CLEO Bottomonium Results

Helmut Vogel
Carnegie Mellon University

EPS 2007 Manchester, UK

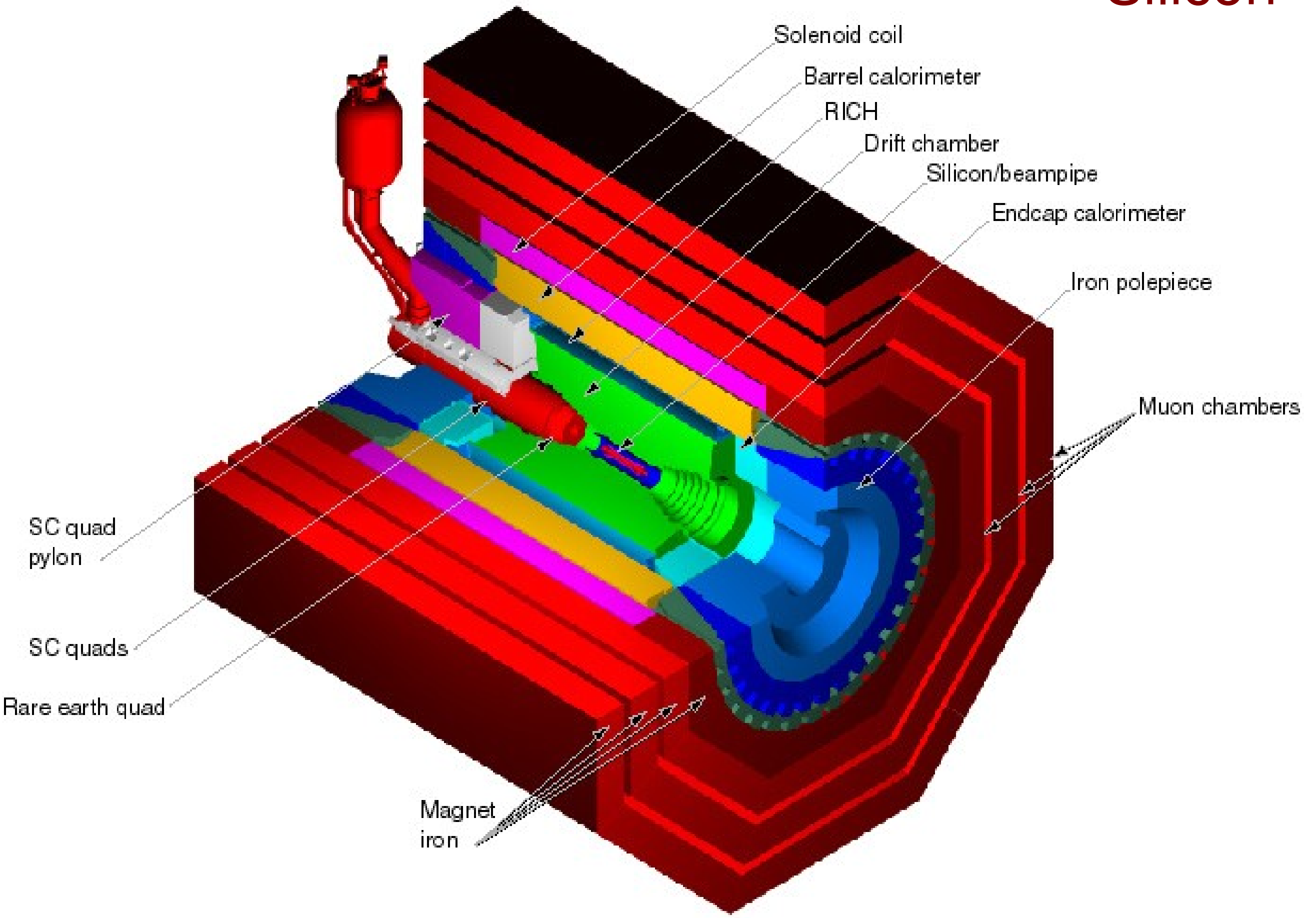
Radiative Decays:
$\Upsilon(1S) \to \gamma\, \eta(')$
$\Upsilon(1S) \to \gamma\, h^0\, h'^0$
$\Upsilon(nS) \to \gamma$ + narrow resonance

Fragmentation/Hadronization:
(anti)Deuterons in $\Upsilon(nS)$ decay
Particle yields in gluon & quark fragmentation
$\chi_{b,J} \to$ open charm
Decay *M.E.* in $\Upsilon(nS) \to \pi\, \pi\, \Upsilon(mS)$

Probing for New Physics:
$\Upsilon(1S) \to$ invisible final state

Detector and Data Sample

CLEO III (like CLEO-c, except B=1.5 T and Silicon Vertex Detector)



Data, taken 2001/2002 at CESR@Cornell:

E(cm)	Ldt	N(Υ)
Υ(1S)	1.1/fb	21 M
Υ(2S)	1.2/fb	9 M
Υ(3S)	1.1/fb	6 M

Radiative Decay: $\Upsilon(1S) \rightarrow \gamma\,\eta(')$

hep-ex/0704.3063

Motivation:

Simple process in theory (no hadronic FSI)

Extensively studied in J/ψ radiative decay -
good agreement with theory

Test scaling models (VDM, NRQCD, η_b mixing)

Previous UL ~ 2 x 10^{-5} (CLEO II)

Choose 3 main decay modes for η

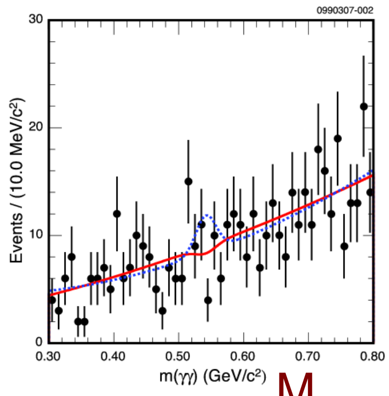
4 modes for η' (3x($\eta\pi^+\pi^-$) and γ ρ).

No signal claimed in any channel;

$B(\Upsilon(1S) \rightarrow \gamma\,\eta) < 1.0 \times 10^{-6}$

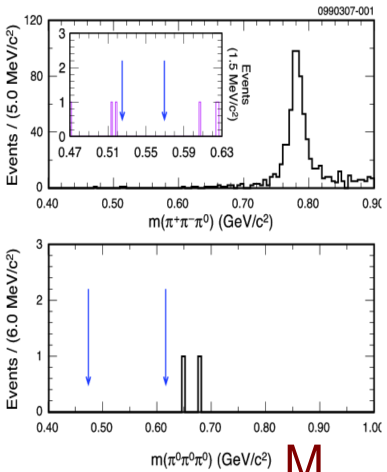
$B(\Upsilon(1S) \rightarrow \gamma\,\eta') < 1.9 \times 10^{-6}$

- compatible with ext'd VDM (Intemann 1983)
- compatible with Higher Twist model (Ma 2002)
- strongly disfavors mixing with η_b (Chao 1990)



