R Measurements at CLEO

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on behalf of the CLEO Collaboration

Why Measure R?

- $e^+e^- \rightarrow$hadrons allows us to explore the point couplings of a virtual γ with $J^{PC}=1^{--}$ final states
  - Similarities of l^+l^- & $q\bar{q}$ production mechanism
- $$R(s) = \sigma_0(e^+e^- \rightarrow \text{hadrons})/\sigma_0(e^+e^- \rightarrow \mu^+\mu^-)$$
  - Initially used to measure quark charges & # flavors
  - Later seen to signal the presence of the strong interaction

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

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

We can measure α_s and Λ

- BUT: R$\not\Rightarrow$ most precise values of α_s and Λ, but it is nevertheless still considered a pillar of e^+e^- physics.
- Will present CLEO III R results for E_{cm} = 7-10 GeV

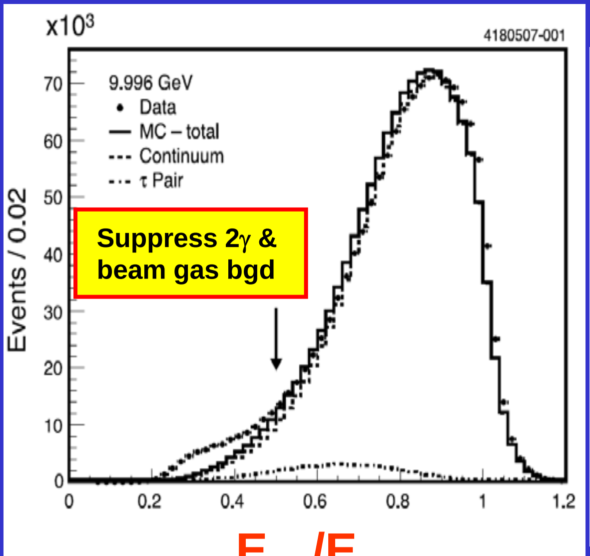
Why R: II

- But R is also necessary for hadronic vacuum polarization, dispersion integrals (e.g. for g-2), & ISR modeling
  - – Needed at all energies, including where there is structure
- Will present R for E_{cm} = 3.97 – 4.26 MeV
- Will also provide exclusive & inclusive open charm decomposition (2-body & multi-body)
  - – Compare to predictions from **Eichten et al. [PRD 21, 203, 1980]** involve coupling of open $cq\ \bar{c}\bar{q}$ 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.
  - – Compare to postdictions of **Dubynskiy & Voloshin [Mod. Phys. Lett. A21, 2779 (2006)]**

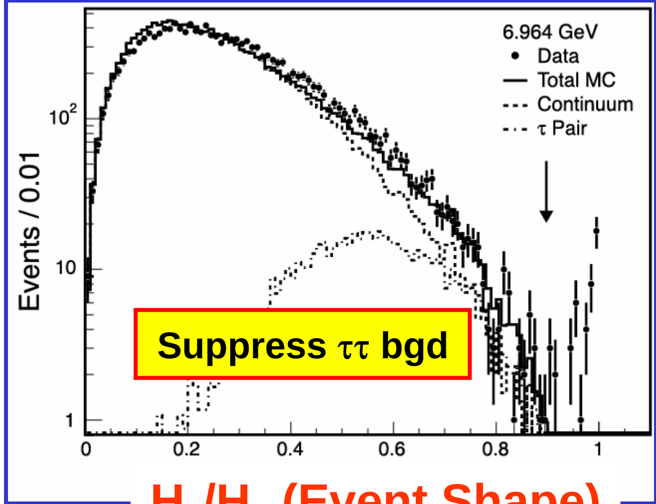
R for E_{cm}=7-10 GeV

- Use CLEO III "continuum" points just below $\Upsilon(4S)$, $\Upsilon(3S)$, $\Upsilon(2S)$, $\Upsilon(1S)$ as well as 3 lower energies
- Evaluate energy-dependent efficiencies
- Remove $e^+e^- \to e^+e^-$ + hadrons ("2γ") bgd
- Reduce & correct for $\tau^+\tau^-$ production
- Correct for tails of narrow resonances
- Make radiative corrections
- Evaluate systematic errors
- Paper accepted by PRD: **D. Besson *et al.* arXiv:0706.2813 [hep-ex]**

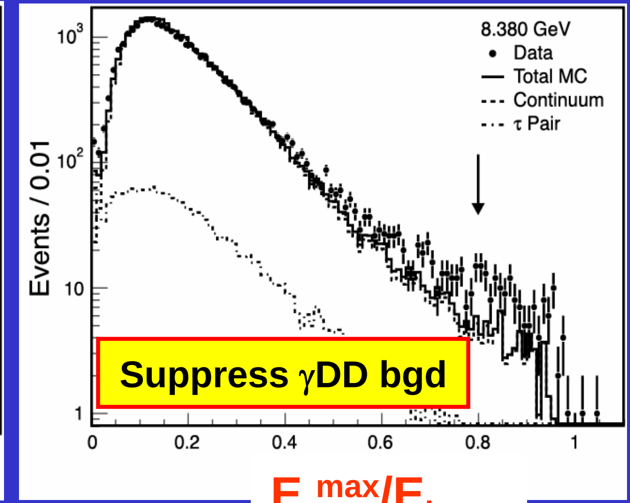
Selection Variables



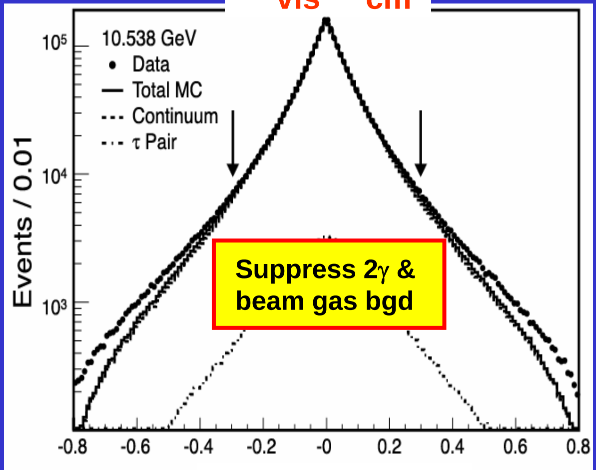
E_{vis}/E_{cm}



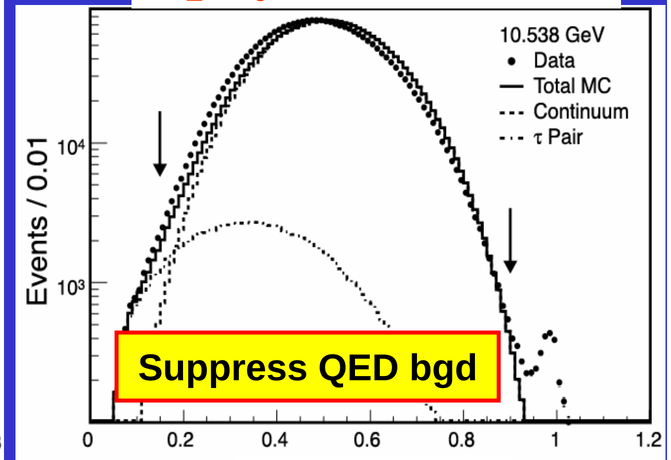
H_2/H_0 (Event Shape)



