Measurements of Hadronic Cross Sections at CLEO

Sheldon Stone,

Syracuse University

Reasons for Measurements

- e^+e^- annihilations of hadrons allows us to explore the point couplings of a virtual γ with $J^{PC}=1^{--}$ final states
- Since $R(s)=\sigma_0\left(e^+e^- \rightarrow \text{hadrons}\right)/\sigma_0\left(e^+e^- \rightarrow \mu^+\mu^-\right)$ and

$$R(s) = R_0\left[1 + C_1\frac{\alpha_s(s)}{\pi} + C_2\left(\frac{\alpha_s(s)}{\pi}\right)^2 + C_3\left(\frac{\alpha_s(s)}{\pi}\right)^3 + O\left(\alpha_s^4(s)\right)\right]$$

with $C_1=1$, $C_2=1.525$ and $C_3=-11.686$

- We can measure α_s and Λ

Reasons for Measurements II

- We can measure exclusive σ's $e^+e^- \to D^{(*)}D^{(*)}$, also $e^+e^- \to D_S^{(*)}D_S^{(*)}$.
- Predictions from Eichten et al (PRD 21, 203, 1980) involve coupling of open $c\bar{q}$ $\bar{c}q$ channels to $c\bar{c}$ states, so called "coupled channel model." New predictions based on updated masses are now available with more modern theoretical inputs to come soon.
- Other predictions (Barnes [hep-ph/0412057]) & postdictions (Dubynskiy & Voloshin [hep-ex/0608179])

Measurement of R

- We measure $\sigma_{obs}(s)=\sigma_{sv}(s)+\sigma_{hard}(s)+\sigma_{res}(s)$
  - $\sigma_{sv}(s)$ is due to soft & virtual γ radiation, $\sigma_{sv}(s) \propto \sigma_0(s)$
  - $\sigma_{hard}(s)$ is due to hard photon radiation, $\propto \sigma_0(s)$
  - $\sigma_{res}(s)$ is due to $e^+e^- \to \gamma qq$, and the qq form a narrow resonance.
- We then extract $\sigma_0(s)$

Experimental Procedure

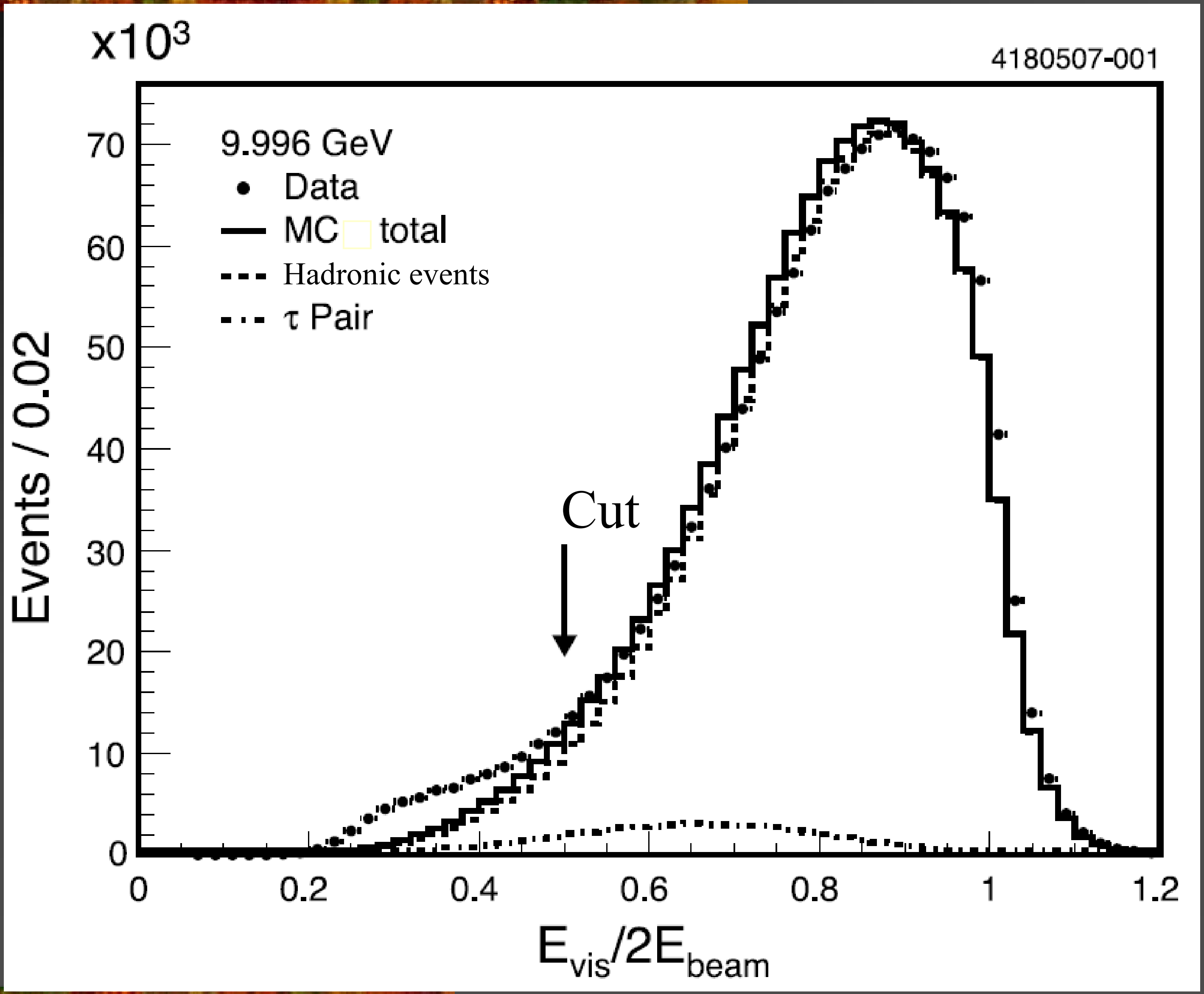
- Must evaluate energy dependent efficiencies
- Must remove $e^+e^- \to e^+e^-$ + hadrons (2γ) background
- Must reduce and correct for $\tau^+\tau^-$ production
- Must correct for tails of narrow resonances
- Must make radiative corrections
- Must evaluate systematic errors
- See D. Besson et al arXiv:0706.2813 [hep-ex] for details

Selection Requirements

- Many requirements for accepting individual tracks and EM showers
- Many requirements on events

Variable	Allowed range	
$\vert Z_{\mathrm{vertex}} \vert$	< 6.0 cm	Reduces beam gas
$E_{\mathrm{vis}}/2E_{\mathrm{beam}}$	> 0.5	} Reduces 2γ & beam gas background
$\vert P_{\mathrm{z}}^{\mathrm{miss}}/E_{\mathrm{vis}} \vert$	< 0.3	
H_2/H_0	< 0.9	Event shape cut for $\ell^+\ell^-$ pair bkgrnd
$E_{\mathrm{cal}}/2E_{\mathrm{beam}}$	$(0.15, 0.9)$	E_{cal} is most energetic shower, reduces Bhabha's and τ-pairs
$E_{\gamma}^{\mathrm{max}}/E_{\mathrm{beam}}$	< 0.8	Reduces E&M
$N_{\mathrm{ChargedTrack}}$	≥ 4	Reduces 2γ, beam gas & τ pair

