Slow pion efficiency

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Introduction

- Charged slow pions (π_s):
  $p_{\pi_s} < 300$ MeV
- Determine data/MC ratio of track reconstruction efficiency
- Monitor charge dependent asymmetries in track finding of π_s
- Study π_s using decays with very limited phase space
- $D^{*-} \to \bar{D}^0 \pi_s^-$:
  $m_{D^*} - m_D \approx 150$ MeV

Dominant systematic uncertainty for measurements including a π_s, e.g. $|V_{cb}|$ from untagged $B \to D^* \ell \nu$

	$\tilde{a}_0$	$\tilde{b}_0$	$\tilde{b}_1$	$\tilde{c}_1$
Statistical	3.7	0.8	65.1	50.8
Background subtraction	2.1	0.4	31.3	21.8
Size of simulated samples	1.5	0.3	26.4	20.5
Lepton ID efficiency	1.6	0.3	3.4	2.8
Tracking of K, π, ℓ	0.4	0.4	0.5	0.4
Slow-pion efficiency	1.6	1.5	23.8	24.7
$N_{B\bar{B}}$	0.8	0.8	0.8	0.8
f_{+0}	1.3	1.3	1.3	1.2
$\mathcal{B}(D^{*+} \to D^0 \pi^+)$	0.4	0.4	0.4	0.4
$\mathcal{B}(D^0 \to K^- \pi^+)$	0.4	0.4	0.4	0.4
B^0 lifetime	0.1	0.1	0.1	0.1
Signal modeling	2.3	0.5	52.1	35.0
Total	5.8	2.5	96.0	73.0

arXiv:2310.01170 (C. Lyu et al.)

Analysis Strategy

1. Reconstruction, Candidate Selection
2. Data and MC corrections
3. Pre-fit data/MC agreement
4. Signal extraction, closure tests
5. Determine data/MC ratio and its uncertainty

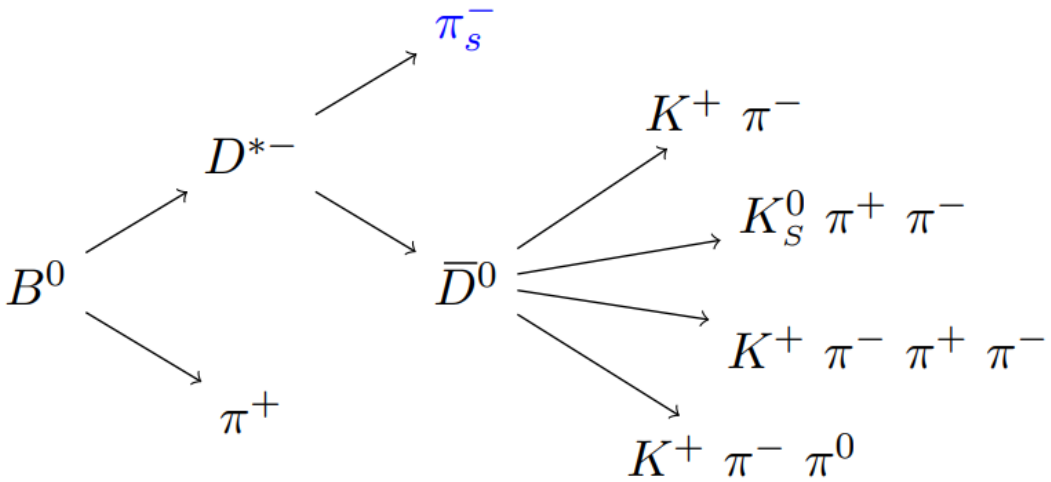
	Branching Fraction
$\mathcal{B}(B \to D^* \pi)$	$(2.74 \pm 0.13) \cdot 10^{-3}$
$\mathcal{B}(D^* \to D \pi_s)$	$(67.7 \pm 0.5)\%$
$\mathcal{B}(D \to K\pi)$	$(3.947 \pm 0.030)\%$
$\mathcal{B}(D \to K\pi\pi\pi)$	$(8.22 \pm 0.14)\%$
$\mathcal{B}(D \to K\pi\pi^0)$	$(14.4 \pm 0.6)\%$
$\mathcal{B}(D \to K_s\pi\pi)$	$(2.80 \pm 0.18)\%$

Challenge

The measurement of the efficiency ratio is limited by statistics!

Current Analysis

- Untagged reconstruction of the following channels:



- Fit method: 2D in bins of ΔE ($E_B - \frac{\sqrt{s}}{2}$) and ΔM (m_{D^*}-m_{D^0}), combining modes pre-fit
- Data-Set: 362 fb^{-1} LS1 data-set (HLT hadron) + 1443 fb^{-1} MC15rd
- Release: light-2303-iriomote
- All results presented today are preliminary and currently under review!
- Documentation: BELLE2-NOTE-PH-2023-035

Signal Selection

Event:

- HLT hadron

Tracks (K, fast π):

- $dr < 2$ cm
- $|dz| < 4$ cm
- θ in CDC acceptance

Continuum suppression:

- FoxWolfram R2 < 0.5

***D* and D^* mesons:**

- $|M_{D^0} - M_{D^0}^{PDG}| < 0.02$ GeV
- $(M_{D*} - M_{D^0}) \in [0.141, 0.156]$ GeV
- $p^*_{D^*} \in [2.0, 2.5]$ GeV

HadronID ($K\pi\pi\pi$, $K\pi\pi^0$):

- binary KaonID (no SVD) > 0.1

K^0_S:

- merged standard list
- $|M_{K_S} - M_{K_S}^{PDG}| < 0.01$ GeV

B^0meson:

- $|\Delta E| < 0.2$ GeV
- $M_{bc} \in [5.270, 5.287]$ GeV

π^0(eff40):

- May2020 Recommendations

Corrections

Data

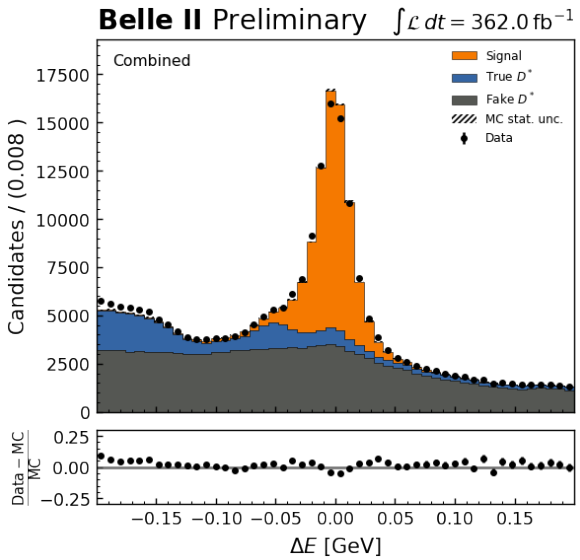
- Track momentum scaling (`tracking_data_Moriond23_v1`)
- Photon energy bias correction (`PhotonEnergyBiasCorrection_MC15ri_Nov2022`)