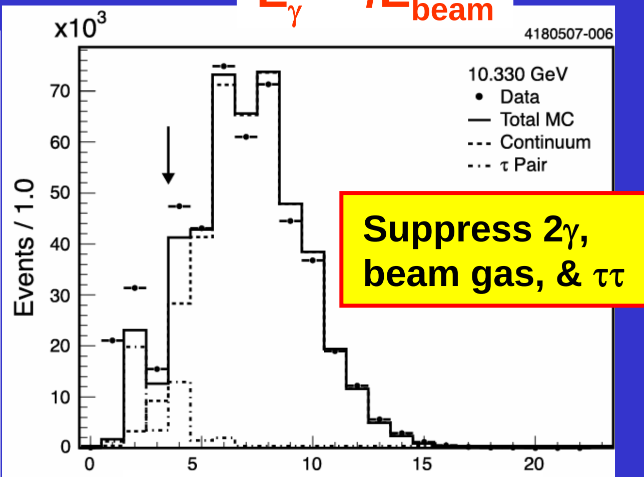
E_γ^{max}/E_{beam}



P_Z^{miss} / E_{vis}



$E_{calorim}/E_{cm}$



charged tracks

Suppress backgrounds by cutting loosely around the edges

Systematic Errors

Errors given in %

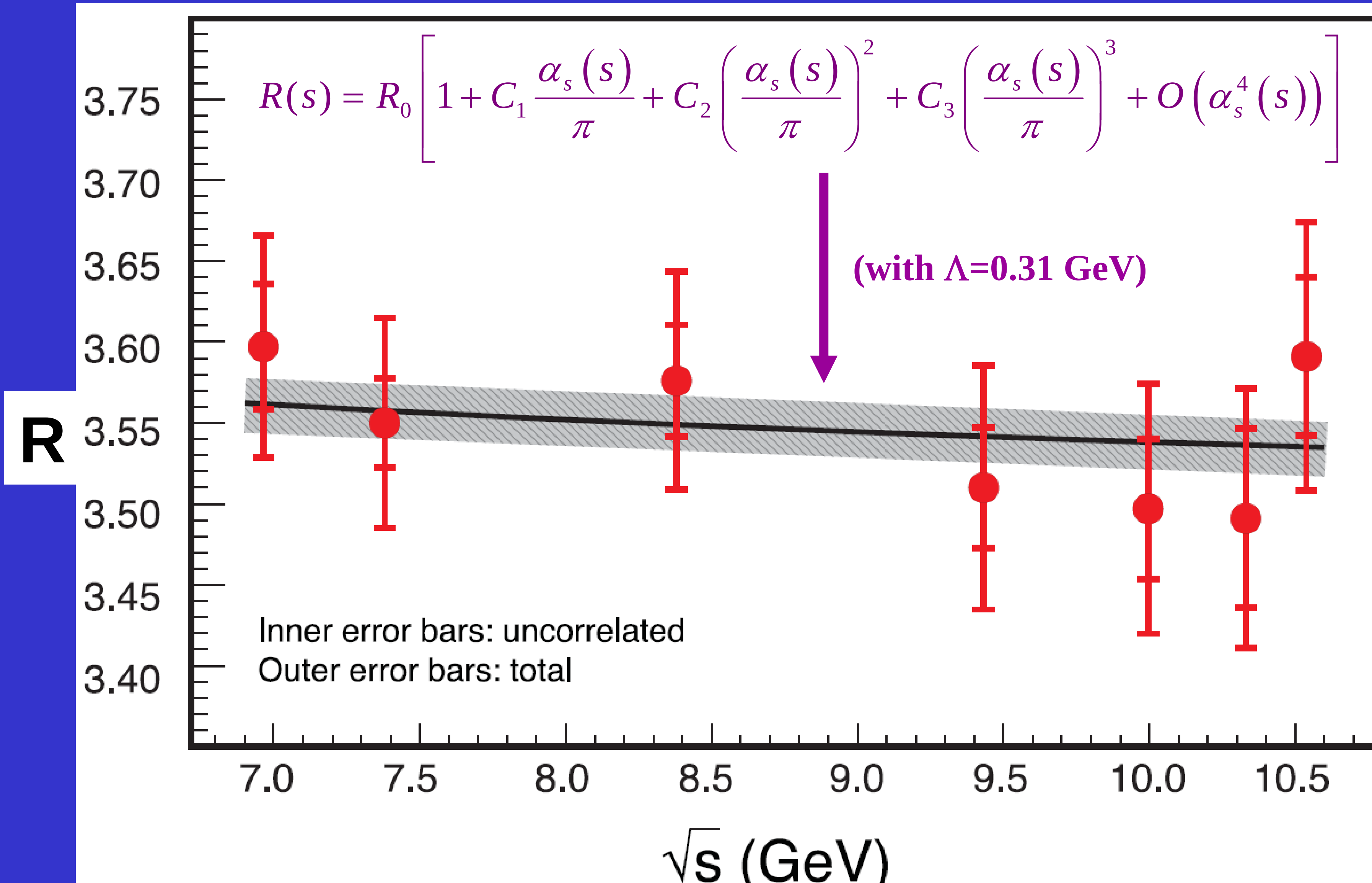
Energy (GeV)	10.538	10.330	9.996	9.432	8.380	7.380	6.964
Luminosity	1.00	1.10	1.10	1.10	0.90	0.90	1.00
Trigger	0.09	0.09	0.11	0.08	0.12	0.13	0.19
Radiative Correction	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Multiplicity Correction	1.06	1.38	0.99	0.84	0.43	0.38	0.38
Event selection **(Incl. bgd)**	1.51	1.09	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

Sources of error spread around

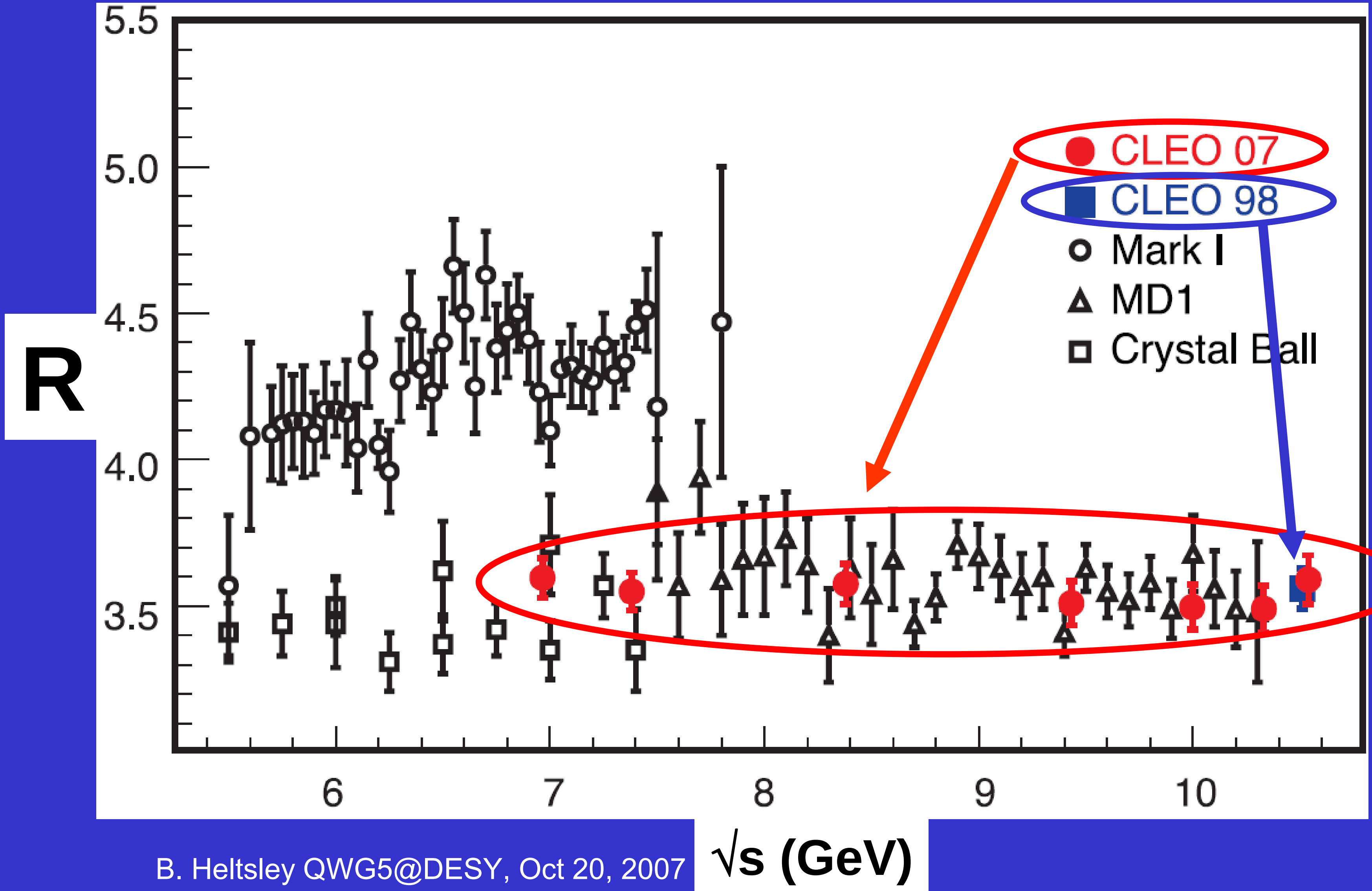
~2%

Mostly common

CLEO R Results



Comparison with other R Measurements



Extraction of α_s

- α_s is determined at each energy point
- Naïvely determine Λ using 4-quark flavors
- Using our average value for Λ, we find

$$\alpha_s\left(M_Z^2\right) = 0.126 \pm 0.005^{+0.015}_{-0.011}, \quad \Lambda = 0.31^{+0.09}_{-0.08}{}^{+0.29}_{-0.21}\ \text{GeV}$$

