High Precision Measurements of $D_{s1}(2536)$

Initial-State-Radiation (ISR) Production of D_s Mesons

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on behalf of

The BABAR Collaboration

(All new results are preliminary)

Modeled by Daryl Oshatz • Berkeley Lab

D_{s1}(2536) Measurements: Motivation

$q\bar{q}$ Quark Model Assignments

$n\ ^{2s+1}\ell_J$	J^{PC}	$c\bar{s};\ \bar{c}s$
$1\ ^1P_1$	1^{+-}	$D_{s1}(2536)^{\pm}$
$1\ ^3P_0$	0^{++}	$D^*_{s0}(2317)^{\pm\dagger}$
$1\ ^3P_1$	1^{++}	$D_{s1}(2460)^{\pm\dagger}$
$1\ ^3P_2$	2^{++}	$D_{s2}(2573)^{\pm}$

† Considerably smaller than most theoretical predictions (RPP 2008)

- *P*-wave D_s masses poorly explained by potential models/HQET
- Alternatives: Tetra quarks
  $D^{(*)}K$ molecules
  Unitarized chiral models
  Lattice calculations
- Clear theoretical picture yet to emerge
- 2009 PDG values:
  $m(D_{s1})$ = (2535.35 ±0.34 ±0.50) MeV/c^2
  $m(D_{s1})$–$m(D^{*\pm})$ = (525.3 ±0.6 ±0.1) MeV/c^2
  $\Gamma(D_{s1})$ < 2.3 MeV/c^2 CL=90%

- ***BaBar* can do better**

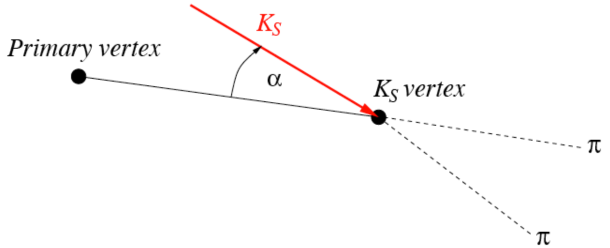
Data and Selection

- PEP-II / BaBar data: 384 fb^{-1} at $\Upsilon(4S)$ and 40 MeV/c^2 below $\Upsilon(4S)$

- Decay:

$$D_{s1}^{+} \rightarrow D^{*+}\ K_S^0$$
$$D^{*+} \rightarrow D^0\pi^+, \quad K_S^0 \rightarrow \pi^+\pi^-$$
$$D^0 \rightarrow K^-\pi^+,\ K^-\pi^+\pi^-\pi^+$$

($K4\pi$, $K6\pi$)

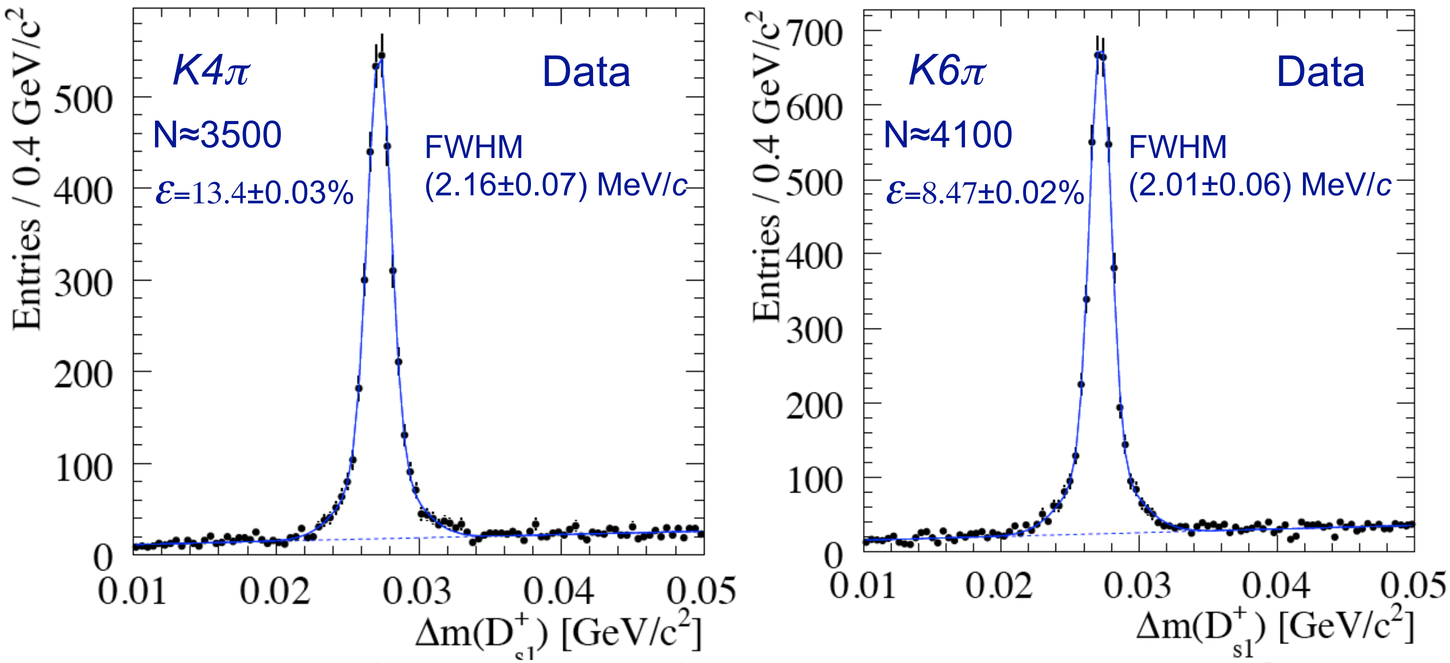


- Particle ID: K and π
  K_s alignment α<0.15 rad

- Entire decay tree topological-only (vertex) constrained fit:
  χ^2 fit prob. > 0.001
  Tie-breaker for multiple entries

- $p^*(D_{s1})$>2.7 GeV/c (suppresses combinatorial backgrounds)

