Fragmentation at CLEO

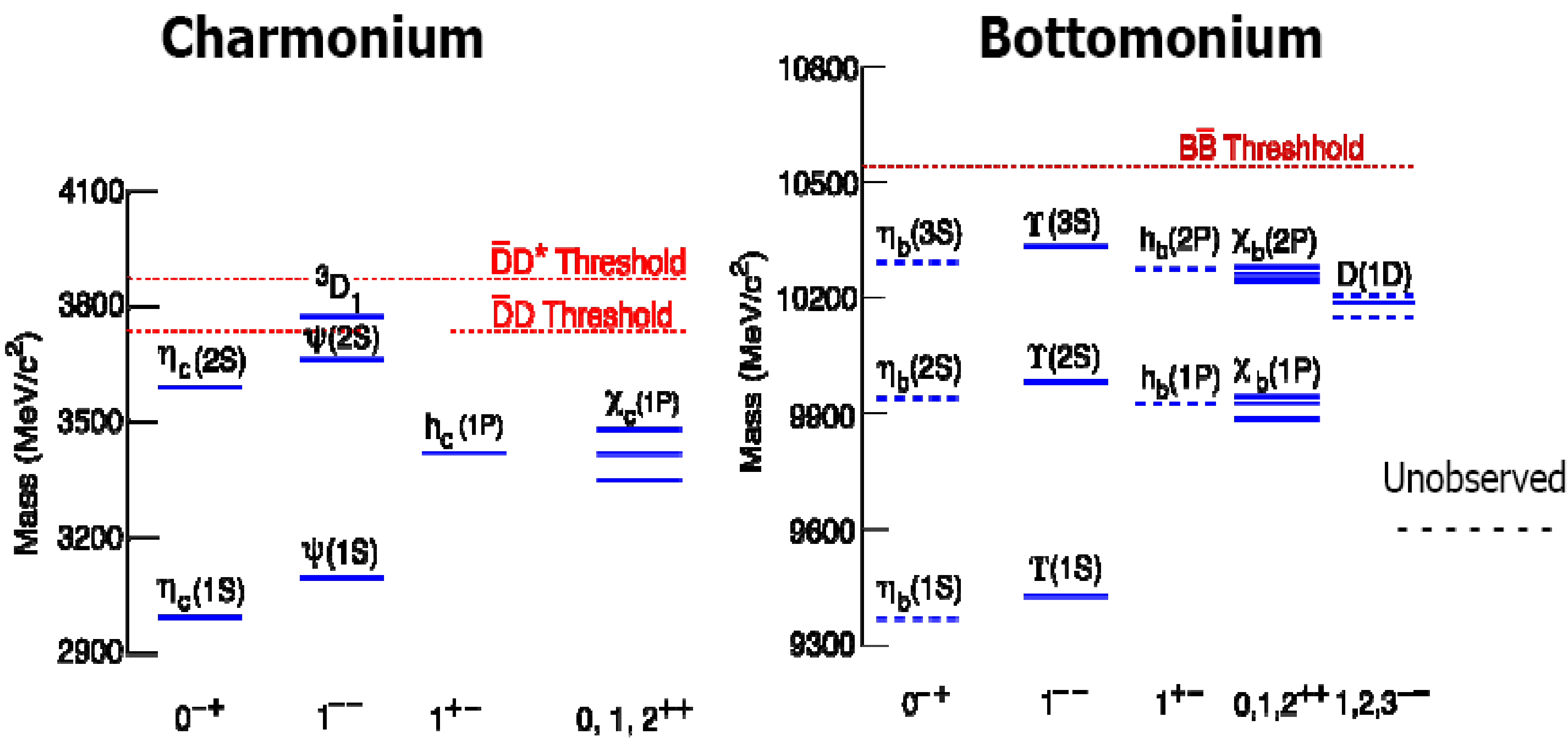
- Data taken over 3 GeV→11 GeV ECM offers opportunity to compare fragmentation effects over range of energies.
- Many results. Will herein focus on:
  - Charm production @ ECM~10 GeV
    - From Upsilon resonances
    - From χ_J resonances (P-states)
    - Correlated charm continuum prod.
    - Baryon production (and dibaryons)
  - Photons from cont, J/ψ, U(1S)
    - Compare gg and qq recoil systems.

ECM=10 GeV Historical Themes

- Baryon production enhancement in ggg decays of narrow resonances vs. qq fragmentation
- Fragmentation of gg~ggg
- U(1S)→ggg→hidden charm (psi), but not D's
- Direct photon dN/dp in quarkonium→ggγ softer than orthopositronium→$\gamma\gamma\gamma$
  - Recoil fragmenting gg system must be included in full calculation of photon momentum spectrum
- From the 80's: "Decuplet" suppression in continuum fragmentation (Δ:p, e.g.).
  - spin (3/2)~0.1(1/2)
- Much recent work on the role of color octet/color singlet gluon contributions in particle-specific fragmentation (Braaten, ψ production @CDF)

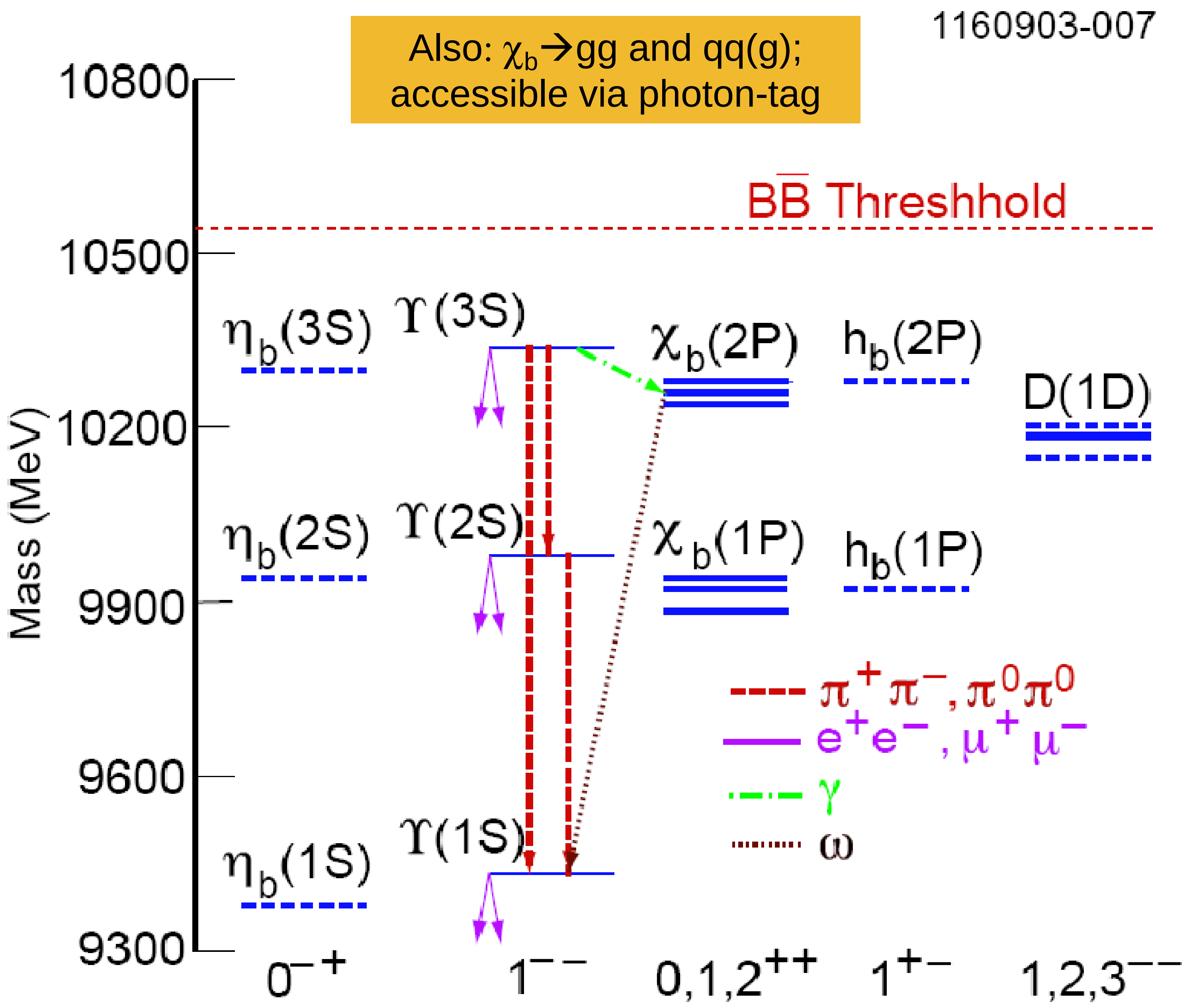
Mass Levels, Schematically:

Upsilon and ψ provide sources of ggg and ggγ decays!



And transitions (Upsilon, e.g.)

