CP-violation measurement in $D^0 \to K^0_S K^0_S$ decays at CMS experiment

Vladimir Sergeychik, Sergey Polikarpov

vladimir.sergeychik@cern.ch, sergey.polikarpov@cern.ch

Moscow International School of Physics 2024

The work is supported by RSF (grant № 24-22-00445)

Agenda

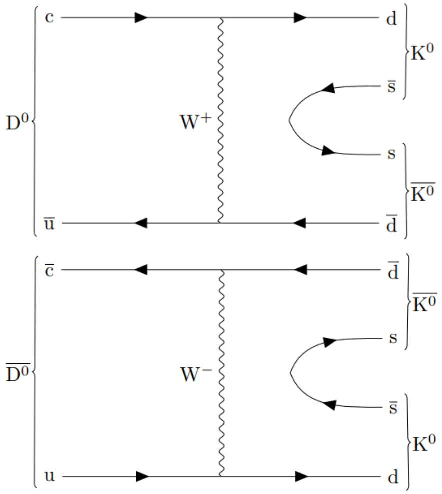
- **Introduction**
- **Data sample**
- **ACP in MC**
- **Fits to data**
- **Systematics uncertainties**
- **Results**
- **Summary**

Introduction to the analysis

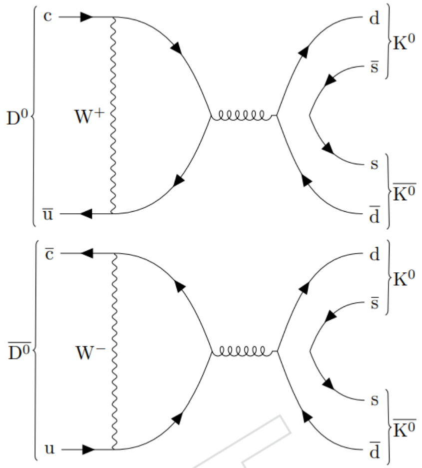
$$A_{CP}(f) \equiv \frac{\Gamma\left(D^0 \to f\right) - \Gamma\left(\bar{D}^0 \to f\right)}{\Gamma\left(D^0 \to f\right) + \Gamma\left(\bar{D}^0 \to f\right)}$$

- We present preliminary results of a measurement of the CP-violation parameter $\mathbf{A_{CP}(D^0 \to K^0_S K^0_S)}$
- CP-violation in up-quark sector is not studied as well as in down-quark sector, but it is crucial for better understanding of BSM effects
- This difference has never been calculated:
  - The only existing observation of CPV in charm:
    $A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-) = (-15.4 \pm 2.9)\times 10^{-4}$
  - Theoretical SM calculations predict CPV in $D^0 \to K^0_S K^0_S$ to be as large as *O(1%)* ← more significant then in in many other D^0 decay channels
  - Latest experimental calculation by LHCb:
    $A_{CP}(D^0 \to K^0_S K^0_S) = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$ **← no CPV**

Exchange diagram,
not Zweig suppressed
Large amplitude

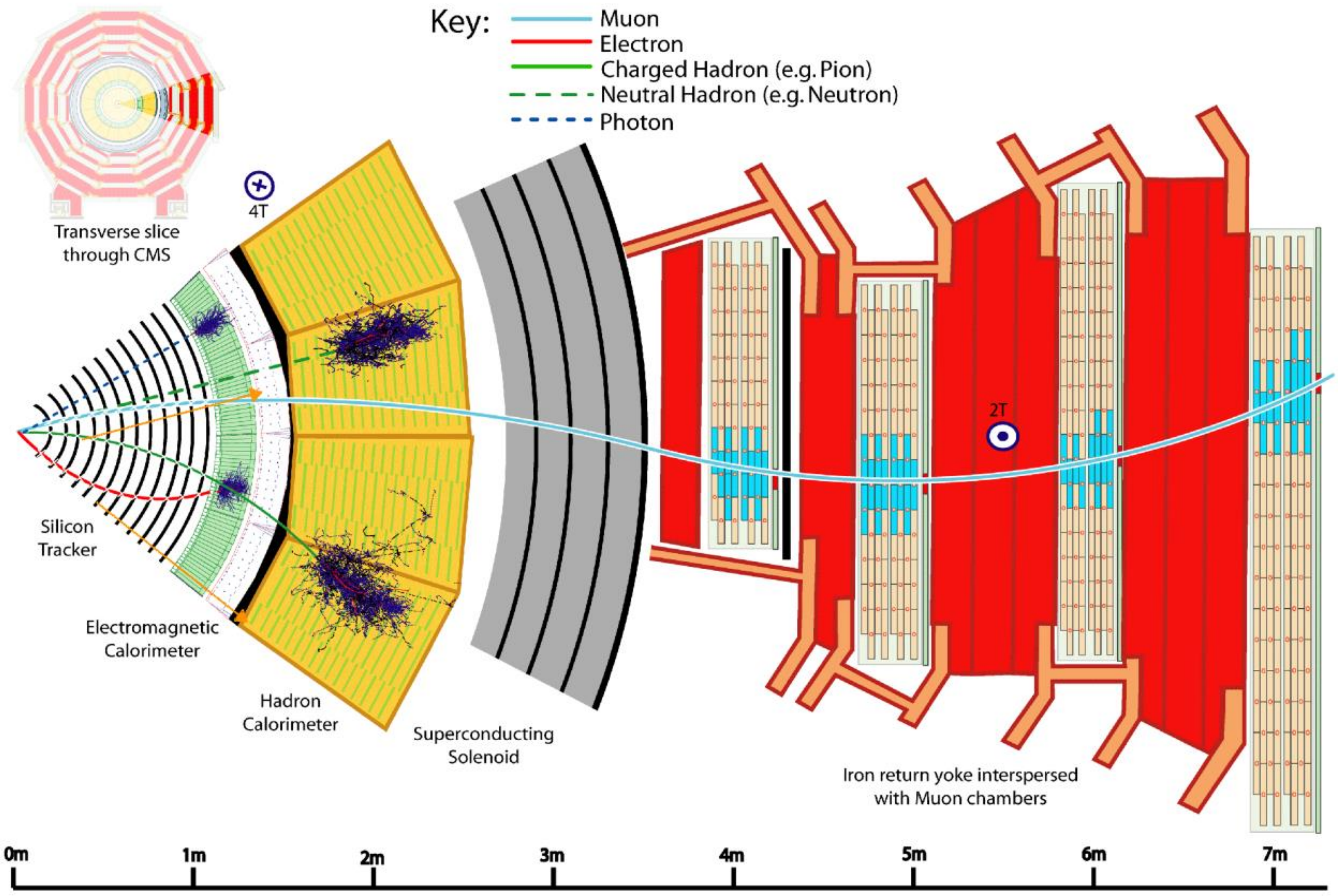


PA diagram,
Zweig suppressed
*The enhancement would point at **new physics***



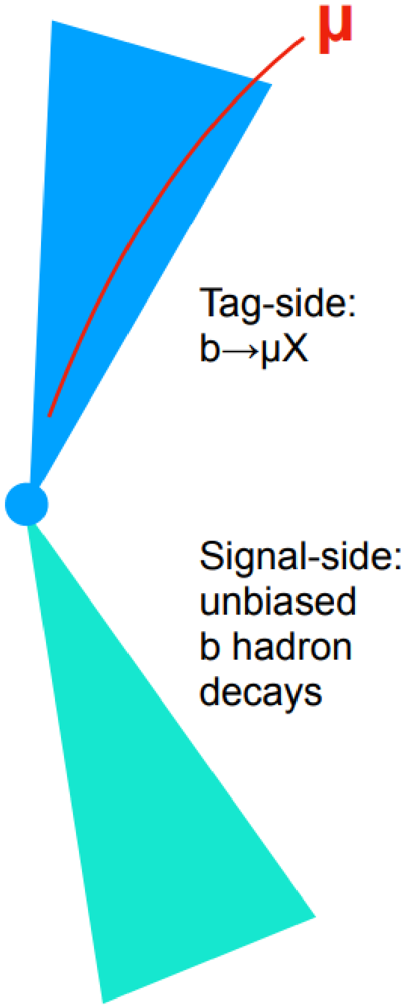
- Many systematic uncertainties in A_{CP} cancel if measured via ΔA_{CP}

CMS experiment at CERN



Bparking miniAOD 2018 data set

- The set of single muon triggers with different thresholds on muon p_T and impact parameter are used
- Due to these thresholds, most(~ 75-80%) of the events in dataset come from beauty semi-leptonic decays $b \rightarrow \mu X$
- Almost every time $b \rightarrow \mu c \nu X$
- The muon p_T cut at trigger level: 7-12 GeV => D has a high p_T, as both c and μ come from energetic b-hadron
- Thus, b-parking has $O(10^{10})$ events with charm hadrons with relatively high p_T => it is perfect for CPV search



ΔA_{CP}^{raw}

- We want to measure the CP asymmetry, defined by the formula:

$$A_{CP}(f) \equiv \frac{\Gamma\left(D^0 \to f\right) - \Gamma\left(\bar{D}^0 \to f\right)}{\Gamma\left(D^0 \to f\right) + \Gamma\left(\bar{D}^0 \to f\right)}$$

- We are tagging flavor of D^0 by the pion charge: $\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+ \qquad \mathrm{D}^{*-} \to \overline{\mathrm{D}}^0\pi^-$

- The number of observable candidates is connected with decay width:

$$N\left(\overset{(-)}{D^0} \to K_S^0 K_S^0\right) \propto \sigma\left(D^{*\pm}\right) \varepsilon^{\pm} \Gamma\left(\overset{(-)}{D^0} \to K_S^0 K_S^0\right)$$

- A_{CP} is connected to raw, production and detection asymmetries as:

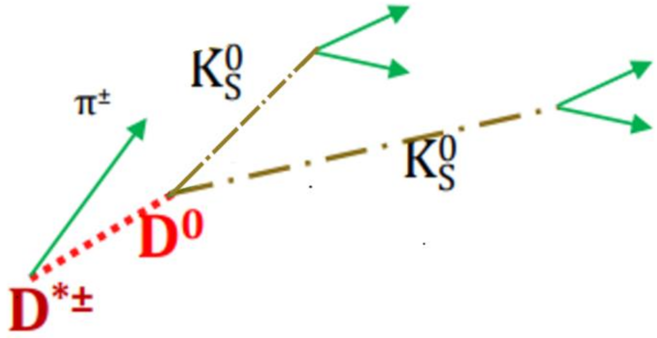
$$A_{CP} = A_{CP}^{raw} - A_\sigma - A_{det} \qquad A_{raw} = \frac{N(D^0) - N(\overline{D}^0)}{N(D^0) + N(\overline{D}^0)} \qquad A_{det} = \frac{\varepsilon_+ - \varepsilon_-}{\varepsilon_+ + \varepsilon_-} \qquad A_\sigma = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

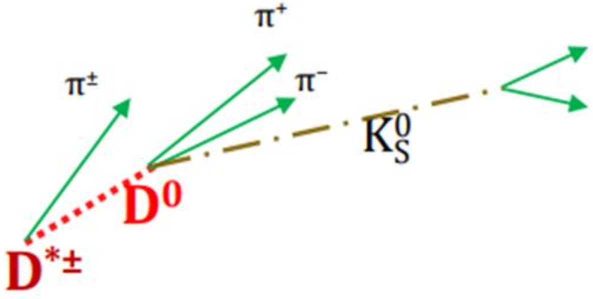
- Assuming that A_σ and A_{det} are almost identical in both channels, $\mathbf{\Delta A_{CP}}$ can be calculated as:

$$\Delta A_{CP} = A_{CP}^{raw}(D^0 \to K_S^0 K_S^0) - A_{CP}^{raw}(D^0 \to K_S^0 \pi^+\pi^-) \longleftarrow$$

Largely insensitive to systematics!

Event selection in data and MC





Data:

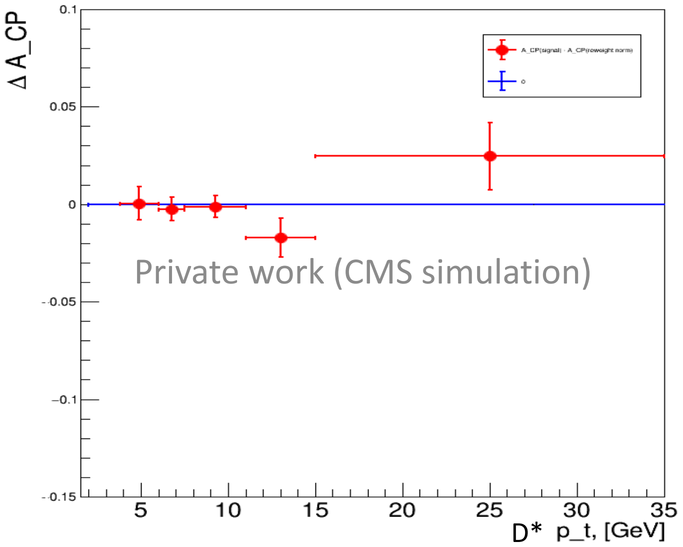
- $\mathbf{K^0_S\pi\pi}$ **(normalization channel)** and $\mathbf{K^0_S K^0_S}$ **(signal channel)** channels have almost identical kinematics and topology => the reconstruction efficiencies asymmetries cancel in the measured difference of differences ΔA_{CP}
- K^0_S reconstructed from ππ fitted to the vertex with PDG mass constraint
- D^0 momentum points to PV
- D^0 is the result of $K^0_S K^0_S$ or K^0_Sππ vertex fit
- $D^{*\pm}$ is the result of D^0 $\pi^{\pm}$ vertex fit
- Selection criteria were optimized for improving accuracy of signal extraction in $D^0 \rightarrow K^0_S K^0_S$

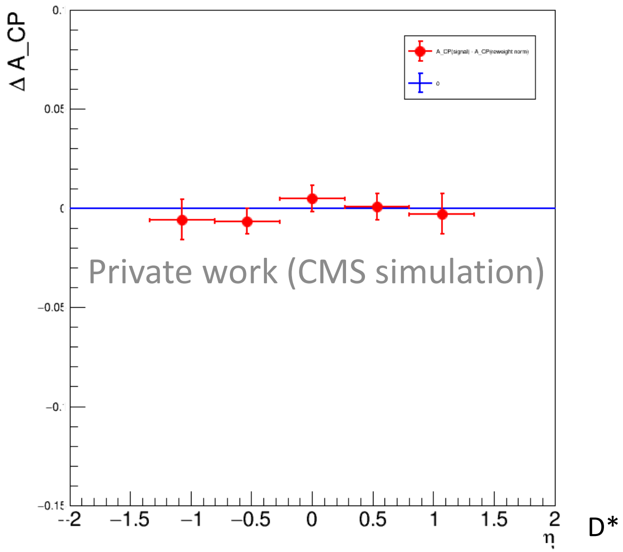
MC:

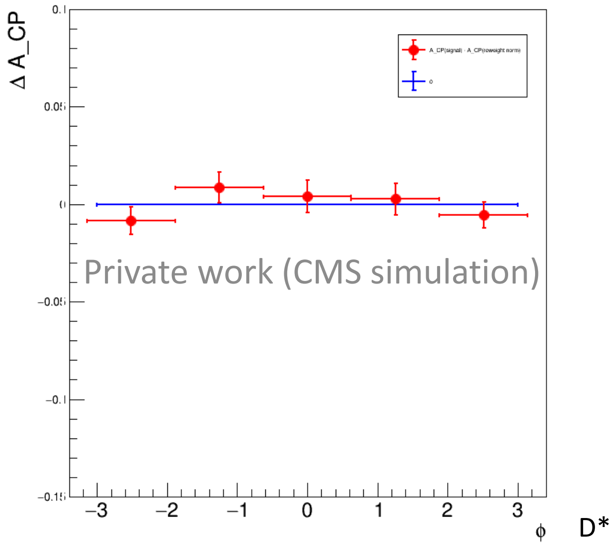
- Generated with PYTHIA 8.230 and processed with GEANT-4 to include CMS detector simulation particularities

ΔA_{CP}^{raw} in MC

$$\Delta A_{CP} = A_{CP}^{2} - A_{CP}^{1} = A_{CP}^{raw2} - A_{CP}^{raw1}$$







ΔA_{CP}^{raw} in whole MC sample: (0.126 ± 0.336)%

Perfect agreement with 0!

Possible p_T, η or φ dependence in individual channel cancels out in ΔA_{CP} – as expected!

Signals and A_{CP}^{raw} in $D^0 \to K_S^0\pi^+\pi^-$

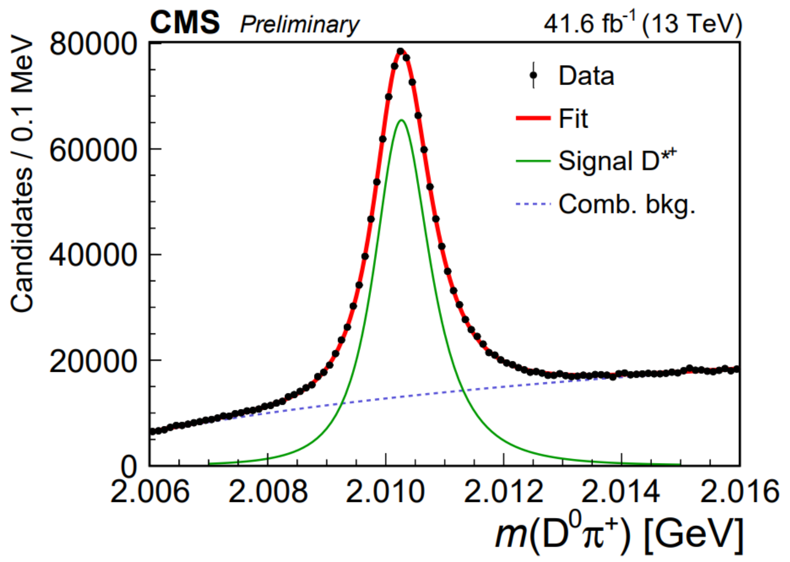
Fits of "+" and "–" are simultaneous:
all parameters of their pdfs are shared;
only yields are floating

1d-fit of $(M(D\,\pi) - M(D) + M_D^{PDG})$ is applied

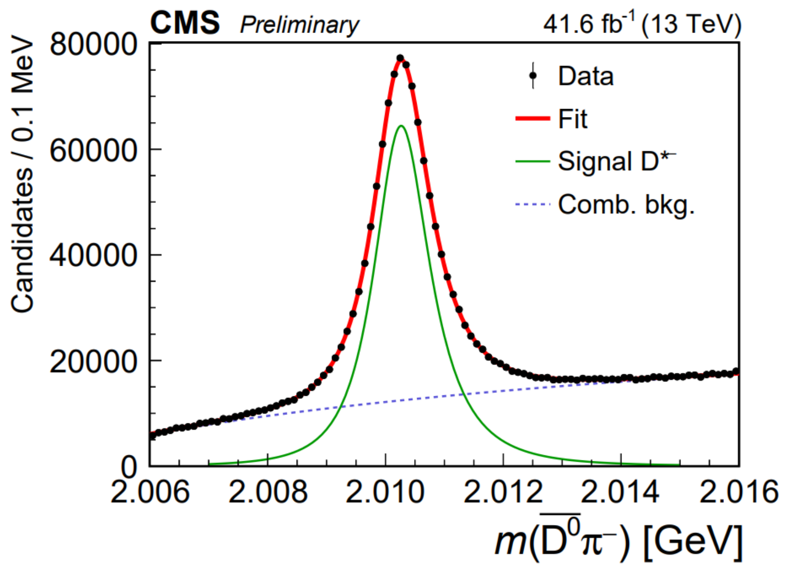
Signal pdf: *Johnson function*
Background pdf: *Threshold function• Pol_1*

