Measurement of the CP violation parameter A_Γ with $D^0 \to \pi^-\pi^+\pi^+\pi^-$ decays

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Motivation

- CPV in charm sector predicted by the standard model to be very small, and has not yet been observed.

- Low SM background environment for new physics.

- A_Γ measures the time-dependent CPV for a D^0 decaying to a CP eigenstate final state f.
  - SM expectations: $A_\Gamma < O(10^{-4})$
  - High precision required.

- Multi body decays allow for CP asymmetries to be measured across the phase space of the decay.

- Singly cabibbo suppressed decays like $D^0 \rightarrow \pi^-\pi^+\pi^+\pi^-$ are especially sensitive to new physics.

- This analysis will be the first measurement of A_Γ in a four-body decay mode

A_Γ

- Violation of flavour quantum numbers by the weak interaction => mass eigenstates of neutral charmed mesons are linear combinations of flavour eigenstates

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D^0}\rangle$$

Mixing parameters

$$x \equiv \frac{m_1 - m_2}{\Gamma}, \quad y \equiv \frac{\Gamma_1 - \Gamma_2}{\Gamma}, \quad \phi = \arg\left(\frac{q}{p}\frac{\overline{A_f}}{A_f}\right)$$

- Due to slow mixing rate of charm mesons ($x, y \sim 10^{-2}$) time dependent CP asymmetry can be approximated at first order as the sum of two terms:

$$A_{CP}(t) = \frac{\Gamma\left(D^0(t) \to f\right) - \Gamma\left(\overline{D^0}(t) \to f\right)}{\Gamma\left(D^0(t) \to f\right) + \Gamma\left(\overline{D^0}(t) \to f\right)} \approx A_{CP}^{dir}(f) + A_{CP}^{ind}(f)\frac{t}{\tau_D}$$

A_Γ

$$A_{CP}(t) = \frac{\Gamma(D^0(t)\to f) - \Gamma(\overline{D^0}(t)\to f)}{\Gamma(D^0(t)\to f) + \Gamma(\overline{D^0}(t)\to f)} \approx A_{CP}^{dir}(f) + A_{CP}^{ind}(f)\frac{t}{\tau_D}$$

$$A_{CP}^{ind}(f) = \frac{\eta_{CP}}{2}\left[y\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\cos\ \phi - x\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\sin\phi \right]$$

CPV in mixing: $\left|\frac{q}{p}\right| \neq 1$ CPV in interference: $\phi \neq 0, \pi$

- A_Γ is defined as the asymmetry between D^0 and $\overline{D^0}$ effective lifetimes.

In the limit of small CP violation in the decay:

$$A_\Gamma \equiv \frac{\hat{\Gamma}(D^0 \to f) - \hat{\Gamma}\left(\overline{D^0} \to f\right)}{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}\left(\overline{D^0} \to f\right)} \approx -A_{CP}^{ind}(f) \qquad \frac{1}{\hat{\Gamma}} = \hat{\tau} = \frac{\int t\Gamma(t)dt}{\int \Gamma(t)dt}$$

- **Thus $A_\Gamma \neq 0$ indicates indirect CPV in the charm sector, sensitive to both mixing and interference.**

A_Γ

- A_Γ is considered universal for all decays with CP-even final states, in approximation.

- $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ is a final state with **mixed** CP content
  - Measured A_Γ picks up a factor of $(2F_+ - 1)$ with respect to pure CP-even or odd final states.
    (*Phys. Rev.* **D 91** (2015) 094032)

- $F_+^{4\pi} = (0.769 \pm 0.021 \pm 0.010\ )$
  - CLEO measured result (JHEP01 (2018) 144)
  - Corresponds to scale factor applied to asymmetry of 1.859

Measuring A_Γ

- Measuring the effective lifetimes requires precise knowledge of their time-dependent reconstruction efficiency.
- Challenging to achieve at hadron colliders given the decay-time-related requirements of the trigger used.
- Instead measure the raw asymmetry between the number of reconstructed D^0 and $\overline{D^0}$ mesons.

$$A_{Raw}(t) = \frac{dN(D^0,t) - dN(\overline{D^0},t)}{dN(D^0,t) + dN(\overline{D^0},t)} \approx A_{CP}(t) + A_D(t) + A_P$$

$A_{CP}(t)$:

$$A_{CP}^{dir} - A_\Gamma \frac{t}{\tau_{D^0}}$$

A_Γ extracted as –ve the slope

$A_D(t)$: Detector induced charge asymmetry. Possible time dependence mimicking fake slope

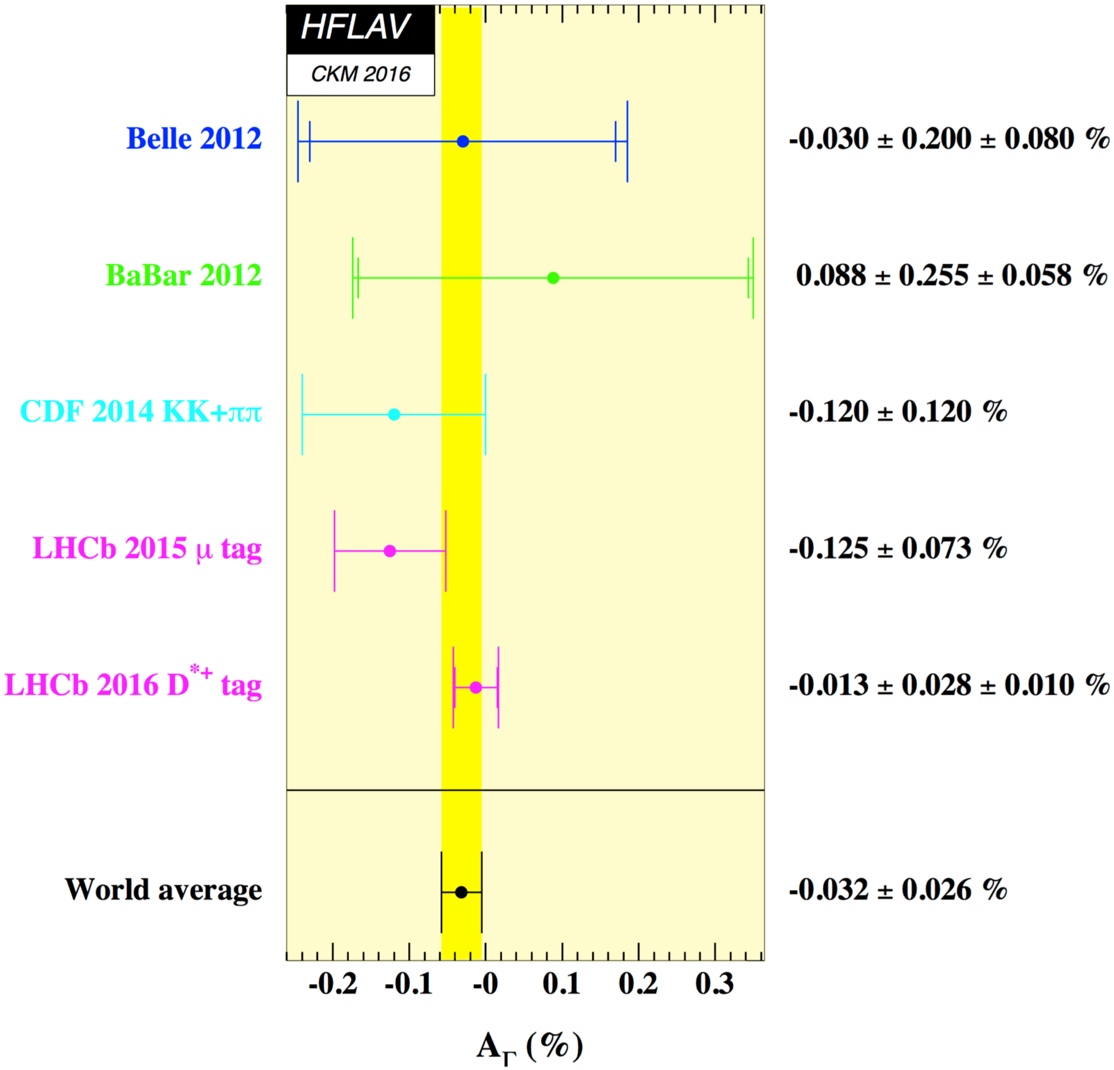
A_P: Time-independent production asymmetry

- $A_D(t)$ depends on time due to correlations between the D0 decay time and the π_s momentum used to infer the D0 flavour.
- Bias to A_Γ as a result cannot be neglected.

