Time-dependent charge asymmetry in $D^0 \rightarrow hh$ (A_Γ)

P. Marino[1,3],
M. J. Morello[1,3], G. Punzi[2,3]

[1]SNS, [2]University of Pisa, [3]INFN-Pisa

LHCb Italia

13 Ottobre 2015

Introduction

effective lifetime

mixing parameters

$$A_\Gamma = \frac{\hat{\Gamma}_{D^0} - \hat{\Gamma}_{\bar{D}^0}}{\hat{\Gamma}_{D^0} + \hat{\Gamma}_{\bar{D}^0}} \approx \eta_{CP}\left[\frac{1}{2}(A_m + A_d) y \cos\phi - x \sin\phi\right]$$

into CP eigenstate final state: K^+K^-, $\pi^+\pi^-$

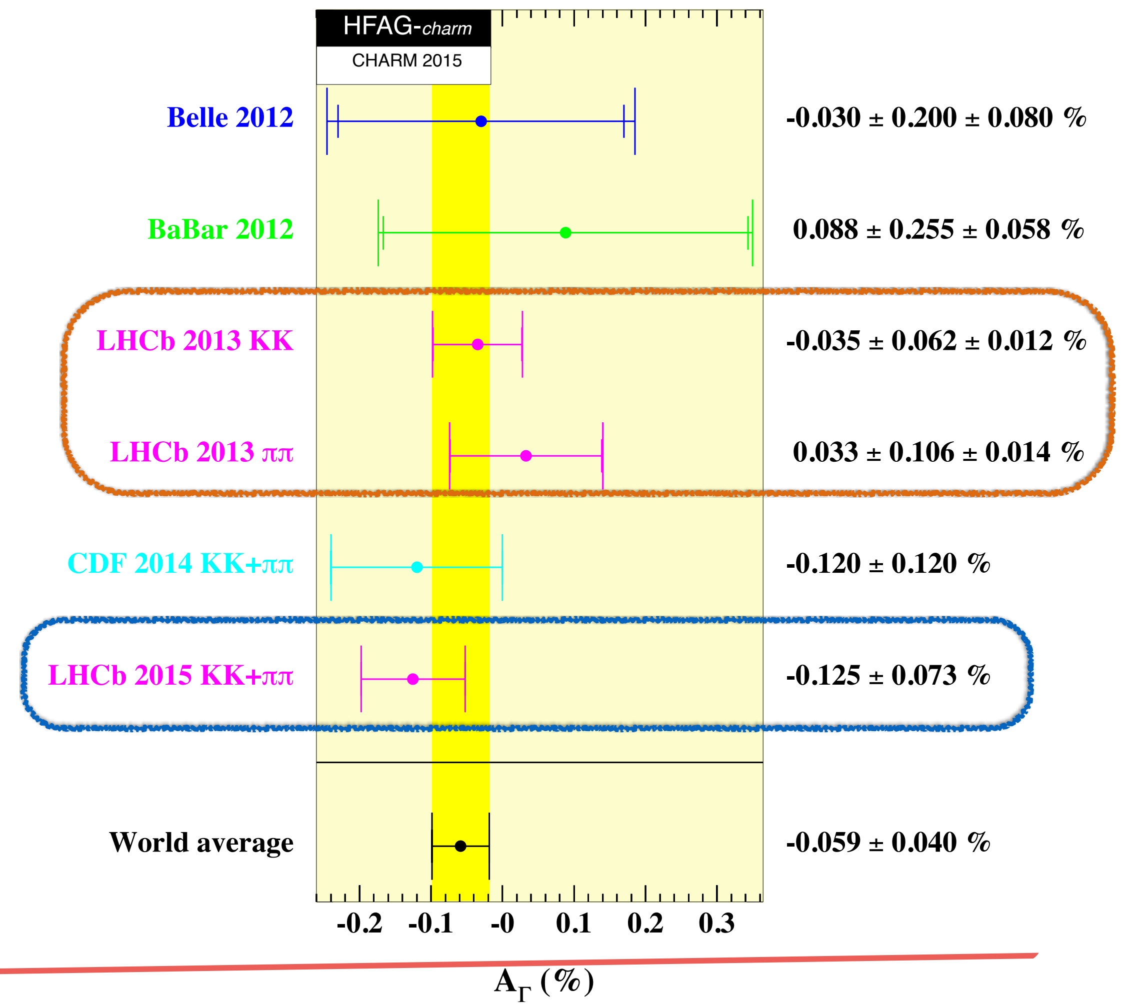
CP violation: mixing and direct

LHCb measurements:

- ✦ soft-pion tagged, from decays $D^* \to D^0 \pi_s$ (1/fb)
- ✦ muon tagged, from semi-leptonic $B \to D^0 \mu X$ decays (3/fb)

Expect statistical error on hadronic A_Γ of:

$$\sigma(A_\Gamma, 3/\text{fb}) \approx \begin{cases} 0.036\% & \text{for } K^-K^+ \\ 0.062\% & \text{for } \pi^-\pi^+ \end{cases}$$



Binned method

- Binned method:
  - Divide the sample into bins of lifetime;
  - in each bin of lifetime: measure the number of signal events performing a simultaneous likelihood fit of Δm between D^0 and $\bar{D}^0$, where A_{raw} is a shared parameter
  - measure A_{raw} in bins of D^0 proper decay time, fitting Δm simultaneously for D^0 and $\bar{D}^0$;
  - extract A_Γ from a linear fit of $A_{raw}(t)$.
  - Acceptance functions cancel out in the ratio.

$$A_{\mathrm{raw}}(t) = \frac{N(D^0; t_i) - N(\overline{D}^0; t_i)}{N(D^0; t_i) + N(\overline{D}^0; t_i)} = \boxed{A_0} - \boxed{A_\Gamma \frac{t}{\tau}}$$

Time-independent term: production, detector, etc.. Only an offset.

Time-dependent term

Stripping

S Stripping 21(21r1):

`CHARMTOBESWUM.DST,`
`D2hhPromptDst2DxxLine`
(xx = RS, KK, PiPi)

year/Mag	# files	# events	size (TB)
2012/Up	7624	223 109 736	22
2012/Down	8173	227 656 810	22.6
2011/Down	4911	92 663 911	8
2011/Up	3989	62 595 702	5.4

Quantity	Requirements	Units
p_T (π)	> 800	MeV/c
p (π)	> 5	GeV/c
Track fit χ^2/ndf (π)	< 3	-
Impact parameter χ^2 (π)	> 9	-
$\Delta \log \mathcal{L}_{\pi-K}(\pi)$	< 0	-
p_T (K)	> 800	MeV/c
p (K)	> 5	GeV/c
Track fit χ^2/ndf (K)	< 3	-
Impact parameter χ^2 (K)	> 9	-
$\Delta \log \mathcal{L}_{\pi-K}(K)$	> 5	-
p_T (D^0)	> 2	GeV/c
p (D^0)	> 5	GeV/c
Decay vertex χ^2 distance from PV	> 40	-
Cosine of D^0 pointing angle (a.k.a. DIRA)	> 0.9999	-
Distance of closest approach of D^0 daughters (a.k.a. DOCA)	< 0.07	mm
p_T of at least one of D^0 daughters	> 1.5	GeV/c
Fit vertex $\chi^2(D^0)$/ndf	< 10	-
$m(hh')$	[1765, 2065]	MeV/c^2
Fit vertex $\chi^2(D^*)$/ndf	< 100	-
$m(hh'\pi_s) - m(hh')$	< 160	MeV/c^2
Track fit χ^2/ndf (π_s)	< 5	-

- `StrippingD2hhPromptDst2D2RSLine`
- `StrippingD2hhPromptDst2D2KKLine`
- `StrippingD2hhPromptDst2D2PiPiLine`

Trigger and Offline selection

No L0 requirement

T

Candidates have to be TOS on:

- `Hlt1TrackAllL0`
- `Hlt2CharmHadD02HH_D02xx || Hlt2CharmHadD02HH_D02xxWideMass || Hlt2CharmHadD02xx || Hlt2CharmHadD02xxWideMass`

O

Base Selection

Quantity	Requirements	Units
$\Delta \log \mathcal{L}_{\pi-K}(K)$	> 5	-
$\Delta \log \mathcal{L}_{\pi-K}(\pi)$	< -5	-
R_{xy}	< 4	mm

$$R_{xy} = \sqrt{(DV_x - PV_x)^2 + (DV_y - PV_y)^2}$$

number of events after S+T+O

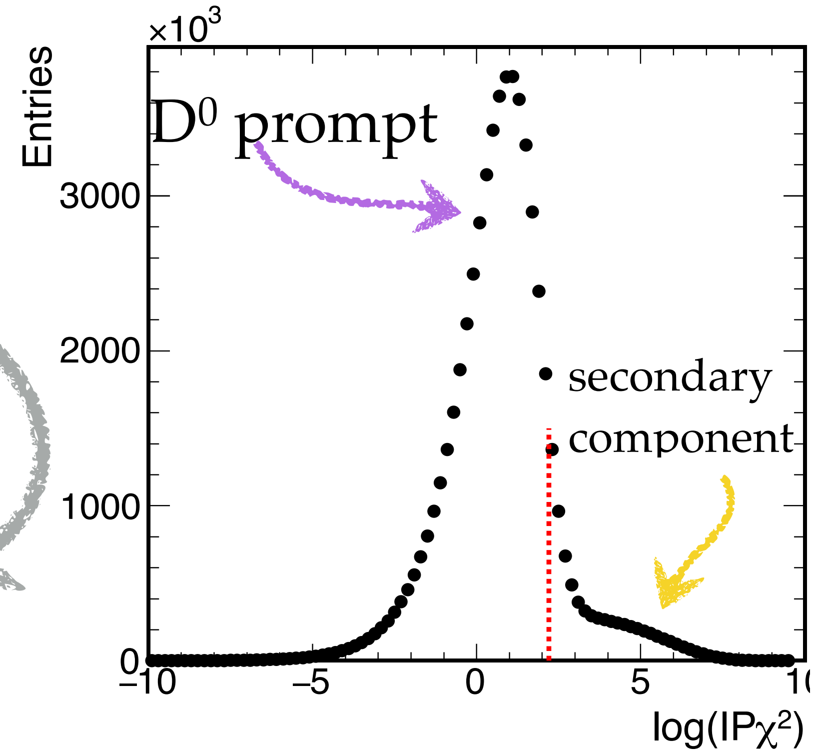
Sample	# events $K\pi$ $[10^6]$
2011 Up	15.9
2011 Down	23.2
2012 Up	46.1
2012 Down	47.8

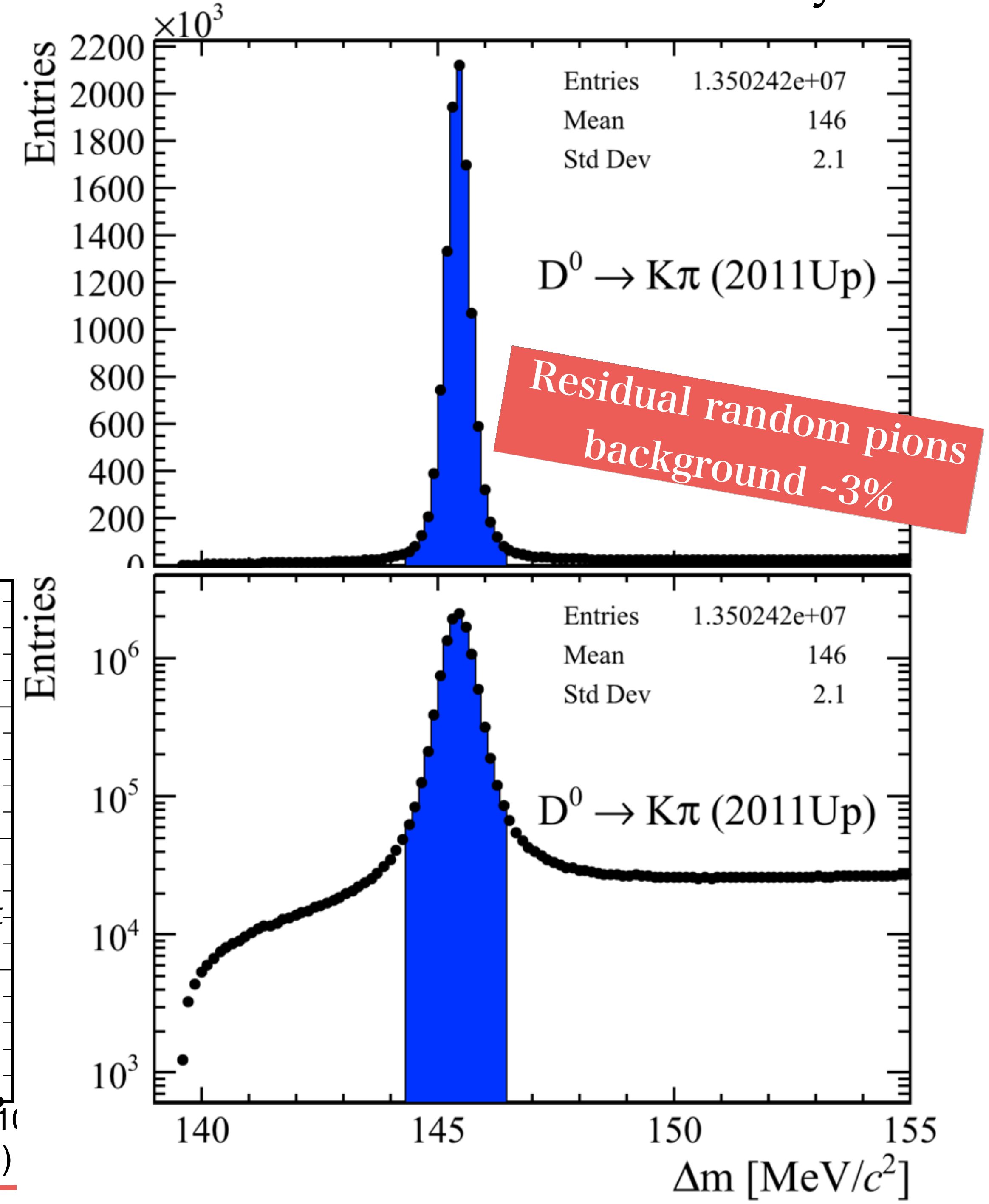
Cross checks on $D^0 \rightarrow K\pi$ (pseudo-A_Γ)

- Time-depend asymmetry in the $D^0 \rightarrow K\pi$ is expected much smaller than that in $D^0 \rightarrow hh$ decays.
- To speed up this first exploratory stage of the analysis we count signal events without performing a likelihood fit in bins of proper decay time:
  - backgrounds reduced tightening requirements on masses and IPχ2.