~10%

- Compared with World Averages from
  Bethke [Prog.Part.Nucl.Phys. 58 (2007) 351]

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

~1%

Alternative α_s Extraction

- **Kühn, Steinhauser, & Teubner** (arXiv:0707.2589 [hep-ph]) (see talk 1 hour ago) include quark mass effects & different matching between 4 & 5 flavor effective theories
- They find

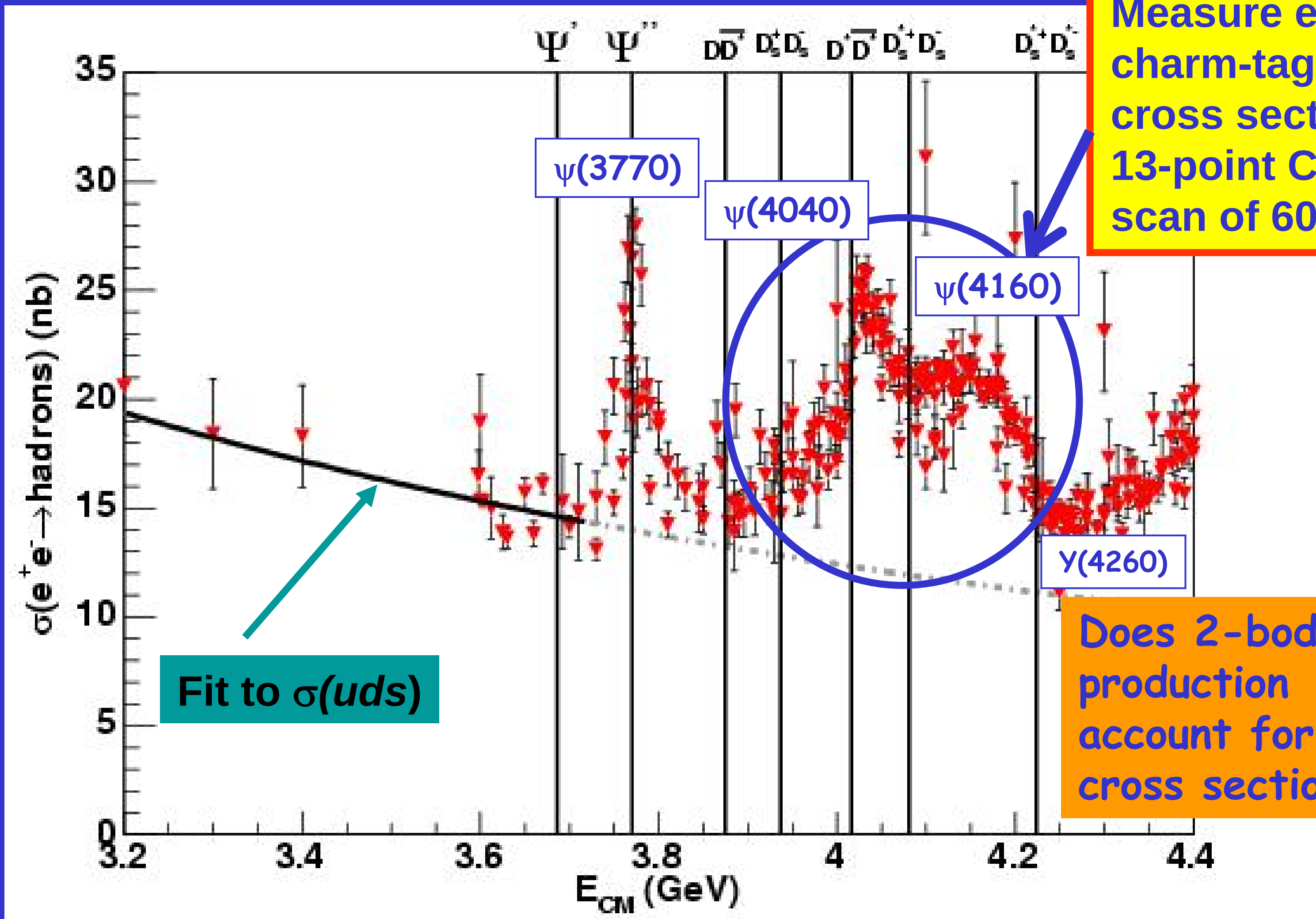
$$\alpha_s\left(M_Z^2\right)=0.110^{-0.010\,+0.010}_{-0.012\,-0.011}, \quad \Lambda=0.13^{+0.11\,+0.11}_{-0.07\,-0.07}\ \text{GeV}$$

compared to the naïve 4-quark method:

$$\alpha_s\left(M_Z^2\right)=0.126\pm0.005^{+0.015}_{-0.011}, \quad \Lambda=0.31^{+0.09\,+0.29}_{-0.08\,-0.21}\ \text{GeV}$$

which is larger by 0.016, or ~1σ_{msmt}

Open Charm Threshold Region



Measure exclusive & charm-tagged-inclusive cross sections using a 13-point CLEO-c energy scan of 60 pb^{-1}

Does 2-body open charm production account for all of non-*uds* cross section?

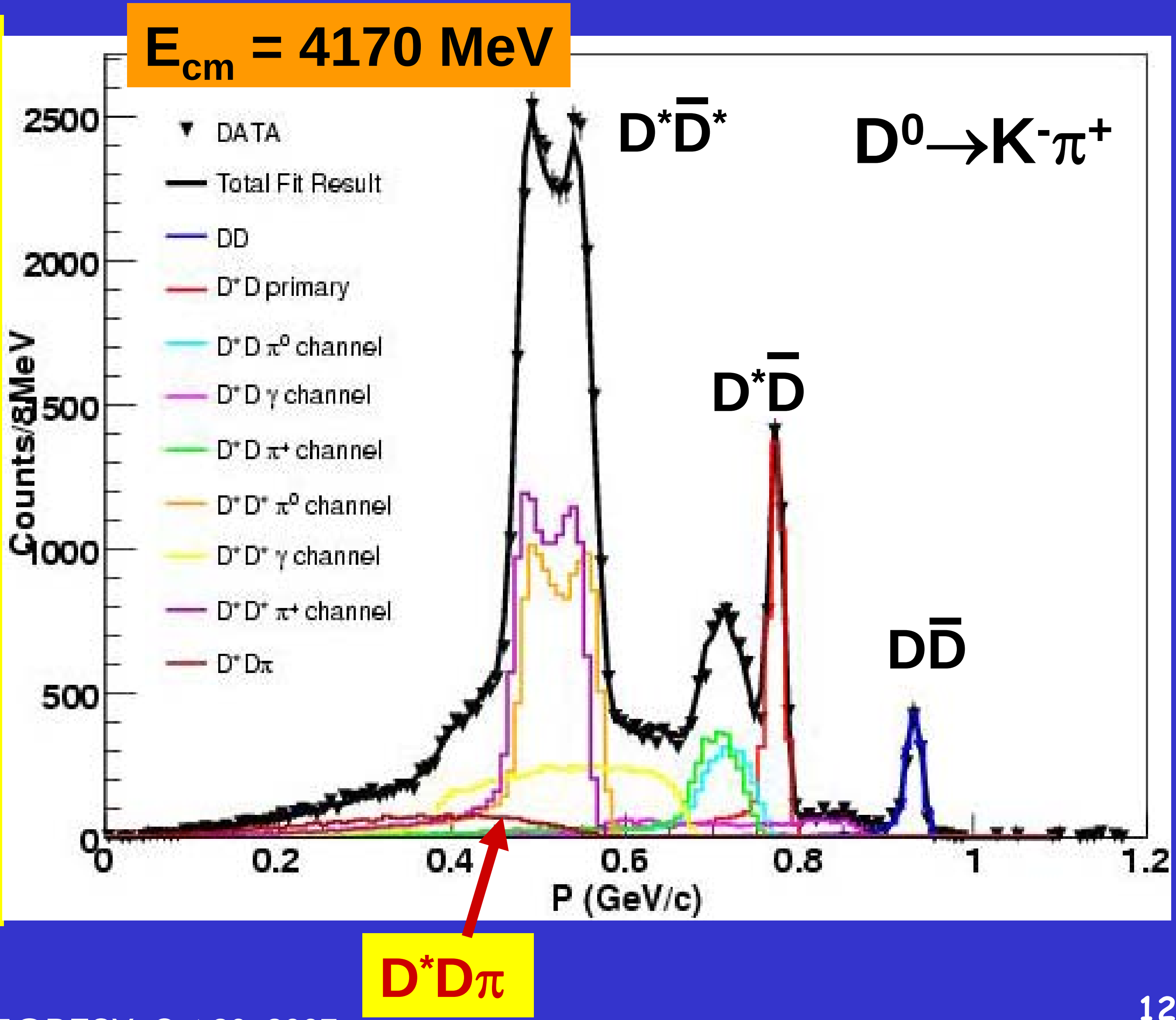
Cross section as a function of E_{cm} from the 2005 PDG

