Observation of Inclusive $D^{*\pm}$ Production in the Decay of $\Upsilon(1S)$ at BaBar

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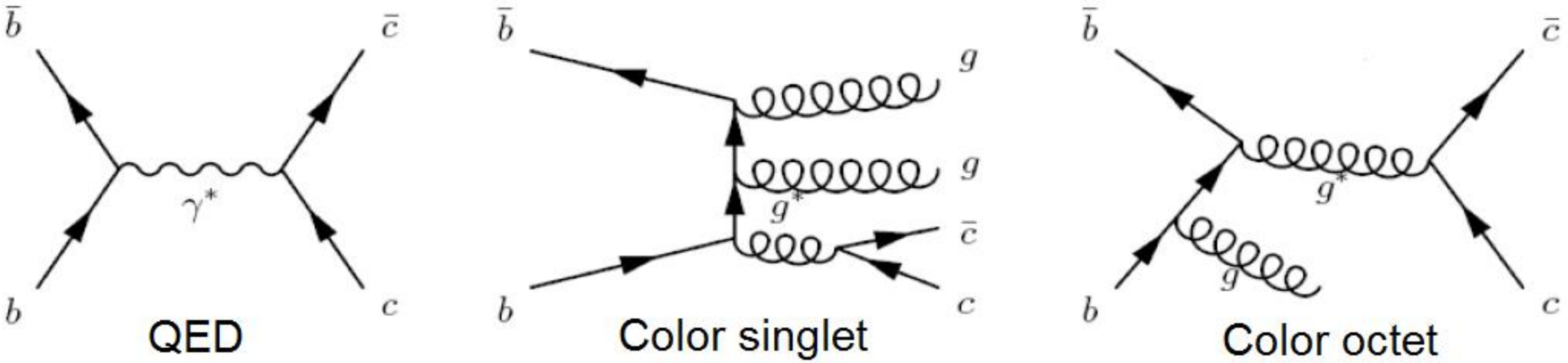
Talk Outline

- Background
  - Previous Theory and Experiment
- Analysis
  - Reconstruction and Selection
  - Background Subtraction
  - Fit Method
- Conclusions
  - Results
  - Systematic uncertainties and cross-checks
  - Interpretation

Introduction

- Only ~10% of $\Upsilon(1S)$ decays have been measured
- Dominant decay mode: $\Upsilon(1S) \rightarrow ggg$

- $\Upsilon(1S) \rightarrow D^{*\pm} + X$ expected to proceed via:



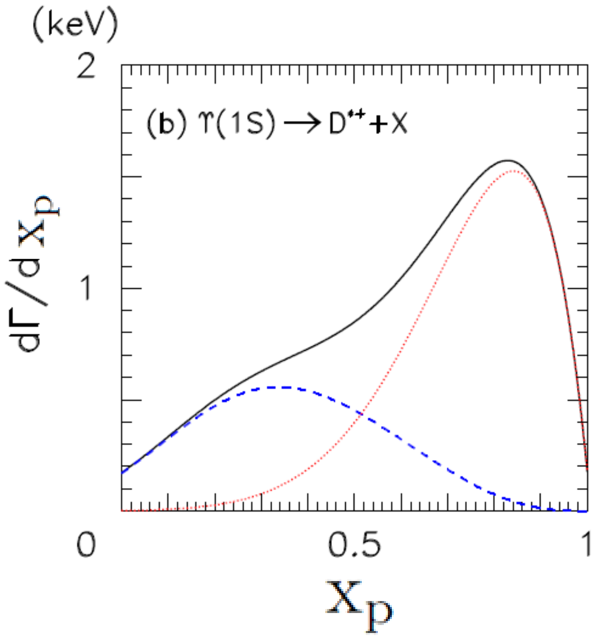
  - Virtual photon annihilation with hadronization
  - Higher-order contributions from color singlet and octet

Introduction

- Theoretical calculations for $\Upsilon(1S)$ decays
  - $\Upsilon(1S) \to D^{*\pm} + X$ momentum distribution prediction
  - QED and color singlet dominate, but color octet may be non-negligible

