Di-electron Widths of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$

Jim Pivarski

CLEO Collaboration

Introduction

Even though Nuclear Strong force is "simpler" than Electroweak,
it is an obstacle to understanding Electroweak

Nuclear Strong force (QCD)

- Highly symmetric
- One tunable parameter (+ quark masses)
- Non-perturbative below 1 GeV

Electroweak interaction

- P, CP symmetries broken
- No obvious pattern in flavor-changing interactions:

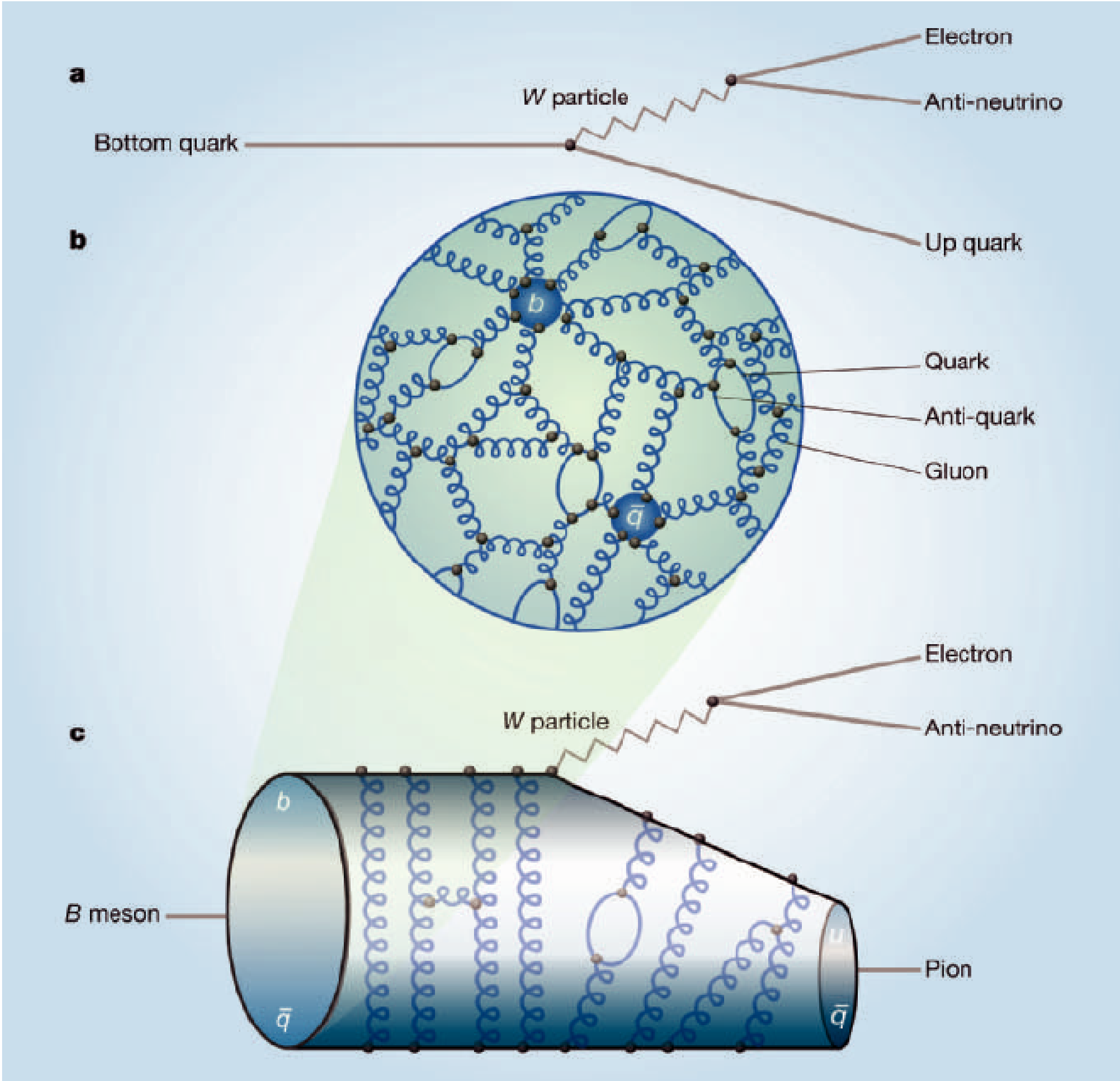
$$P(q_1 \to q_2) \propto \left| q_2 \cdot \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot q_1 \right|^2$$

- Perturbative

All measurements of quark properties must involve QCD

To learn more about electroweak interactions, we need to understand QCD better!

A typical electroweak measurement: $b \to u$ process



Outline for this Talk

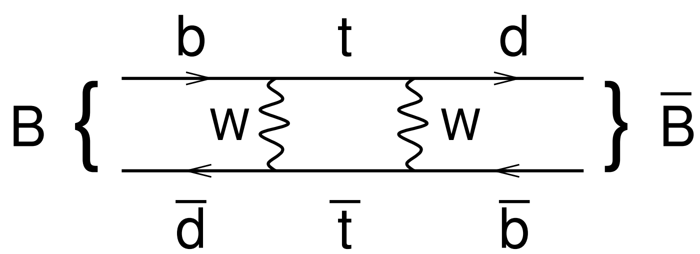
1. Show how V_{td} is obfuscated by QCD and how our knowledge of it is limited by our ability to compute QCD

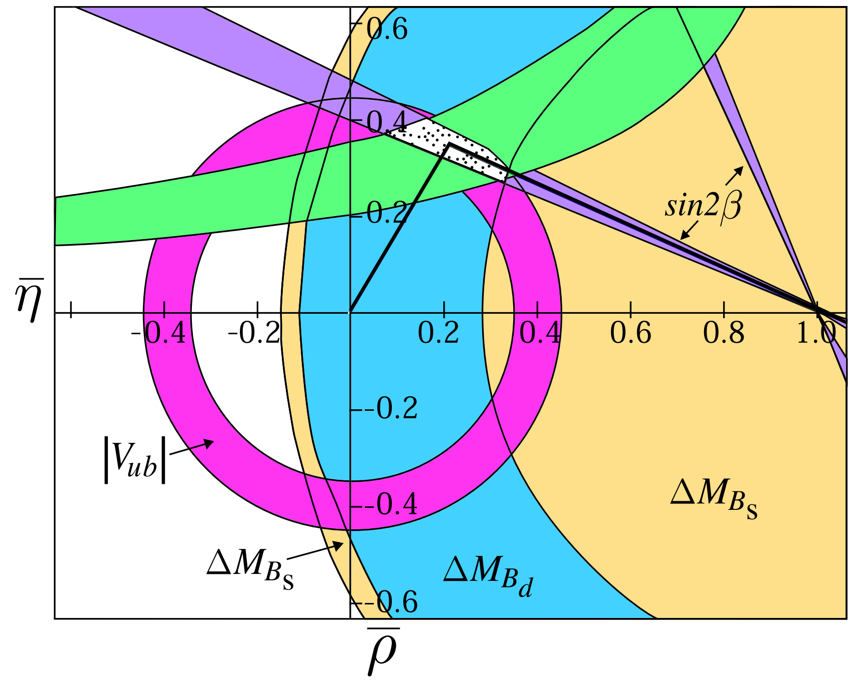
2. Introduce Lattice QCD as a tool which can help to compute the necessary parameter

3. Describe a CLEO experiment which tests this calculation: di-electron widths of $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$

Measuring V_{td}

B-$\bar{B}$ mixing:





$\Delta M_{B_d} = (known) \times ({f_B}^2 B_B) \times |V_{td}|^2 =$ 0.510 $\pm$ 0.005 ps^{-1}, a 1% measurement!

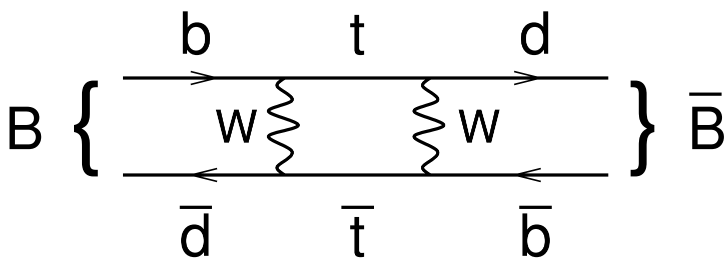
But f_B is only known to 20% of itself

Hence the 20% uncertainty in V_{td} (blue band)

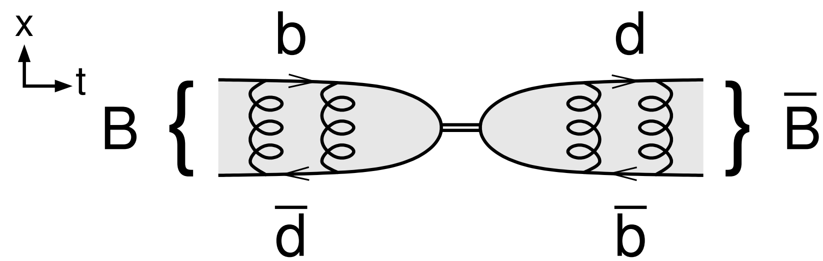
What is f_B?

QCD corrections to b-$\bar{d}$-electroweak "vertex"

On QCD length scales, B-mixing diagram

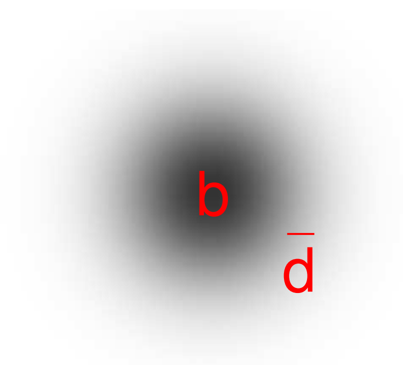


looks like this:



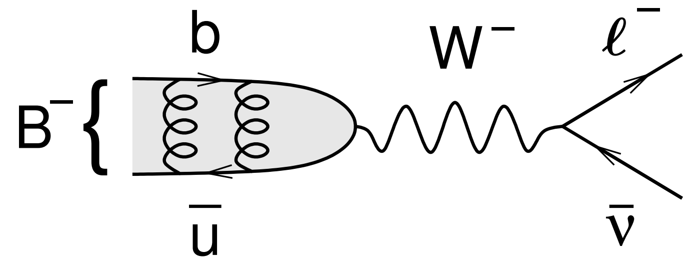
f_B expresses the probability that the $\bar{d}$ will fluctuate onto the b quark

That is, the value of the spatial wavefunction at the origin



Determining f_B

Experimentally? $B^- \to \ell^- \bar{\nu}$

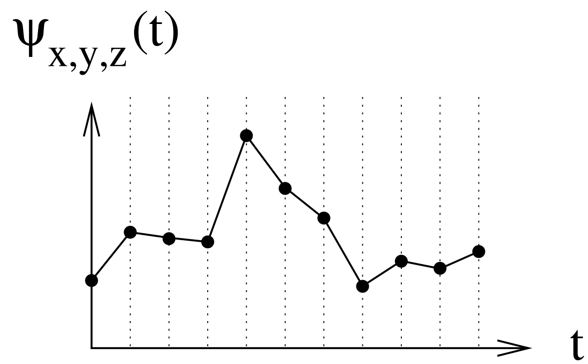


- $\Gamma(B^- \to \ell^- \bar{\nu}) = \frac{{G_F}^2}{8\pi} \underbrace{|V_{ub}|^2}_{\text{small}} \underbrace{{m_l}^2 M_B \left(1 - \frac{{m_l}^2}{{M_B}^2}\right)^2}_{\text{small}} {f_B}^2$

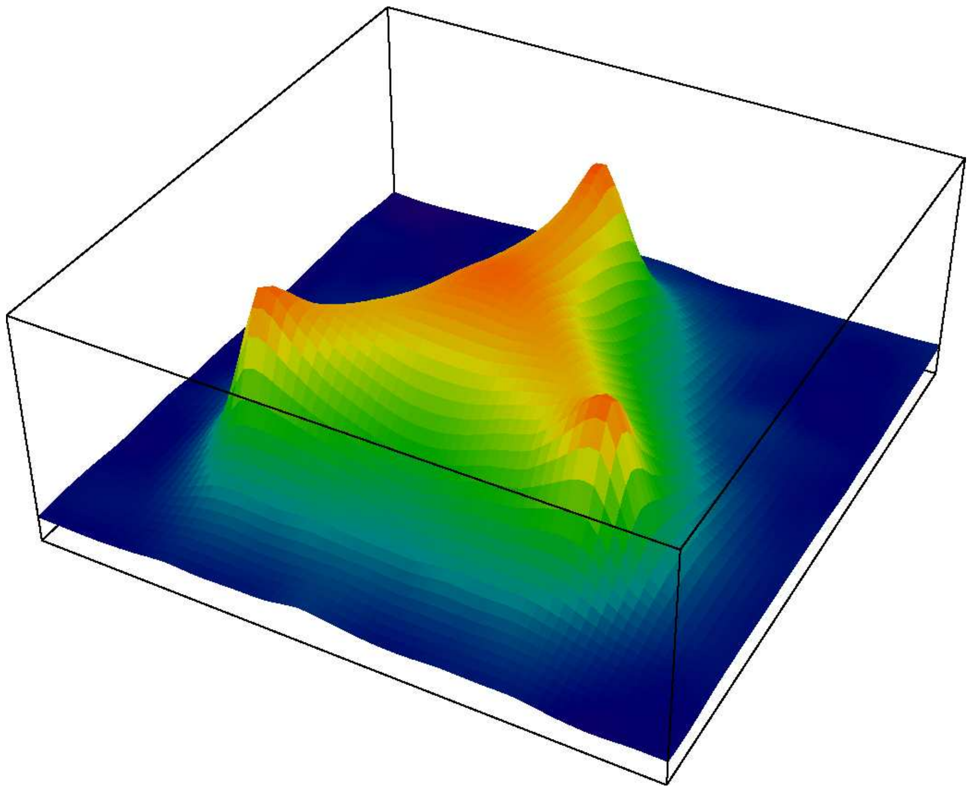
- $\mathcal{B}(B^- \to \tau^- \bar{\nu}) < 1.8 \times 10^{-4}$ at 90% C.L. (253 fb^{-1} at Belle 2005)

Theoretically? Need non-perturbative techniques...

