# Precision measurement of CP violation in charm decays at CDF

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# CP violation in charm: an unique probe

- Processes involving K and B mesons have always been regarded as the most interesting probe of flavor and CP violation

- In the SM, the largest flavor/CP violating effects appear in the down sector, since the top mass is the main source of flavor violation and charged-current loops are needed to communicate symmetry breaking, in agreement with the GIM mechanism

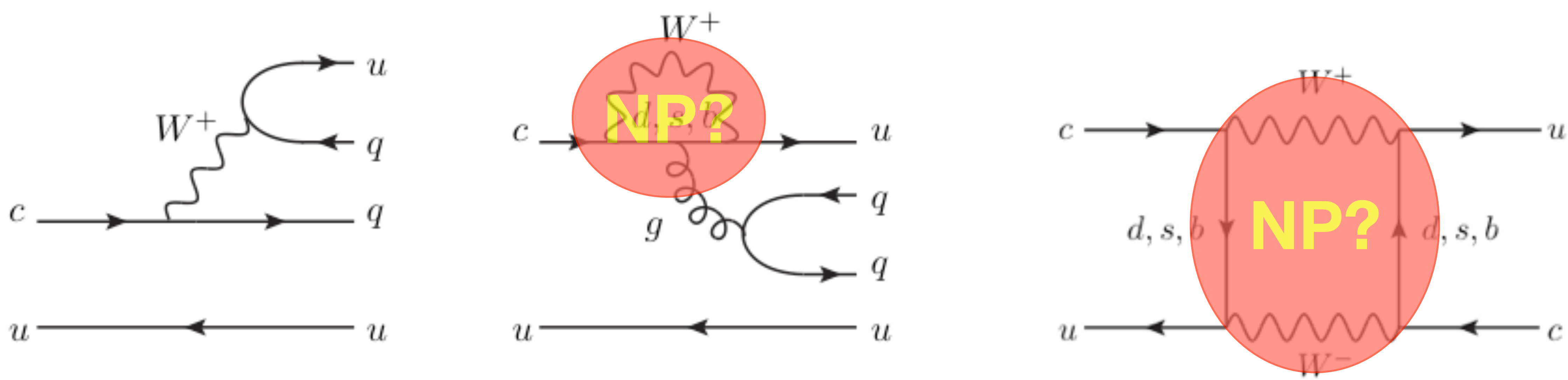
- While these properties hold in the SM, there is no good reason for them to be true if NP is present at the electroweak scale

    - In particular, it is quite plausible that NP contributions affect mostly the up-type sector, possibly in association with the mechanism responsible for the large top mass

- Charm is the only up-type quark where we can look for flavor/CP violation

# $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ decays

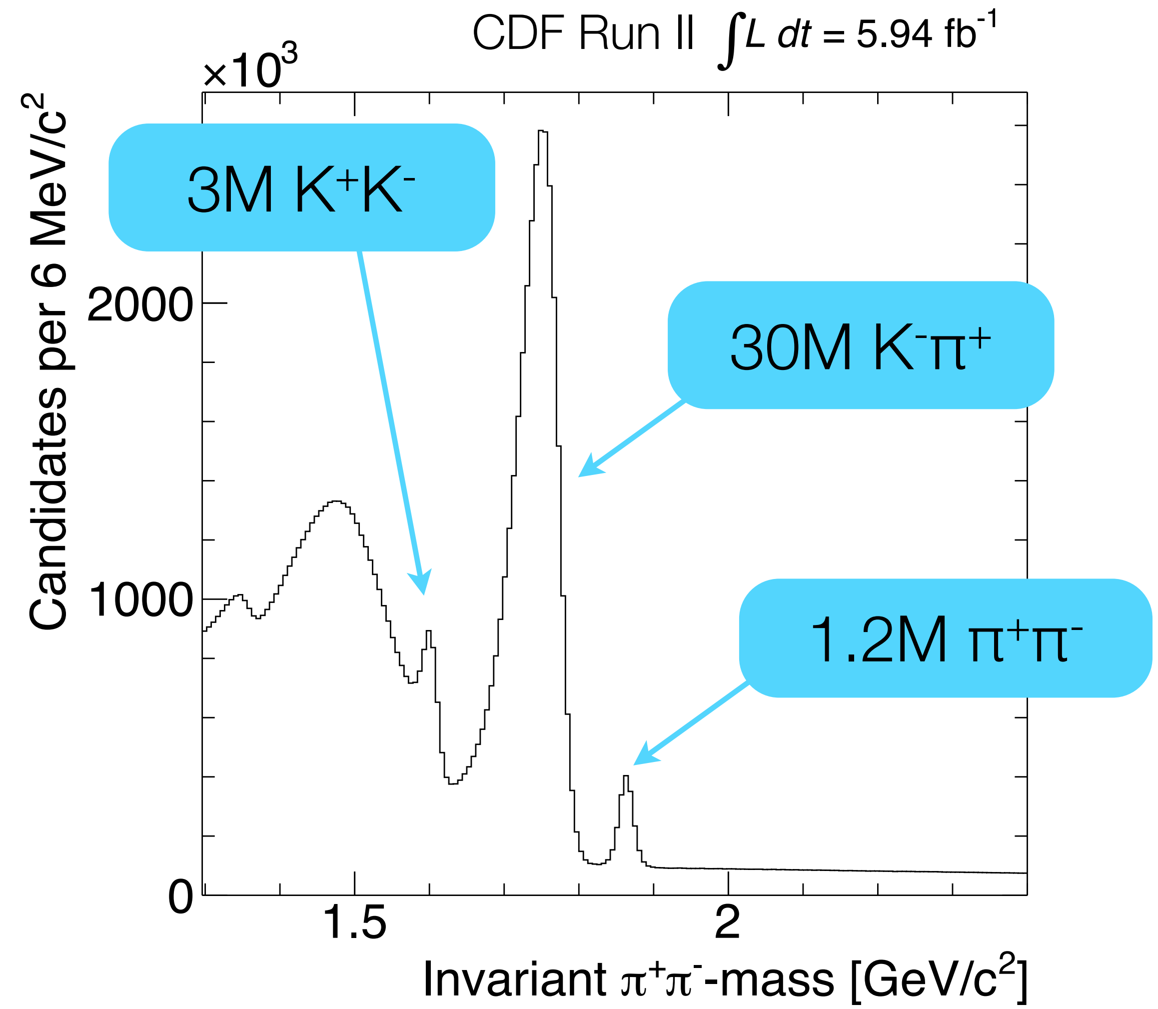
- Singly–Cabibbo–suppressed decays ($c \rightarrow uq\bar{q}$) are interesting channels to be analyzed
  - Interference between tree and penguin amplitudes can generate O(0.1%)direct CP asymmetries
  - Good candidate for NP to show up inducing O(1%) asymmetries

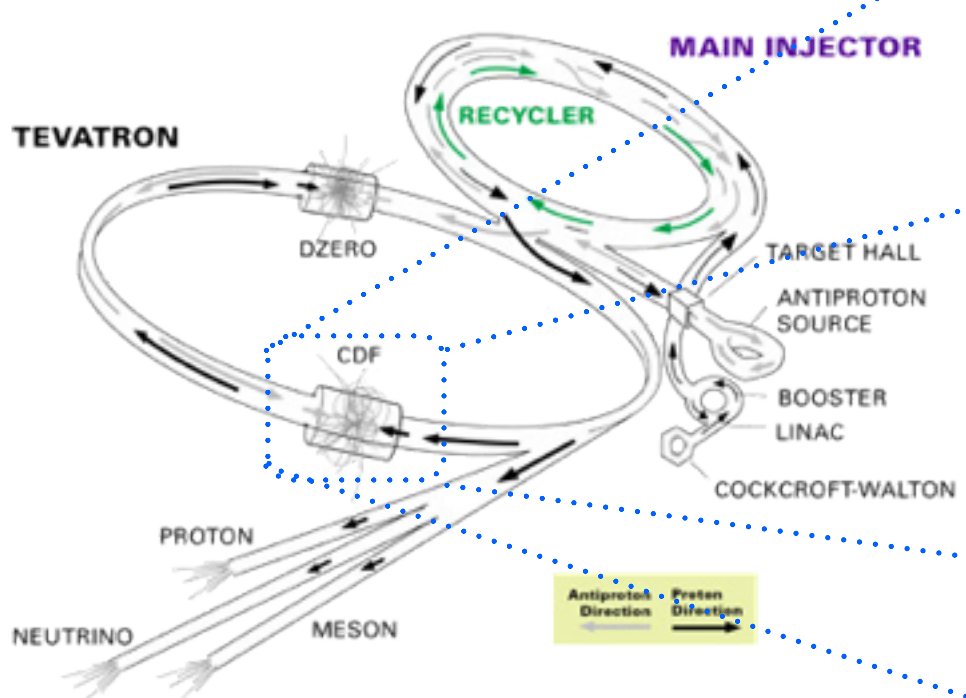


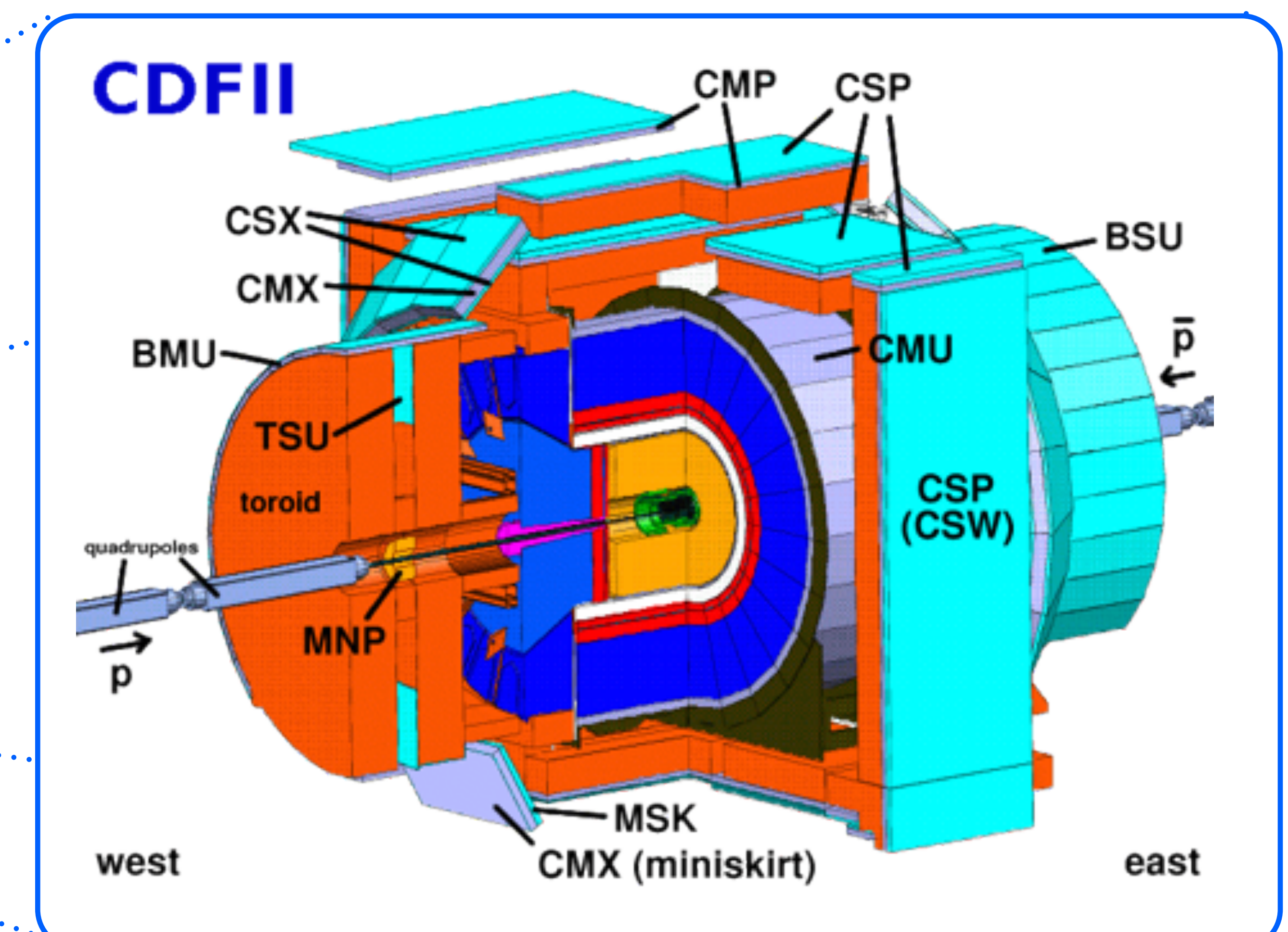

- Precision reached by B-factories (0.3-0.5%) is not enough to be conclusive
- Decays into two charged bodies are also experimentally easy

# Charm at CDF

- 10 years of successful TeVatron operations: ~$10^{13}$ $p\bar{p}$ collisions at 1.96 TeV
- High $c\bar{c}$ cross section: ~1% of collisions yields a D meson
- Millions of decays collected



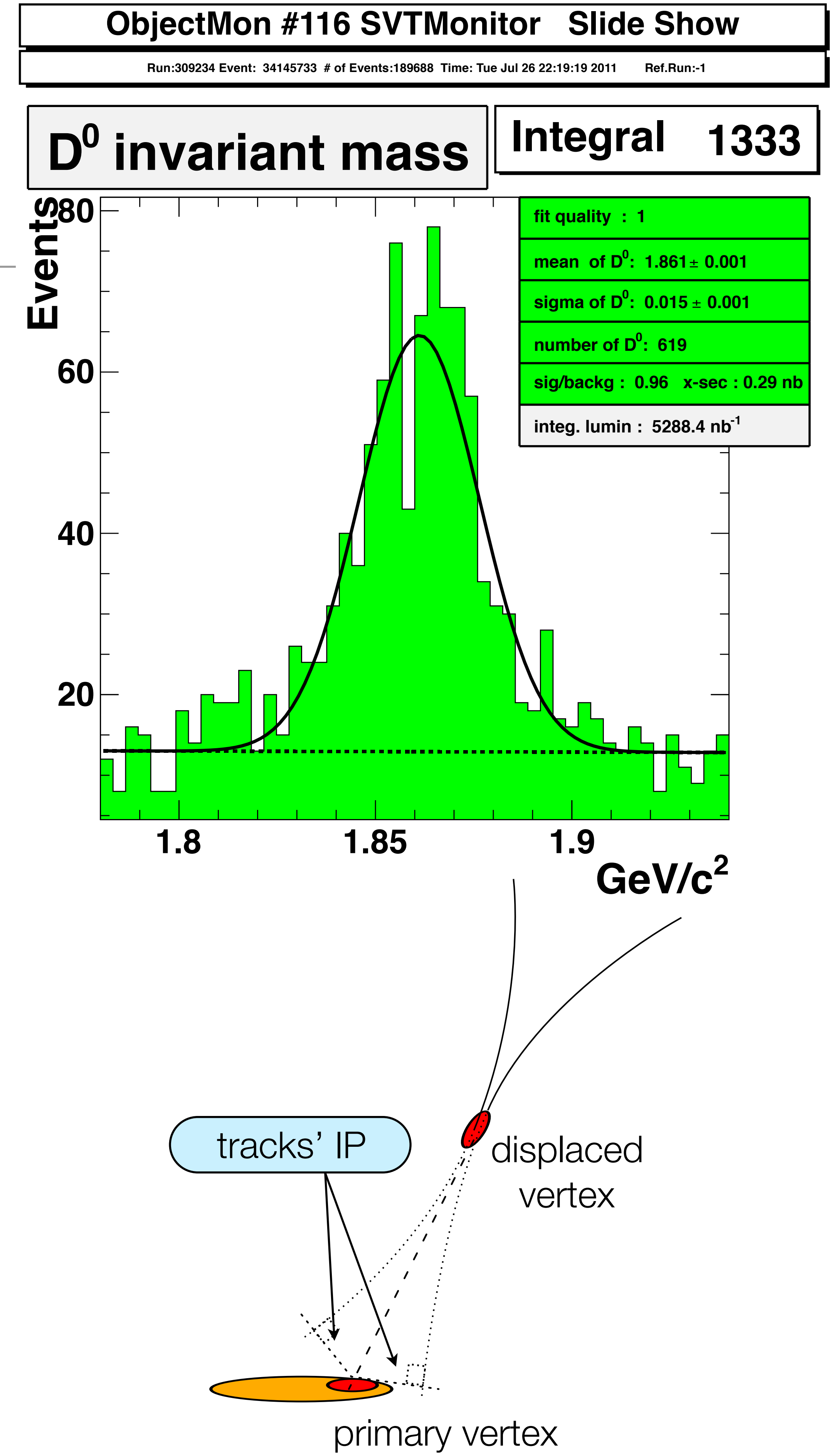



# Silicon Vertex Trigger

- Dedicated hardware combines information from drift chamber and silicon

- In 20μs finds all central tracks with $p_T > 2$ GeV/c and determines their impact parameters with ~40μm resolution