$M_{\gamma\gamma}$

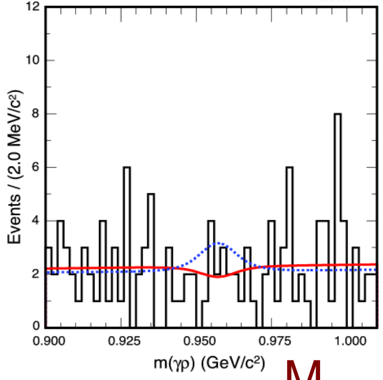
η



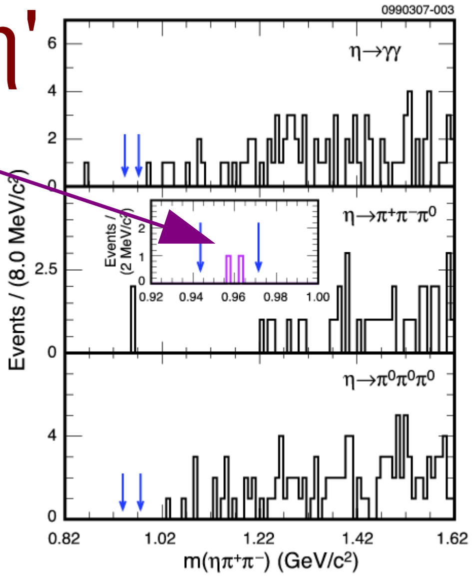
$M_{3\pi}$

2 "signal" (?)
events

η'



$M_{\gamma\rho}$



$M_{\eta\pi+\pi-}$

Radiative Decay: $\Upsilon(1S) \to \gamma\, h^0\, h'^0$

hep-ex/0512003
PRD 75 (2007) 072001

Motivation: comparison with charmonium, glueball search

LQCD (Morningstar *et al.*) predicts lightest glueball: $J^{PC}=0^{++}$, M~1.6 GeV, decay to *PP'*

Final states studied: $\gamma\,\pi^0\pi^0$, $\gamma\,\eta\,\eta$, $\gamma\,\pi^0\,\eta$

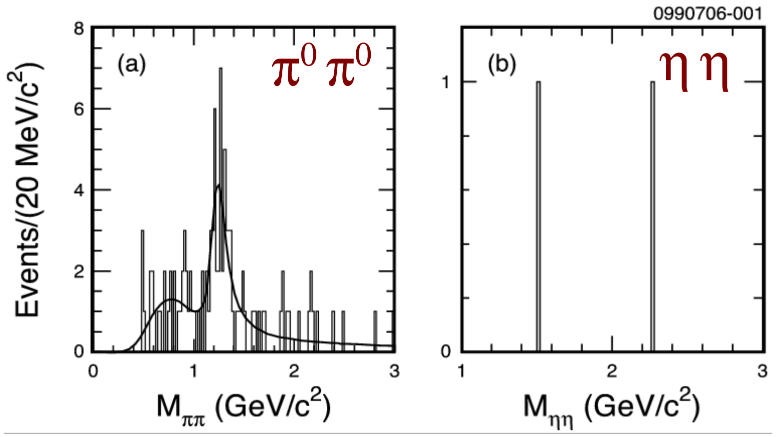
Signature: 1 photon of $E_\gamma > 4$ GeV

+ 4 photons of $E_\gamma \sim 0.5 - 2$ GeV

Results:

Observe $f_2(1270)$ signal in $\gamma\,\pi^0\pi^0$;

establish UL's on other modes.



$B(\Upsilon \to \gamma\, f_2(1270))$ x $B(f_2(1270) \to \pi^0\pi^0) = (3.0\pm0.5)\text{x}10^{-5}$

$B(\Upsilon \to \gamma\, f_2(1270)) = (10.5\pm1.6\pm1.9)\text{x}10^{-5}$

cf. $(10.2\pm0.8\pm0.7)\text{x}10^{-5}$ from $\gamma\pi^+\pi^-$ channel

CLEO III PRD 73 (2006) 032001

$B(\Upsilon \to \gamma\, f_0(1500)) < 1.5\text{x}10^{-5}$ ($\pi^0\pi^0$ mode)

$B(\Upsilon \to \gamma\, f_0(1500))$ x $B(f_0(1500) \to \eta\eta) < 3.0\text{x}10^{-6}$

$B(\Upsilon \to \gamma\, f_0(1710))$ x $B(f_0(1710) \to \pi^0\pi^0) < 1.4\text{x}10^{-6}$

$B(\Upsilon \to \gamma\, f_0(1710))$ x $B(f_0(1710) \to \eta\eta) < 1.8\text{x}10^{-6}$

$B(\Upsilon \to \gamma\, \pi^0\, \eta) < 2.4\text{x}10^{-6}$

Tests LQCD;
QCD factorization model
strongly disfavored.

Radiative Decay: $\Upsilon(\mathrm{nS}) \to \gamma +$ *narrow resonance*

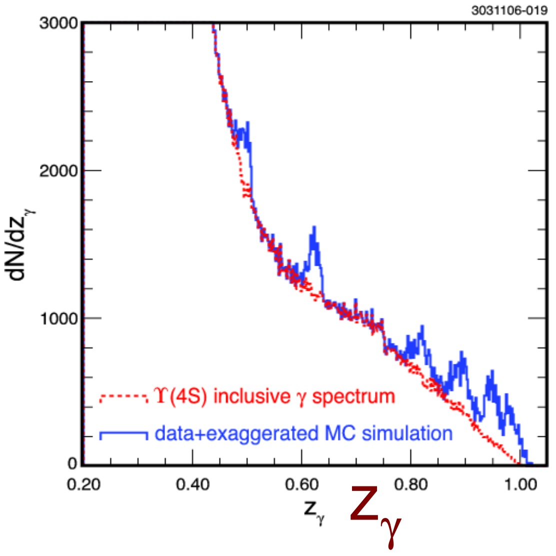
hep-ex/0704.2773

Probes hadronization in

$\Upsilon \to \gamma\, gg \to \gamma + R$

R = narrow resonance, assumed to decay to $n \geq 4$ tracks

$z_\gamma := E_\gamma / E_{beam}$, $M_R = 2\, E_{beam} \sqrt{(1-z_\gamma)}$



Select hadronic events with isolated photon.

Fit inclusive γ spectra from $\Upsilon(1,2,3,4S)$

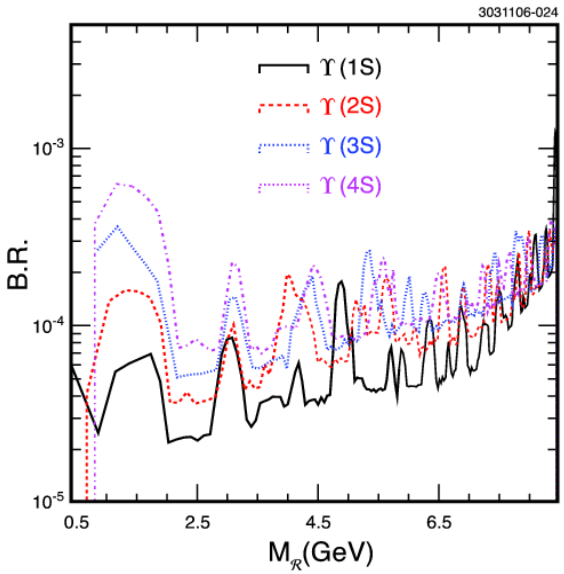
with bkgd(Chebyshev) + narrow Gaussian.