Lattice QCD

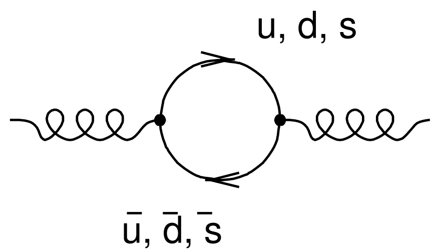


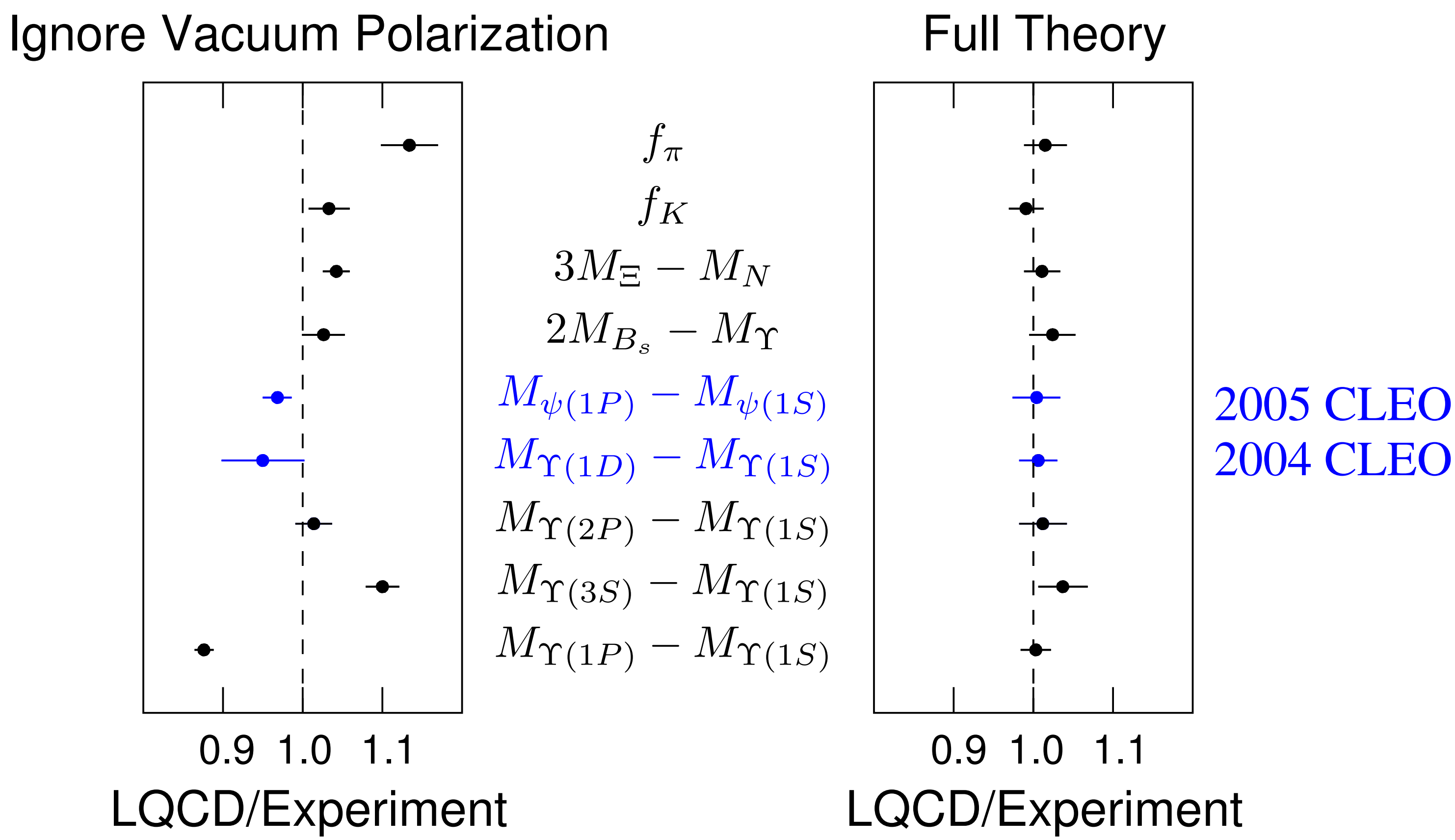
- Evaluate path integral with Monte Carlo integration
- Very computationally intensive



Recent Breakthrough (c. 1999)

Allows for calculation of vacuum polarization



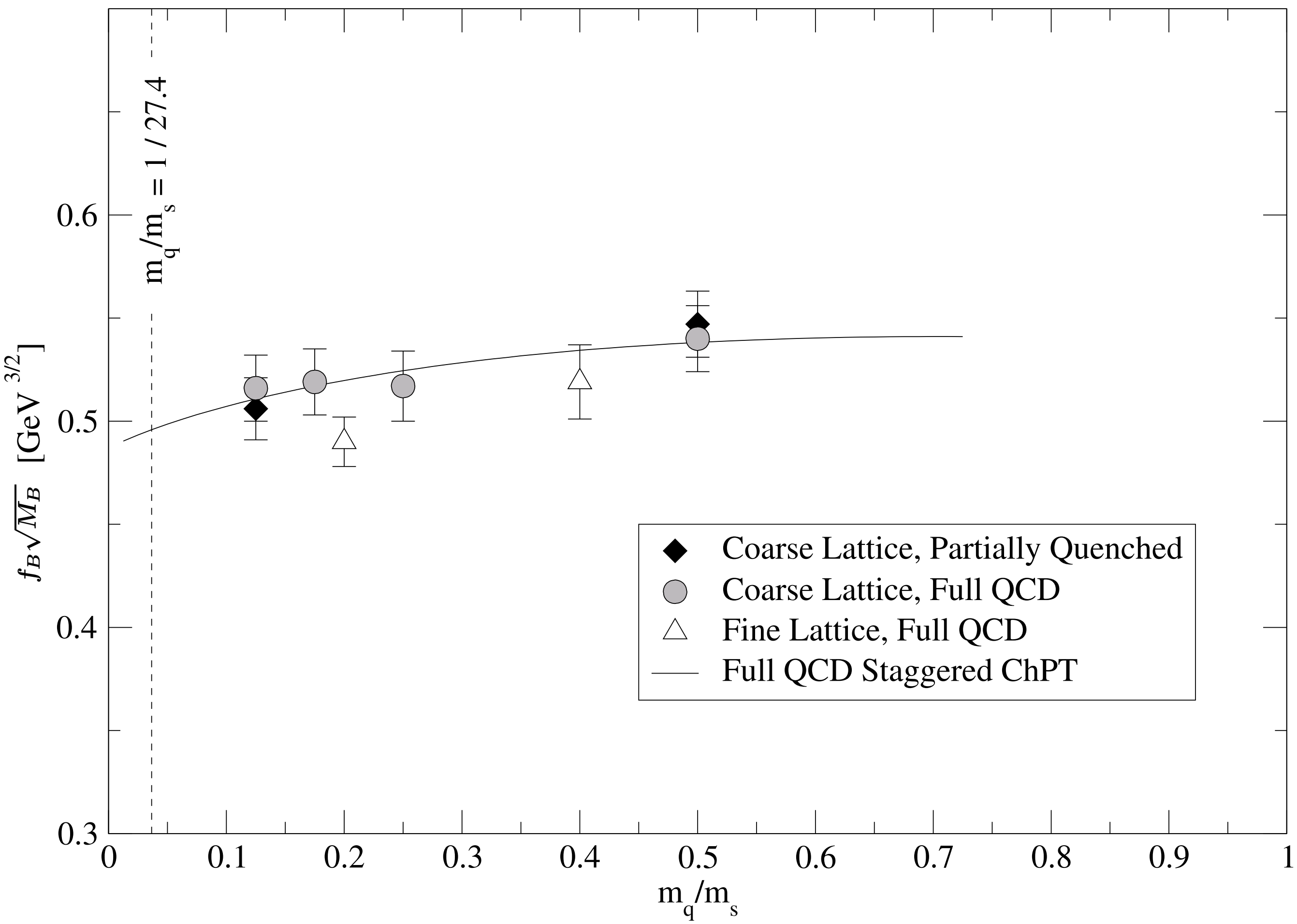


Ω^- and B_c masses also confirmed to high accuracy

f_B from Lattice QCD

$f_B = 216 \pm 9 \pm 19 \pm 4 \pm 6$ MeV

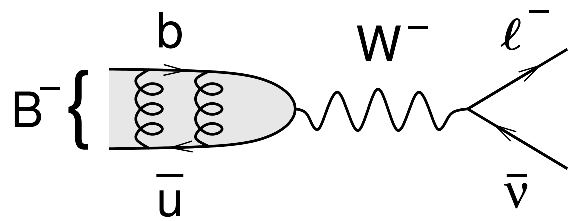
Phys. Rev. Lett. **95**, 212001 (2005)



But how can we *verify* this?

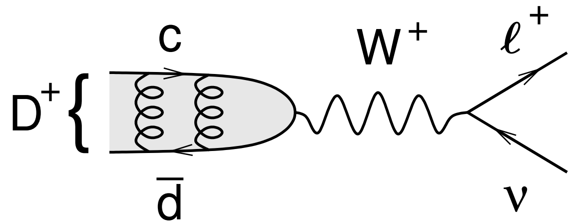
Test with Processes that Differ by One Quark Flavor

f_B



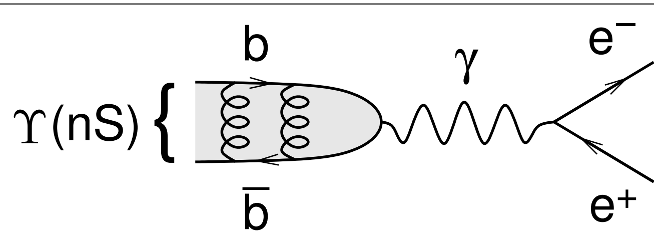
LQCD only

f_D



LQCD vs CLEO

$$\Gamma(\Upsilon \rightarrow e^+e^-)$$

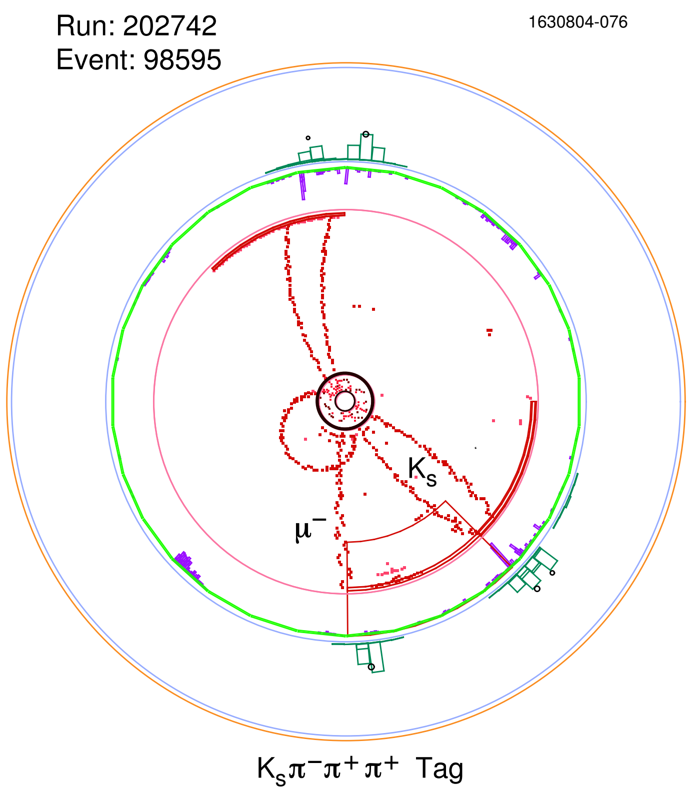


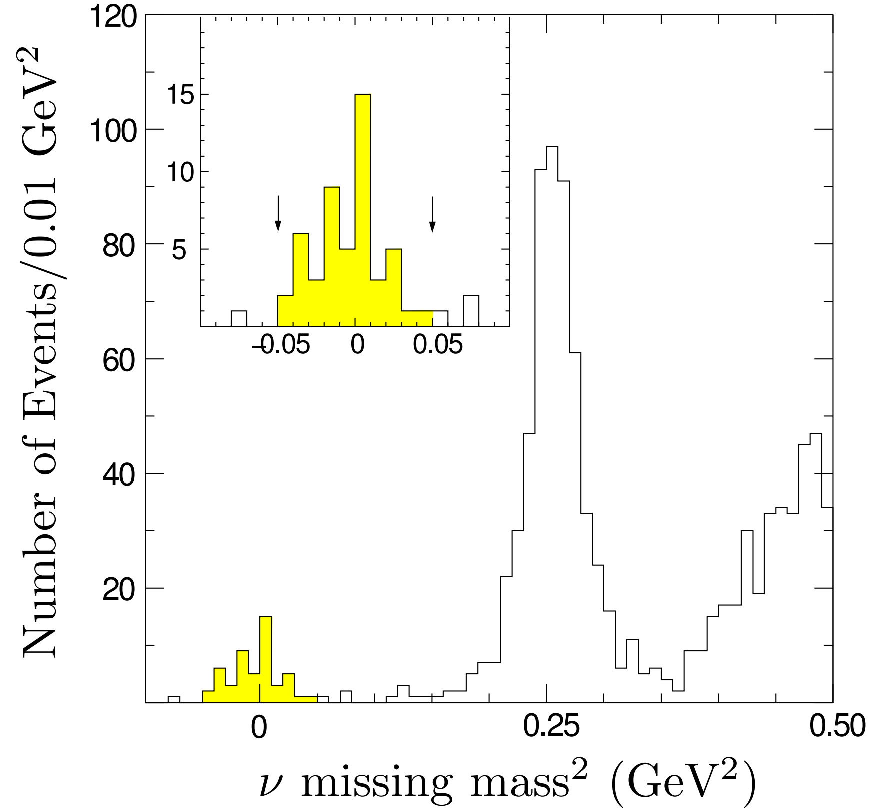
LQCD vs CLEO

"Di-electron Width"