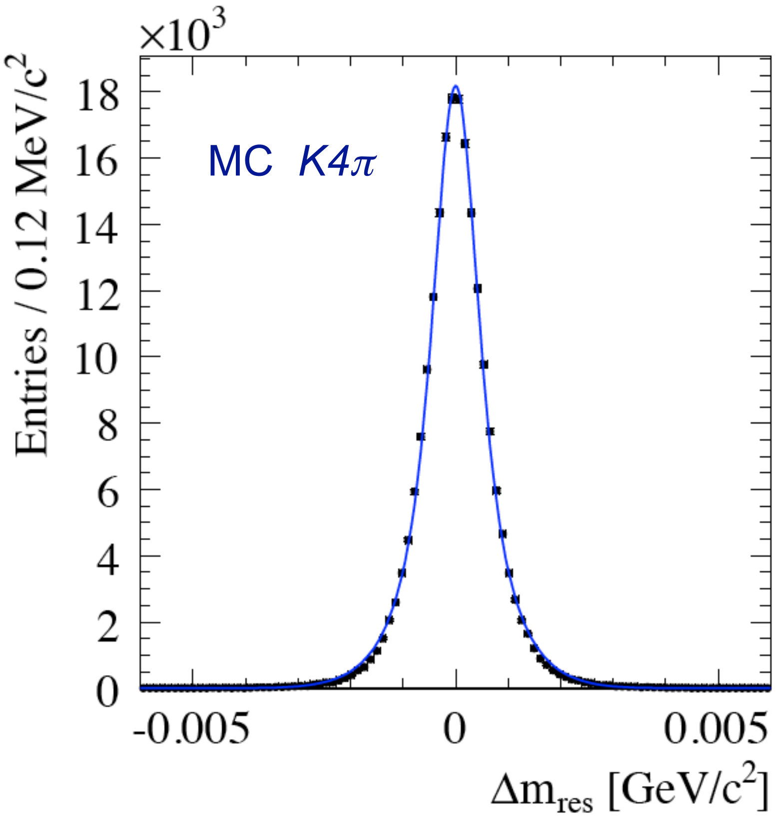
$D_{s1}(2536)$ Signal



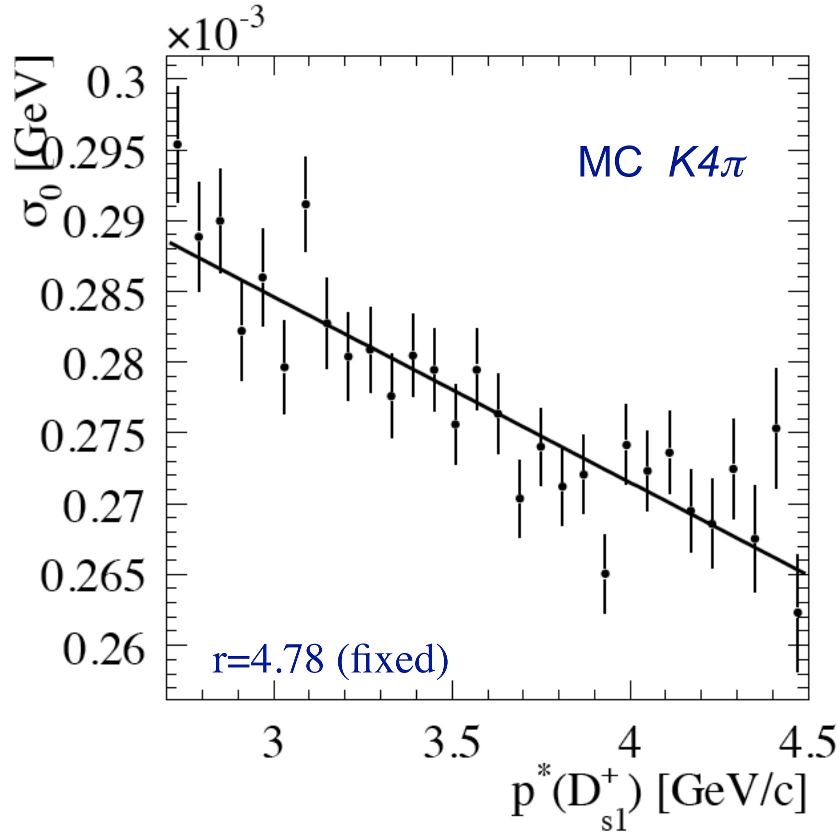
$$\Delta m(D_{s1}^{+}) = m(D_{s1}^{+}) - m(D^{*+}) - m(K_S^0)$$

Momentum-Dependent Resolution Function

Continuous sum of Gaussians: $R(\Delta m_{res}) = \int_{\sigma_0}^{r\sigma_0} \frac{1}{r\sigma^2} e^{-\frac{(\Delta m_{res} - \Delta m_{res0})^2}{2\sigma^2}} d\sigma$



Determine r=4.78 for full MC sample



Determine σ_0 for each momentum bin

Fit: $R \otimes$ Relativistic L=0 Breit-Wigner

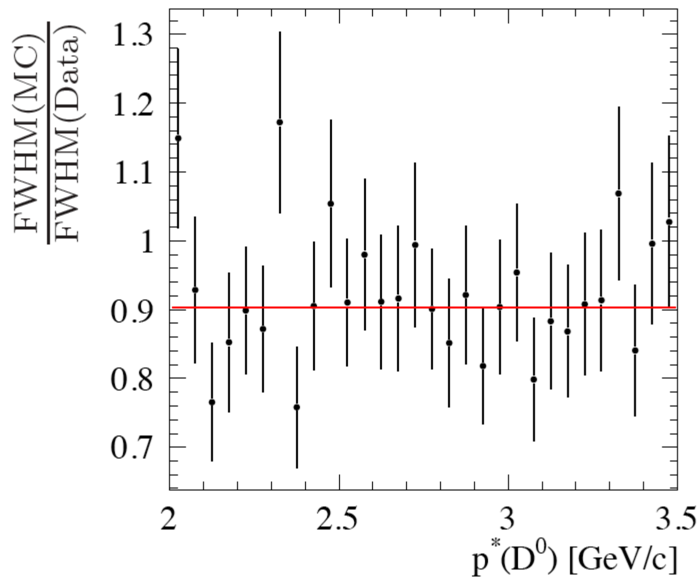
- Fitting MC reproduces input values

Fit Validation

Parameter	$K4\pi$	$K6\pi$	generated
$\Delta m(D_{s1})$ [MeV/c^2]	27.737±0.003	27.734±0.003	27.74
$\Gamma(D_{s1})$ [MeV/c^2]	1.001±0.005	0.991±0.006	1.0
$\Delta m(D_{s1})$ [MeV/c^2]	27.728±0.008	27.725±0.010	27.744
$\Gamma(D_{s1})$ [MeV/c^2]	2.003±0.016	2.017±0.022	2.0

- …but MC mass resolution too good

D^0 Mass Resolution Study



- Biases fit to Γ
- Apply correction to $\Gamma(D_{s1})$

$K4\pi$: -48 keV/c^2
$K6\pi$: -50 keV/c^2

Systematic: ±34 keV/c^2 for correction

Systematic Uncertainties

Systematic uncertainty	$\Delta_{\Delta m}$ / keV/c^2 $K4\pi$	$K6\pi$	Δ_{Γ} / keV $K4\pi$	$K6\pi$
Resolution +10 %	< 0.5	< 0.5	± 34	± 34
MC validation	± 7	± 10	± 1	± 9
Alternative resolution models	< 0.5	< 0.5	± 2	± 12
Multi-Gaussian resolution: $r \pm \delta r$	< 0.5	< 0.5	± 6	± 7
Multi-Gaussian resolution: Param of σ_0	< 0.5	< 0.5	± 3	± 2
Breit-Wigner signal lineshape: L	± 9	± 8	± 2	± 3
Numerical precision of convolution	< 0.5	< 0.5	< 0.5	< 0.5
Mass window for $\Delta m(D_{s1}^{+})$	< 0.5	< 0.5	± 9	± 3
Background parameterization	< 0.5	< 0.5	± 5	± 7
Tracking region material density	± 21	± 13	± 14	± 15
SVT Alignment	± 6	± 7	± 2	± 14
Magnetic field strength	± 12	± 19	± 19	± 11
Length scale	± 4	± 6	± 8	± 4
Drift chamber hits	± 11	± 15	± 7	± 7
ϕ-dependency	± 13	± 14	-	-
Results	± 33	± 35	± 45	± 46

New Precision $D_{s1}(2536)$ Measurements

(All measurements are preliminary)