Find no signal;

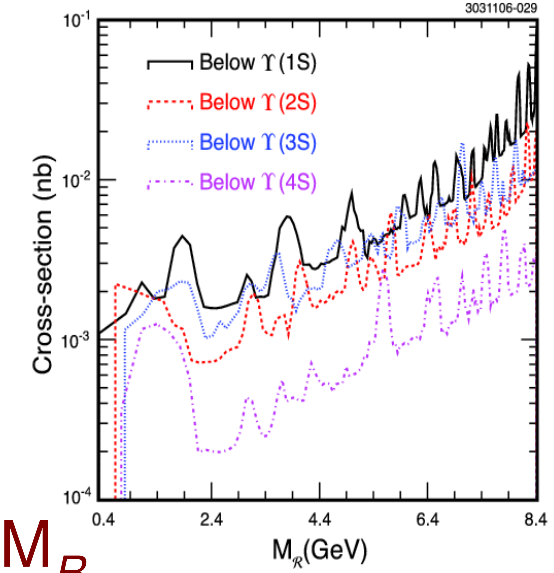
UL ~ 10^{-4} across most of spectrum for all $\Upsilon(1,2,3,4S)$ (track multiplicity ≥ 4)

Same analysis of continuum data:

UL on $\sigma\,(e^+e^- \to \gamma + R)$ *vs.* M_R



M_R



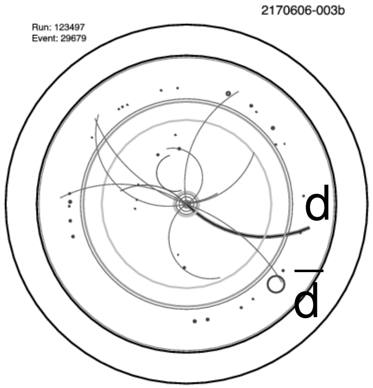
(anti)Deuterons in Υ Decay: $\Upsilon(nS) \rightarrow \bar{d}\,X$

hep-ex/0612019

PRD 75 (2007) 012009

First observed by ARGUS (1990): 19 events total (PID: ToF)

This experiment (CLEO III): > 300 events



$\Upsilon(1S)\rightarrow 3(\pi^+\pi^-)d\bar{d}\,X$ candidate

Goal: measure yield in direct decay $\Upsilon(nS) \rightarrow ggg\ (\gamma gg) \rightarrow \bar{d}\,X$

Subtract contribution from re-annihilation via virtual photon

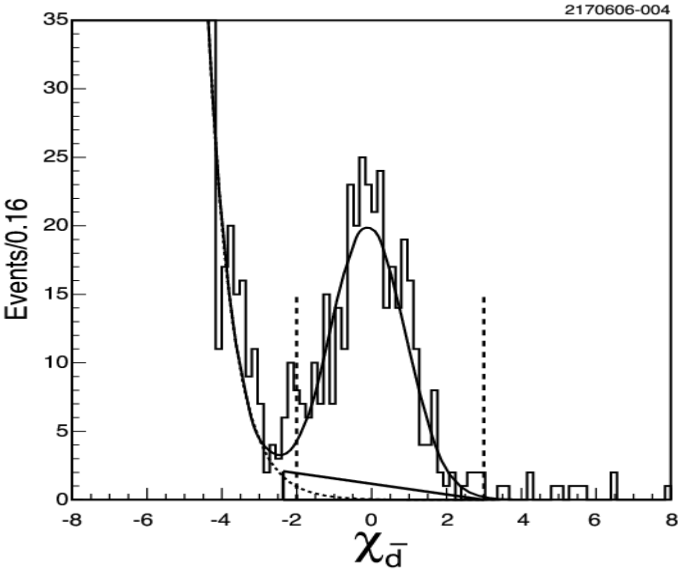
Theory: Coalescence/string model (Gustafson & Hakkinen 1994, extending Gutbrod *et al*. 1976, Sato & Kazaki 1983)

Select *anti*deuterons to avoid beam-gas, beam-wall bkgd

PID: *dE/dx* in momentum range 0.45 to 1.45 GeV/c

RICH to veto pions and (anti)protons

χ_d = normalized deviation from *dE/dx* value expected for measured track momentum, cosθ, number of hits



Extract yield for each of 5 momentum bins

(anti)Deuterons in Υ Decay: $\Upsilon(nS) \rightarrow \bar{d}\,X$

hep-ex/0612019

PRD 75 (2007) 012009

Results

$B(\Upsilon(1S) \rightarrow \bar{d}\,X) = (2.86 \pm 0.19 \pm 0.21) \times 10^{-5}$ (total)

$B^{dir}(\Upsilon(1S) \rightarrow \bar{d}\,X) = (3.36 \pm 0.23 \pm 0.25) \times 10^{-5}$ (direct)

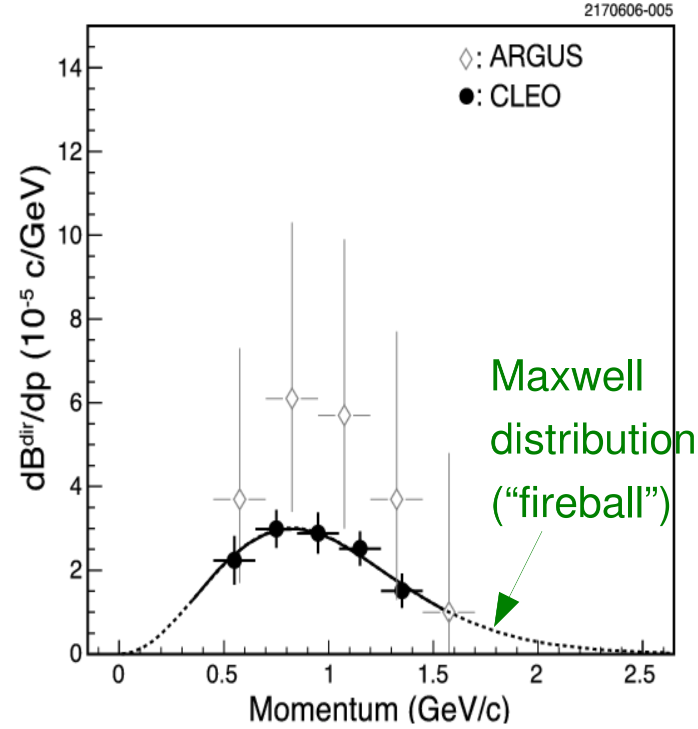
baryon number compensated via pp, pn, np, pp

(only ~1% via d)

$B(\Upsilon(2S) \rightarrow \bar{d}\,X) = (3.37 \pm 0.50 \pm 0.25) \times 10^{-5}$ (total),

after subtraction of $\pi\pi/\gamma\gamma$ cascades to $\Upsilon(1S)$)

$B(\Upsilon(4S) \rightarrow \bar{d}\,X) < 1.3 \times 10^{-5}$ (total)



Maxwell distribution ("fireball")

Continuum production of (anti)deuterons:

$\sigma(e^+e^- \rightarrow \bar{d}\,X) < 0.031\ pb$, at $\sqrt{s} = 10.5\ GeV$,

compared to $\sigma(e^+e^- \rightarrow hadrons) > 3000\ pb$

Fewer than 1 in 10^5 $q\bar{q}$ hadronizations produce (anti)deuterons

BUT more than 3 in 10^5 ggg, $gg\gamma$ hadronizations do!