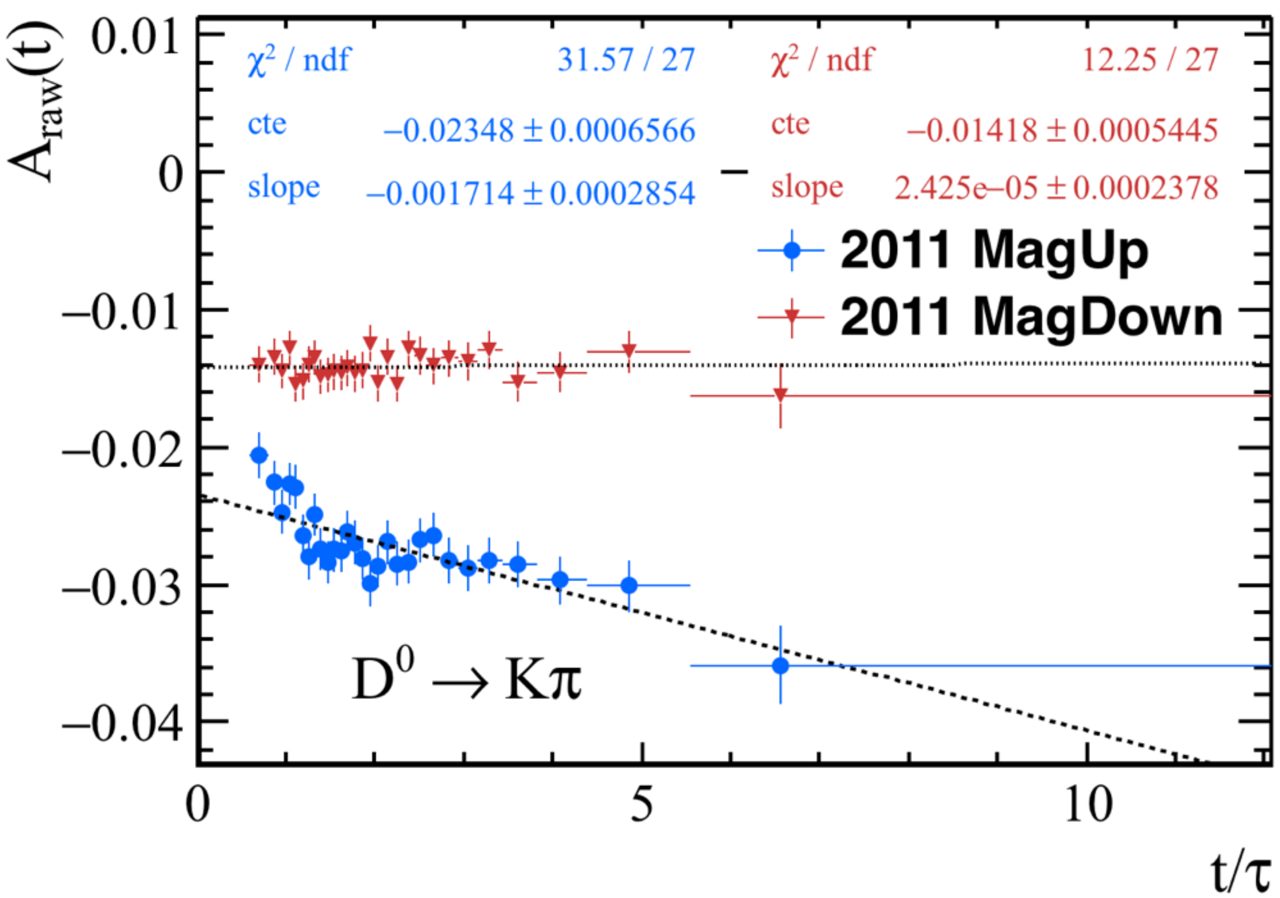
A. Random pion background
B. Secondary background
C. combinatorial background

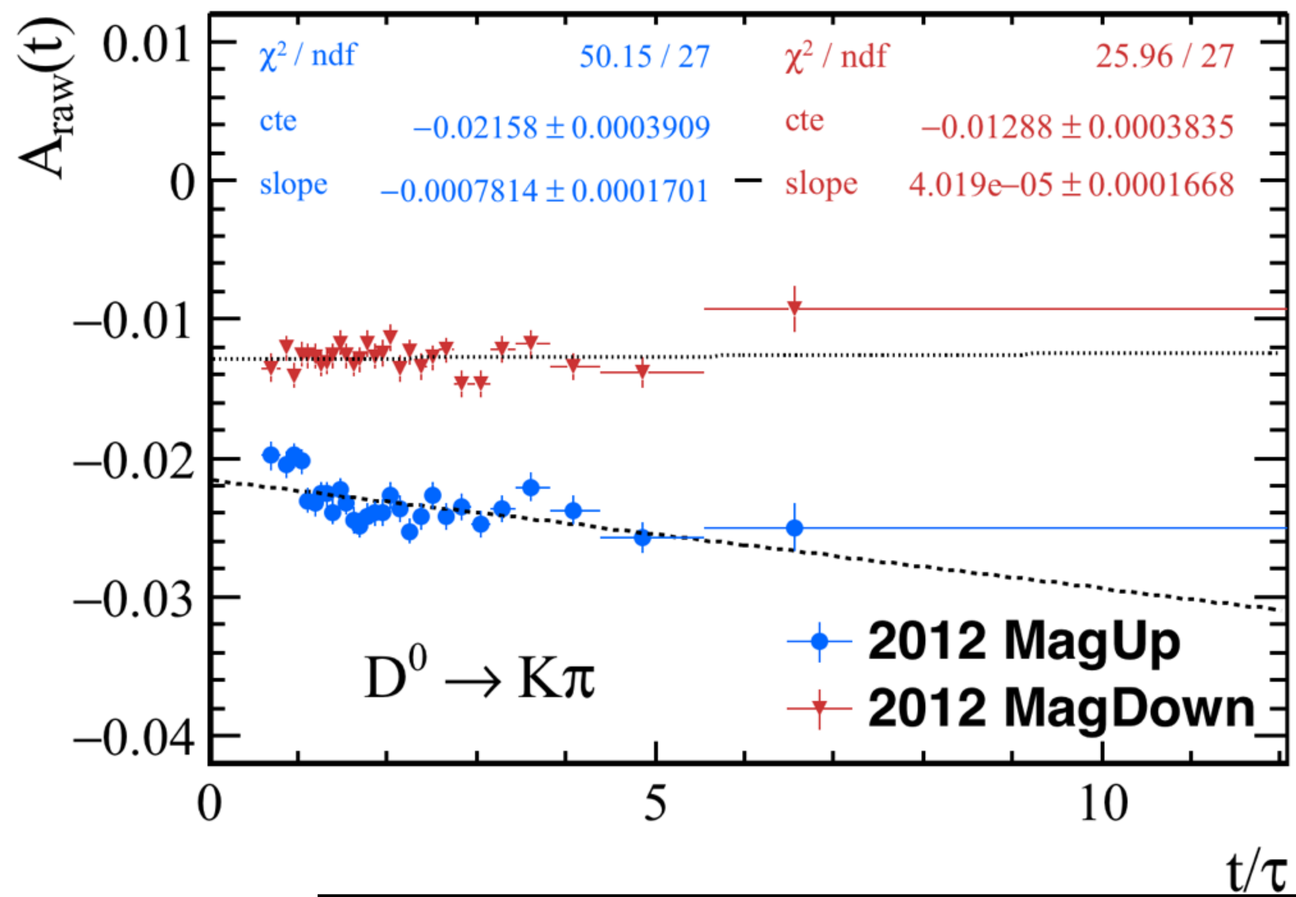
A. abs[deltaM -145.45] < 1 MeV/c^2
B. IPχ2(D^0) < 9
C. abs[m(Kπ) - m_{D^0}] < 3*8 MeV/c^2





pseudo-A_Γ results





- Current experimental sensitivity not sufficient to measure a significant pseudo-A_Γ for the $D^0 \to K\pi$ different from zero. Any observed slope is a clear indication of a dangerous detector induced effects.

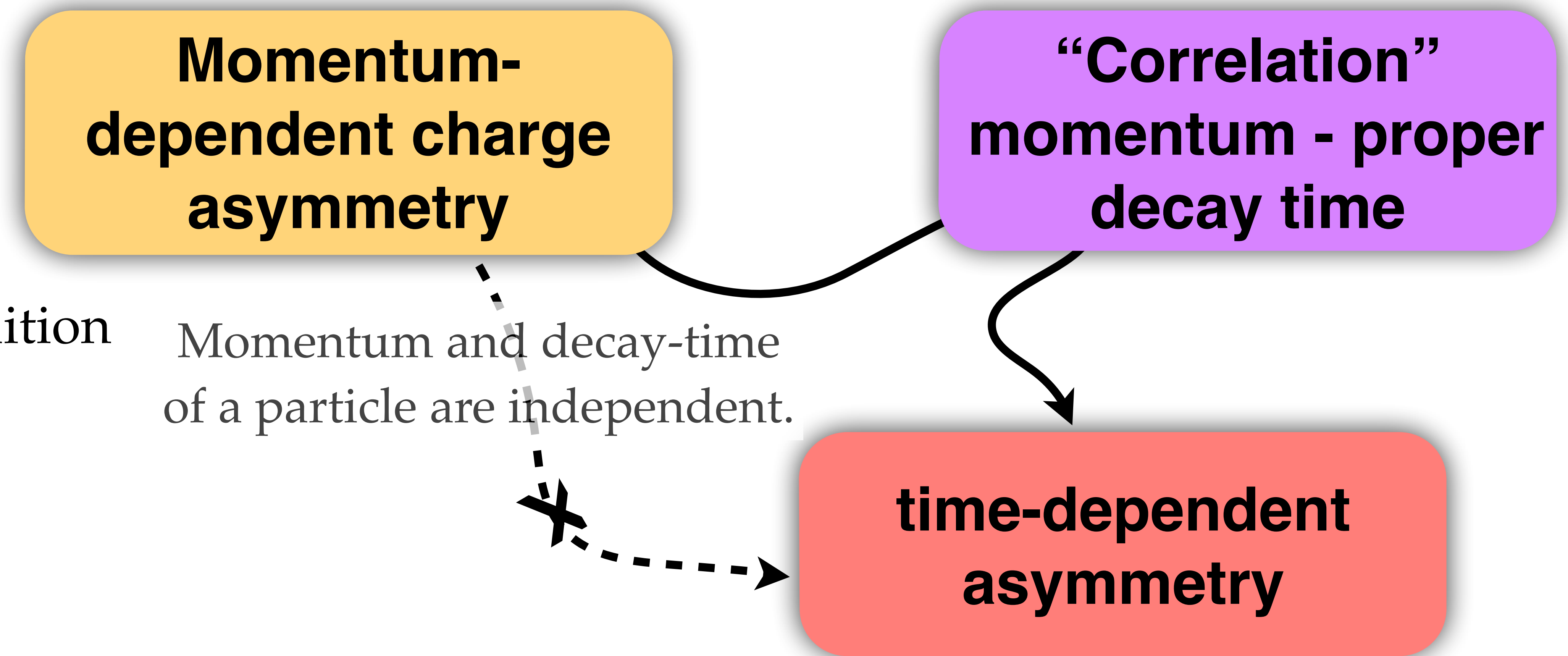
sample	$A_\Gamma[10^{-3}]$	χ^2/ndf
2011 Up	1.71 ± 0.29	32/27
2011 Down	-0.02 ± 0.24	12/27
2012 Up	0.78 ± 0.17	50/27
2012 Down	-0.04 ± 0.17	26/27
average	0.46 ± 0.10	

4.6σ from zero → average

Time-dependent asymmetry vs. momentum-dependent charge asymmetry

- Observed significant slope different from zero;
  - removing regions with large asymmetries reduces the effect.
- Data seem to tell us that charge asymmetry is correlated to the the proper decay time. How is it possible?