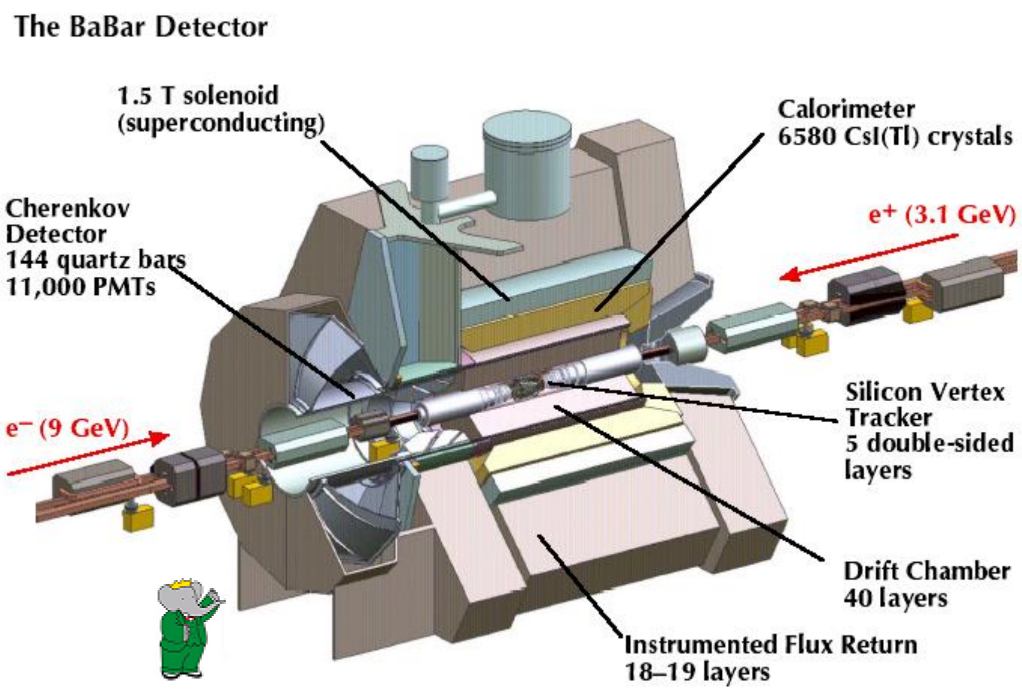
    Kang et al., PRD 76, 114018 (2007)
  - May be up to ~50% of color singlet

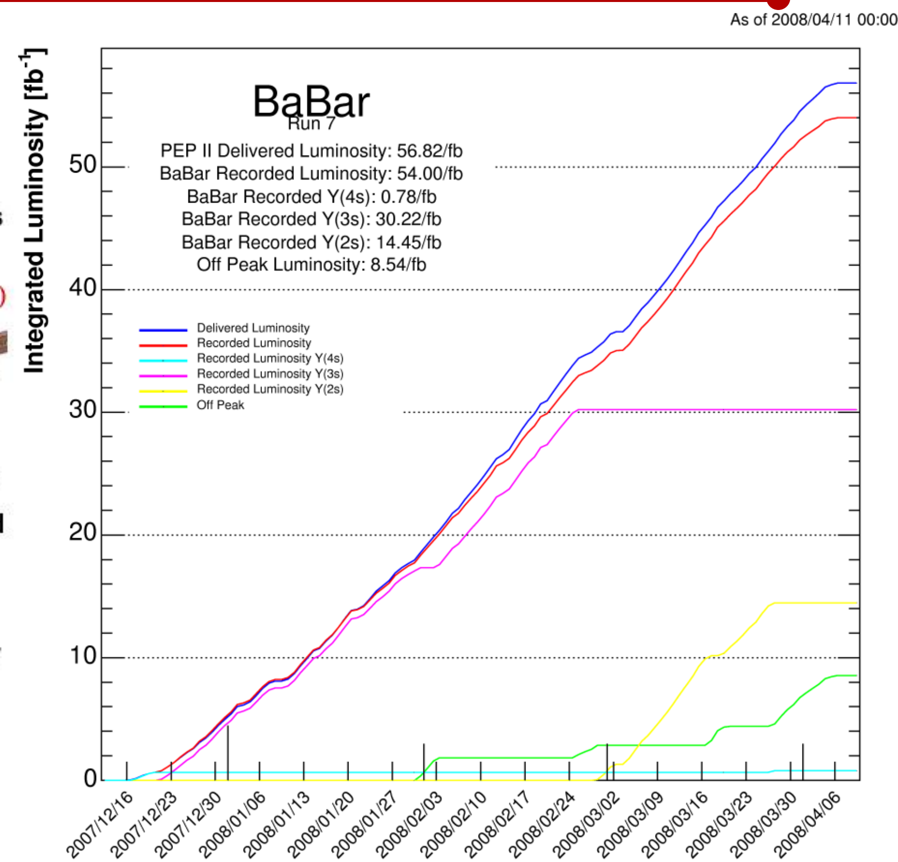
    Zhang & Chao, PRD 78, 094017 (2008)



- χ_{bJ} decay: color octet ~9% of color singlet CLEO, PRD 78, 092007 (2008)
- $\Upsilon(1S)$ decays to open charm not yet observed
  - $BF(\Upsilon(1S) \to D^{*\pm} + X) < 1.9$ % ARGUS, Z Phys C55, 25 (1992)

The BaBar Experiment





$\Upsilon(2S)$ Data: 14.4 $fb^{-1} \approx (98.6 \pm 0.9)$ M events

$\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$: ~17.8 M events

$\Upsilon(4S)$ Off-peak: 44.5 fb^{-1}

Analysis Strategy

- Reconstructed decay chain:

$$
\begin{array}{l}
\Upsilon(2S) \rightarrow \Upsilon(1S)\,\pi^+\pi^- \\
\qquad\qquad \hookrightarrow \Upsilon(1S) \rightarrow D^{*\pm} + X \\
\qquad\qquad\qquad\qquad \hookrightarrow D^{*\pm} \rightarrow D^0\pi^\pm \\
\qquad\qquad\qquad\qquad\qquad\qquad \hookrightarrow D^0 \rightarrow K^\mp\pi^\pm
\end{array}
$$

