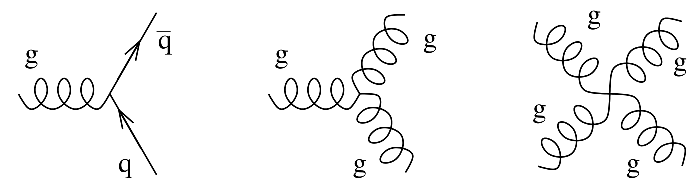
Γ_{ee} and f_D: Testing the Flavors of Lattice QCD

Jim Pivarski

CLEO Collaboration

The basics

- Nuclear strong force is well-described by QCD, in calculable limits



- At low energies, coupling α_s is $\mathcal{O}(1)$, perturbation theory breaks down, and problems are notoriously difficult to solve

- But, formally, it's a simple theory
  - Highly symmetric
  - 1 tunable parameter + quark masses

- Electroweak force is also described by a model, but it is less satisfying:
  - CP symmetry broken (only a little bit!)
  - No obvious pattern in flavor-changing transitions; in general, a matrix:

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

known as CKM

- Electroweak physics seems to point to something beyond itself, which makes it very exciting

- Well-recognized at SLAC, as seen in the attention given to precision electroweak observables at SLD and the B meson at BaBar

- Most recently, studies have focused on pinning down the exact values of the CKM matrix, as departures from unitarity would be sure evidence of new physics

- Doing so has reminded us that QCD plays a role, one which is often not $quantitatively$ understood

- To understand flavor physics, we need to understand color physics better

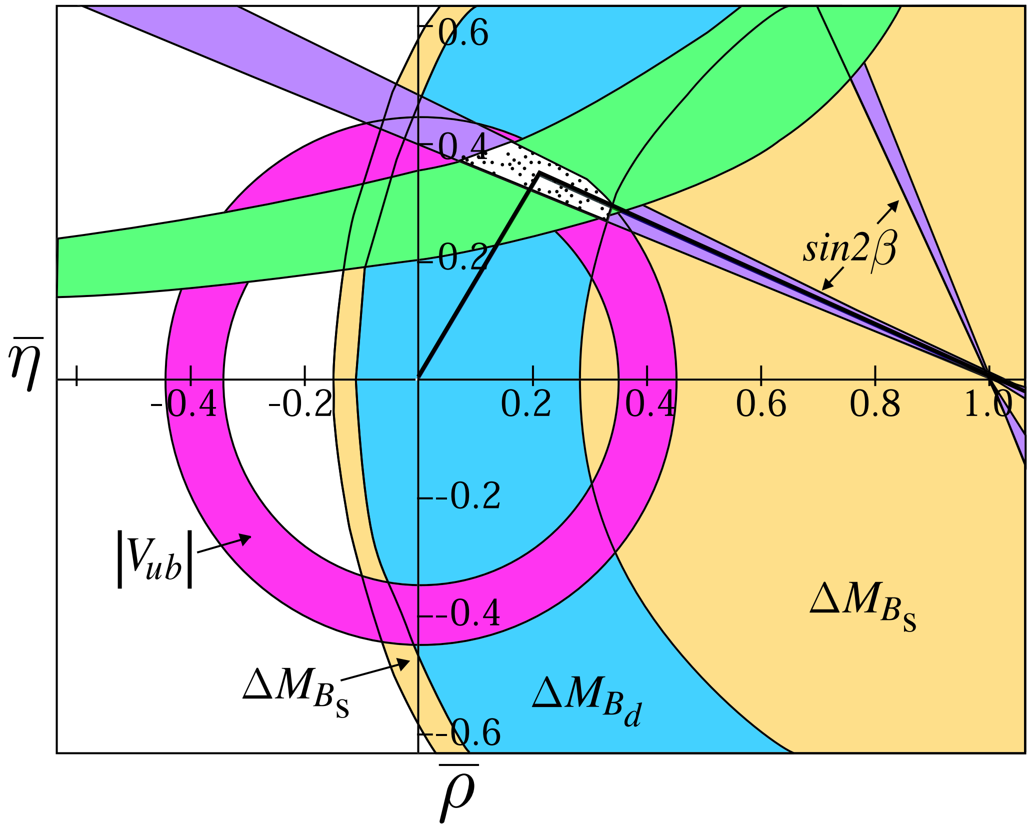
Outline

1. Follow an example of a CKM matrix element that is strictly limited by our ability to compute QCD

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

3. Describe two CLEO experiments which test the calculation closely: each will be measuring the same process, substituting one quark for another

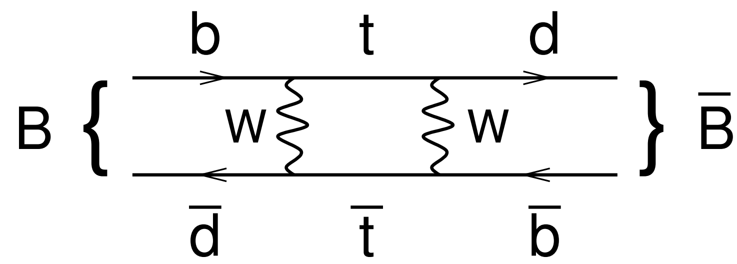
QCD is needed to understand electroweak physics



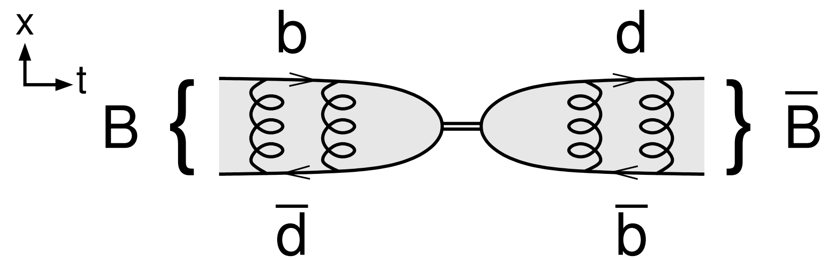
- Some of the largest uncertainties are theory uncertainties
- $\Delta M_{B_d} = (known) \times ({f_B}^2 B_B) \times |V_{td}|^2 =$ 0.510 $\pm$ 0.005 ps^{-1} (HFAG)
- 1% measurement!
- The band is $\sim$20% because QCD factors ${f_B}^2 B_B$ are uncertain

What is this factor?

- B-mixing (ΔM_{B_d}) "box diagram"



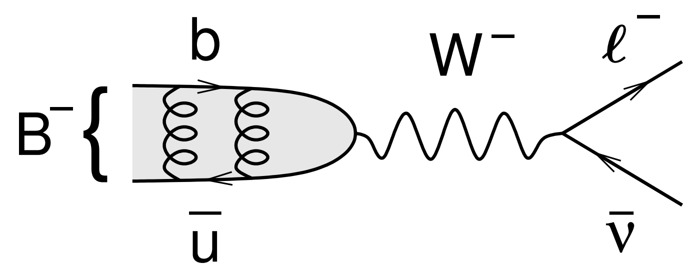
- Would really look more like this



- W is very short-range; most often $\bar{d}$ is in a diffuse cloud around b quark
- Spatial extent of this wavefunction (and its value at the origin) is determined by QCD potential

Can f_B be measured experimentally?

- Leptonic mode: $B^- \to \ell^- \bar{\nu}$



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

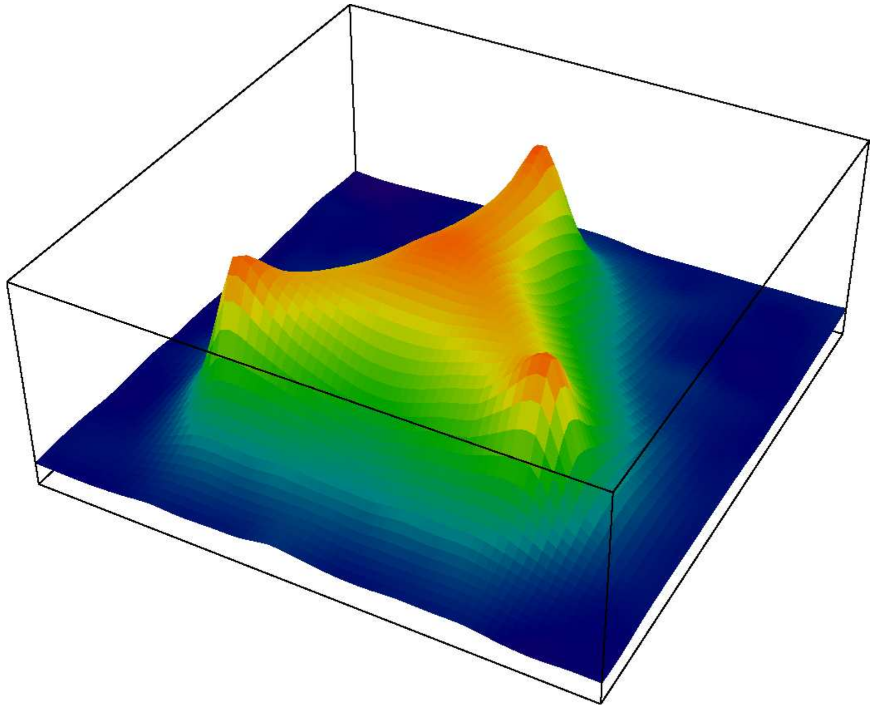
- $\mathcal{B}(B^- \to \tau^- \bar{\nu}) < 2.6 \times 10^{-4}$ at 90% C.L. (BaBar)

Can f_B be calculated theoretically?

- Deriving the QCD potential is a non-perturbative problem

- Most promising technique: Lattice QCD (LQCD)

- Represent space-time as a 4-D grid of quark and gluon field values



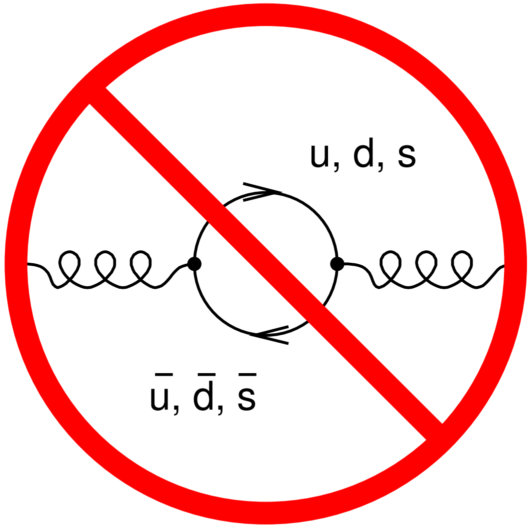
- Evaluate Feynman path integral

- Number of *dimensions* in that integral scales with number of pixels

- Very computationally intensive— many problems are intractable

Approximation to simplify calculation

- Ignore light quark loops (“quenched”)

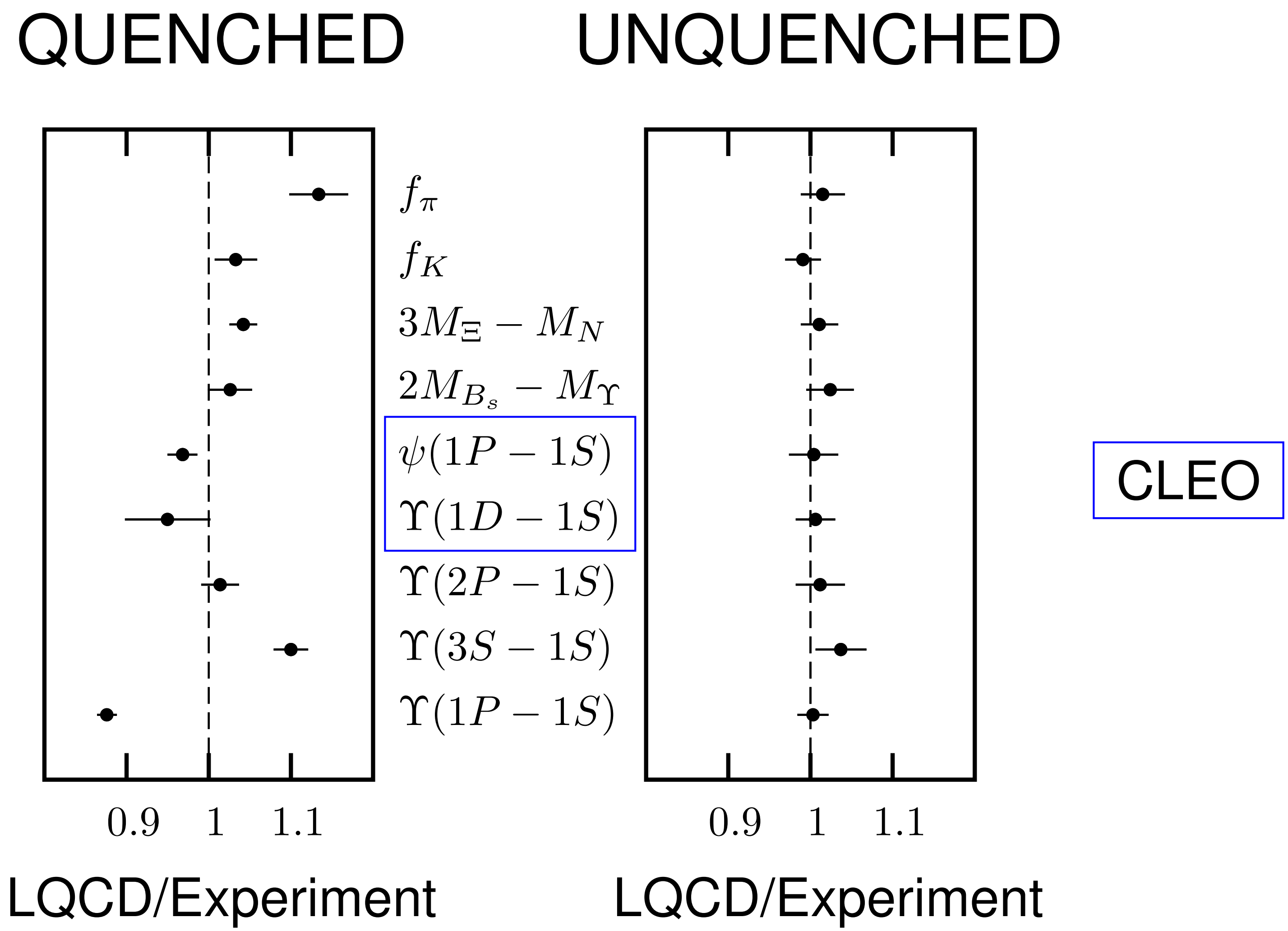


- Until c. 2000, this was necessary for physical calculations

- Introduces large (10–20%) uncertainties that are difficult to assess

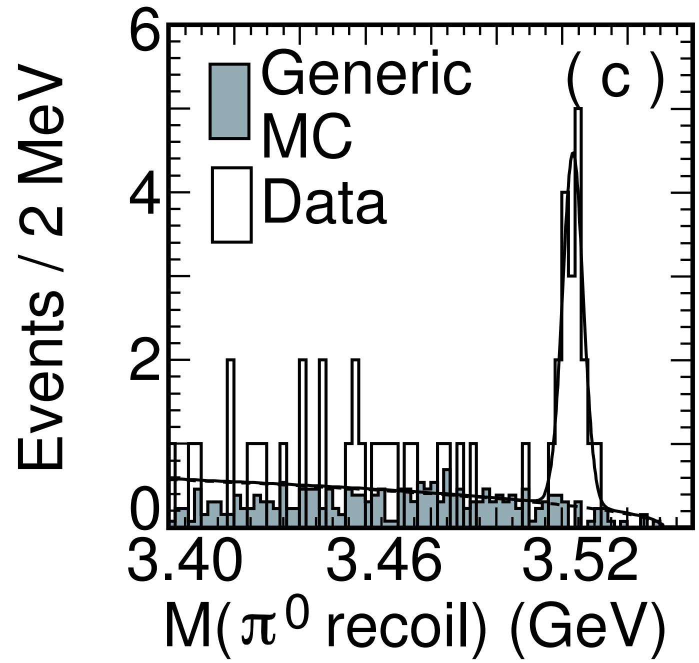
Precision LQCD

- Improved algorithms allow “unquenched,” realistic calculations with few percent uncertainties

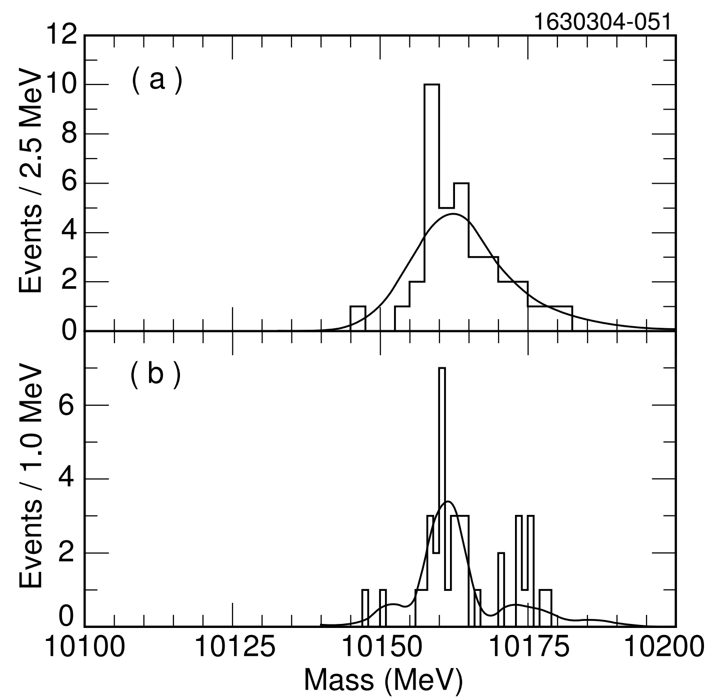


- Update: Ω^- and B_c masses work also

CLEO contributions



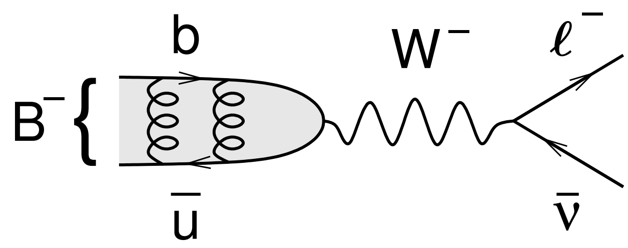
- "$\psi(1P-1S)$": observation of h_c with mass $3524.4 \pm 0.6 \pm 0.4$ MeV (2005)



