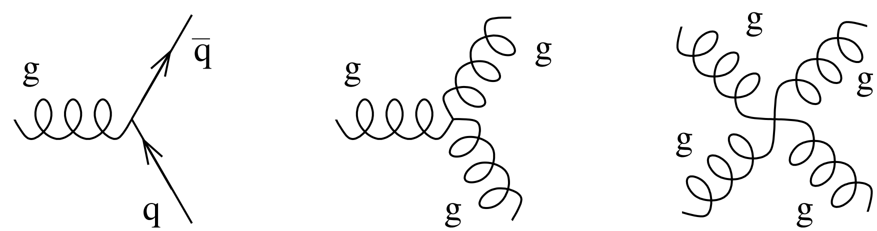
Lattice QCD

- Strong force governed by QCD

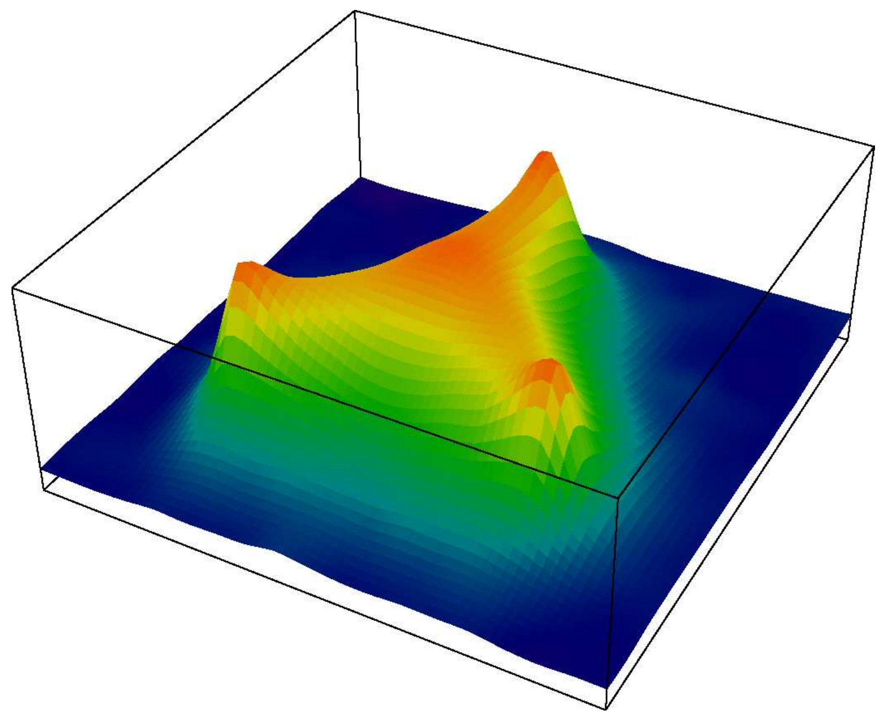


- It's hard to make quantitative predictions for low-energy phenomena, such as spatial wavefunctions, because coupling is too strong for a perturbative expansion.

- Lattice QCD (LQCD): represent space-time as a 4-D grid of quark and gluon field values

- Evaluate path integrals as very high-dimensional integral

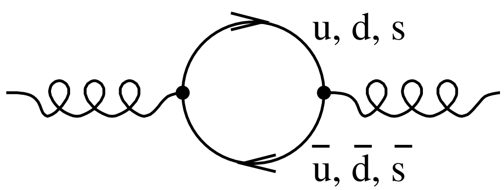
- Computationally intensive



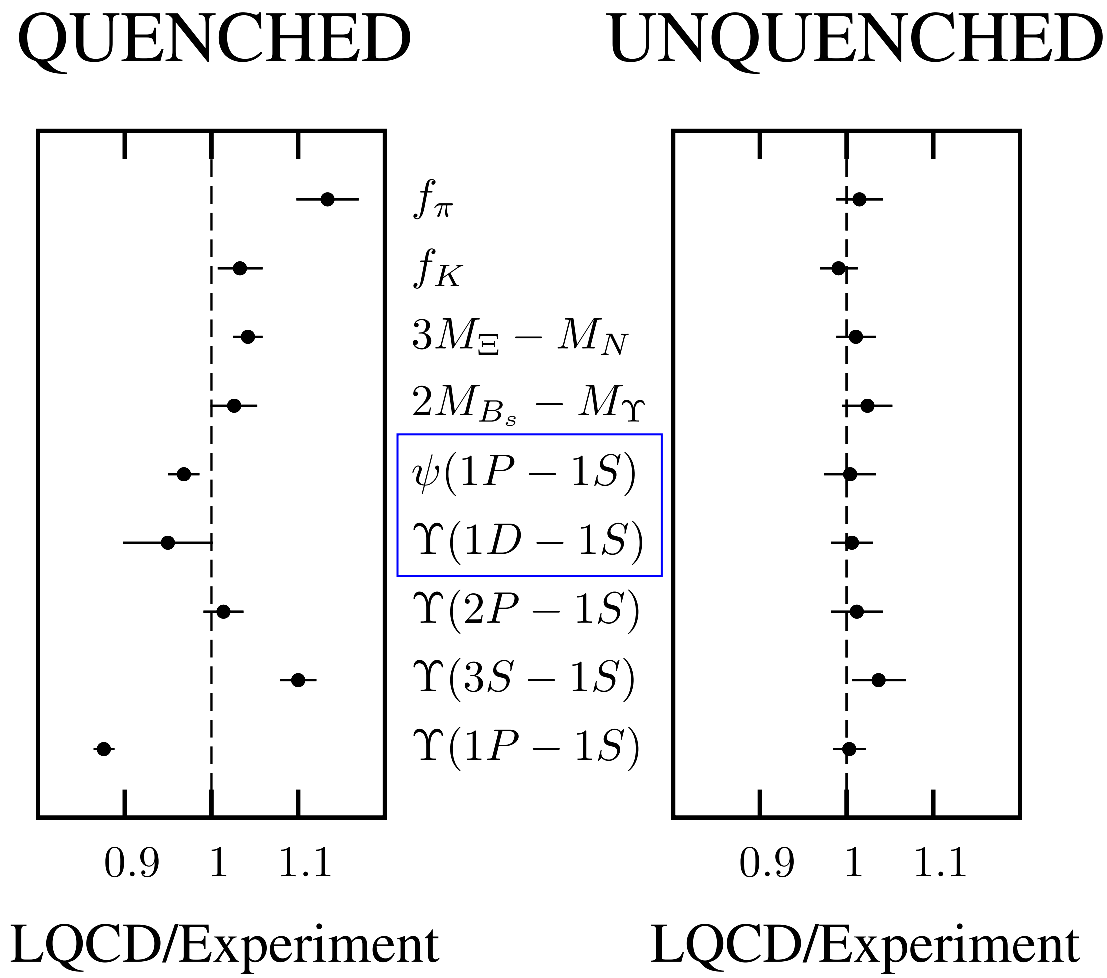
(This is a slice through a proton in action density.)

Precision LQCD: quenched → unquenched

"Quenched" means ignoring
light quark loops ($m_q = \infty$)



"Unquenched" calculations
are made feasible by improved
algorithms

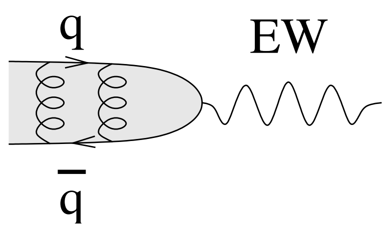


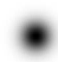
Update: Ω^- and B_c masses also agree with experiment

CLEO observations of h_c ($= \psi(1P)$) and $\Upsilon(1D)$ were an important part of this program

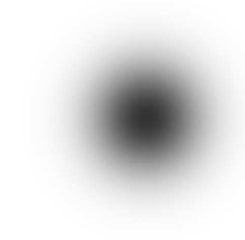
LQCD for flavor physics: heavy meson decay rates

- Matrix elements (transition probabilities) rather than eigenvalues (masses)
- Electroweak interactions are point interactions on the scale of the spatial wavefunction
- Quarks have to find each other: decay rate is governed by $|\psi(0,0,0)|^2$





yields a faster rate than



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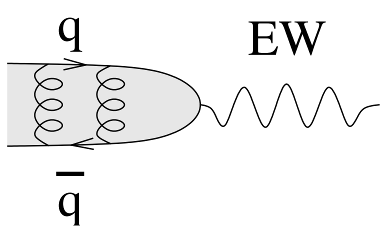
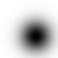
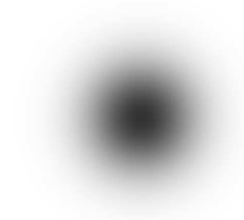
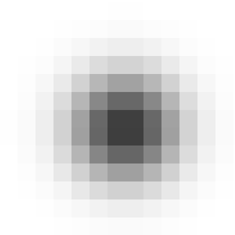


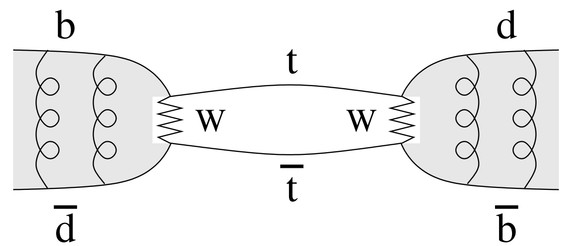
 yields a faster rate than 

- Probes fine-grain structure, which is not smooth on the lattice

- The continuum limit is more challenging for decay rates

Main goal: B meson decay constant f_B



- $B\bar{B}$ mixing could tightly constrain V_{td}

$$\Delta M_{B^0,\,\bar{B}^0} = (\text{known})\, {f_B}^2 B_B |V_{td}|^2 = 0.502 \pm 0.007 \text{ ps}^{-1}\ (1.4\%!)$$

if QCD factors f_B and B_B could be determined.

