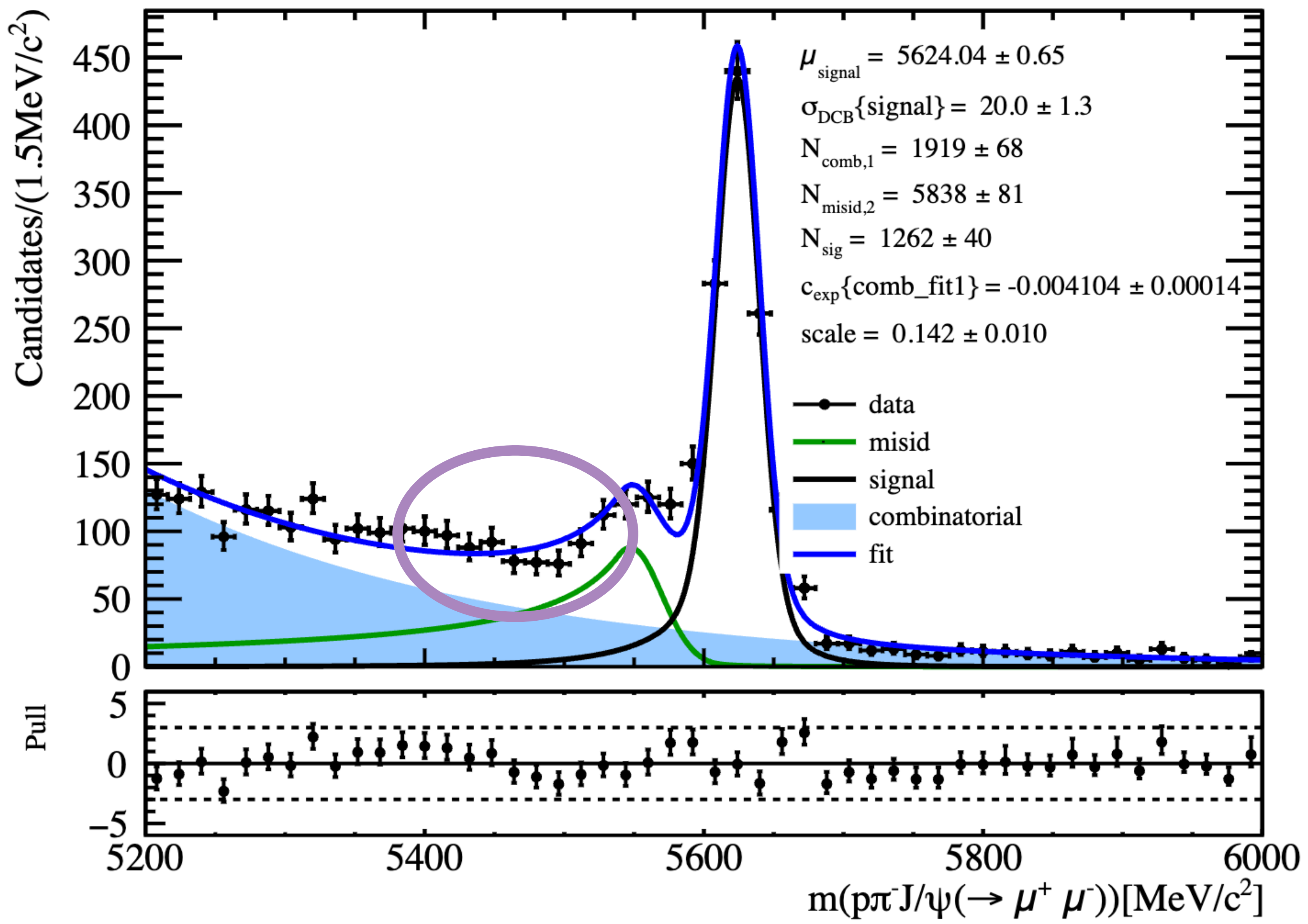
  Main background components

  - $B^0 \to K^*(\to K\pi)\mu\mu$ double misID, $B_s \to \phi(\to KK)\mu\mu$, $B_{(s)} \to \pi\pi\mu\mu$

B^0 background

- Highest contamination background: $(36 \pm 7)\ \%$ in Run 2 and $(33 \pm 6)\ \%$ in Run 1

- Tested tight B^0veto: abs(Lb_M0123_Subst2_p2K - 5280) > X | (Proton_ProbNNp>Proton_ProbNNk + Y)



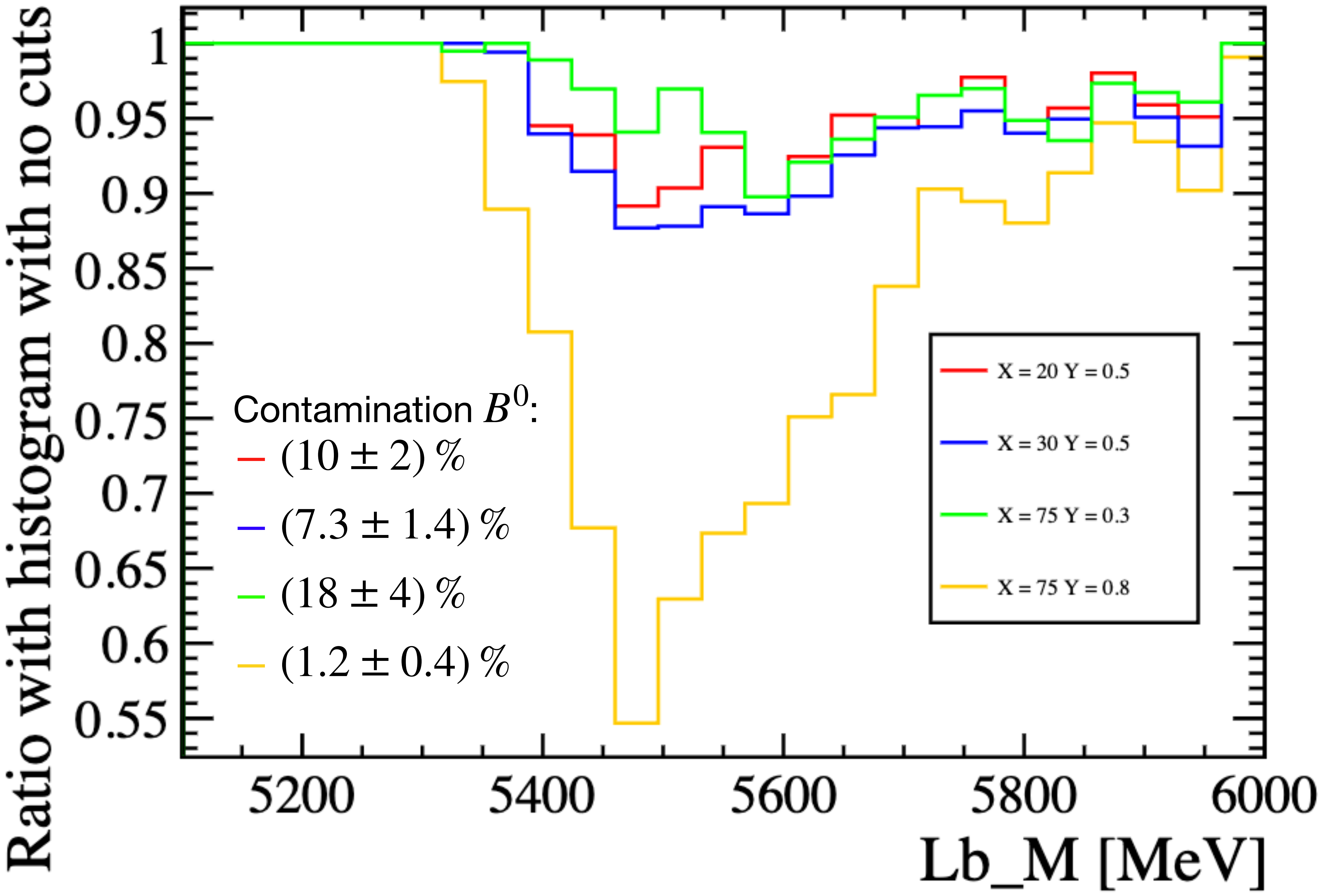
Tight B^0 veto: X = 75, Y = 0.8

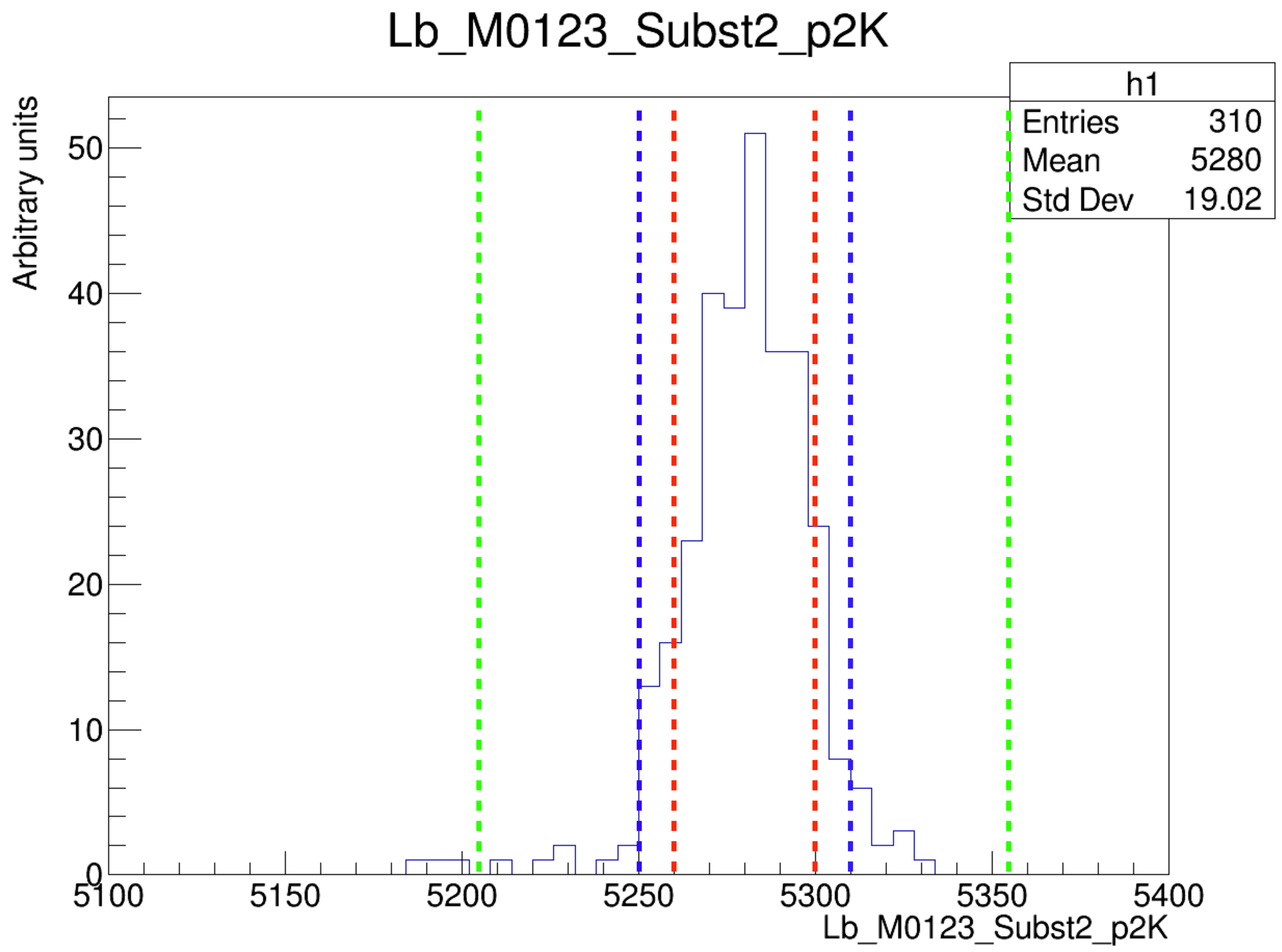
Contamination: $(1.2 \pm 0.4)\ \%$ in full mass range in Run 1

—> Leads to **sculpting** of combinatorial background

B^0 background

- Looked at the sculpting in data events with BDT cut bdt<0.5





X = 20, Y = 0.5 chosen

Simultaneous fit

- Idea: Fit $\Lambda_b^0 \to p\pi^-\mu^+\mu^-$ and $\Lambda_b^0 \to pK^-\mu^+\mu^-$ simultaneously sharing the $\Lambda_b^0 \to pK^-\mu^+\mu^-$ yield to control the $K \to \pi$ misID in $\Lambda_b^0 \to p\pi^-\mu^+\mu^-$

$$\boxed{N_{PID>X}(\Lambda_b^0 \to pK^-(\to \pi^-)\mu^+\mu^-) = N_{PID<X}(\Lambda_b^0 \to pK^-\mu^+\mu^-)\frac{\varepsilon(K^- \to \pi^-)}{\varepsilon(K^- \to K^-)}}$$

Simultaneous fit

- Idea: Fit $\Lambda_b^0 \to p\pi^-\mu^+\mu^-$ and $\Lambda_b^0 \to pK^-\mu^+\mu^-$ simultaneously sharing the $\Lambda_b^0 \to pK^-\mu^+\mu^-$ yield to control the $K \to \pi$ misID in $\Lambda_b^0 \to p\pi^-\mu^+\mu^-$

$$N_{PID>X}(\Lambda_b^0 \to pK^-(\to \pi^-)\mu^+\mu^-) = N_{PID<X}(\Lambda_b^0 \to pK^-\mu^+\mu^-)\frac{\varepsilon(K^- \to \pi^-)}{\varepsilon(K^- \to K^-)}$$

$$\boxed{\frac{\epsilon(K^- \to \pi^-)}{\epsilon(K^- \to K^-)} = \frac{N^{MC}_{PID>X}(\Lambda_b^0 \to pK^-(\to \pi^-)J/\psi)}{N^{MC}_{PID<X}(\Lambda_b^0 \to pK^-J/\psi)}}$$

yield of the pKJ/ψ MC with $p\pi$ PID selection
ProbNNpi*(1-ProbNNk) > 0.4

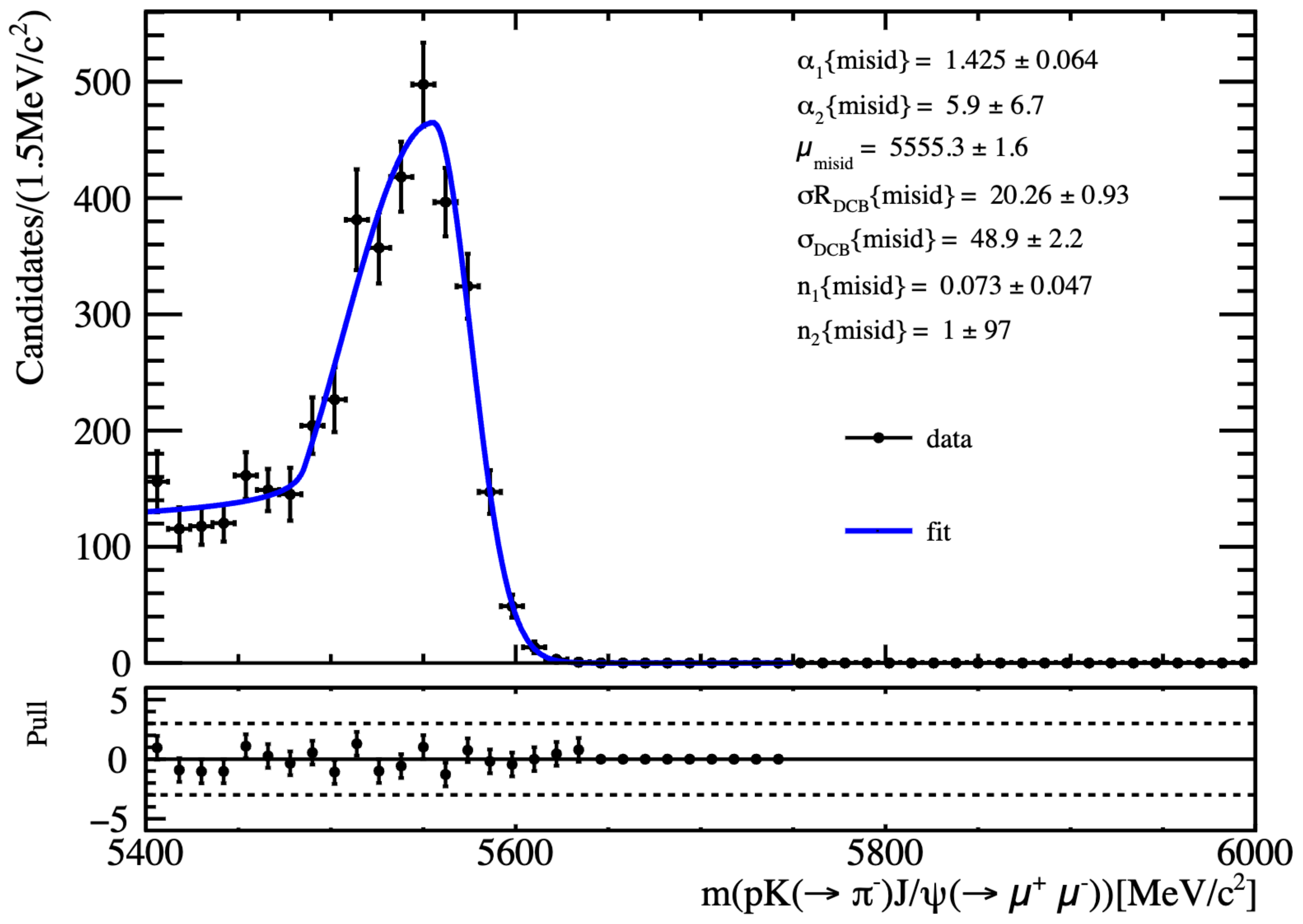
yield of the pKJ/ψ MC with pK PID selection
ProbNNpi*(1-ProbNNk) < 0.4