- "$\Upsilon(1D-1S)$": discovery of $\Upsilon(1D)$ with mass $10161.1 \pm 0.6 \pm 1.6$ MeV (2004) (two methods)

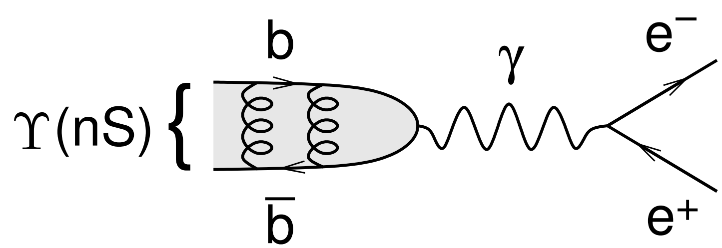
How to check $\boldsymbol{f_B}$ calculation: swap quarks

- f_B



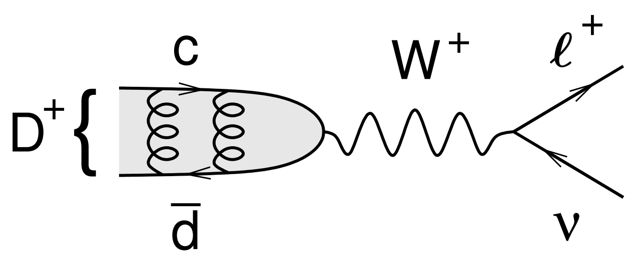
LQCD only

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



LQCD vs CLEO-III

- f_D



LQCD vs CLEO-c

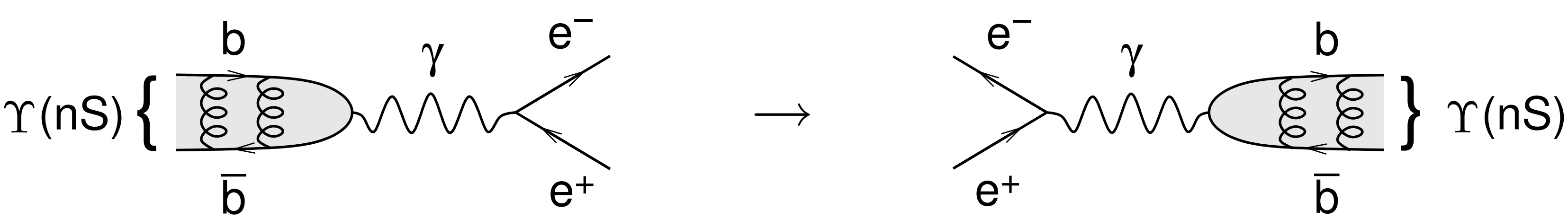
$\boxed{\Gamma_{ee} \text{ for } \Upsilon(1S), \Upsilon(2S), \text{ and } \Upsilon(3S)}$

- Three results; potentially three contacts with theory
- All three are narrow resonances: below $B\bar{B}$ threshold
- Outline will be at the top of the screen

- By definition, $\Gamma_{ee}(\Upsilon)$ is the decay rate of Υ to e^+e^-

$$\Gamma_{ee} = \Gamma \times \mathcal{B}_{ee} \text{ where } \Gamma \text{ is the resonance width}$$

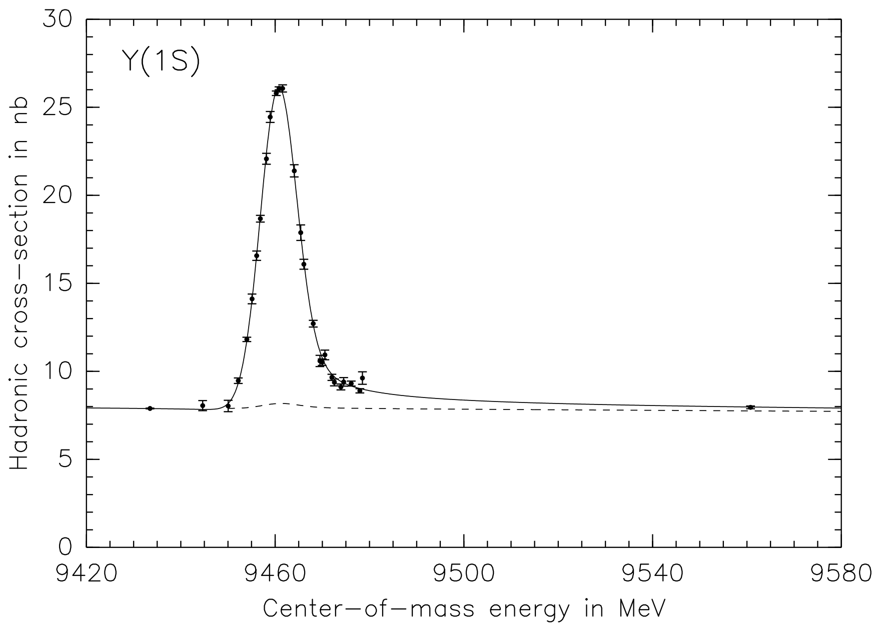
- It may seem that a measurement would consist of counting e^+e^-, but
  - this measures $\mathcal{B}_{ee}$, which is a step removed from Γ_{ee}
  - Γ can't be measured directly
- Alternative method: consider time-reversed process



- Measure Υ *production* from e^+e^- beams

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

- Scan Υ resonance to perform dE integration
- Cross-section versus beam energy $\longrightarrow$ integrated cross-section $\longrightarrow$ Γ_{ee}

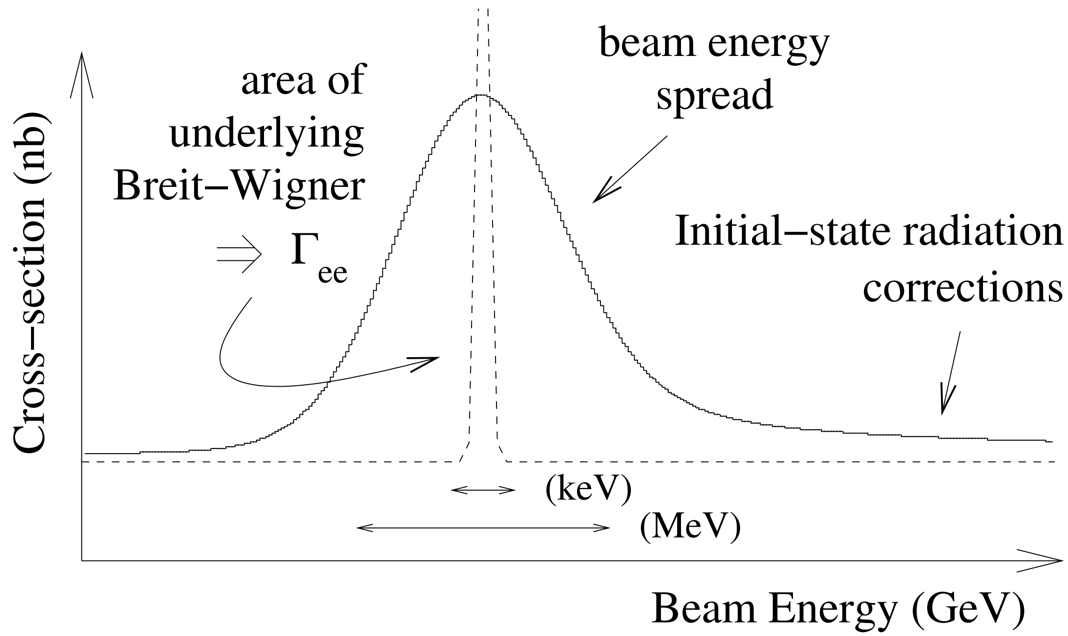


Cornell Electron Storage Ring

- Dedicated scans
- $\int$ Luminosity in fb^{-1}

	scan	off-res
1S	0.10	0.18
2S	0.06	0.44
3S	0.10	0.16

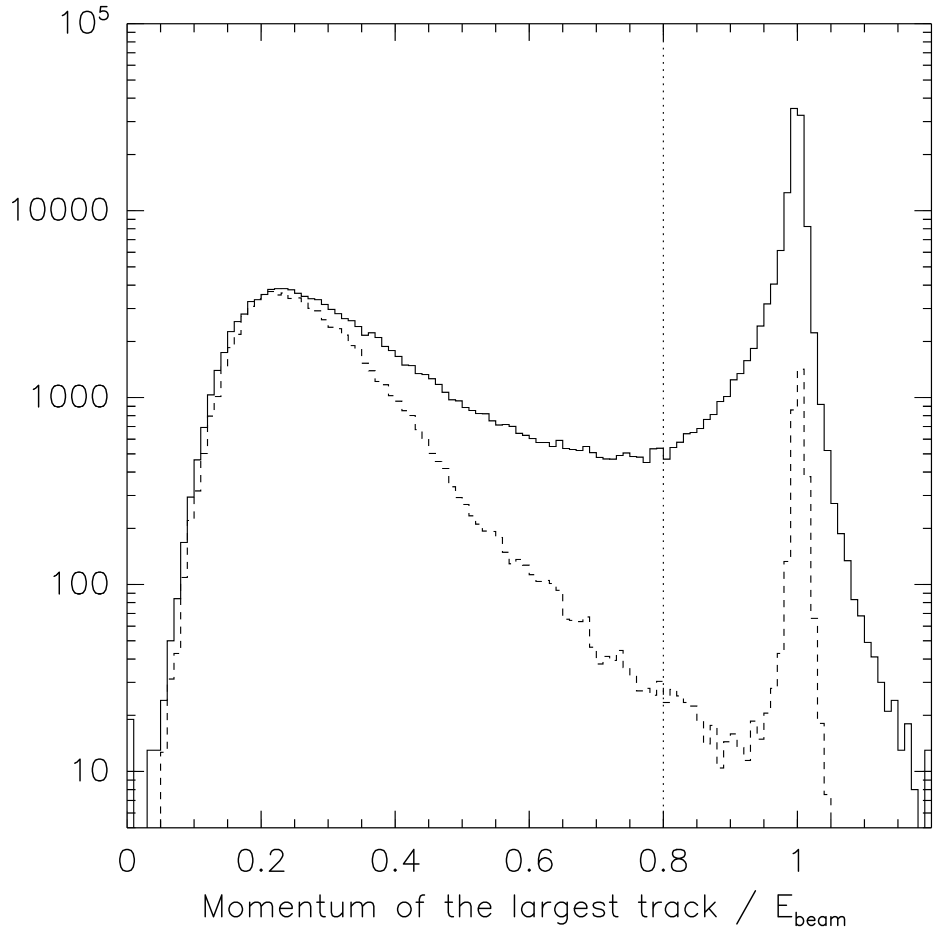
- Nov 2001 – Aug 2002



- Most background processes scale as $1/s$
- Breit-Wigner (BW) lineshape is convoluted with beam energy spread: does not affect $area$ $(= \Gamma_{ee})$
- Also convoluted with ISR tail $(e^+e^- \to \gamma\Upsilon)$ which diverges
- Fit to BW $\otimes$ Gauss $\otimes$ ISR, quote BW area

- Majority of Υ events are hadronic; well-measured fraction are $\ell^+\ell^-$
- Design event selection for $\Upsilon \to$ hadrons

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



Cut out

1. Bhabhas
2.
3.
4.

- Majority of Υ events are hadronic; well-measured fraction are $\ell^+\ell^-$
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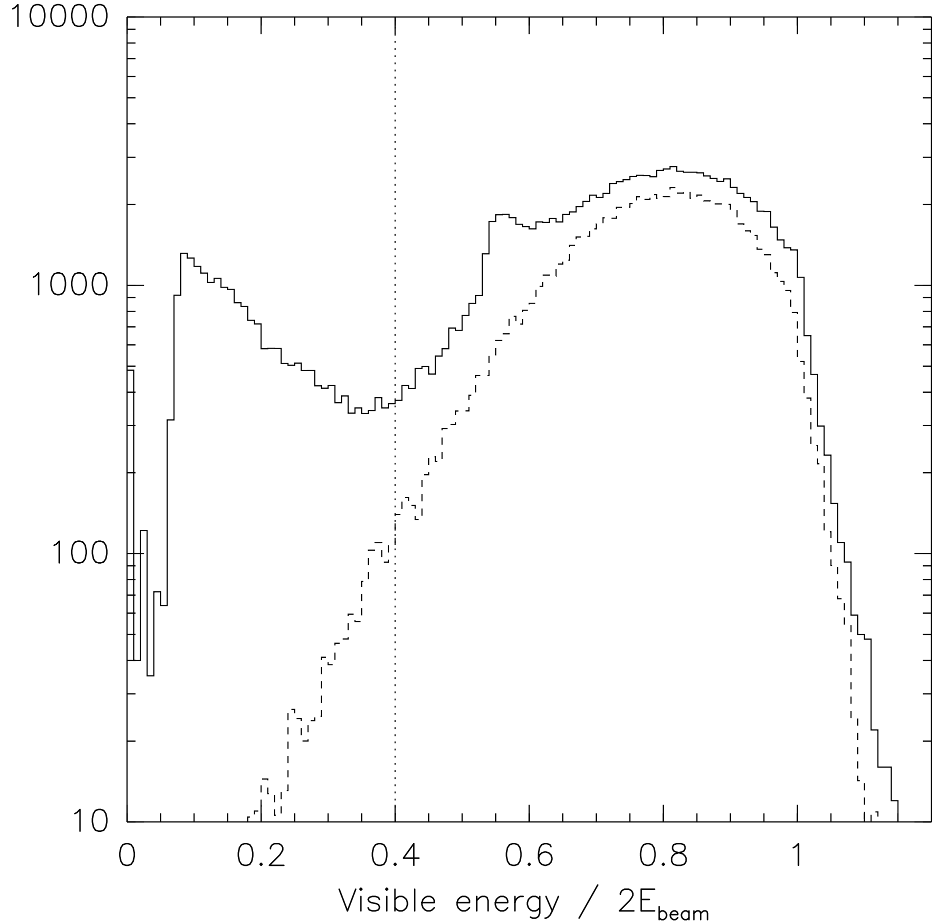

Cut out

1. Bhabhas

2. Two-photon fusion

3.

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- Majority of Υ events are hadronic; well-measured fraction are $\ell^+\ell^-$
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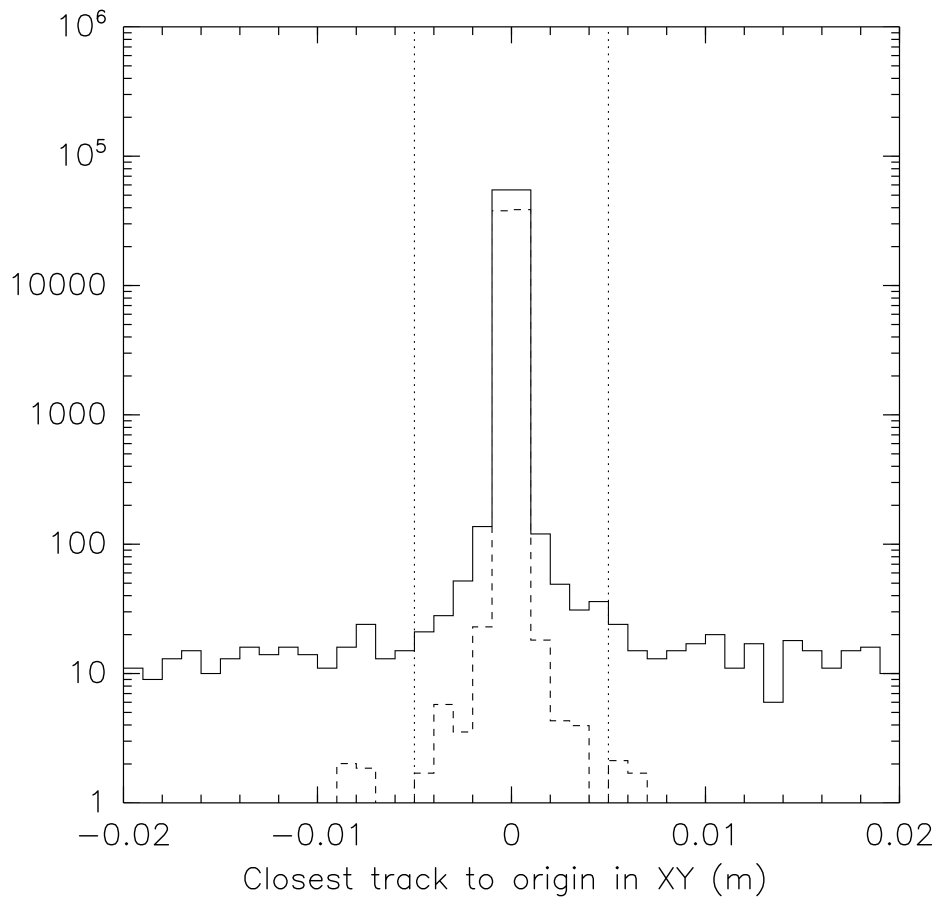


Cut out

1. Bhabhas

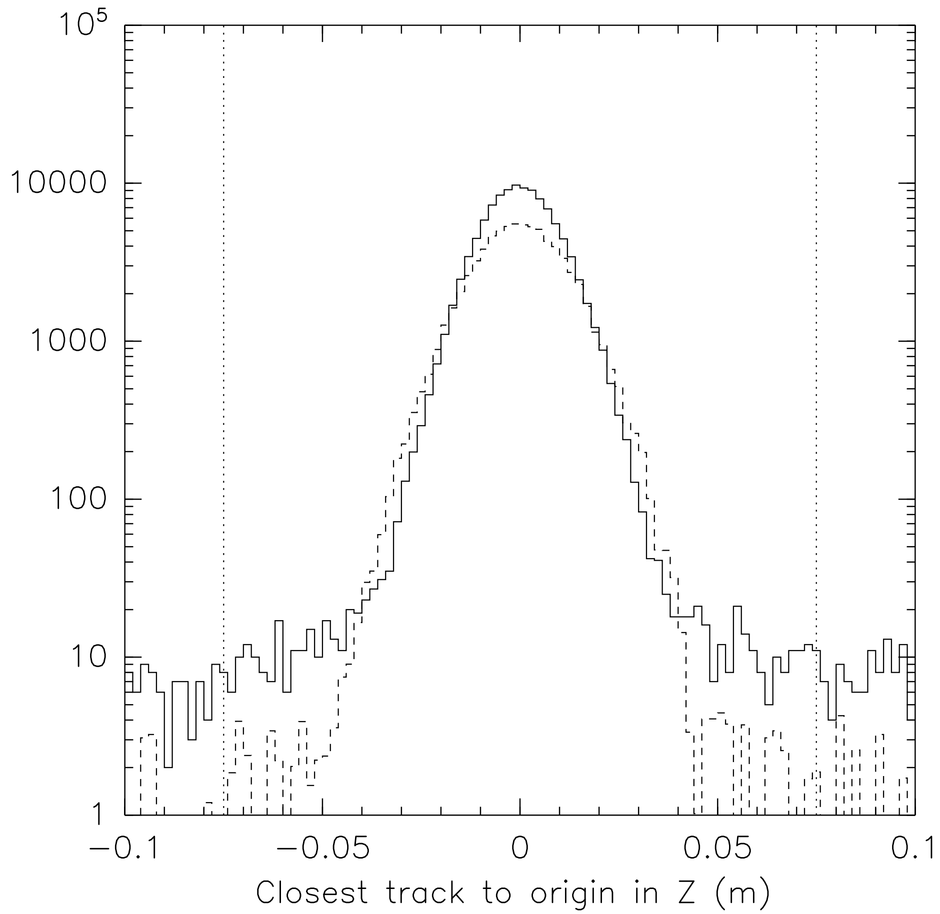
2. Two-photon fusion

3. Cosmic rays

4.

