Search for rare and forbidden charm meson decays $D^0 \to hh^{(\prime)}ll^{(\prime)}\ (h^{(\prime)} = K, \pi\,;\, l^{(\prime)} = e, \mu)$

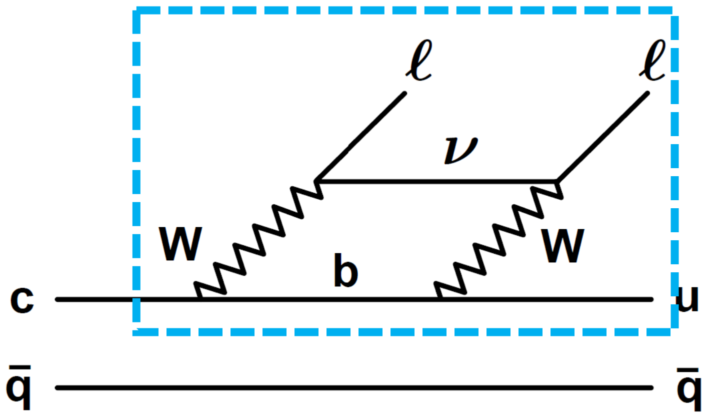
Belle II summer workshop 2022

Shuaiyan Kang (Iowa State University)

August 5th , 2022

Standard model (SM) rare charm meson decay $D \to h\, h^{(\prime)} l^+ l^-$

- Short Distance (SD)



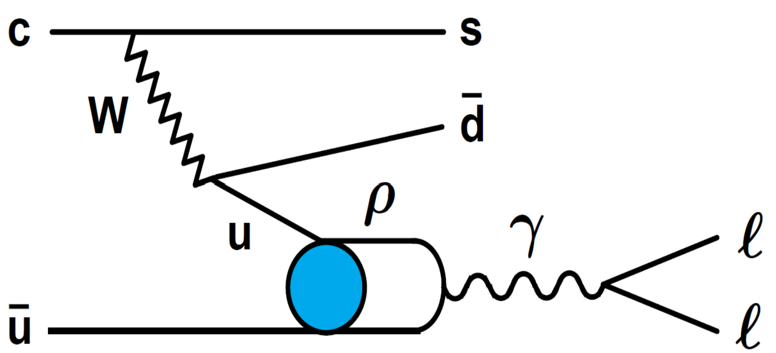
- Flavor Changing Neutral Current transition, only occurs at box/penguin diagrams in SM

$$BF_{SD} \sim 10^{-10} - 10^{-9}$$

L. Cappiello et al. *J. High Energ. Phys.*,(04)**2013**

- Give room for new physics (NP), can influence the BF and angular distributions

- Long Distance (LD)



CLEO Collaboration Phys.Rev.Lett. 76 (1996):3065-3069

- Vector Meson Dominance mode (VMD)
greatly contributes to BF (affects negatively for probing NP)

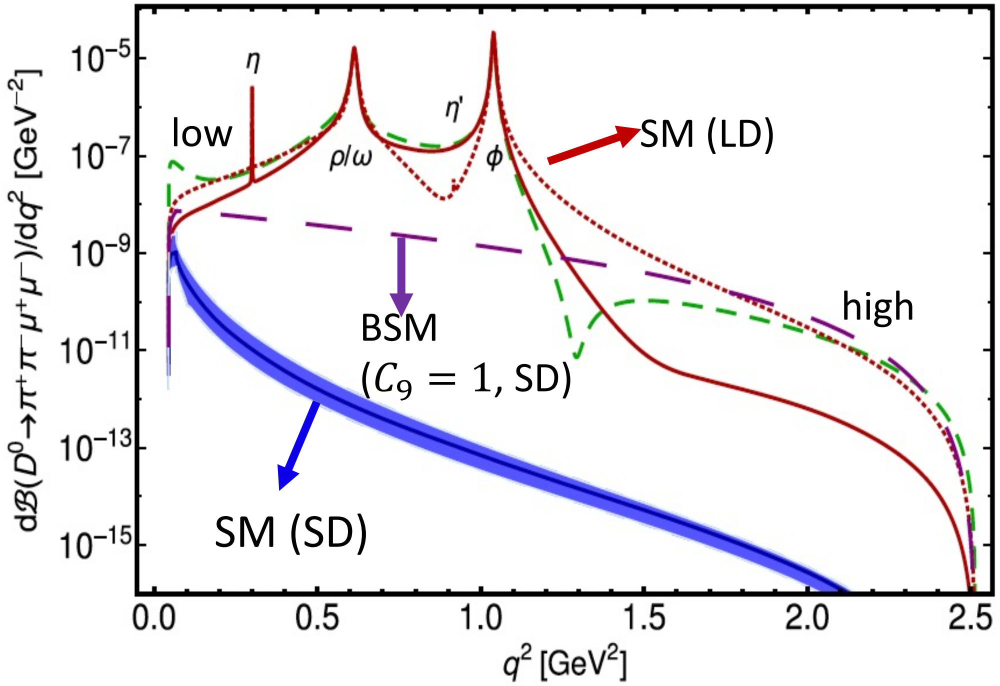
$$D^0 \to h_1 h_2\, V^0(l^- l^+); (V^0\!: \phi, \omega, \rho^0)$$

$$BF_{LD}(\mathrm{D}^0 \to K^+\pi^-\, l^+ l^-) \sim 10^{-6}$$

A. Paul et al. Phys. Rev., D83(2011):114006

Motivation

- Search for new physics through loop-suppressed decay $\mathrm{D}^0 \to \pi^+\pi^-\ l^+l^-(l = e, \mu)$
  - SM estimation: $BF_{LD} \sim 10\times10^{-7}$ L. Cappiello et al. *J. High Energ. Phys.*,(04)**2013**
  - LHCb observation $\mathrm{D}^0 \to \pi^+\pi^-\ \mu^+\mu^-$(2017):
    $(9.64 \pm 0.48 \pm 0.51 \pm 0.97)\times10^{-7}$ Phys. Rev. Lett., 119(2017):181805
- New physics models:
  - Minimal Supersymmetric Standard Models (MSSM): $BF_{MSSM}(D^0 \to \pi^-\pi^+l^+l^-) \sim 10\times10^{-7}$ S. Fajfer et al.Phys. Rev., D64(2001):114009
  - Leptoquark (LQ): Lepton flavor violation (LFV) $\mathrm{BF}_{LQ}\left(D^0 \to \pi^-\pi^+e^\pm\mu^\mp\right) \lesssim 10^{-7}$ S. Boer and G. Hiller Phys. Rev., D98(2018):035041
- Lepton flavor universality tests
  - i.e. $\mathrm{BF}(\mathrm{D}^0 \to K^-\pi^+\ \mu^+\mu^-)/\mathrm{BF}(\mathrm{D}^0 \to K^-\pi^+\ e^+e^-) \simeq 1$ in SM
- Focus on study $\mathrm{D}^0 \to h\ h\ l^+l^-$ in m_{ll} at low/high mass regions using **Belle MC**



Differential branching ratio $\mathrm{d}\mathcal{B}(D^0 \to \pi^-\pi^+\mu^+\mu^-)/dq^2$. Solid blue line corresponds to SM short-distance prediction including uncertainties. The long dashed purple curve corresponds to BSM short-distance prediction (Wilson Coefficient $C_9 = 1$). The green and red curves are SM long-distance predictions.

S. de Boer, G. Hiller Phys. Rev., D98(2018):035041

Recent Measurements and Searches of $\mathrm{D}^0 \to hh^{(\prime)}ll$

- Babar (2019): Observation of $\mathrm{D}^0 \to K^-\pi^+e^+e^-$
- BESIII (2019): Search for $\mathrm{D}^0 \to h\,h^{(\prime)}\,e^+e^-$
- LHCb (2016 - 2017): Observation of $\mathrm{D}^0 \to h\,h^{(\prime)}\mu^+\mu^-$

Measured BFs and ULs @ 90% CL $[10^{-7}]$

Experiment	$K^-K^+e^+e^-$	$\pi^-\pi^+e^+e^-$	$K^-\pi^+e^+e^-$
Babar (2019)			$\sim 40\ (\rho^0/\omega)$
BESIII (2019)	< 110	< 70	< 410
	$K^-K^+\mu^+\mu^-$	$\pi^-\pi^+\mu^+\mu^-$	$K^-\pi^+\mu^+\mu^-$
LHCb (2016-2017)	~1.5	~9.6	~42 (ρ^0/ω)