Simultaneous fit

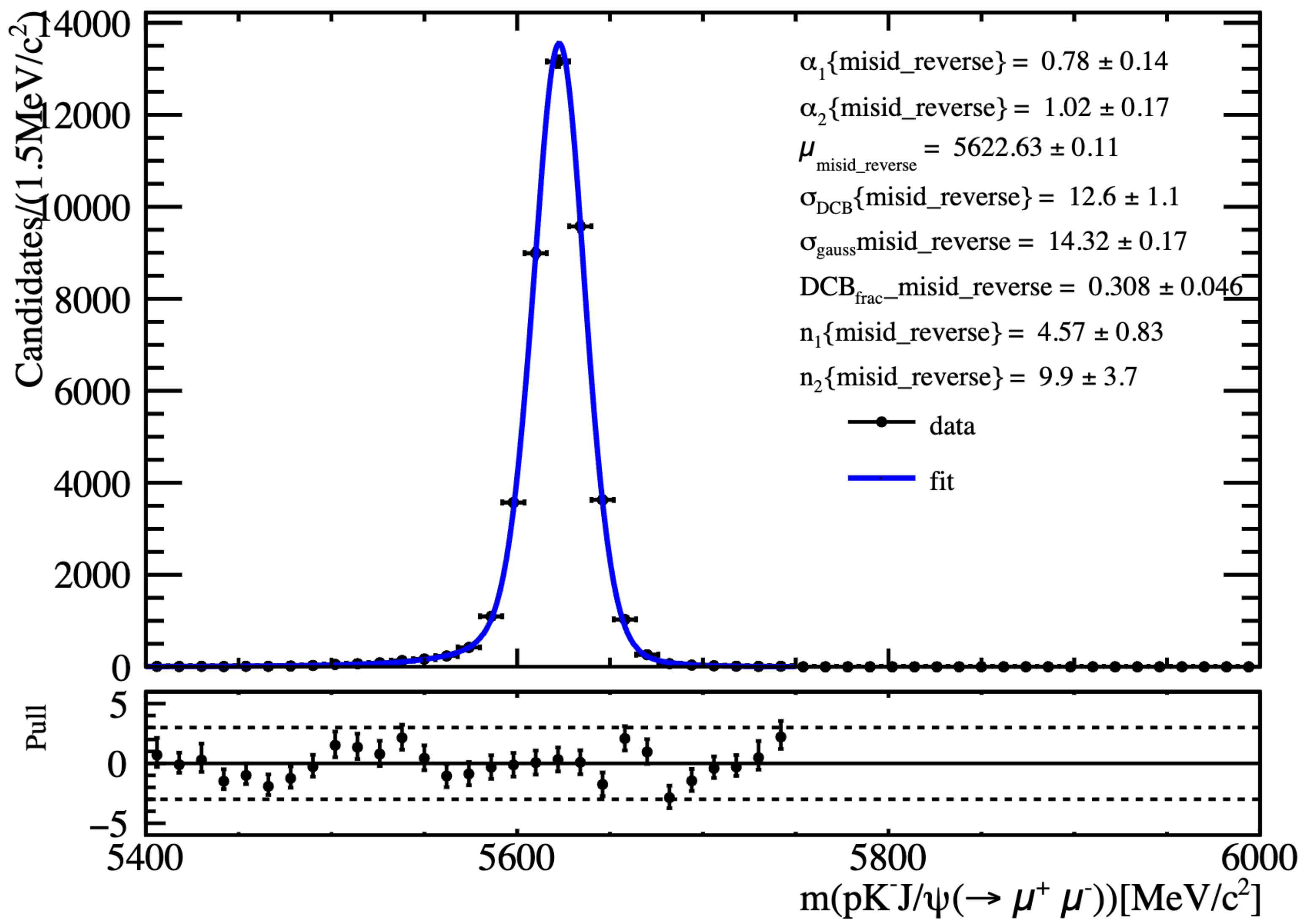
- Fits on MC are performed to extract shape parameters (α, n) that are fixed in the simultaneous fit on data

$$N_{PID>X}(\Lambda_b^0 \to pK^-(\to \pi^-)\mu^+\mu^-) = N_{PID<X}(\Lambda_b^0 \to pK^-\mu^+\mu^-)\frac{\varepsilon(K^- \to \pi^-)}{\varepsilon(K^- \to K^-)}$$

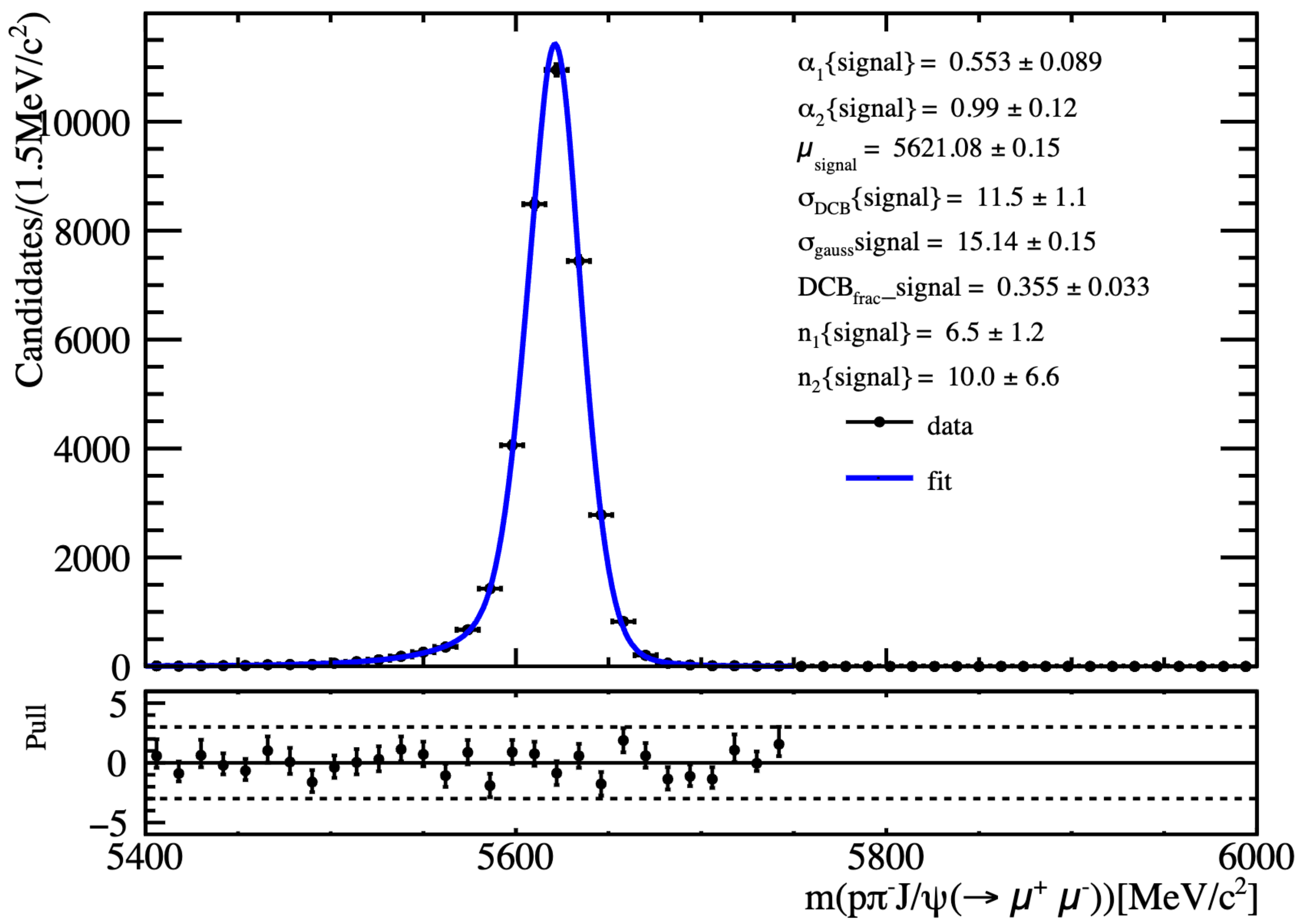
$\Lambda_b^0 \to pK^-J/\psi$ MC as $\Lambda_b^0 \to p\pi^-J/\psi$



