Studies of charmed particle decays at Belle

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For Belle Collaboration

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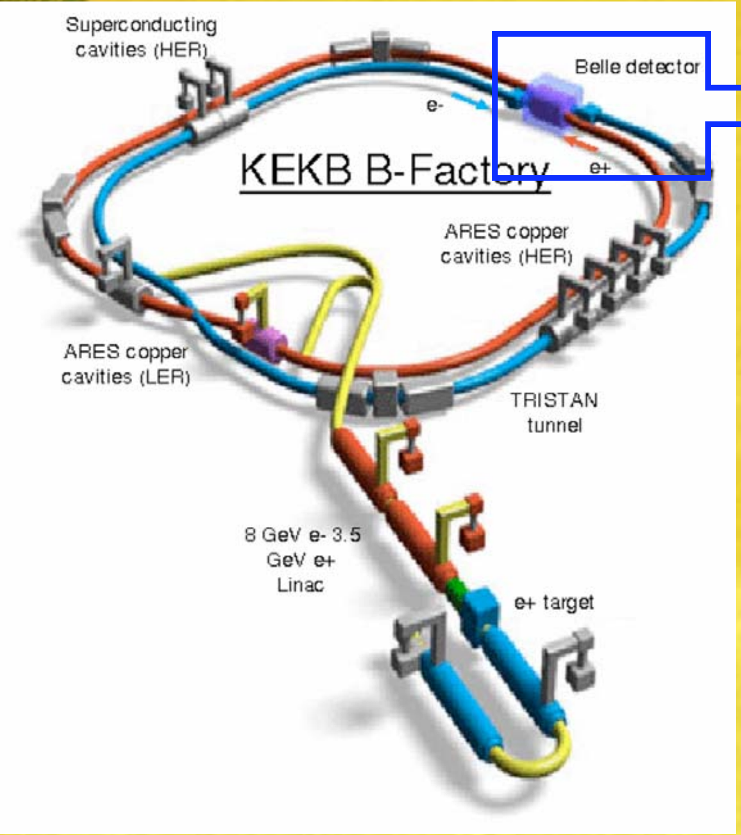
Branching Fraction(BF) and Form Factor(FF) measured in the charm sector by Belle recently...

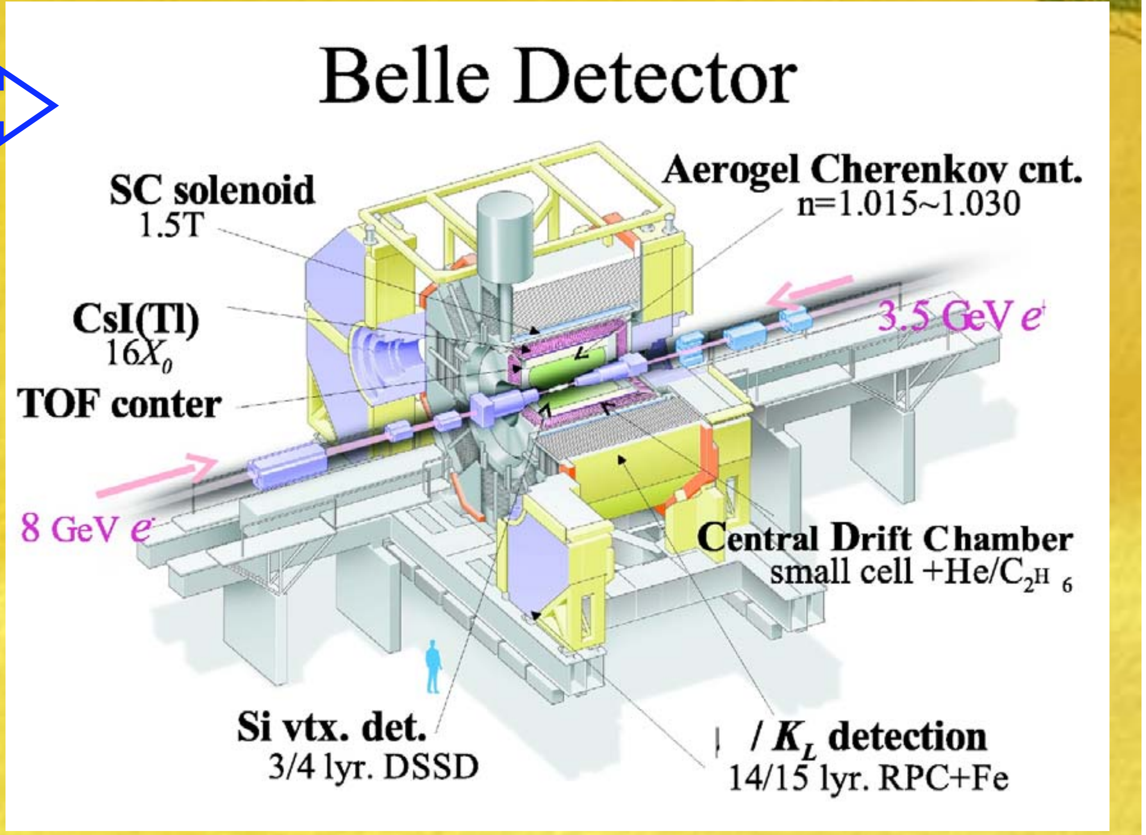
- $D^0 \rightarrow \pi^+ \pi^- \pi^0$: Relative BF
- $D^0 \rightarrow (\pi^- / K^-) l^+ \nu$: Absolute BF & FF
- $\Lambda_c^+ \rightarrow p^+ K^- \pi^+$: Absolute BF
- $D_s^+ \rightarrow K^- K^+ \pi^+$: Absolute BF

These BF measurements were motivated by the fact that…

- Many B-meson decay analyses and CPV studies rely on the knowledge of D-meson BF
- Double tag BF measurement method uses charm production at the threshold. (BES-III, CLEO-c)
- The high luminosity of B-factories provides competitive results in charm
- Quasi 2-body e^+e^- annihilation processes at 10.5 GeV allow us to obtain clean samples of tags

The measurements were carried out at the Belle Detector situated in the KEKB B-Factory.

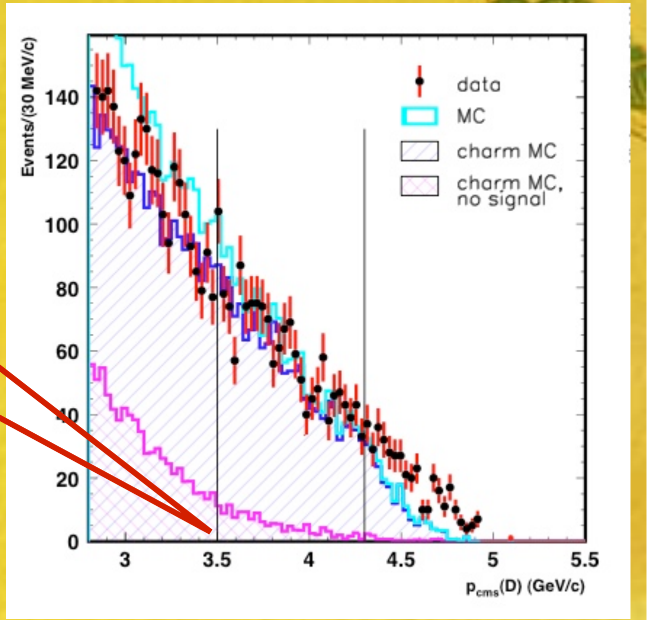




3.5(e^+) × 8(e^-) GeV
3 km circumference
11 mrad crossing angle

$\int L\,dt = 630\ \mathrm{fb}^{-1}$

$D^0 \to \pi^+ \pi^- \pi^0$ BF, measured relative to the $D^0 \to K^- \pi^+ \pi^0$ BF
hep-ex/0610062

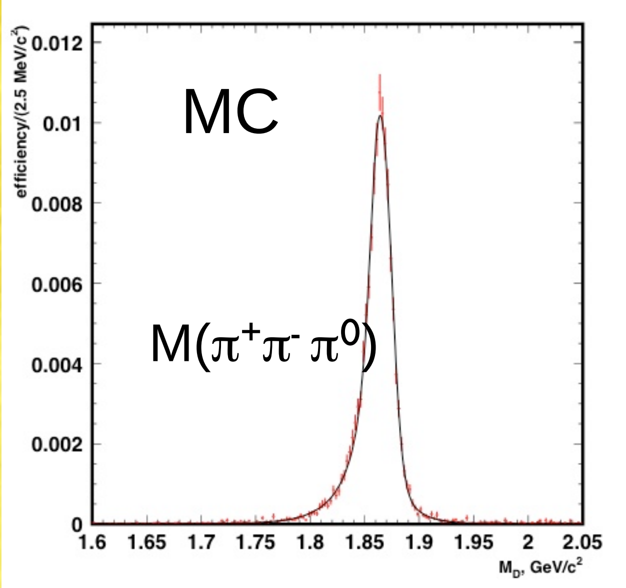


Lower cut rejects fake combinatorial D^* from B-mesons

PID efficiencies
π= 93%, K = 86
K misidentification = 9%
π misidentification = 4%

Event Selection

- tagged by $D^{*+} \to D^0 \pi_{slow}^+$ or cc mode
- 3.5 GeV/c < p_{D^*} in Υ(4s) cm frame < 4.3 GeV/c
- Likelihood ratio cut for charged K/π selection
- π^0's from photon pairs, selection on invariant mass and energy of the pair.
- $D^0 \to K_s^0 \pi^0$ rejected by veto on $(\pi^+\pi^-)$ inv. mass