A Brief Look at f_D

CLEO-c: 281 pb^{-1} at $\psi(3770)$ = 3 million D^+D^- (30 times MARK-III, 8.5 times BES-II)



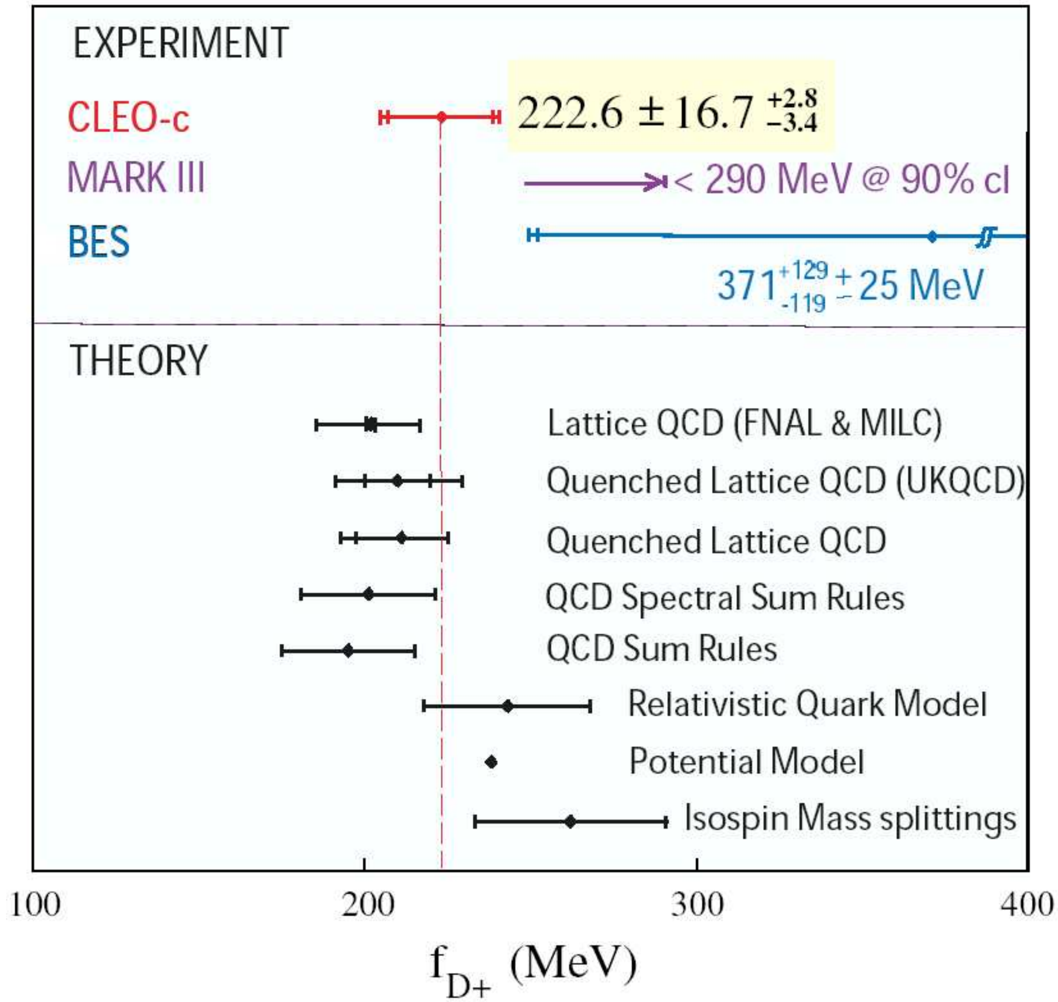


$$50 \text{ events} - 2.8 \text{ background} = 47.2 \pm 7.1 \, {}^{+0.3}_{-0.8}$$

$$\mathcal{B}(D^+ \to \mu^+\nu) = (4.40 \pm 0.66 \, {}^{+0.09}_{-0.12}) \times 10^{-4}$$

$$f_{D^+} = (222.6 \pm 16.7 \, {}^{+2.8}_{-3.4}) \text{ MeV}$$

A Brief Look at f_D



Projected final precision: 4.5% on f_D and 4.5% on f_{D_s}

M. Artuso *et al.* (CLEO Collaboration) Phys. Rev. Lett. **95**, 251801 (2005)

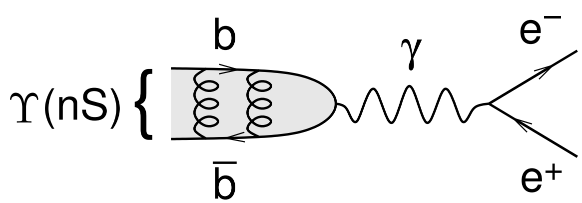
Di-electron widths of $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$

- Three high-precision measurements (1.5%, 1.8%, and 1.8%)
- Largely share systematics
- See top of screen for an outline

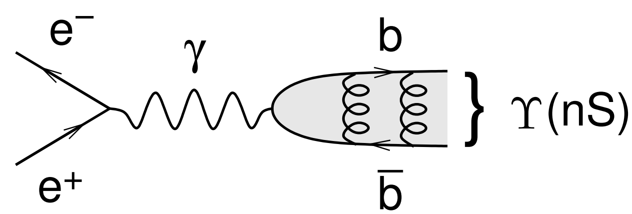
Di-electron width Γ_{ee} = rate of $\Upsilon \to e^+e^- = \Gamma \times \mathcal{B}_{ee}$

Cannot obtain Γ_{ee} from $\mathcal{B}_{ee}$ because Γ is unresolvable

Instead, determine



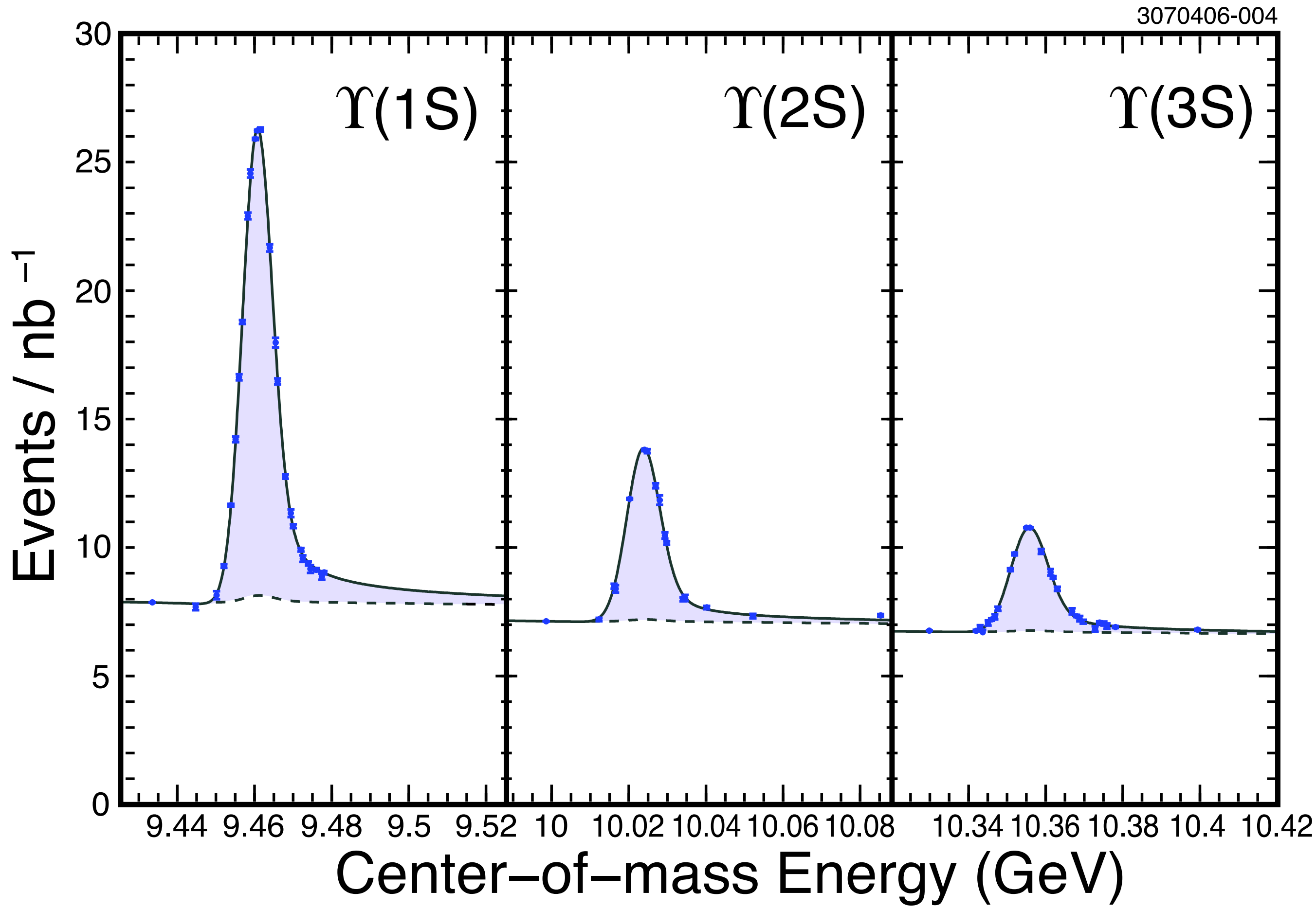
from



$$\Gamma_{ee} = \frac{{M_\Upsilon}^2}{6\pi^2} \int \sigma(e^+e^- \to \Upsilon)\, dE$$

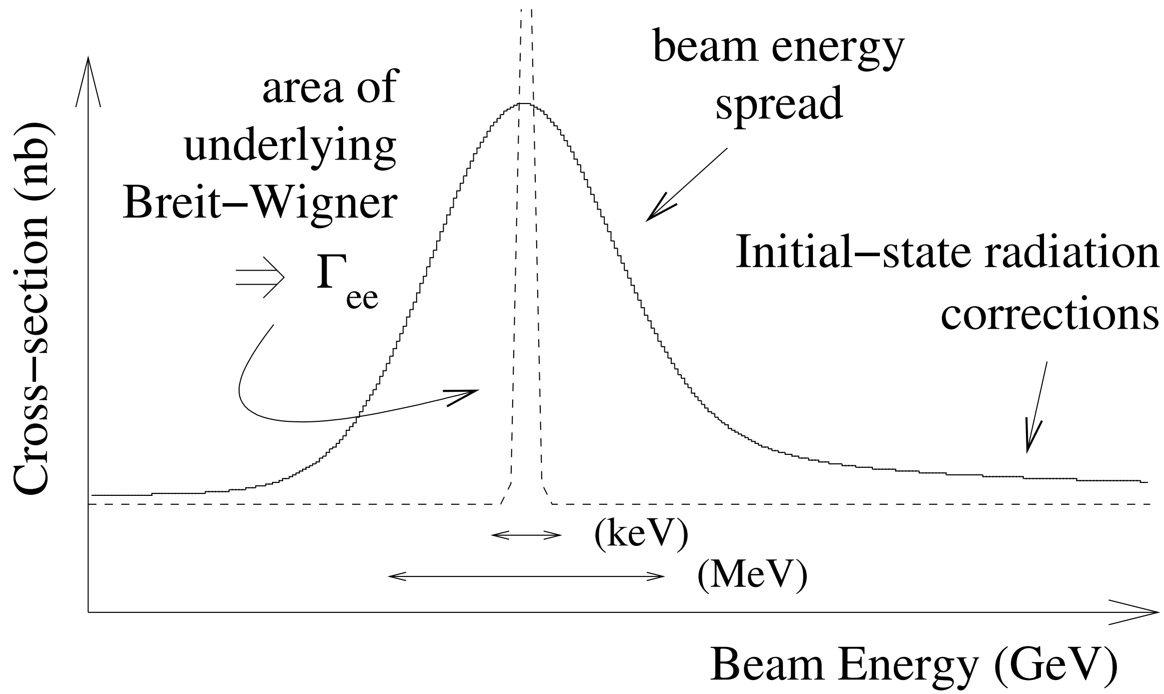
Scan e^+e^- collision energies across M_Υ, measure cross-section $\sigma(E)$, and integrate

$$\Gamma_{ee} = \frac{M_\Upsilon{}^2}{6\pi^2} \int \sigma(e^+e^- \to \Upsilon)\, dE$$