$\Lambda_b^0 \to pK^-J/\psi$

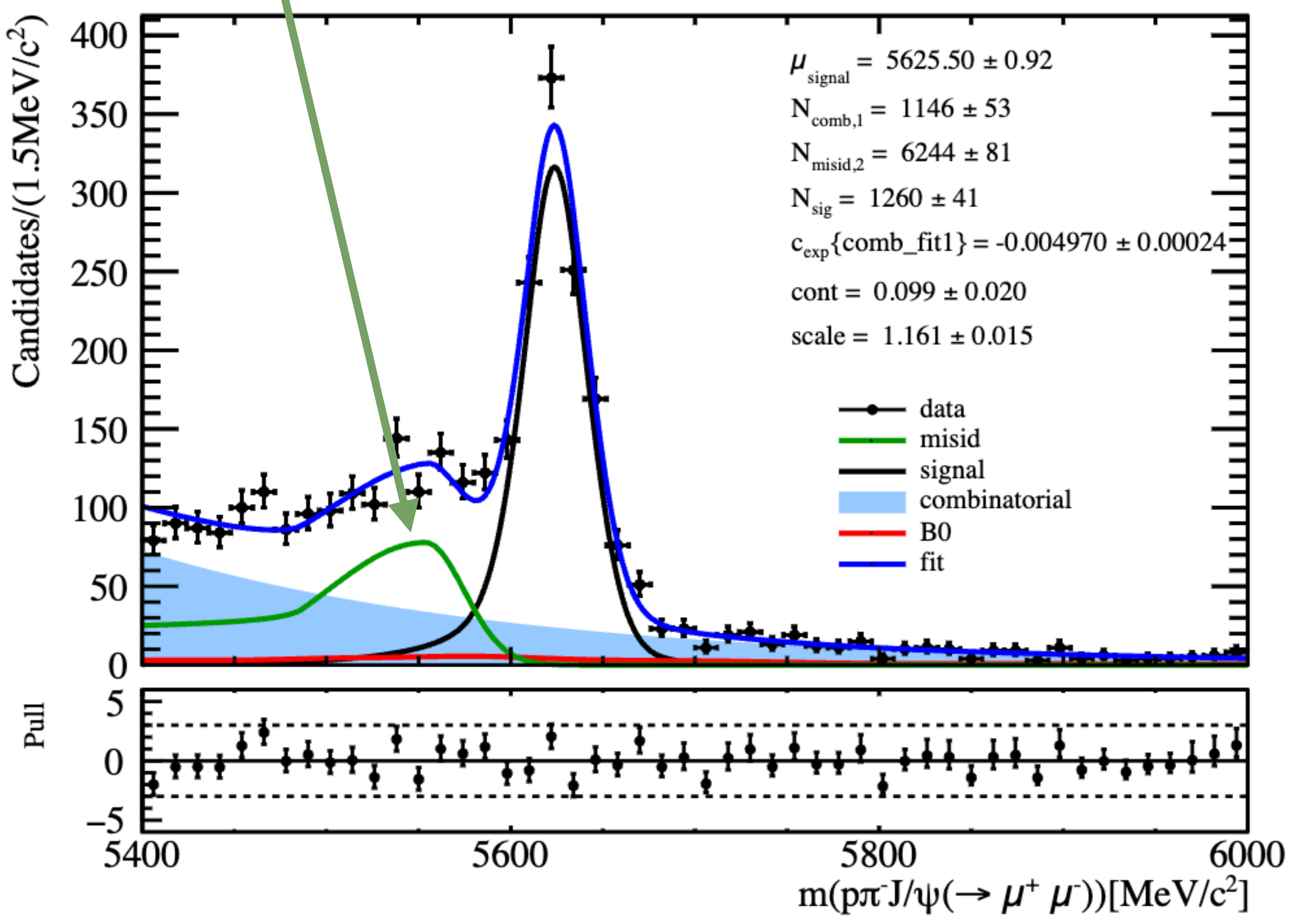


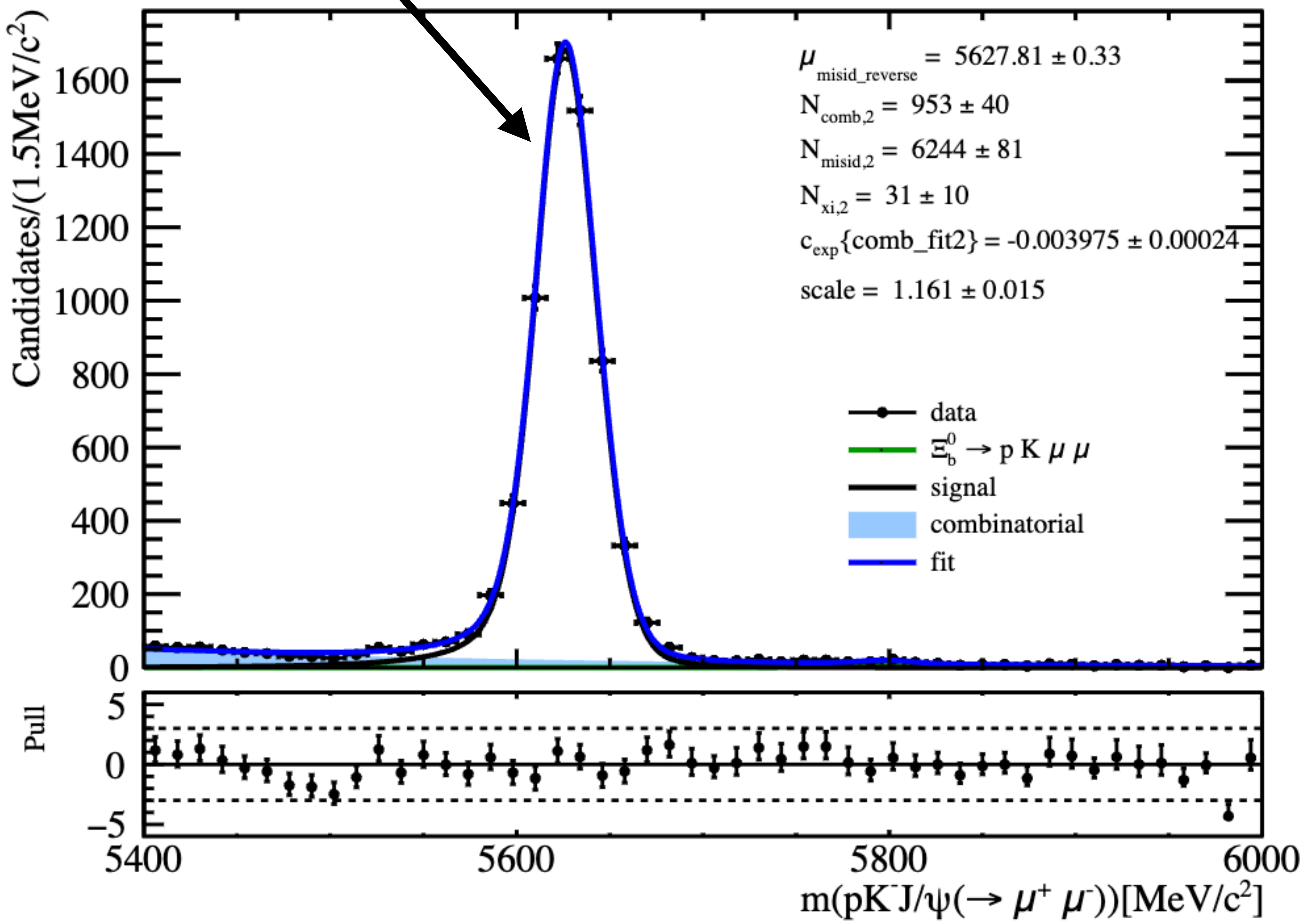
$\Lambda_b^0 \to p\pi^-J/\psi$



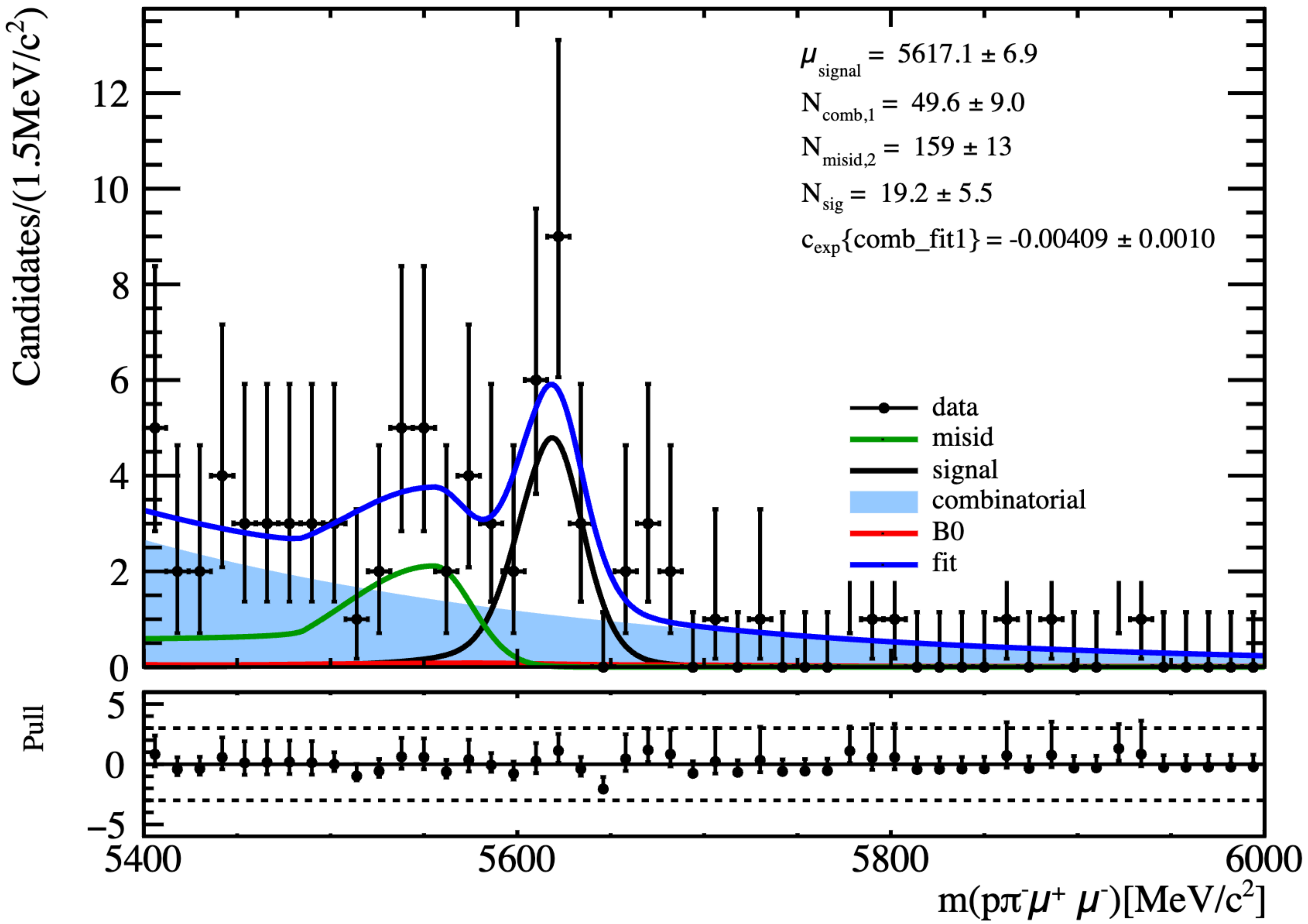
Simultaneous fit

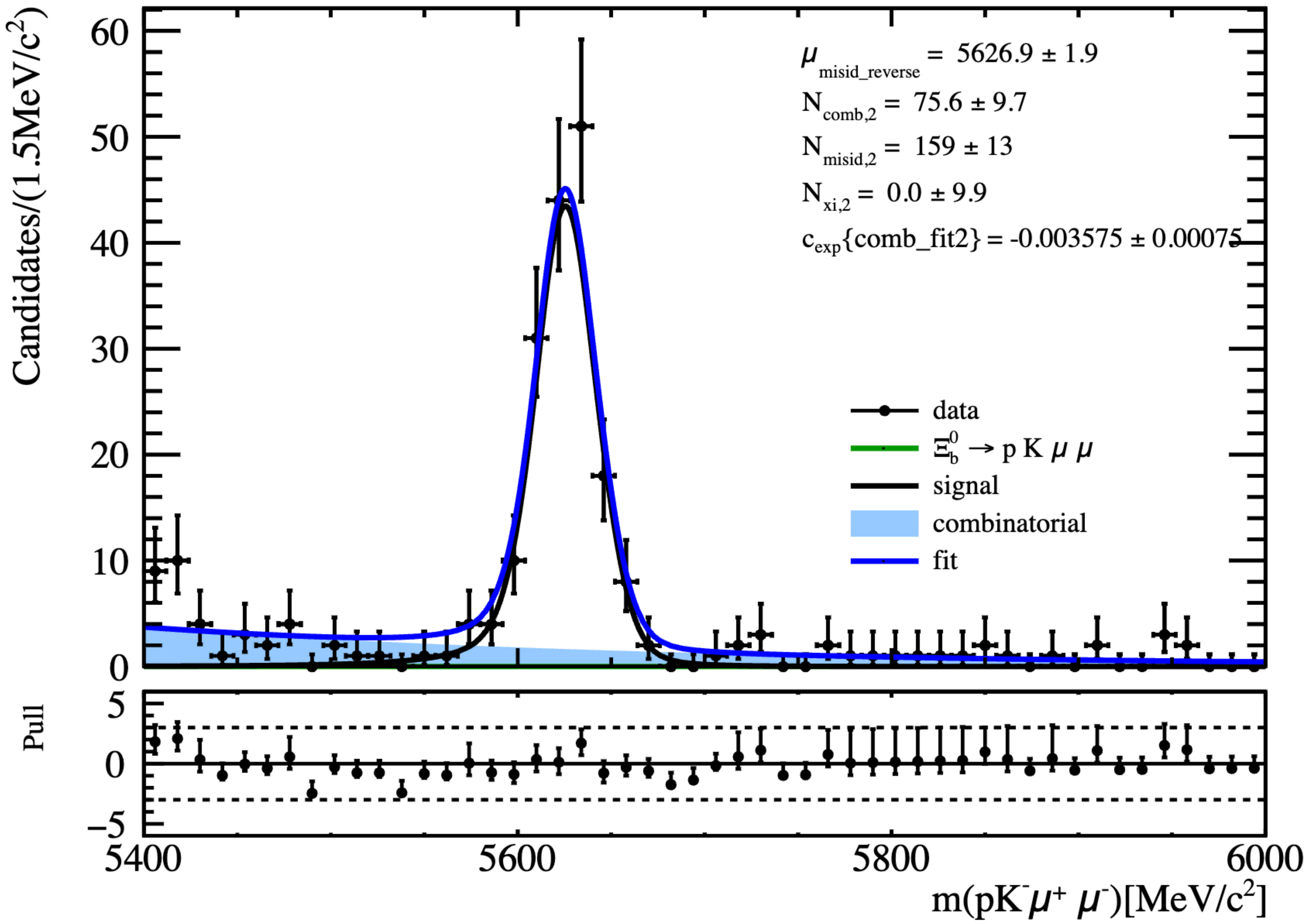
$$\boxed{N_{PID>X}(\Lambda_b^0 \to pK^-(\to \pi^-)\mu^+\mu^-)} = \boxed{N_{PID<X}(\Lambda_b^0 \to pK^-\mu^+\mu^-)}\frac{\varepsilon(K^- \to \pi^-)}{\varepsilon(K^- \to K^-)}$$