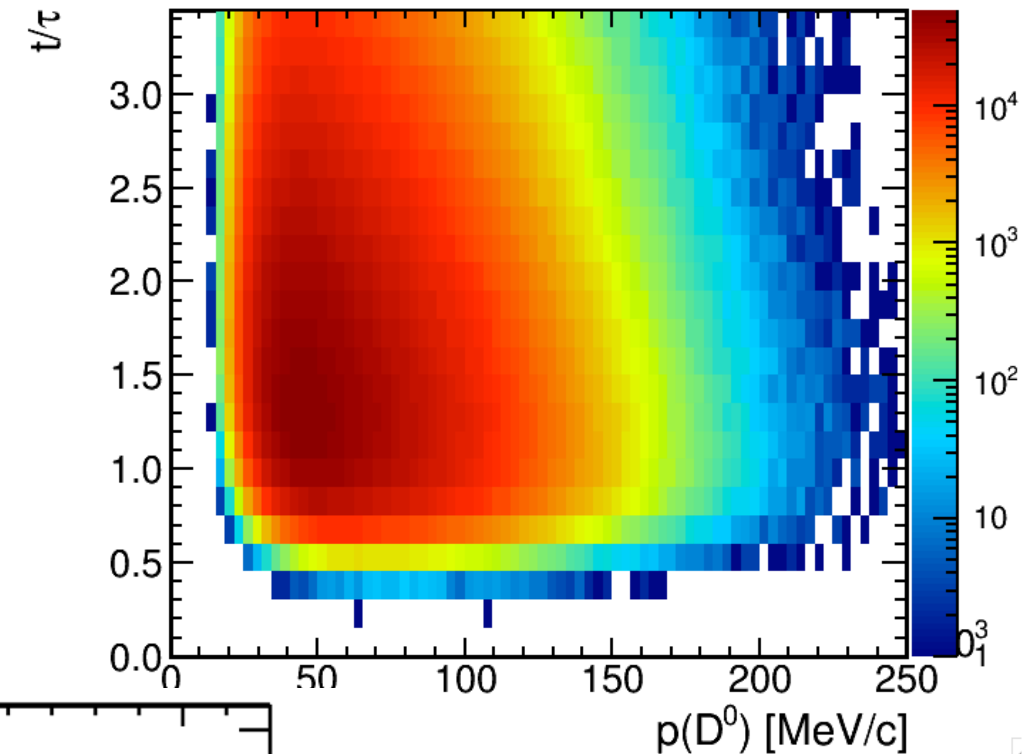
Due to:
- detector
- selection
- run condition
- etc….

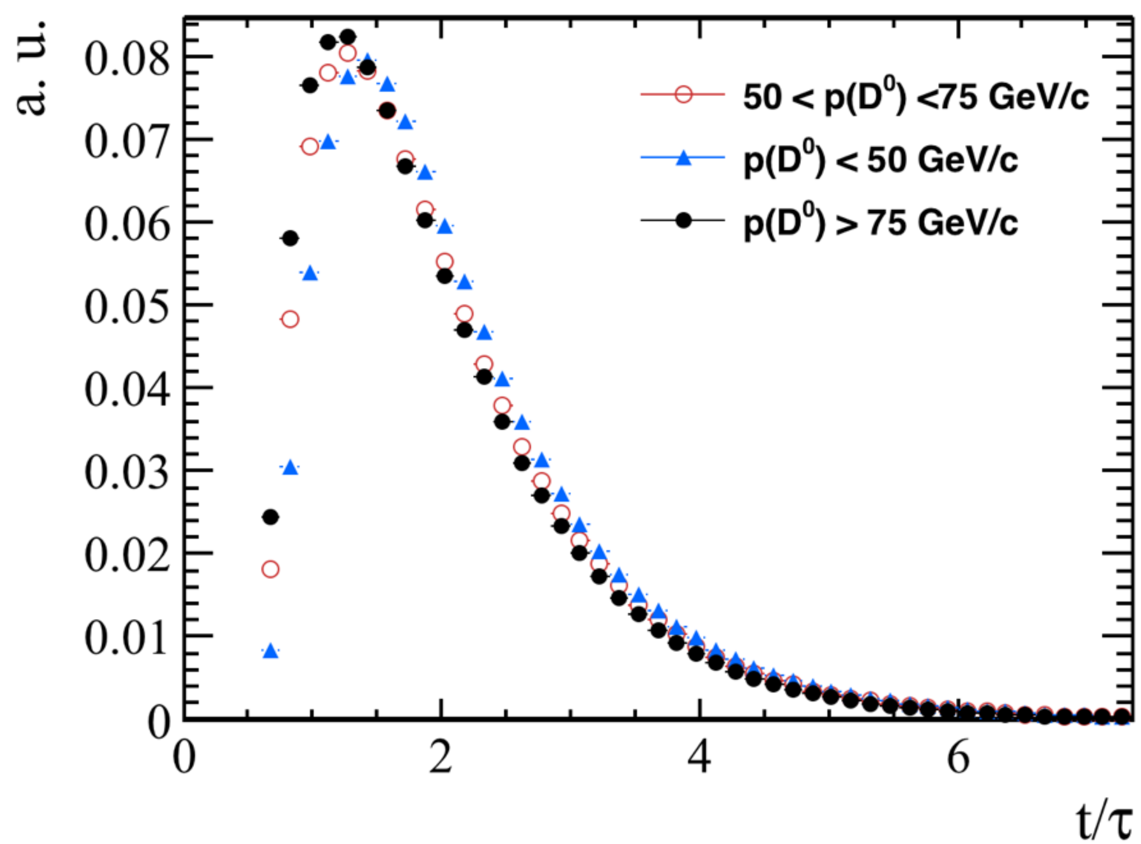


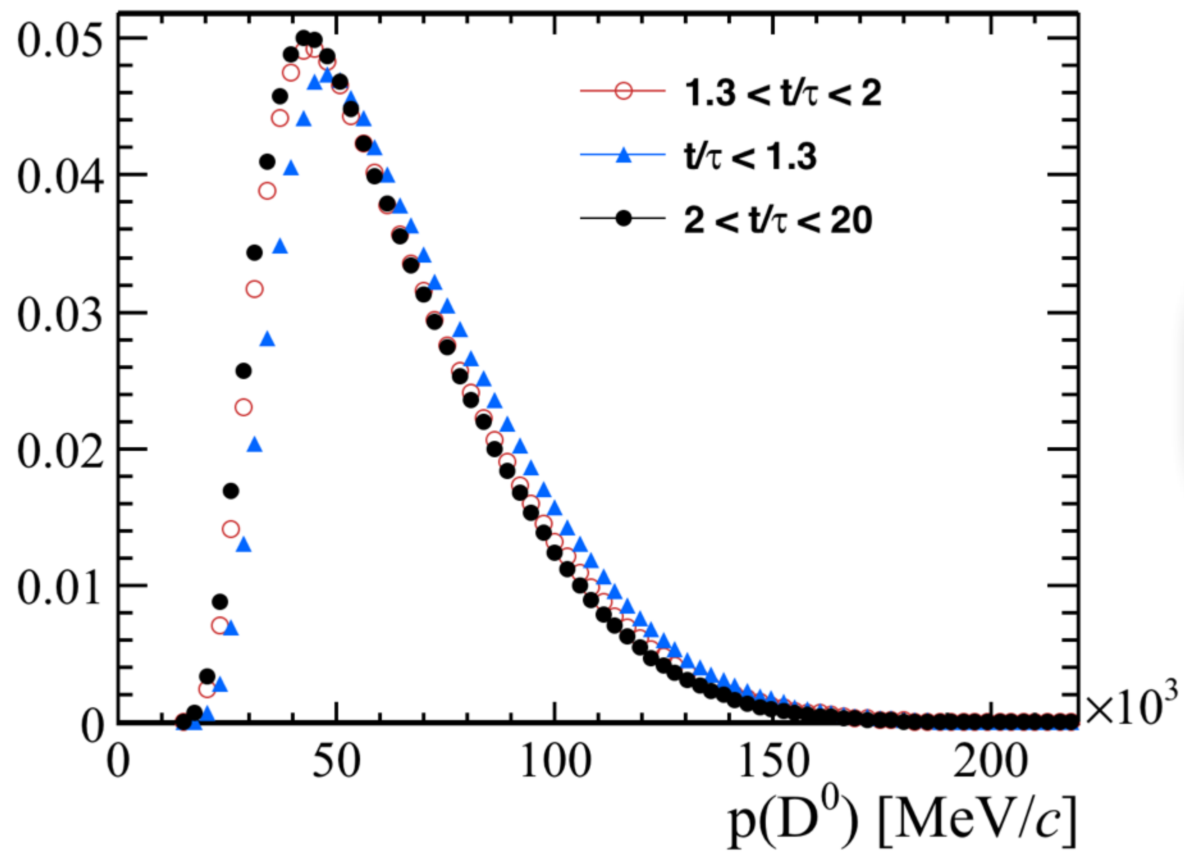
- A time-dependent effect may be generated by a detector charge asymmetry if:
  - momentum and proper decay time are correlated.
  - charge asymmetry is momentum dependent.

First ingredient: $p(D^0)$-$ct(D^0)$ correlation

- "Short-lived"(long) D^0s have a harder(looser) momentum distribution.
- Correlation holds even removing edge effects.





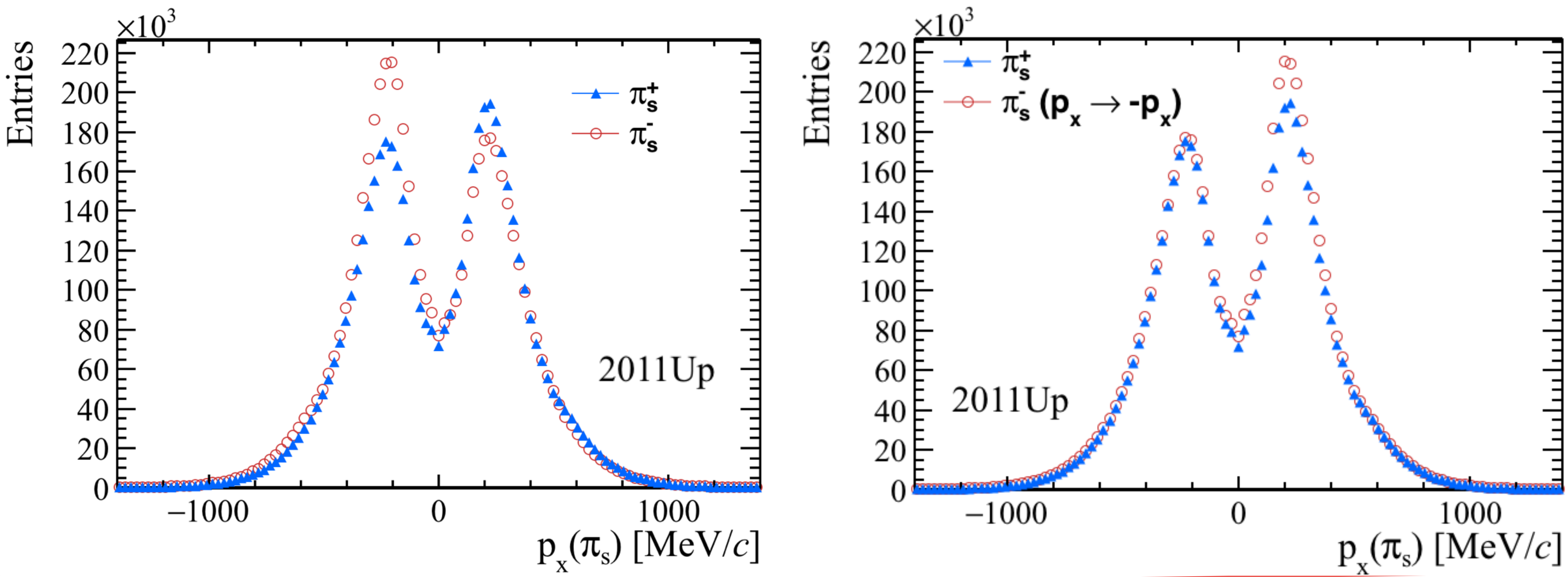


"Correlation" momentum - proper decay time

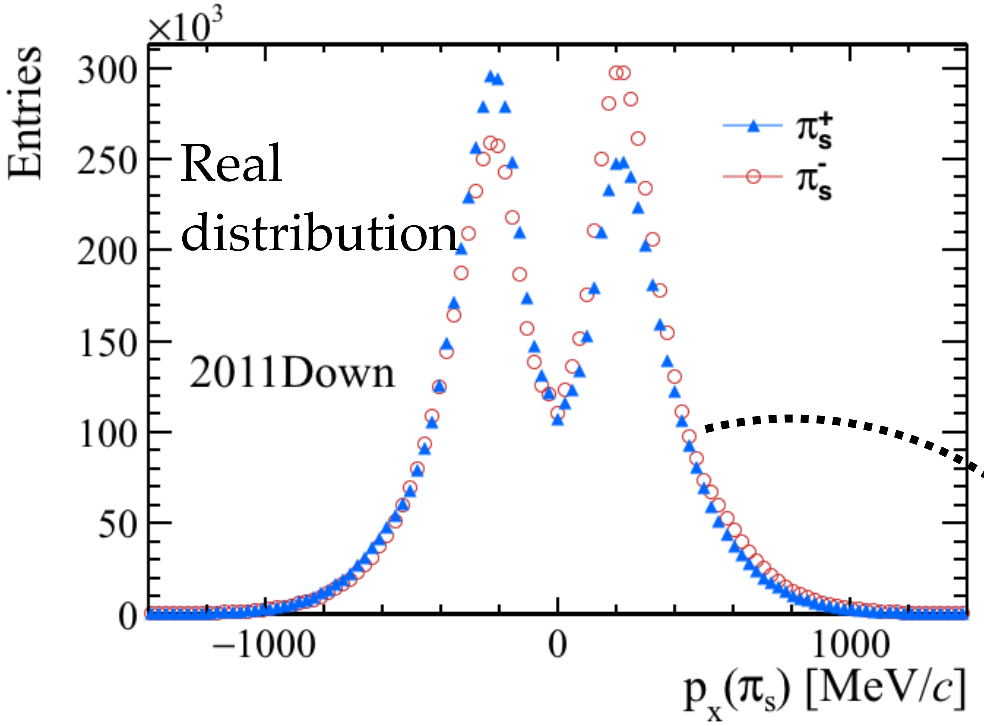
Second ingredient: charge-asymmetries

- Charge asymmetries are present;
- large variations as function of p_x.