Method first utilised in 2-body A_Γ analysis
(Phys. Rev. Lett. 118, 261803 (2017))

Current Experimental Status

- World best measurements of the parameter A_Γ with $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays.
- Average is compatible with zero within 3×10^{-4}, dominated by LHCb two-body run 1 measurement.



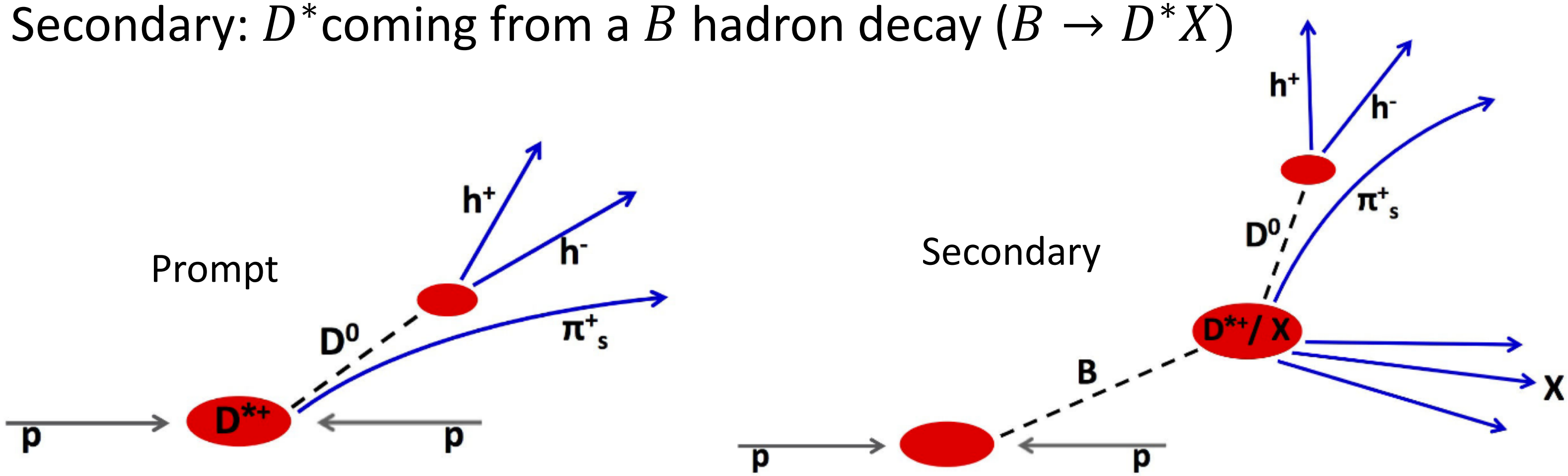
Plot obtained from HFLAV. Eur. Phys. J. C77 (2017) 895

Analysis Method

- Phase space integrated initially.
- Strong decays $D^{*+} \to D^0 \pi_s^+$ $(D^{*-} \to \overline{D}^0 \pi_s^-)$ used for D^0 flavour tagging.
- High statistics $D^0 \to K^- \pi^+ \pi^+ \pi^-$ control channel used to validate procedure.
  - $A_\Gamma(D^0 \to K^- \pi^+ \pi^+ \pi^-)$ should be zero in the absence of any detector effects.
- $A_\Gamma(D^0 \to \pi^- \pi^+ \pi^+ \pi^-)$ blinded.
- Full run 1 and run 2 data measurement intended.
  - Today presenting preliminary results up to 2016 (control) and 2012 (signal)
- Samples are split by year and magnet polarity.
- Each sample is split into 30 approximately equally populated decay time bins to 6.0 ps.
- A_Γ is measured through a linear fit to $A_{\mathrm{CP}}(t)$

Secondary decays

- Source of background
- ${D^*}^+ \to D^0\pi^+$ decays have two components:
  - Prompt: D^*coming from the primary vertex of an interaction
  - Secondary: D^*coming from a B hadron decay ($B \to D^*X$)



- Secondaries contribute to A_raw(t) because the fraction of secondary decays depends strongly on reconstructed decay time.
- Systematic uncertainty must be applied if not accounted for.

Data sample

- No constraint that D*+ be produced in the PV
- L0: D^0 TOS L0HadronDecision or D^{*+}TIS L0Global
  - No requirements on π_s^+

Run 1:
Stripping 21r1: DstarPromptWithD02HHHHLine

D^0 TOS HltTrackAllL0Decision
4Pi:
D^{*+} TOS Hlt2CharmHadD02HHHH_4piDecision OR D^{*+} TOS Hlt2CharmHadD02HHXDst_hhXDecision
K3Pi:
D^{*+} TOS Hlt2CharmHadD02HHHH(Dstr_K3pi) OR Hlt2CharmHadD02HHXDst_hhXDecision

Run 2:
Hlt2CharmHadDstp2D0Pip_D02PimPipPimPipTurbo
Hlt2CharmHadDstp2D0Pip_D02KmPipPimPipTurbo

HLT1: D0 TOS for one or both:
Hlt1TrackMVA OR Hlt1TwoTrackMVA

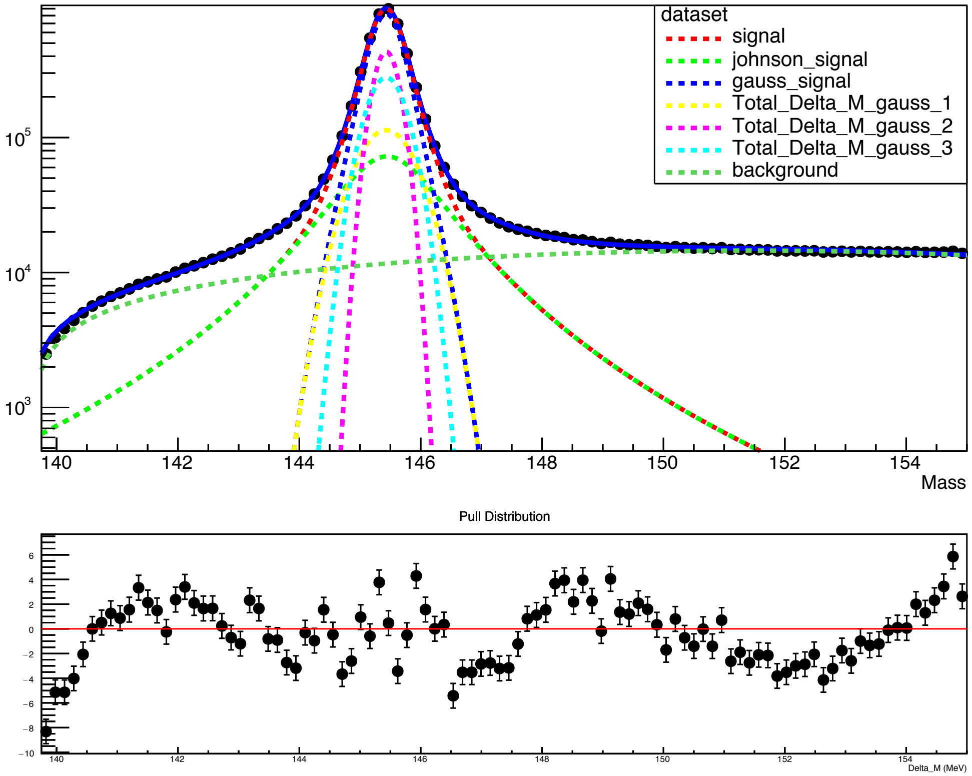
Further offline cuts

- $\chi^2_{IP} < 9$ to suppress secondary decays.
  - χ^2_{IP}: difference between χ^2 of PV fit with/without including particle/track in fit.
  - Particles that do not come from the PV have a larger χ^2_{IP} on average.
- $p_{\pi_s} > 3000\ \mathrm{MeV}$
- $(139.57 < \Delta m\ (m(D^{*+}) - m(D^0)) < 155.00)\ \mathrm{MeV}$
- $(1845 < m(D^0) < 1885)\ \mathrm{MeV}$
- $\chi^2_{FD} > 50$

Fit Model

- Signal: Johnson SU-distribution in Δm [$m(D^*) - m(D)$] + 3 gaussians
- Random pion background:
  - $\Delta m : f(\Delta m) = \left(\sqrt{\Delta m - \Delta m_\pi}\right)[1 + \alpha(\Delta m - m_\pi) + \beta(\Delta m - \Delta m_\pi)^2$
- **WIP**