- Identify $\Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S)$ events by recoil mass:

$$M_{\rm recoil} \equiv \sqrt{(P_{e^+e^-} - P_{\pi\pi})^2}$$

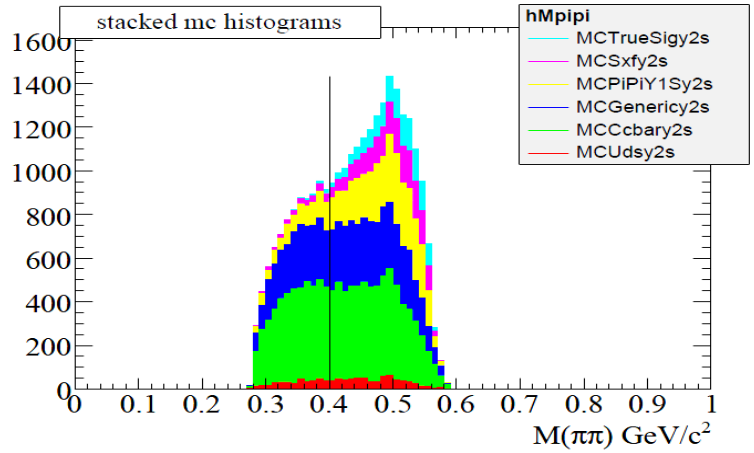
- Subtract $\pi^+\pi^-$ sideband and wrong-sign decay backgrounds
- Fit yield from m_{D0} distribution in bins of scaled momentum:

$$\mathrm{x_p} = \frac{p_{D^{*\pm}}}{p_{\max}} \qquad p_{\max} = \sqrt{(m_{\Upsilon(1S)}/2)^2 - m^2_{D^{*+}}}$$

Selection Criteria

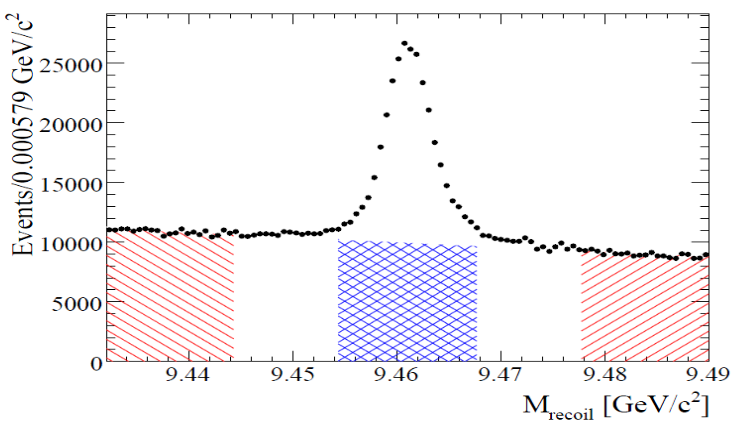
- MC $m_{\pi^+\pi^-}$ tuned to match CLEO

CLEO, PRD76 072001 (2007)

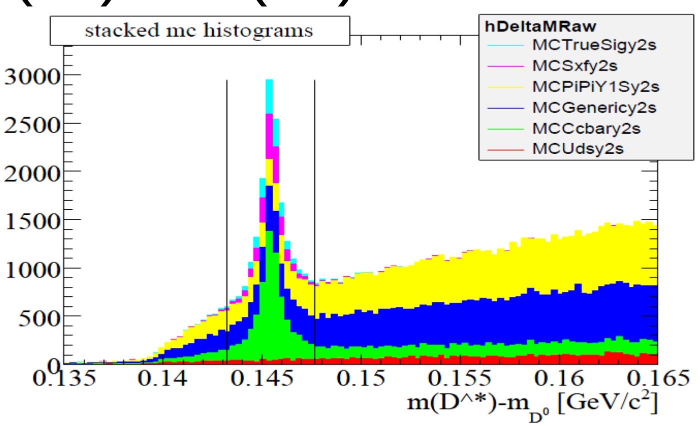


Variable	Criterion
$m(\pi\pi)$	> 400 MeV$/c^2$
$P_{vtx}(\pi\pi)$	$> 1\%$
recoil mass	$[9.43 : 9.49]$ GeV$/c^2$
$m(D^0)$	$m_{D0}^{pdg} \pm 75$ MeV$/c^2$
$P_{vtx}(D^0)$	$> 1\%$
$m(D^*)$	$m_{D*}^{pdg} \pm 0.5$ GeV$/c^2$
$P_{vtx}(D^*)$	$> 1\%$
$m(D^*) - m(D^0)$	$[143.20 : 147.64]$ MeV$/c^2$
$P_{vtx}(D^*\pi\pi)$	$> 1\%$
best candidate	best P_{vtx}