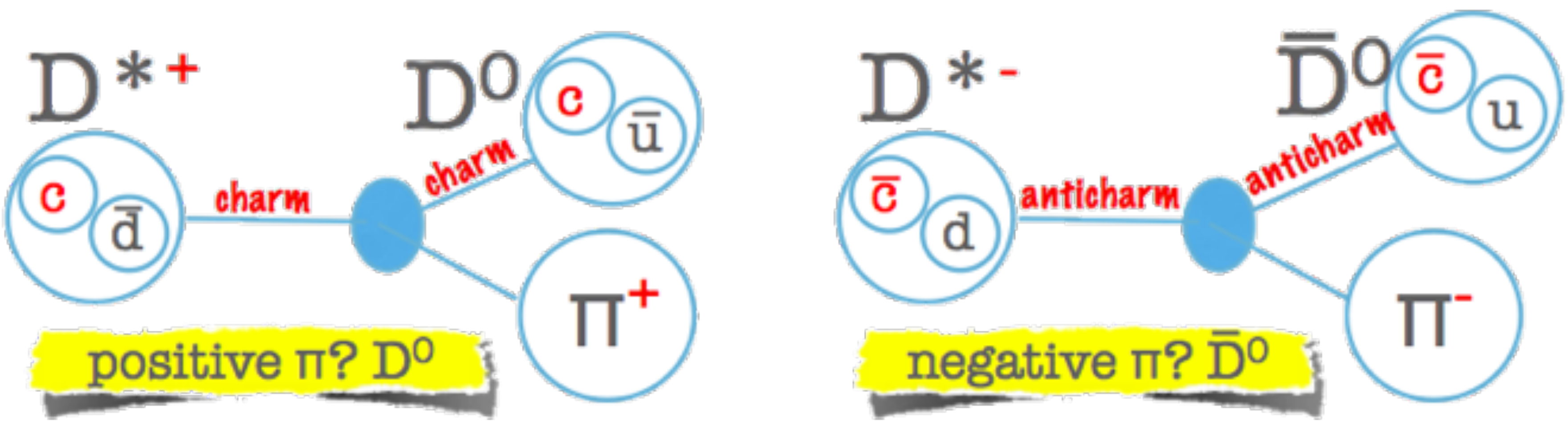
- Without it these (as many other flavor) measurements would have never been possible



# What do we measure?

$$A_{CP}(D^0 \to h^+h^-) = \frac{\Gamma(D^0 \to h^+h^-) - \Gamma(\overline{D}^0 \to h^+h^-)}{\Gamma(D^0 \to h^+h^-) + \Gamma(\overline{D}^0 \to h^+h^-)}$$

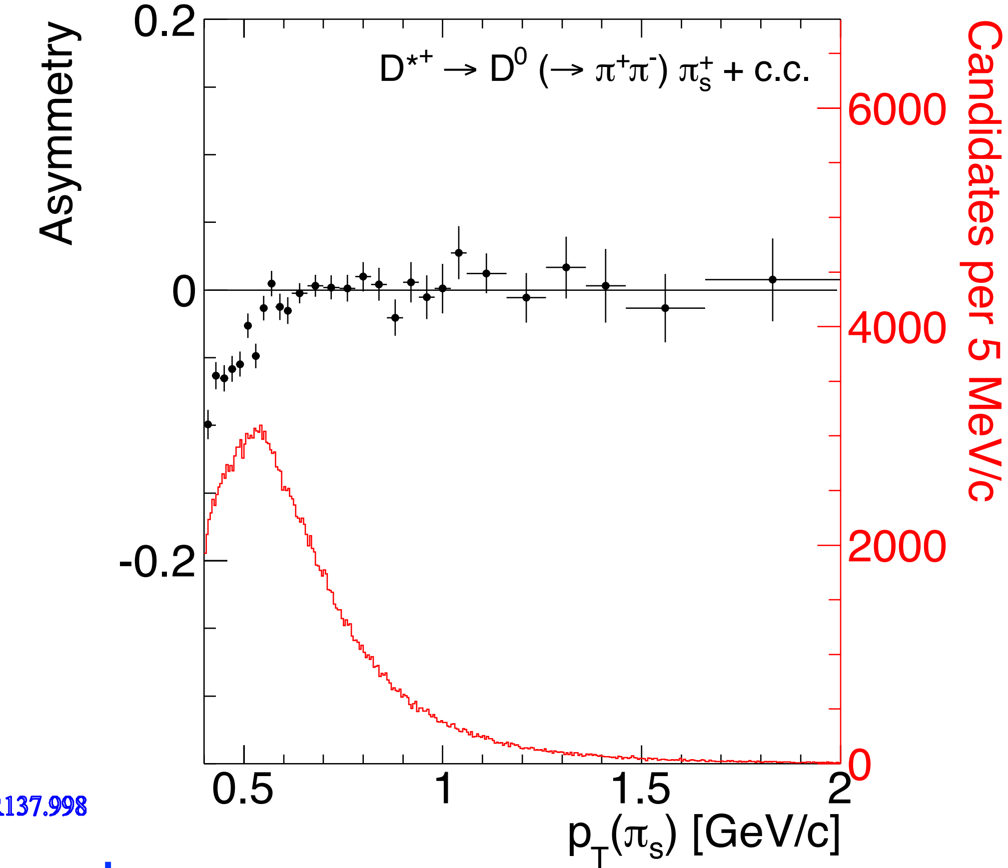
- CP symmetric initial state ($p\bar{p}$) ensures $D^0$ and $\bar{D}^0$ are produced in same amount
- Tag flavor at production time through strong D* decay

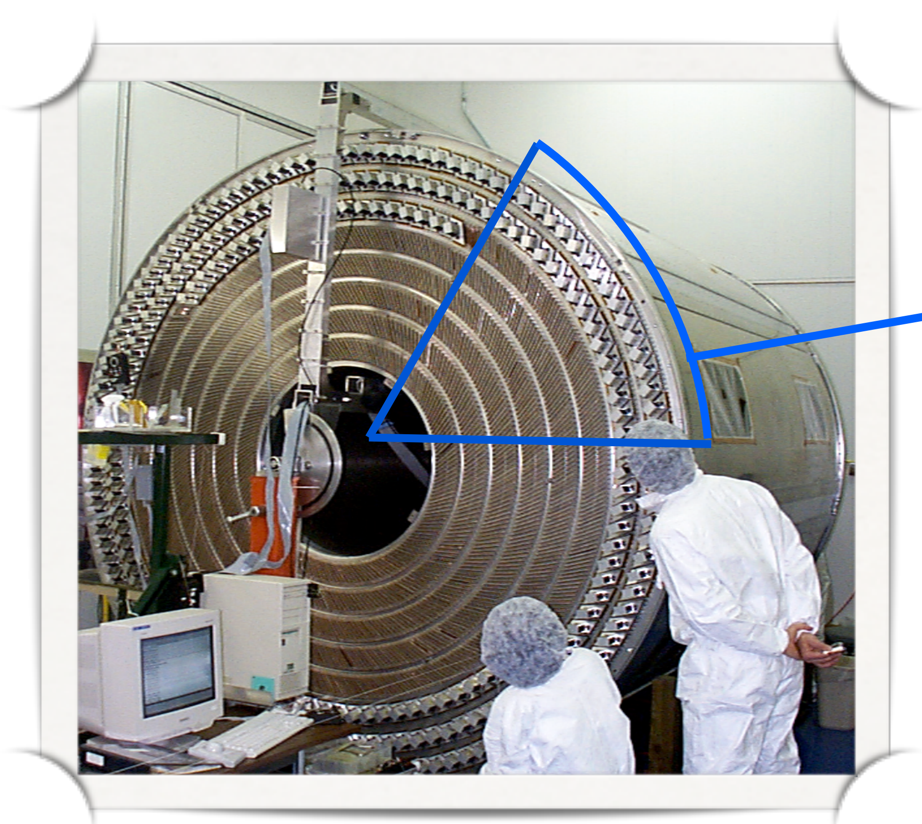


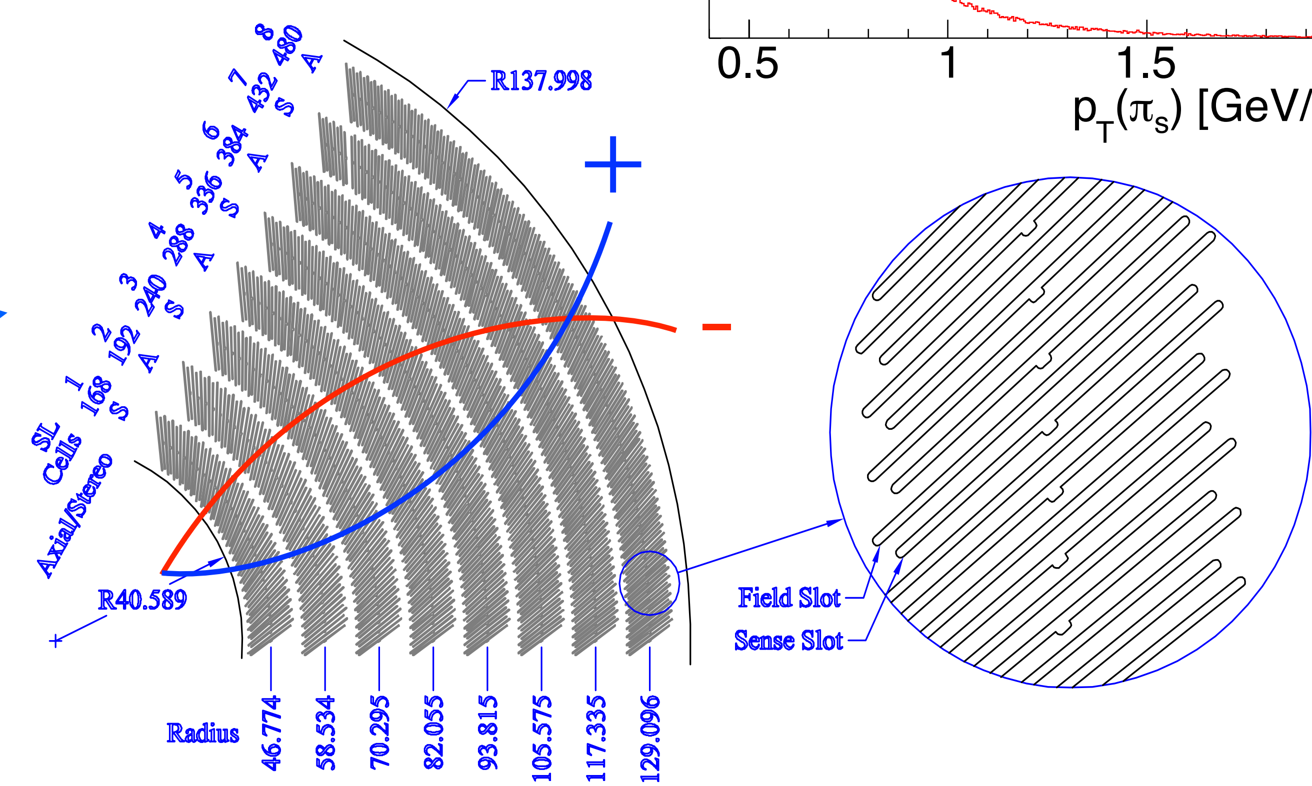

- Additional charged pion induces instrumental asymmetries of few percents that spoil physics asymmetry

# CDF is not charge-symmetric

- Central drift chamber has cells tilt of 35° wrt radial direction
- Positive and negative particles hit cells at different angles
- Positive and negative pions have differences in absorption rates
- Asymmetry in reconstruction efficiency particularly large at low momentum