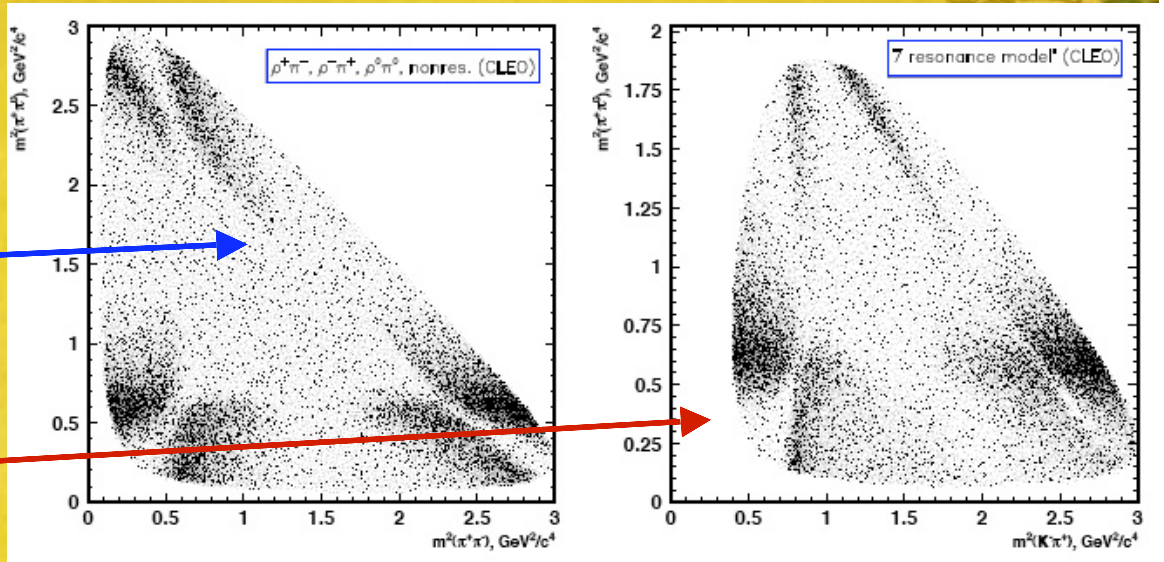


Efficiency calculation

$D^0 \to \pi^+\pi^-\pi^0$, Relative BF

3 resonance model for $\pi^+ \pi^- \pi^0$ (ρ^+, ρ^-, ρ^0 and non-resonance contribution)

7 resonance model for $K^- \pi^+ \pi^0$ (ρ^+, K^{*-}, $\overline{K}^{0*}$, $K^0(1430)^-$, $K_0(1430)^0$, $\rho(1700)^+$, $K^{*-}(1680)$ and non-resonance contribution)



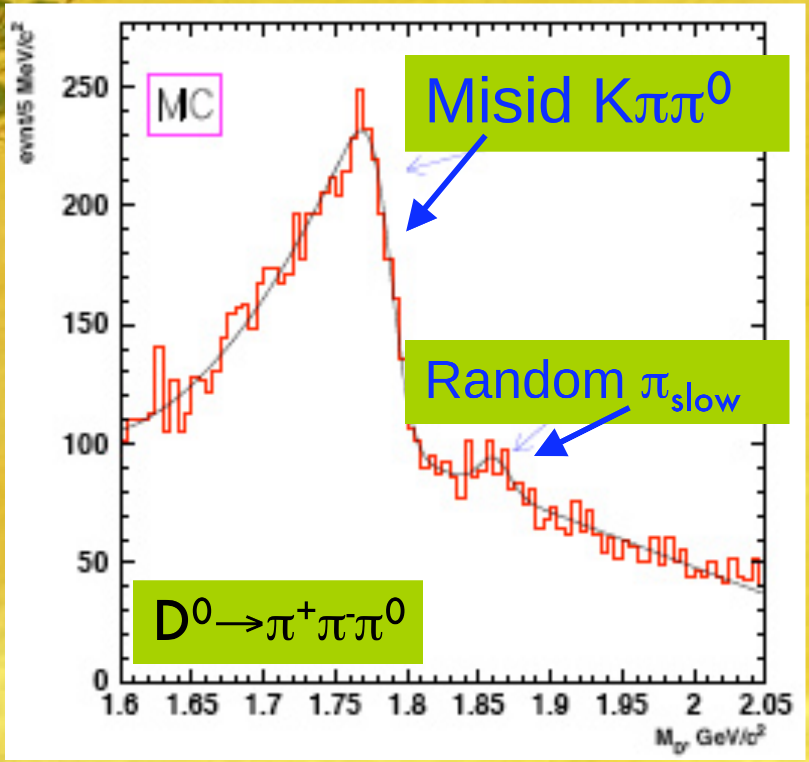
D. Cronin-Hennessy et al. (CLEO Collaboration), Phys. Rev. D 72, 031102 (2005), 3-resonance

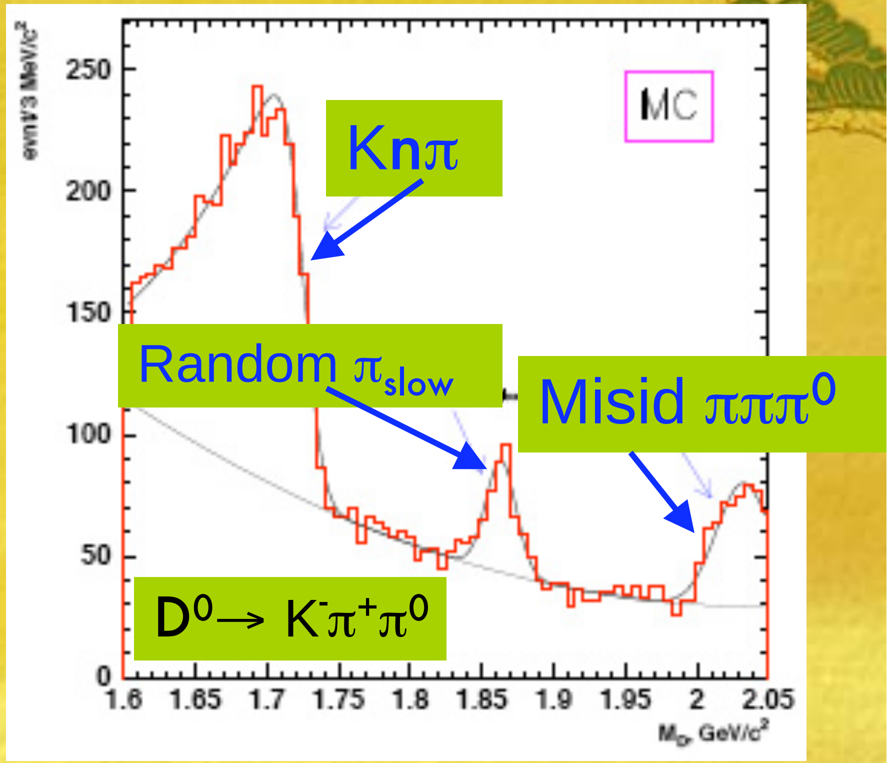
S. Kopp et al. (CLEO Collaboration), Phys. Rev. D 63, 092001 (2001), 7-resonance

- 1.2 million phase space MC, each decay mode
- Events weighted by resonance models from CLEO
- Efficiency $\varepsilon(\pi^+\pi^-\pi^0) = 13.433\%$, $\varepsilon(K^-\pi^+\pi^0) = 13.065\%$

Backgrounds

$D^0 \to \pi^+\pi^-\pi^0$, Relative BF





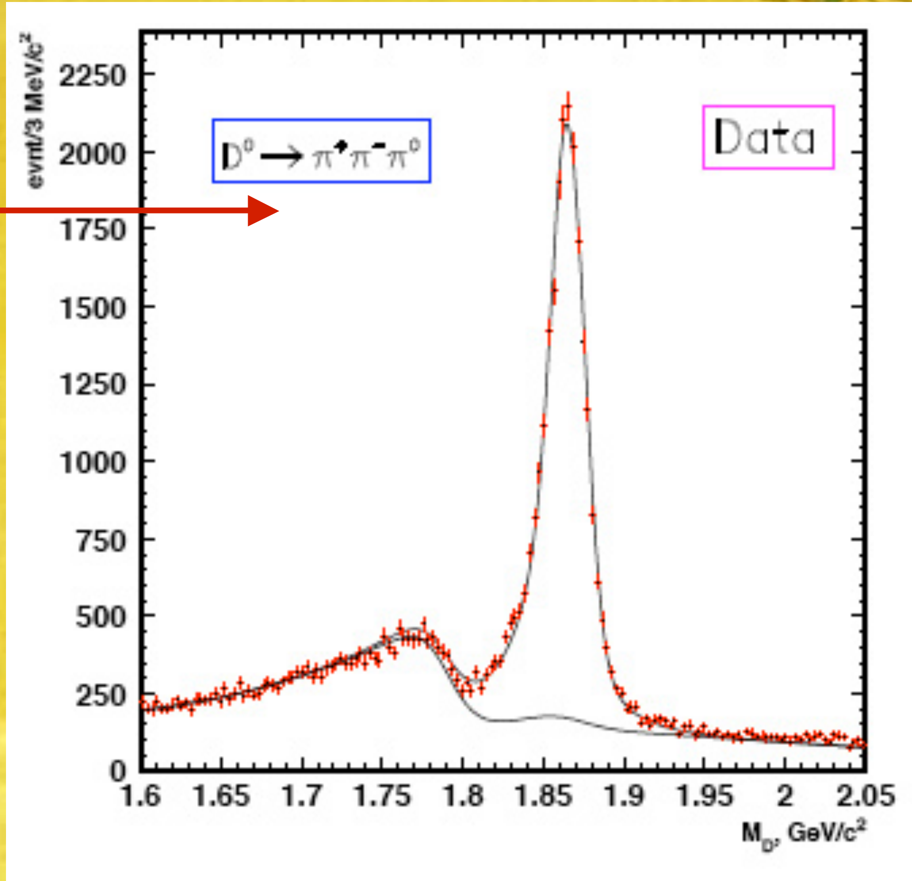
- Nontrivial features coming from misidentified kaons or pions, peaks under the signal from random π_{slow} and true D^0 combination or $D^0 \to K\ n\pi$, $n \geq 3$ in case of $K^-\pi^+\pi^0$
- Has been fitted to Gaussians and polynomial and polynomial X error function.