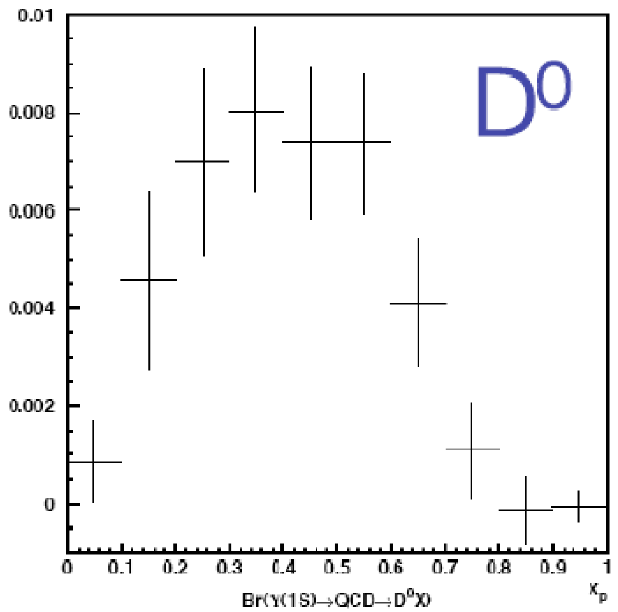
Also: $\chi_b \rightarrow gg$ and qq(g); accessible via photon-tag



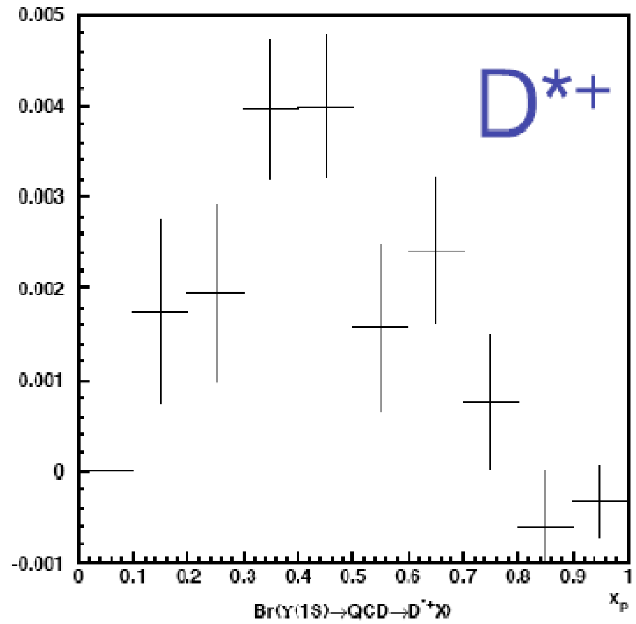
QUARKS vs GLUONS

THUMBNAIL of recent results

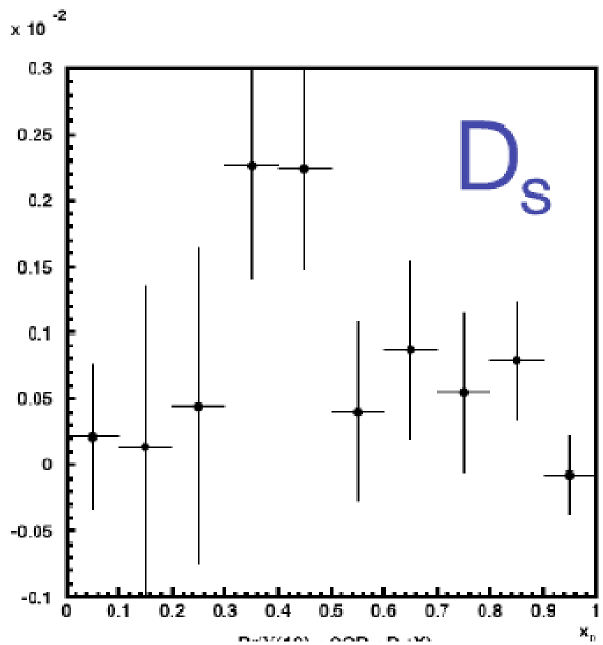
1) Open Charm from U(1S)→gluons (Mike Watkins thesis, pre-preliminary)

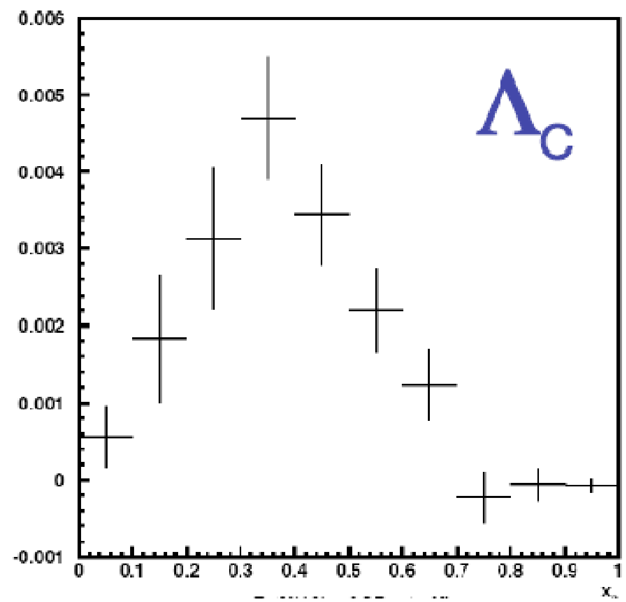


Per-event yields shown



Softer by ~0.2 units in x_p vs. contin



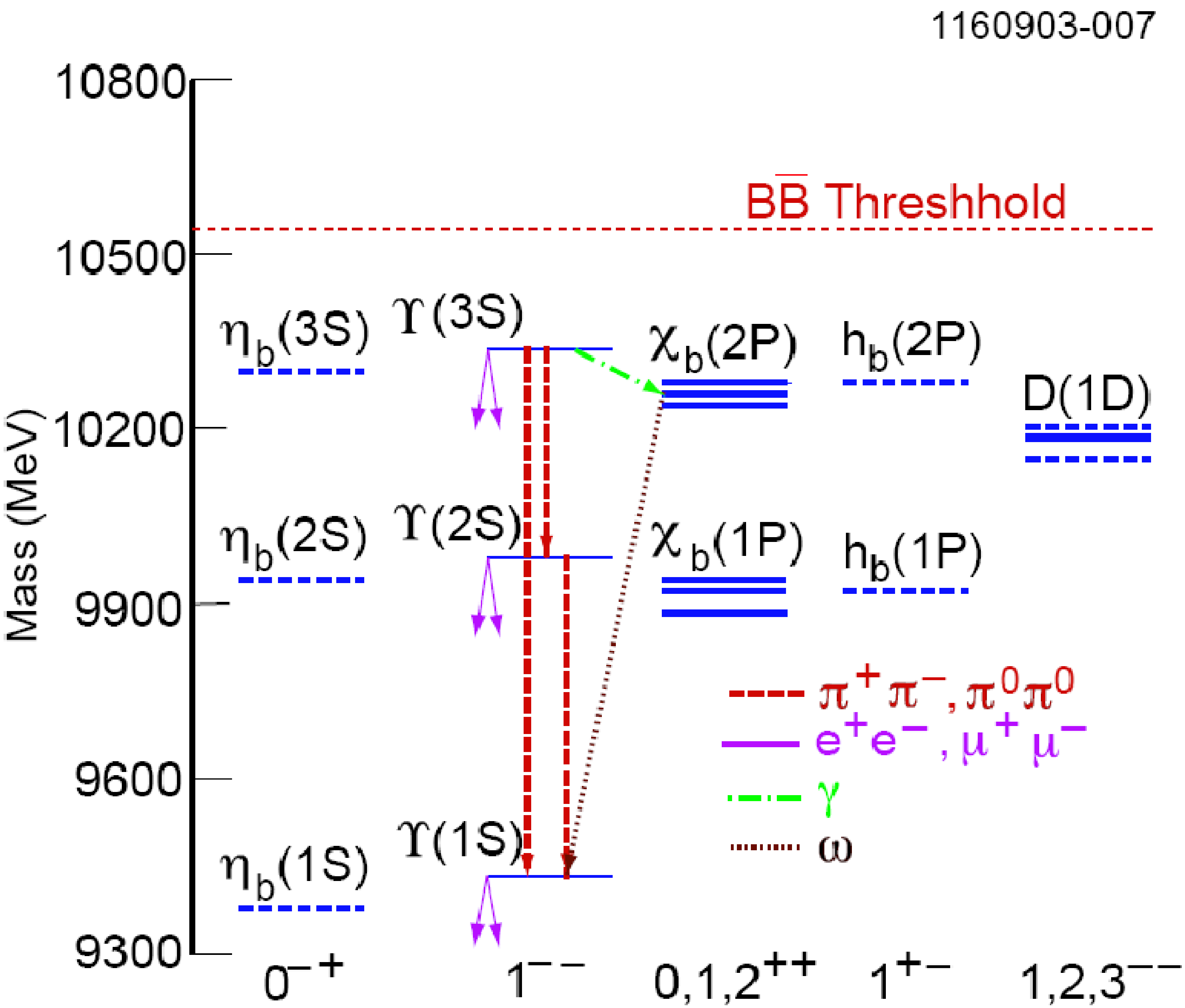


$\Upsilon(1S) \to$ QCD $\to$	*Br %*	$\pm\delta_{stat}$ %	$\pm\delta_{sys}$ %	$\pm\delta_{\Upsilon C}$ %
D^0X	4.03	0.42	0.48	0.0741
$D^{*+}X$	1.55	0.24	0.15	0.0308
D_s^+X	0.78	0.25	0.12	0.1356
Λ_c^+X	1.67	0.19	0.22	0.4353

Br(Υ (1S) $\to$	Br %	Stat %	Sys %	Br %
Open c + cbar	8.6604	1.0095	1.5018	0.5410
Hidden c cbar	0.1714			0.0571
Total c cbar	4.5016	0.5048	0.7509	0.2765