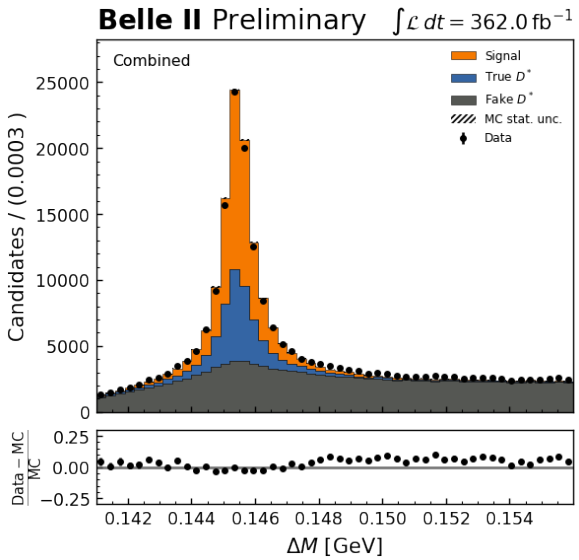
MC

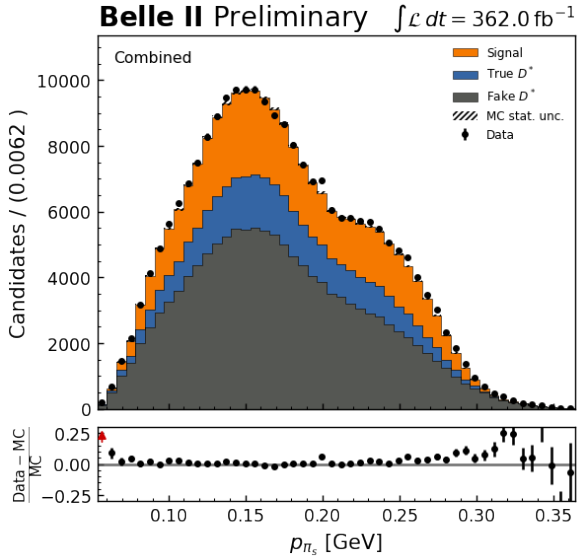
- Gamma efficiency (`PhotonEfficiencyDataMCRatio_proc13MC15_November2022`)
- HadronID corrections (Systematics Correction Framework and PIDvar)

Pre-fit data-MC agreement

- **Signal:** B^0 isSignal $= 1$
- **Fake D^*Background:** B^0 isSignal $= 0$ and D^* isSignal $= 0$
- **True D^*Background**: B^0 isSignal $= 0$ and D^* isSignal $= 1$
- Failed truth matches set to 0
- Pre-fit distributions are luminosity scaled ($\frac{362}{1443}$) and corrected
- Combined pre-fit below: $K\pi$, $K\pi\pi\pi$, K^0_s, $K\pi\pi^0$

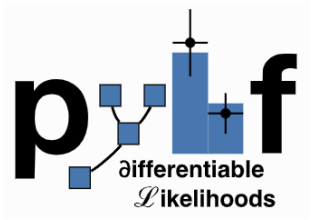






Signal Extraction

- Binned maximum likelihood fit using pyhf

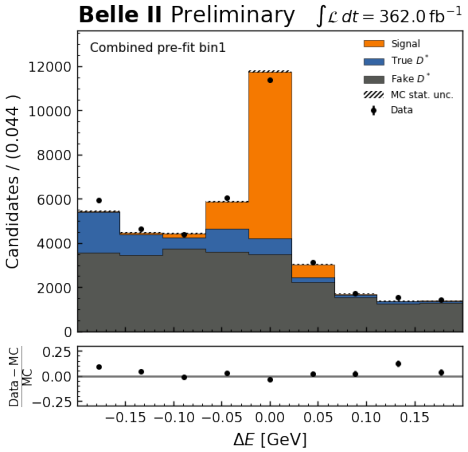


- Split ntuple into 4 p_{π_s} bins: [0.05, 0.12], [0.12, 0.16], [0.16, 0.2], [0.2, 0.35] GeV
- 2D-Fit in ΔE (9 bins) and ΔM (5 bins) distribution for each p_{π_S} bin to extract signal yield
- Fitted 3 MC templates onto data: Signal, Fake D^*, True D^*
- Nuisance parameters: MC uncertainty, HadronID