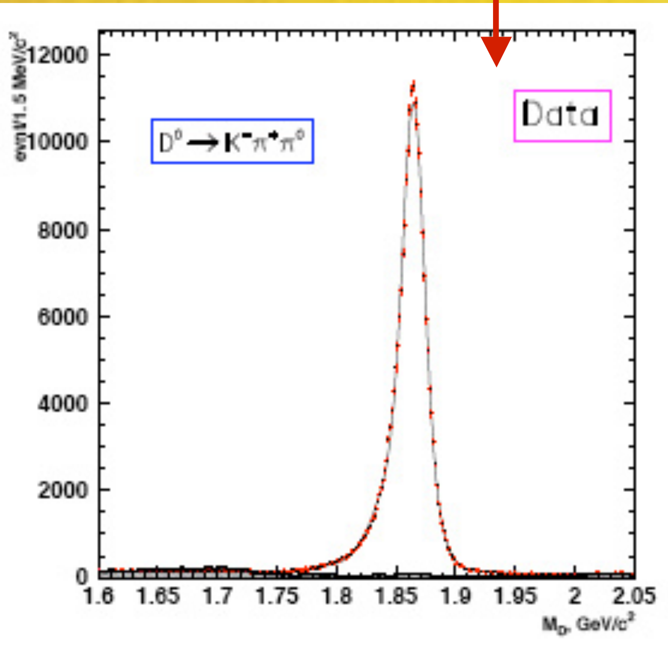
Signal fit and yield in data

$D^0 \to \pi^+\pi^-\pi^0$, Relative BF

- $\pi^+\pi^-\pi^0$ signal is fitted to a bifurcated Gaussian and a regular Gaussian.

- $K^-\pi^+\pi^0$ signal is fitted to two bifurcated Gaussian





D^0 decay mode	N_{ev}	ε, %
$\pi^+\pi^-\pi^0$	22803 ± 203	13.433 ± 0.077
$K^-\pi^+\pi^0$	237520 ± 500	13.065 ± 0.074

Systematic uncertainties $D^0 \to \pi^+\pi^-\pi^0$, Relative BF

π^0 and tracking efficiency uncertainties cancel

Leading sources of systematics

- Data/MC PID efficiency difference
- Decay model
- Ks veto requirement

Error estimated by varying this requirement

Source	Error, %
MC statistics	0.8
PID efficiency of K/π	1.6
Decay model	1.8
Fit (background & signal)	0.7
$p_{cms}(D^*)$ cut	0.4
K_S^0 veto	1.6
Total	3.1

Recalculate efficiency
$\pi^+\pi^-\pi^0$: 3 model resonance without interference.
$K^-\pi^-\pi^0$: 3 model resonance

Correction estimated using large independent sample of $D^0 \to K^- \pi^+$, tagged by $D^* \to D^0\pi$

Summary & conclusion

$D^0 \to \pi^+ \pi^- \pi^0$, Relative BF

357 fb^{-1} data at Belle detector

$BF(D^0 \to \pi^+\pi^-\pi^0)/BF(D^0 \to K^-\pi^+\pi^0) = 0.0971 \pm 0.0009_{stat} \pm 0.0030_{syst}$

Our preliminary result 0.0971±0.0031

World Average 0.0929±0.0054

Our result is compatible with WA but more precise.

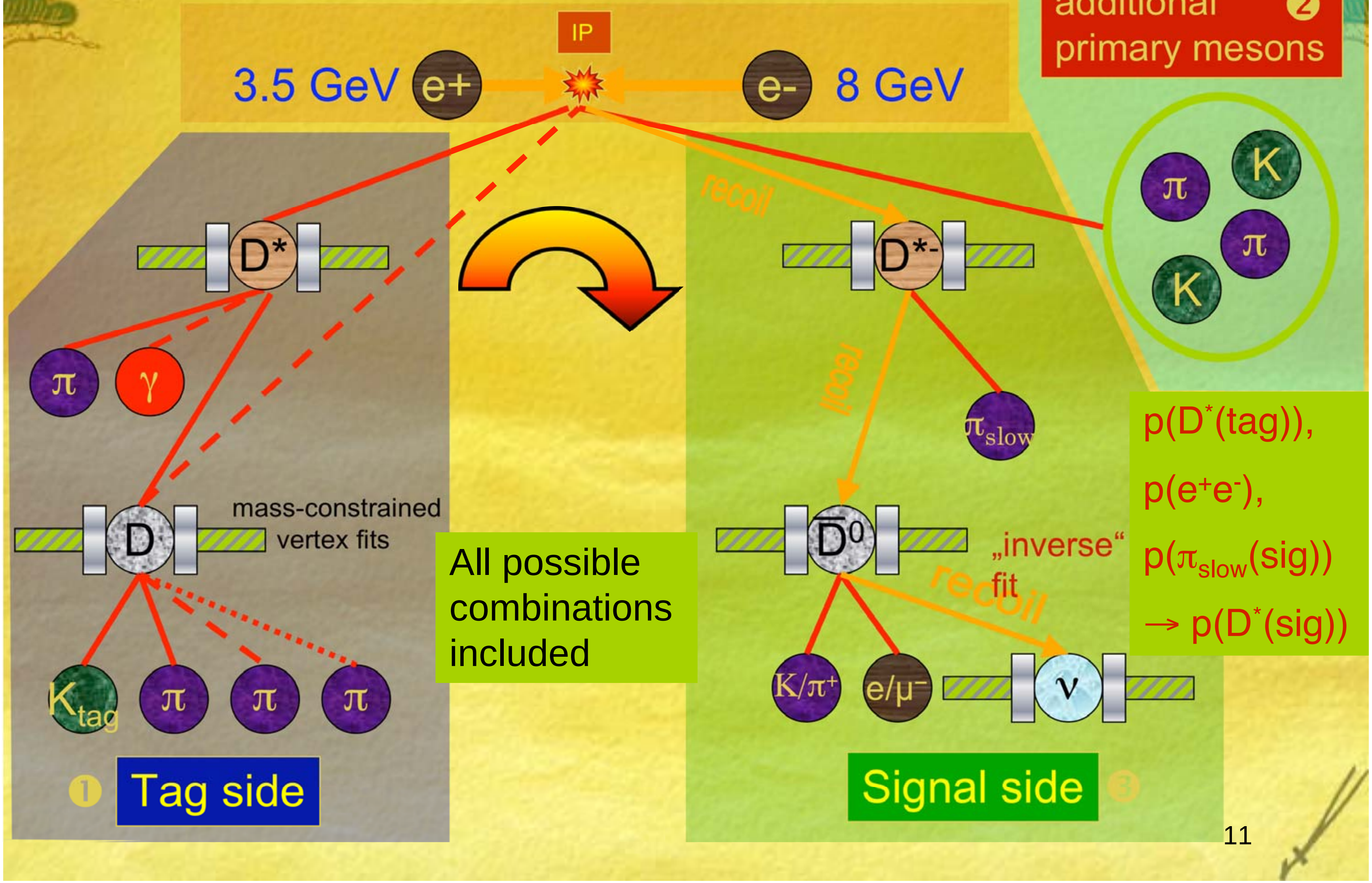
Known $BF(D^0 \to K^-\pi^+\pi^0)$, for Belle, Known $BF(D^0 \to K^-\pi^+)$, for CLEO

	$N_{ev.}$	$\mathcal{B}(D^0 \to \pi^+\pi^-\pi^0)$, 10^{-3}
Belle	22803 ± 203	$13.69 \pm 0.13_{stat} \pm 0.42_{syst} \pm 0.49_{norm}$
CLEO-c	10834 ± 164	$13.2 \pm 0.2_{stat} \pm 0.5_{syst} \pm 0.2_{norm} \pm 0.1_{CPcorr.}$

A High Statistics Dalitz Plot Analysis is Underway

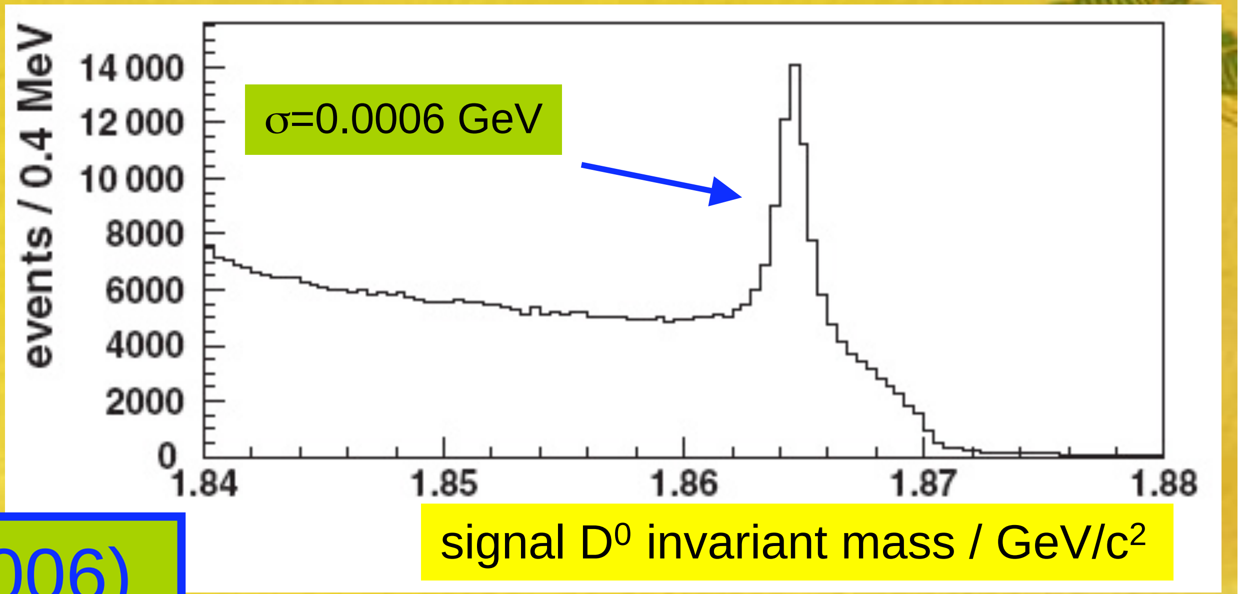
$D^0 \to (\pi^-/K^-) l^+ \nu$: Absolute BF & FF