Old theory ('79): ~ 2%

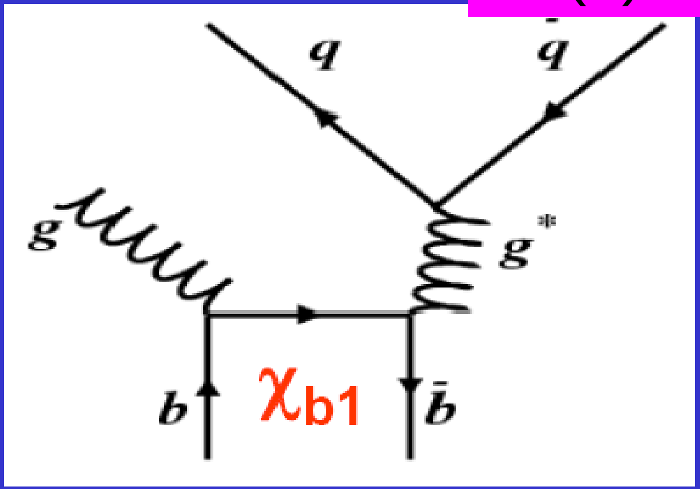
Photon-tagging to access χ_b states

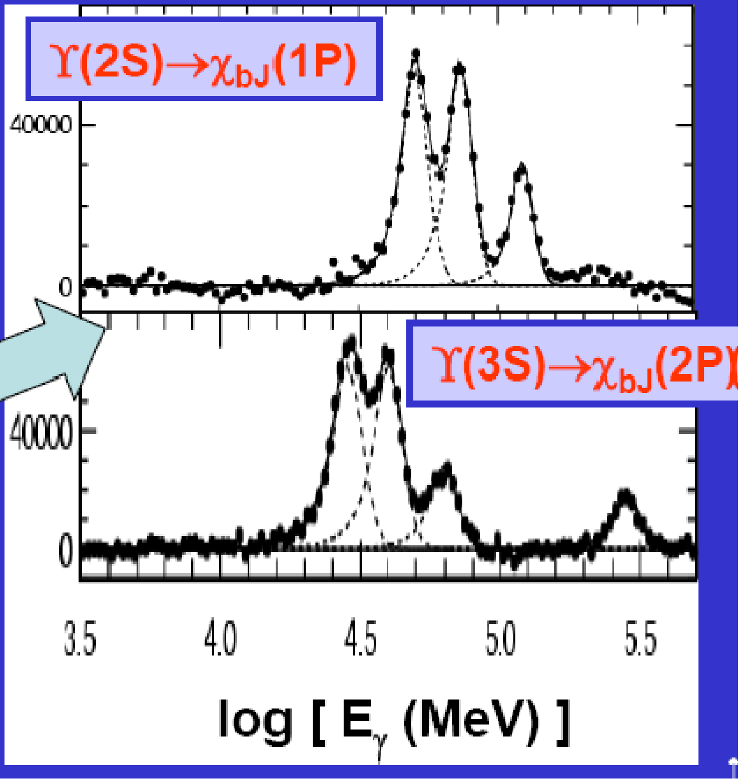


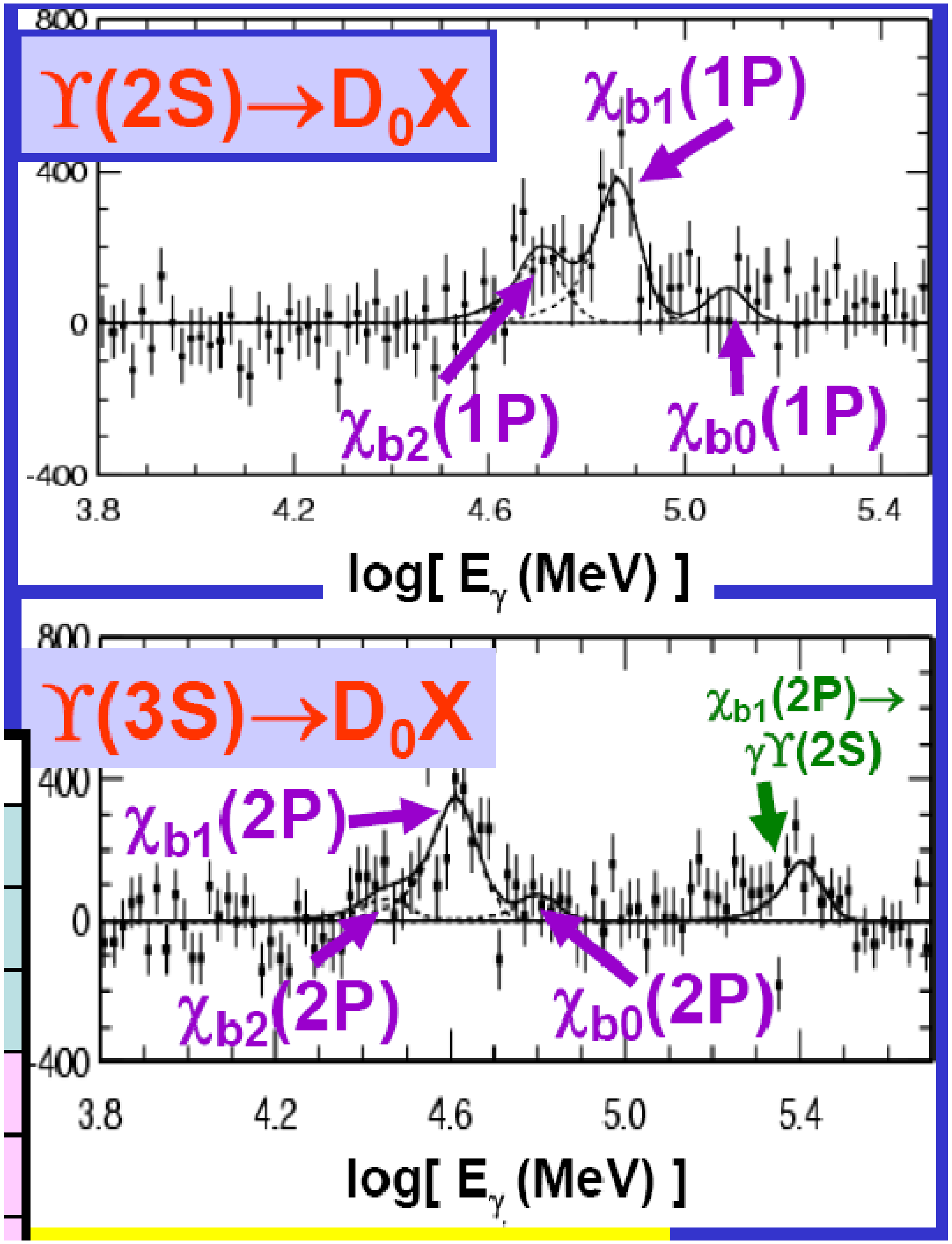
$\chi_{bJ} \rightarrow$ Open Charm

(2)

- Unlike χ_{b0} & χ_{b2}, χ_{b1} cannot decay to 2-gluons on-shell
  - $\chi_{b1} \rightarrow g^* g \rightarrow q\bar{q}\ \ g$
- χ_{b1} expected to yield more open charm than χ_{b0}, χ_{b2}
- Investigate w/CLEO III
  - Select inclusive γ, find # χ_{bJ}
  - Select inclusive $D^0 \rightarrow K\pi$, $K\pi\pi$, $K\pi\pi\pi$
    - Require $p(D^0)$>2.5 GeV/c
    - Find # χ_{bJ} in such events
- First step is reproducing previous CLEO III results on B[$\Upsilon(nS) \rightarrow \gamma\chi_{bJ}$]
  - Suppress fake photons w/shower shape
  - Suppress π^0 decays by pairing with other γ's
  - Fit background, subtract, fit signal
  - Obtained same result: we have denominator for branching fraction
- Exploit RICH & dE/dx for K & π identification







- Plot E_γ for tagged D_0 near M_D
  - D-sideband subtraction
  - Smooth bgd subtraction
  - Fit using lineshapes from inclusive γ's
- $>7\sigma$ signals for $\chi_{b1}(1P)$, $\chi_{b1}(2P$
- Correct for efficiency
  - Assume $\rho_8 = 0.1$ (non-perturbative model parameter) for p>2.5 GeV/c cut
- Subtract secondary sources of χ_{bJ}
- Correct for $\chi_{bJ} \rightarrow \Upsilon X$: quote B^*

Bodwin, Braaten et al (NRQCD)

Update model used to explain psi production at Tevatron: One non-perturbative parameter ρ_8

=m_b^2<Octet 4-quark operator>/<Singlet 4-quark op.>

~0.10

Original model from 1995 recently updated→2007

2) Charm production from $\bar{q}q(g)$ decays

"NEW"=new CLEO result / "TEST"=consistency check with varied bkgnd parameters

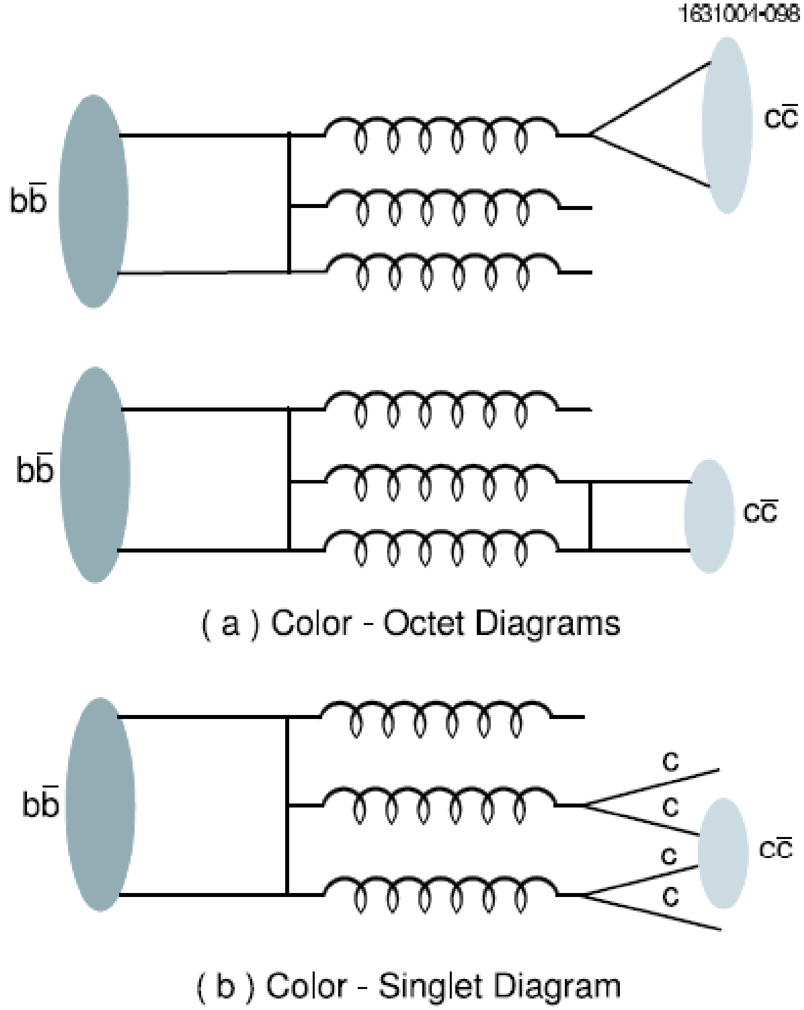
Numbers in excellent agreement with NRQCD prediction with one free parameter (ρ_8)=0.086+/-0.011 (from fit)

Final state	$\chi_{b0}(1P)$	$\chi_{b1}(1P)$	$\chi_{b2}(1P)$
Br($\chi_{bJ}(1P) \to D^0X$) /NEW γ-background	5.63±3.61 %	12.58±1.94 %	5.35±1.89 %
Br($\chi_{bJ}(1P) \to D^0X$) /TEST for γ-background	6.42±3.60 %	12.93±1.92 %	5.73±1.88 %
Final state	$\chi_{b0}(2P)$	$\chi_{b1}(2P)$	$\chi_{b2}(2P)$
Br($\chi_{bJ}(2P) \to D^0X$) /NEW γ-background	4.12±3.00 %	8.74±1.47 %	0.16±1.36 %
Br($\chi_{bJ}(2P) \to D^0X$) /TEST for γ-background	4.40±3.00 %	8.80±1.46 %	0.29±1.35 %