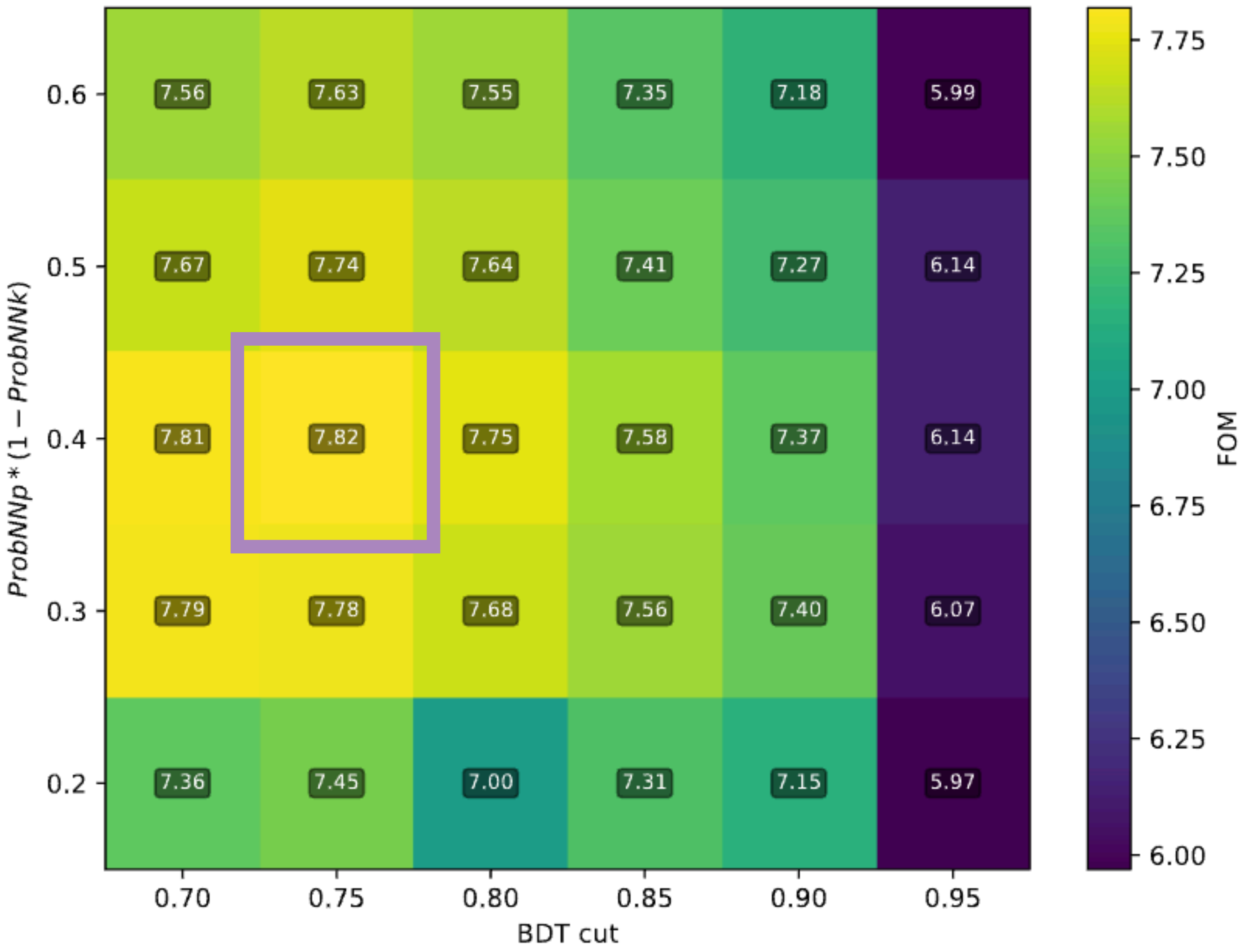
Results run1 rare

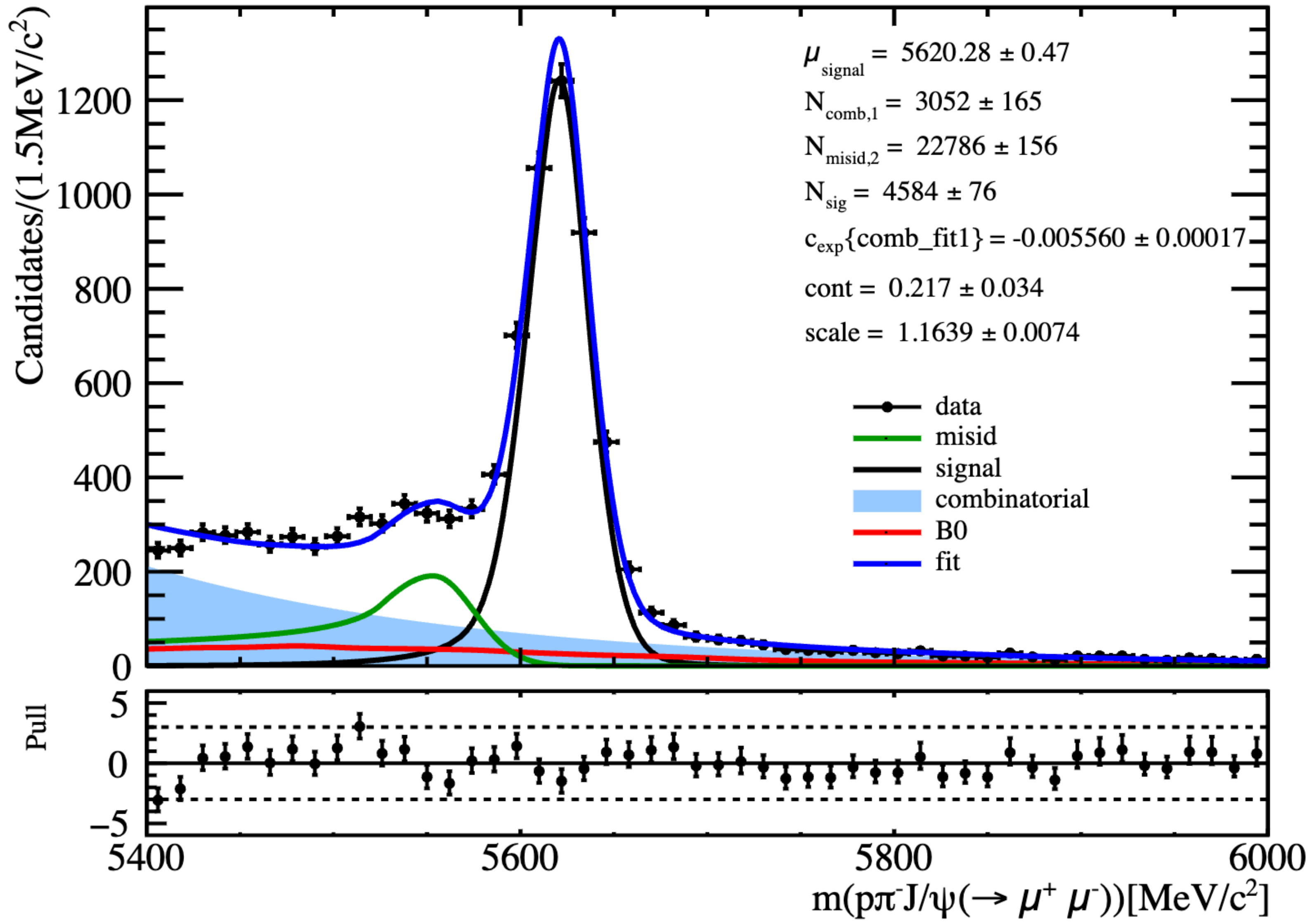


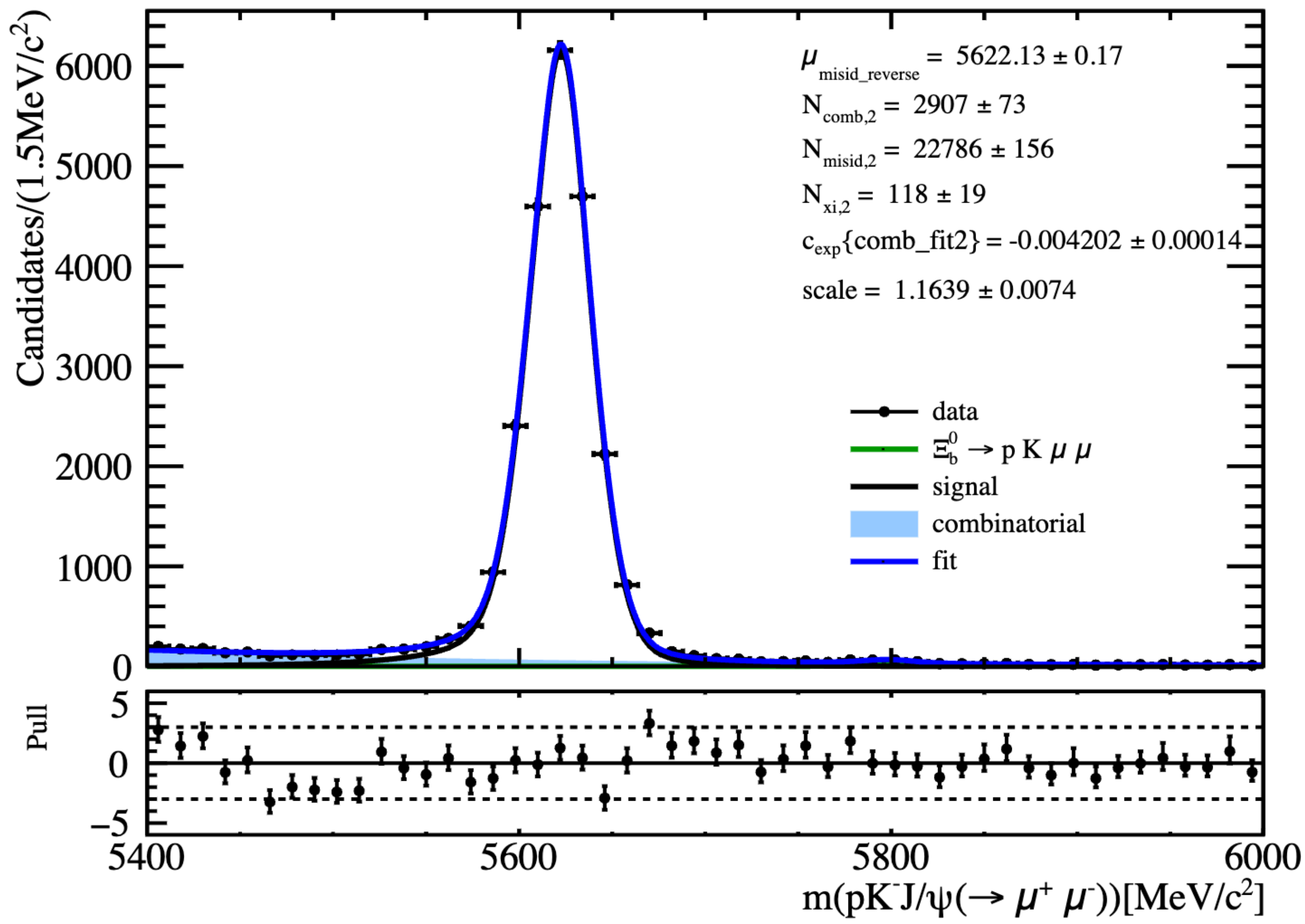


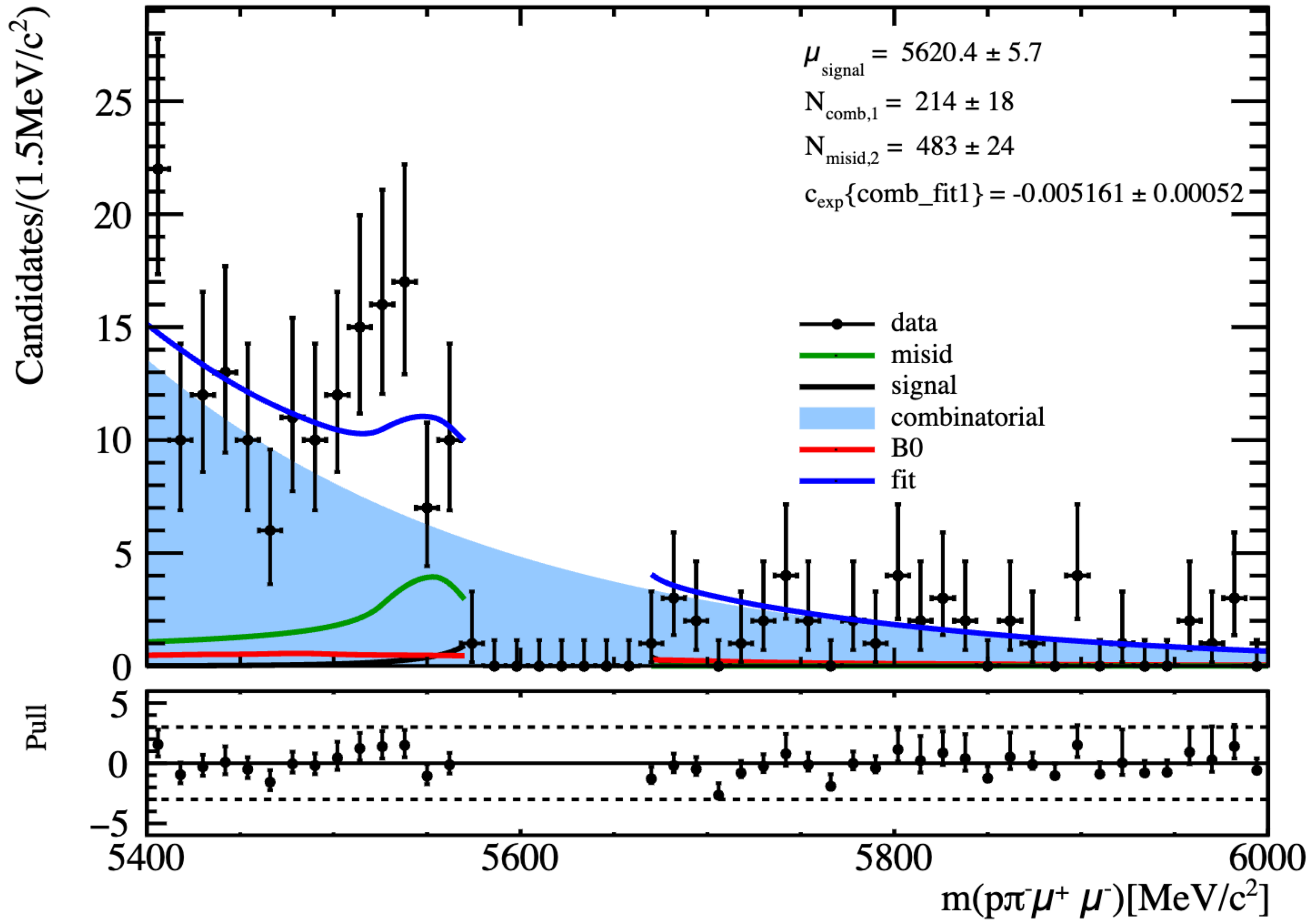
Expected number of events: 21 ± 9

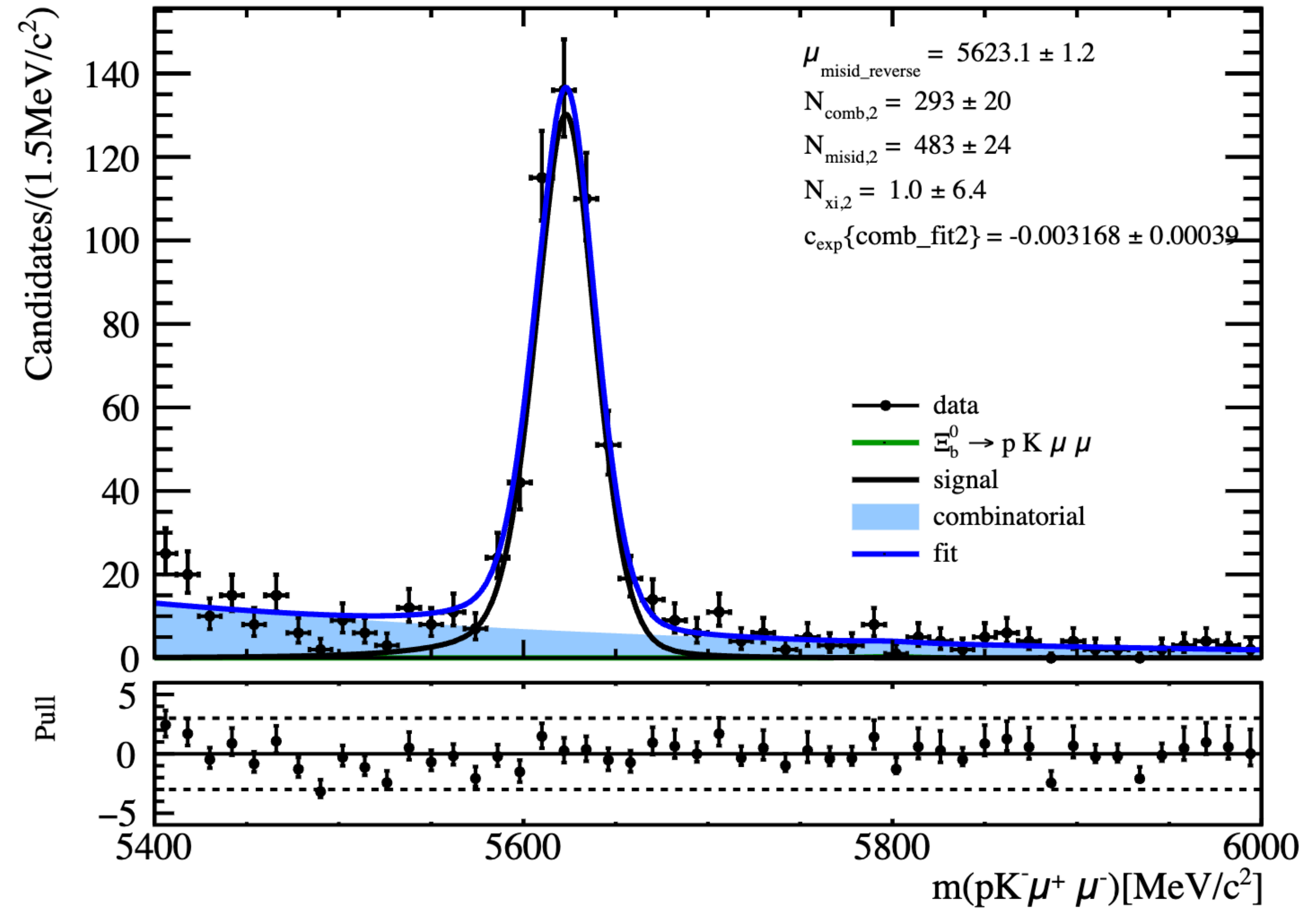
Results run2











Expected number of events: 71 ± 30

Conclusion

$$\frac{\mathscr{B}(\Lambda_b \to p\pi\mu\mu)}{\mathscr{B}(\Lambda_b \to p\pi J/\psi(\to \mu\mu)}$$

Run1 analysis	0.044 ± 0.012 ± 0.007
Run1	0.041 ± 0.012 ± XXX
Run2*	0.045 ± 0.005 ± XXX

- Run 2 blinded
- Run toys for the integrated BF measurement
- Start thinking about systematic uncertainties (mass window, fit choice etc..)

Task	Run 1	Run 2
Tuples	✅	✅
Background studies	✅	✅
MVA	✅	✅
Fits & yields	🔄	🔄
Simulation corrections	✅	✅
Efficiencies	✅	✅
Toys		
Systematics		

*Used expected number of events for Run2 computation with statistical error $\sqrt{N_{expected}}$

Thank you for your attention

15.05.2025

Trigger cuts

B2XMuMu stripping line for
$B \to K^*(\to K^+\pi^-)\mu^+\mu^-$,
w/o PID requirements on K^+

Trigger	RunI	RunII
L0	L0MuonDecision_TOS	L0MuonDecision_TOS
HLT1	TrackAllL0 TrackMuonDecision	TrackMVA
HLT2	Topo(2,3,4)BodyBBDTDecision TopoMu(2,3,4)BodyBBDTDecision	Topo(2,3,4)BodyDecision TopoMu(2,3,4)BodyDecision

Variable	Stripping value
$B^0_{(s)}$ χ^2_{vtx}/ndf	< 8
$B^0_{(s)}$ χ^2_{IP}	< 16
$B^0_{(s)}$ DIRA	> 0.9999
$B^0_{(s)}$ χ^2_{FD}	> 121
$m_{B^0_{(s)}}$	4900 MeV $< m_{B^0_{(s)}} <$ 7000 MeV
m_N	0 MeV $< m_N <$ 6200 MeV
N χ^2_{FD}	> 9
N χ^2_{vtx}/ndf	< 12
$m_{\mu^+\mu^-}$	$<$ 7100 MeV
$\mu^+\mu^-$ χ^2_{vtx}/ndf	< 12
μ^+,μ^- $DLL_{\mu\pi}$	$> -3^*$
μ^+,μ^- isMUON	*true**
tracks min χ^2_{IP}	> 9
tracks ghost Prob	< 0.4

Selections

Run 1 selection

- Very tight PID cuts
  - Proton PID
  - all misID

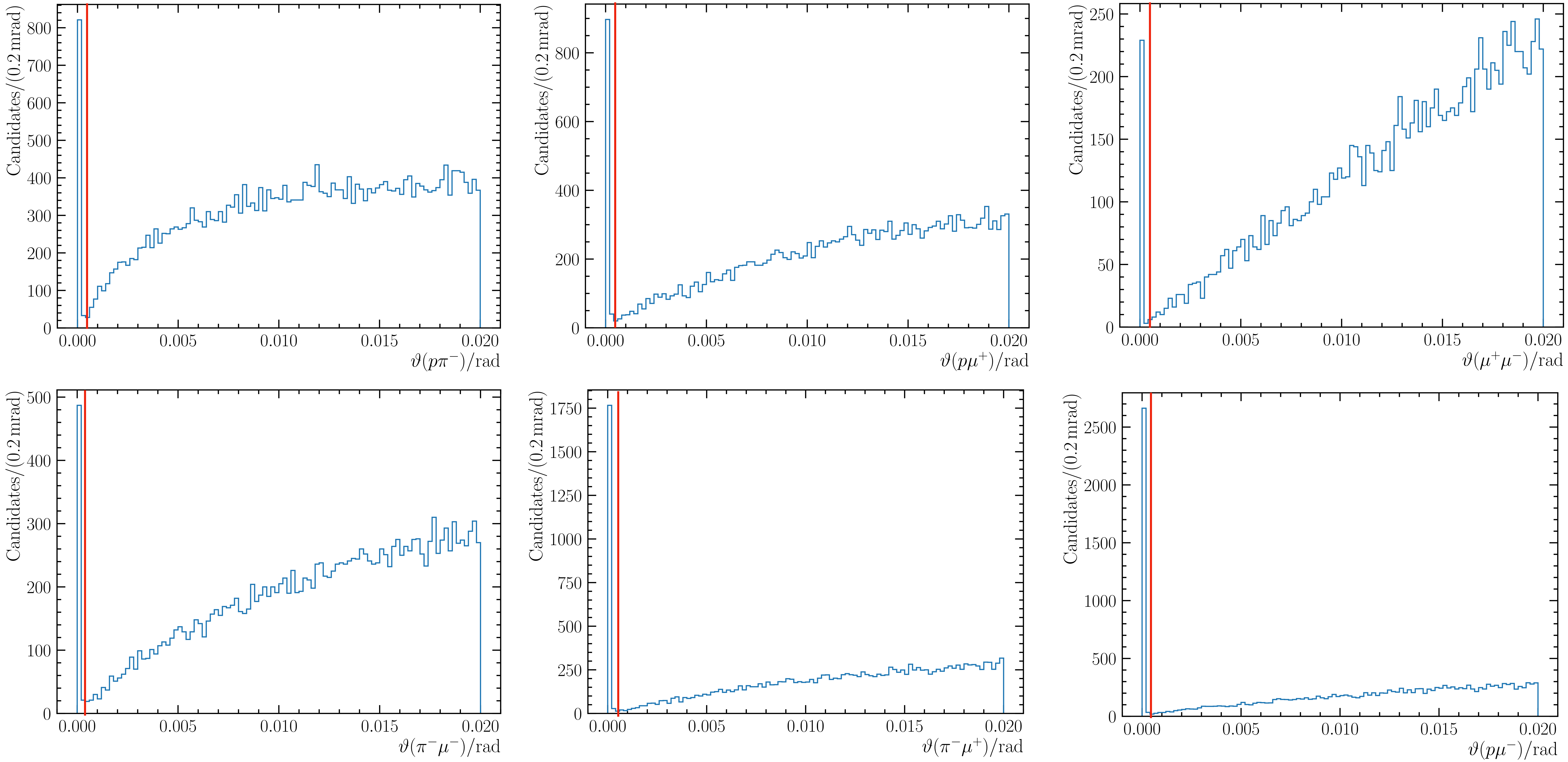
Now

- Loosen PID cuts
- Use simultaneous fit to fit pk misID

Target	Selection DLL	Selection ProbNN
Λ_b^0	ENDVERTEX_CHI2 $<$ 20	ENDVERTEX_CHI2 $<$ 20
p	PIDp $>$ 0	ProbNN_p*(1-ProbNN_k) $>$ 0.4
p	(PIDp - PIDK) $>$ 8	
π	PIDK $<$ -5	ProbNN_pi*(1-ProbNN_k) $>$ 0.4
π	PT $>$ 400 MeV P $>$ 2000 MeV	PT $>$ 400 MeV P $>$ 2000 MeV
p	PT $>$ 400 MeV P $>$ 7500 MeV	PT $>$ 400 MeV P $>$ 7500 MeV
π, p	isMuon $=$ 0	isMuon $=$ 0
μ	ProbNNmu $>$ 0.1	ProbNNmu $>$ 0.1

Target	Selection DLL		Selection ProbNN	
	Region (MeV)	Cut	Region	Cut
B^0 misID	5246-5330	pDLL$_{pK}$ >17	$\lvert m_{B^0} - m(p\pi\mu\mu)_{K\leftarrow p}\rvert < 30$	p_ProbNN_p $>$ p_ProbNN_k+ 0.5
B^0 double misID	/	/	$\lvert m_{B^0} - m(p\pi\mu\mu)_{Kp\leftarrow p\pi}\rvert < \sigma_{B^0}$	p_ProbNN_p $>$ p_ProbNN_pi+0.3 & π_ProbNN_pi $>$ π_ProbNN_k+0.3
B_s^0 misID	5348-5406	πDLL$_K$ <-10	$\lvert m_{B_s^0} - m(p\pi\mu\mu)_{KK\leftarrow\pi p}\rvert < \sigma_{B_s^0}$	p_ProbNN_p $>$ p_ProbNN_k+0.3 & π_ProbNN_pi $>$ π_ProbNN_k+0.3
$\pi\pi$ misID	5247-5329 5348-5406	pDLL$_p$ >5	$m(p\pi\mu\mu)_{\pi\leftarrow p} > m_{B^0} - \sigma_{B^0}$ & $m(p\pi\mu\mu)_{\pi\leftarrow p} < m_{B_s^0} - \sigma_{B_s^0}$	p_ProbNN_p $>$ p_ProbNN_pi+0.3
$\Lambda_b^0 \to pK$ misID	5569-5669	πDLL$_K$ < -15	/	/
ϕ veto	/	/	$\lvert m(p\pi)_{KK\leftarrow p\pi} - m_\phi\rvert > 12$	/
clones	/	/	all	$\theta_{p_1p_2} > 0.0005$ rad $[p_1 \neq p_2;\ p_i \in \{p, \pi, \mu^+, \mu^-\}]$
Λ_c semileptonic	/	/	$m(p\pi\mu^+)_{\pi\leftarrow\mu} > 2320$ & $m(p\pi\mu^+)_{\pi K\leftarrow\mu\pi} > 2320$	/
$\Lambda \to p\pi$	/	/	$\lvert m(p\pi) - m_\Lambda\rvert > 5$	/

Clone track cuts



Run2 (15-18) data after preselection

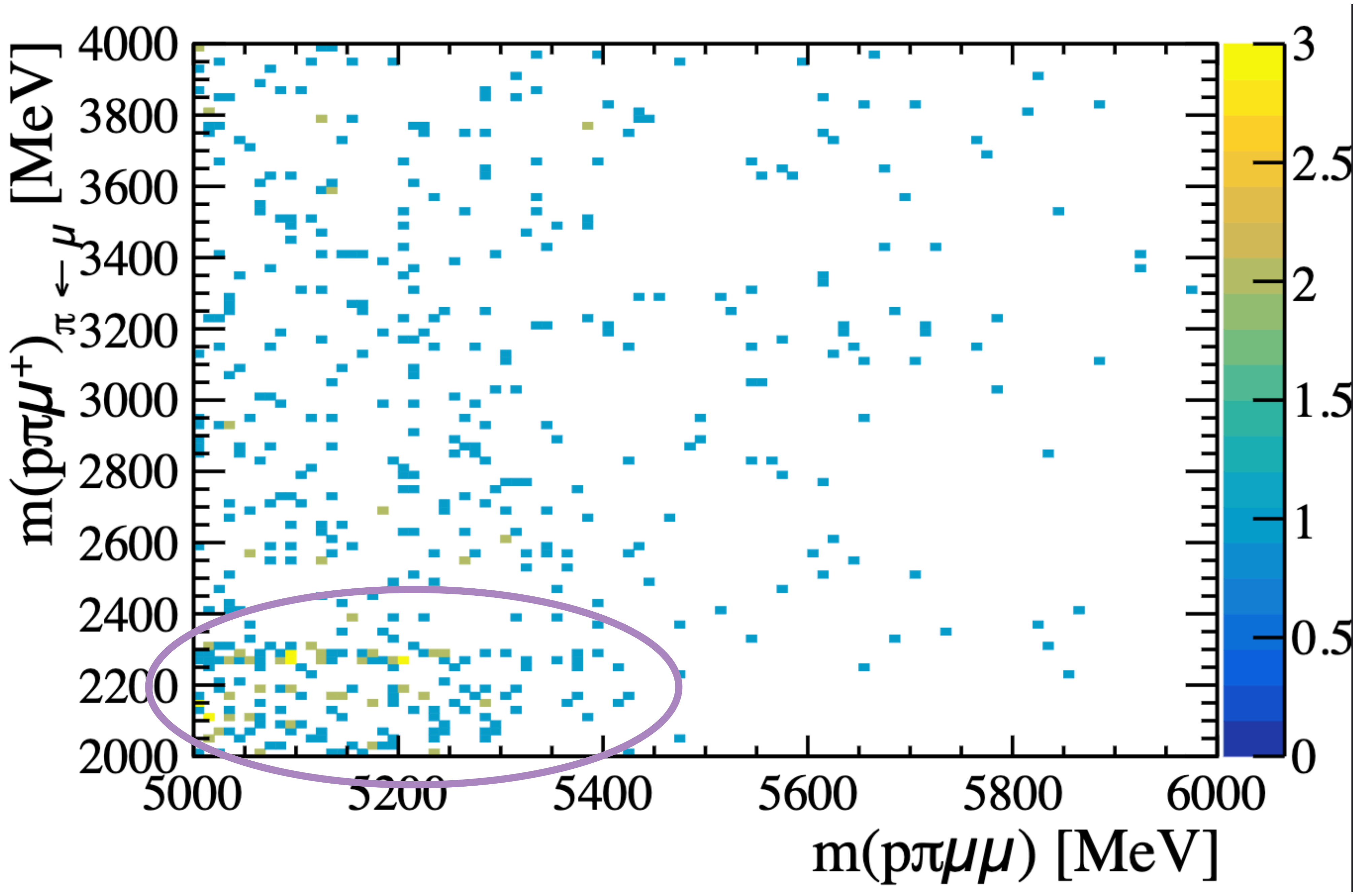
Opening angle ϑ:

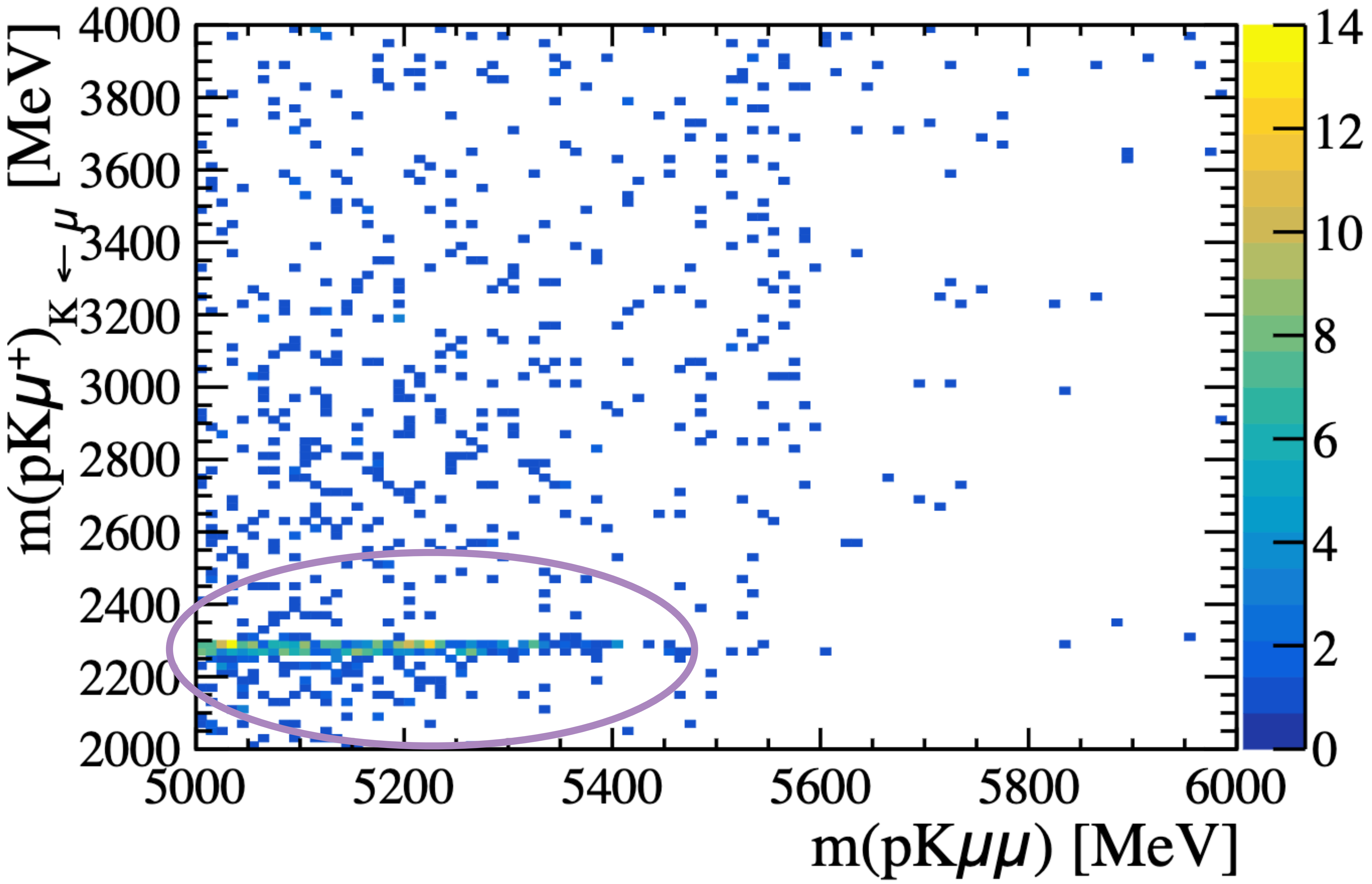
$$\boxed{\cos(\vartheta(\mu^+,\mu^-)) = \frac{\vec{p}(\mu^+)\vec{p}(\mu^-)}{|\vec{p}(\mu^+)||\vec{p}(\mu^-)|}}$$

- Removing remaining clone tracks by requiring $\vartheta(t_1, t_2) > 0.5\,\mathrm{mrad}$, $\varepsilon_{\mathrm{sig}}(\vartheta > 0.5\,\mathrm{mrad}) \approx 100\,\%$

Λ_c semileptonic vetoes

- Semileptonic: $\Lambda_b \to \Lambda_c(\to p\pi\pi)\mu\nu$, $\Lambda_b \to \Lambda_c(\to p\pi K)\mu\nu$
- Double semileptonic: $\Lambda_b \to \Lambda_c(\to p\pi\mu\nu)\mu\nu$, $\Lambda_b \to \Lambda_c(\to pK\mu\nu)\mu\nu$





Λ_c semileptonic vetoes

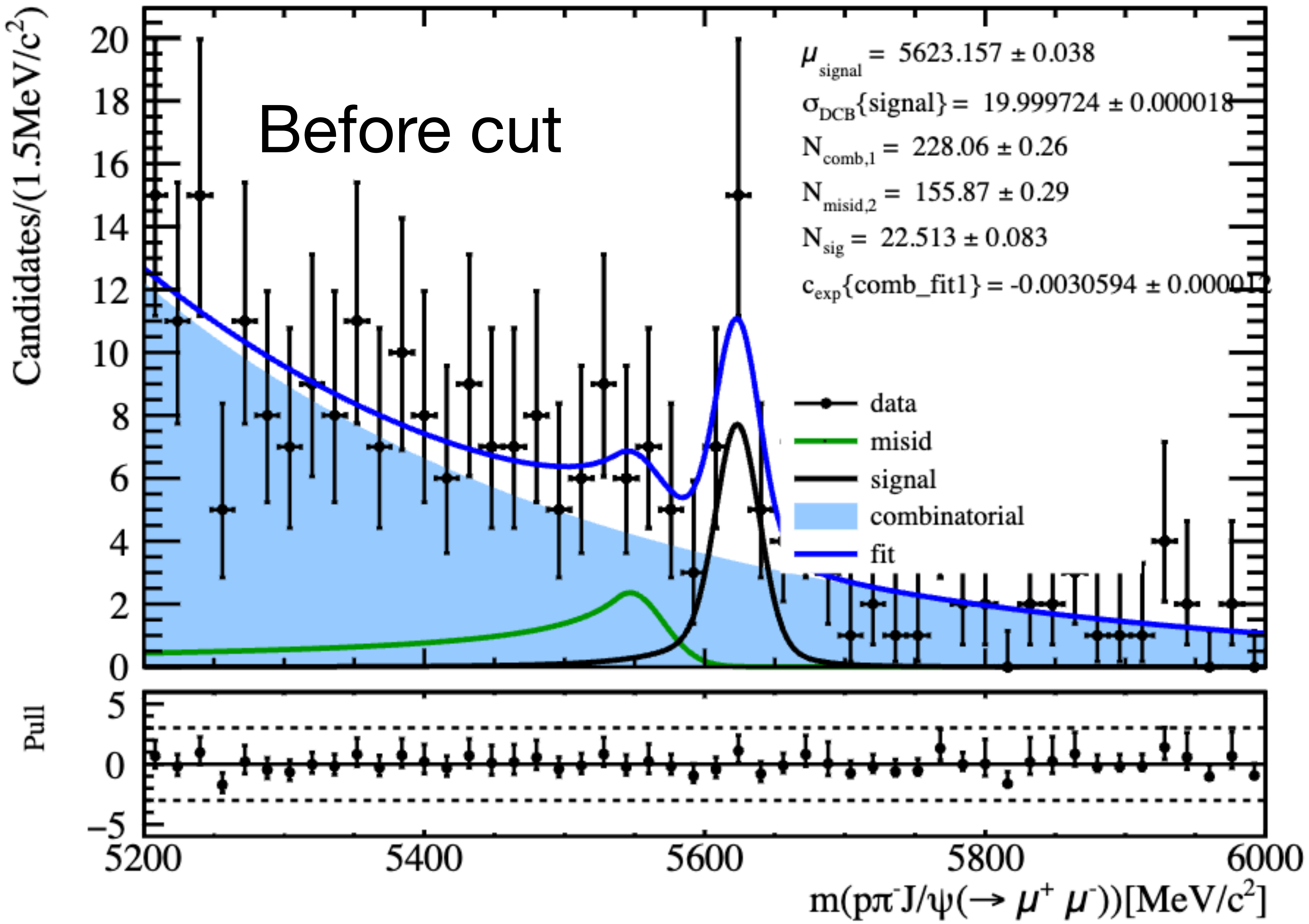
- Semileptonic: $\Lambda_b \to \Lambda_c(\to p\pi\pi)\mu\nu$, $\Lambda_b \to \Lambda_c(\to p\pi K)\mu\nu$
- Double semileptonic: $\Lambda_b \to \Lambda_c(\to p\pi\mu\nu)\mu\nu$, $\Lambda_b \to \Lambda_c(\to pK\mu\nu)\mu\nu$

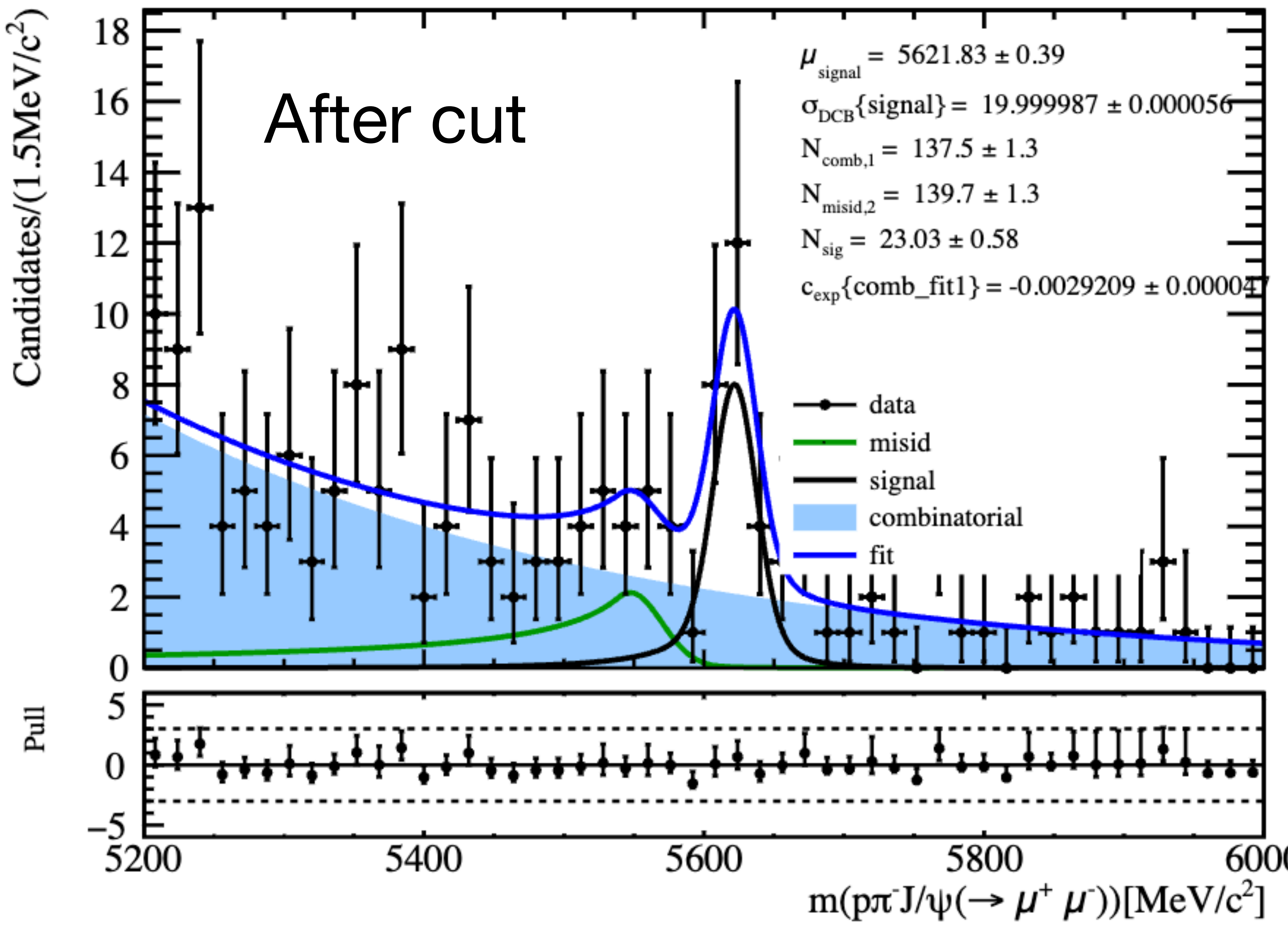
Vetoes to add: $m(p\pi\mu)_{\pi\leftarrow\mu} > 2300$ MeV and $m(p\pi\mu)_{K\pi\leftarrow\pi\mu} > 2300$ MeV

This double semileptonic veto also cuts the single semileptonic backgrounds $\Lambda_c \to p\pi\pi$ and $\Lambda_c \to p\pi K$

Adding μ ProbNNmu

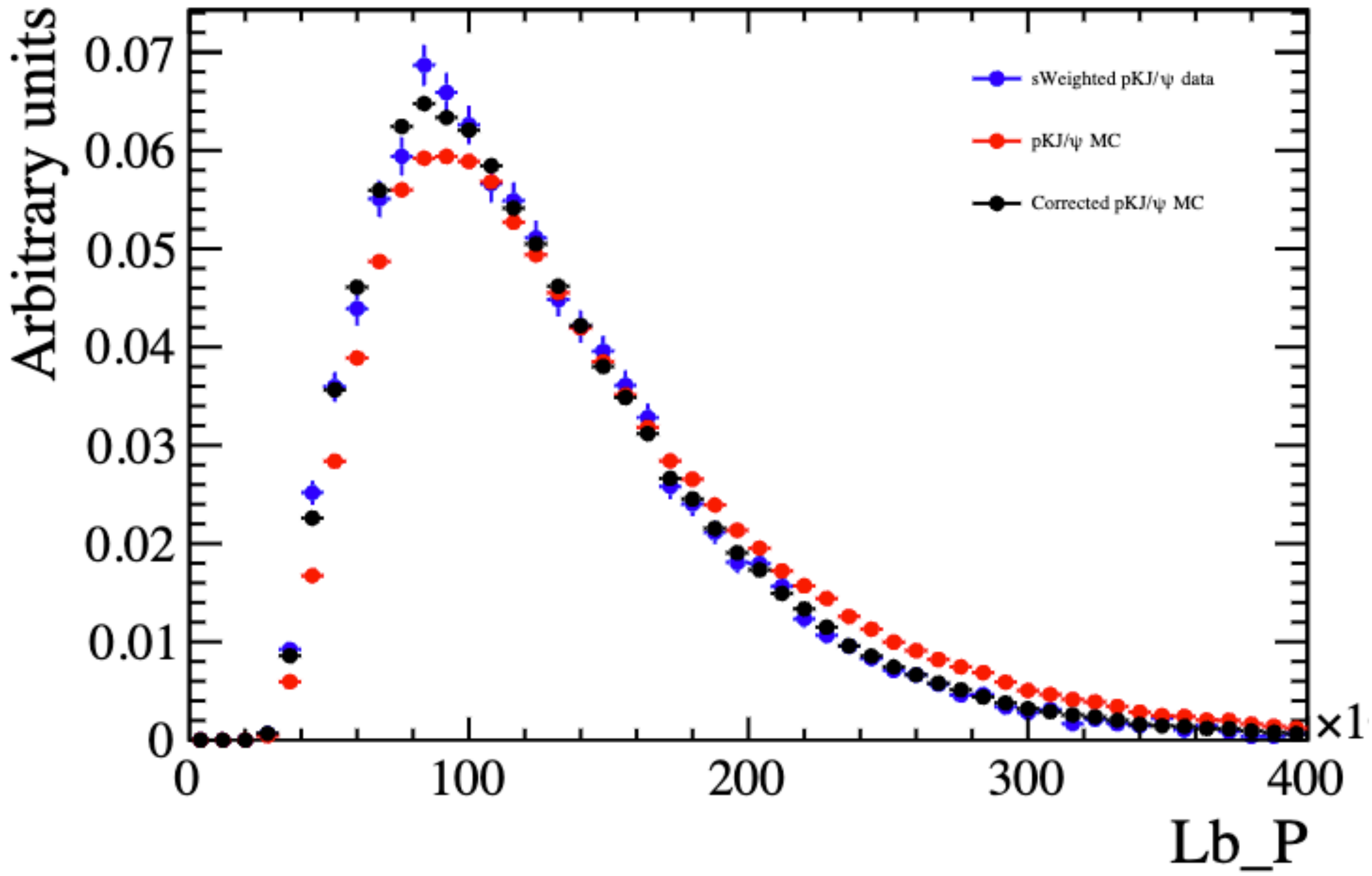
- L1_ProbNNmu > 0.1 && L2_ProbNNmu > 0.1