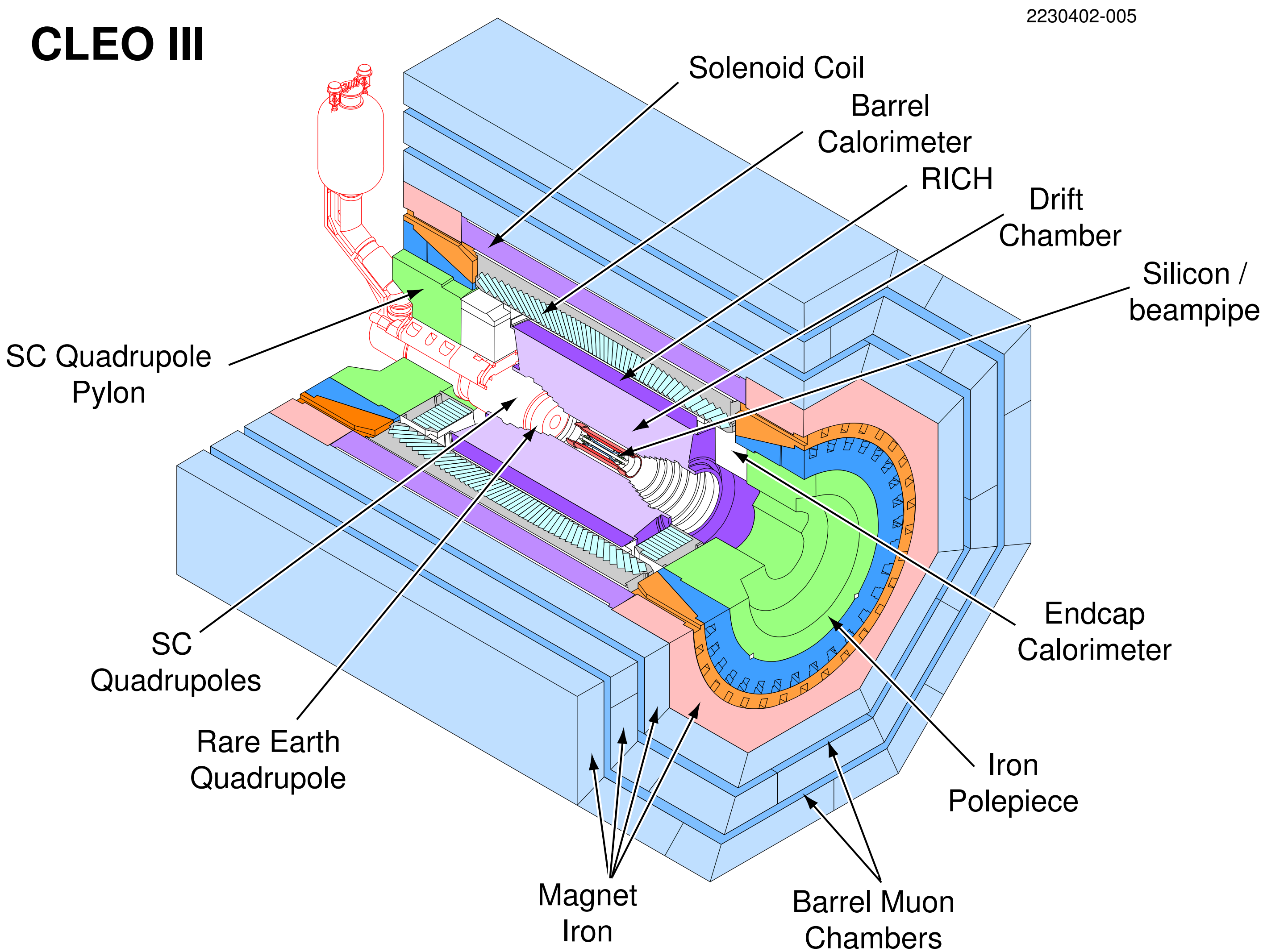
10% of CLEO's $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ program

Anatomy of an Υ Lineshape



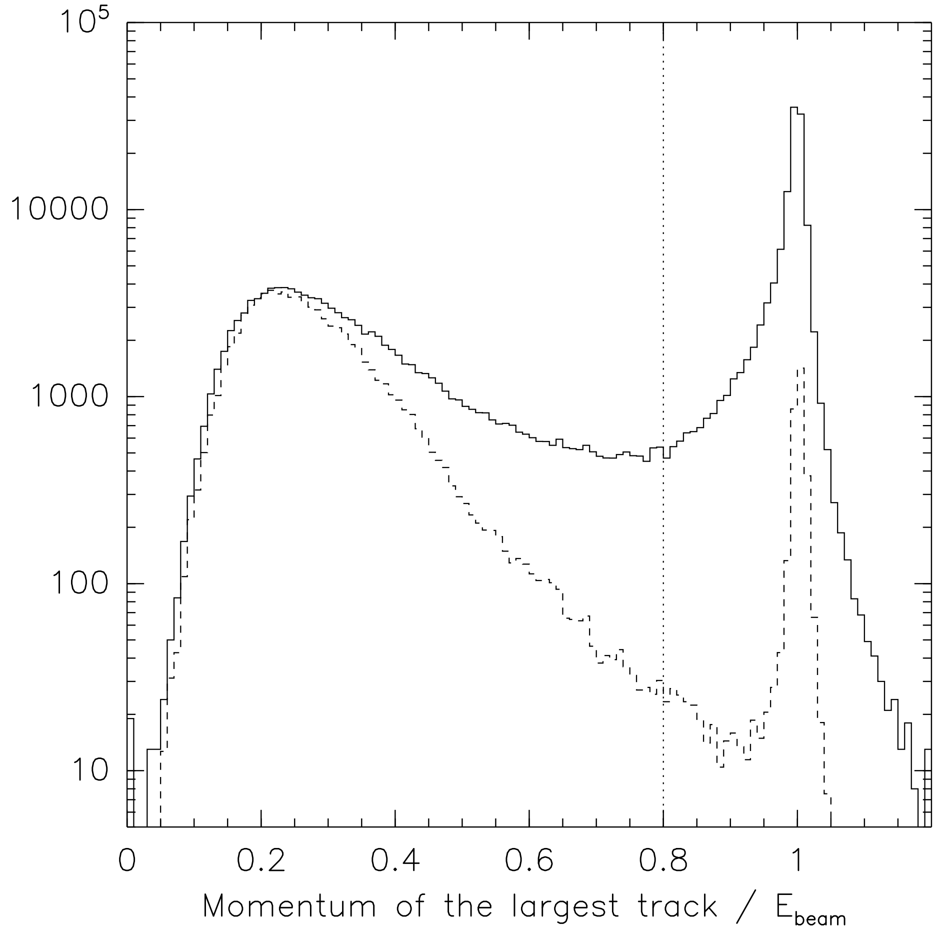
- Breit-Wigner resonance is convoluted by beam energy spread
- Further spread by initial-state radiation ($e^+e^- \to \gamma\Upsilon$)
- Flat backgrounds

Simulate all effects with a fit function, report Breit-Wigner area only


CLEO III
2230402-005
Solenoid Coil
Barrel
Calorimeter
RICH
Drift
Chamber
Silicon /
beampipe
SC Quadrupole
Pylon
SC
Quadrupoles
Rare Earth
Quadrupole
Magnet
Iron
Barrel Muon
Chambers
Iron
Polepiece
Endcap
Calorimeter

Event Selection

Solid = data, dashed = scaled Monte Carlo, log scale



Rejects

1. Bhabhas

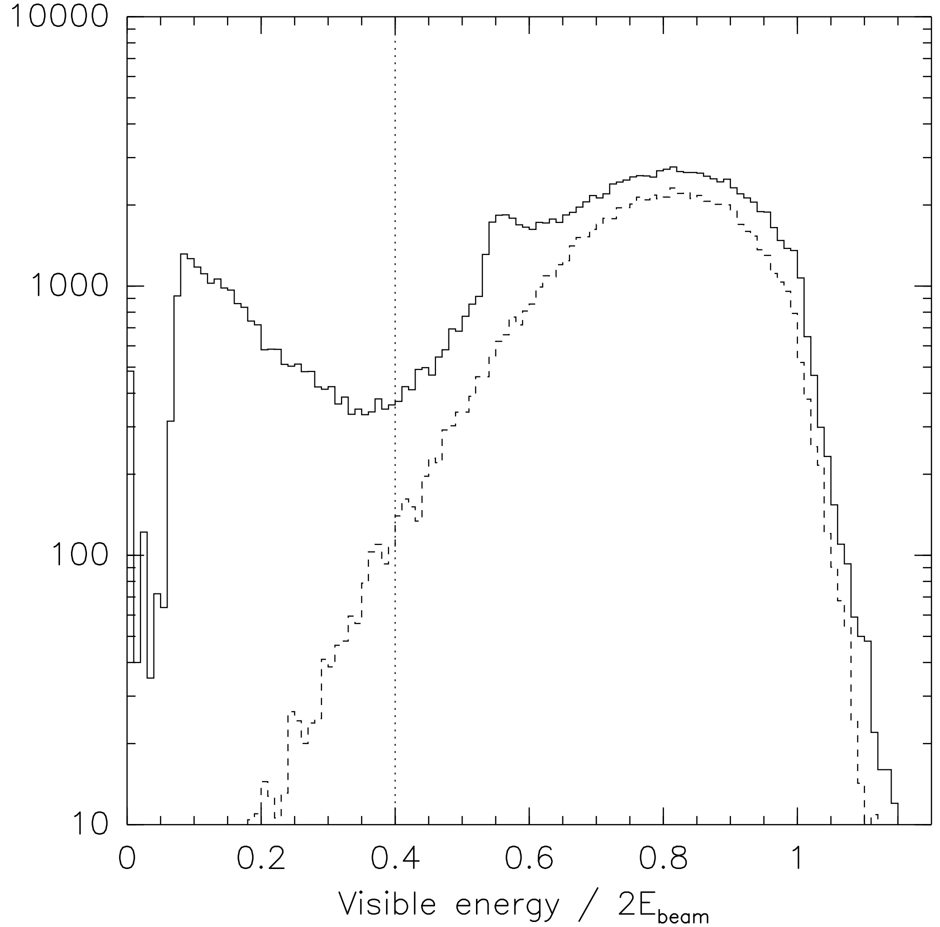
2.

3.

4.