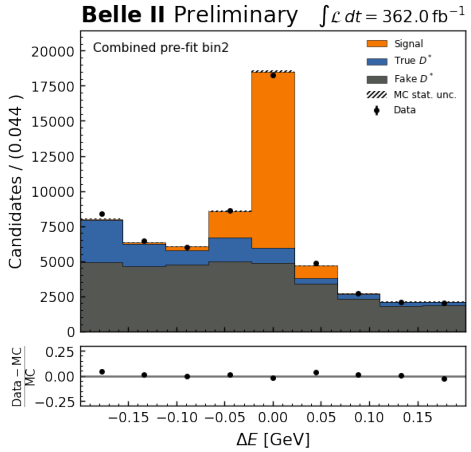
Pre- and post-fit comparison, ΔE

Pre-fit

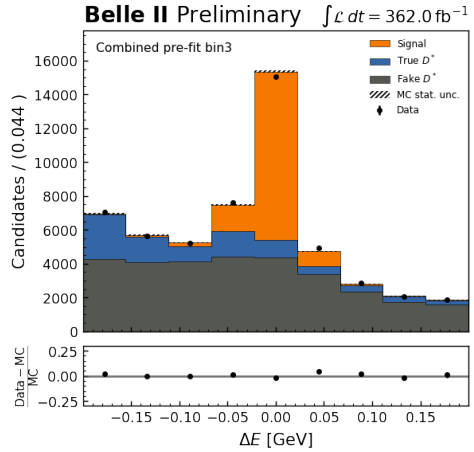
$[0.05, 0.12]$ GeV



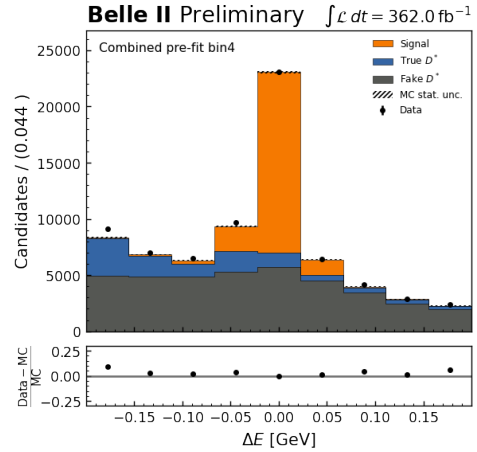
$[0.12, 0.16]$ GeV



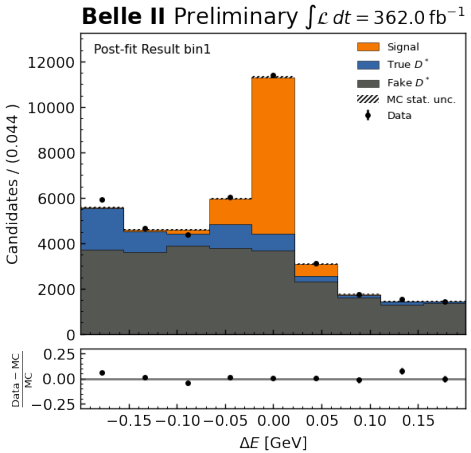
$[0.16, 0.2]$ GeV

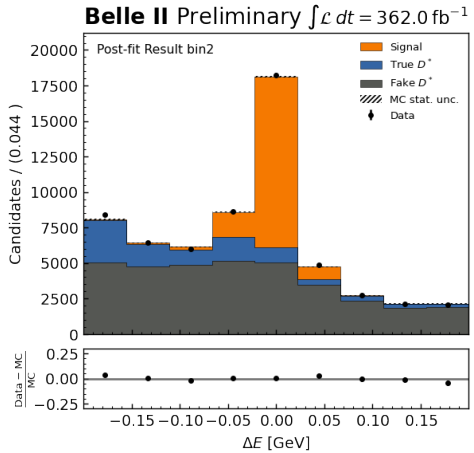


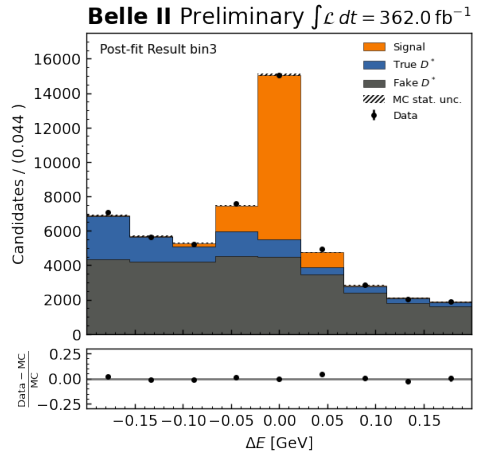
$[0.2, 0.35]$ GeV

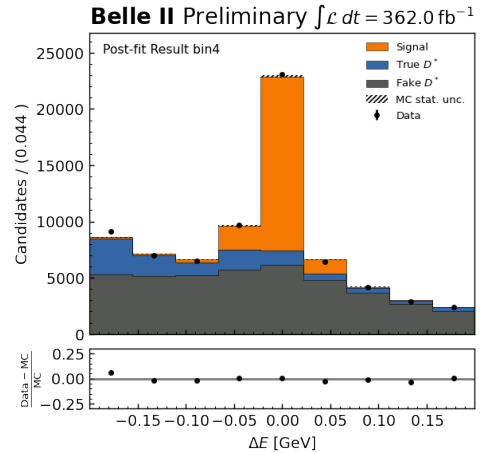


Post-fit





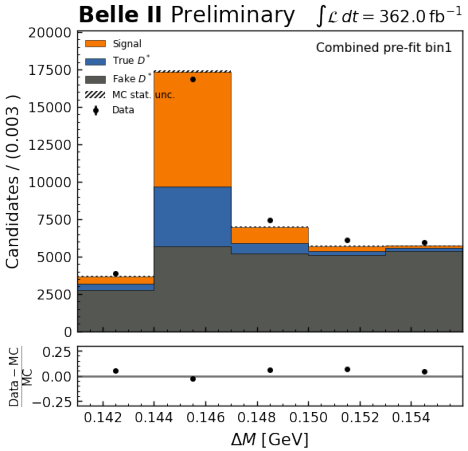




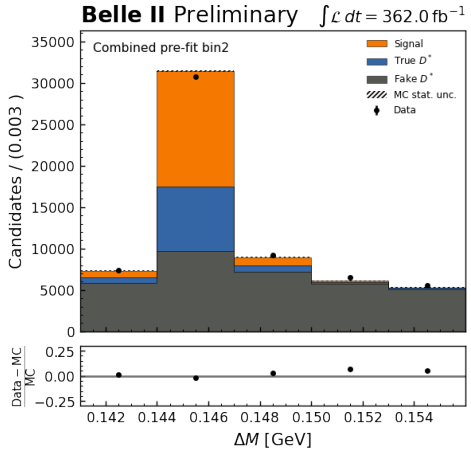
Pre- and post-fit comparison, ΔM

Pre-fit

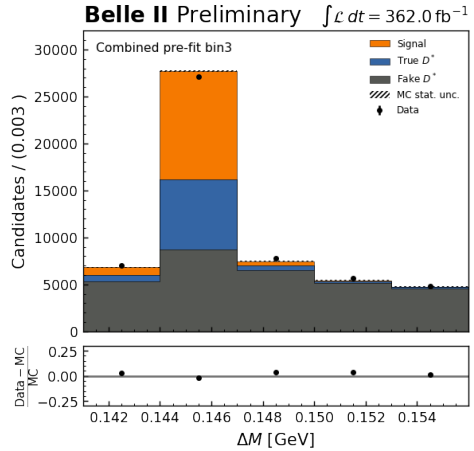
$[0.05, 0.12]$ GeV



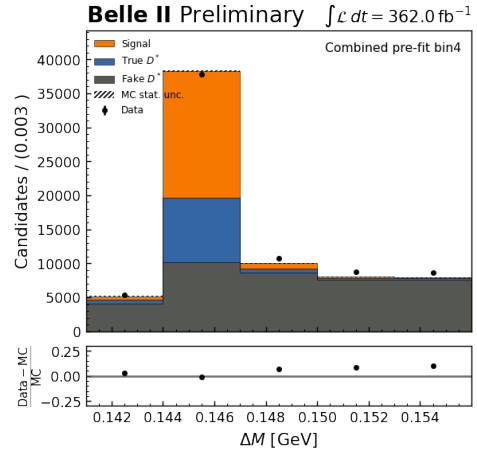
$[0.12, 0.16]$ GeV



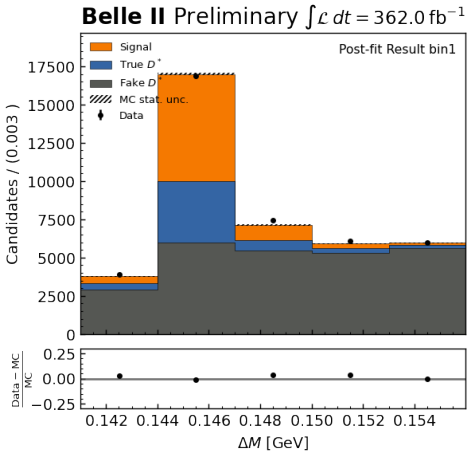
$[0.16, 0.2]$ GeV

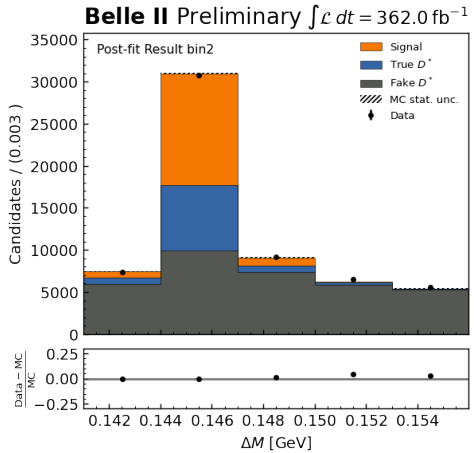


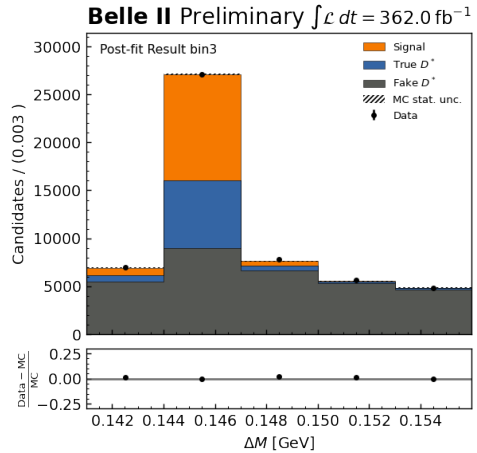
$[0.2, 0.35]$ GeV

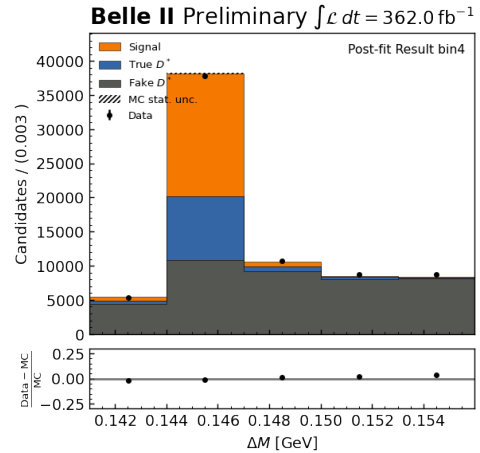


