Lambda transverse polarization in p+p@158 GeV/c beam momentum at NA61/SHINE

Yehor Bondar

Jan Kochanowski University of Kielce

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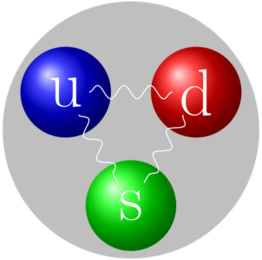
Outline

Λ hyperon particle

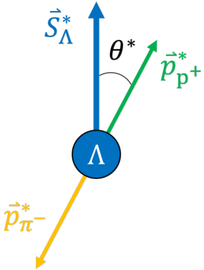
- Discovered in 1950
- $\Lambda = uds$
- $J^P = \frac{1}{2}^+$
- Mass: $m = 1.116$ GeV/c
- Lifetime: $\tau = 2.6 \cdot 10^{-10}$ s,
  $c\tau = 7.89$ cm.
- Main decay mode: $p\pi^-$ (BR = 63.9%)



In the weak decay $\Lambda \to p + \pi^-$, daughter proton distribution function has the following form:

$$\frac{dN}{d\Omega} = \frac{1}{4\pi}(1 + \alpha \cos\theta^*),$$

where θ^* is the angle between daughter proton momentum and Λ spin vector in hyperon rest frame, and $\alpha = 0.732 \pm 0.014$.



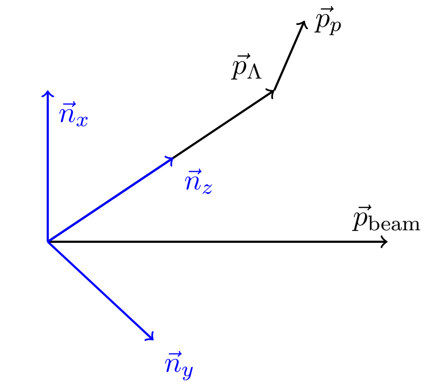
PDG 2020

Transverse polarization definition and calculation

Transverse polarization definition:

1. Rotate from Lab frame to production plane coordinate system:

$$\hat{n}_x = \frac{\vec{p}_{\text{beam}} \times \vec{p}_\Lambda}{|\vec{p}_{\text{beam}} \times \vec{p}_\Lambda|}, \quad \hat{n}_z = \frac{\vec{p}_\Lambda}{|\vec{p}_\Lambda|}, \hat{n}_y = \hat{n}_z \times \hat{n}_x$$



2. Boost along $\hat{n}_z$ to Λ rest frame.
3. Calculate cosine of angles between proton momentum $\vec{p}_p$ and axes: $\cos\theta_i = p_{p\,i}/|\vec{p}_p|$, $i = x, y, z$
4. Fit distribution of the $\cos\theta_i$ to the theoretical prediction and extract P_i – projection of polarization.

$$f(\cos\theta_i) = \frac{1 + \alpha P_i \cos\theta_i}{2},$$

where $\alpha = 0.732 \pm 0.014$.

A

ccording to parity conservation in the strong interaction, $P_y \equiv P_z \equiv 0$ if the incident proton beam is unpolarized. Thus the measurements of P_y and P_z are usually used for checking the systematic uncertanties.

Wanted result:

Wanted result: $\cos\theta_{x,y,z}$ distributions of the proton momentum in (p_{T}, y) bins in the rest frame of Λ produced in a primary vertex of inelastic proton-proton collisions at beam momentum 158 GeV/c ($\sqrt{s_{NN}}$ =17.3 GeV) by strong and electromagnetic interaction processes.

Measured result: Distributions of Λ candidates[1] in $(p_{\mathrm{T}}, y, \cos\theta_{x,y})$ bins in selected[2] proton-proton events at beam momentum 158 GeV/c ($\sqrt{s_{NN}}$ =17.3 GeV).

[1] selected with track and vertex candidate cuts
[2] with respect to event cuts

p-p (2009-2011) data analysis

Event (collision) selection cuts

- T2 trigger
- BPD
- no off-time beam particle in $\pm 1.5 \mu s$ window (WFA S1_1)
- Main vertex exists
- Vertex fit is perfect
- Interaction VtxZ within the target or less than 10 cm.

Tracks selection cuts

- One track is negatively charged, second - positive
- Min 10 clusters in at least one of VTPC1 and VTPC2 for both tracks
- Energy loss cut: dE/dx within 3σ around Bethe-Bloch. In MC, proton and pion track matching

V^0 candidate selection cuts

- difference between Λ vertex and primary vertex $\Delta z = z_\Lambda - z_{PV} \geq 10$ cm

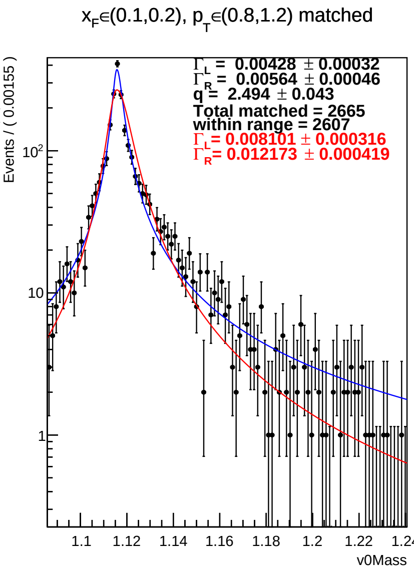
Bullet • corresponds to cuts that cannot be transformed directly in MC

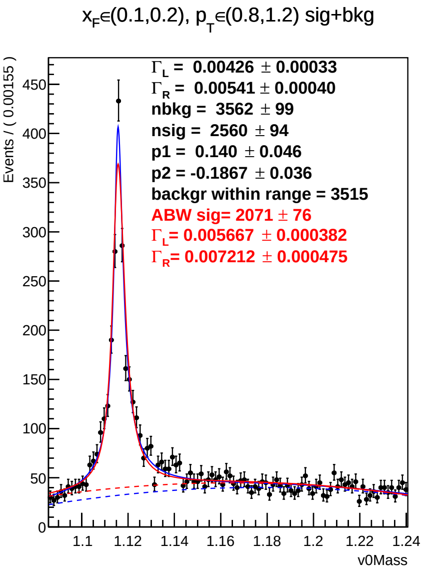
m_{inv} distributions fitting procedure

Signal as asymmetric q-Gaussian (Breit-Wigner if $q = 2$):

$$S(m) = N\left[1 + (q-1)\frac{(m - m_\Lambda)^2}{0.25\Gamma^2}\right]^{-\frac{1}{q-1}}$$

Unbinned extended log-likelihood fit with signal and background PDF with parameters Γ_{L}, Γ_{R}, p_1, p_2, N_{sig}, N_{bkg}, **fixed** q **value** is from the fit of matched Λ m_{inv} distr.
For data, the q value is taken as weighted from EPOS and FTFP.
Problem: sometimes bad description at $m_{\text{inv}} \approx 1.09, 1.14$ GeV.
Background part is fitted with 2nd order polynomial, fit is in region $1.085\ \text{GeV}/c^2 \leq m \leq 1.24\ \text{GeV}/c^2$.





$x_F \in (0.2, 0.3), p_T \in (0.8, 1.2)\ \text{GeV}/c, \cos\theta_x \in (0.9, 1)$

MC correction on MC data: closure test

Use **first half** of the MC data to calculate N_i^{MCsim}, and **second half** is to be corrected.
Divide 4D space $(x_F, p_T, \cos\theta_j, \phi), j = x, y$ to bins.
Based on invariant mass m_{inv} distribution in particular $(x_F, p_T, \cos\theta_j, \phi), j = x, y$ bin, and calculate amount of Λ's in this bin as N_i^{sel}.

$$N_i^{\text{corrected}} = N_i^{\text{sel}} \times \frac{N_i^{\text{MCsim}}}{N_i^{\text{MCsel}}}, \tag{1}$$

Uncertainty of the yields is $\Delta N = \sqrt{N}$ and ΔN_i^{sel} is from fit, hence

$$\frac{\Delta N_i^{\text{corrected}}}{N_i^{\text{corrected}}} = \sqrt{\left(\frac{\Delta N_i^{\text{sel}}}{N_i^{\text{sel}}}\right)^2 + \left(\frac{\Delta N_i^{\text{sel}}}{N_i^{\text{sel}}}\right)^2 + \left(\frac{\sqrt{N_i^{\text{MCsim}}}}{N_i^{\text{MCsim}}}\right)^2}$$

N_i — number of entries at bin i of $(p_T, y, \cos\theta_i)$,

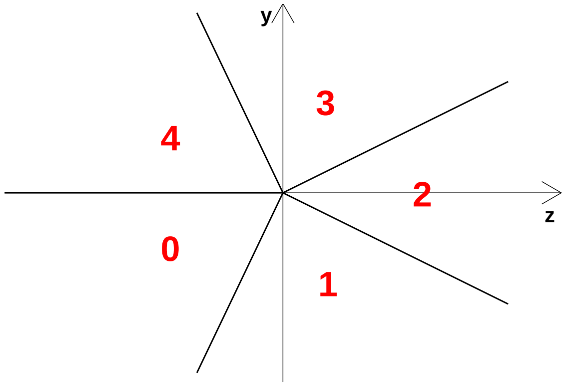
$N_i^{\text{corrected}}$ — corrected number of Λ,

N_i^{sel} — number of Λ candidates fitted in m_{inv} distributions,

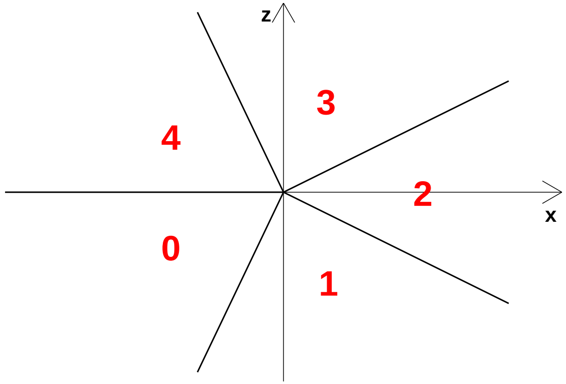
N_i^{MCsim} — number of Λ hyperons produced in the simulated primary interactions.

Binning

x_F : $-0.5, -0.3, -0.2, -0.1, -0.05, 0, 0.05, 0.1, 0.2, 0.3, 0.5.$
$p_T(\mathrm{GeV}/c)$: $0, 0.2, 0.4, 0.8, 1.2$
$\cos\theta_{x,y}$: 10 bins in $[-1, 1]$
$\phi \in [-\pi, \pi]$ is defined as polar angle in (z, y) and (x, z) plane, 5 bins



ϕ binning in (z, y) plane for $\cos\theta_x$



ϕ binning in (x, z) plane for $\cos\theta_y$

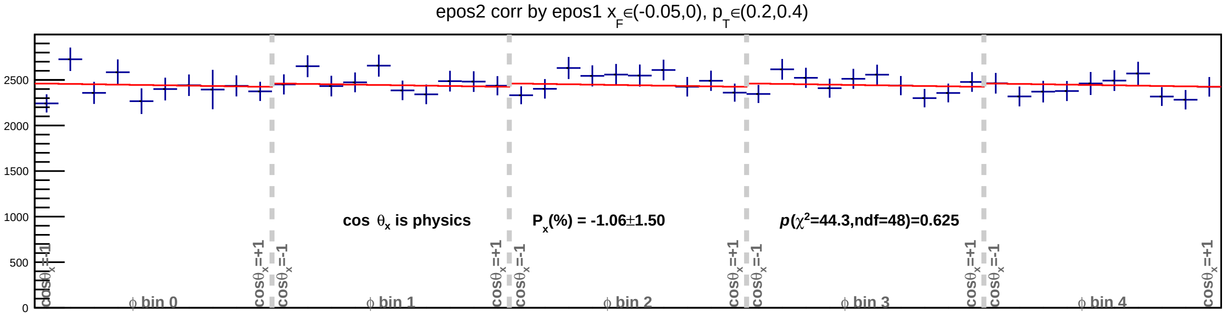
$\cos\theta$ yields fitting

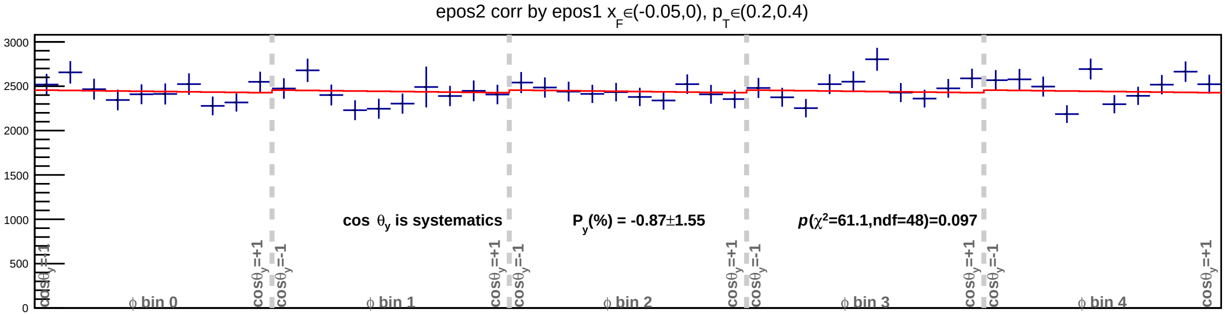
We expect independence of spectra on ϕ, but different acceptance leads to different yields in these ϕ bins.
Ways to fit $(\cos\theta, \phi)$ yields:

- Fit all 50 points to $f(\cos\theta, \phi) = (1 + 0.732\,P\cos\theta)/2$,
- Find average across 5 ϕ bins, reject max 1 point if χ^2 contribution > 3,
  then in $\cos\theta$ distr, reject max 2 point if χ^2 contribution > 3.

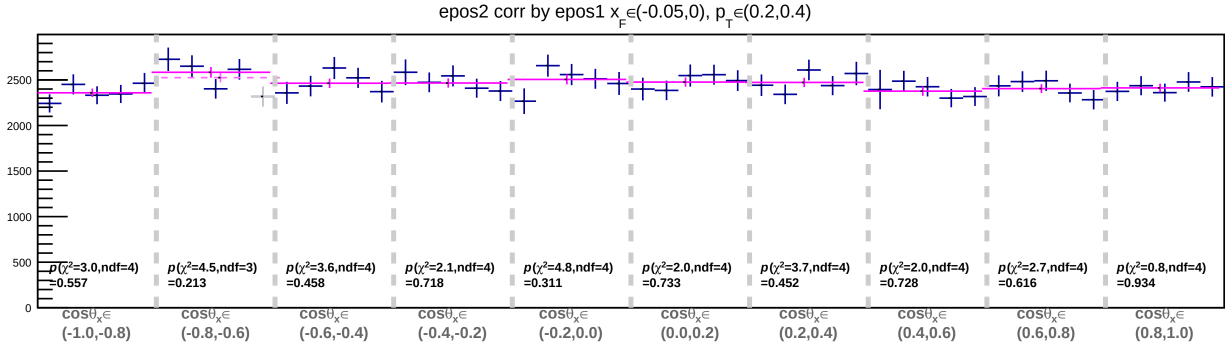
For EPOS and FTFP, we expect $P_x \equiv P_y \equiv 0$.
Let's try these methods for closure test on two halves of EPOS (**EPOS1**,**EPOS2**),
EPOS/FTFP and vice versa.

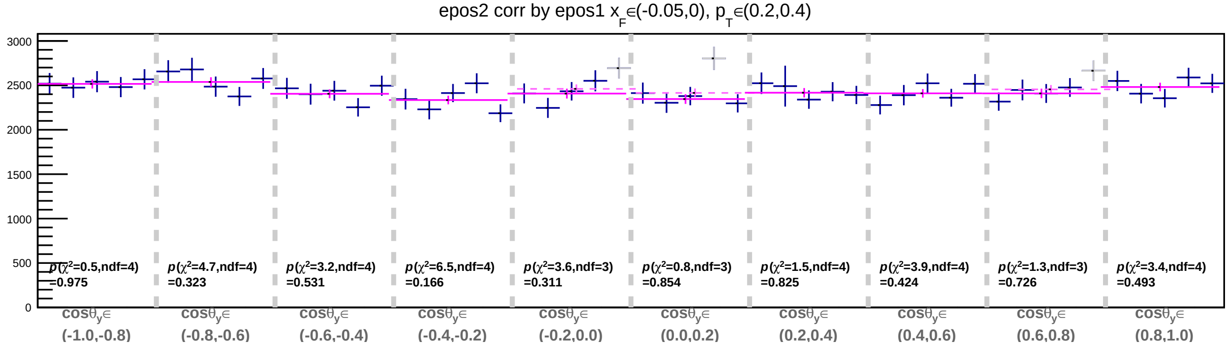
Epos1/Epos2 correction - all points - $x_F \in (-0.05, 0), p_T \in (0.2, 0.4)$



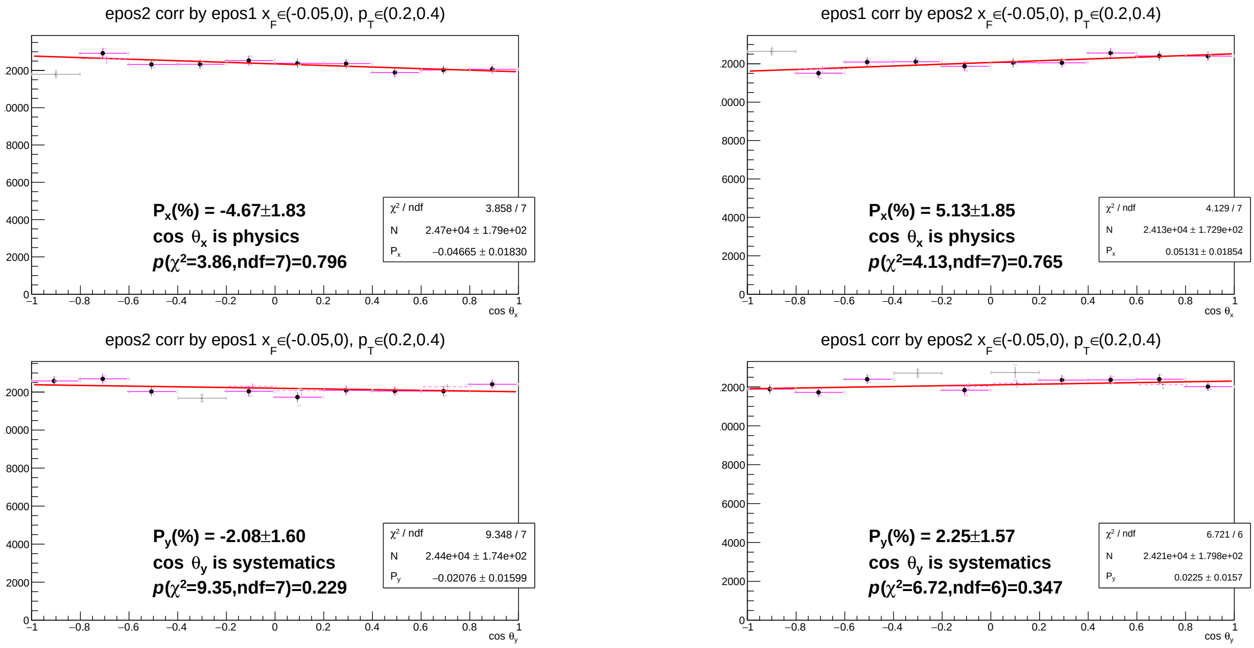


Epos1/Epos2 correction - point removal - $x_F \in (-0.05, 0), p_T \in (0.2, 0.4)$

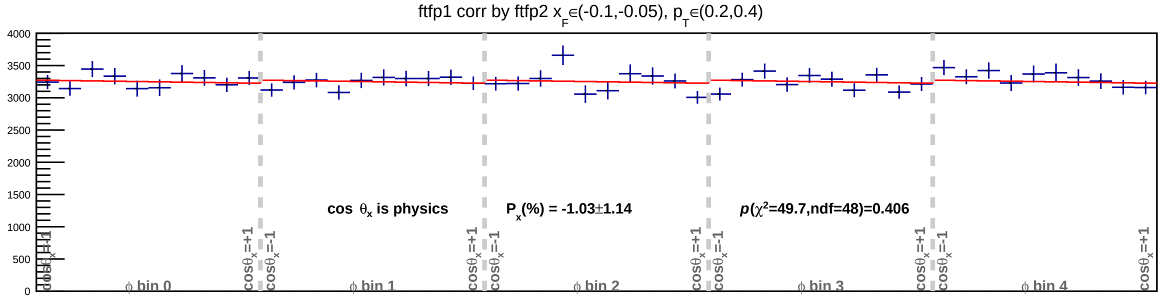


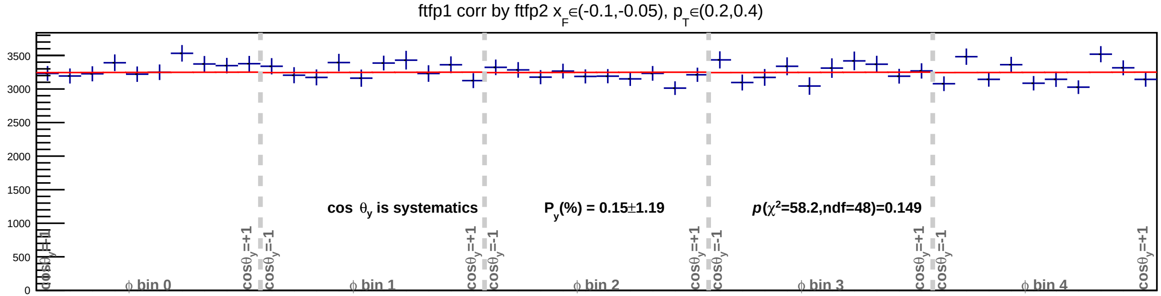


Epos1/Epos2 and v.v. correction - point removal - $x_F \in (-0.05, 0), p_T \in (0.2, 0.4)$