Example



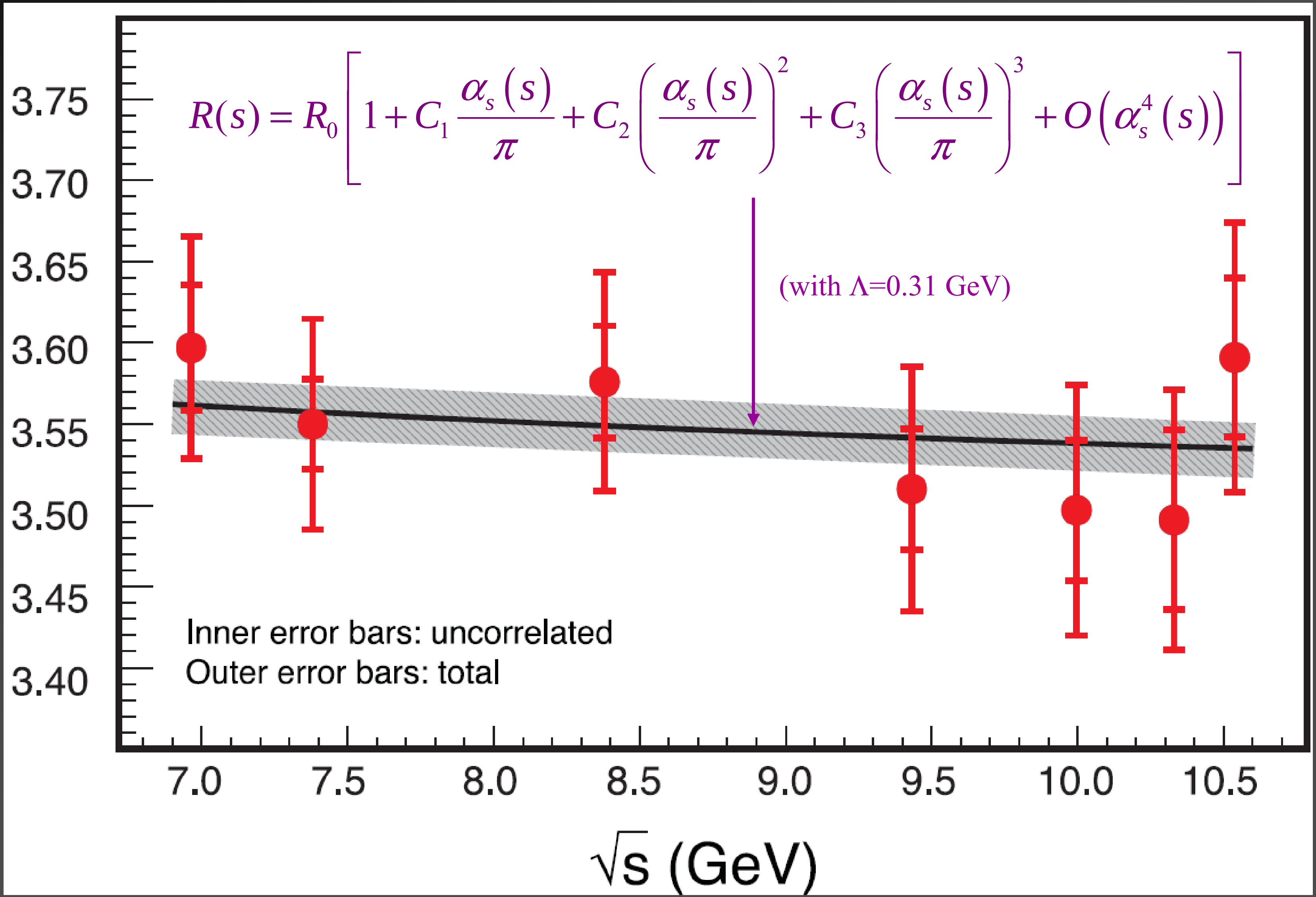
x10³
4180507-001
9.996 GeV
Data
MC total
Hadronic events
τ Pair
Cut
Events / 0.02
0
10
20
30
40
50
60
70
0
0.2
0.4
0.6
0.8
1
1.2
E_vis/2E_beam

Systematic Errors

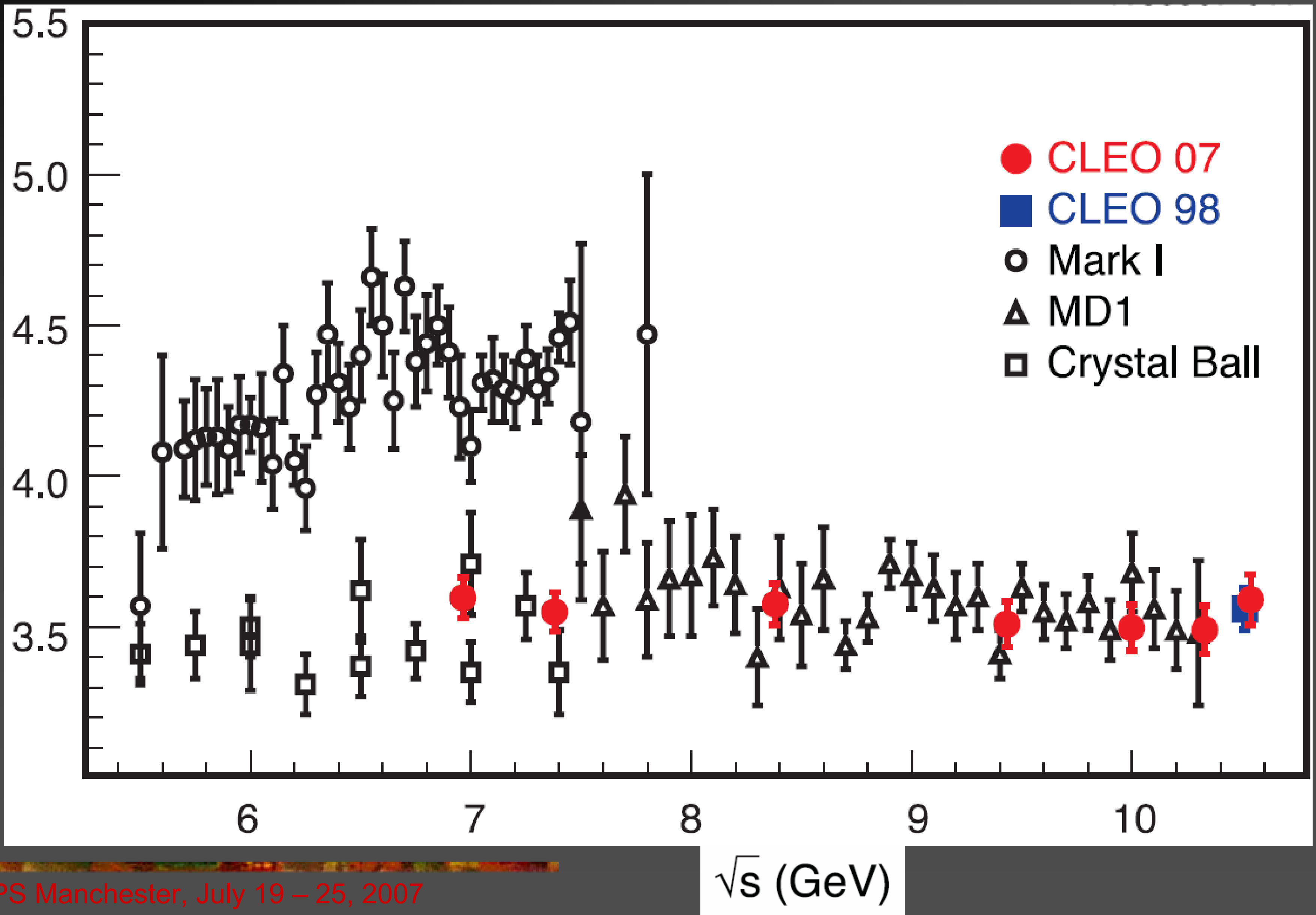
- Dominant source. Errors given in %

Energy (GeV)	10.538	10.330	9.996	9.432	8.380	7.380	6.964
Luminosity	1.00	1.10	1.10	1.10	0.90	0.90	1.00
Trigger	0.09	0.09	0.11	0.08	0.12	0.13	0.19
Radiative Correction	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Multiplicity Correction	1.06	1.38	0.99	0.84	0.43	0.38	0.38
Event selection	1.51	1.09	1.31	1.31	1.05	1.02	0.79
Total	2.32	2.30	2.21	2.15	1.76	1.74	1.68
Common	1.87	1.67	1.85	1.87	1.62	1.64	1.58
Uncorrelated	1.37	1.59	1.22	1.05	0.70	0.57	0.55

CLEO Results for R



Comparison with other R Measurements



Extraction of α_s

- α_s is determined at each energy point
- We then determine Λ using 4-quark flavors
- Using our average value for Λ, we find
- $$\alpha_s\left(M_Z^2\right) = 0.126 \pm 0.005^{+0.015}_{-0.011}, \quad \Lambda = 0.31^{+0.09\,+0.29}_{-0.08\,-0.21}\ \text{GeV}$$
- Compared with World Averages from Bethke