$K^-\pi^+\pi^+\pi^-$ 2015 MagDown



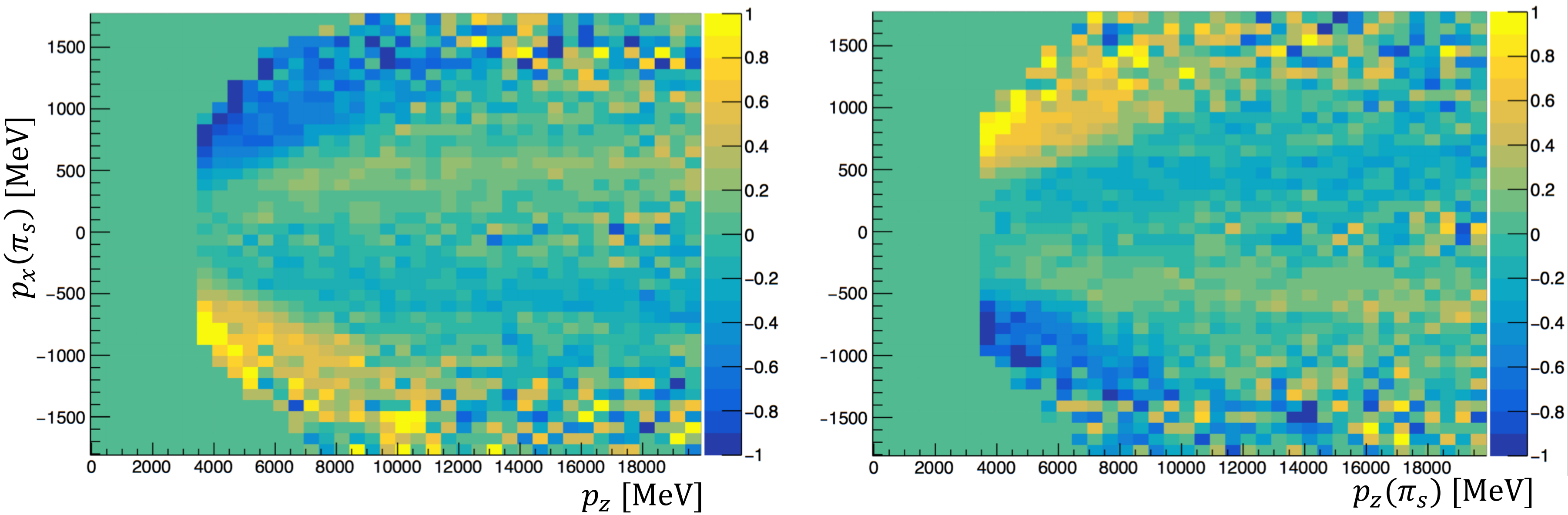
Momentum charge asymmetries

$$A_{Raw}(t) = \frac{dN(D^0,t) - dN(\overline{D^0},t)}{dN(D^0,t) + dN(\overline{D^0},t)} \approx A_{CP}^{direct} - A_\Gamma \frac{t}{\tau_{D^0}} + A_D(t) + A_P$$

LHCb detector acceptance not CP-symmetric over the whole space

In reconstruction and selection of the π_s charge asymmetries are present and strongly depend on the π_s momentum.

Averaging between magnet up and magnet down polarities does not necessarily eliminate this problem with the degree of precision needed due to variation of run conditions over time.



Raw asymmetry of soft pion charges in p_x against p_z for 2012 MagUp(left) and MagDown (right)

Reweighting

To restore the CP symmetry a correction is applied in time-integrated $(C, q_{\pi_s}\theta_x, \theta_y)$ distribution, where C is proportional to track curvature in the magnetic field, q_{π_s} is the charge of the soft pion, and θ_x θ_y are the pion emission angles in the bending and vertical planes, respectively.

$$C = \frac{1}{\sqrt{p_x^2 + p_z^2}}$$

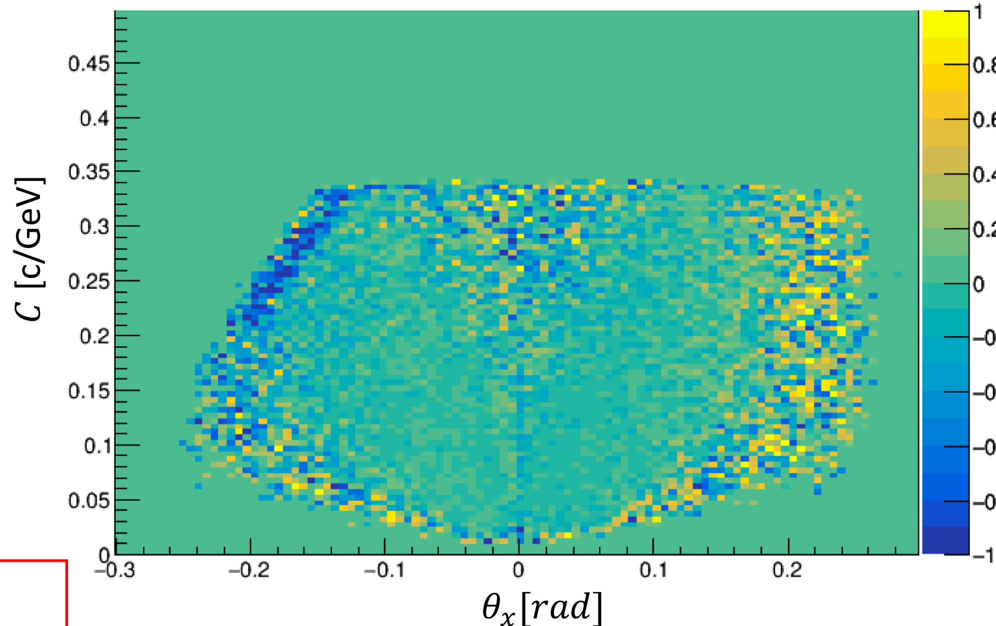
$$\theta_x = \arctan\left(\frac{p_x}{p_z}\right)$$

$$\theta_y = \arctan\left(\frac{p_y}{p_z}\right)$$

Reweigh the 3D momentum distributions of p+ and pi- to make them equal

$$\mathrm{N}^+(C, \theta_x, \theta_y) = N^-(C, -\theta_x, \theta_y)$$

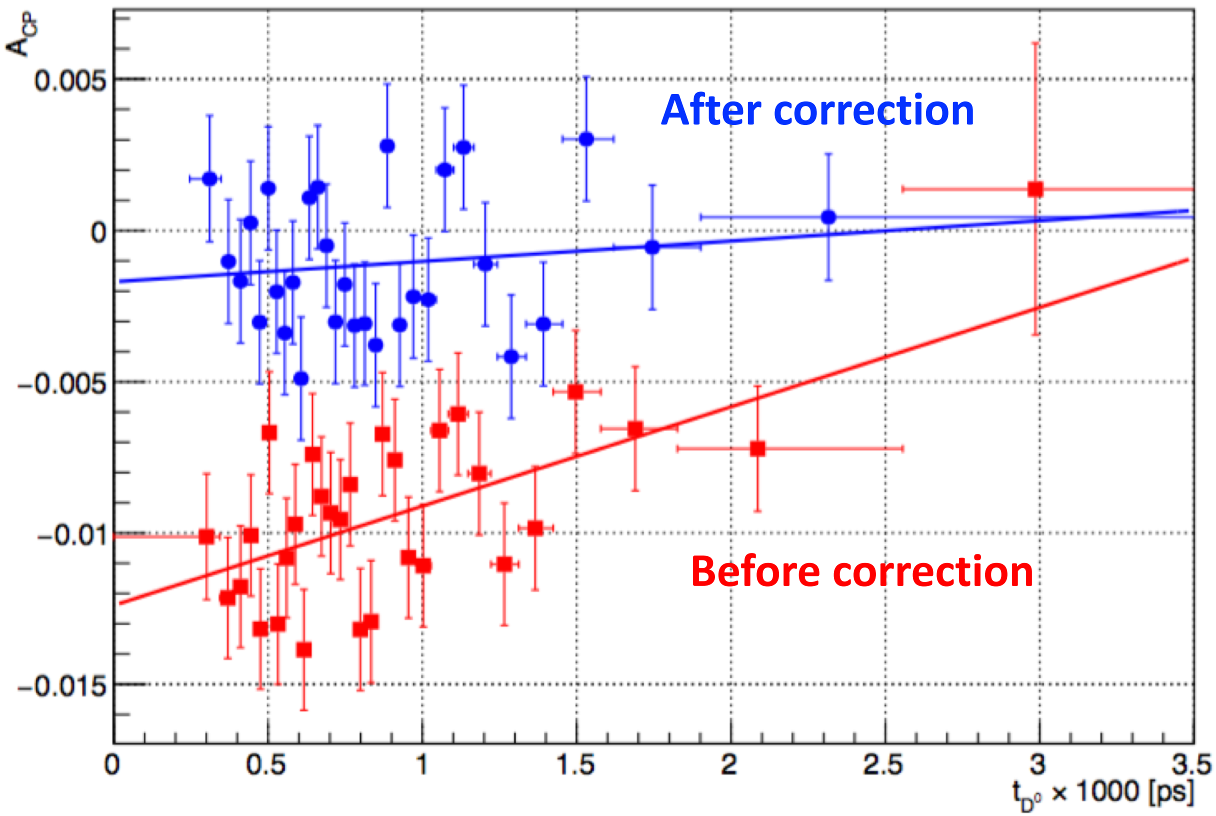
$$\sqrt{\omega_{i,j,k}} = \sqrt{\frac{\Sigma_\alpha n^{\alpha^+}_{i,-j,k}}{\Sigma_\alpha n^{\alpha^-}_{i,-,k}}} \quad \text{and} \quad \sqrt{\nu_{i,j,k}} = \sqrt{\frac{\Sigma_\alpha n^{\alpha^-}_{i,-j,k}}{\Sigma_\alpha n^{\alpha^+}_{i,-,k}}}$$



Time-integrated raw asymmetry in $(C, q_{\pi_s}\theta_x)$ of 2011 MagUp

Reweighting

A_Γ is inconsistent with zero before weighting, and consistent after weighting.