- M_{recoil} includes sidebands

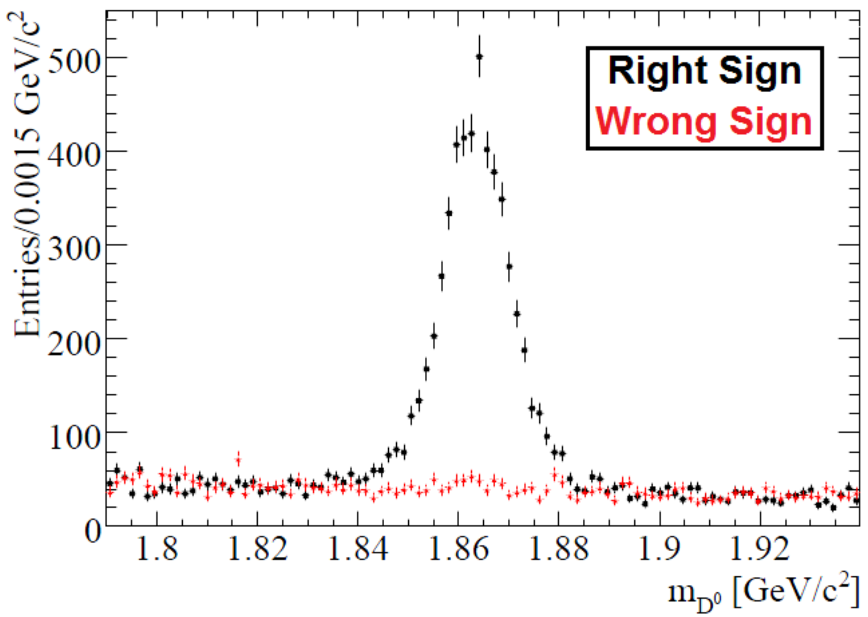


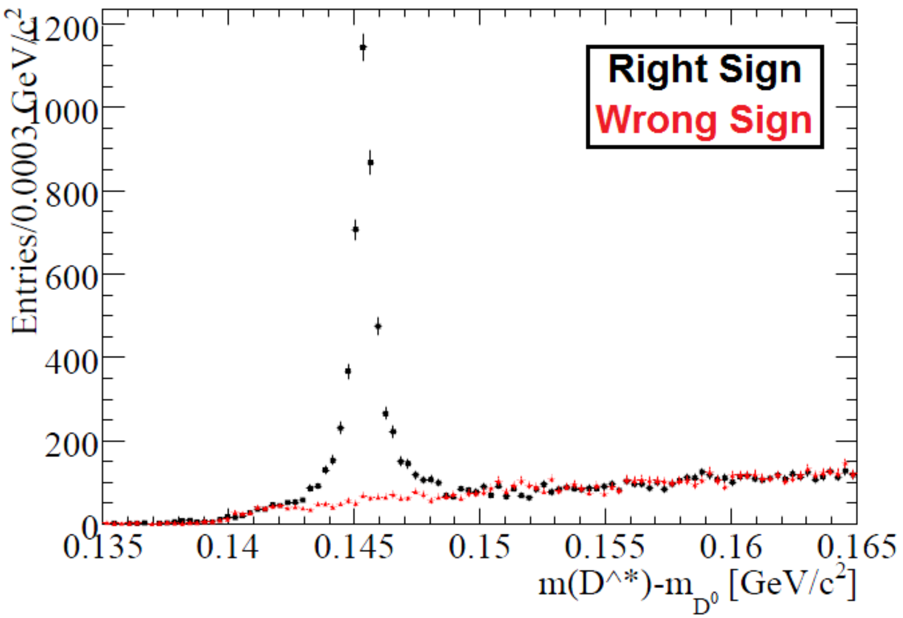
- $m(D^*) - m(D^0)$ to select D^*



Combinatoric Background

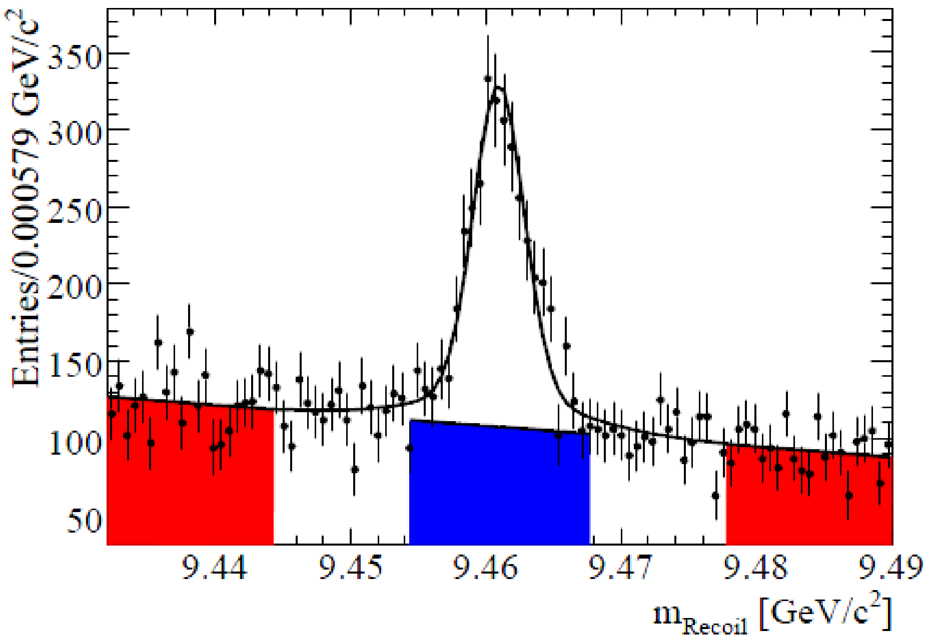
- Define "wrong sign" sample ($D^{*\pm} \to D^0\pi^-$, $D^0 \to K^-\pi^+$)
  - Fake soft pions in D^* or D^0 candidate (dominant)
  - Doubly Cabibbo suppressed ($D^{*-} \to \bar{D}^0\pi^-$, $\bar{D}^0 \to K^-\pi^+$) (0.4%)
  - K and π double-misidentification (<0.02%)