- **Mass**

$$m(D_{s1}^{+}) - m(D^{*+}) = (524.85 \pm 0.01 \pm 0.04)\ MeV/c^2$$

$$m(D_{s1}^{+}) = (2535.12 \pm 0.01 \pm 0.18)\ MeV/c^2$$

- **Width**

$$\Gamma(D_{s1}^{+}) = (0.94 \pm 0.03 \pm 0.04)\ MeV/c^2$$

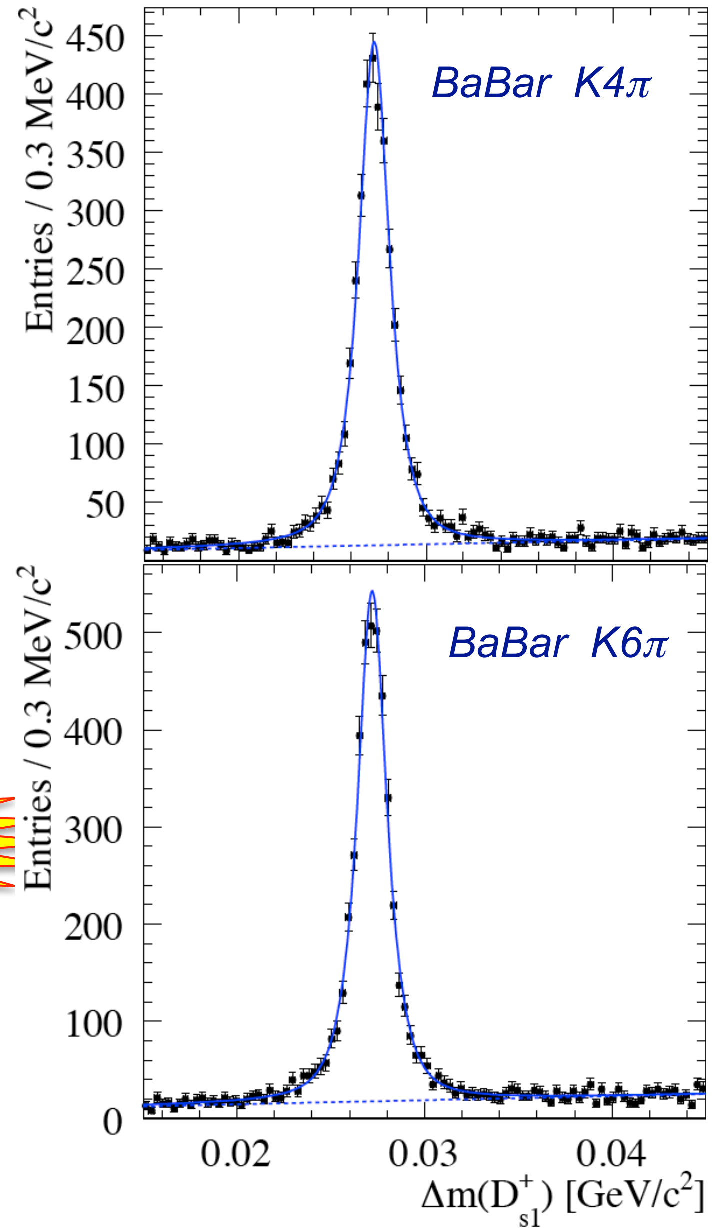
First non-limit!

Compare to PDG 2008:

$$m(D_{s1}^{+}) - m(D^{*+}) = (525.3 \pm 0.6 \pm 0.1)\ MeV/c^2$$

$$m(D_{s1}^{+}) = (2535.35 \pm 0.34 \pm 0.5)\ MeV/c^2$$

$$\Gamma(D_{s1}^{+}) < 2.3\ MeV/c^2$$



Motivation for $e^+e^- \to \gamma_{ISR} D_s^{(*)} D_s^{(*)}$

- Search for $J^{PC}=1^{--}$ states and structures
  - Use Initial State Radiation (ISR) to scan E_{CM}
- Measure $D_s^+ D_s^- / D_s^{*+} D_s^- / D_s^{*+} D_s^{*-}$ cross section
- Exploration of *Y(4260)* decays
  - *Y(4260)* $\to \pi\pi J/\psi$ observed
  - *Y(4260)* $\to D^{(*)}D^{(*)}$ not found
  - Tetraquark hypothesis: *Y(4260)* $\to D_s D_s$ *"dominant"*
    - *Maiani, et al., PRD 72, 031502 (2005)*

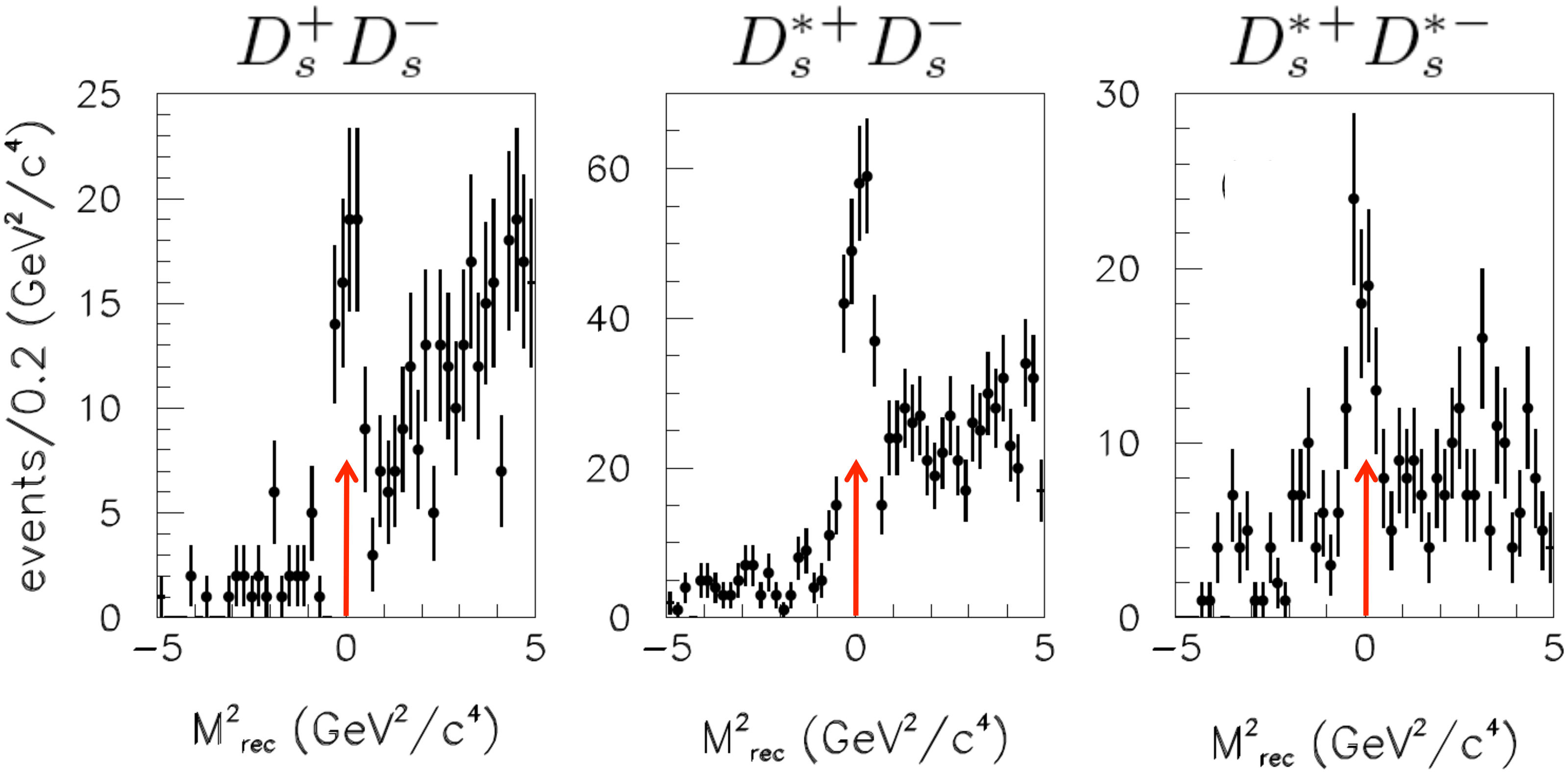
Data and Preliminary Selection

- Entire PEP-II / BaBar data: 525 fb^{-1}
  - Most at ϒ(4S) and 40 MeV/c^2 below ϒ(4S)
  - 16 fb^{-1} at ϒ(2S), 31 fb^{-1}at ϒ(3S), 4 fb^{-1} above ϒ(4S)
- Select events with D_sD_s *(+ photons, $E\gamma$ > 30 MeV)*

Channel	First D_s decay mode	Second D_s decay mode
(1)	$K^+\ K^-\ \pi^+$	$K^+\ K^-\ \pi^-$
(2)	$K^+\ K^-\ \pi^+$	$K^+\ K^-\ \pi^-\ \pi^0$
(3)	$K^+\ K^-\ \pi^+$	$K^0_S\ K^-$