Method of Reconstruction (Event Topology)



$D^0 \to (\pi^-/K^-)l^+\nu$: Absolute BF & FF

Inclusive D^0 Signal



PRL 97, 061804 (2006)

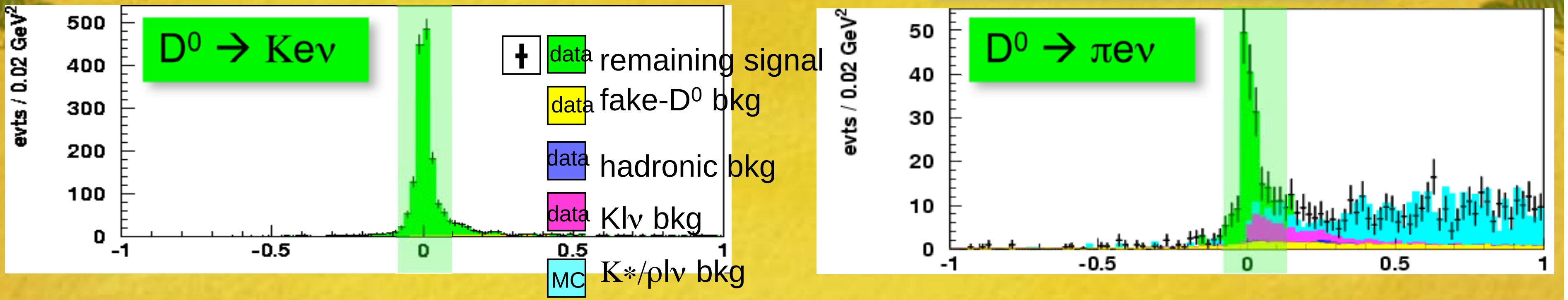
Result 282 fb^{-1} of BELLE data	Yield
After cuts	95250
Background	38789 ± 830
Signal	56461 ± 309 ± 830

WS events used to estimate amount of fake D^0

$D^0 \to (\pi^-/K^-) l^+ \nu$: Absolute BF & FF

Signal, Background Decomposition

Similar for $D^0 \to K/\pi\ \mu\nu$



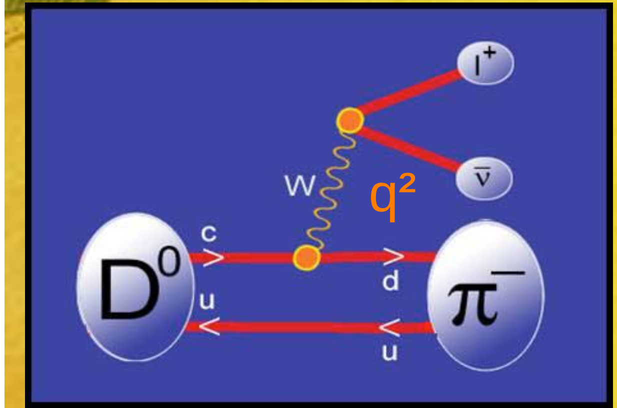
ν mass via recoil of K/π and lepton(e/μ) on signal side, m_ν^2 / GeV²

- Fake D^0: estimated from the side bands using WS events
- $Kl\nu$ (in $\pi l\nu$): Simulated $Kl\nu$, reweighted to the observed number in data
- Hadronic: Opposite sign of lepton, π_{slow} ensures no semileptonic background or signal events. Positively identified K and π in MC assigned a lepton mass, distributions fitted to the OS data sample

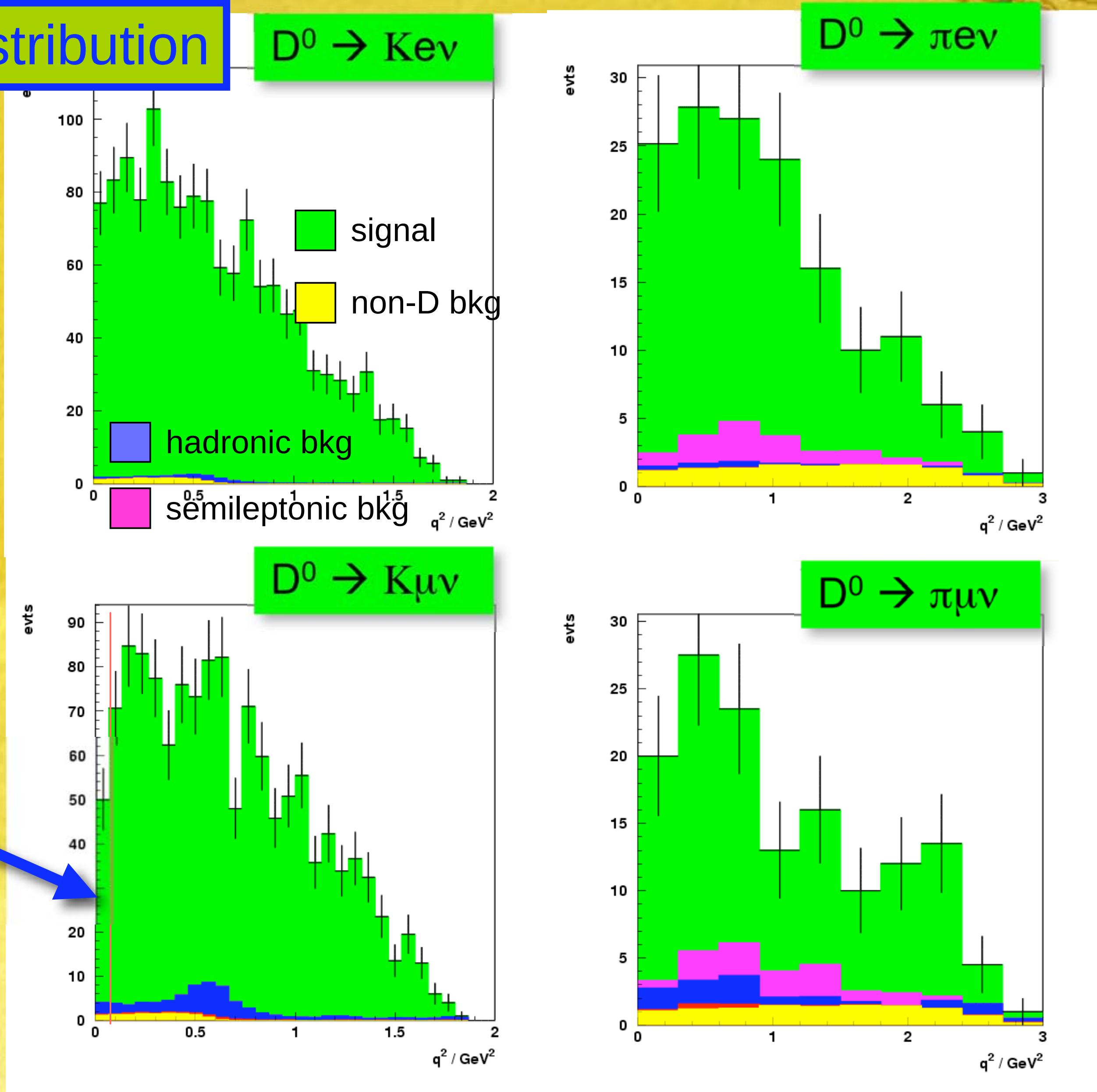
Result 282 fb^{-1}	$Ke\nu$	$K\mu\nu$	$\pi e\nu$	$\pi\mu\nu$
Signal	1318 ± 37 ± 7	1249 ± 37 ± 25	126 ± 12 ± 3	106 ± 12 ± 6

$D^0 \to (\pi^-/K^-) l^+ \nu$: Absolute BF & FF

Form Factors – q² distribution



$\sigma(q^2) = 0.0145\ GeV^2/c^2$
(width of red line)
→ no unfolding necessary!