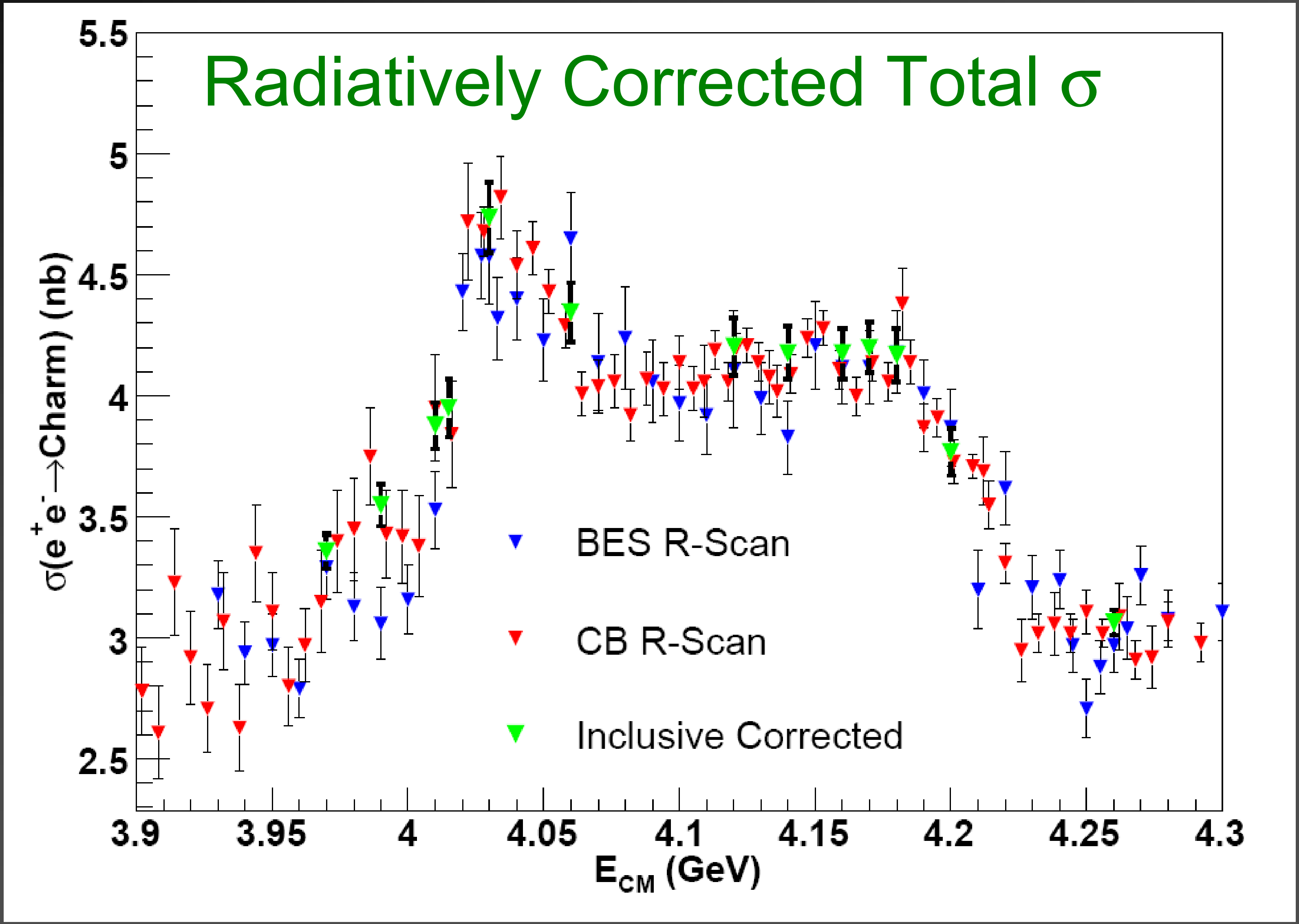
$$\alpha_s\left(M_Z^2\right) = 0.1189 \pm 0.0010, \quad \Lambda = 0.29 \pm 0.04\ \text{GeV}$$

Alternative Extraction

- Kühn et al (LTH 749) include quark mass effects and different matching between 4 & 5 flavor effective theories
- They find

$$\alpha_s\left(M_Z^2\right) = 0.110^{-0.010\,+0.010}_{-0.012\,-0.011}, \quad \Lambda = 0.13^{+0.11\,+0.11}_{-0.07\,-0.07}\ \text{GeV}$$

Charm Threshold: The Territory



Techniques For Measuring Exclusive Charm Production

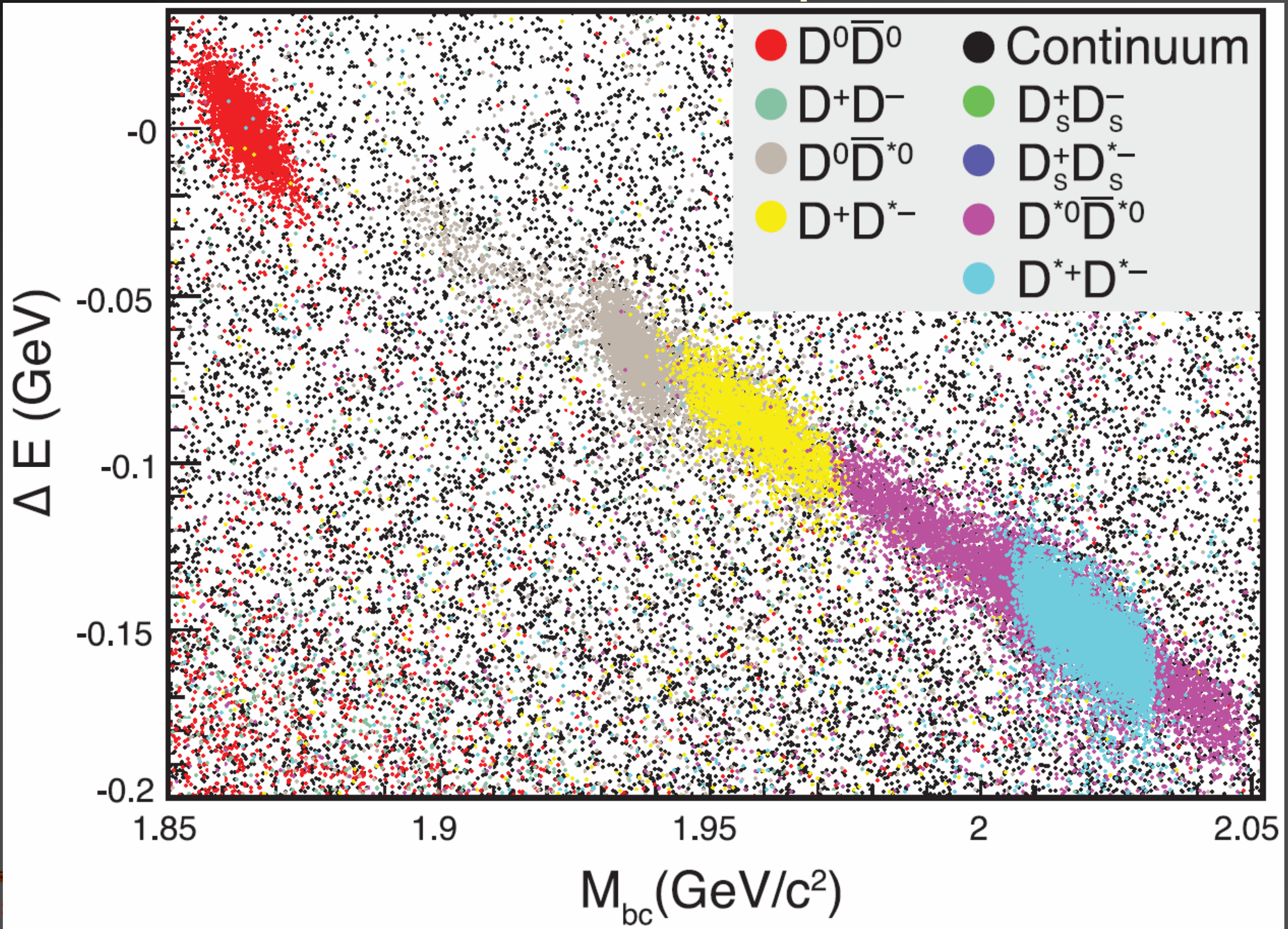
- Many different modes are produced DD, DD*, D*D*, D_sD_s, $D_sD_s^*$, ...
- Need to distinguish each variant & measure its cross-section
- Fully reconstruct charm decays, e.g. $D^o \to K^- \pi^+$
  - Use invariant mass of decay products
  - beam constrained mass