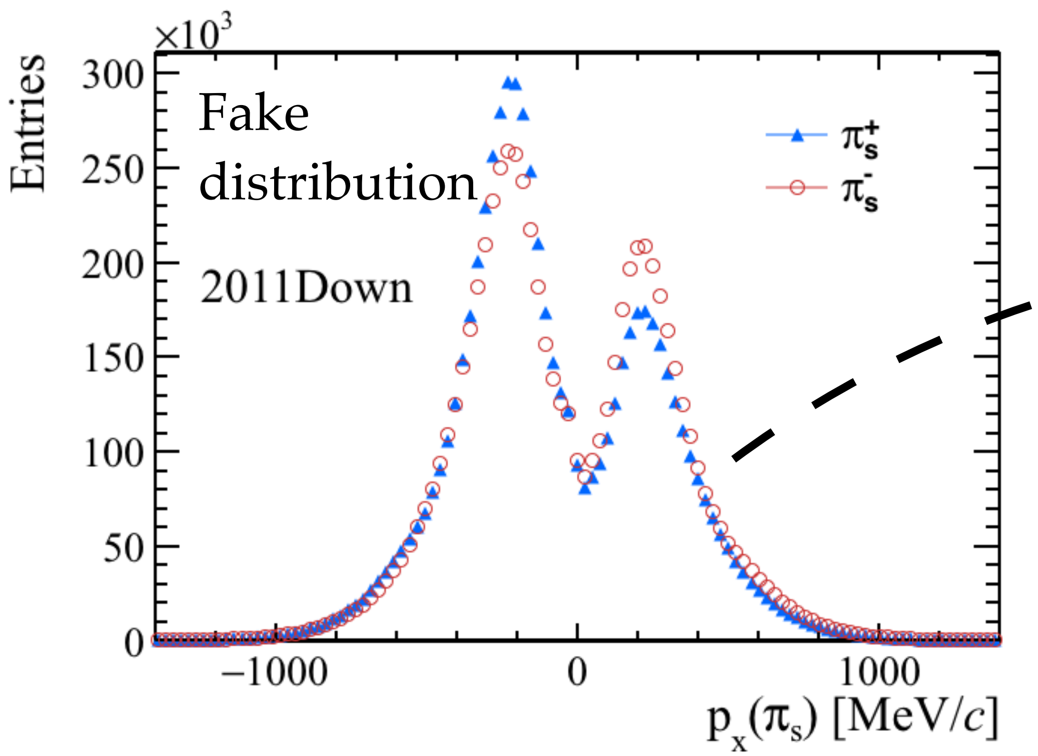
Momentum-dependent charge asymmetry

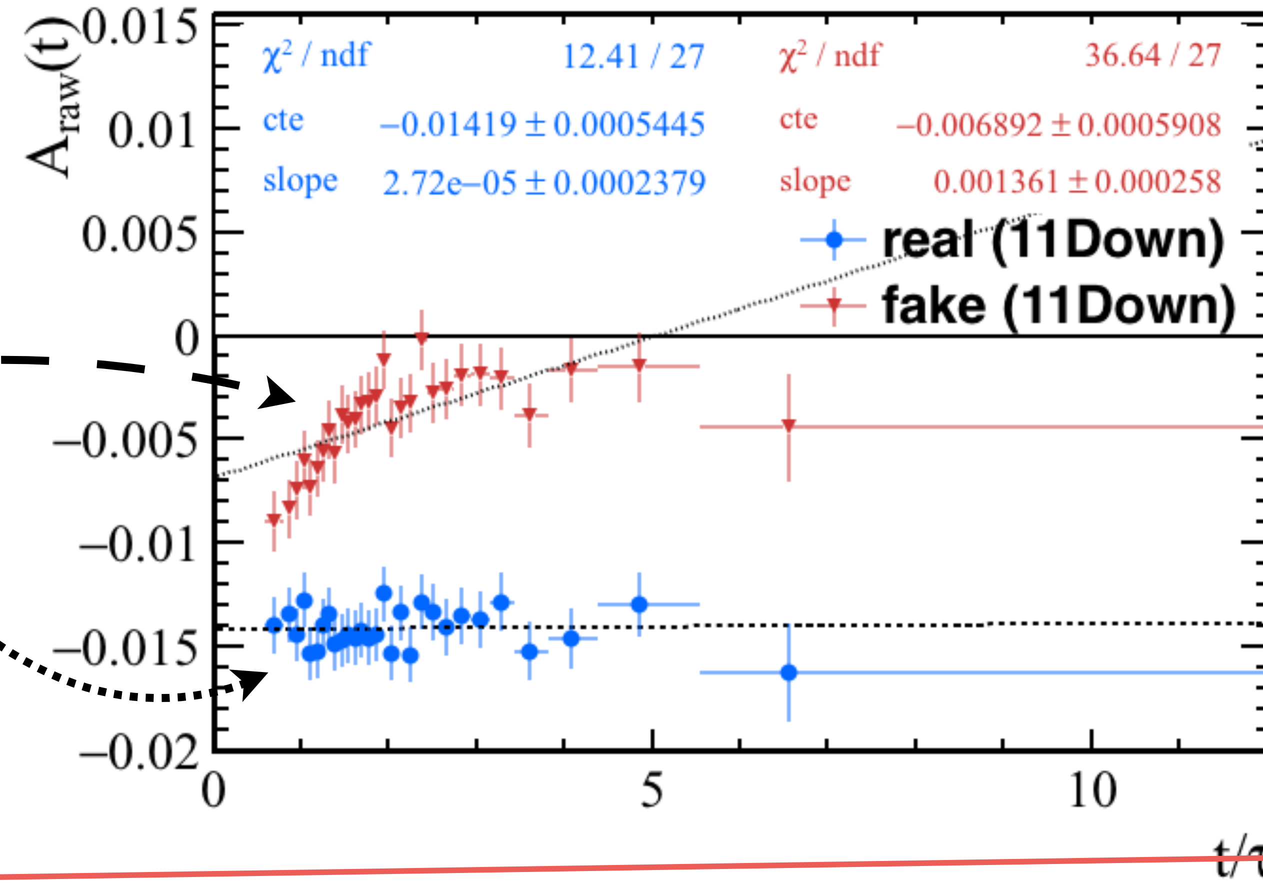


Proving the conjecture



- Conjecture: a momentum-dependent charge asymmetry generates a time-dependent charge asymmetry through the detector-induced p-ct correlation:
  - By reweighting the p_x-distribution of positively and negatively charged soft pions it is possible to create an artificial slope in the 2011 Down sample.





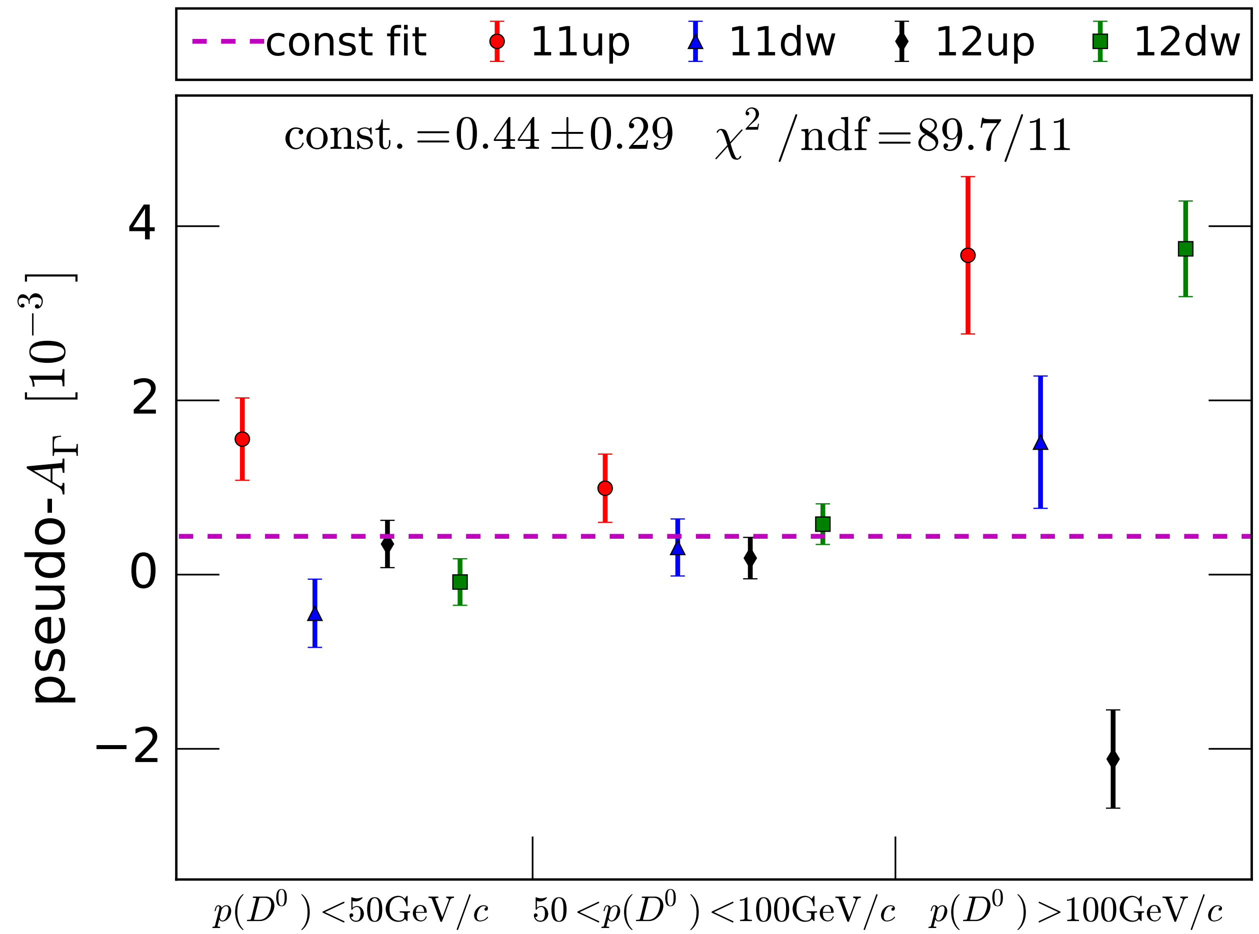
pseudo-A_Γ as function of $p(D^0)$

- The kinematics of the soft pions (or D0 meson) strongly affects pseudo-A_Γ extraction. In particular momentum seems to play a key role.

pseudo-A_Γ results as function of $p(D^0)$

	$A_\Gamma[10^{-3}]$		
sample/[GeV/c]	$p(D^0) < 50$	$50 < p(D^0) < 100$	$p(D^0) > 100$
2011 Up	1.56 ± 0.47	0.99 ± 0.39	3.67 ± 0.91
2011 Down	-0.44 ± 0.39	0.31 ± 0.33	1.52 ± 0.76
2012 Up	0.35 ± 0.27	0.19 ± 0.24	-2.12 ± 0.56
2012 Down	-0.08 ± 0.27	0.58 ± 0.23	3.74 ± 0.55

$$\text{const.} = 0.44 \pm 0.29$$
$$\chi^2/\text{ndf} = 90/11$$



- All values should be compatible with each other, and should be also compatible with zero.

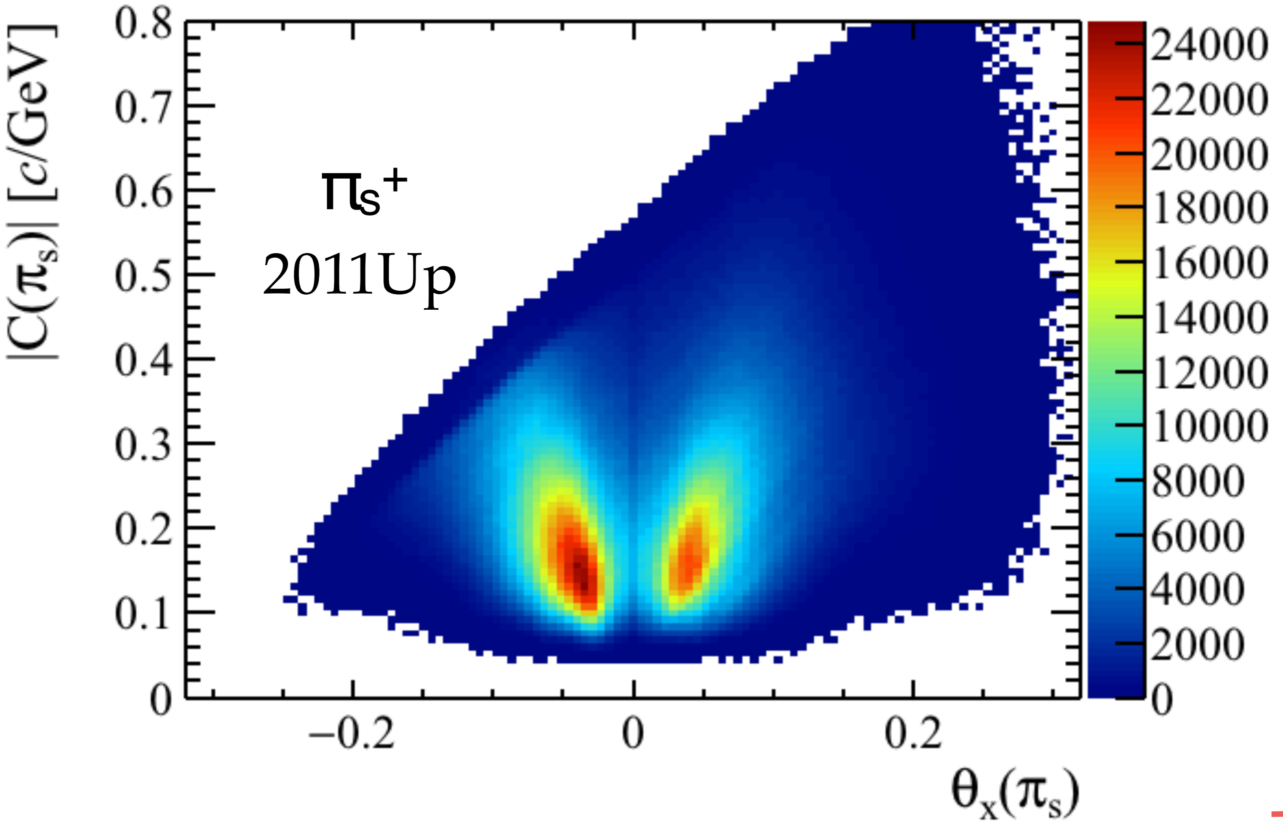
A simple χ^2 fit indicates that this is not the case.