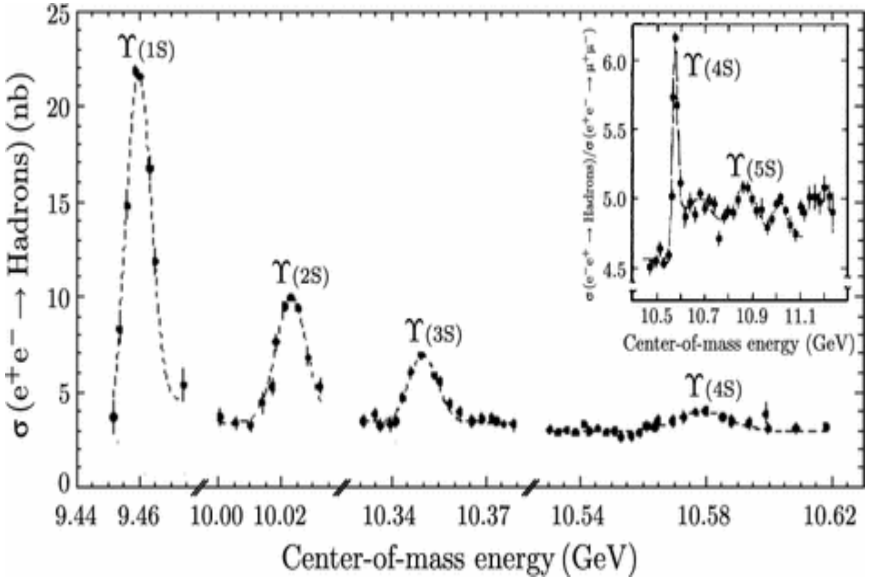
LHCb Collaboration Phys. Rev. Lett., 119(2017):181805
Phys. Lett., B757(2016):558
BES III Collaboration Phys. Rev., D97(2019):072015
BABAR Collaboration Phys. Rev. Lett.,122(2019):081802

$D^{*+} \to [D^0 \to hh^{(\prime)}\, l^+l^-]\, \pi^+$ Reconstruction: Data & MC samples

Belle Data & MC samples studied for signal modes:

- Data:
  - Collected @ $\Upsilon(4S)$, $\Upsilon(5S)$ on/off-resonance, $\Upsilon(5S)$ scan[E_{CM}($\Upsilon(4S)$, $\Upsilon(6S)$]; in total ~942fb^{-1} --> ~395M $D^0(\overline{D}^0)$
- MC:
  - Generic MC (background study)
  - Total MC samples: ~6x data integrated luminosity
  - Signal MC: run-independent MC, scaled with $\mathcal{L}$ by experiment

Cross-section for inclusive hadrons production vs CM energy



Röhrken M. (2014) The Belle Experiment.

Normalization mode: $\mathrm{D}^0 \to K^-\pi^+\,\pi^+\pi^-$ (BF ~ 8.1%)

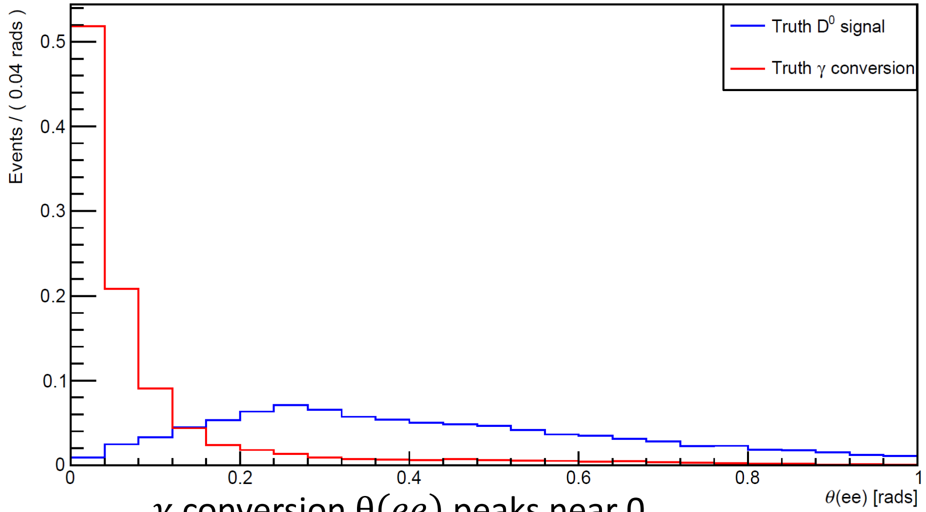
Signal mode BF is measured relative to normalization mode in order to cancel many of the systematic uncertainties

$D^{*+} \to [D^0 \to hh^{(\prime)}\ e^+e^-]\,\pi^+$ Reconstruction

- Candidate selection:
  - D^* tagged D^0 reconstruction: limits combinatorial background of low momentum tracks from B decays
  - Kinematic cuts (in backup)
  - Best candidate selection: select candidate with $\Delta m(m_{D^{*+}} - m_{D^0})$ closest to nominal value.

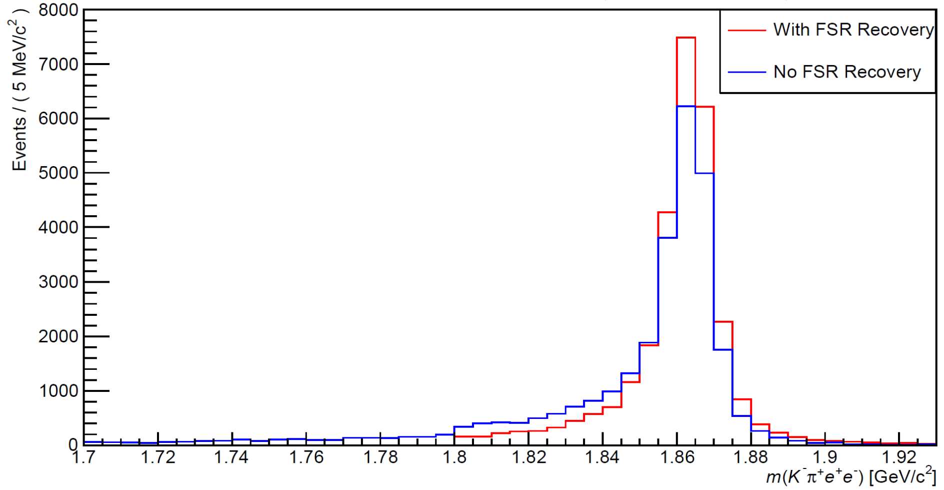
  - $\boldsymbol{hh^{(\prime)}\ e^+e^-}$ **modes:**
    - Photon conversion veto: reconstruct photon conversion
    - D^0 hadronic veto: reconstruct $\mathrm{D}^0 \to K^-\pi^+\pi^+\pi^-, K^+K^-\pi^+\pi^-, 4\pi$
    - Electron bremsstrahlung recovery

γ conversion reconstruction: **MC** $\theta(ee)$



γ conversion $\theta(ee)$ peaks near 0

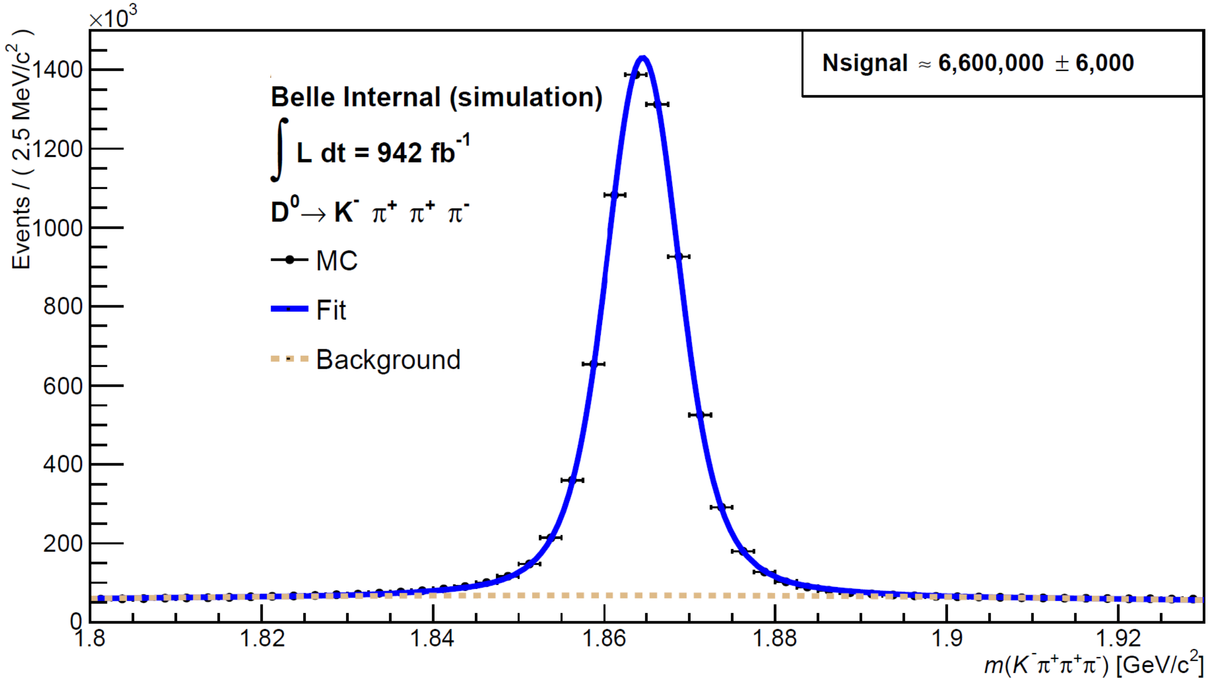
Electron FSR recovery: **MC** $m(K^-\pi^+e^+e^-)$



Bremsstrahlung recovery applied for both lepton final states. $\theta(e\gamma) < 5°$, $E_\gamma > 0.05$ GeV