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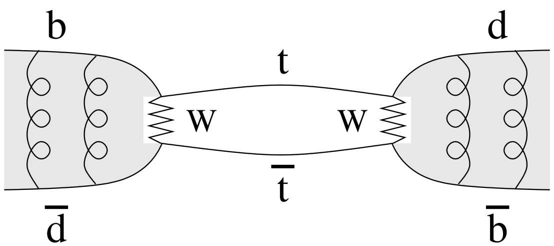

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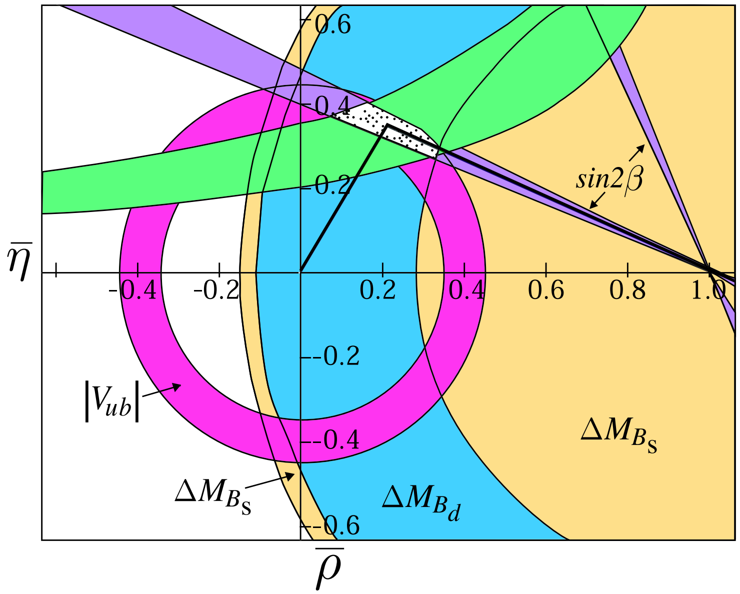
if QCD factors f_B and B_B could be determined.

- Would shrink the 20% B_d (blue) band to a narrow annulus (few percent)

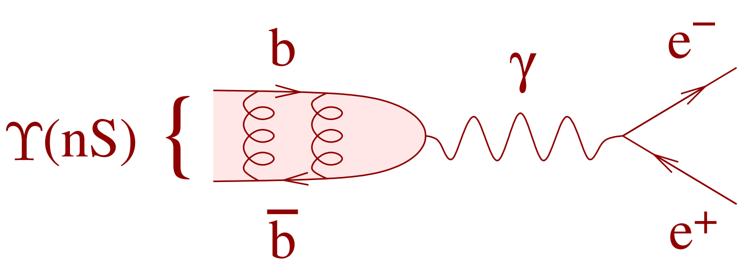
- f_B and B_B can't be measured directly

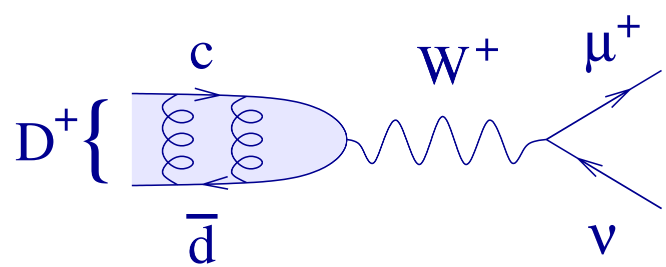
- LQCD is the most promising technique for calculating f_B and B_B



The program: LQCD calculates f_B and related, verifiable quantities

	heavy–heavy		heavy–light
bottom	$\boxed{\Gamma_{ee}(\Upsilon)}$	$\longrightarrow$	$\boxed{f_B}$
	theory vs experiment $\Upsilon \to e^+e^-$		theory only $\uparrow$
charm	$\boxed{\Gamma_{ee}(\psi)}$		$\boxed{f_D}$
			theory vs experiment $D^+ \to \mu^+\nu$





$$\Gamma_{\Upsilon\to e^+e^-} = \frac{16\pi\,\alpha^2}{3{M_\Upsilon}^2}\,|\psi(0)|^2 \qquad \Gamma_{D^+\to\ell^+\nu} = \frac{{G_F}^2\,|V_{cd}|^2}{8\pi}{m_\ell}^2 M_D\left(1-\frac{{m_\ell}^2}{{M_D}^2}\right)^2 {f_D}^2$$

For the remainder of this talk, I will present

- a high-precision measurement (1.5–2.5%) of Γ_{ee} for $\Upsilon(1S, 2S, 3S)$ (15 slides)

- observation of 47 ± 7 $D^+ \to \mu^+\nu$ events, which determines f_D to 7.6% (7 slides)

- a 4% measurement of Γ_{ee} for $\psi(2S)$ through radiative returns (1 slide)

- future confrontations between LQCD and experiment at CLEO-c (2 slides)

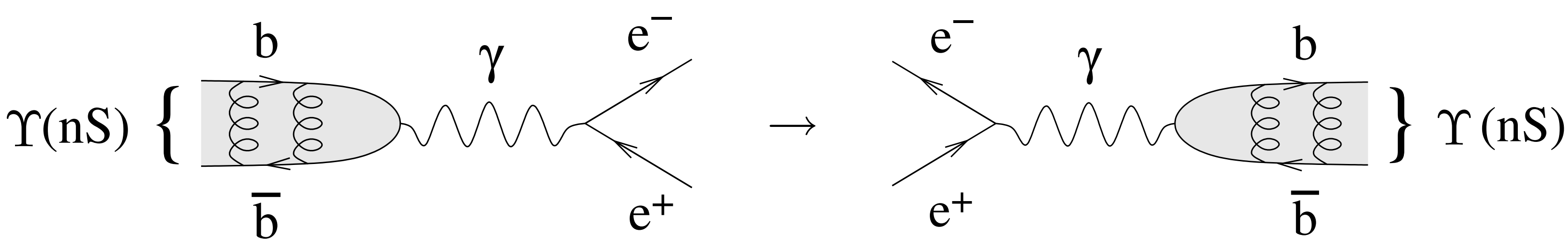
Γ_{ee} Table of Contents

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

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

- 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 (narrower than collider beam energy spread)

- Alternative method: consider time-reversed process

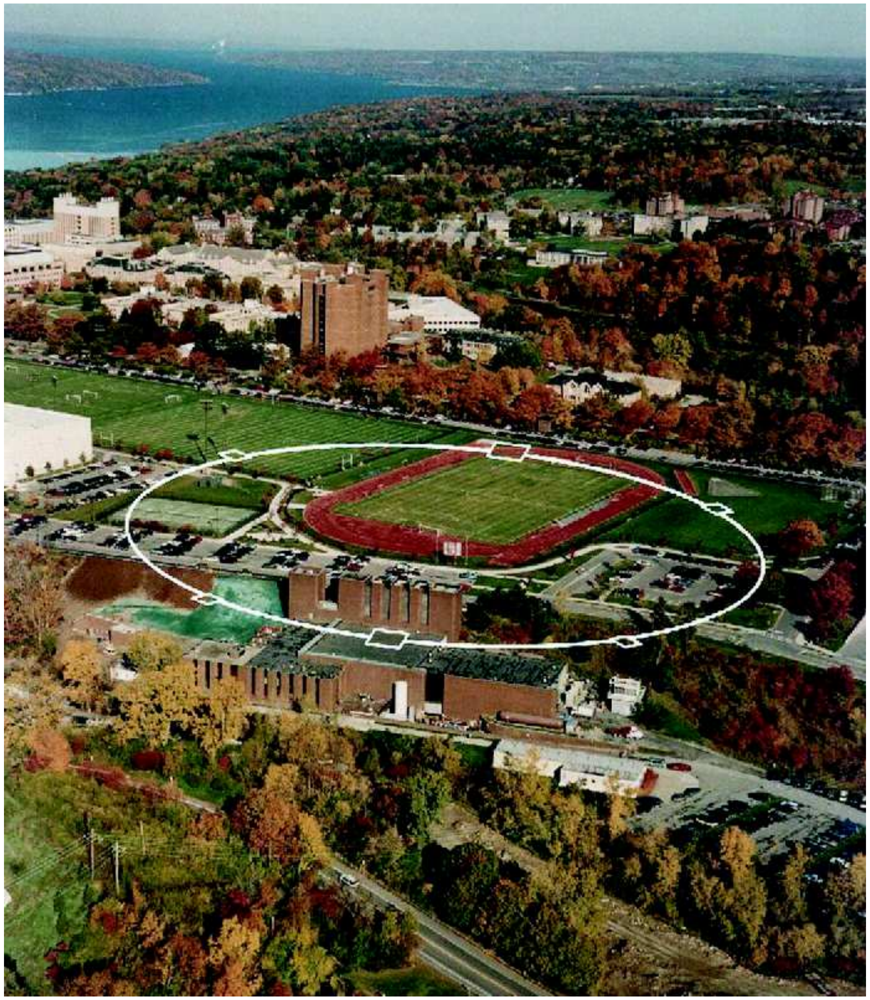


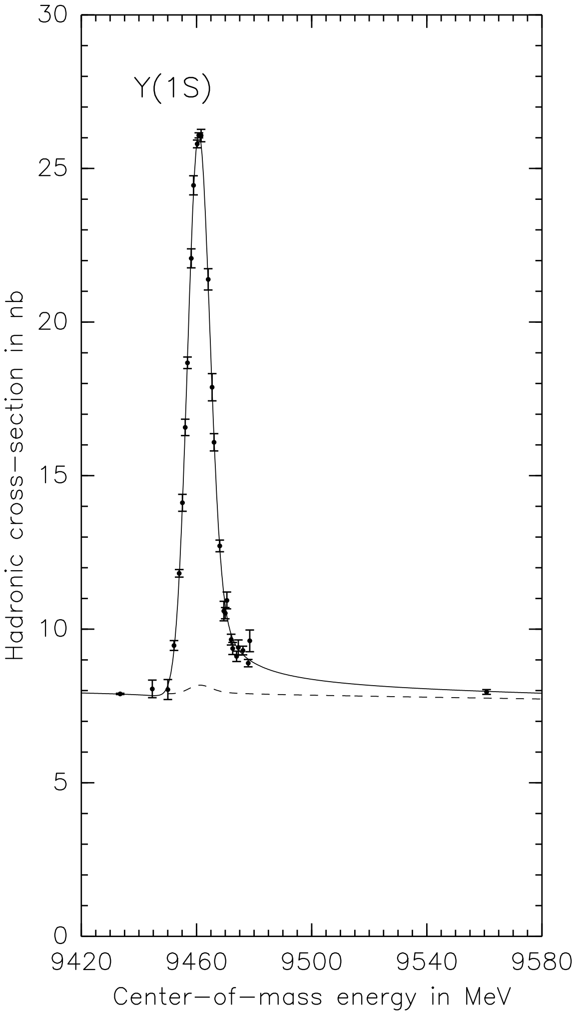
- Measure Υ *production* from e^+e^- beams