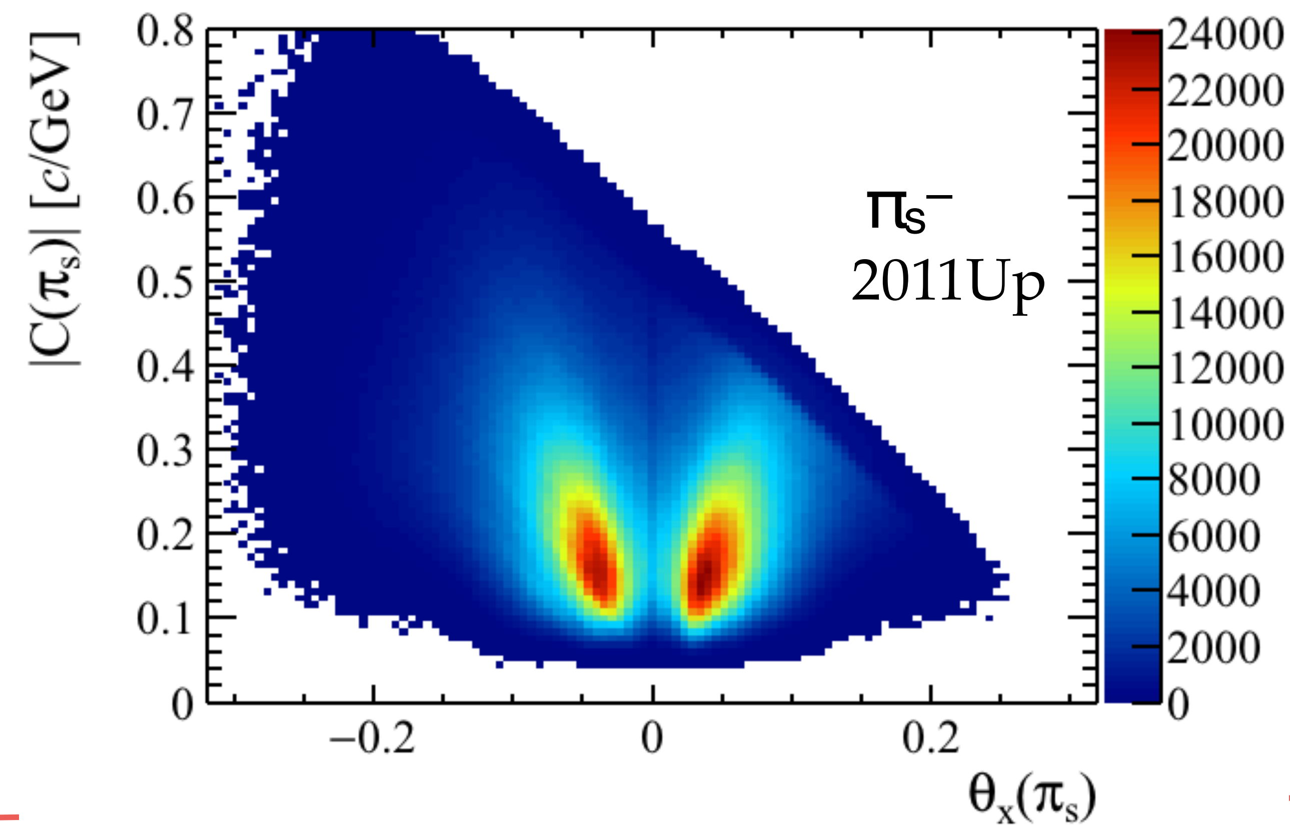
- Large variation observed in same entries of the table:
  - 2012Up: bin1 vs. bin3→4.4σ; 2012Down: bin1 vs. bin3→~7σ;

Symmetrisation

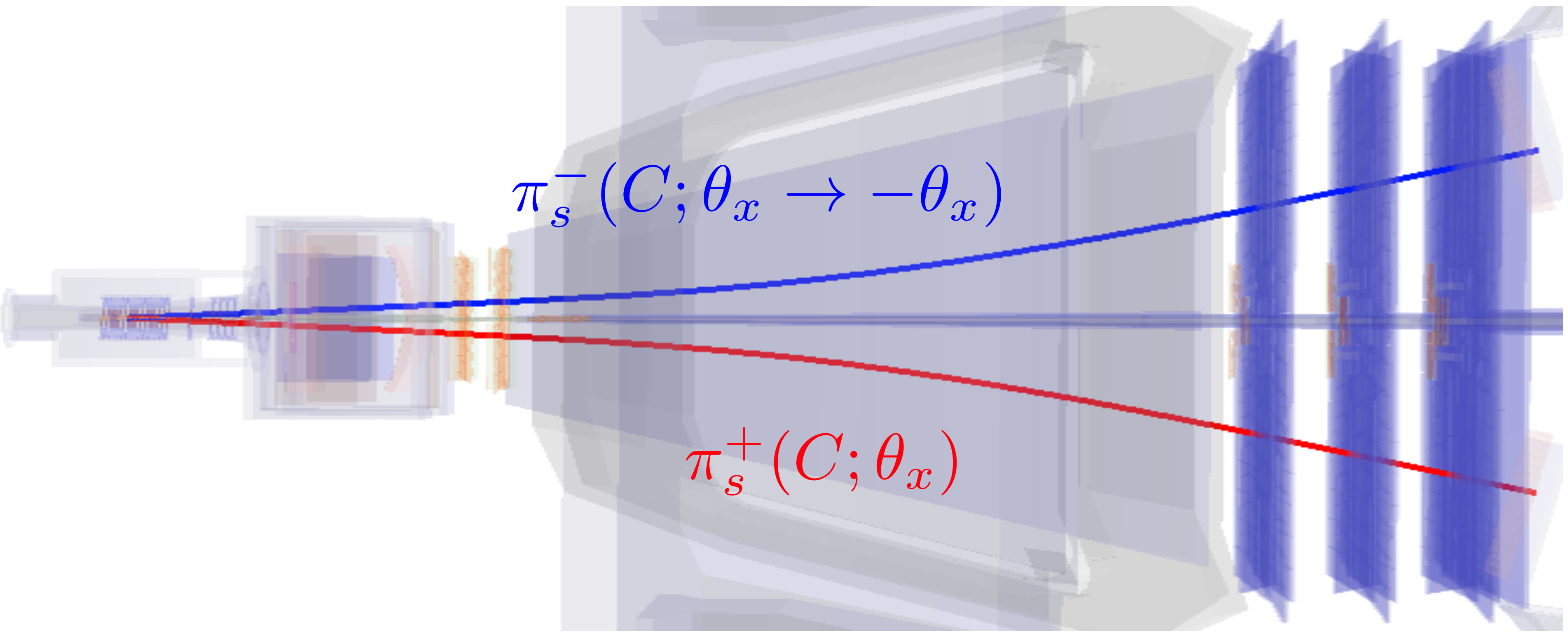
- kinematics of positively charged pions is re-weighted to the kinematics of negatively charged pions:
  - p_x is flipped to $-p_x$.
- symmetrisation performed in the 2D space: C and θ_x

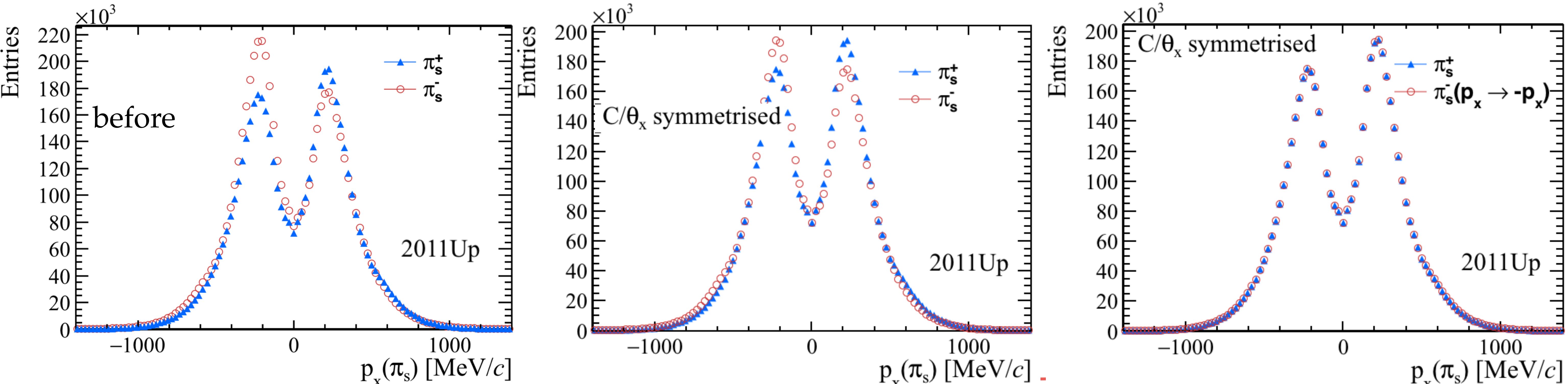
$$C = \frac{|qB|}{\sqrt{p_x^2 + p_z^2}} \qquad \theta_x = \arctan\left(\frac{p_x}{p_z}\right)$$



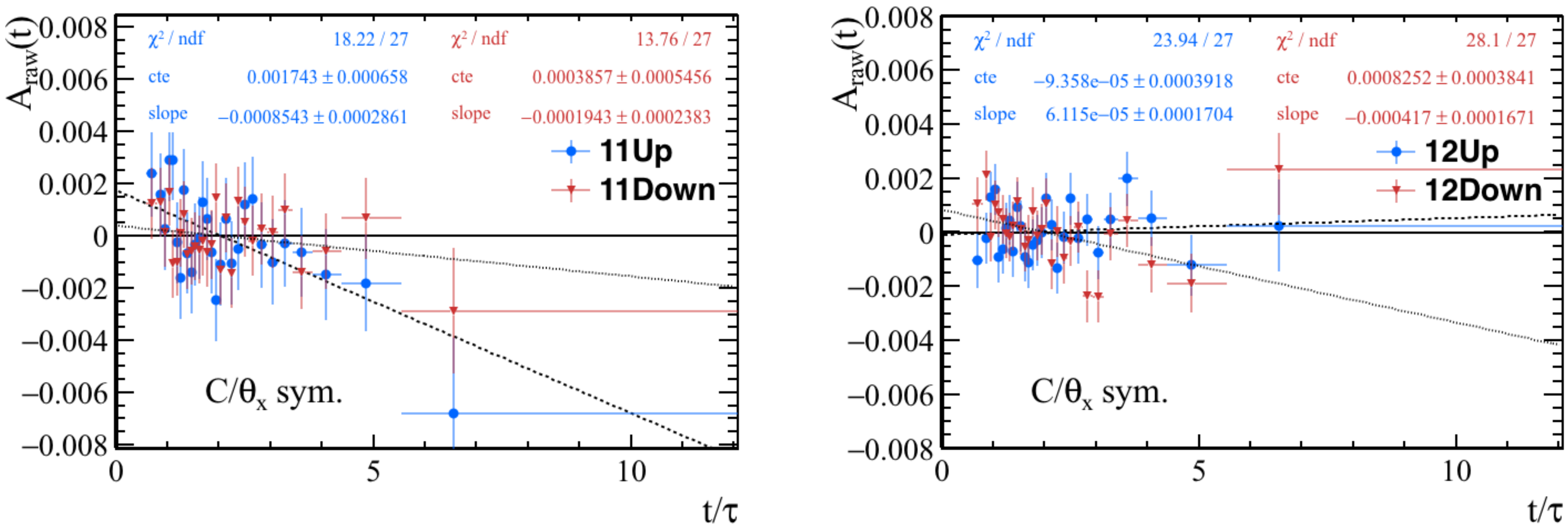


Symmetrisation II





pseudo-A_Γ results after symmetrisation



- The discrepancy from zero reduces (average from 4.6σ to 2.7σ);
- $A_{raw}(t)$ fits well to a straight line (χ^2 is better).
- Still discrepancies remain, in particular on 2011 MagUp sample (2.9σ)