$$M_{bc} = \sqrt{E_{beam}^2 - \left(\sum_i \vec{p}_i \right)^2}$$

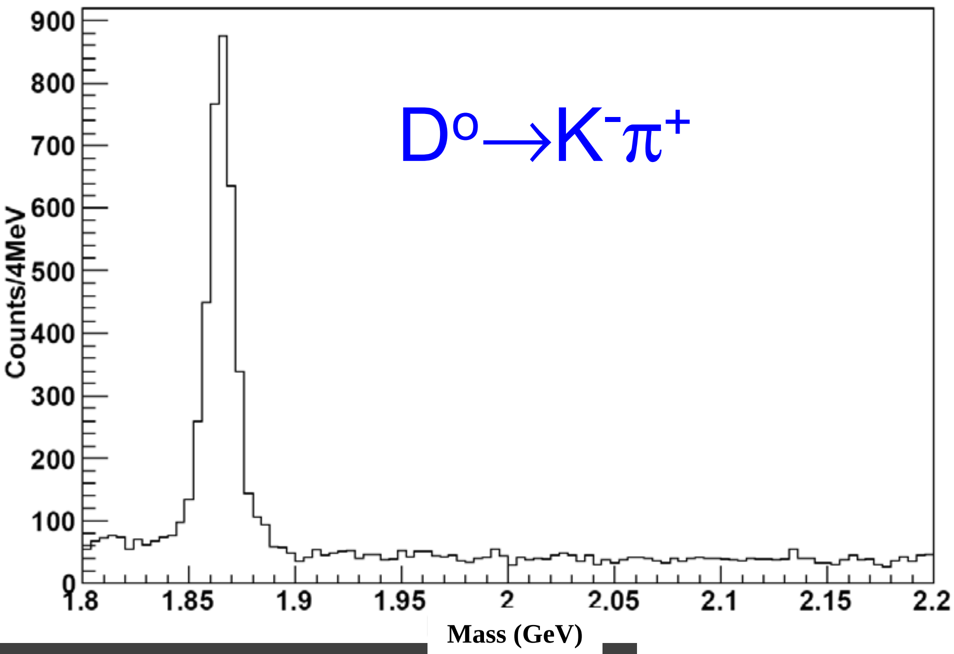
  - $\Delta E = E_{beam} - E_D$,

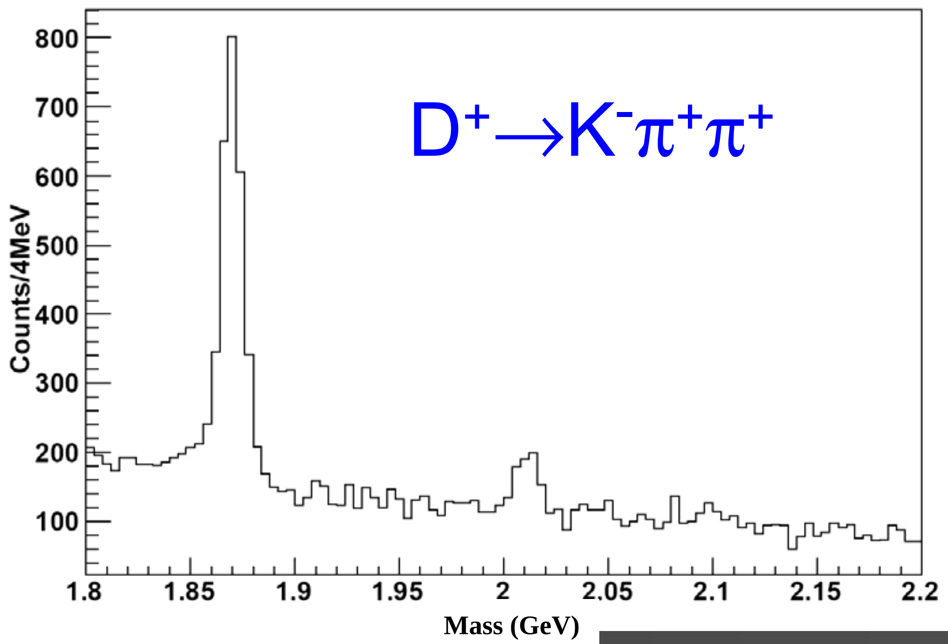
Simulation: ΔE vs M_{bc} at 4160 MeV

Reconstruct $D^o \to K^- \pi^+$, clean separations