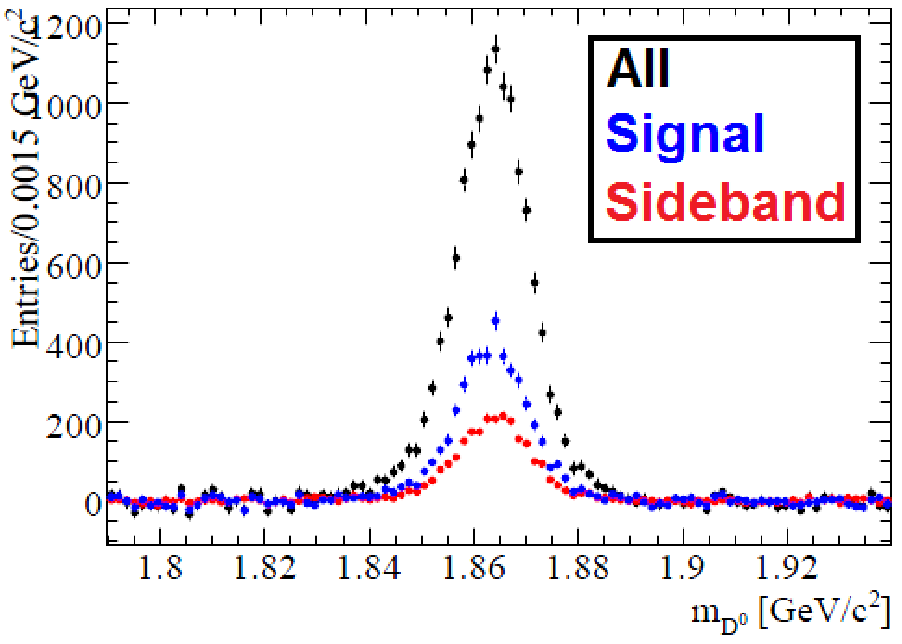




Dipion Sideband Subtraction

- Subtract m_{D0} distribution from M_{recoil} sidebands
  - Real D^* / Non – $\Upsilon(2S) \to \pi^+\pi^- \Upsilon(1S)$ backgrounds
- Scale m_{D0} distribution to signal region and subtract
  - Ratio: linear (sideband) / double-Gaussian (signal)





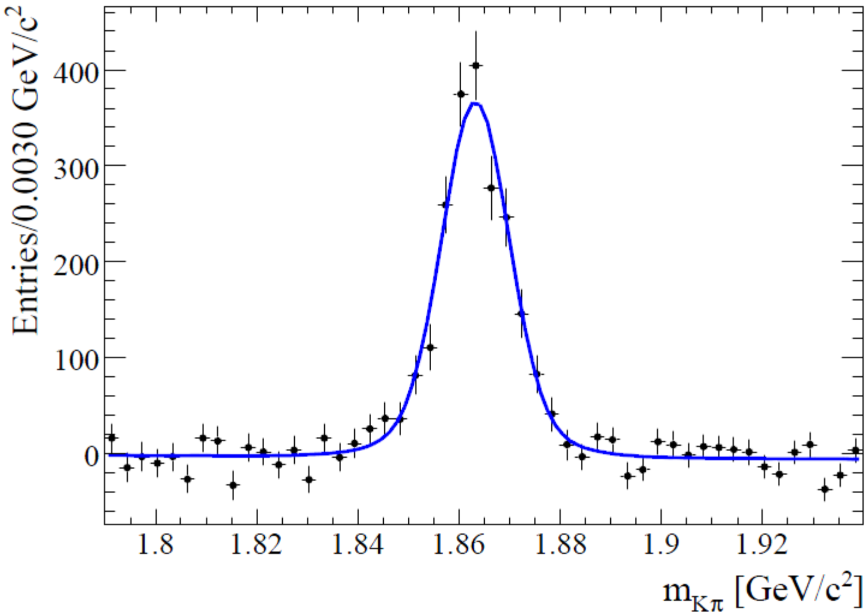
Signal Extraction

- Signal yield from fit to m_{D0} in slices of x_p = [0.1,1.0]
- PDF parameterization:

$$P(m) = n_{\text{sig}} \times P_{\text{sig}}(m) + n_{\text{bkg}} \times P_{\text{bkg}}(m)$$

$$P_{\text{sig}}(m; f, \mu, \sigma_1, \sigma_2) = f G(m; \mu, \sigma_1) + (1-f) G(m; \mu, \sigma_2)$$