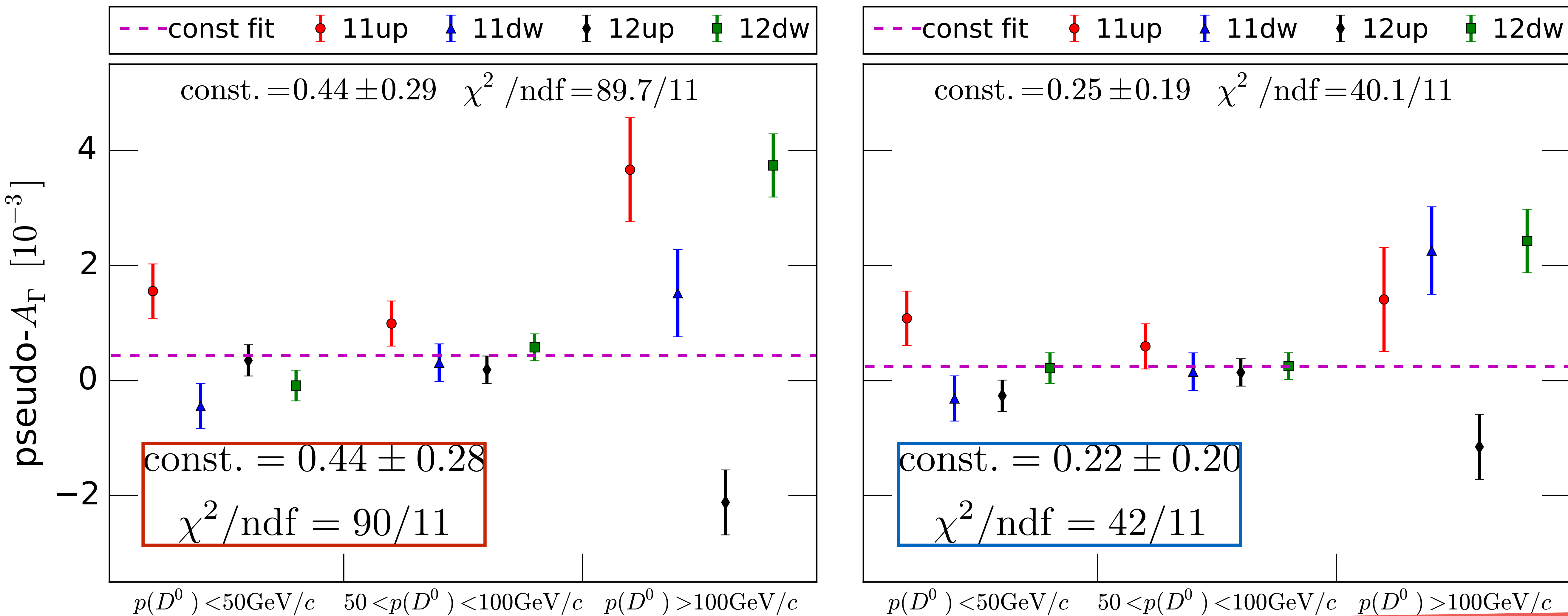
	base sel. (ndf=27)		base sel., C/θ sym.	
sample	$A_\Gamma[10^{-3}]$	χ^2	$A_\Gamma[10^{-3}]$	χ^2
2011 Up	1.71 ± 0.29	32	0.85 ± 0.29	18
2011 Down	-0.02 ± 0.24	12	0.19 ± 0.24	14
2012 Up	0.78 ± 0.17	50	-0.06 ± 0.17	23
2012 Down	-0.04 ± 0.17	26	0.42 ± 0.17	28
average	0.46 ± 0.10		0.26 ± 0.10	

Robustness of the method

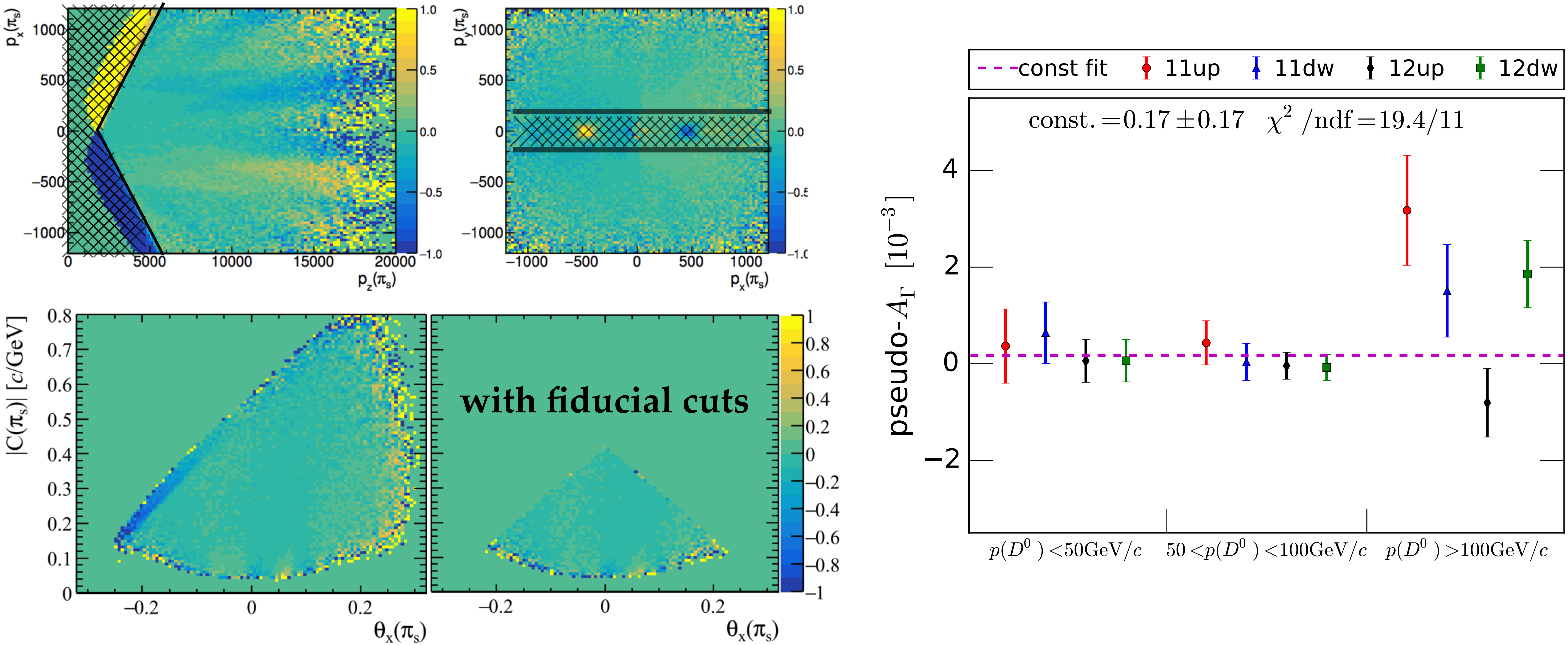
- Pseudo-A_Γ calculated as function of the D^0 momentum, to check if some residual momentum dependences is still there.

pseudo-A_Γ results with base selection as function of D^0 momentum

pseudo-A_Γ results with base sel. after the symmetrisation as function of D^0 momentum



Robustness of the method II (fiducial cuts)



- χ^2/ndf of the fit to a constant moves from 90/11 (base selection) to 19/11 (base selection + fiducial cuts + symmetrisation), corresponding to an improvement of 71/11 units.

Conclusion

- A significant time-dependent asymmetry observed when a loose selection is required (4.6σ from zero over all data samples).
- pseudo-A_Γ depends on the momentum requirements.
- A "plausible source or part of source" of this may be the combination of two effects:
  - a momentum-dependent charge asymmetry of the soft pion
  - an artificial detector-induced correlation between the momentum and the proper decay time of the D^0 meson.
- A combination of fiducial requirements plus "symmetrisation" of kinematic distributions of soft pions seems to cancel out the artificial time dependence of the asymmetry.
  - Over all data sample effect moves from 4.6σ to 1σ (where **$1\sigma = 1.5\times10^{-4}$**)
  - pseudo-A_Γ compatible to be a constant in different periods and different momentum bins ($\chi2$/ndf moves from 90/11 → 19/11)
- **$A_\Gamma(K\pi)$ is now compatible with zero and flat in momentum bins and different periods.**

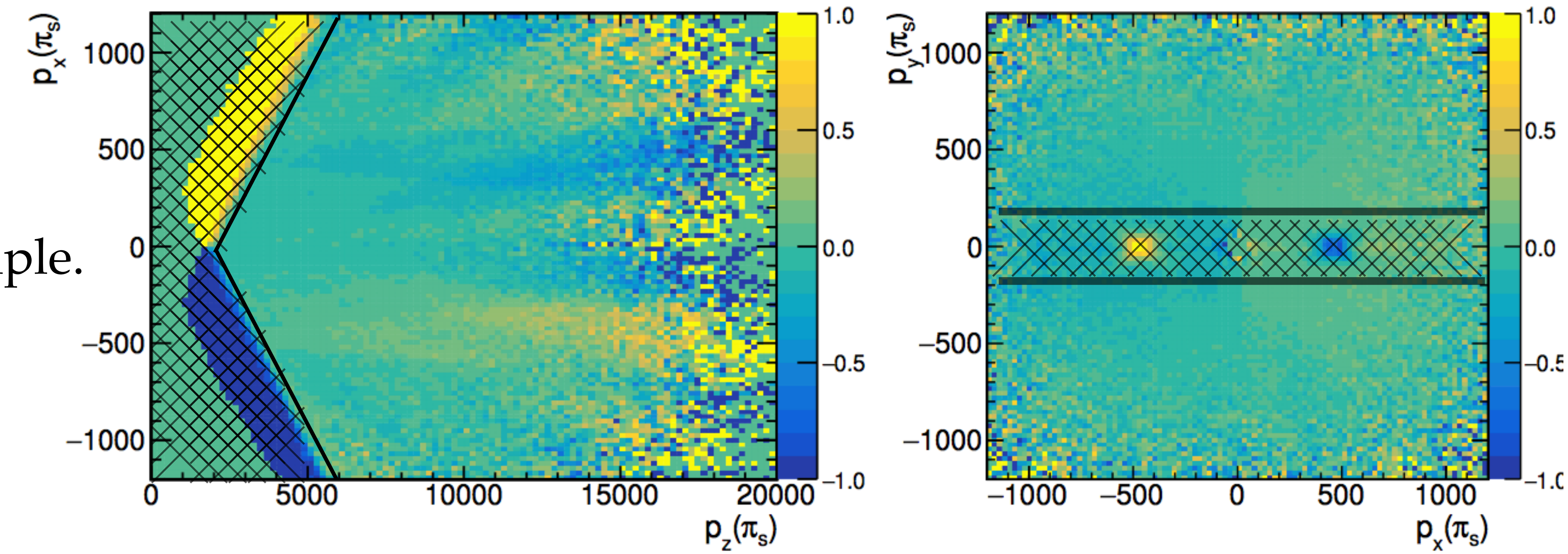
Backup Slides

Removal of soft pions acceptance-induced asymmetries

- It is well known there are kinematic regions of the soft pions with charge asymmetries up to 100% level.*
- Large asymmetries induced by acceptance factors can be removed by excluding kinematic region of the space.
  - $|p_x(\pi_s)| \leq 0.317(p_z(\pi_s) - 2400)$;
  - $|p_y(\pi_s)/p_z(\pi_s)| \leq 0.02$.