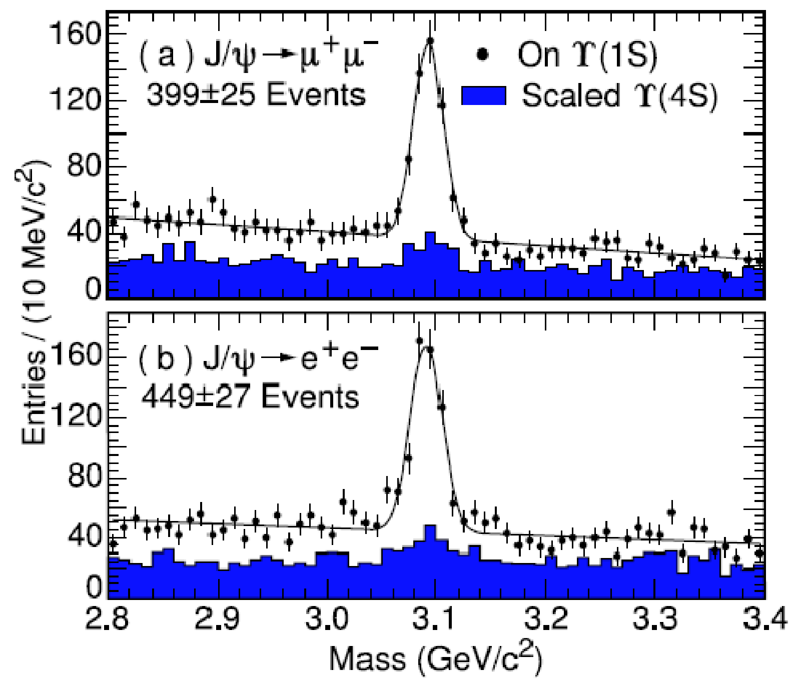
Significant signal for J=1 state (decays to qqbar+gluon) for both states

Slightly weaker for n=2 state (more decay width for other transitions)

Hidden charm(onium) production in ϒ(1S)

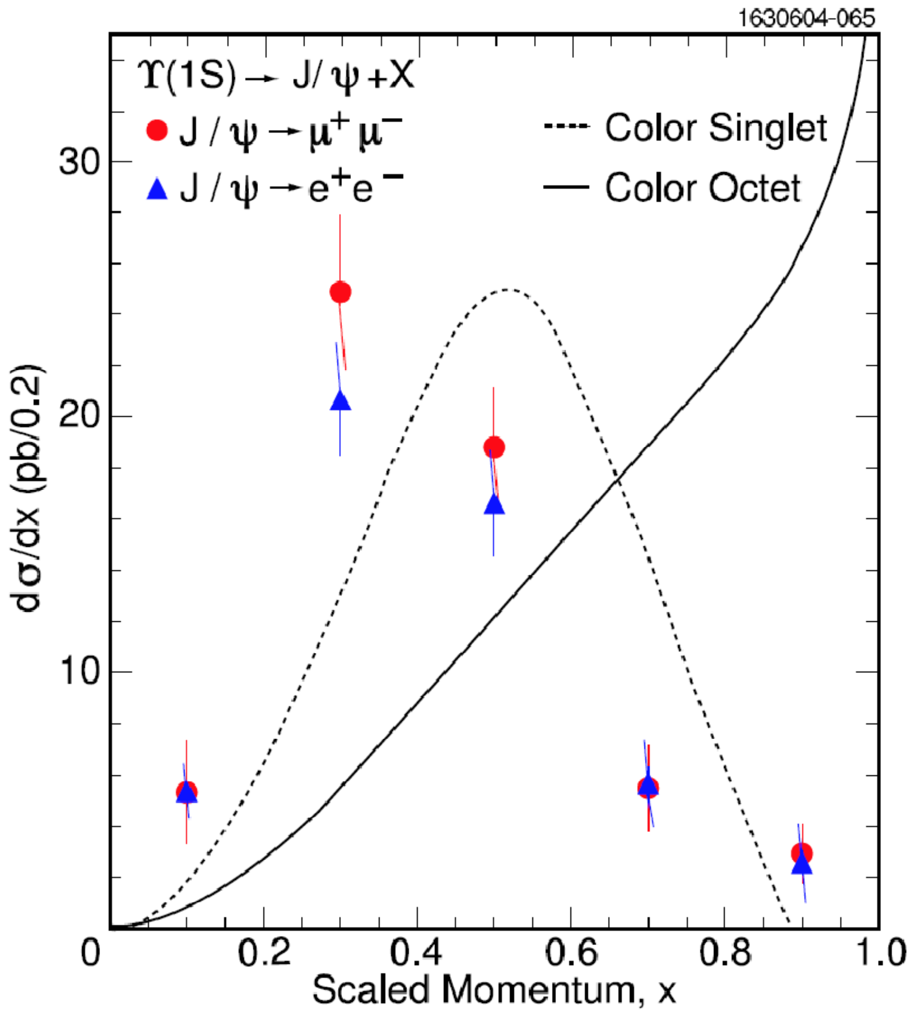


- Phys.Rev. D70 (2004) 072001
- Also probes color-octet vs. color-singlet contributions



Comparison vs. model

Final state, f	$\mathcal{B}(\Upsilon(1S) \to f + X)$	Feed-down to J/ψ
J/ψ	$(6.4 \pm 0.4 \pm 0.6) \times 10^{-4}$	-
	$\mathcal{B}(\Upsilon(1S) \to f + X)/\mathcal{B}(\Upsilon(1S) \to J/\psi + X)$	
$\psi(2S)$	$0.41 \pm 0.11 \pm 0.08$	$0.24 \pm 0.06 \pm 0.05$
χ_{c0}	<7.4	<0.082
χ_{c1}	$0.35 \pm 0.08 \pm 0.06$	$0.11 \pm 0.03 \pm 0.02$
χ_{c2}	$0.52 \pm 0.12 \pm 0.09$	$0.10 \pm 0.02 \pm 0.02$



Although shape not quite right,

Color octet prediction: 6.2×10^{-4}

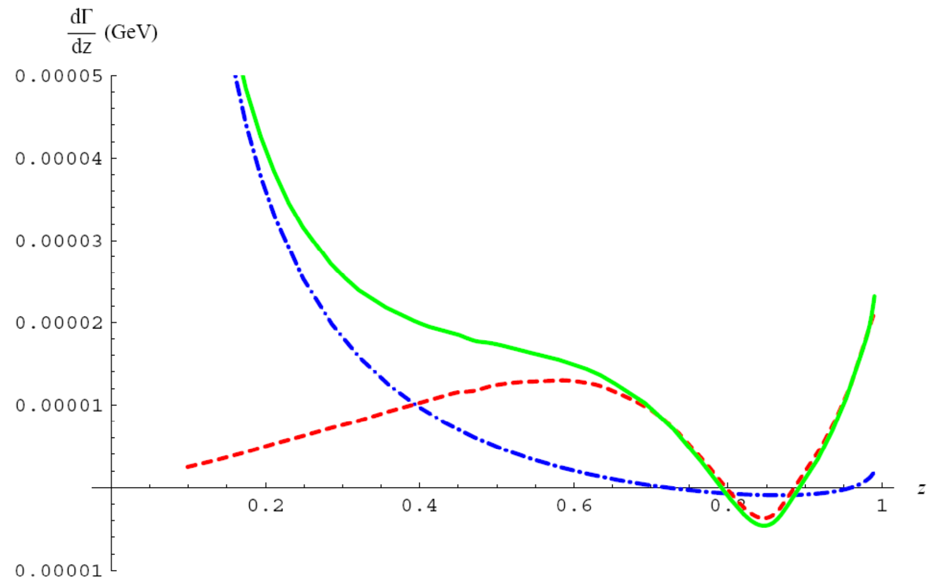
3) Continuum/quarkonium direct photons

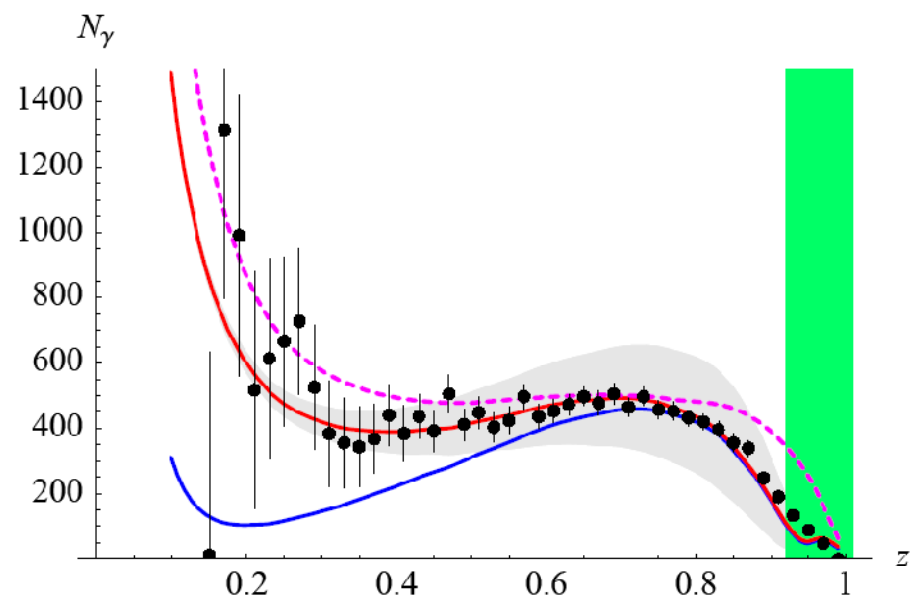
- Quarkonium production of direct photons:
  - Via $gg\gamma$; photon spectrum calculable via SCET
  - Requires some model of recoil system
    - Sum color octet and color singlet contributions of recoil state.
    - Also include ‘fragmentation’ photons off final-state quark lines (Catani&Hautmann)