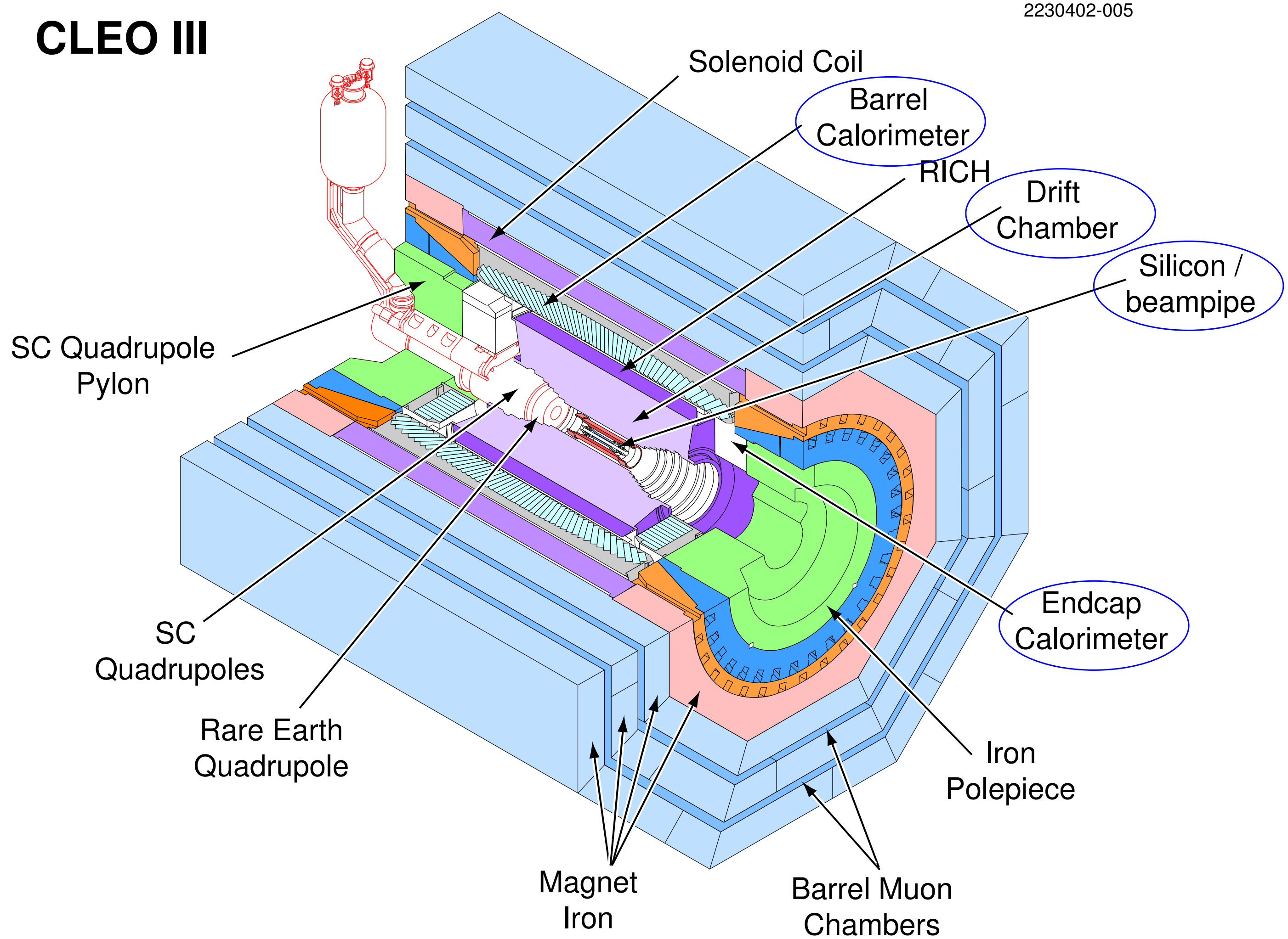
$$\Gamma_{ee} = \frac{M_\Upsilon{}^2}{6\pi^2} \int \sigma(e^+e^- \to \Upsilon)\, dE$$

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

Cornell Electron Storage Ring





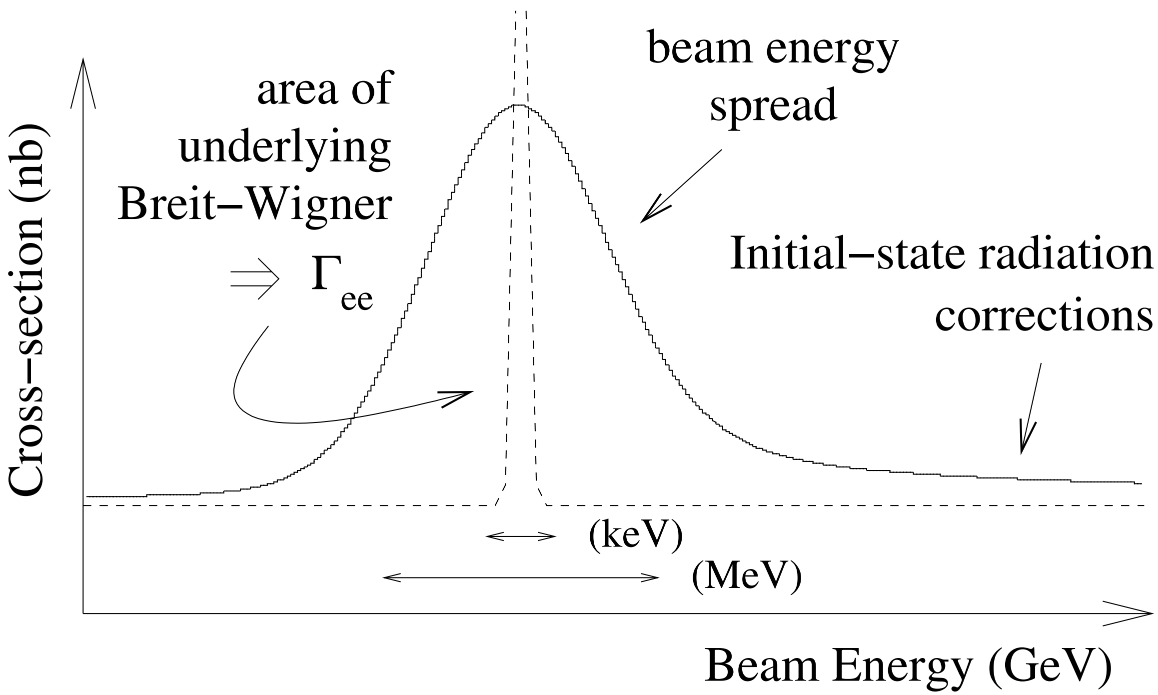


Event selection

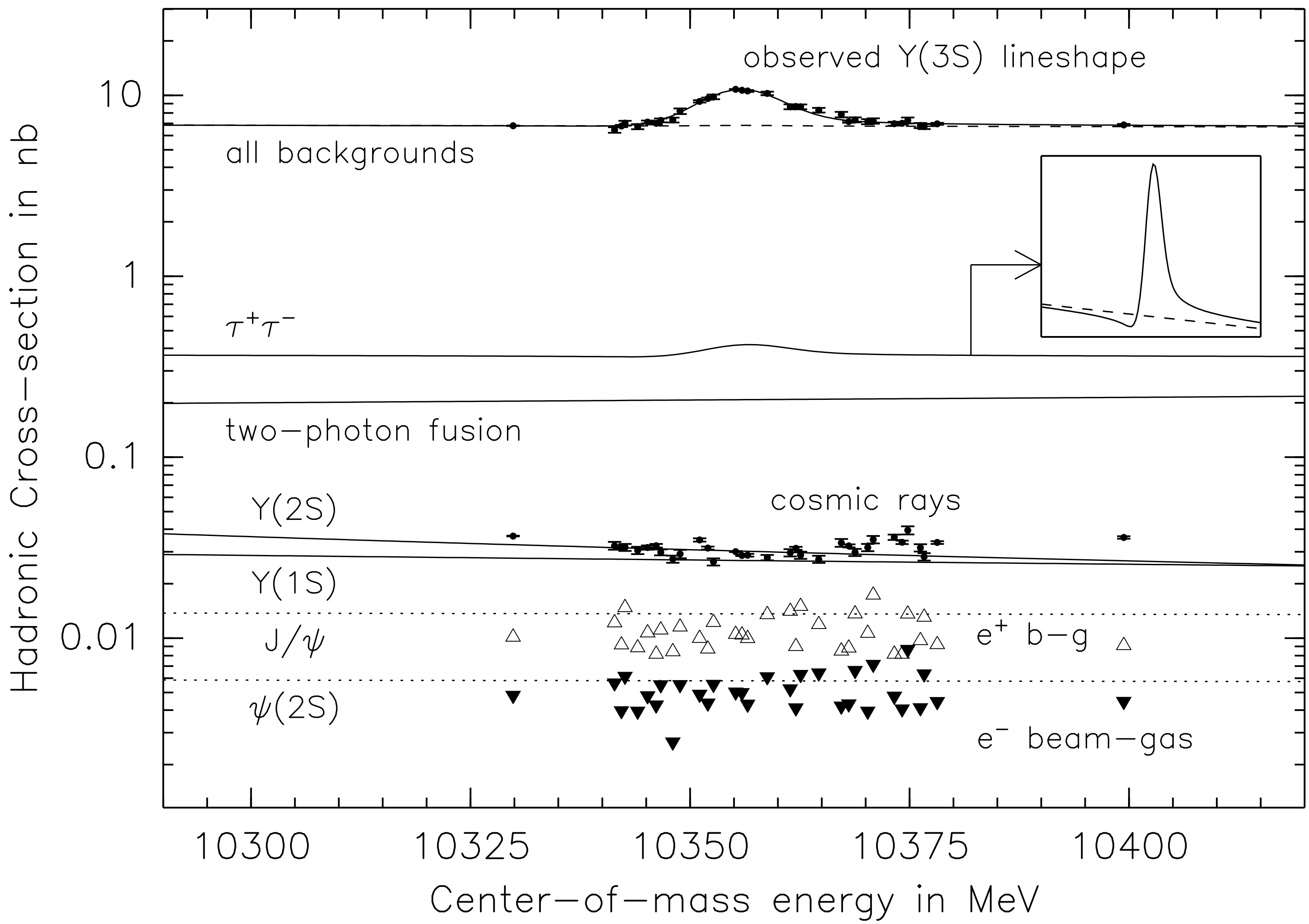
1. largest track $|\vec{p}| <$ 80% E_{beam}
2. observed energy $>$ 40% $2 \times E_{beam}$
3. $\exists$ track within 5 mm of beamspot in XY
4. and within 7.5 cm of beamspot in Z