- Majority of Υ events are hadronic; well-measured fraction are $\ell^+\ell^-$
- Design event selection for $\Upsilon \longrightarrow$ hadrons

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



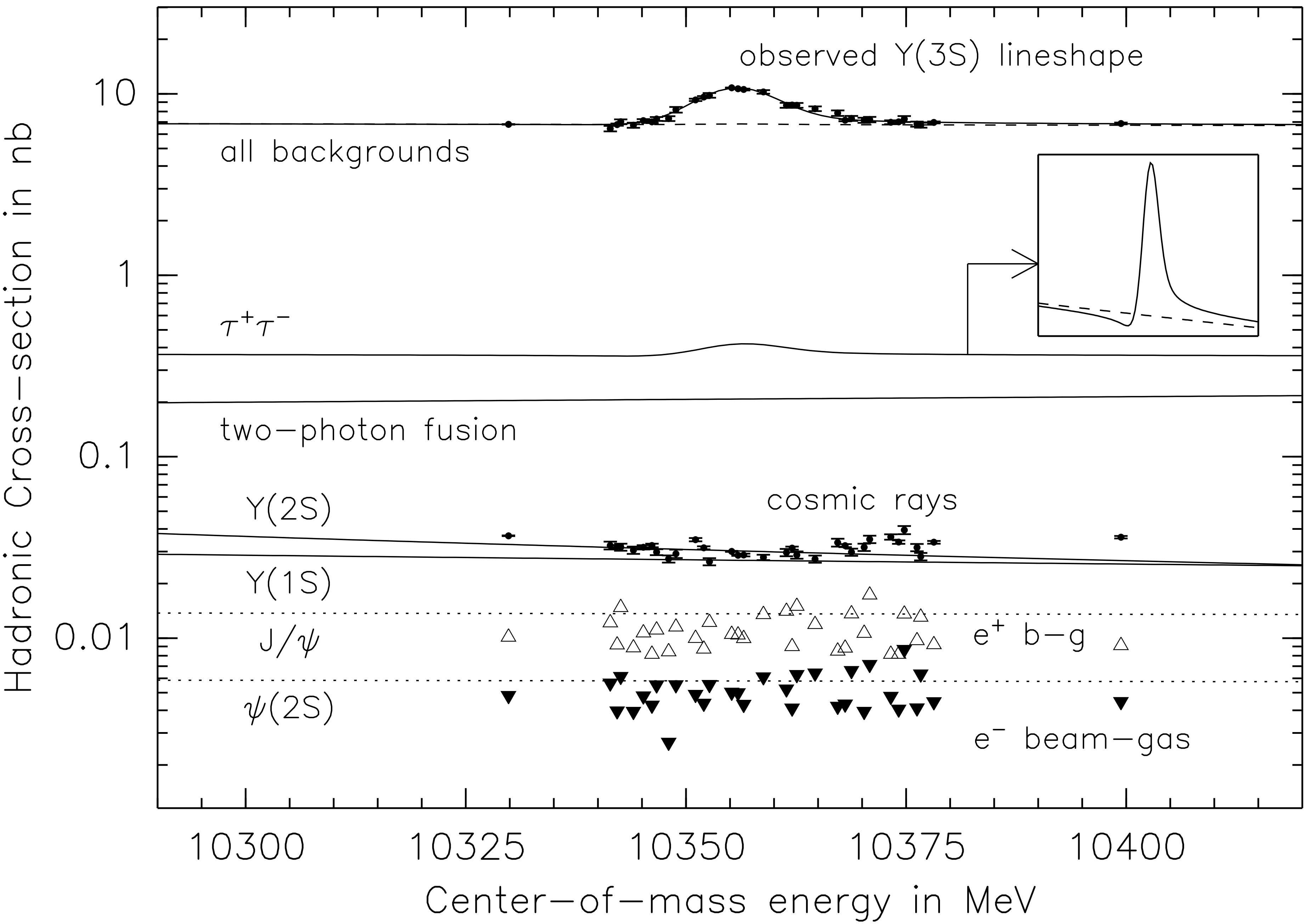
Cut out

1. Bhabhas

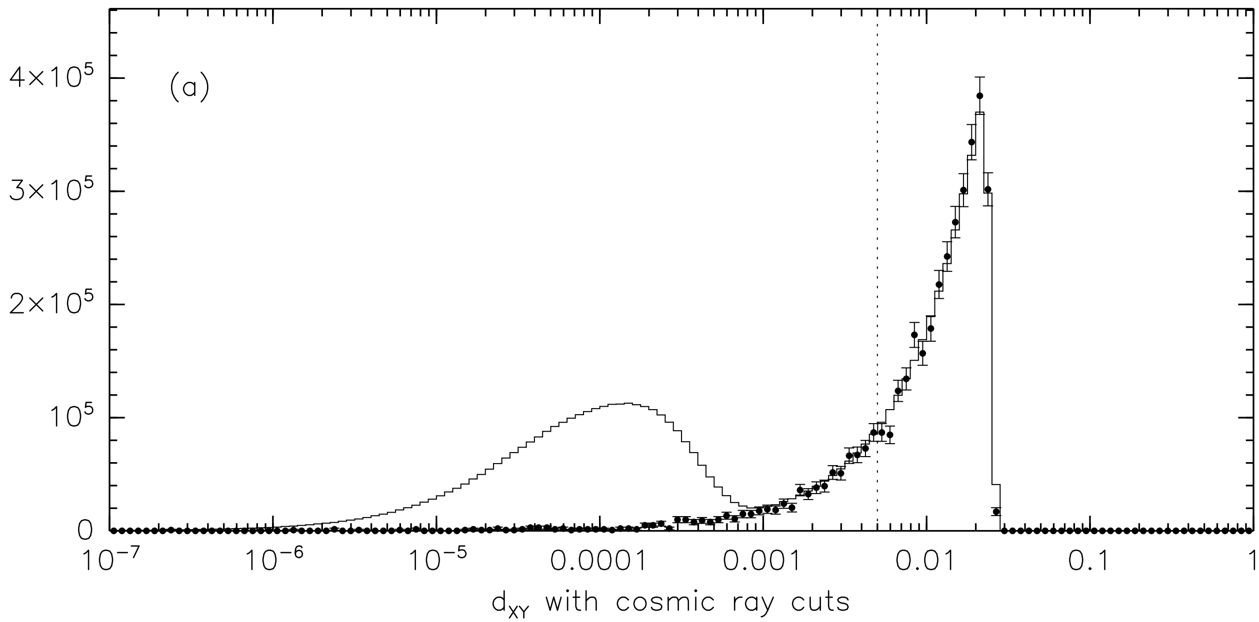
2. Two-photon fusion

3. Cosmic rays

4. Beam-gas

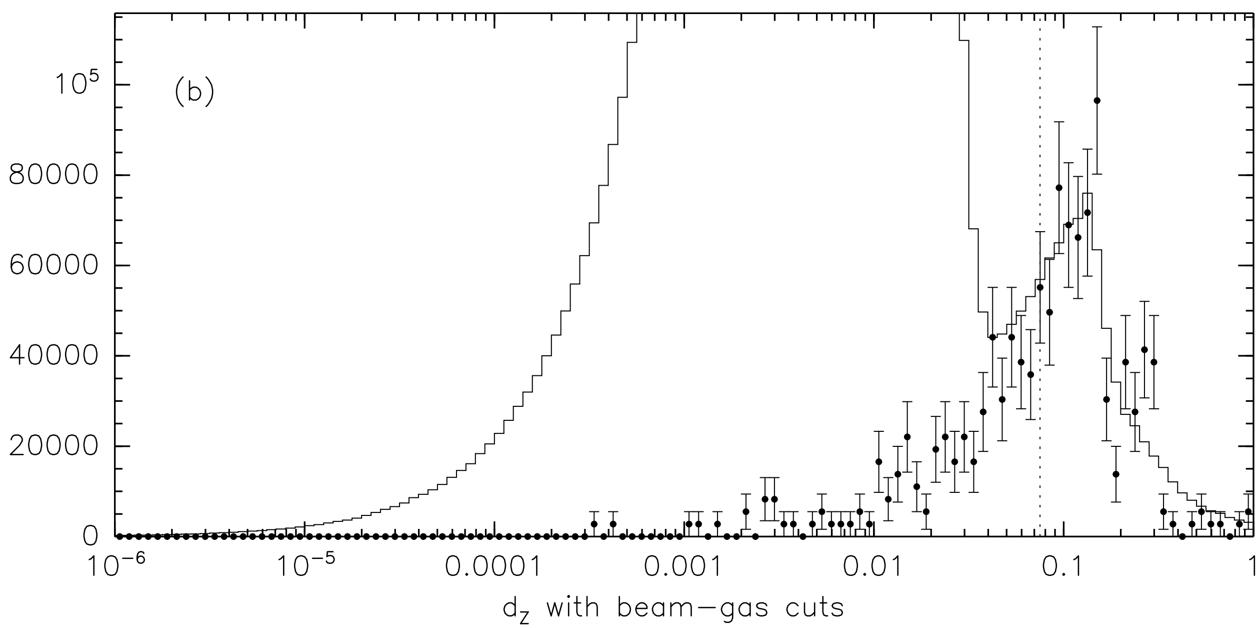

observed Υ(3S) lineshape
10
all backgrounds
1
$\tau^+\tau^-$
two−photon fusion
0.1
Υ(2S)
cosmic rays
Υ(1S)
0.01
J/ψ
e^+ b−g
ψ(2S)
e^- beam−gas
Hadronic Cross−section in nb
10300
10325
10350
10375
10400
Center−of−mass energy in MeV

Histogram is side-band data, points are control sample, log-x axis



(a) Cosmic ray side-band: normalize with "no-beam" sample

(XY distance from beamspot)

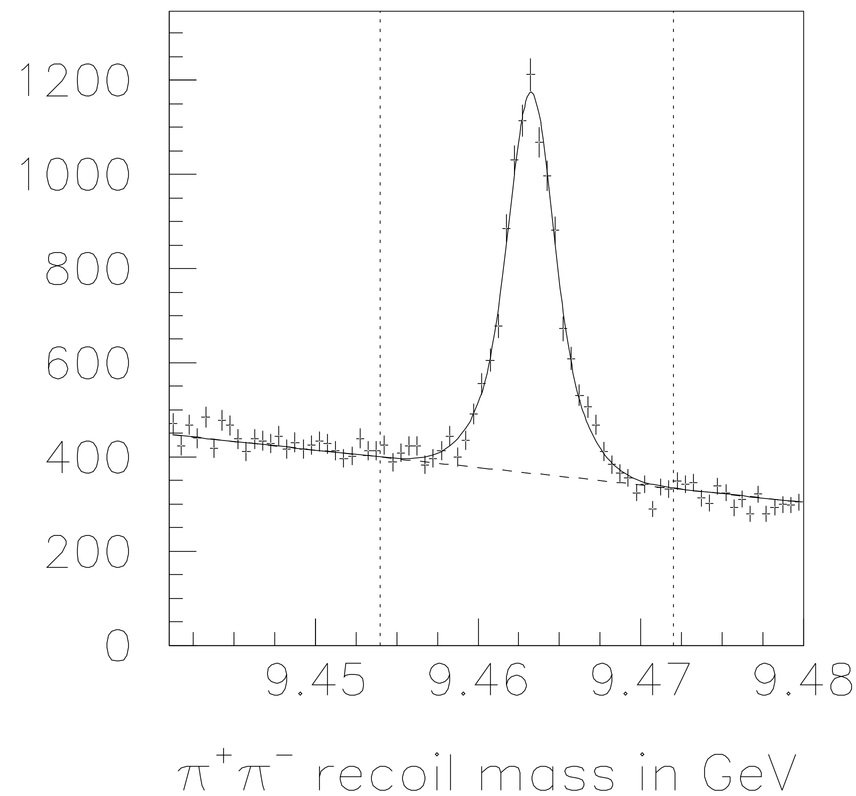


(b) Beam-gas side-band: normalize with "single-beam" sample

(Z distance from beamspot)

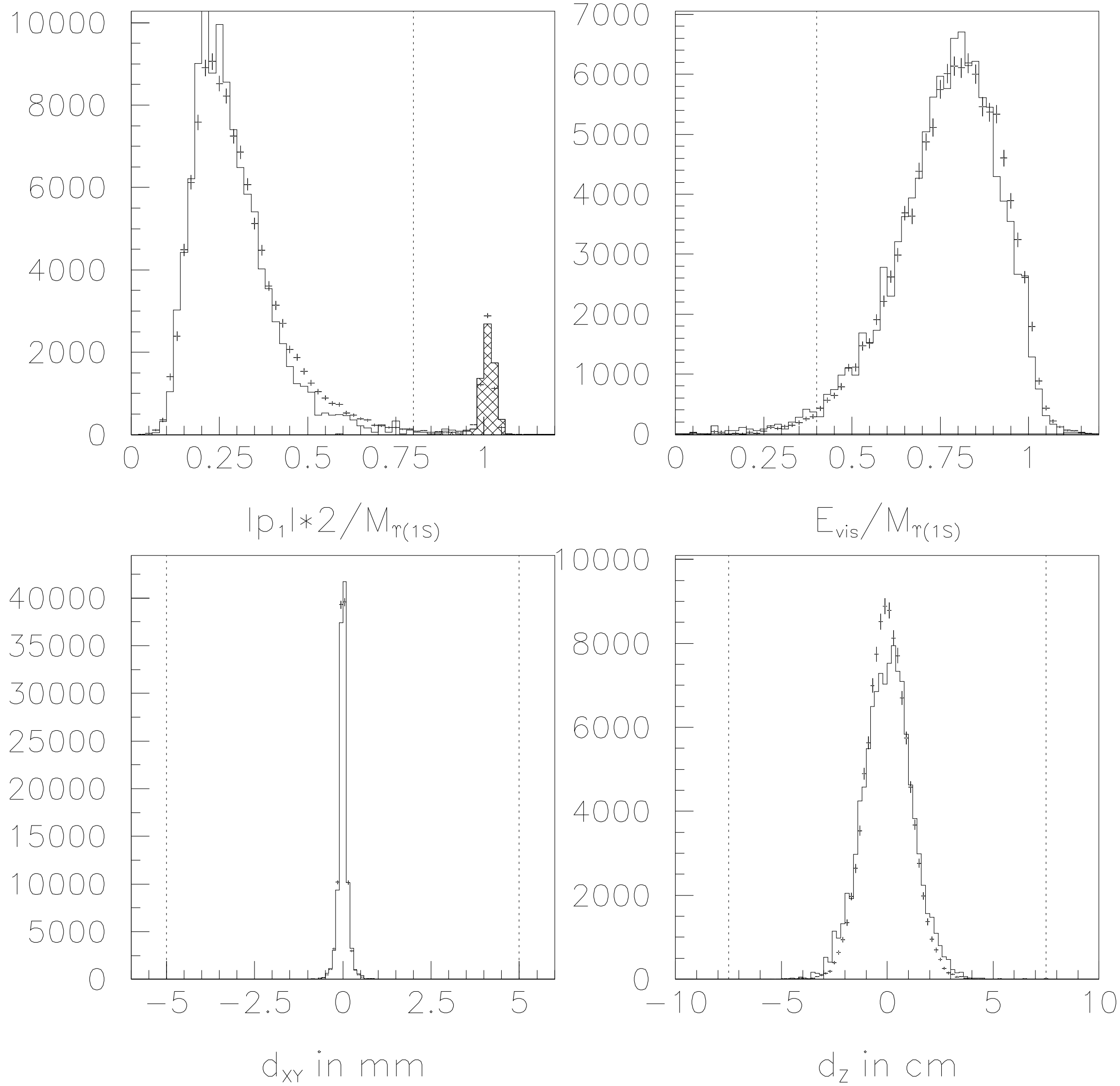
- How many hadronic Υ decays pass event selection?
- Model-independent method for measuring hadronic efficiency:
  - Select $\Upsilon(2S) \to \pi^+\pi^- \Upsilon(1S)$ based on $\pi^+\pi^-$ only
  - Choose $\pi^+\pi^-$ to be sufficient for all cuts, trigger
  - Set of $\Upsilon(1S)$ events is unbiased