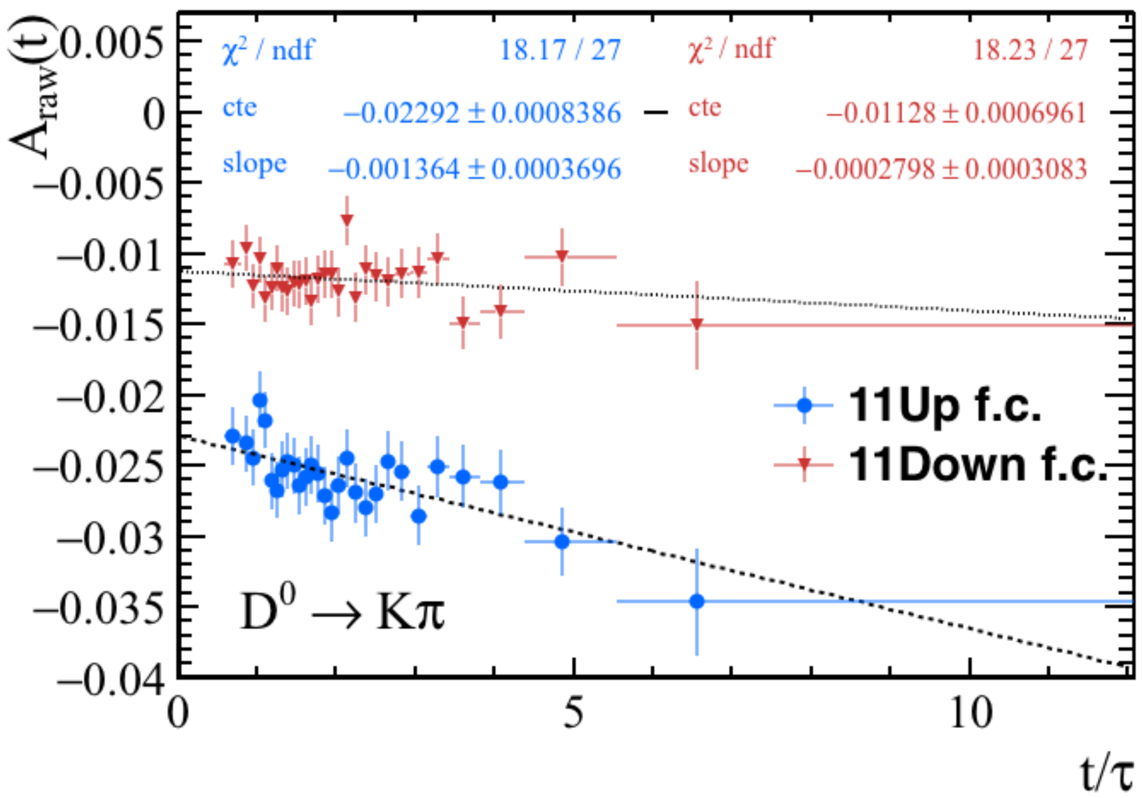
~ 60% of the events retained

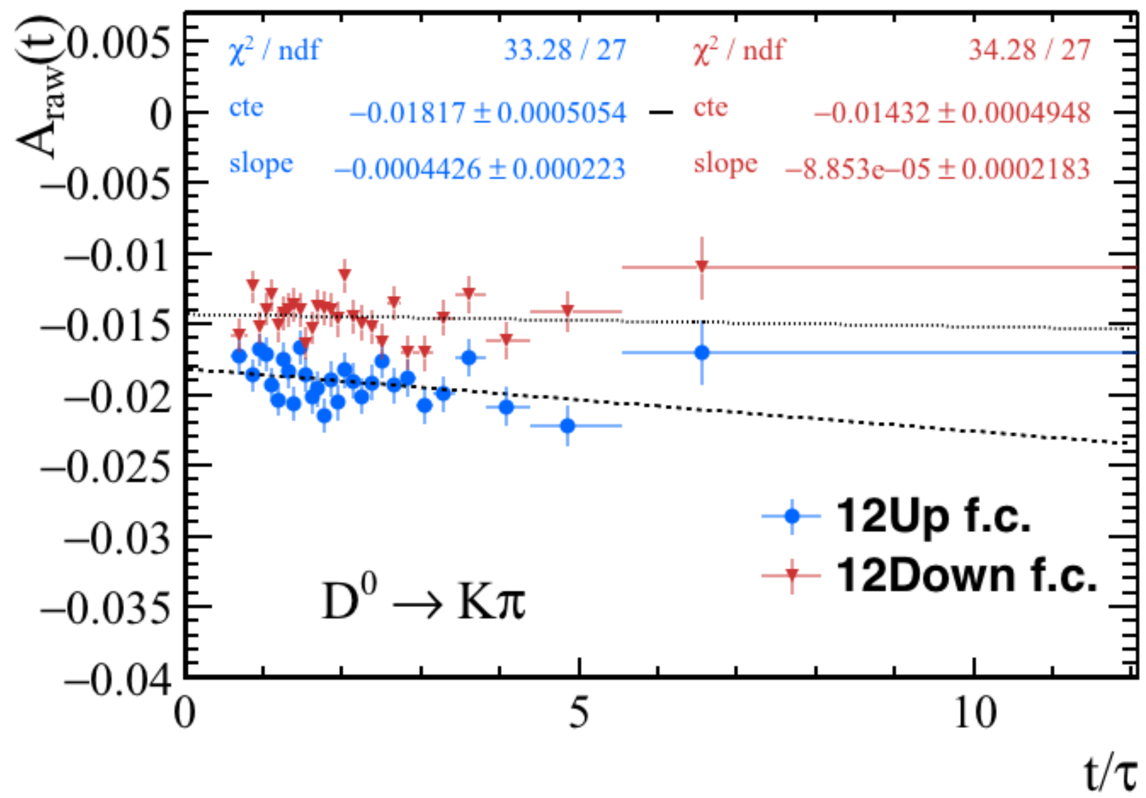
crosshatched regions are removed from the sample.



* LHCb-ANA-2011-059 & LHCb-ANA-2012-011

pseudo-A_Γ results in soft pion fiducial regions





- Discrepancy from zero of the average reduce to 3.1σ (before 4.6σ), with also:
  - 2011MagUp 3.7σ (before 5.9σ)
  - 2012MagUp 2σ (before 4.5σ)
  - MagDown samples remain compatible with zero (@1σ).

	base sel. (ndf = 27)		base sel.+f.c (ndf = 27)	
sample	$A_\Gamma[10^{-3}]$	χ^2	$A_\Gamma[10^{-3}]$	χ^2
2011 Up	1.71 ± 0.29	32	1.36 ± 0.37	18
2011 Down	-0.02 ± 0.24	12	0.28 ± 0.31	18
2012 Up	0.78 ± 0.17	50	0.44 ± 0.22	33
2012 Down	-0.04 ± 0.17	26	0.09 ± 0.22	34
average	0.46 ± 0.10		0.40 ± 0.13	

Comparison with Oxford analysis (binned A_Γ 1/fb)

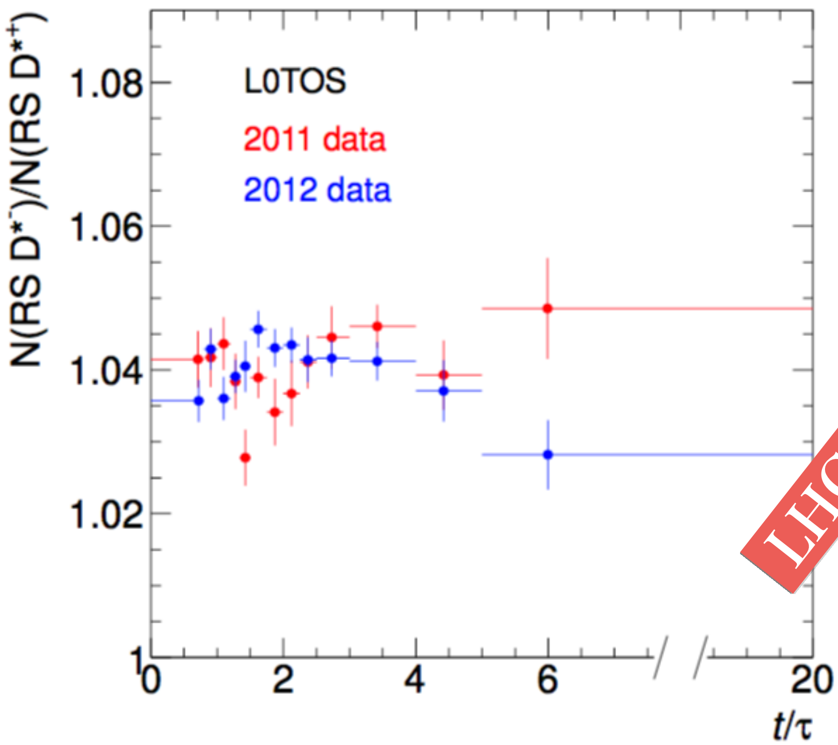
LHCb-ANA-2012-039

sample	A_Γ $[10^{-3}]$	A_Γ $[10^{-3}]$ (oxford)	Δ(my-oxf)/σ
2011 *MagUp* before TS	1.42 ± 0.45	0.56 ± 0.49	1.7
2011 *MagUp* after TS	1.86 ± 0.37	1.11 ± 0.39	1.9
2011 *MagDown* before TS	0.39 ± 0.40	1.04 ± 0.48	−1.3
2011 *MagDown* after TS	-0.24 ± 0.30	0.49 ± 0.31	−2.3
average	0.68 ± 0.18	0.76 ± 0.19	−0.4
total	0.72 ± 0.18	-0.08 ± 0.19	4.2

Average: weighted average.

Total: pseudo-A_Γ performed with the all samples in one shot.

Check of time-dependent asymmetries with selection from "D0-Mixing analysis"



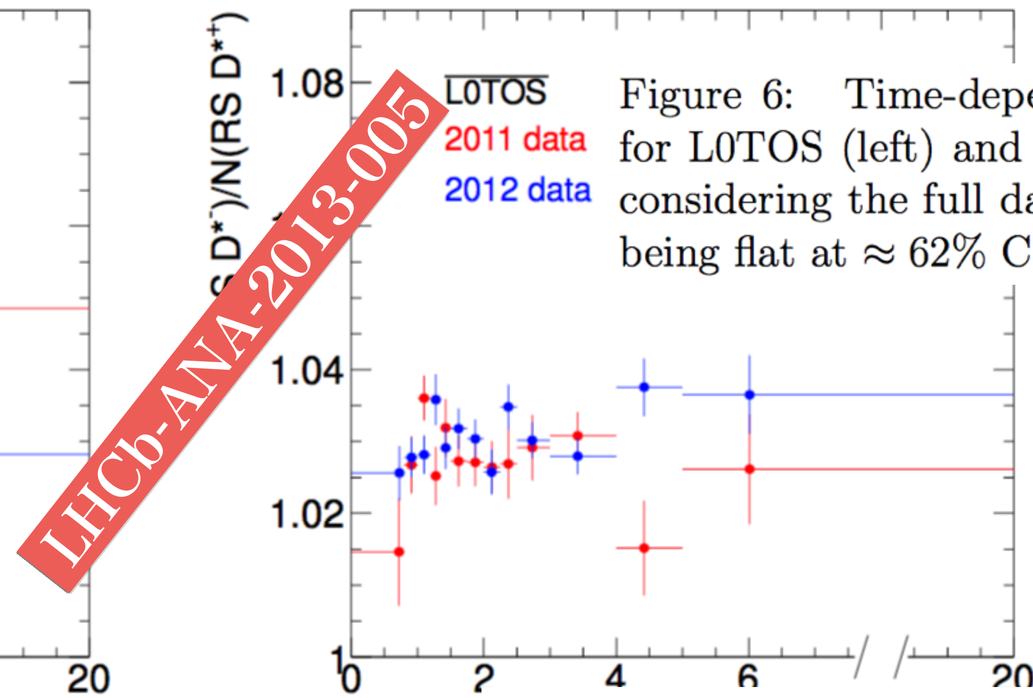
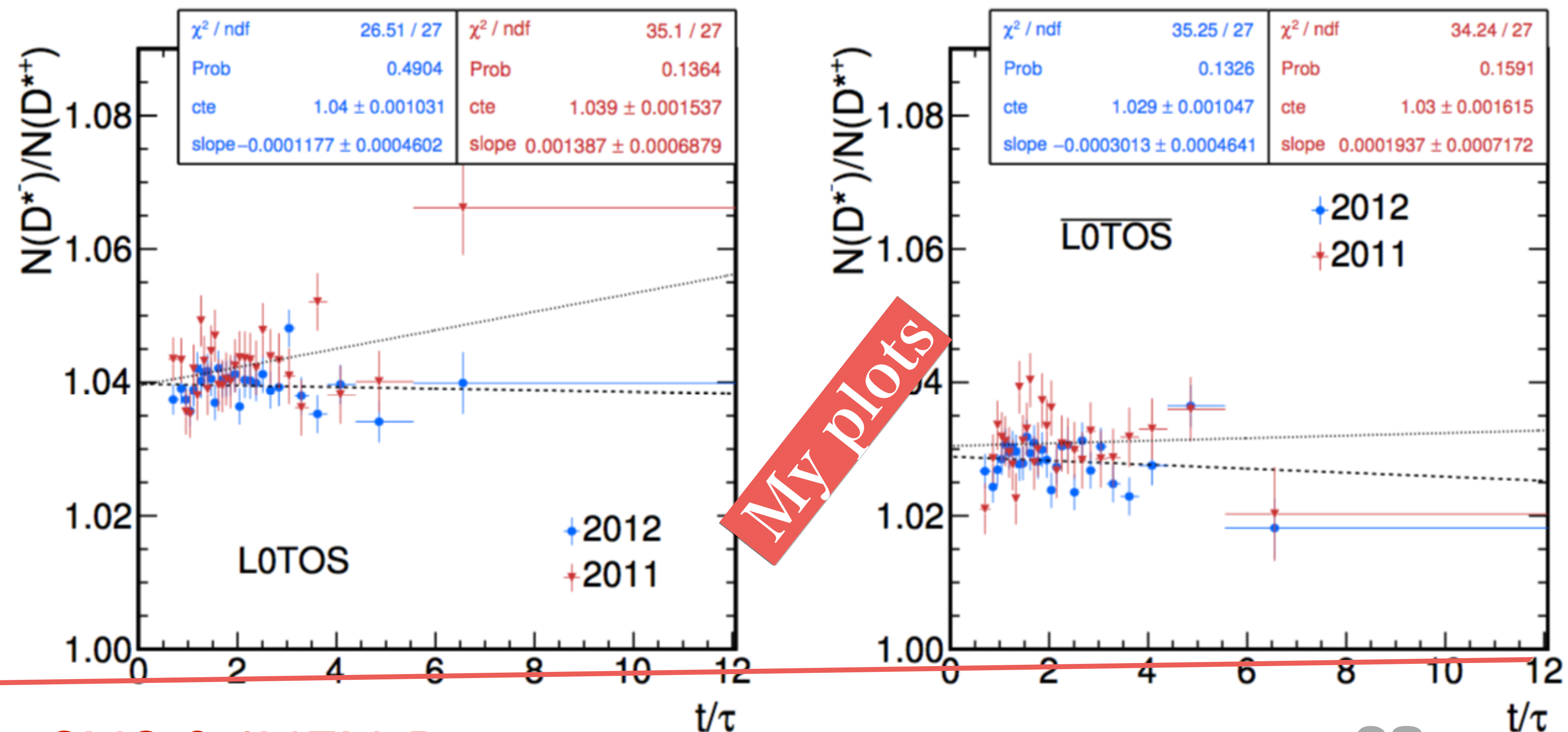


Figure 6: Time-dependent yield ratio between D^{*-} and D^{*+} RS decays, separately for L0TOS (left) and $\overline{\text{L0TOS}}$ (right), and for 2011 (red) and 2012 (blue) data. When considering the full dataset, the distribution of the ratio versus time is consistent with being flat at ≈ 62% C.L. with RMS about the average of 0.15%.