Momentum Spectra

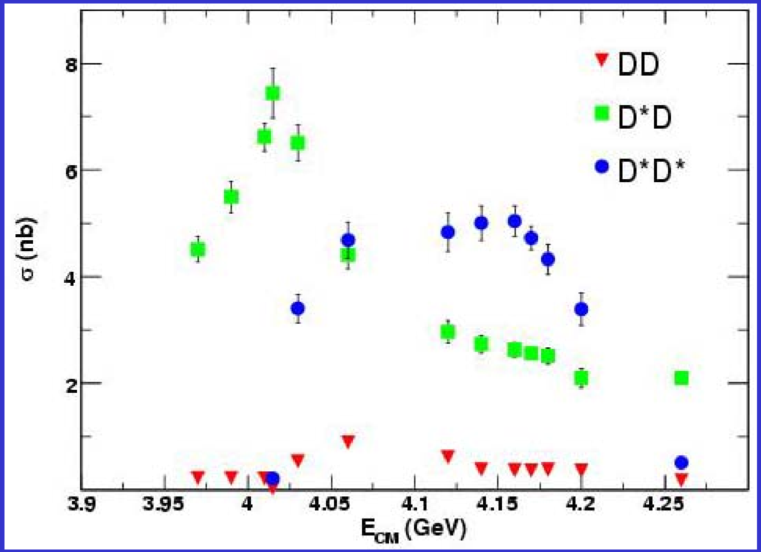
Do NOT recontruct D*; instead use D **momentum spectrum**.

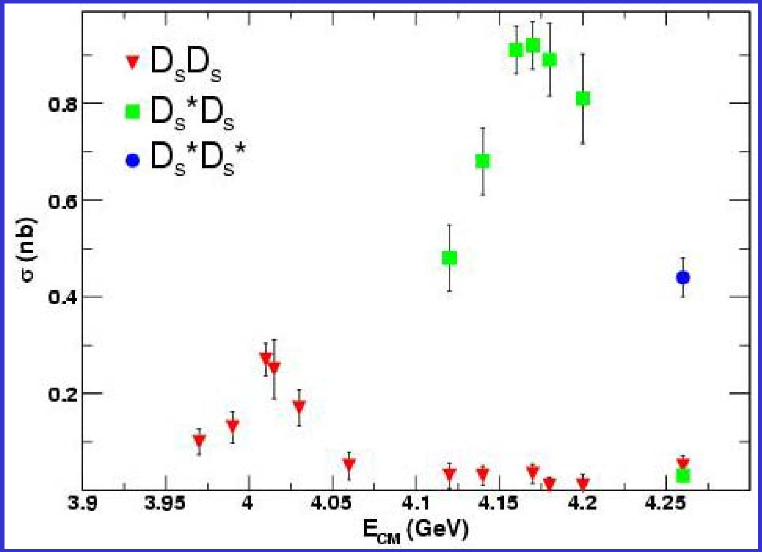
2-body production shows up as peaks &/or Doppler-smeared peaks

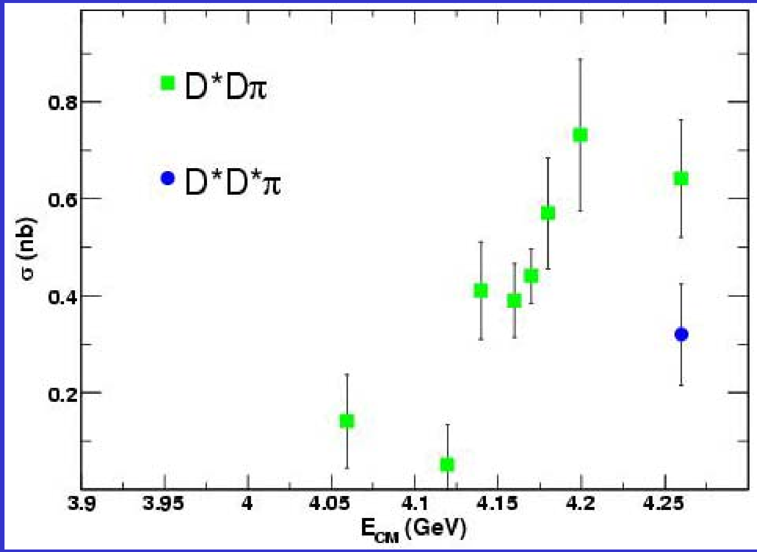
Example at right: $D^0 \to K^- \pi^+$ momentum spectrum after D^0-sideband subtraction