Charge of pion	N	χ^2 with 100 bins
π^+	944817 ± 3489	78
π^-	930148 ± 3395	93

Fit to D*+ candidates



Fit to D*- candidates



$$A_{CP}^{raw} = \frac{N^+ - N^-}{N^+ + N^-}$$

$$\boxed{A_{CP}^{raw}(D^0 \to K_S^0\pi^+\pi^-) = (0.78 \pm 0.10)\%}$$

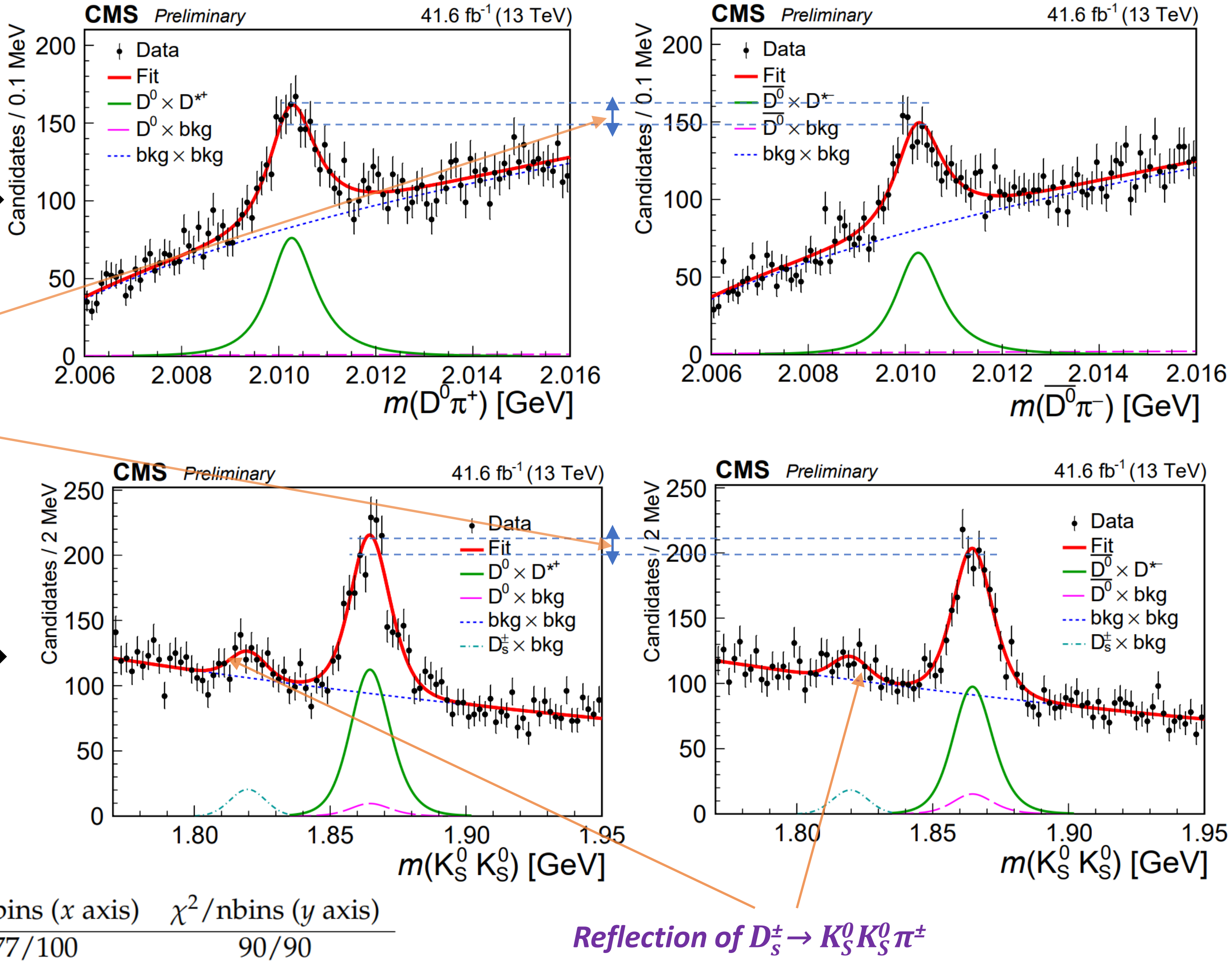
Signals and A_{CP}^{raw} in $D^0 \rightarrow K_S^0 K_S^0$

2d-fit of $(M(D\pi^{\pm}) - M(D) + M_D^{PDG})$ vs $M(K_S^0 K_S^0)$ is used

Projections on $x^+ = m(D\pi^+)$ and $x^- = m(D\pi^-)$ axes of 2d-fit

$$A_{CP}^{raw} = \frac{N^+ - N^-}{N^+ + N^-}$$

Projections on $y^+ = m(K_S^0 K_S^0)$ and $y^- = m(K_S^0 K_S^0)$) axes of 2d-fit



$\mathbf{A_{CP}^{raw}(D^0 \rightarrow K_S^0 K_S^0) = (7.065 \pm 3.022)\%}$

Charge of pion	$N_{sig\cdot sig}$	$N_{sig\cdot bgd}$	$N_{bgd\cdot bgd}$	$N_{Ds\cdot bgd}$	χ^2/nbins (x axis)	χ^2/nbins (y axis)
π^+	1095 ± 46	94 ± 52	8653 ± 115	165 ± 45	77/100	90/90
π^-	951 ± 44	149 ± 52	8397 ± 115	144 ± 46	93/100	62/90

Sources of systematical uncertainties

Source	Uncertainty, %
$m(D\pi^{\pm})$ signal model	0.10
$m(D\pi^{\pm})$ background model	0.02
$m(K^0_S K^0_S)$ signal model	0.04
$m(K^0_S K^0_S)$ background model	0.02
$m(K^0_S K^0_S)$ fit range	0.04
Reweighting	0.09
ΔA_{CP} in MC	0.13
Total	0.20

Systematics is much smaller than statistics: 0.2% vs. 3%

Summary

- We present the first measurement of CP-violation in charm in CMS

$$A_{CP}(D^0 \to K^0_S K^0_S) \ \ (via\ \Delta A_{CP} = A_{CP}(D^0 \to K^0_S K^0_S) - A_{CP}(D^0 \to K^0_S \pi^+\pi^-))$$

- Using 2018 b-parking dataset with a lot of charm hadrons produced in semileptonic b decays
- The resulting ΔA^{raw}_{CP}:

$$\boxed{\Delta A^{raw}_{CP} = (6.3 \pm 3.0\ (stat) \pm 0.2\ (syst))\%}$$

- Using PDG A_{CP} ($D^0 \to K^0_S \pi^+\pi^-$), we derive the A_{CP} ($D^0 \to K^0_S K^0_S$):

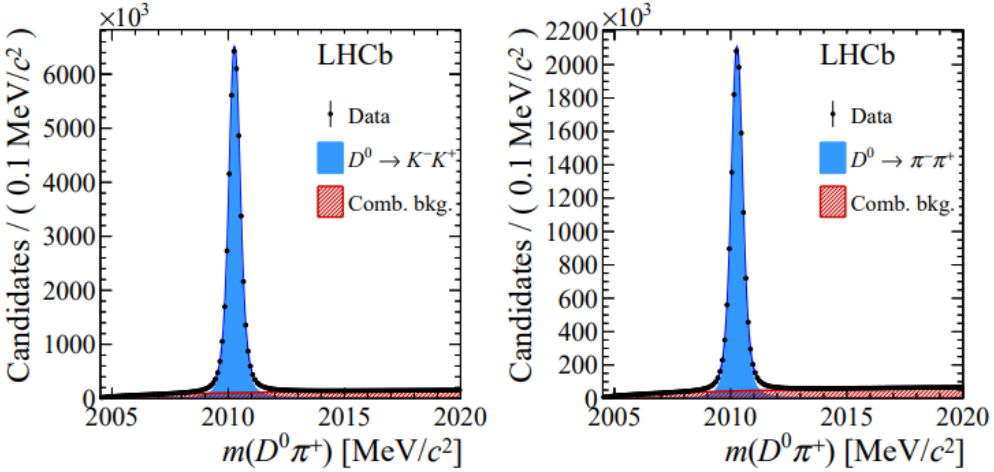
$$\boxed{A_{CP}\ (D^0 \to K^0_S K^0_S) = (6.2 \pm 3.0\ (stat) \pm 0.2\ (syst) \pm 0.8\ (A_{CP}\ (D^0 \to K^0_S \pi^+\pi^-)))\%}$$

- The result is consistent with **no CPV in $D^0 \to K^0_S K^0_S$** at the level of 2.0σ
- The value is consistent with LHCb measurement at the level of 2.7σ (**(6.2 ± 3.1)%** vs. **(-3.1 ± 1.3)%**)
- This measurement paves the way for future charm CP-violation searches in CMS

Thank you!

Back-up

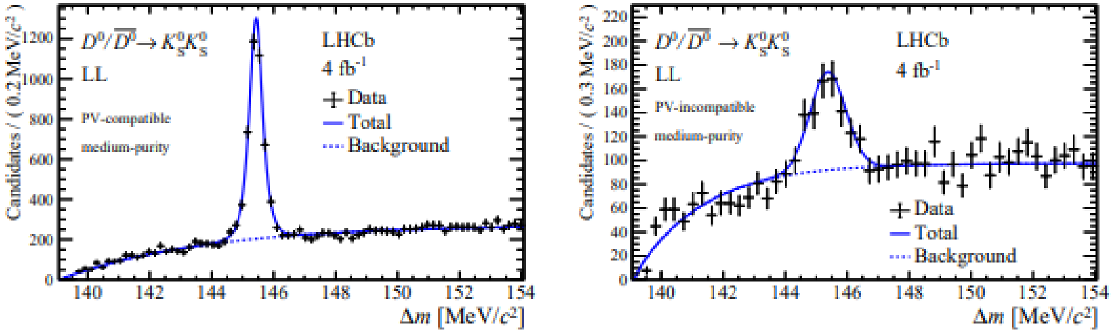
Motivation: LHCb results



Observation of CP violation in charm (2019)

$$A_{CP}\left(D^0 \longrightarrow K_S^0 K_S^0\right)$$

LHCb Coll. "Measurement of CP asymmetry in D0 K S0 K S0 decays." Physical Review D 104 (2021): L031102.



m(D*) – m(D⁰) distribution, PV-compatible (left) and PV-incompatible (right)

$$A_{CP}(D^0 \longrightarrow K_S^0\ K_S^0) = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$$

statistical

systematical

Uncertainty in norm channel (K^+K^-)

2.4σ agreement with 0

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\ \pi^-)$$

LHCb Coll. "Observation of CP violation in charm decays." Physical review letters 122, no. 21 (2019): 211803.

m(D*) distribution in $D^0 \rightarrow K^+ K^-$ and in $D^0 \rightarrow \pi^+ \pi^-$

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

Both statistical and systematical uncertainties

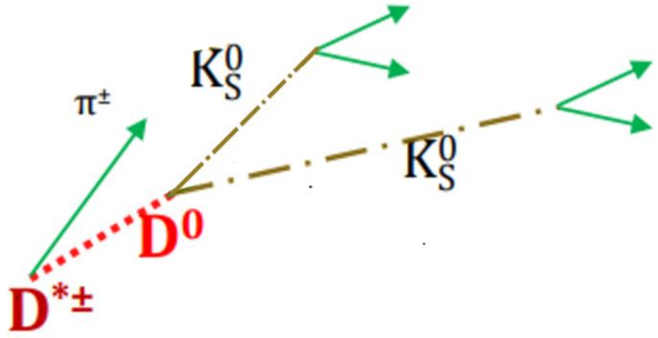
deviation from 0: 5.3σ

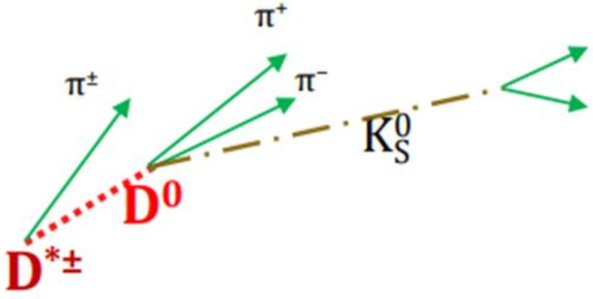
Event selection

Event selection in data and MC

Data:

- $\mathbf{K_S^0}$**ππ (normalization channel)** and $\mathbf{K_S^0K_S^0}$ **(signal channel)** channels have almost identical kinematics and topology => the reconstruction efficiencies asymmetries cancel in the measured difference of differences ΔA_{CP}
- PV is selected from offlinePrimaryVertices (miniAOD), as the one with the smallest angle (α) between the D0 momentum and vector joining PV with the fitted D0 vertex
- K_S^0 reconstructed from ππ fitted to the vertex with PDG mass constraint
- D^0 momentum points to PV
- D^0 is the result $K_S^0K_S^0$ or K_S^0ππ vertex fit
- $D^{*\pm}$ is the result of D^0 $\pi^{\pm}$ vertex fit
- Muon firing the trigger is not used
- Selection criteria were optimized for improving accuracy of signal extraction in $D^0 \rightarrow K_S^0 K_S^0$

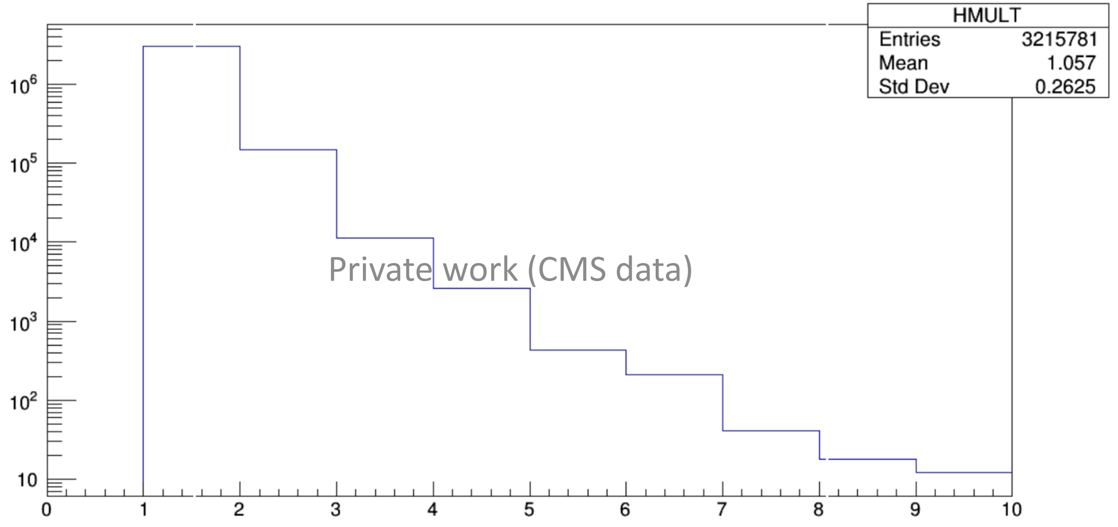




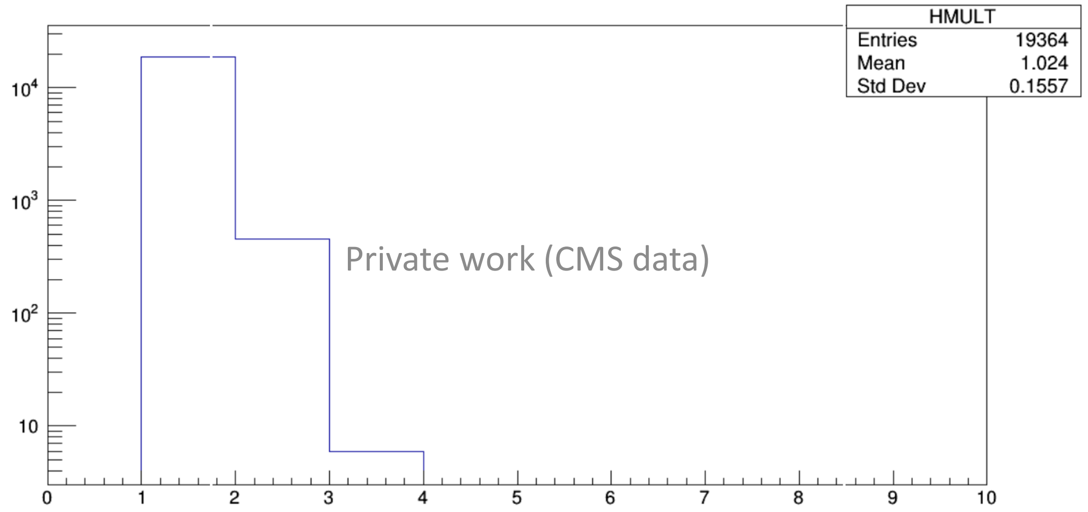
MC:

- Generated with PYTHIA 8.230 and processed with GEANT-4 to include CMS detector simulation particularities
- prompt $D^{*\pm}$ sample (60 million events)
- $D^{*\pm}$ produced in the decay B^0->$D^{*\pm}$X (30 million events)
- $D^{*\pm}$ produced in the decay B^0->$D^{*\pm}$X (30 million events)
- The same selection criteria as in data

Multiplicity



Candidates/events distribution in **$D^0 \rightarrow K^0_S \pi^+ \pi^-$ channel.**
Average multiplicity – 1.057

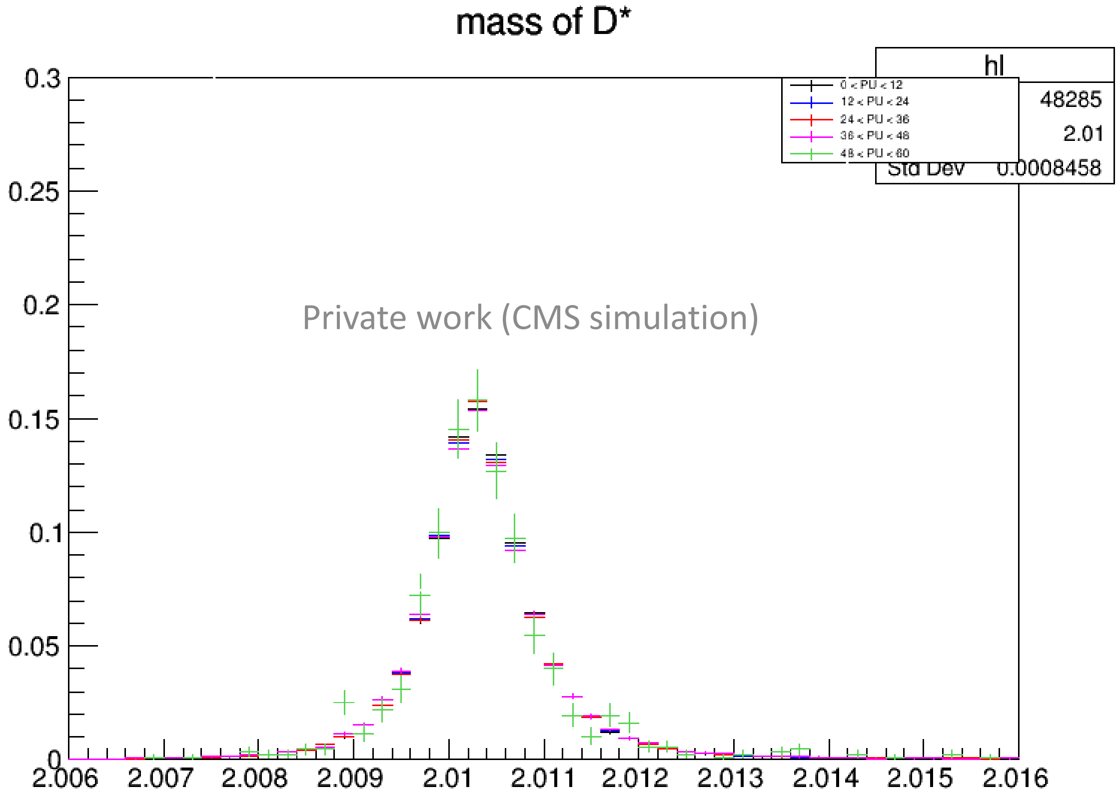


Candidates/events distribution in **$D^0 \rightarrow K^0_S K^0_S$ channel.**
Average multiplicity – 1.024