background shapes from data

$D^0 \to (\pi^-/K^-) l^+ \nu$: Absolute BF & FF

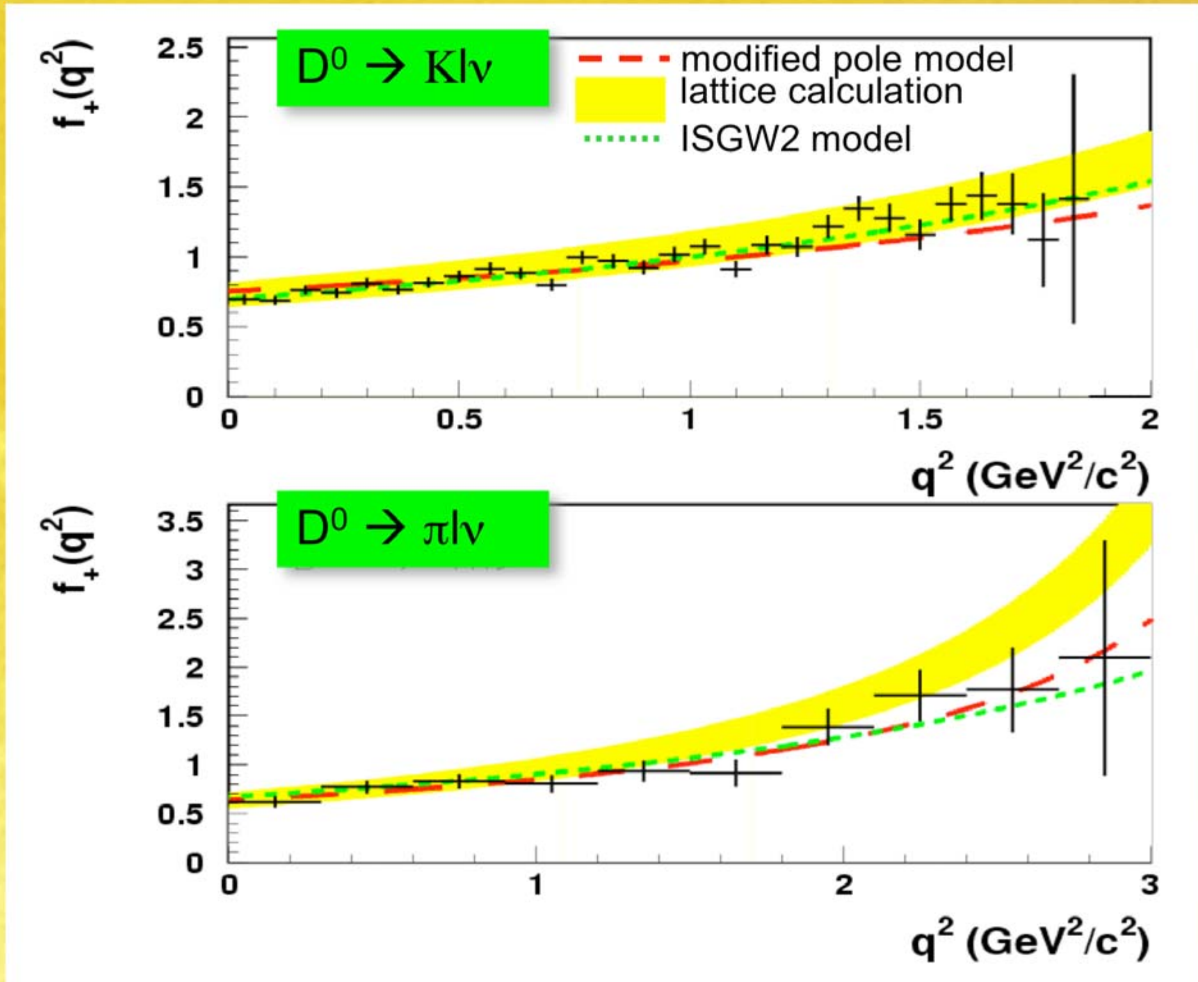
Form Factors and Comparison with Models

two form factors $f^+(q^2)$ and $f^-(q^2)$,
$f^-(q^2)$ suppressed by m_l^2
three models in literature

$$\frac{f_+^\pi(0)^2|V_{cd}|^2}{f_+^K(0)^2|V_{cs}|^2} = 0.042 \pm 0.003_{\rm stat} \pm 0.003_{\rm syst}$$

simple pole	pole mass (GeV)
$Kl\nu$	$1.82 \pm 0.04_{stat} \pm 0.03_{syst}$
$\pi l\nu$	$1.97 \pm 0.08_{stat} \pm 0.04_{syst}$

modified pole (poles fixed at theo. values)	$f_+(0)$
$Kl\nu$	$0.695 \pm 0.007_{stat} \pm 0.022_{syst}$
$\pi l\nu$	$0.624 \pm 0.020_{stat} \pm 0.030_{syst}$
	α
$Kl\nu$	$0.52 \pm 0.08_{stat} \pm 0.06_{syst}$
$\pi l\nu$	$0.10 \pm 0.21_{stat} \pm 0.10_{syst}$



$D^0 \to (\pi^-/K^-) l^+ \nu$: Absolute BF & FF

Summary & Conclusion

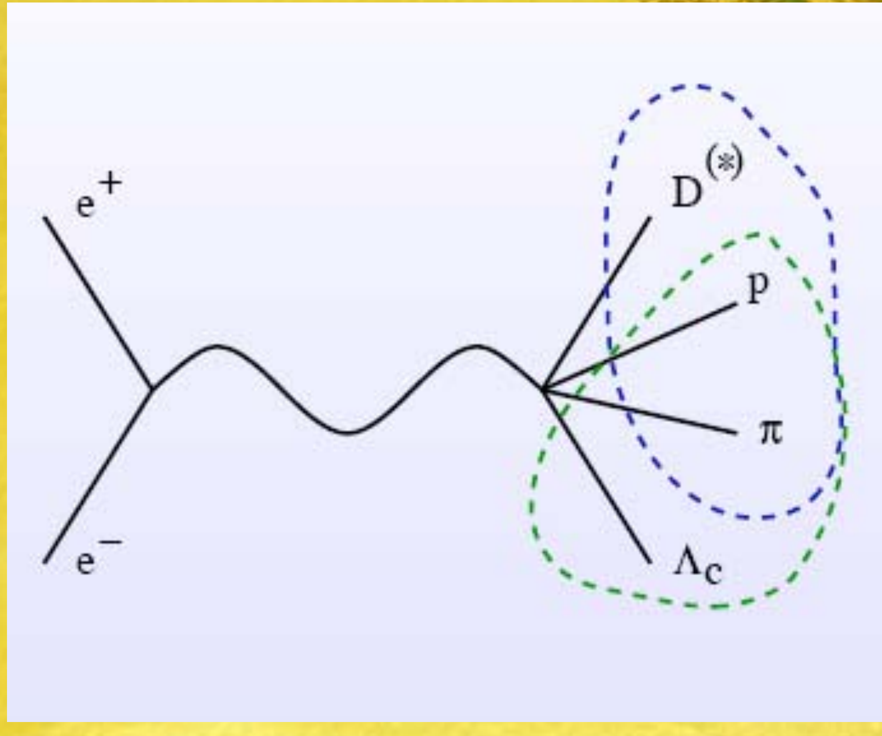
❖ Four D^0 semiletonic absolute BF measurements, $D^0 \to \pi\ell\nu$ / $K\ell\nu$, $\pi\mu\nu$ being the first such measurement.

❖ Measurement of q^2 dependent decay widths with very good q^2 resolution

❖ Absolute BRs of better accuracy than previous experiments, good agreement with recent CLEO measurements

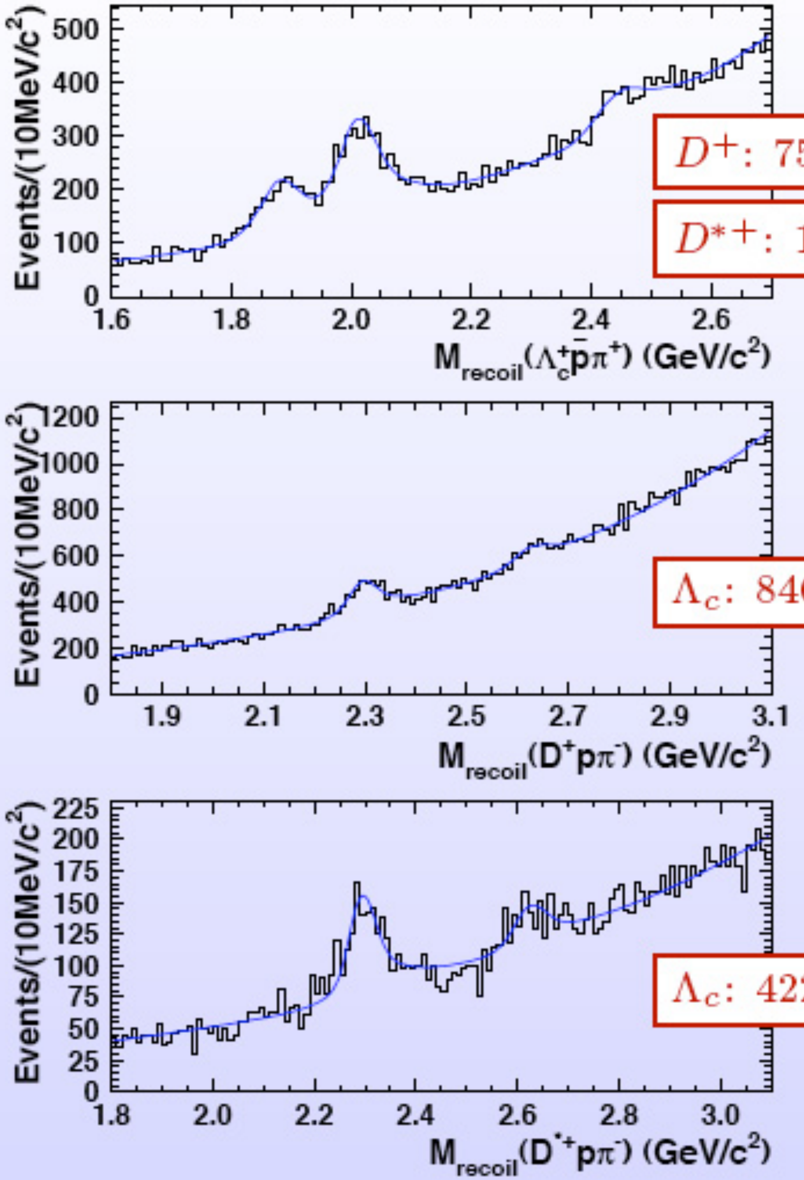
❖ Form factor measurements, good agreement with theory and other experiments, competitive with recent CLEO-c measurements

$\Lambda_c^+ \to p^+ K^- \pi^+$: Absolute BF



- This is a poorly measured BF, all other Λ_c BFs are measured wrt this decay, use $e^+e^- \to \Lambda_c \pi p D^*$
- Reconstruct D, p, π and look at Λ_c/Λ_c^* mass in the recoil mass distribution, yield α measured BF
- Reconstruct Λ_c, p, π and look at the $D^{(*)}$ mass in the recoil mass distribution, yield α known $D^{(*)}$ BFs

$\Lambda_c^+ \to p^+ K^- \pi^+$: Absolute BF



Source	error, %
Fit	4.2
ISR	1.2
MC statistics	1.2
Identification	5.7
Tracking	4.4
$\mathcal{B}(D^*)$	1.6
Total	8.7