$$P_{\text{bkg}}(m; \mu, p_1) = 1/w + p_1(m - \mu)$$

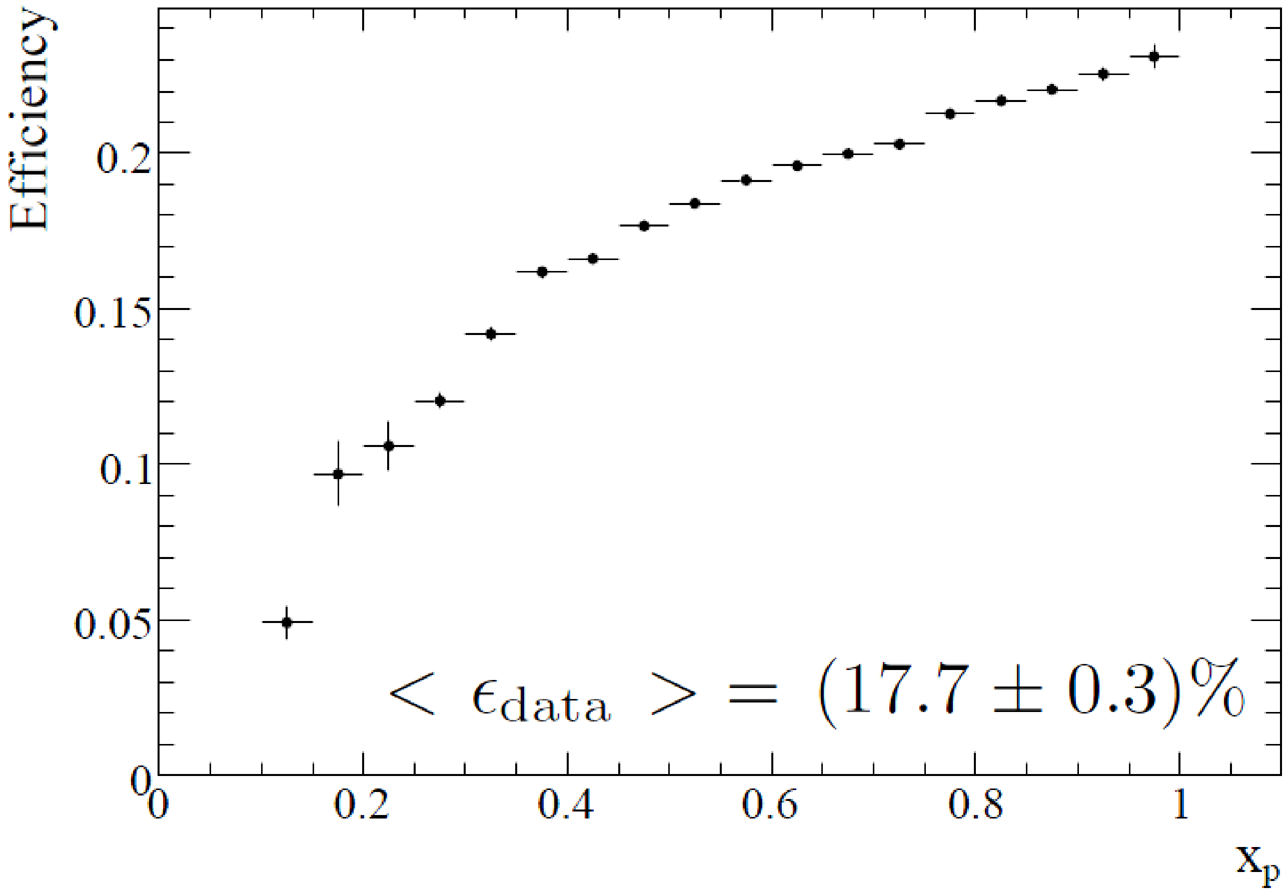


  - f, σ_1, σ_2 determined from MC
  - μ from full x_p range data

- Parameterization stability verified on MC across x_p

Efficiency

- Determined from fits to MC in slices of x_p

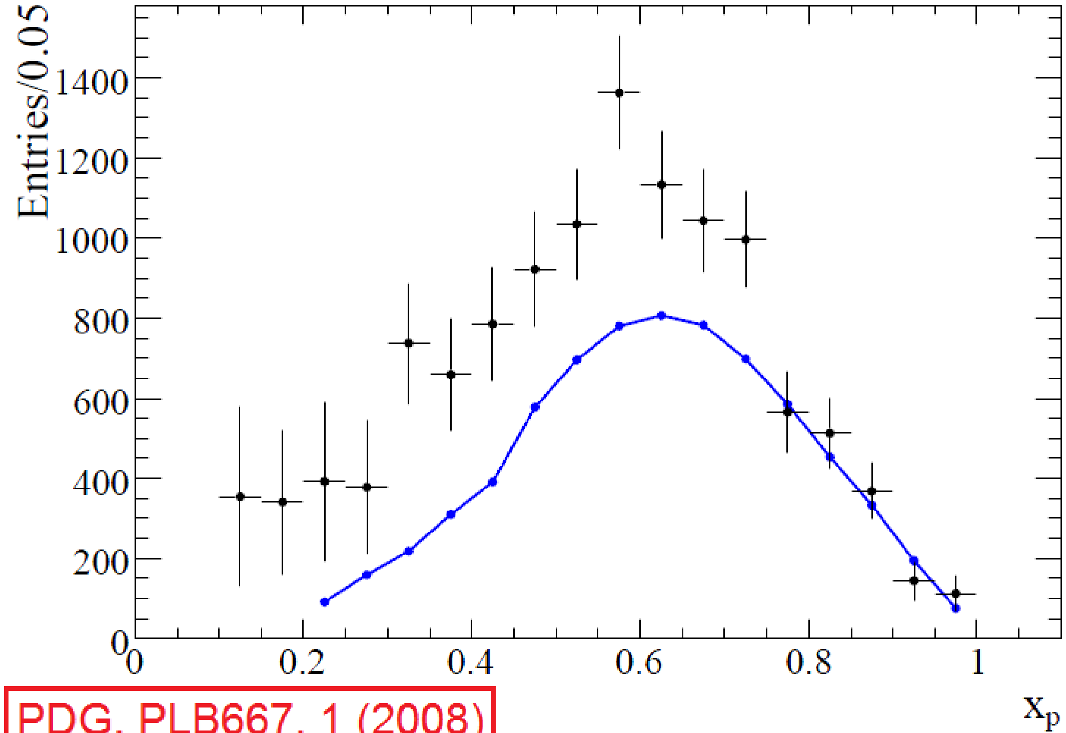


- $x_p < 0.1$ dominated by combinatorial background

Results

- n_{sig} = 11845 ± 596

$$\mathcal{B}[\Upsilon(1S) \rightarrow D^{*\pm} X] = \frac{n_{\rm sig}}{k_{\rm DCS} \times \mathcal{B}_{\rm