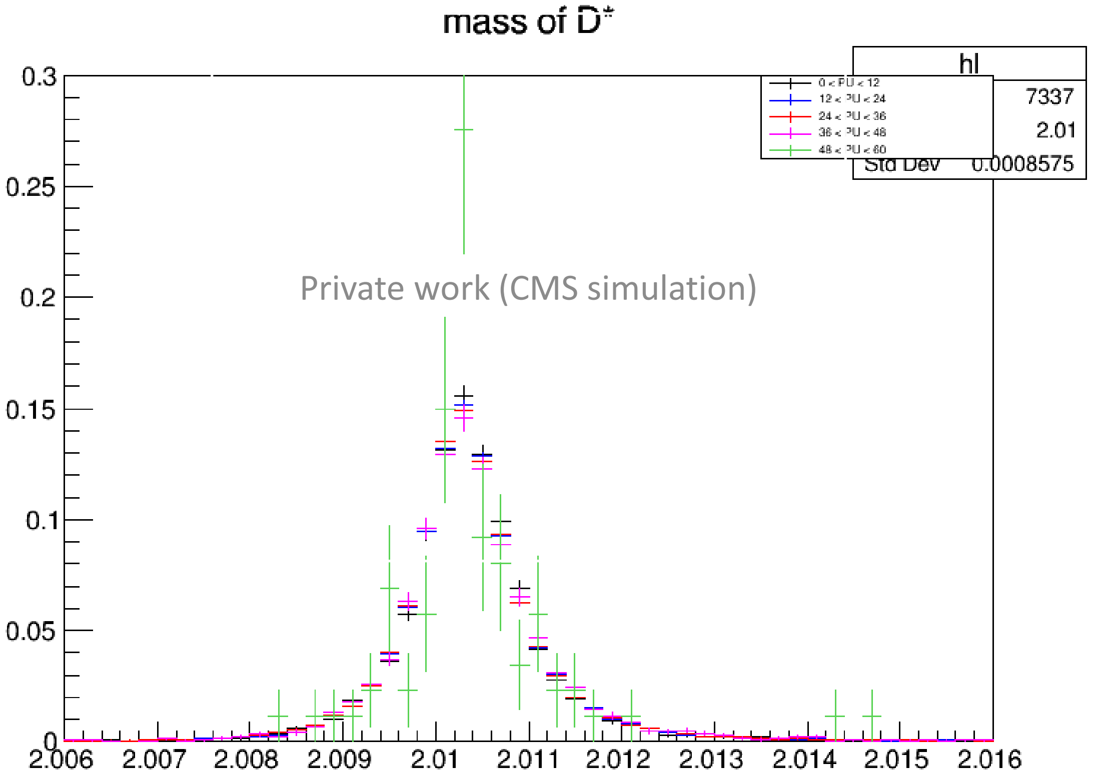
- The multiplicities are studied with final cuts
- The vast majority of events have just **1 candidate**
- ***The effect of multiplicity is neglected and we can ignore it***

Impact of pile-up

New!



(MC) Normalized M(D π) distributions in $\mathbf{D^0 \rightarrow K^0_S \pi^+ \pi^-}$ with different PU. No impact of PU.

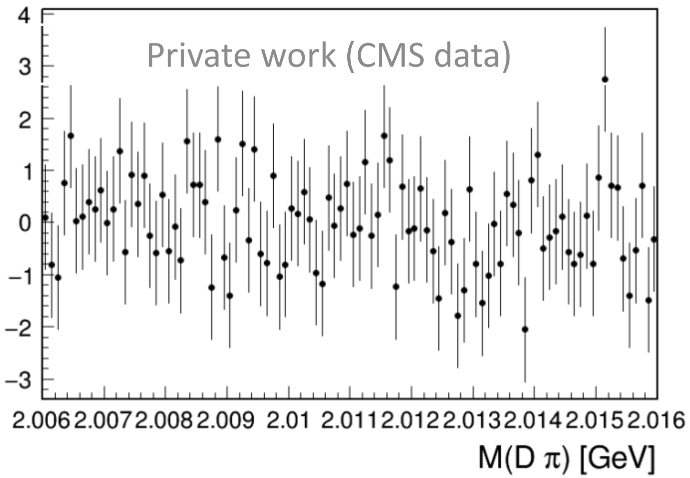


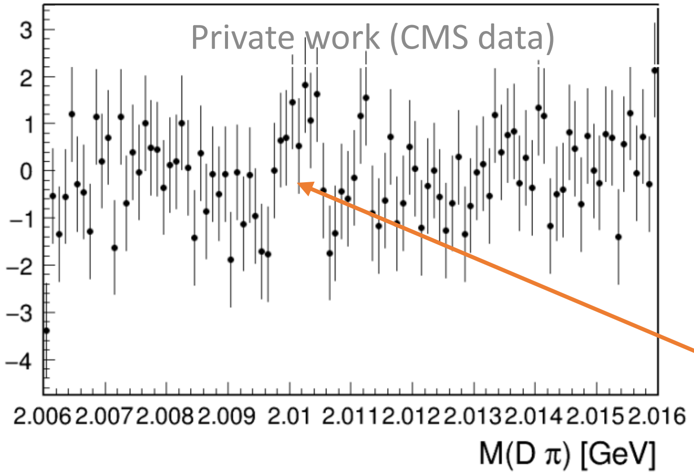
(MC) Normalized M(D π) distributions in $\mathbf{D^0 \rightarrow K^0_S K^0_S}$ with different PU. No impact of PU.

PU in the analysis does not effect the essential distribution of M(D π)
=> it can be neglected

2d-fit

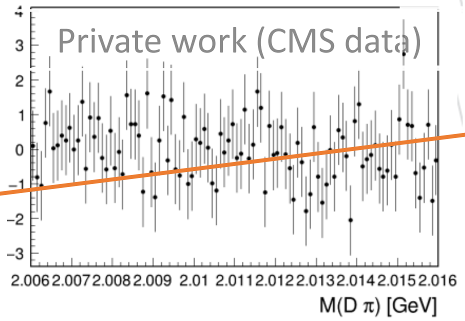
Cross-checks: different masses D^{*+} and D^{*-}

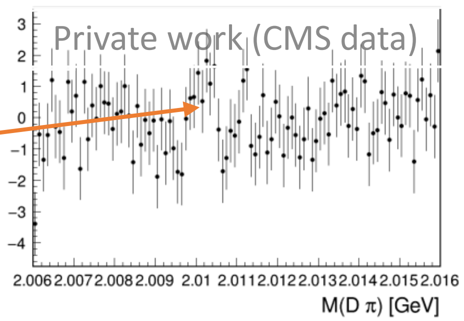




Strange peak for D^{*-} pull, but not for D^{*+}

- Simultaneous fit **does not model** m(D^{*-}) distribution **perfectly**
- ***(Possible explanation)***: asymmetry in π^+ and π^- calibration
- **Cross check:** model of pdf with different masses for D^{*+} and D^{*-}
- **Results:**





not improved!

	$A_{CP}^{\text{raw}}(K_S^0 K_S^0)$	$A_{CP}^{\text{raw}}(K_S^0 \pi^+ \pi^-)$	ΔA_{CP}
baseline	$(7.047 \pm 3.027)\%$	$(0.782 \pm 0.096)\%$	$(6.265 \pm 3.029)\%$
different masses	$(7.0306 \pm 3.027)\%$	$(0.783 \pm 0.096)\%$	$(6.253 \pm 3.029)\%$

not significantly changed!

- **Conclusions:** the deviation is not significant **--** *just a fluctuation?*

Cross-checks: floating width

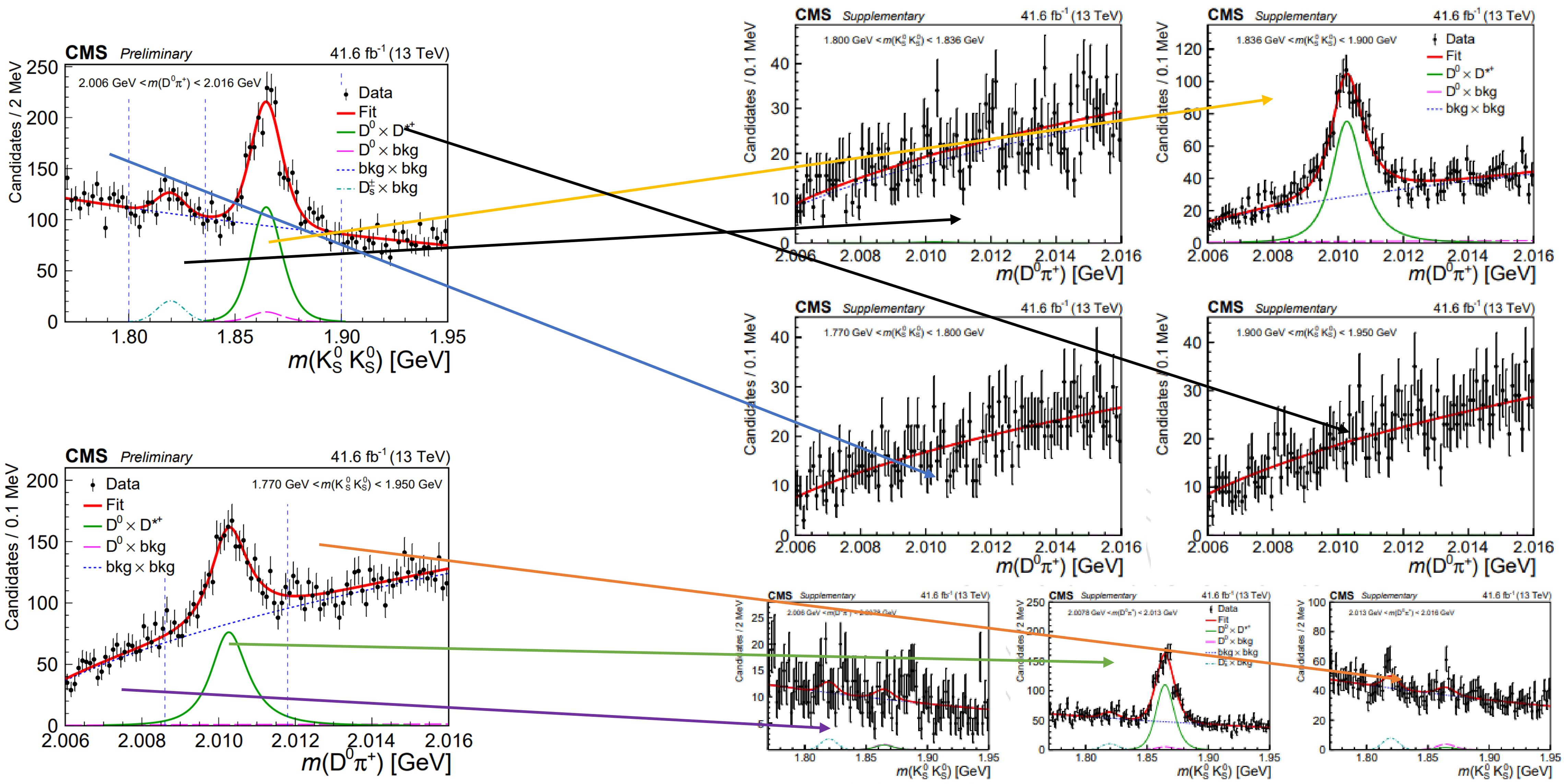
$$\sigma_{datasign} = \sigma_{MCsign} \bullet \frac{\sigma_{datanorm}}{\sigma_{MCnorm}} \longrightarrow \sigma_{datasign} \text{ floating!}$$

- **MC is not well-modelled**, hence, could be a bit unreliable
- **Alternative:** to float the width of first Johnson from DJH of 2D-fit, instead of setting it equal to the data/MC scaling (the ratio of the widths of Johnson functions is fixed from MC)
- **Results:**

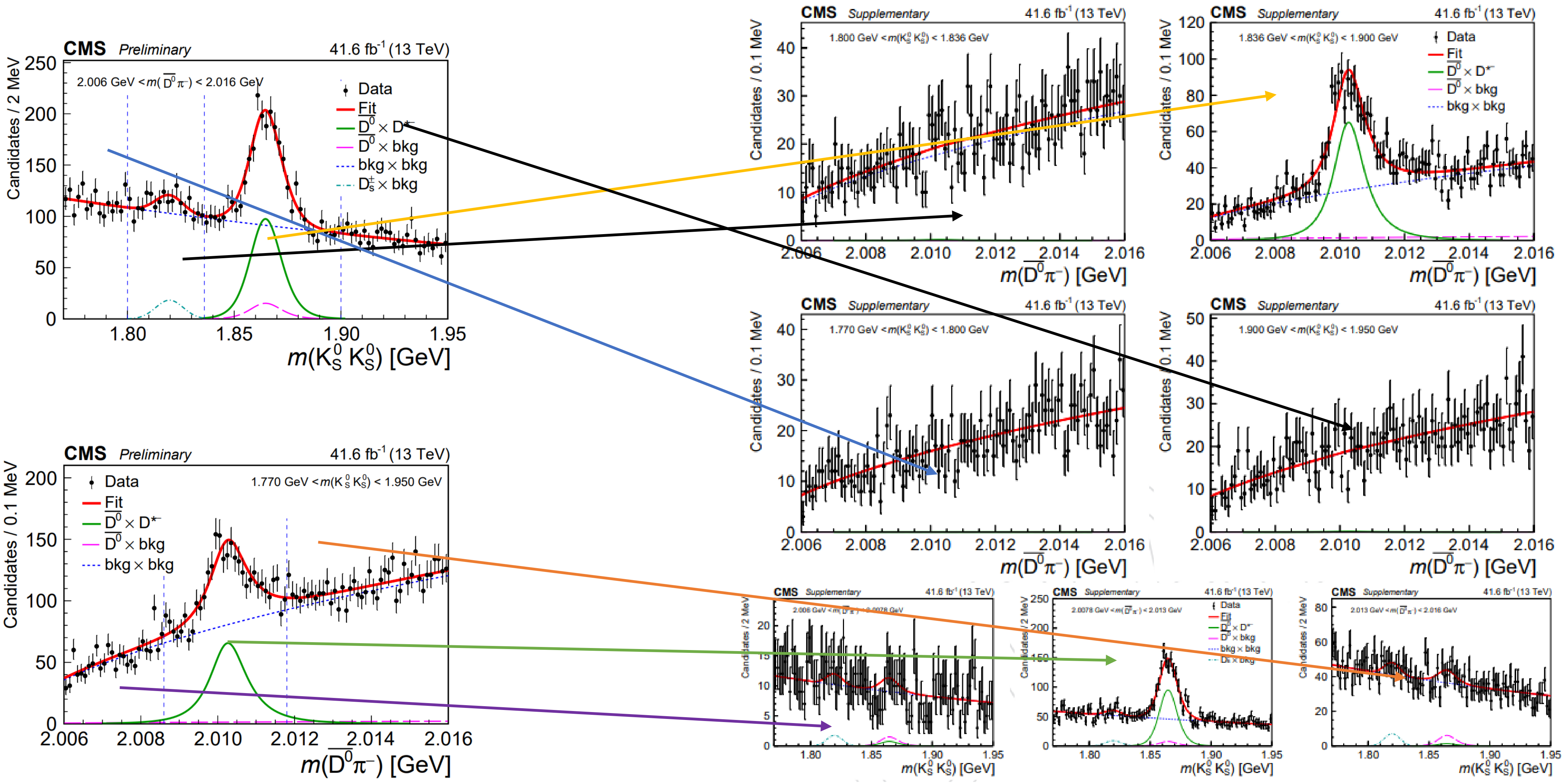
$$A_{CP}^{raw}(D^0 \rightarrow K_S^0 K_S^0) = (7.047 \pm 3.027)\% \longrightarrow A_{CP}^{raw}(D^0 \rightarrow K_S^0 K_S^0) = (7.065 \pm 3.021)\%$$

- **Not significant change (0.018%)**
- **This model is chosen as the baseline**

Projections of 2D-fit of m(D*) vs m(D^0): D^0 candidates



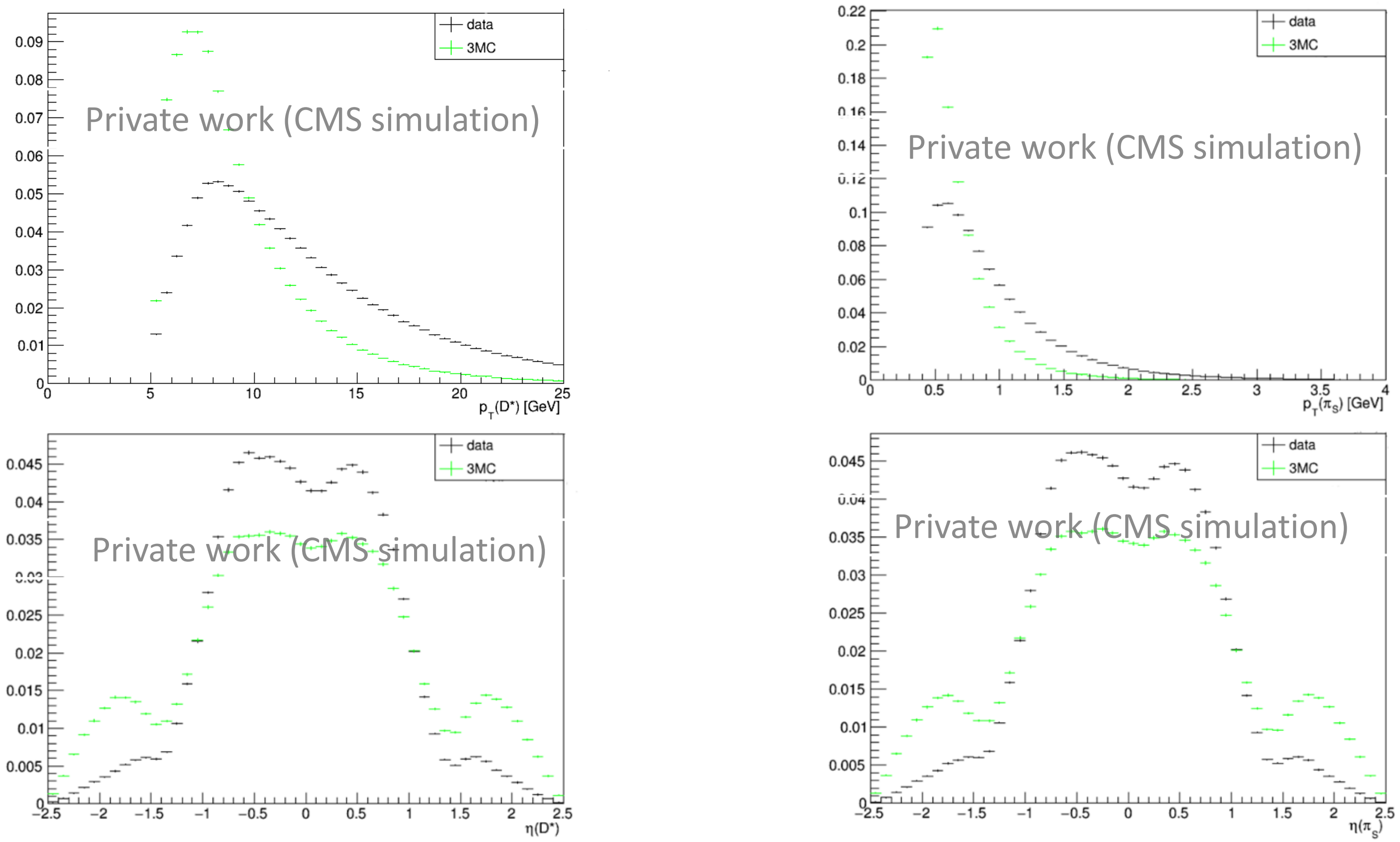
Projections of 2D-fit of m(D*) vs m(D⁰): $\overline{D}^0$ candidates