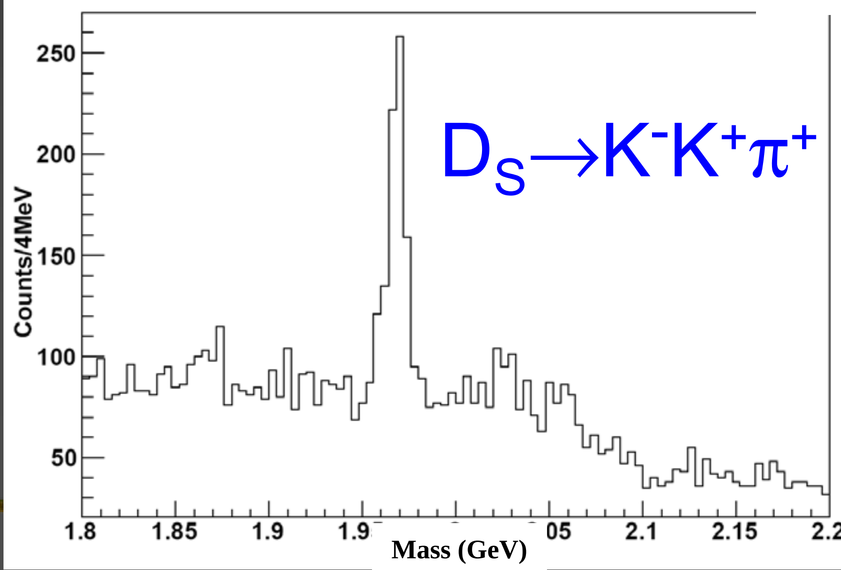


Also Measure Inclusive $D_{(S)}$ Yields



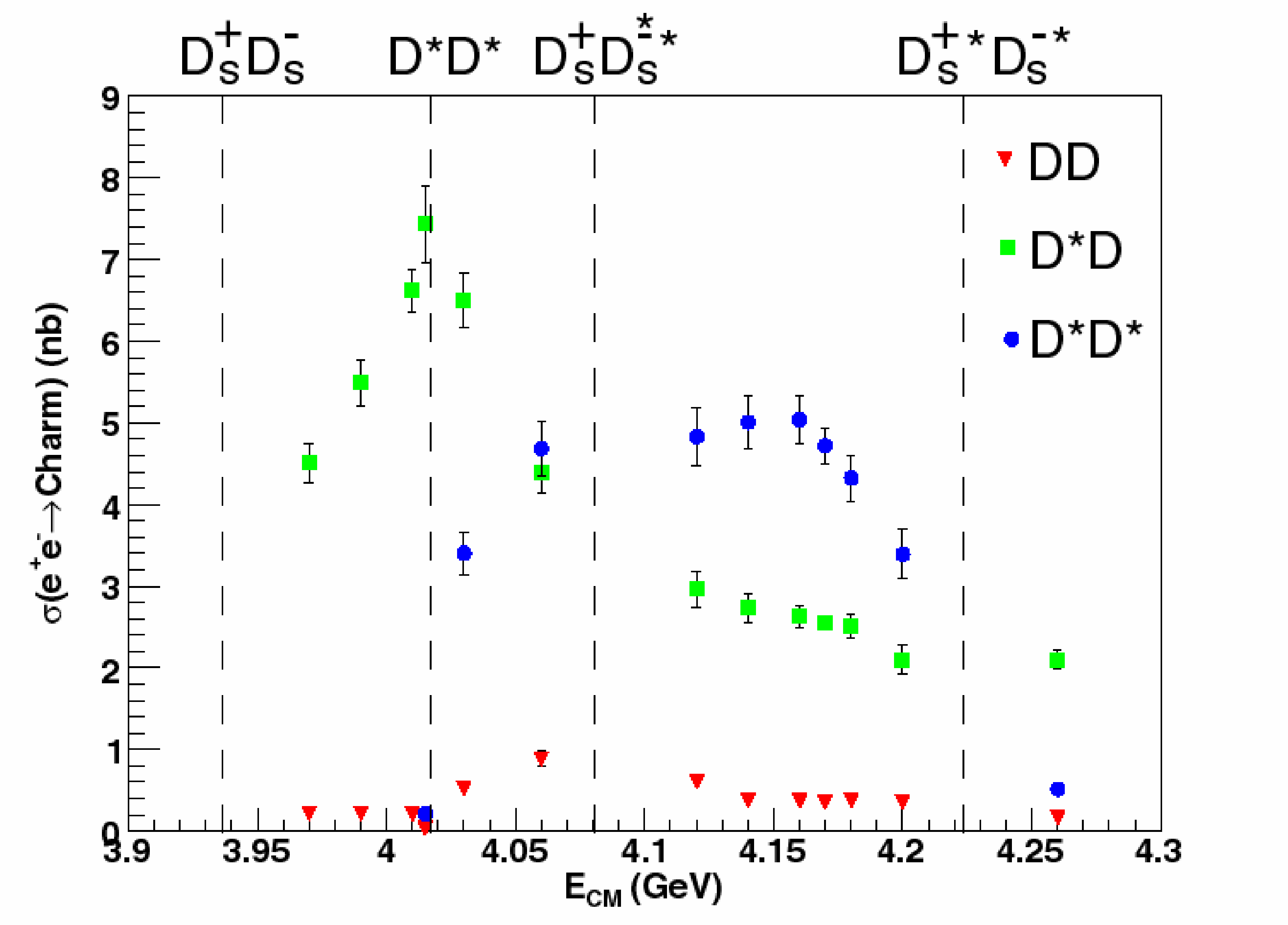


- Invariant mass plots at E_{cm}=4160 MeV

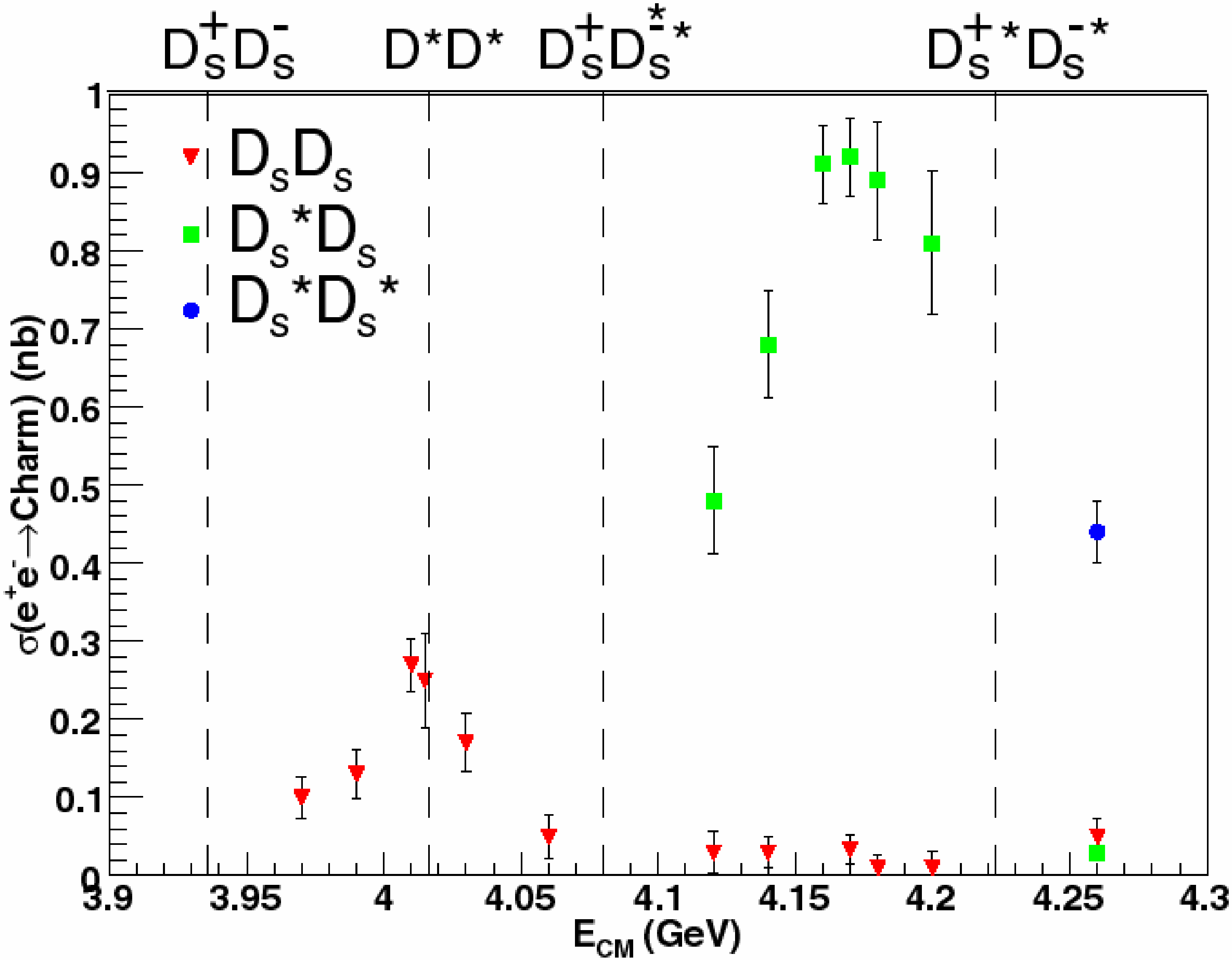


- Other modes too