Models

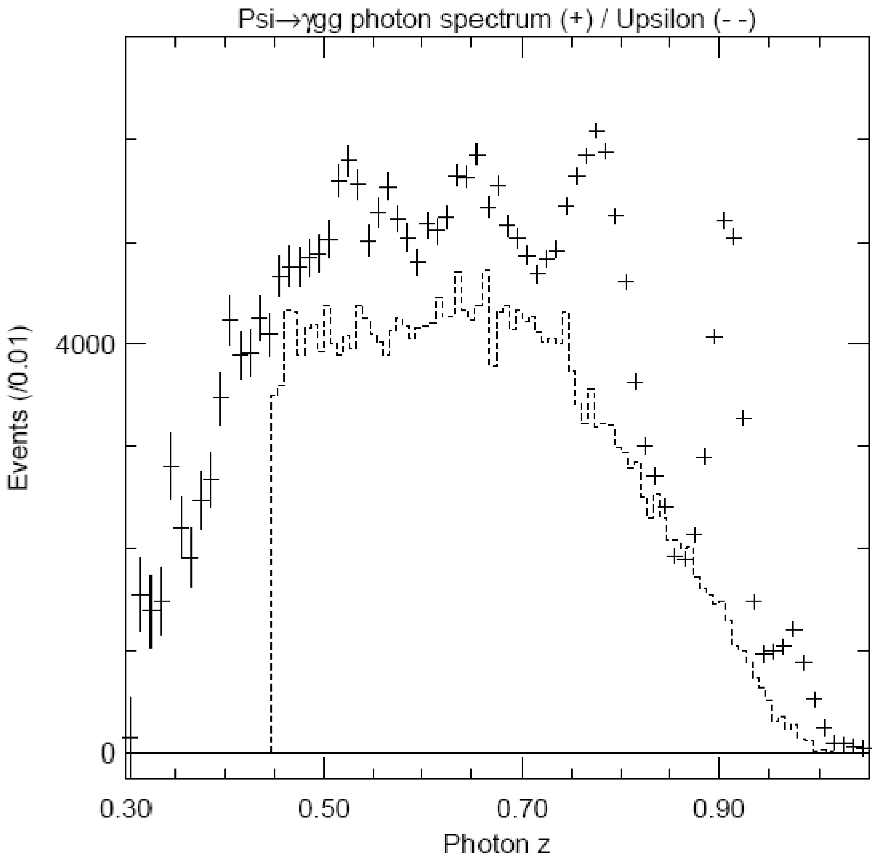
- Fleming & Liebovich (SCET, 2003), Garcia-Soto (2005,2007)

  ψ prediction on top, Upsilon bottom (pink=color singlet contributions only) with data overlaid





Direct photon production in quarkonia



U(1S): Measure ratio of ggγ:ggg rates

Experiment	$R_\gamma(\%)$
CLEO 1.5 ($\Upsilon(1S)$)[7]	$2.54 \pm 0.18 \pm 0.14$
ARGUS ($\Upsilon(1S)$)[10]	$3.00 \pm 0.13 \pm 0.18$
Crystal Ball ($\Upsilon(1S)$)[9]	$2.7 \pm 0.2 \pm 0.4$
CLEO II ($\Upsilon(1S)$)[11]	$2.77 \pm 0.04 \pm 0.15$
CLEO III ($\Upsilon(1S)$)	$2.70 \pm 0.01 \pm 0.13 \pm 0.24$
CLEO III ($\Upsilon(2S)$)	$3.18 \pm 0.04 \pm 0.22 \pm 0.41$
CLEO III ($\Upsilon(3S)$)	$2.72 \pm 0.06 \pm 0.32 \pm 0.37$

Taglines: a) psi ‘continuum’ spectra very similar to Upsilon spectra b) rate for psi

BUT: one calculation at U(1S) unphysical for z>0.7

For psi: R=0.134+/-0.001 (stat) +/-0.015 (sys) +/-0.004 (extrapolation→0)

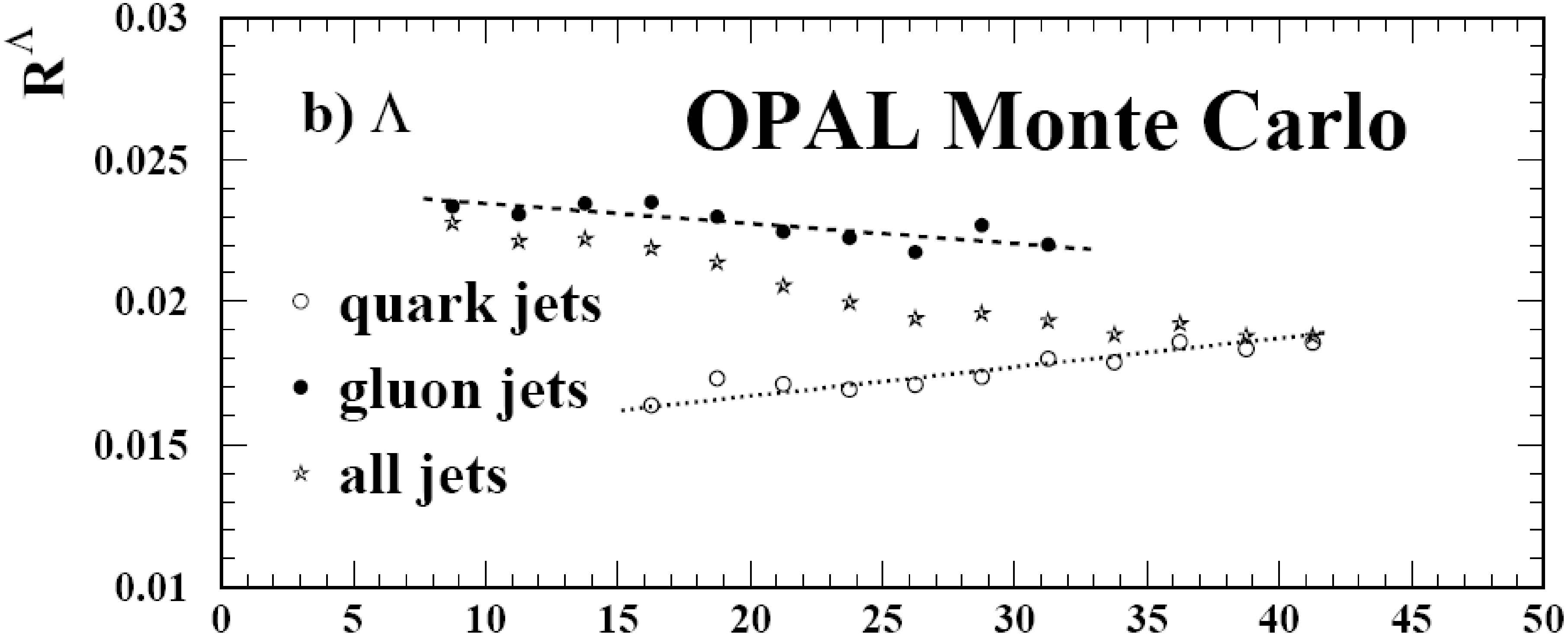
Scaling Upsilon msrmnt, accounting for running of α_s→expect ~0.095 (Voloshin)

Aside: Lowest-order QCD: dN/dz~z

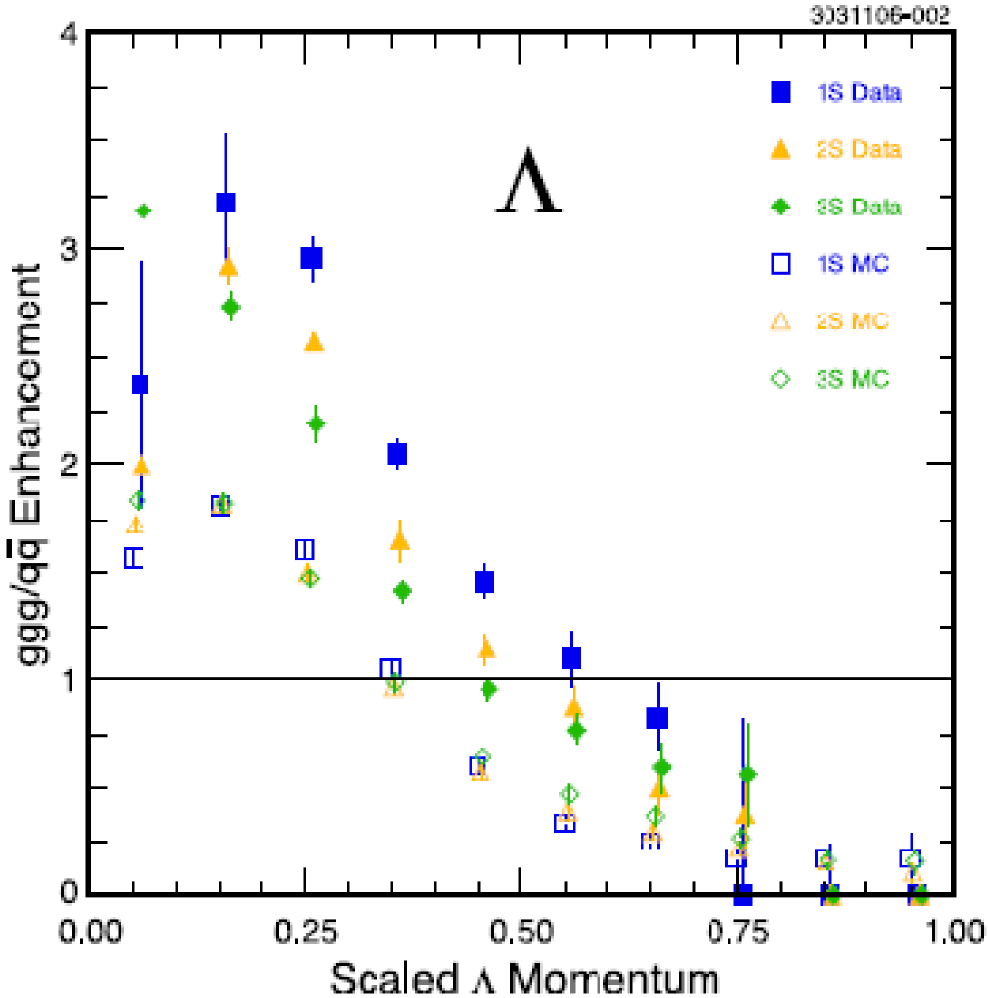
4) Direct Photon-tagged events to probe $gg\gamma$ vs. $q\bar{q}\gamma$