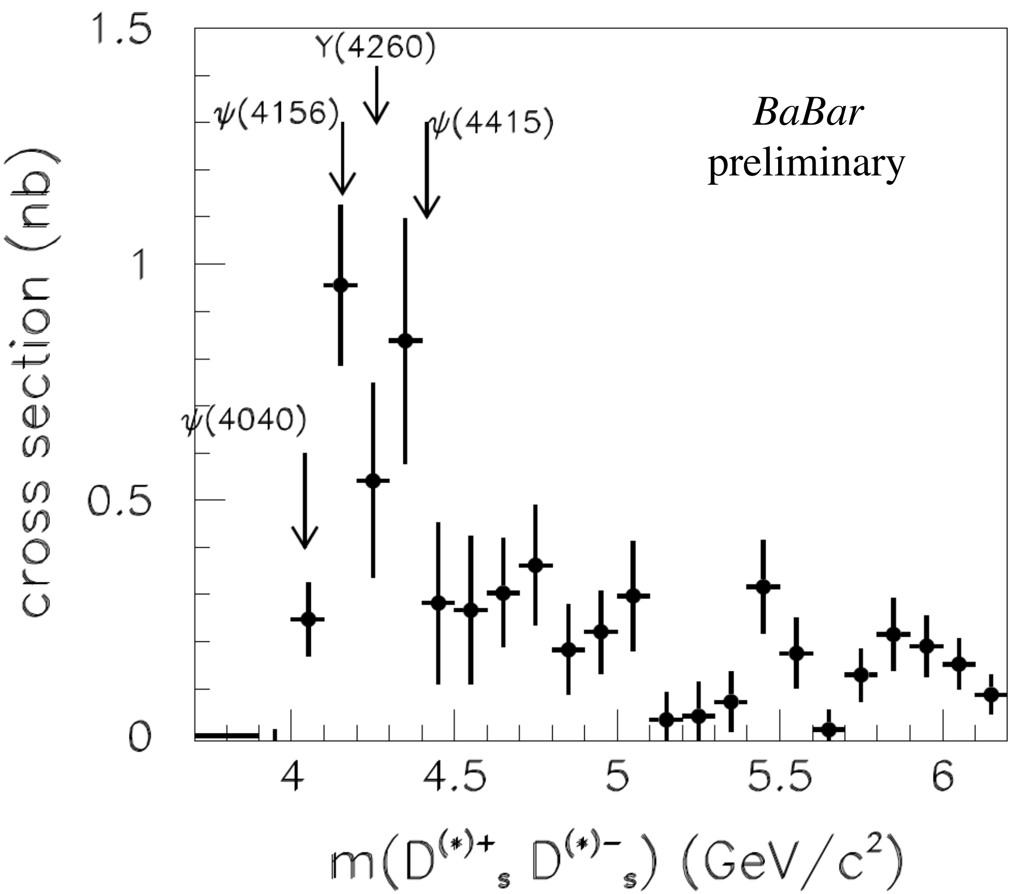
  - Vertex constraint, K_s mass constraint (prob. >0.1%)
  - D_s: $\Delta m = m(K^+K^-\pi^+\gamma) - m(K^+K^-\pi^+)$ within 2σ
- Likelihood ratio formed from discriminating variables
  - Resolve ambiguities, reject bg back
- $D_s^*D_s^{(*)}$ candidates removed from $D_sD_s^{(*)}$ sample
- $m(D_s^{(*)}D_s^{(*)})$<6.2 GeV/c^2

ISR Selection: $|M^2_{rec}|<0.8\ GeV^2/c^4$



- γ_{ISR} detected kinematically in $D_s^{(*)}D_s^{(*)}$recoil
  - not explicitly reconstructed
  - ~90% lost down beampipe

Total $D_s^{(*)}D_s^{(*)}$ Cross Section

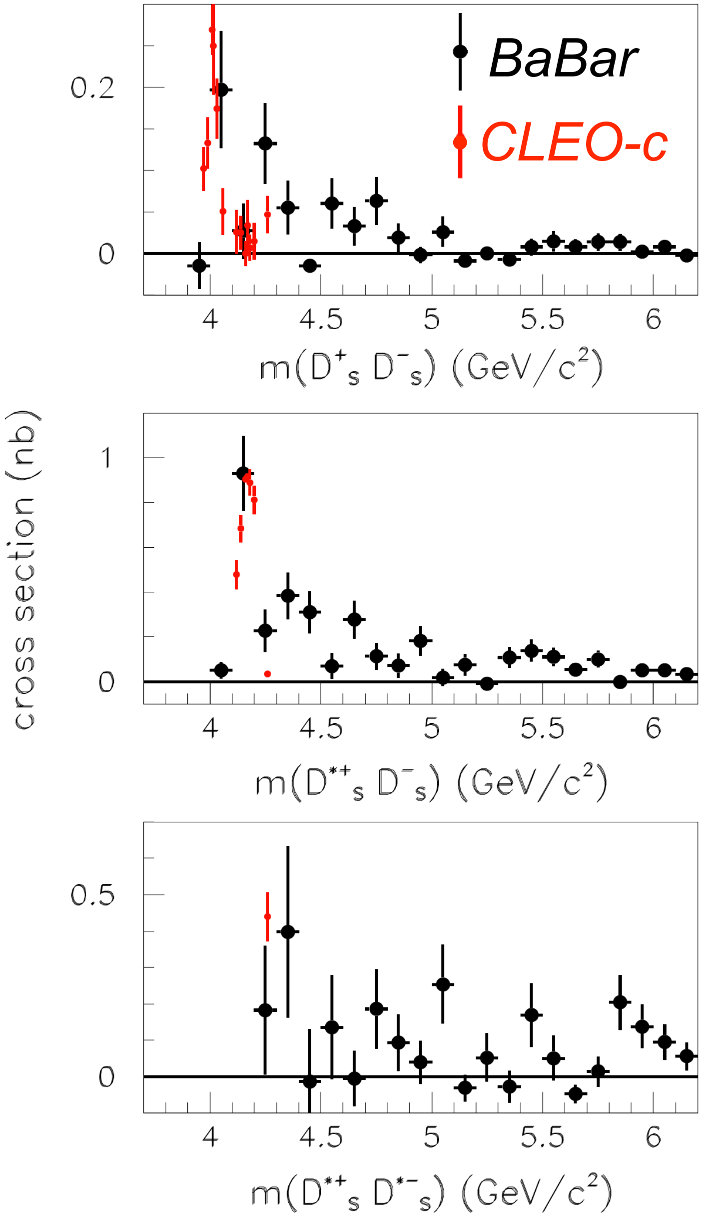


Systematic Uncertainty (%)

Source	$D_s^+D_s^-$	$D_s^{*+}D_s^-$	$D_s^{*+}D_s^{*-}$
Background subtraction	18.0	4.2	4.9
Branching fractions	10.0	10.0	10.0
Particle identification	5.0	5.0	5.0
Tracking efficiency	1.4	1.4	1.4
π^0's and γ	1.1	2.9	4.7
Likelihood cut	8.7	4.0	
Total	23	13	13