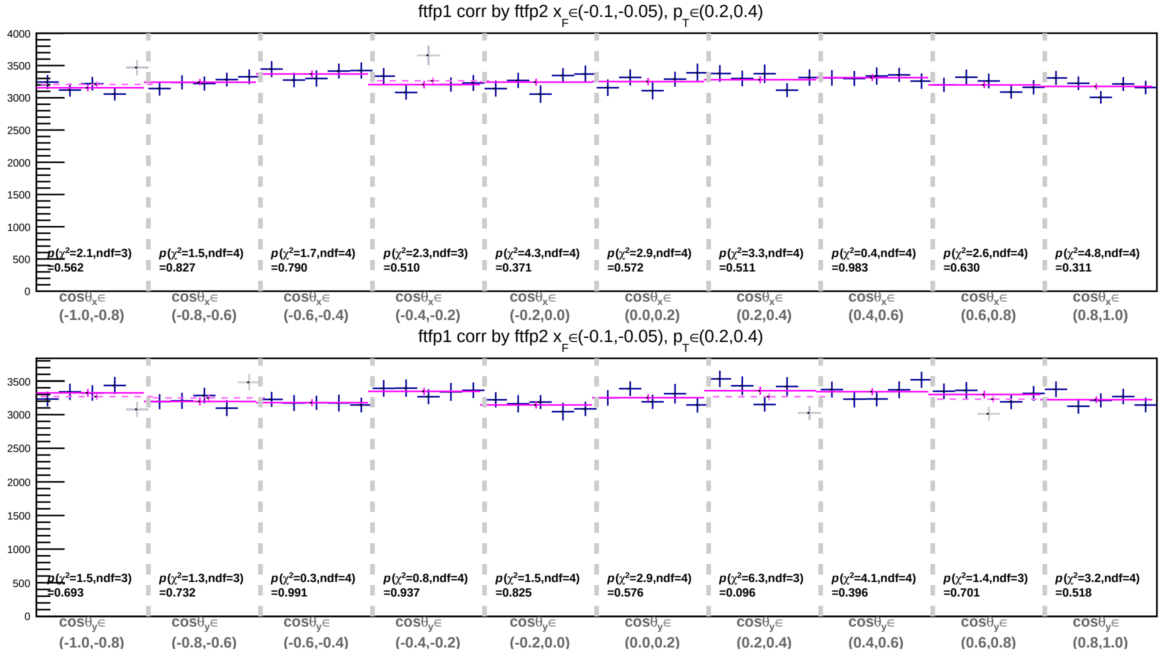


FTFP1/FTFP2 correction - all points - $x_F \in (-0.1, -0.05), p_T \in (0.2, 0.4)$

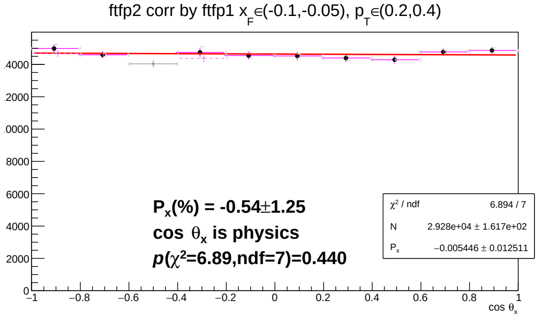


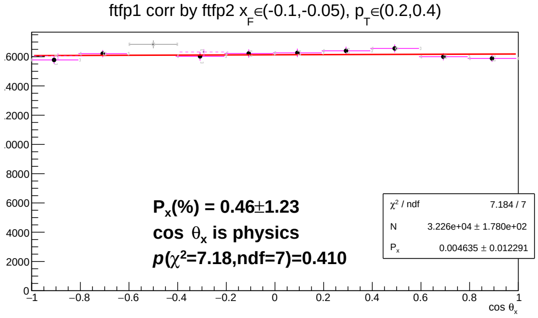


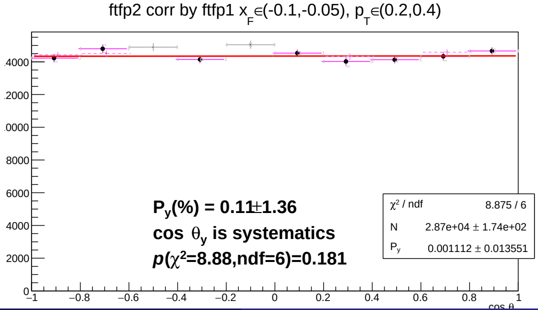
FTFP1/FTFP2 correction - point removal - $x_F \in (-0.1, -0.05), p_T \in (0.2, 0.4)$

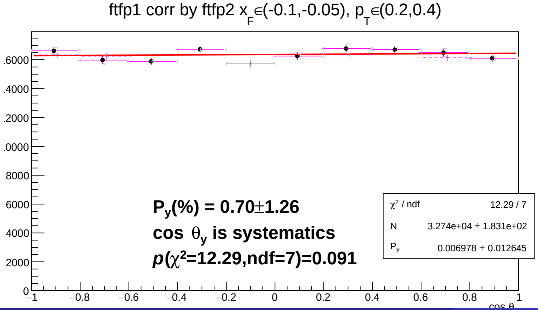


FTFP1/FTFP2 and vice versa correction - point removal - $x_F \in (-0.1, -0.05), p_T \in (0.2, 0.4)$

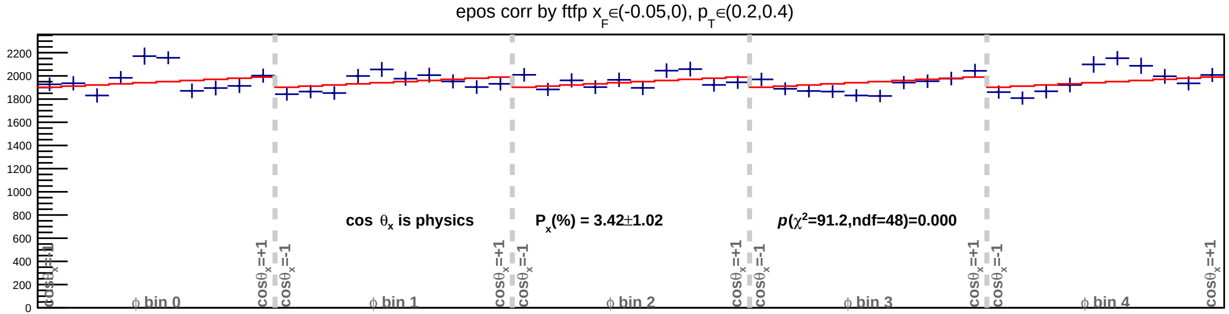


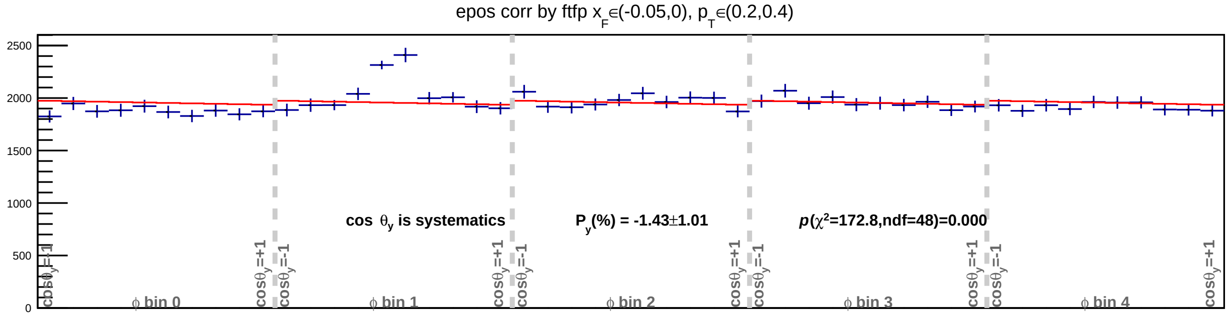




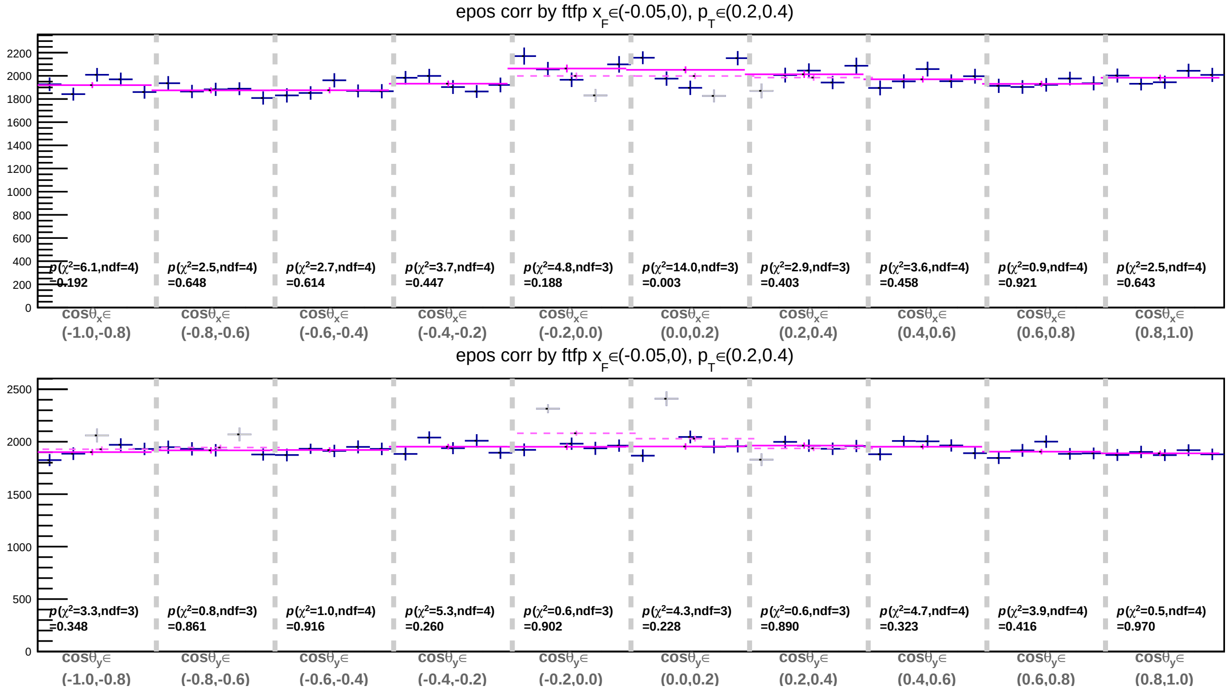


EPOS/FTFP correction - all points - $x_F \in (-0.05, 0), p_T \in (0.2, 0.4)$

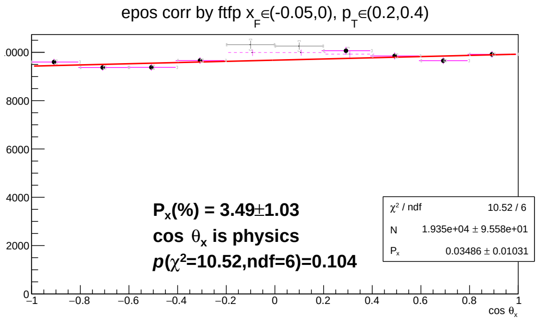


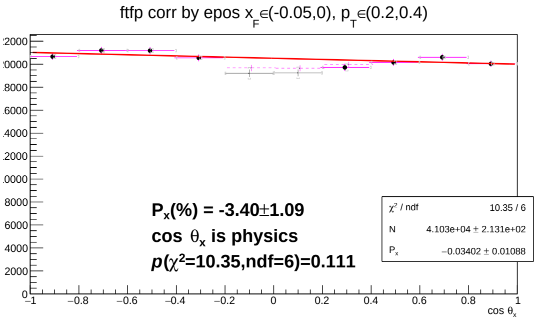


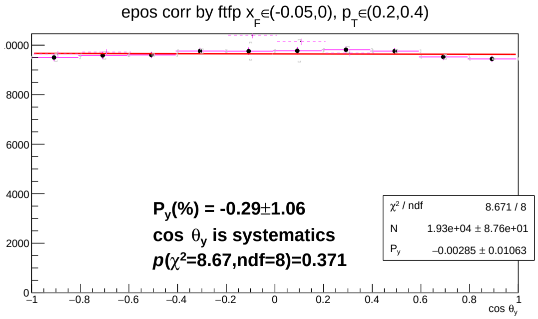
EPOS/FTFP correction - point removal - $x_F \in (-0.05, 0), p_T \in (0.2, 0.4)$

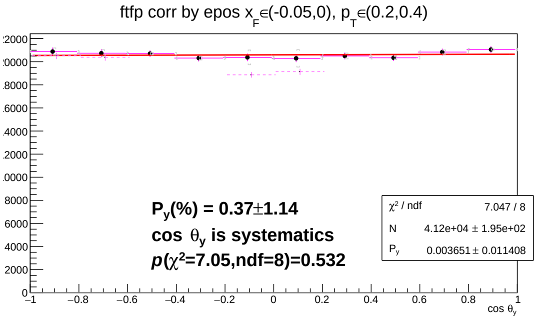


EPOS/FTFP and v.v. correction - point removal - $x_F \in (-0.05, 0), p_T \in (0.2, 0.4)$









Conclusions and Further steps

- EPOS-EPOS and FTFP-FTFP corrections: all-points and with-removal methods compatible with 0,
- EPOS-FTFP and vice versa corrections: introduces bias up to several % that may be treated (?) as systematic uncertainty
- In result, effect is expected around 10% with syst. and stat. uncertainties of several %

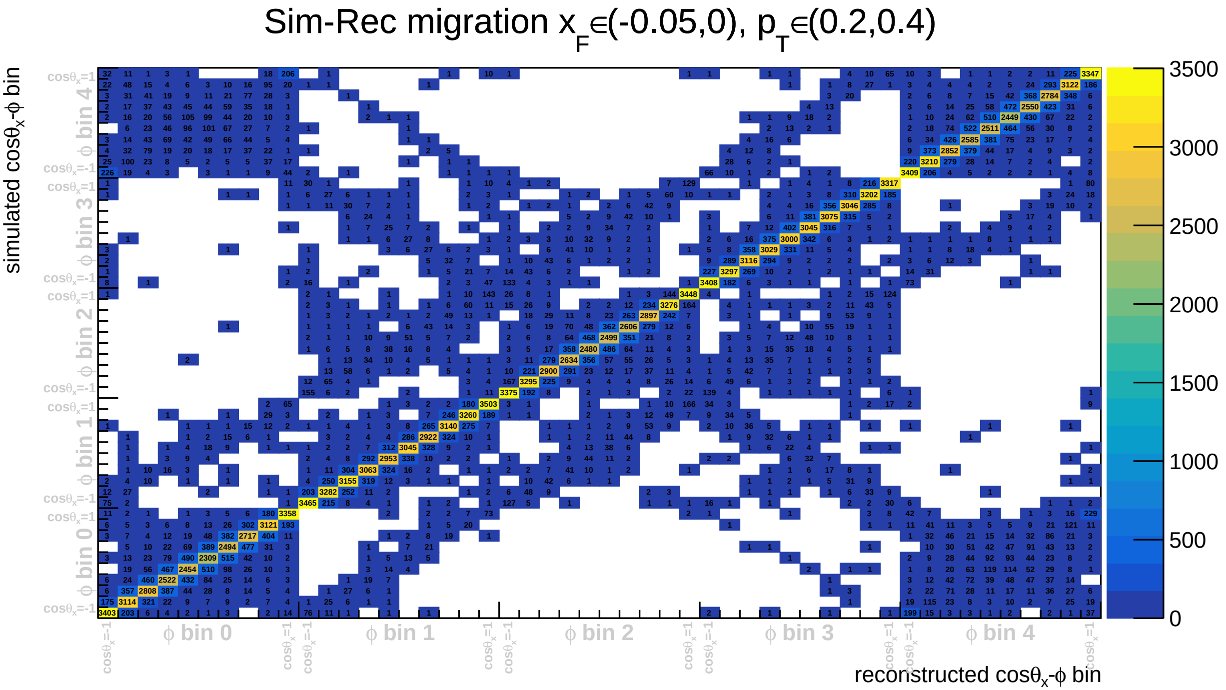
Unfolding

Problem: As measured distribution m_i is disturbed truth distribution t by some response matrix R by $m_i = \sum_j R_{ij} t_j$, the problem is to find an estimator for t, $\hat{t}$ from known m and R.
In my case, R_{ij} is probability Λ reconstructed in bin i given generated in bin j, and was constructed using matched Λ.
1. Simple matrix inversion: $\hat{t} = R^{-1} m$.
Drawback: high variance
2. Bayesian Unfolding: init guess $\hat{t}_i^{(0)}$ is uniform, then update using Bayes' theorem:

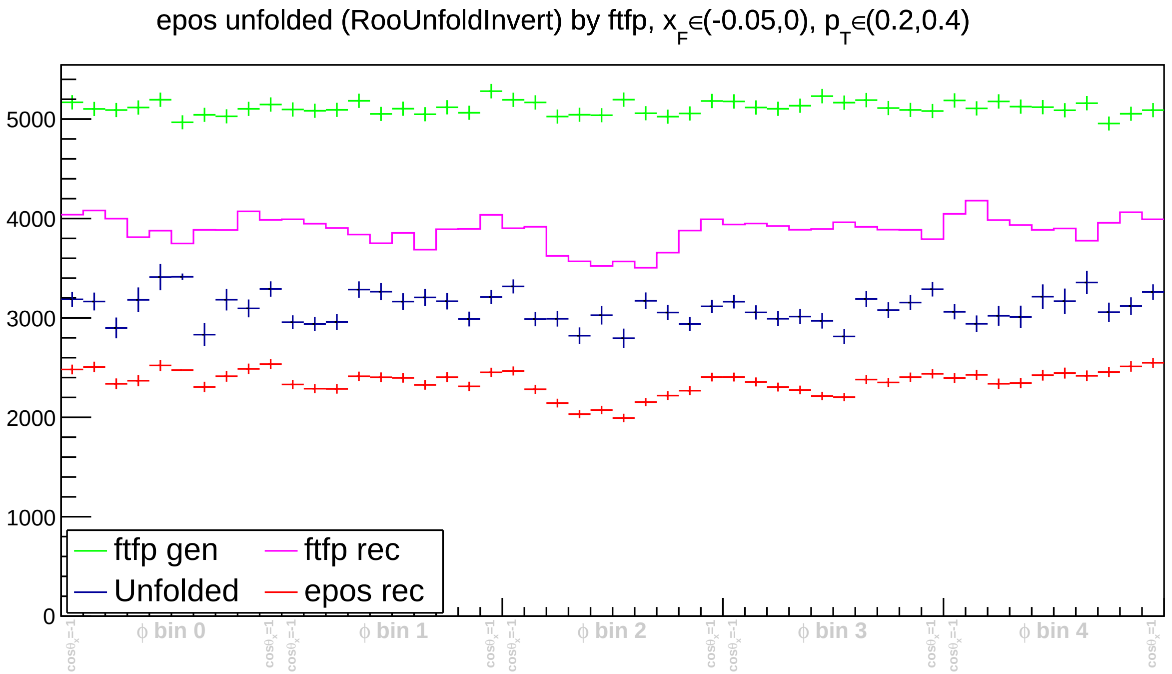
$$\hat{t}_i^{(new)} = \frac{1}{\sum_{j=1}^{N} R_{ji}} \sum_{j=1}^{N} \left(\frac{R_{ji} t_i}{\sum_{k=1}^{N} R_{jk} t_k} \right) m_j$$

Regularization parameter is no. of iterations: 3 iterations was used (the fourth iteration introduced change of $\chi^2 < 1$). Drawback: Not actually Bayesian.