Post-fit









Results

MC15rd result

p range(GeV)	**0.05-0.12**	**0.12-0.16**	**0.16-0.20**	**0.20-0.35**
MC prediction	9733 ± 49	15832 ± 63	12863 ± 57	20259 ± 71
Fitted yield	8889 ± 133	15070 ± 167	12327 ± 155	19434 ± 190
r_i	0.913 ± 0.014	0.952 ± 0.011	0.958 ± 0.013	0.959 ± 0.010
r_i / r_{max}	0.952	0.992	0.999	
$\sigma_{uncorr} \pm \sigma_{corr}$	0.015 ± 0.010	0.012 ± 0.010	0.013 ± 0.010	
σ_{track}	± 0.0023	± 0.0024	± 0.0024	

MC15ri result

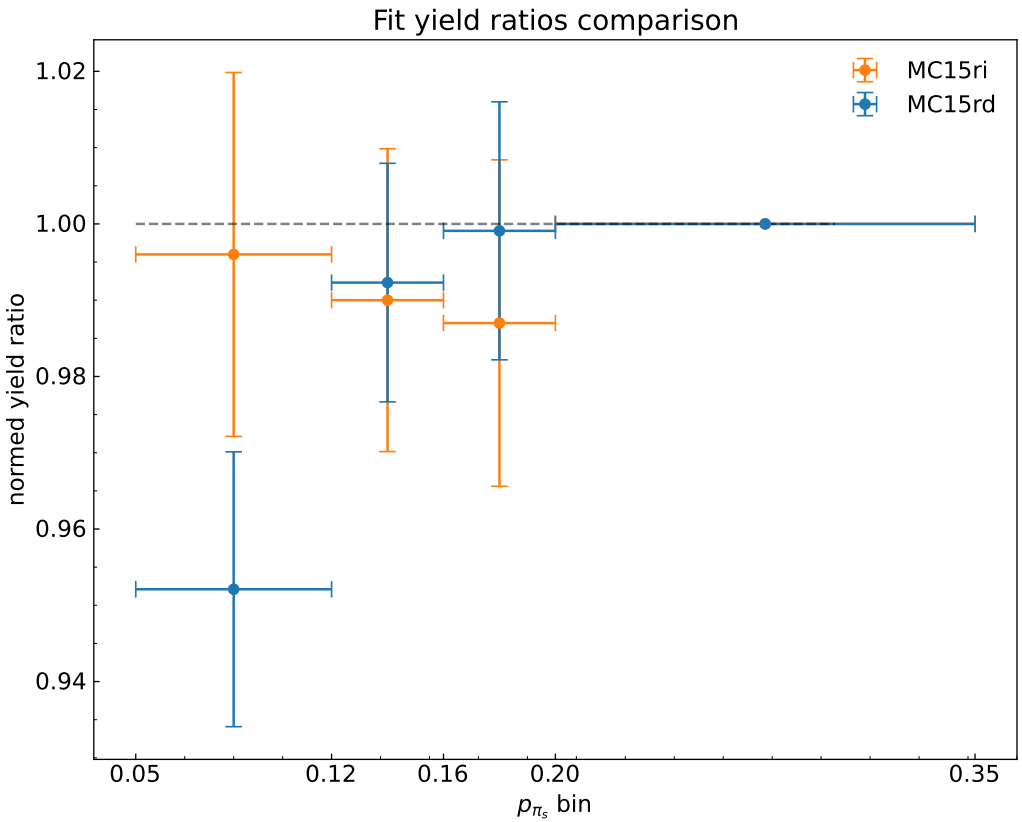
p range(GeV)	**0.05-0.12**	**0.12-0.16**	**0.16-0.20**	**0.20-0.35**
MC prediction	6976 ± 50	11069 ± 63	9294 ± 63	14448 ± 72
Fitted yield	6453 ± 122	10175 ± 146	8516 ± 137	13410 ± 164
r_i	0.924 ± 0.019	0.919 ± 0.014	0.916 ± 0.016	0.928 ± 0.013
r_i / r_{max}	0.996	0.990	0.987	
$\sigma_{uncorr} \pm \sigma_{corr}$	0.020 ± 0.013	0.015 ± 0.013	0.017 ± 0.013	
σ_{track}	± 0.003	± 0.003	± 0.003	