    Includes all decays, even if undetectable ($\nu\bar{\nu}$)
  - #pass/#total $= (97.8 \pm 0.5)\%$

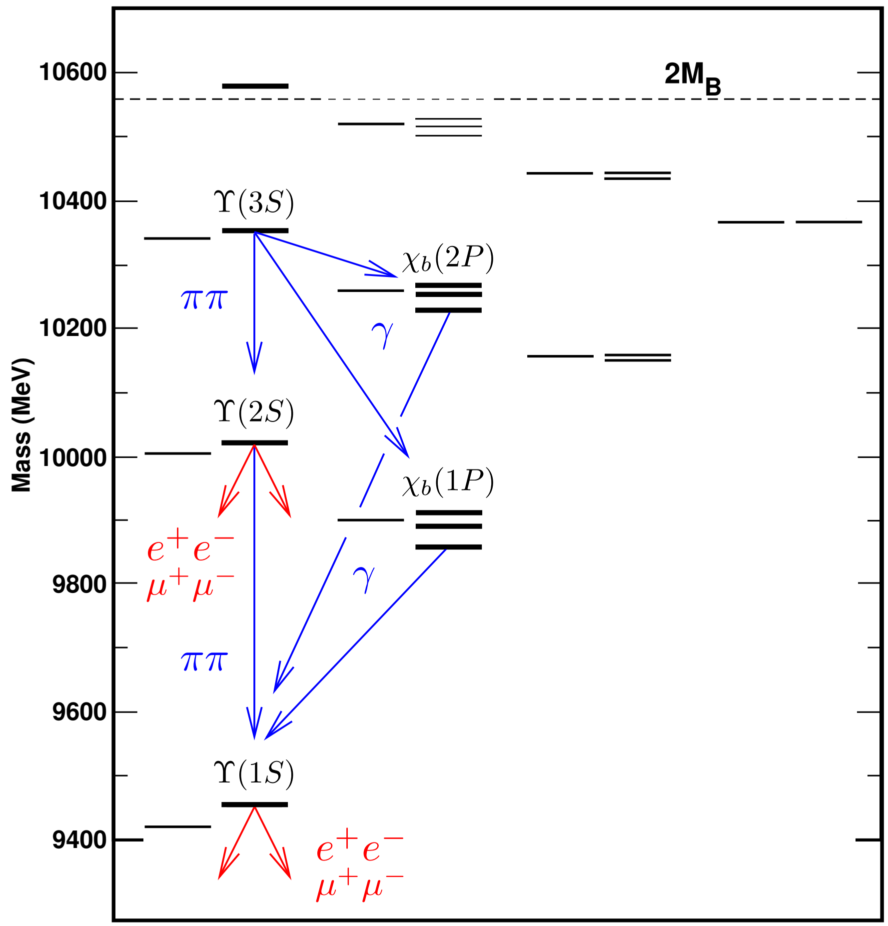


- Events in Υ peak (cut variables)

Histogram is Monte Carlo, points are data

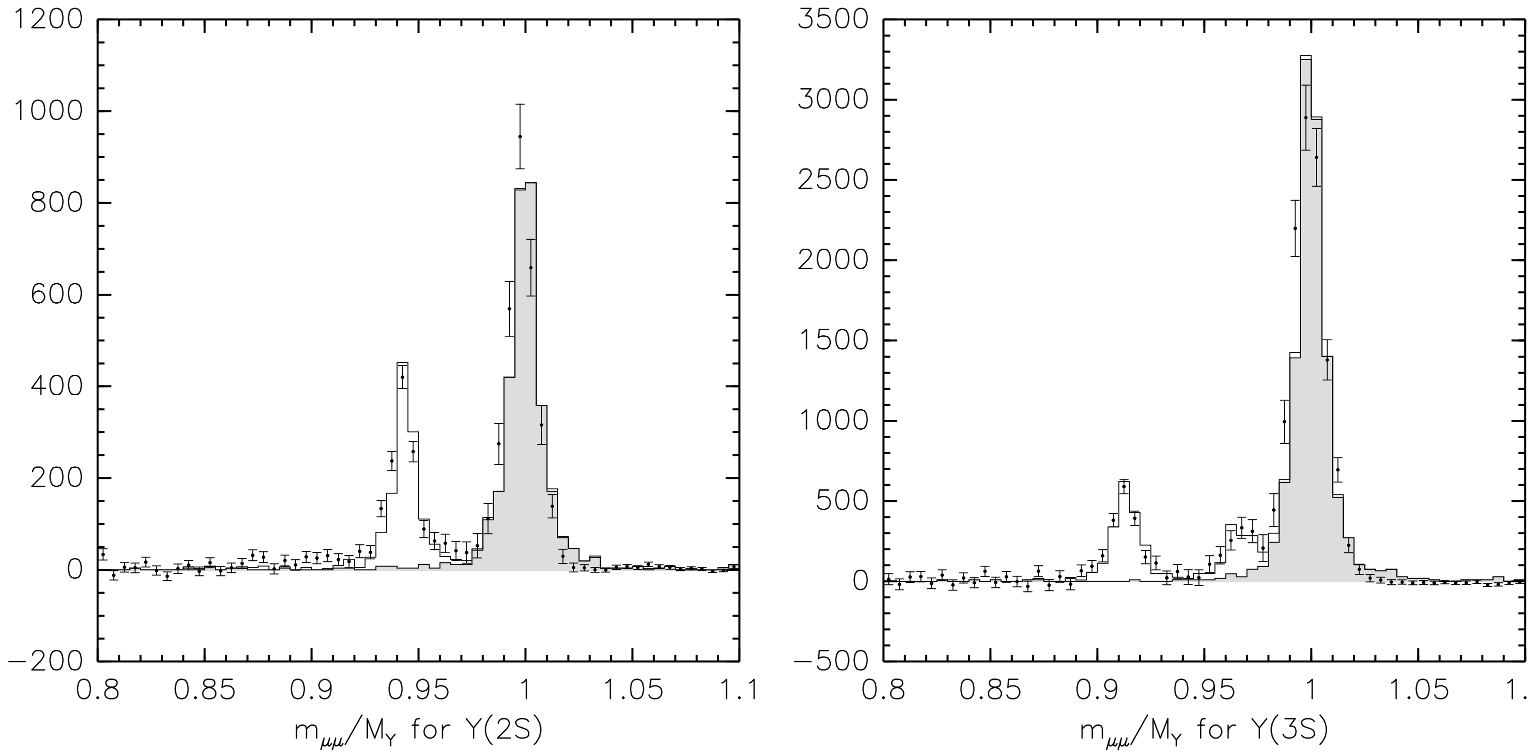


- For $\Upsilon(2S)$, $\Upsilon(3S)$, most modes are unchanged
- Exception: Xe^+e^- and $X\mu^+\mu^-$, which have zero efficiency (track momentum cut)



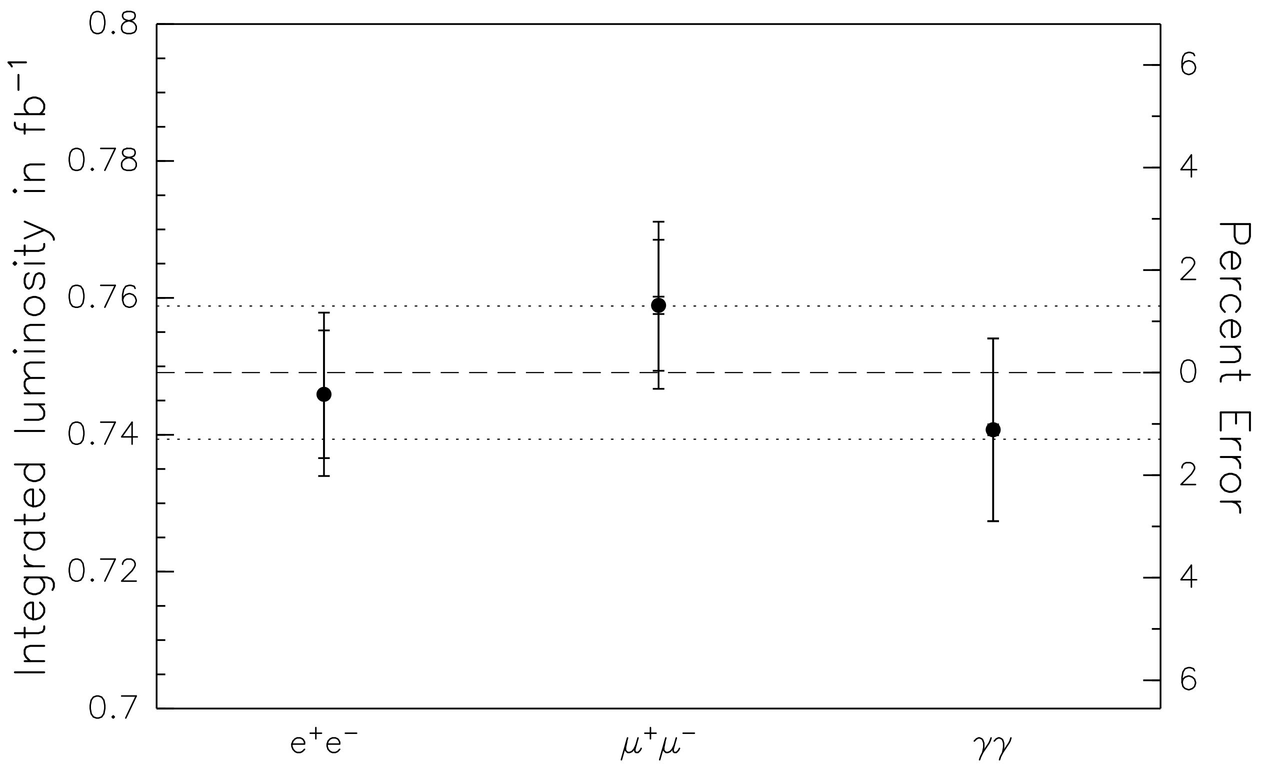
- $\Upsilon(2S)$, $\Upsilon(3S)$ efficiency is essentially $1 - \mathcal{B}(X\ell^+\ell^-)$
- Mini-analysis to determine these branching fractions in data

$\mu^+\mu^-$ invariant mass, histogram is Monte Carlo, points are data, shaded is *prompt* $\mu^+\mu^-$ (no X)

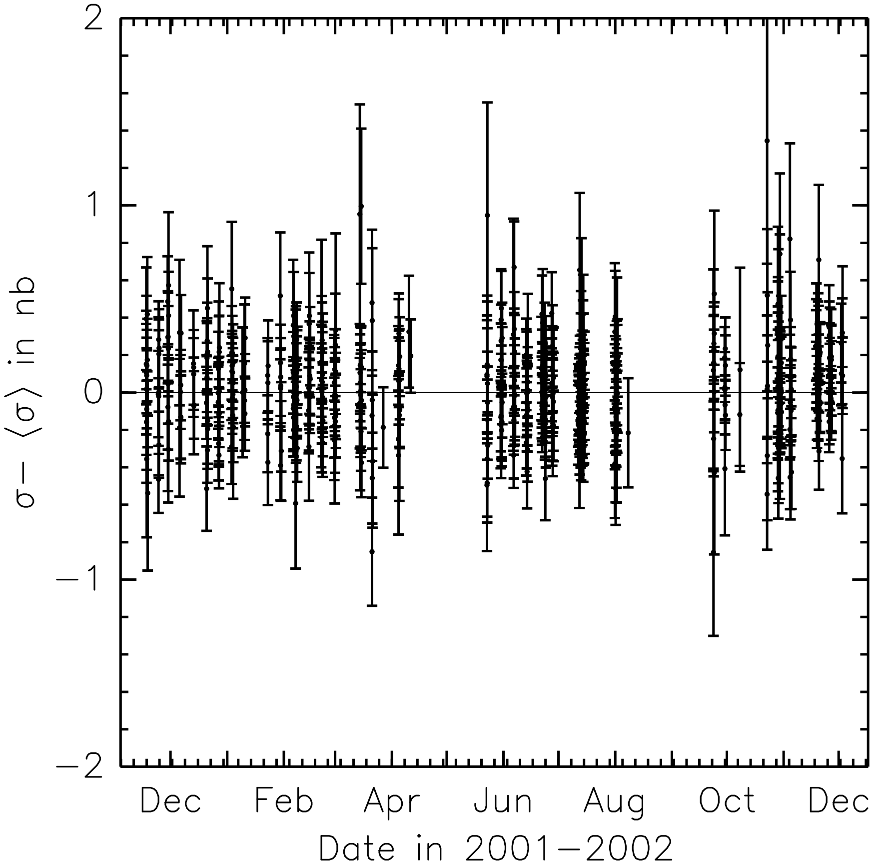


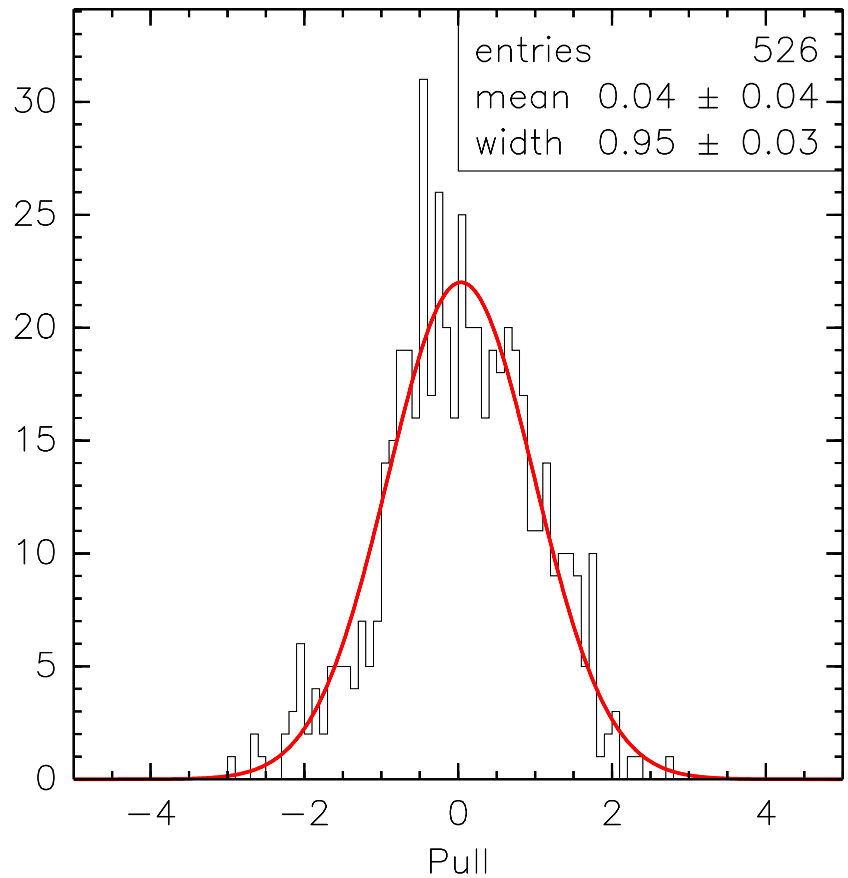
- $\mathcal{B}(2S \to X\ell^+\ell^-) = (1.58 \pm 0.16)\%$ $\qquad$ $\mathcal{B}(3S) = (1.34 \pm 0.13)\%$

- Need to know integrated luminosity for each scan point: count $\gamma\gamma$ events
- Need to normalize scale: careful analysis using e^+e^-, $\mu^+\mu^-$, $\gamma\gamma$