Event Selection

Solid = data, dashed = scaled Monte Carlo, log scale

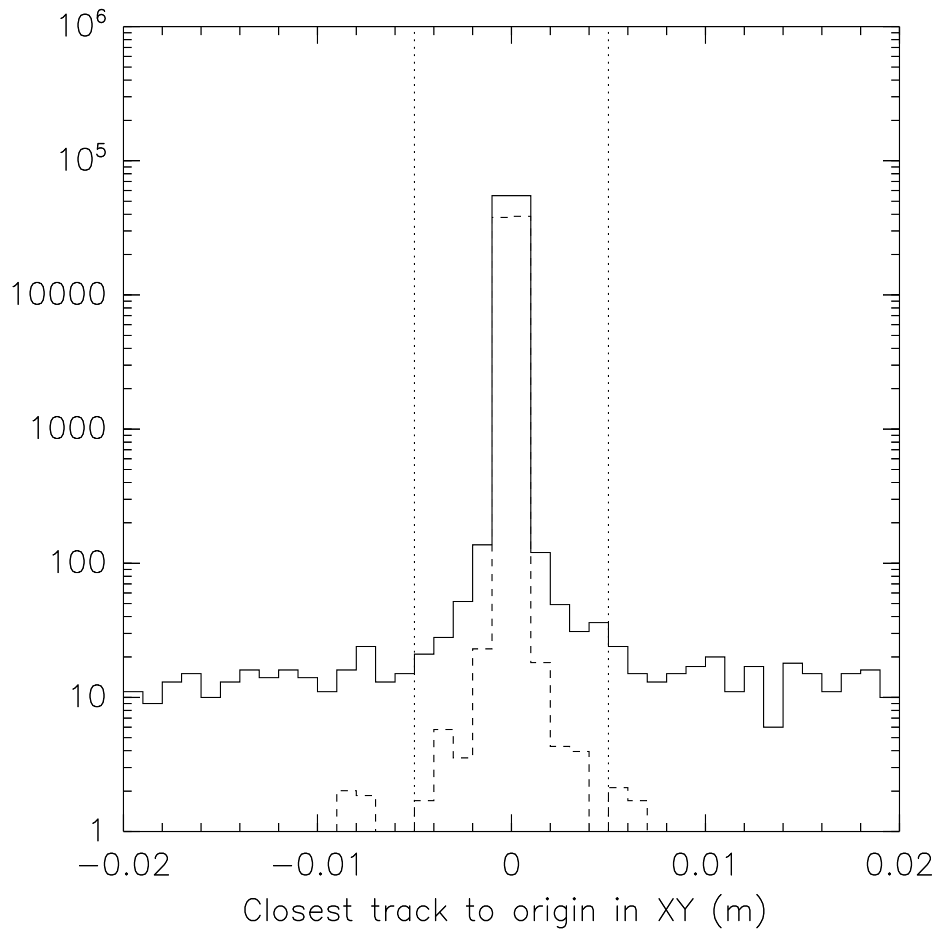


Rejects

1. Bhabhas
2. Two-photon fusion
3.
4.

Event Selection

Solid = data, dashed = scaled Monte Carlo, log scale

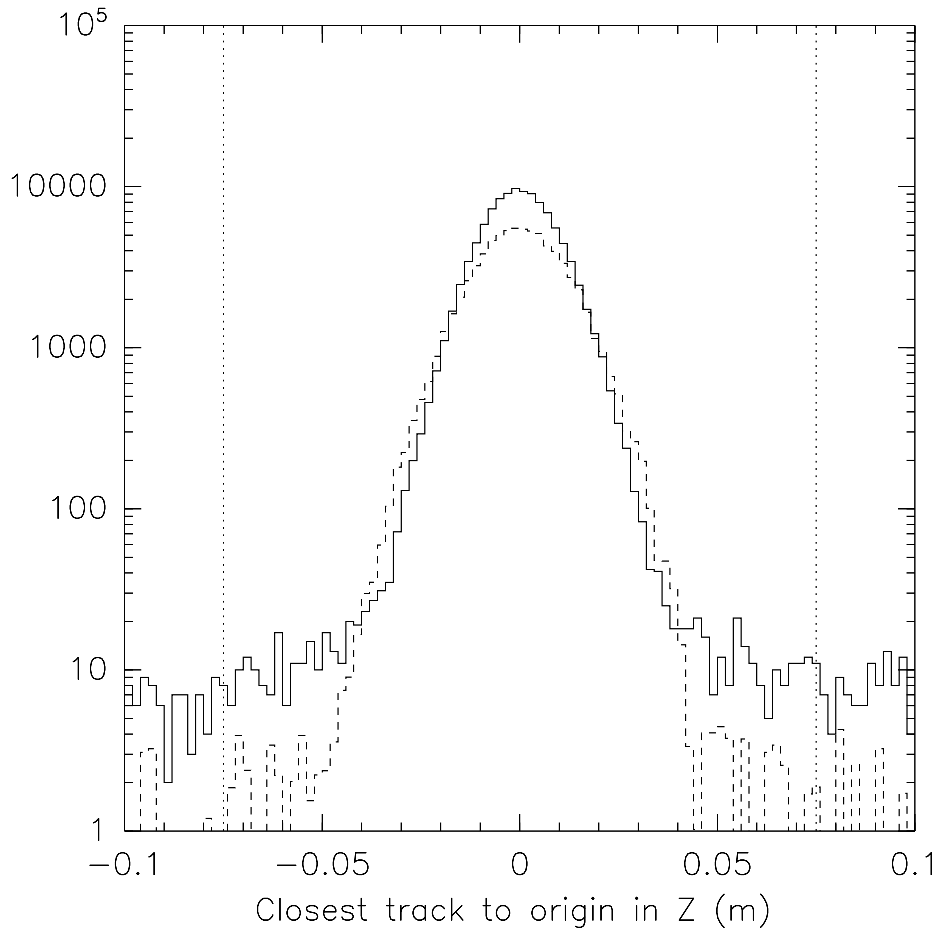


Rejects

1. Bhabhas
2. Two-photon fusion
3. Cosmic rays
4.

Event Selection

Solid = data, dashed = scaled Monte Carlo, log scale



Rejects

1. Bhabhas
2. Two-photon fusion
3. Cosmic rays
4. Beam-gas

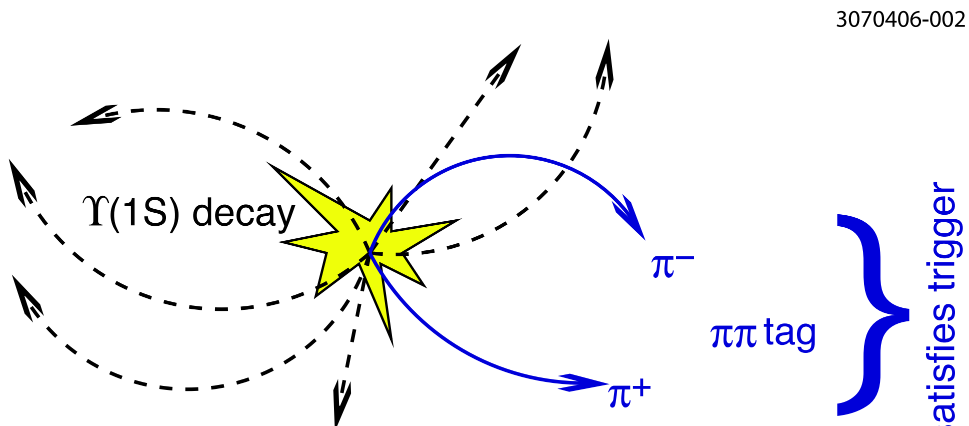
Event selection rejects e^+e^-, $\mu^+\mu^-$, and 43% of $\tau^+\tau^-$

Correct apparent cross-section with $\dfrac{1}{1 - 2.43\mathcal{B}_{\mu\mu}}$

Define hadronic efficiency $=$ probability that non-leptonic decays pass cuts and trigger

Data-Derived Efficiency Study

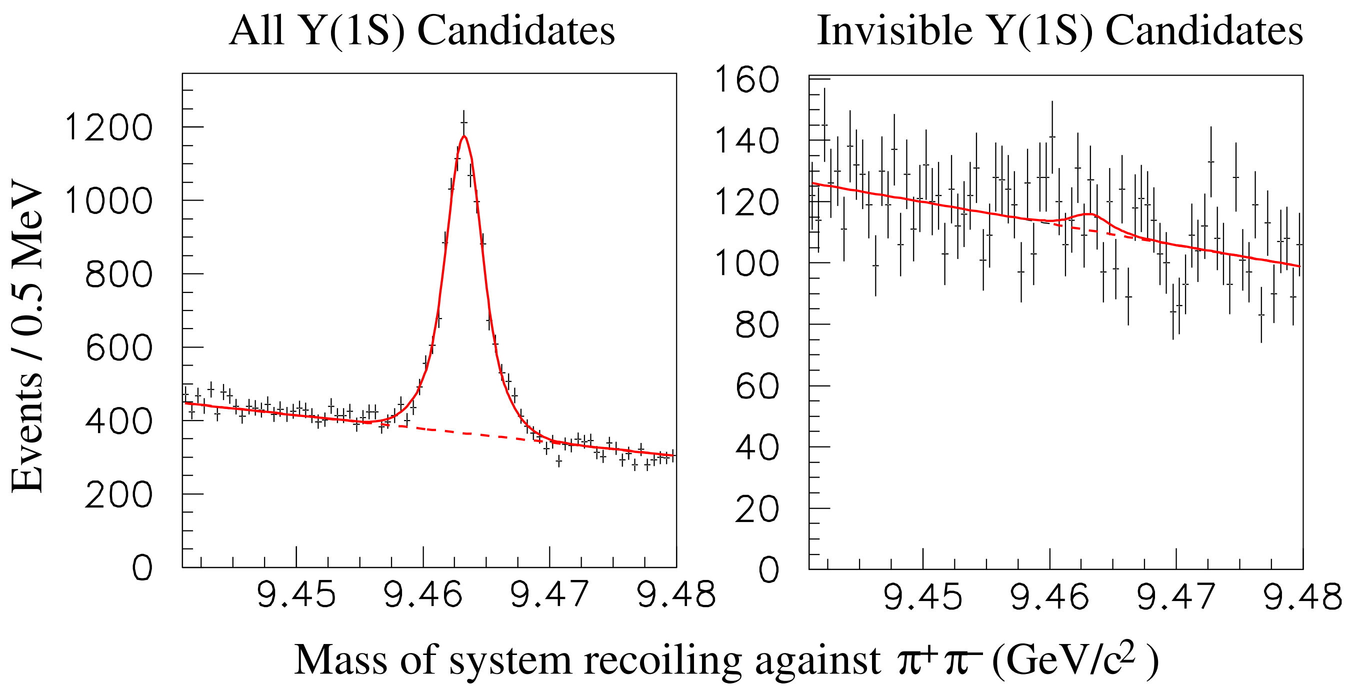
- Select $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ events by the $\pi^+\pi^-$ only
- Count how many $\Upsilon(1S)$ decays pass cuts and trigger



Includes as-yet unknown decay modes

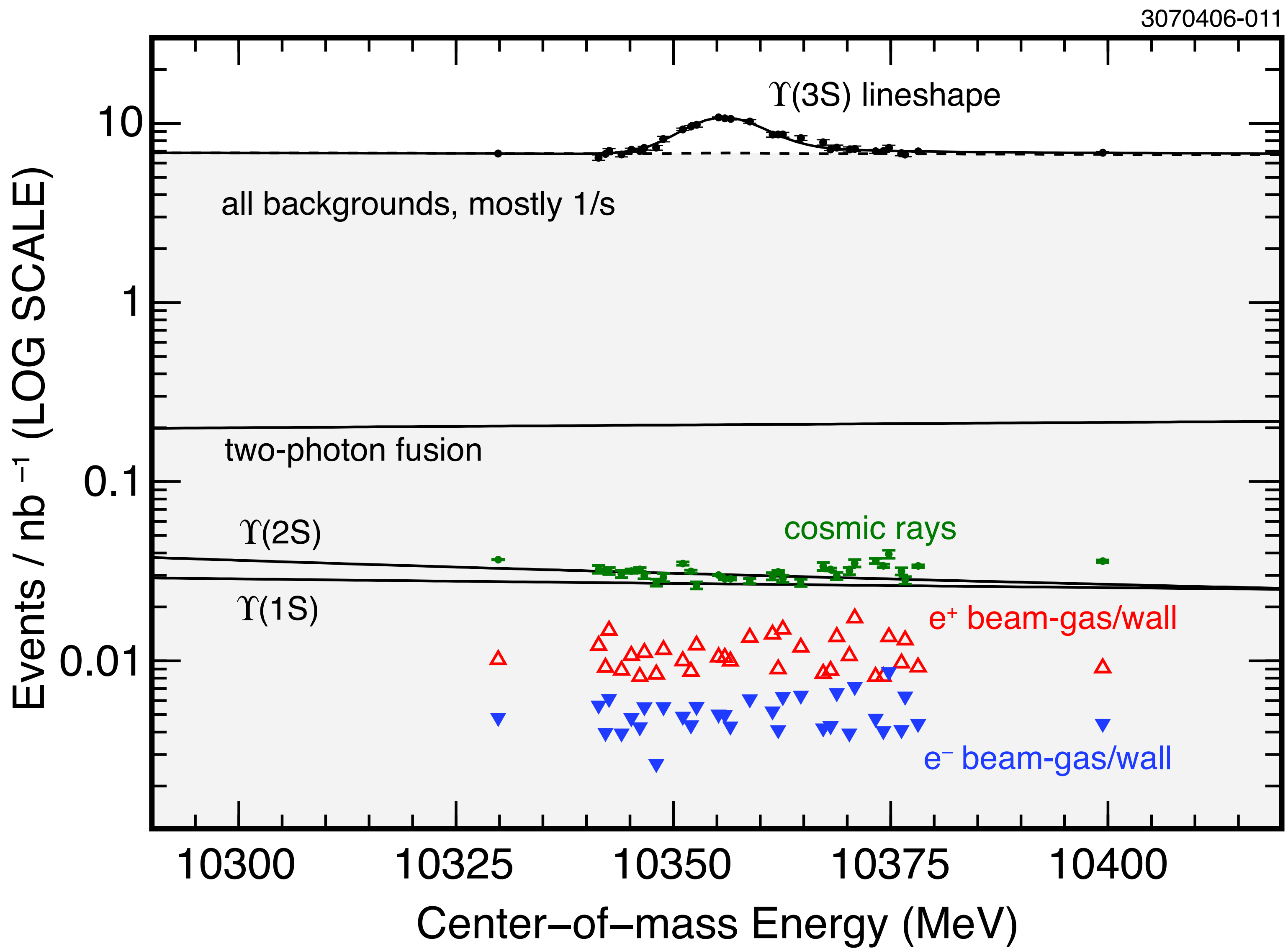
Data-Derived Efficiency Study

- Select $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ events by the $\pi^+\pi^-$ only
- Count how many $\Upsilon(1S)$ decays pass cuts and trigger