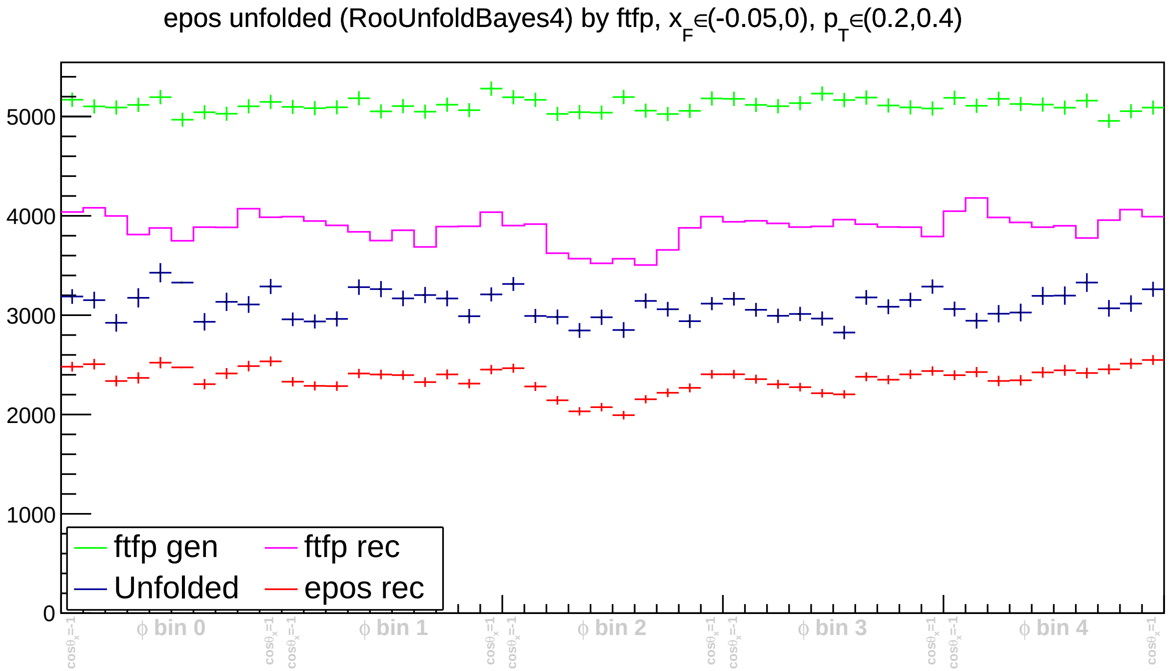
Response Matrix: FTFP

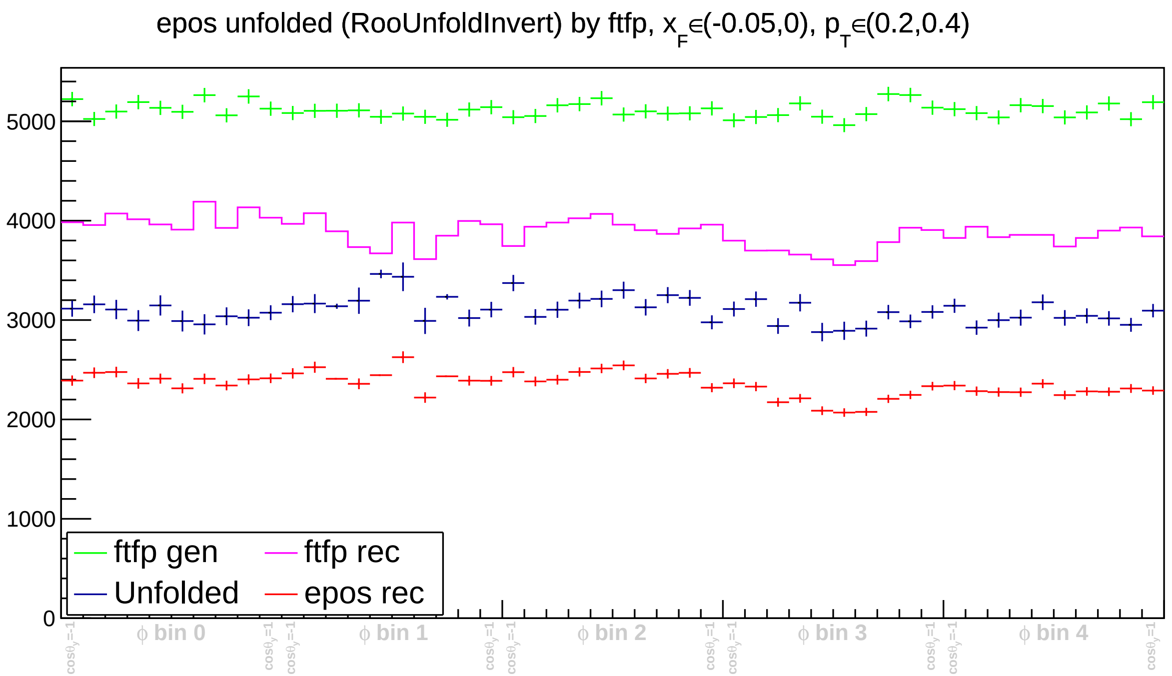


Unfolding by inversion: FTFP

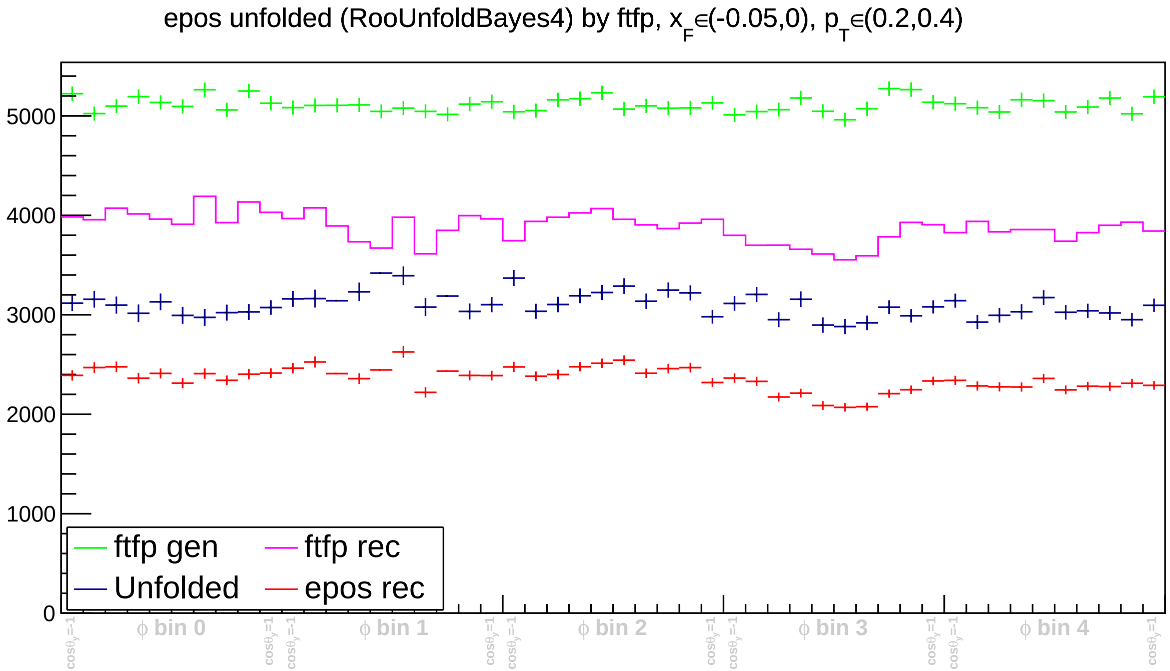


Unfolding by Bayes: FTFP

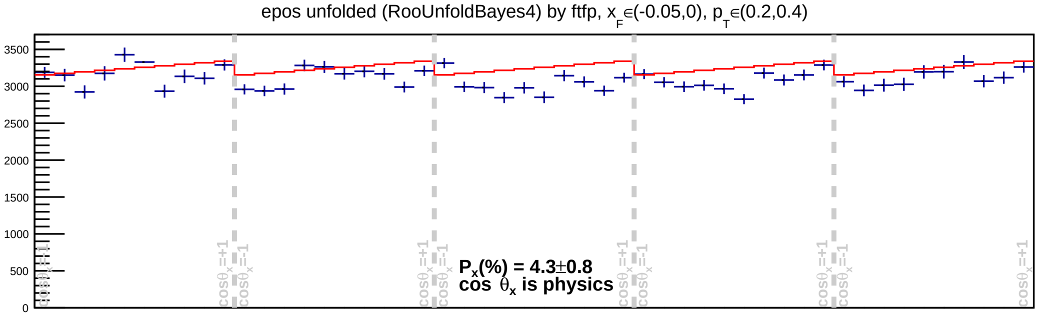


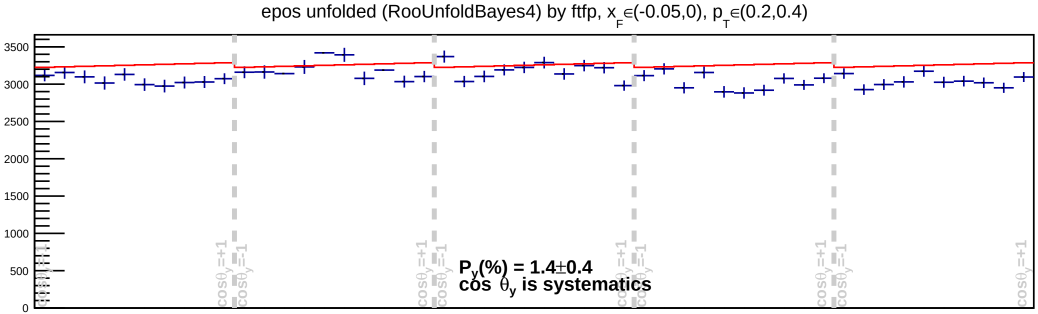

epos unfolded (RooUnfoldInvert) by ftfp, $x_F \in (-0.05,0)$, $p_T \in (0.2,0.4)$
5000
4000
3000
2000
1000
0
ftfp gen
ftfp rec
Unfolded
epos rec
ϕ bin 0
ϕ bin 1
ϕ bin 2
ϕ bin 3
ϕ bin 4
$\cos\theta_y$=-1

Unfolding by Bayes: FTFP

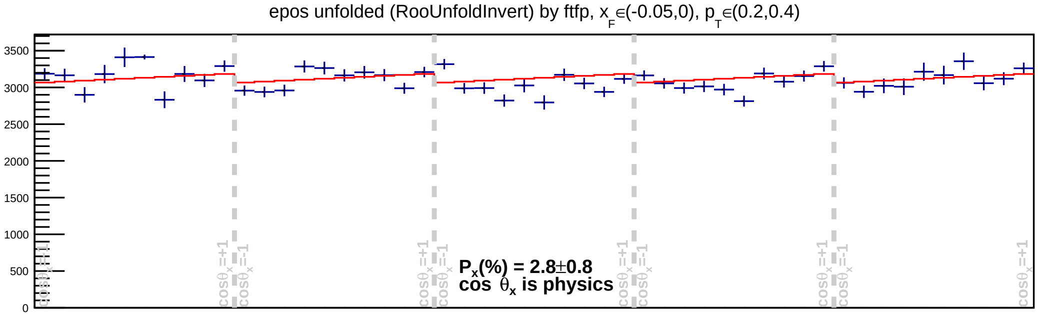


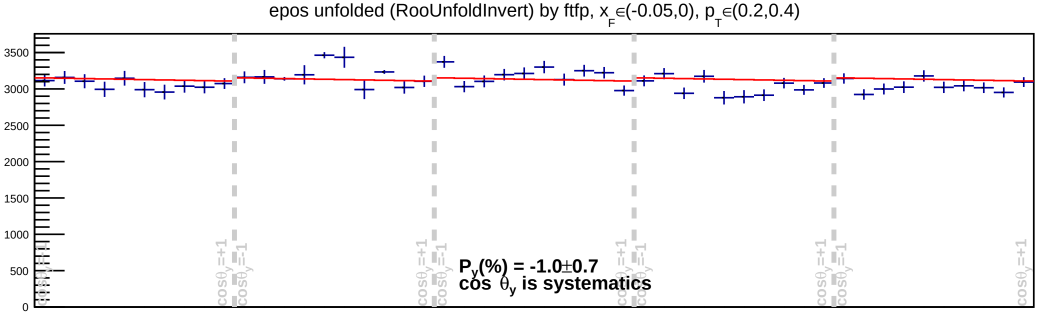
Unfolding by Bayes: FTFP





Unfolding by inversion: FTFP



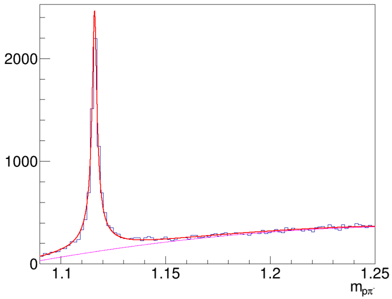


MC Correction: Summary

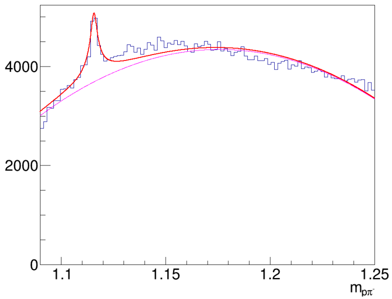
In bin $x_F \in (-0.05, 0), p_T \in (0.2, 0.4)$:

Method	$P_x(\%)$	$P_y(\%)$	
Unfold Bayes	4.3±0.8	1.4±0.4	
Unfold Invert	2.8±0.8	-1.0±0.7	
Bin-by-bin all points	3.4±1.0	-1.4±1.0	
Bin-by-bin point removal	3.5±1.0	-0.3±1.1	

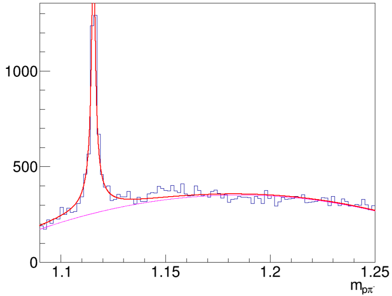
dE/dx cut analogy in MC



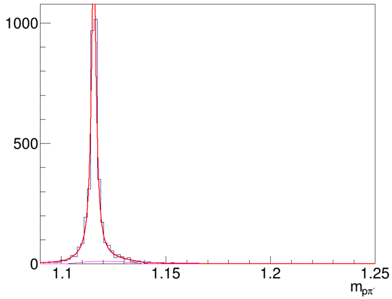
recorded data with dE/dx cut



MC data without matching



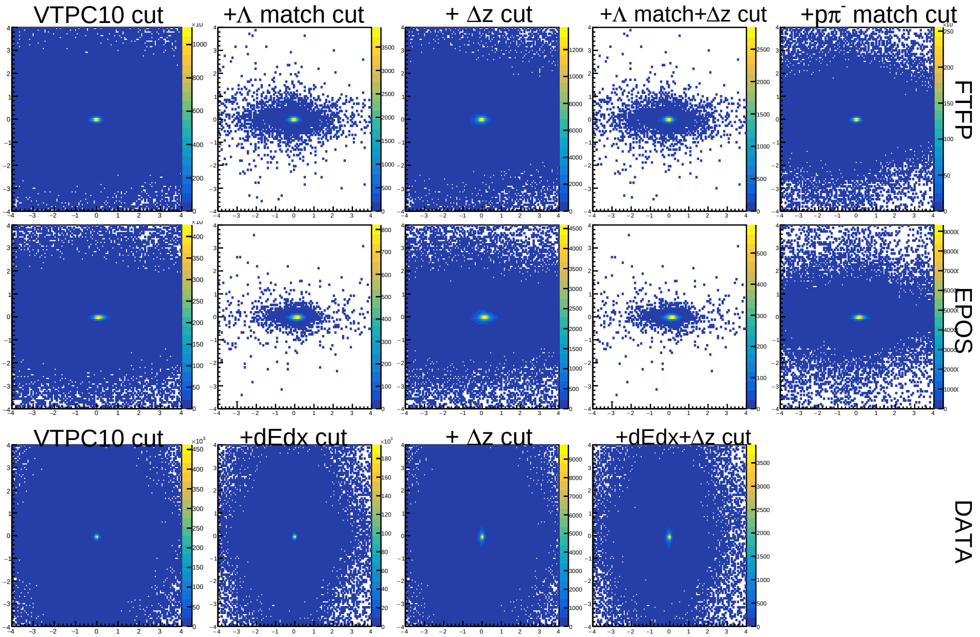
MC data that only matching to p and π^+ tracks

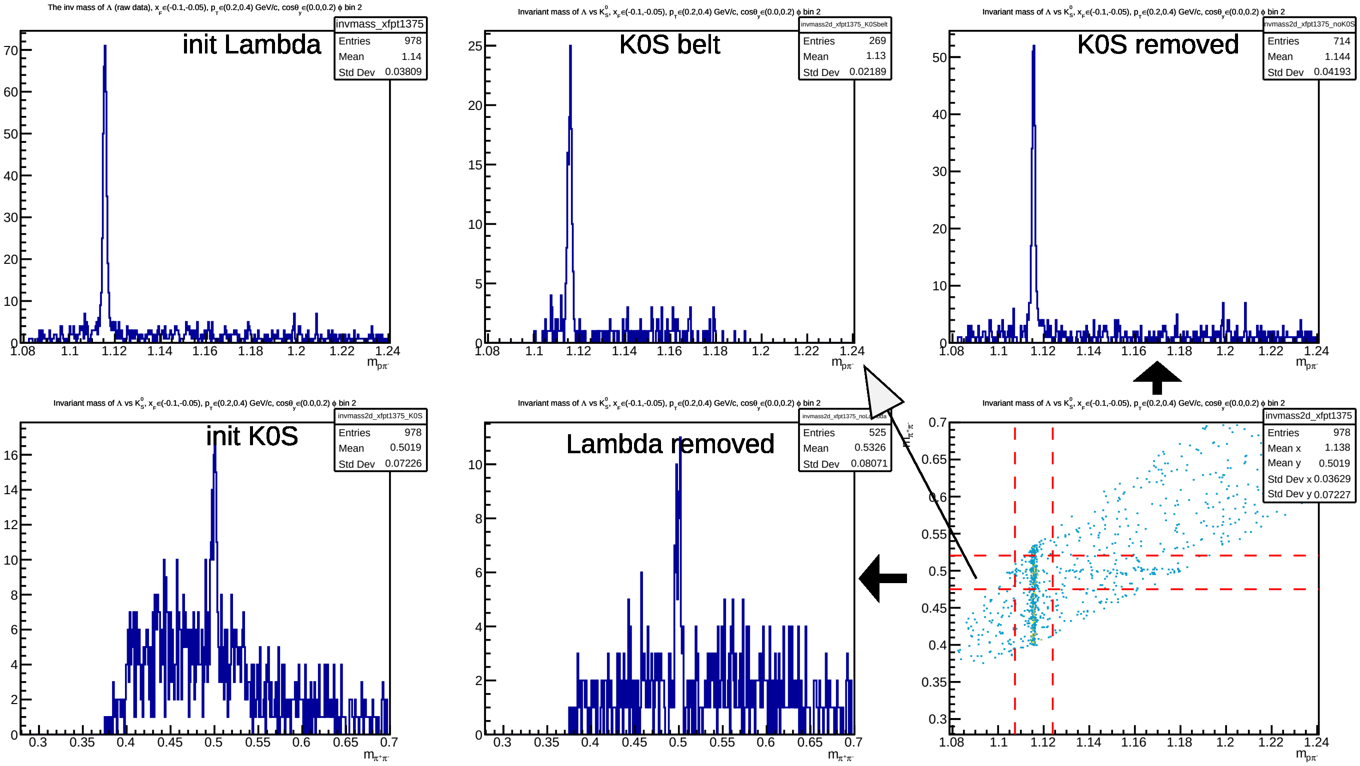


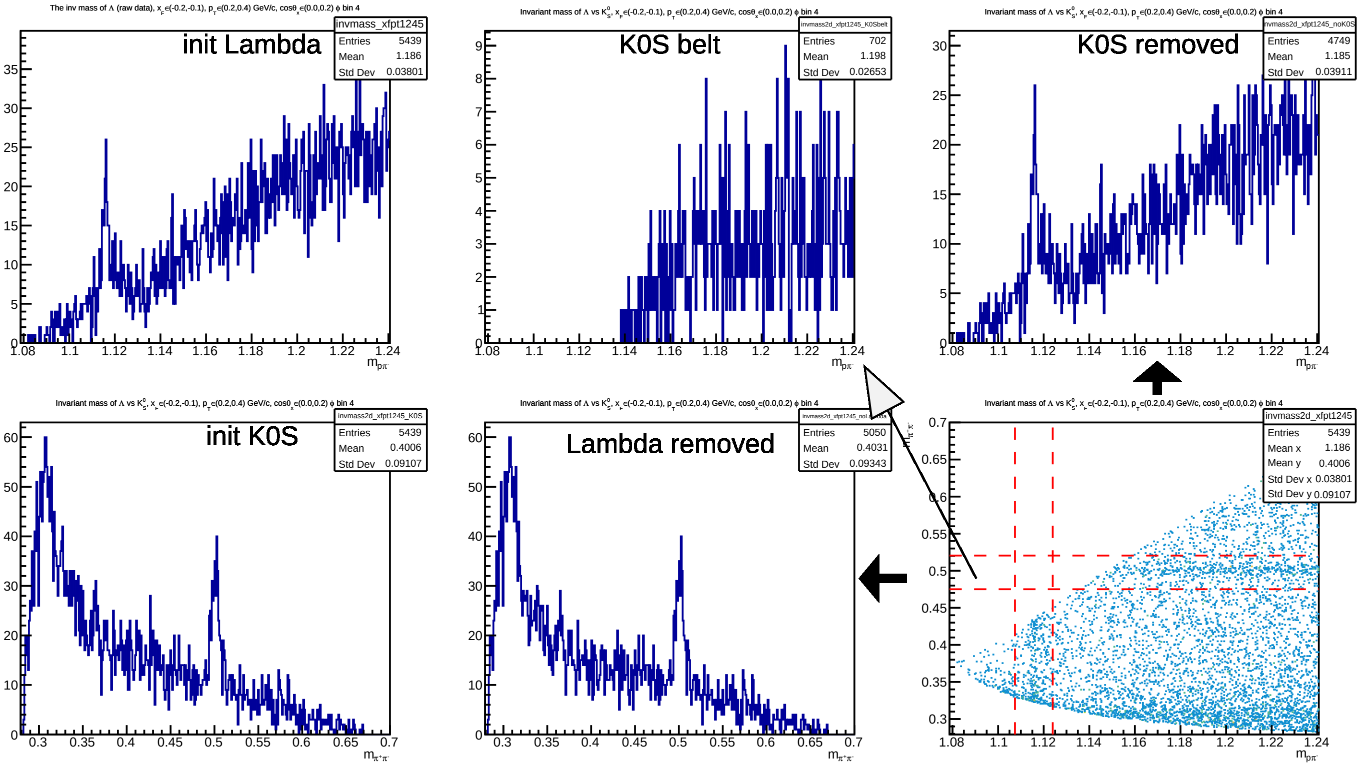
MC data that matching Λ vertex

Impact parameter cut

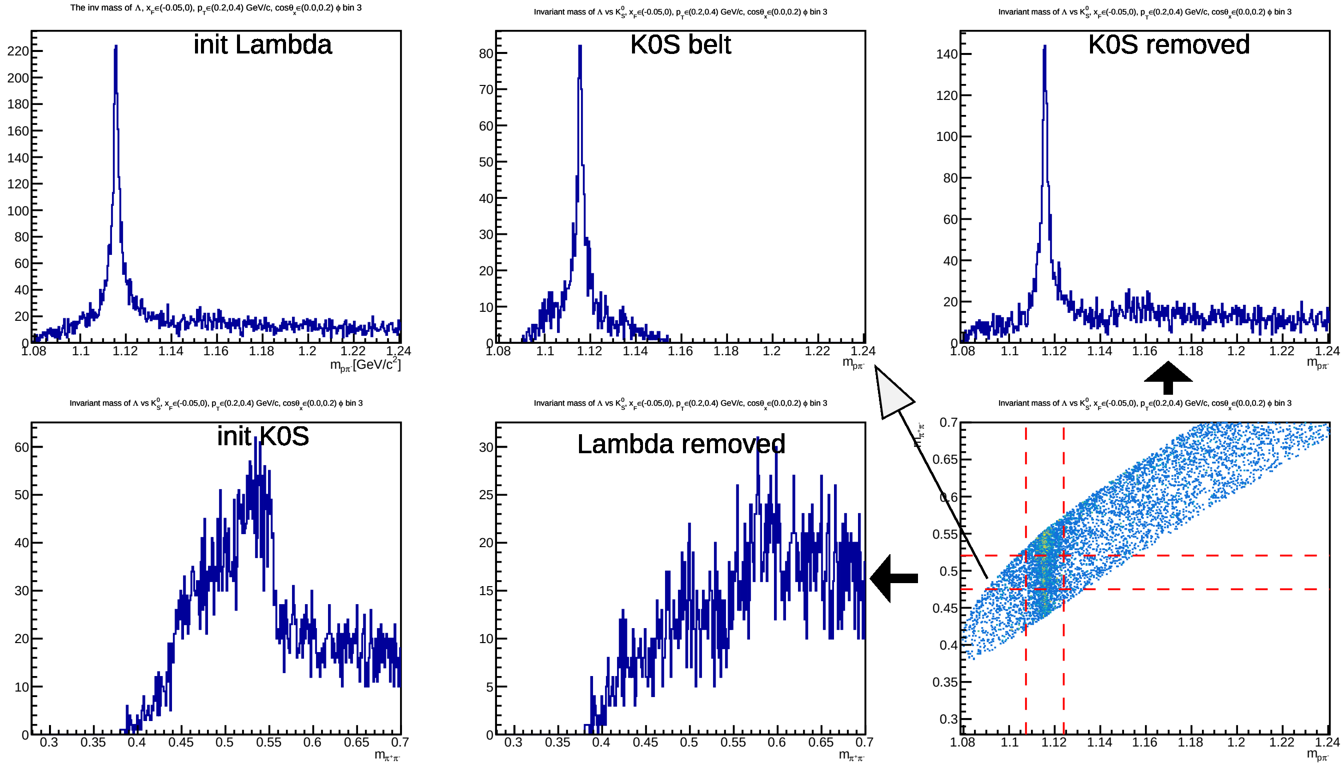
The cut is an ellipse with semi-axes along x 2 cm and along y 1 cm. Pretty y-pT independent picture.