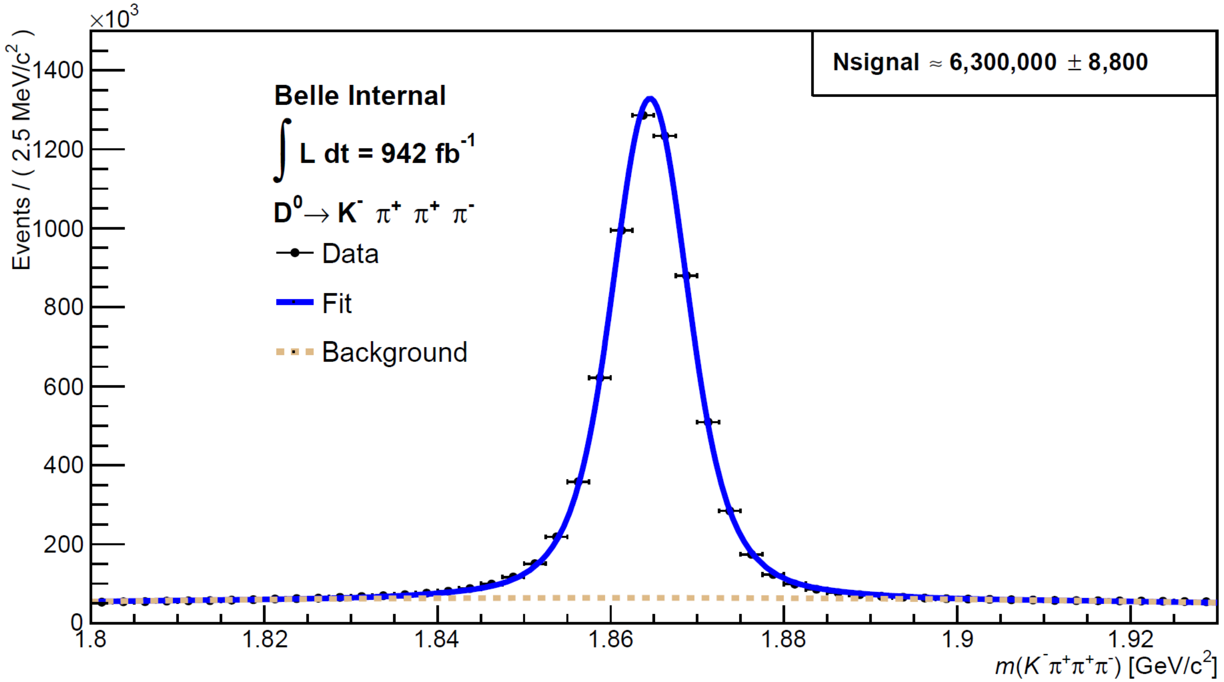
Normalization mode $D^{*+} \to [D^0 \to K^-\pi^+\pi^+\pi^-]\,\pi^+$ Reconstruction:

$m(D^0)$ Fit to **MC**



MC $m(D^0)$ resolution: ~ $5.9\mathrm{MeV/c^2}$

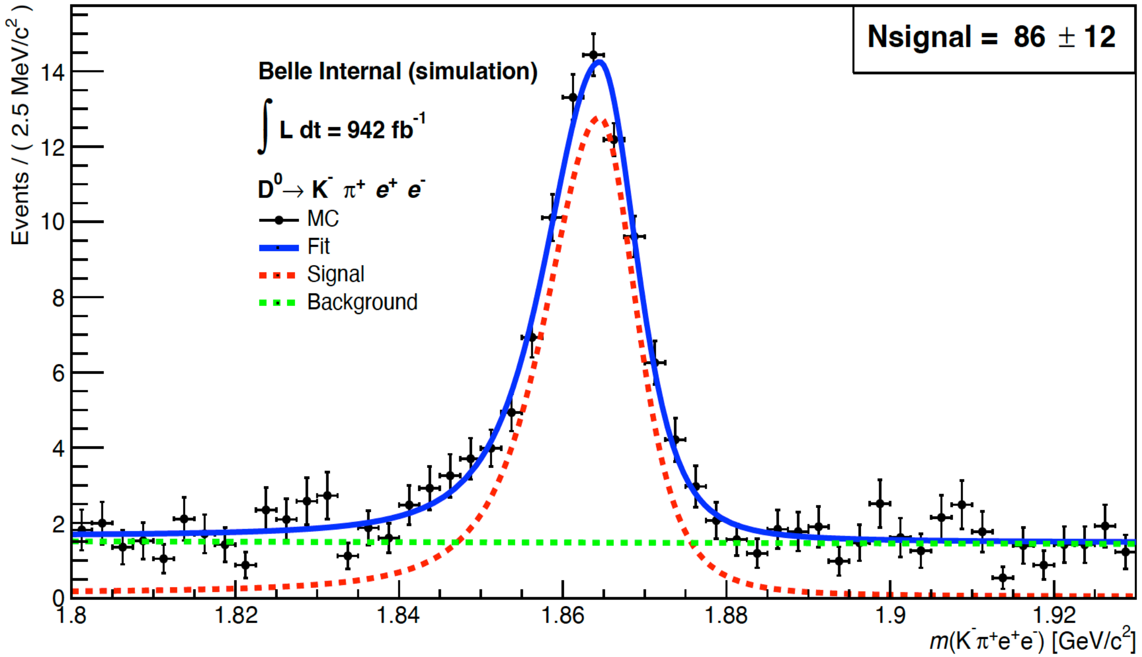
$m(D^0)$ Fit to **data**



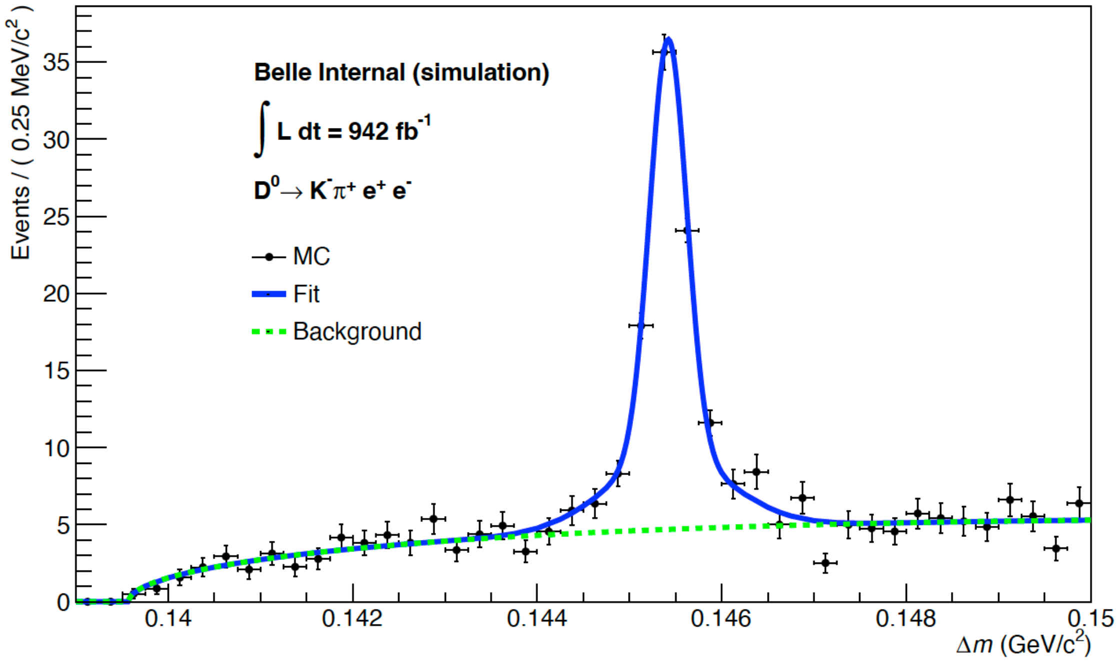
Data $m(D^0)$ resolution: ~ $6.0\mathrm{MeV/c^2}$

$D^{*+} \to [D^0 \to K^-\pi^+ e^+e^-]\,\pi^+$ Reconstruction: m_{ee} @ ρ, ω mass region

$m(D^0)$ Fit to **MC**



Δm Fit to **MC**



Δm cut applied for all $m(D^0)$ distributions:
$|\Delta m - \mathbf{\Delta m}| < 0.5\ \mathrm{MeV/c^2}$

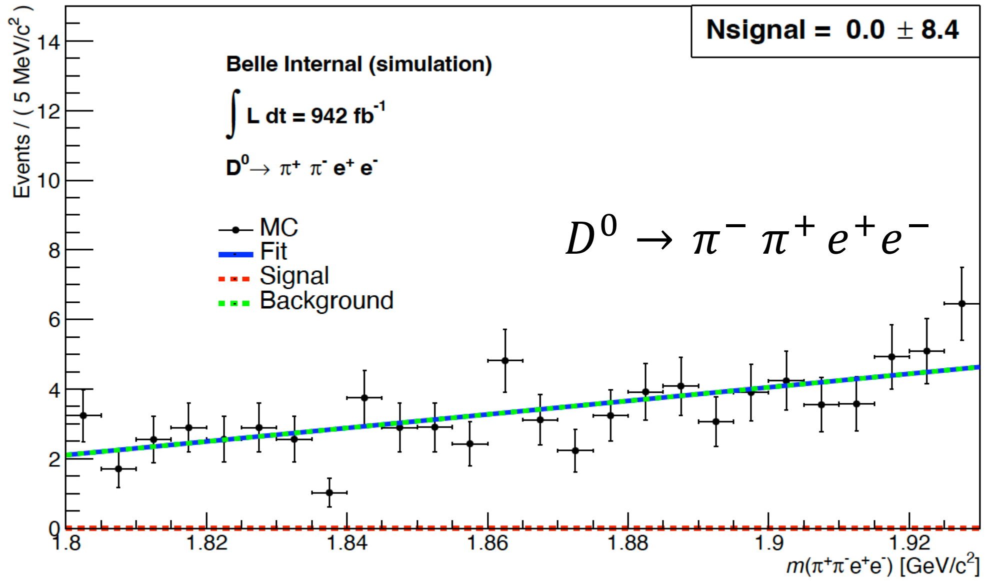
$m(D^0)$ cut applied for all Δm distributions:
$|m - \mathbf{m}(D^0)| < 30\ \mathrm{MeV/c^2}$