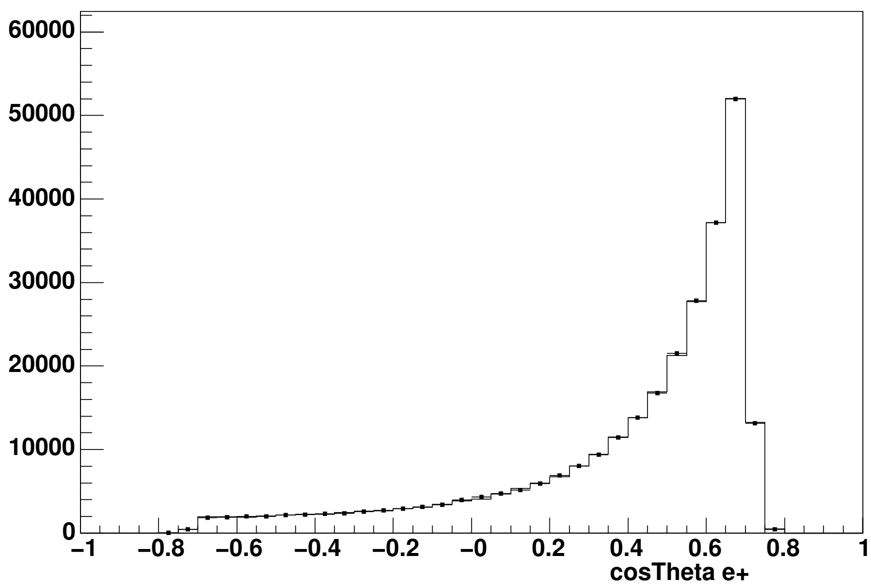
- $\Upsilon(1S)$ hadronic efficiency is 97.8% $\pm$ 0.5%
- 90% upper limit on invisible $\Upsilon(1S)$ decays is $\mathcal{B}_{\text{inv}} < 1.0\%$

For $\Upsilon(2S)$ and $\Upsilon(3S)$ efficiency, we extrapolate using Monte Carlo

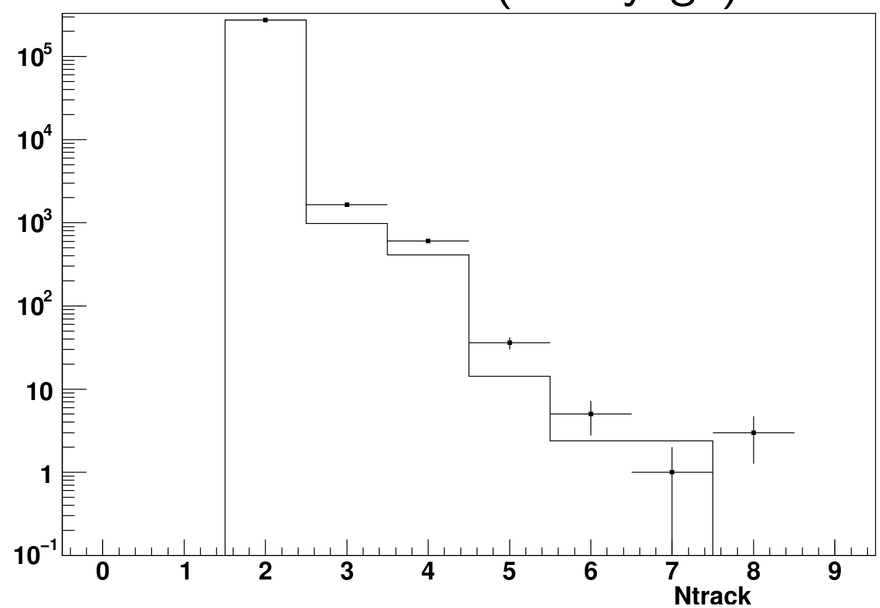

3070406-011
ϒ(3S) lineshape
all backgrounds, mostly 1/s
two-photon fusion
ϒ(2S)
ϒ(1S)
cosmic rays
e⁺ beam-gas/wall
e⁻ beam-gas/wall
10
1
0.1
0.01
Events / nb⁻¹ (LOG SCALE)
10300
10325
10350
10375
10400
Center–of–mass Energy (MeV)

Integrated luminosity = observed Bhabhas / efficiency-weighted Bhabha cross-section

Points are data, solid histograms are scaled Monte Carlo (Babayaga)

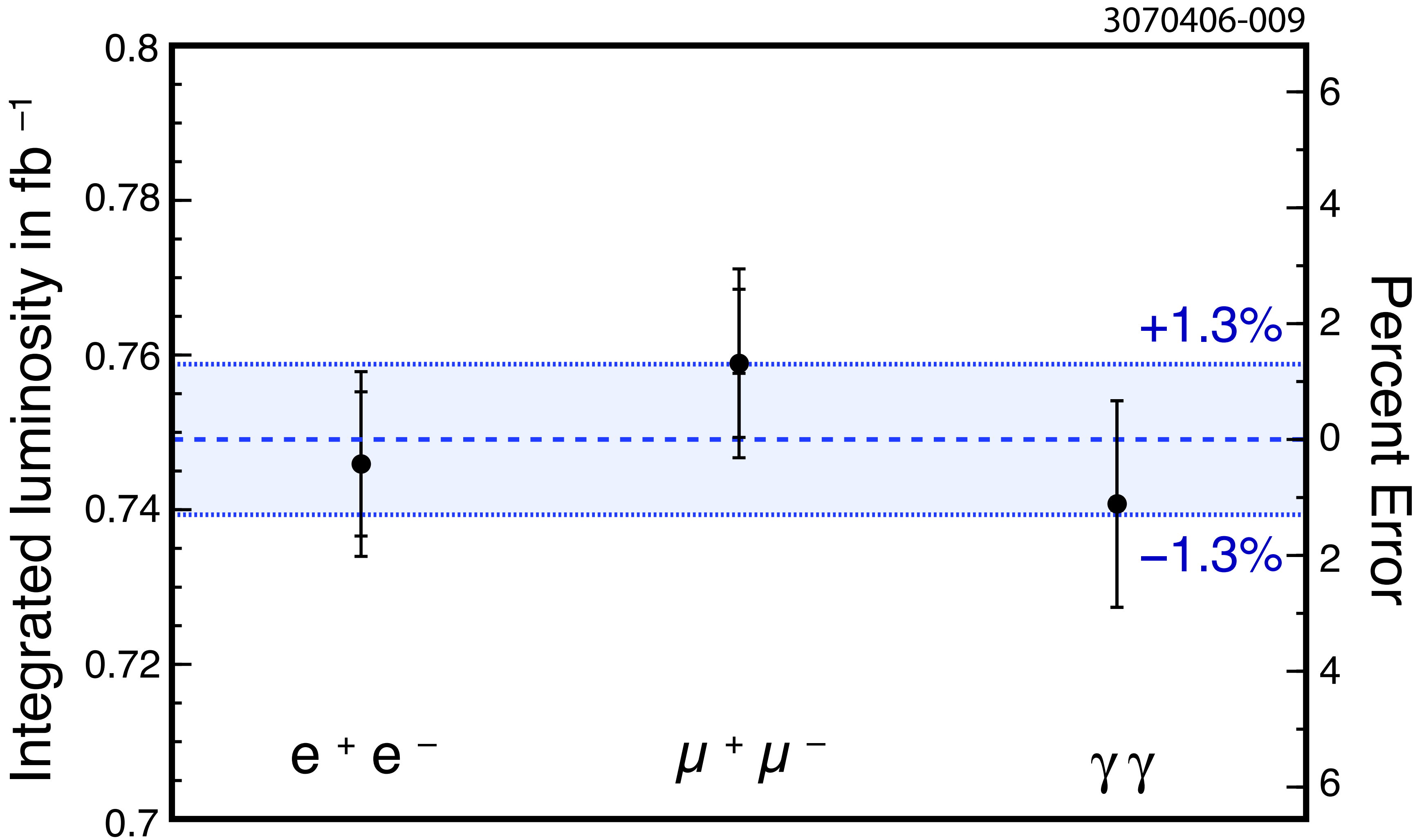


cosθ of the e^+

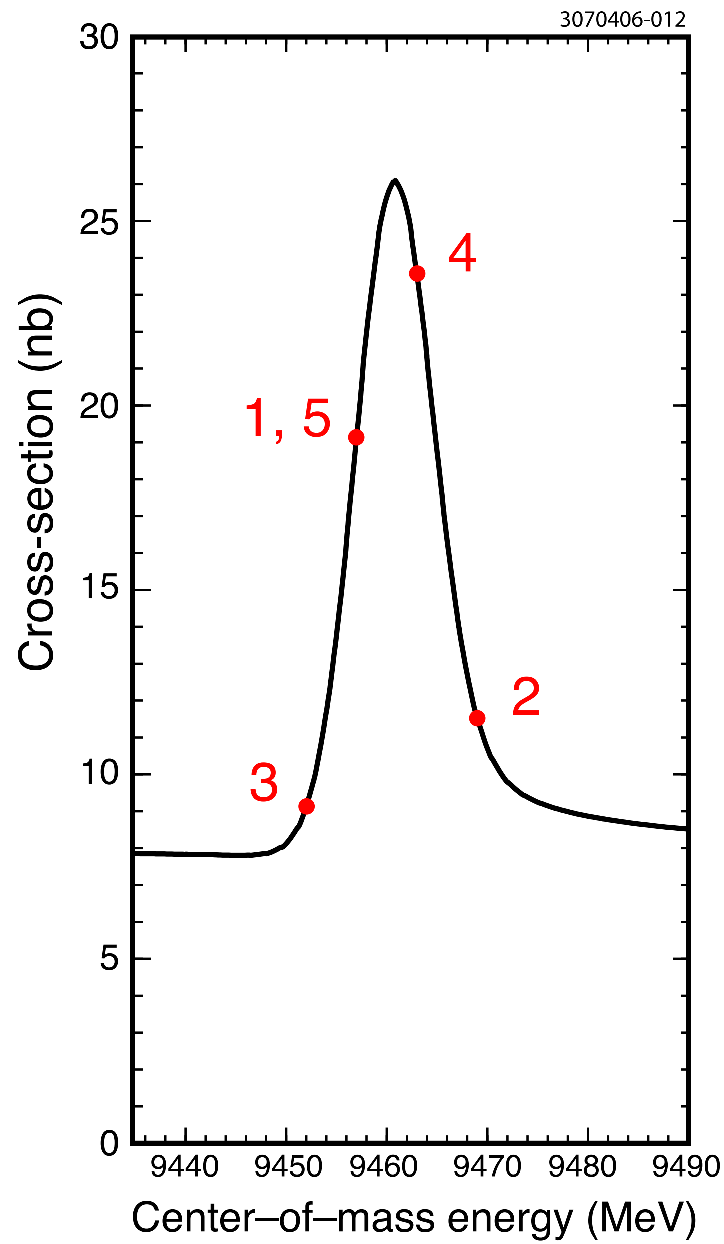


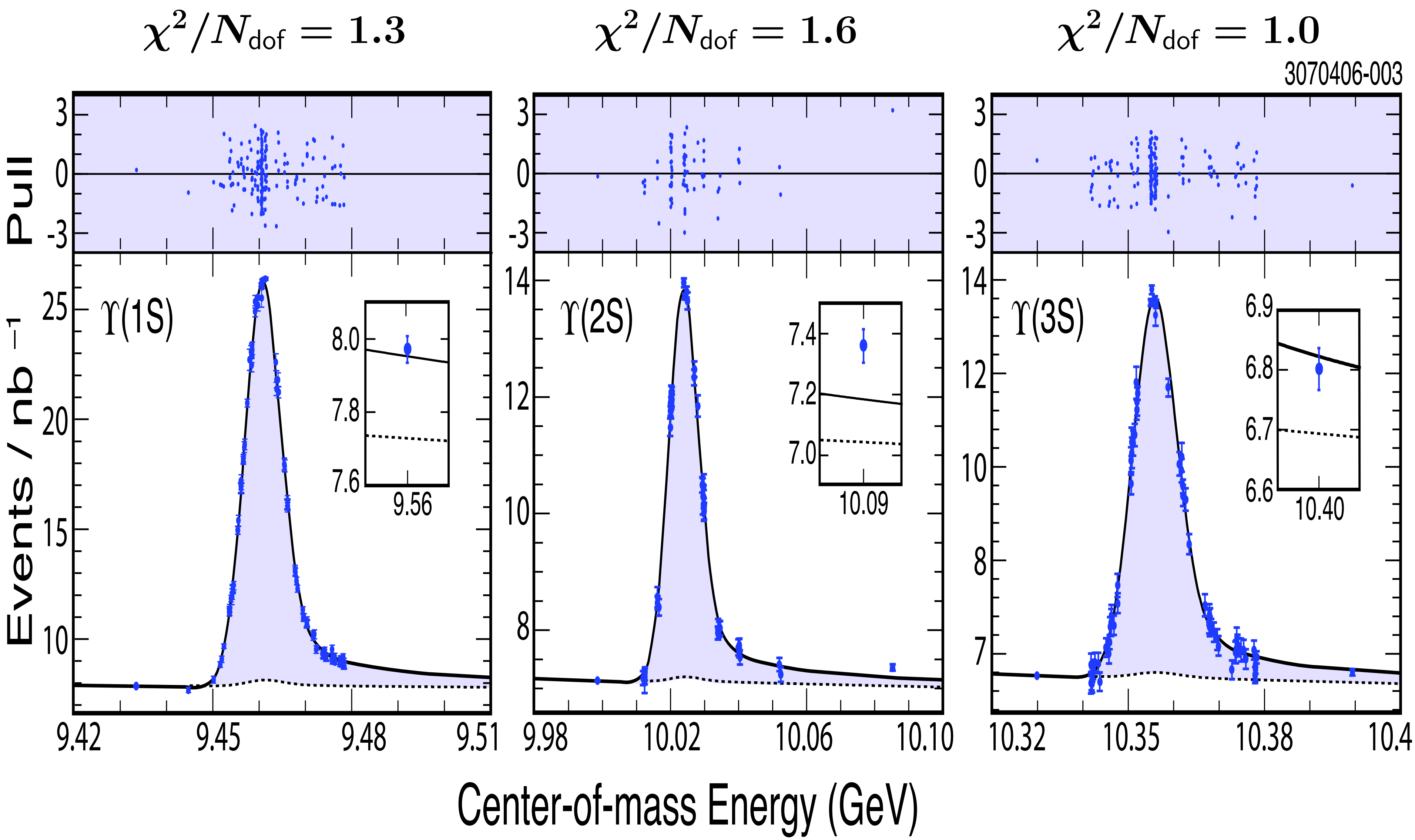
Number of Observed Tracks

Overall scale of e^+e^- calculation is checked by $\mu^+\mu^-$ and $\gamma\gamma$