Data and MC

Normalization channel: comparison of MC and data

- Disagreement in MC and data variables distribution



MC does not have the “right mixture” of triggers, in MC they are always-on and the event is recorded even if no trigger fired

Triggers

- There are 9 triggers in B-parking data/MC

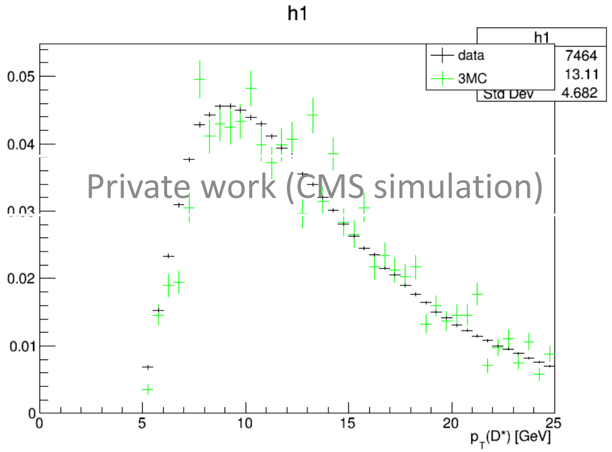
  - HLT_Mu10p5_IP3p5_p
  - HLT_Mu9_IP6_p
  - HLT_Mu9_IP5_p
  - HLT_Mu9_IP4_p
  - HLT_Mu8p5_IP3p5_p
  - HLT_Mu8_IP6_p
  - HLT_Mu8_IP5_p
  - HLT_Mu8_IP3_p
  - HLT_Mu7_IP4_p

- We call "Trigger 10" as "<u>any of triggers 1-9 fired</u>"
- We compare D* signals (Norm channel) in MC and in data: the p_T, and η distributions

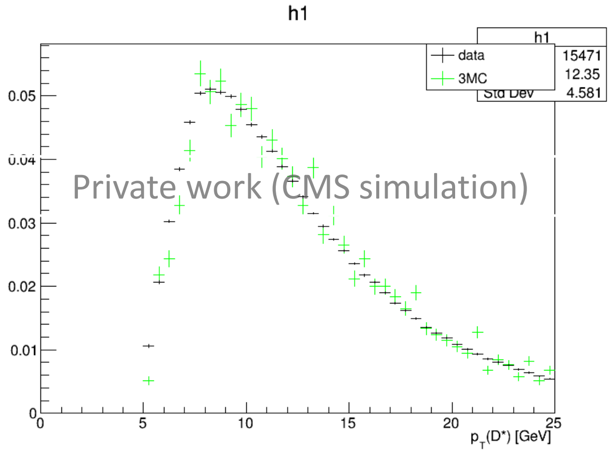
Amount of signal in MC and data

№ of trigger	Trigger in Xbframe	Signal in data	Signal in MC
TRIG_0	HLT_Mu12_IP6_p	609458±2390	7153±104
TRIG_1	HLT_Mu10p5_IP3p5_p	15841±373	0
TRIG_2	HLT_Mu9_IP6_p	1266200±3260	14254±134
TRIG_3	HLT_Mu9_IP5_p	872601±2780	16084±153
TRIG_4	HLT_Mu9_IP4_p	0	18083±163
TRIG_5	HLT_Mu8p5_IP3p5_p	22380±449	0
TRIG_6	HLT_Mu8_IP6_p	368729±1730	18942±175
TRIG_7	HLT_Mu8_IP5_p	420141±1930	21423±190
TRIG_8	HLT_Mu8_IP3_p	148801±1140	27599±232
TRIG_9	HLT_Mu7_IP4_p	571352±2200	32684±220
TRIG_10	At least one of them	1846890±4750	68352±616

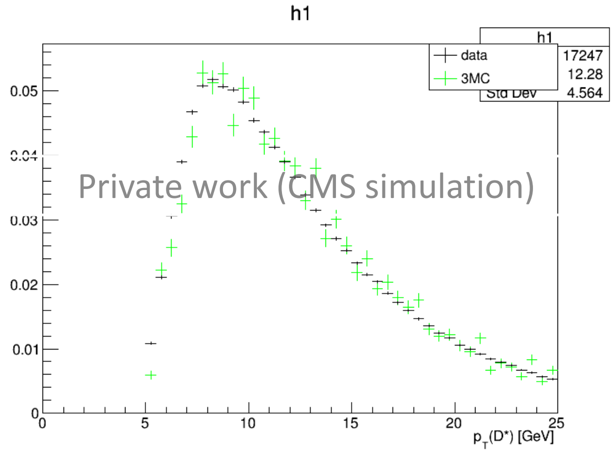
The shapes when a particular trigger has triggered (p_T(D*))



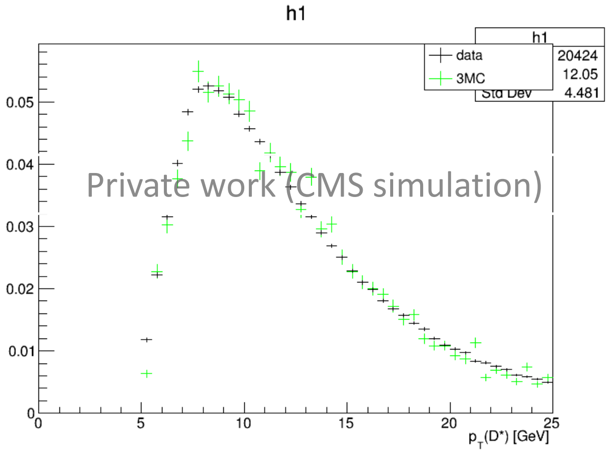
TRIG_0



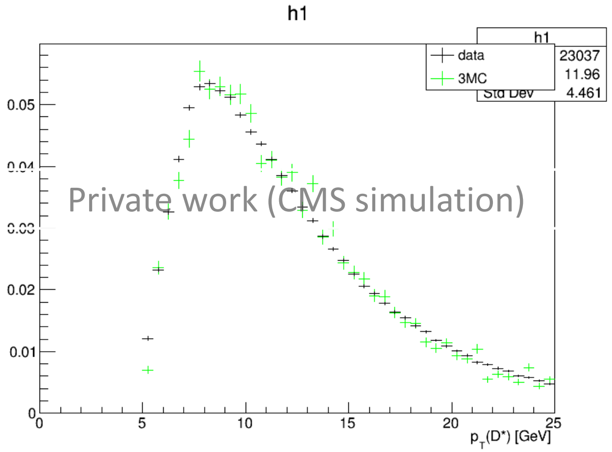
TRIG_2



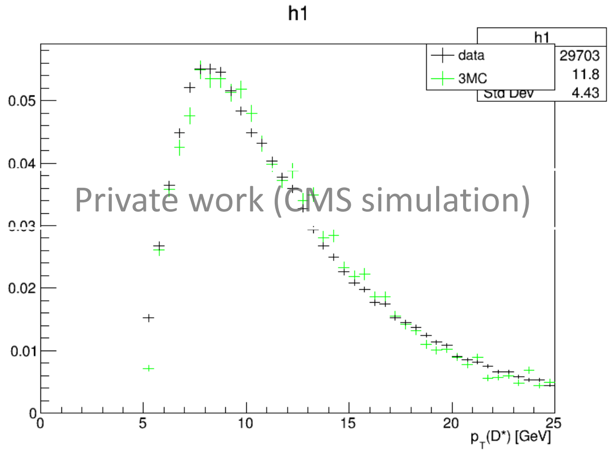
TRIG_3



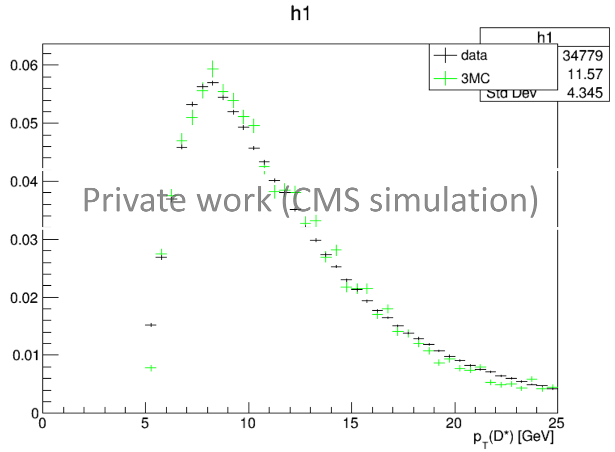
TRIG_6



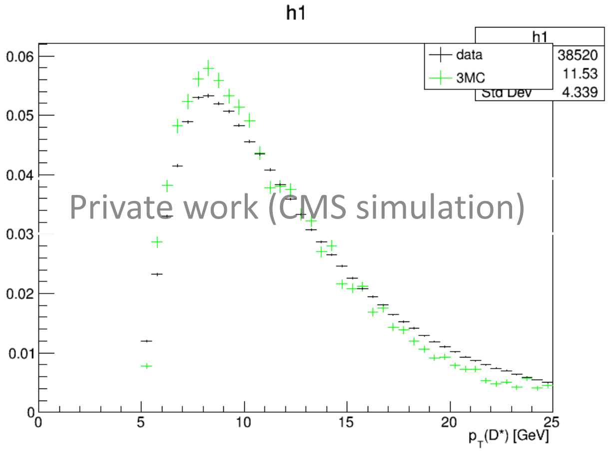
TRIG_7



TRIG_8



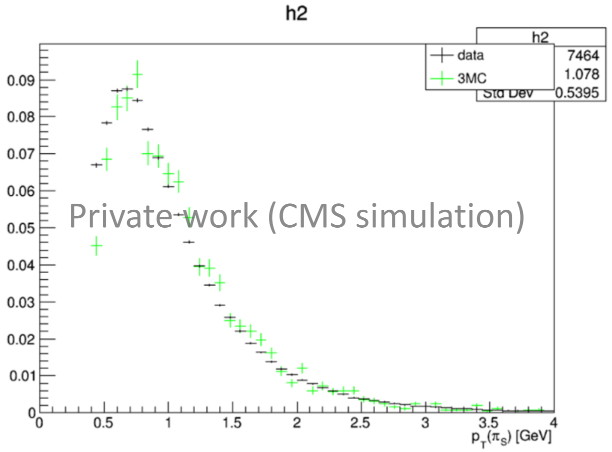
TRIG_9



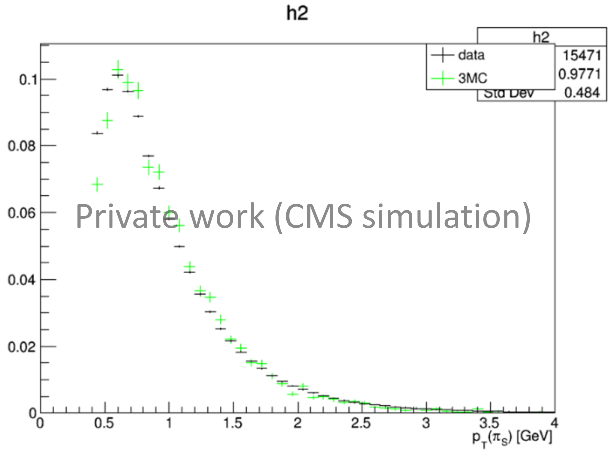
TRIG_10

In each individual trigger the shapes are in agreement!

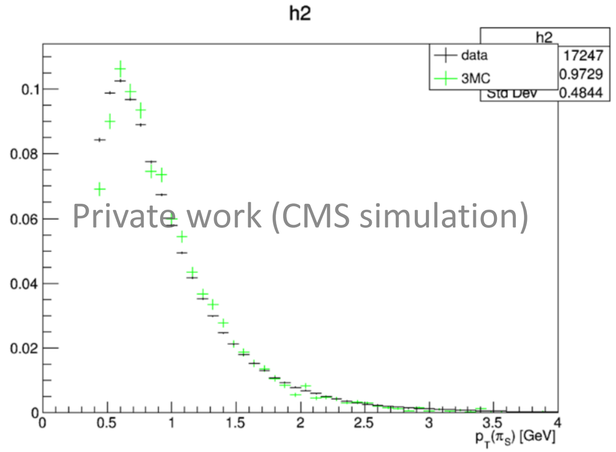
The shapes when a particular trigger has triggered ($p_T(\pi)$)



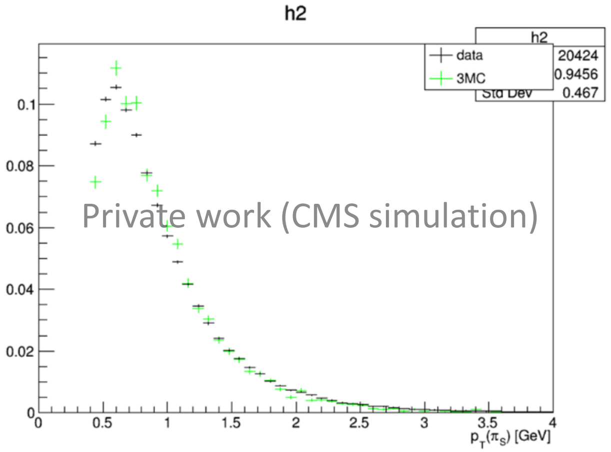
TRIG_0



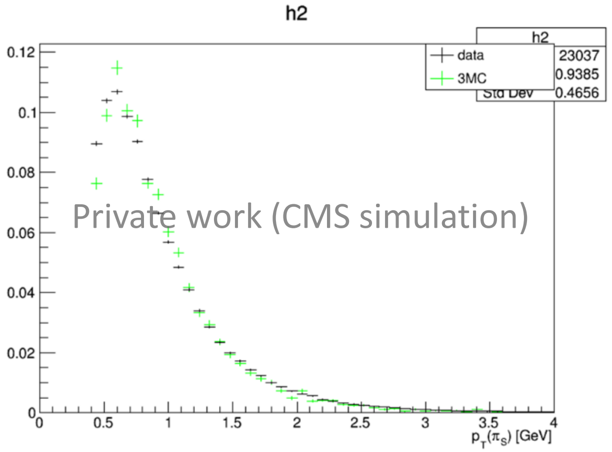
TRIG_2



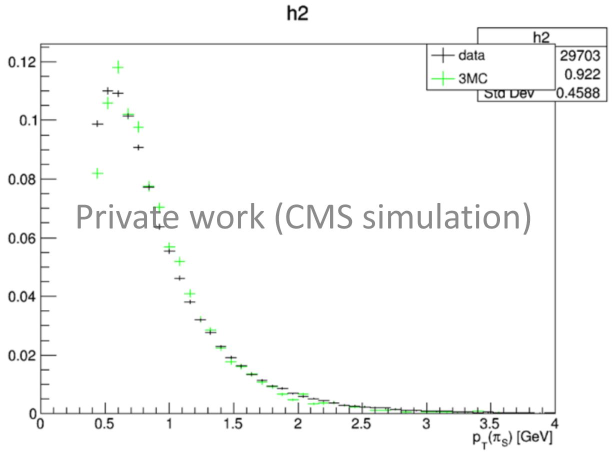
TRIG_3



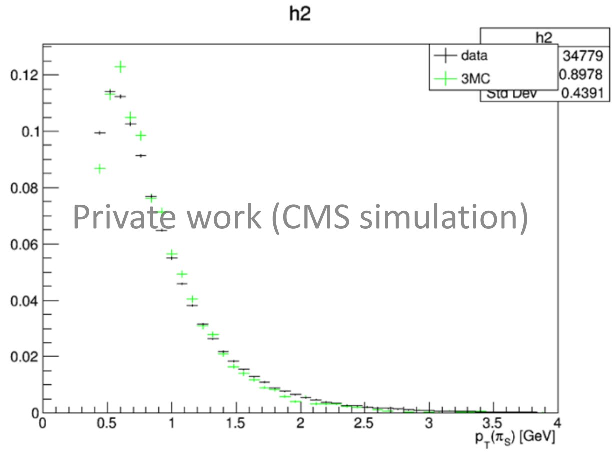
TRIG_6



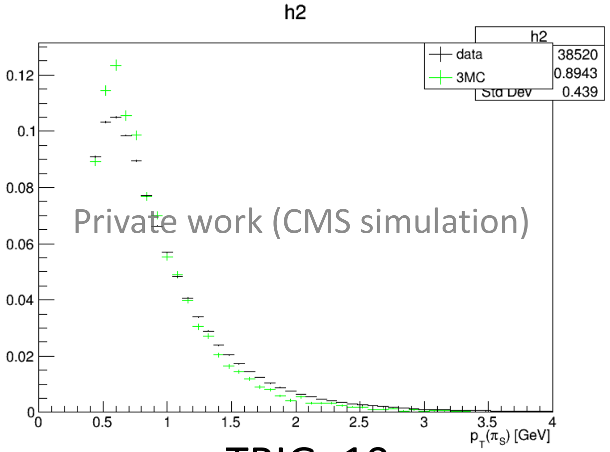
TRIG_7



TRIG_8



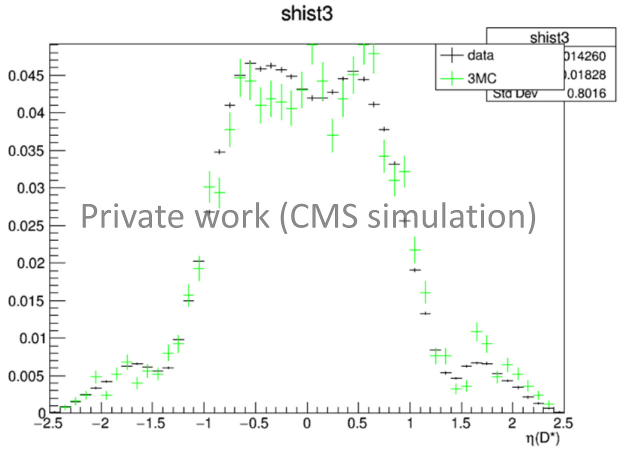
TRIG_9



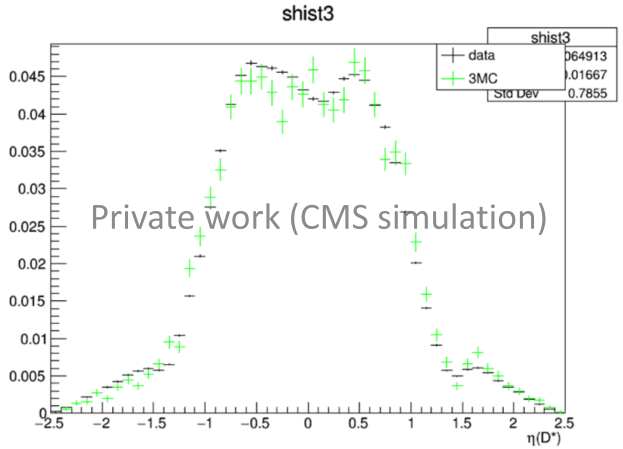
TRIG_10

In each individual trigger the shapes are in agreement!