- Y(4260) is at a $D_s^{(*)}D_s^{(*)}$ cross section minimum

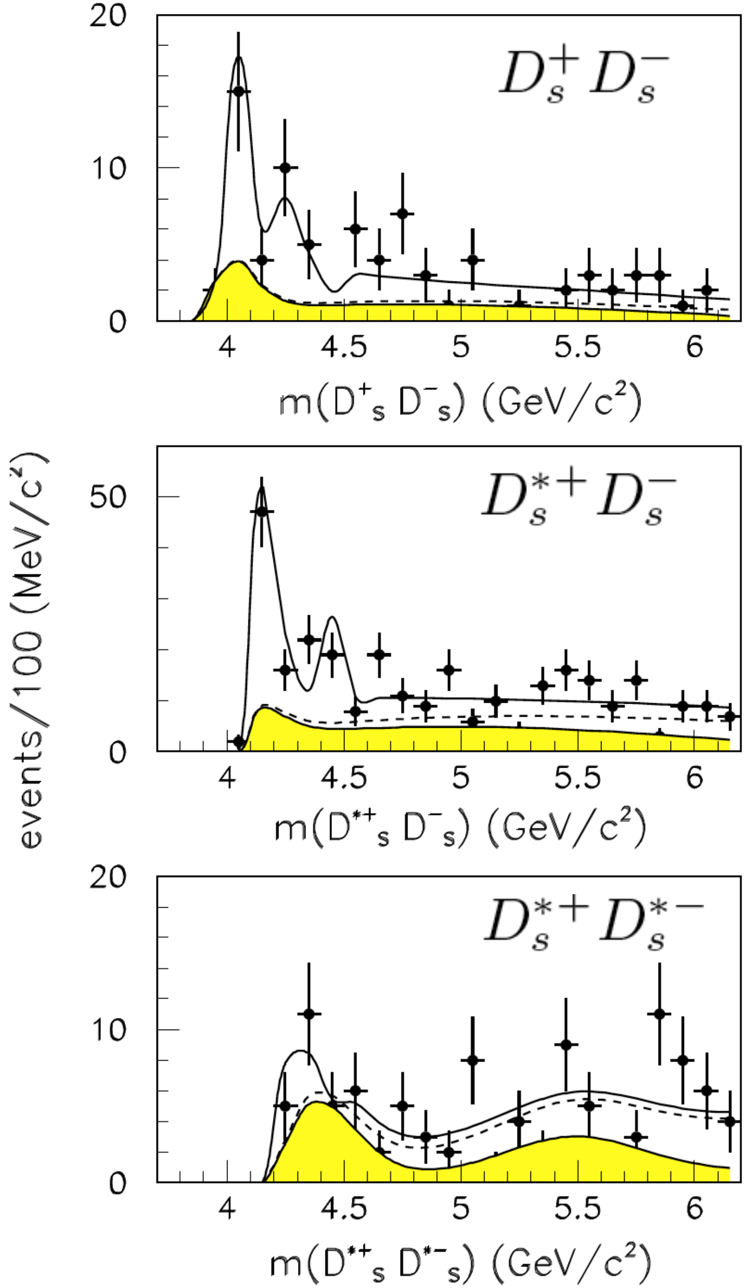
Comparison with Previous Measurements



- Good agreement with CLEO-c energy scan cross section measurements
  PRD 80, 072001 (2009)

- *BaBar* measurement extends E_{CM} range to 6.2 GeV/c^2

Fit to Charmonia + Y(4260) + Coherent BG



Only statistical errors here

Resonance	Fraction $D_s^+ D_s^-$	$D_s^{*+} D_s^-$	$D_s^{*+} D_s^{*-}$
$P(m)$	11 ± 5	27 ± 5	71 ± 20
$\psi(4040)$	62 ± 21		
$\psi(4160)$	23 ± 26	53 ± 8	
$\psi(4415)$	6 ± 11	4 ± 2	5 ± 12
$Y(4260)$	0.5 ± 3.0	18 ± 24	11 ± 16
Sum	103	102	87

Systematic errors here incl. res. Parameters, bg , meson radii in BW terms

$$\frac{\mathcal{B}(Y(4260) \to D_s^+ D_s^-)}{\mathcal{B}(Y(4260) \to J/\psi\pi^+\pi^-)} < 0.7$$

$$\frac{\mathcal{B}(Y(4260) \to D_s^{*+} D_s^-)}{\mathcal{B}(Y(4260) \to J/\psi\pi^+\pi^-)} < 44$$

$$\frac{\mathcal{B}(Y(4260) \to D_s^{*+} D_s^{*-})}{\mathcal{B}(Y(4260) \to J/\psi\pi^+\pi^-)} < 30$$

95% confidence level

(All measurements are preliminary)

- Yellow: scaled M^2_{rec} sideband
- Dash: Yellow + coherent background
- Line: Dash + resonances

Conclusions

- $D_s^{(*)} D_s^{(*)}$ cross section measurements
  - E_{CM} from threshold to 6.2 GeV
- No evidence for $Y(4260) \rightarrow D_s^{(*)} D_s^{(*)}$
  - Constrains Tetraquark interpretation
- New high precision measurements of $D_{s1}(2536)$

$$m(D_{s1}^{+}) - m(D^{*+}) = (524.85 \pm 0.01 \pm 0.04)\, MeV/c^2$$

$$m(D_{s1}^{+}) = (2535.12 \pm 0.01 \pm 0.18)\, MeV/c^2$$

$$\Gamma(D_{s1}^{+}) = (0.94 \pm 0.03 \pm 0.04)\, MeV/c^2$$

(All results preliminary)

Supplemental Slides

Relativistic Breit-Wigner

$$BW(m) = \left(\frac{p_m}{p_{m_0}}\right)^{2L+1} \left(\frac{m_0}{m}\right) \frac{mF_L(p_m)^2}{(m_0^2 - m^2)^2 + \Gamma_m^2 m_0^2}$$

$L = 0$ or $L = 2$ due to parity conservation.

$$F_0(p_m) = 1$$

$$F_2(p_m) = \frac{\sqrt{9 + 3(Rp_{m_0})^2 + (Rp_{m_0})^4}}{\sqrt{9 + 3(Rp_m)^2 + (Rp_m)^4}}$$

$R = 1.5\ (\mathrm{GeV}/c)^{-1}$

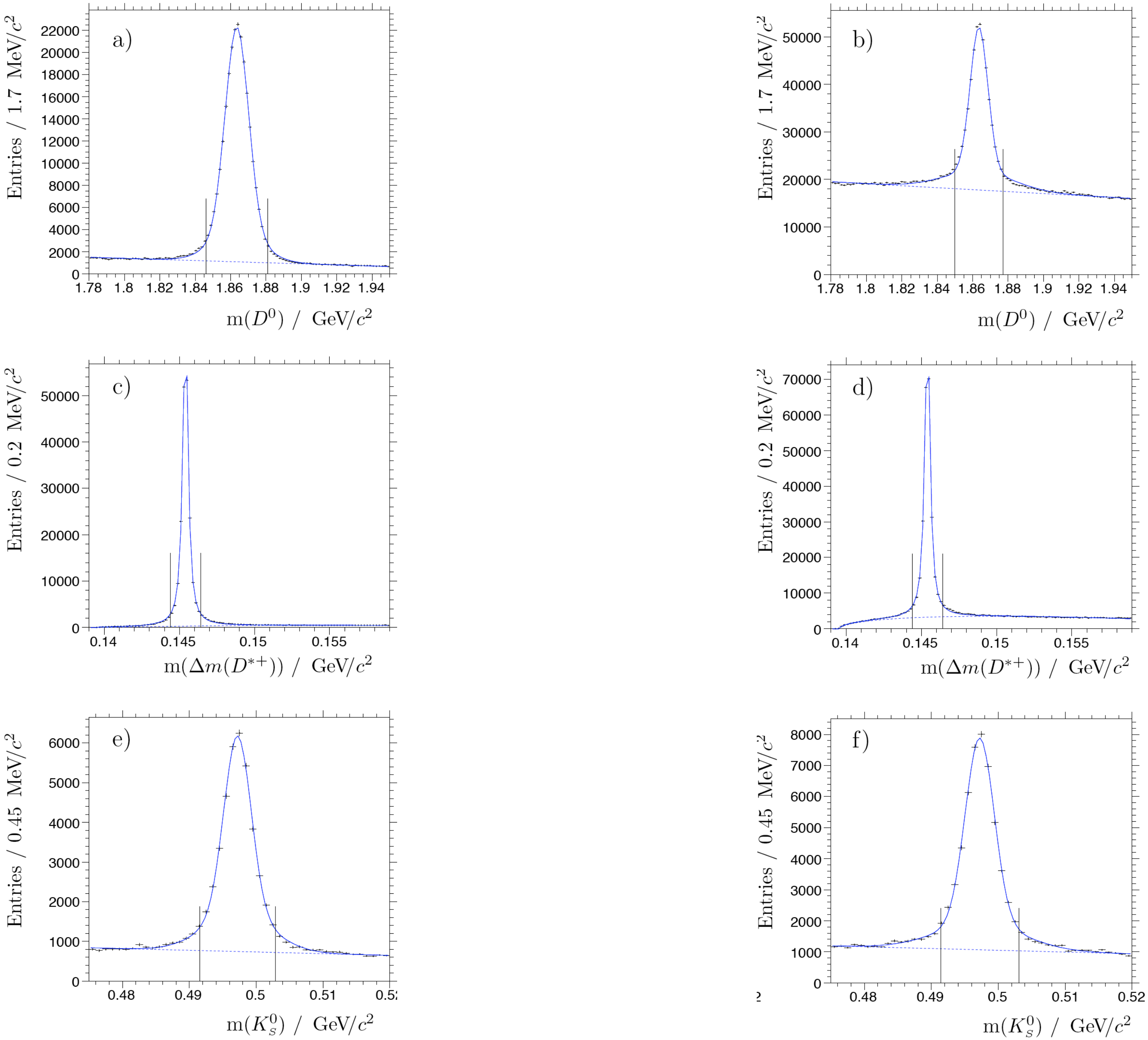
F. von Hippel, C. Quigg, Phys. Rev. D **5**, 624 (1972)