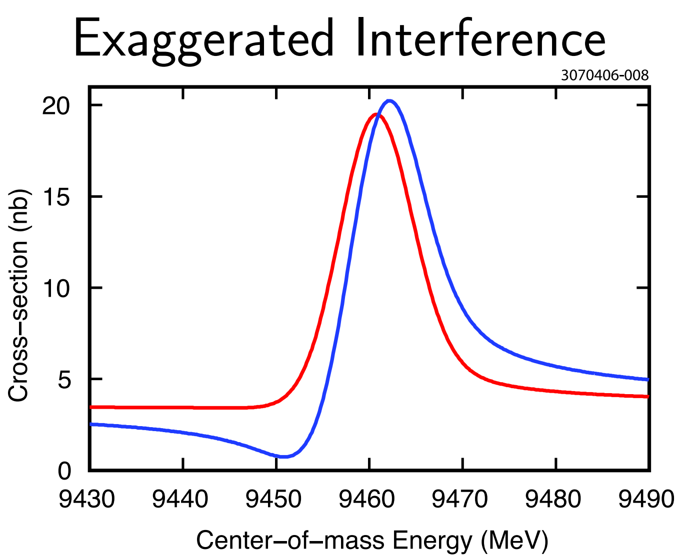
- Beam energy determined by dipole magnet measurement
- Calibration drifts with time (0.5 MeV/month)
- Each resonance completely scanned in 48 hours (repeated scans for statistical precision)
- Measurements alternated above and below resonance peak
- Repeated point of high slope (1 & 5): convert cross-section reproducibility into beam energy reproducibility
- $\Rightarrow$ 0.07 MeV uncertainty in center-of-mass differences, 0.2% in Γ_{ee}

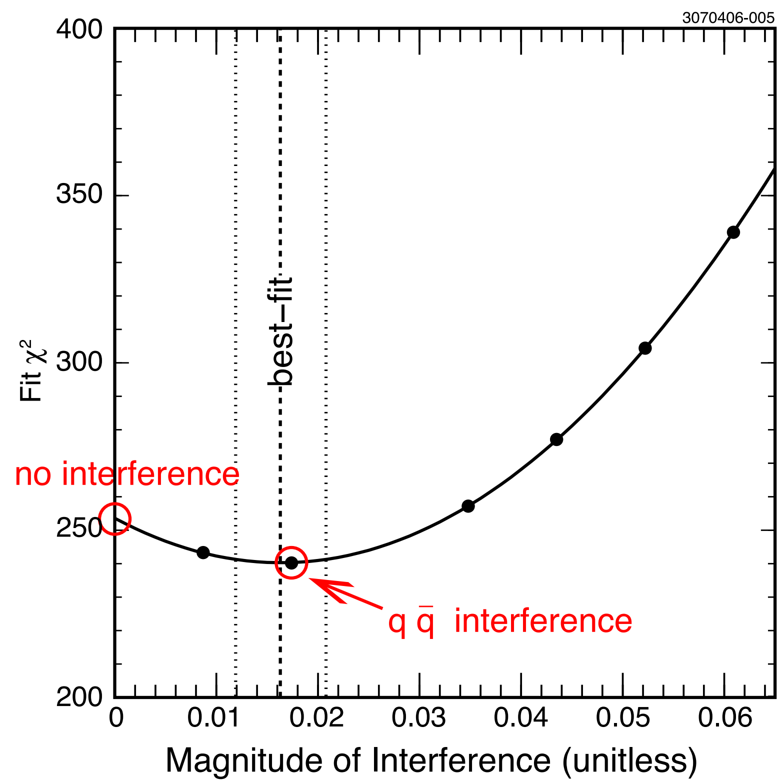



$\chi^2/N_{\text{dof}} = 1.3$
$\chi^2/N_{\text{dof}} = 1.6$
$\chi^2/N_{\text{dof}} = 1.0$
3070406-003
Pull
Events / nb $^{-1}$
Υ(1S)
Υ(2S)
Υ(3S)
9.56
10.09
10.40
Center-of-mass Energy (GeV)

Lineshape Distortions

- Non-Gaussian beam energy spread? **No**, not observed with 0.3% statistical precision
- Variable beam energy spread? **Yes**, we observed 1% variation in a month
- Interference between $e^+e^- \to \Upsilon \to$ hadrons and $e^+e^- \to$ hadrons? **Yes!**





*Common to all resonances

Contribution to Γ_{ee}	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
Correction for leptonic modes	0.2%	0.2%	0.3%
Hadronic efficiency*	0.5%	0.5%	0.5%
Xe^+e^-, $X\mu^+\mu^-$ correction	0	0.15%	0.13%
Overall luminosity scale*	1.3%	1.3%	1.3%
Bhabha/$\gamma\gamma$ inconsistency	0.4%	0.4%	0.4%
Beam energy measurement drift	0.2%	0.2%	0.2%
Fit function shape	0.1%	0.1%	0.1%
χ^2 inconsistency	0.2%	0.6%	0
Total systematic uncertainty	1.5%	1.6%	1.5%
Statistical uncertainty	0.3%	0.7%	1.0%
Total	1.5%	1.8%	1.8%

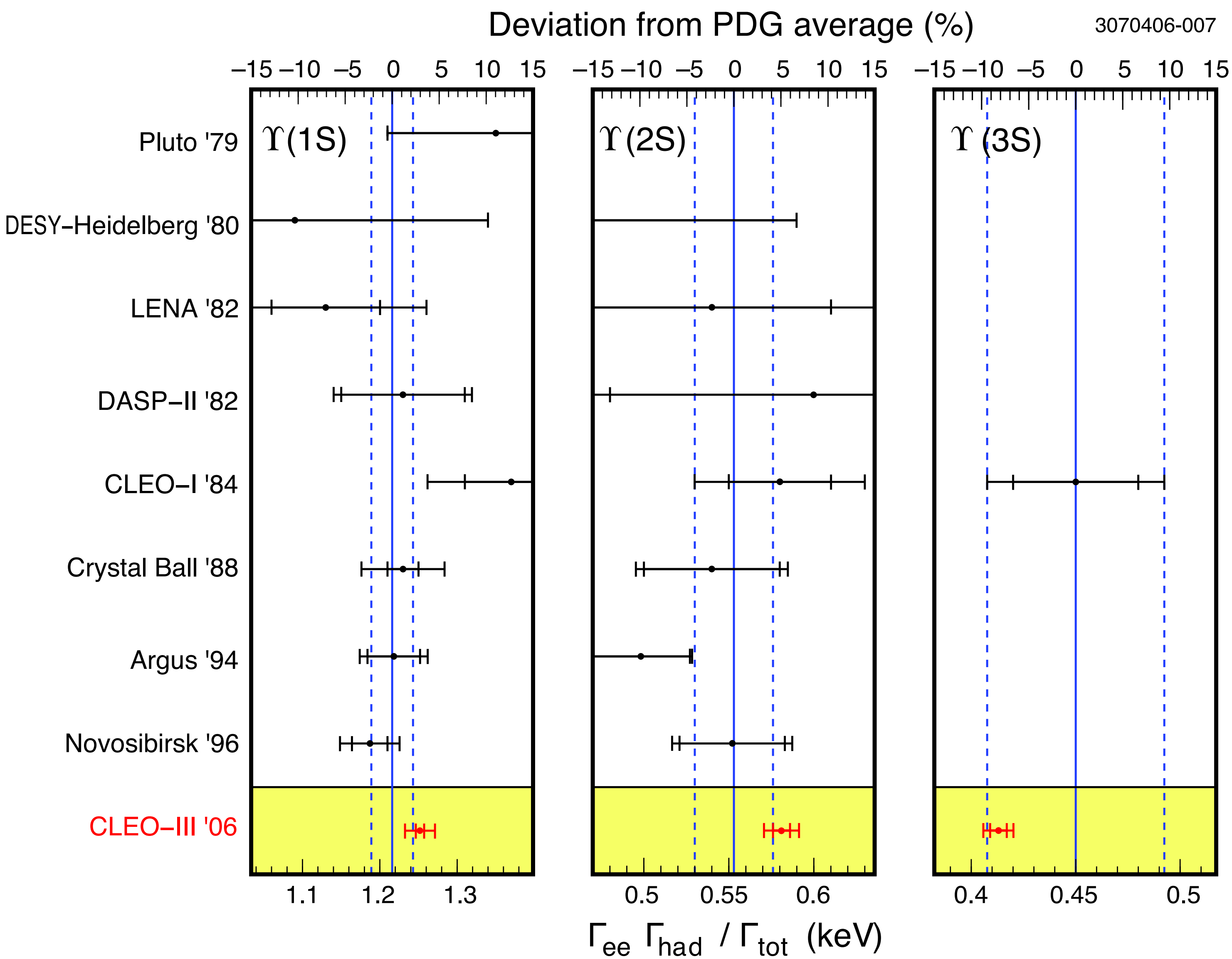
$$\Gamma_{ee}(1S) = 1.354 \pm 0.004 \pm 0.020 \text{ keV} \quad 1.5\%$$
$$\Gamma_{ee}(2S) = 0.619 \pm 0.004 \pm 0.010 \text{ keV} \quad 1.8\%$$
$$\Gamma_{ee}(3S) = 0.446 \pm 0.004 \pm 0.007 \text{ keV} \quad 1.8\%$$

$$\Gamma_{ee}(2S)/\Gamma_{ee}(1S) = 0.457 \pm 0.004 \pm 0.004 \text{ keV} \quad 1.2\%$$
$$\Gamma_{ee}(3S)/\Gamma_{ee}(1S) = 0.329 \pm 0.003 \pm 0.003 \text{ keV} \quad 1.3\%$$
$$\Gamma_{ee}(3S)/\Gamma_{ee}(2S) = 0.720 \pm 0.009 \pm 0.007 \text{ keV} \quad 1.6\%$$

$$\Gamma(1S) = 54.4 \pm 0.2 \pm 0.8 \pm 1.6 \text{ keV} \quad 3.3\%$$
$$\Gamma(2S) = 30.5 \pm 0.2 \pm 0.5 \pm 1.3 \text{ keV} \quad 4.6\%$$
$$\Gamma(3S) = 18.6 \pm 0.2 \pm 0.3 \pm \underbrace{0.9}_{\mathcal{B}_{\mu\mu}} \text{ keV} \quad 5.2\%$$

Γ_{ee}: J.L. Rosner *et al.* (CLEO Collaboration) Phys. Rev. Lett. **96**, 092003 (2006)

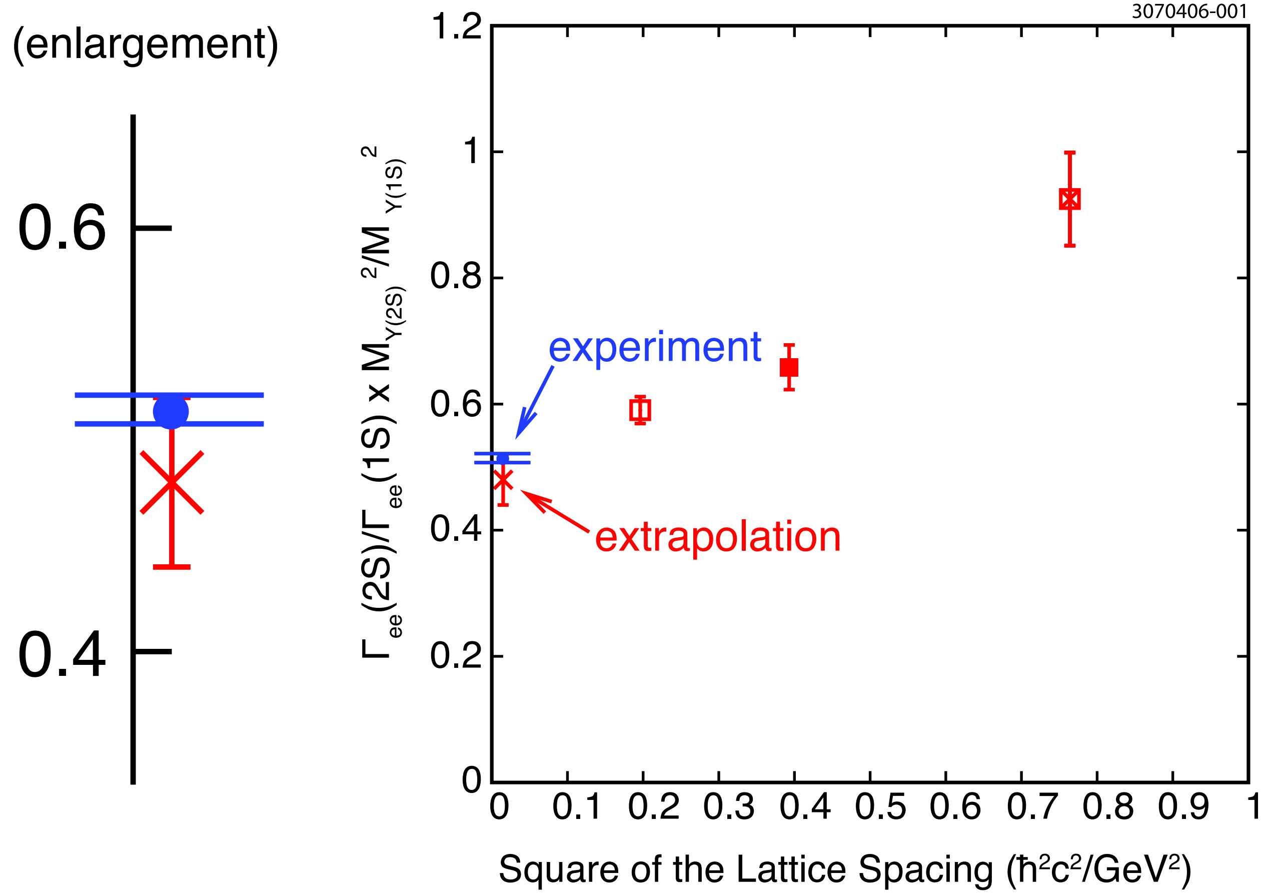
$\mathcal{B}_{\mu\mu}$: G.S. Adams *et al.* (CLEO Collaboration), Phys. Rev. Lett. **94**, 012001 (2005)