Signal pdf: Babar Cruijff function[1]: Gaussian with different left and right resolutions and tails

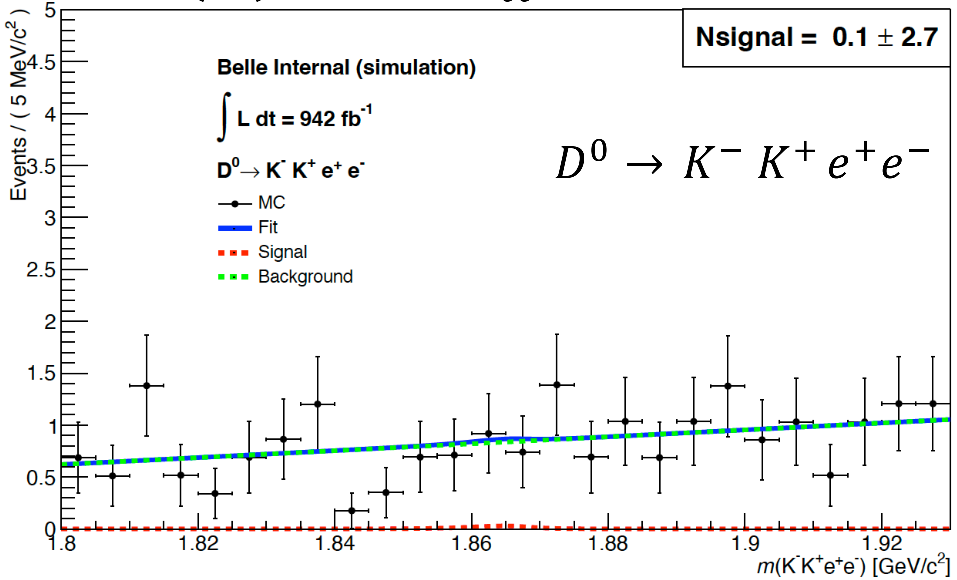
Estimated significance (statistical error included only): $\sqrt{-2\Delta\ln\mathcal{L}} \sim 10$,
where $\Delta\ln\mathcal{L}$ is the change of maximum log likelihood when fitting only bkg (signal yield 0)

$D^{*+} \to [D^0 \to h\, h\, e^+e^-]\, \pi^+$ Reconstruction: m_{ee} (low/high mass & m_ϕ)

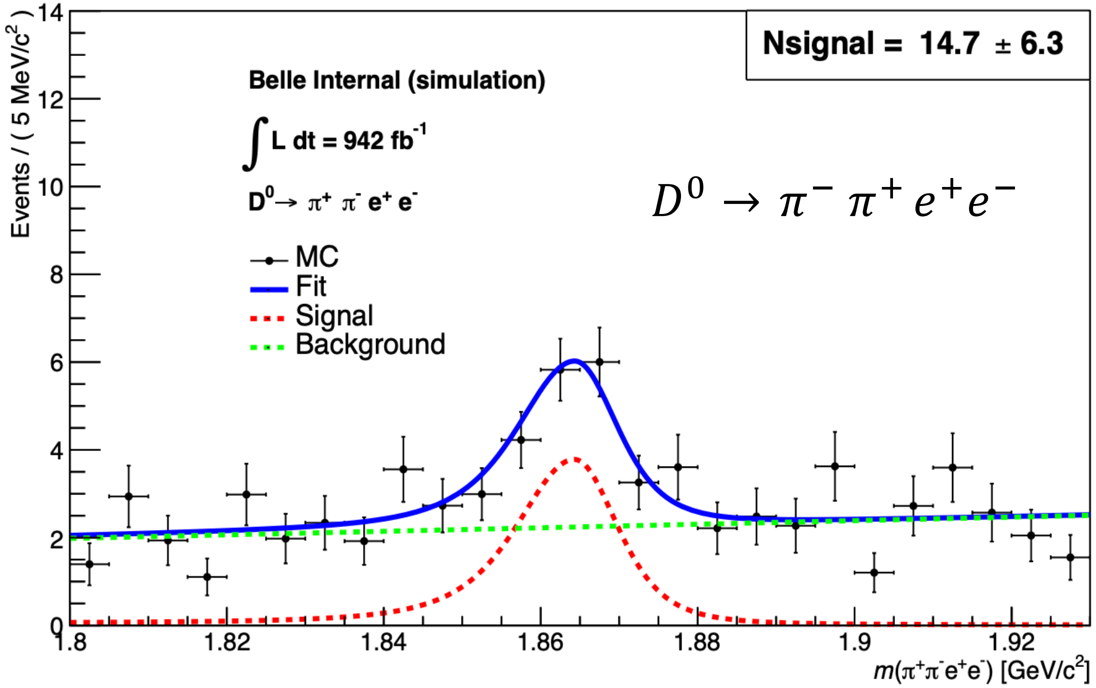
$m(D^0)$ Fit to **MC** (m_{ee} @ high mass)



$m(D^0)$ Fit to **MC** (m_{ee} @ low mass)

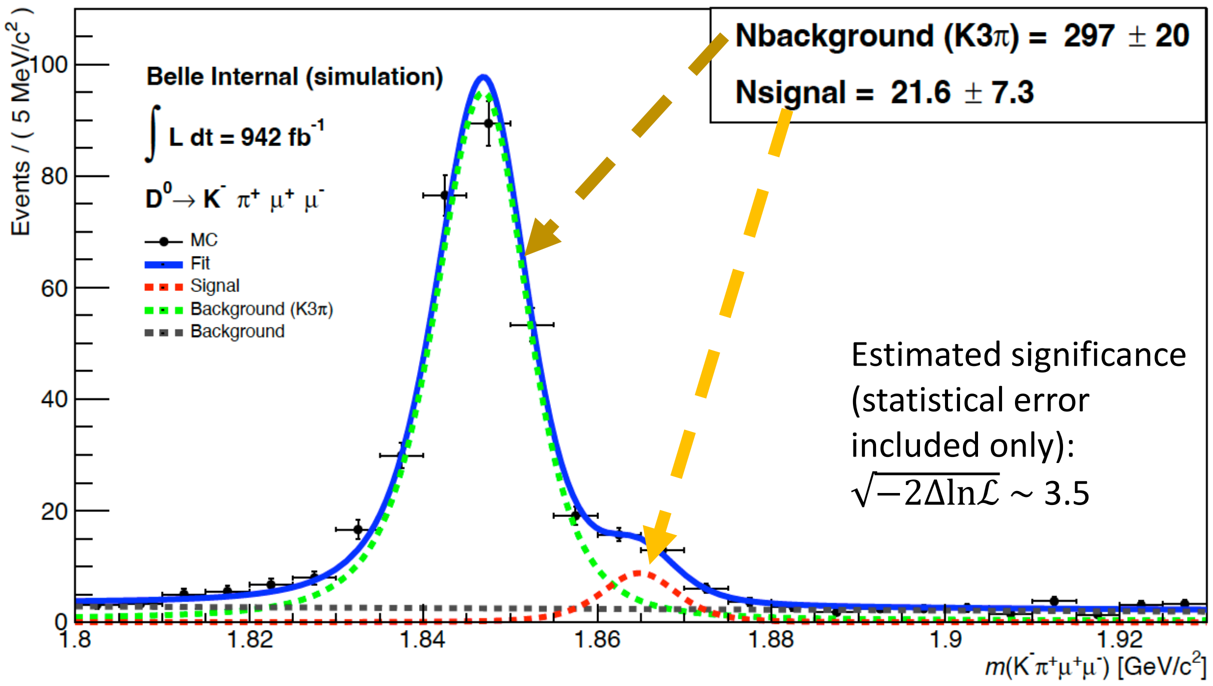


$m(D^0)$ Fit to **MC** (m_{ee} @ m_ϕ, BF ~5 times larger)