MC prediction: #signal in MC×lumiData/lumiMC

r_i: fitted yield / MC prediction

$$\sigma^2_{uncorr} + \sigma^2_{corr} = \left(\frac{1}{r_{max}}\right)^2 \sigma^2_{r_i} + \left(\frac{r_i}{r^2_{max}}\right)^2 \sigma^2_{r_{max}}$$

Yield Comparison



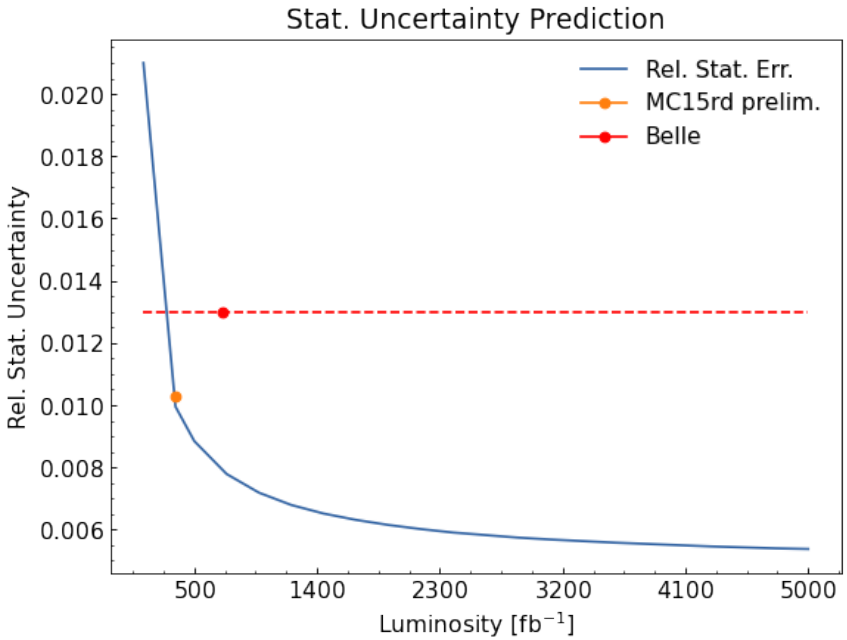
MC15ri weighted average:
$(99.099 \pm 1.270_{stat} \pm 0.297_{track})\%$

MC15rd weighted average:
$(98.289 \pm 0.978_{fit} \pm 0.236_{track})\%$

Measurements include fast track systematic from MC15ri (0.3% v.s. 0.24%)
σ_{fit}: includes statistical + hadronID uncertainty
Caveat: Different templates used for fit, no π^0 channel for MC15ri

Future prediction

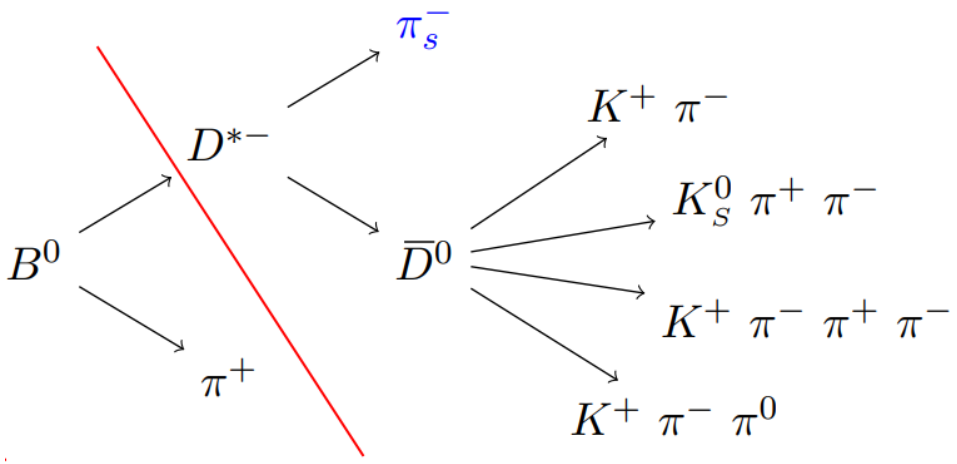
- Prediction of development of stat. uncertainty with increasing luminosity
- Probably optimistic prediction
- Binning of ratios will also get finer
- Even at 5 ab^{-1} heavily dominated by statistics $\approx 0.54\%$
- Systematics will only slowly start to contribute significantly
- Belle slow pion efficiency rel. uncertainty of $\sim 1.3\%$ at 711 fb^{-1}



Possible improvements

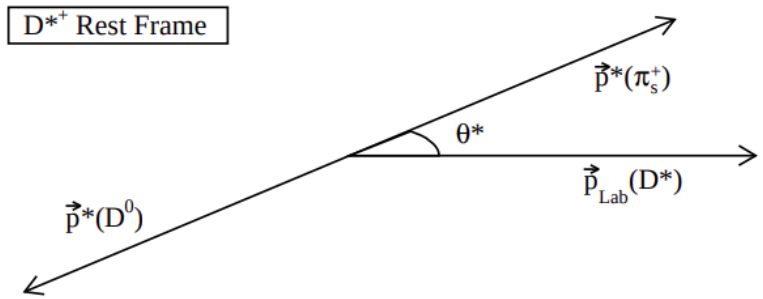
Are there possibilities to increase our statistics beyond waiting for more data?

1. Optimize candidate selection:
   - Possible variables, that have cleaner signal distinction?
   - Loosen cuts? What kind of signal purity do we need?
2. Change the signal definition:
   - Ultimately correct D^* reconstruction most important
   - Correct B^0 reconstruction needed for: $\Delta E, m_{bc}$
   - Find other variables for signal extraction and candidate selection?