- Blinded Γ_{ee} by applying this normalization at the end



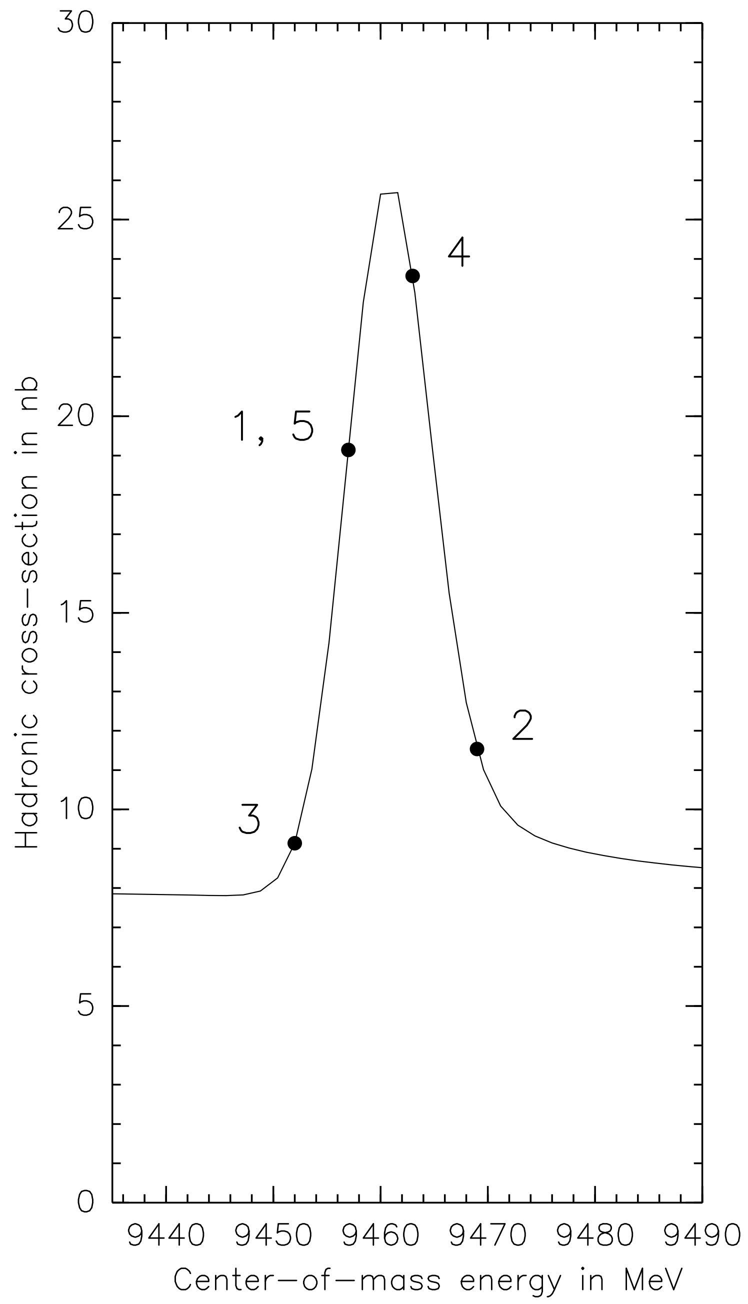


- All off-resonance runs at a given energy reproduce the same cross-section

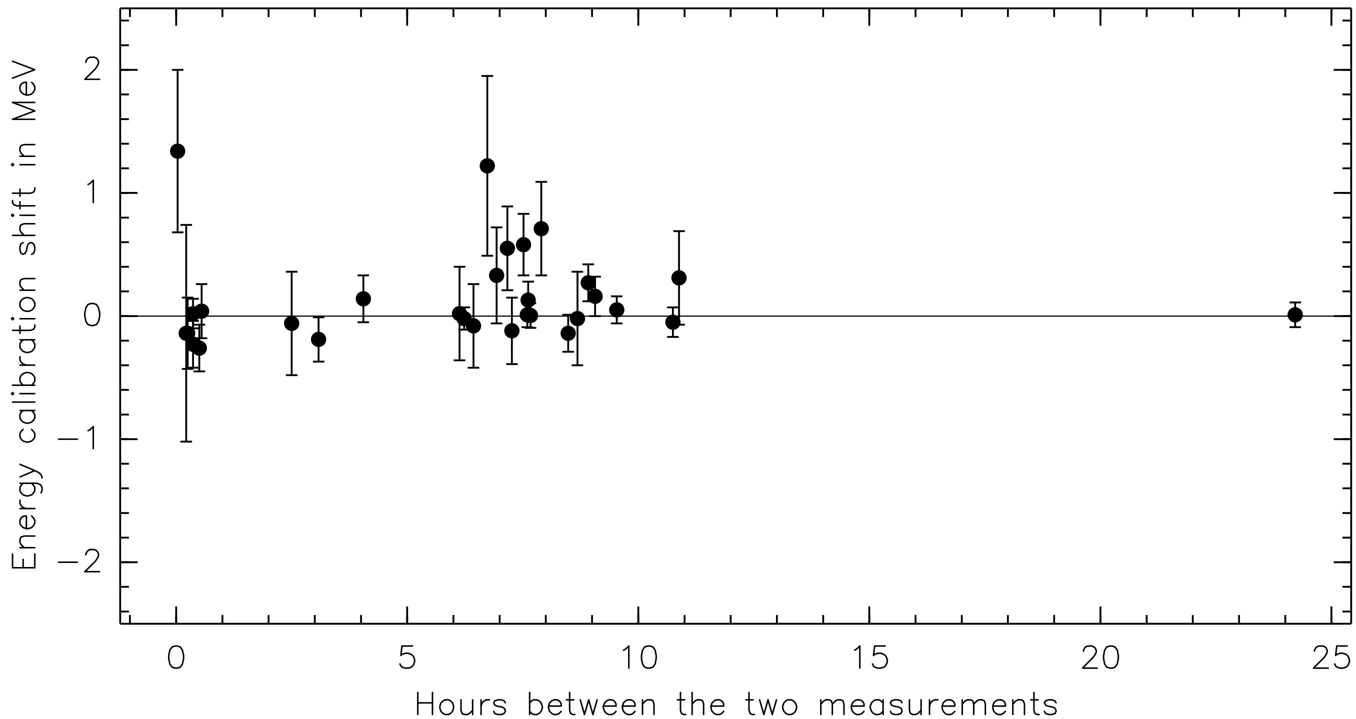
- Cross-section instability $\lesssim$ 0.03 nb

Beam energy reproducibility

- Each resonance was completely scanned once a week
- Measurements alternated above and below resonance peak
- A point of high slope was repeated in the scan



- Repeated point $\longrightarrow$ beam energy reproducibility
- Total of 30 pairs



- Beam-energy measurement instability $\lesssim$ 0.07 MeV

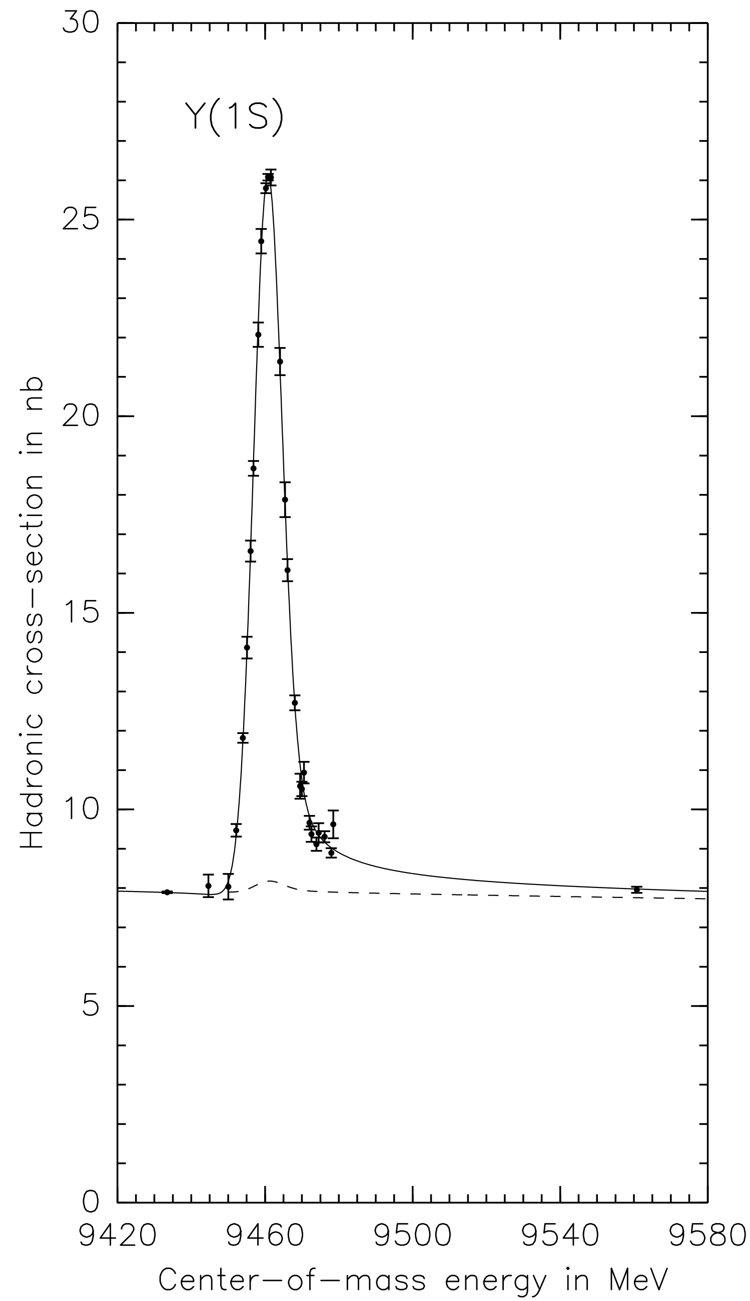
Parameters:

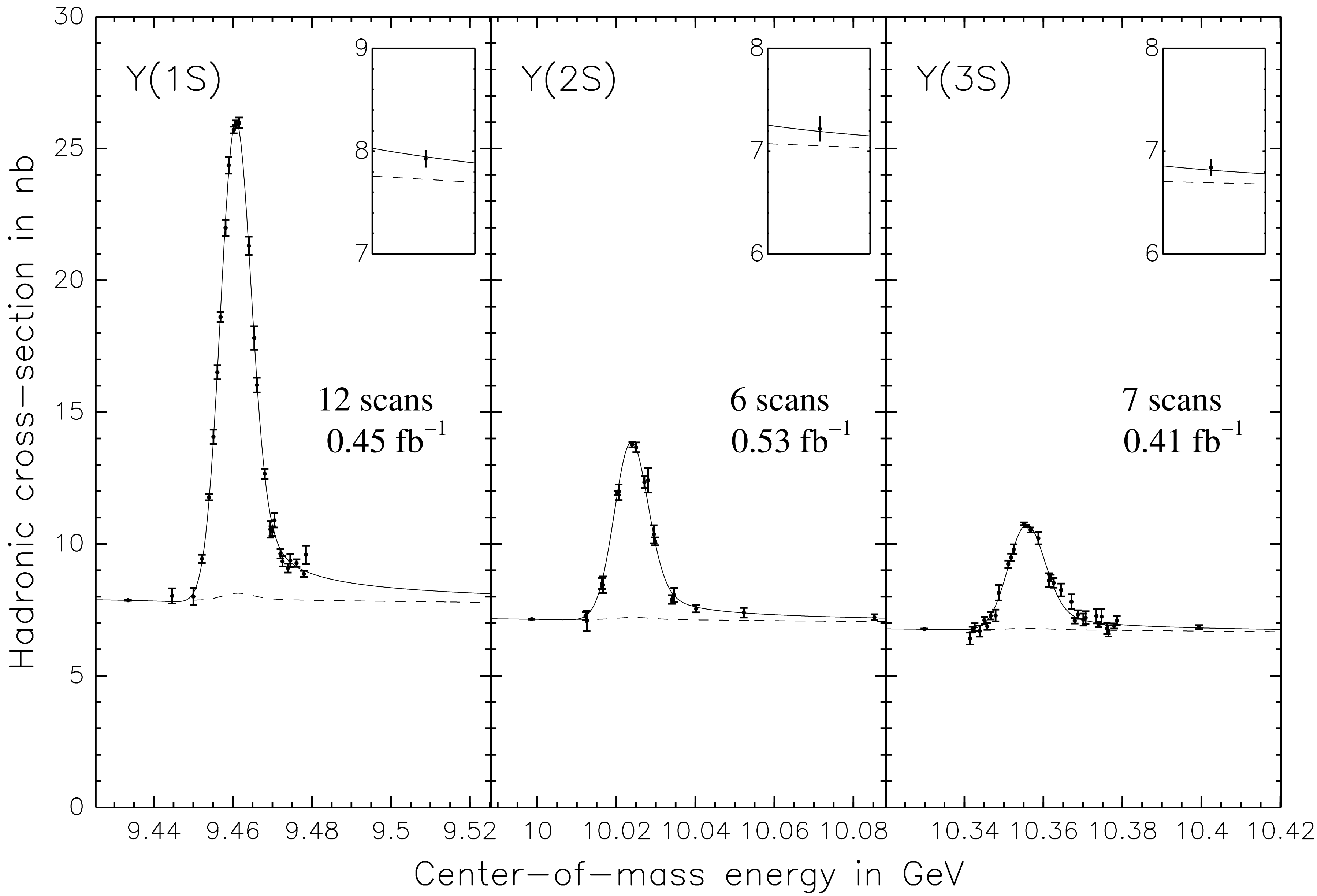
1. Area without tail (MeV nb) $\longrightarrow \Gamma_{ee}$ (keV)

2. Beam energy spread (MeV)

3. Background level (nb)

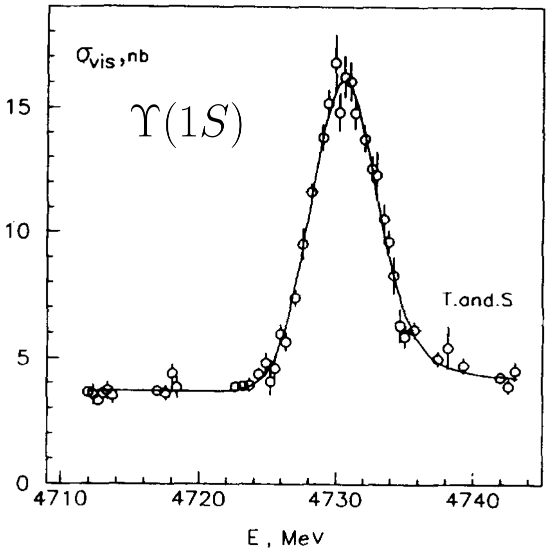
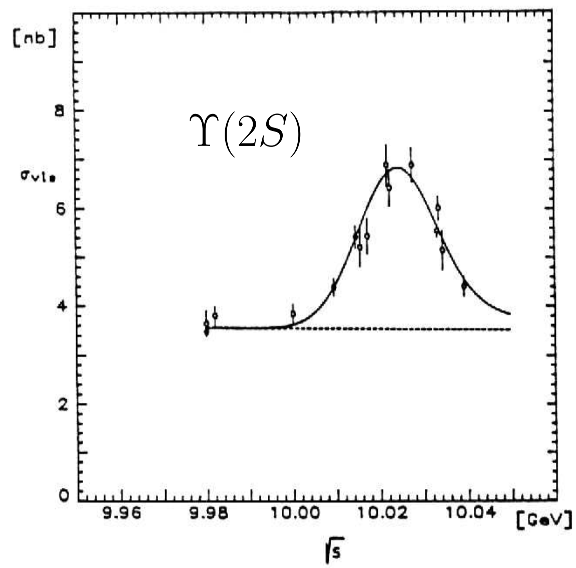
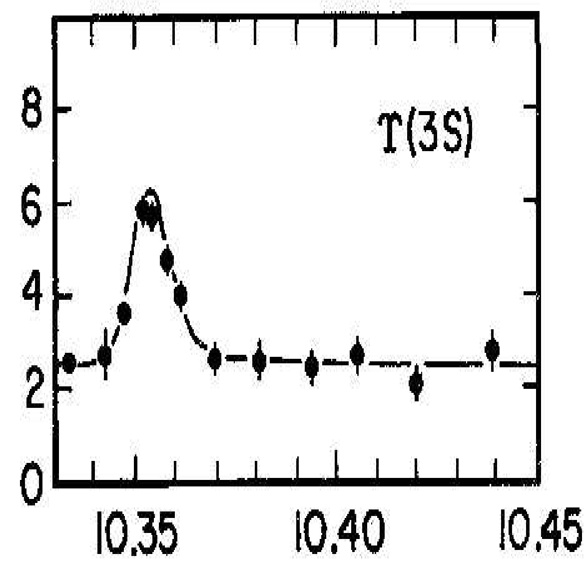
4–15. Υ mass for each weekly scan (MeV)