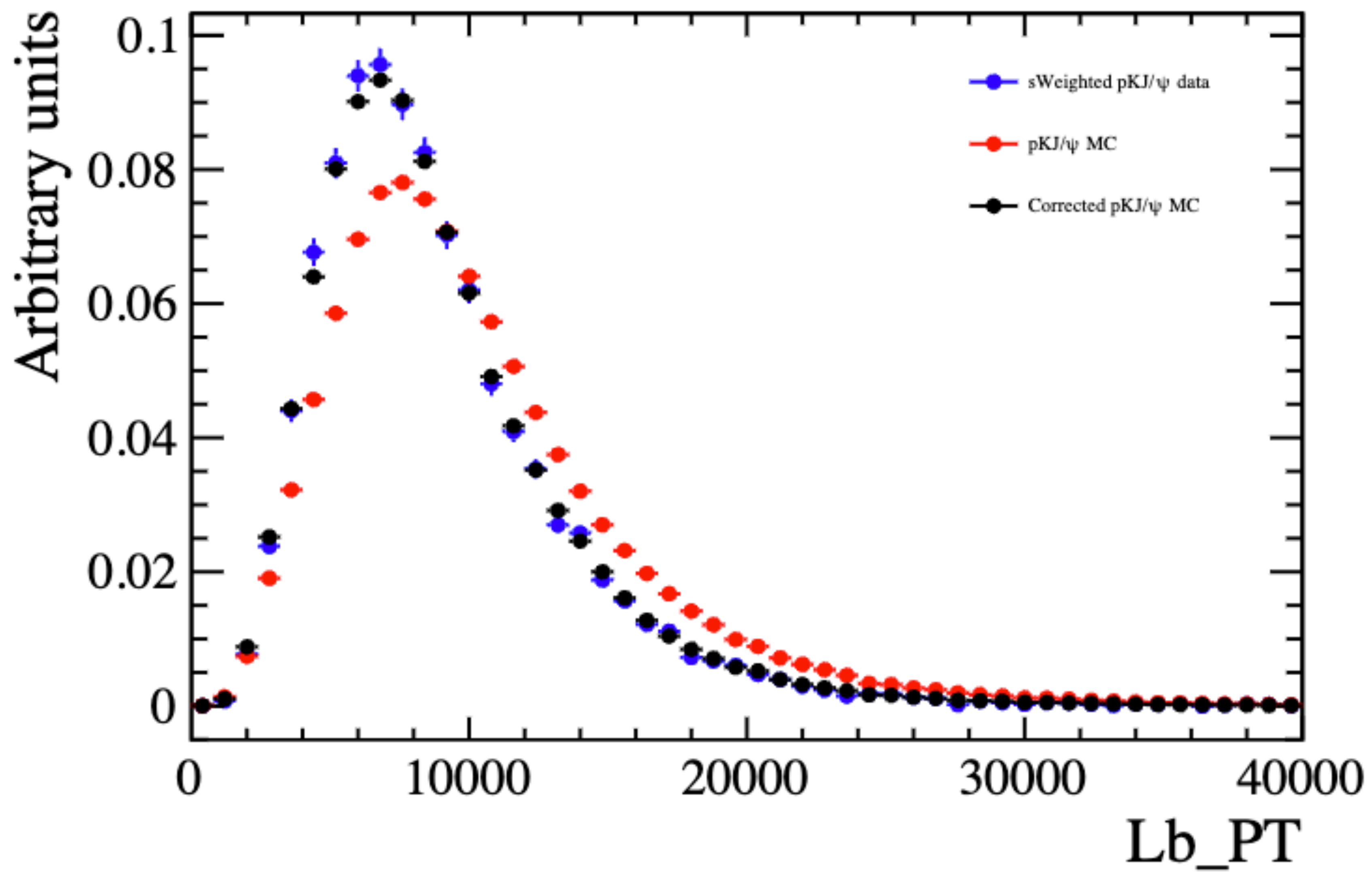


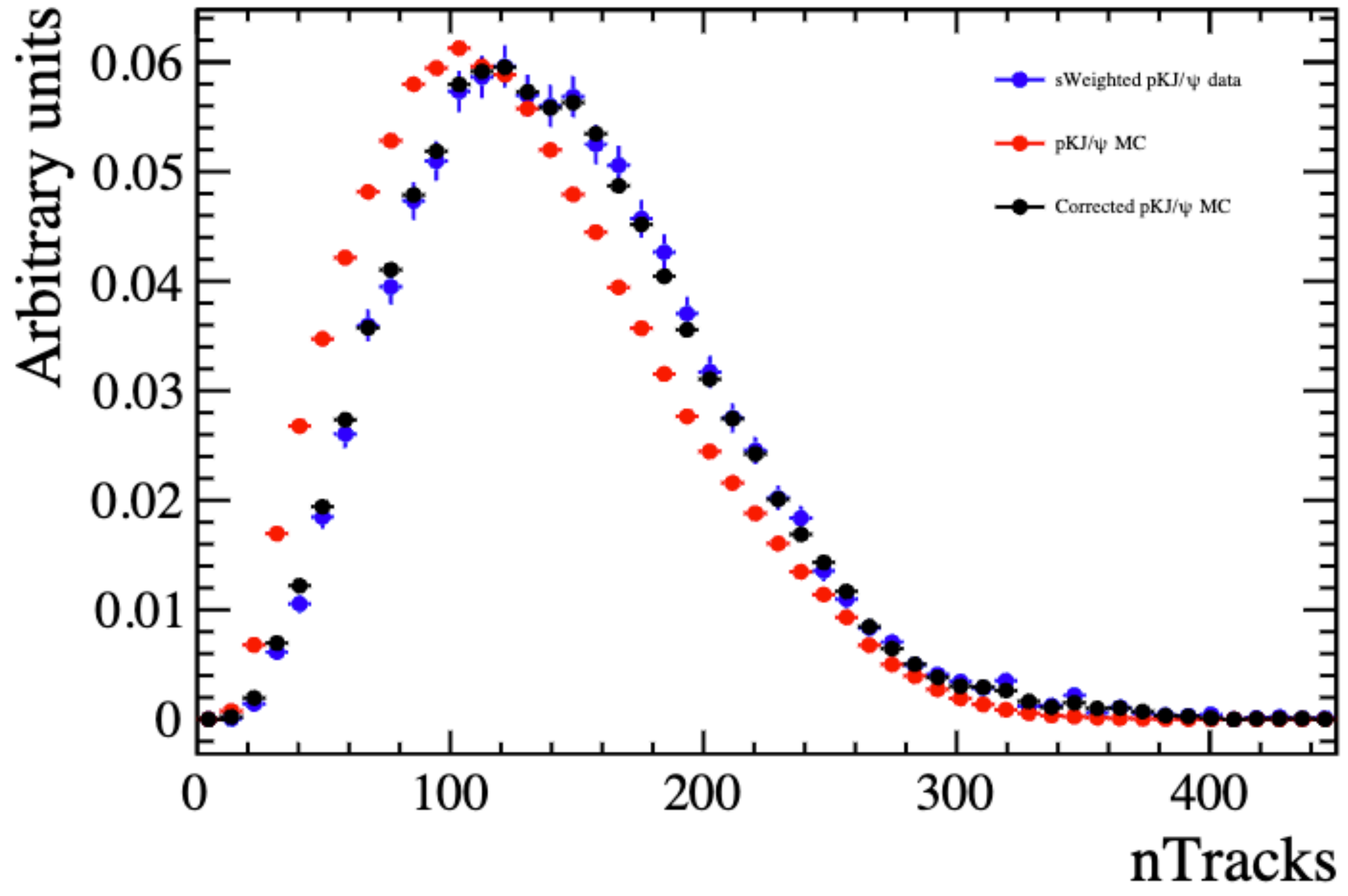


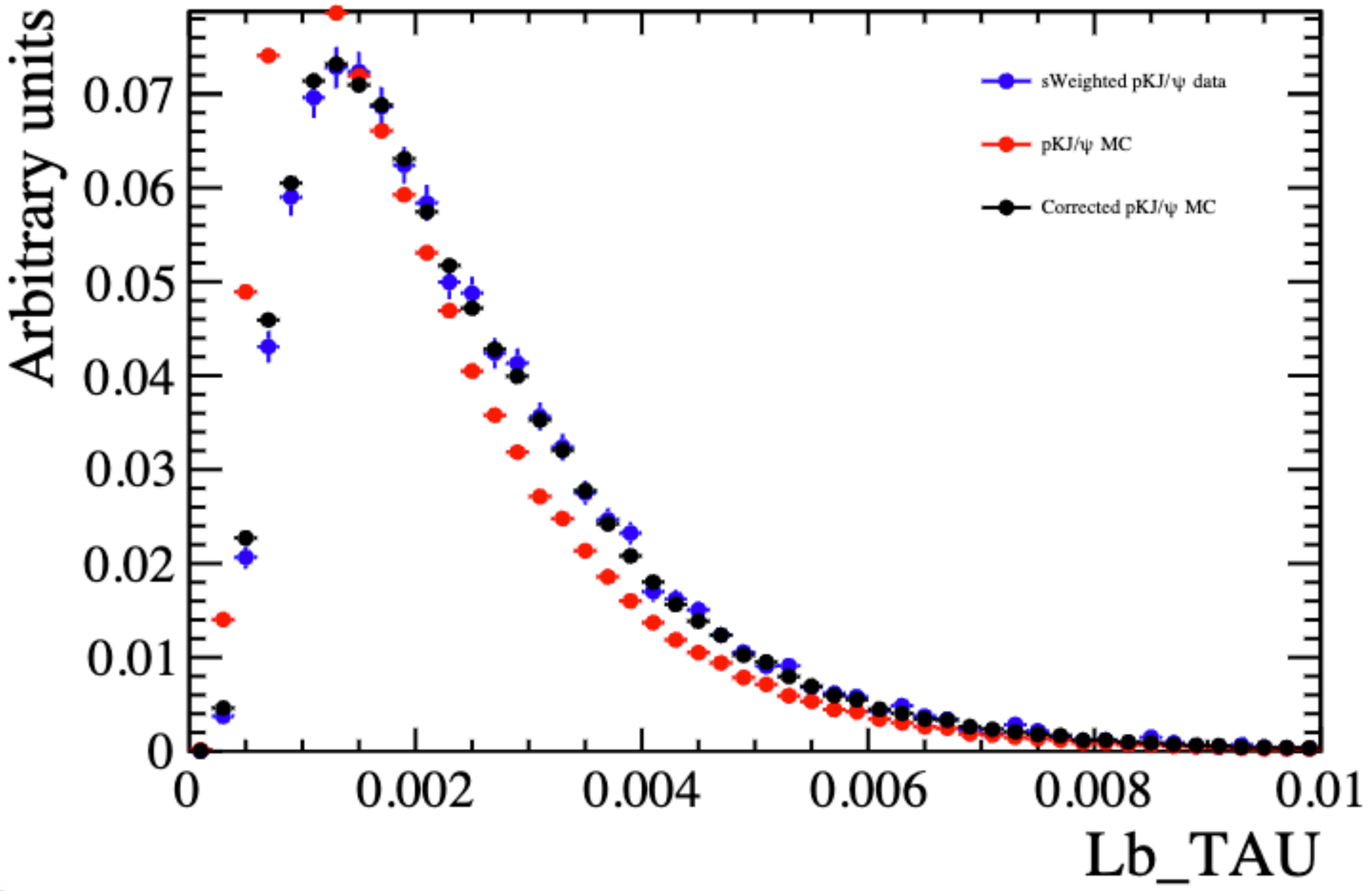
Kinematic corrections

- Run2



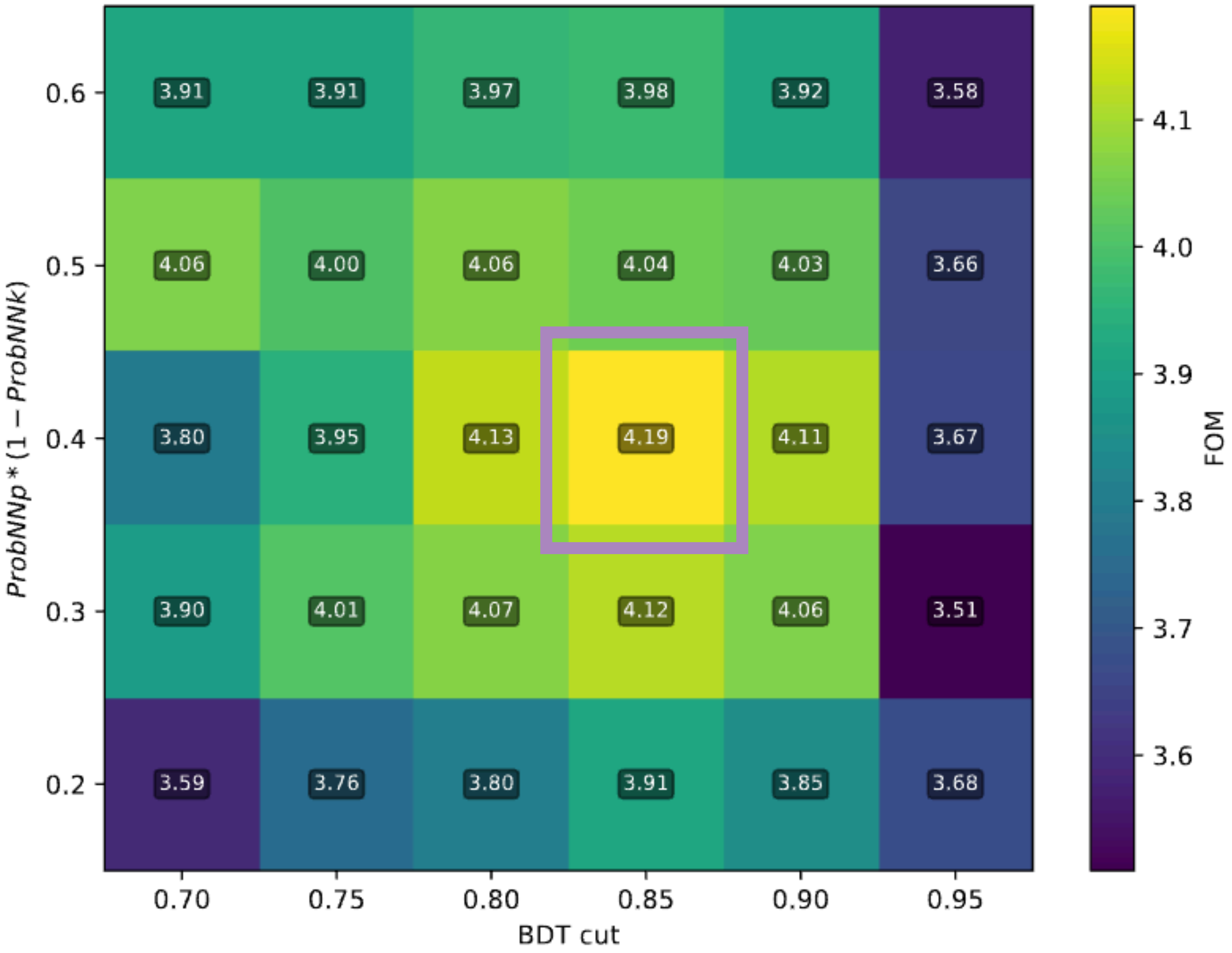




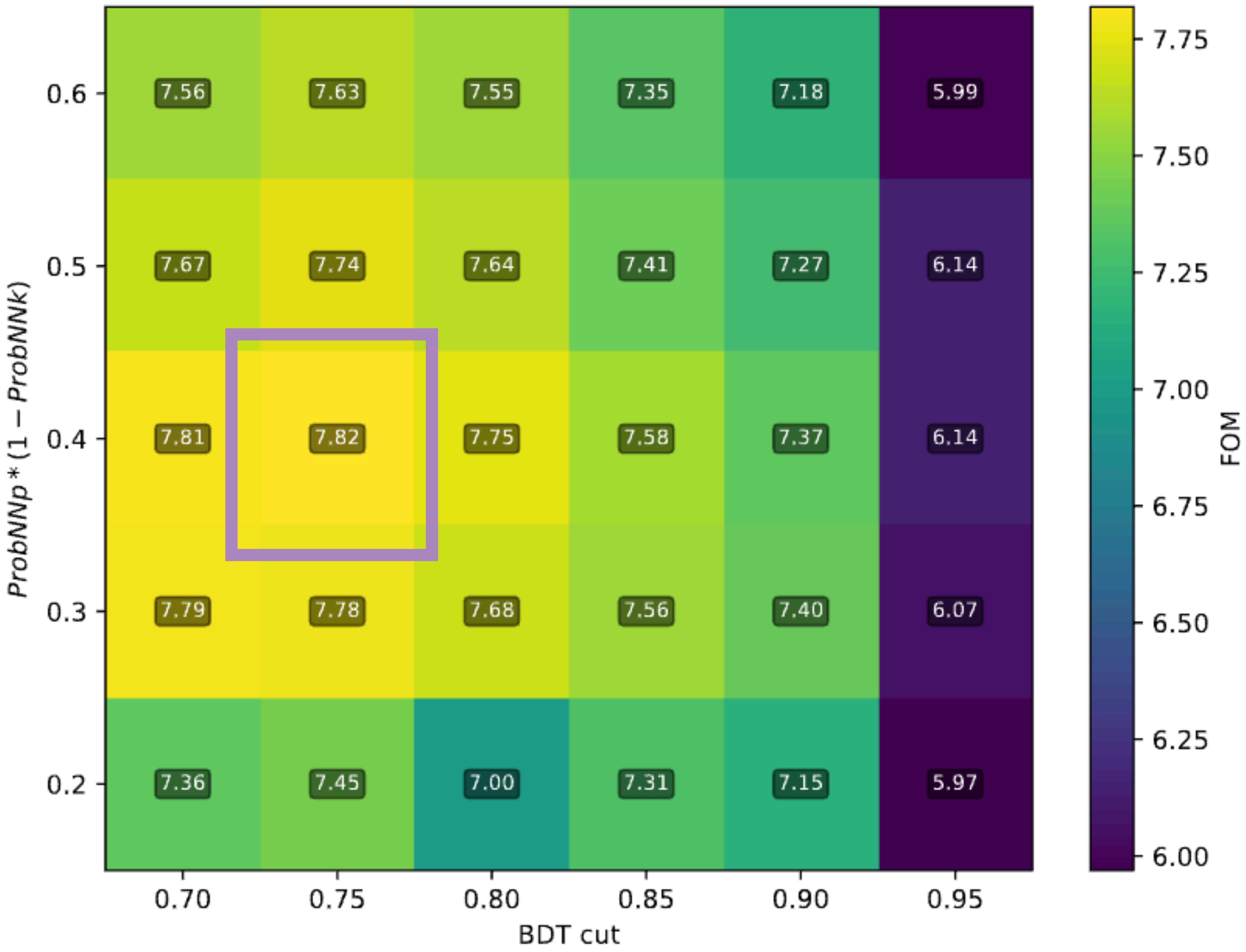


2D optimisation

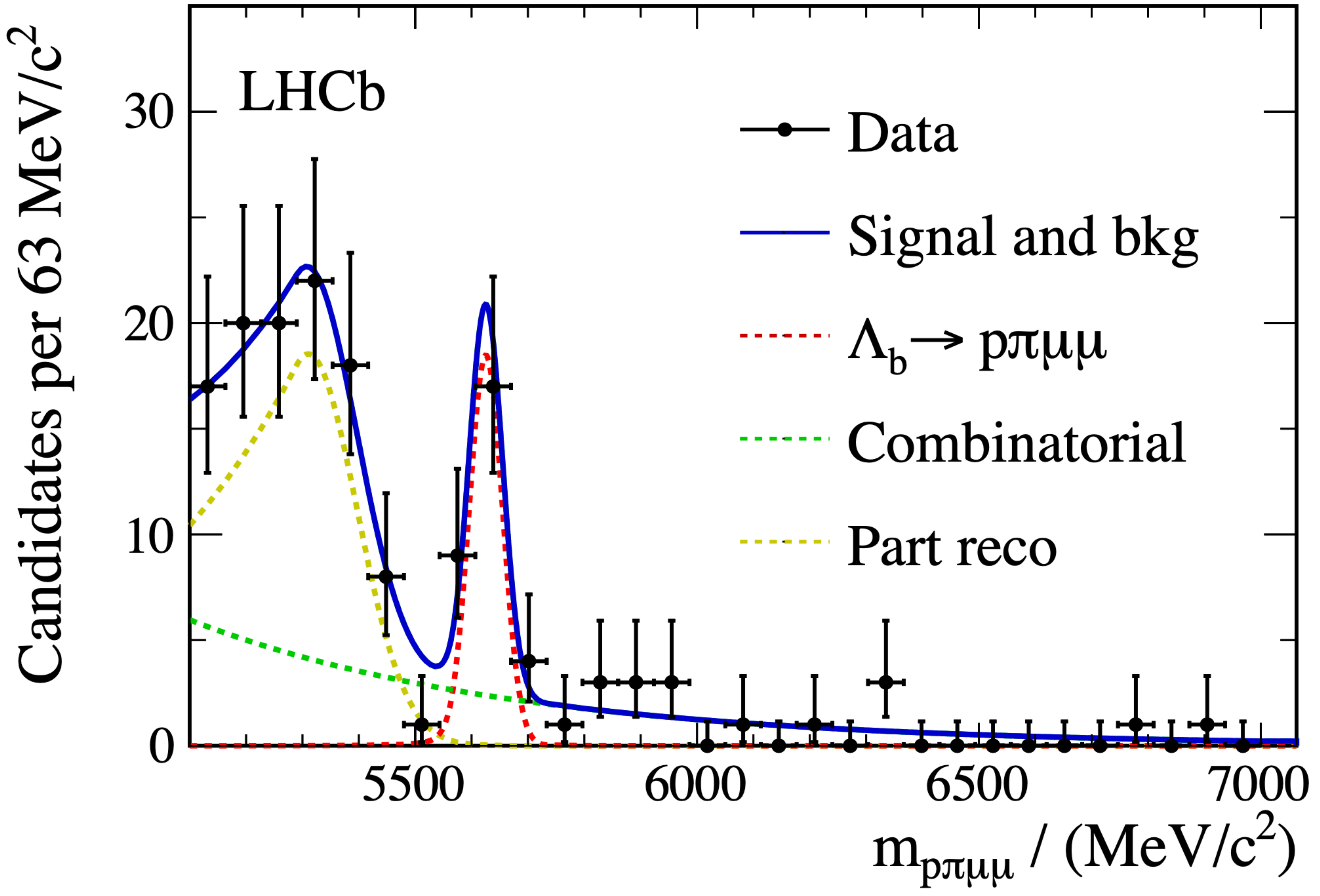
Run1

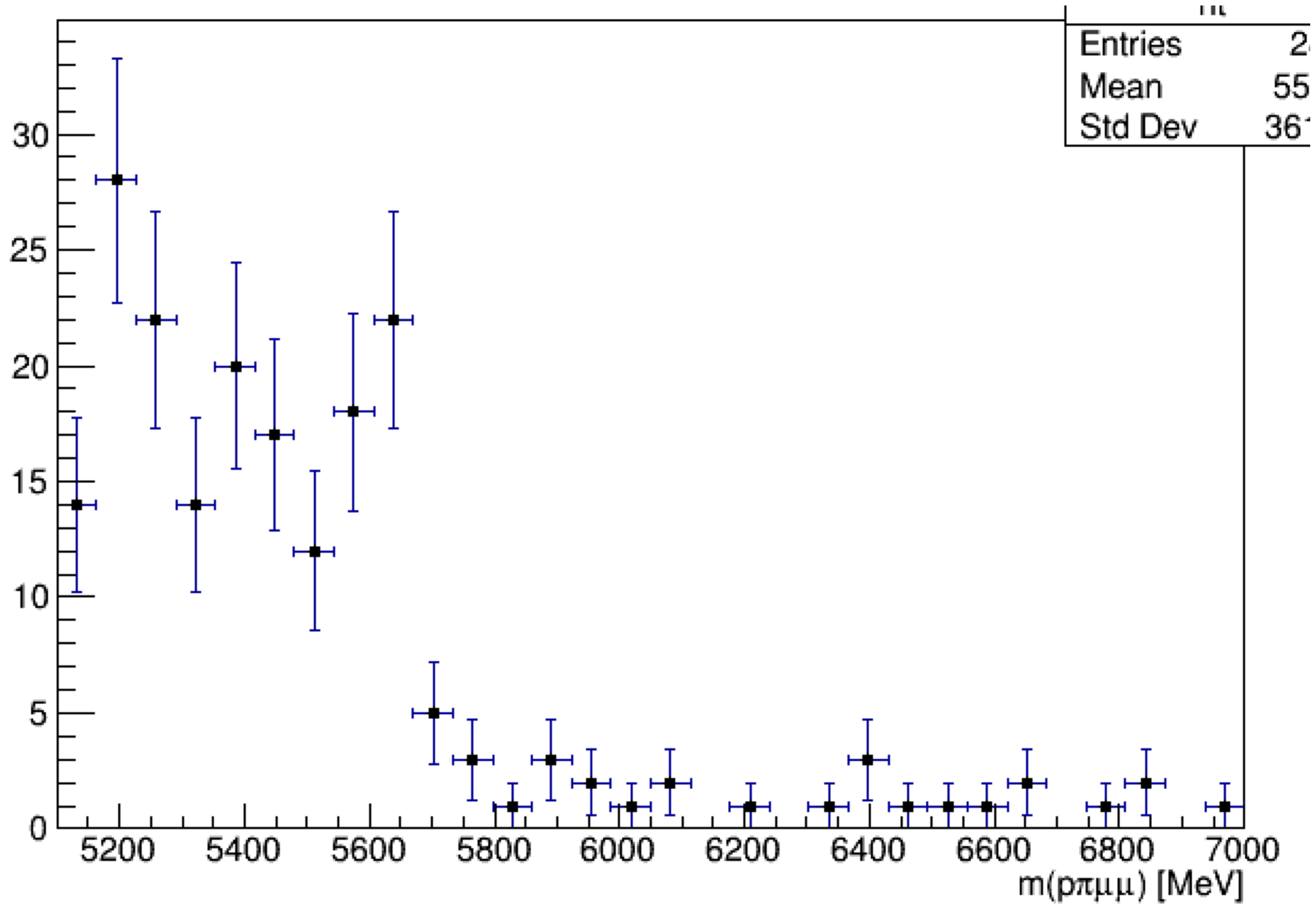


Run2

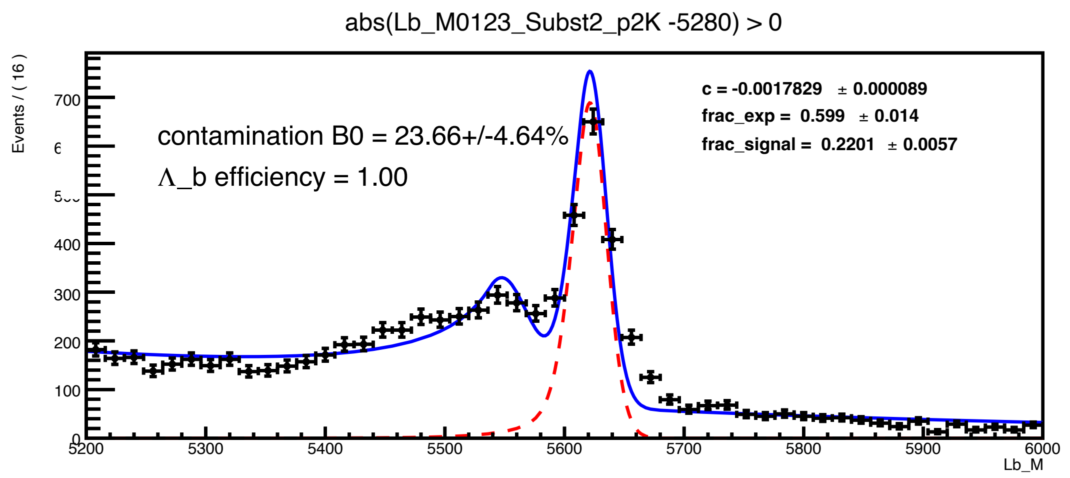


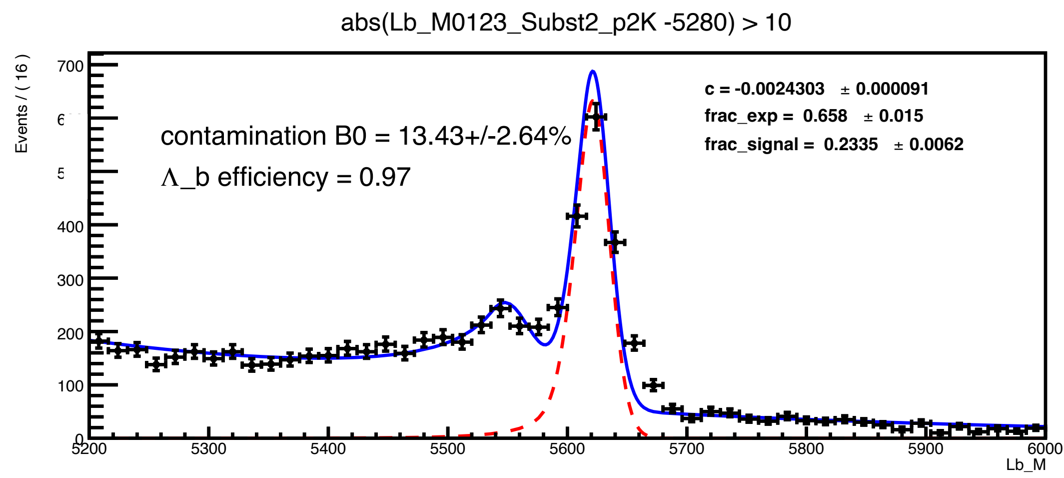
Comparison with run1

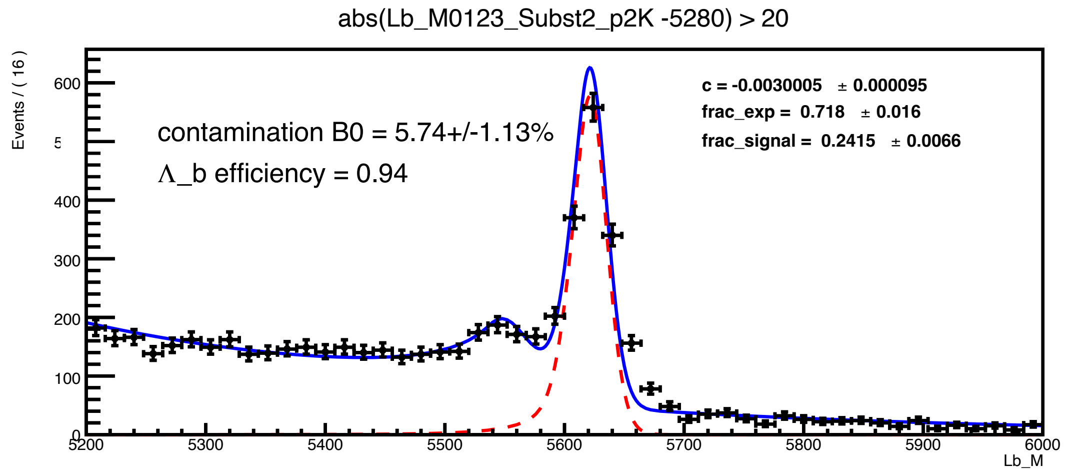


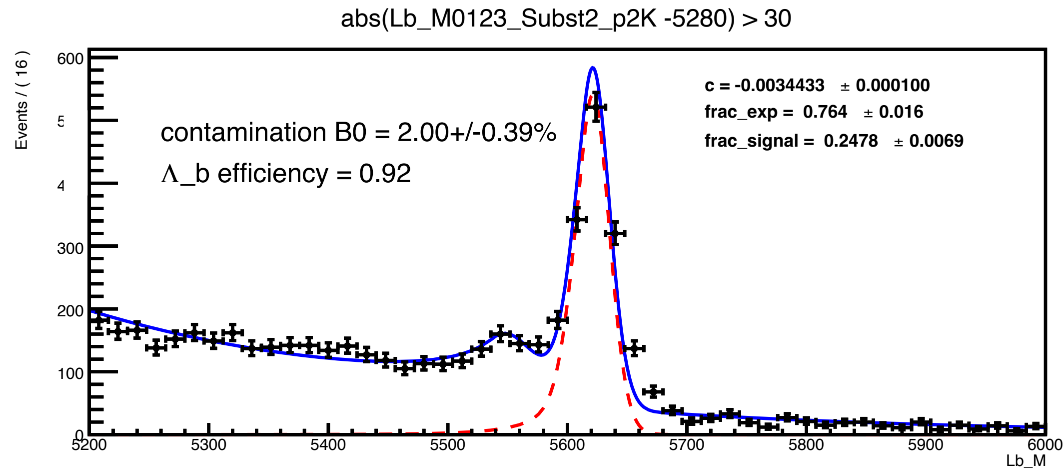


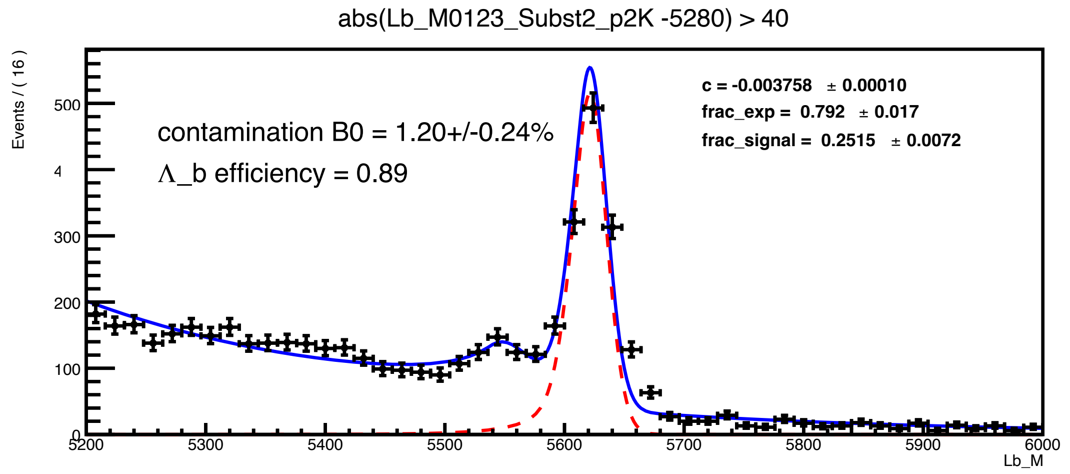
B^0 background