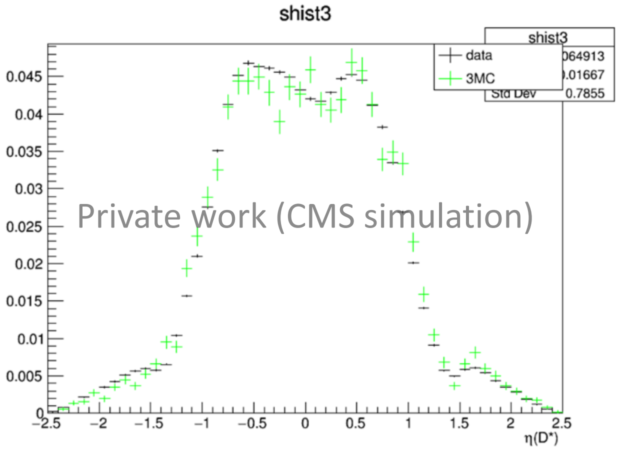
The shapes when a particular trigger has triggered (η (D*))



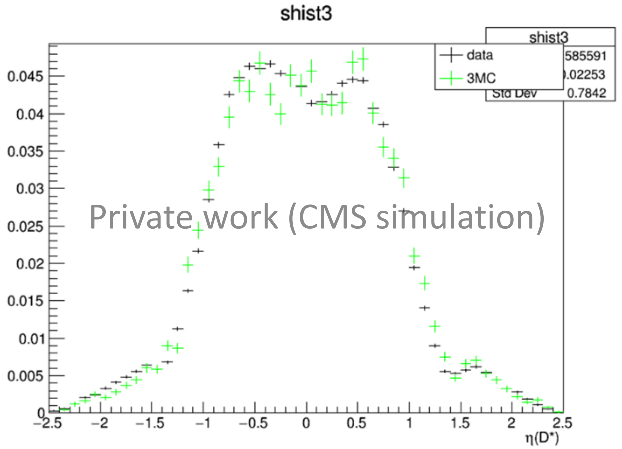
TRIG_0



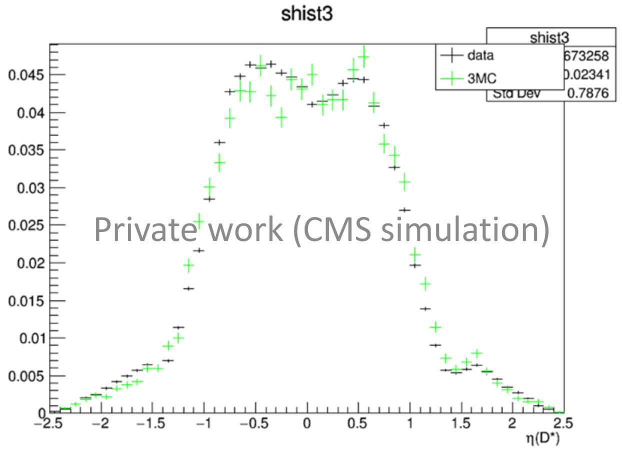
TRIG_2



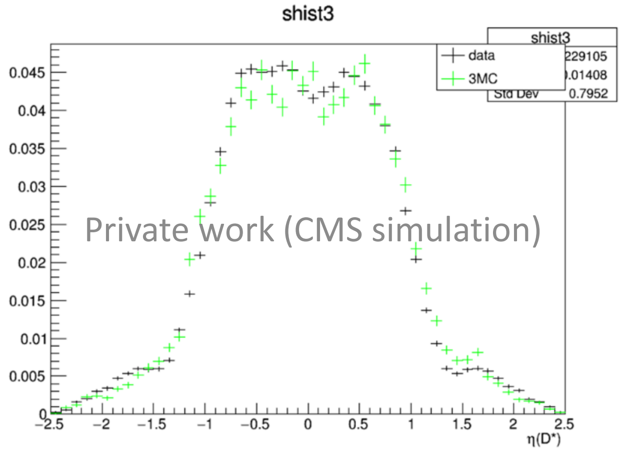
TRIG_3



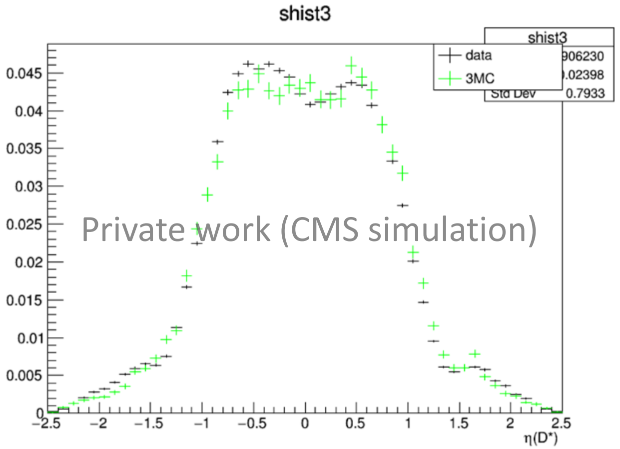
TRIG_6



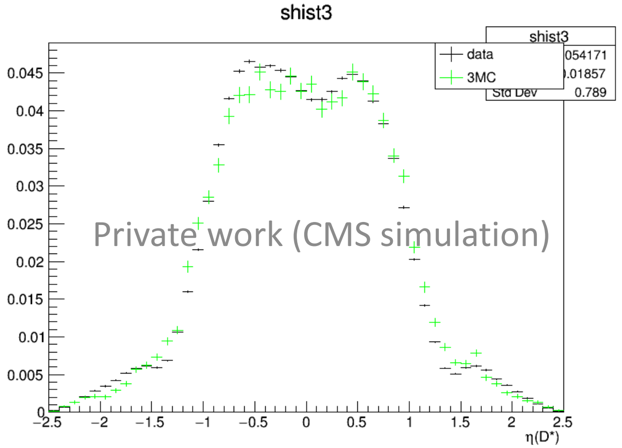
TRIG_7



TRIG_8



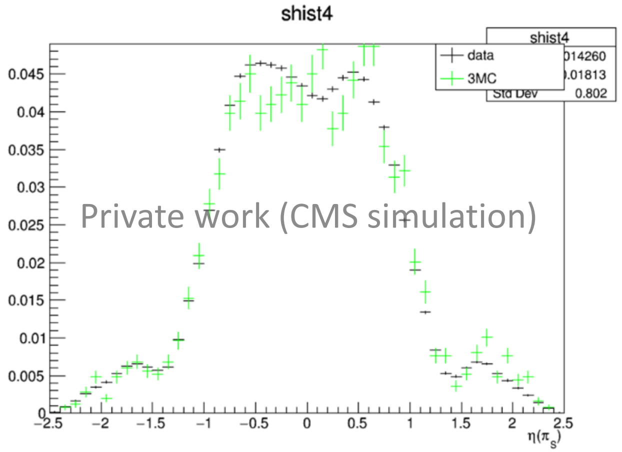
TRIG_9



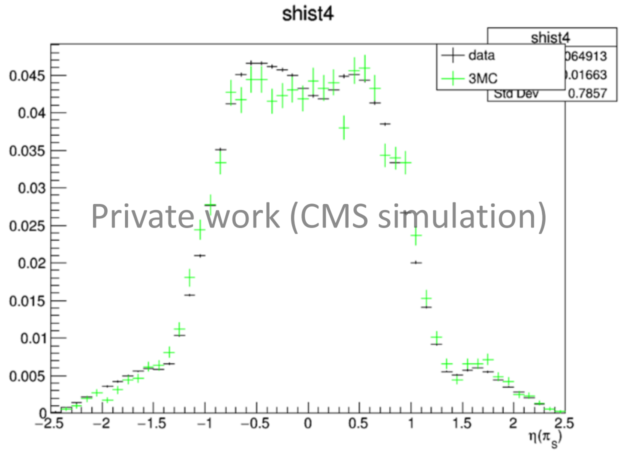
TRIG_10

In each individual trigger the shapes are in agreement!

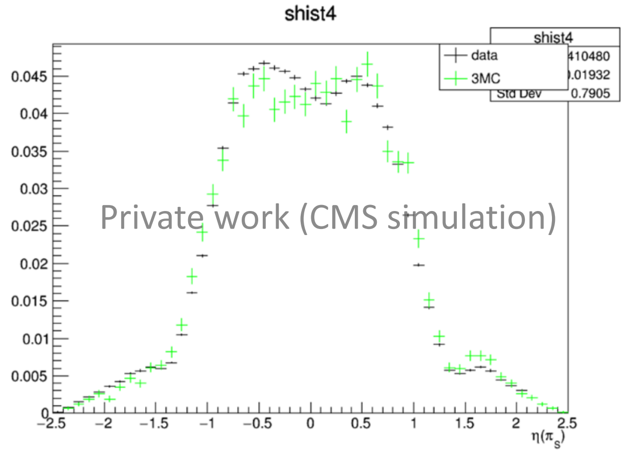
The shapes when a particular trigger has triggered (η (π))



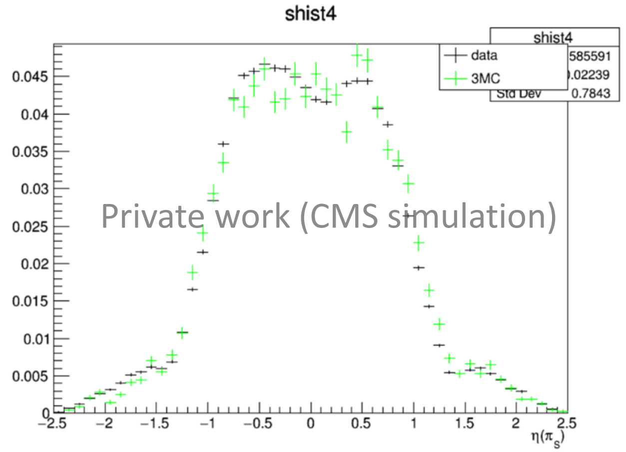
TRIG_0



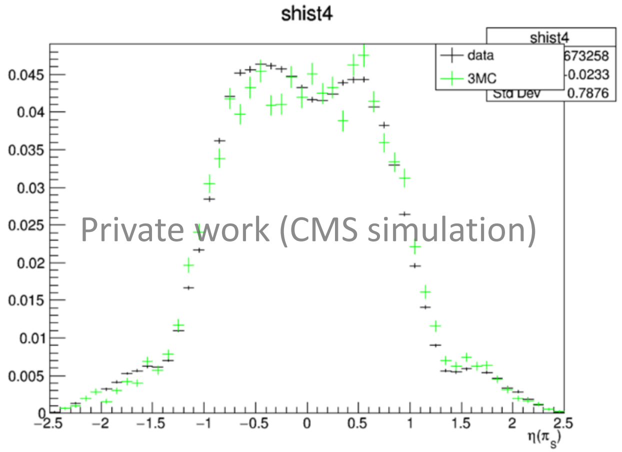
TRIG_2



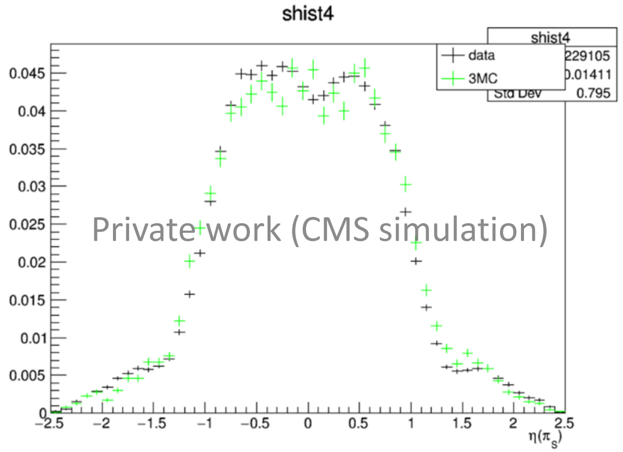
TRIG_3



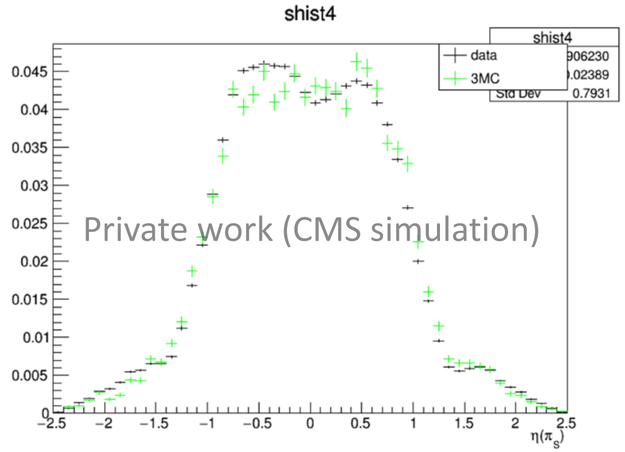
TRIG_6



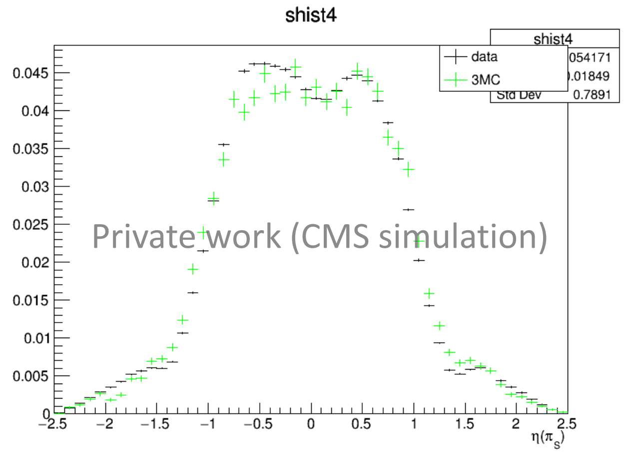
TRIG_7



TRIG_8



TRIG_9



TRIG_10

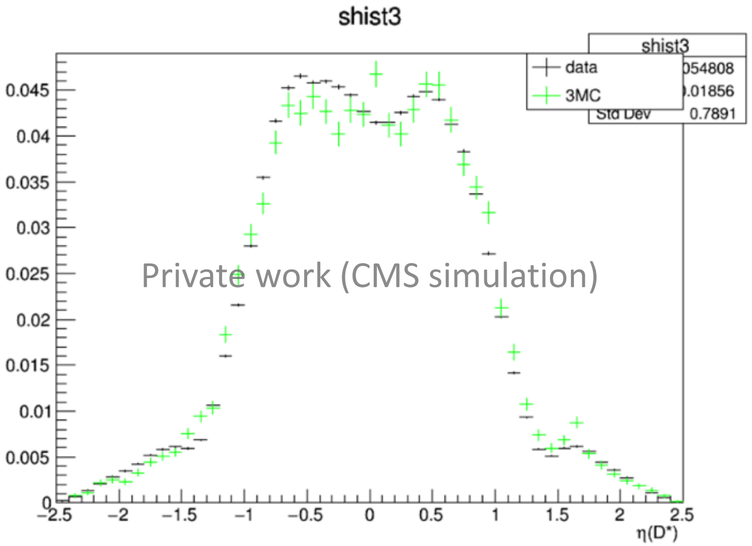
In each individual trigger the shapes are in agreement!

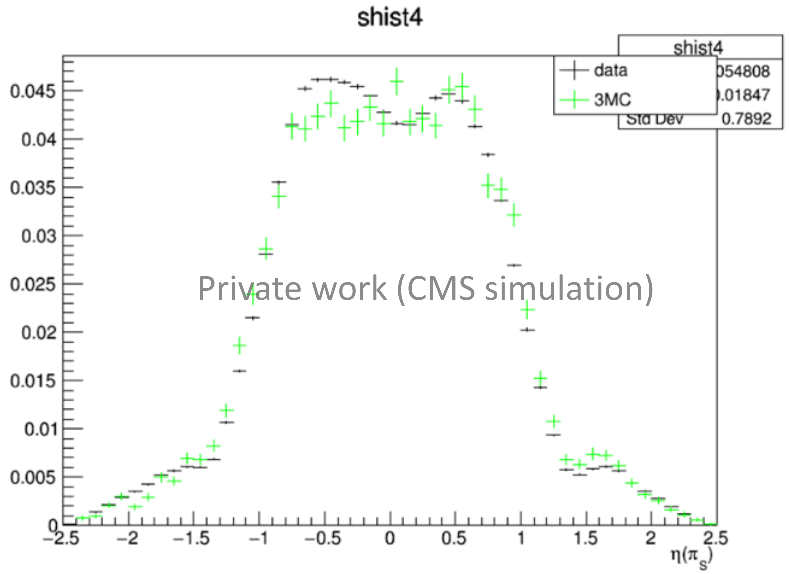
Weight coefficients for MC events

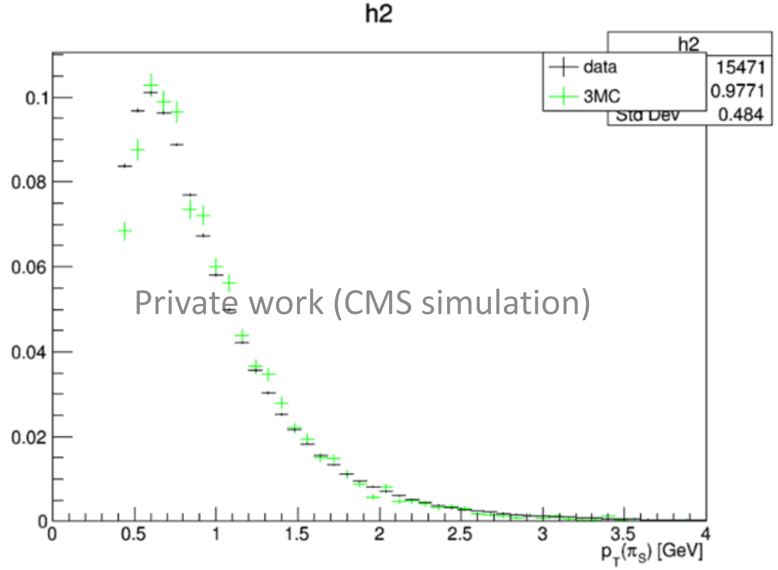
implemented as selection based on event number, not the “proper” weight

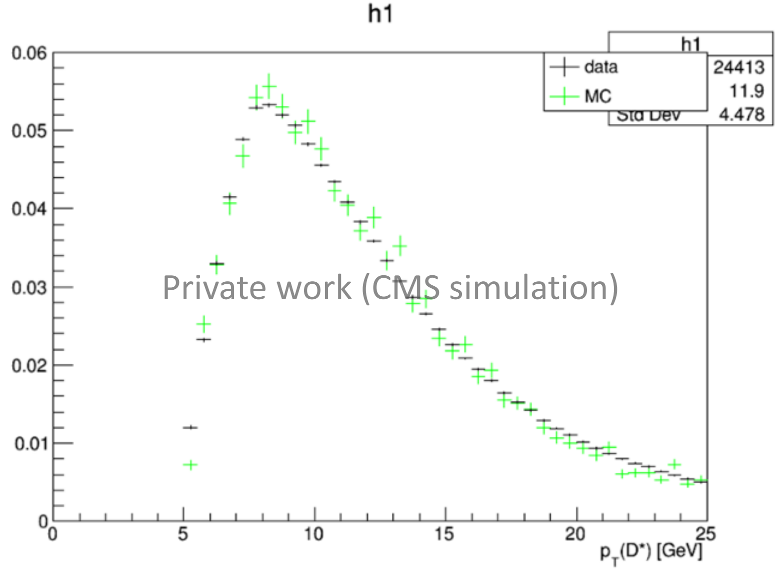
Trigger number	Name in Xb_frame	Weight coefficient
TRIG_0	HLT_Mu12_IP6_p	**0.959158**
TRIG_1	HLT_Mu10p5_IP3p5_p	**1**
TRIG_2	HLT_Mu9_IP6_p	**1**
TRIG_3	HLT_Mu9_IP5_p	**1**
TRIG_4	HLT_Mu9_IP4_p	**1**
TRIG_5	HLT_Mu8p5_IP3p5_p	**1**
TRIG_6	HLT_Mu8_IP6_p	**0.219137**
TRIG_7	HLT_Mu8_IP5_p	**0.220775**
TRIG_8	HLT_Mu8_IP3_p	**0.060694**
TRIG_9	HLT_Mu7_IP4_p	**0.19679**

The shapes after reweighting

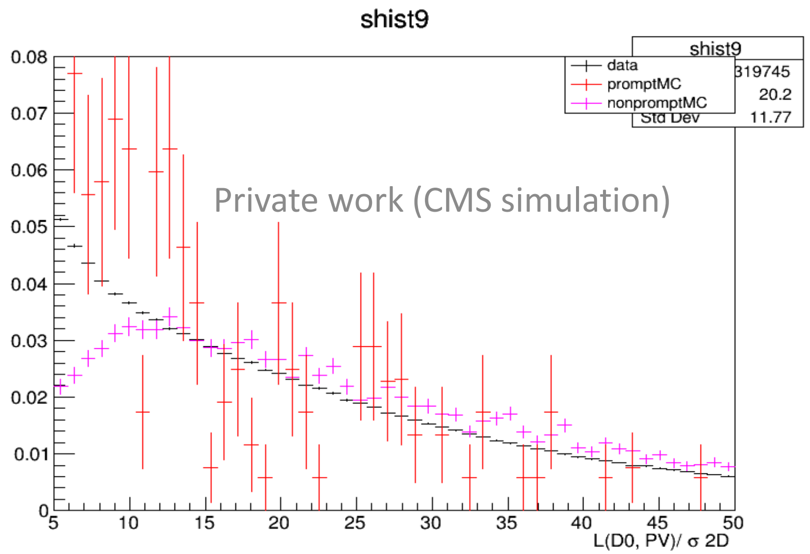


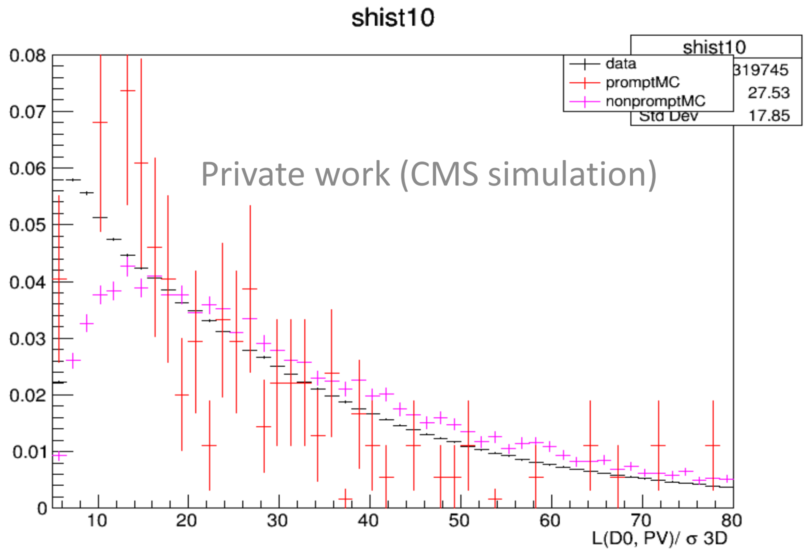






Disagreement in some variables





Probably could be fixed by generating more prompt MC and summing prompt and non-prompt MC in the right proportion?