Baryon & Meson Yields from *ggg*, $q\bar{q}$, γgg, and $\gamma q\bar{q}$

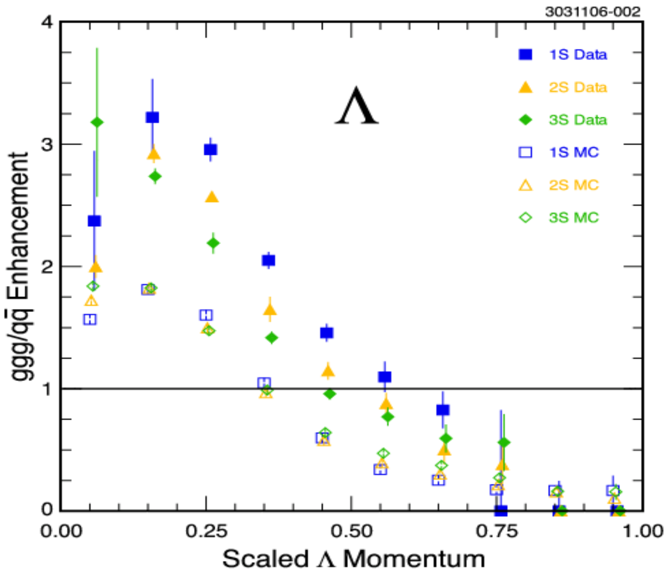
hep-ex/0704.2766

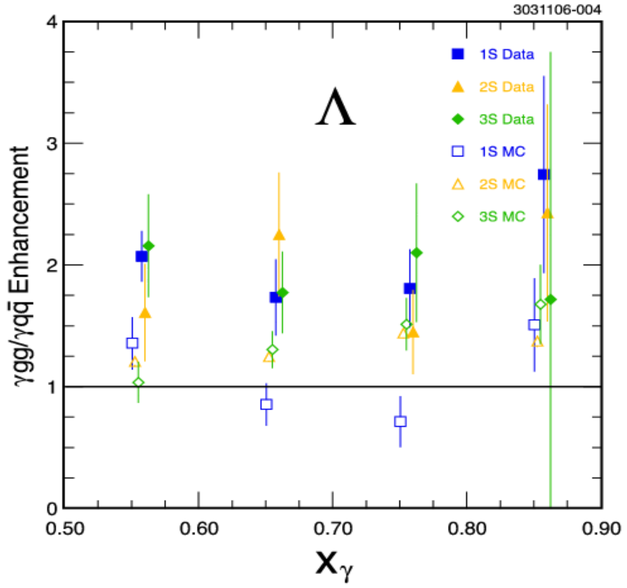
Study yields of particle types: **Λ , p , $\bar{p}$, ϕ , f_2(1270)** in

-> Υ(nS) → *hadrons* (*ggg* fragmentation)
-> off-resonance $e^+e^- \rightarrow$ *hadrons* ($q\bar{q}$ fragmentation)
-> Υ(nS) → γ + *hadrons* (γgg fragmentation)
-> off-resonance $e^+e^- \rightarrow \gamma$ + *hadrons* ($\gamma q\bar{q}$ fragmentation)

Measure momentum dependence of production and *p*-integrated yield ratios

$ggg/q\bar{q}$





$\gamma gg/\gamma q\bar{q}$

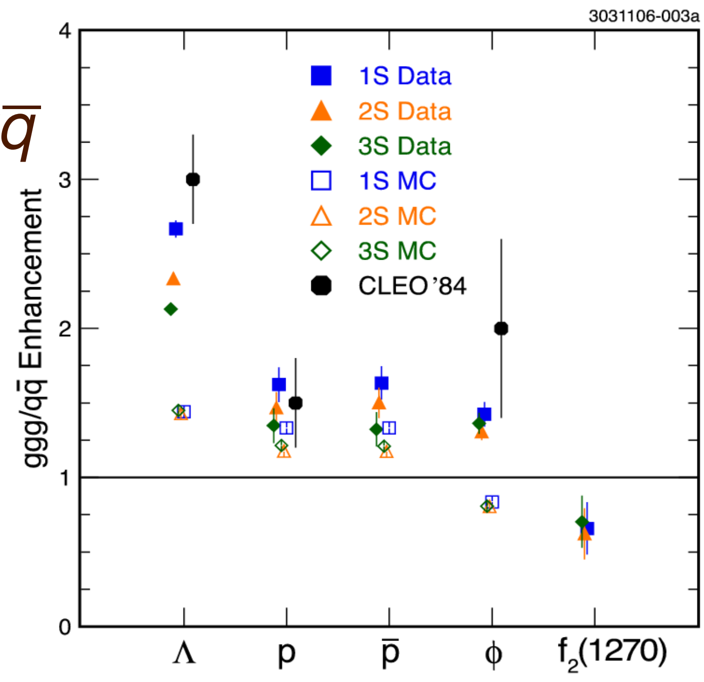
Baryon & Meson Yields from *ggg*, $q\bar{q}$, γgg, and $\gamma q\bar{q}$

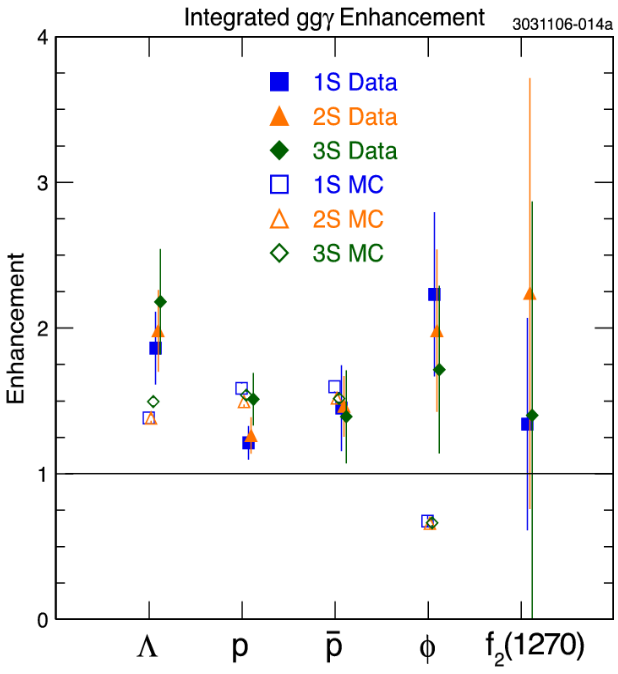
hep-ex/ 0704.2766

Main Results (*MANY* more in the paper, with detailed figures & tables!) :

- Study of particle yields extended from Υ(1S) to Υ(2S) and Υ(3S)
- Baryon production on Υ(2S) (Υ(3S)) is 5% (10%) lower than on Υ(1S)
- Baryon production per event on any Υ(nS) is > 2x higher than in continuum at similar √s
- Λ yield is strongly (~2x) enhanced in *gluon* over *quark* fragmentation; by contrast, proton yield is only slightly enhanced
- The JETSET generator, while successful w.r.t. gross features of particle production is in need of tuning at the single-particle yield level

ggg/$q\bar{q}$





$\gamma gg/\gamma q\bar{q}$

$\chi_{b,J} \rightarrow$ open charm

Hadronic decays of $\chi_{b,J}$ probe

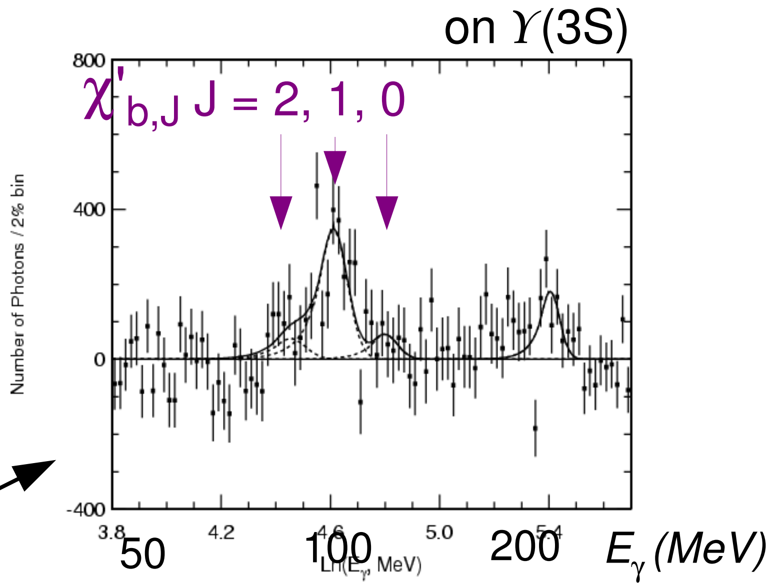
-- *gg* fragmentation (J = 0, 2)