decay} \times N_{\Upsilon(1S)}} = (2.52 \pm 0.13({\rm stat}) \pm 0.15({\rm syst}))\%$$



- Derived QED contribution:

$$\mathcal{B}[\Upsilon(1S) \rightarrow \gamma^* \rightarrow D^{*\pm} X] = \frac{\sigma_{D^{*\pm}}}{\sigma_{q\bar{q}}} \times \mathcal{B}[\Upsilon(1S) \rightarrow \mu^+\mu^-] \times \sigma(e^+e^- \rightarrow {\rm hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-) = (1.52 \pm 0.20)\%$$

PDG, PLB667, 1 (2008)

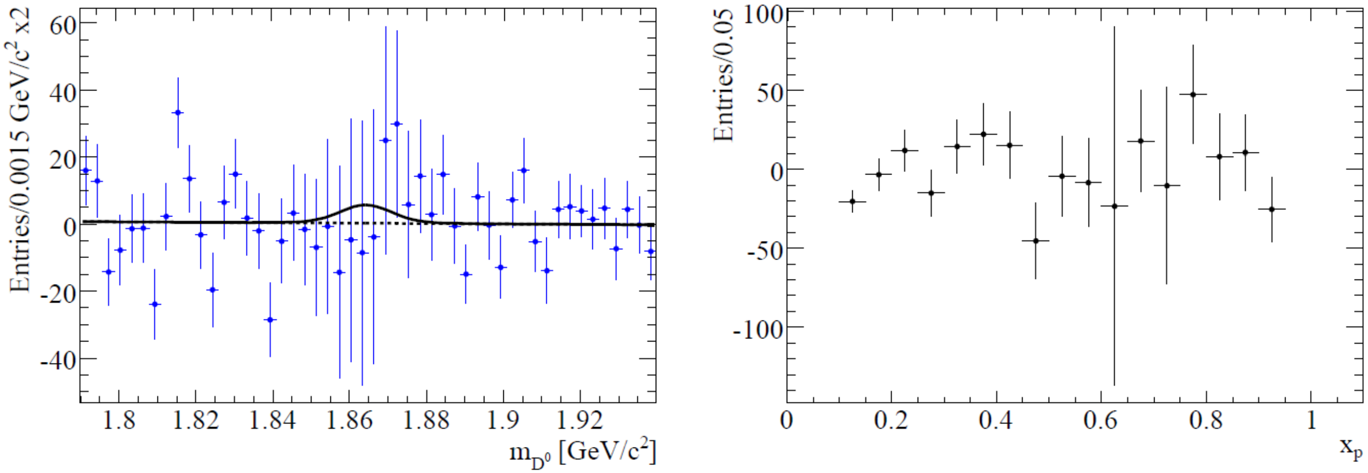
ARGUS, Z.Phys C54, 13 (1992)