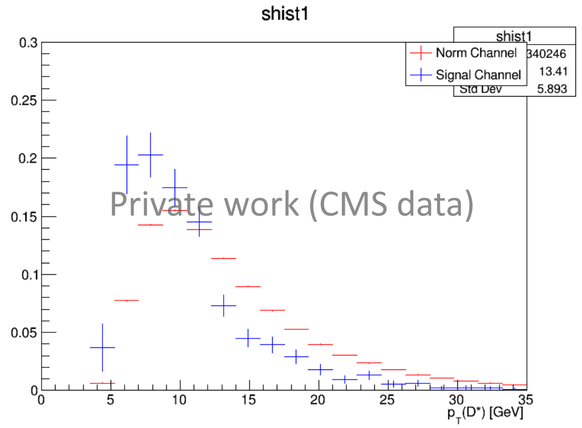
- The reweighting resulted in better agreement between MC and data in kinematic variables
- However, some variables, such as vertex displacement, still disagree between MC and data
- <u>We also have too few MC events left in the signal channel after weighting&trigger</u>

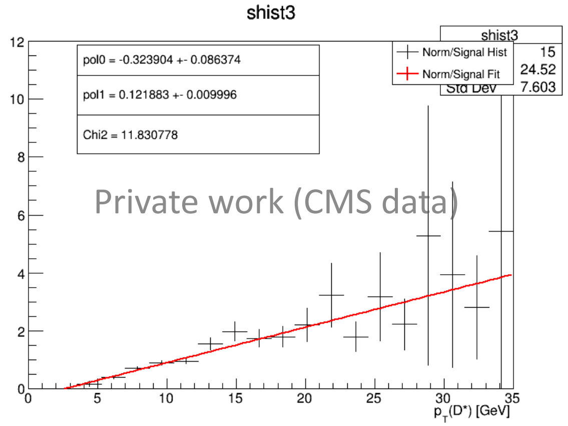
- **Hence, it was decided to perform optimization on data directly, instead of MC**
  - *This will not bias the ACP measurement, if done carefully*
  - *since at no point we use the D* meson charge in the optimization*

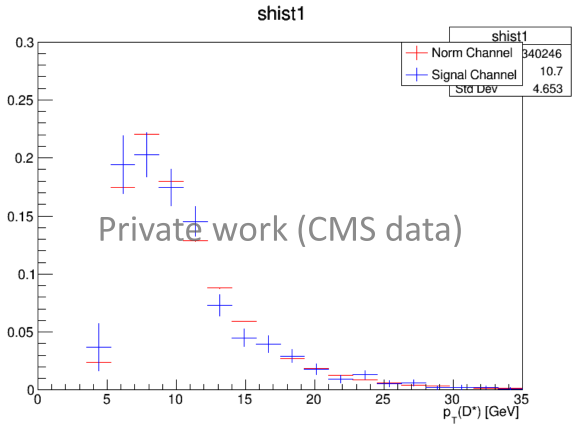
p_T-reweighting

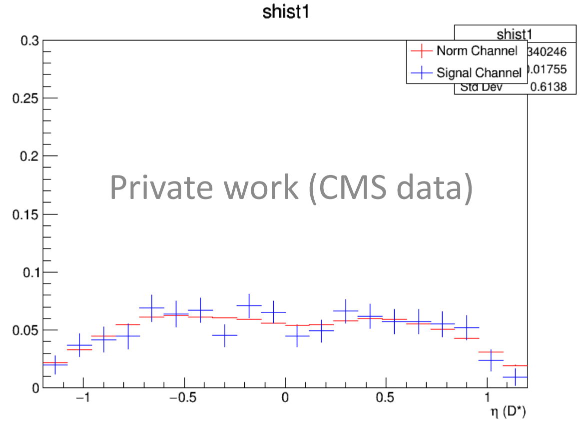
p_T-reweighting in $D^0 \to K^0_S \pi^+\pi^-$

- Different kinematics in norm and signal channels => detection and production asymmetries do not fully cancel out (can be seen from the comparison of $p_T(D^{*\pm})$ distributions in $D^0 \to K^0_S \pi^+\pi^-$ and $D^0 \to K^0_S K^0_S$)
- Fixed by reweighting of $D^0 \to K^0_S \pi^+\pi^-$ events to match the $p_T(D^{*\pm})$ distributions in $D^0 \to K^0_S K^0_S$



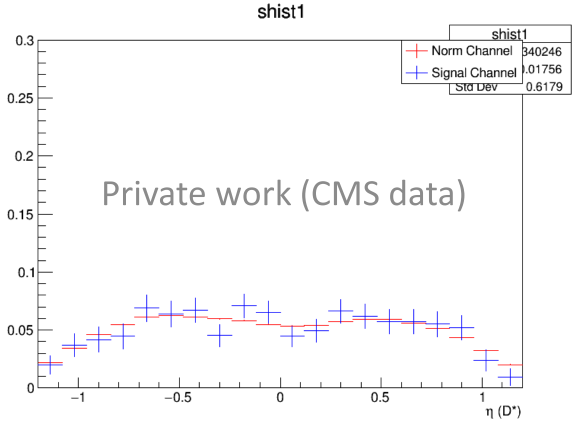






Reweighting

$$weight(event) = 1/(pol1 \cdot p_T(D^{*\pm})(event) + pol0)$$

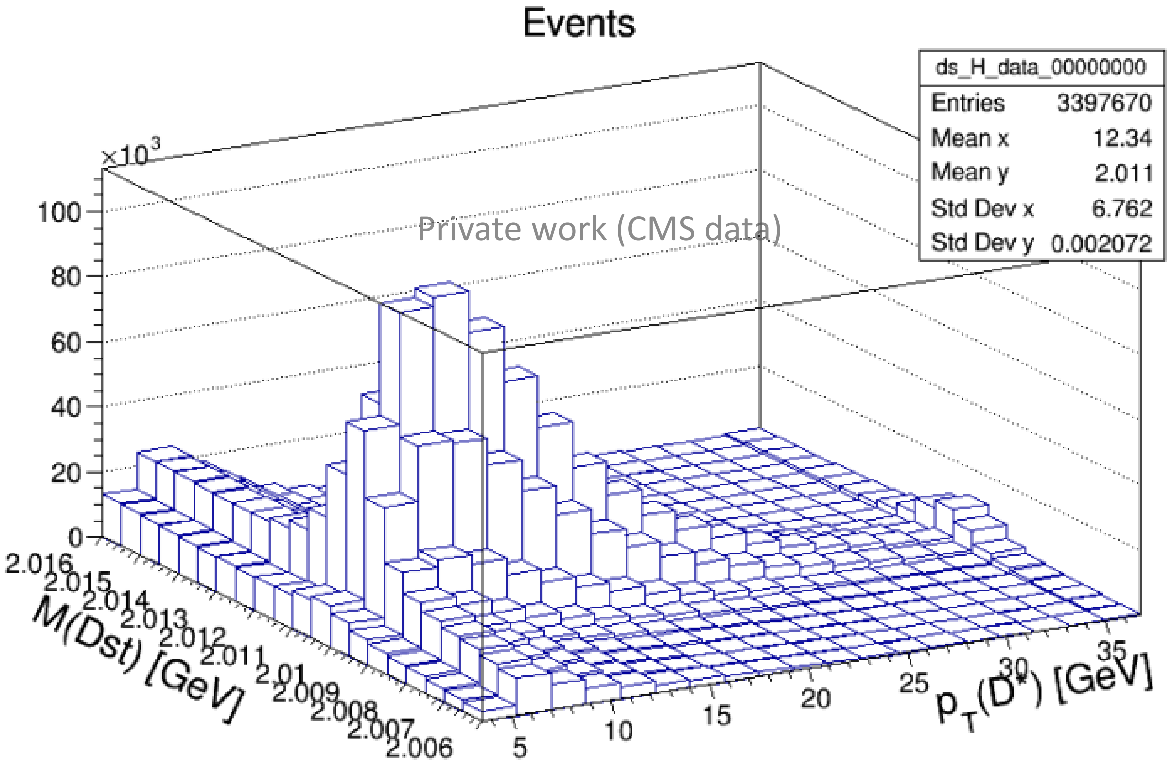


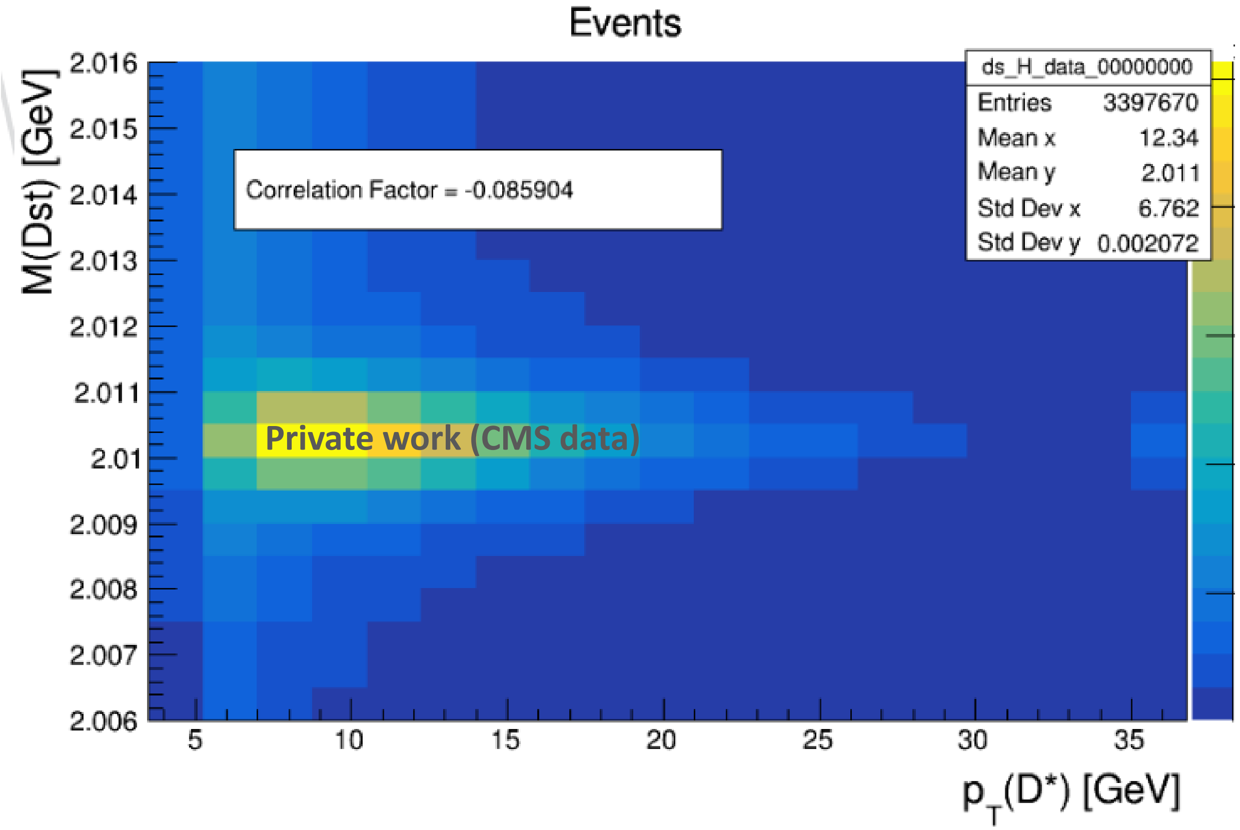
$p_T(D^{*\pm})$ and η $(D^{*\pm})$ spectra in $D^0 \to K^0_S \pi^+\pi^-$ and $D^0 \to K^0_S K^0_S$ prior to reweighting

$p_T(D^{*\pm})$ and η $(D^{*\pm})$ spectra in $D^0 \to K^0_S \pi^+\pi^-$ and $D^0 \to K^0_S K^0_S$ after the reweighting

Agreement achieved!

$M(K^0_S\pi^+\pi^-)$ vs $p_T(D^*)$ correlation

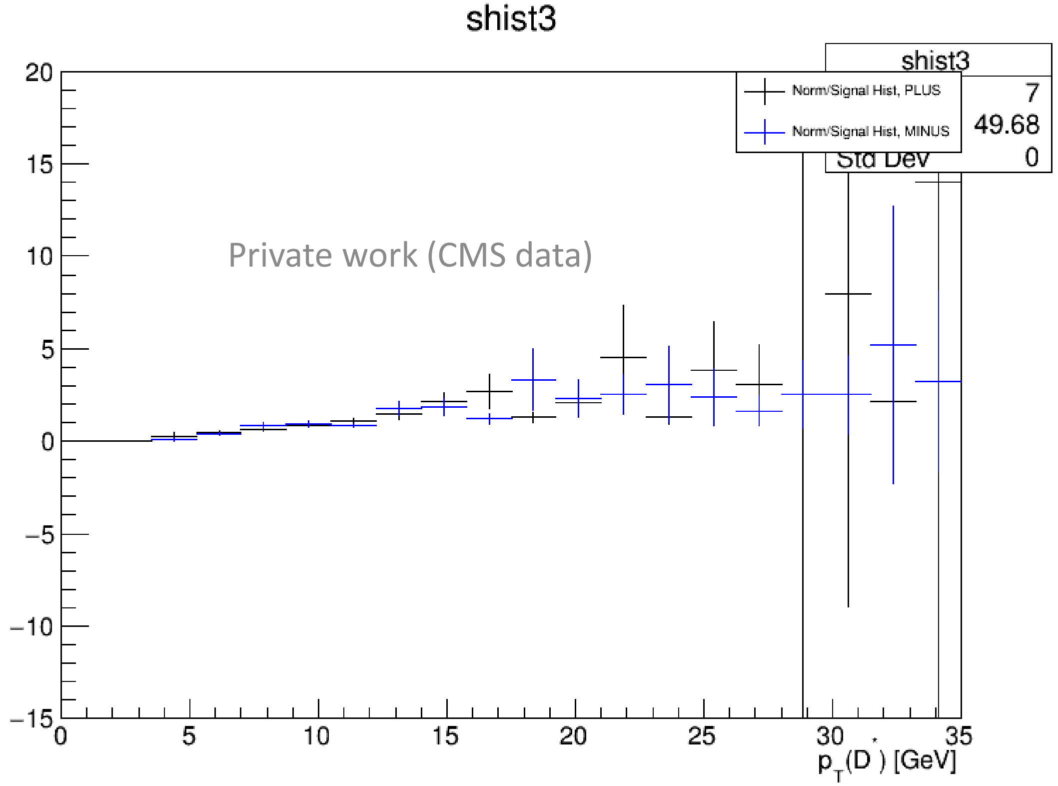




Hence, we can freely use splot based on $M(K^0{}_S\,\pi^+\pi^-)$ distribution for Pt-reweighting

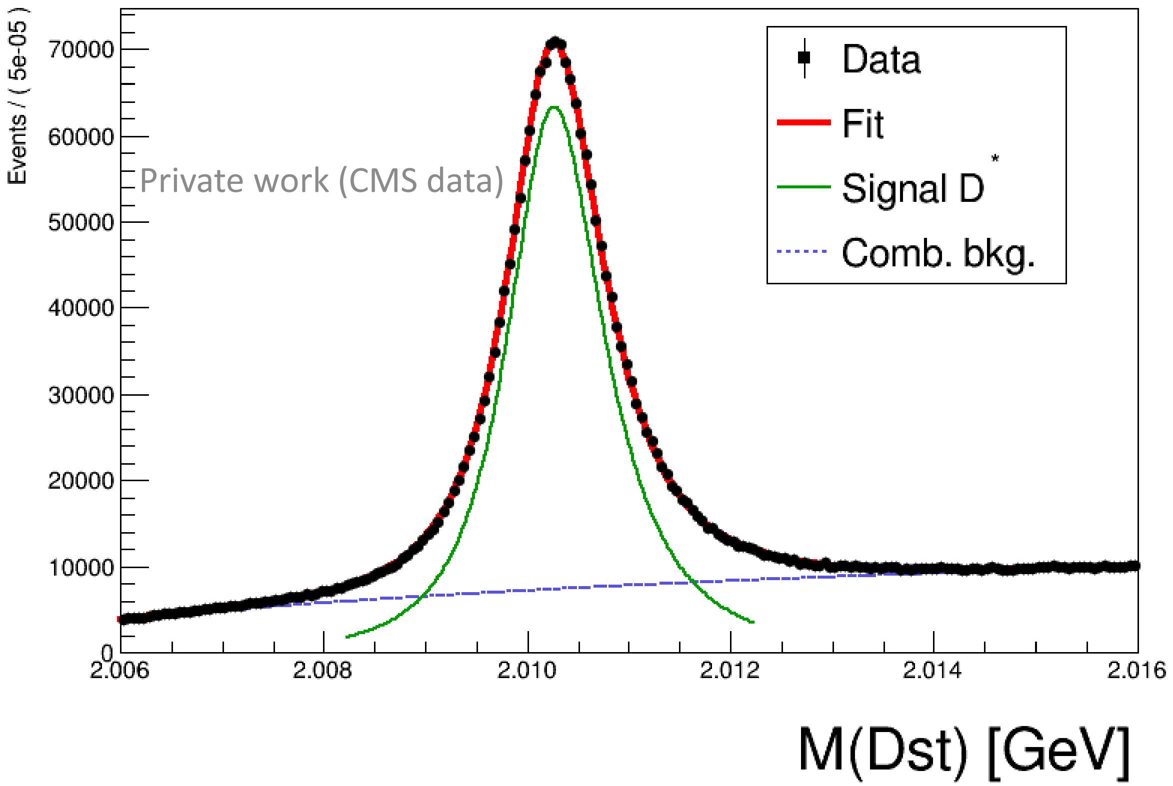
p_T-reweighting for π^+ and π^-

- Mismatch of $D^0 \to K^0_S \pi^+\pi^-$ and $D^0 \to K^0_S K^0_S$ can be different for π^+ and π^-
- *Can be checked through the comparison of Norm/signal ratio for* ***$p_T(D^{*+})$*** *and* ***$p_T(D^{*-})$*** *:*