After reweighting both the intercept and slope become consistent with zero demonstrating CP symmetry has been restored

Magdown 2012

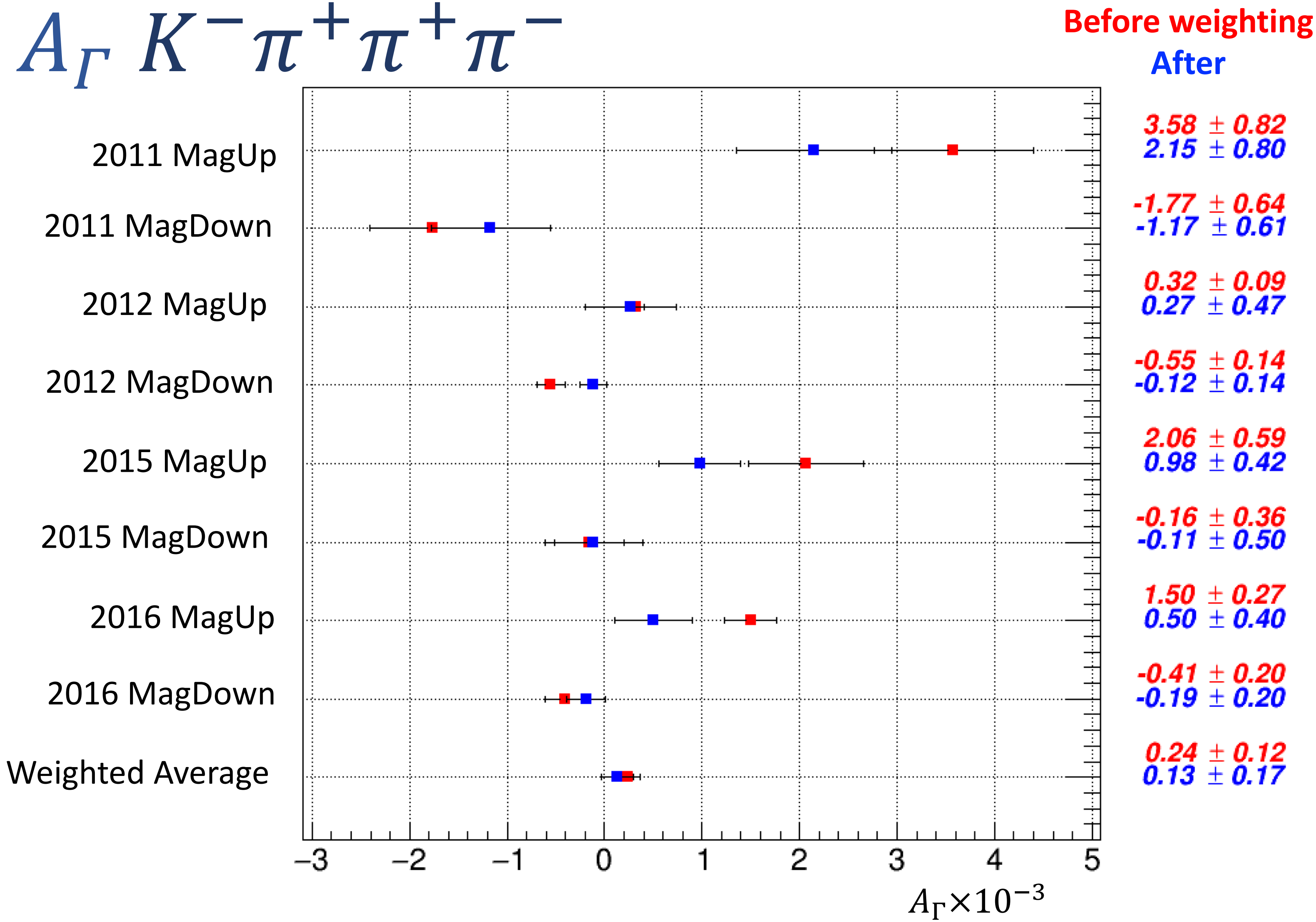
Before:

$$A_\Gamma^{K3\pi} = -(0.55 \pm 0.14)\times 10^{-3}$$

After:

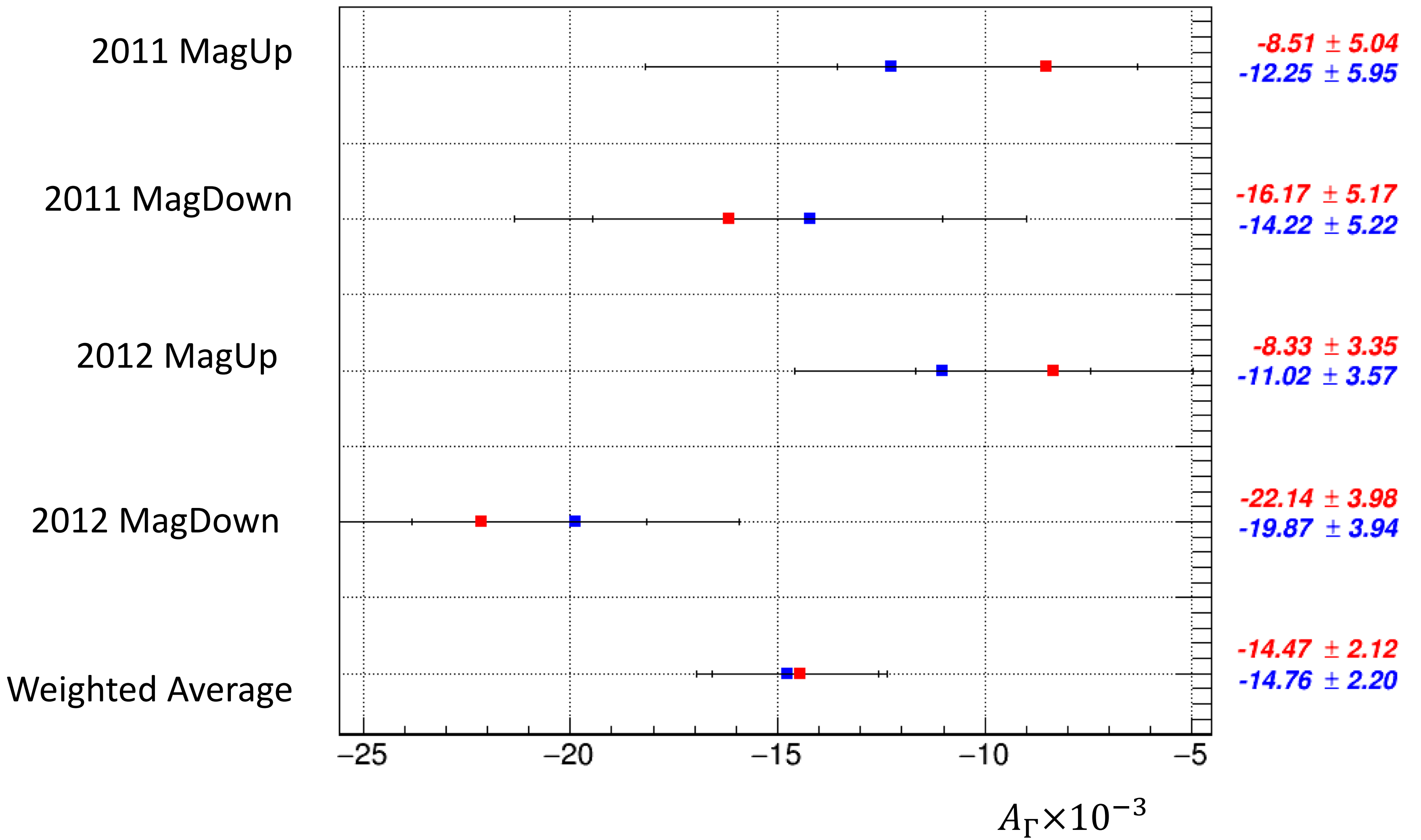
$$A_\Gamma^{K3\pi} = -(0.12 \pm 0.14)\times 10^{-3}$$