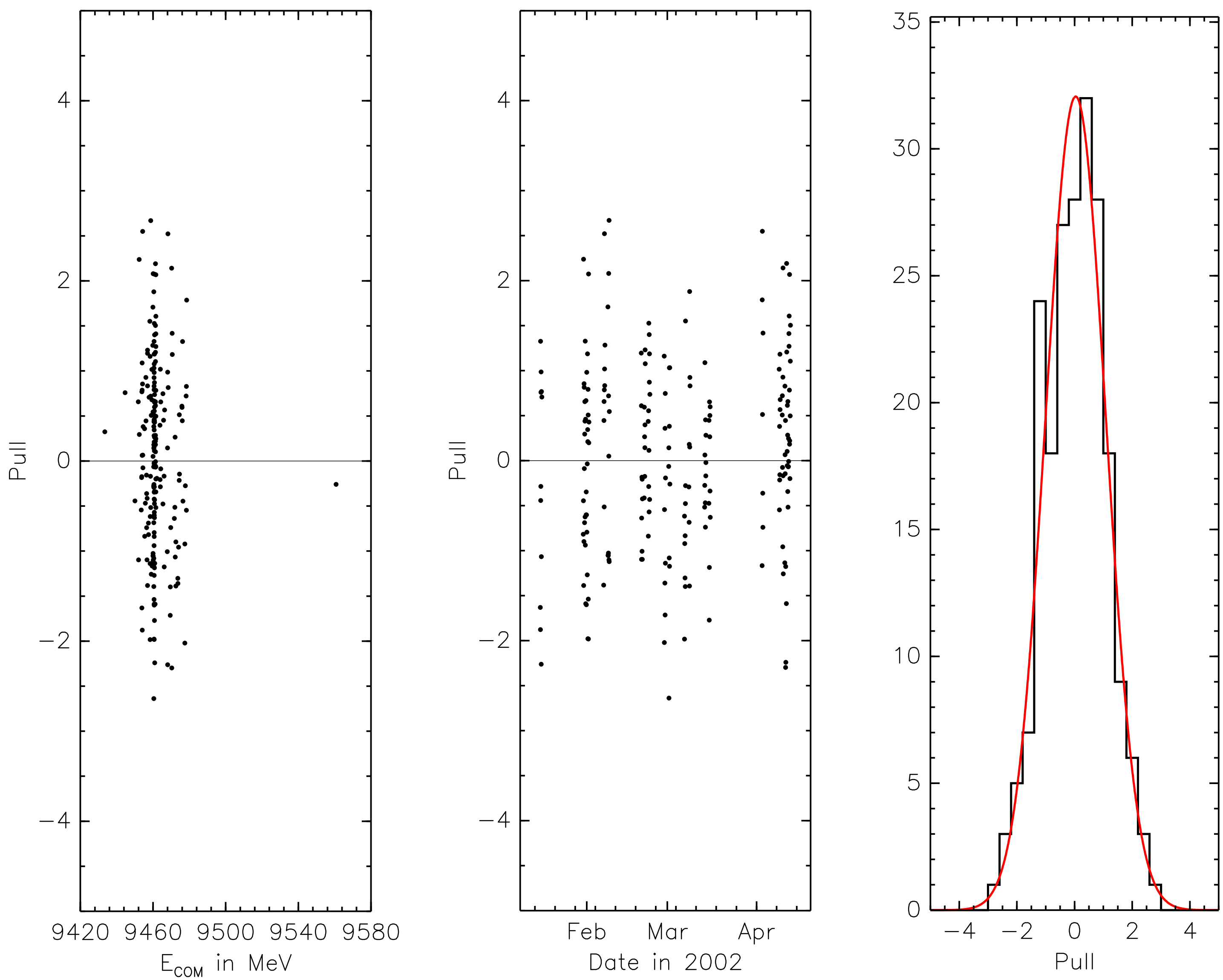




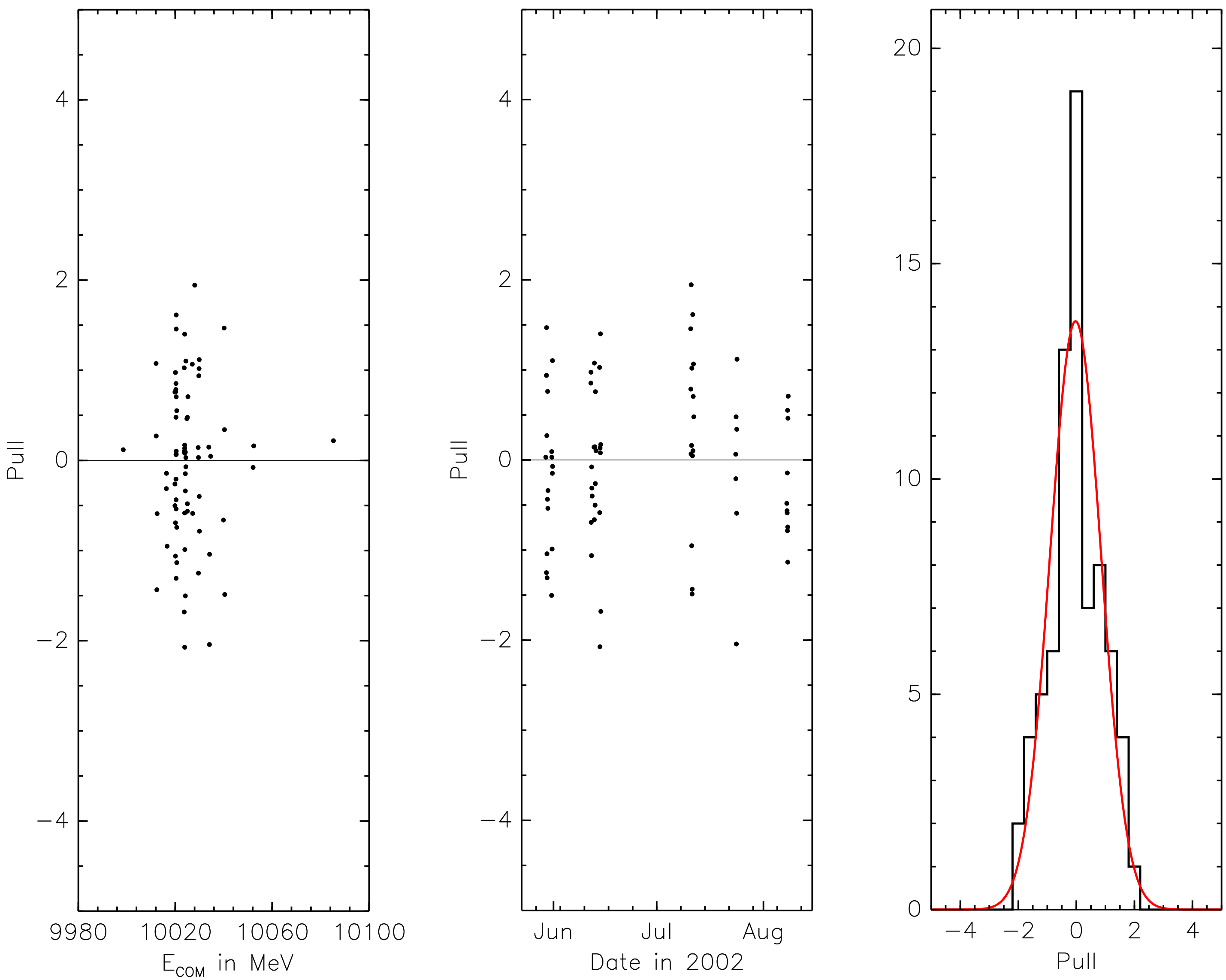
Y(1S)
Y(2S)
Y(3S)
12 scans
0.45 fb^{-1}
6 scans
0.53 fb^{-1}
7 scans
0.41 fb^{-1}
Hadronic cross−section in nb
Center−of−mass energy in GeV

- Best before CLEO-III

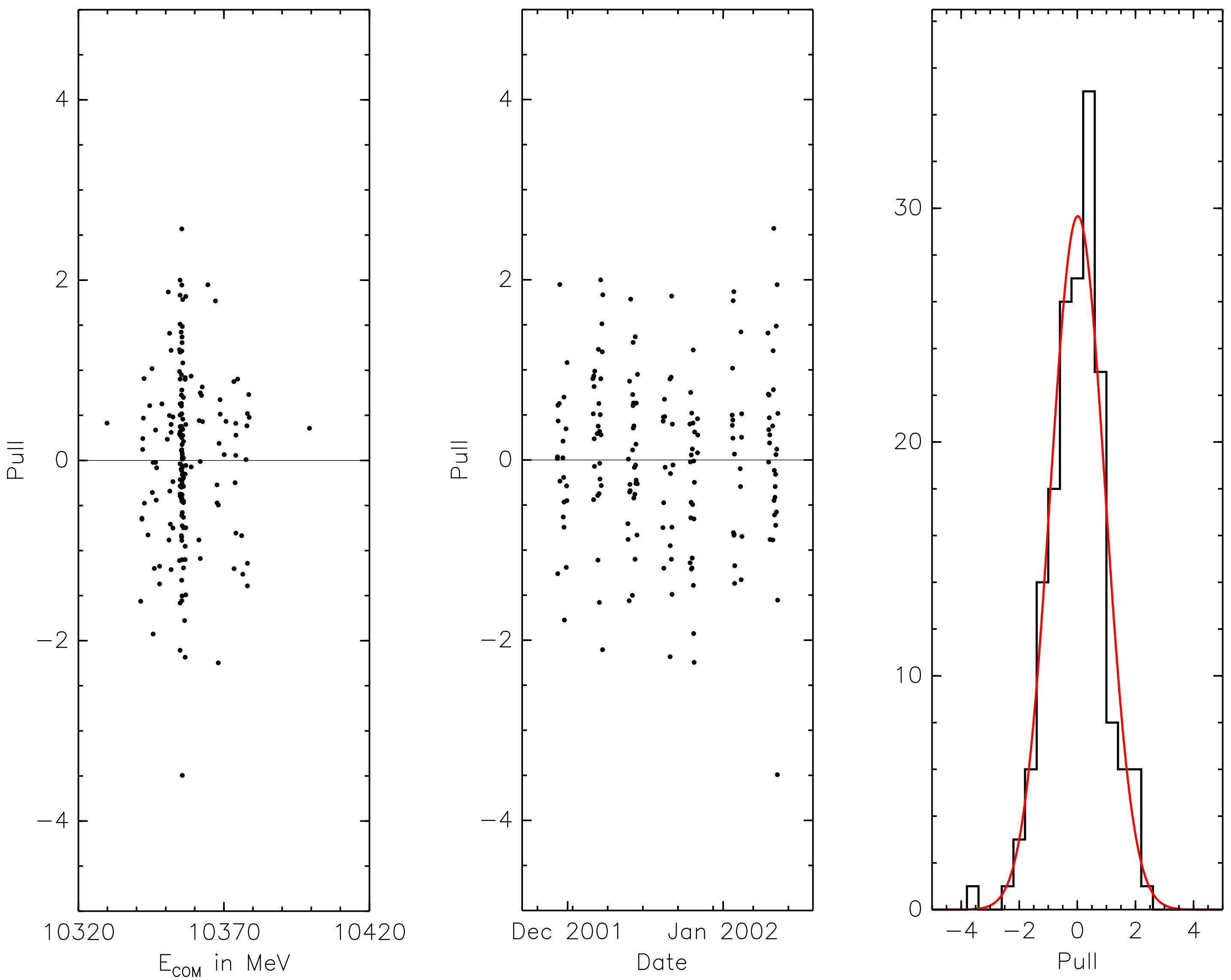
Novosibirsk 1996	ARGUS 1994	CLEO-I 1984
		
3.3%	6.1%	9.4%



$\Upsilon(1S)$ Pull Distributions: χ^2/ndf $=$ 230/195 $=$ 1.2, C.L. $=$ 4%



$\Upsilon(2S)$ Pull Distributions: $\chi^2/\text{ndf} = 58/66 = 0.87$, C.L. $= 76\%$



$\Upsilon(3S)$ Pull Distributions: χ^2/ndf $= 155/165 = 0.94$, C.L. $= 70\%$

Summary of Uncertainties

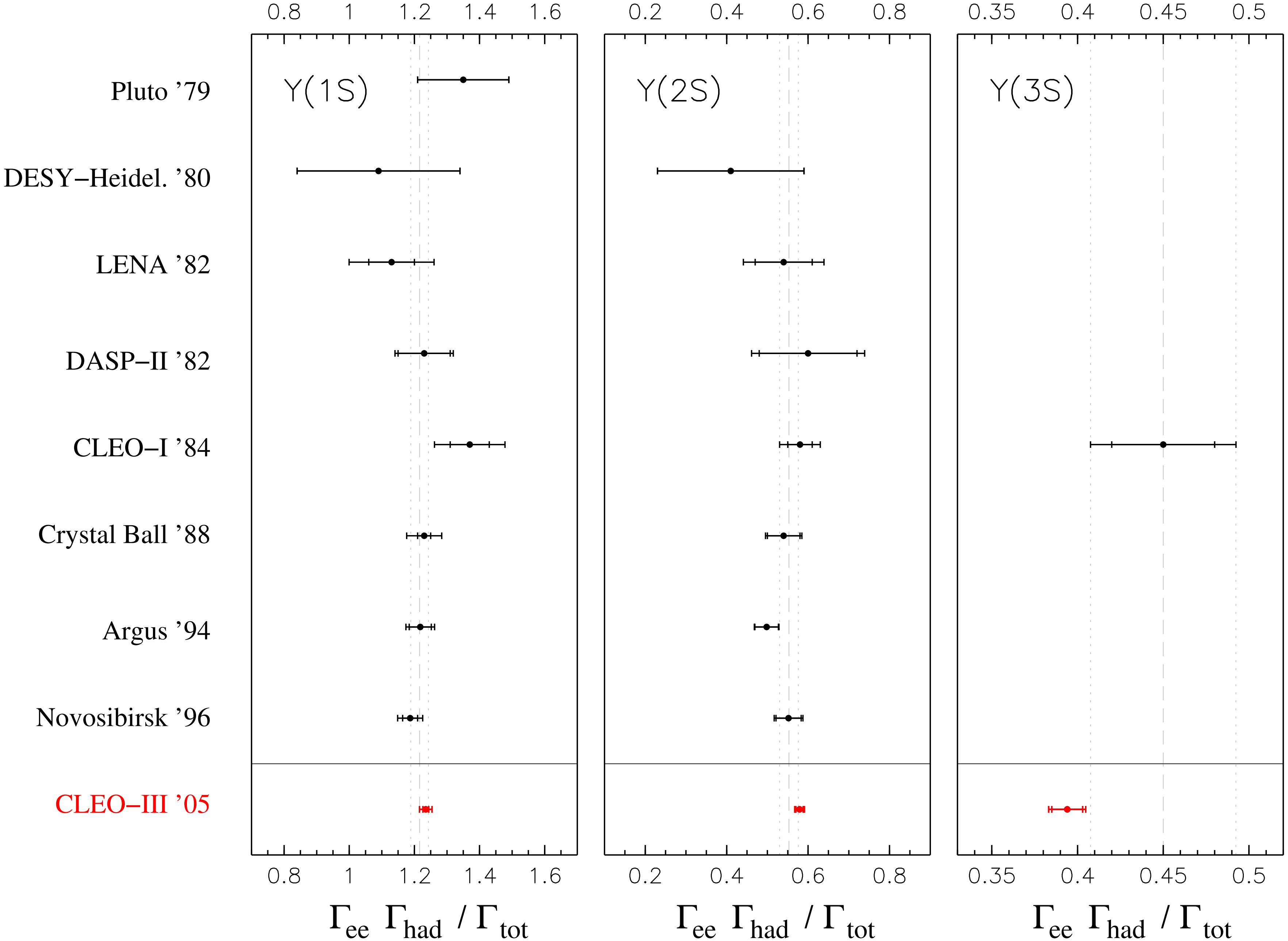
Contribution to Γ_{ee}	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
Statistical*	0.7%	1.6%	2.2%
$(1-3\mathcal{B}_{\mu\mu})$	0.2%	0.2%	0.3%
Hadronic efficiency	0.5%	0.6%	0.7%
Luminosity calibration	1.3%	1.3%	1.3%
Cross-section stability	0.1%	0.1%	0.1%
Beam-energy stability	0.2%	0.2%	0.2%
Shape of the fit function	0.05%	0.06%	0.05%
Total	1.6%	2.2%	2.7%

*Statistical uncertainty is dominated by run-by-run luminosity measurement ($\gamma\gamma$ counting)

Preliminary Results

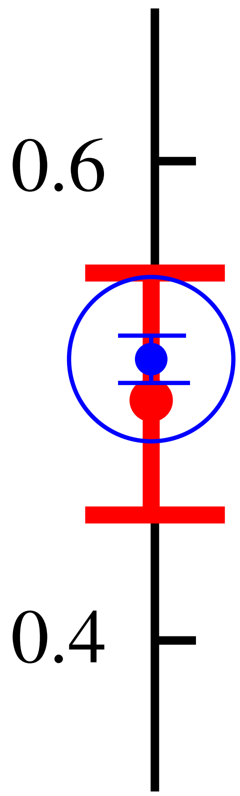
Quantity	Value	Uncertainty
$\Gamma_{ee}(1S)$	$1.336 \pm 0.009 \pm 0.019$ keV	1.6%
$\Gamma_{ee}(2S)$	$0.616 \pm 0.010 \pm 0.009$ keV	2.2%
$\Gamma_{ee}(3S)$	$0.425 \pm 0.009 \pm 0.006$ keV	2.7%
$\Gamma_{ee}(2S)/\Gamma_{ee}(1S)$	$0.461 \pm 0.008 \pm 0.003$	1.8%
$\Gamma_{ee}(3S)/\Gamma_{ee}(1S)$	$0.318 \pm 0.007 \pm 0.002$	2.4%
$\Gamma_{ee}(3S)/\Gamma_{ee}(2S)$	$0.690 \pm 0.019 \pm 0.006$	2.8%

Presented at EPS, Lattice05

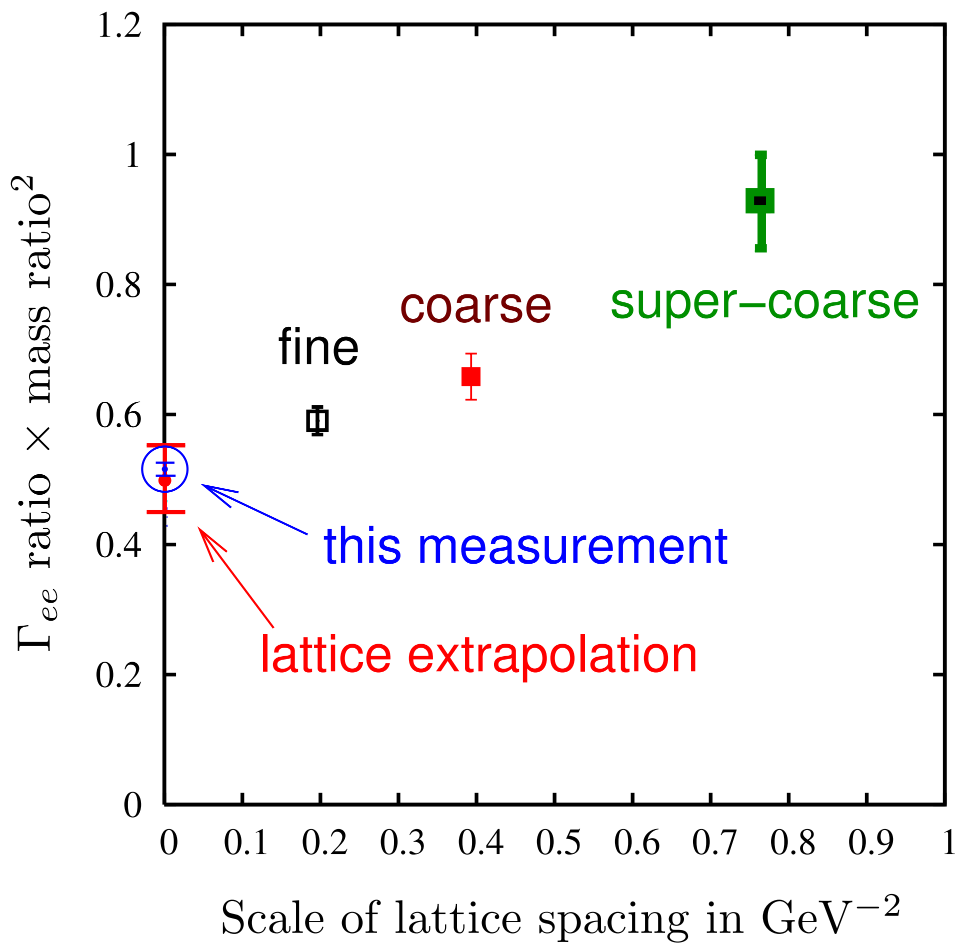

Pluto '79
DESY–Heidel. '80
LENA '82
DASP–II '82
CLEO–I '84
Crystal Ball '88
Argus '94
Novosibirsk '96
CLEO–III '05
Υ(1S)
Υ(2S)
Υ(3S)
0.8 1 1.2 1.4 1.6
0.2 0.4 0.6 0.8
0.35 0.4 0.45 0.5
$\Gamma_{ee}\,\Gamma_{had}\,/\,\Gamma_{tot}$
$\Gamma_{ee}\,\Gamma_{had}\,/\,\Gamma_{tot}$
$\Gamma_{ee}\,\Gamma_{had}\,/\,\Gamma_{tot}$

- LQCD result not yet complete
- But we can compare *ratio* of $\Gamma_{ee}(2S)/\Gamma_{ee}(1S)$ (missing factors cancel)