- I.e. compare inclusive particle production in recoil two-gluon system with qq fragmenation via ISR: e+e- → qqbar+photon on continuum
  - – Direct quark vs. gluon probe – no jet-identification needed
  - – Statistically unfold continuum contamination to resonance (~20% effect)
- Start by repeating previous studies (CLEO,ARGUS) of baryon production from quarkonium→ggg vs. nearby continuum (qqbar)

OPAL result (shown yesterday) – Lambda enhancement 1-1.5 for all jet-finders



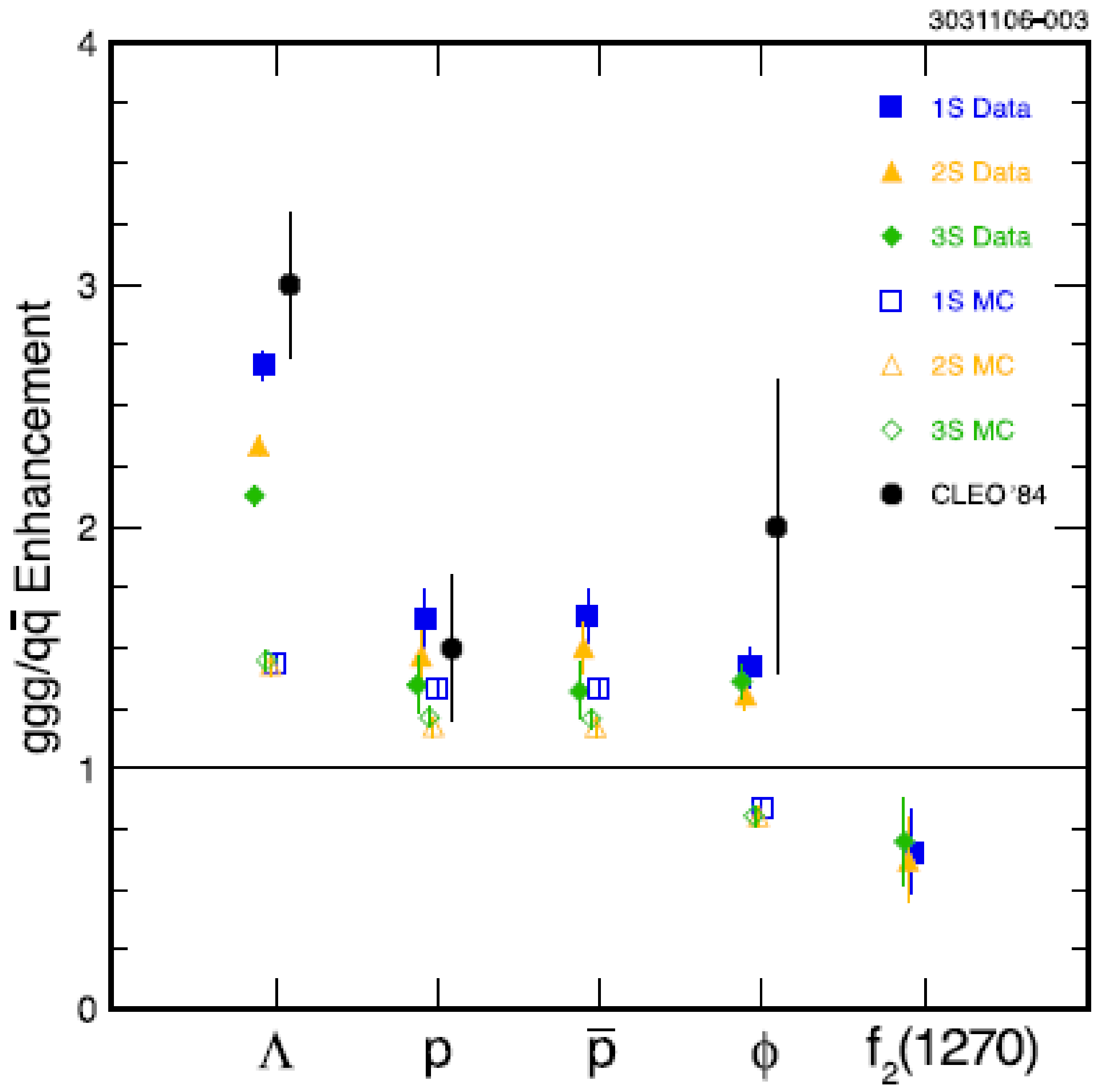
CLEO: Momentum-dependent ggg/$q\bar{q}$ enhancements (no photon tagging)



Enhancement dominant at Low momenta (cf. DELPHI)

Note: avg. multiplicity in gg decays
Same as qqbar to within 5%

Several particles ggg vs. qqbar (10 GeV)



Enhanced proton/antiproton rate~1.5

Enhanced lambda rate~2.7

(not in JETSET)

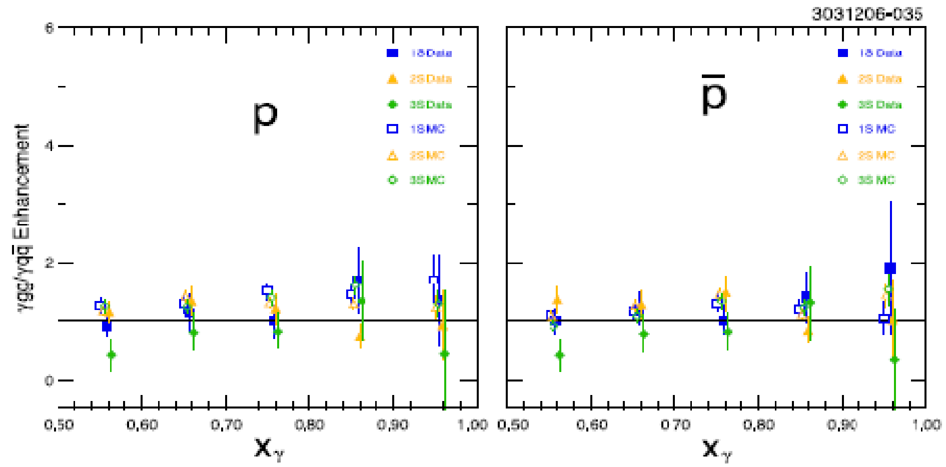
Proton rate in $\chi_b \rightarrow gg/q\bar{q}(g)$ decays

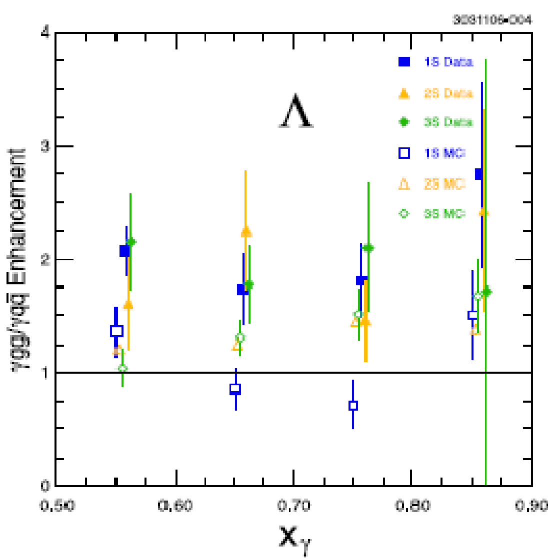
Dataset	particle identification	$(\chi_{b2} \rightarrow p + X)/$ $(\chi_{b1} \rightarrow p + X)/$	$(\chi_{b0} \rightarrow p + X)$ $(\chi_{b1} \rightarrow p + X)$
(3S A)	loose	1.116 ± 0.017	1.19 ± 0.046
(3S B)	loose	1.080 ± 0.016	1.00 ± 0.034
(3S C)	loose	1.086 ± 0.011	1.054 ± 0.047
(3S D)	tight	1.103 ± 0.027	1.091 ± 0.097
3S, all		$1.109 \pm 0.007 \pm 0.040$	$1.082 \pm 0.025 \pm 0.060$
(2S A)	tight	1.066 ± 0.028	1.03 ± 0.13
(2S B)	loose	1.075 ± 0.018	1.36 ± 0.15
(2S C)	loose	1.076 ± 0.017	0.99 ± 0.11
(2S D)	loose	1.065 ± 0.015	1.06 ± 0.11
(2S B)	tight	1.076 ± 0.047	1.39 ± 0.28
(2S C)	tight	1.039 ± 0.040	1.17 ± 0.22
(2S D)	tight	1.024 ± 0.035	0.88 ± 0.20
2S, all		$1.068 \pm 0.010 \pm 0.040$	$1.11 \pm 0.15 \pm 0.20$
Monte Carlo (3S A)	loose	1.057 ± 0.016	1.030 ± 0.072
Monte Carlo (3S A)	tight	1.034 ± 0.015	1.042 ± 0.066
Monte Carlo (3S B)	tight	1.041 ± 0.013	1.051 ± 0.049
MC, 3S all sets		1.043 ± 0.008	1.043 ± 0.036
Monte Carlo (2S A)	tight	1.052 ± 0.014	1.121 ± 0.058
Monte Carlo (2S A)	loose	1.043 ± 0.015	1.076 ± 0.061
MC, 2S all sets		1.046 ± 0.010	1.061 ± 0.025

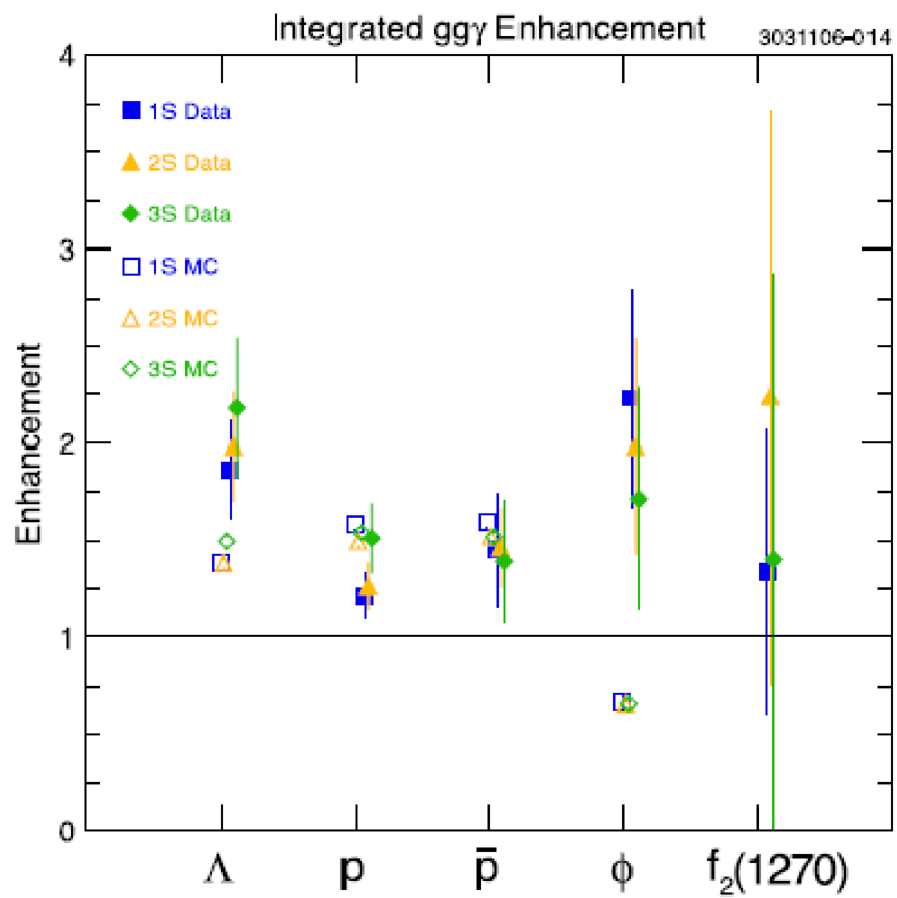
JETSET gets this ratio right.