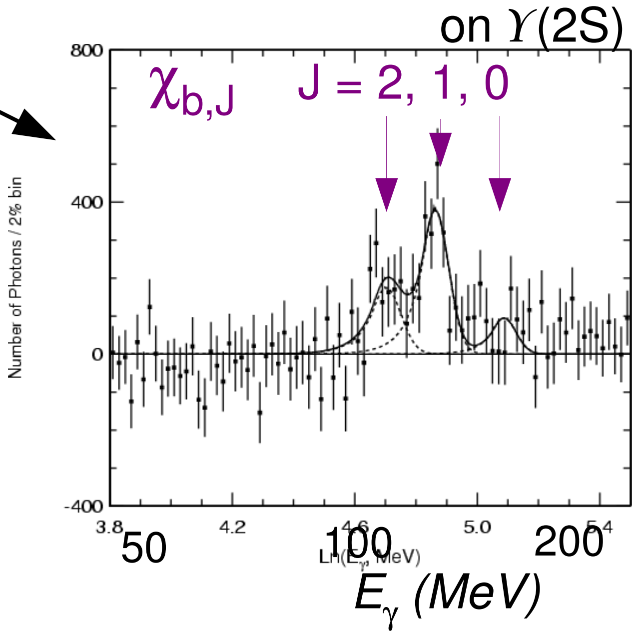
-- *g*g* ($q\bar{q}g$) fragmentation (J = 1)

Select $\Upsilon(2S), \Upsilon(3S) \rightarrow \gamma + hadrons$

Find inclusive D^0 among the hadrons

Plot photon energy spectrum for events
containing a reconstructed D^0





Result: clear signals for $\chi_{b,J}$ and $\chi'_{b,J}$

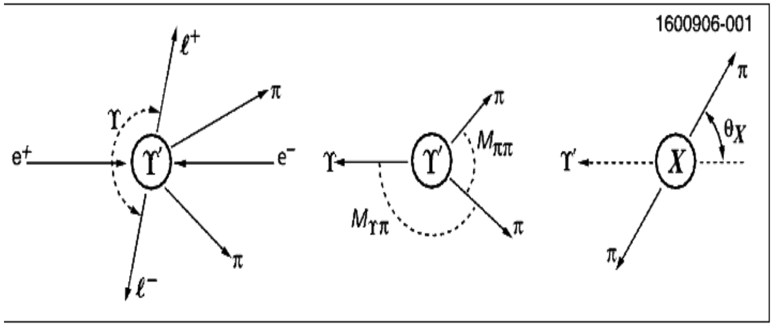
Paper with quantitative results is forthcoming

Most recent theory paper on this subject:
Bodwin, Braaten, & Lee, hep-ex/0704.2599

Decay Matrix Elements in $\Upsilon(nS) \rightarrow \pi\,\pi\,\Upsilon(mS)$

hep-ex/0706.2317

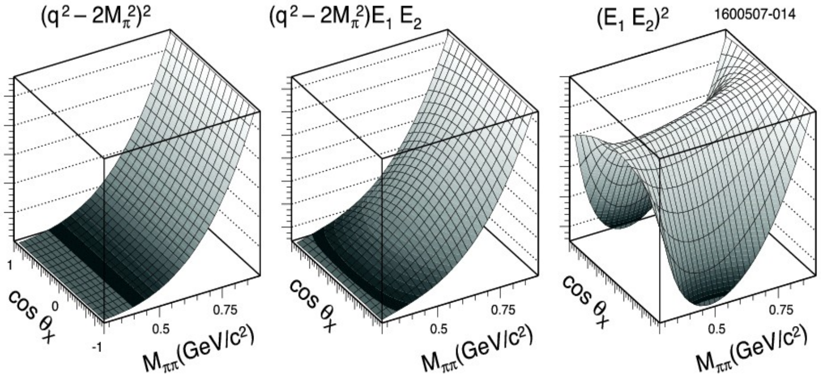
Motivation: Understanding the puzzling behavior of $\pi\,\pi$ cascade transitions between quarkonium states.



Use $M_{\pi\pi}$, $\cos\theta_x$
as kinematic variables

$M_{\pi\pi}$ spectra differ drastically from phase space
AND from each other for different transitions n→m :
high mass peak in 2→1, double peak in 3→1
(Babar, Belle: h.m.p. in 4→1, double peak in 4→2)

Theory: multipole expansion of the E1 gluon field
(Brown & Kahn 1975, Gottfried 1978, Yan 1980,
Voloshin & Zakharov 1980)



pure *A* interference pure *B*

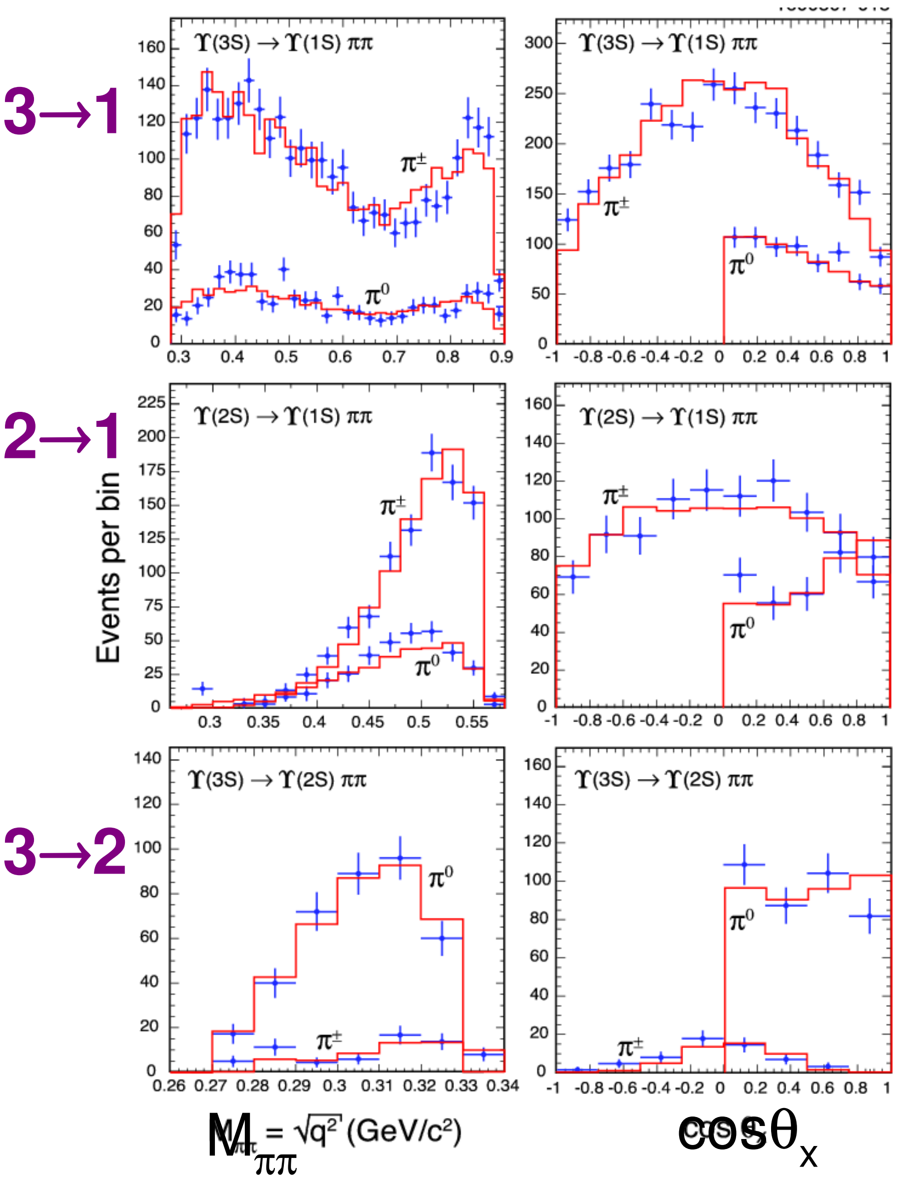
We perform 2-D analysis of CLEO data
$\Upsilon(nS) \rightarrow \pi\,\pi\,\Upsilon(mS) \rightarrow \pi\,\pi\,(e^+e^-, \mu^+\mu^-)$
Fit complex constant form factors *A*, *B*, *(C)*
of the general M.E.,