Exclusive Two-Body Rates for D's



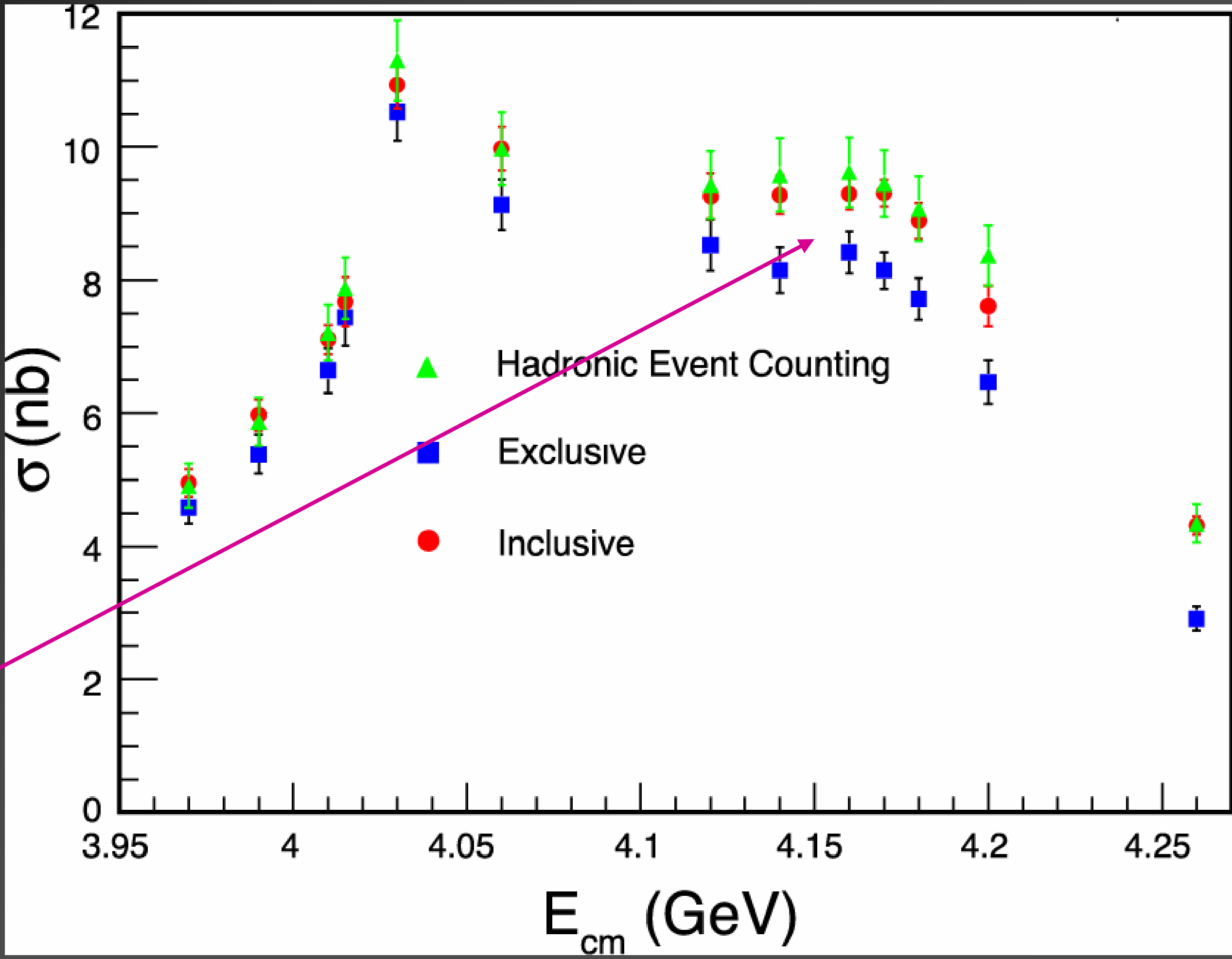
Exclusive Two-Body Rates for D_s



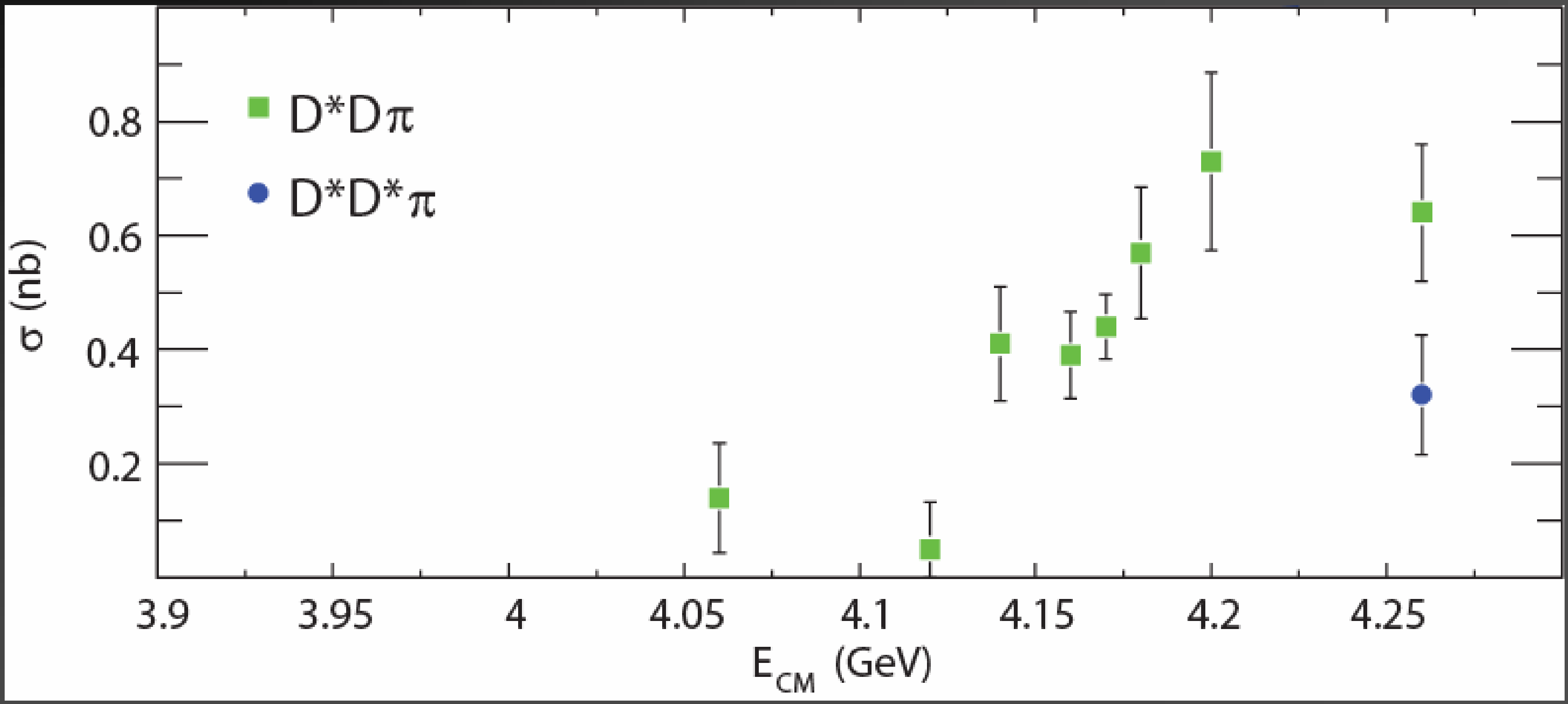
E

Compare 3 methods

- Hadronic event counting is R (not radiatively corrected)
- Discrepancy in exclusive rate and total