Possible improvements

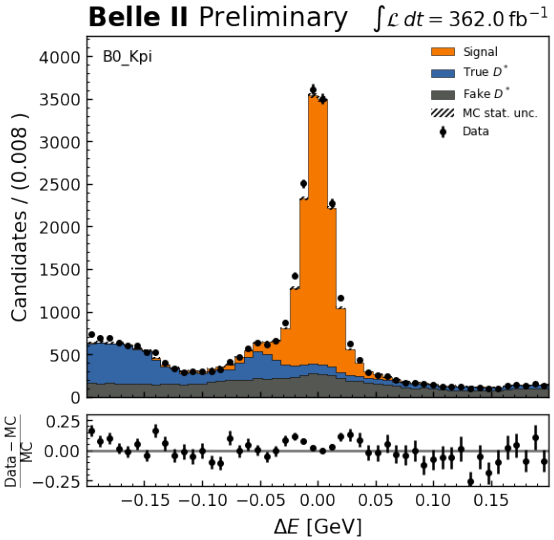
3. Inclusive D^0 decays:
   - Reconstruct $D \to KX$ instead of four channels
   - Background suppresion
4. Prompt D^* production:
   - D^* from $q\bar{q}$ events
   - Phase space not as tightly restricted
   - New signal extraction variables
5. Inclusive D^0 production:
   - Combine D^* from B decays and $q\bar{q}$ events
   - Reconstruct $e^- e^+ \to D^{*+} X, D^{*+} \to D^0 \pi_s^+$
   - $D^0 \to K^- \pi^+$ chosen for cleaner sample
   - Angular efficiency analysis in bins of $p^*_{D^*}$
   - Was previously done by BaBar
   - Currently ongoing by J. Borah et al. (Latest Update)