$$M = A(\varepsilon'.\varepsilon)(q^2-2M^2_\pi) + B(\varepsilon'.\varepsilon)\,E_1\,E_2 + C(\text{chromo-magn.})$$

Decay Matrix Elements in $\Upsilon(nS) \rightarrow \pi\pi\Upsilon(mS)$

Results (data/fit)

hep-ex/0706.2317

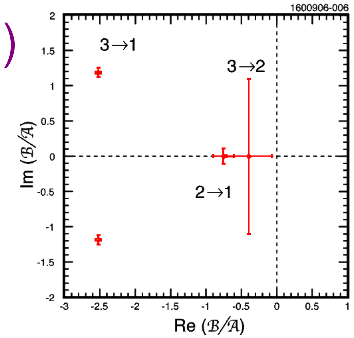


Fit, no $\mathcal{C}$, total error		
$\Upsilon(3S) \rightarrow \Upsilon(1S)\pi\pi$	$\Re(\mathcal{B}/\mathcal{A})$	-2.52 ± 0.04
	$\Im(\mathcal{B}/\mathcal{A})$	$\pm 1.19 \pm 0.06$
	$\lvert\mathcal{B}/\mathcal{A}\rvert$	2.79 ± 0.05
	δ_{BA}	$155(205) \pm 2$
$\Upsilon(2S) \rightarrow \Upsilon(1S)\pi\pi$	$\Re(\mathcal{B}/\mathcal{A})$	-0.75 ± 0.15
	$\Im(\mathcal{B}/\mathcal{A})$	0.00 ± 0.11
	$\lvert\mathcal{B}/\mathcal{A}\rvert$	0.75 ± 0.15
	δ_{BA}	180 ± 9
$\Upsilon(3S) \rightarrow \Upsilon(2S)\pi\pi$	$\Re(\mathcal{B}/\mathcal{A})$	-0.40 ± 0.32
	$\Im(\mathcal{B}/\mathcal{A})$	0.00 ± 1.1
Fit, float $\mathcal{C}$, total error		
$\Upsilon(3S) \rightarrow \Upsilon(1S)\pi\pi$	$\lvert\mathcal{B}/\mathcal{A}\rvert$	2.89 ± 0.25
	$\lvert\mathcal{C}/\mathcal{A}\rvert$	0.45 ± 0.40

$|C/A| < 1.09$ at 90% C.L. (not very stringent)

- Good fits with C=0 and constant A, B
  (but different for different (n,m))
- $|B/A|$ large in 3→1,
  with significant phase!

??(Voloshin, arXiv:0707.1272)



Search for Invisible Decays of Υ(1S)

hep-ex/0612051
PRD 75 (2007) 031104

In SM, $B(\Upsilon(1S) \rightarrow Z^0 \rightarrow \nu\bar{\nu}) \sim 10^{-5}$

Motivation: (1) Confirm that $\Gamma_{invis}(\Upsilon(1S))$ is negligible

(which we assumed in earlier measurements of Γ_{tot})

(2) Test recent BSM predictions (*e.g.*, Fayet 2006; McElrath 2005: $B(\Upsilon(1S) \rightarrow \chi\chi \rightarrow \mathit{invisible}) = 0.41\%$!)

Analysis method:

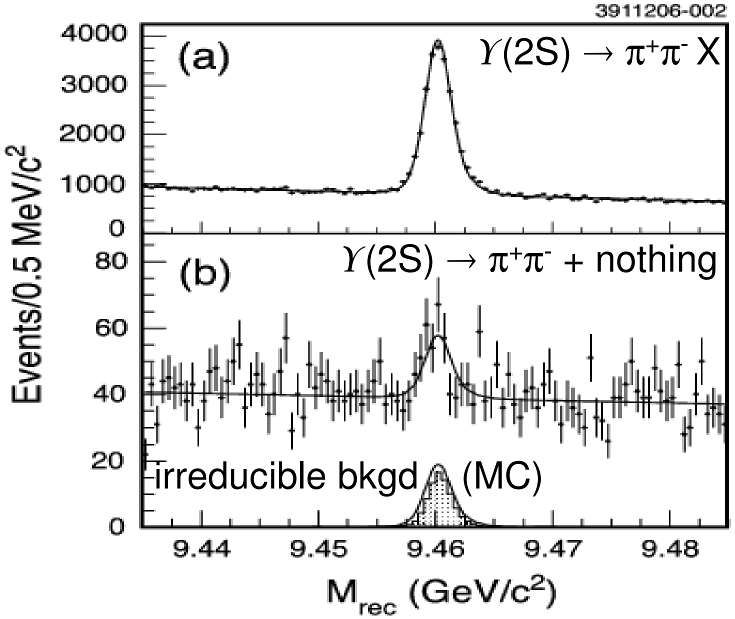
- tag via $\Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S) \rightarrow \pi^+\pi^-$ + *"nothing"*
- subtract sidebands in recoil mass spectrum
- suppress background from two-photon events
- simulate irreducible backgrounds from $\Upsilon(1S) \rightarrow l^+l^-$