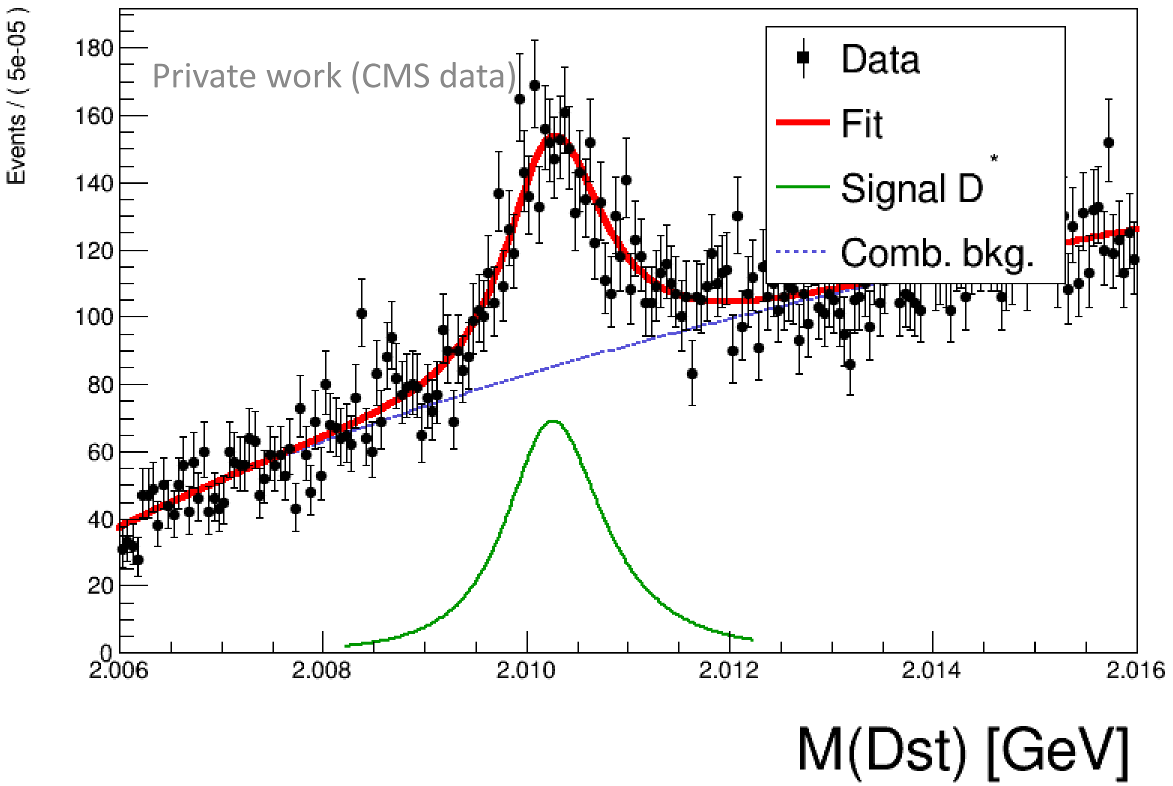


The weights are consistent between "+" and "-" across the relevant p_T range!

sPlots to extract the signals



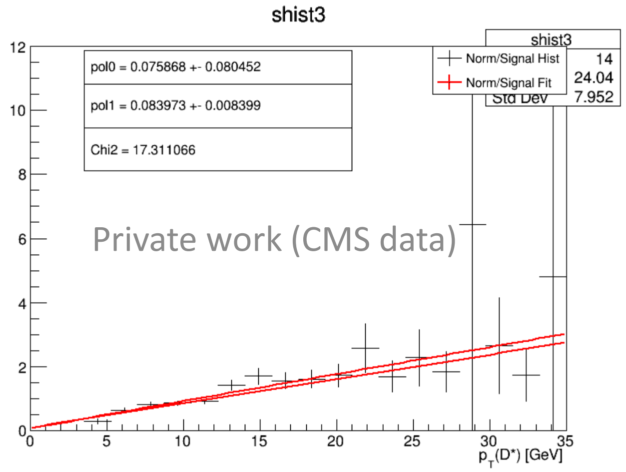
The plot for normalization channel background subtraction



The plot for signal channel background subtraction

Alternative Pt-reweighting: splot vs sideband-subtraction

splot



$A_{CP}^{raw}(D^0 \rightarrow K_S^0\pi^+\pi^-)$ = (0.572 ± 0.096)%

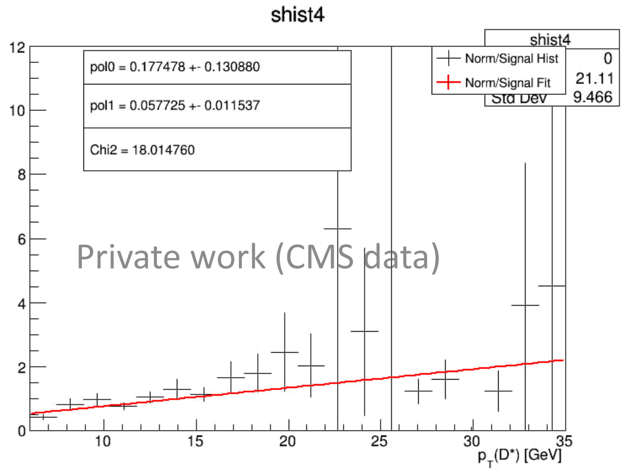
Sideband:

LSB: 2.006 GeV < M($K^0_S\pi^+\pi^-$) < 2.0078 GeV

SIG: 2.0078 GeV < M($K^0_S\pi^+\pi^-$) < 2.013 GeV

RSB: 2.013 GeV < M($K^0_S\pi^+\pi^-$) < 2.016 GeV

Pt_{SIG} - 0.5*Bgd_{SIG}*($\mathrm{Pt}_{LSB}/\ Bgd_{LSB}$ + $\mathrm{Pt}_{RSB}/\ Bgd_{RSB}$)



$A_{CP}^{raw}(D^0 \rightarrow K_S^0\pi^+\pi^-)$ = (0.516 ± 0.086)%

Identical values!

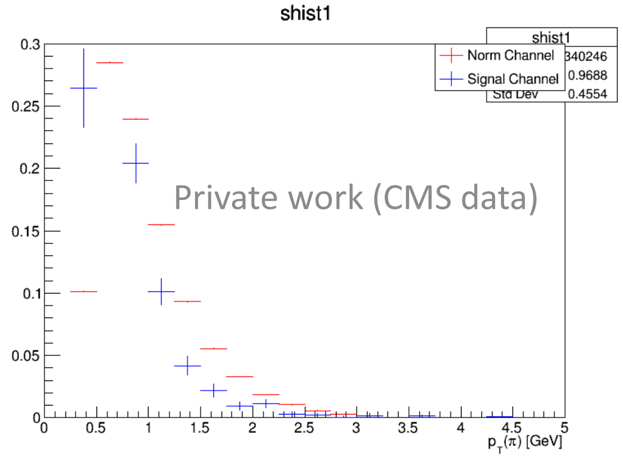
Cross-check: p_T of tagging pion

- Asymmetries are actually sensitive to the asymmetries between π^+ and π^-

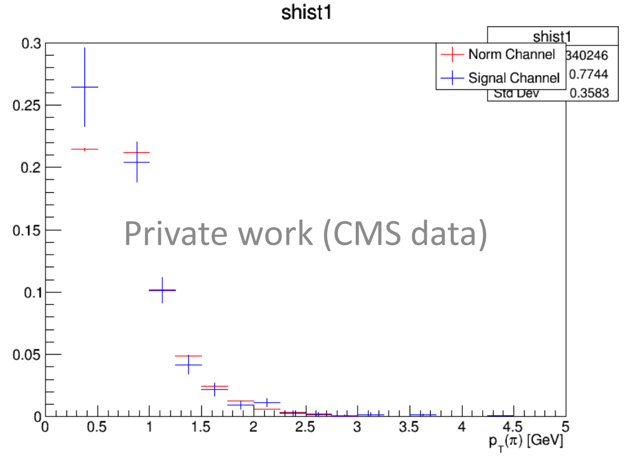
- **BUT:** we use identical selection criteria for $D^0 \to K^0_S K^0_S$ and $D^0 \to K^0_S \pi^+\pi^-$ during $D^{*\pm}$ reconstruction => $p_T(D^{*\pm})$ and $p_T(\pi^\pm)$ are highly correlated and all the differences between the shapes of $p_T(D^{*\pm})$ spectra signify that pion pt spectra have such deviations as well

- The $p_T(D^{*\pm})$-reweighting results in the fixing of $p_T(\pi^\pm)$ as well!

$p_T(\pi^\pm)$ spectra in $D^0 \to K^0_S \pi^+\pi^-$ and $D^0 \to K^0_S K^0_S$ prior to reweighting



$p_T(D^{*\pm})$-reweighting of the events



$p_T(\pi^\pm)$ spectra in $D^0 \to K^0_S \pi^+\pi^-$ and $D^0 \to K^0_S K^0_S$ after reweighting

- **As alternative:** we performed the same procedure but with p_T-reweighting based on **$p_T(\pi^\pm)$ spectra comparison.** We include the difference between the final value with **$p_T(\pi^\pm)$** and **$p_T(D^{*\pm})$** reweighting it into the systematics, but it is not leading contribution (see systematics section).

A_{CP}^{raw} in MC

A_{CP}^{raw} as function of p_T, η and ϕ

- Cross-check the A_{CP}^{raw} in MC vs. p_T, η and φ
  - Also compare to data, in the normalization channel
- η ranges: [-1.340;-0.804], [-0.804;-0.268], [-0.268;0.268], [0.268;0.804], [0.804;1.340]
- φ ranges: [-3.140;-1.884], [-1.884;-0.628], [-0.628;0.628], [0.628;1.884], [1.884;3.140]
- p_T ranges in GeV: [3.78; 6.00], [6.00; 7.50], [7.50; 11.00], [11.00; 15.00], [15.00; ∞)

- pion charge tags the flavor: $Q > 0 \rightarrow D^0$, $Q < 0 \rightarrow anti - D^0$

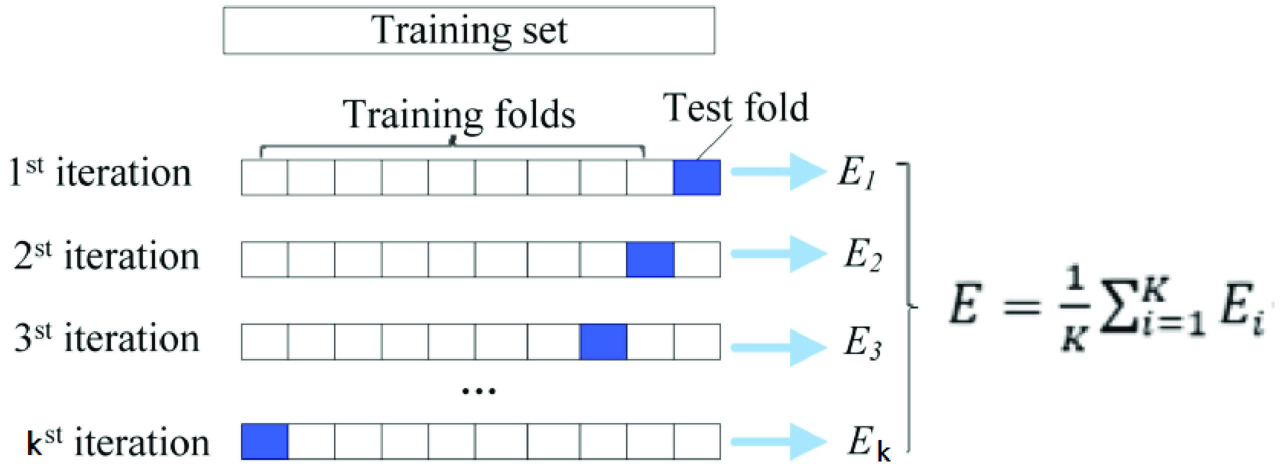
Optimization of selection criteria

The strategy of the selection optimization

- *dN/N* – the relative uncertainty in signal channel N^{raw} is optimized

  (D^0 and $\overline{D^0}$ are not split during the optimization in order not to bias $A_{CP}(D^0 \to K^0_S K^0_S)$)!

- The procedure *of k-fold cross-validation* is performed (k = 6) while choosing the optimal cut:



- Then the procedure is looped over other cuts

Local and global minimum

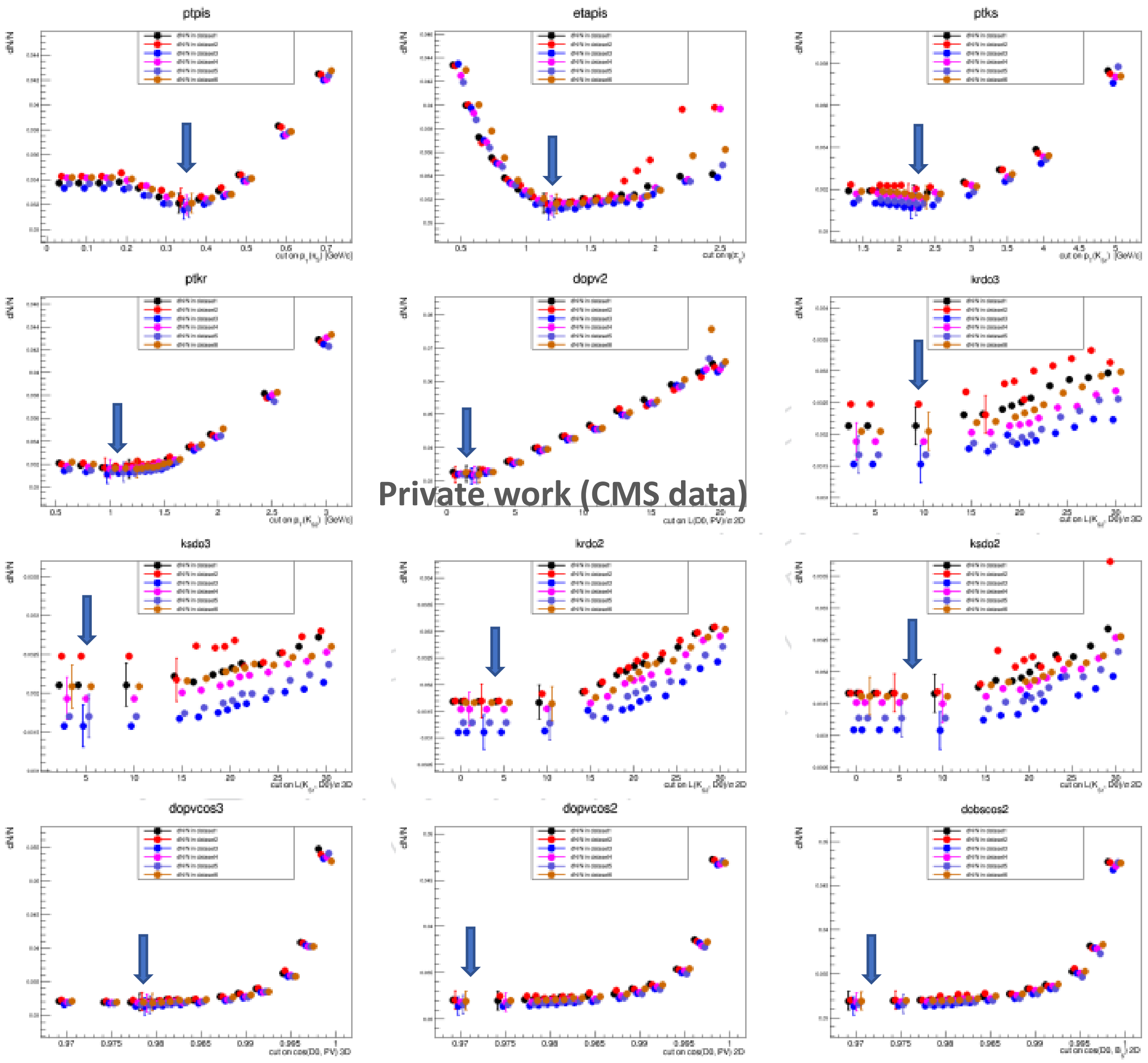
- The procedure is repeated until the criteria remain unchanged with further iterations (=> *the value is at "local minimum"*)
- Different starting point or another order of parameters may lead to another local minimum
- Among all found local minima the one with the smallest value of dN/N is chosen => **global minimum**

- The procedure was checked to be robust against different sets of starting cuts and orders of cuts to be optimized

The variables to cut

- p_T and η of tagging pion
- Topological variables of the fitted vertices
  - flight significances
  - Vertex fit probabilities
  - angle between the flight length and the momentum of D*, D^0, K_S^0
- p_T of soft K_S^0, hard K_S^0
- η and p_T and D^0 and D* are not considered, as being highly correlated with the slow pion

Optimization of selection



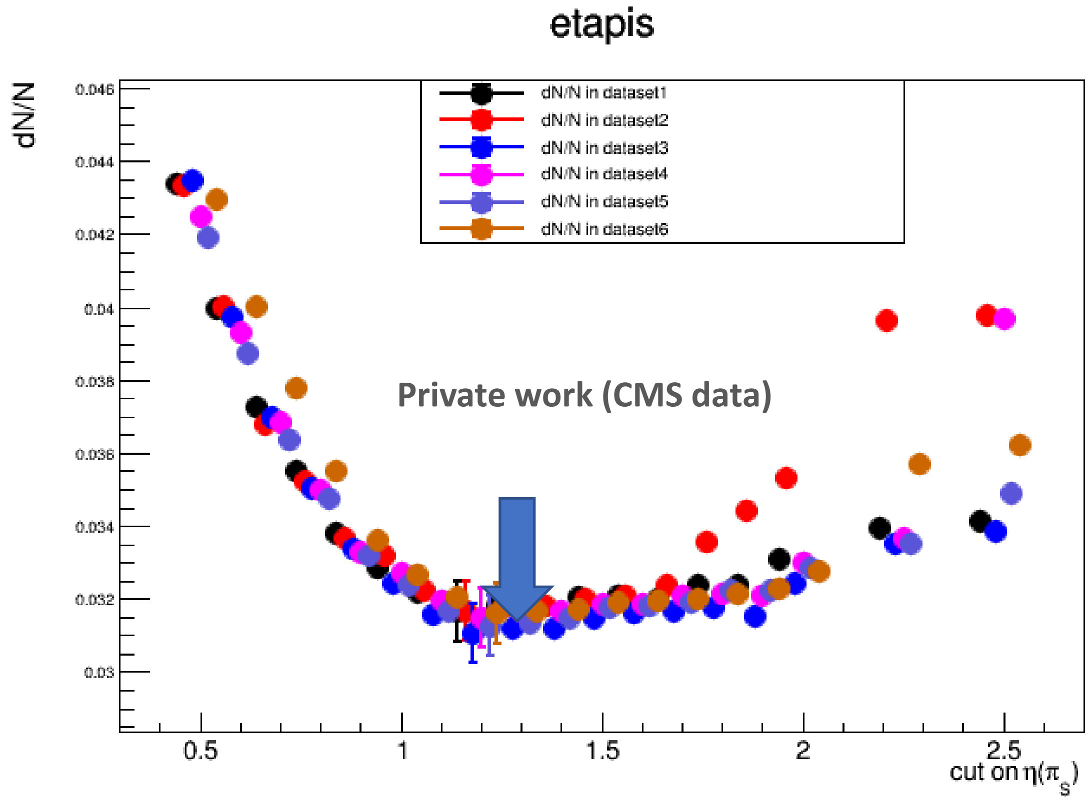
Different colors: 6 different combinations of subdatasets.