The inv mass of Λ (raw data), x_F∈(-0.1,-0.05), p_T∈(0.2,0.4) GeV/c, cosθ_y∈(0.0,0.2) ϕ bin 2
invmass_xfpt1375
Entries 978
Mean 1.14
Std Dev 0.03809
init Lambda
m_pπ-
Invariant mass of Λ vs K0S, x_F∈(-0.1,-0.05), p_T∈(0.2,0.4) GeV/c, cosθ_y∈(0.0,0.2) ϕ bin 2
invmass2d_xfpt1375_K0Sbelt
Entries 269
Mean 1.13
Std Dev 0.02189
K0S belt
K0S removed
invmass2d_xfpt1375_noK0S
Entries 714
Mean 1.144
Std Dev 0.04193
init K0S
invmass2d_xfpt1375_K0S
Entries 978
Mean 0.5019
Std Dev 0.07226
m_π+π-
Lambda removed
Entries 525
Mean 0.5326
Std Dev 0.08071
invmass2d_xfpt1375
Entries 978
Mean x 1.138
Mean y 0.5019
Std Dev x 0.03629
Std Dev y 0.07227

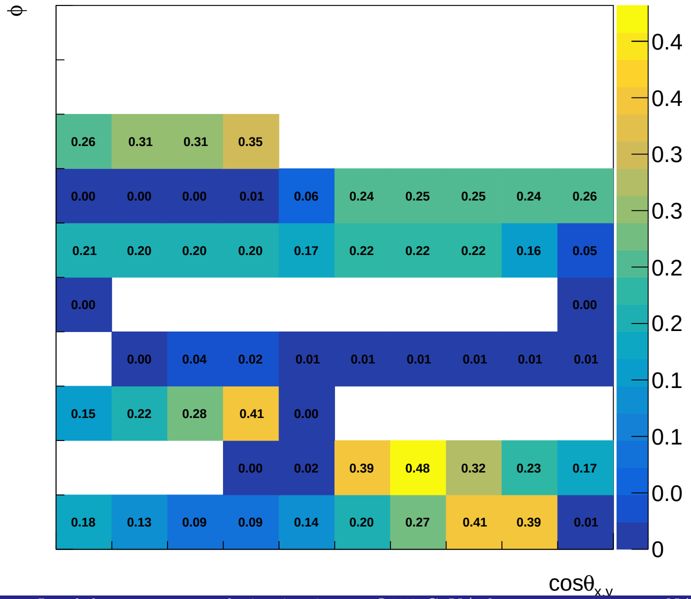


The inv mass of Λ (raw data), x_F∈(-0.2,-0.1), p_T∈(0.2,0.4) GeV/c, cosθ_x∈(0.0,0.2) ϕ bin 4
init Lambda
invmass_xfpt1245
Entries 5439
Mean 1.186
Std Dev 0.03801
m_pπ-
Invariant mass of Λ vs K^0_S, x_F∈(-0.2,-0.1), p_T∈(0.2,0.4) GeV/c, cosθ_x∈(0.0,0.2) ϕ bin 4
K0S belt
invmass2d_xfpt1245_K0Sbelt
Entries 702
Mean 1.198
Std Dev 0.02653
K0S removed
invmass2d_xfpt1245_noK0S
Entries 4749
Mean 1.185
Std Dev 0.03911
init K0S
invmass2d_xfpt1245_K0S
Entries 5439
Mean 0.4006
Std Dev 0.09107
m_π+π-
Lambda removed
Entries 5050
Mean 0.4031
Std Dev 0.09343
invmass2d_xfpt1245
Entries 5439
Mean x 1.186
Mean y 0.4006
Std Dev x 0.03801
Std Dev y 0.09107


The inv mass of Λ, x_F∈(-0.05,0), p_T∈(0.2,0.4) GeV/c, cosθ_x∈(0.0,0.2) ϕ bin 3
init Lambda
m_pπ- [GeV/c²]
Invariant mass of Λ vs K⁰_S, x_F∈(-0.05,0), p_T∈(0.2,0.4) GeV/c, cosθ_x∈(0.0,0.2) ϕ bin 3
K0S belt
m_pπ-
K0S removed
m_pπ-
init K0S
m_π+π-
Lambda removed
m_π+π-
m_π+π-
m_pπ-

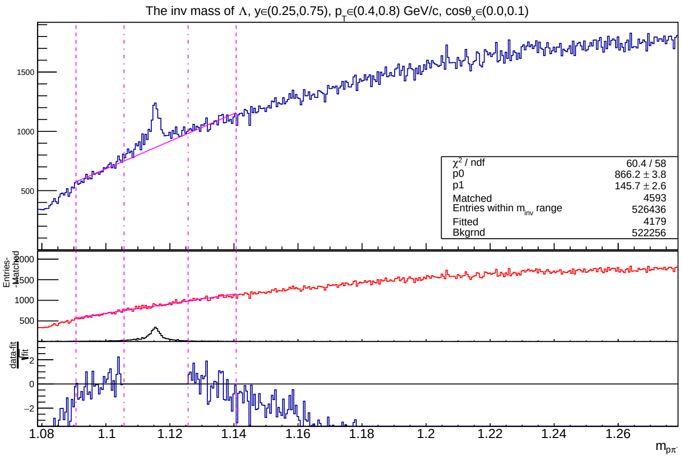
fraction of of both Lambda and K0S candidates per all Lambda candidates:

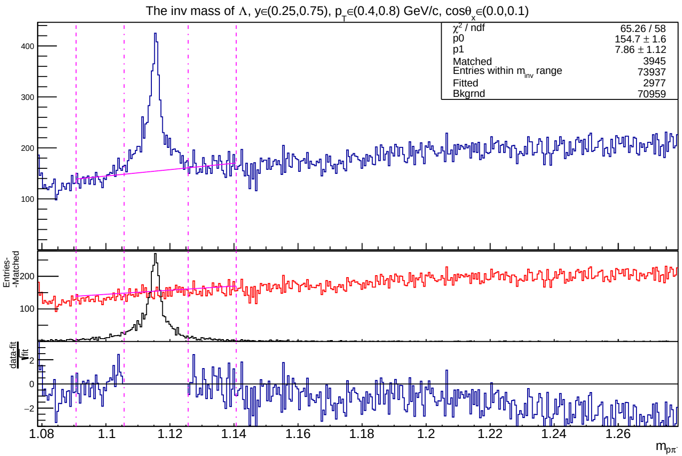
$$\frac{\#(|m_{\pi^+\pi^-} - m_{K0S}| < 0.02) \cup \#(|m_{p\pi^-} - m_{\Lambda}| < 0.02)}{\#\text{ entries in Lambda hist}}$$



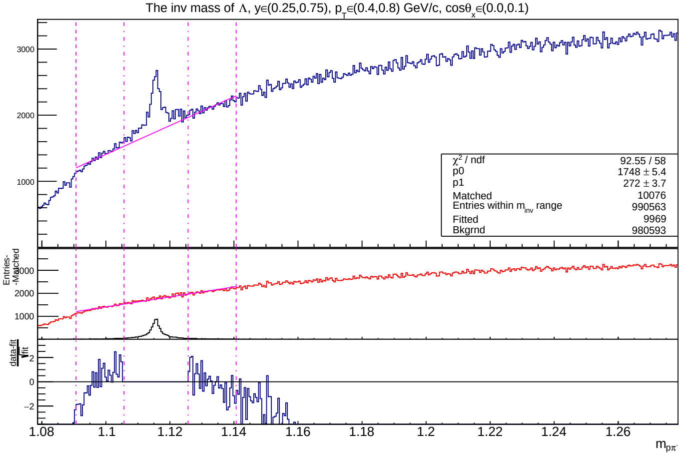
- m_{inv} (K_0^S,Λ) for MC (proton-pion matching) is useless, for data (dE/dx cut) shows both candidates
- Idea is to somehow count no. of K_0^S that mimic in Lambda and subtract it

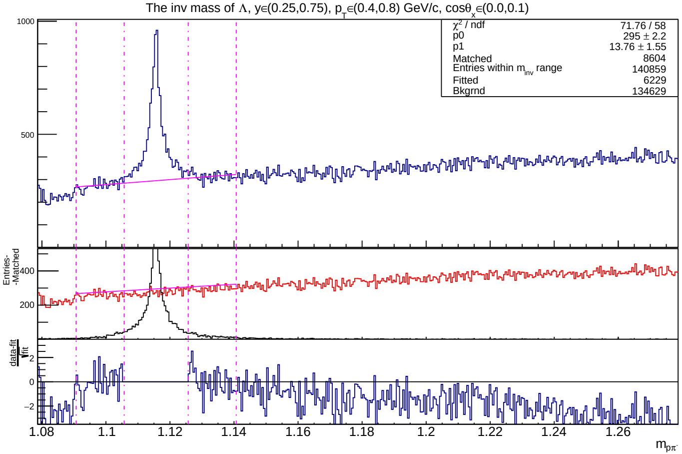
Epos, With/without Delta z cut



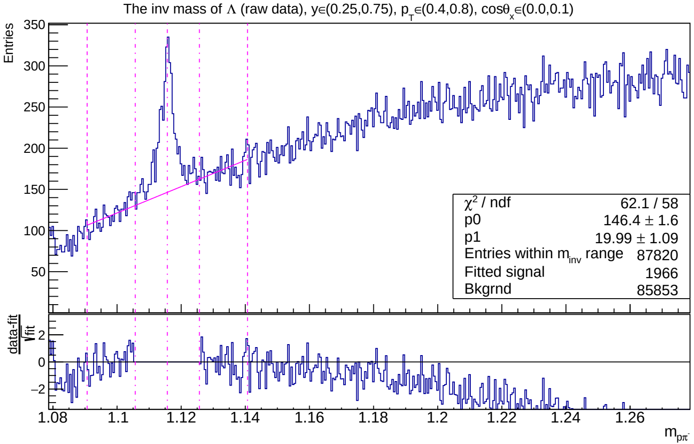


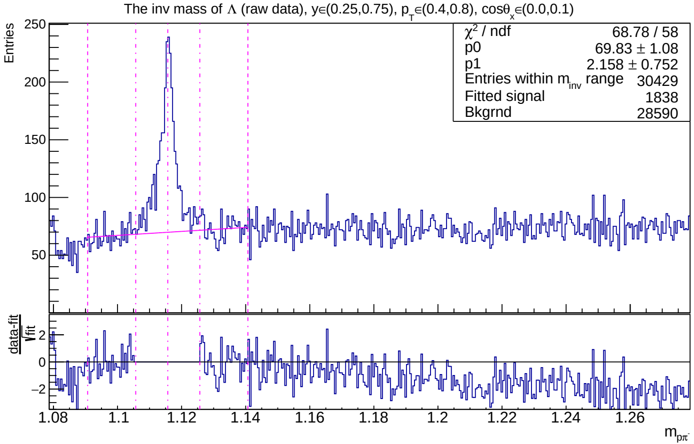
FRITIOF, With/without Delta z cut



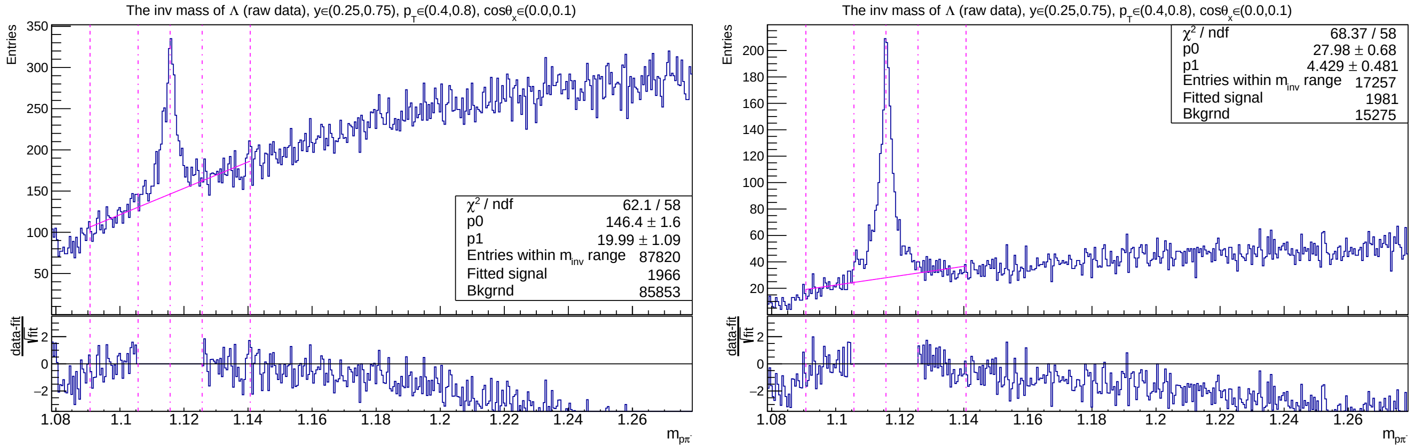


Data, With/without Delta z cut

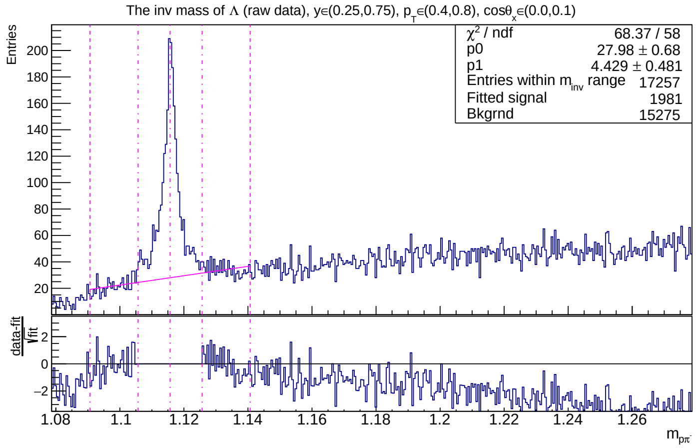


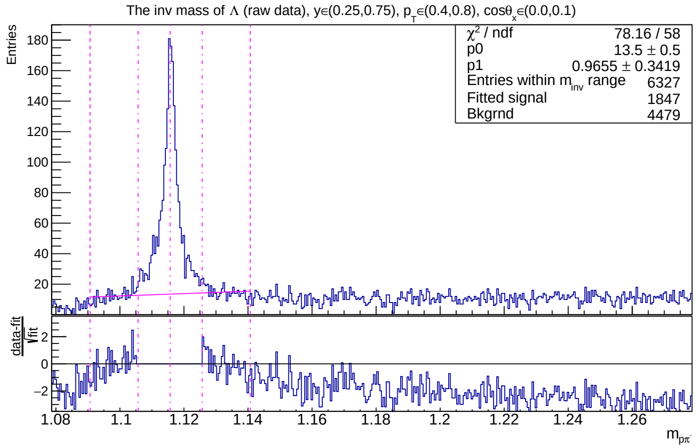


Data, With/without dEdx cut

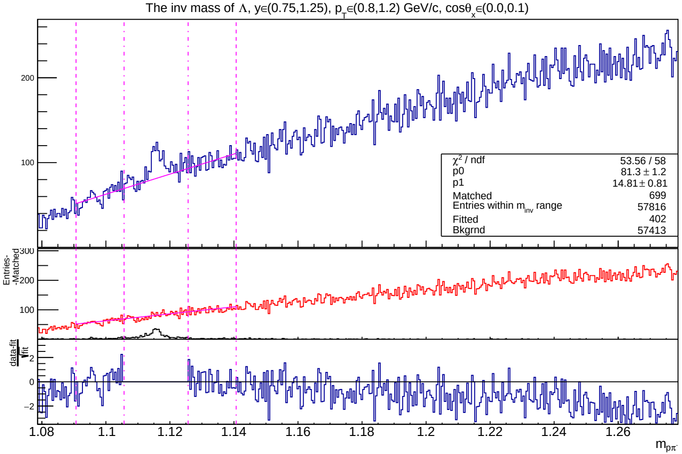


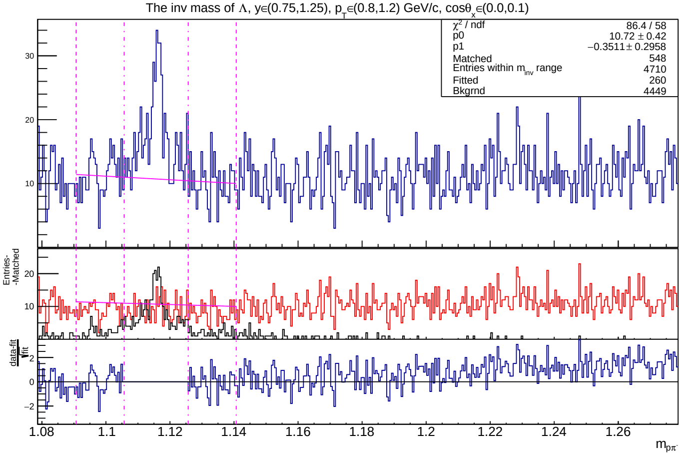
Data, With/without Delta z cut (+dEdxcut)

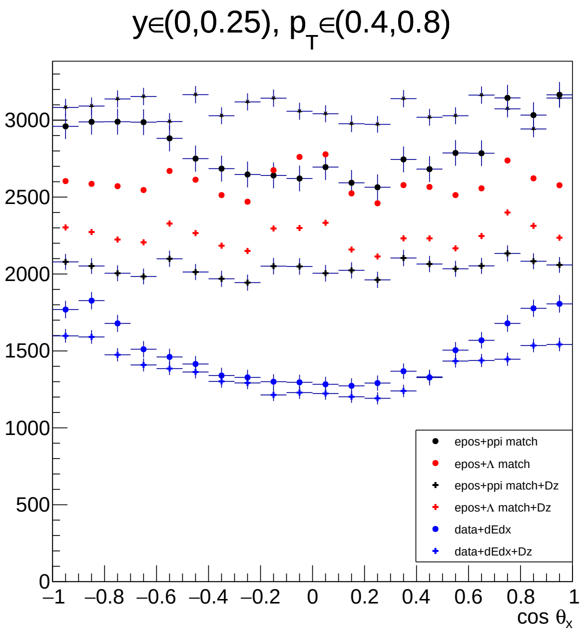


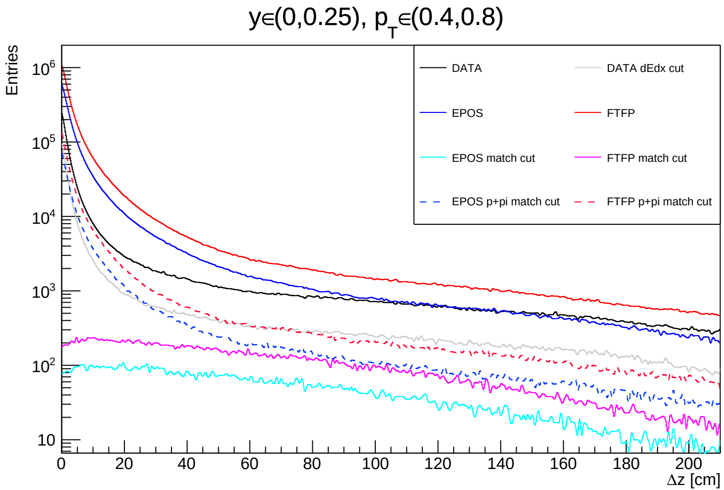


Epos, With/without Delta z cut

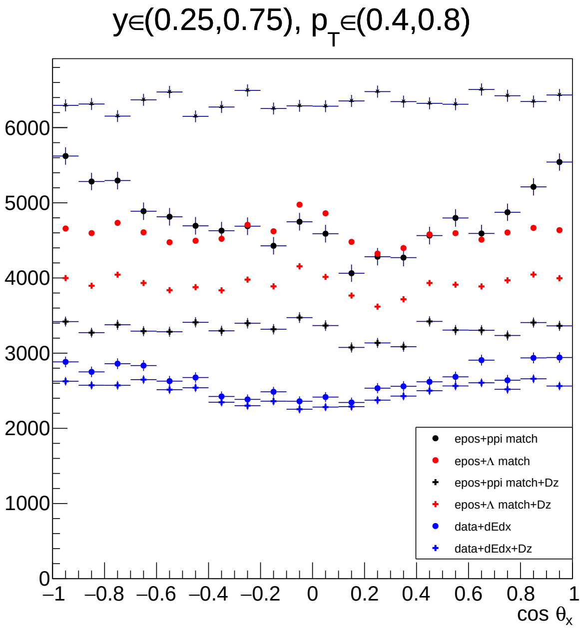


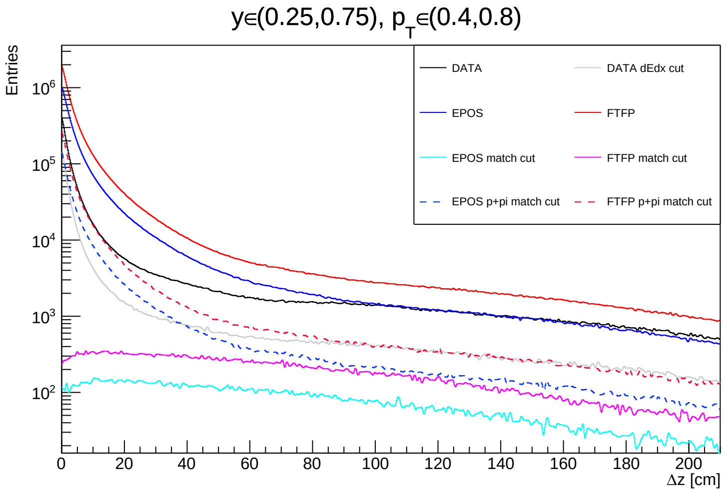



y∈(0,0.25), p_T∈(0.4,0.8)
3000
2500
2000
1500
1000
500
0
–1
–0.8
–0.6
–0.4
–0.2
0
0.2
0.4
0.6
0.8
1
cos θ_x
epos+ppi match
epos+Λ match
epos+ppi match+Dz
epos+Λ match+Dz
data+dEdx
data+dEdx+Dz

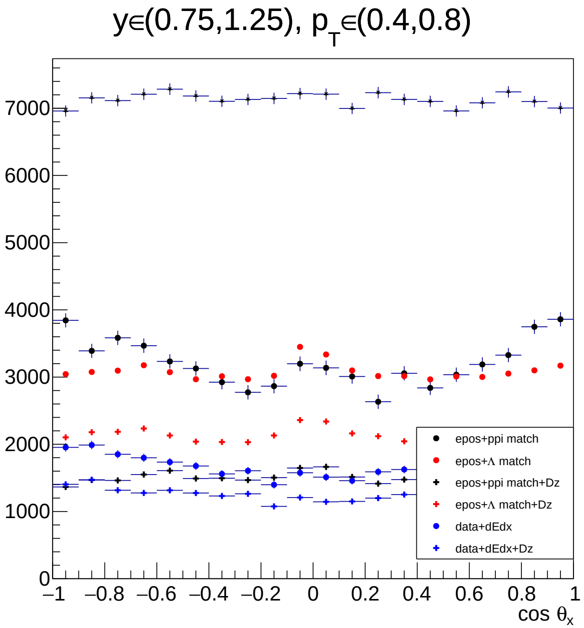

y∈(0,0.25), p_T∈(0.4,0.8)
Entries
10^6
10^5
10^4
10^3
10^2
10
0
20
40
60
80
100
120
140
160
180
200
Δz [cm]
DATA
DATA dEdx cut
EPOS
FTFP
EPOS match cut
FTFP match cut
EPOS p+pi match cut
FTFP p+pi match cut

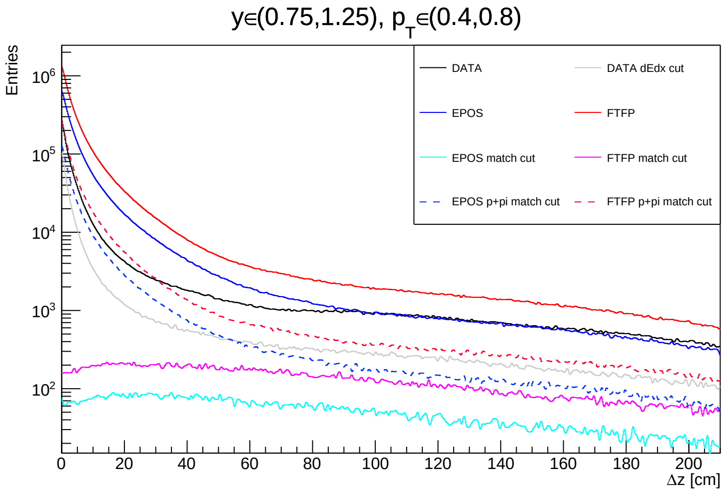
$\Delta z > 15$ cm, $y \in (0.25, 0.75)$