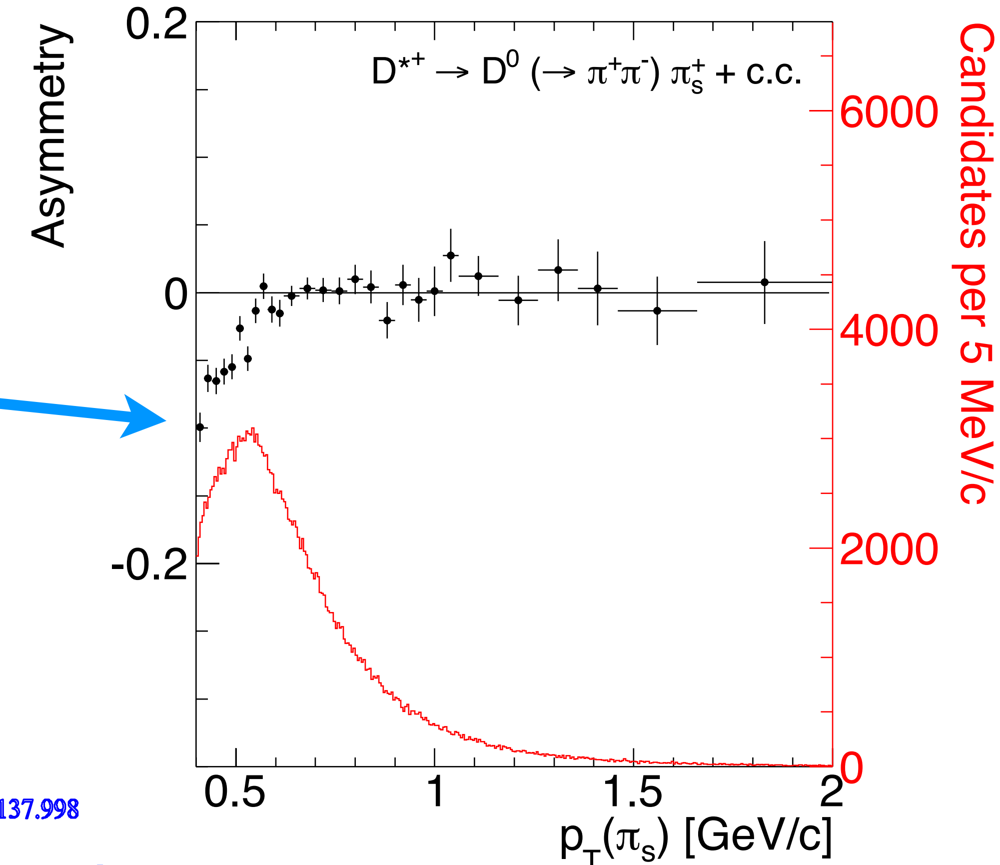



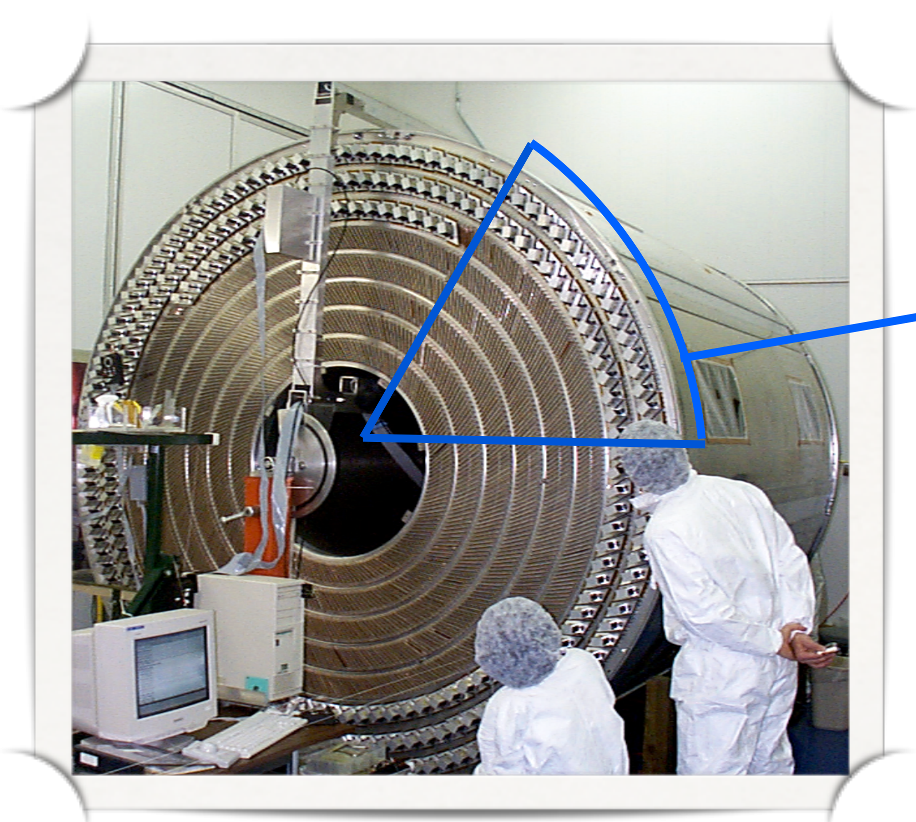


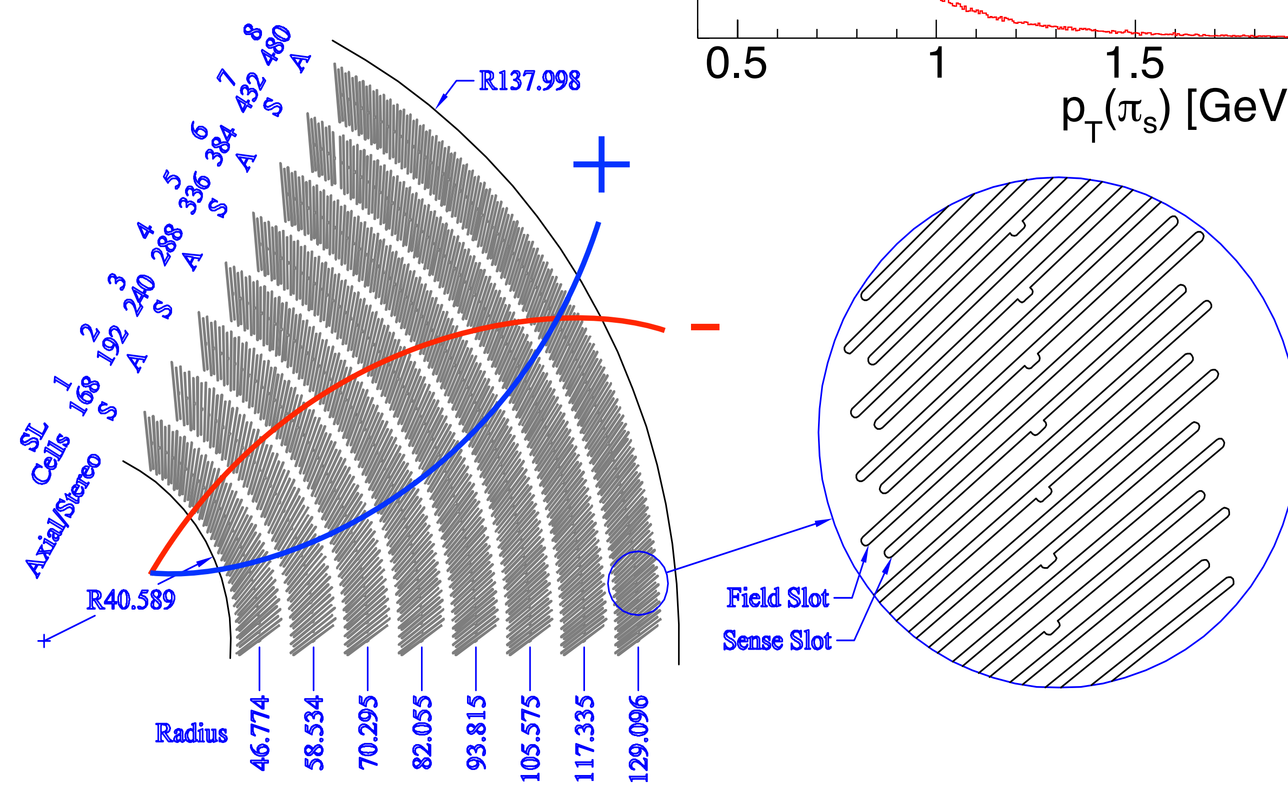
# CDF is not charge-symmetric

- Central ... radial direc...
- Posi... ent angl...
- Posi... absc...
- Asym... arly large at low momentum

Expected statistical resolution is ~0.2%, need to suppress detector charge asymmetry by one order of magnitude!





# How are we doing it?

- Need to correct measured “raw” asymmetry for instrumental effects

$\checkmark$ $\boldsymbol{D^\star \to D^0 \pi_s \to [h\, h]\, \pi_s}$ $A(hh^\star) = A_{\mathrm{CP}}(hh) + \delta(\pi_s)^{hh^\star}$

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✓ $D^\star \to D^0 \pi_s \to [h\ h]\ \pi_s$ $\qquad A(hh^\star) = A_{\mathrm{CP}}(hh) + \delta(\pi_s)^{hh^\star}$

↕ cancel asymmetry due to $\pi_s^+/\pi_s^-$ different reconstruction efficiencies

✓ $D^\star \to D^0 \pi_s \to [K\pi]\ \pi_s$ $\qquad A(K\pi^\star) = A_{\mathrm{CP}}(K\pi) + \delta(\pi_s)^{K\pi^\star} + \delta(K\pi)^{K\pi^\star}$

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✓ $D^\star \to D^0\pi_s \to [K\pi]\, \pi_s$ $\qquad A(K\pi^\star) = A_{\text{CP}}(K\pi) + \delta(\pi_s)^{K\pi^\star} + \delta(K\pi)^{K\pi^\star}$

cancel asymmetry due to $K^+/K^-$
different interaction with matter
+
possible CPV
in $D^0 \to K\pi$

✓ $D^0 \to [K\pi]$ $\qquad A(K\pi) = A_{\text{CP}}(K\pi) + \delta(K\pi)^{K\pi}$

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cancel asymmetry due to $\pi_s^+/\pi_s^-$
different reconstruction efficiencies

✓ $D^\star \to D^0\pi_s \to [K\pi]\,\pi_s$ $\quad A(K\pi^\star) = A_{\rm CP}(K\pi) + \delta(\pi_s)^{K\pi^\star} + \delta(K\pi)^{K\pi^\star}$

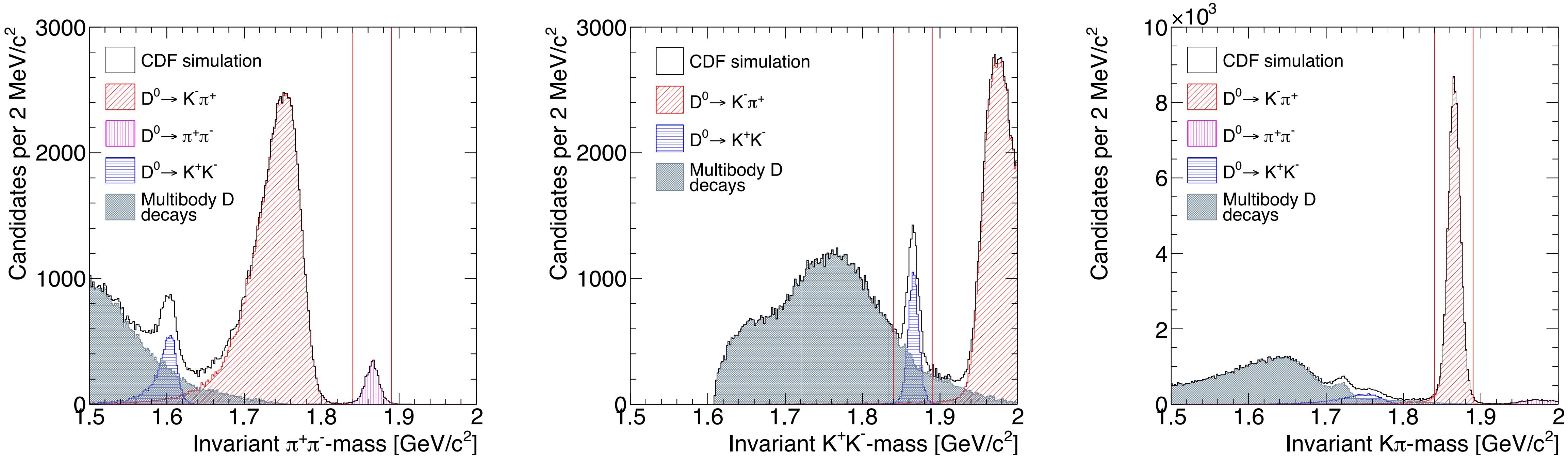
cancel asymmetry due to $K^+/K^-$
different interaction with matter
+ possible CPV in $D^0 \to K\pi$

✓ $D^0 \to [K\pi]$ $\quad A(K\pi) = A_{\rm CP}(K\pi) + \delta(K\pi)^{K\pi}$

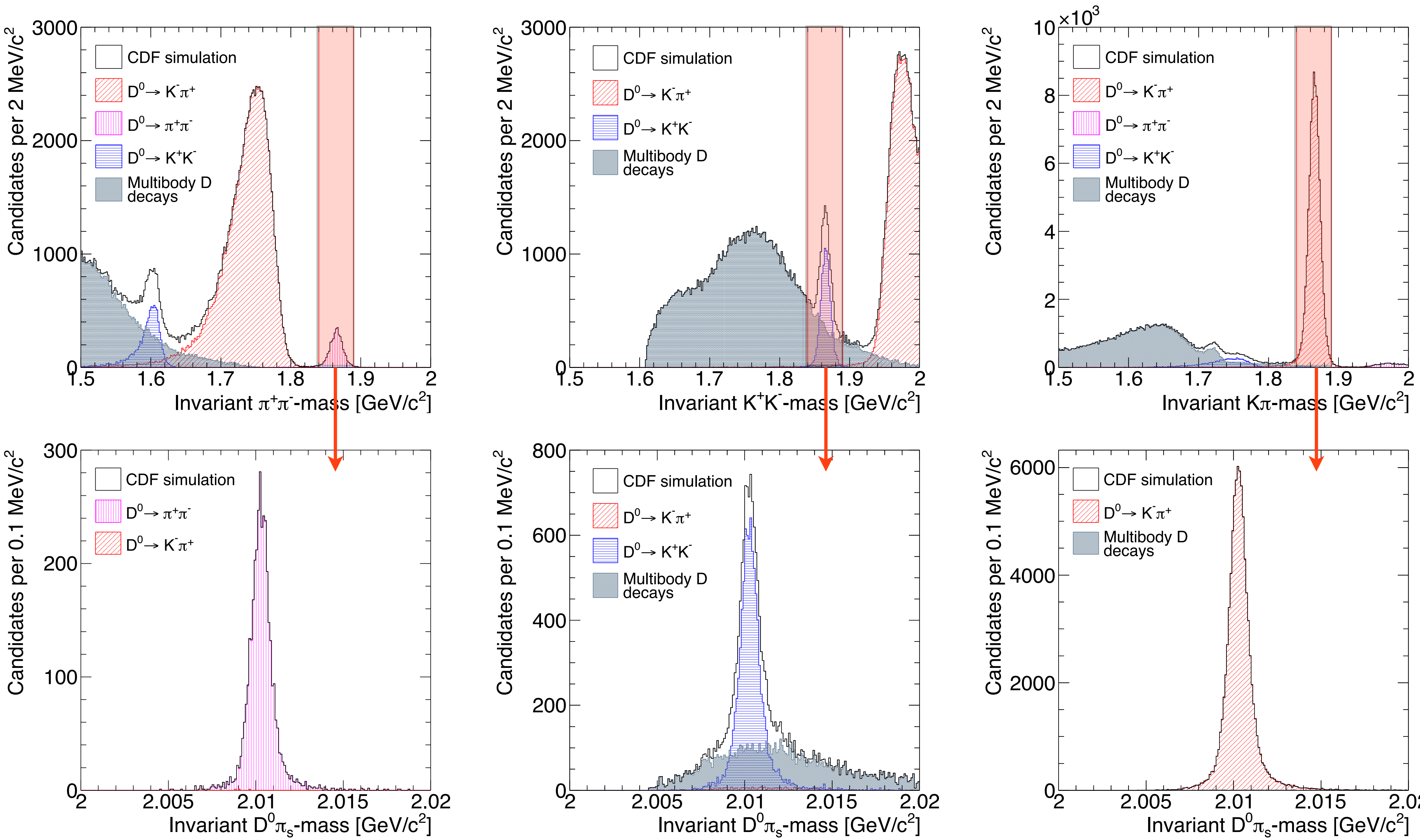
- Extract the physical $A_{CP}$ through the combination:

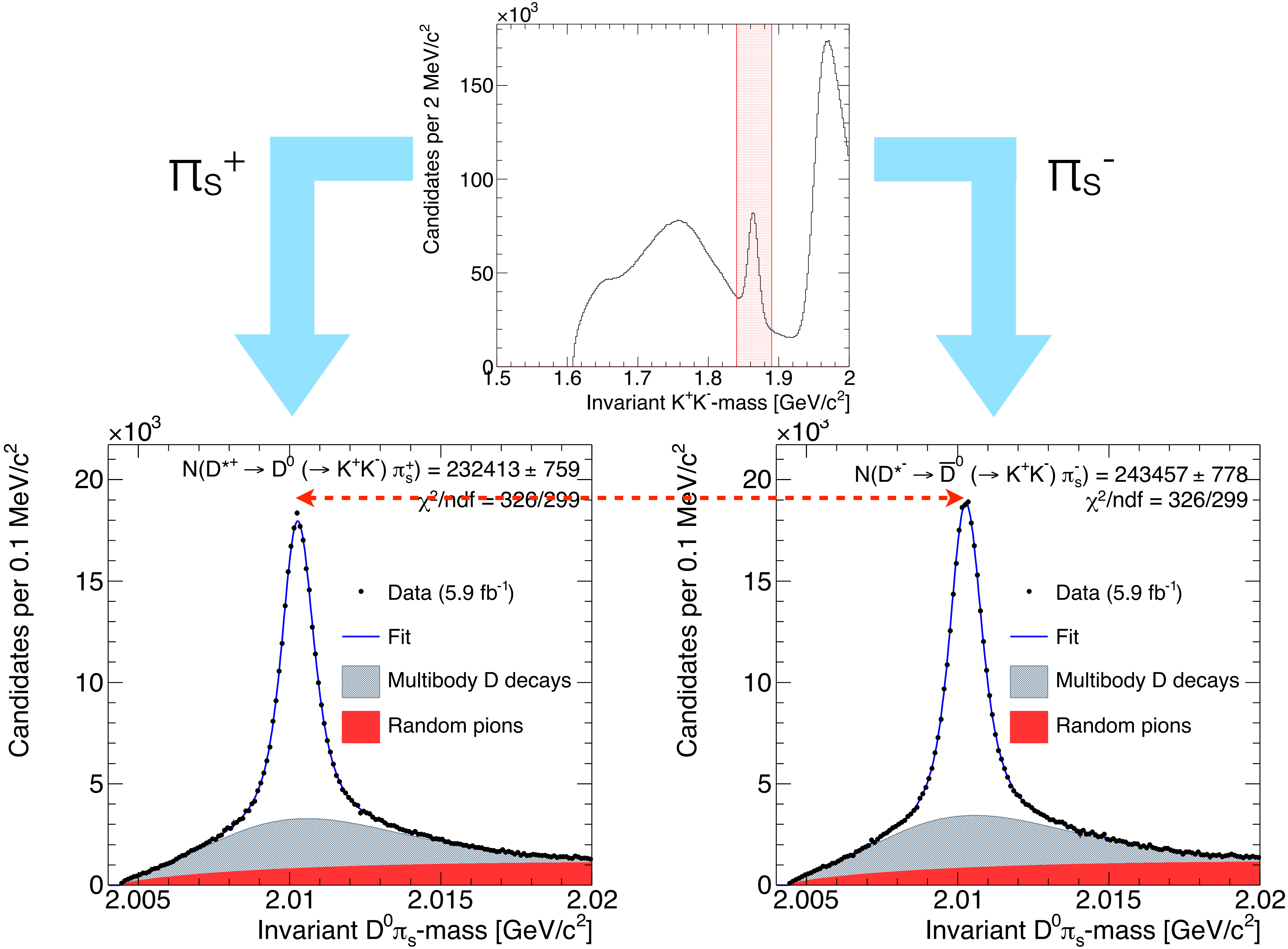
$$A_{CP}(hh) \approx A(hh^*) - A(K\pi^*) + A(K\pi)$$

# D*–tagged samples composition



# D*–tagged samples composition

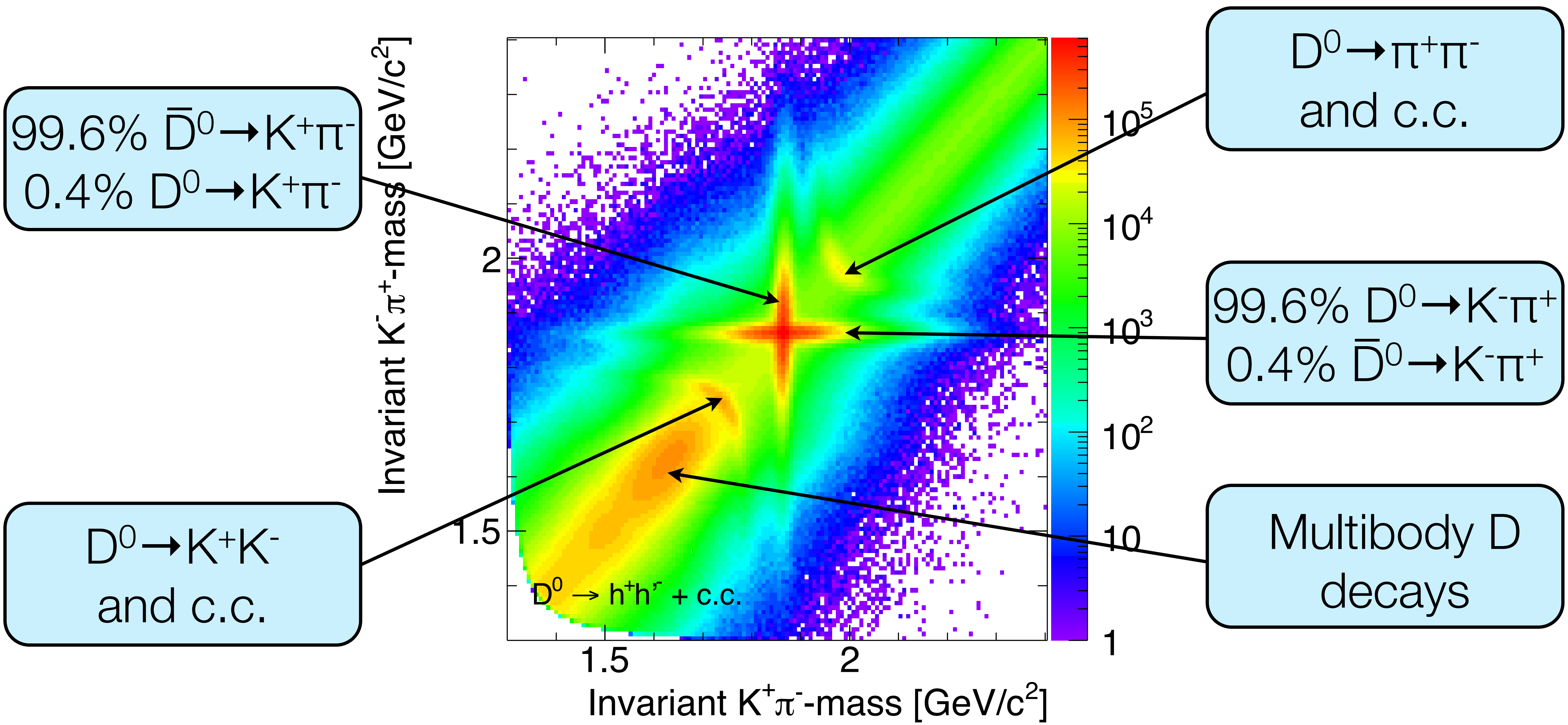




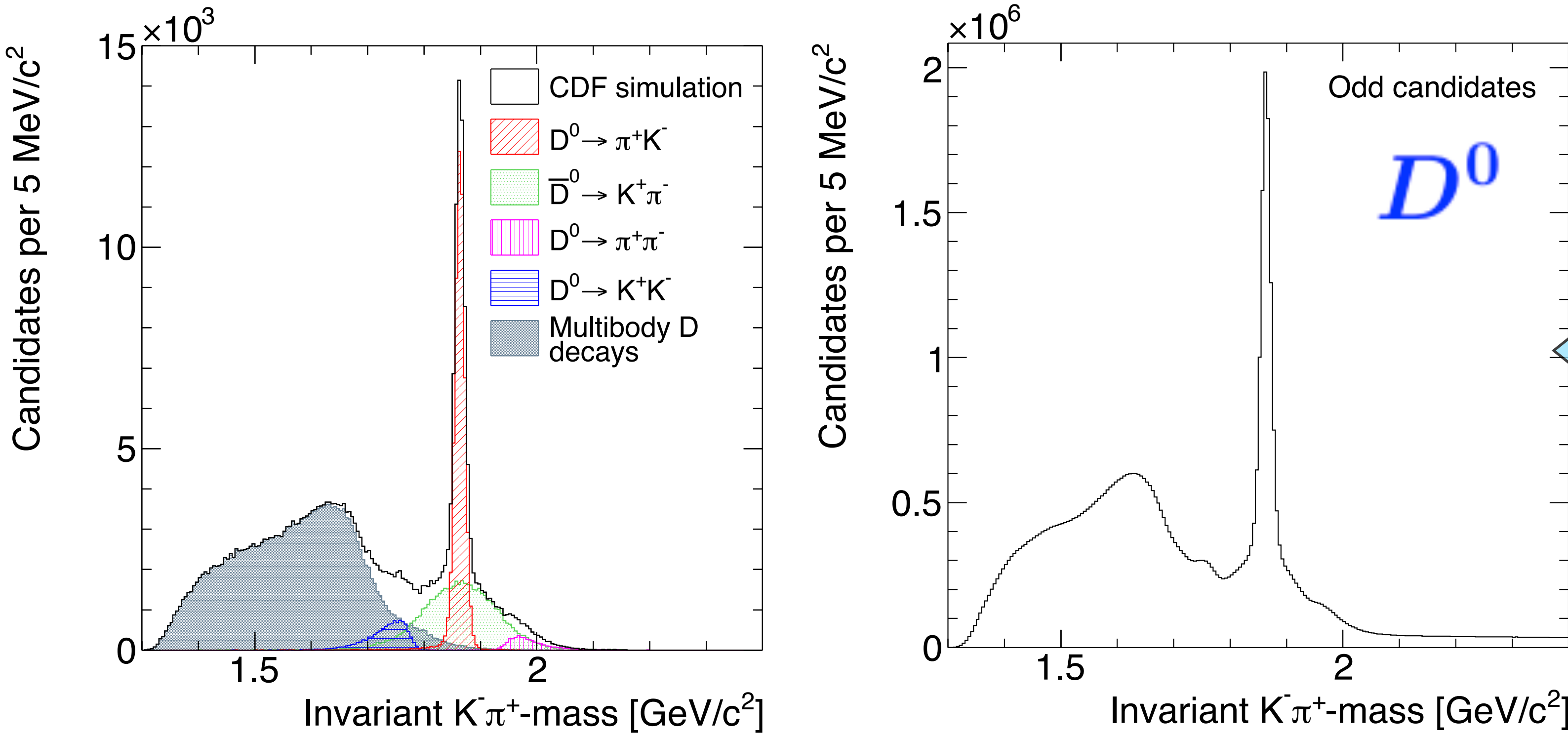

$A(KK^*) = (-2.32 \pm 0.21)\%$

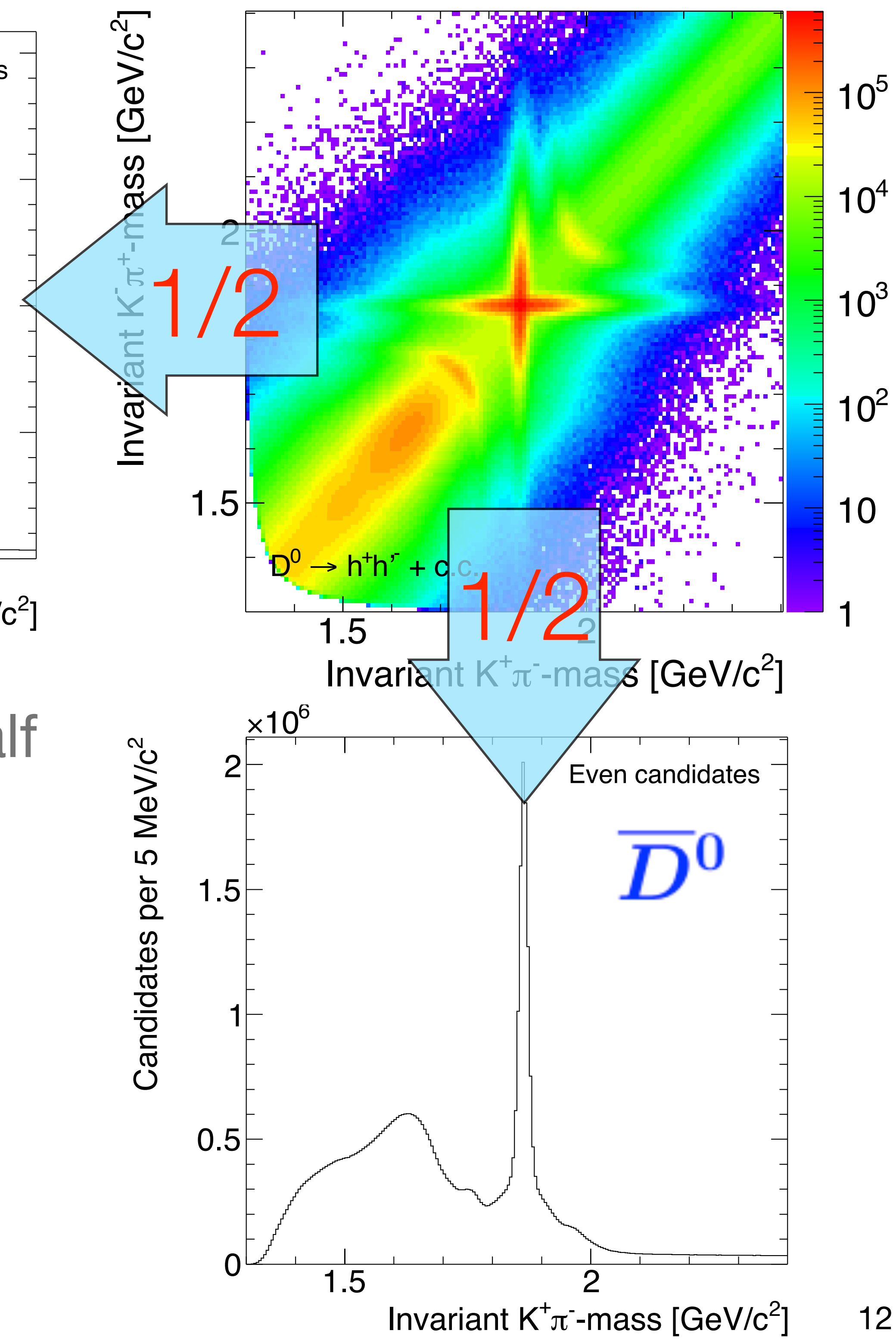
# Untagged $D^0 \to K^- \pi^+$ sample composition

- No soft pion to tell which is $D^0$ and which is $\bar{D}^0$... but $K\pi$ final state is almost flavor specific:



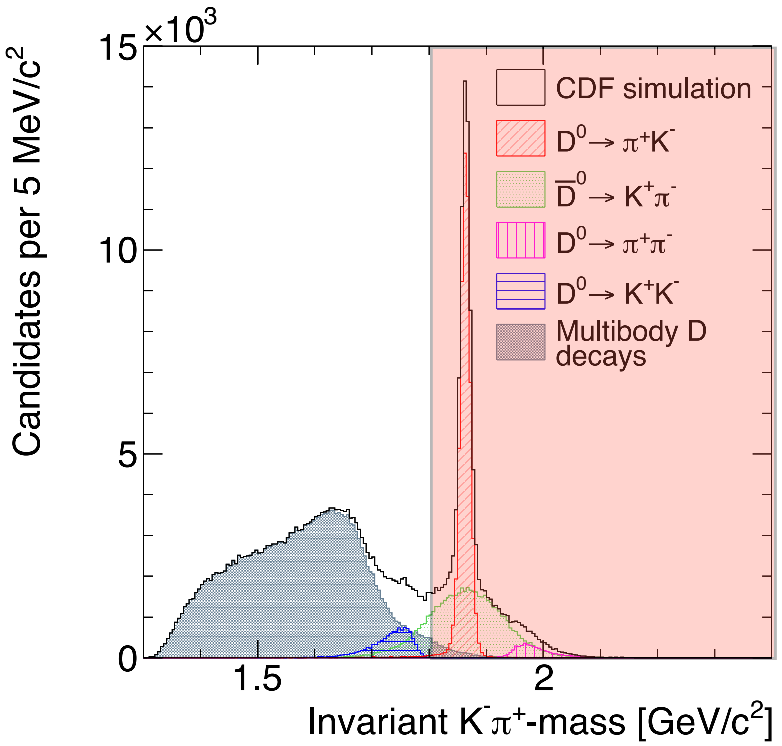
# Kinematic $D^0$–tagging

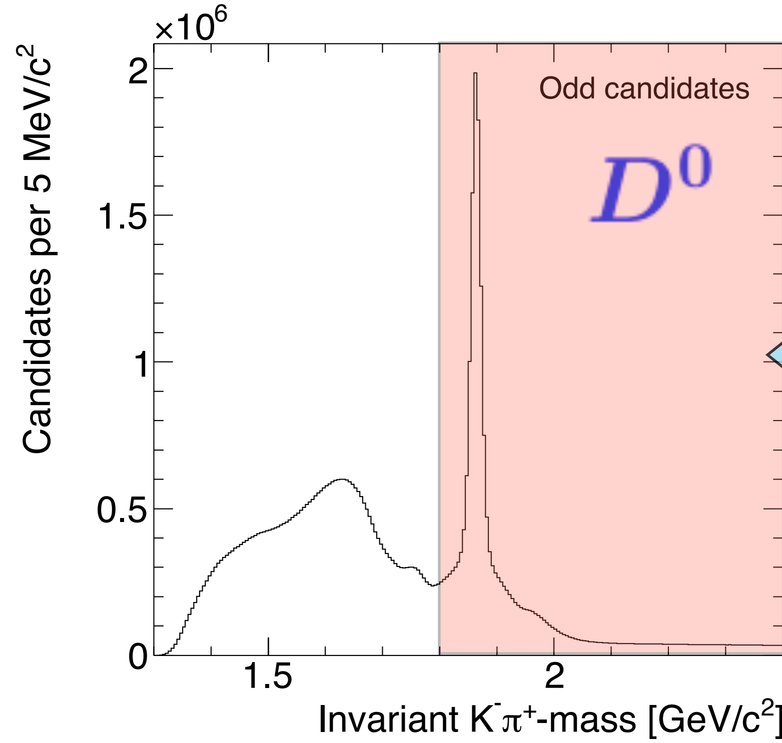


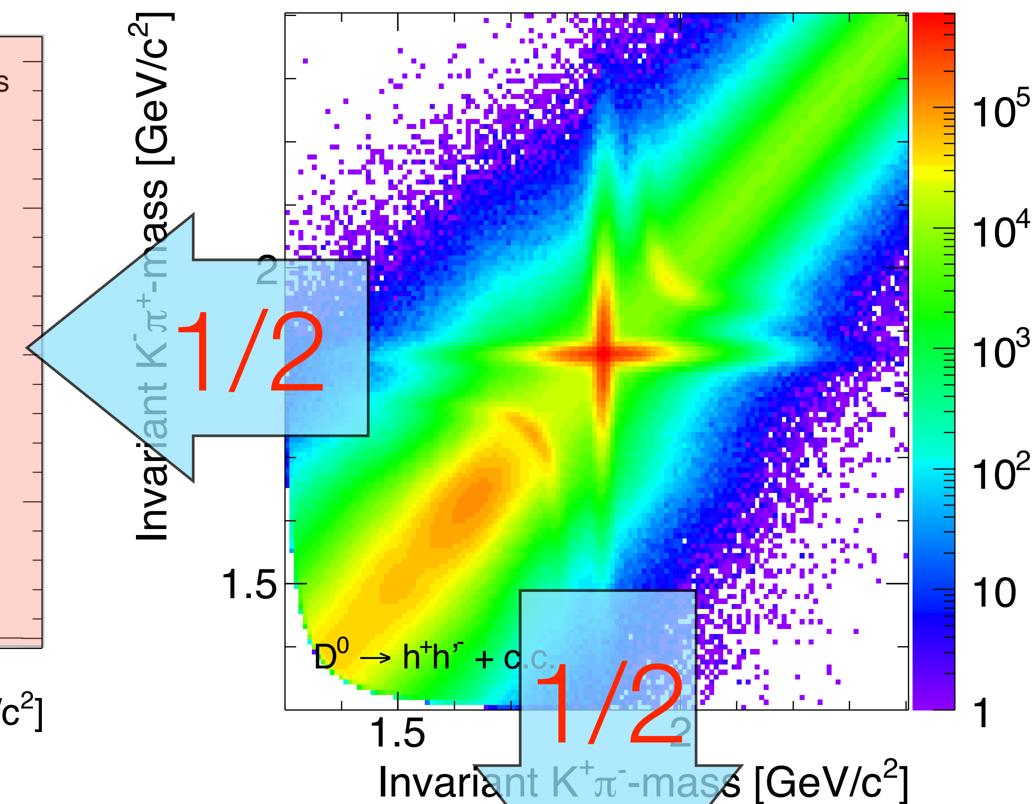



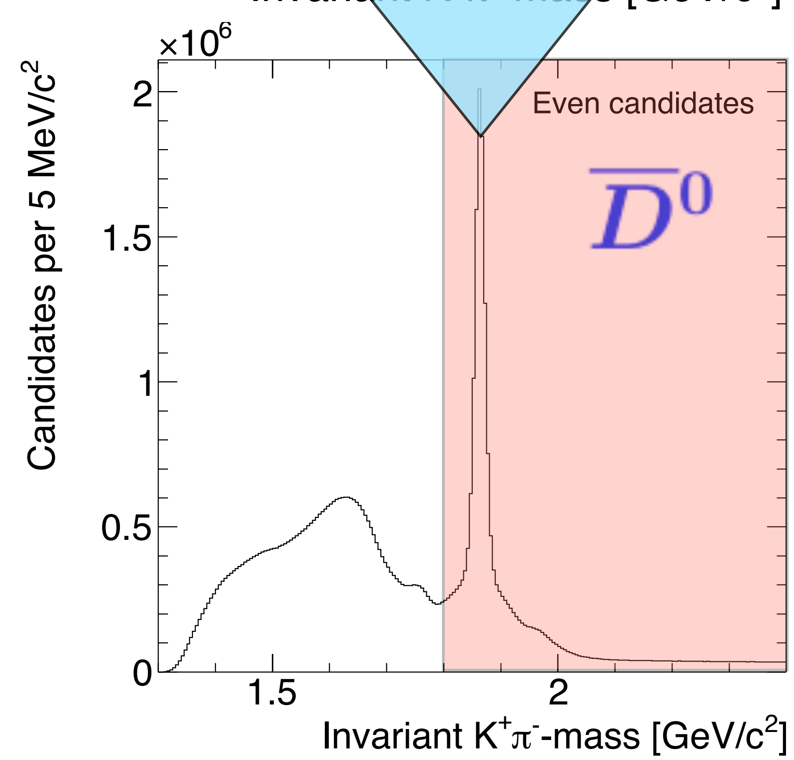

- Two statistically independent samples with half the events each
- Can easily afford to loose a factor of two in statistics here
- Signal is in narrow peak (ignore 0.4% DCS contribution)

# Kinematic D$^0$–tagging

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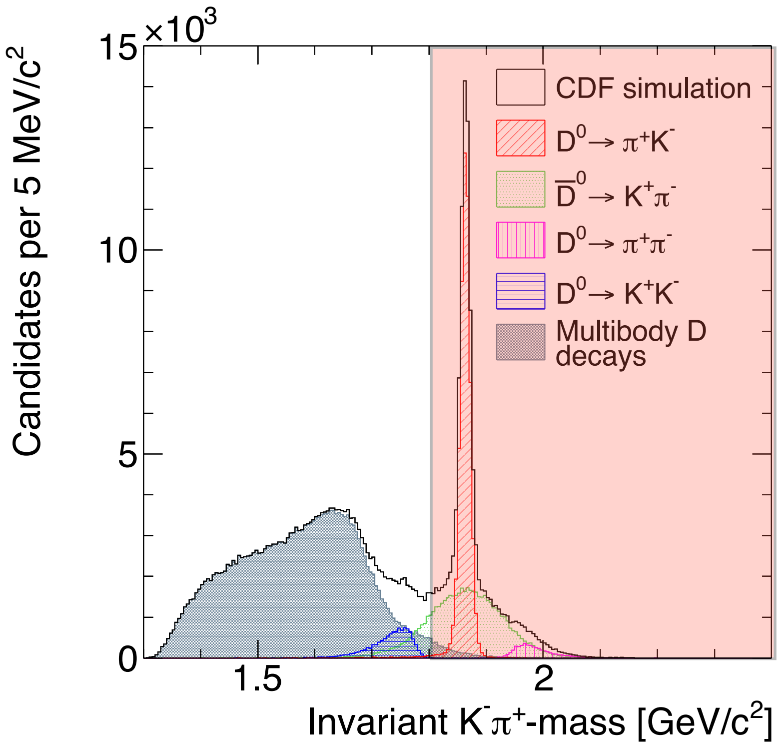
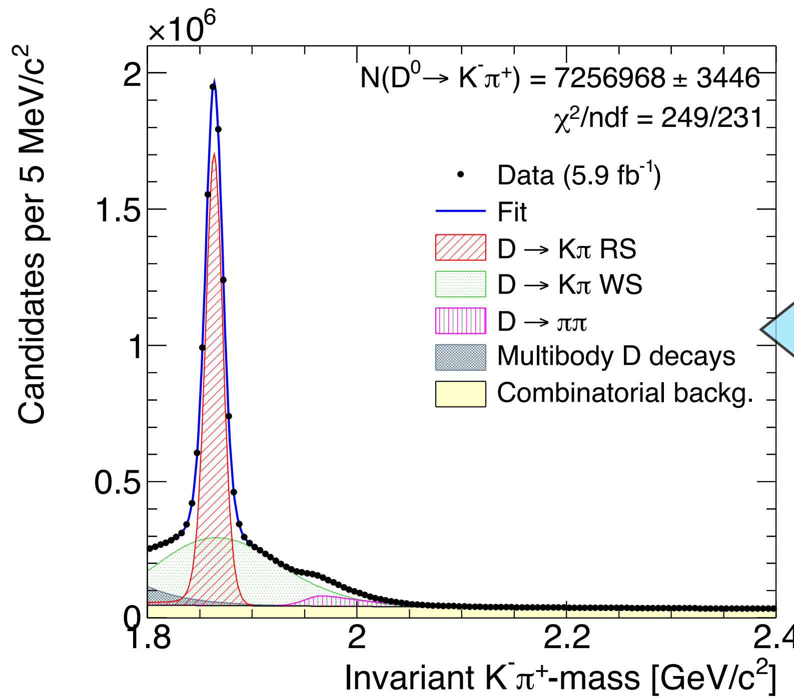
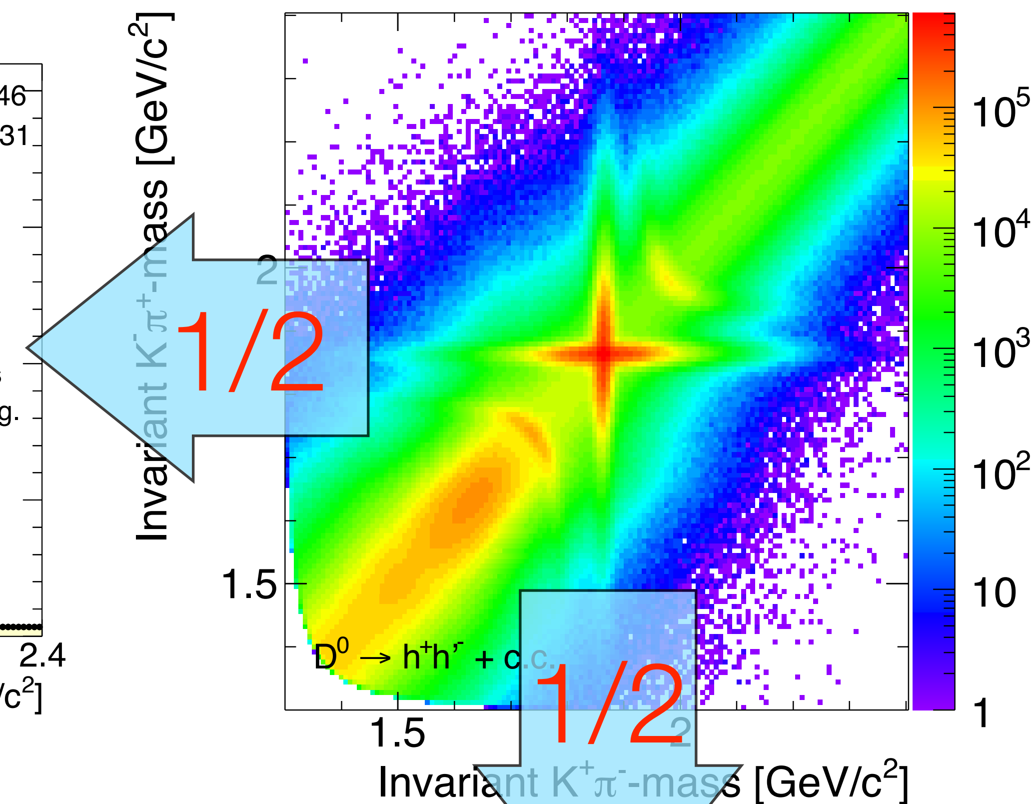
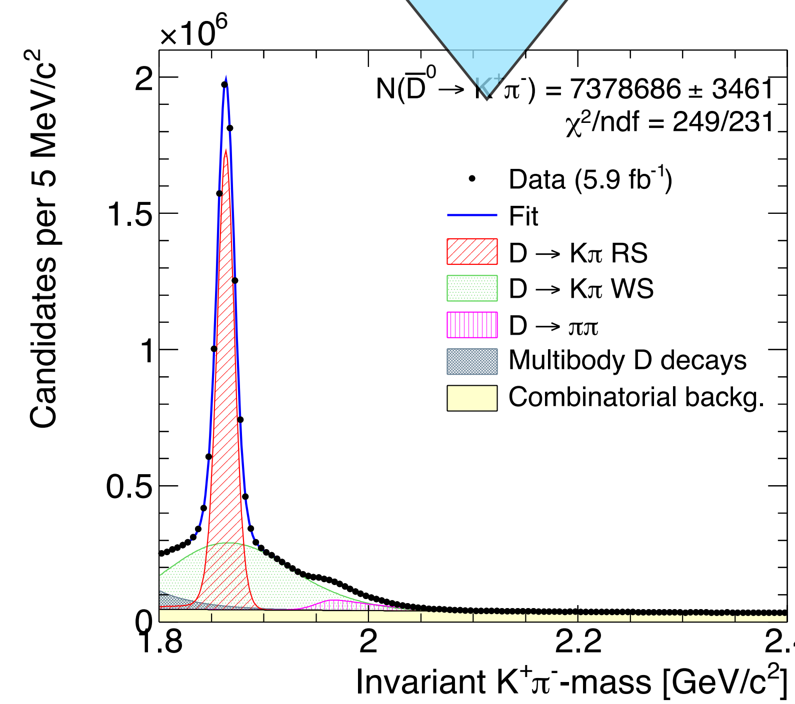



- Two statistically independent samples with half the events each
- Can easily [...] statistics here

**$A(K\pi) = (-0.83 \pm 0.03)\%$**

- Signal is in narrow peak (ignore 0.4% DCS contribution)