(detail)



extrapolation to continuum



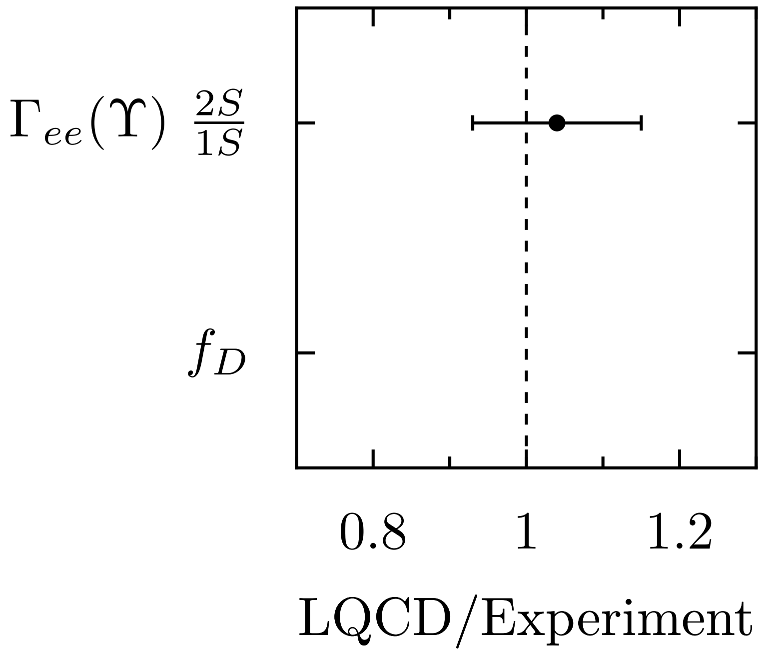
- Why does the lattice result have 10% uncertainty?

$$\Gamma_{ee} = \frac{16\pi\alpha^2 e_b^2}{6{M_\Upsilon}^2} \underbrace{\langle\Upsilon|J_\nu|0\rangle^2}_{\text{wavefunction at origin}} {Z_{match}}^2$$

- Wavefunction at origin is particularly sensitive to discretization

- Z_{match} is the missing factor, it contains discrete $\rightarrow$ continuum matching
- Predicted precision: few percent on ratios, 10% on absolute values

Conclusion for $\Gamma_{ee}(\Upsilon)$

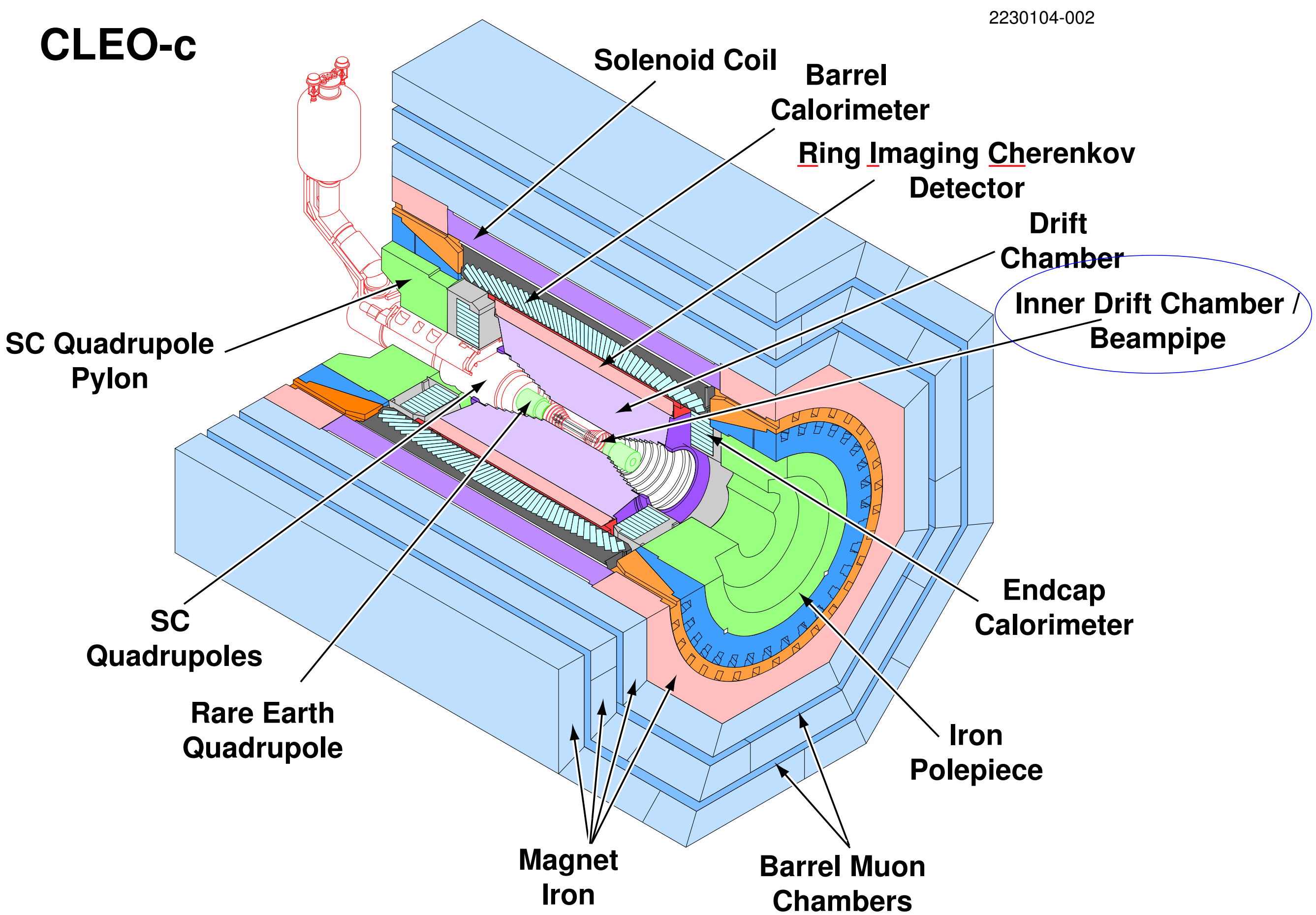


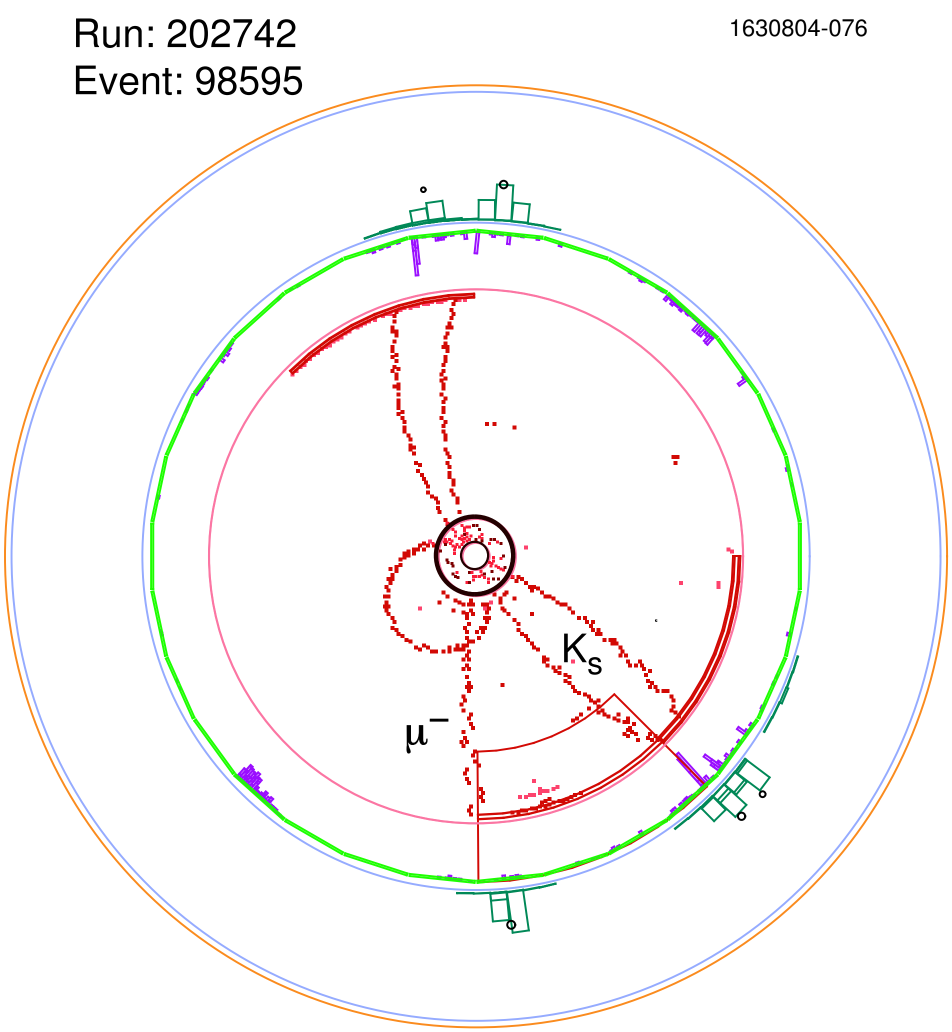
- Improvement to experiment:
  - If we measure point-by-point luminosity with e^+e^- rather than $\gamma\gamma$, we can gain a factor of two in statistical uncertainty
  - This would especially help ratios, which are statistically-limited
  - But this may introduce systematic error
- Improvements to theory are forthcoming

$$\boxed{f_D \text{ from } D^+ \to \mu^+\nu}$$

- CLEO-c, the next generation of CLEO
- Very different kind of analysis: discovery, statistics-limited

- CLEO-c: new inner tracker, charm energies
- 281 pb^{-1} at $\psi(3770)$: 3 million $D\bar{D}$



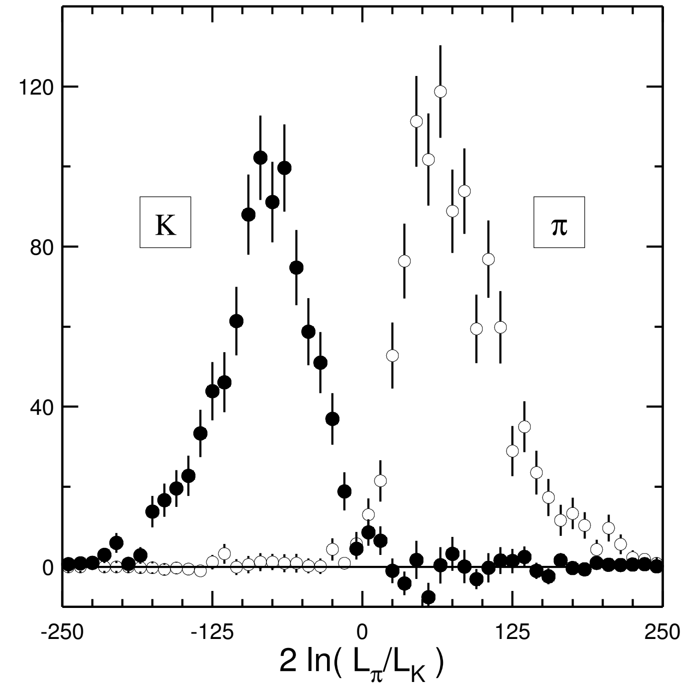


$K_s\pi^-\pi^+\pi^+$ Tag

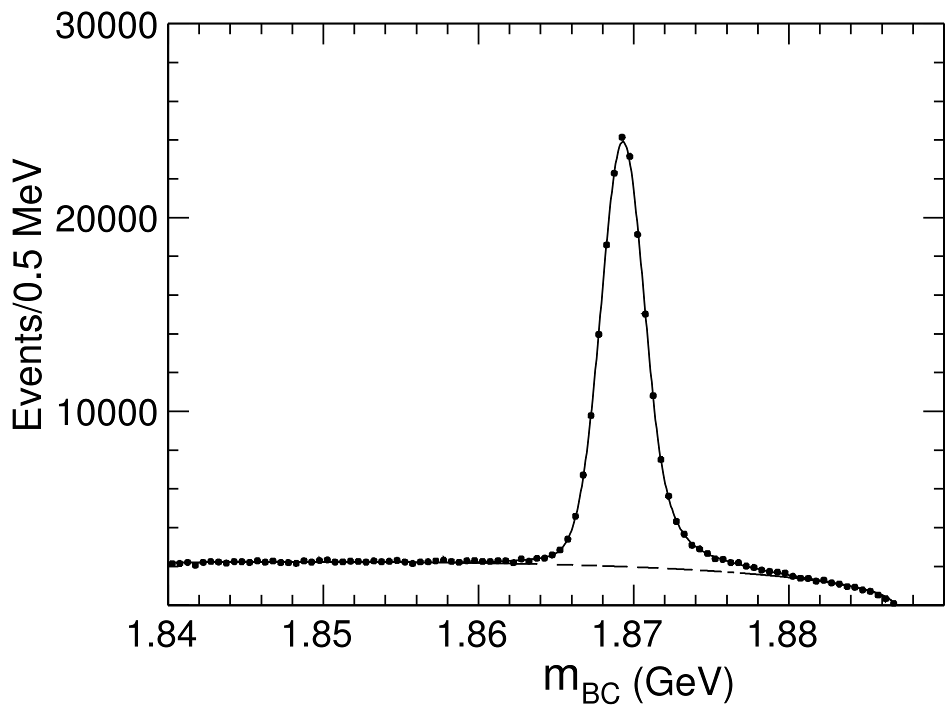
- MARK-III procedure
- Fully reconstruct D^- decay, search for $D^+ \to \mu^+\nu$

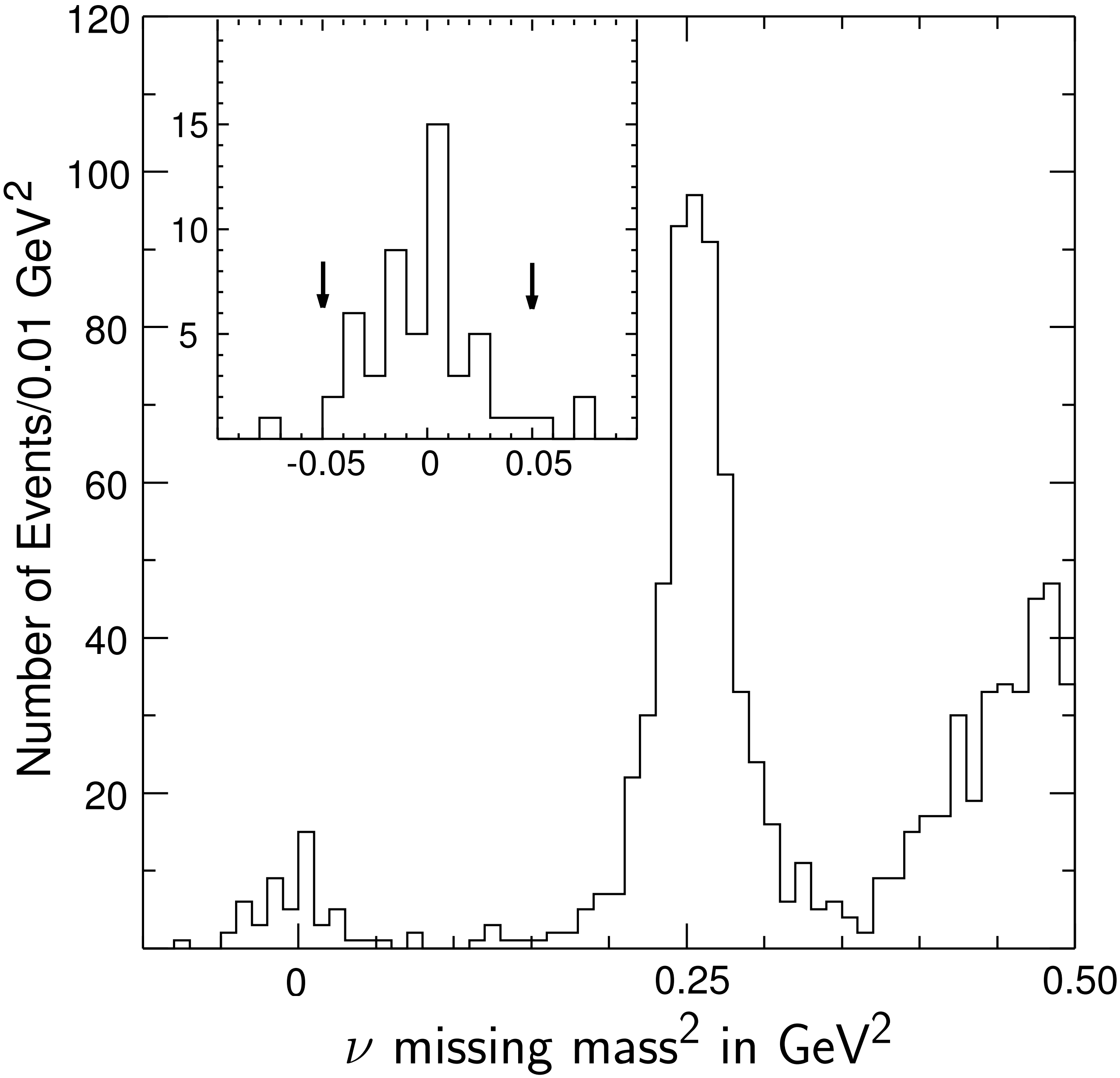
D^- Tag Modes
$K^+\pi^-\pi^-$
$K^+\pi^-\pi^-\pi^0$
$K_S\pi^-$
$K_S\pi^-\pi^-\pi^+$
$K_S\pi^-\pi^0$
$K^+K^-\pi^-$