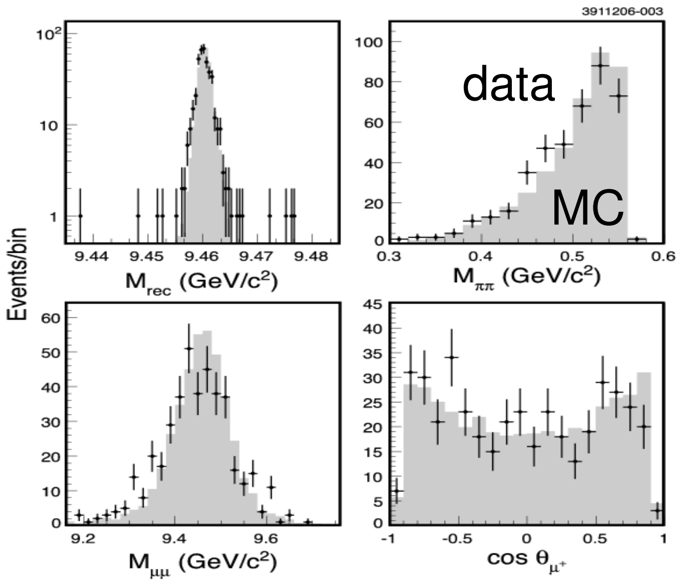
Result: $B[\Upsilon(1S) \rightarrow \mathit{invisible}] = (0.16 \pm 0.13 \pm 0.05)\ \%$

$B[\Upsilon(1S) \rightarrow \mathit{invisible}] < 0.39\ \%$ (90% CL)

(*cf.* Belle: < 0.25%, PRL 98 (2007) 132001)

$\Gamma_{invis}(\Upsilon(1S))$ is indeed negligible compared to Γ_{tot}





Summary

Using the CLEO III bottomonium data sample
we have studied **particle yields** and **hadronization mechanisms**
in great detail and in many different environments --

Radiative Decays:	$\Upsilon(1S) \rightarrow \gamma\,\eta(')$
	$\Upsilon(1S) \rightarrow \gamma\,h^0\,h'^0$
	$\Upsilon(nS) \rightarrow \gamma$ + narrow resonance
Hadronic Decays:	(anti)Deuterons in $\Upsilon(1S)$ decay
	Particle yields in gluon & quark fragmentation
	$\chi_b \rightarrow$ open charm
	Decay *M.E.* in $\Upsilon(nS) \rightarrow \pi\,\pi\,\Upsilon(mS)$

We also set an **upper limit on Υ(1S) decay into invisible final states**.

Backup Slides

$B_{\tau\tau}$ of Υ(nS) and Lepton Universality

hep-ex/0607019
PRL 98 (2007) 052002

First Measurement of $B_{\tau\tau}(\Upsilon(3S))$

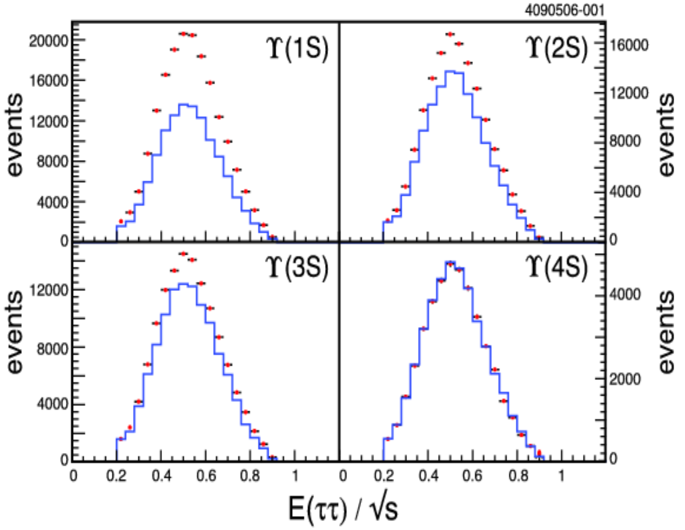
Updated $B_{\tau\tau}(\Upsilon(1S, 2S))$ results

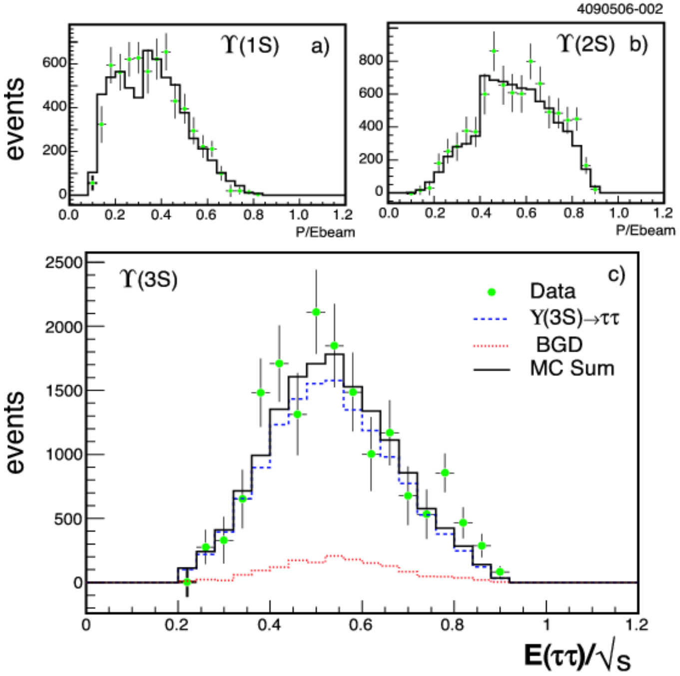
Completes the series of precision measurements of Γ_{ee} , $B_{\mu\mu}$, and $B_{\tau\tau}$ of all bound Υ(nS) states at CLEO III

Tau pair selection: 2 tracks of opp. charge and $0.1 < |p|/E_{beam} < 0.9$ each.

Analyze and simulate all combinations (ee, μμ, eμ, eX, μX, XX),

Use $\Upsilon(nS) \rightarrow \mu^+\mu^-$ data as reference



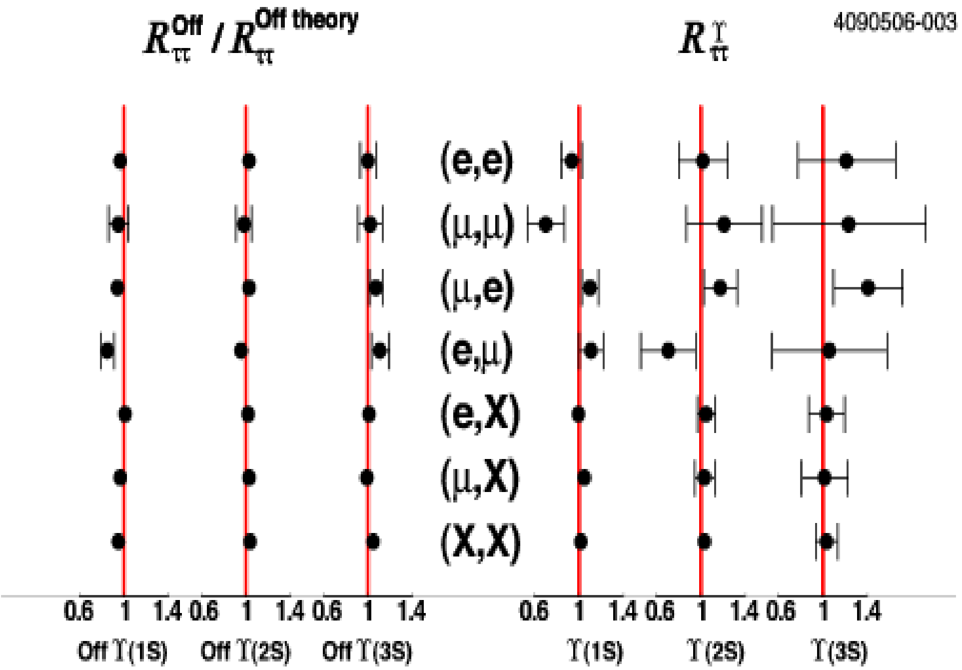


$B_{\tau\tau}$ of Υ(nS) and Lepton Universality

hep-ex/0607019

PRL 98 (2007) 052002

	$R^{\Upsilon}_{\tau\tau}$	$B_{\tau\tau}(\%)$	
Υ(1S)	1.02±0.02±0.05	2.54±0.04±0.12	(most precise)
Υ(2S)	1.04±0.04±0.05	2.11±0.07±0.13	(much improved precision)
Υ(3S)	1.05±0.08±0.05	2.52±0.19±0.15	(first time measurement)