Selection criteria accept only *hadronic* decays: total cross-section is $\sigma_{tot} = \dfrac{\sigma_{had}}{1 - 3\mathcal{B}_{\mu\mu}}$

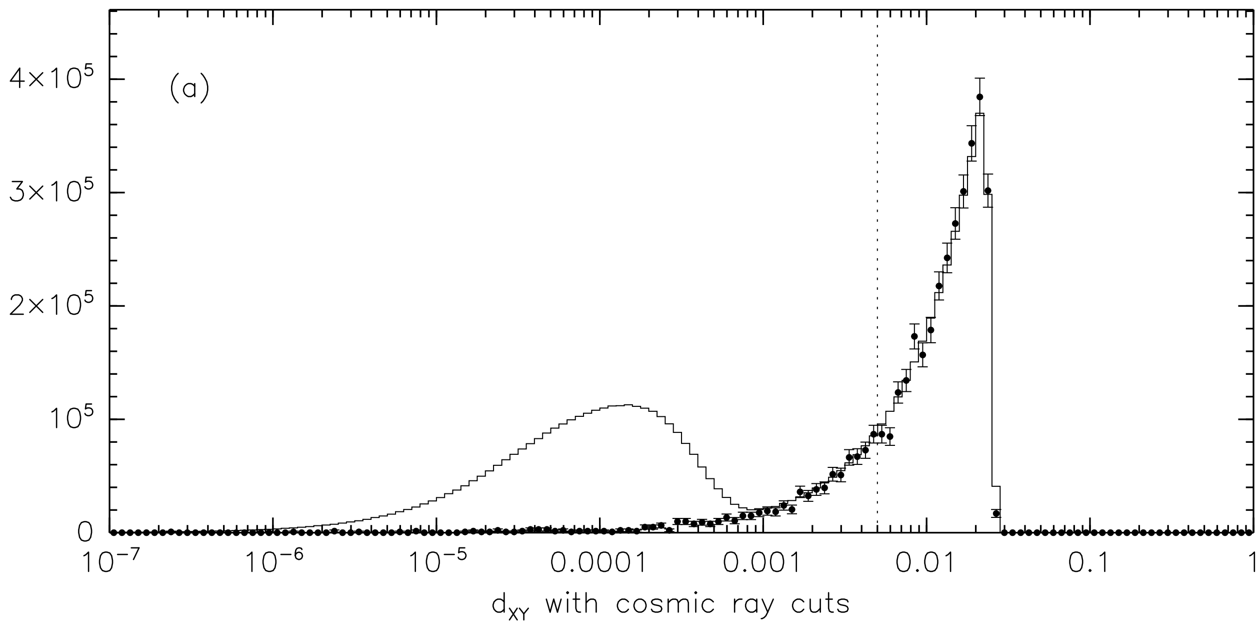
$\mathcal{B}_{\mu\mu}$ of $\Upsilon(1S, 2S, 3S)$ measured precisely (3%, 4%, 5%) by CLEO-III



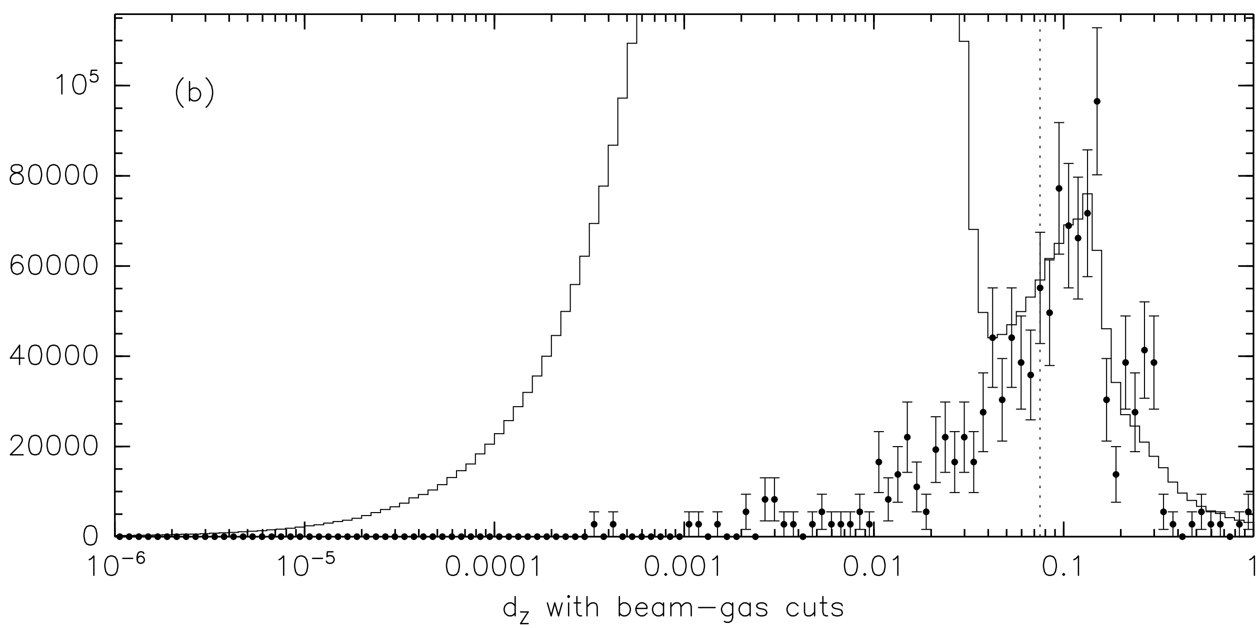
- Most background processes scale as $1/s$
- Breit-Wigner (BW) lineshape is convoluted with beam energy spread: does not affect *area* $(= \Gamma_{ee})$
- Also convoluted with ISR tail $(e^+e^- \to \gamma\Upsilon)$ which diverges; we remove this by
  - constructing a fit function which is BW $\otimes$ Gauss $\otimes$ ISR, and
  - fitting measured points for BW area



- Lines are represented in the fit function
- Points (cosmic rays, beam-gas) are explicitly subtracted

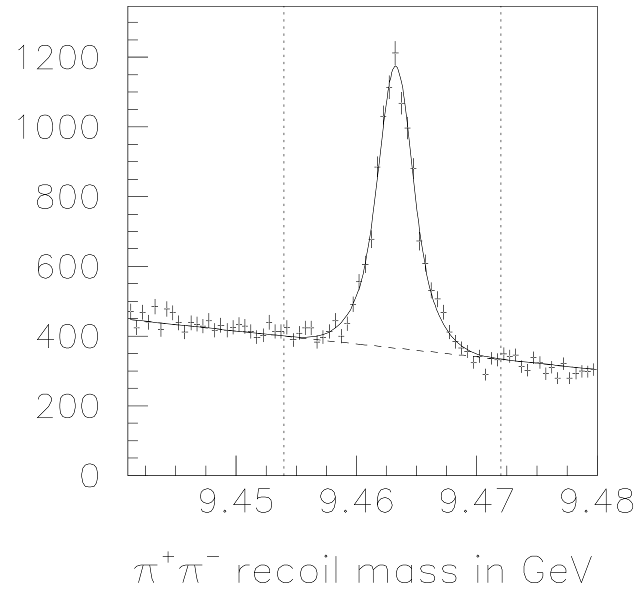


Cosmic rays in scan data (hist) and **no-beam** control sample (points)



Beam-gas in scan data (hist) and **single-beam** control sample (points)

- How many hadronic Υ decays pass event selection?
- Model-independent method for measuring $\Upsilon(1S)$ hadronic efficiency (ϵ_{1S}):
  - Select $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ events such that $\pi^+\pi^-$ alone are sufficient for event selection
  - Supplies an unbiased set of $\Upsilon(1S)$ events (includes invisible decays like $\Upsilon \to \nu\bar{\nu}$ and Beyond the Standard Model decays)
  - Count (#pass event selection)/(#total)
  - ϵ_{1S} is $(97.8 \pm 0.5)\%$



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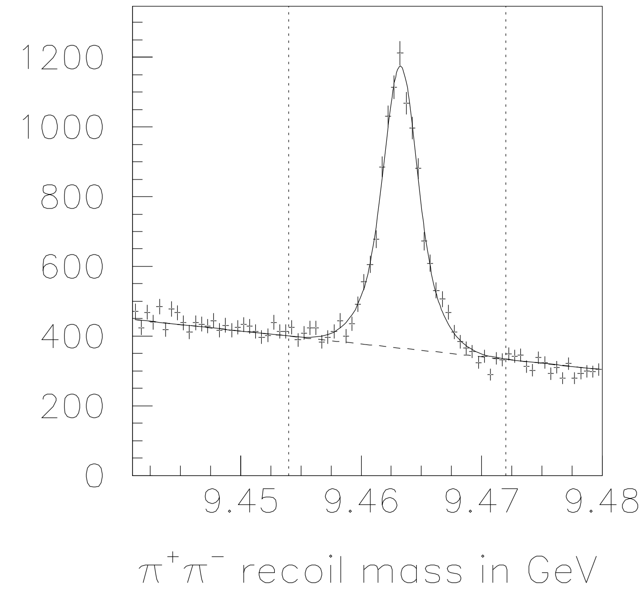
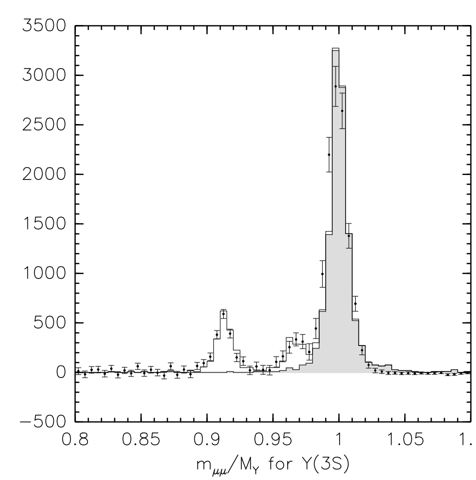