results for ratio slopes

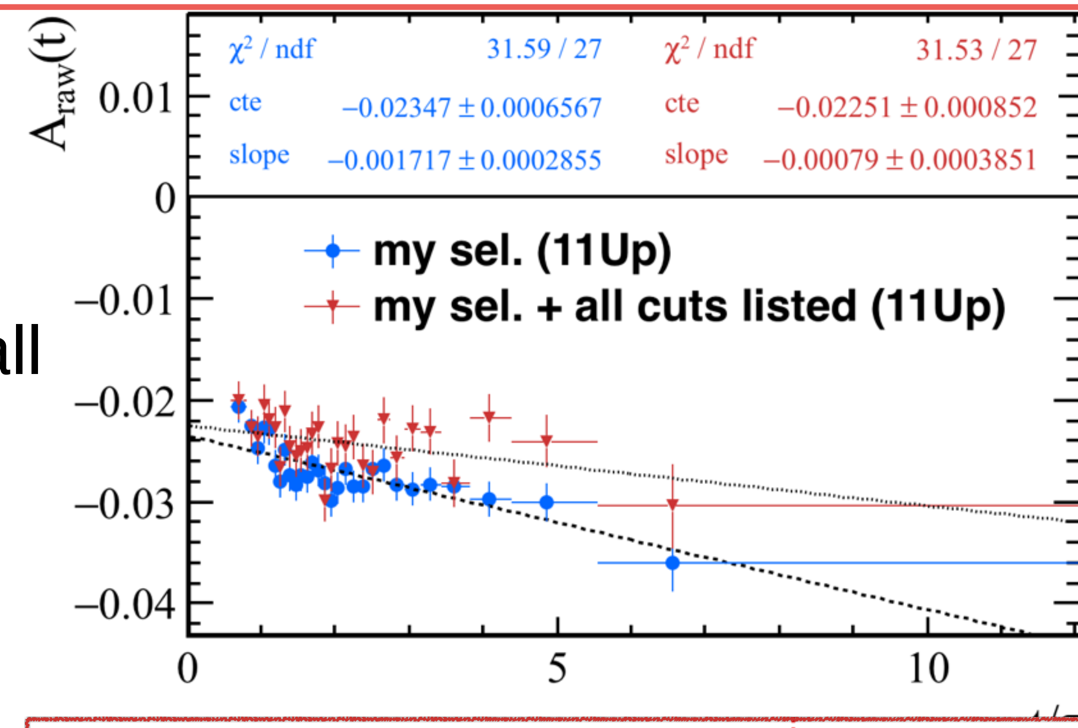
sample	mixing cuts TOS	mixing cuts $\overline{\text{TOS}}$
	slope $[10^{-3}]$	
2011	1.38 ± 0.69	0.19 ± 0.72
2012	-0.12 ± 0.46	-0.30 ± 0.46
average	0.34 ± 0.38	-0.15 ± 0.39

- ✦ All numbers are compatible with zero within statistical uncertainty.



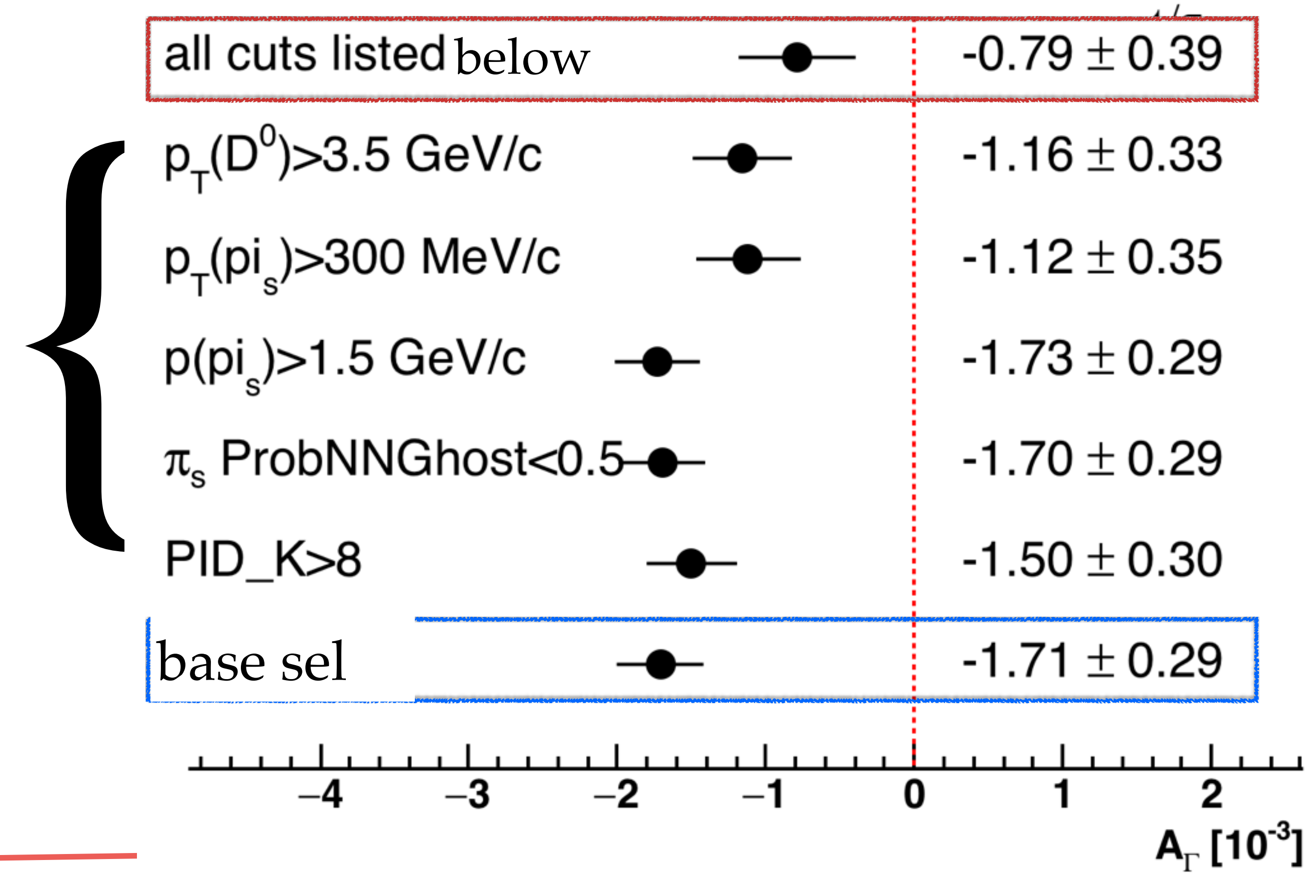
pseudo-A_Γ results with mixing analysis selection

- We study the effects of the cuts of mixing analysis selection one by one.
- Discrepancy on 2011Up sample becomes ~ 2.1σ with all the cuts listed, from a initial value of ~ 6.1σ.



sample	$A_\Gamma [10^{-3}]$ mixing sel.
2011 Up	0.77 ± 0.37
2011 Down	0.06 ± 0.31
2012 Up	0.14 ± 0.23
2012 Down	-0.37 ± 0.22
average	0.02 ± 0.13

base sel. +



Symmetrise sample with mixing selection

$\text{const.} = 0.01 \pm 0.16$

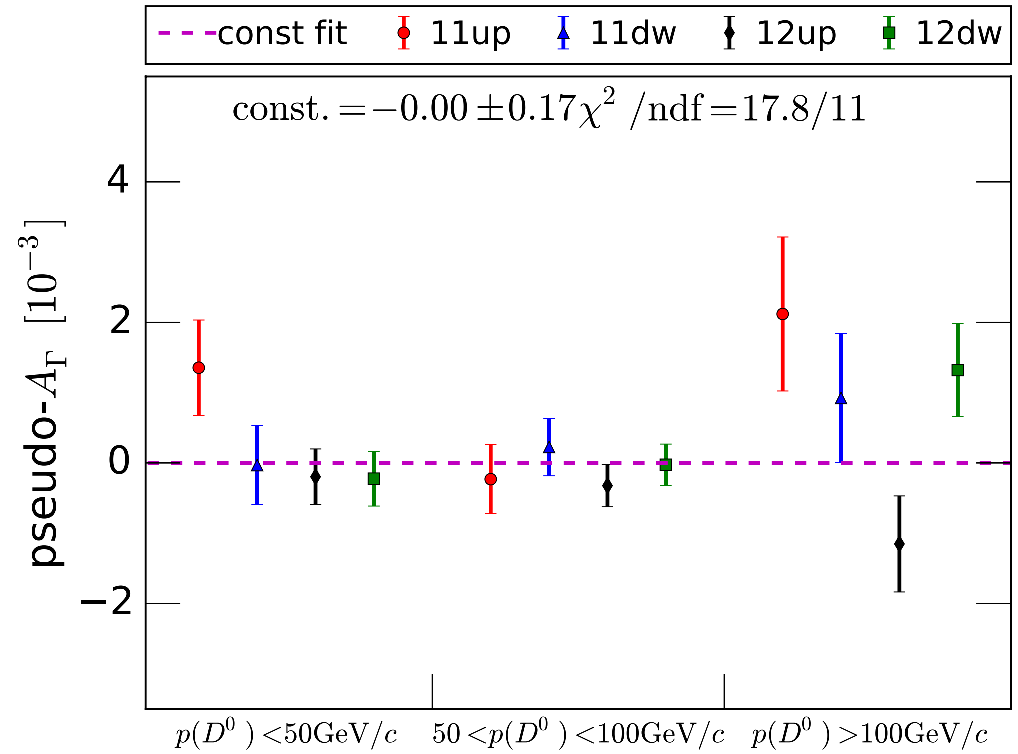
$\chi^2/\text{ndf} = 17/11$

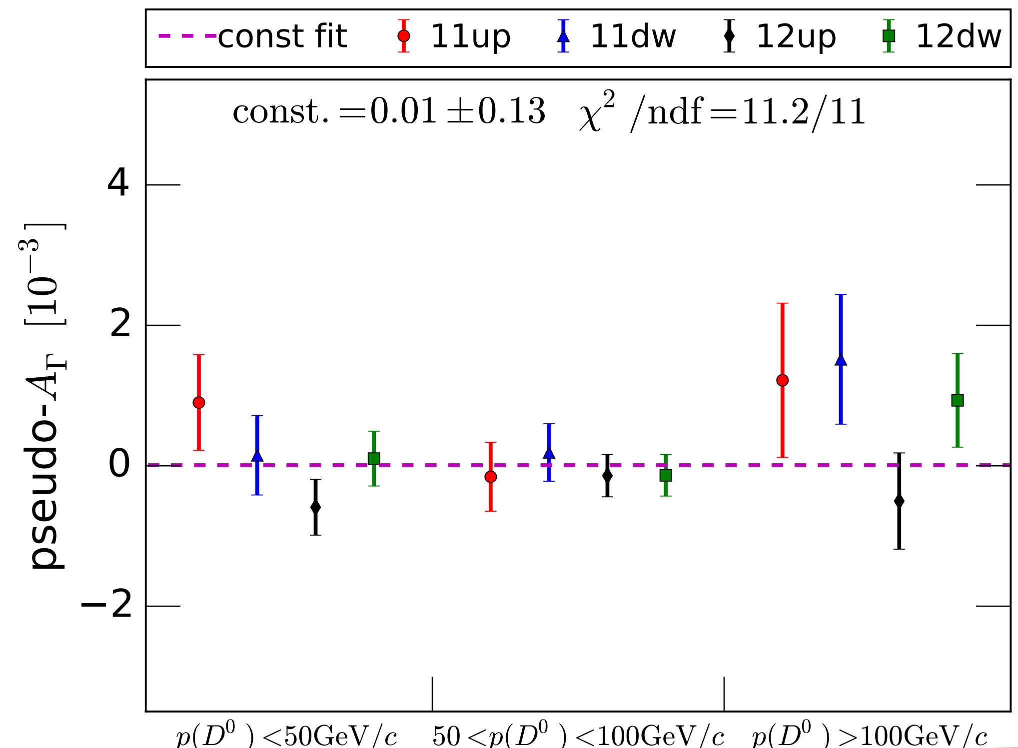
$A_\Gamma[10^{-3}]$ base sel. + mixing cuts			
sample/[GeV/c]	$p(D^0) < 50$	$50 < p(D^0) < 100$	$p(D^0) > 100$
2011 Up	1.35 ± 0.68	-0.23 ± 0.49	2.12 ± 1.10
2011 Down	-0.03 ± 0.56	0.23 ± 0.41	0.92 ± 0.92
2012 Up	-0.19 ± 0.40	-0.32 ± 0.30	-1.15 ± 0.68
2012 Down	-0.22 ± 0.39	-0.03 ± 0.29	1.13 ± 0.66

$\text{const.} = 0.01 \pm 0.13$

$\chi^2/\text{ndf} = 11/11$

$A_\Gamma[10^{-3}]$ base sel. + mixing cuts, C/θ_x sym.			
sample/[GeV/c]	$p(D^0) < 50$	$50 < p(D^0) < 100$	$p(D^0) > 100$
2011 Up	0.90 ± 0.68	-0.16 ± 0.49	1.22 ± 1.10
2011 Down	0.15 ± 0.56	0.19 ± 0.41	1.52 ± 0.92
2012 Up	-0.59 ± 0.40	-0.14 ± 0.30	-0.50 ± 0.69
2012 Down	0.10 ± 0.39	-0.14 ± 0.29	0.93 ± 0.67





- Also with the D^0-mixing selection the symmetrisation works properly, given an improvement in the χ^2.