- RICH detector for μ/K, π/K separation



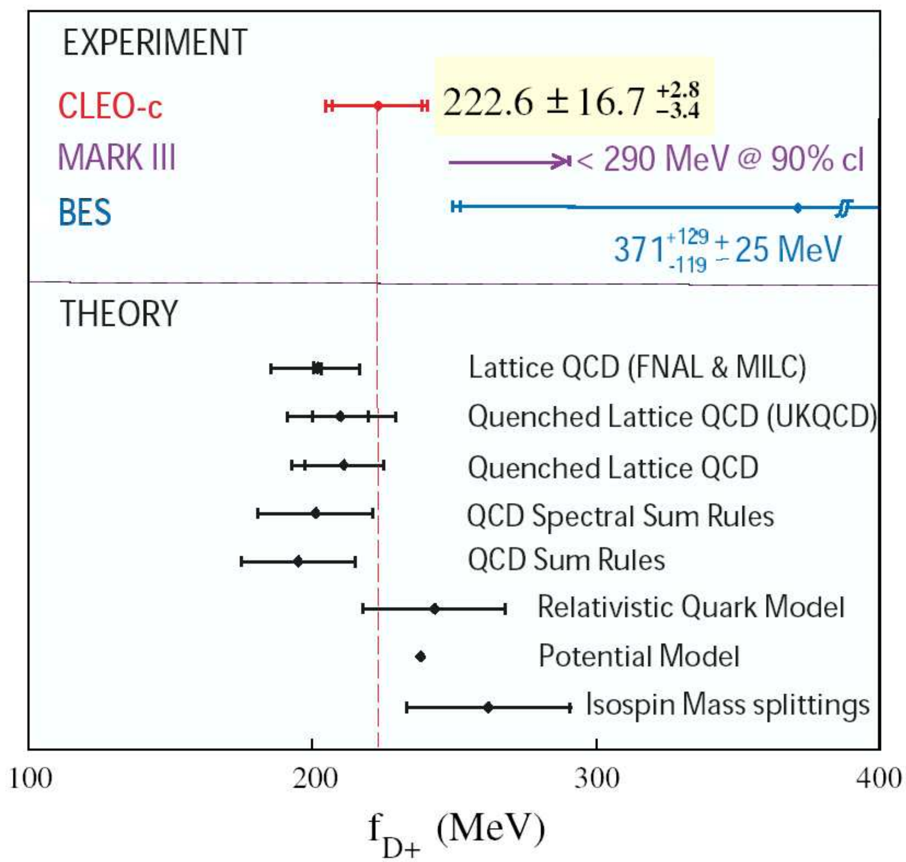
- Mass of reconstructed D^-



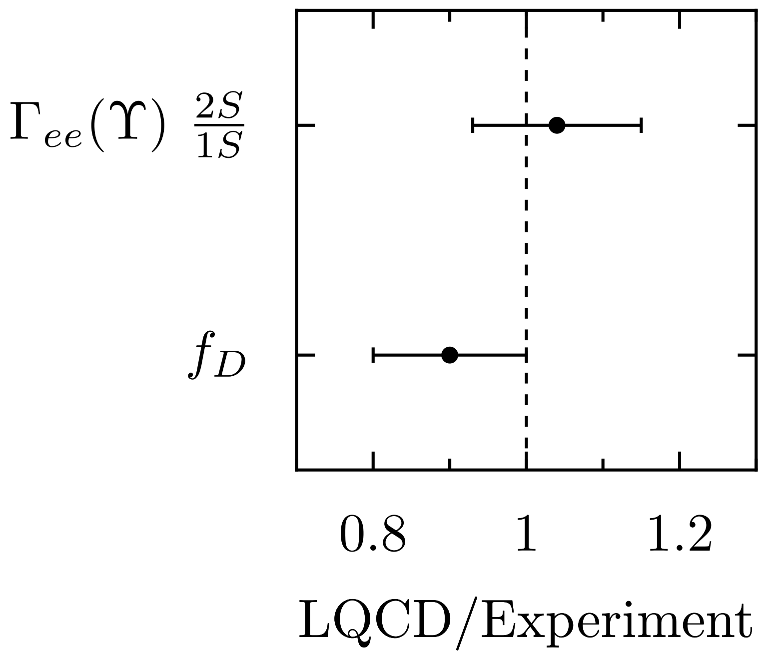


$$\begin{array}{r} 50 \text{ events} \\ -\ 2.8 \text{ background} \\ \hline 47.2 \pm 7.1\ ^{+0.3}_{-0.8} \end{array}$$

- 2% systematic uncertainty, 15% statistical uncertainty
- $\mathcal{B}(D^+ \to \mu^+\nu) = (4.40 \pm 0.66 \, ^{+0.09}_{-0.12}) \times 10^{-4}$
- $f_{D^+} = (222.6 \pm 16.7 \, ^{+2.8}_{-3.4})$ MeV



Conclusion for f_D



- Experimental f_D is likely to acquire more data
- LQCD also predicts f_{D_s} and f_D/f_{D_s} (5.4% uncertainty in ratio)
- CLEO-c is preparing for a $D_s\overline{D_s^{(\star)}}$ run, which will measure $D_s \to \mu^+\nu$

Decay constant ratios

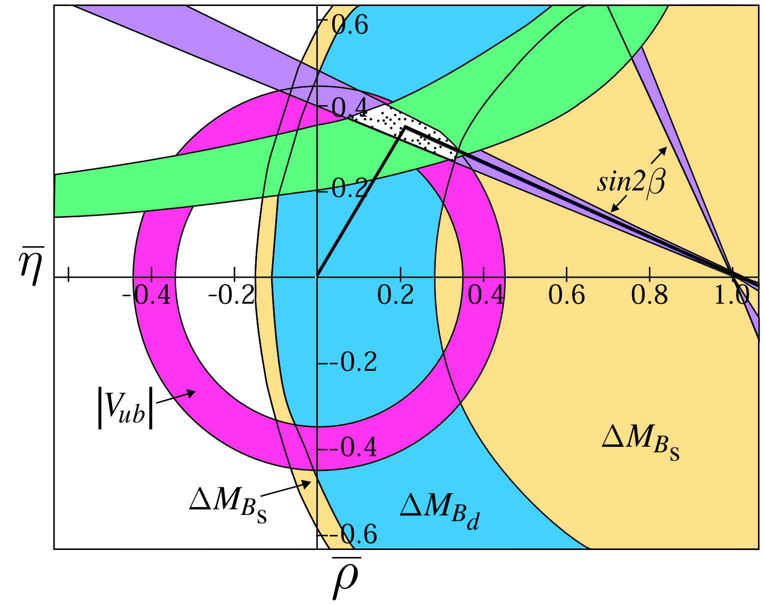
- LQCD uncertainties cancel significantly in ratios
- After *tests* of LQCD, *applications* are likely to come in the form:

$$f_B = \left(f_D \right)_{\text{experiment}} \times \left(\frac{f_B}{f_D} \right)_{\text{LQCD}}$$

and

$$f_{B_s}/f_B = \left(f_{D_s}/f_D \right)_{\text{experiment}} \times \left(\frac{f_{B_s}/f_B}{f_{D_s}/f_D} \right)_{\text{LQCD}}$$

- D and D_s measurements are directly applicable to CKM bands



Related and interesting

$$\boxed{\Gamma(\psi(2S) \to e^+e^-)}$$

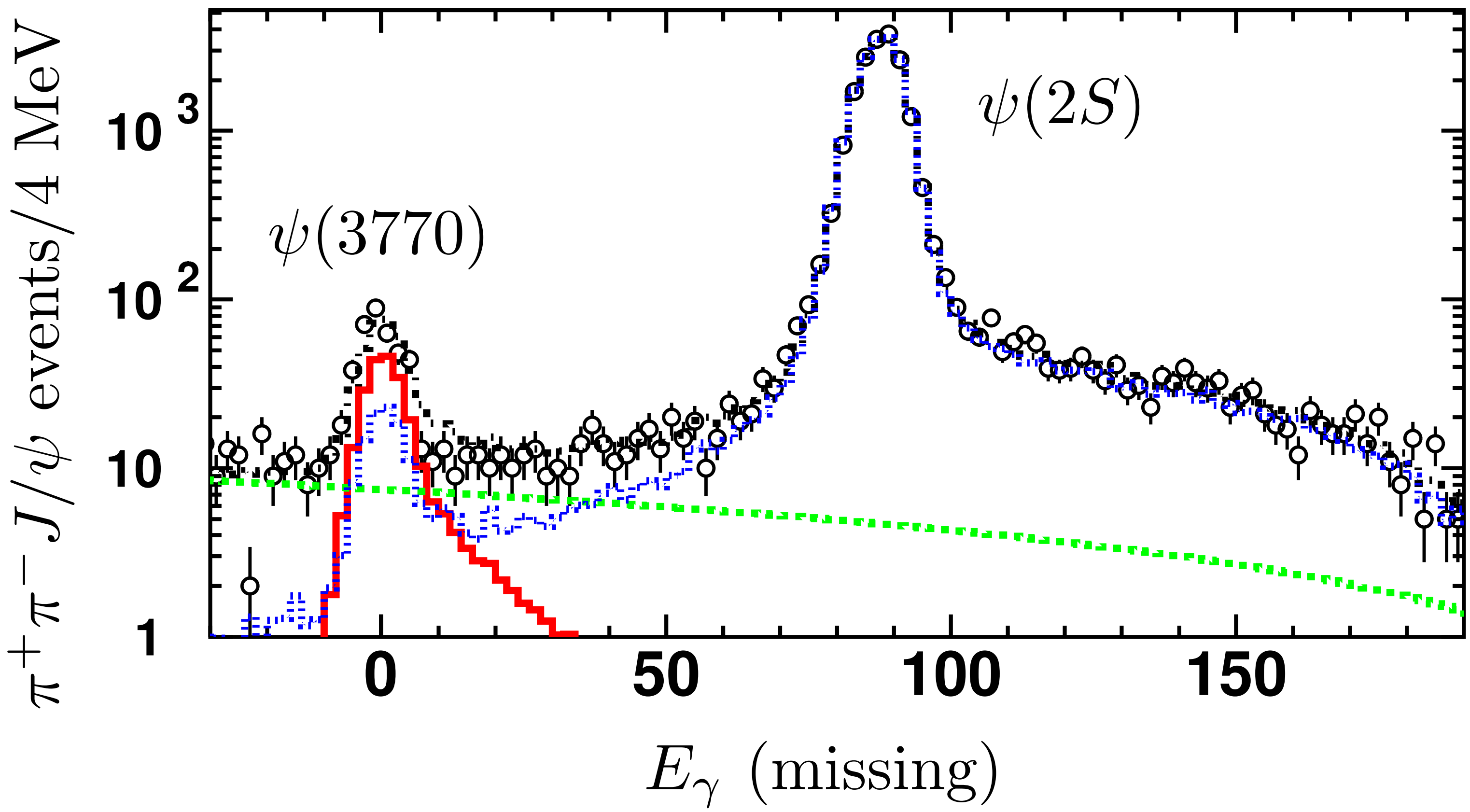
- Physically very similar to $\Gamma(\Upsilon \to e^+e^-)$ ($\Upsilon = b\bar{b}$ and $\psi = c\bar{c}$)

- Not measured by a scan, but by $e^+e^- \to \gamma\psi(2S)$ where $\sqrt{s} \gg M_{\psi(2S)}$
  - Cross-section on a resonance depends on beam energy spread (wide beam $\Rightarrow$ low cross-section)

  - Cross-section far above depends only on coupling to e^+e^-

- BaBar recently measured $\Gamma(J/\psi \to e^+e^-)$ this way

- Look for $\psi(2S)$ in specific final states, such as $\pi^+\pi^- J/\psi$



- Limited by branching fraction measurements, which CLEO-c is improving

- $\Gamma_{ee}(\psi(2S)) = 2.13 \pm 0.03 \pm 0.08$ keV

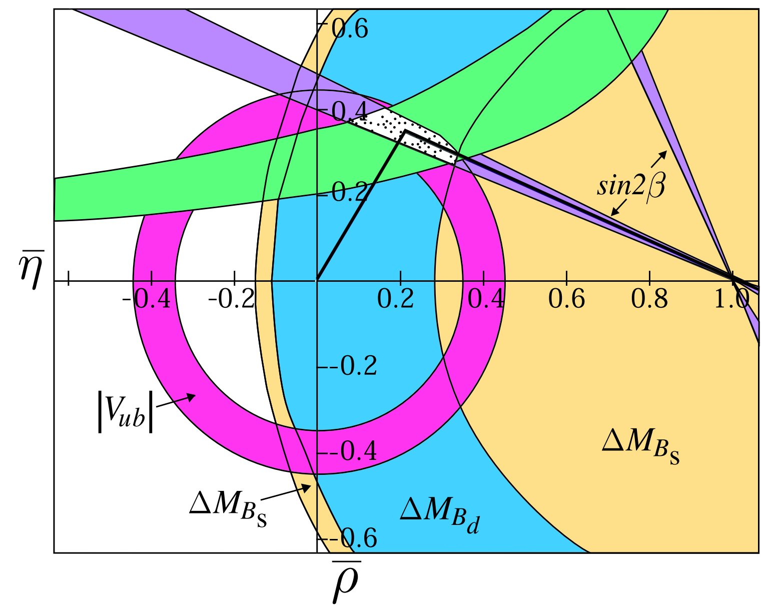
- CLEO measurement of $\Gamma_{ee}(J/\psi)$ is in the works

- Another relevant test of LQCD: try all the flavor combinations!

	heavy-heavy	heavy-light
bottom	$\Gamma_{ee}(\Upsilon)$	f_B
charm	$\Gamma_{ee}(\psi)$	f_D

- LQCD can and will calculate $\Gamma_{ee}(\psi)$
- For Υ, discretization is more significant
- For ψ, relativistic corrections are more significant

Semileptonic form factors

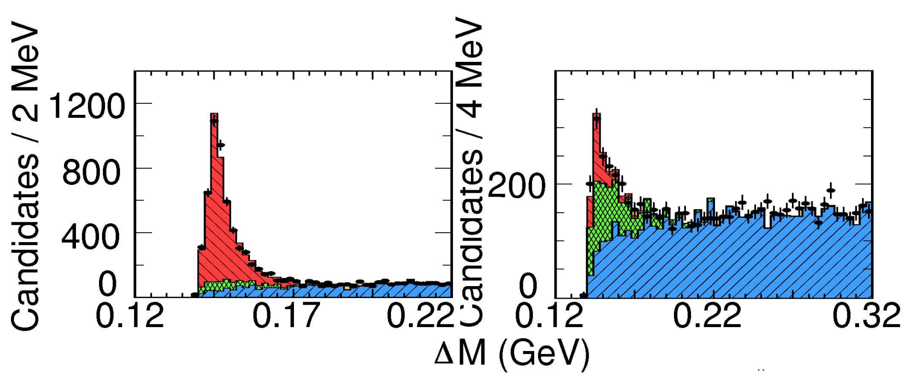


- $|V_{ub}|$ limited by form factor $f(q^2)$
- Much the same story as f_B:

  Can be calculated by LQCD and extrapolated from D measurements

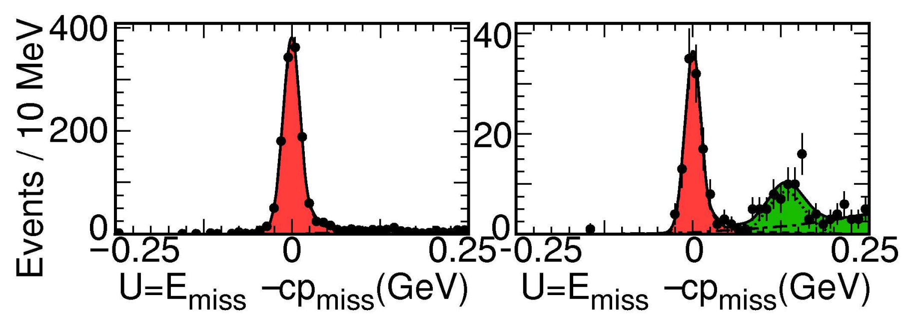
- D measurements near threshold are much easier: less cross-feed, better q^2 resolution

CLEO-III



$D^0 \to K^- e^+ \nu$ $D^0 \to \pi^- e^+ \nu$

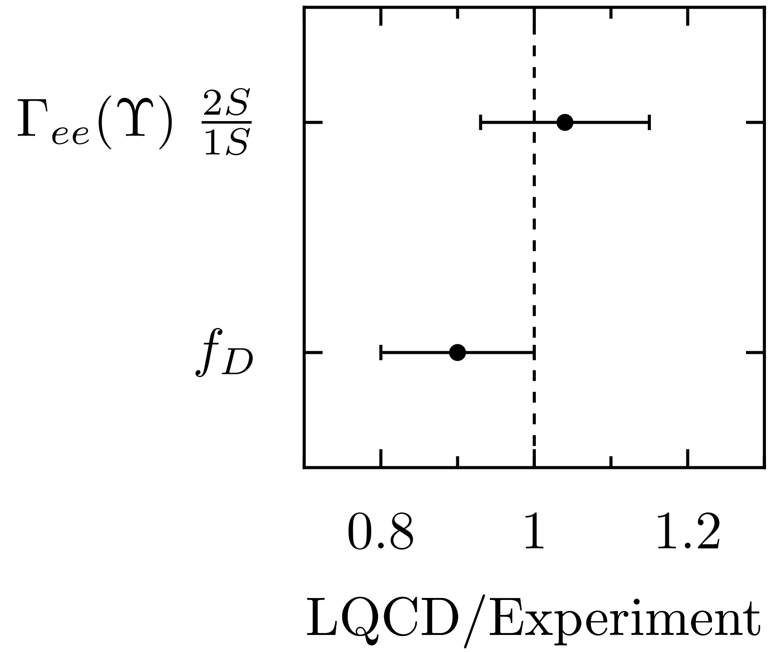
CLEO-c



$D^0 \to K^- e^+ \nu$ $D^0 \to \pi^- e^+ \nu$

Conclusions

- Two new points of contact between LQCD and experiment



- LQCD $\Gamma_{ee}(\Upsilon)$ result will improve substantially

- f_D and f_{D_s} will improve and be used directly in f_B, f_{B_s}

- $\Gamma_{ee}(\psi)$ probes differences in treatment of charm and bottom quarks

- This is only part of the program: similar studies are being made of semileptonic form factors

- All of this is only a small part of the implications of precision QCD: low energy hadrons are a jungle of overlapping resonances that could be hiding surprises

- And wouldn't it be nice to understand the proton?