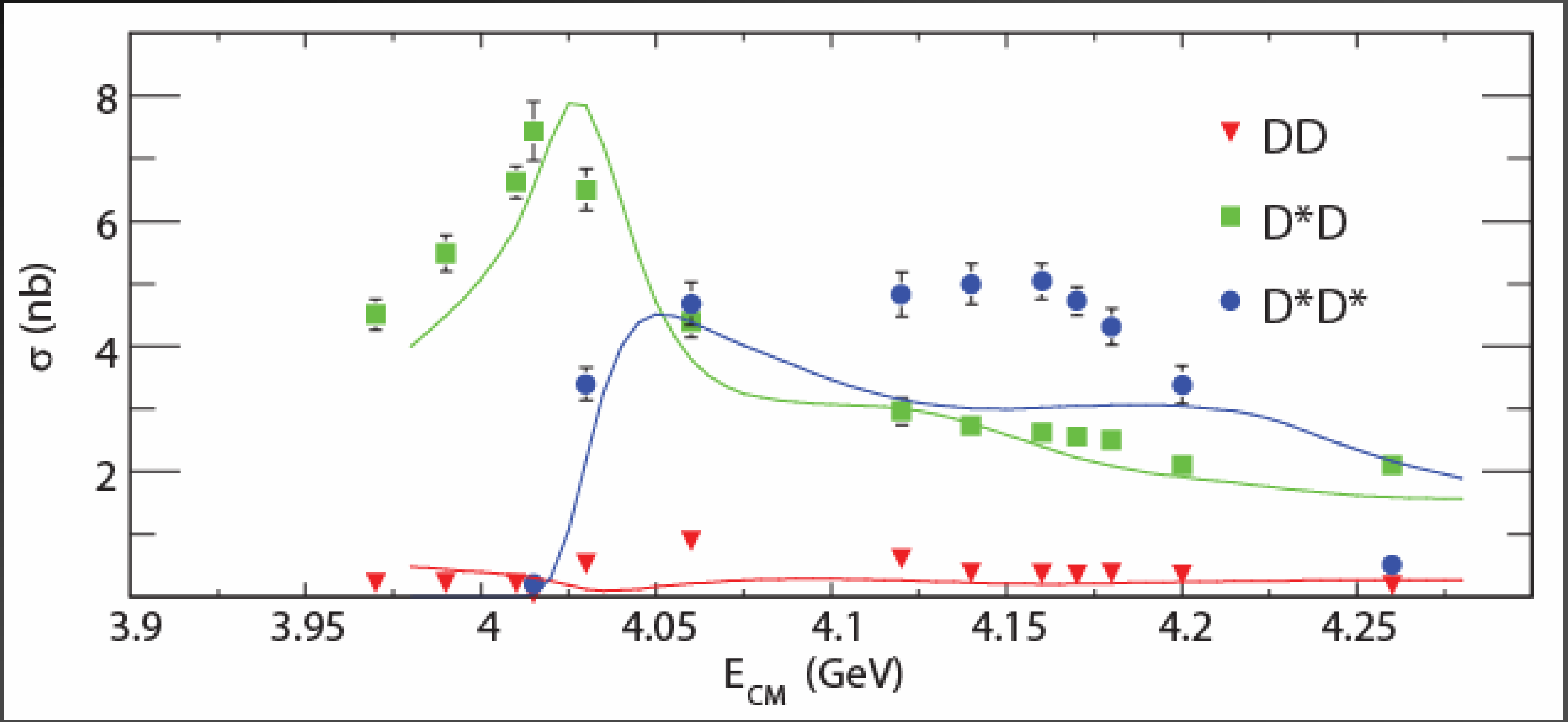


Discovery of D*Dπ Production



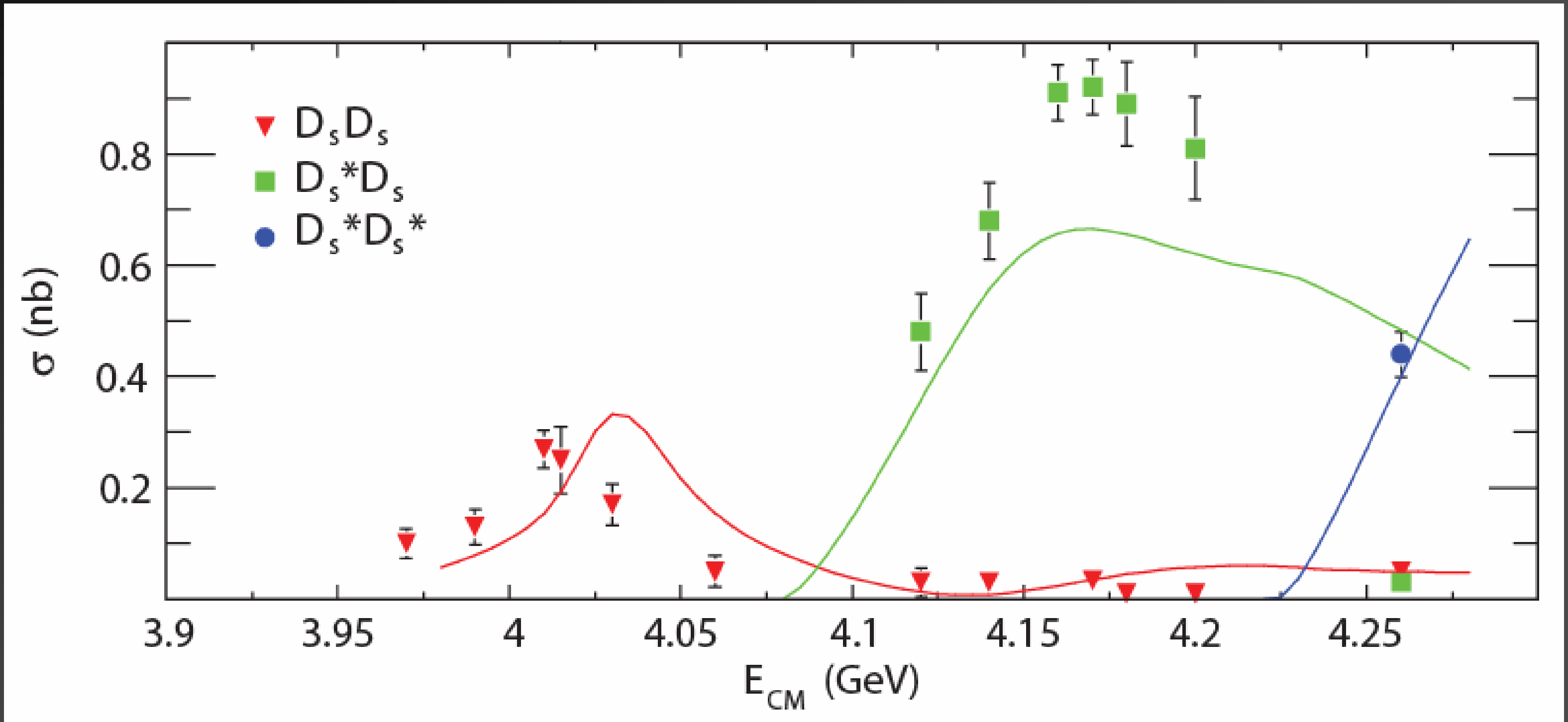
- No evidence for $D\bar{D}\pi$
- No theoretical predictions

Coupled Channel Model (D's)



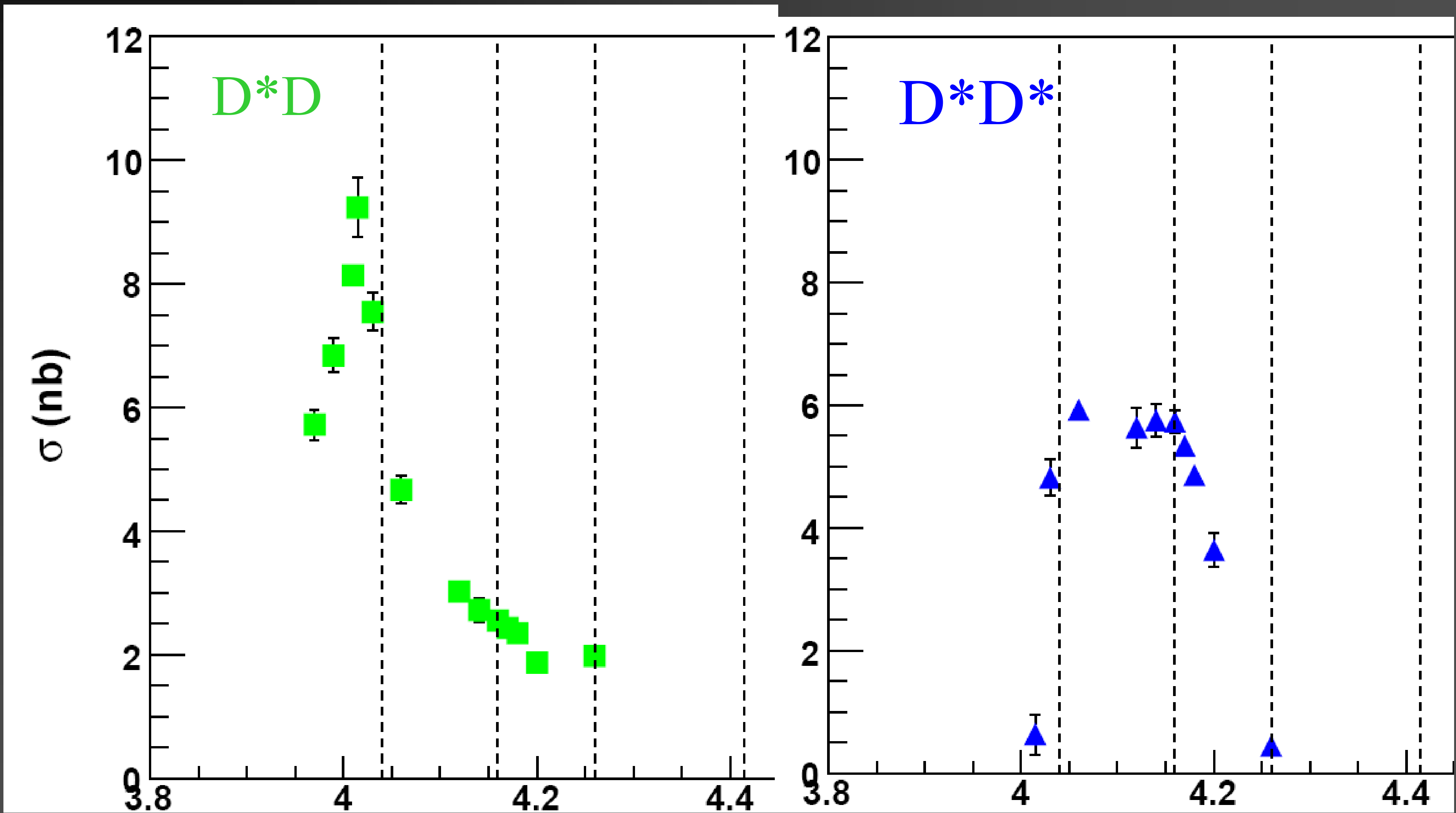
- New Eichten (intermediate) predictions "agree" with D*D but are much lower for D*D*

Coupled Channel Model (D_S)



- Doesn't agree at $D_S^+D_S^-$ threshold
- Lower than $D_S^*D_S$

D*D(*) Radiatively Corrected



See also Belle hep-ex/0608018

New Resonance at $D^*\bar{D}^*$ Threshold?