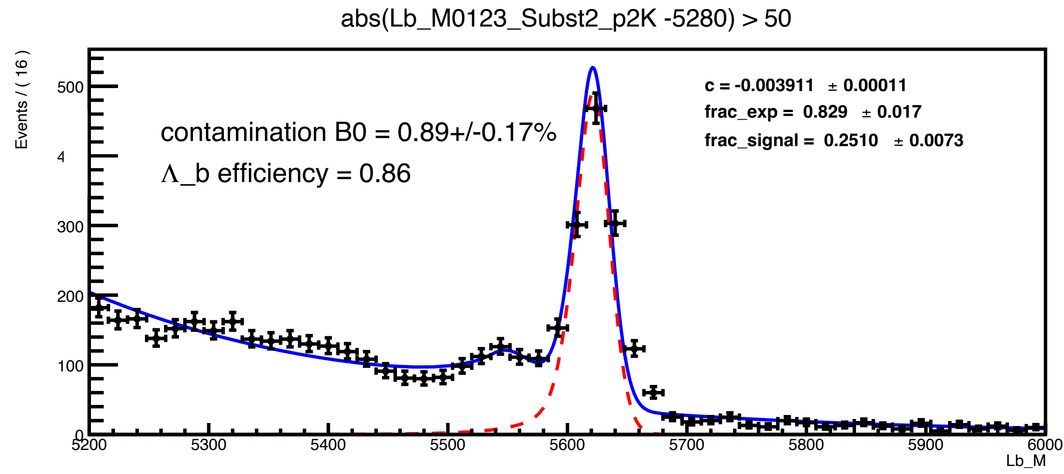


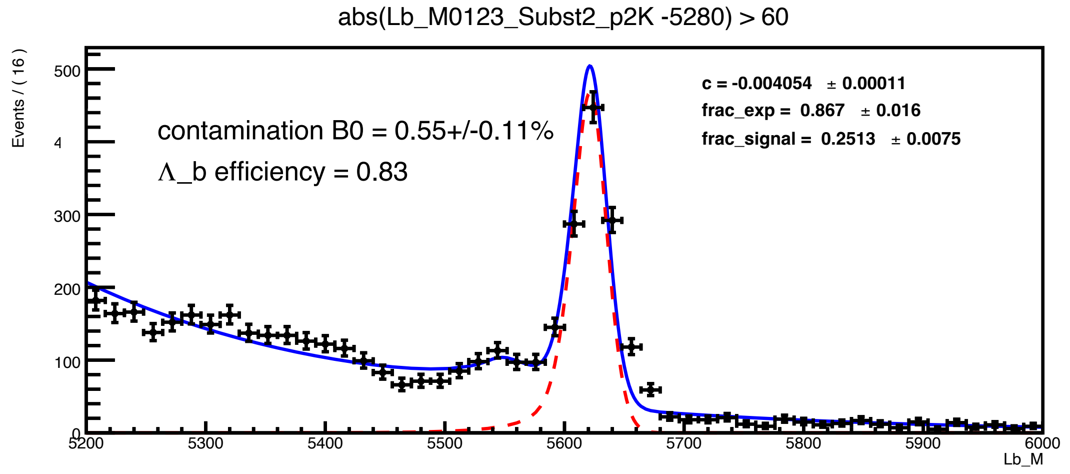


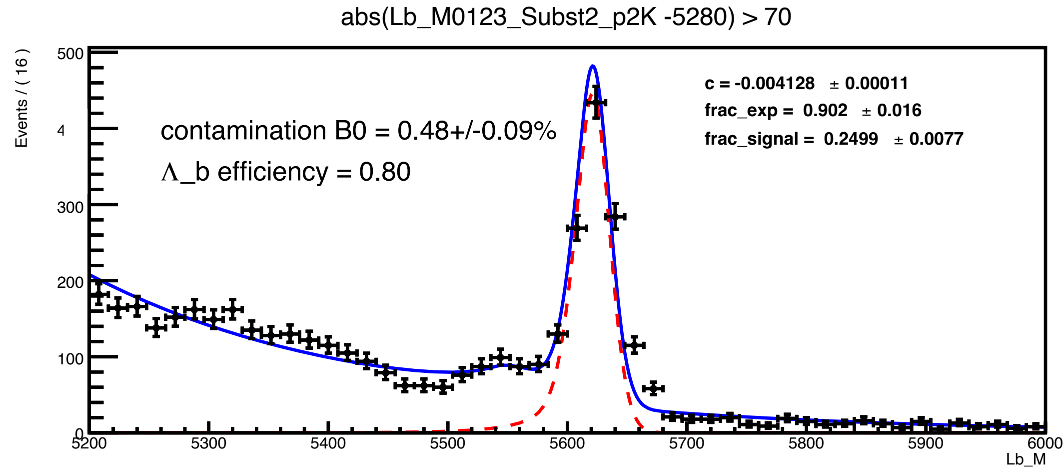


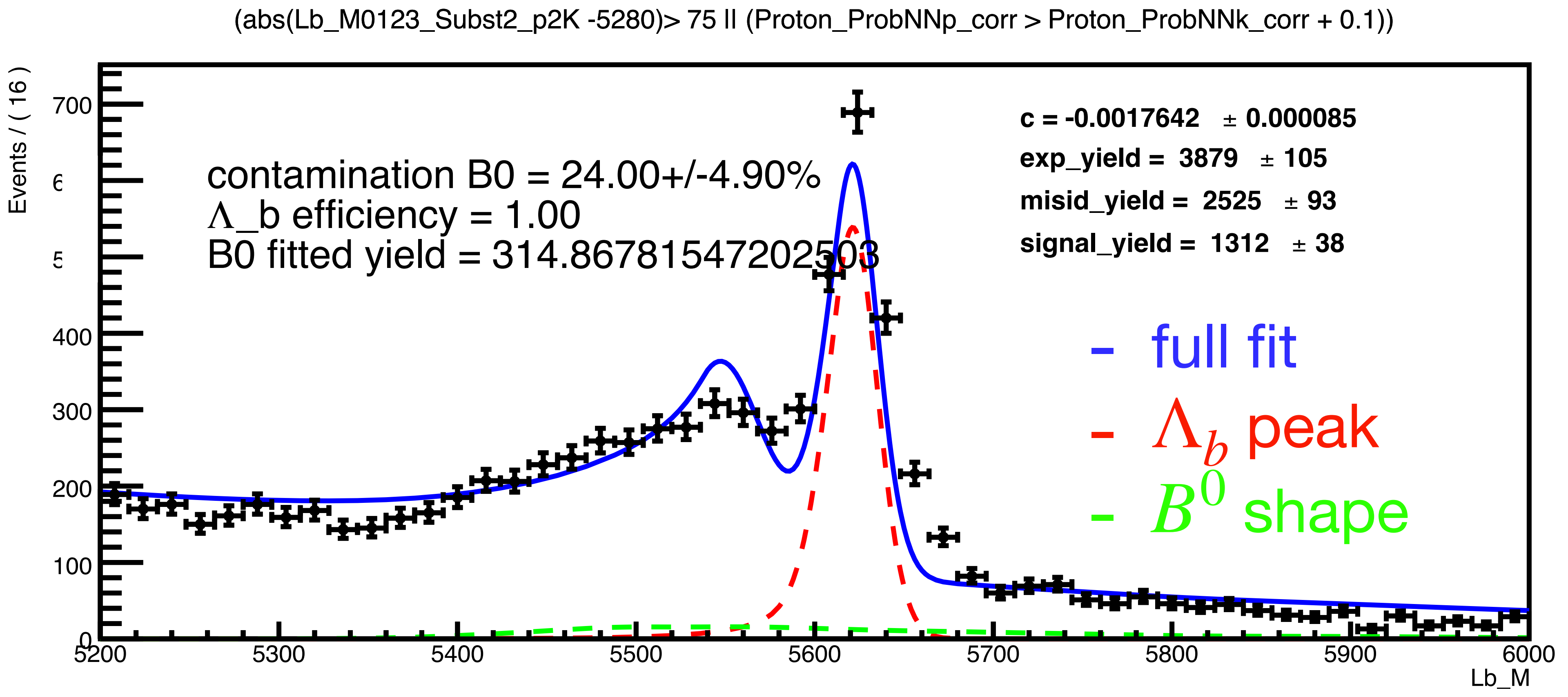


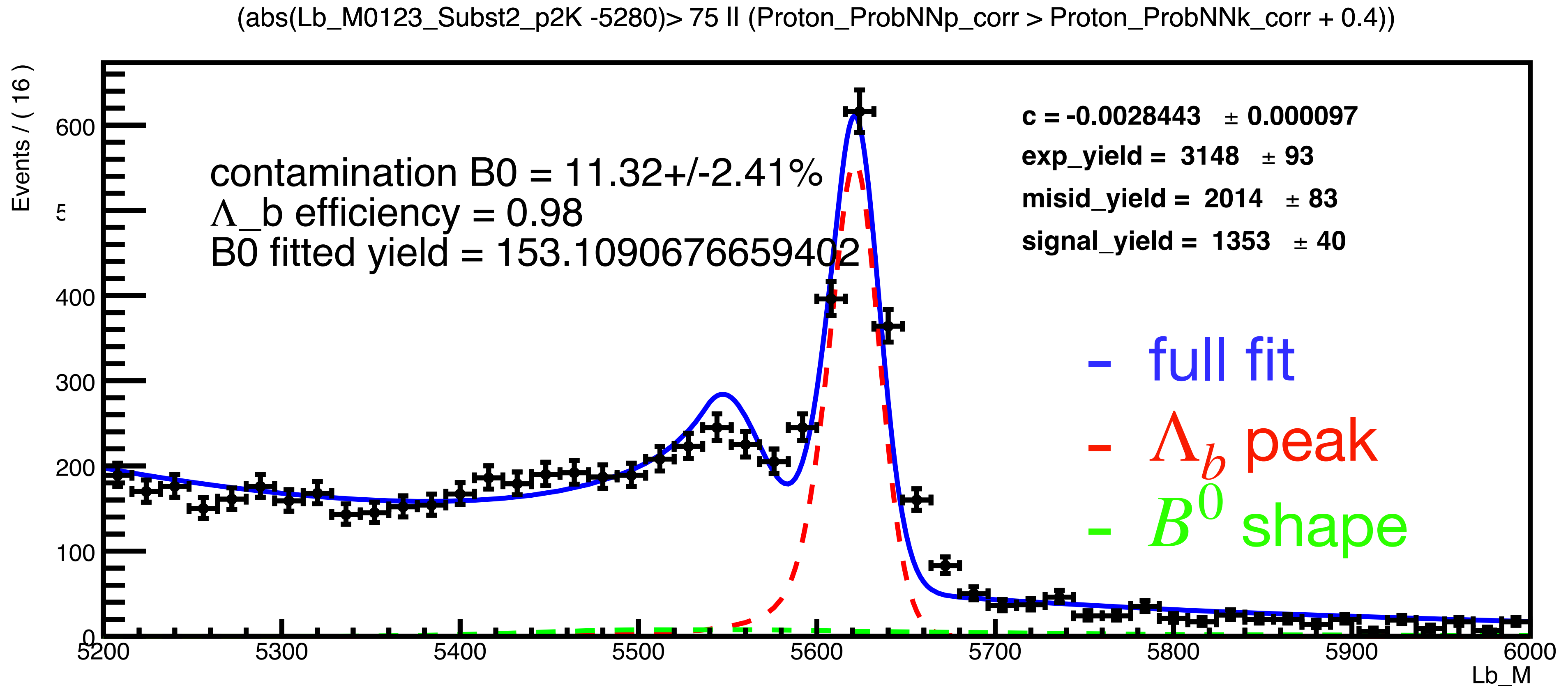


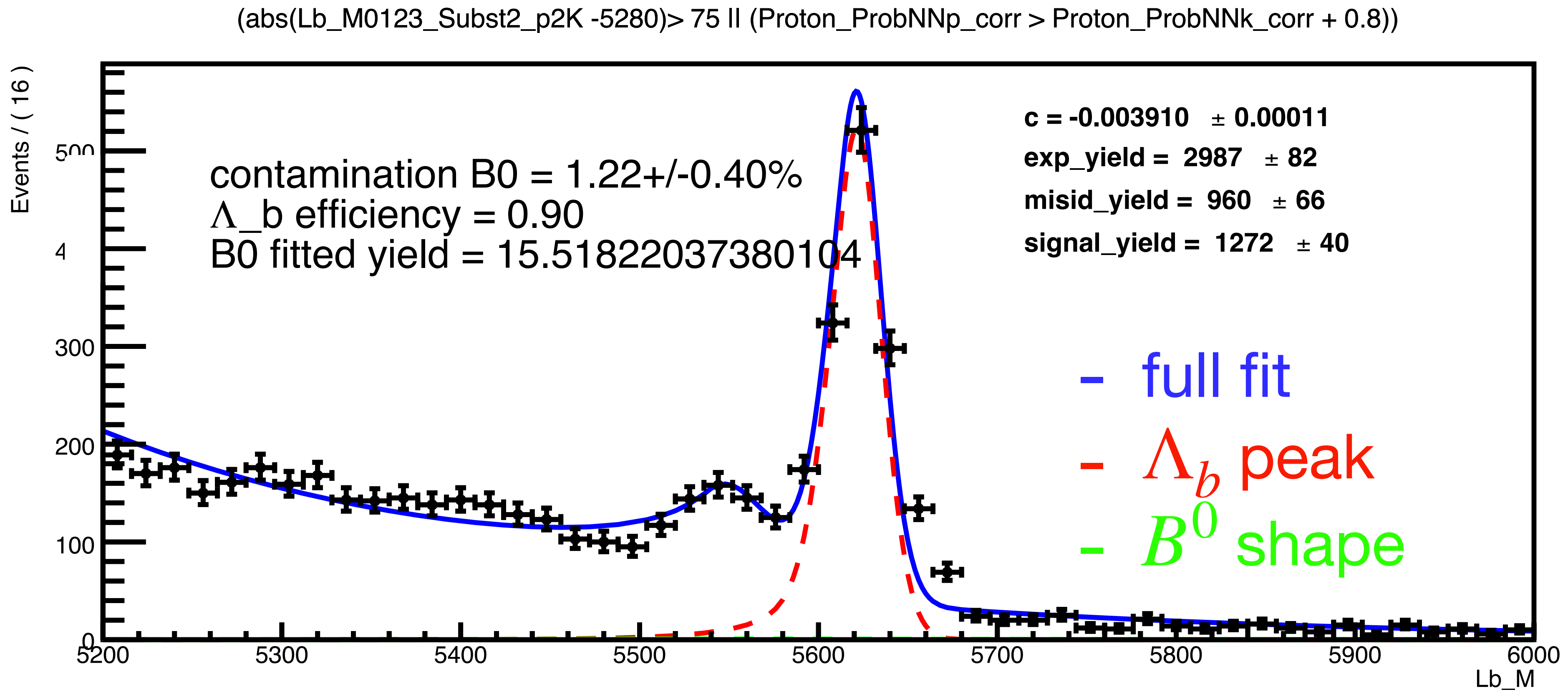






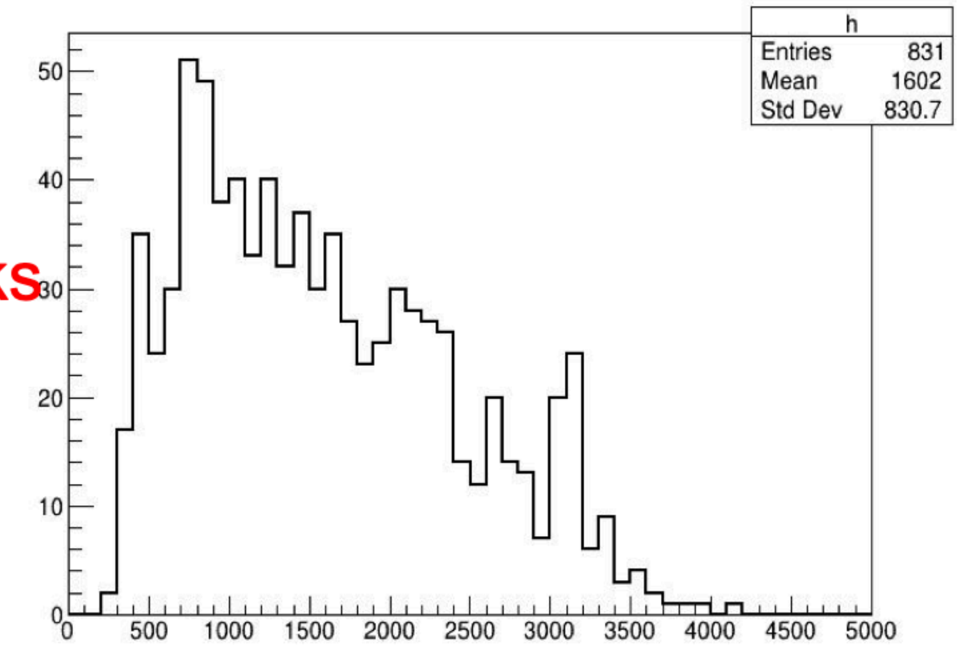






Other backgrounds

Λ_b^0 decay	D^0 decay Comment	Process	Description
$\Lambda_b^0 \to pD^0\pi$	$D^0 \to \pi^-\pi^+$	Double pion MisID	close to $m(D^0)$PDG
$\Lambda_b^0 \to pD^0\pi$	$D^0 \to \pi^-\mu^+\nu_\mu$	Semileptonic With pion misID	below $m(D^0)$PDG
$\Lambda_b^0 \to pD^0\mu\nu_\mu$	$D^0 \to \pi^-\pi^+$	Semileptonic With pion misID	close to $m(D^0)$PDG
$\Lambda_b^0 \to pD^0\mu\nu_\mu$	$D^0 \to \pi^-\mu^+\nu_\mu$	Double semileptonic	Below $m(D^0)$PDG



D⁰: m($\pi\mu$) in $p\pi\mu\mu$ data,

Mode	
$B^0_{(s)} \to \pi\pi J/\psi$	Vetoed
$B^0 \to K\pi J/\psi$ single misID	Vetoed
$B^0 \to K\pi J/\psi$ double misID	Vetoed
$B_s \to K\pi J/\psi$ single misID	Not significant
$B_s \to K\pi J/\psi$ double misID	Not significant
part reco θ_{DIRA}	Not significant
$B_s \to \phi(\to KK)J/\psi$	Vetoed
$B_s \to KKJ/\psi$	Not significant

Pion cut decision

- Only preselection and triggers applied