Deviation from PDG average (%)
3070406-007
−15 −10 −5 0 5 10 15
Υ(1S)
Υ(2S)
Υ(3S)
Pluto '79
DESY−Heidelberg '80
LENA '82
DASP−II '82
CLEO−I '84
Crystal Ball '88
Argus '94
Novosibirsk '96
CLEO−III '06
1.1 1.2 1.3
0.5 0.55 0.6
0.4 0.45 0.5
Γee Γhad / Γtot (keV)

Lattice QCD Calculations of Γ_{ee}

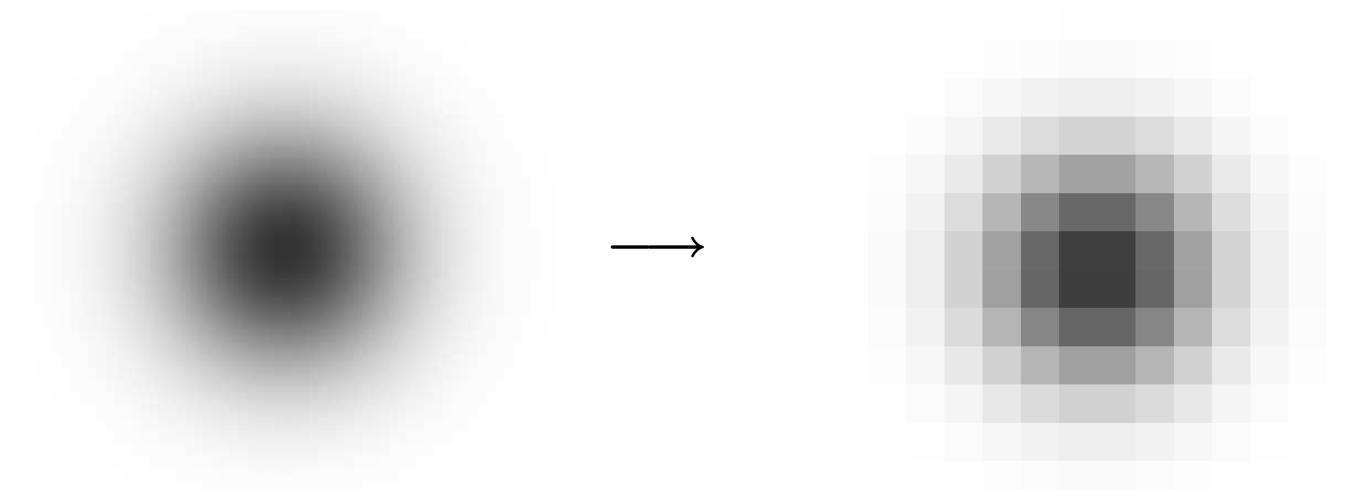
Summer 2005: 10%-level prediction of $\Gamma_{ee}(2S)/\Gamma_{ee}(1S)$ ratio
Later this summer: few-percent ratios, 10% absolute Γ_{ee}



A. Gray *et al.* (HPQCD Collaboration), Phys. Rev. D **72**, 094507 (2005)

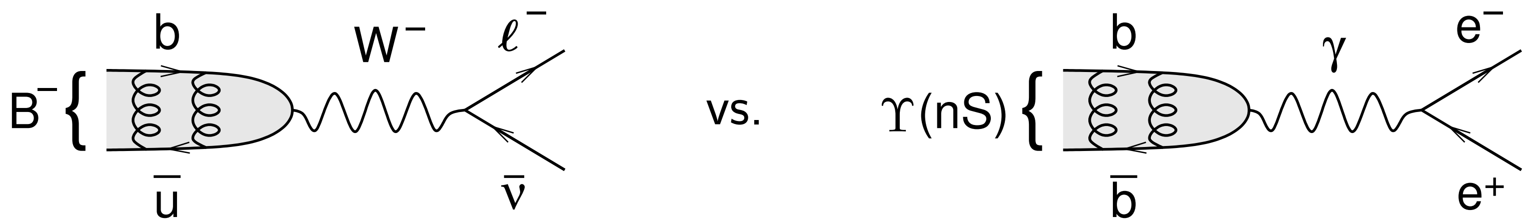
Why the Steep Dependence on Lattice Spacing?

Decay constants sample wavefunction at the origin, which is discretized



Υ is a small meson, making discretization more severe

How Relevant is this Test to f_B?



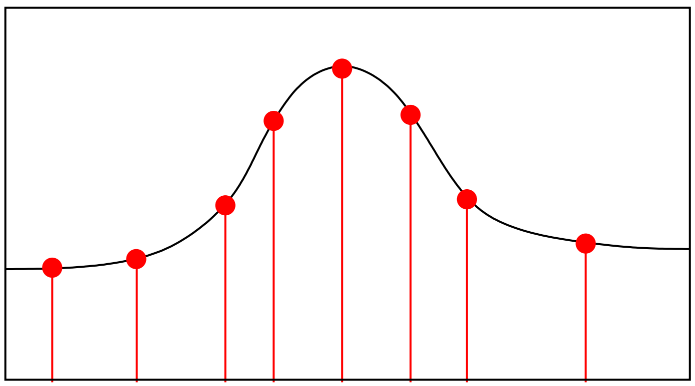
- Γ_{ee} and f_B calculations share the same NRQCD action and staggered-quark formalism
- Discretization errors in f_B are smaller than discretization errors in Γ_{ee}
- Though Υ couples to vector current, the factor this introduces cancels in ratios of Γ_{ee}

Compliments f_D and $\Gamma(\psi \to e^+e^-)$ tests

CLEO has also measured Γ_{ee} for J/ψ and $\psi(2S)$

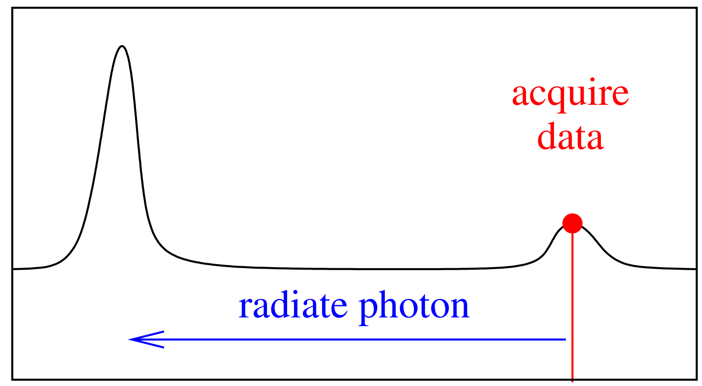
Measured with initial-state radiation, rather than scans

Scan Method



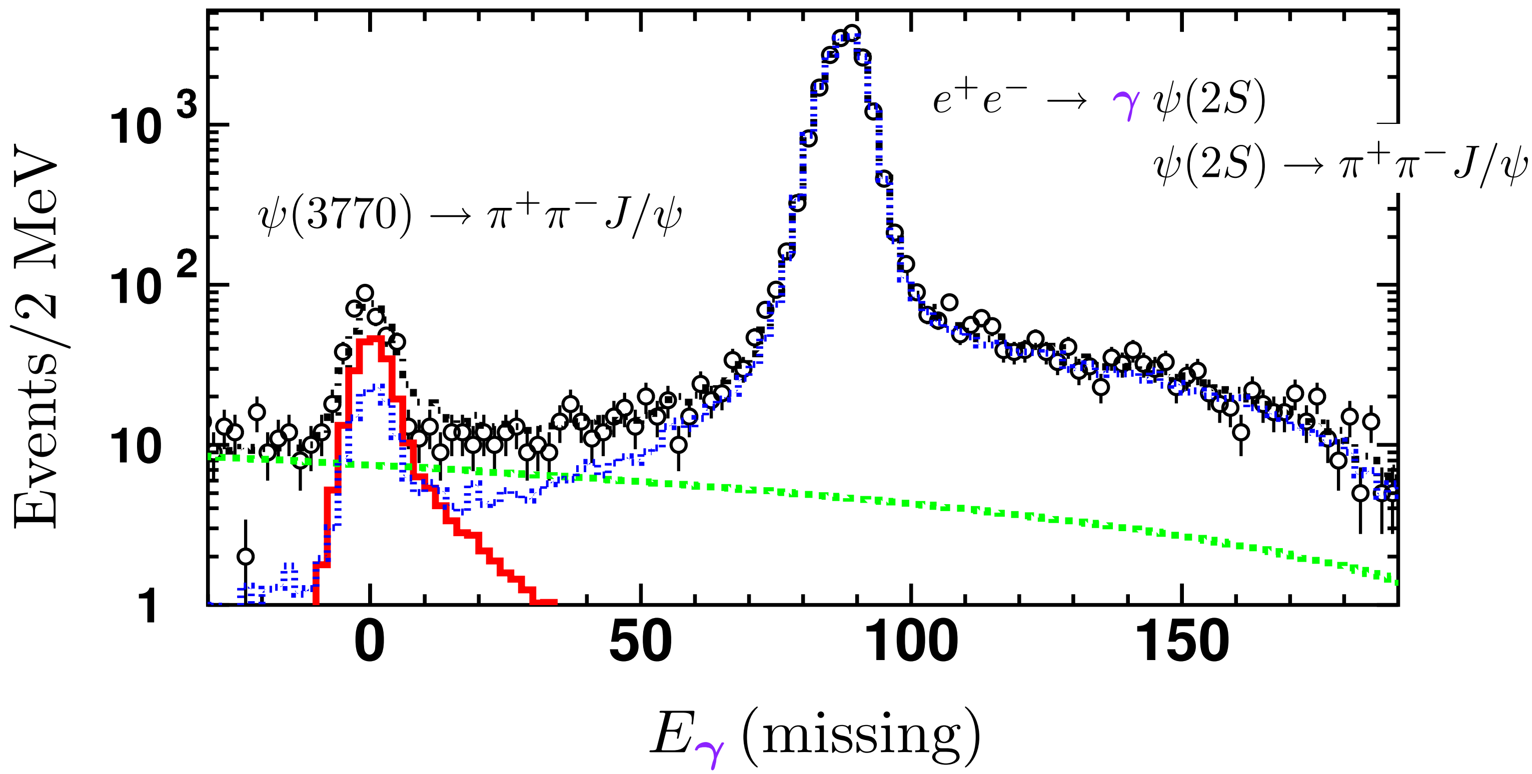
- Requires dedicated scans
- Measure inclusive cross-section
- Requires detailed understanding of the lineshape

ISR Method



- Select events from a large dataset
- Distinctive final states ($\pi^+\pi^- J/\psi$)
- Requires precise knowledge of $\mathcal{B}(\pi^+\pi^- J/\psi)$

Γ_{ee} for J/ψ and $\psi(2S)$



$\Gamma_{ee}(J/\psi)$	$=$	$5.68 \pm 0.11 \pm 0.13$ keV	3.0%
$\Gamma_{ee}(\psi(2S))$	$=$	$2.54 \pm 0.03 \pm 0.11$ keV	4.5%
$\Gamma_{ee}(\psi(2S))/\Gamma_{ee}(J/\psi)$	$=$	$0.45 \pm 0.01 \pm 0.02$ keV	5.0%

N.E. Adam (CLEO Collaboration) Phys. Rev. Lett. **96** 082004 (2006) and
G.S. Adams (CLEO Collaboration) Phys. Rev. **D73** 051103 (2006)

Summary

CLEO provides key tests of Lattice QCD relevant for f_B

	heavy-heavy	heavy-light
bottom	Γ_{ee} for Υ	f_B
charm	Γ_{ee} for ψ	f_D

Γ_{ee} for $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, and ratios have better than 2% precision

Few-percent calculations of Γ_{ee} from Lattice QCD are expected this summer

If they compare favorably, we can have greater confidence in V_{td} determinations and our understanding of QCD in general