Exclusive Cross Sections

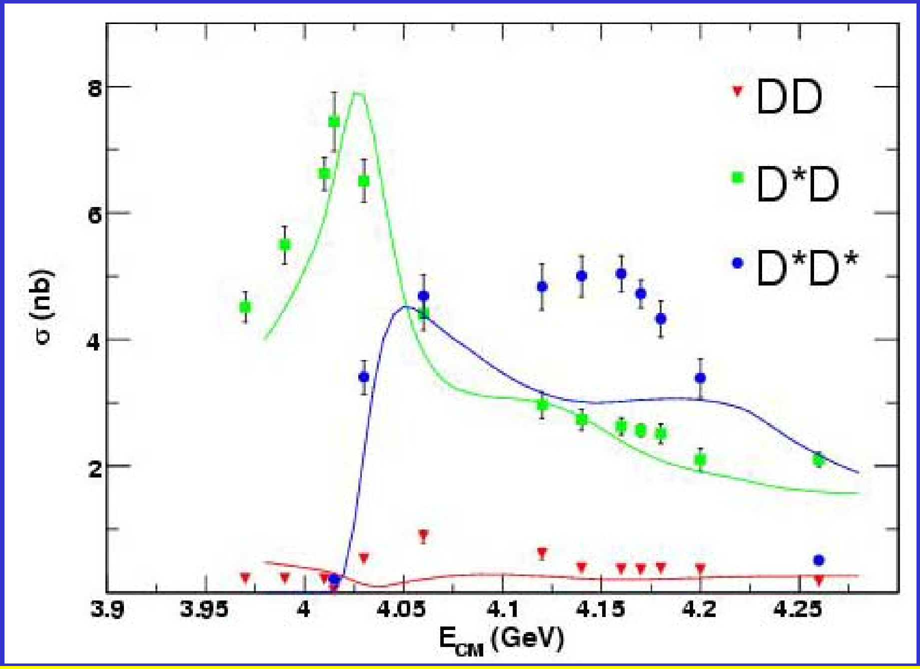


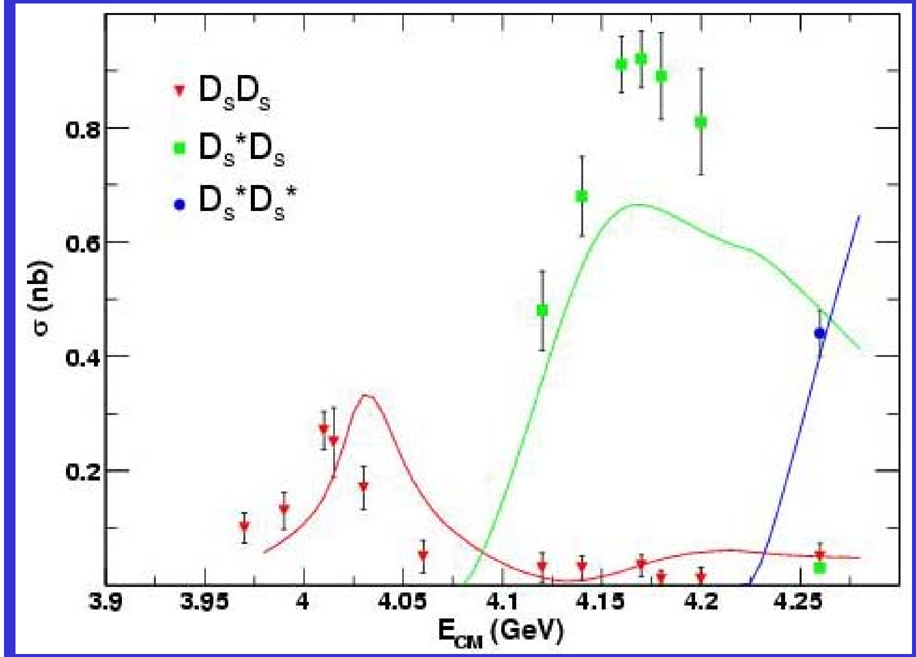




- No theoretical predictions for multi-body.
- No evidence of $D\bar{D}\pi$ in this region
  - Turns on above 4.3 GeV via $DD_2{}^*$ (Belle, arXiv:0708.3313 [hep-ex]) [see next session]

Comparison w/ Updated Eichten et al.



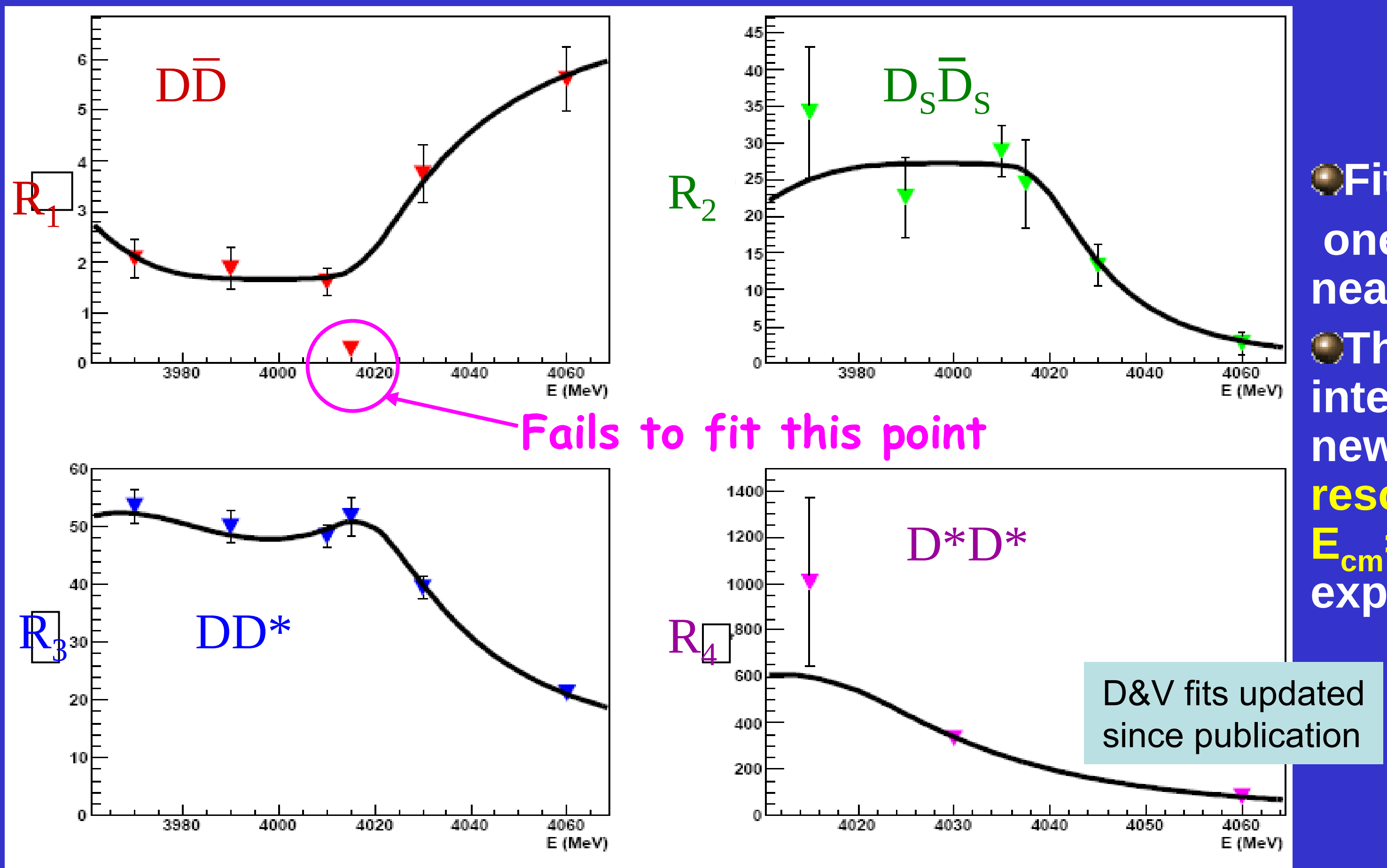


E. Eichten, International Workshop on Heavy Quarkonium (BNL 2006) and private communication

- Most noticeable difference in $D^*\bar{D}^*$ channel.
- Reasonable qualitative agreement.

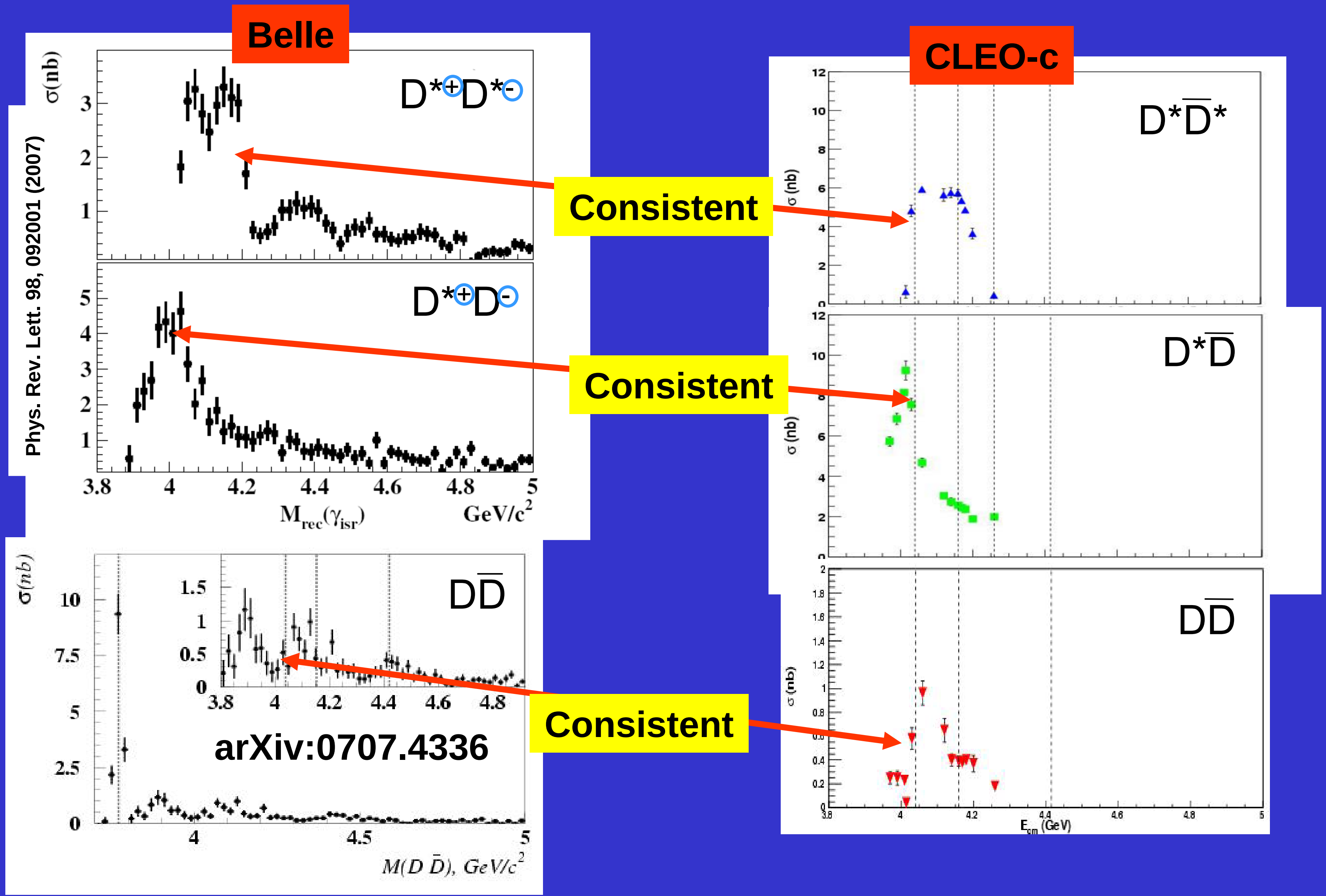
New Resonance at D*D* Threshold?