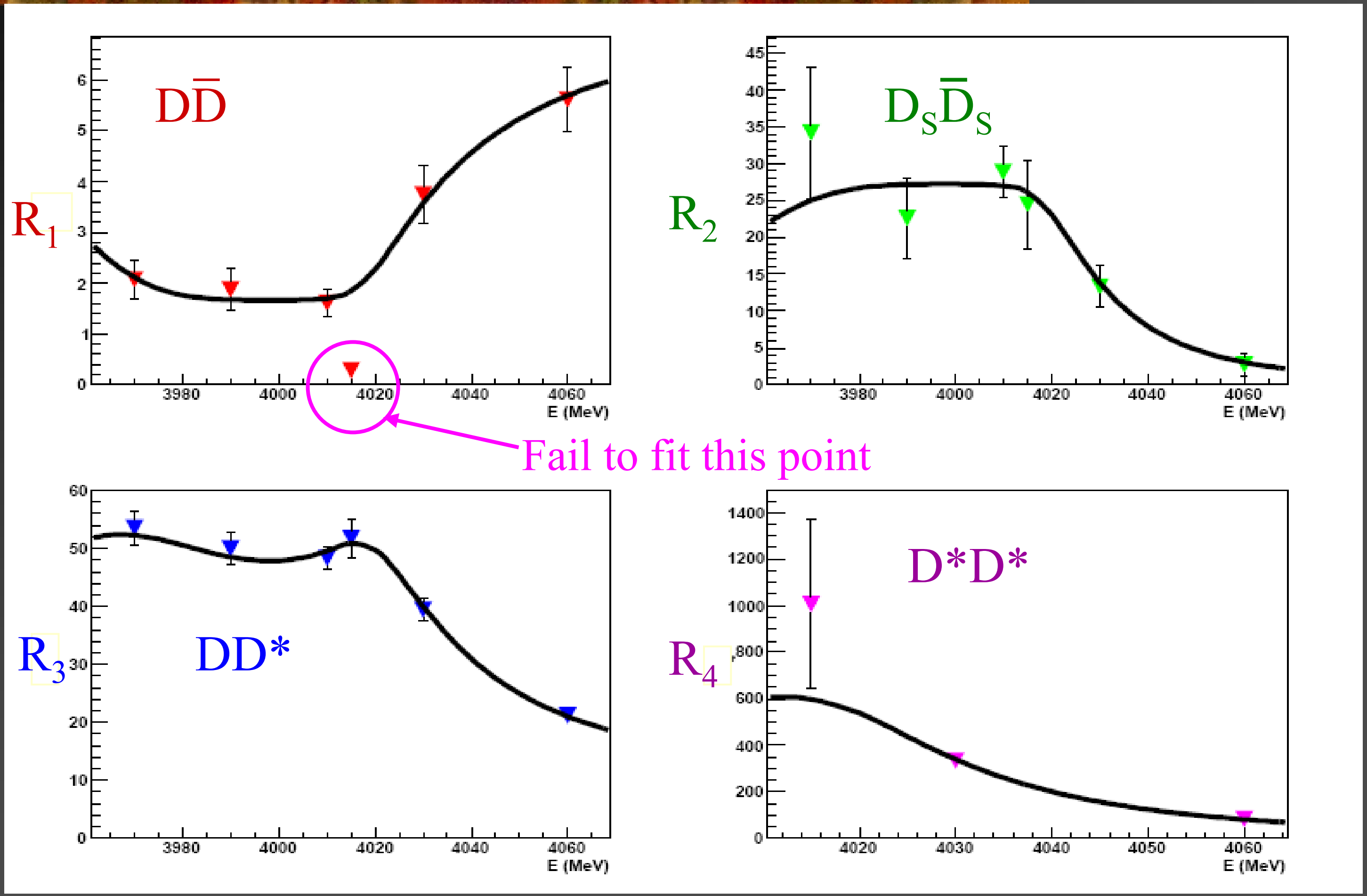
- Dubynskiy & Voloshin (DV) [hep-ph/0608179]
- They model behavior of individual σ's as
  - $\sigma(D\bar{D})=\sigma_0 2v^3 R_1$
  - $\sigma(D_S D_S)=\sigma_0 v^3 R_2$
  - $\sigma(D^*D)=\sigma_0 6(2p/\sqrt{s}) R_3$
  - $\sigma(D^*\bar{D}^*)=\sigma_0 14v^3 R_4$

$\sigma_0=\pi\alpha^2/3s$
v is velocity of D
#'s take care of spin counting

- The $R_k=|a_k+(b_k+ic_k/D(E))|^2$, where

$$D(E)=E-W_0+\frac{i}{4}\left[2\Gamma_0+\frac{(E-2M)^{3/2}}{w^{1/2}}\right]$$, where w is the coupling to the $D^*\bar{D}^*$ resonance

DV Fits To CLEO Data



- Resonance at 4013±4 MeV, Γ=66±8 MeV explains most data
- But need interfering narrow new resonance to explain dip in $D\bar{D}$ at 4015 MeV (See B. Lang thesis, Univ. of Minnesota)

Conclusions

- CLEO has measured R precisely between 6.96–10.54 GeV
- Determining $\alpha_s\left(M_Z^2\right) = 0.126 \pm 0.005^{+0.015}_{-0.011}, \quad \Lambda = 0.31^{+0.09}_{-0.08}{}^{+0.29}_{-0.21}\ \mathrm{GeV}$
- Exclusive charm production above threshold has been measured.
  - $\sigma(D_S D_S)$ peaks at 4010 MeV with a value of 0.27 nb
  - $\sigma(D_S^* D_S)$ peaks at 4170 MeV with a value of 0.92 nb, the energy CLEO has used for D_S decay studies
- Experimentally, new charmonium states are being detected at an alarming rate. Perhaps we are even now seeing the evidence of resonances in distribution dips (i.e. 4015 & 4260 MeV)
- These studies should lead to a better understanding of QCD

The End

Reasons for Measurements

- e^+e^- annihilations of hadrons allows

The problem we face is most aptly summarized by Fig. 5, which shows the observed resonances that we ascribe to $c\bar{c}$ states, and the spectra of the known quasi-two-body charmed meson states in the vicinity of the charm threshold. This is a classic problem of quantum mechanics: a discrete set of states in one portion of the Hilbert space suspended in a continuum of states belonging to another subspace

(3) The decay amplitudes for $c\bar{c} \to \bar{c}q + q\bar{c}$ are oscillatory functions of momentum, with a node structure that is determined by the radial nodes in the $c\bar{c}$ wave function. This provides a qualitative understanding of the peculiar branching ratios into various charmed-meson channels observed at 4.03 GeV. The prediction of a zero in $\sigma(e^+e^- \to D\bar{D})$ near 4.0 GeV should be tested experimentally because it would, for the first time, confirm in detail the structure of a quark-antiquark radial wave function.

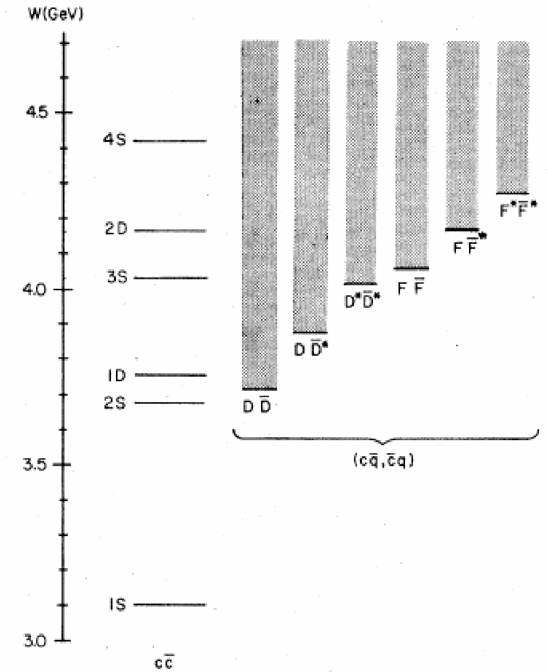


FIG. 5. The spectra of the $c\bar{c}$ system, and of the lowest-lying charmed-meson decay channels.

D_s Branching Fractions (%)

Modes	Branching Fraction
D^0 decay mode	
$K^-\pi^+$	$3.91 \pm 0.12\%$
$K^-\pi^+\pi^0$	$14.94 \pm 0.56\%$
$K^-\pi^+\pi^+\pi^-$	$8.29 \pm 0.36\%$
D^+ decay mode	
$K^-\pi^+\pi^+$	$9.52 \pm 0.37\%$
$K^-\pi^+\pi^+\pi^0$	$6.04 \pm 0.28\%$
$K_s\pi^+$	$1.55 \pm 0.08\%$
$K_s\pi^+\pi^0$	$7.17 \pm 0.43\%$
$K_s\pi^+\pi^-\pi^+$	$3.2 \pm 0.19\%$
$K^+K^-\pi^+$	$0.97 \pm 0.06\%$

Modes	Branching Fraction
$\phi\pi^+$, 10 MeV cut on the Invariant $\phi \to K^+K^-$ Mass [16]	1.98 ± 0.15
$K^{*0}K^+, K^{*0} \to K^-\pi^-$ [1]	2.2 ± 0.6
$\eta\pi^+, \eta \to \gamma\gamma$ [1, 16]	0.58 ± 0.07
$\eta\rho^+, \eta \to \gamma\gamma, \rho^+ \to \pi^+\pi^0$ [1]	4.3 ± 1.2
$\eta^{'}\pi^+, \eta^{'} \to \pi^+\pi^-\eta, \eta \to \gamma\gamma$ [1, 16]	0.7 ± 0.01
$\eta^{'}\rho^+, \eta^{'} \to \pi^+\pi^-\eta, \eta \to \gamma\gamma, \rho^+ \to \pi^+\pi^0$ [1]	1.8 ± 0.5
$\phi\rho^+, \phi \to K^+K^-, \rho^+ \to \pi^+\pi^0$ [1]	3.4 ± 1.2
$K_sK^+, K_s \to \pi^+\pi^-$ [1, 16]	1.0 ± 0.07