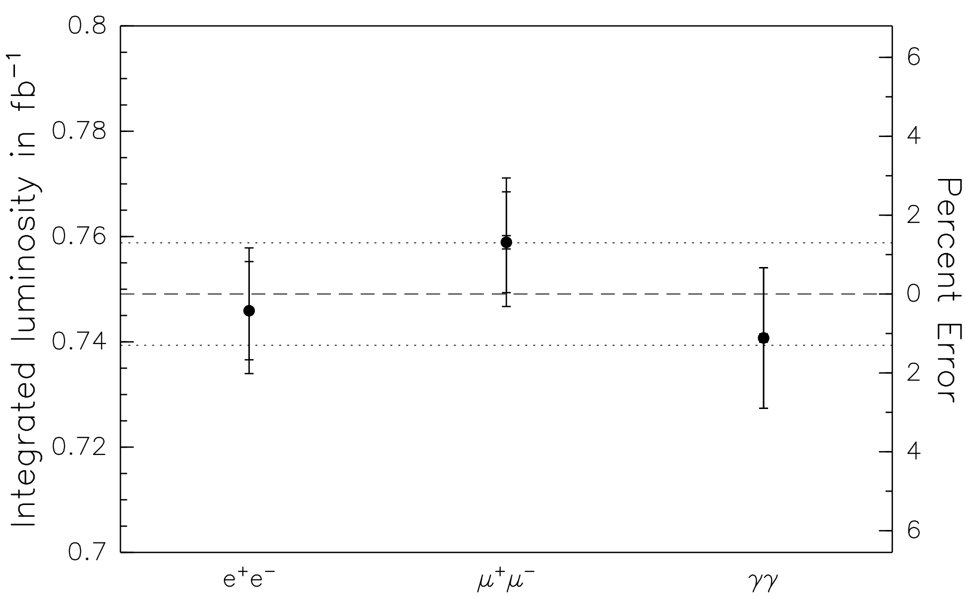
- For ϵ_{2S}, ϵ_{3S}, most modes are unchanged

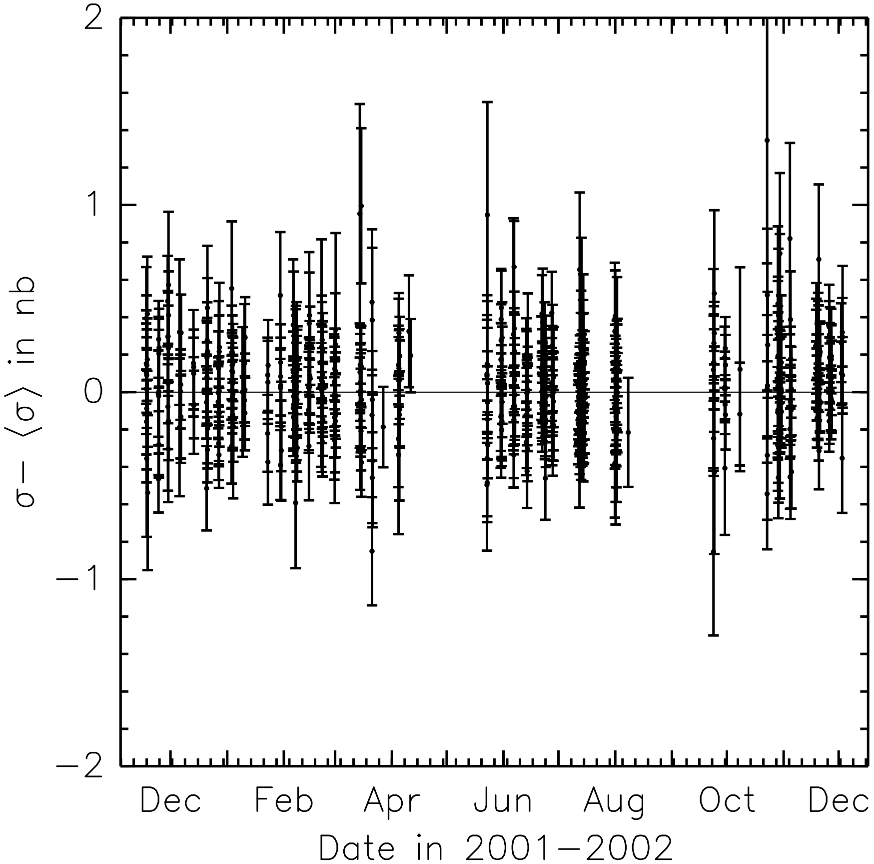
- $\Upsilon(nS) \to X\Upsilon$ where $\Upsilon \to e^+e^-$, $\mu^+\mu^-$ have zero efficiency

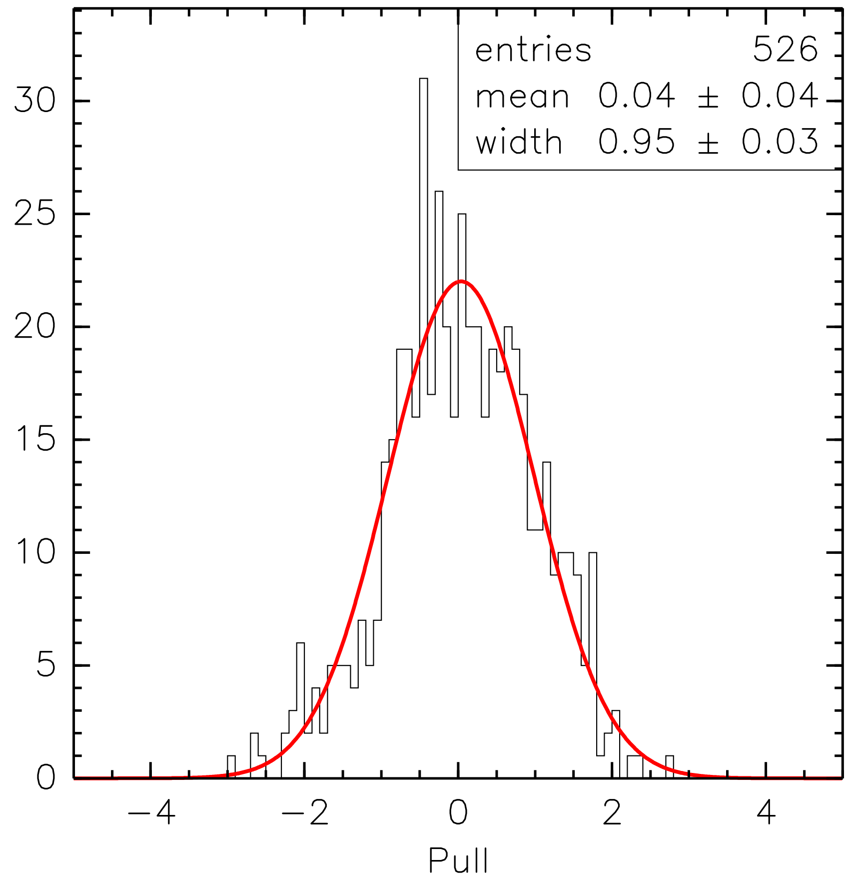
- Mini-analysis to determine these branching fractions in data



- Need to know integrated luminosity for each scan point
- Int lumi for a point relative to other scan points:
  - Int lumi $\propto$ $(\#e^+e^- \to \gamma\gamma) \times {E_{beam}}^2$
  - This is enough to do fits, with cross-section in unknown units
- Determine overall scale for int lumi:
  - Separate analysis involving e^+e^-, $\gamma\gamma$, and $\mu^+\mu^-$ final states
  - Blinded Γ_{ee} analysis by applying this correction at the end



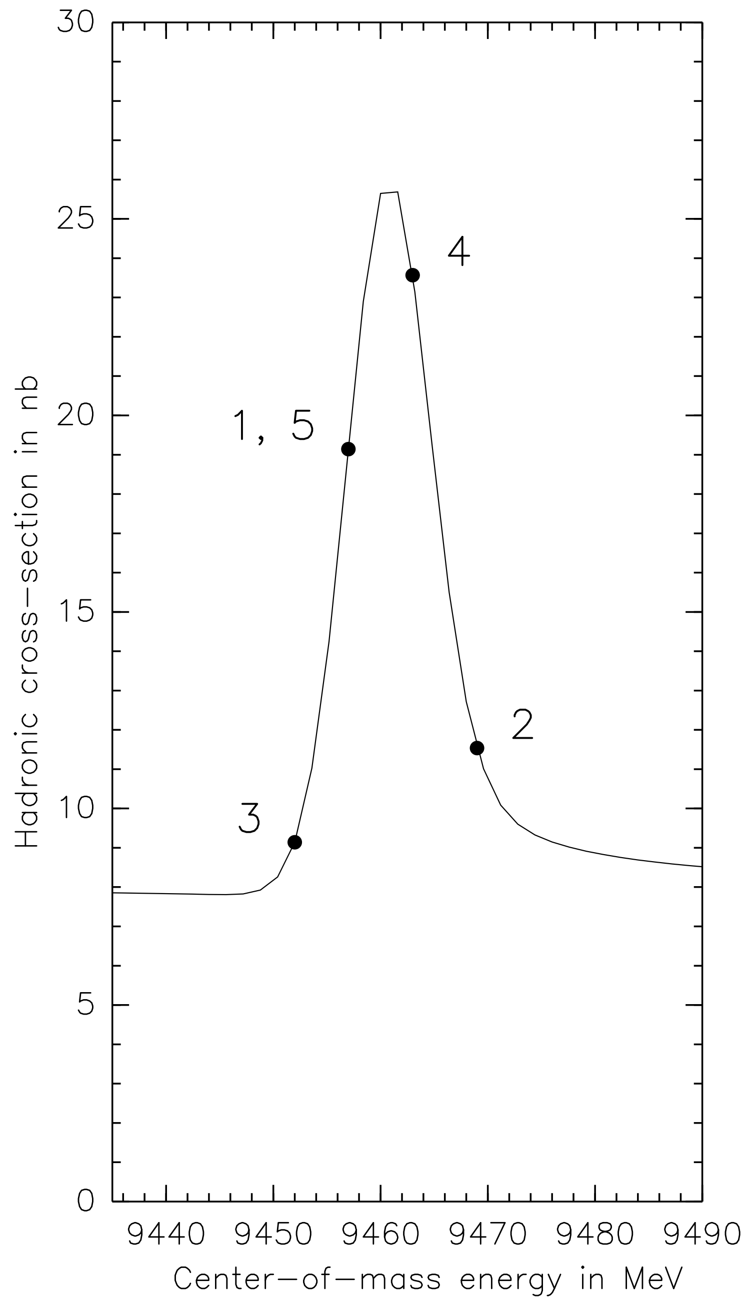




- All off-resonance runs at a given energy reproduce the same cross-section

- Cross-section **in**stability $\lesssim 0.03$ nb

- weekly scans were short and independent
- measurements alternated above and below resonance peak
- a point of high slope was repeated in the scan