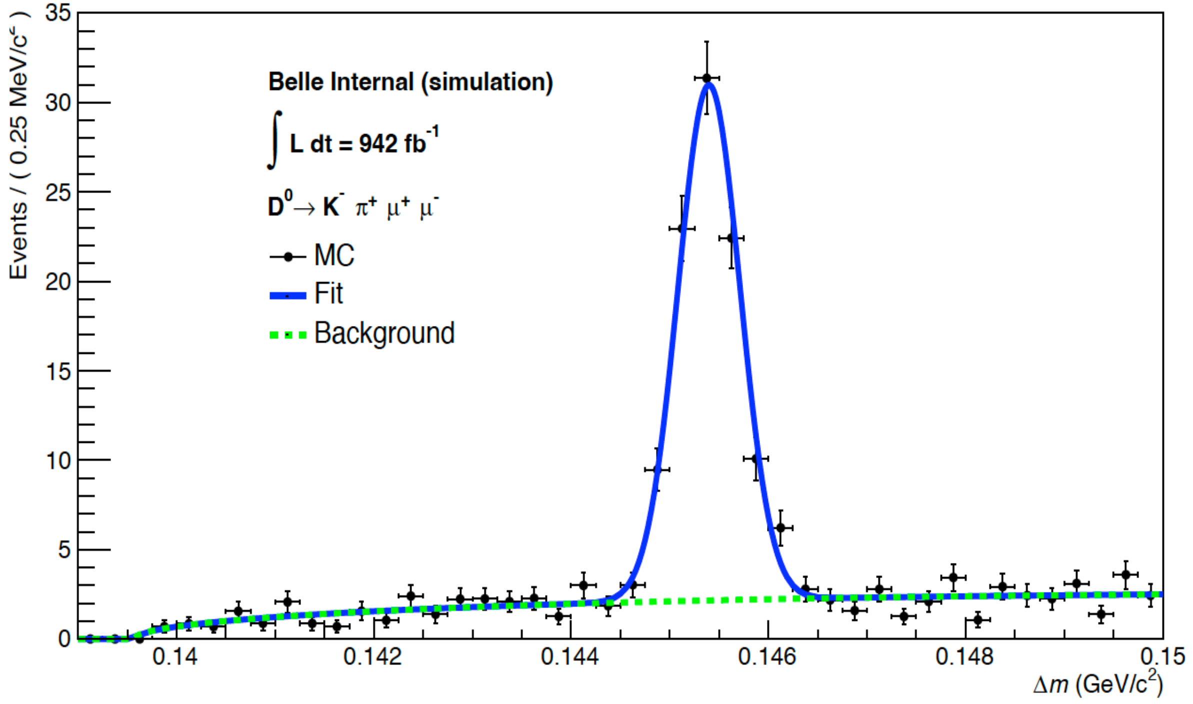
$D^{*+} \to [D^0 \to K^-\pi^+\,\mu^+\mu^-]\,\pi^+$ Reconstruction: $m_{\mu\mu}$ @ ρ, ω mass region

$m(D^0)$ Fit to **MC**



Fit function: same as $K^-\pi^+\,e^+e^-$ mode

Δm Fit to **MC**

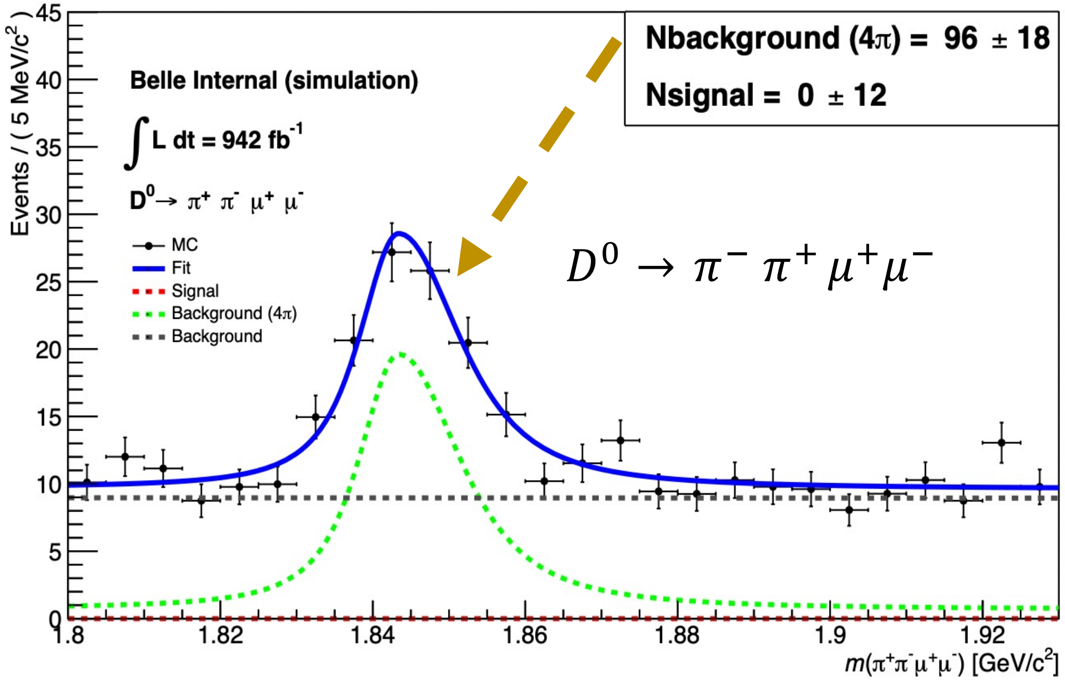


Peaking background (K + 3π): from decay $D^0 \to K^-\pi^+\,\pi^+\pi^-$, where π reconstructed as μ. The reconstructed mass is less than nominal D^0 mass.

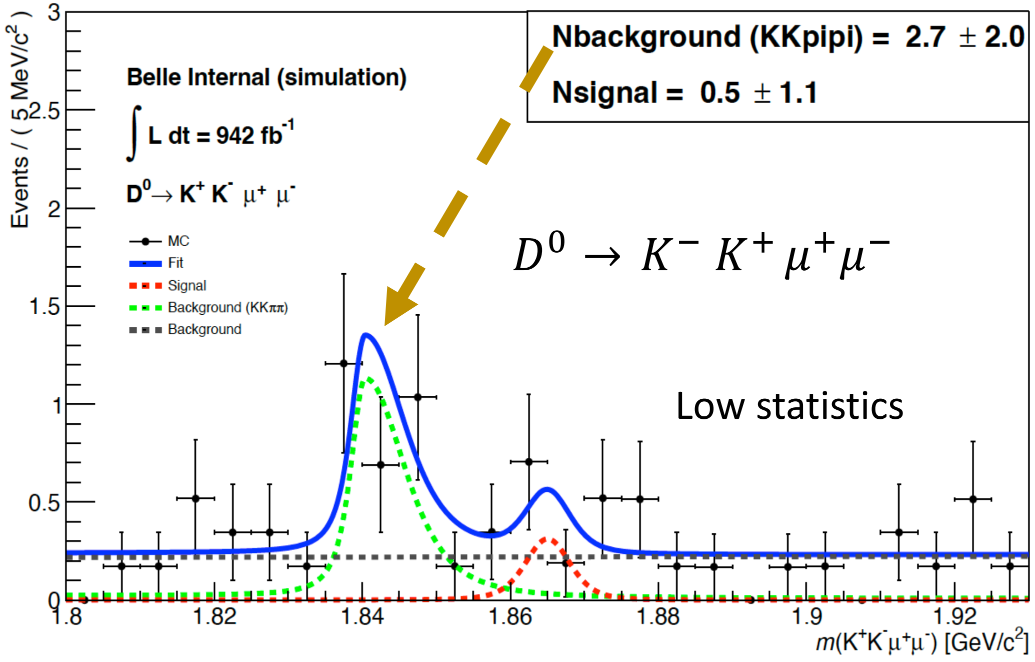
Background ($K + 3\pi$) pdf parameters are obtained from fitting truth $D^0 \to K^-\pi^+\,\pi^+\pi^-$, π recon as μ

$D^{*+} \to [D^0 \to h\, h\, \mu^+\mu^-]\, \pi^+$ Reconstruction: $m_{\mu\mu}$ (low mass)

$m(D^0)$ Fit to **MC** ($m_{\mu\mu}$ @ low mass)



$m(D^0)$ Fit to **MC** ($m_{\mu\mu}$ @ low mass)



Background (4π) pdf parameters are obtained from fitting truth $D^0 \to \pi^-\pi^+\,\pi^+\pi^-$, π recon as μ

$D^0 \to hh^{(\prime)}\, ll$ reconstruction: estimated BF and ULs

- Determine signal mode BF relative to normalization mode:

$$BR(D^0 \to \text{sig}) = \frac{N_{sig}}{N_{norm}} \frac{\epsilon_{norm}}{\epsilon_{sig}} \frac{\mathcal{L}_{norm}}{\mathcal{L}_{sig}} BR(D^0 \to \text{norm})$$

Estimated BF and UL @ 90% CL from Belle generic MC and Babar, BESIII measurements $[10^{-7}]$
(values in blue: Babar measurement of $K^-\pi^+\, e^+e^-$, error is statistical; BESIII limits)

TABLE VIII. Estimated BF $[10^{-7}]$ (Normalization mode: $K^-\pi^+\pi^-\pi^+$)

Modes $D^0 \to$	$K^-K^+e^+e^-$	$\pi^-\pi^+e^+e^-$	$K^-\pi^+e^+e^-$
ρ,ω: $675 < m_{ll} < 875$	< 3.7	< 12.6	38.5 ± 5.5 (40 ± 5)
ϕ: $875 < m_{ll} < 1050$	-	< 8.9	< 3.8
Total:	< 9.3	< 41.1	< 140 $(m_{ee} \notin m_{(\rho,\omega)})$
BES III:	< 110	< 70	< 410