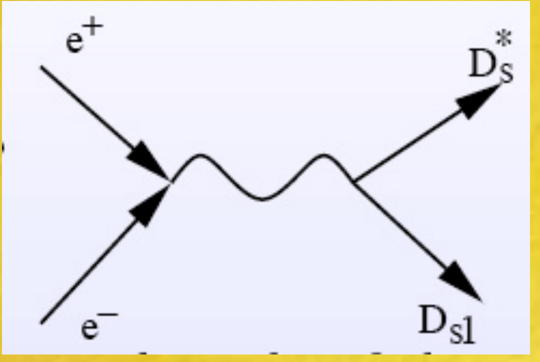
$$\mathcal{B}(\Lambda_c \to pK\pi) = 4.86 \pm 0.30(stat.) \pm 0.42(syst.)\%$$

PRELIMINARY

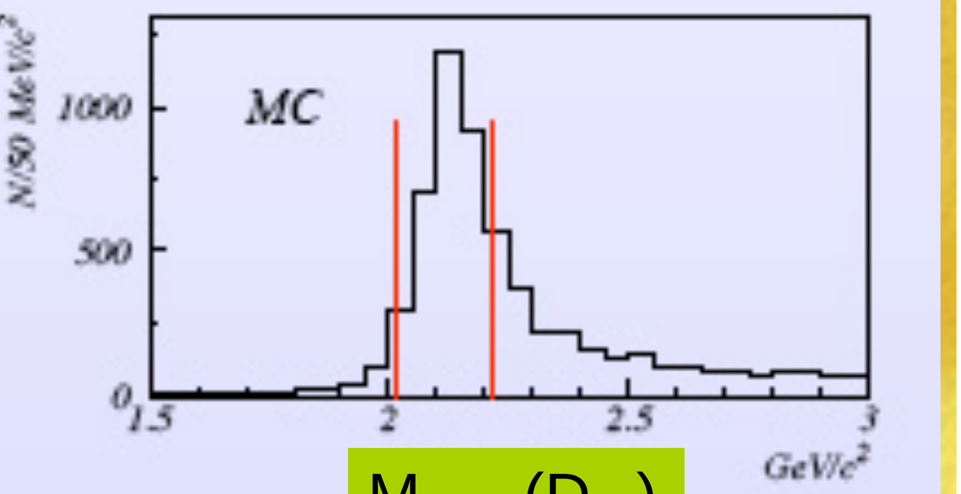
$D_s^+ \to K^+ K^- \pi^+$: Absolute BF

Double Partial Reconstruction

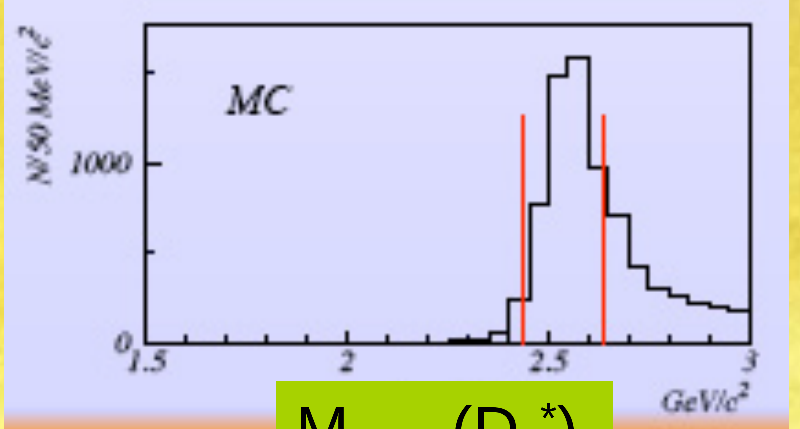
$$M_{recoil}(D_{s1}) = \sqrt{(\sqrt{s} - E(D_{s1}))^2 - P^2(D_{s1})}$$



- Use $e^+e^- \to D_{s1}D_s^*$, $D_s^{*+} \to D_s^+ \gamma$, $D_{s1}^- \to DK(D^{*0}K^- / D^{*-}K_s^0)$
- 1st tag: full D_{s1}^- reconstruction, γ from $D_s^* \to D_s^+ \gamma$, yield α absolute D^* BF
- 2nd tag: full D_s^{*+}(in $D_s^+\gamma$) and K from $D_{s1}^- \to DK$, yield related to BF of $D_s^+ \to K^+K^-\pi^+$



$M_{recoil}(D_{s1})$



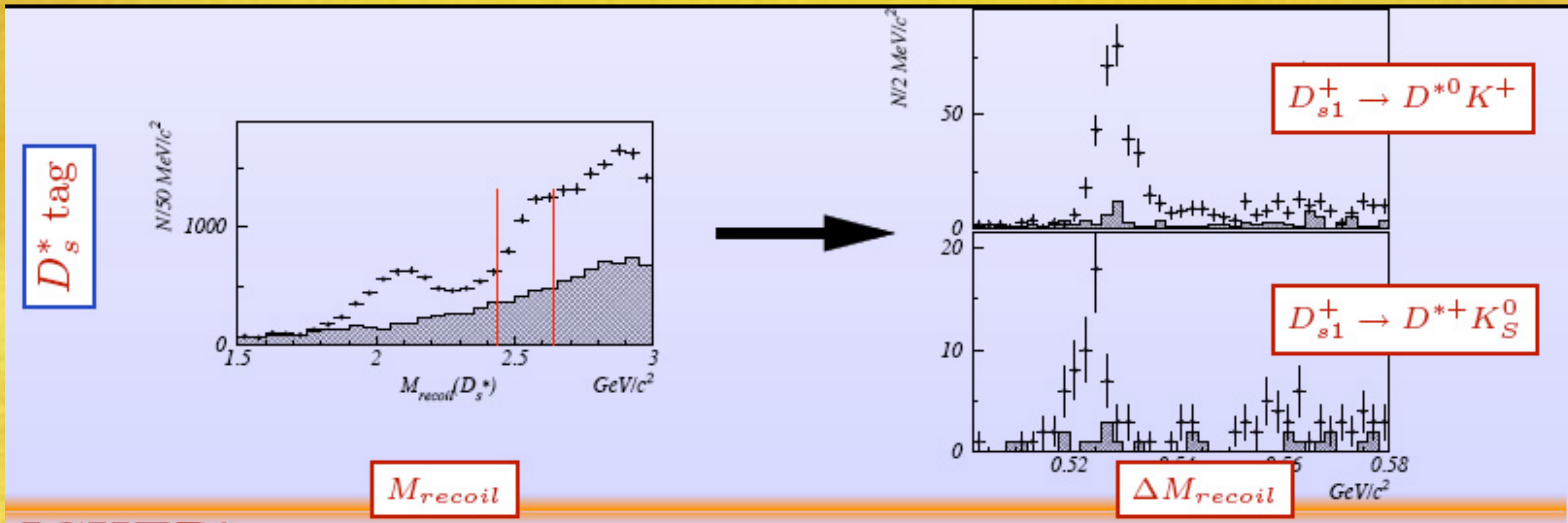
$M_{recoil}(D_s^*)$

$D_s^+ \to K^+ K^- \pi^+$: Absolute BF

Recoil mass difference, ΔM_{recoil}

$$\Delta M_{recoil}(D_{s1}) = M_{recoil}(D_{s1}) - M_{recoil}(D_{s1}\gamma)$$

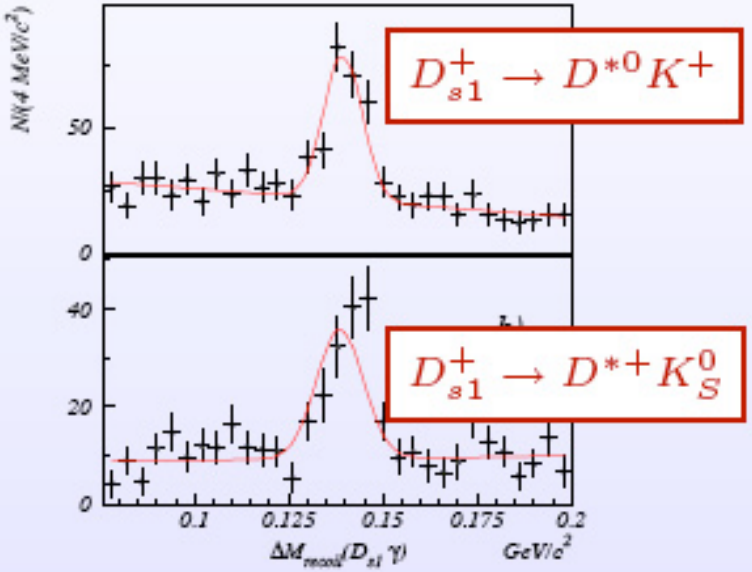
Narrow signal peak, no peaking background, similar for D_s^*

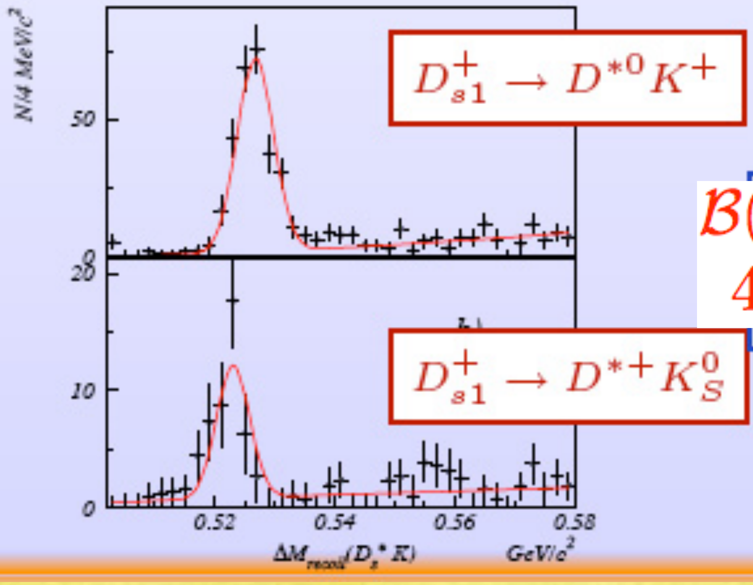


- much better resolution than M_{recoil}
- Reduce background to negligible level, most systematics cancel out