$A_\Gamma \; K^-\pi^+\pi^+\pi^-$



$A_{\Gamma}\ \pi^{-}\pi^{+}\pi^{+}\pi^{-}$ (blinded)

Scale factor applied



Systematics

Possible sources of systematic uncertainty to be considered:

- Contribution of secondaries
  - Suppressed by cut on χ^2_{IP} but some may still be present
- Reweighting procedure
- Uncertainty on F_+
  - Should translate to uncertainty of relative size on A_Γ
- Efficiency as function of phase space

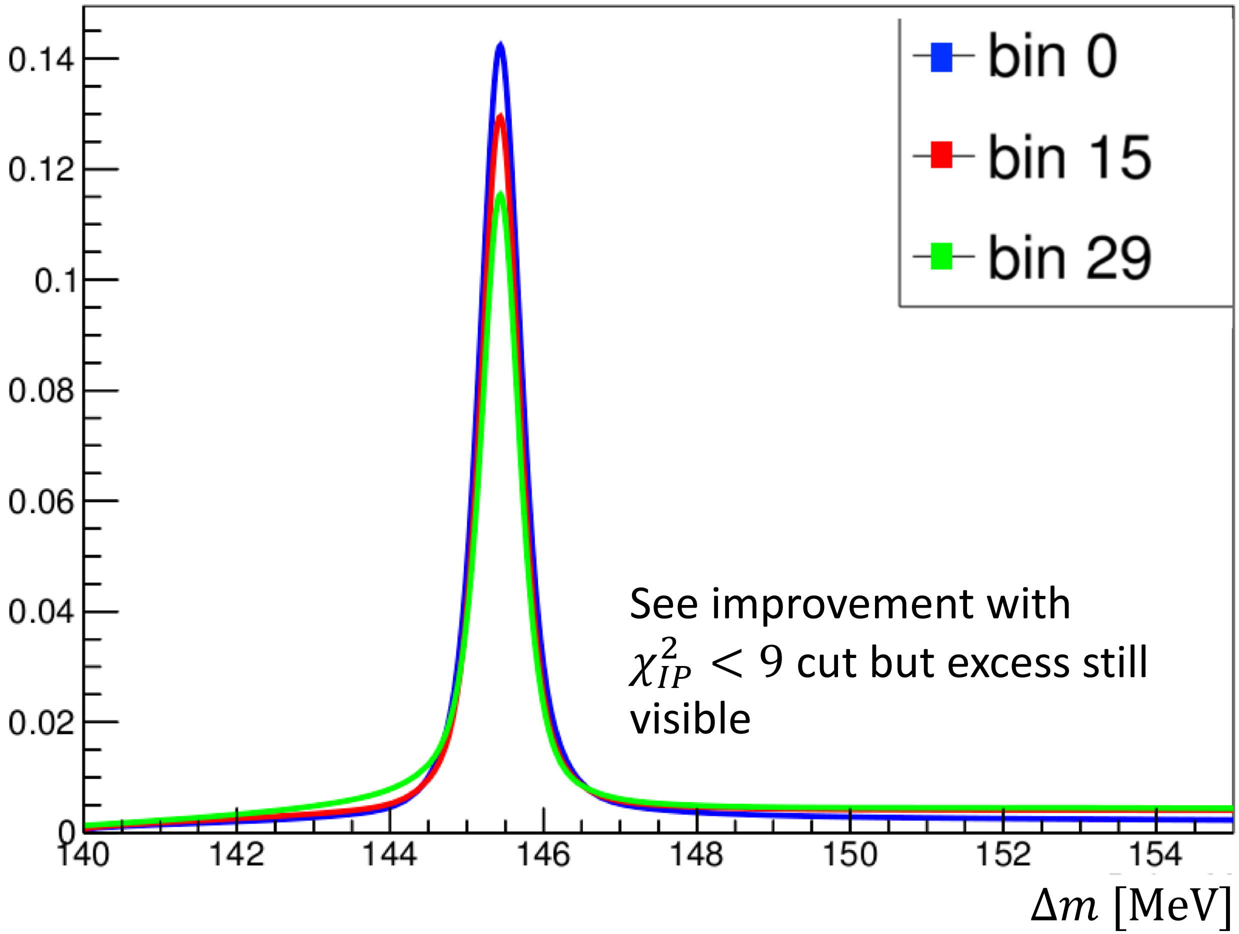
Conclusion

- A_{Γ} is a sensitive probe of CP violation in the charm sector.
- Preliminary results of A_{Γ} $(\pi^{-}\pi^{+}\pi^{+}\pi^{-})$ presented for run 1.
- Expected uncertaint of ~10^{-3}on A_{Γ} with full dataset.

Backup

DTF and Δm

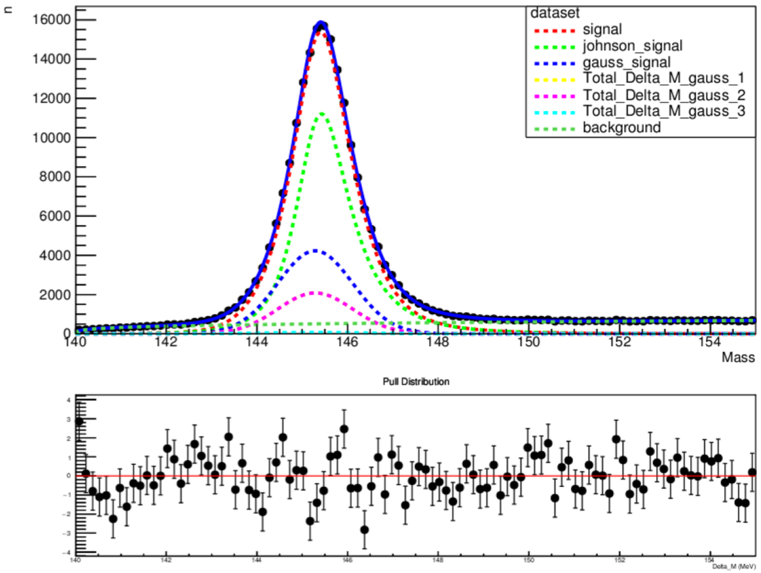
$D^0 \to K^- \pi^+ \pi^+ \pi^-$ 2015 MagUp



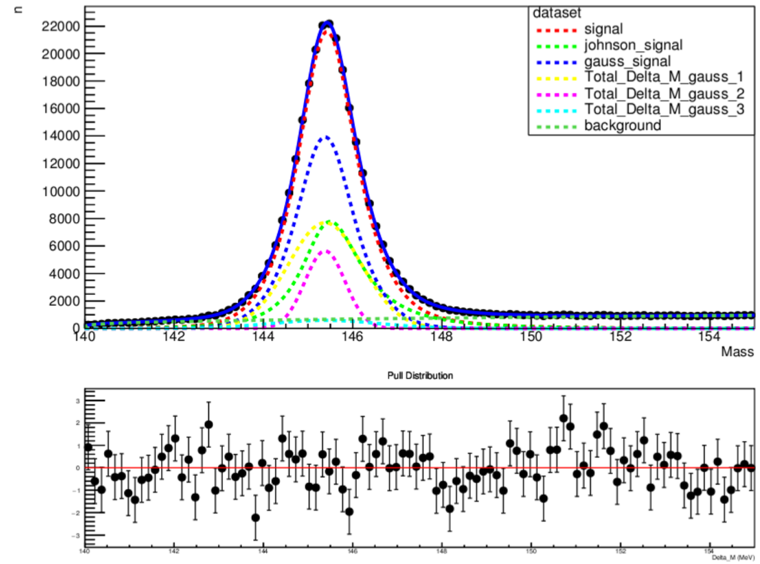
- Decay Tree Fitter
  - Forces D^{*+} DV to coincide with the PV
  - Produces a time-dependent artificial tail in Δm due to secondary decays
  - Excess is largest in highest decay time bin
  - DTF is not used in this analysis