$$\Gamma_m = \Gamma_{m_0}^{tot} \left(\mathcal{B}_1 \left(\frac{p_m}{p_{m_0}}\right)^{2L+1} \left(\frac{m_0}{m}\right) F_L(p_m)^2 + \mathcal{B}_2 \left(\frac{p'_m}{p'_{m_0}}\right)^{2L+1} \left(\frac{m_0}{m}\right) F_L(p'_m)^2 \right)$$

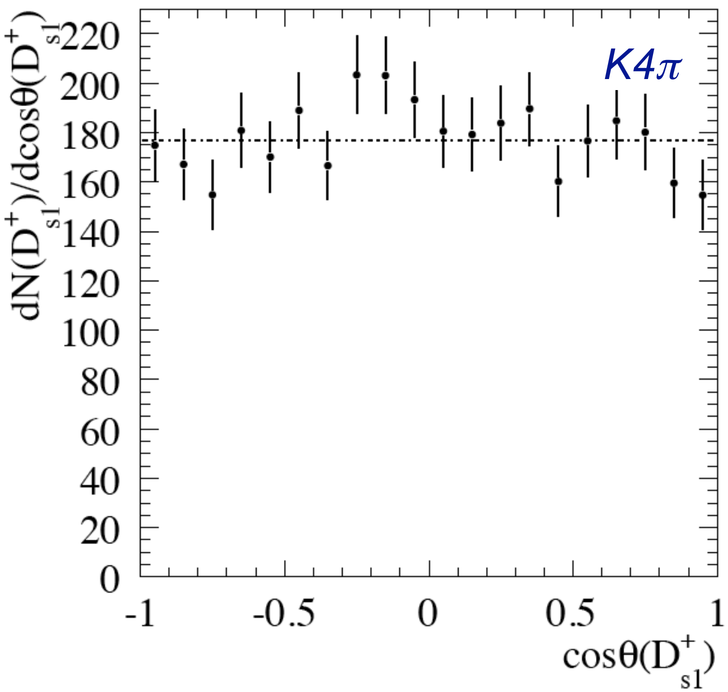
p_{m_0} denotes the momentum of a D_{s1}^+ daughter in the CM system defined by the mean of the Breit-Wigner m_0 obtained from a fit. The variable p_m is the momentum of the same daughter in the CM system of the D_{s1}^+ resonance candidate with mass m.

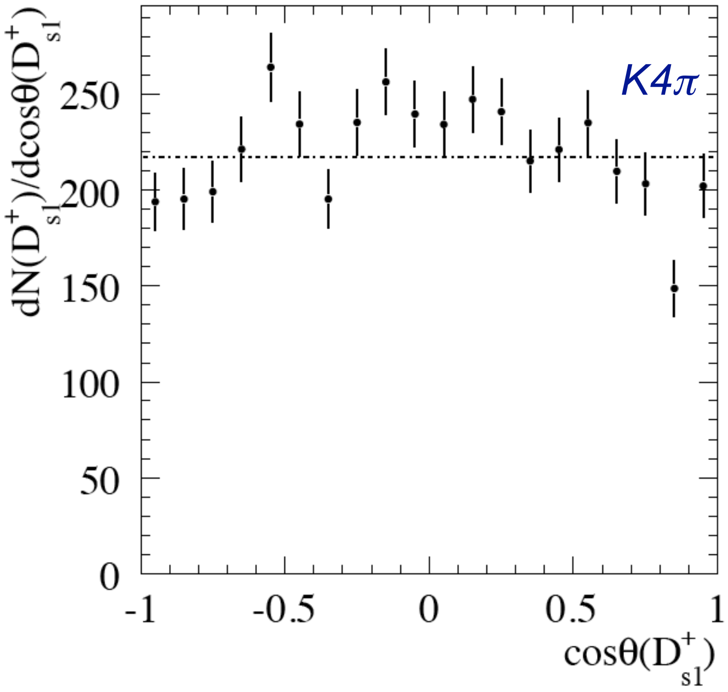
p'_m, p'_{m_0} correspond to p_m, p_{m_0}, respectively, but are calculated for the $D^{*0}K^+$ decay mode.

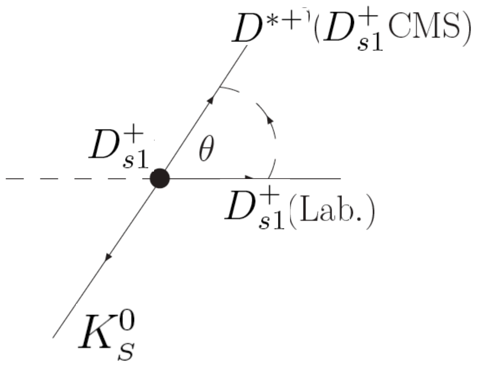
Comparison of D_{s1} Modes: ($K4\pi$, $K6\pi$)