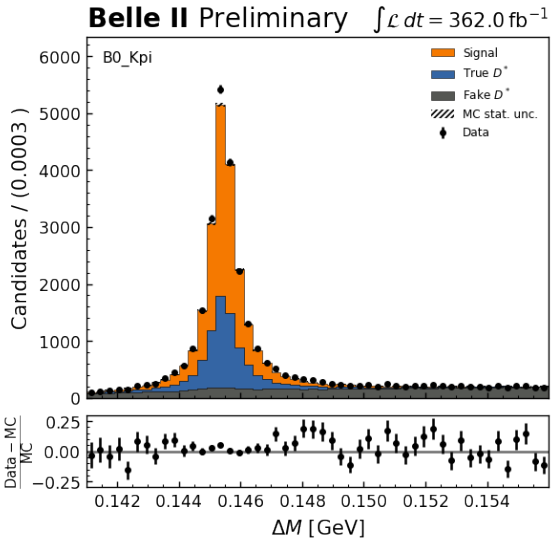


Backup

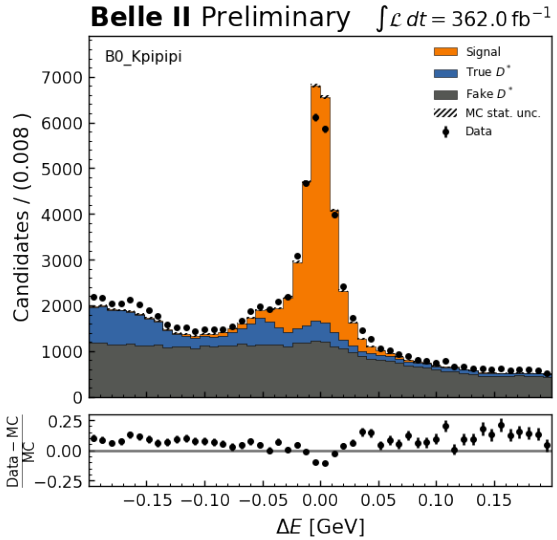
Pre-fit data-MC agreement

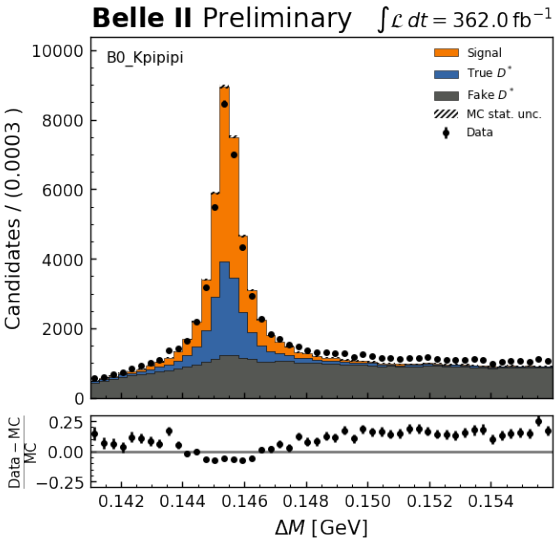
$K\pi$



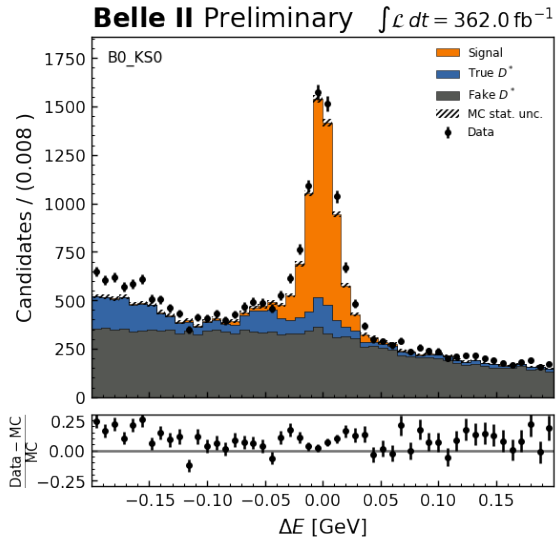


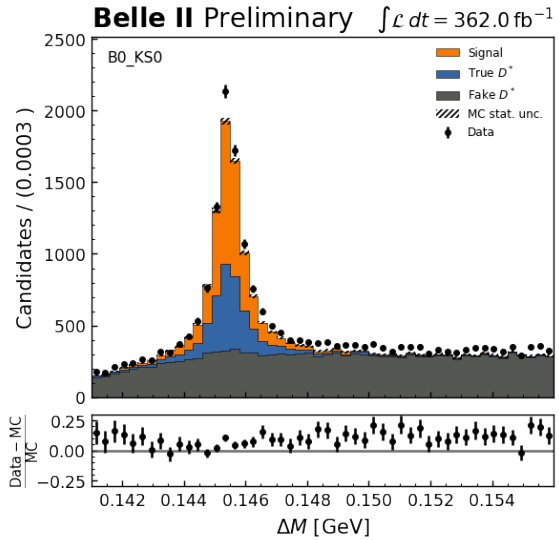
$K\pi\pi\pi$





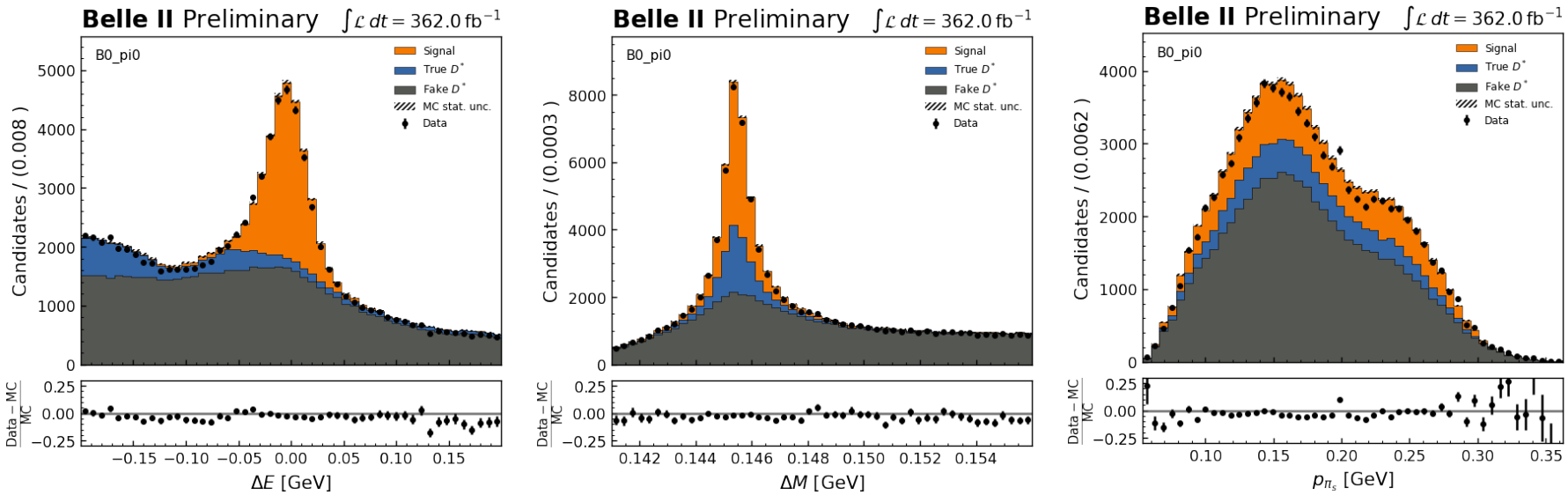
K^0_s





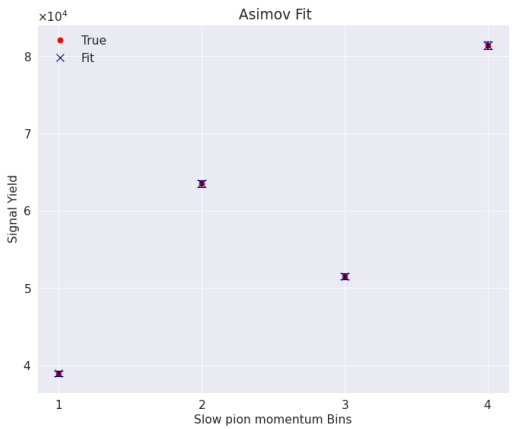
Pre-fit data-MC agreement

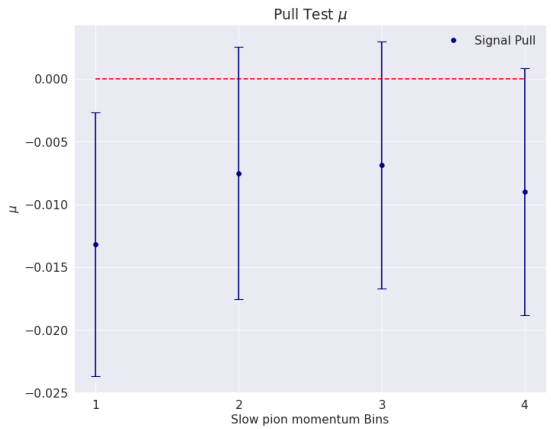
- $K\pi\pi^0$ channel now shows good agreement in MC15rd

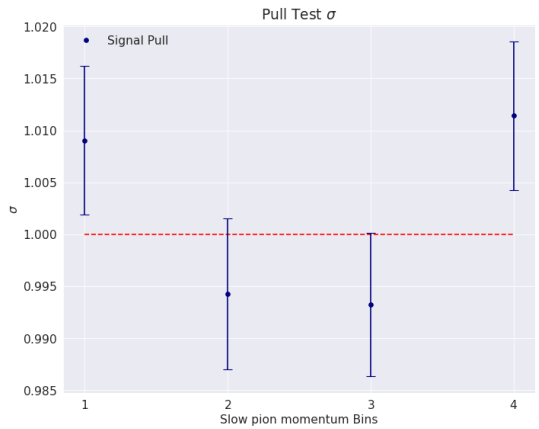


Fit Closure Tests

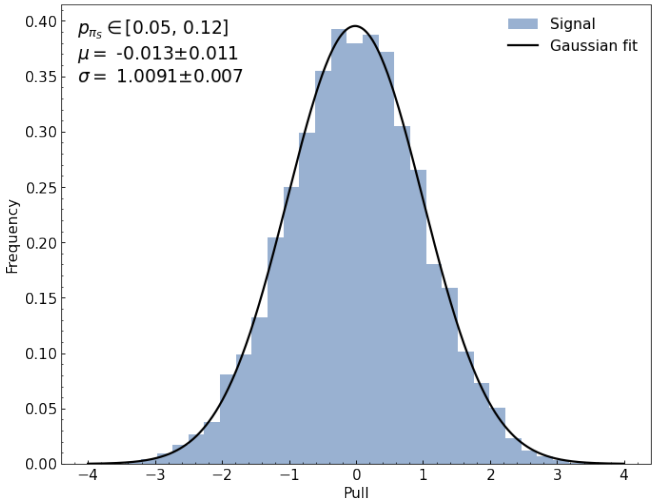
- Use asimov test and pull distributions for fit closure tests
- Asimov test: Fit MC on itself as pseudo data (left)
- Pull test:
  - Calculate: $pull = \frac{\mu_{fit} - \mu}{\sigma_{fit}}$ ($n_{toys} = 10000$)
  - Fit distribution using unbinned gaussian to test bias (μ, middle) and error estimate (σ, right) of signal strength given by pyhf