Momentum-integrated ggγ vs. qqγ

Enhancements approximately 3/4 of ggg enhancements (~N_{parton})







Summary of results on previous slides data vs. JETSET

Particle	$gg\gamma/q\bar{q}\gamma$ data	$gg\gamma/q\bar{q}\gamma$ MC	$ggg/q\bar{q}$ data	$ggg/q\bar{q}$ MC
Λ (1S)	$1.86 \pm 0.25 \pm 0.03$	1.38 ± 0.039	$2.668 \pm 0.027 \pm 0.051$	1.440 ± 0.003
Λ (2S)	$1.98 \pm 0.27 \pm 0.08$	1.38 ± 0.018	$2.333 \pm 0.019 \pm 0.021$	1.428 ± 0.002
Λ (3S)	$2.18 \pm 0.36 \pm 0.02$	1.49 ± 0.023	$2.128 \pm 0.021 \pm 0.010$	1.450 ± 0.002
p (1S)	$1.21 \pm 0.11 \pm 0.03$	1.582 ± 0.034	$1.623 \pm 0.014 \pm 0.116$	1.331 ± 0.005
p (2S)	$1.26 \pm 0.11 \pm 0.06$	1.495 ± 0.018	$1.469 \pm 0.011 \pm 0.103$	1.177 ± 0.003
p (3S)	$1.51 \pm 0.17 \pm 0.06$	1.53 ± 0.021	$1.348 \pm 0.013 \pm 0.116$	1.214 ± 0.003
$\overline{p}$ (1S)	$1.45 \pm 0.14 \pm 0.26$	1.589 ± 0.034	$1.634 \pm 0.014 \pm 0.111$	1.333 ± 0.005
$\overline{p}$ (2S)	$1.46 \pm 0.12 \pm 0.17$	1.513 ± 0.018	$1.500 \pm 0.011 \pm 0.102$	1.175 ± 0.003
$\overline{p}$ (3S)	$1.39 \pm 0.17 \pm 0.27$	1.51 ± 0.020	$1.323 \pm 0.013 \pm 0.115$	1.210 ± 0.003
ϕ (1S)	$1.78 \pm 0.49 \pm 0.08$	0.673 ± 0.013	$1.423 \pm 0.051 \pm 0.065$	0.836 ± 0.003
ϕ (2S)	$1.73 \pm 0.52 \pm 0.06$	0.658 ± 0.012	$1.308 \pm 0.041 \pm 0.041$	0.805 ± 0.001
ϕ (3S)	$1.87 \pm 0.81 \pm 0.06$	0.662 ± 0.015	$1.355 \pm 0.054 \pm 0.047$	0.808 ± 0.002
$f_2(1270)$ (1S)	$1.34 \pm 0.84 \pm 0.15$ (< 2.74)	–	$0.658 \pm 0.058 \pm 0.175$	–
$f_2(1270)$ (2S)	$2.22 \pm 1.53 \pm 0.20$ (< 4.68)	–	$0.621 \pm 0.094 \pm 0.171$	–
$f_2(1270)$ (3S)	$1.41 \pm 1.48 \pm 0.10$ (< 3.87)	–	$0.702 \pm 0.104 \pm 0.175$	–

5) Correlated baryon-antibaryon production (BaBar re-analysis)

Charmed baryons 3x more likely to appear opposite an anti-charmed baryon than an anti-charmed meson (per tag)

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TABLE III. Production rates; statistical errors only.

$\frac{\text{Double tags}}{\text{Single tags}}$	Data fraction	Monte Carlo fraction
$2\times\frac{\Lambda_c^+\vert\overline{\Lambda}_c^-}{\overline{\Lambda}_c^-}$	$(7.19\pm1.08)\times10^{-3}$	$(1.49\pm0.62)\times10^{-3}$
$\frac{\Lambda_c^+\vert\overline{D}^0}{\overline{D}^0}$	$(2.05\pm0.16)\times10^{-3}$	$(1.82\pm0.08)\times10^{-3}$
$\frac{\Lambda_c^+\vert D^-}{D^-}$	$(2.03\pm0.26)\times10^{-3}$	$(1.82\pm0.14)\times10^{-3}$
$\frac{\Lambda\vert\overline{\Lambda}_c^-}{\overline{\Lambda}_c^-}$	$(19.3\pm1.1)\times10^{-3}$	$(8.28\pm0.66)\times10^{-3}$

Also, Λ–$\overline{\Lambda}$ correlations

	DATA	MC	DATA-MC
$(\Lambda_c\|\overline{\Lambda}_c)/(\Lambda_c+\overline{\Lambda}_c)$ $(\times 10^{-3})$	3.91 ± 0.47	1.05 ± 0.44	2.86 ± 0.64
$(\overline{\Lambda}_c\Lambda\| + \Lambda_c\overline{\Lambda}\|)/(\Lambda+\overline{\Lambda})$ $(\times 10^{-4})$	3.43 ± 0.36	2.16 ± 0.30	1.27 ± 0.46
$(\overline{\Lambda}_c\|\Lambda + \Lambda_c\|\overline{\Lambda})/(\Lambda+\overline{\Lambda})$ $(\times 10^{-4})$	20.2 ± 1.0	7.1 ± 0.7	13.1 ± 1.2
$(\Lambda\,\overline{\Lambda})/(\Lambda+\overline{\Lambda})$ $(\times 10^{-2})$	1.01 ± 0.01	0.67 ± 0.01	0.34 ± 0.02
$(\Lambda\overline{\Lambda}\|)/(\Lambda+\overline{\Lambda})$ $(\times 10^{-2})$	1.16 ± 0.01	1.17 ± 0.01	-0.01 ± 0.01
$(\Lambda\Lambda\|)/(\Lambda+\overline{\Lambda})$ $(\times 10^{-5})$	3.93 ± 2.10	3.73 ± 1.27	0.20 ± 2.45
$(\Lambda\,\Lambda)/(\Lambda+\overline{\Lambda})$ $(\times 10^{-5})$	33.0 ± 5.1	41.2 ± 4.1	-8.2 ± 6.6

JETSET 7.4 reproduces same hemisphere /\/\(c) correlations, but deficit of opposite hemisphere correlations

http://xxx.lanl.gov/PS_cache/hep-ex/pdf/0205/0205085v1.pdf

Recent CLEO results:η’ production

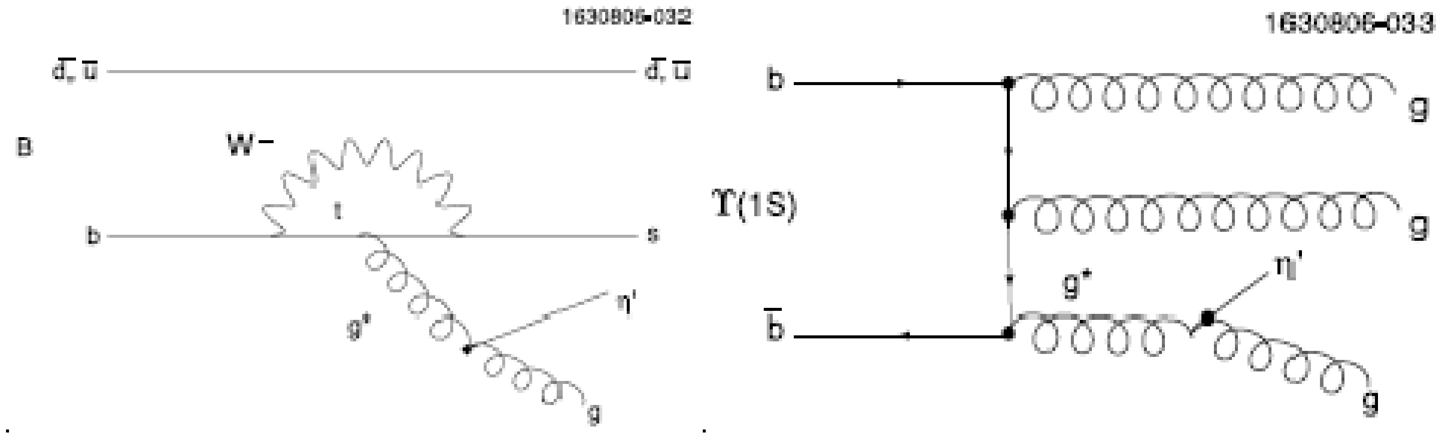


FIG. 1: Feynman Diagram for $b \to s(g^* \to g\eta')$ (left) and $\Upsilon(1S) \to ggg^* \to \eta' X$ (right).

Expect: enhanced coupling of eta’ in gluon-rich environment?