- Model of **Dubynskiy & Voloshin** [Mod. Phys. Lett. A21, 2779 (2006)]
- Express exclusive channels in terms of dimensionless R_k
- Parametrize R_k in terms of expected threshold behavior & relative production rates in the presence of a $\psi(4040)$



- Fit to CLEO data: one large deviation near D*D* threshold
- This model needs interference with a new **narrow resonance at E_{cm}=4015 MeV** to explain dip in DD

Comparison with Belle



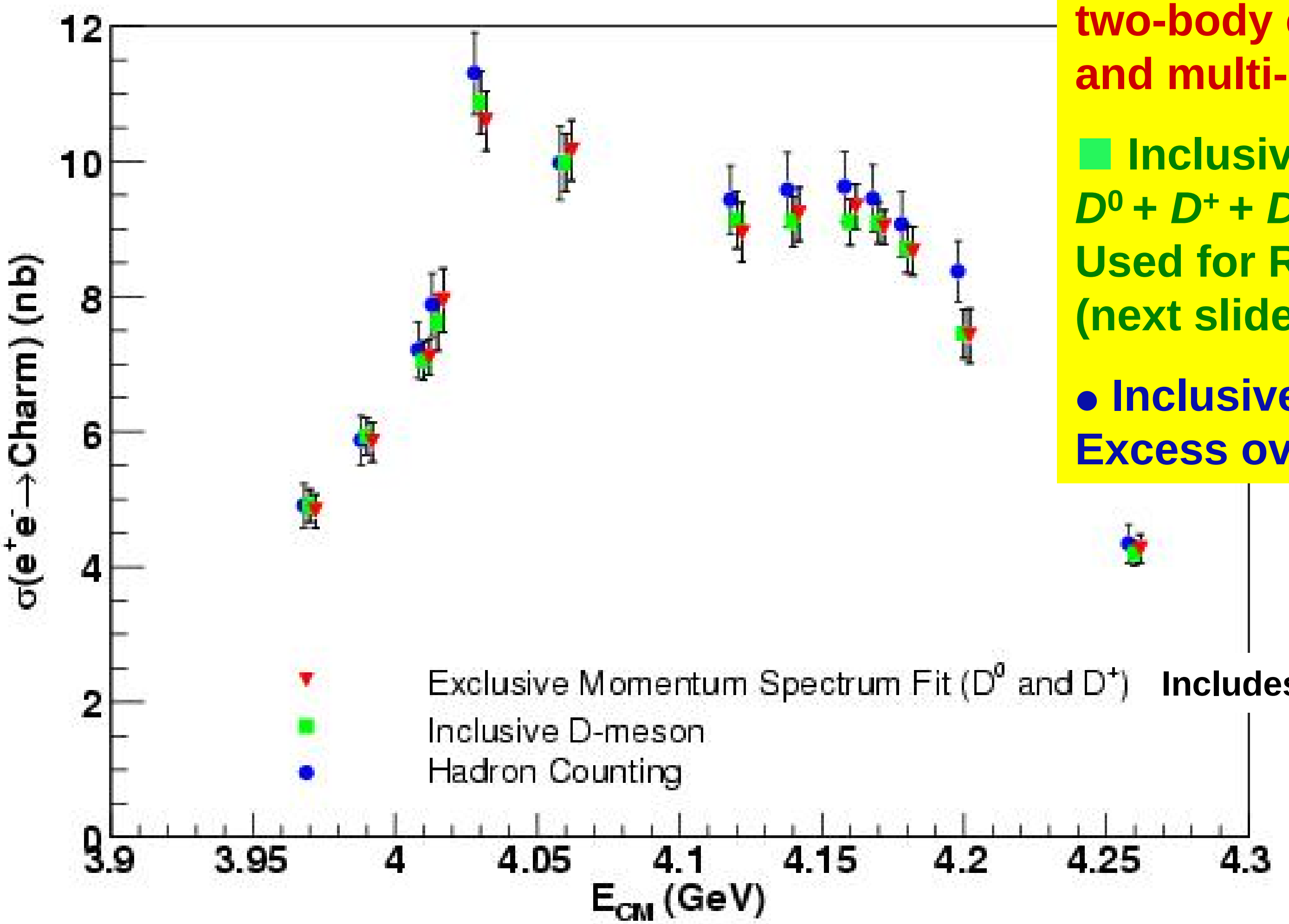
Limits on Y(4260) Decays

Mode	$\frac{Y(4260) \to X}{Y(4260) \to \pi^+\pi^- J/\psi}$
$D\bar{D}$	<4.0
$D^*\bar{D}$	<45
$D^*\bar{D}^*$	<11
$D^*\bar{D}\pi$	<15
$D^*\bar{D}^*\pi$	<8.2
$D_s^+ D_s^-$	<1.3
$D_s^{*+} D_s^-$	<0.8
$D_s^{*+} D_s^{*-}$	<9.5

Upper limits @90%CL

$c\bar{c}g$ models like D_1D decays (← <15)

Inclusive Cross Checks



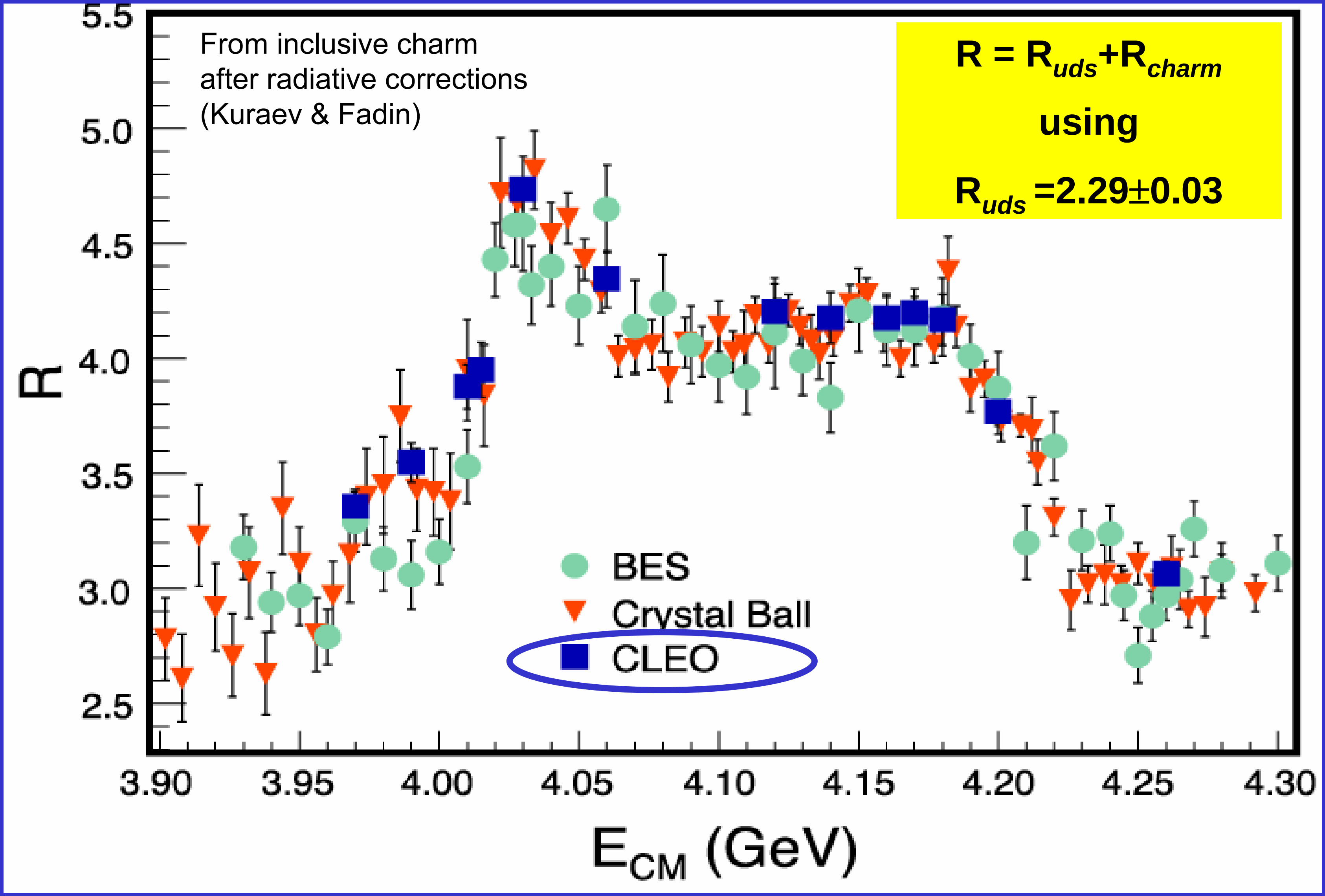
▼ **Exclusive: Sum of the two-body charmed mesons and multi-body**