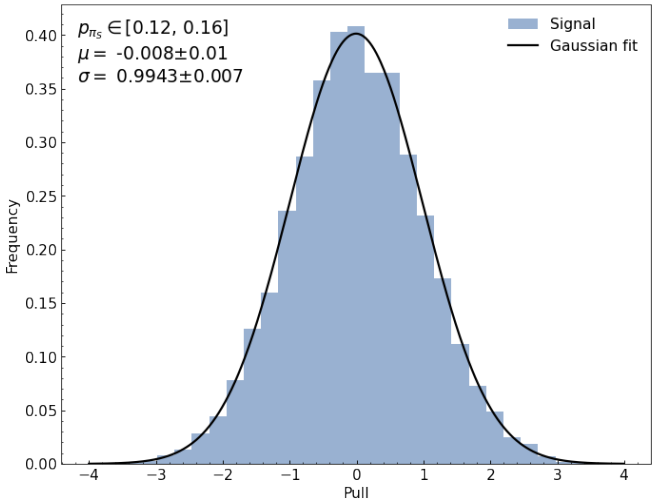


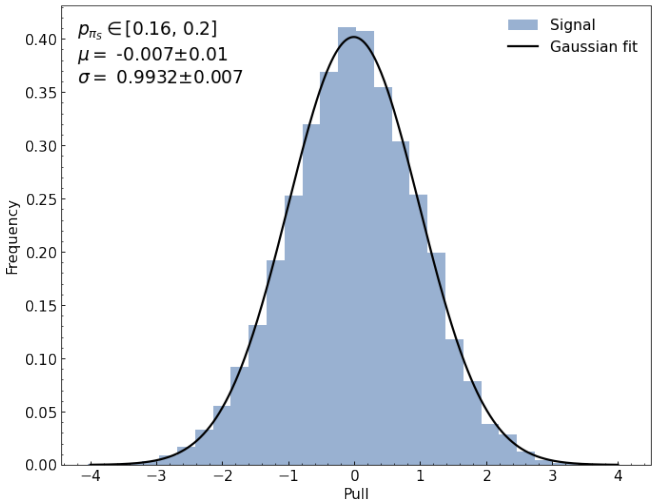


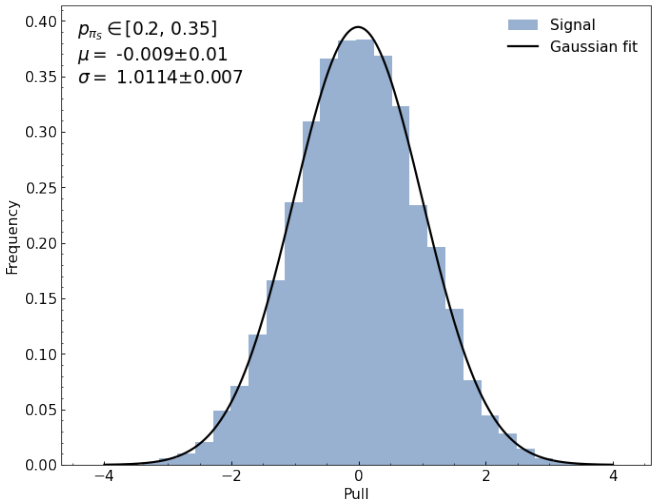


Fit Closure Tests



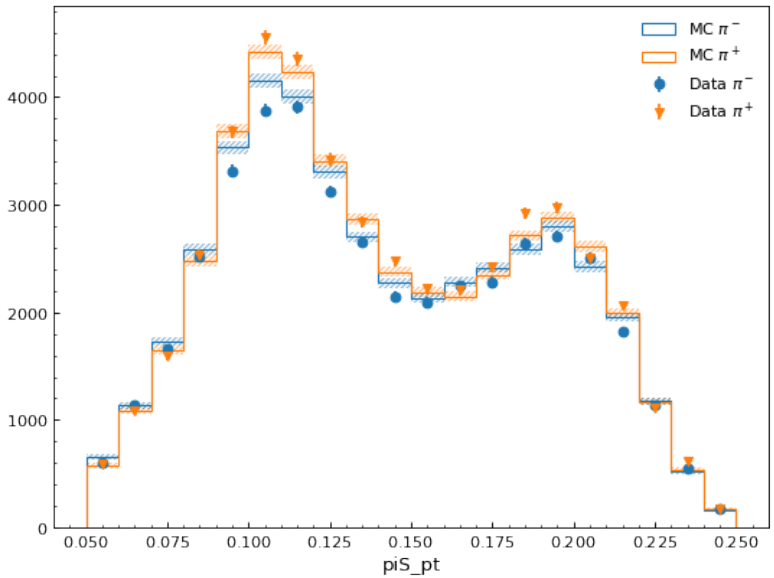


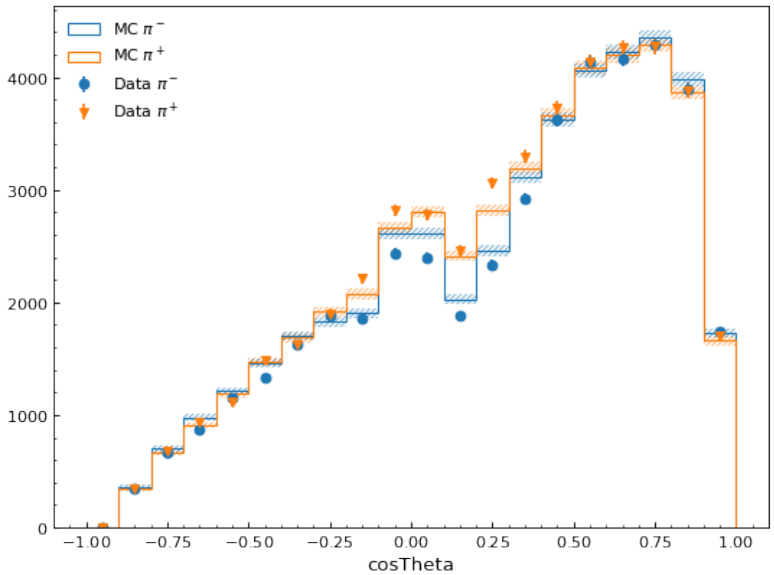




Charge asymmetries

- Determine asymmetry in track finding efficiency based on π charge
- Select signal enriched region: $|\Delta E| < 0.05$
- Calculate asymmetry factor: $\frac{N^{\pi^+} - N^{\pi^-}}{N^{\pi^+} + N^{\pi^-}}$
- Asymmetry calculated in bins of p_T and $cos\theta$ of π_s
- MC15rd samples below scaled with luminosity





Charge asymmetries

- Asymmetry factor in bins of p_T and $cos\theta$ for data(left) and MC15rd (right)
- Uncertainty only statistical, estimated using toys ($n_{toys} = 500$)
- Further information about low momentum tracks ($p_T < 250$ MeV) charge asymmetries in Angelo's latest overview talk