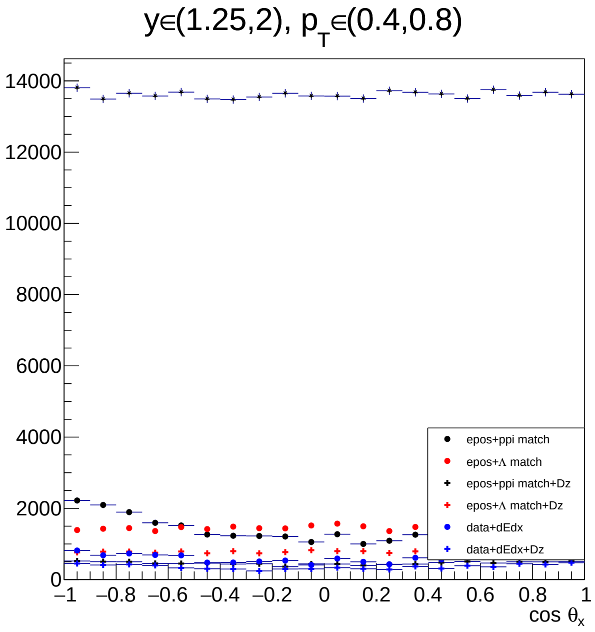


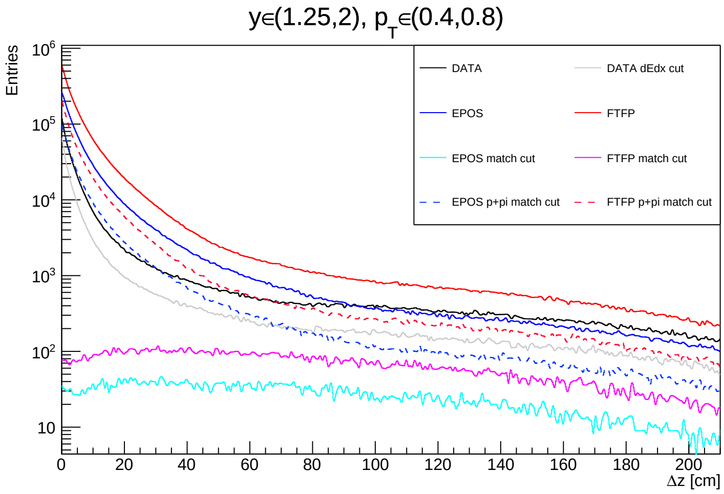
$\Delta z > 40$ cm, $y \in (0.75, 1.25)$



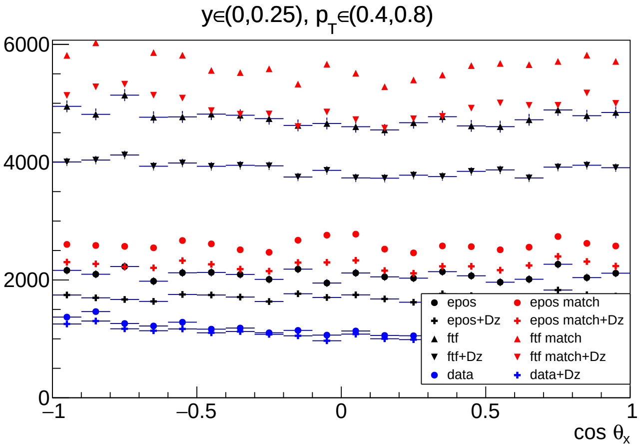


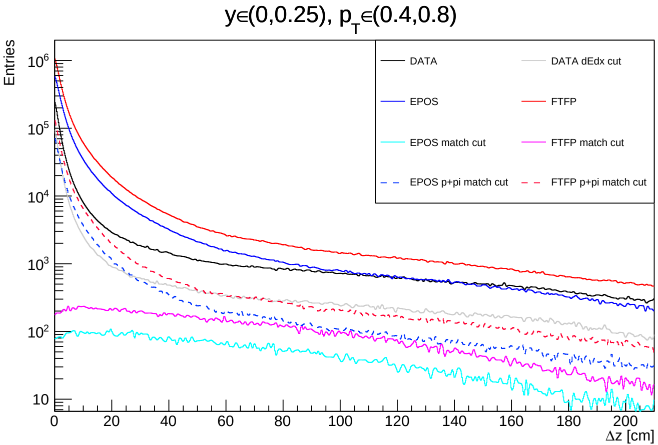
$\Delta z > 60$ cm, $y \in (1.25, 2)$



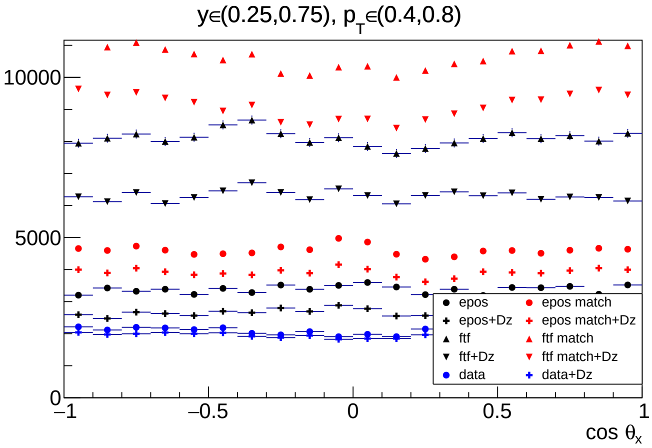


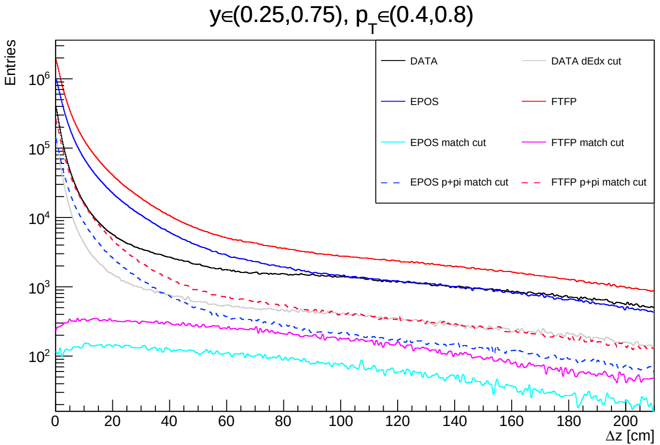
$\Delta z > 10$ cm, $y \in (0, 0.25)$



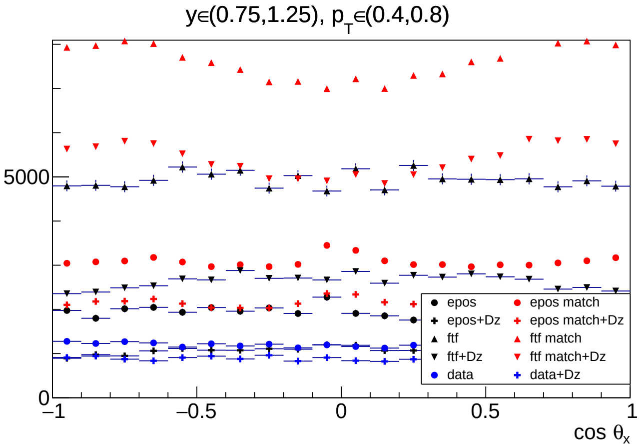


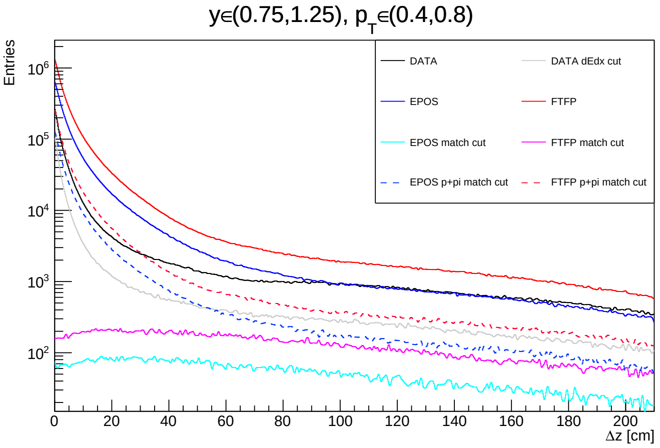
$\Delta z > 15$ cm, $y \in (0.25, 0.75)$



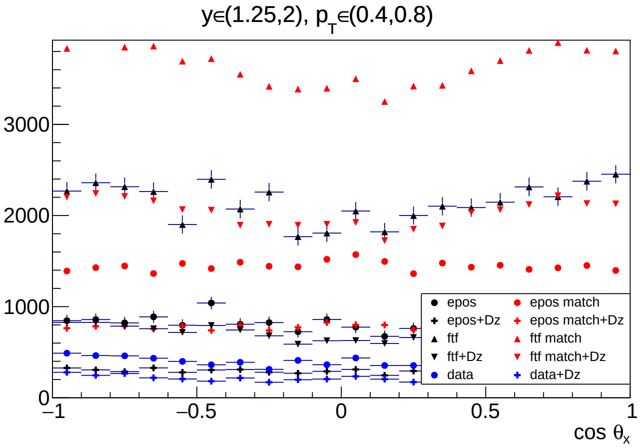


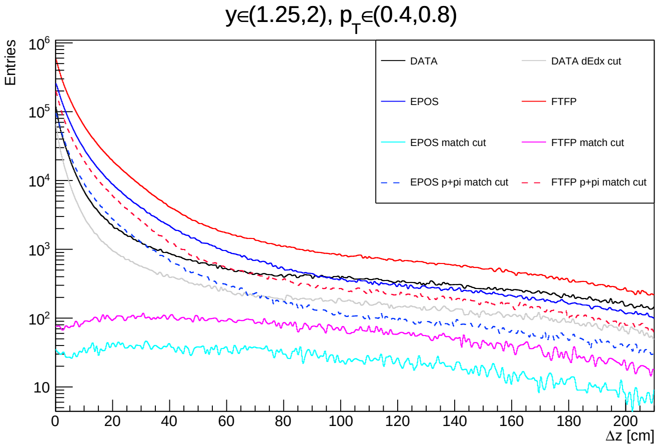
$\Delta z > 40$ cm, $y \in (0.75, 1.25)$

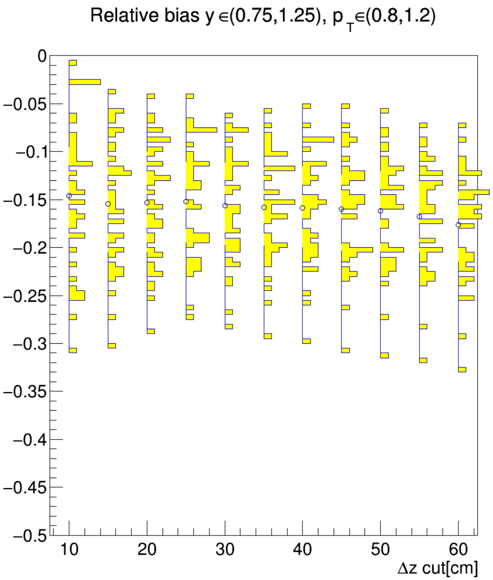


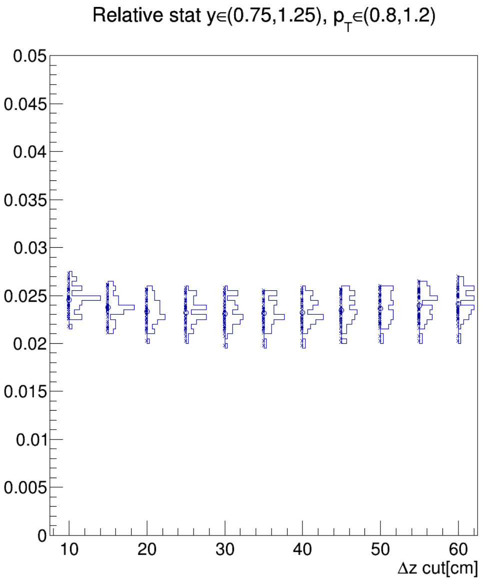


$\Delta z > 60$ cm, $y \in (1.25, 2)$

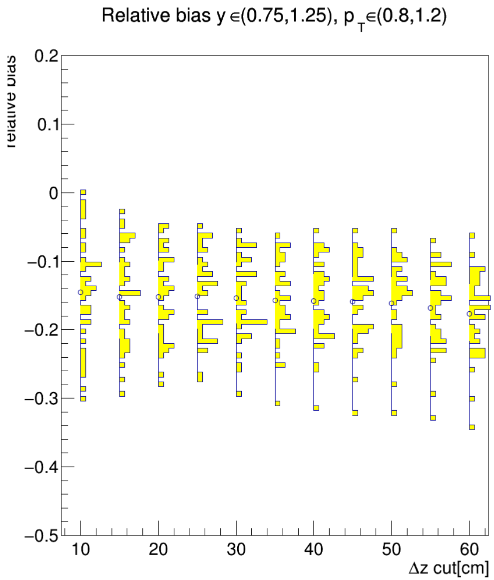


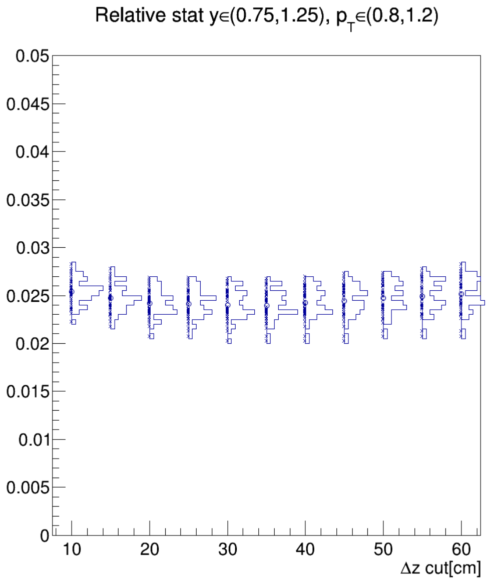



Relative bias y ∈(0.75,1.25), p_T∈(0.8,1.2)
0
−0.05
−0.1
−0.15
−0.2
−0.25
−0.3
−0.35
−0.4
−0.45
−0.5
10
20
30
40
50
60
Δz cut[cm]


Relative stat y∈(0.75,1.25), p_T∈(0.8,1.2)
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
10
20
30
40
50
60
Δz cut[cm]

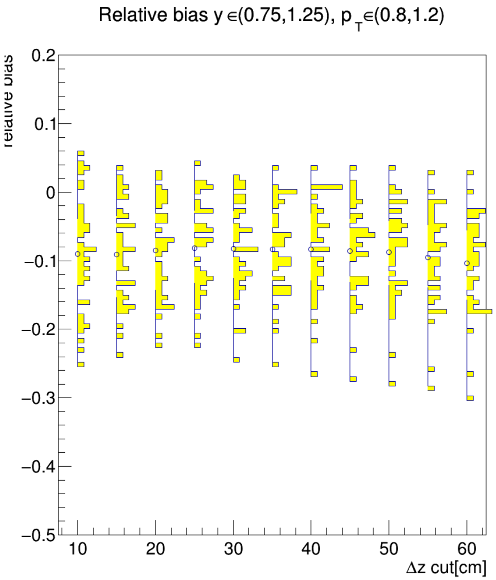
VTPC1+VTPC2 great or equal 20

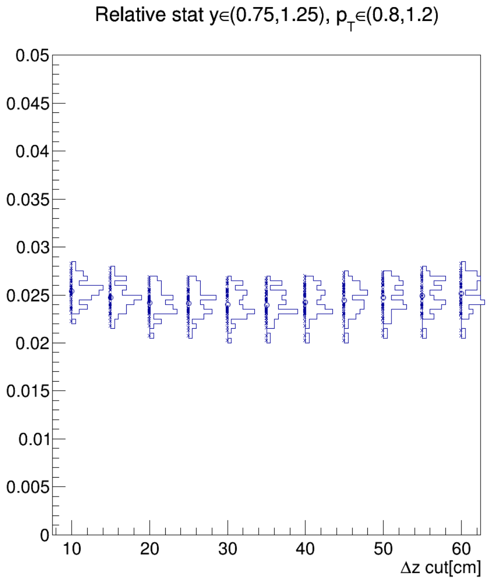




VTPC1+VTPC2 great or equal 20

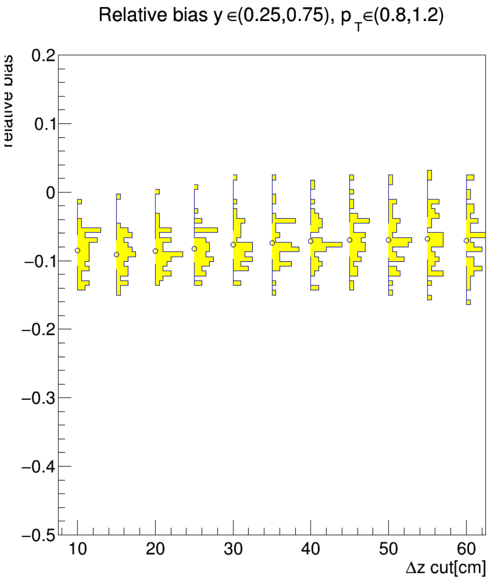
But, the signal is integral of asymm BreitWigner PDF

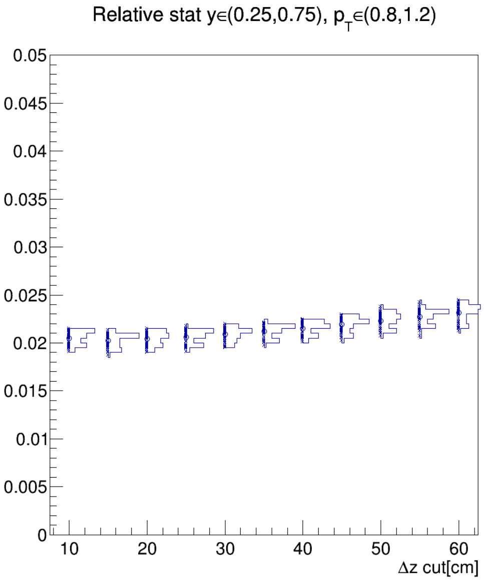




VTPC1+VTPC2 great or equal 20

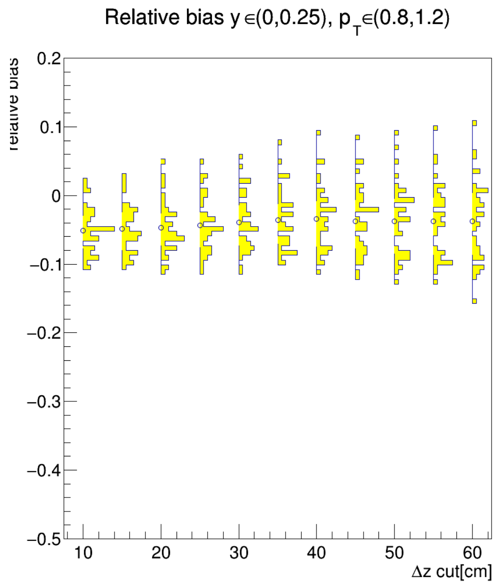
But, the signal is integral of asymm BreitWigner PDF. The farther from midrapidity the worse...

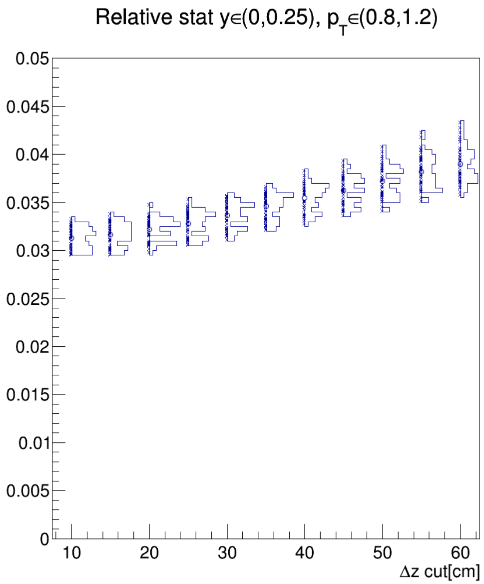




VTPC1+VTPC2 great or equal 20

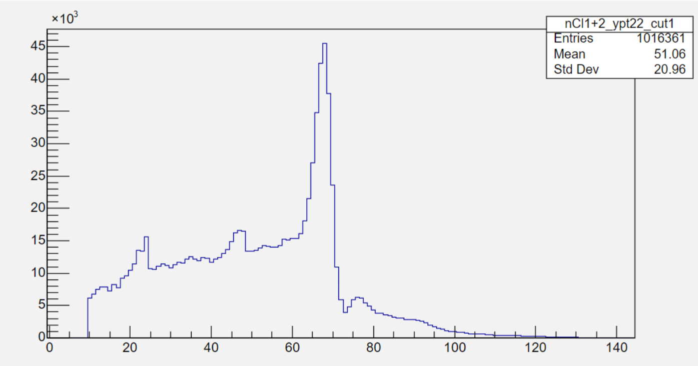
But, the signal is integral of asymm BreitWigner PDF. The farther from midrapidity the worse...