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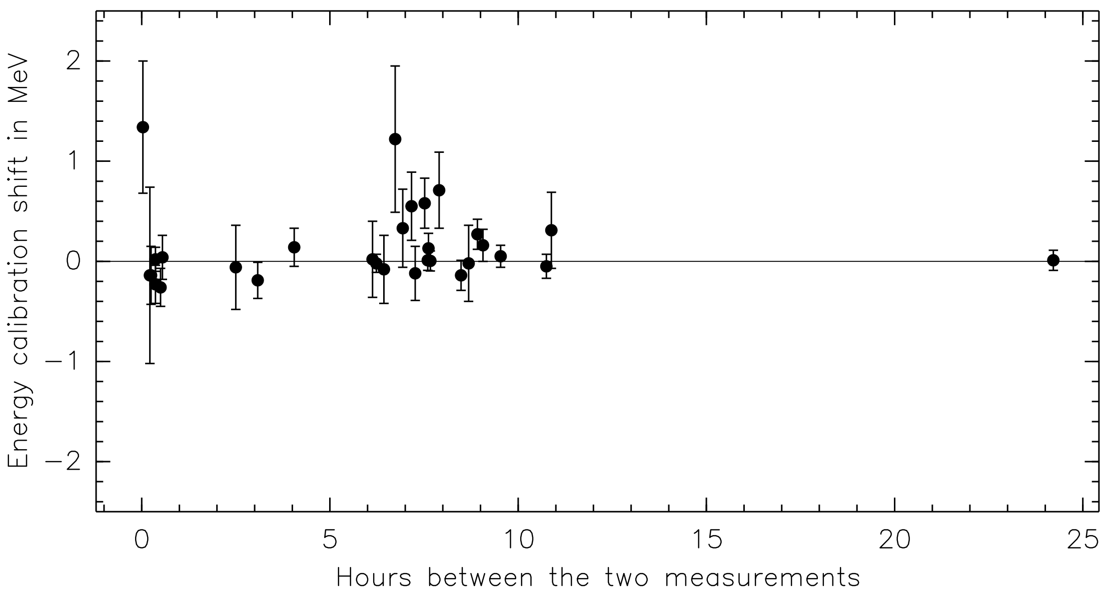
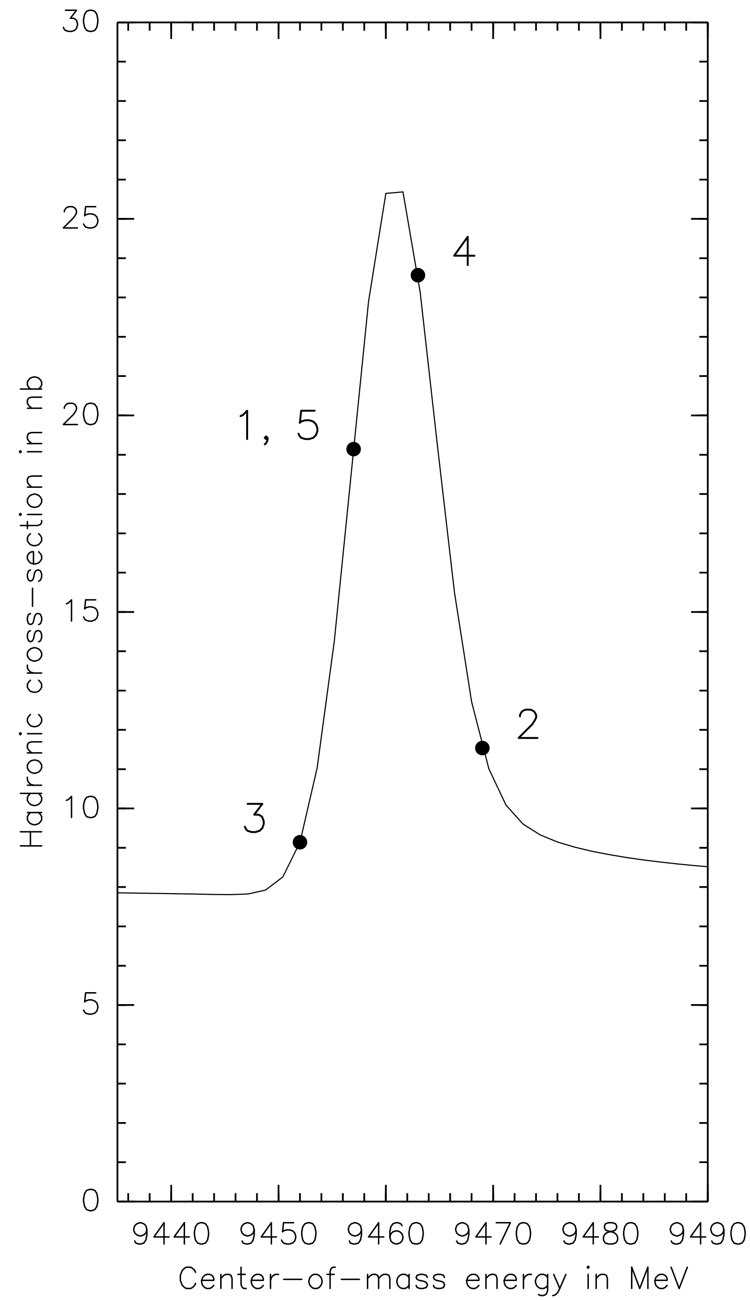


Beam-energy **in**stability $\lesssim 0.07$ MeV



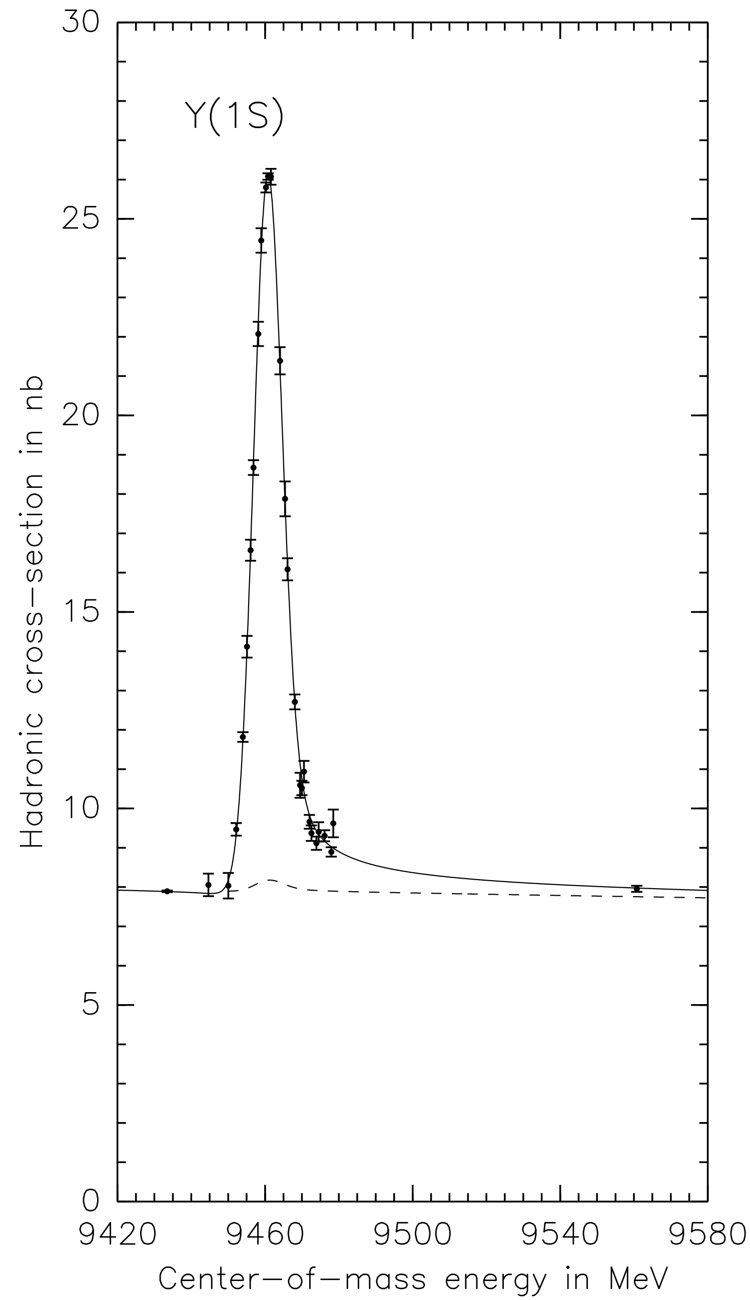
Parameters:

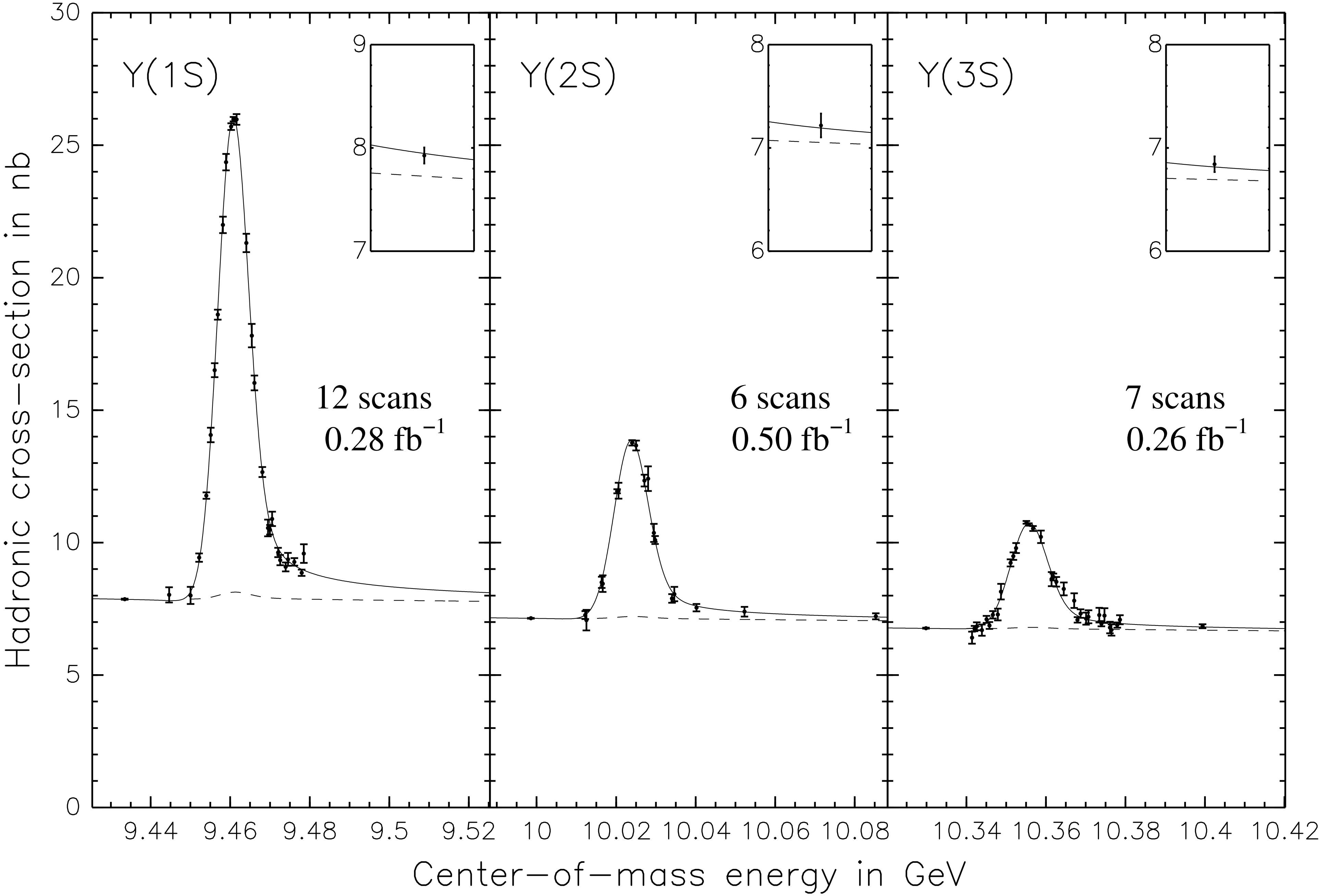
1. Area without tail (MeV nb) $\longrightarrow \Gamma_{ee}$ (keV)
2. Beam energy spread (MeV)
3. Background level (nb)

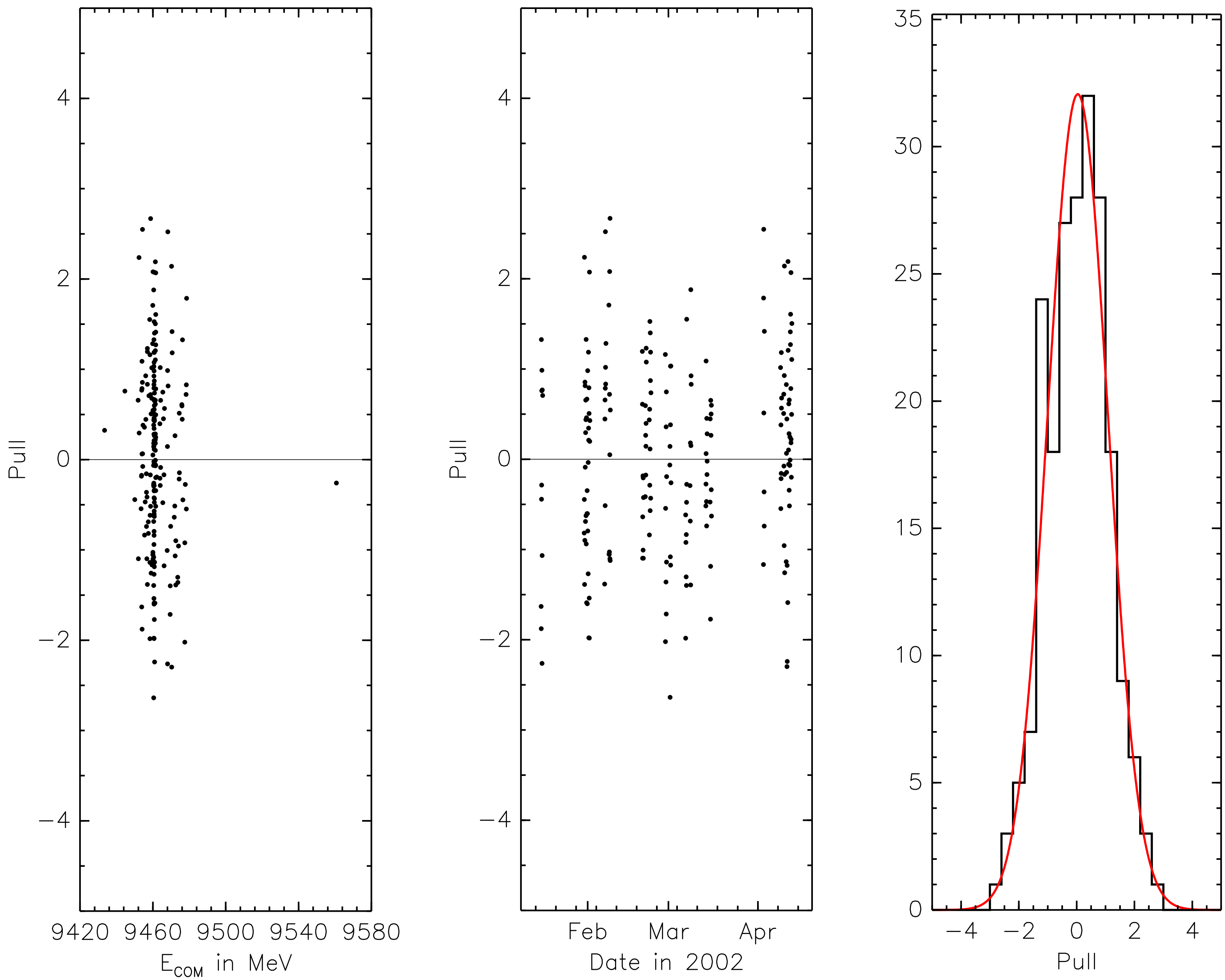
4–15. Upsilon mass for each weekly scan (MeV)

Fit function:

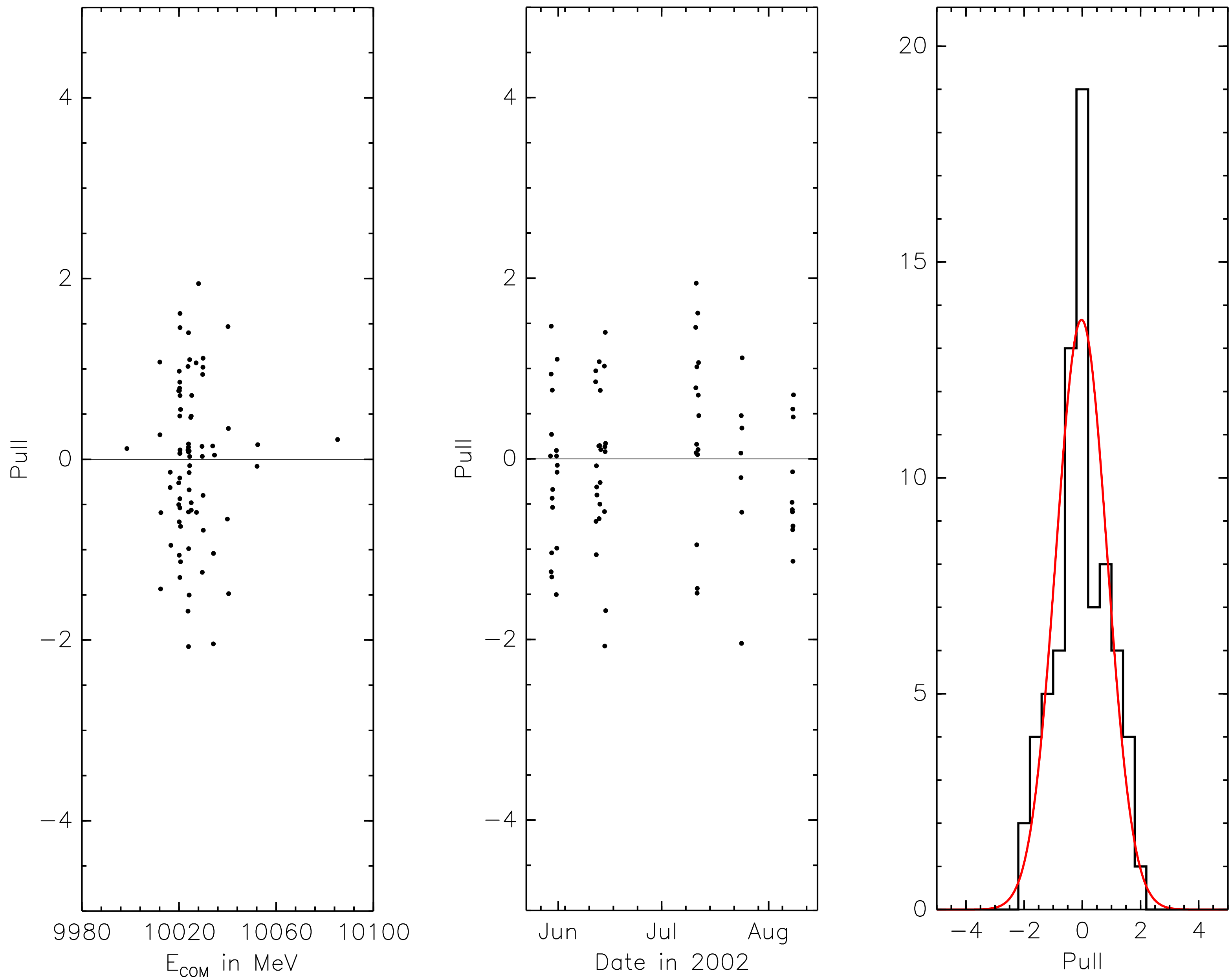
1. Breit-Wigner $\otimes$ Gaussian $\otimes$ ISR tail (Kuraev and Fadin 0.1% calculation) Includes interference term (small effect)
2. $\tau^+\tau^-$ background peaks under signal, precisely subtracted with CLEO-III $\mathcal{B}_{\tau\tau}$
3. Smooth backgrounds: $1/s$, $\log s$, ISR tails