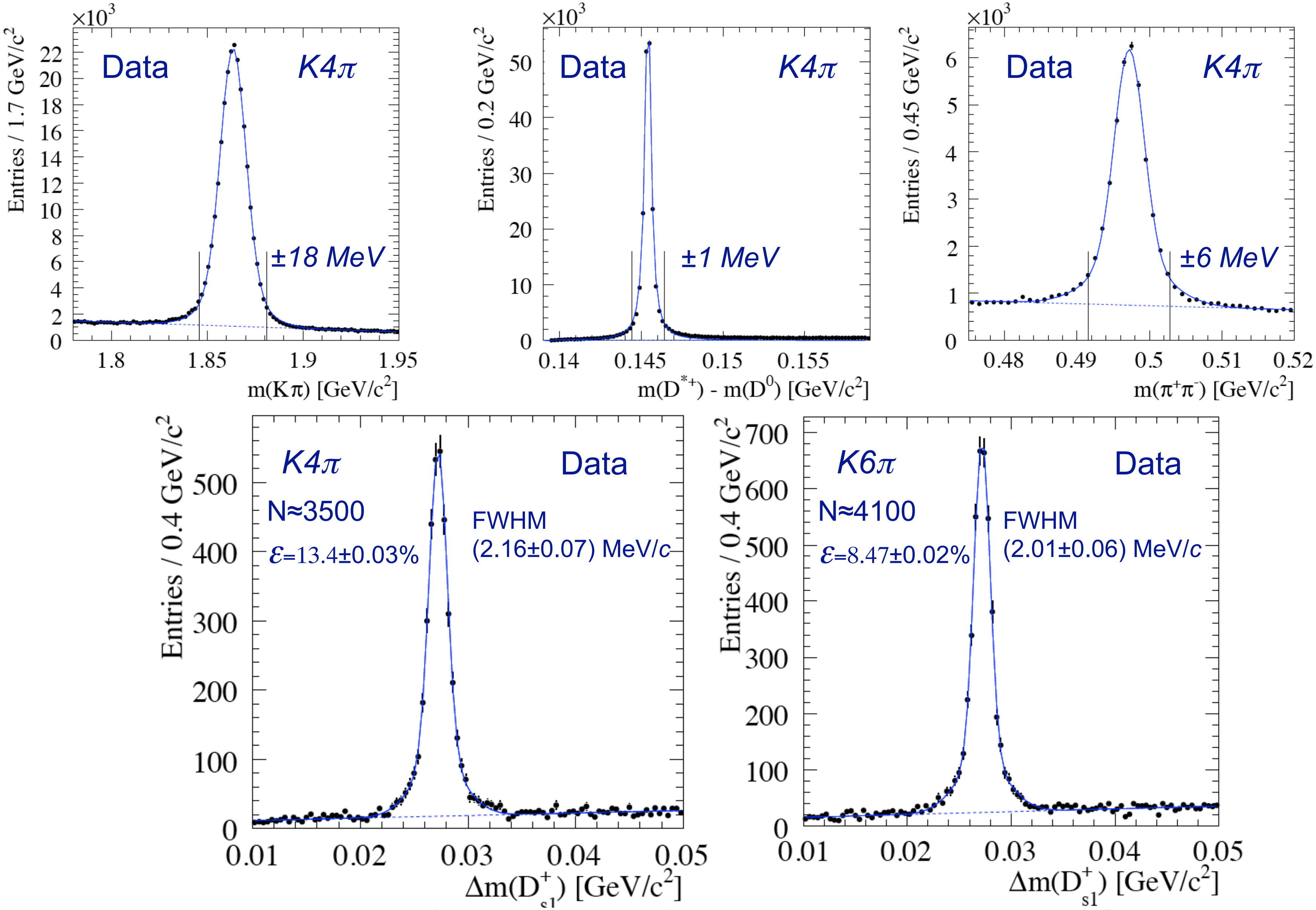
Helicity of D_{s1} Decay





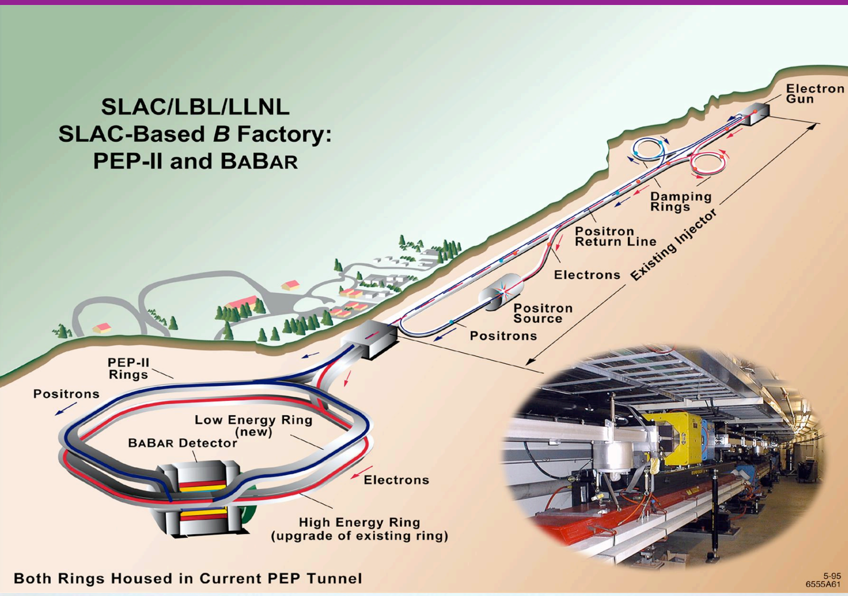


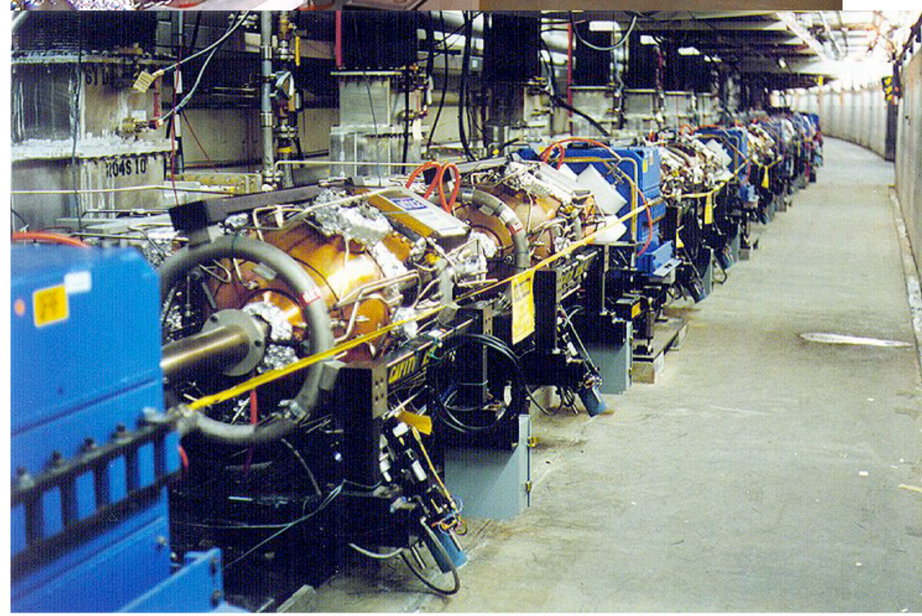
$D_{s1}(2536)$ Signal



$$\Delta m(D_{s1}^{+}) = m(D_{s1}^{+}) - m(D^{*+}) - m(K_S^0)$$

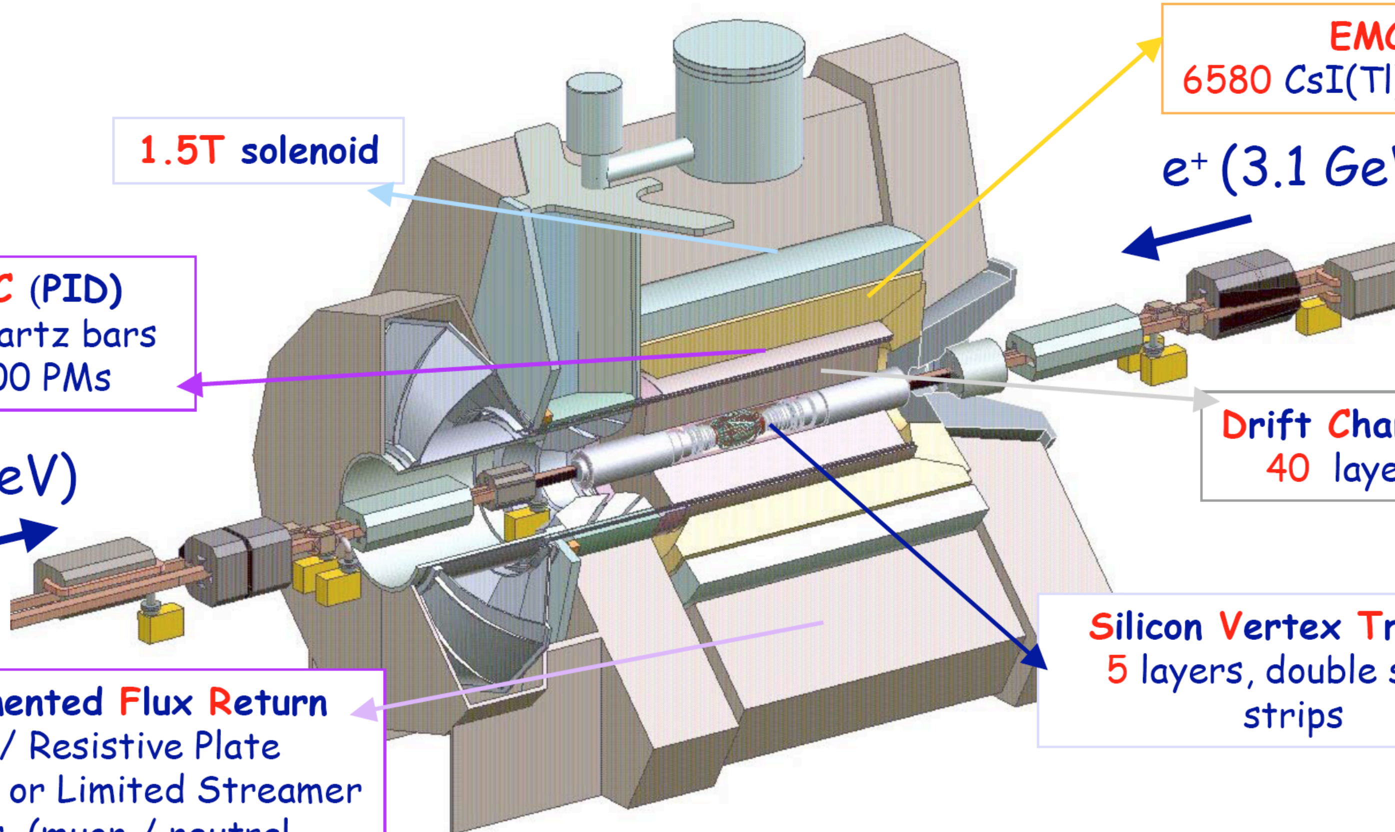
The PEP-II e^+e^- Storage Rings





BR_049 HER Cavities Region 12 8-19-97

The *BaBar* Spectrometer



1.5T solenoid

EMC
6580 CsI(Tl) crystals

e^+ (3.1 GeV)

DIRC (PID)
144 quartz bars
11000 PMs

Drift Chamber
40 layers

e^- (9 GeV)

Silicon Vertex Tracker
5 layers, double sided strips

Instrumented Flux Return
Iron / Resistive Plate Chambers or Limited Streamer Tubes (muon / neutral hadrons)

Collaboration founded in 1993
Detector commissioned in 1999

Data and Preliminary Selection

- Entire PEP-II / BaBar data: 525 fb^{-1}
  - Most at $\Upsilon(4S)$ and 40 MeV/c^2 below $\Upsilon(4S)$
  - 16 fb^{-1} at $\Upsilon(2S)$, 31 fb^{-1}at $\Upsilon(3S)$, 4 fb^{-1} above $\Upsilon(4S)$
- Select events with $D_sD_s(n\gamma)$

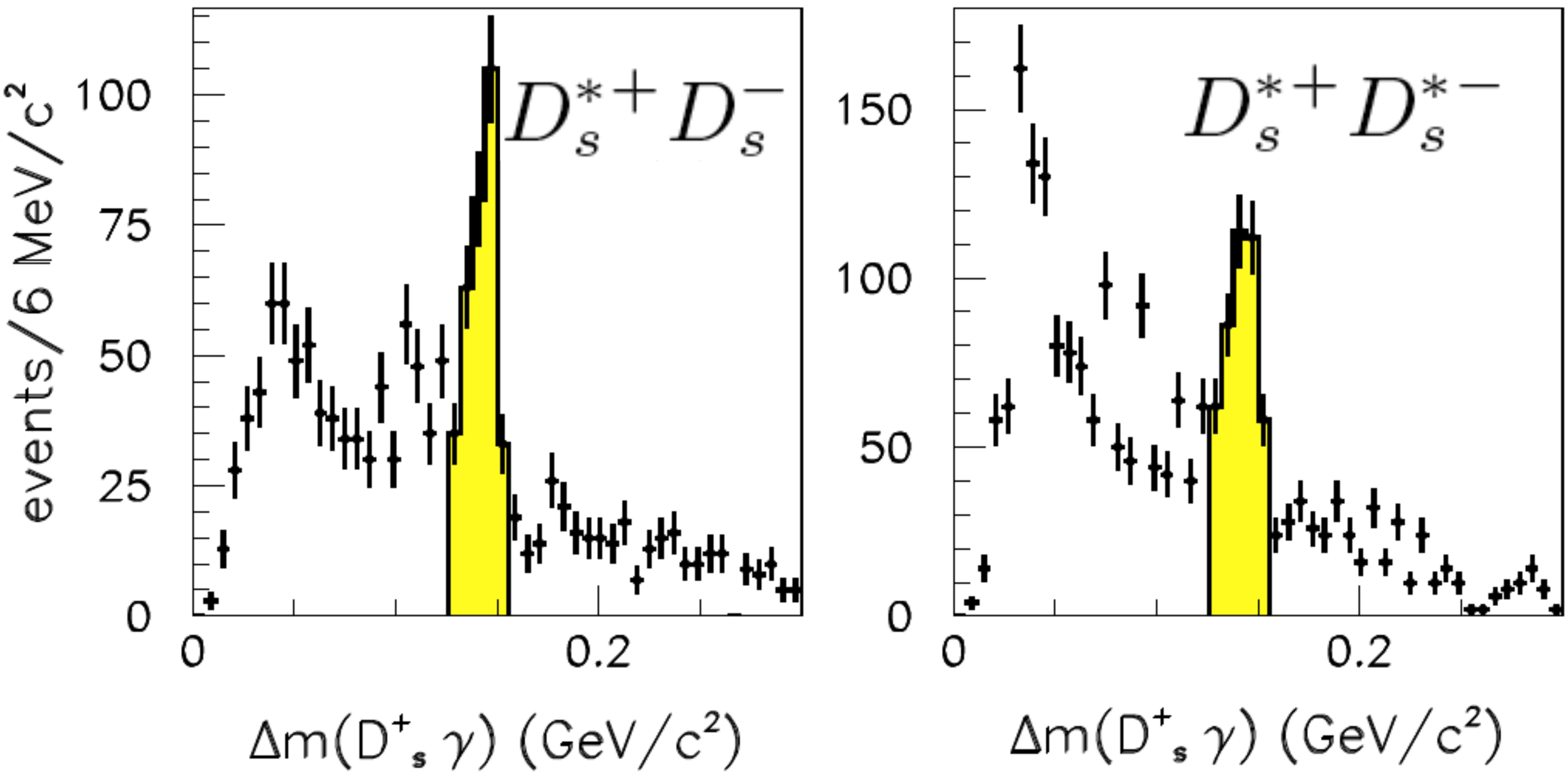
Channel	First D_s decay mode	Second D_s decay mode