$D^0 \to \pi^-\pi^+\pi^+\pi^-$ Run 1

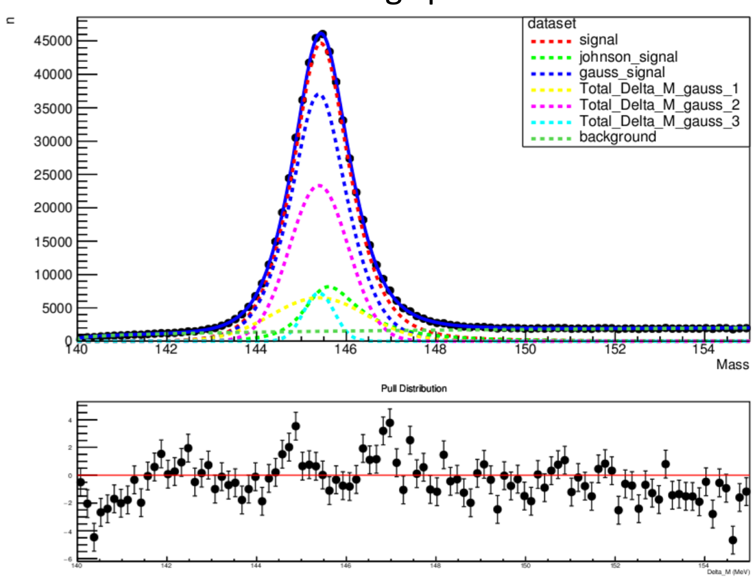
2011 MagUp



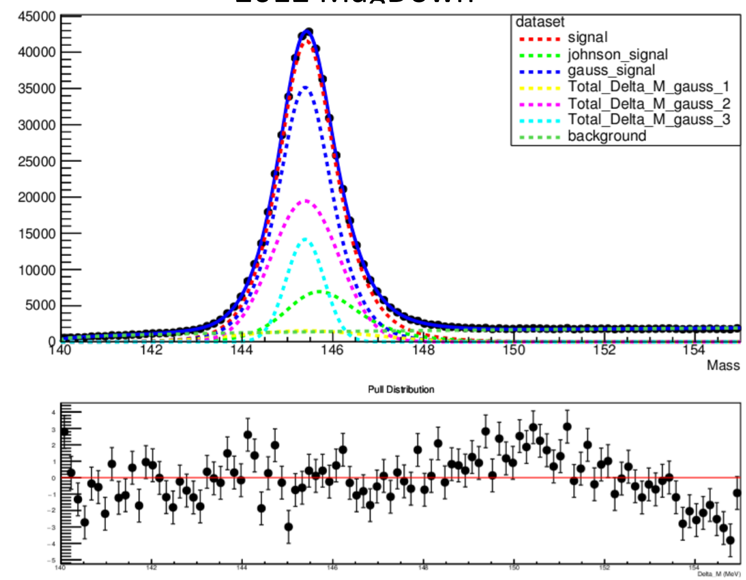
2011 MagDown



2012 MagUp

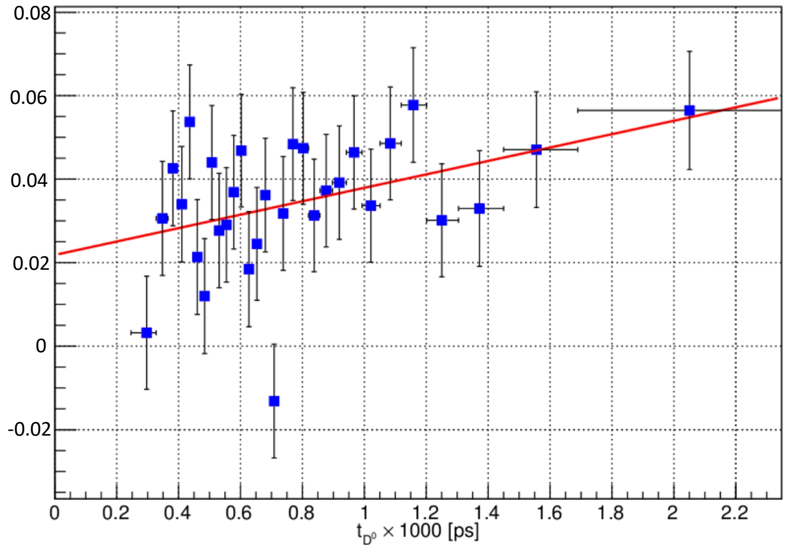


2012 MagDown

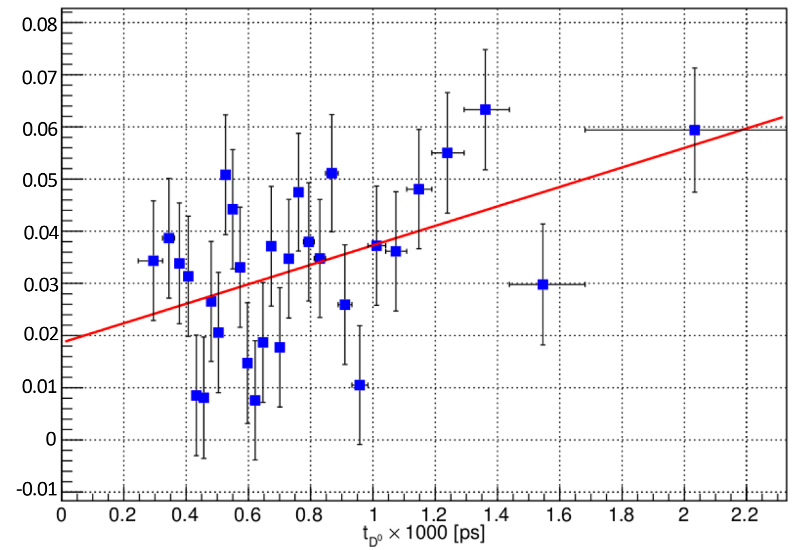


$D^0 \to \pi^-\pi^+\pi^+\pi^-$ Run 1 **(Slope and Intercept Blinded)**

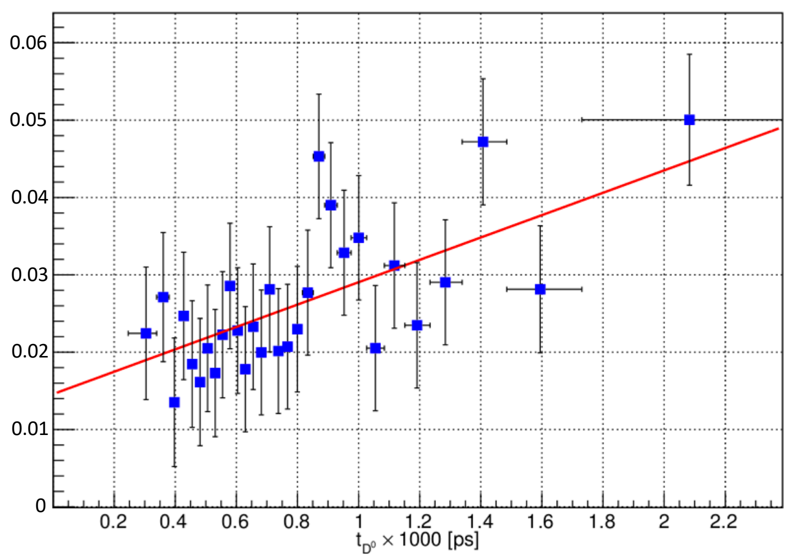
2011 MagUp



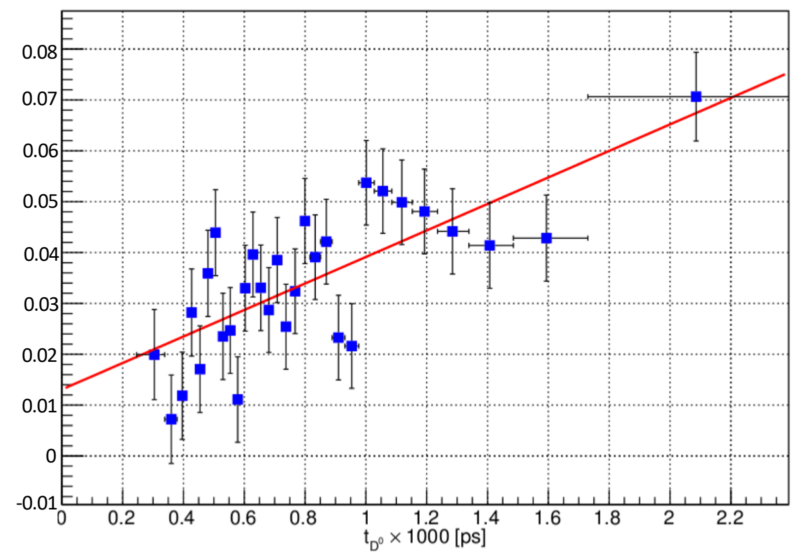
2011 MagDown