- Expect to observe $D^0 \to K^-\pi^+\, e\, e$
- Expect to find evidence for $D^0 \to K^-\pi^-\, \mu^+\mu^-$
- Expect to have an improved ULs for the $D^0 \to hh^{(\prime)}\, e^+e^-$ modes

LHCb Collaboration Phys. Rev. Lett., 119(2017):181805
BES III Collaboration Phys. Rev., D97(2019):072015
BABAR Collaboration Phys. Rev. Lett.,122(2019):081802

Summary & Next step

- Estimate sensitivity of $\mathrm{D}^0 \to h\, h\, l^+ l^-$ from Belle (MC)
  - Expect to give the better sensitivity for the decay $\mathrm{D}^0 \to hh^{(\prime)}\, e^+e^-$ $(h = K, \pi)$
    - Expect to have an improved ULs for the $\mathrm{D}^0 \to hh^{(\prime)}\, e^+e^-$ decay modes compared to Babar and BES III.
  - From previous studies:
    - Expect to observe $\mathrm{D}^0 \to K^-\pi^-\, e^+e^-$ and confirm the BF results from Babar using Belle data.
      - Expected sensitivity (statistical error included only): ~10σ
    - Expect to find evidence for $\mathrm{D}^0 \to K^-\pi^-\, \mu^+\mu^-$
      - Expected sensitivity (statistical error included only): ~3.5σ

- Next step
  - Study systematics, test of LFU
  - Update Belle note

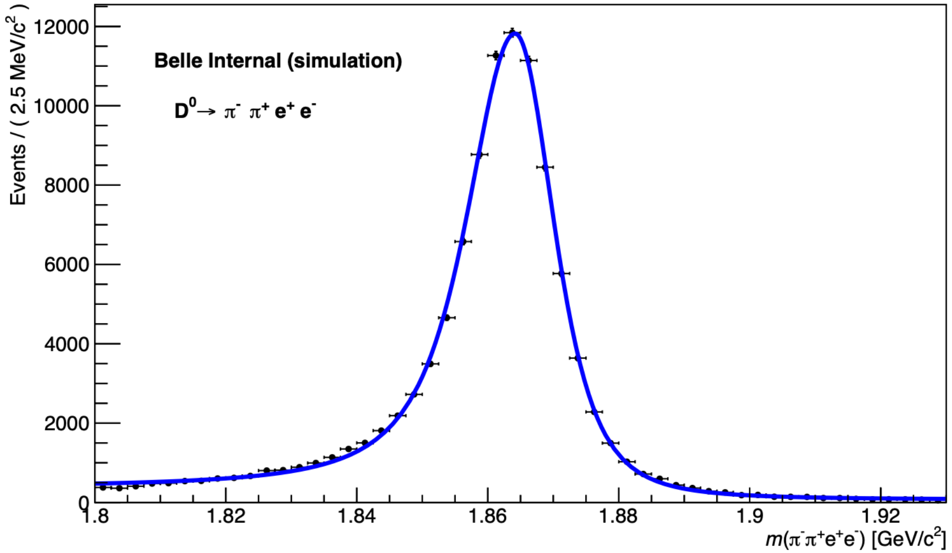
Back up: $D^{*+} \to [D^0 \to \pi^+\pi^- \, e^+e^-] \, \pi^+$ Reconstruction: low & high mass region

- Cuts:
  - Low/ high mass region: low: $0.2 < m(ee) < 0.525$, high: $m(ee) > 0.525$ [GeV/c^2]
  - Optimized cuts:
    - Each track: $|d0| < 0.25\text{cm}, |z0| < 4.5\text{cm}$
    - Electron selection: eID > 0.9, $p(e)$ > 0.3 GeV/c
    - Pion selection: eID < 0.05, KID < 0.4
    - Signal: treeFit D^{*+} vertex χ^2probability > 0, $p^*(D^{*+}) > 2.5$ GeV/c, distance to nominal $\Delta m < 0.5\text{MeV/c}^2$
  - Photon conversion veto:
    - Photon conversion: vertex χ^2 fit prob > 0; $\theta(ee) < 0.08$ rads or $m(ee) < 0.04$ GeV/c^2
    - Discard signal D^0 candidates if any of the two lepton tracks are used for photon conversion reconstruction
  - D^0 hadronic veto:
    - D^0 hadronic: vertex χ^2 probability > 0, distance to nominal: $m(D^0) < 5$ MeV/c^2, $\Delta m < 0.7\text{MeV/c}^2$
    - Discard signal D^0 candidates if any of the four tracks are used for D^0 hadronic reconstruction
  - Best candidate selection: select candidate with Δm closest to nominal value. Multiplicity ~1.01
- Electron bremsstrahlung recovery:
  - Selection: angle between e and γ candidates $\theta(e\gamma) < 5°$, accept all γ passed selection
  - Basf2 module: BelleBremsRecovery
- Yield extraction: 1D unbinned maximum likelihood fit to $m(D^0)$
- Release: *light-2102-nemesis*[2]

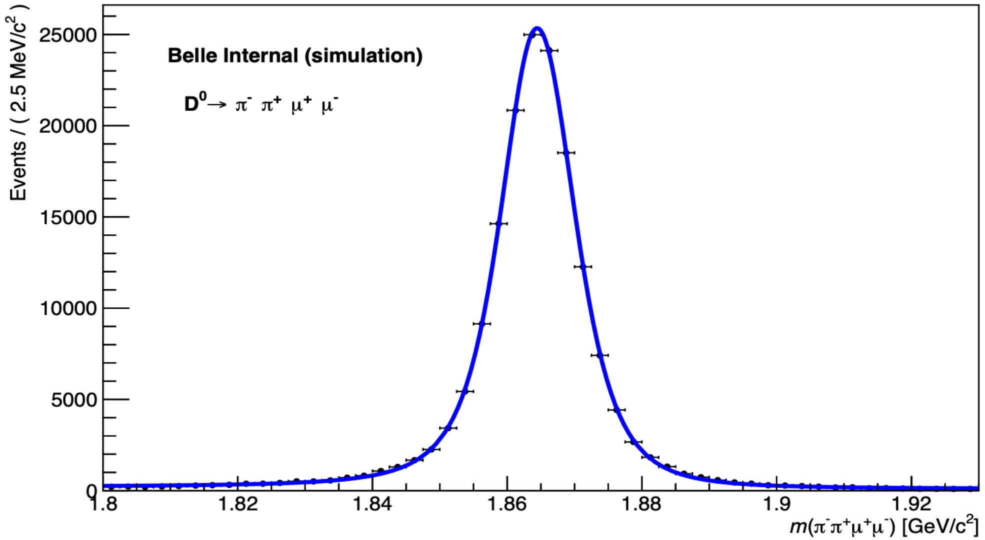
1: candidate-based truth matching
2: Belle MC track smearing, applied to all decay modes

Back up: $D^{*+} \to [D^0 \to \pi^-\pi^+ l^+l^-]\, \pi^+$ Reconstruction: signal MC $m(D^0)$ & Δm distribution[15]

$m(D^0)$ Fit to signal MC $\pi^-\pi^+ e^+e^-$

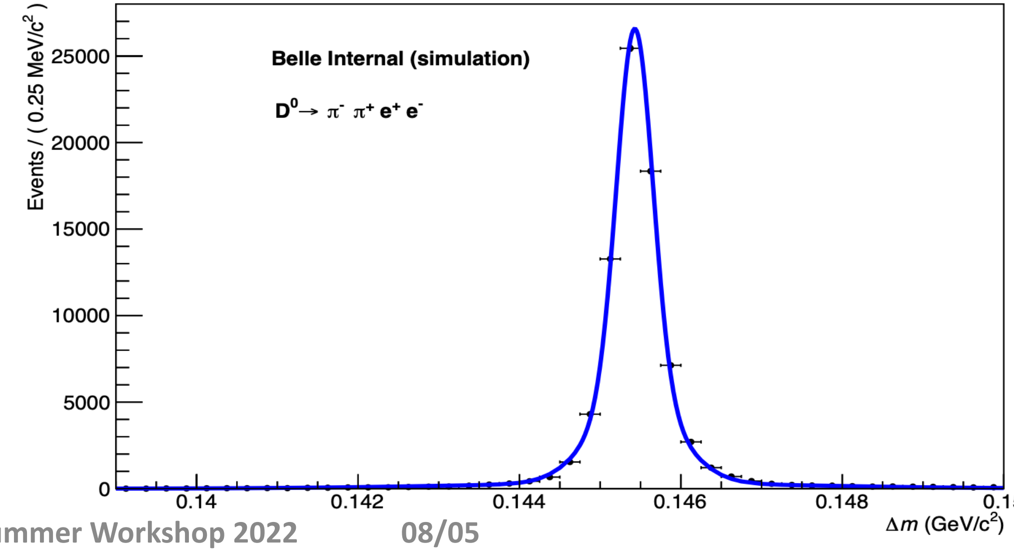


$m(D^0)$ Fit to signal MC $\pi^-\pi^+ \mu^+\mu^-$



Signal pdf parameters are obtained from fit to truth-matched signal MC

Δm Fit to signal MC $\pi^-\pi^+ e^+e^-$



Signal $m(D^0)$ Fit function:
Babar Cruijff function[1]: Gaussian with different left and right resolutions and tails