(1)	$K^+\ K^-\ \pi^+$	$K^+\ K^-\ \pi^-$
(2)	$K^+\ K^-\ \pi^+$	$K^+\ K^-\ \pi^-\ \pi^0$
(3)	$K^+\ K^-\ \pi^+$	$K^0_S\ K^-$

  - Topological vertex constraint, K_s mass constraint
  - Fit probability > 0.1%
  - Candiate m within 2σ
- D_s^*selection: $E\gamma$ > 30 MeV, extra γ,π^0 tolerated
  - $\Delta m = m(K^+K^-\pi^+\gamma) - m(K^+K^-\pi^+)$ within 2σ

Further $D_s^{(*)}D_s^{(*)}$ Selection

- $m(D_s^{(*)}D_s^{(*)})<6.2$ GeV/c^2
- Likelihood ratio $$L = \sum_{i=1}^{N} log(PDF_s) - \sum_{i=1}^{N} log(PDF_b)$$
  - Resolve ambiguities, reject backgrounds
  - PDF_s : signal MC
  - PDF_b : data (all cuts but $m(D_s^{(*)}D_s^{(*)})<6.2$ GeV/c^2 relaxed)
  - Discriminating variables
    - # extra π^0s
    - Residual energy in calorimeter (γ_{ISR} removed)
    - Polar angle of ($D_s^{(*)}D_s^{(*)}$) system
    - p_{π^0} (CM) for ($KK\pi\pi^0$)
    - $E\gamma$ for candidate D_s^* photons
- $D_s^*D_s^{(*)}$ candidates removed from $D_sD_s^{(*)}$ sample

ISR Signal: D_s* Transitions



- Clear $D_s^*D_s^{(*)}$ signal in $|M^2_{rec}|<0.8$ GeV^2/c^4 sample