Find: Total η’ rate in ggg events comparable to qqbar

Thus we obtain

$$n(\Upsilon(1S) \to (ggg^*) \to \eta' X) \equiv \frac{N(\Upsilon(1S) \to ggg^* \to \eta' X)}{N(\Upsilon(1S) \to ggg^*)} = (3.2 \pm 0.2 \pm 0.2)\%,$$
$$n(\Upsilon(1S) \to (q\bar{q}) \to \eta' X) \equiv \frac{N(\Upsilon(1S) \to q\bar{q} \to \eta' X)}{N(\Upsilon(1S) \to q\bar{q})} = (3.8 \pm 0.2 \pm 0.3)\%,$$
$$n(\Upsilon(1S) \to \eta' X) \equiv \frac{N(\Upsilon(1S) \to \eta' X)}{N(\Upsilon(1S))} = (3.0 \pm 0.2 \pm 0.2)\%. \quad (6)$$

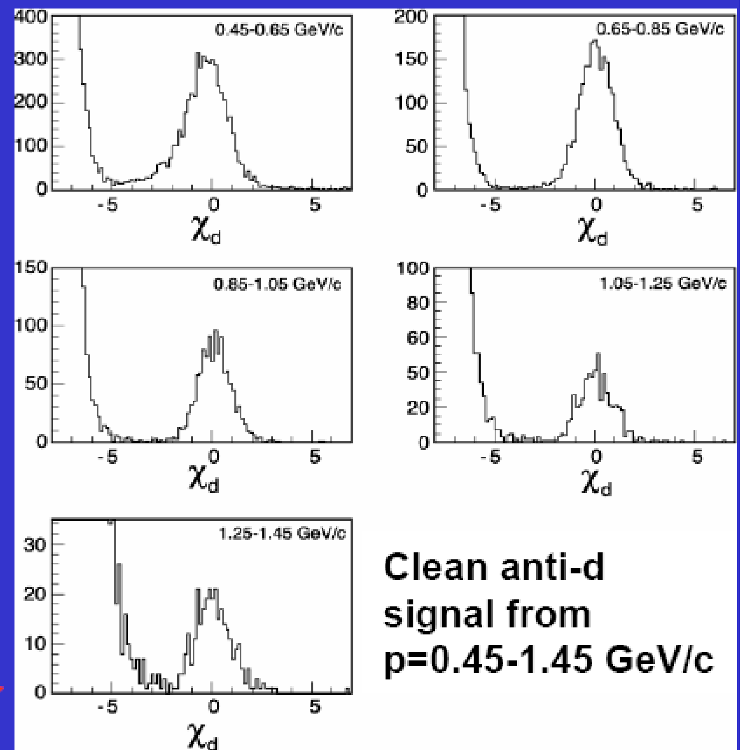
The $\Upsilon(1S) \to \eta' X$ branching fractions at high momentum (Z > 0.7) are measured to be

$$n(\Upsilon(1S) \to (ggg^*) \to \eta' X)_{Z>0.7} = (3.7 \pm 0.5 \pm 0.3) \times 10^{-4},$$
$$n(\Upsilon(1S) \to (q\bar{q}) \to \eta' X)_{Z>0.7} = (22.5 \pm 1.2 \pm 1.8) \times 10^{-4},$$
$$n(\Upsilon(1S) \to \eta' X)_{Z>0.7} = (5.1 \pm 0.4 \pm 0.4) \times 10^{-4}. \quad (7)$$

Deuteron production in $ggg+\gamma gg$ vs $\gamma^* \to qq$

Phys.Rev. D75 (2007) 012009

- d=bound (pn)
- "Coalescence models" attempt to describe appearance in fragmentation
  - How often do p & n appear "close enough" in phase space to combine into d ?
- Studies from ARGUS [PLB 236, 102 (1990)] in $\Upsilon \to d+X$ & ALEPH [PLB 639, 192 (2006)] in $Z \to d+X$
  - Accommodated by string model of Gustafson & Hakkinen [Zeit. Phys. C61, 683 (1994)]
  - Appearance in Υ ($ggg+\gamma gg$) vs γ^* or $Z \to qq$
  - Statistics-limited
- Experimental challenge is that d's can easily be produced in beam-gas and beam-material collisions
  - Look only for anti-d's
    - dE/dx in drift chamber
- Will present CLEO III data for inclusive anti-d's
  - Separate results for Υ vs continuum
  - For Υ(1S), rescale branching fraction to reflect DIRECT production from $ggg+\gamma gg$: B^*



Normalized dE/dx for anti-d

N.B. Raw deuteron:antideuteron rate ~10 (beam-gas/beam-wall interactions

Anti-d Production Result

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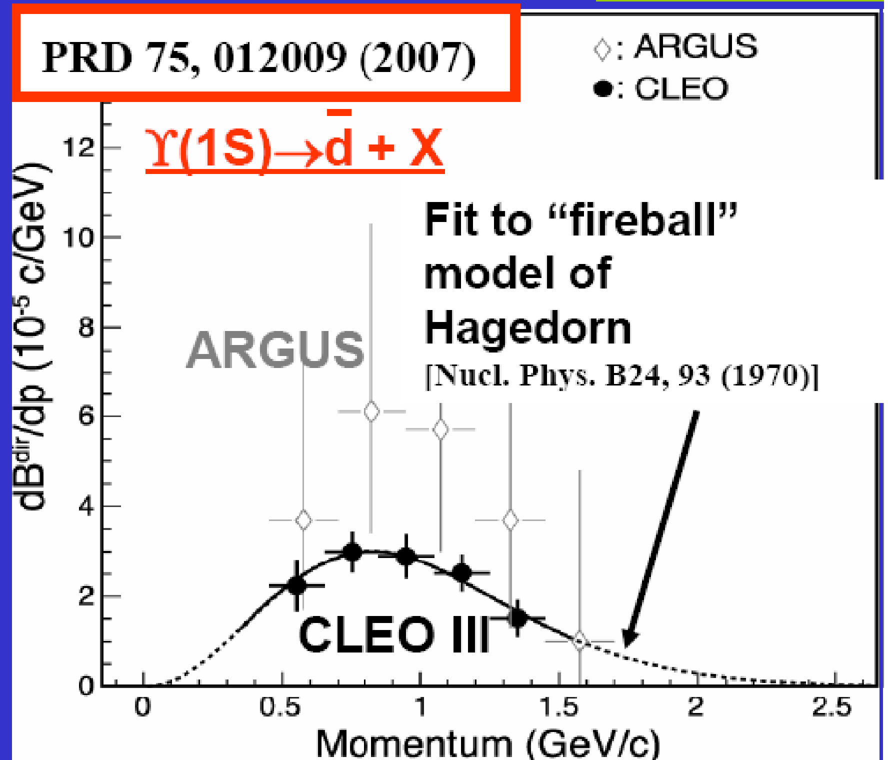
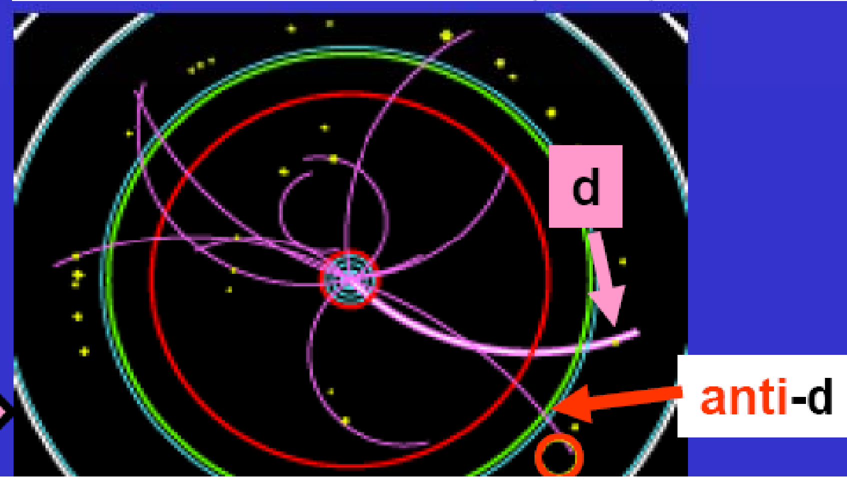
- $B^*(\Upsilon(1S) \to \bar{d}X) = (3.36 \pm 0.23 \pm 0.25) \times 10^{-5}$
  - based on 338 events
- $B(\Upsilon(2S) \to \bar{d}X) = (3.37 \pm 0.50 \pm 0.25) \times 10^{-5}$
  - based on 58 events
- $B(\Upsilon(4S) \to \bar{d}X) < 1.3 \times 10^{-5}$
  - based on 3 events
- $B(\gamma^* \to q\bar{q} \to \bar{d}X) < 1 \times 10^{-5}$
  - based on 4.5 events



- Hence $(ggg + \gamma gg)$ is about 3 times more likely than $\gamma^* \to q\bar{q}$ to produce deuterons

- How often is an anti-d compensated by a d as compared to (n, p) combinations?
  - We see roughly equal compensation by nn, np, pp relative to each other
  - ~1% of the time a d compensates
  - 3 d anti-d events observed



Implications for coalescence model

- Unclear.
- If anti-deuterons always compensated by deuterons, coalescence disfavored.
  - This result not inconsistent with coalescence…

Conclusions (part 1)

- Open charm produced in gluon hadronization @10 GeV, but at rate ~15% wrt qqbar
- Hidden charm enhanced
- Dibaryon production (anti-deuterons) enhanced by factor ~ square of single baryon enhancement from gluons
- Two gluons→baryons~2/3-3/4 3gluons-baryons, based on ggγ decays
  - Although shape of photon spectrum doesn't match with theory (yet)
- Color octet+singlet models still need some tuning (but an improvement over old school)

Intermezzo (sans music)

CLEO run plan for next few months.

Orange=good.

Everything else=bad.

Conclusions (2)

- “Rumors of my death are exaggerated” (M. Twain)
  - Unfortunately, not in this case: After 30-year physics program, CLEO data-taking ending in 97 hours.
- Still some fragmentation physics to be done:
  - More detailed studies of gg vs. ggg fragmentation
  - BE correlations at ECM=10 GeV vs. ECM=3 GeV

    $\Lambda\Lambda$ correlations again at 10 GeV and also at 3 GeV, with polarization correlations.
- Systematics-limited analyses (e.g., $D/D^*/D_s/\Lambda_c$ fractions on continuum) likely competitive for awhile
- and nice spectroscopy at threshold (e.g., first observation of $D_s \rightarrow$ p+antineutron)
- Expect active physics for another 12-18 mos., then the deluge…