The ratio $R^{\Upsilon}_{\tau\tau} = (B_{\tau\tau}/B_{\mu\mu})$ (=1 in SM)

is sensitive to CP-odd Higgs, A_0, via Υ

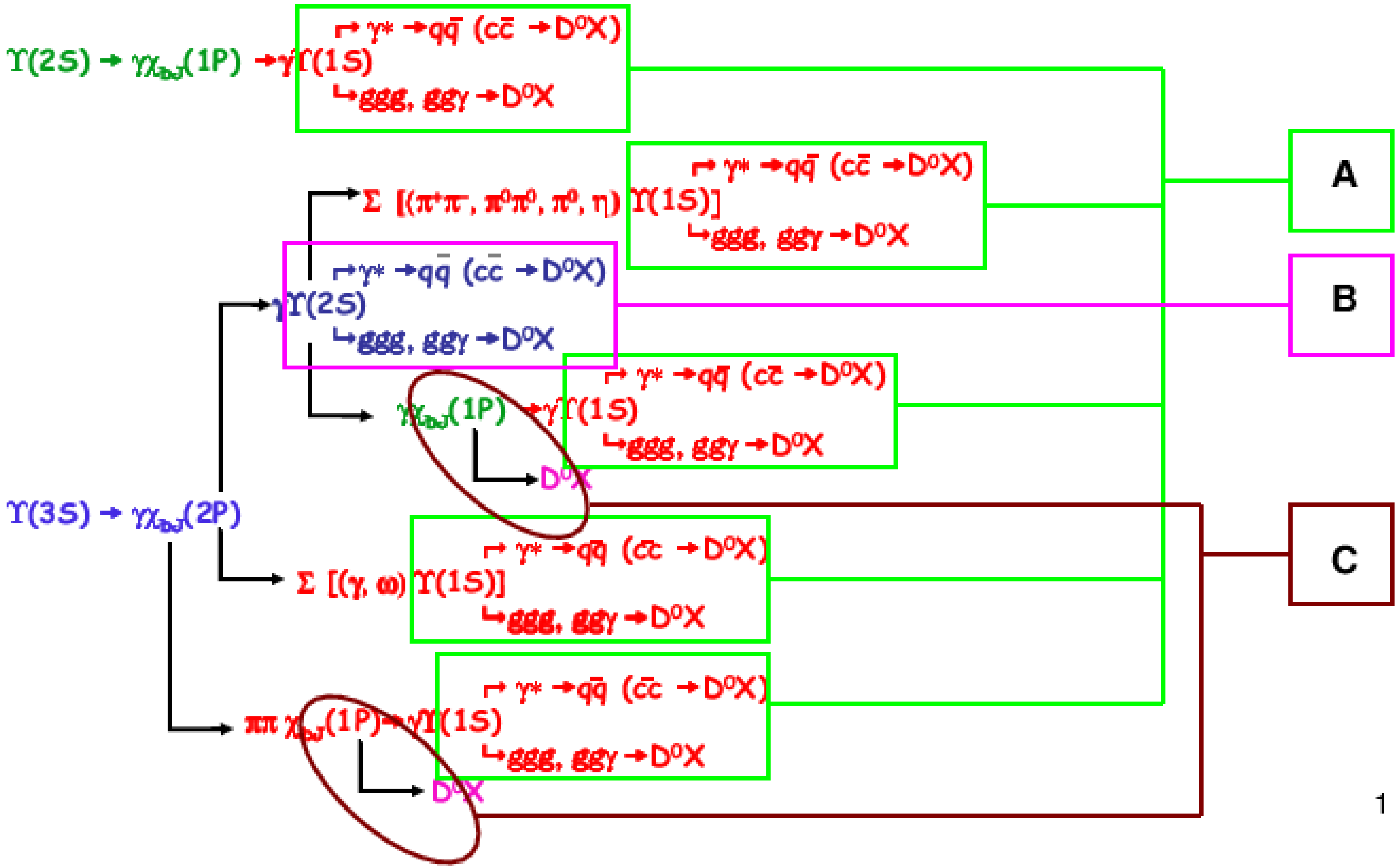
$\Upsilon(1S) \rightarrow \gamma\, \eta_b$, $\eta_b \rightarrow A_0 \rightarrow \tau^+ \tau^-$

(Sanchis-Lozano 2004)

Our result: product BF < 0.27% for

$M(\Upsilon(1S)) - M(\eta_b) + G(\eta_b) < O(100\ \mathrm{MeV})$

Non-direct sources of D^0's in $\Upsilon(2S)/\Upsilon(3S)$ decays:



$\Upsilon(2S) \rightarrow \gamma\chi_{bJ}(1P) \rightarrow \gamma\Upsilon(1S)$

$\rightarrow \gamma^* \rightarrow q\bar{q}$ ($c\bar{c} \rightarrow D^0X$)

$\rightarrow ggg, gg\gamma \rightarrow D^0X$

$\rightarrow \Sigma\ [(\pi^+\pi^-, \pi^0\pi^0, \pi^0, \eta)\ \Upsilon(1S)]$

$\rightarrow \gamma^* \rightarrow q\bar{q}$ ($c\bar{c} \rightarrow D^0X$)

$\rightarrow ggg, gg\gamma \rightarrow D^0X$

$\rightarrow \gamma\Upsilon(2S)$

$\rightarrow \gamma^* \rightarrow q\bar{q}$ ($c\bar{c} \rightarrow D^0X$)

$\rightarrow ggg, gg\gamma \rightarrow D^0X$

$\rightarrow \gamma\chi_{bJ}(1P) \rightarrow \gamma\Upsilon(1S)$

$\rightarrow \gamma^* \rightarrow q\bar{q}$ ($c\bar{c} \rightarrow D^0X$)

$\rightarrow ggg, gg\gamma \rightarrow D^0X$

$\rightarrow D^0X$

$\Upsilon(3S) \rightarrow \gamma\chi_{bJ}(2P)$

$\rightarrow \Sigma\ [(\gamma, \omega)\ \Upsilon(1S)]$

$\rightarrow \gamma^* \rightarrow q\bar{q}$ ($c\bar{c} \rightarrow D^0X$)

$\rightarrow ggg, gg\gamma \rightarrow D^0X$

$\rightarrow \pi\pi\ \chi_{bJ}(1P) \rightarrow \gamma\Upsilon(1S)$

$\rightarrow \gamma^* \rightarrow q\bar{q}$ ($c\bar{c} \rightarrow D^0X$)

$\rightarrow ggg, gg\gamma \rightarrow D^0X$

$\rightarrow D^0X$

Decay Matrix Elements in $\Upsilon(nS) \to \pi\pi\Upsilon(mS)$

hep-ex/0706.2317