2012 MagUp

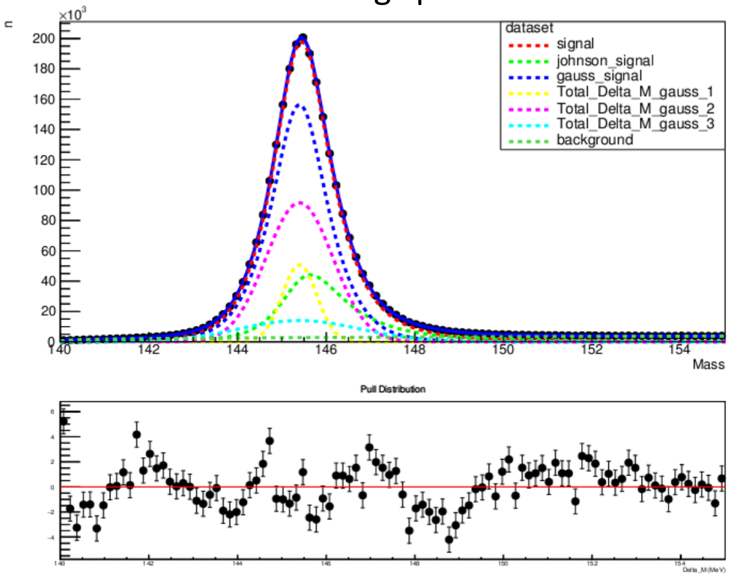


2012 MagDown

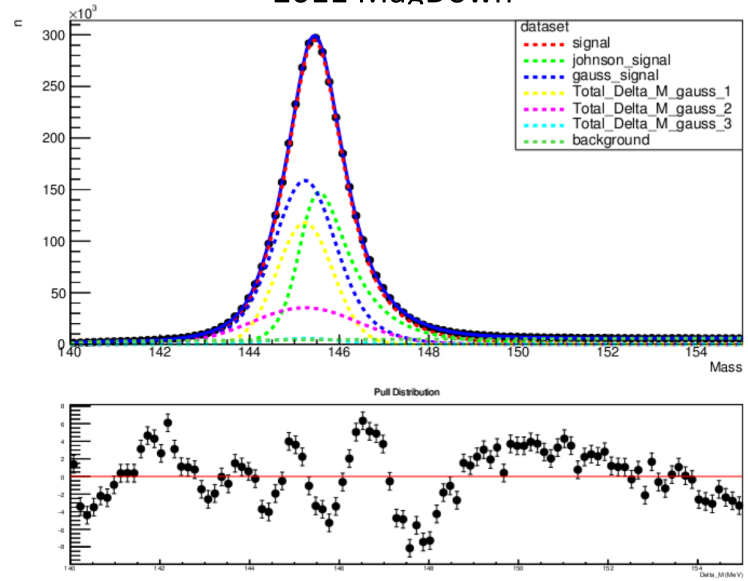


$D^0 \to K^-\pi^+\pi^+\pi^-$ Run 1

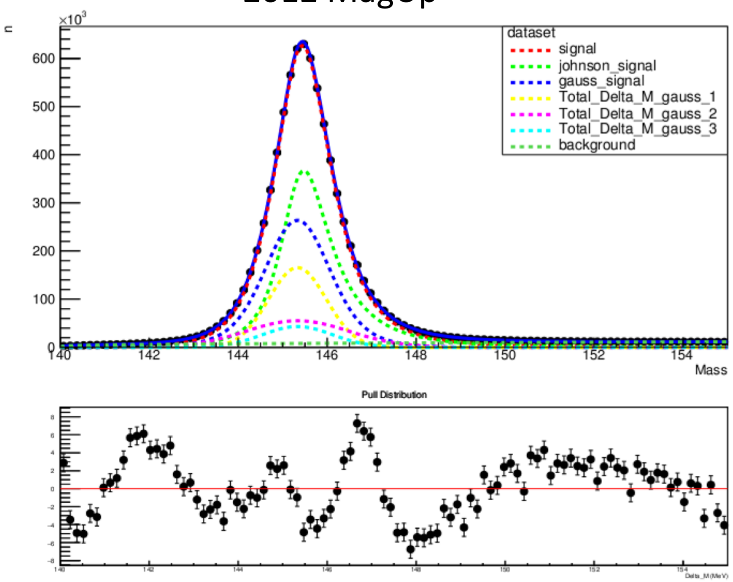
2011 MagUp



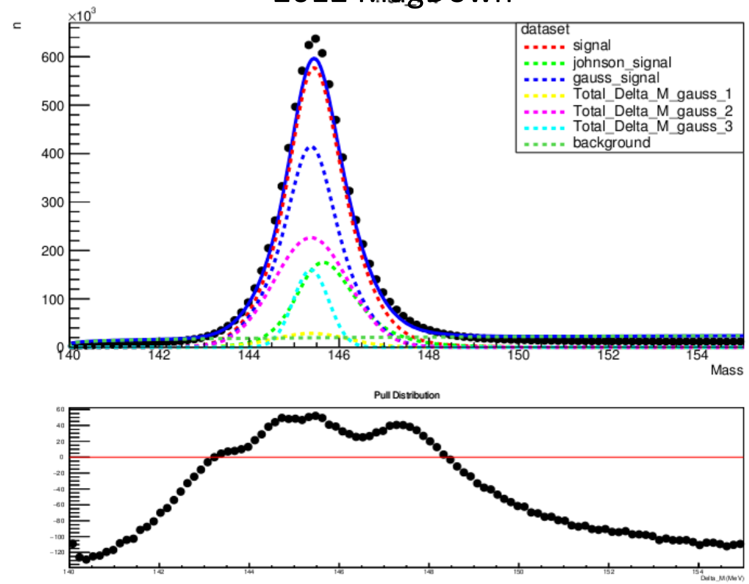
2011 MagDown



2012 MagUp

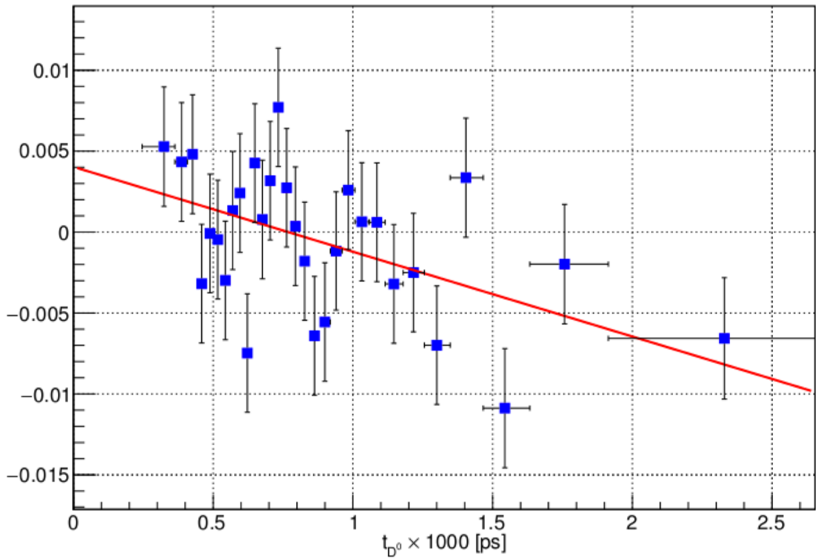


2012 MagDown

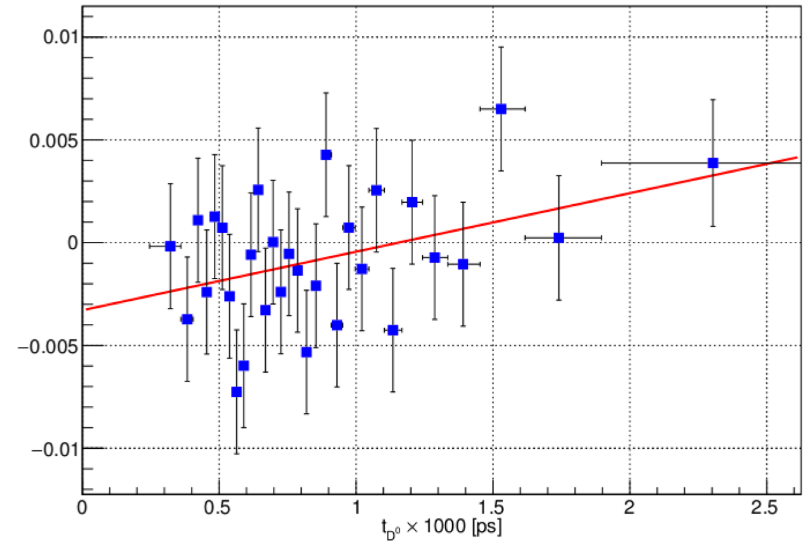


$D^0 \rightarrow K^-\pi^+\pi^+\pi^-$ Run 1 (symmetrisation applied)