$$f(x) = exp(-(x-m_0)^2/(2\sigma_{L/R}^2+\alpha_{L/R}((x-m_0)^2))$$

$$x - m_0 < 0: \sigma = \sigma_L, \alpha_L$$

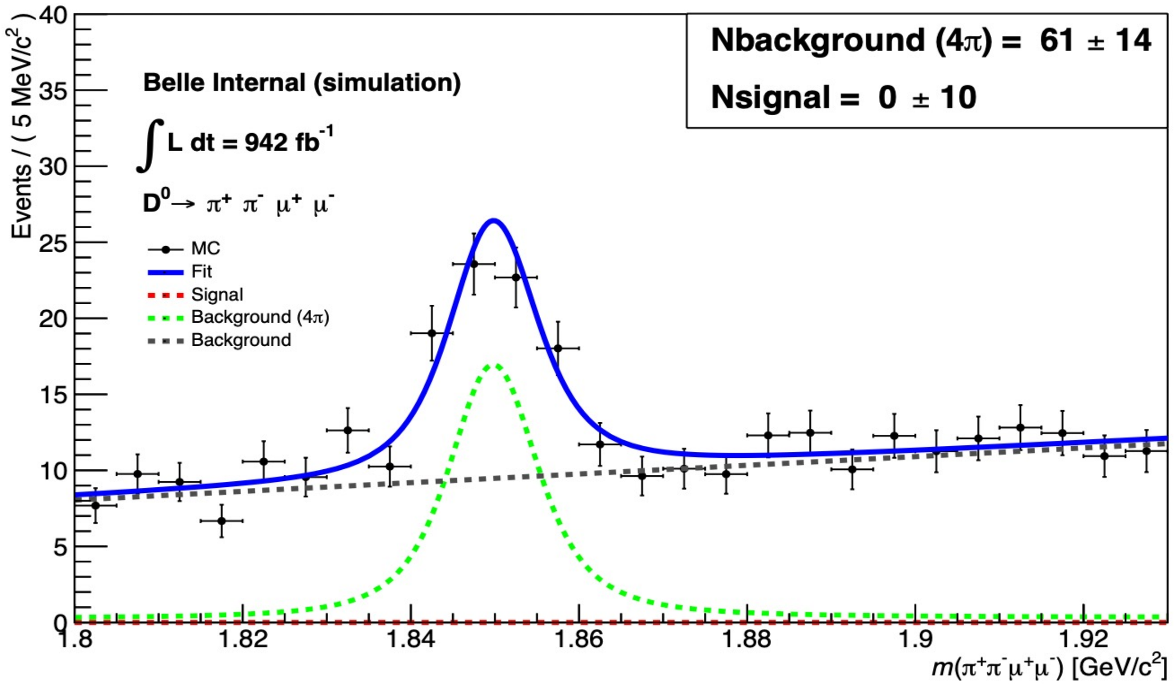
$$x - m_0 > 0: \sigma = \sigma_R, \alpha_R$$

Signal Δm Fit function: Gaussians with shared mean

1. BABAR Collaboration Phys. Rev. Lett.,122(2019):081802

Back up: $D^{*+} \to [D^0 \to \pi^-\pi^+ \mu^+\mu^-]\, \pi^+$ Reconstruction: $m_{\mu\mu}$ (high mass)

$m(D^0)$ Fit to MC

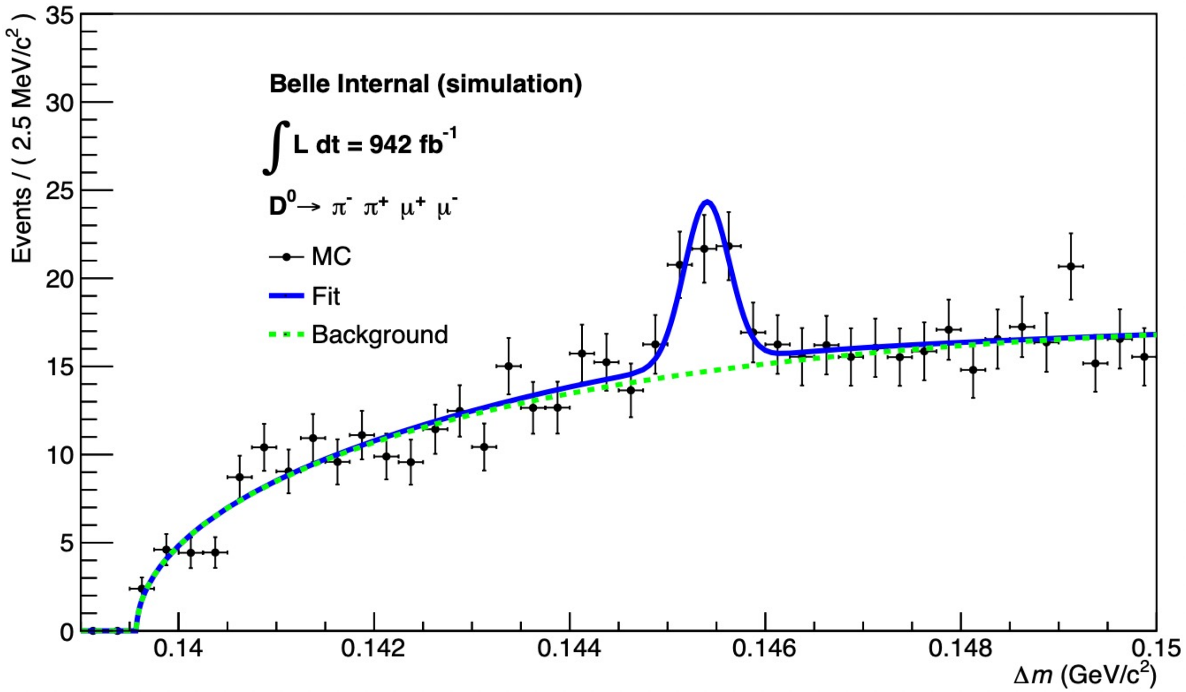


Δm cut applied: distance to nominal $< 0.5\ \mathrm{MeV/c^2}$

Fit function: same as $K^-\pi^+ e^+e^-$ mode

Peaking background (4π): from decay $D^0 \to \pi^-\pi^+ \pi^+\pi^-$, where π reconstructed as μ.

Δm Fit to MC



$m(D^0)$ cut applied: distance to nominal $< 30\mathrm{MeV/c^2}$

Back up: No. of D^{*+} from charm and B decays

- No. of D^{*+} from charm: ~583M
  - $\mathcal{L}$ $(942.442\ \mathrm{fb}^{-1})$ * $\sigma_{c\bar{c}}$ $(1.3\ \mathrm{nb})$ * 2 * fragmentation $c \rightarrow D^{*+}$ (0.238)

- No. of D^{*+} from $\mathrm{B}\overline{\mathrm{B}^0}$: ~77M
  - Total No. of neutral B (771.581 M) * BF($\overline{\mathrm{B}^0} \rightarrow D^{*+}\ e\ v_e; D^{*+}\ \mu\ v_\mu$) (10%)

$D^0 \to hh^{(\prime)}\, ll$ reconstruction: estimated ULs

- Determine signal mode BF relative to normalization mode:

$$BR(D^0 \to \text{sig}) = \frac{N_{sig}}{N_{norm}} \frac{\epsilon_{norm}}{\epsilon_{sig}} \frac{\mathcal{L}_{norm}}{\mathcal{L}_{sig}} BR(D^0 \to \text{norm})$$

Estimated UL @ 90% CL from Belle generic MC $[10^{-7}]$

TABLE VIII. Estimated upper limits $[10^{-7}]$ (Normalization mode: $K^-\pi^+\pi^-\pi^+$)

Modes $D^0 \to$	$K^-K^+e^+e^-$	$\pi^-\pi^+e^+e^-$	$K^-\pi^+e^+e^-$	$K^-K^+\mu^+\mu^-$	$\pi^-\pi^+\mu^+\mu^-$	$K^-\pi^+\mu^+\mu^-$
Low mass: $200 < m_{ee} < 525$, $m_{\mu\mu} < 525$	< 4.5	< 19.6	< 16.6	< 25.3	< 44.3	< 33.8
η: $525 < m_{ll} < 565$	< 1.1	< 2.0	< 3.1	< 3.9	< 11.2	< 6.0
ρ, ω: $675 < m_{ll} < 875$	< 3.7	< 12.6		< 9.9	< 29.5	
ϕ: $875 < m_{ll} < 1050$	-	< 8.9	< 3.8	-	< 14.2	< 7.4
High mass: $m_{ll} > 1050$	-	< 30.0	< 119	-	< 36.3	< 141

$D^{*+} \to [D^0 \to hh^{(\prime)}\, ll]\, \pi^+$: BF and upper limit (UL) calculation

- Determine signal mode BF relative to normalization mode:

$$BR(D^0 \to \text{sig}) = \frac{N_{sig}}{N_{norm}} \frac{\epsilon_{norm}}{\epsilon_{sig}} \frac{\mathcal{L}_{norm}}{\mathcal{L}_{sig}} BR(D^0 \to \text{norm})$$

ϵ: reconstruction efficiency
N: fitted yield
$\mathcal{L}$: luminosity

- Profile likelihood method

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\nu}})}{L(\hat{\mu}, \hat{\nu})}$$