■ **Inclusive charm:**
$D^0 + D^+ + D_s$
Used for R measurement (next slide)

● **Inclusive Hadrons: Excess over *uds***

Includes multi-body

R for E_{CM}=3.97-4.26 GeV



Conclusions

- Precise R measured for E_{cm}=6.96–10.54 GeV
  - Region of no structure as expected
  - Most precise; removes any doubts about old Mark I points
  - Determines $\alpha_s(M_Z^2)$ with ~10% uncertainty
    - Consistent with world average w/other methods
    - Determination also depends, at ~10% level, on method of tying together 4 & 5 flavor regimes
- Exclusive & inclusive charm for E_{CM}=3.97-4.26 GeV
  - Region of many thresholds & much structure!
    - We have exclusively deconstructed its composition
    - This deconstruction is useful input for model builders
      - In one such model, hints at a narrow resonance near 4015 MeV?
      - Qualitative agreement with coupled channel predictions
  - Precision of R is improved at these 13 points
  - Multi-body production of open charm measured for 1st time
    - Yes $D^*D\pi$ but no $DD\pi$ below 4.3 GeV. Model post-dictions?
- Should lead to a better understanding of QCD

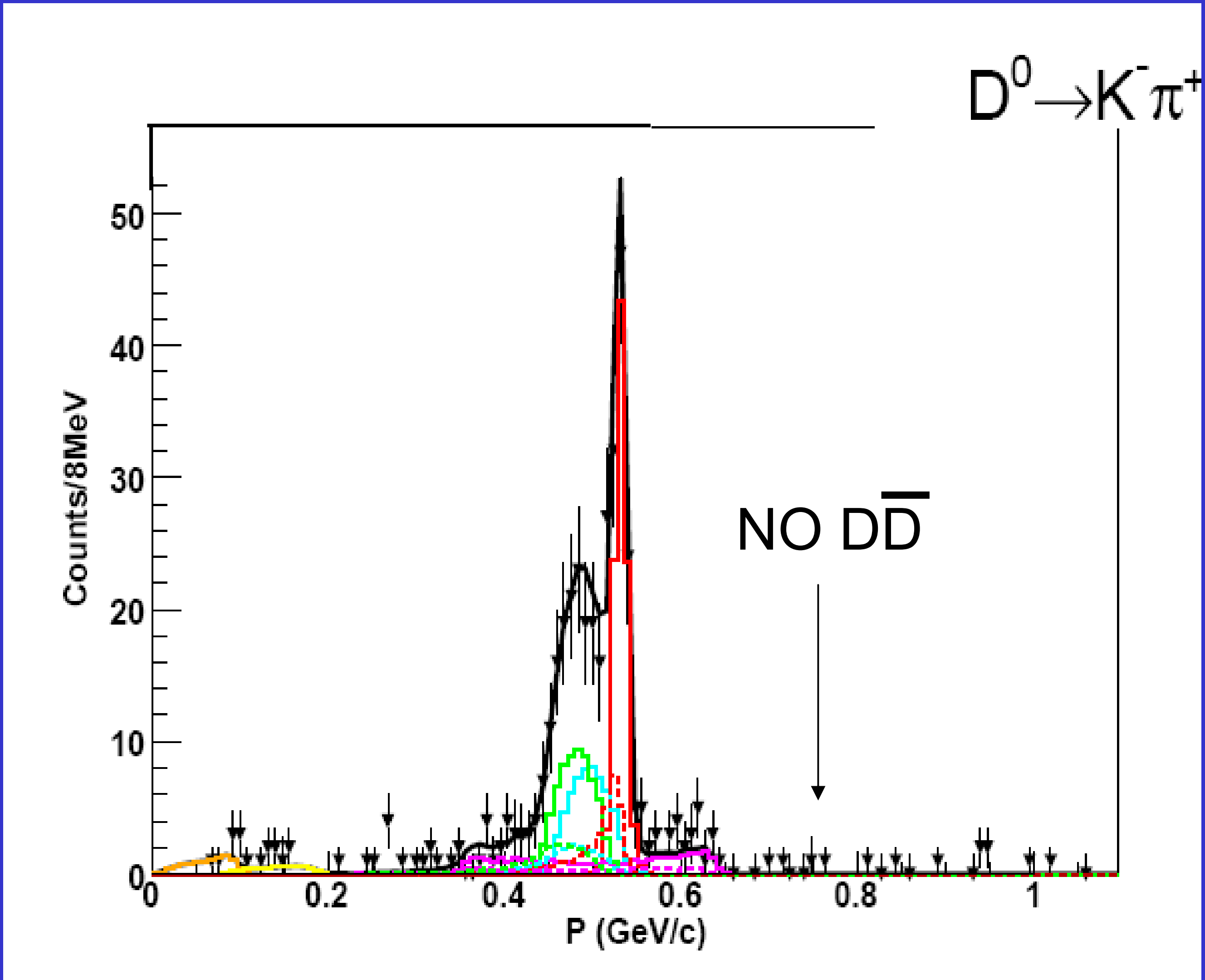
Backup Slides

Event Selection for R at E_{cm}=7-10 GeV

- Require good quality tracks & showers
- Loose event cuts: very high eff for signal

$\mid Z_{\mathrm{vertex}} \mid$	< 6.0 cm	Suppress beam gas
$E_{\mathrm{vis}}/2E_{\mathrm{beam}}$	> 0.5	Suppress 2γ & beam gas bgd
$\mid P_z^{\mathrm{miss}}/E_{\mathrm{vis}} \mid$	< 0.3	
H_2/H_0	< 0.9	Event shape for $\ell^+\ell^-$ pair bgd
$E_{\mathrm{cal}}/2E_{\mathrm{beam}}$	$(0.15, 0.9)$	Suppress ττ (low) & ee (high)
$E_\gamma^{\mathrm{max}}/E_{\mathrm{beam}}$	< 0.8	Suppress QED (ee, γγ, …)
$N_{\mathrm{ChargedTrack}}$	≥ 4	Suppress 2γ, beam gas, & ττ