$D_s^+ \to K^+ K^- \pi^+$: Absolute BF

Perform fit in ΔM_{recoil}, reduce residual background





Source	error, %
recoil mass cut	4.8
ISR	2.3
angular	3.9
Tracking	2.5
Branchings	7.6
Total	10.1

$$\mathcal{B}(D_s \to K^- K^+ \pi^+) = 4.1 \pm 0.4(stat.) \pm 0.4(syst.)\%$$

PRELIMINARY

Summary

- Two-body and quasi-two-body e^+e^- annihilation processes provides a good tag and can be used for charm studies.
- $D_s \to KK\pi$ branching is measured with 10% accuracy (competitive to the world average; the result is consistent with the world average and somewhat below the preliminary CLEO-c results)
- $D^0 \to K(\pi)l\nu$ branchings are measured (better than world average)
- D^0 form-factors are measured in wide q^2 range (good agreement with both theory and previous measurements)
- $\Lambda_c \to pK\pi$ branching fraction is determined (better than world average)
- $\frac{\mathcal{B}(D^0 \to \pi^-\pi^+\pi^0)}{\mathcal{B}(D^0 \to K^-\pi^-\pi^0)}$ is determined(competitive to last CLEO-c measurements). Dalitz analysis is under way.
- B-factory seems a suitable place for charm studies

Backup slides

$D^0 \to \pi^+\pi^-\pi^0$, Relative BF

Comparison with BaBar

Belle:

$ß(D^0 \to \pi^+\pi^-\pi^0)/ß(D^0 \to K^-\pi^+\pi^0) = 0.0971 \pm 0.0009_{stat} \pm 0.0030_{syst}$.

BaBar:

$0.1059 \pm 0.0006 \pm 0.0013$.

The Belle result differs by ~ 2.8 σ

REF. B. Aubert et al. (BABAR Collaboration), hep-ex/0608009.

$D^0 \to \pi^+ \pi^- \pi^0$, Relative BF measurement, hep-ex/0610062

- A high statistics Dalitz plot analysis is underway

1. Insight into s wave $\pi^+\pi^-$ contribution in these decays
2. Sensitive CP violation study in neutral D Mesons

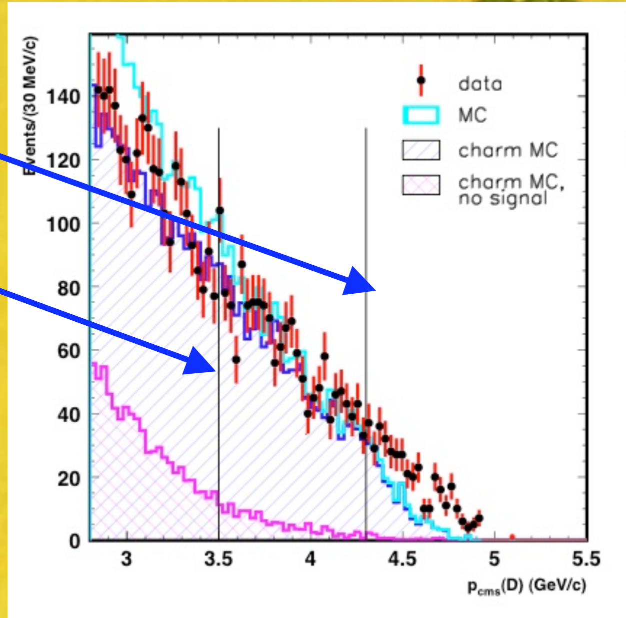
Event selection

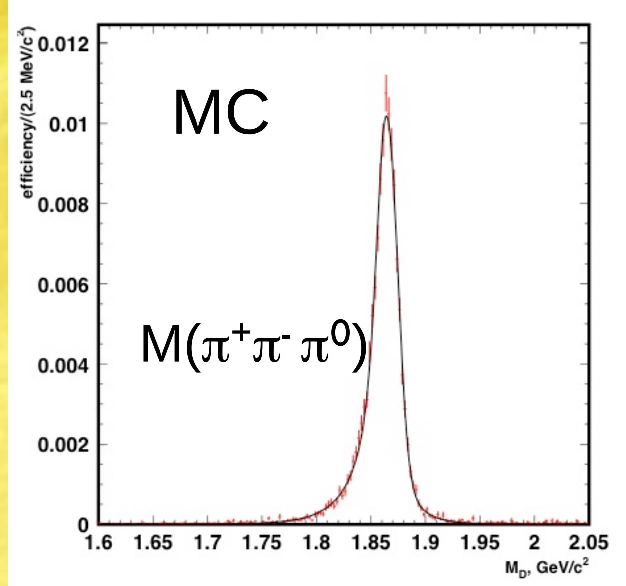
$D^0 \to \pi^+ \pi^- \pi^0$, Relative BF

PID efficiencies
π= 93%, K = 86
K misidentification = 9%
π misidentification = 4%

data/MC agreement. Rejects fake combinatorial D^* from B-mesons

- tagged by $D^{*+} \to D^0 \pi_{slow}^+$ or cc mode
- 3.5 GeV/c < p_{D^*} in $\Upsilon(4s)$ cm frame < 4.3 GeV/c
- PID Likelihood ratio cut for K/π selection
- energy of photons forming π^0 > 0.06 GeV
- 0.124 GeV/c^2 < photon pair invariant mass < 0.148 GeV/c^2
- π^0 lab momentum > 0.3 GeV/c
- $0.1442 < M(\pi_{slow} \pi^+ \pi^- \pi^0) - M(\pi^+ \pi^- \pi^0) < 0.1448$
- $0.1440 < M(\pi_{slow} K^- \pi^+ \pi^0) - M(K^- \pi^{-+} \pi^0) < 0.1470$
- 0.21 GeV^2/c^4 < $M^2(\pi^+\pi^-)$ < 0.29 GeV^2/c^4:vetoes $D^0 \to K_s^0 \pi^0$



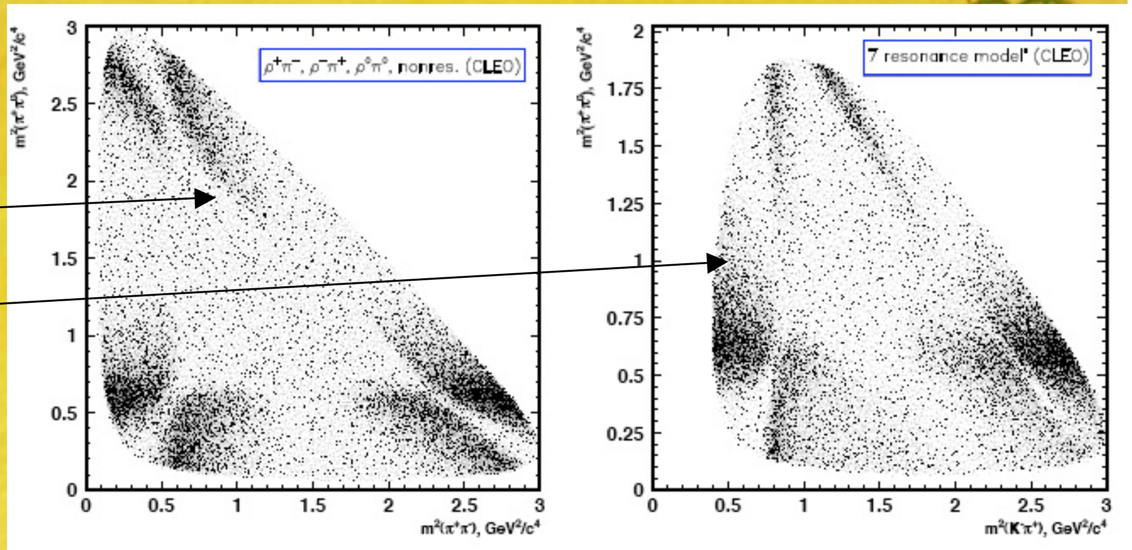


Efficiency calculation

$D^0 \to \pi^+ \pi^- \pi^0$, Relative BF

3 resonance model for $\pi^+ \pi^- \pi^0$ (ρ^+, ρ^-, ρ^0 and non-resonance contribution)

7 resonance model for $K^- \pi^+ \pi^0$ (ρ^+, K^{*-}, $\bar{K}^{0*}$, $K^0(1430)^-$, $K_0(1430)^0$, $\rho(1700)^+$, $K^{*-}(1680)$ and non-resonance contribution)