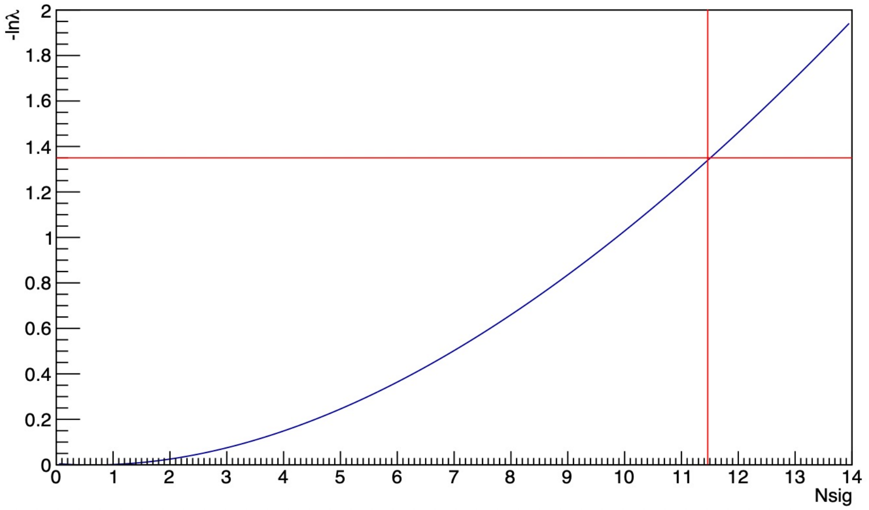
μ: parameter of interest
ν: other free parameters of fit
$L(\hat{\mu}, \hat{\nu})$: likelihood from best fit
$L(\mu, \hat{\hat{\nu}})$: likelihood from best fit with μ fixed

The upper limit on μ can be found by solving

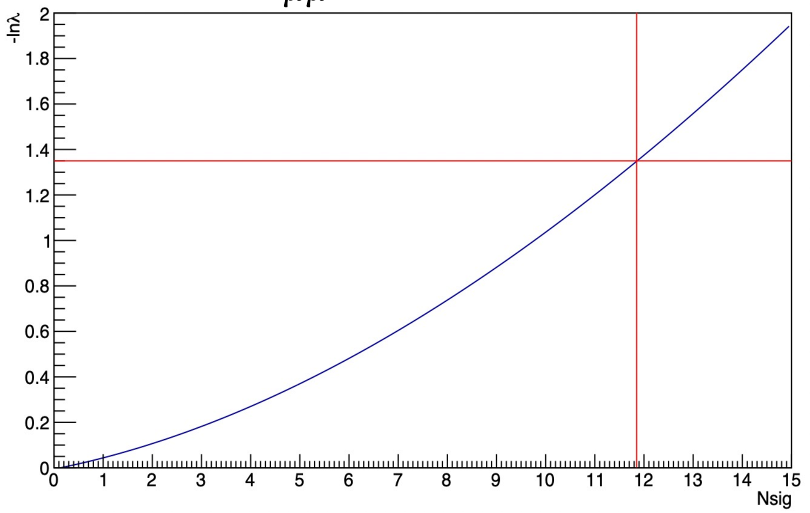
$-ln\lambda(\mu) = 1.35$ (@ 90% confidence level CL)

$D^{*+} \rightarrow [D^0 \rightarrow \pi^-\pi^+ \, l^+l^-] \, \pi^+$ Reconstruction: negative logarithm of the profile likelihood

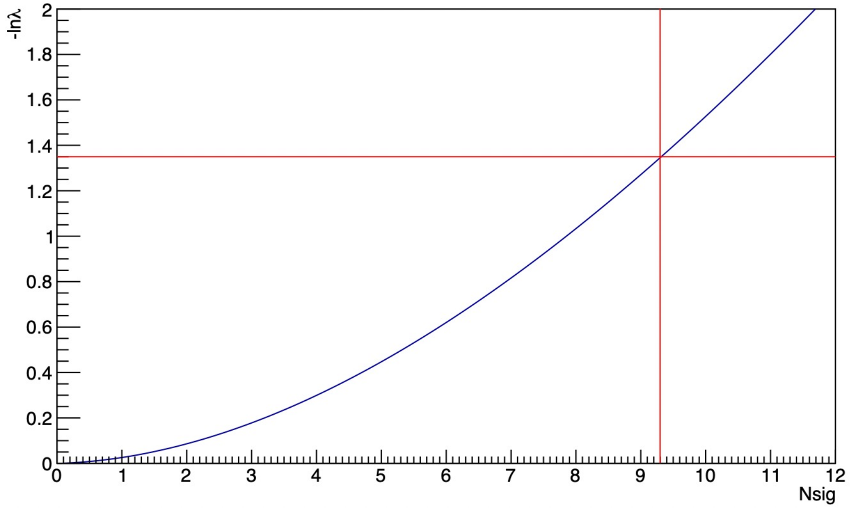
m_{ee} @ low mass



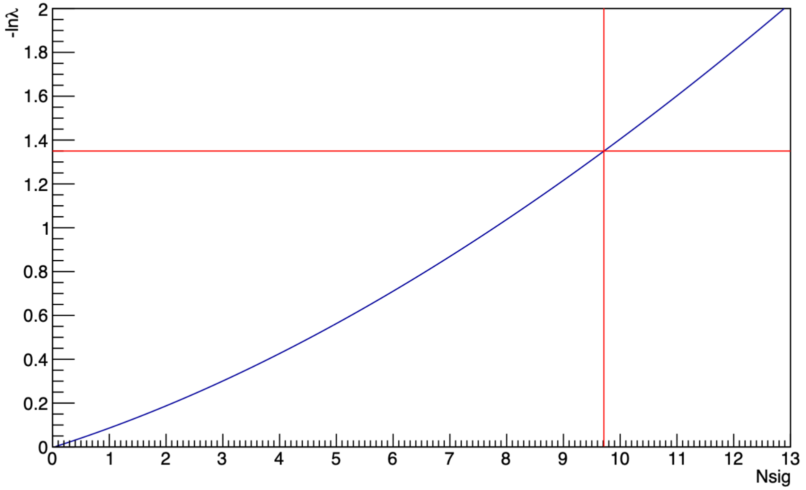
$m_{\mu\mu}$ @ low mass



m_{ee} @ high mass



$m_{\mu\mu}$ @ high mass



Back up: $D^{*+} \to [D^0 \to hhll]\,\pi^+$ Reconstruction: selection criteria

TABLE VI. Optimized selection criteria. ($\delta(m_{D^0}) \equiv m_{D^0} - m_{D^0}^{\rm PDG}$, $\delta(\Delta m) \equiv \Delta m - \Delta m^{\rm PDG}$)

Modes $D^0 \to$	$K^-\pi^+e^+e^-$	$K^-K^+e^+e^-$	$\pi^-\pi^+e^+e^-$	$K^-\pi^+\mu^+\mu^-$	$K^-K^+\mu^+\mu^-$	$\pi^-\pi^+\mu^+\mu^-$	$K^-\pi^+\pi^-\pi^+$
Ipmpact parameter selection:							
$\|d_0\|$ [cm]	< 0.25					$< 0.25\ (0.1)$	< 0.25
$\|z_0\|$ [cm]	< 4.5					$< 4.5\ (4.0)$	< 4.5
K selection:							
`atcPIDBelle(K,π)`	> 0.1	$> 0.1\ (0.2)$	-	> 0.1		-	> 0.1
`eIDBelle`	$< 0.6\ (0.2)$	< 0.2	-	-			
π selection:							
`atcPIDBelle(K,π)`	-		< 0.4	-			
`eIDBelle`	$< 0.6\ (0.2)$	< 0.2	< 0.05	-			
e selection:							
p_e [GeV/c]	$> 0.25\ (0.35)$	> 0.25	$> 0.3\ (0.25)$	-			
`eIDBelle`	> 0.8	$> 0.8\ (0.9)$	0.9	-			
μ selection:							
p_μ [GeV/c]	-			$> 0.5\ (0.7)$	> 0.5		-
`muIDBelle`	-			> 0.97		> 0.95	-
$p^*(D^{*+})$ [GeV/c]	$> 2.4\ (2.5)$	$> 2.4\ (2.5)$	> 2.5	$> 2.2\ (2.4)$	$> 2.4\ (2.5)$	> 2.2	> 2.4
$P(\chi^2_{D^{*+}})$	> 0						
$\delta(\Delta m)$ [MeV/c^2]	< 0.5						
Photon conversion veto:							
$P(\chi^2_{\gamma^*})$	> 0						
θ_{ee} [rads]	$< 0.07\ (0.06)$ or	< 0.06 or	$< 0.04\ (0.08)$ or				
m_{ee} [GeV/c^2]	$< 0.1\ (0.06)$	$< 0.06\ (0.04)$	$< 0.06\ (0.04)$				
D^0 hadronic decay veto:							
$P(\chi^2_{D^{*+}})$	> 0						
$\delta(\Delta m)$ [MeV/c^2]	$< 0.4\ (0.5)$	< 0.5	$< 0.8\ (0.7)$				
$\delta(m_{D^0})$ [MeV/c^2]	< 3	< 5	$< 10\ (5)$				
Best candidate selection:	closest to nominal value of Δm						—