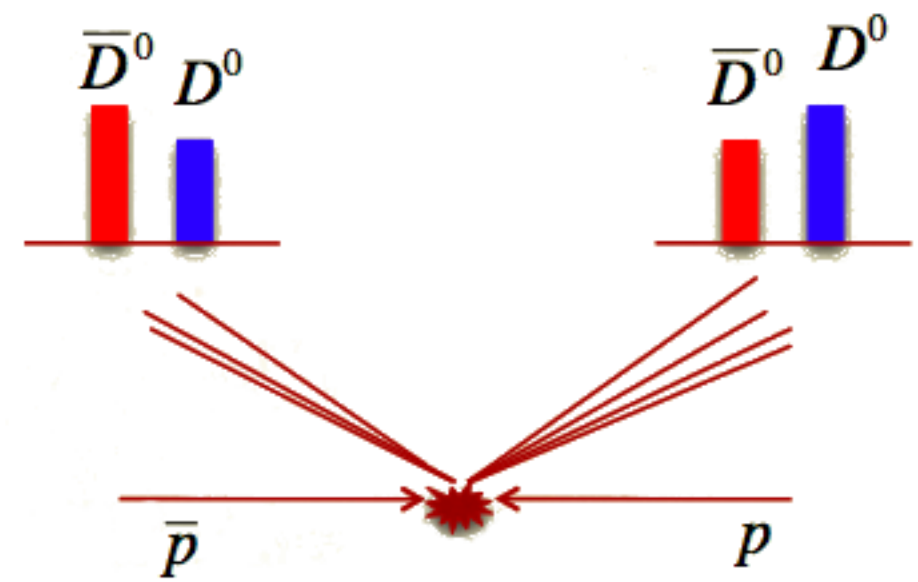
# Systematics

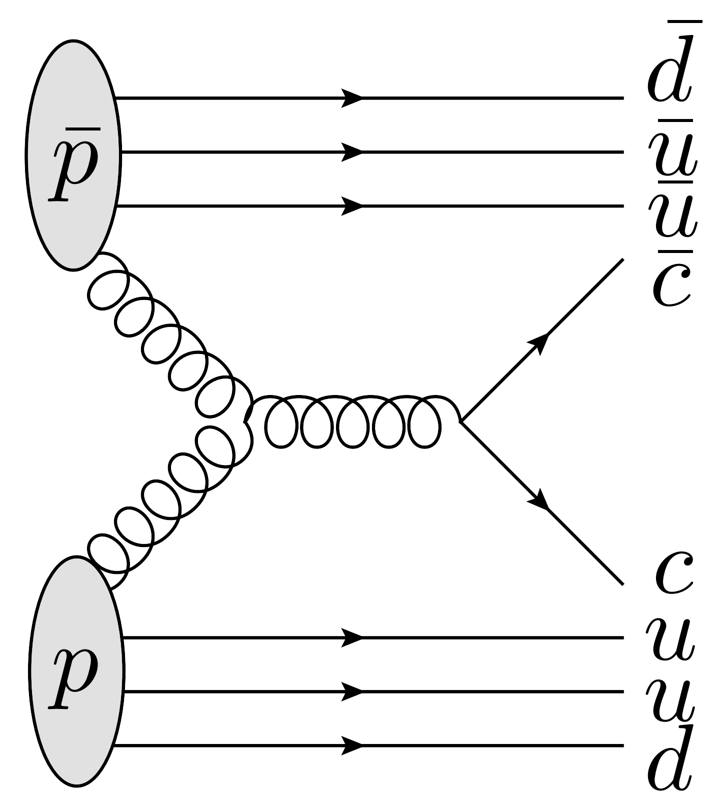
| Source | $A_{CP}(\pi^+\pi^-)$ [%] | $A_{CP}(K^+K^-)$ [%] |
|---|---|---|
| Approximations in the suppression of detector-induced effects | 0.009 | 0.009 |
| Production asymmetries | 0.040 | 0.030 |
| Contamination of secondary $D$ mesons | 0.034 | 0.034 |
| Shapes assumed in fits | 0.010 | 0.058 |
| Charge-dependent mass distributions | 0.098 | 0.052 |
| Asymmetries from residual backgrounds | 0.014 | 0.014 |
| Limitations of sample reweighting | <0.001 | <0.001 |
| Total | 0.113 | 0.092 |

- Intrinsically suppressed by data-driven method
- Major offenders: effects that impact differently $D^0$ and $\overline{D}^0$, e. g.
  - Production asymmetries
  - Possible asymmetric contribution of D from B decays
  - Charge-dependent differences in mass shape

# Production asymmetry

- $D^0$ and $\bar{D}^0$ mesons are produced in equal amount in $p\bar{p}$ collisions...
    - ...but correlation with the initial state beam particles may induce a forward-backward charge asymmetry
- Strong interactions ensure that the effect is anti-symmetric in rapidity
    - No impact on $A_{CP}$ if the samples have symmetric $\eta$ distributions
- Assign syst by enforcing $\eta$-symmetry (reweight) and take difference between the resulting $A_{CP}$'s and the central ones



# Results

| | |
|---|---|
| **$A_{CP}(D^0 \rightarrow \pi^+\pi^-)$** | **[+0.22 ± 0.24 (stat.) ± 0.11 (syst.)]%** |
| Babar 2008 | [-0.24 ± 0.52 (stat.) ± 0.22 (syst.)]% |
| Belle 2008 | [+0.43 ± 0.52 (stat.) ± 0.12 (syst.)]% |

| | |
|---|---|
| **$A_{CP}(D^0 \rightarrow K^+K^-)$** | **[-0.24 ± 0.22 (stat.) ± 0.09 (syst.)]%** |
| Babar 2008 | [+0.00 ± 0.34 (stat.) ± 0.13 (syst.)]% |
| Belle 2008 | [-0.43 ± 0.30 (stat.) ± 0.11 (syst.)]% |

Babar 2008 = *Phys. Rev. Lett.* **100** (2008) 061803
Belle 2008 = *Phys. Lett.* **B 670** (2008) 190

# LHCb enters the game

- Soon after these results were published LHCb showed a first evidence for CP violation in charm decays by measuring the difference of asymmetries

$\Delta A_{CP}(\text{LHCb}) = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = A_{CP}(KK^*) - A(\pi\pi^*) = (-0.82 \pm 0.21 \pm 0.11)\%$

[PRL 108, 111602 (2012)]

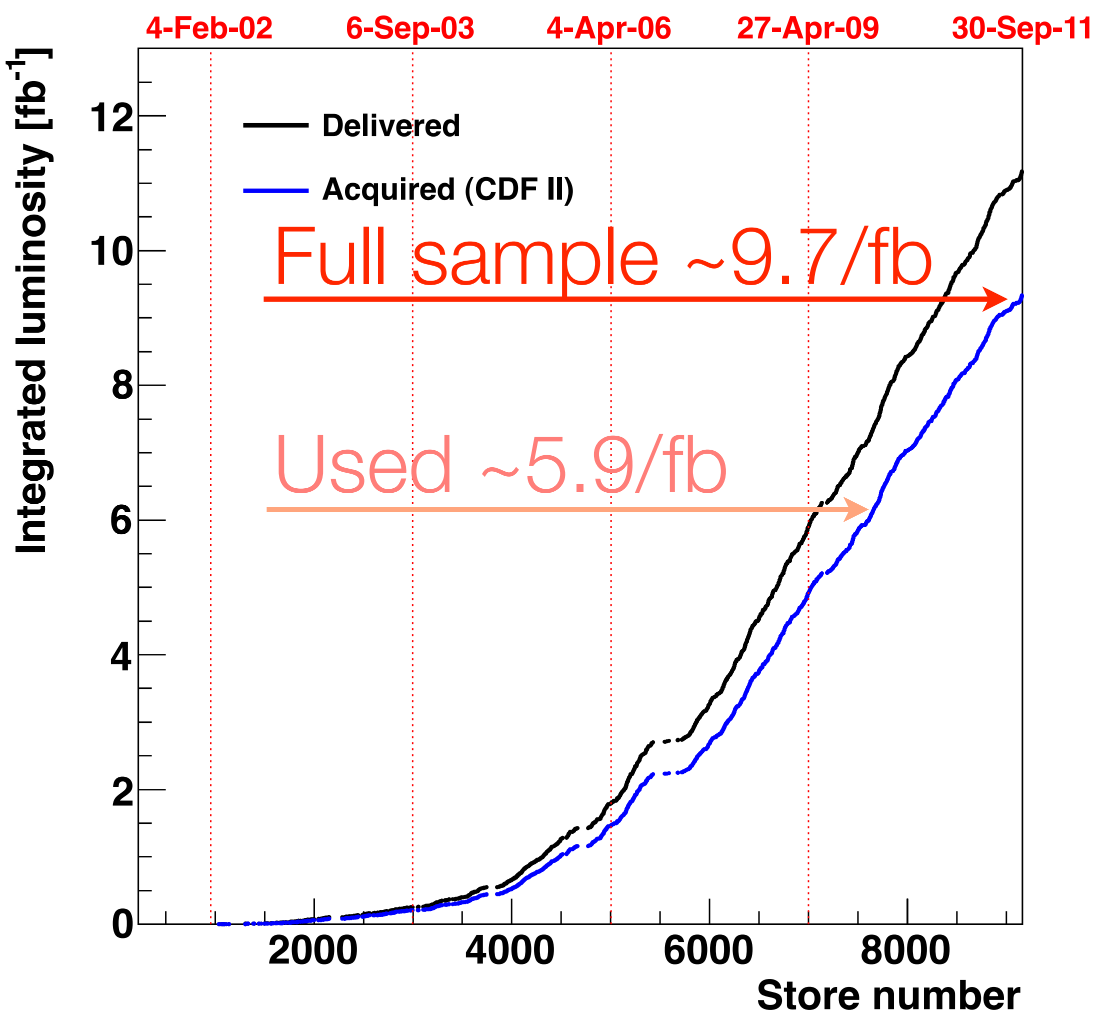
- LHCb is a forward spectrometer: need to measure $\Delta A_{CP}$ to cancel the D* production asymmetry

- Compatible with CDF's result but slightly more precise

$\Delta A_{CP}$ (CDF 5.9/fb) = $(-0.46 \pm 0.31 \pm 0.12)\%$

- Decided to update to the full Run II dataset, tuning the analysis toward the measurement of $\Delta A_{CP}$

$\Delta A_{CP}$ (CDF 9.7/fb) = $(-0.62 \pm 0.21 \pm 0.10)\%$

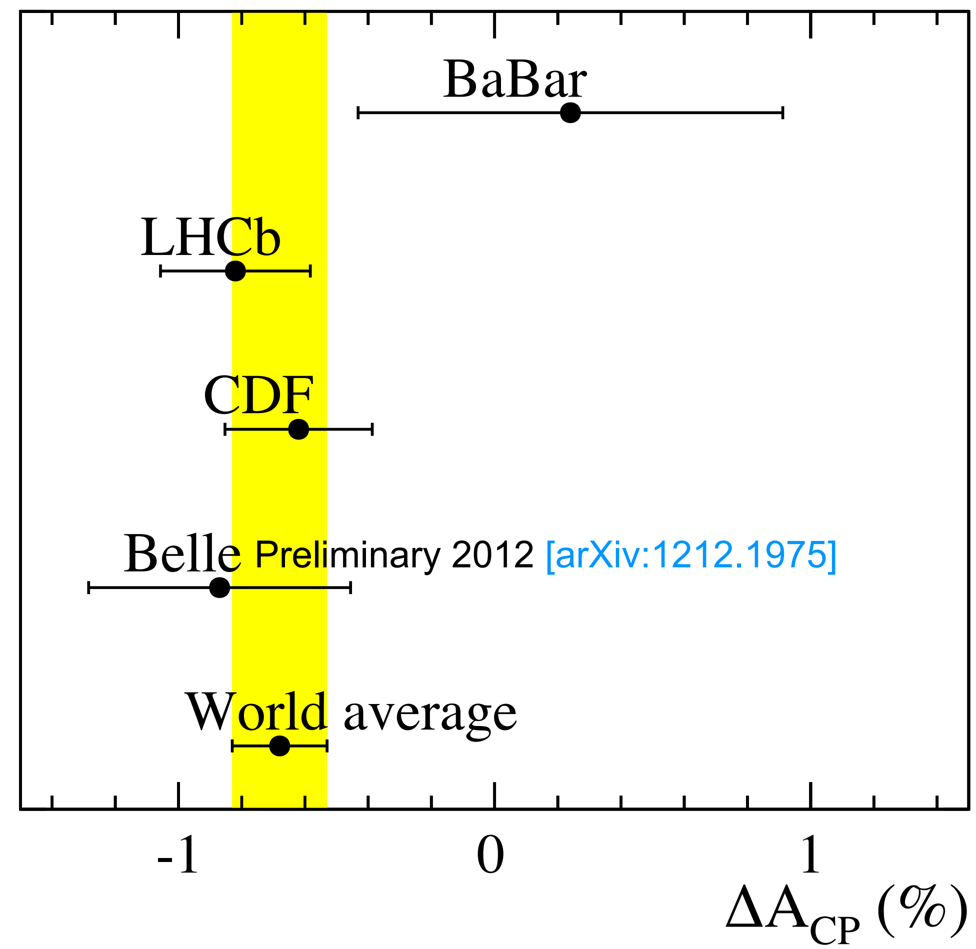


# SM or NP?

- Available measurements of $\Delta A_{CP}$ gives strong evidence (~4.6σ) of direct CPV in charm
- Central value of $\Delta A_{CP}$ much larger than what naively expected in SM... hint of NP?
- Raised a lot of excitement in the heavy flavor theory community:

| | |
|---|---|
| Isidori, Kamenik, Ligeti, Perez [1111.4987] | Brod, Kagan, Zupan [1111.5000] |
| Wang, Zhu [1111.5196] | Rozanov, Vysotsky [1111.6949] |
| Hochberg, Nir [1112.5268] | Pirtskhalava, Uttayarat [1112.5451] |
| Cheng, Chiang [1201.0785] | Bhattacharya, Gronau, Rosner [1201.2351] |
| Chang, Du, Liu, Lu, Yang [1201.2565] | Giudice, Isidori, Paradisi [1201.6204] |
| Altmannshofer, Primulando, C. Yu, F. Yu [1202.2866] | Chen, Geng, Wang [1202.3300] |
| Feldmann, Nandi, Soni [1202.3795] | Li, Lu, Yu [1203.3120] |
| Franco, Mishima, Silvestrini [1203.3131] | Brod, Grossman, Kagan, Zupan [1203.6659] |
| Hiller, Hochberg, Nir [1204.1046] | Grossman, Kagan, Zupan [1204.3557] |
| Cheng, Chiang [1205.0580] | ... |

Different hypotheses, but general agreement that available experimental information cannot yield to a conclusive statement