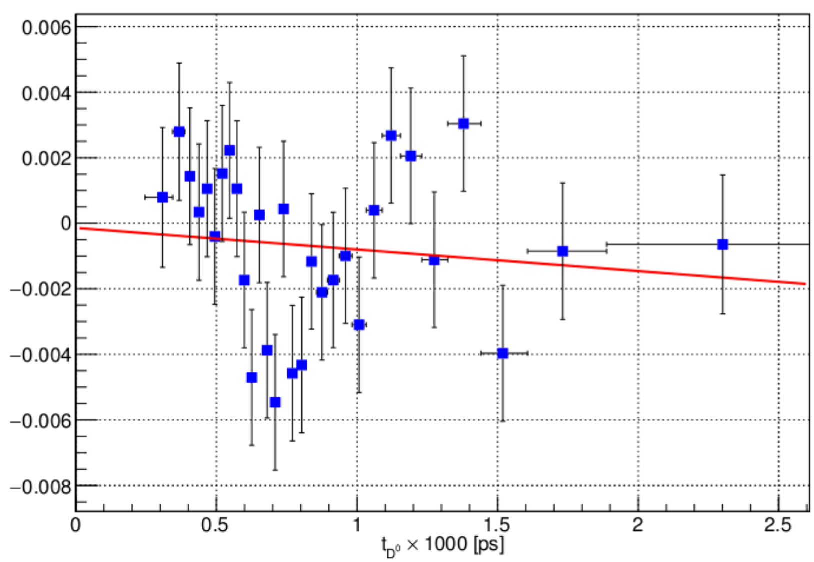
2011 MagUp



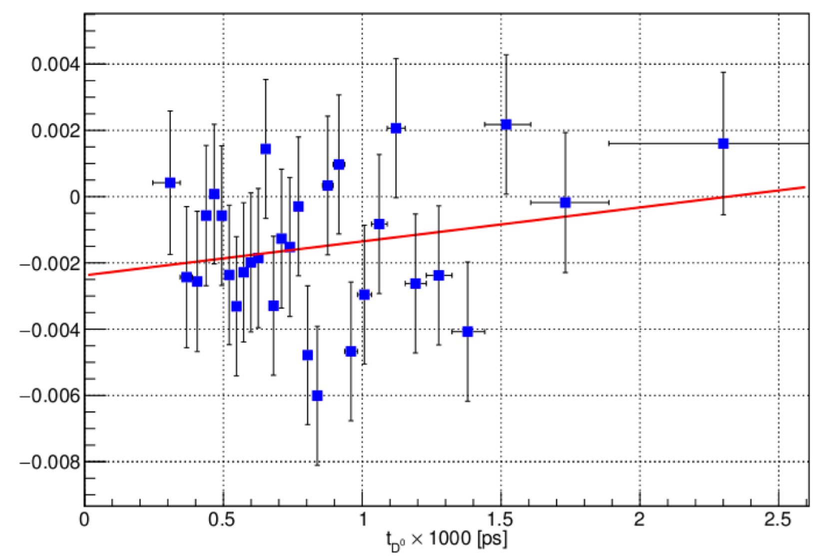
2011 MagDown



2012 MagUp

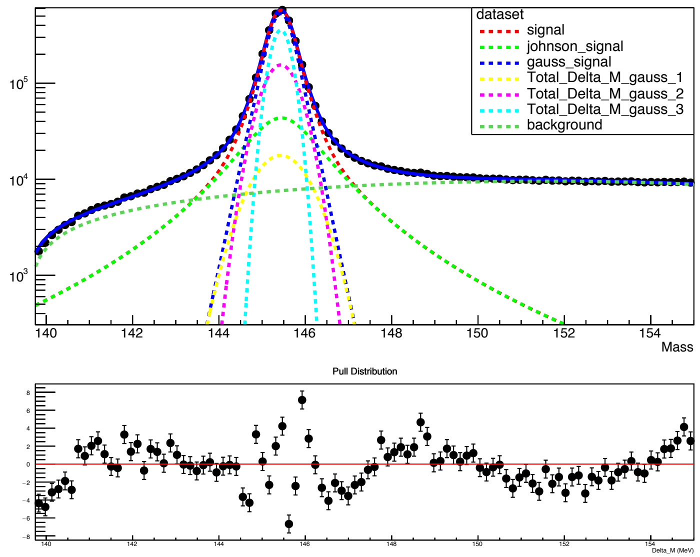


2012 MagDown

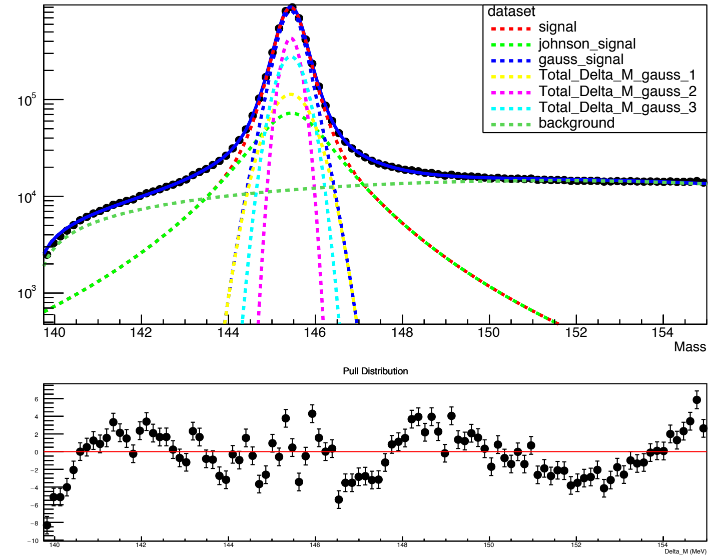


$D^0 \to K^-\pi^+\pi^+\pi^-$ Run 2

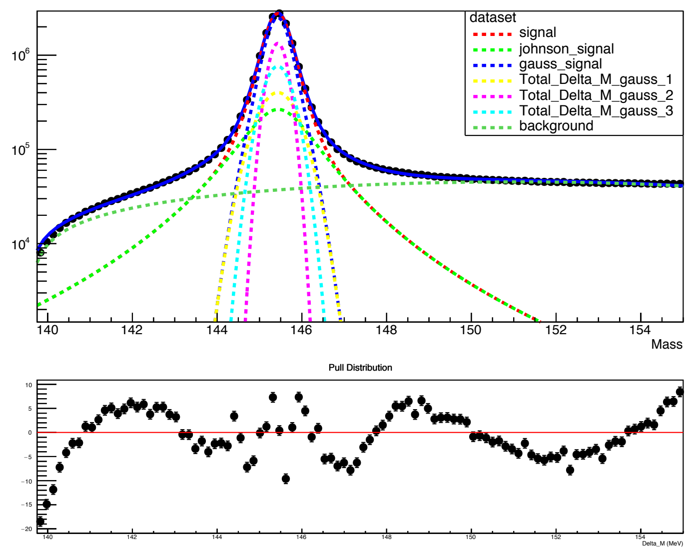
2015 MagUp



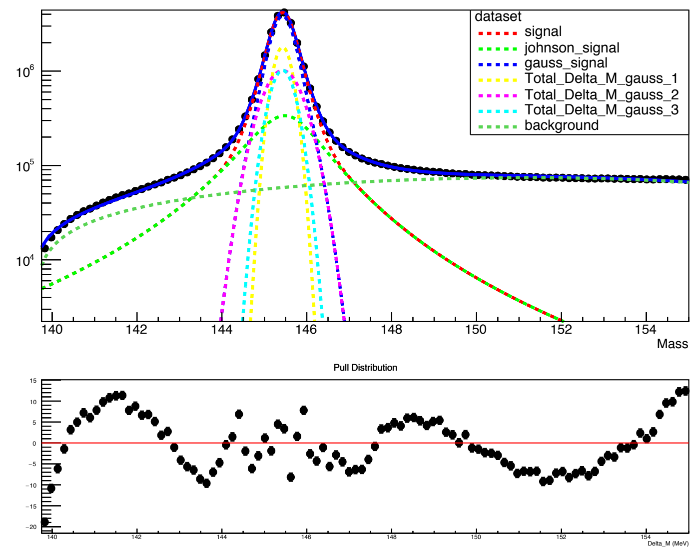
2015 MagDown



2016 MagUp



2016 MagDown



$D^0 \to K^-\pi^+\pi^+\pi^-$ Run 2