Points with error bars: dN/N minimum

(sorry that the plots are not readable: to be fixed next time)

Resulting optimized selection criteria

Example of parameter optimization: dN/N with different cuts on η of tagging pion. Different colors: 6 different subdatasets. Dots with errorbars are minimizing.



Optimized selection criteria:

Variable	Requirement
mass of $D^{*\pm}$	$2.006\,\mathrm{GeV} < M(D^{*\pm}) < 2.016\,\mathrm{GeV}$
mass of D^0 ($\overline{D}^0$)	$1.770\,\mathrm{GeV} < M(D^0\,(\overline{D}^0)) < 1.950\,\mathrm{GeV}$
p_T of tagging pion from $D^{*\pm} \to D\pi^\pm$	$> 0.35\,\mathrm{GeV}$
η of tagging pion from $D^{*\pm} \to D\pi^\pm$	$-1.2 < \eta < 1.2$
$max(p_T(K))$	$> 2.2\,\mathrm{GeV}$
$min(p_T(K))$	$> 1.0\,\mathrm{GeV}$
$P_{vtx}(D^{*\pm})$	$> 5\%$
$P_{vtx}(D^0)$	$> 1\%$
$P_{vtx}(max(K^0_S))$	$> 1\%$
$P_{vtx}(min(K^0_S))$	$> 1\%$
$L_{xy}/\sigma_{L_{xy}}$, D^0 2D displacement significance,	> 2
$L_{xyz}/\sigma_{L_{xyz}}$, D^0 3D displacement significance,	> 9
$L_{xyz}/\sigma_{L_{xyz}}$, soft K^0_S 3D displacement from D^0 significance,	> 9
$L_{xyz}/\sigma_{L_{xyz}}$, hard K^0_S 3D displacement from D^0 significance,	> 7
$\cos(\vec{L}_{xyz}(D^0), \vec{p}(D^0))$ (3D)	> 0.979
$\cos(\vec{L}_{xy}(D^0), \vec{p}(D^0))$ (2D)	> 0.972
$\cos(\vec{L}_{xy}(D^0, Beamspot)$ (2D)	> 0.972

The same cuts are applied for final $K^0_S\,\pi^+\pi^-$ fit: $p_T(\pi^+\pi^-) > 1.0$ GeV; $p_T\,(K^0_S) > 2.2$ GeV)

Optimized selection criteria

Normalization channel cuts were chosen to match the cuts of the signal channel

Optimized selection criteria in signal channel:

Variable	Requirement
mass of $D^{*\pm}$	$2.006\,\text{GeV} < M(D^{*\pm}) < 2.016\,\text{GeV}$
mass of D^0 ($\overline{D}^0$)	$1.770\,\text{GeV} < M(D^0\,(\overline{D}^0)) < 1.950\,\text{GeV}$
p_T of tagging pion from $D^{*\pm} \to D\pi^\pm$	$> 0.35\,\text{GeV}$
η of tagging pion from $D^{*\pm} \to D\pi^\pm$	$-1.2 < \eta < 1.2$
$max(p_T(K))$	$> 2.2\,\text{GeV}$
$min(p_T(K))$	$> 1.0\,\text{GeV}$
$P_{vtx}(D^{*\pm})$	$> 5\%$
$P_{vtx}(D^0)$	$> 1\%$
$P_{vtx}(max(K^0_S))$	$> 1\%$
$P_{vtx}(min(K^0_S))$	$> 1\%$
$L_{xy}/\sigma_{L_{xy}}$, D^0 2D displacement significance,	> 2
$L_{xyz}/\sigma_{L_{xyz}}$, D^0 3D displacement significance,	> 9
$L_{xyz}/\sigma_{L_{xyz}}$, soft K^0_S 3D displacement from D^0 significance,	> 9
$L_{xyz}/\sigma_{L_{xyz}}$, hard K^0_S 3D displacement from D^0 significance,	> 7
$\cos(\vec{L}_{xyz}(D^0), \vec{p}(D^0))$ (3D)	> 0.979
$\cos(\vec{L}_{xy}(D^0), \vec{p}(D^0))$ (2D)	> 0.972
$\cos(\vec{L}_{xy}(D^0, Beamspot)$ (2D)	> 0.972

Optimized selection criteria in normalization channel:

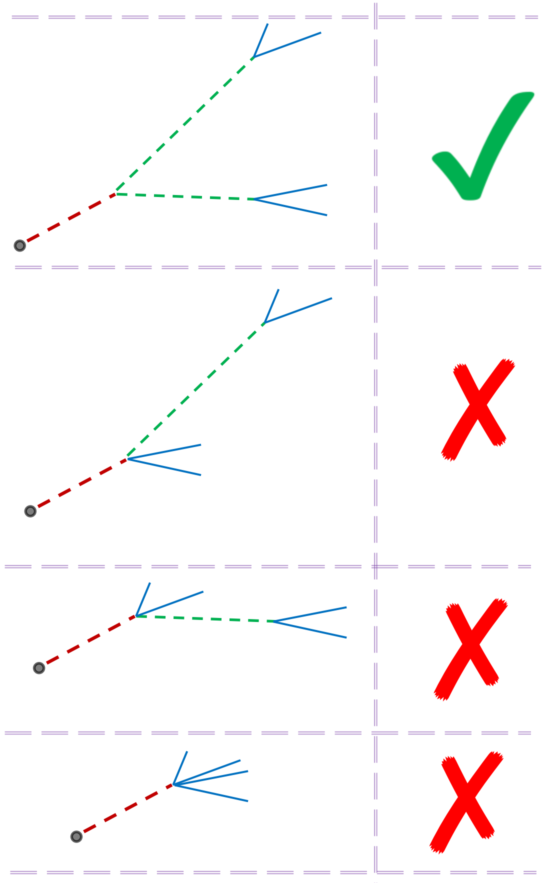
Variable	Requirement
mass of $D^{*\pm}$	$2.006\,\text{GeV} < M(D^{*\pm}) < 2.016\,\text{GeV}$
mass of D^0 ($\overline{D}^0$)	$1.823\,\text{GeV} < M(D^0\,(\overline{D}^0)) < 1.908\,\text{GeV}$
p_T of tagging pion from $D^{*\pm} \to D\pi^\pm$	$> 0.35\,\text{GeV}$
η of tagging pion from $D^{*\pm} \to D\pi^\pm$	$-1.2 < \eta < 1.2$
$p_T(K)$	$> 2.2\,\text{GeV}$
$p_T(\pi^-) + p_T(\pi^+)$	$> 1.0\,\text{GeV}$
$P_{vtx}(D^{*\pm})$	$> 5\%$
$P_{vtx}(D^0)$	$> 1\%$
$P_{vtx}(K^0_S)$	$> 1\%$
$L_{xy}/\sigma_{L_{xy}}$, D^0 2D displacement significance,	> 2
$L_{xyz}/\sigma_{L_{xyz}}$, D^0 3D displacement significance,	> 9
$L_{xyz}/\sigma_{L_{xyz}}$, K^0_S 3D displacement from D^0 significance,	> 7
$\cos(\vec{L}_{xyz}(D^0), \vec{p}(D^0))$ (3D)	> 0.979
$\cos(\vec{L}_{xy}(D^0), \vec{p}(D^0))$ (2D)	> 0.972
$\cos(\vec{L}_{xy}(D^0, Beamspot)$ (2D)	> 0.972

Wrong vertex fit selection criteria

- "Wrong" vertex fits are performed:
  - In **signal $\mathbf{K_S^0 K_S^0}$ channel**:
    - ❑ Attempt to fit all 4 pions into one vertex → $P^{x}_{4\pi}$ *(fit probability)*
    - ❑ Attempt to fit one $\mathbf{K_S^0}$ and two pions from another $\mathbf{K_S^0}$ into one vertex

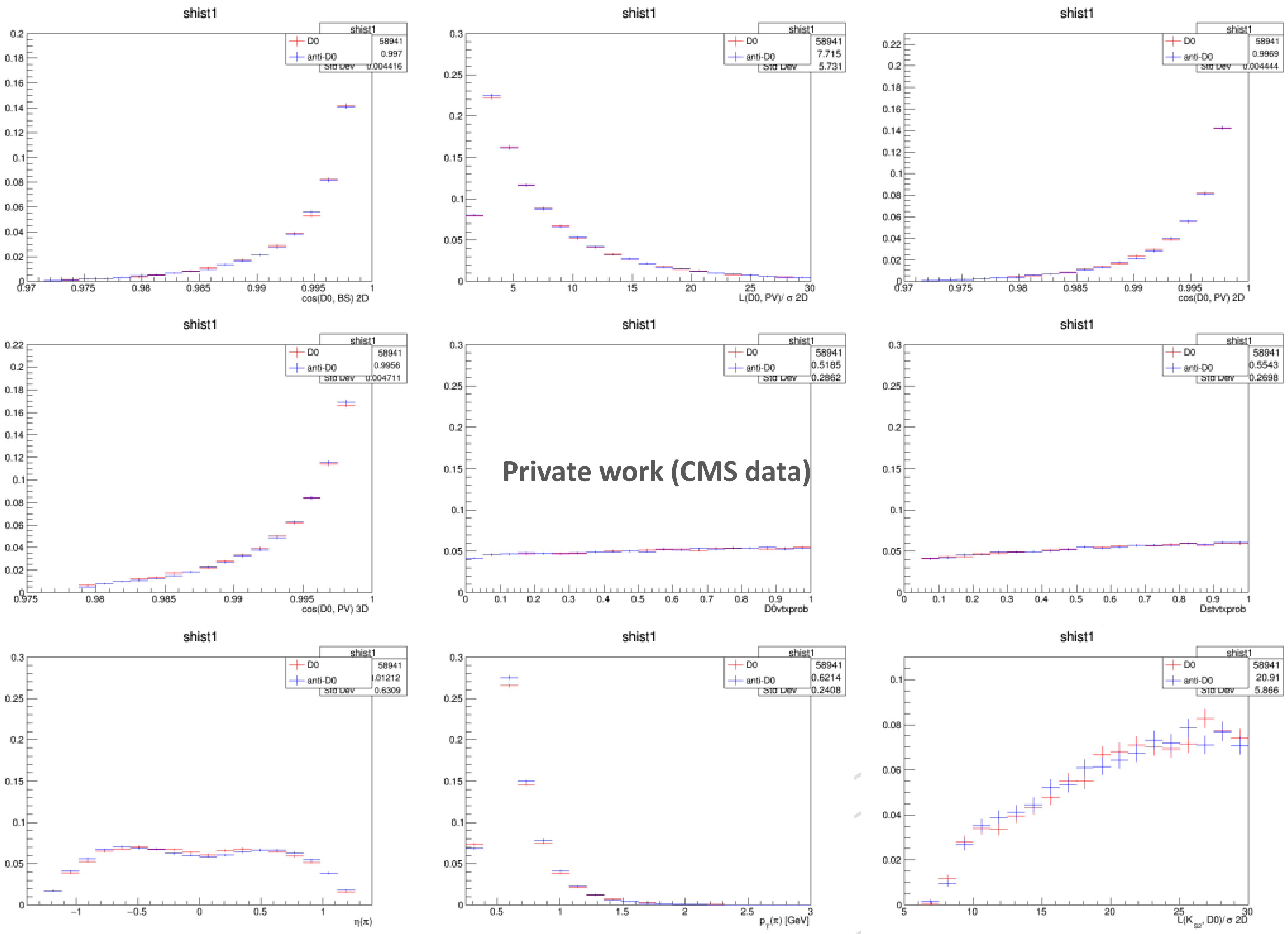
      reproducing topology of normalization channel,

      Done twice since we have two $\mathbf{K_S^0}$ candidates → $P^{x1}_{K\pi\pi}$ and $P^{x2}_{K\pi\pi}$
  - In **reference channel**:
    - ❑ Attempt to fit all 4 pions into one vertex → $P^{x}_{4\pi}$
- Suppress background by:
  - ➢ $P^{x}_{4\pi} < 10^{-8}$ (efficiency is 99.7% in both channels)
- Suppression $\mathbf{K_S^0 \pi^+ \pi^-}$ cross-feed into $\mathbf{K_S^0 K_S^0}$:
  - $P^{x1}_{K\pi\pi} < 10^{-8}$ and $P^{x2}_{K\pi\pi} < 10^{-8}$
  - Verified on MC: zero events cross-feed

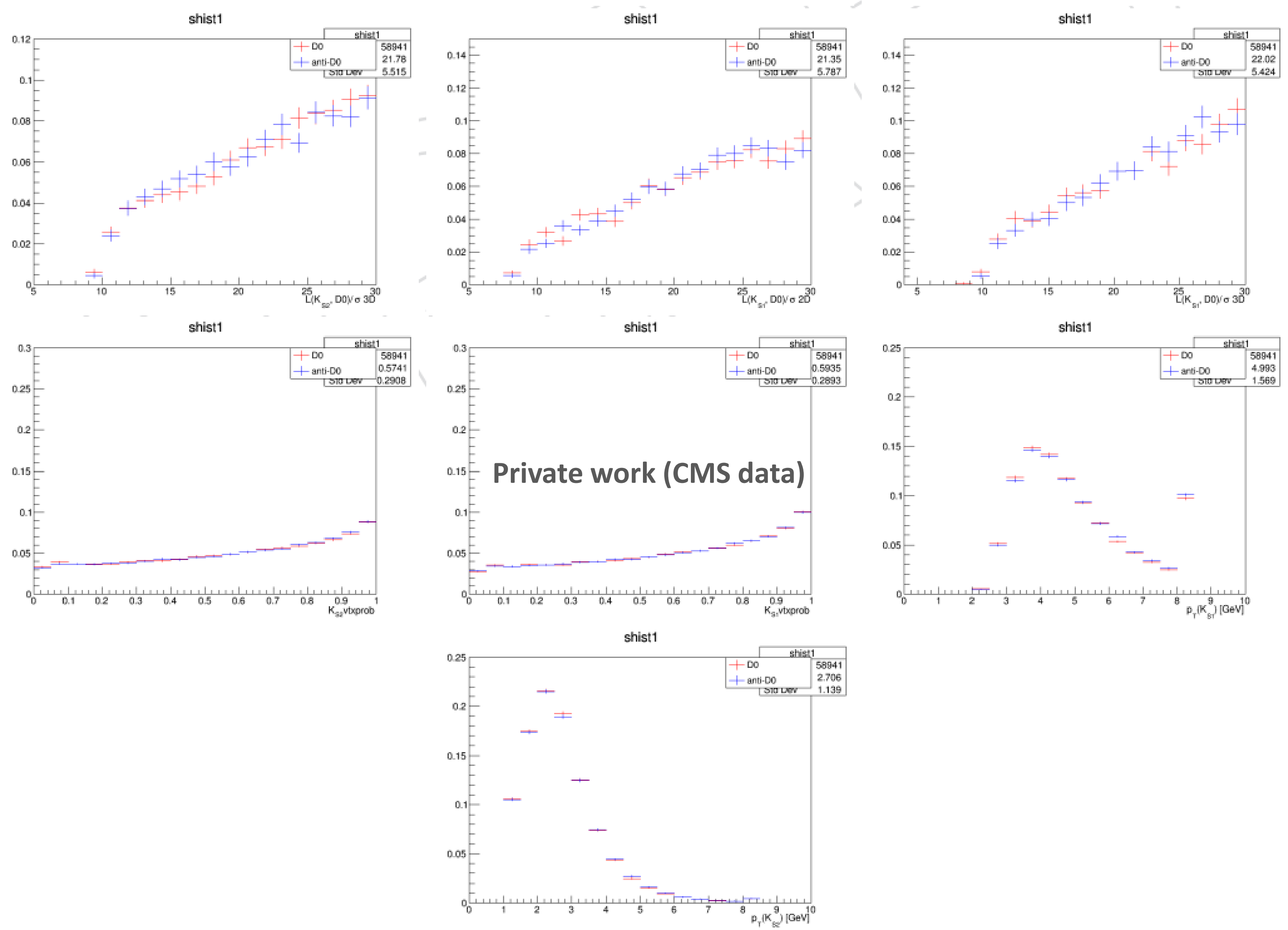


D^0 vs. anti-D^0 in MC

optimized variables in MC: D^0 vs. anti-D^0



optimized variables in MC: D^0 vs. anti-D^0



Signal shape vs the D^0 flavour

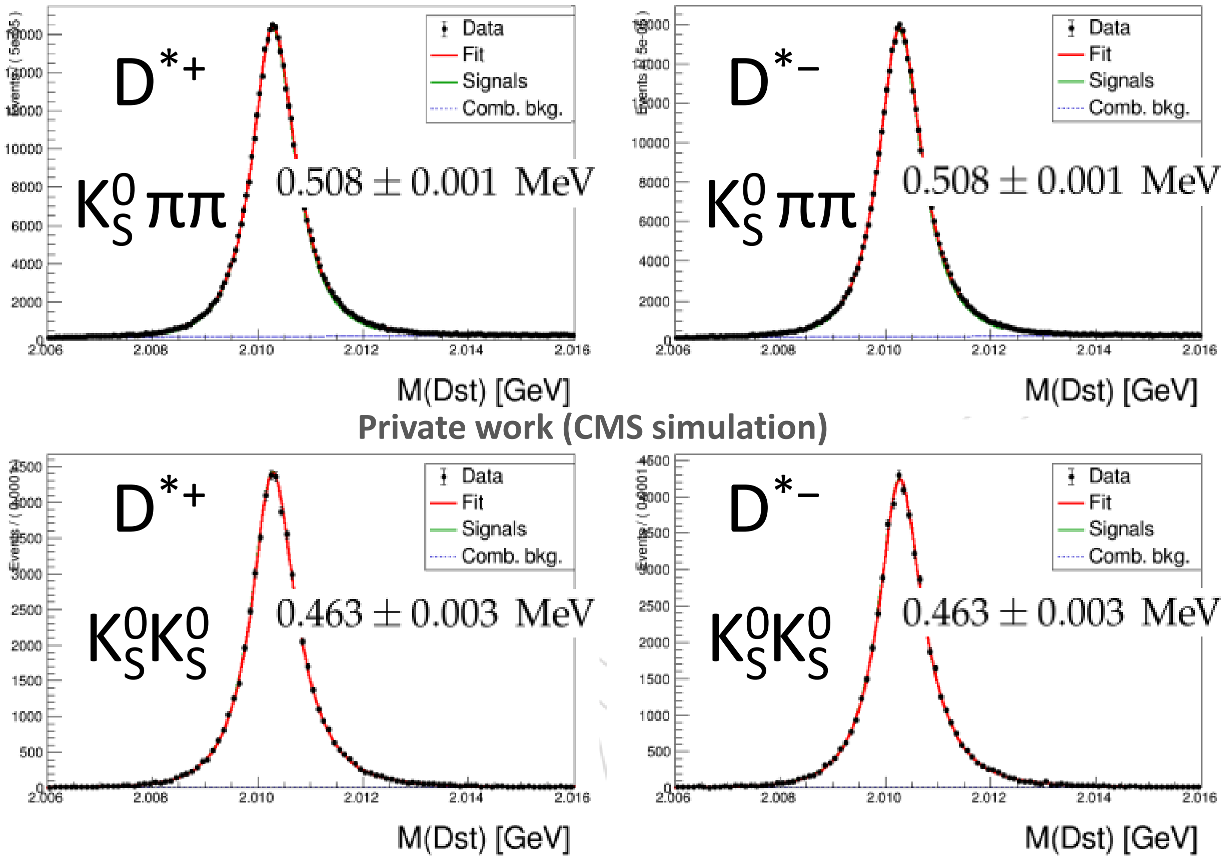
(no trigger requirement)

- Does the signal shape differ for D^{*+} and D^{*-} ?
- Comparing signal width in MC

(with all other Johnson parameters fixed)

Widths are found to be identical between + and –

- Also in case of D^0 signal
- Also in case we apply trigger&weights
- χ^2/ndf show good fit quality



The shapes are the same.
We are implementing a ***simultaneous fit*** *on D^{*+} and D^{*-} samples,*
sharing the shape parameters and leaving only the yields to be independent