Individual asymmetries help to discriminate between different scenarios

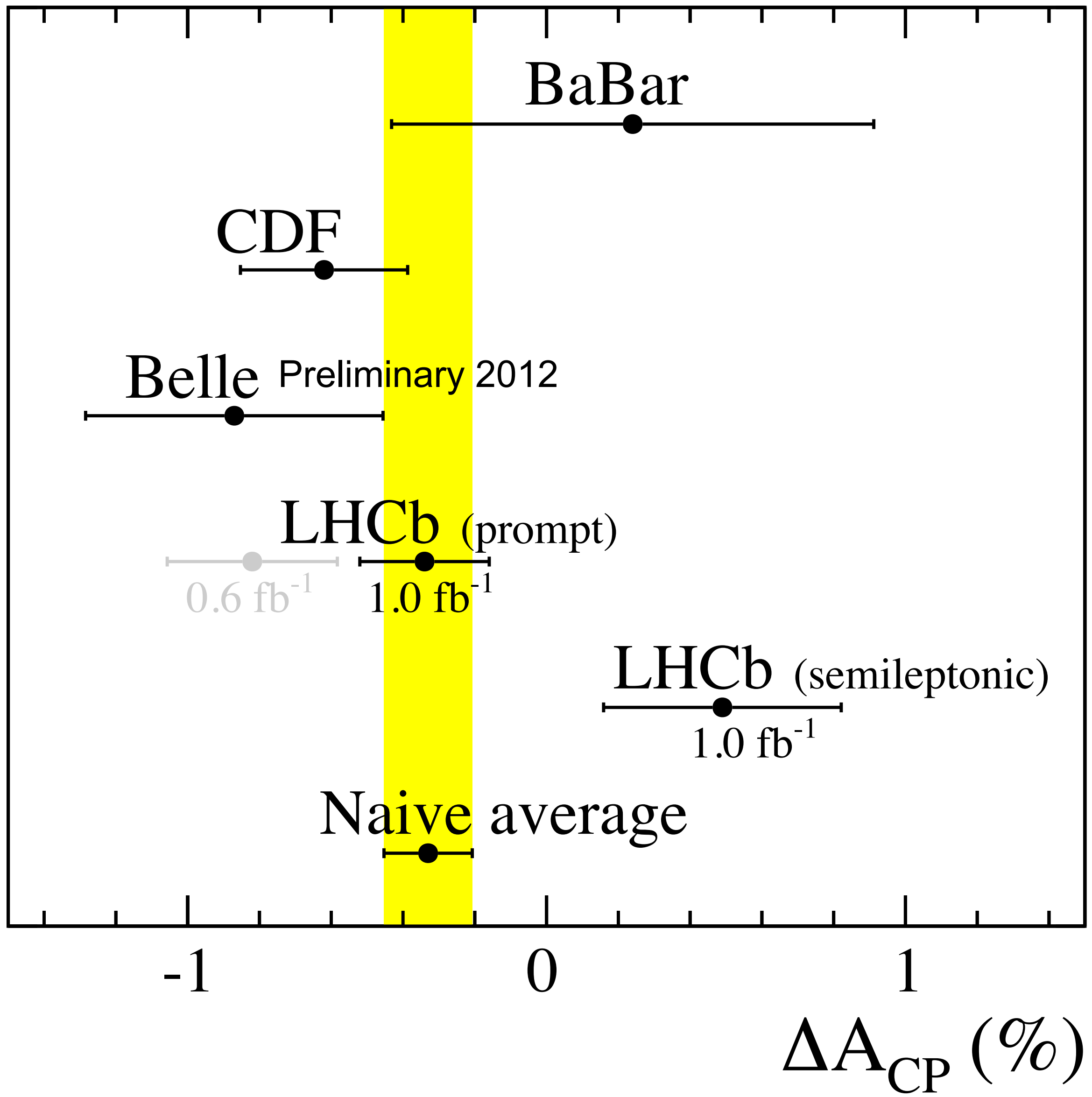
# Latest update

- Two new LHCb results presented at Moriond QCD 2013:
  - Preliminary update of previous analysis to full 2011 statistics [LHCb-CONF-2013-003]

$\Delta A_{CP}(\text{prompt}) = (-0.34 \pm 0.15 \pm 0.10)\%$

  - New independent measurement based on $D^0$'s from inclusive semileptonic b-hadron decays [PLB 723 (2013) 33]

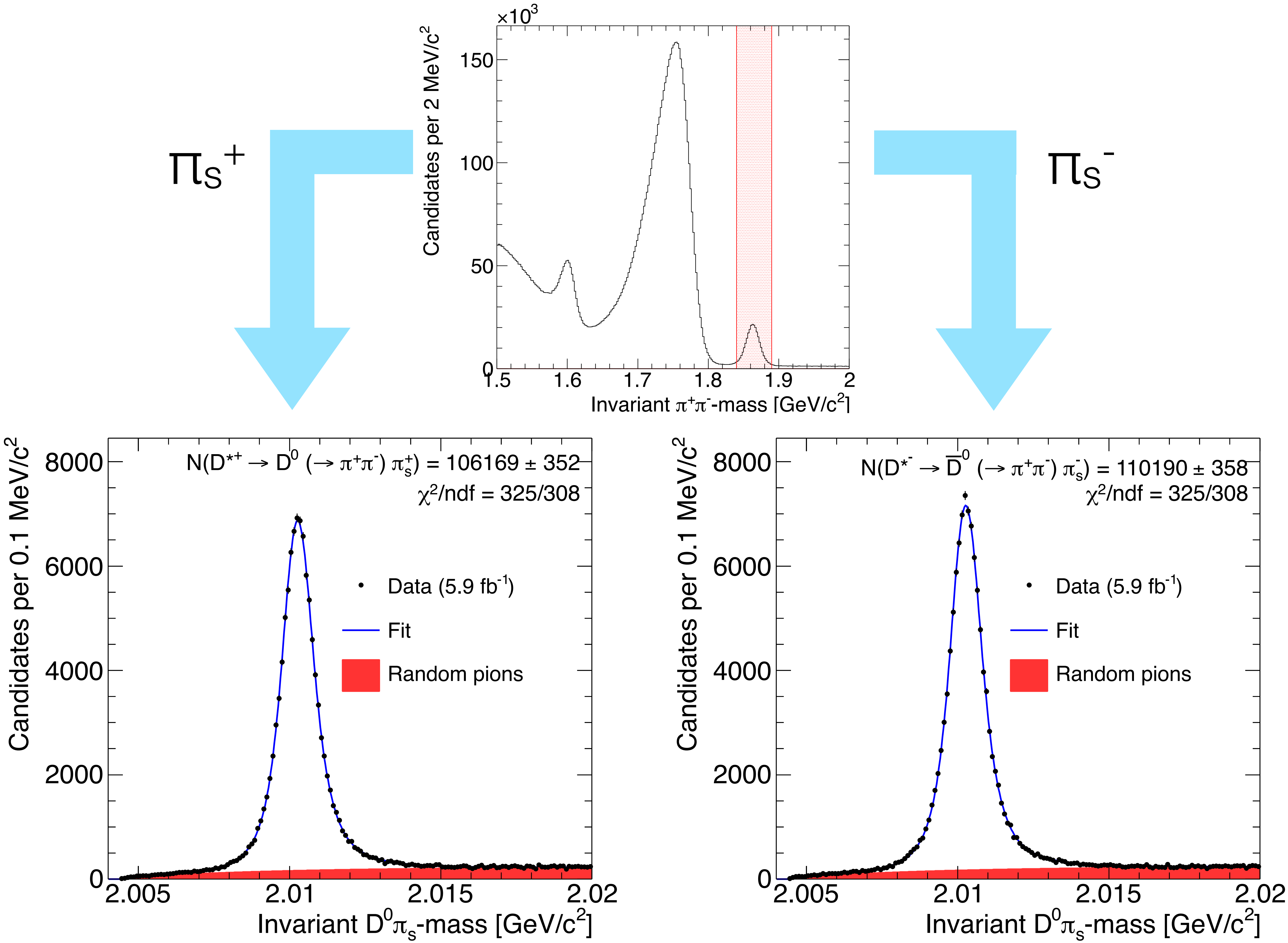
$\Delta A_{CP}(\text{semileptonic}) = (+0.49 \pm 0.30 \pm 0.14)\%$



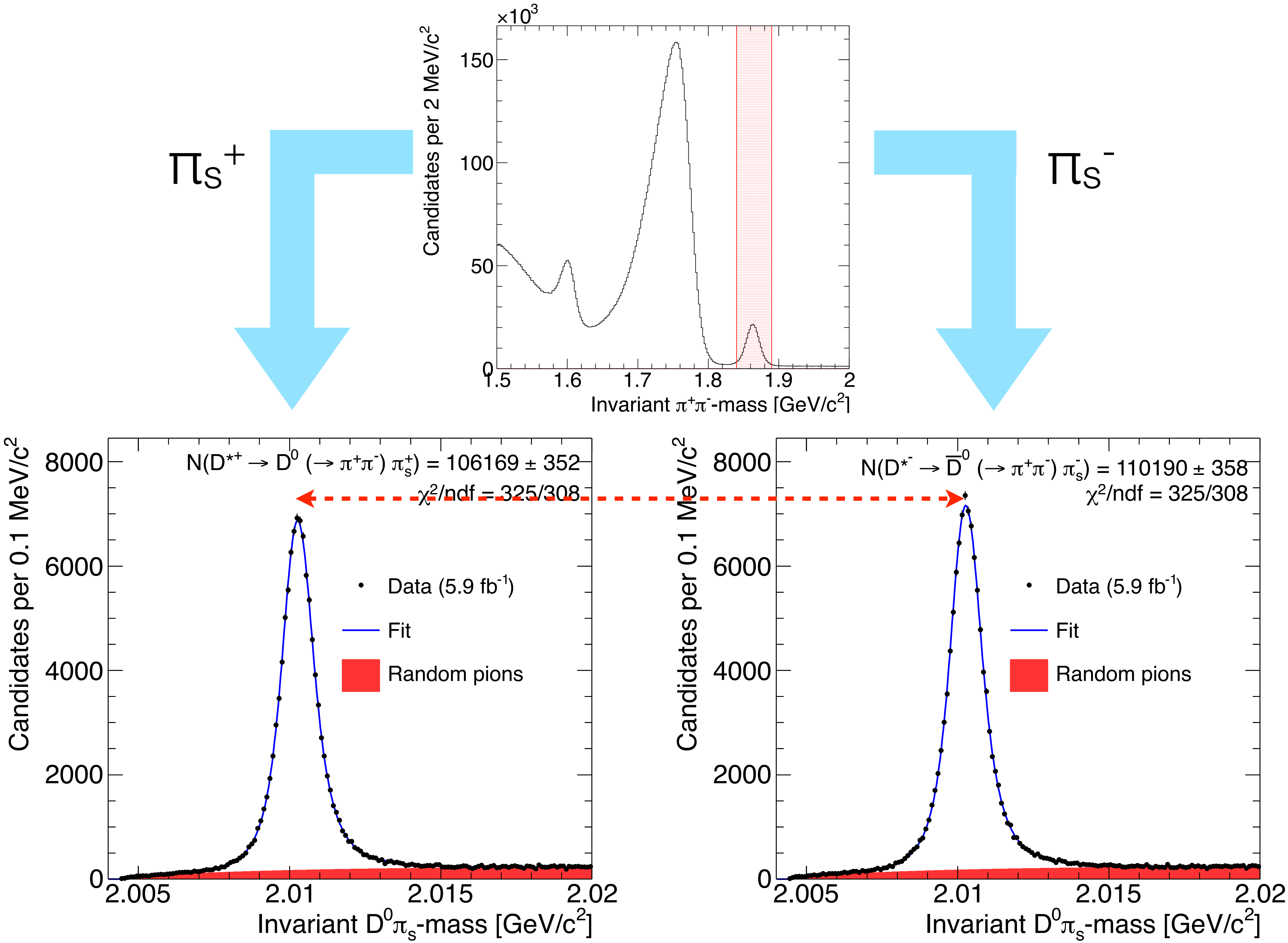
# Conclusions

- CP violation in charm is a promising (unique) probe for beyond-SM physics, quite complementary to studies in the K and B sectors
- Experimental evidence for large direct CPV in charm, even if recently not confirmed by LHCb, has renewed the interest of the heavy flavor community towards charm physics
- CDF has been a pioneer of high precision measurement of CP violation in the charm sector
    - The measured individual CP asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays are still the most precise to date
    - The analysis techniques developed by CDF have been of inspiration for LHCb