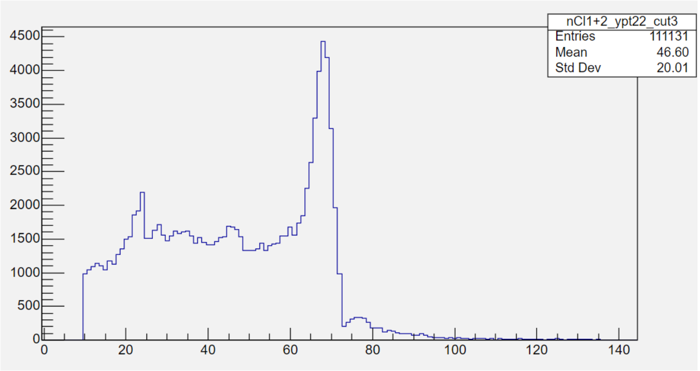


VTPC1+VTPC2 Clusters in $y \in (0.75, 1.25), p_T \in (0.8, 1.2)$ in data

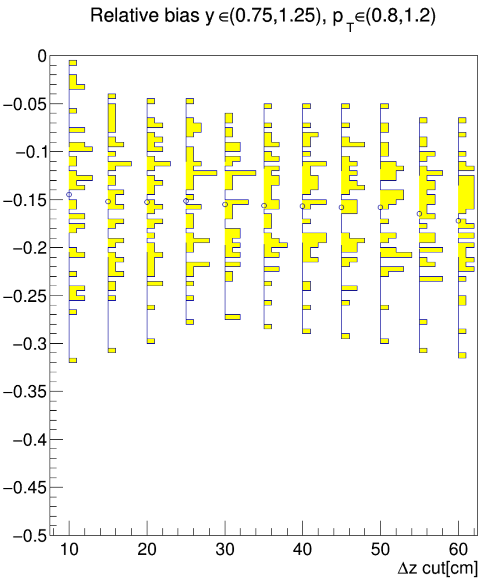
with dE/dx cut

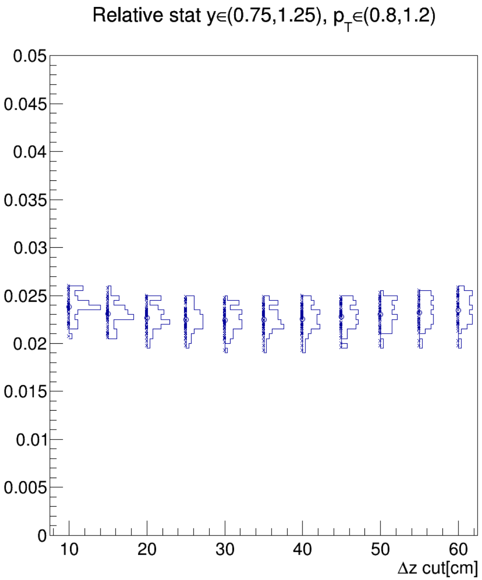


with dE/dx cut and $\Delta z > 40$ cm



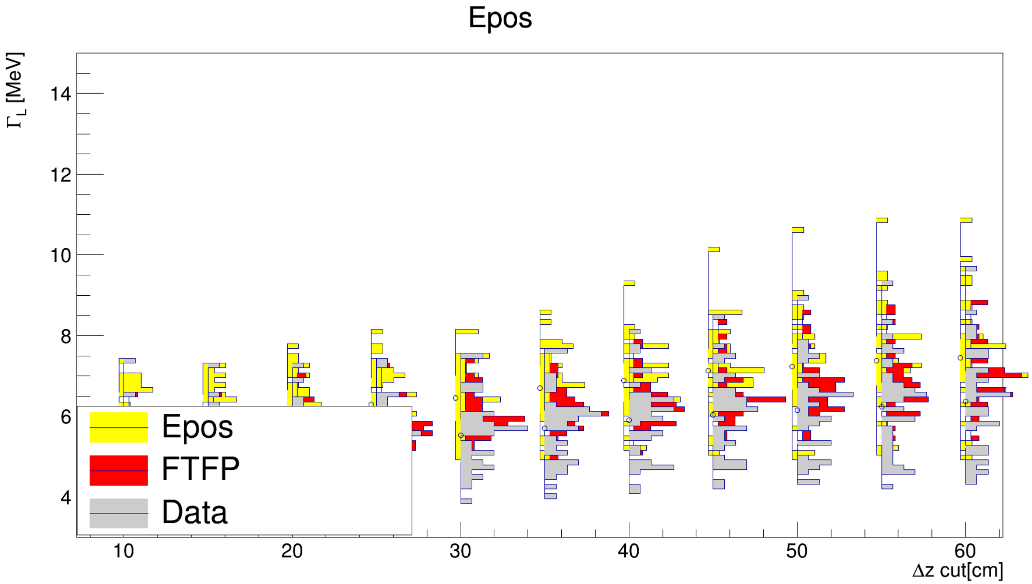
$Max(VTPC1, VTPC2) \geq 10$





Γ_L on invmass hists

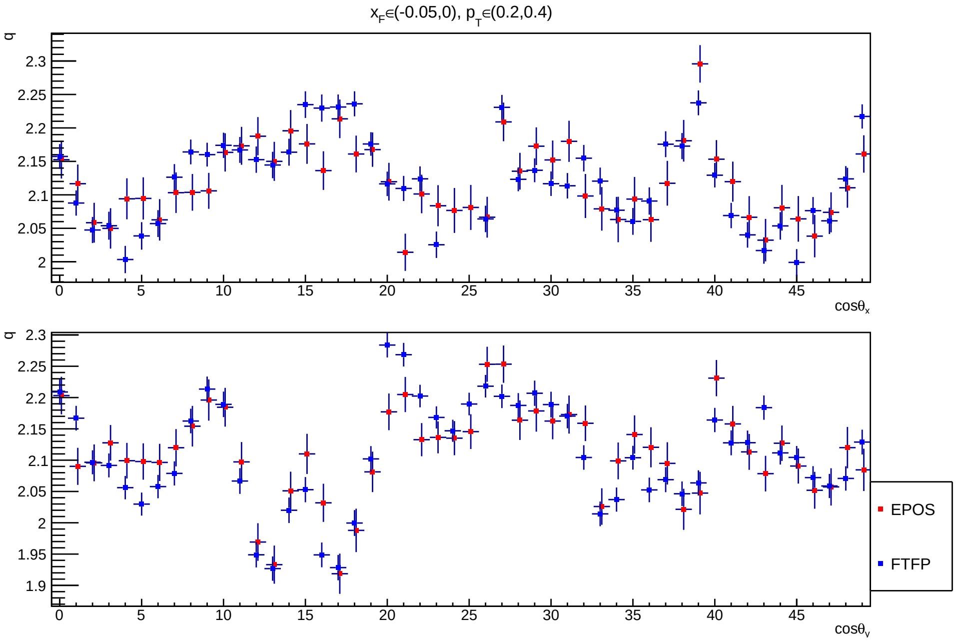
Γ_L on invmass hists $y \in (0.25, 0.75), p_T \in (0.8, 1.2)$:



Width for EPOS/FTFP/data are different

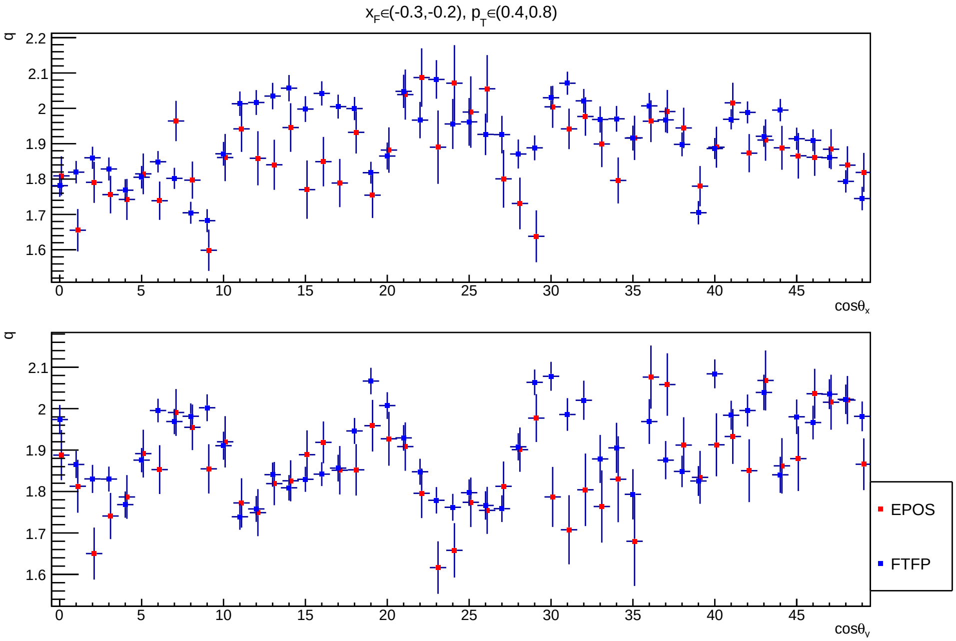
q value

q value on invmass hists $x_F \in (-0.05, 0), p_T \in (0.2, 0.4)$:



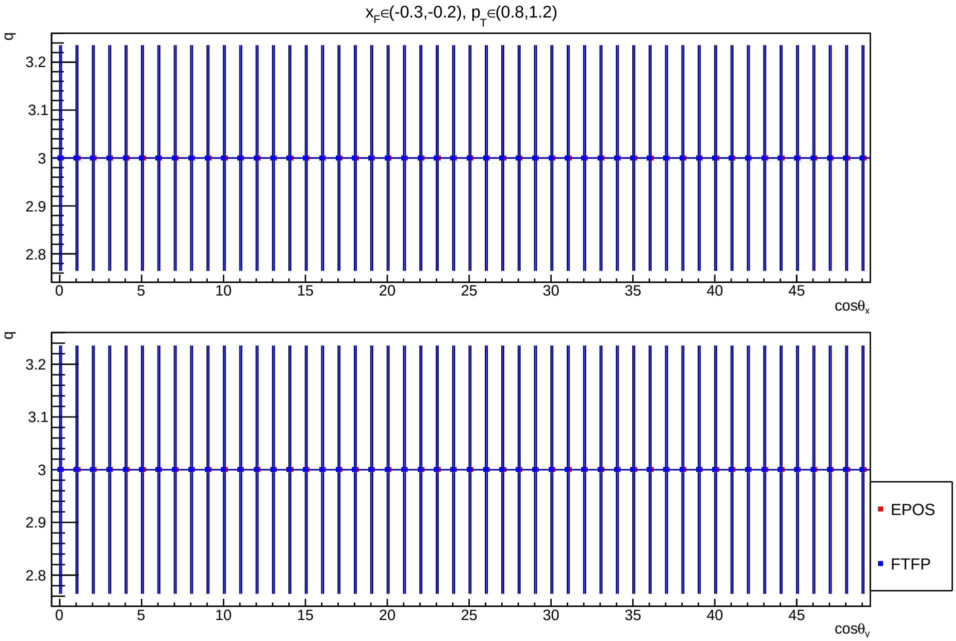
q value

q value on invmass hists $x_F \in (-0.3, -0.2), p_T \in (0.4, 0.8)$:



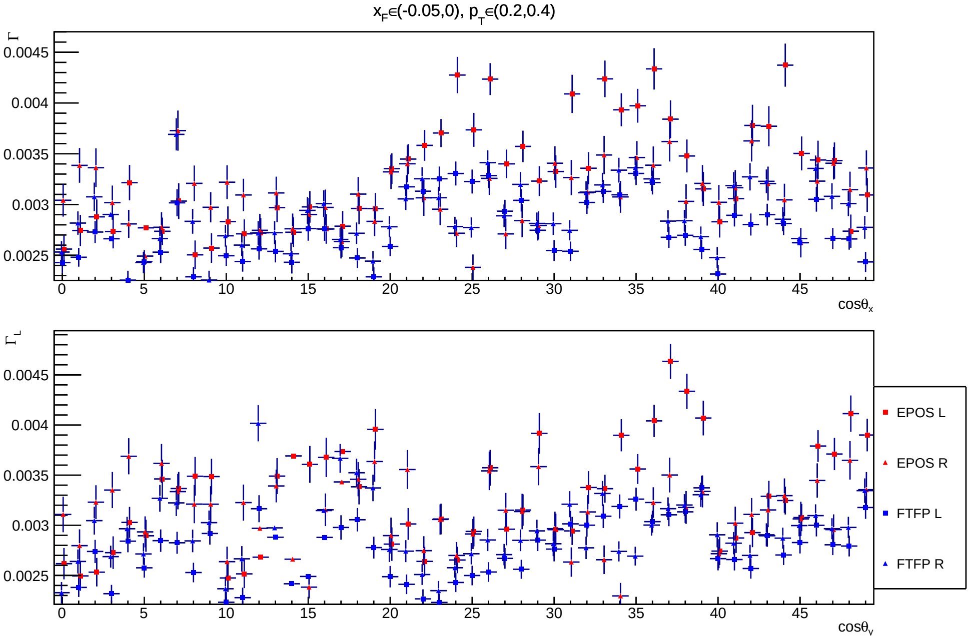
q value

q value on invmass hists $x_F \in (-0.3, -0.2), p_T \in (0.8, 1.2)$:



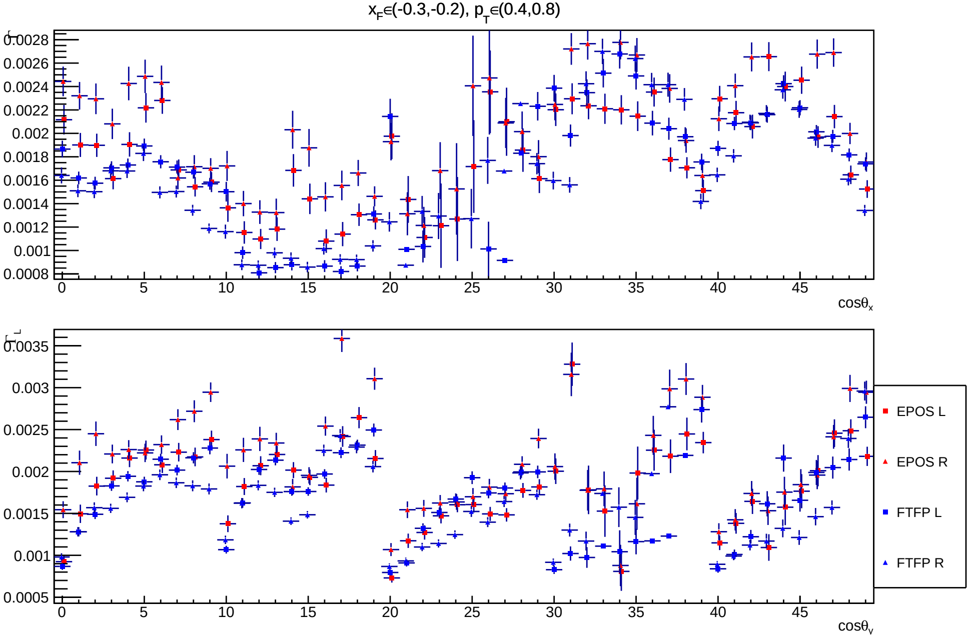
$\Gamma_{L,R}$ on invmass hists

q value on invmass hists $x_F \in (-0.05, 0), p_T \in (0.2, 0.4)$:



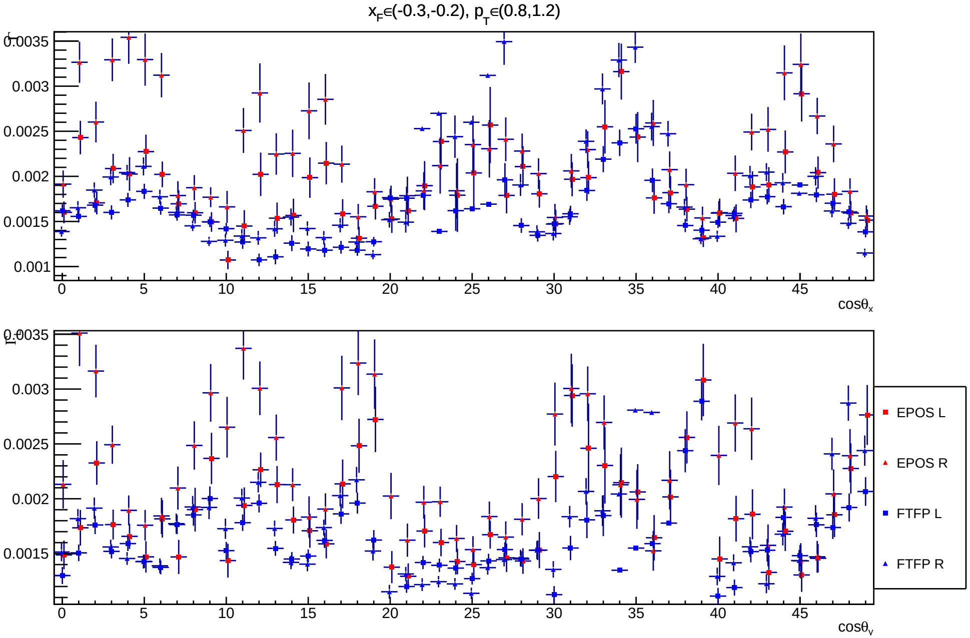
$\Gamma_{L,R}$ on invmass hists

q value on invmass hists $x_F \in (-0.3, -0.2), p_T \in (0.4, 0.8)$:



$\Gamma_{L,R}$ on invmass hists

q value on invmass hists $x_F \in (-0.3, -0.2), p_T \in (0.8, 1.2)$:



Weighted MC correction data

Without weighting for 4-dim bin i, the multiplicative factor is:

$$c_{MC} = \frac{\int_{\text{bin}} \left[\frac{d^2n}{dx_F dp_T}\right]^{\text{MC}}}{\int_{\text{bin}} \left[\frac{d^2n}{dx_F dp_T}\right]^{\text{MC}} \epsilon(x_F, p_T, \cos\theta, \phi)} = \frac{\frac{1}{N_{\text{evt}}} \sum_{gen \in bin} 1}{\frac{1}{N_{\text{evt}}} \sum_{sel \in bin} 1}, \tag{2}$$

(The fact that MC distribution is uniform in $(\cos\theta, \phi)$ was taken into account)
With weighting for bin i, we have to include $w = (\frac{d^2n}{dx_F dp_T})^{\text{DATA}}/(\frac{d^2n}{dx_F dp_T})^{\text{MC}}$ term in both integrals/sums:

$$c_{MC} = \frac{\sum_{gen} 1 \cdot (\frac{d^2n}{dx_F dp_T})^{\text{DATA}}/(\frac{d^2n}{dx_F dp_T})^{\text{MC}}}{\sum_{sel} 1 \cdot w} = \frac{N_{\text{evt}}^{\text{DATA}} (\frac{d^2n}{dx_F dp_T})^{\text{DATA}}}{\sum_{sel} 1 \cdot w} \tag{3}$$

So, the value $w = w(x_F, p_T)$ is a weight for each Λ candidate for m_{inv} fitting calculated for specific (x_F, p_T) of this Λ candidate, hence interpolation is needed.

Weighting issues

- linear interpolation for $(\frac{d^2n}{dx_F dp_T})^{\mathrm{MC}}$ is possible using the distribution showm below (histogram).
- Data interpolation: linear across x_F, p_T spectra based on fitted inversed slope parameter T for fixed x_F bin. (at midrapidity, $x_F \in (-0.1, 0)$ gives $T = 143.2 \pm 2.7$, $x_F \in (0, 0.1)$ gives $T = 140.9 \pm 2.8$, $y \in (-0.25, 0.25)$ gives $T = 158.2 \pm 3.6$, A.Wilczek paper says $T = 160.7$)

Weighted EPOS-FTFP and FTFP-EPOS correction

EPOS corrected by FTFP:

$$N_i^{\text{corrected}} = N_i^{\text{EPOS sel}} \times \frac{N_{\text{evt}}^{\text{FTFP}} (\frac{d^2n}{dx_F dp_T})^{\text{EPOS}}}{\sum_{sel \in bin}^{\text{FTFP}} 1 \cdot \left[(\frac{d^2n}{dx_F dp_T})^{\text{EPOS}} / (\frac{d^2n}{dx_F dp_T})^{\text{FTFP}} \right]} \tag{4}$$

FTFP corrected by EPOS:

$$N_i^{\text{corrected}} = N_i^{\text{FTFP sel}} \times \frac{N_{\text{evt}}^{\text{EPOS}} (\frac{d^2n}{dx_F dp_T})^{\text{FTFP}}}{\sum_{sel \in bin}^{\text{EPOS}} 1 \cdot \left[(\frac{d^2n}{dx_F dp_T})^{\text{FTFP}} / (\frac{d^2n}{dx_F dp_T})^{\text{EPOS}} \right]} \tag{5}$$

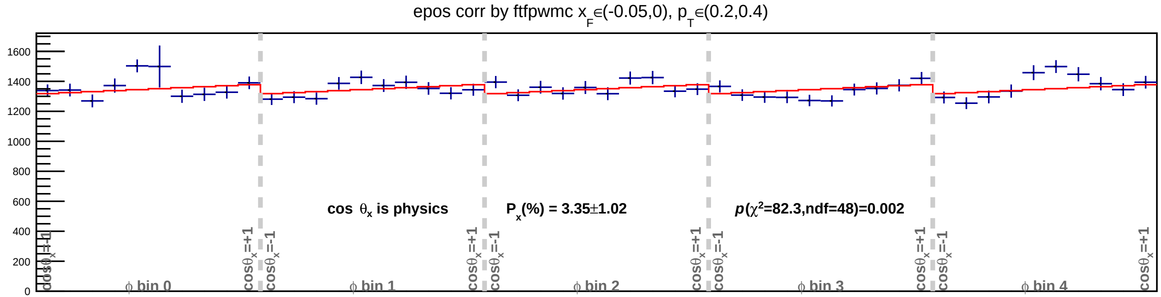
Data corrected by FTFP:

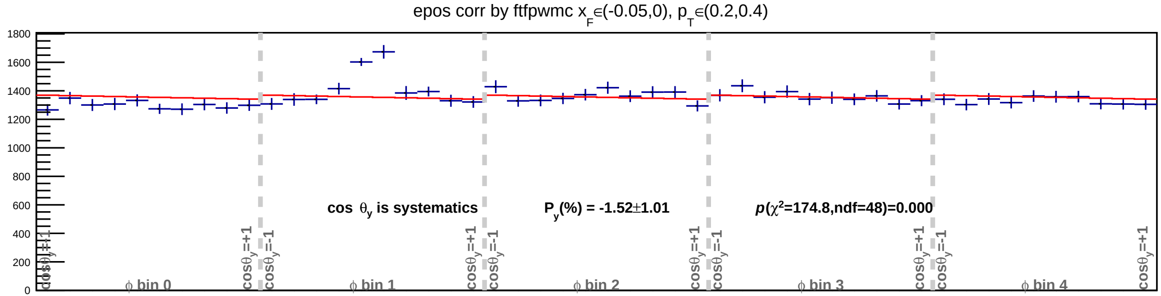
$$N_i^{\text{corrected}} = N_i^{\text{DATA sel}} \times \frac{N_{\text{evt}}^{\text{FTFP}} (\frac{d^2n}{dx_F dp_T})^{\text{DATA}}}{\sum_{sel \in bin}^{\text{FTFP}} 1 \cdot \left[(\frac{d^2n}{dx_F dp_T})^{\text{DATA}} / (\frac{d^2n}{dx_F dp_T})^{\text{FTFP}} \right]} \tag{6}$$

Data corrected by EPOS:

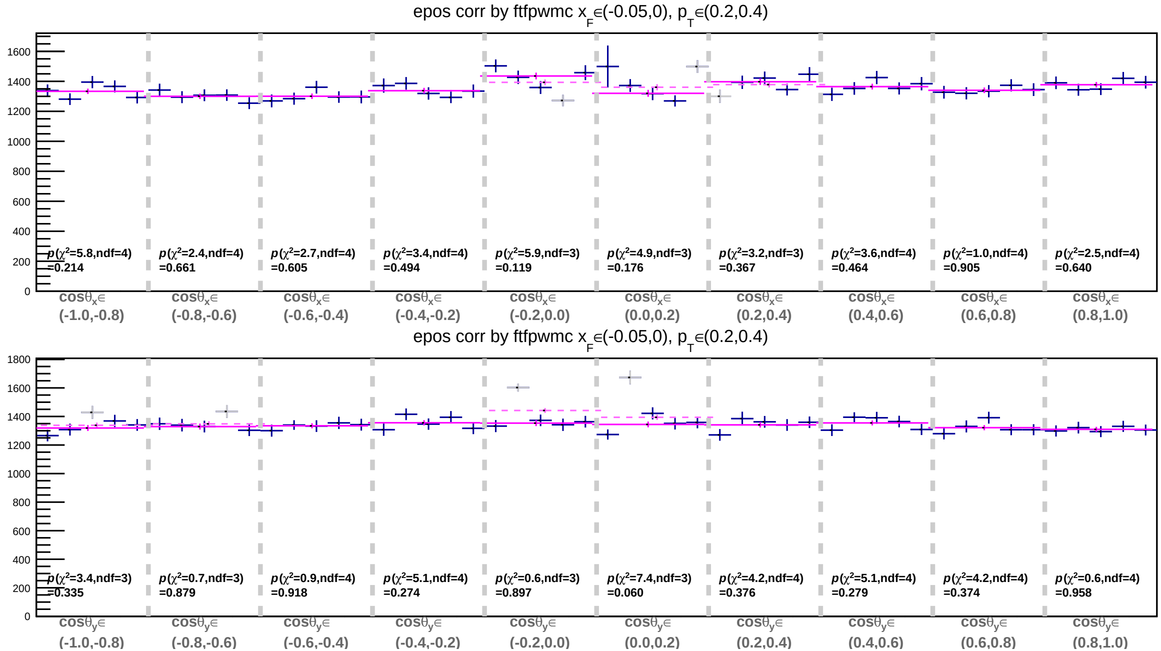
$$N_i^{\text{corrected}} = N_i^{\text{DATA sel}} \times \frac{N_{\text{evt}}^{\text{EPOS}} (\frac{d^2n}{dx_F dp_T})^{\text{DATA}}}{\sum_{sel \in bin}^{\text{EPOS}} 1 \cdot \left[(\frac{d^2n}{dx_F dp_T})^{\text{DATA}} / (\frac{d^2n}{dx_F dp_T})^{\text{EPOS}} \right]} \tag{7}$$

EPOS/FTFP *weighted* correction - all points - $x_F \in (-0.05, 0), p_T \in (0.2, 0.4)$





EPOS/FTFP *weighted* correction - point removal - $x_F \in (-0.05, 0), p_T \in (0.2, 0.4)$



Backup Slides

Model Feeddown EPOS

EPOS1.99 CRMC v1.4 generator, `eGeneratorFinal`
Lambdas have the following parent:
Summary: No Ξ — probably because no weak decay in EPOS, Ξs are `eGeneratorFinal` and decayed in Geant.