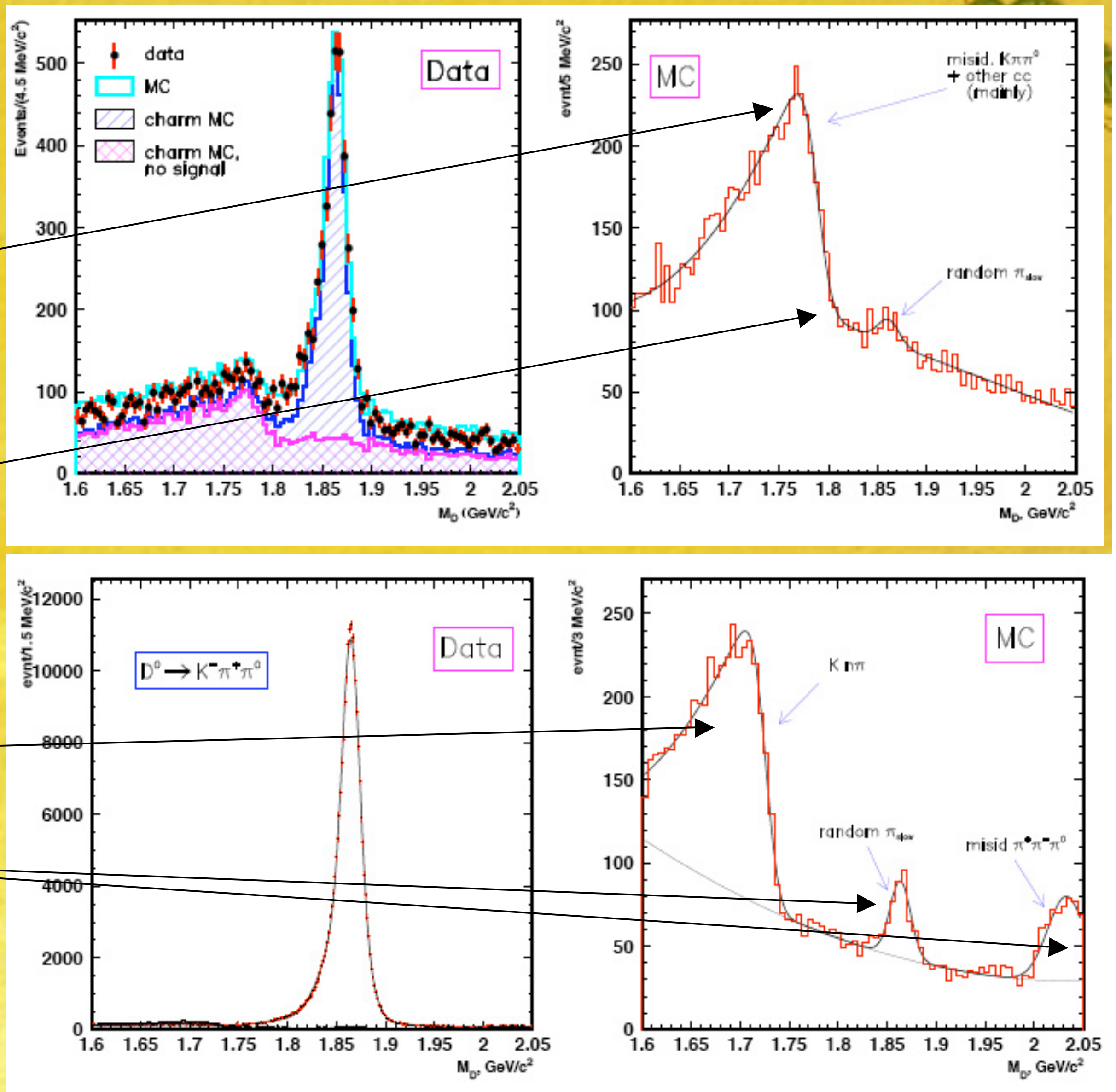


- ❑ 1.2 million phase space distributed MC events for each decay mode restricted to D^* momentum region, 3.5 GeV/c to 4.3 GeV/c in Υ(4s) cm frame
- ❑ Events for both samples weighted by resonance models from CLEO
- ❑ Obtained yield normalized to same MC data before detector simulation or event selection
- ❑ $\varepsilon(\pi^+ \pi^- \pi^0) = 13.433 \pm 0.077$ %, $\varepsilon(K^- \pi^+ \pi^0) = 13.065 \pm 0.074$ %

Background description

$D^0 \to \pi^+ \pi^- \pi^0$, Relative BF

- ❑ 250 fb^{-1} generic MC and corresponding data for comparison.
- ❑ 1st order polynomial x error function + 1st order polynomial (combinatoric background) + Gaussian peak in the signal region
- ❑ sum of a 2nd order polynomial and a 2nd order polynomial X an error function + two Gaussians.



Signal fit and yield in data

$D^0 \to \pi^+ \pi^- \pi^0$, Relative BF

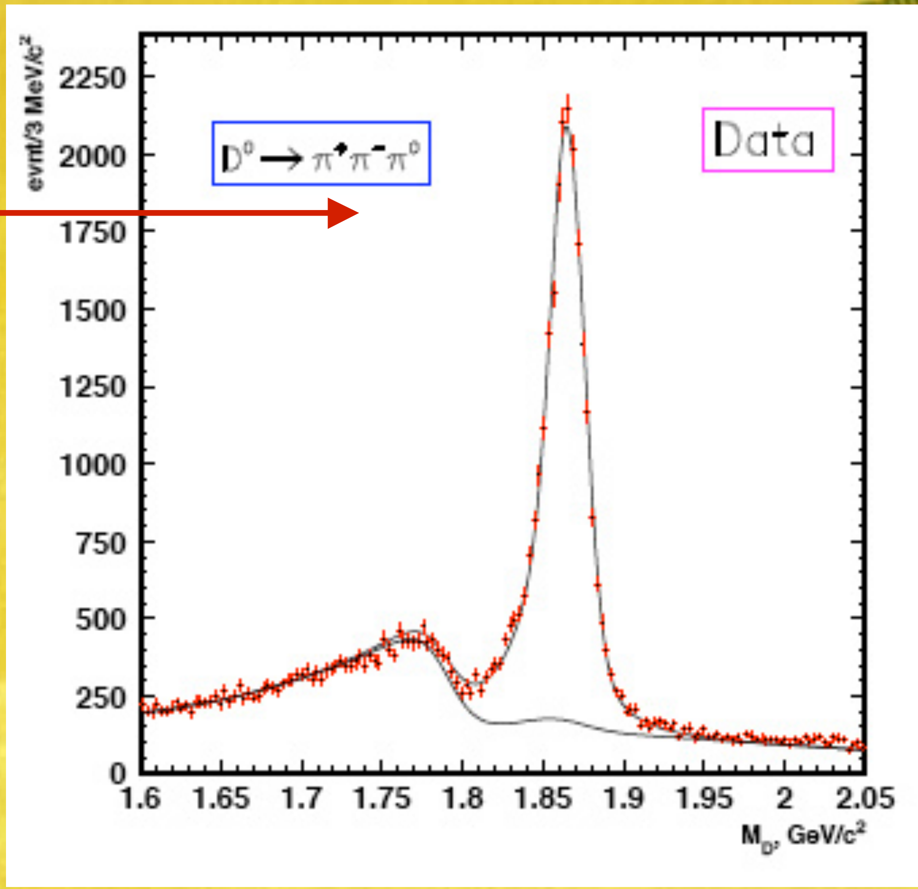
- For $\pi^+ \pi^- \pi^0$

background shape in MC with floating normalizations and partially fixed MC signal shape with floating normalization and σ's. MC signal function is a bifurcated hyperbolic Gaussian and a regular Gaussian.

- For $K^- \pi^+ \pi^0$

background shape in MC with floating normalizations and

sum of 2 bifurcated hyperbolic Gaussians and a regular Gaussian with floating parameters(background is low and statistics is high)



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$\pi^+\pi^-\pi^0$	22803 ± 203	13.433 ± 0.077
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Systematic uncertainties

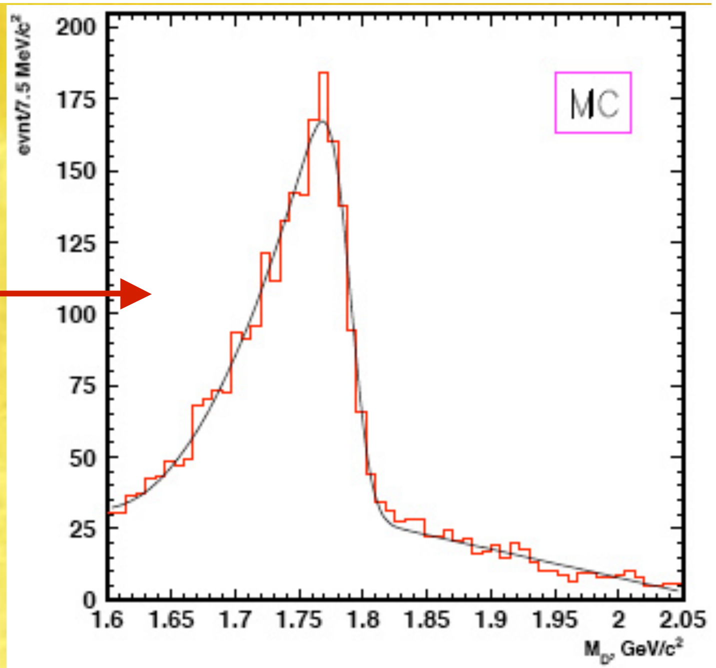
$D^0 \to \pi^+ \pi^- \pi^0$, Relative BF

Pipipi0: 3 model resonance with and Without interference. Kpipi0: 7 model and 3 model resonance

Correction to BF gives uncertainty, estimated using large independent sample of $D^0 \to K^- \pi^+$

Source	Error, %
MC statistics	0.8
PID efficiency of K/π	1.6
Decay model	1.8
Fit (background & signal)	0.7
$p_{cms}(D^*)$ cut	0.4
K^0_S veto	1.6
Total	3.1

- Uncertainty on tracking efficiency ($\pi^+\pi^-$ or $K^-\pi^+$) and π^0 and π_{slow} reconstruction efficiencies cancel out
- Possible data/MC PID efficiency difference
- Systematics due to decay model
- Alternative background fitting function
- Alternative signal fitting function
- Change in PID requirement: negligible error
- Change in p_{D^*} requirement
- Change in Ks veto requirement



Summary

$D^0 \to \pi^+ \pi^- \pi^0$, Relative BF

- Using 357 fb^{-1} of data collected with the Belle detector first direct measurement of the relative branching fraction $ß(D^0 \to \pi^+ \pi^- \pi^0) / ß(D^0 \to K^- \pi^+ \pi^0) = 0.0971 \pm 0.0009_{stat} \pm 0.0030_{syst}$. has been performed.
- Our preliminary result 0.0971±0.0031 is compatible with the world average 0.0929±0.0054 but more precise.
- Using 2006 world average the $D^0 \to \pi^+ \pi^- \pi^0$ absolute BF is compared with CLEO's value.

	$N_{ev.}$	$\mathcal{B}(D^0 \to \pi^+\pi^-\pi^0)$, 10^{-3}
Belle	22803 ± 203	$13.69 \pm 0.13_{stat} \pm 0.42_{syst} \pm 0.49_{norm}$
CLEO-c	10834 ± 164	$13.2 \pm 0.2_{stat} \pm 0.5_{syst} \pm 0.2_{norm} \pm 0.1_{CPcorr.}$