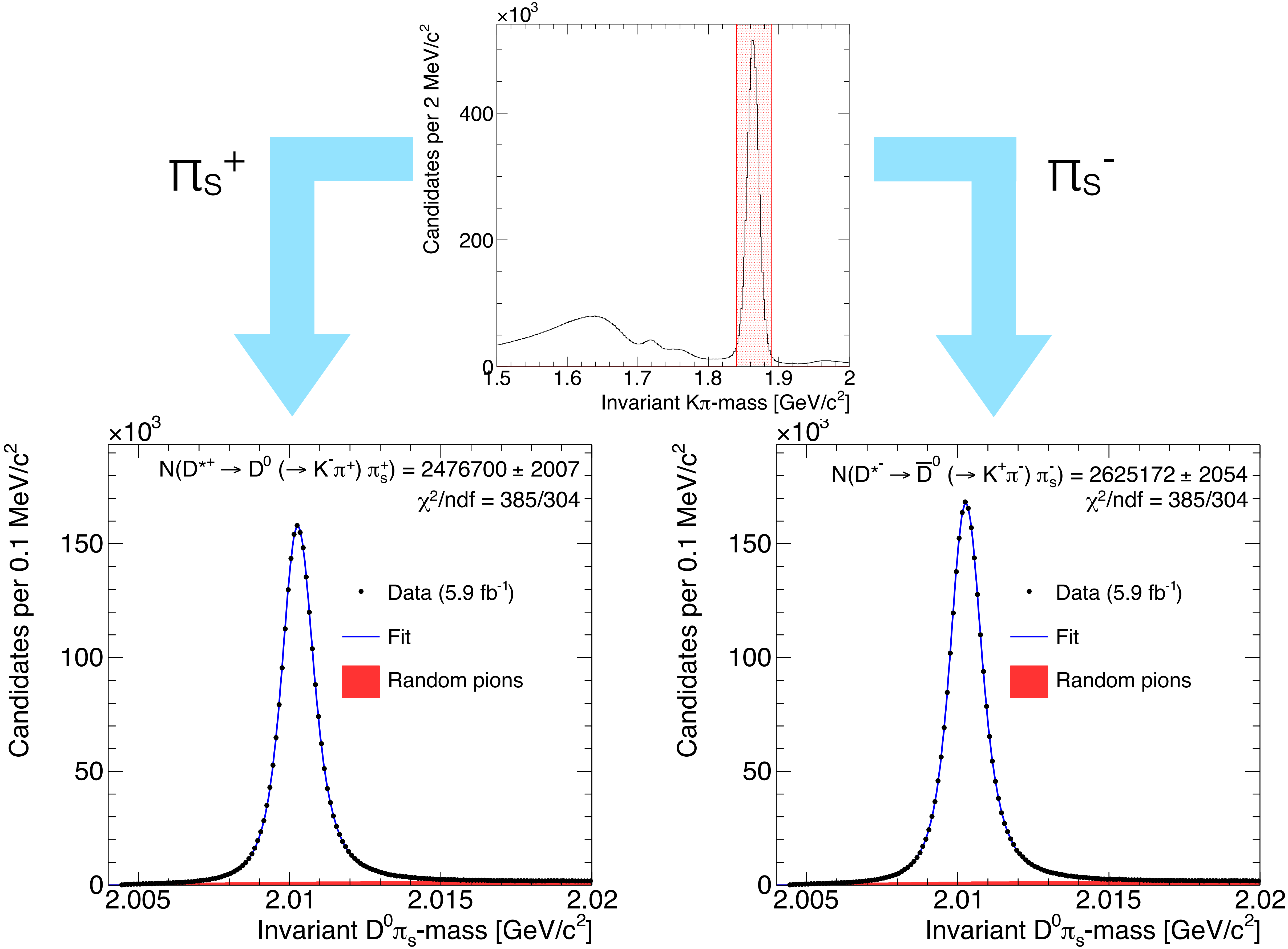
# Backup



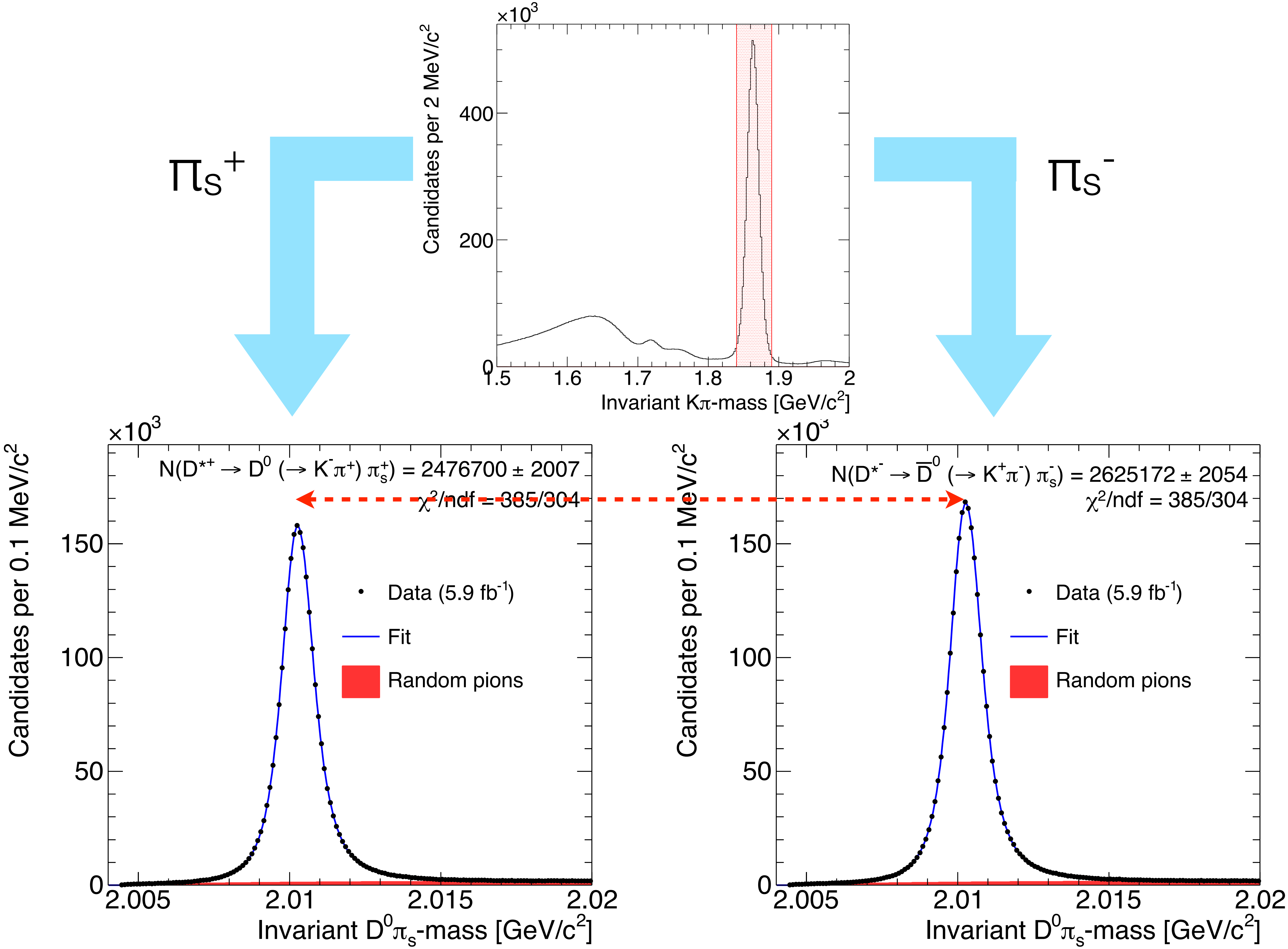
$\pi_s^+$
$\pi_s^-$
×10^3
Candidates per 2 MeV/c^2
150
100
50
0
1.5
1.6
1.7
1.8
1.9
2
Invariant π+π−-mass [GeV/c^2]
N(D*+ → D0 (→ π+π−) πs+) = 106169 ± 352
χ2/ndf = 325/308
Data (5.9 fb−1)
Fit
Random pions
Candidates per 0.1 MeV/c^2
8000
6000
4000
2000
0
2.005
2.01
2.015
2.02
Invariant D0πs-mass [GeV/c^2]
N(D*− → D̄0 (→ π+π−) πs−) = 110190 ± 358
χ2/ndf = 325/308
Data (5.9 fb−1)
Fit
Random pions
Candidates per 0.1 MeV/c^2
8000
6000
4000
2000
0
2.005
2.01
2.015
2.02
Invariant D0πs-mass [GeV/c^2]




$A(\pi\pi^*) = (-1.86 \pm 0.23)\%$



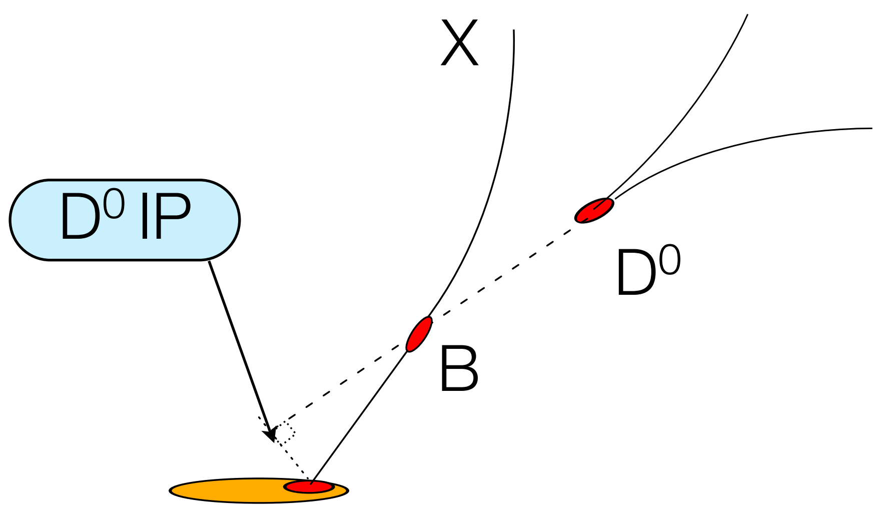
πs+
πs-
×10³
Candidates per 2 MeV/c²
400
200
0
1.5
1.6
1.7
1.8
1.9
2
Invariant Kπ-mass [GeV/c²]
×10³
N(D*+ → D⁰ (→ K⁻π⁺) πs⁺) = 2476700 ± 2007
χ²/ndf = 385/304
Candidates per 0.1 MeV/c²
150
100
50
0
Data (5.9 fb⁻¹)
Fit
Random pions
2.005
2.01
2.015
2.02
Invariant D⁰πs-mass [GeV/c²]
×10³
N(D*- → D̄⁰ (→ K⁺π⁻) πs⁻) = 2625172 ± 2054
χ²/ndf = 385/304
Candidates per 0.1 MeV/c²
150
100
50
0
Data (5.9 fb⁻¹)
Fit
Random pions
2.005
2.01
2.015
2.02
Invariant D⁰πs-mass [GeV/c²]

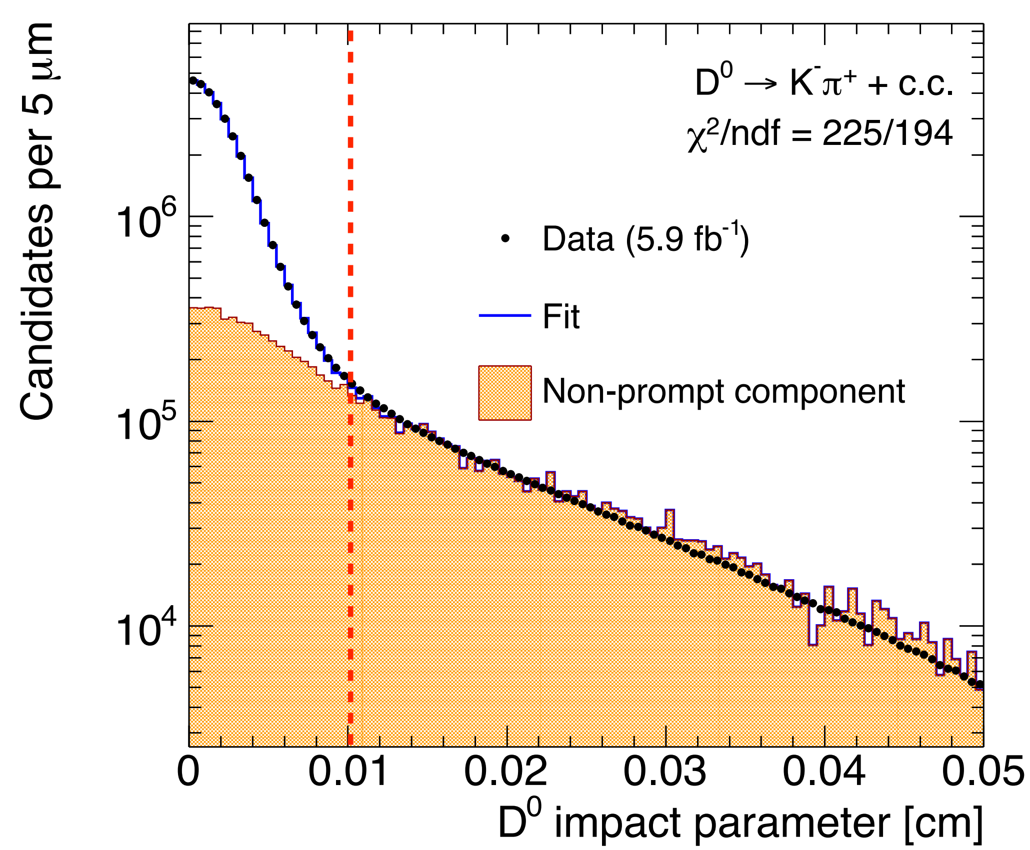



$A(K\pi^*) = (-2.91 \pm 0.05)\%$

# Secondary D mesons

- CPV in B decays could induce asymmetric production of D mesons
- $c\tau(B) \approx 450\mu m$, D mesons from B decays have non-zero impact parameter
  - 100µm cut removes most of them but still 17% of our candidates are likely to come from a B decay
- Cut inverted and analysis repeated on events enriched in D from B
  - Asymmetry in the sideband is consistent with the central one, then we evaluate $A_{CP}(B \to D^0 X) = (-0.21 \pm 0.20)\%$
- Assign 0.17×0.21% systematic



# Shapes' systematics

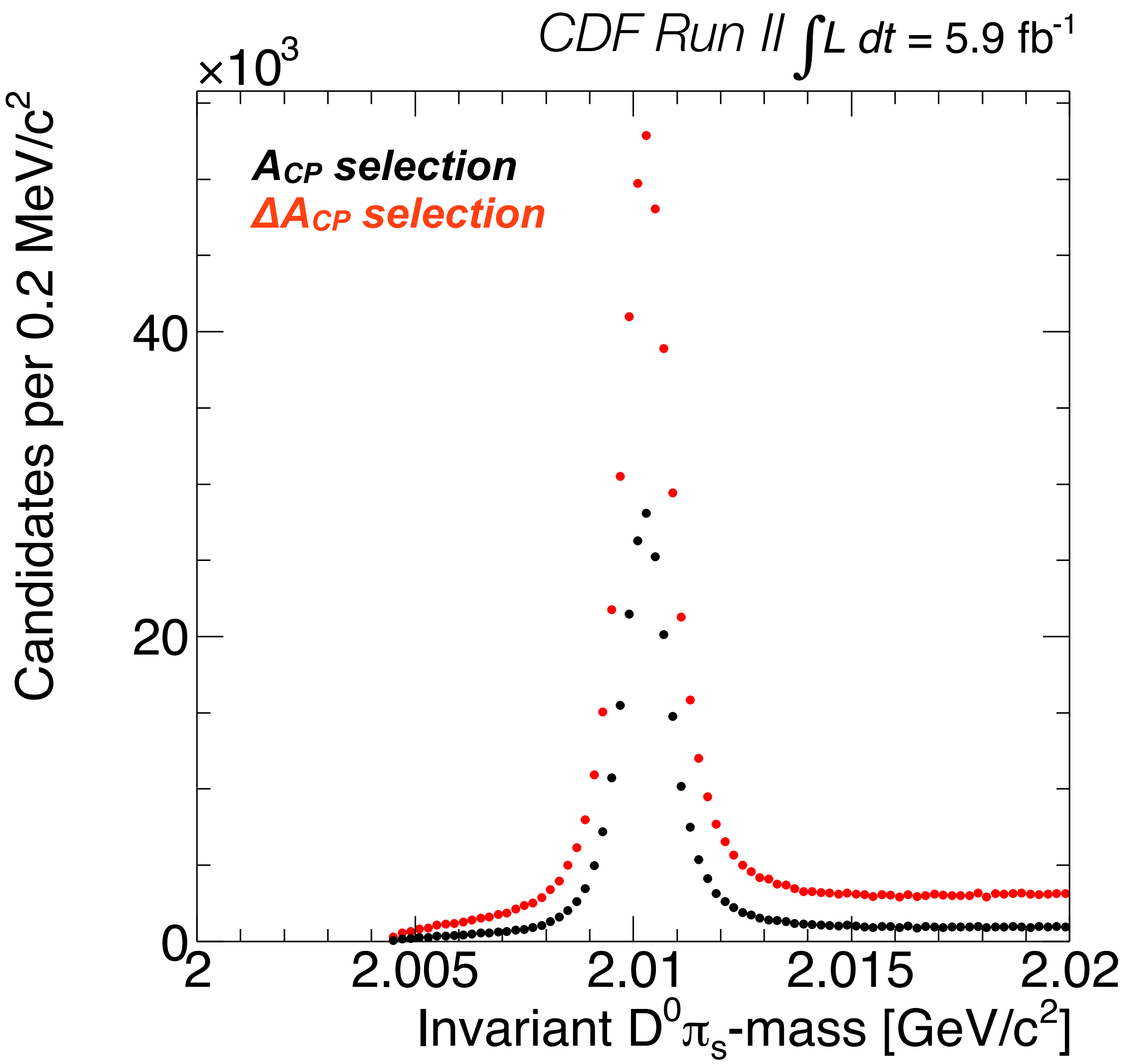
- In order to assess a systematic error associated with the particular shapes of the mass distributions of the signal assumed in the fits, we let them vary within reasonable limits and observe the corresponding change in the measured asymmetry

- When the same shape is used for the $D^0$ and $\bar{D}^0$ samples, the small changes in estimated yields tend to compensate and cause a negligible effect on the measured asymmetry

- The largest effect is obtained when the shapes used for the positive and negative samples are varied independently, we estimate a worst case effect of 0.098% (0.052%) for the $D^0 \to \pi^+\pi^-$ ($D^0 \to K^+K^-$) case

# Squeezing the most out of data

- No large gain from 5.9→9.7 $fb^{-1}$ (displaced-track triggers heavily suppressed in late data)
- Redesign selection on $D^0$ daughters toward the measurement of $\Delta A_{CP}$:
  - Loosen track hits requirements
  - Relax $p_T$ and $\eta$ thresholds
  - Use ~12% D from B decays




- Doubled signal yields. Costs some more background. Expect resolution on final result competitive with LHCb

# Update of individual asymmetries

- The measured value of $\Delta A_{CP}$ in the subsample of additional events selected by the new criteria (yellow band) is combined with the statistically independent results of the previous analysis (dashed bands), to obtain a more precise determination of the individual asymmetries:

$A_{CP}(D^0 \rightarrow \pi^+\pi^-) = (+0.31 \pm 0.22)\%$

$A_{CP}(D^0 \rightarrow K^+K^-) = (-0.32 \pm 0.21)\%$