PID	particle	abundance
2212	p	0.4775
3212	Σ^0	0.1987
3224	Σ^{*+}	0.0768
3214	Σ^{*0}	0.0541
3114	Σ^{*-}	0.0303
13224	$\Sigma^+(1670)$	0.0125
13222	$\Sigma^+(1660)$	0.0125
42212	$N^+(1710)$	0.0118
22124	$N^+(1700)$	0.0118
32124	$N^+(1720)$	0.0117
42112	$N^0(1710)$	0.0070
21214	$N^0(1700)$	0.0070
31214	$N^0(1720)$	0.0070
13216	$\Sigma(1915)^0$	0.0059
23214	$\Sigma(1940)^0$	0.0058
⋮	⋮	⋮

Model Feeddown FTFP

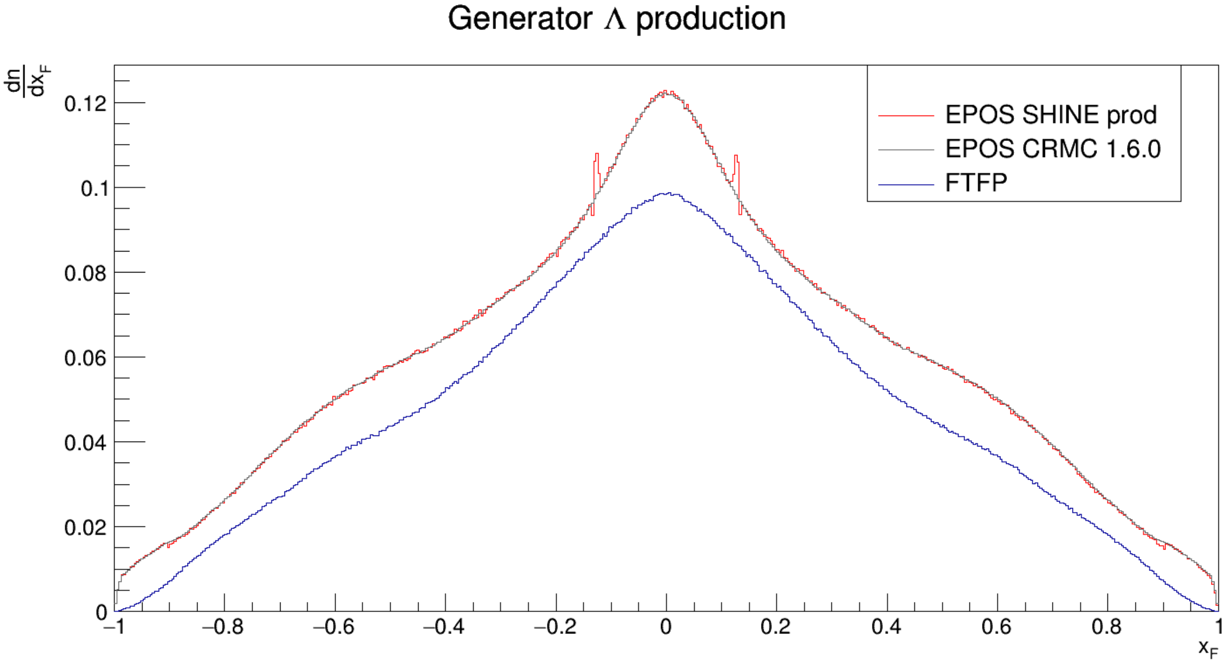
In FTFP (Geant4 v10.7.0), no info about resonance source, only implemented since Shine v1r21p0 (Geant4 v10.7.0.shine.2).

- directly from proton
- from Σ^0 (e.-m. decay), weak decays: Ξ, Ω, Ξ_c^0, etc.
- Double cascades: from $\Omega^- \to \Xi^0, \Xi^-$, $\Omega_c^0 \to \Xi^0$

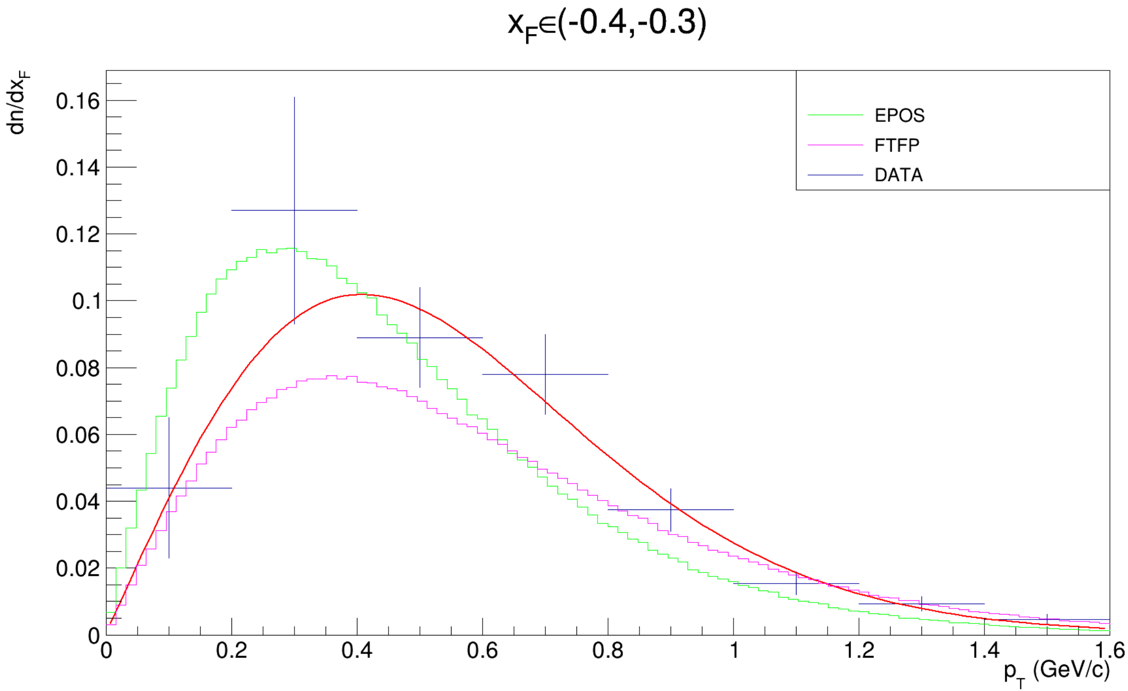
Direct parent:

PID	particle	abundance
2212	p	0.73517
3212	Σ^0	0.254763
3312	Ξ^-	0.00518028
3322	Ξ^0	0.0039818
4132	Ξ_c^0	0.000741412
3334	Ω^-	0.000163111

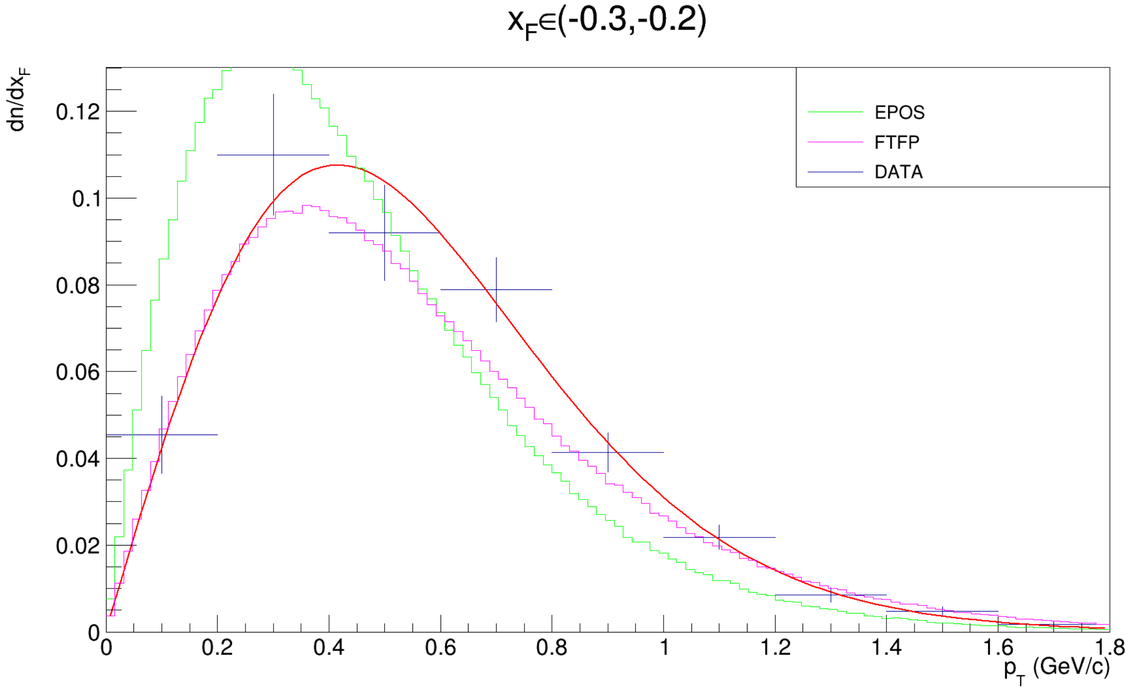
FTFP/EPOS Lambda production



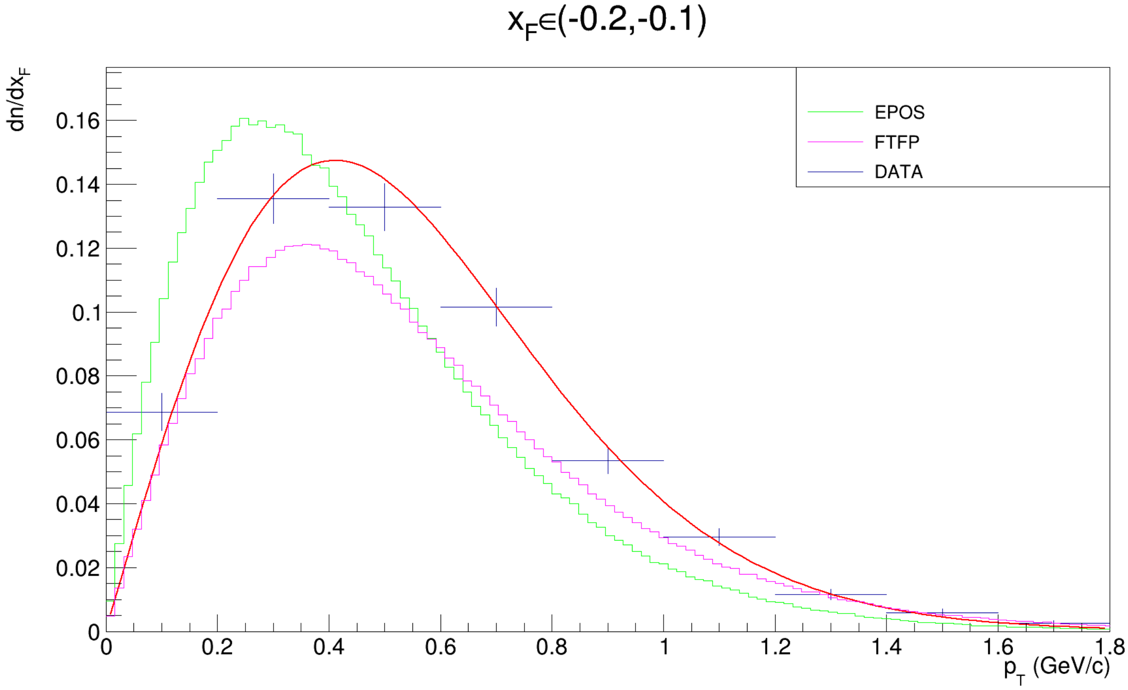
FTFP/EPOS/DATA Lambda production



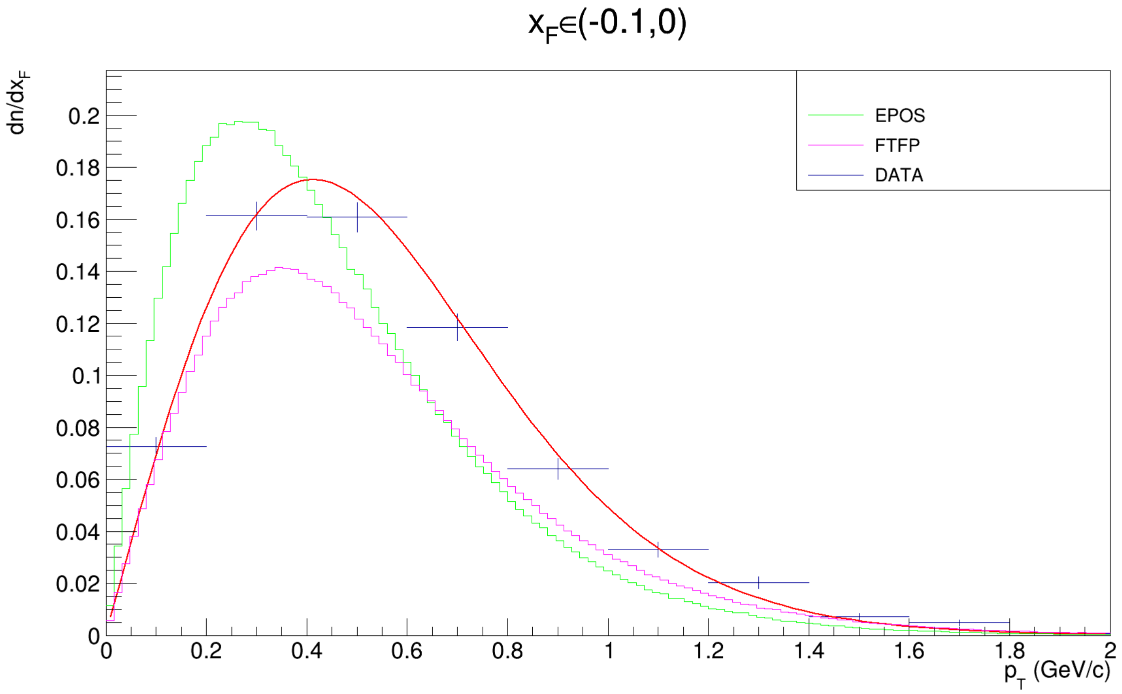
FTFP/EPOS/DATA Lambda production



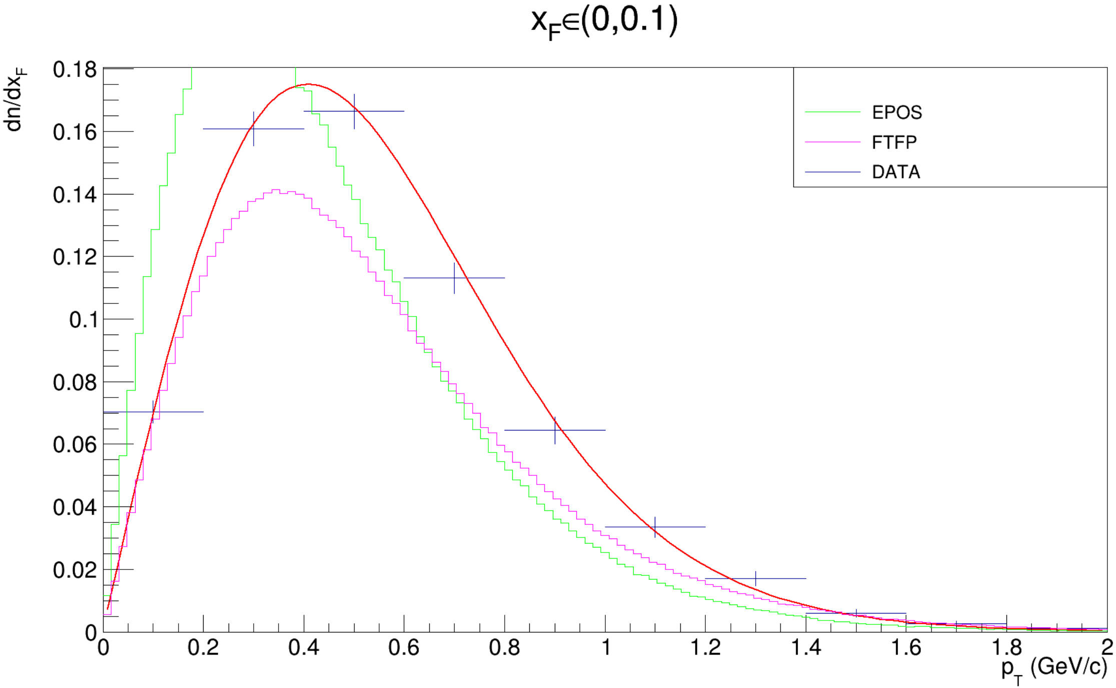
FTFP/EPOS/DATA Lambda production



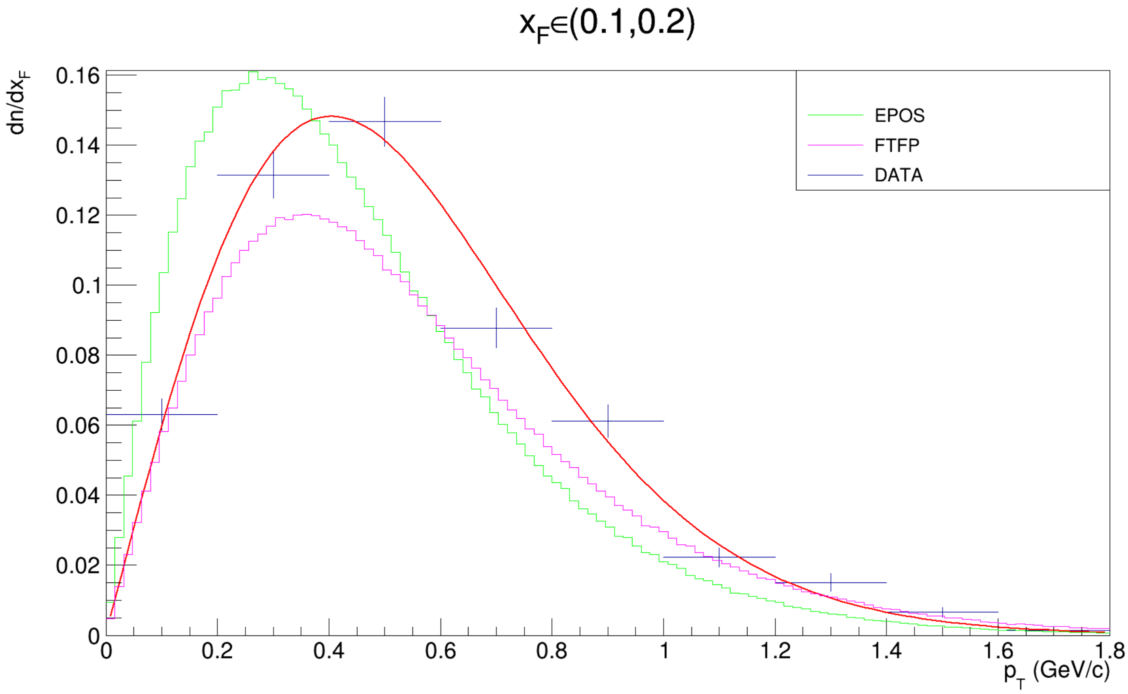
FTFP/EPOS/DATA Lambda production



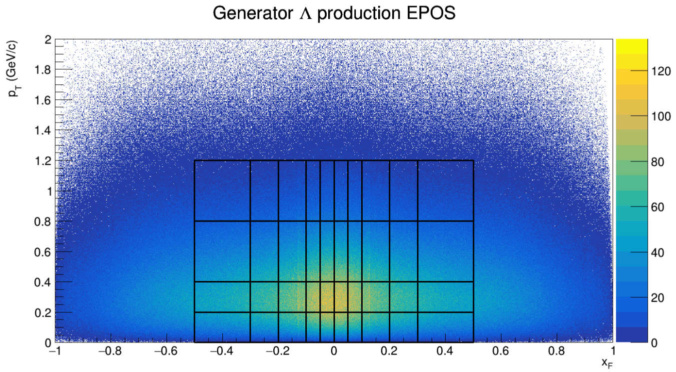
FTFP/EPOS/DATA Lambda production

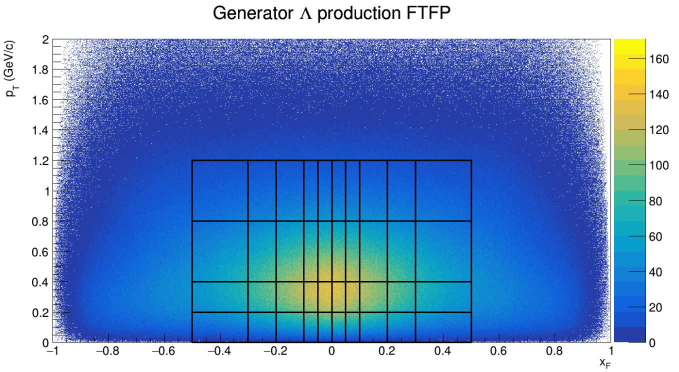


FTFP/EPOS/DATA Lambda production



FTFP/EPOS Lambda production + binning





Data set

The study was performed on the following data:

/eos/experiment/na61/data/prod/p_LH_158_09/026_14b_v0r8p0_pp_slc6_phys_PP/
/eos/experiment/na61/data/prod/p_LHT_158_10/047_17c_v1r17p1_pp_centos7_phys/
/eos/experiment/na61/data/prod/p_LHT_158_11/075_17c_v1r17p1_pp_centos7_phys/

FROTIOF MC Luminance production (200 mln events):

/eos/experiment/na61/data/Simulation/p_LHT_158_09_beam_mode_Luminance/v1r19p1/
/eos/experiment/na61/data/Simulation/p_LHT_158_10_beam_mode_Luminance/v1r19p1/

EPOS MC production (100 mln events):

/eos/experiment/na61/data/Simulation/p_LHT_158_09/v14b026_v0r8p0_pp_slc5_pp/SHOE
/eos/experiment/na61/data/Simulation/p_LHT_158_10/v14e032_v1r6p0_pp_slc5_pp/SHOE

p–p 2009-2011 Data Statistics

Event (collision) selection cuts

	Events, mln
Events	56.0
T2 cut	52.0
WFA S11 cut	49.4
BPD cut	44.4
Primary Vertex exists	44.1
Vertex Fitted perfectly	38.4
Vertex Z position cut	31.5
Events with > 1 Lambda candidates that passed track cuts	0.4

Tracks and Λ candidate selection cuts

	V0's, mln
V0 vertices	443.0
Two track good status	147.9
VTPC clusters >15	124.8
Δz cut	20.2
impact parameter cut	12.2
topology $(\cos\phi)$ cut	5.5
proton dE/dx cut	2.4
pion dE/dx cut	2.2

FRITIOF Data Statistics

Event (collision) selection cuts

	Events, mln
Events	462.3
Primary Vertex exists	44.1
Vertex Fitted perfectly	201.9
Vertex Z position cut	182.8
T2 (S4!=0) cut	156.5

Tracks and Λ candidate selection cuts

	V0's, mln

EPOS Data Statistics

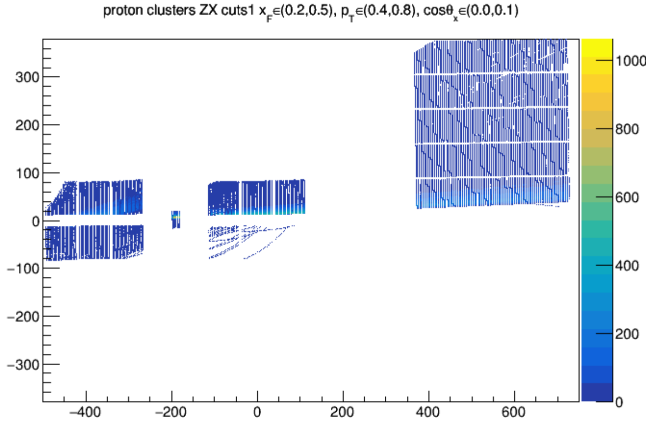
Event (collision) selection cuts

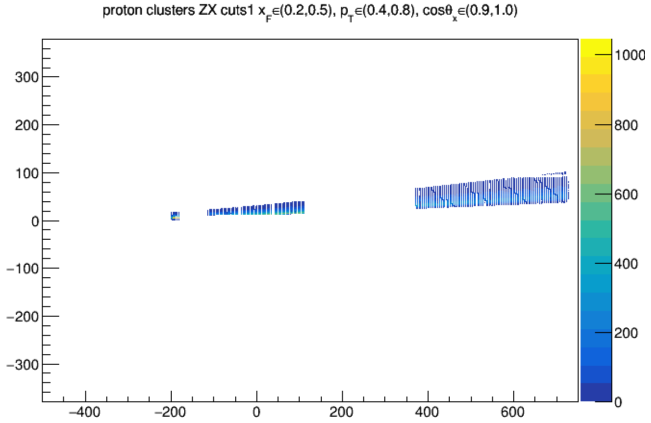
	Events, mln
Events	119.288
Primary Vertex exists	113.0
Vertex Fitted perfectly	109.73
Vertex Z position cut	103.02
S4 (T2) inelastic cut	90.37
Events with > 1 Lambda candidates that passed track cuts	

Tracks and Λ candidate selection cuts

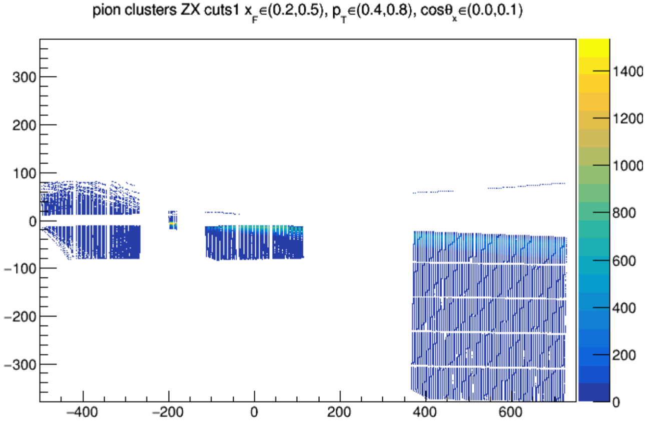
	V0's, mln
Two track good status	1045
$p_{\Lambda} < 160$ GeV	1045

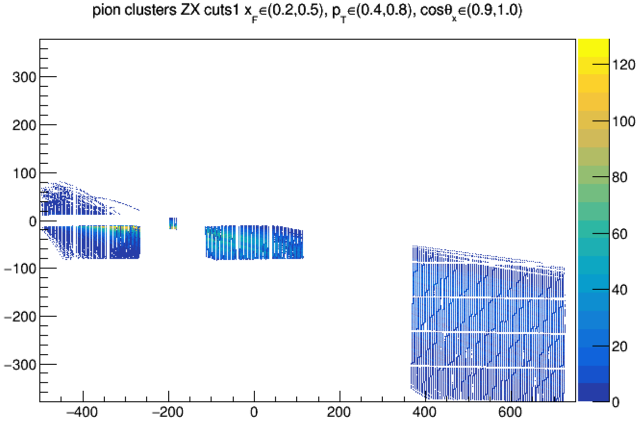
Different acceptance for different $\cos\theta_x$ protons



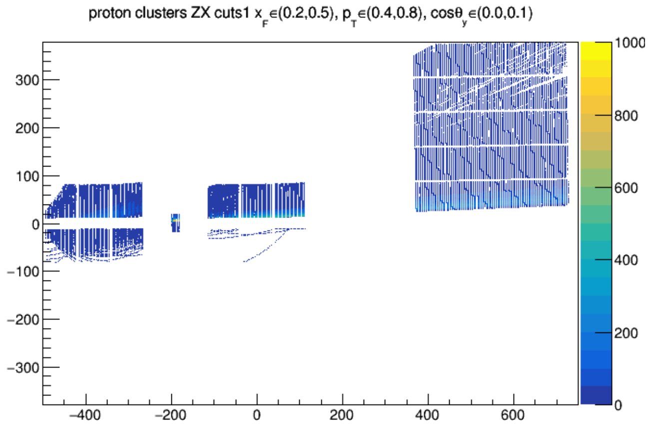


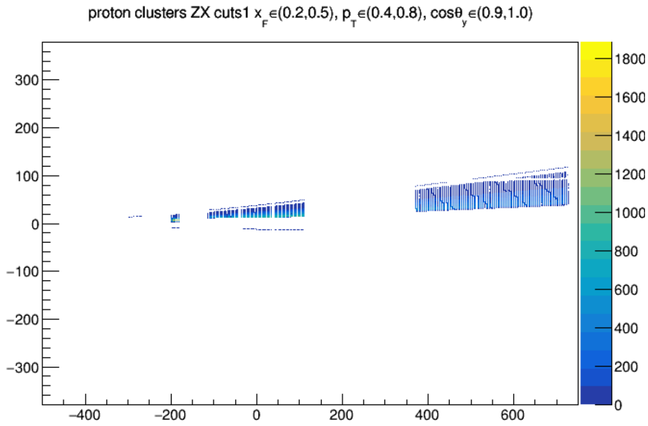
Different acceptance for different $\cos\theta_x$: pions



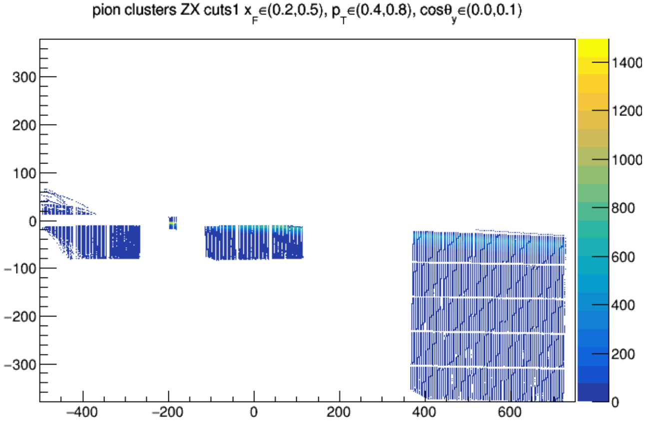


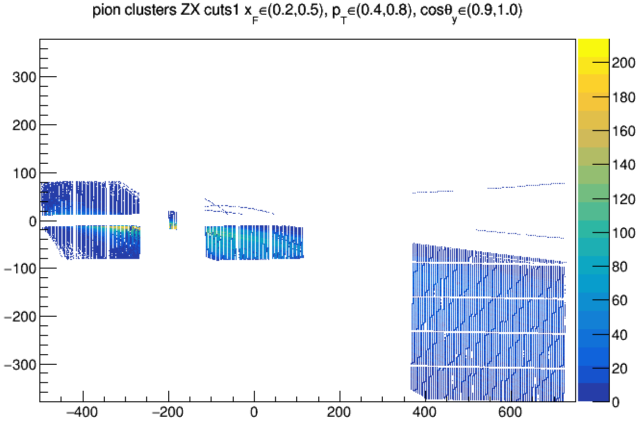
Different acceptance for different $\cos\theta_y$ protons





Different acceptance for different $\cos\theta_y$: pions





MC correction Uncertainty

Why someone use $c_{MC} = N_{\text{gen}}/N_{\text{sel}}$ uncertainty $\sigma^2(c_{MC})/(c_{MC})^2 = 1/N_{\text{sel}} - 1/N_{\text{gen}}$?
If N_{gen} obeys Poissonian distr, and N_{sel} obeys Binomial distr:

$$\sigma^2(N_{\text{gen}}) = N_{\text{gen}}, \sigma^2(N_{\text{sel}}) = \sigma(N_{\text{gen}}N_{\text{sel}}) = N_{\text{sel}}$$

$$\frac{\sigma(c_{MC})^2}{c_{MC}^2} = \frac{\sigma^2(N_{\text{gen}})}{N_{\text{gen}}^2} + \frac{\sigma^2(N_{\text{gen}})}{N_{\text{gen}}^2} - 2\frac{\sigma(N_{\text{gen}}N_{\text{sel}})}{N_{\text{gen}}N_{\text{sel}}} =$$
$$= \frac{1}{N_{\text{gen}}} + \frac{1}{N_{\text{sel}}} - 2\frac{N_{\text{sel}}}{N_{\text{gen}}N_{\text{sel}}} = \frac{1}{N_{\text{sel}}} - \frac{1}{N_{\text{gen}}} = \frac{N_{\text{gen}} - N_{\text{sel}}}{N_{\text{gen}}N_{\text{sel}}}.$$

I implemented assumption "all 3 independent" - **overestimation**.

```
const double_t wfaTime1[3] = { -100., 300., -200.};//2009,2010,2011
const double_t wfaTime2[3] = {0., 400., -100.};    // two main wfa values
const double_t wfaTimeCut = 1500;
const evt::raw::Trigger& trigger = rawEvent.GetBeam().GetTrigger();
if (!trigger.IsTrigger(det::TriggerConst::eT2, det::TriggerConst::ePrescaled)) co
eventCuts->Fill("T2", 1.);
if (!isMC) { // WFA S1_1 cut
  const vector<Double_t>& WFA_beam_time = trigger.GetTimeStructure(det::TimeStruct
  unsigned int WFA_n_beam =  trigger.GetNumberOfSignalHits(det::TimeStructureConst
  bool beamExist = false;
  if (WFA_n_beam != WFA_beam_time.size()) eventCuts->Fill("WFA_n_beam != WFA_beam
  for (unsigned int i = 0; i < WFA_beam_time.size(); ++i)
  {
    if (!beamExist && (WFA_beam_time.at(i) == wfaTime1[wfaTimeIndex] || WFA_beam_
      beamExist = true;
    else if (fabs(WFA_beam_time.at(i) - (wfaTime1[wfaTimeIndex] + wfaTime2[wfaTim
    {
      beamExist = false;
      break;
```

Vertex, Beamcut

```
if (!recEvent.HasPrimaryVertex(rec::VertexConst::ePrimaryFitZ)) continue;
eventCuts->Fill("primaryVertex", 1.);
const rec::Vertex& vertexFIT = recEvent.GetPrimaryVertex(rec::VertexConst::eP
if (vertexFIT.GetFitQuality() != rec::FitQuality::ePerfect) continue;
eventCuts->Fill("VertexFit", 1.);
if (!recEvent.HasMainVertex()) continue;
eventCuts->Fill("MainVertex", 1.);
const Point& vertexpoint = vertexFIT.GetPosition();
const double ZVertex = vertexpoint.GetZ();
if (ZVertex > maxZVertex || ZVertex < minZVertex) continue;
eventCuts->Fill("ZPosition", 1.);
int testTrack = 0, chargeOfTheLast;
double momentumOfTheLast;
for (auto trackIter = vertexFIT.DaughterTracksBegin(),
     trackEnd = vertexFIT.DaughterTracksEnd(); trackIter != trackEnd; ++trackI
  const auto& vmain = recEvent.Get(*trackIter);
  if (vmain.HasTrack()) {
    const auto& tmain = recEvent.Get(vmain.GetTrackIndex());
    if (tmain.GetCharge() != 0 &&
```

VTPC Clusters and dEdx

```
        pClusters1 = pos.GetNumberOfClusters(eVTPC1);
        pClusters2 = pos.GetNumberOfClusters(eVTPC2);
        nClusters1 = neg.GetNumberOfClusters(eVTPC1);
        nClusters2 = neg.GetNumberOfClusters(eVTPC2);
        if ((pClusters1 < 10) && (pClusters2 < 10)) continue;
        if ((nClusters1 < 10) && (nClusters2 < 10)) continue;
        rectrackCuts->Fill("VTPC10", 1.);
inline double dEdxsigma(double p_gammabeta, unsigned points, const bool vtpc = tru
   if (points <= 5) return 0;
   const double sigma0 = vtpc ? 0.425 : 0.375;
   return sigma0 / sqrt(double(points)) * pow(bethe(p_gammabeta), 0.625);
}
          pDedx = pos.GetEnergyDeposit(eAll);
          nDedx = neg.GetEnergyDeposit(eAll);
          pSigmaDedx = dEdxsigma(p_pos.GetMag() / protonMass, pos.GetNumberOfdEdXC
                                 pos.GetNumberOfdEdXClusters(eVTPC1) + pos.GetNumbe
          nSigmaDedx = dEdxsigma(p_neg.GetMag() / pionMass,   neg.GetNumberOfdEdXC
                                 neg.GetNumberOfdEdXClusters(eVTPC1) + neg.GetNumbe
          pSigmaDedxNative = pos.GetEnergyDepositVariance(rec::TrackConst::eAll);
```

Matching to tracks

```
int pidN = 0, pidP = 0, nCommonPointsN = 0;
const sim::VertexTrack *simVtxTrackMatchedN = nullptr, *simVtxTrackMatchedP = nul
//Check negative track
for (auto simVtxTrackIter  = neg.SimVertexTracksBegin();
          simVtxTrackIter != neg.SimVertexTracksEnd(); ++simVtxTrackIter) {
  const sim::VertexTrack& simVtxTrack = simEvent.Get(*simVtxTrackIter);
  if (simVtxTrack.GetRecTrackWithMaxCommonPoints() == neg.GetIndex()) {
    auto number_of_shared_points = simVtxTrack.GetNumberOfCommonPoints(neg.GetInde
    if ( number_of_shared_points > nCommonPointsN ) {
      nCommonPointsN = number_of_shared_points;
      simVtxTrackMatchedN = &simVtxTrack;
      pidN = simVtxTrack.GetParticleId();
    }
  }
}
```

Matching to Lambda vertex

```
match = 0;
if (simVtxTrackMatchedN != nullptr && simVtxTrackMatchedP != nullptr) { match +=
if (match & 1) if (simVtxTrackMatchedN->HasStartVertex() && (pidN == ParticleConst
if (match & 1) if (simVtxTrackMatchedP->HasStartVertex() && (pidP == ParticleConst
if (match == 7) if (simVtxTrackMatchedN->GetStartVertexIndex() == simVtxTrackMatch
if (match == 15) {
  const sim::Vertex& matchVtx1 = simEvent.Get(simVtxTrackMatchedN->GetStartVertexI
  if (matchVtx1.GetNumberOfParentTracks() == 1) {
    match += 16;
    const sim::VertexTrack& lambdaTrack = simEvent.Get(matchVtx1.GetFirstParentTra
    if (lambdaTrack.GetParticleId() == 3122) {
      match += 32;
      rectrackCuts->Fill("nIdentifiedLambdaVertex", 1.);
      const Vector& protonMomentum = simVtxTrackMatchedP->GetMomentum(),
                    pionMomentum = simVtxTrackMatchedN->GetMomentum();
      //pSim[6]
      pSim[0] = protonMomentum.GetX(); pSim[1] = protonMomentum.GetY(); pSim[2] =
      pSim[3] = pionMomentum.GetX(); pSim[4] = pionMomentum.GetY(); pSim[5] = pion
      //const auto& simvertexpoint = simEvent.GetMainVertex().GetPosition();
```

xf pt bin	EPOS P_x	EPOS P_y	FTFP P_x	FTFP P_y
$x_F \in (-0.5, -0.3), p_T \in (0.8, 1.2)$	-0.175 ± 0.053	-0.170 ± 0.047	-0.158 ± 0.038	-0.059 ± 0.044
$x_F \in (-0.3, -0.2), p_T \in (0.8, 1.2)$	-0.070 ± 0.039	-0.268 ± 0.039	-0.030 ± 0.030	-0.184 ± 0.043
$x_F \in (-0.2, -0.1), p_T \in (0.8, 1.2)$	-0.057 ± 0.027	-0.087 ± 0.028	-0.015 ± 0.023	-0.108 ± 0.026
$x_F \in (-0.1, -0.05), p_T \in (0.8, 1.2)$	-0.083 ± 0.037	0.026 ± 0.040	-0.045 ± 0.030	0.029 ± 0.031
$x_F \in (-0.05, 0), p_T \in (0.8, 1.2)$	-0.053 ± 0.055	0.147 ± 0.039	0.009 ± 0.041	-0.009 ± 0.037
$x_F \in (0, 0.05), p_T \in (0.8, 1.2)$	-0.176 ± 0.049	0.182 ± 0.047	-0.321 ± 0.058	-0.006 ± 0.042

$x_F \in (-0.3, -0.2), p_T \in (0.8, 1.2)$

	EPOS P_x	EPOS P_y	FTFP P_x	FTFP P_y
point removal in phi, point removal in cos theta	-0.070 ± 0.039	-0.268 ± 0.039	-0.030 ± 0.030	-0.184 ± 0.043
point removal in phi, no point removal in cos theta:	-0.051 ± 0.038	-0.187 ± 0.034	-0.045 ± 0.030	-0.189 ± 0.030
no point removal in phi, point removal in cos theta:	-0.054 ± 0.035	-0.324 ± 0.041	-0.137 ± 0.035	-0.202 ± 0.028
no point removal in phi, no point removal in cos theta:	-0.081 ± 0.035	-0.202 ± 0.032	-0.077 ± 0.029	-0.199 ± 0.027

$x_F \in (-0.2, -0.1), p_T \in (0.8, 1.2)$

	EPOS P_x	EPOS P_y	FTFP P_x	FTFP P_y
point removal in phi, point removal in cos theta	-0.057 ± 0.027	-0.087 ± 0.028	-0.015 ± 0.023	-0.108 ± 0.026
point removal in phi, no point removal in cos theta:	-0.056 ± 0.028	-0.087 ± 0.028	-0.017 ± 0.023	-0.134 ± 0.024
no point removal in phi, point removal in cos theta:	-0.058 ± 0.027	-0.118 ± 0.028	0.009 ± 0.022	-0.151 ± 0.023
no point removal in phi, no point removal in cos theta:	-0.057 ± 0.027	-0.126 ± 0.027	0.008 ± 0.023	-0.151 ± 0.023

$x_F \in (-0.1, -0.05), p_T \in (0.8, 1.2)$

	EPOS P_x	EPOS P_y	FTFP P_x	FTFP P_y
point removal in phi, point removal in cos theta	-0.083 ± 0.037	0.026 ± 0.040	-0.045 ± 0.030	0.029 ± 0.031
point removal in phi, no point removal in cos theta:	-0.087 ± 0.038	0.057 ± 0.038	-0.056 ± 0.030	0.029 ± 0.031
no point removal in phi, point removal in cos theta:	-0.082 ± 0.035	0.048 ± 0.036	-0.010 ± 0.035	0.043 ± 0.033
no point removal in phi, no point removal in cos theta:	-0.096 ± 0.037	0.045 ± 0.037	-0.075 ± 0.030	0.004 ± 0.031

$x_F \in (-0.05, 0.), p_T \in (0.8, 1.2)$

	EPOS P_x	EPOS P_y	FTFP P_x	FTFP P_y
point removal in phi, point removal in cos theta	-0.053 ± 0.055	0.147 ± 0.039	0.009 ± 0.041	-0.009 ± 0.037
point removal in phi, no point removal in cos theta:	-0.044 ± 0.038	0.158 ± 0.038	-0.059 ± 0.033	0.027 ± 0.034
no point removal in phi, point removal in cos theta:	-0.162 ± 0.046	0.149 ± 0.038	-0.157 ± 0.038	0.064 ± 0.033
no point removal in phi, no point removal in cos theta:	-0.060 ± 0.039	0.149 ± 0.038	-0.055 ± 0.032	0.064 ± 0.033

$x_F \in (0., 0.05), p_T \in (0.8, 1.2)$

	EPOS P_x	EPOS P_y	FTFP P_x	FTFP P_y
point removal in phi, point removal in cos theta	-0.176 ± 0.049	0.182 ± 0.047	-0.321 ± 0.058	-0.006 ± 0.042
point removal in phi, no point removal in cos theta:	-0.120 ± 0.045	0.143 ± 0.045	-0.103 ± 0.037	0.013 ± 0.039
no point removal in phi, point removal in cos theta:	-0.153 ± 0.048	0.132 ± 0.044	-0.268 ± 0.054	0.131 ± 0.044
no point removal in phi, no point removal in cos theta:	-0.104 ± 0.044	0.132 ± 0.044	-0.094 ± 0.036	0.069 ± 0.037