- Apply this normalization to fragmentation function

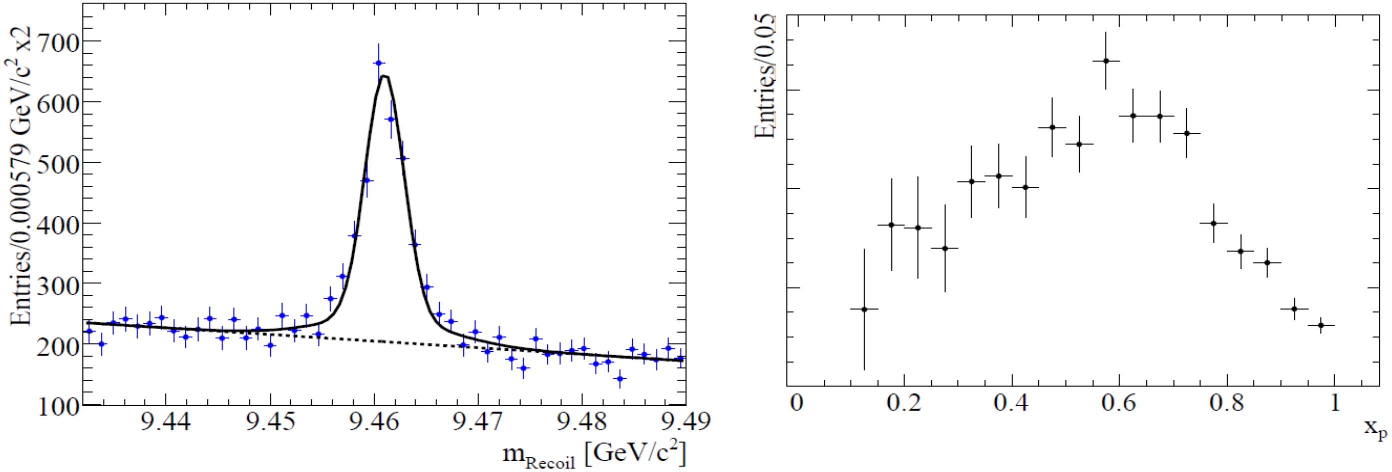
CLEO, PRD 70, 112001 (2004)

Cross-Checks

- Off-resonance fit consistent with 0 events



- Alternate fit to M_{recoil} returns consistent results

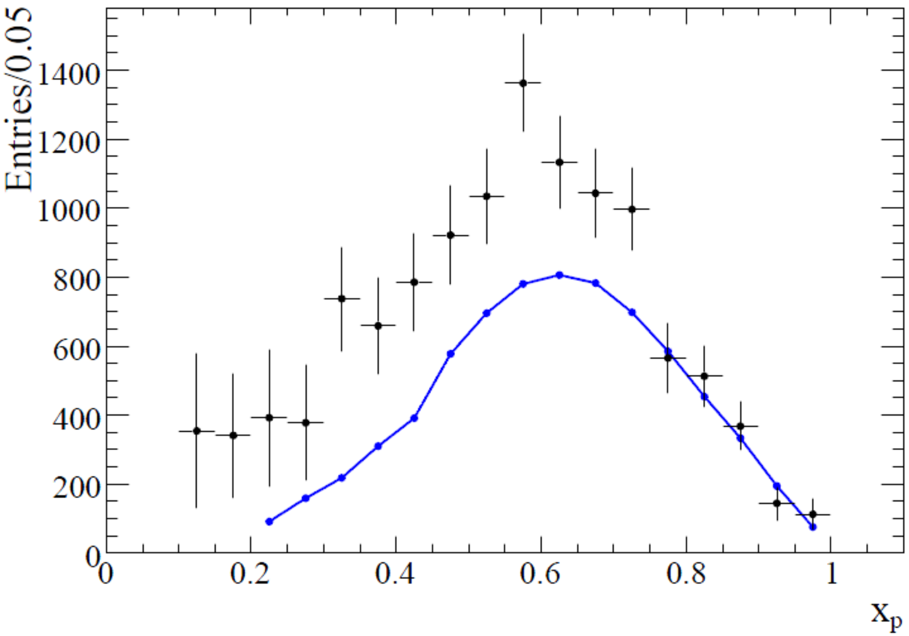


Systematic Uncertainties

Sources of systematic uncertainty	
Slow $\pi^{\pm}$ reconstruction	3.0%
M_{recoil} selection	2.8%
$\mathcal{B}_{\mathrm{decay}}$	2.3%
Generated x_p distribution	2.2%
PID	1.6%
Tracking efficiency	1.6%
$\Upsilon(2S)$ decay model	1.2%
Υ counting	0.9%
Background curvature	0.4%
MC efficiency	0.4%
Signal shape	0.3%
k_{DCS}	0.02%
Total	5.9%

- π reconstruction
  - $D^* \rightarrow D^0\pi$: p_π related to θ^*
  - $\Delta\varepsilon$ between data / MC
- M_{recoil}
  - Peak differs in MC and data
  - Fit with double-Gaussian
  - Compare $\Delta\varepsilon$
- B_{decay} PDG, PLB667, 1 (2008)
  - $B(\Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S))$
- x_p distribution
  - Fit empirically
  - Reweight and refit MC

Discussion and Conclusion



- $B(\Upsilon(1S) \rightarrow D^{*\pm} + X)$ $= (2.52 \pm 0.13 \pm 0.15)\%$
- $x_p > 0.75$: consistent with QED
- $x_p < 0.75$: significant excess
- $P(\chi^2) = 1.6 \times 10^{-5}$
- Exceeds QED by $(1.00 \pm 0.28)\%$
- Consistent with color singlet prediction $(1.20 \pm 0.29)\%$ Kang et al., PRD 76, 114018 (2007)
- Disfavors large color octet contribution

- For full details, please see our publication:
  BABAR, PRD 81, 011102(R) (2010)