"Missing" $D\bar{D}$ @ E_{cm}=4015 MeV



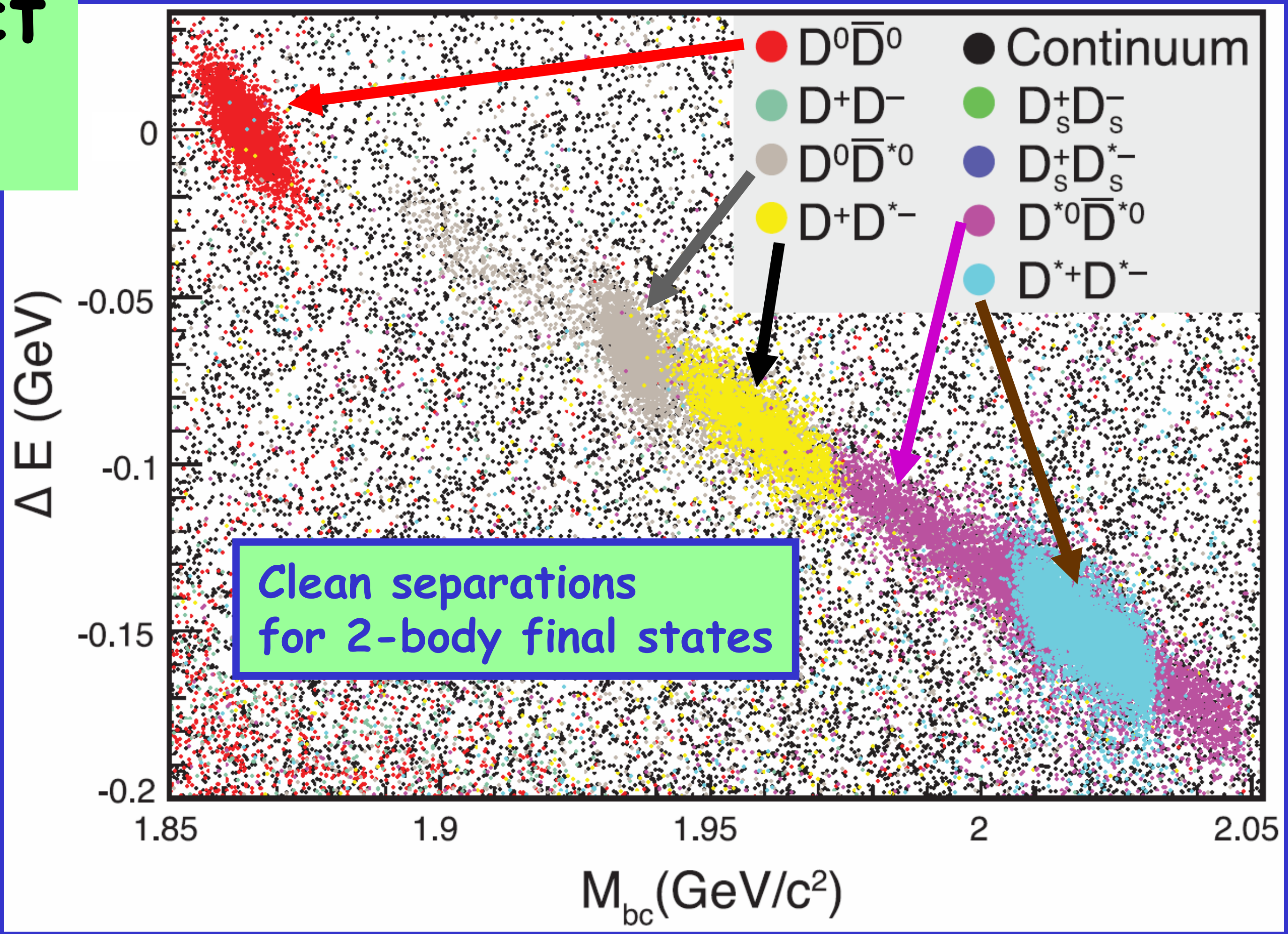
$D_{(s)}$ Modes & Branching Fractions (%)

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	
$K^-\pi^+\pi^+$	$9.52 \pm 0.37\%$
$K^-\pi^+\pi^+\pi^0$	$6.04 \pm 0.28\%$
$K_s\pi^+$	$1.55 \pm 0.08\%$
$K_s\pi^+\pi^0$	$7.17 \pm 0.43\%$
$K_s\pi^+\pi^-\pi^+$	$3.2 \pm 0.19\%$
$K^+K^-\pi^+$	$0.97 \pm 0.06\%$

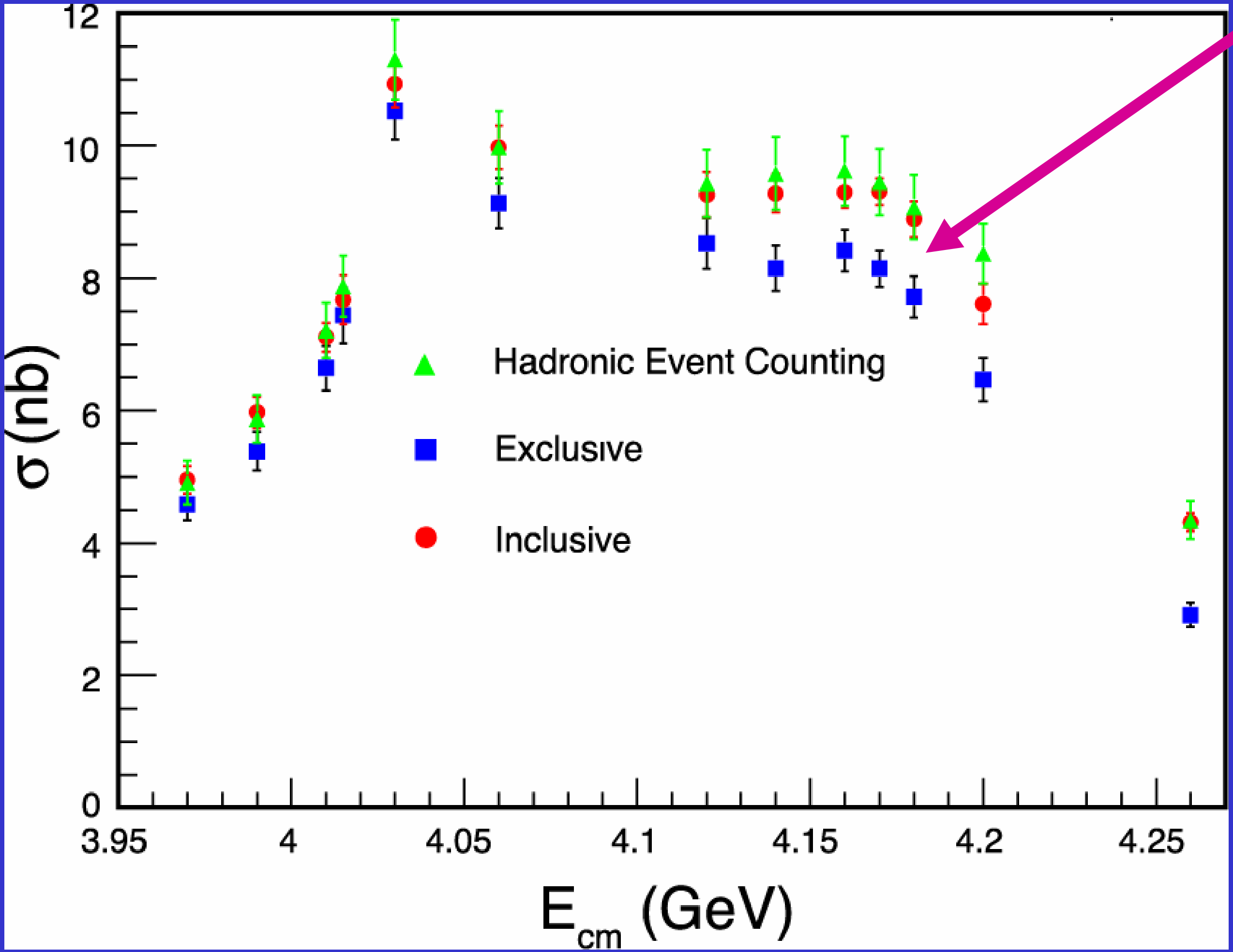
Modes	Branching Fraction
$\phi\pi^+$, 10 MeV cut on the Invariant $\phi \to K^+K^-$ Mass [16]	1.98 ± 0.15
$K^{*0}K^+, K^{*0} \to K^-\pi^-$ [1]	2.2 ± 0.6
$\eta\pi^+, \eta \to \gamma\gamma$ [1, 16]	0.58 ± 0.07
$\eta\rho^+, \eta \to \gamma\gamma, \rho^+ \to \pi^+\pi^0$ [1]	4.3 ± 1.2
$\eta^{'}\pi^+, \eta^{'}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

MC Study: ΔE vs M_{bc} at 4160 MeV

Reconstruct $D^0 \to K^- \pi^+$



Compare 3 methods
(no radiative corrections)



Discrepancy between exclusive rate and total