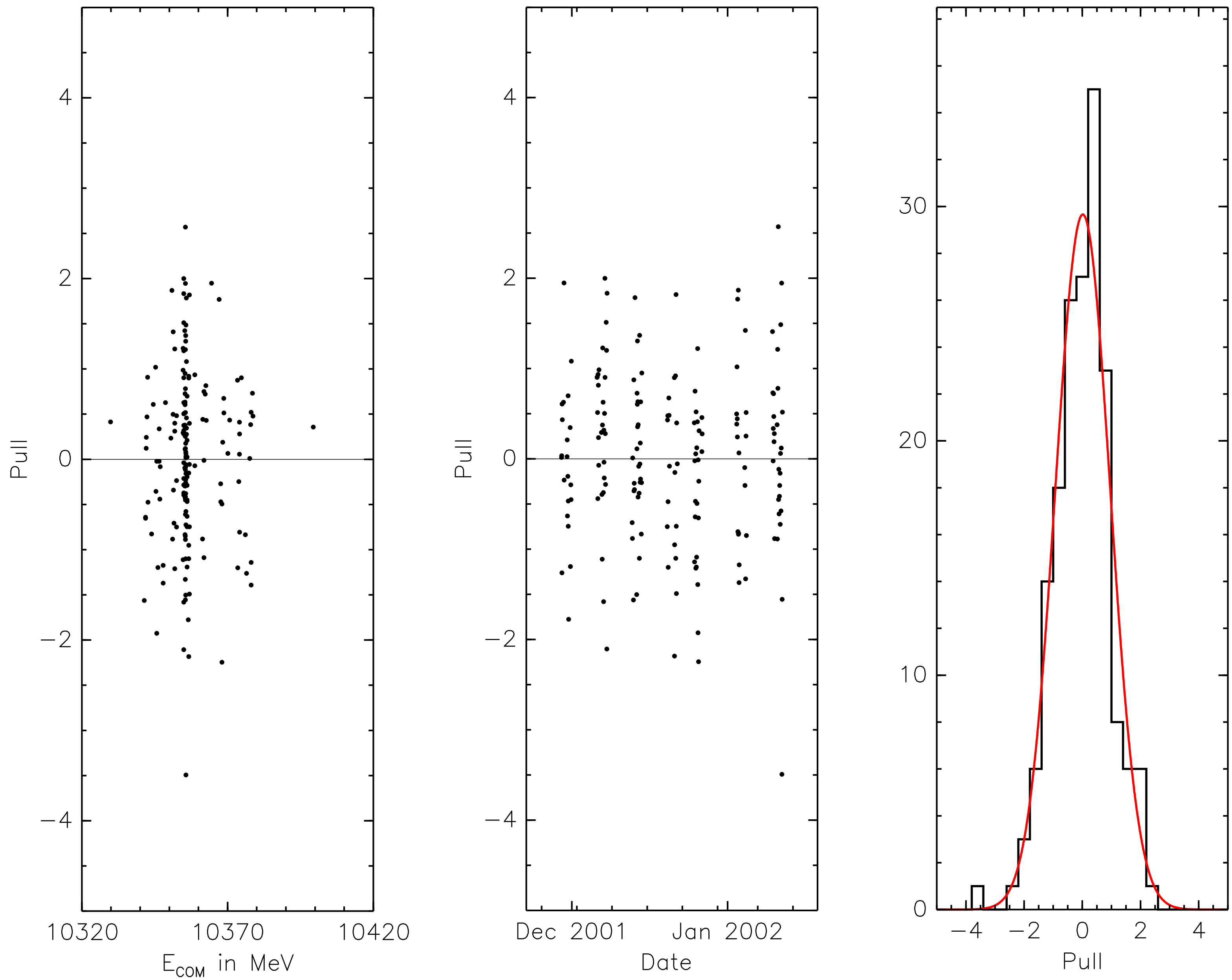

Υ(1S)
Υ(2S)
Υ(3S)
12 scans
0.28 fb^{-1}
6 scans
0.50 fb^{-1}
7 scans
0.26 fb^{-1}
Hadronic cross-section in nb
Center-of-mass energy in GeV
0
5
10
15
20
25
30
9.44
9.46
9.48
9.5
9.52
10
10.02
10.04
10.06
10.08
10.34
10.36
10.38
10.4
10.42
9
8
7
8
7
6
8
7
6



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



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



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

Summary of Uncertainties

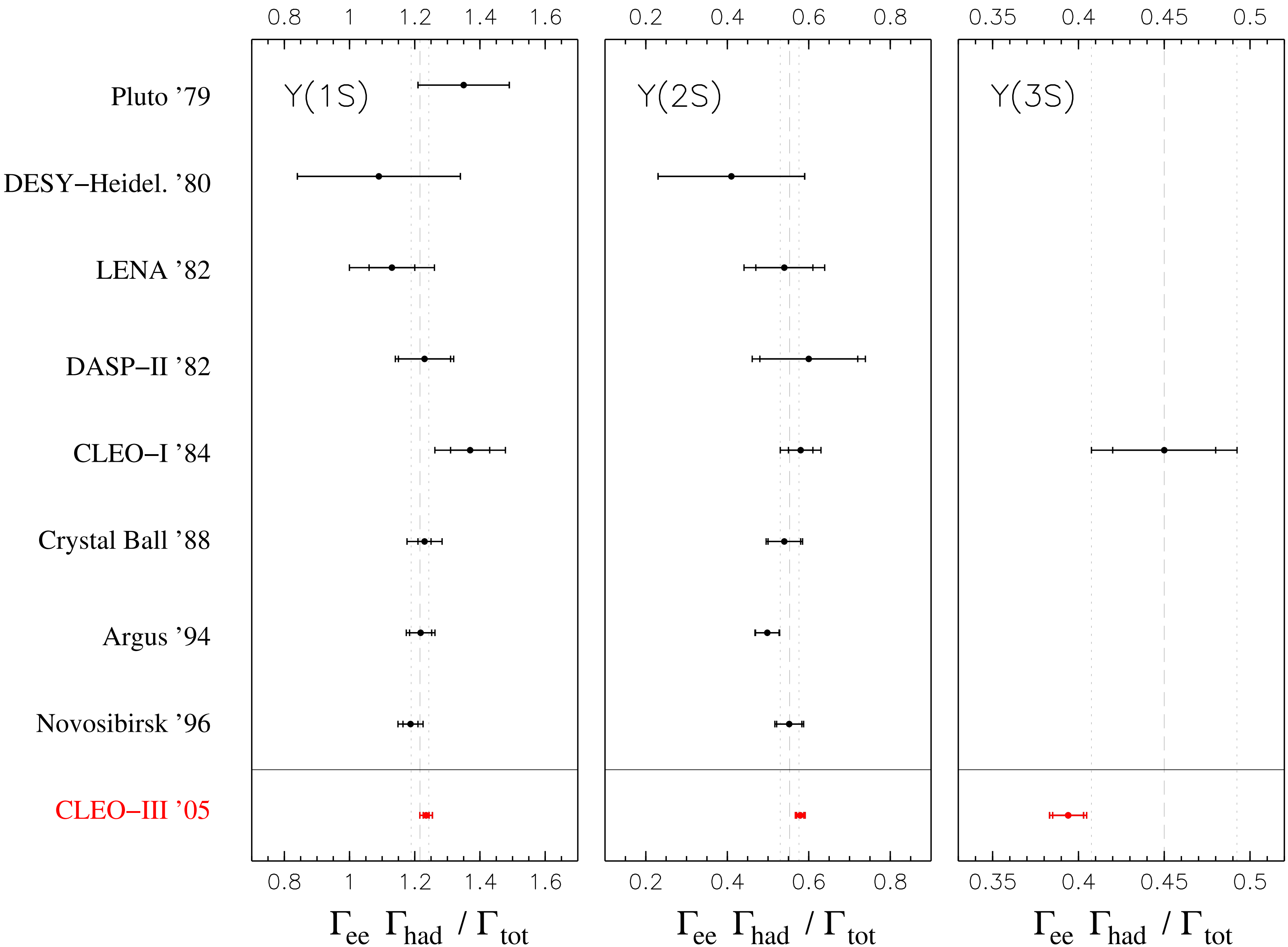
Contribution to Γ_{ee}	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
Statistical*	**0.7%**	**1.6%**	**2.2%**
$(1 - 3\mathcal{B}_{\mu\mu})$	0.2%	0.2%	0.3%
Hadronic efficiency	0.5%	0.6%	0.7%
Luminosity calibration	**1.3%**	**1.3%**	**1.3%**
Cross-section stability	0.1%	0.1%	0.1%
Beam-energy stability	0.2%	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 ($e^+e^- \to \gamma\gamma$ counting) and contains background subtractions.

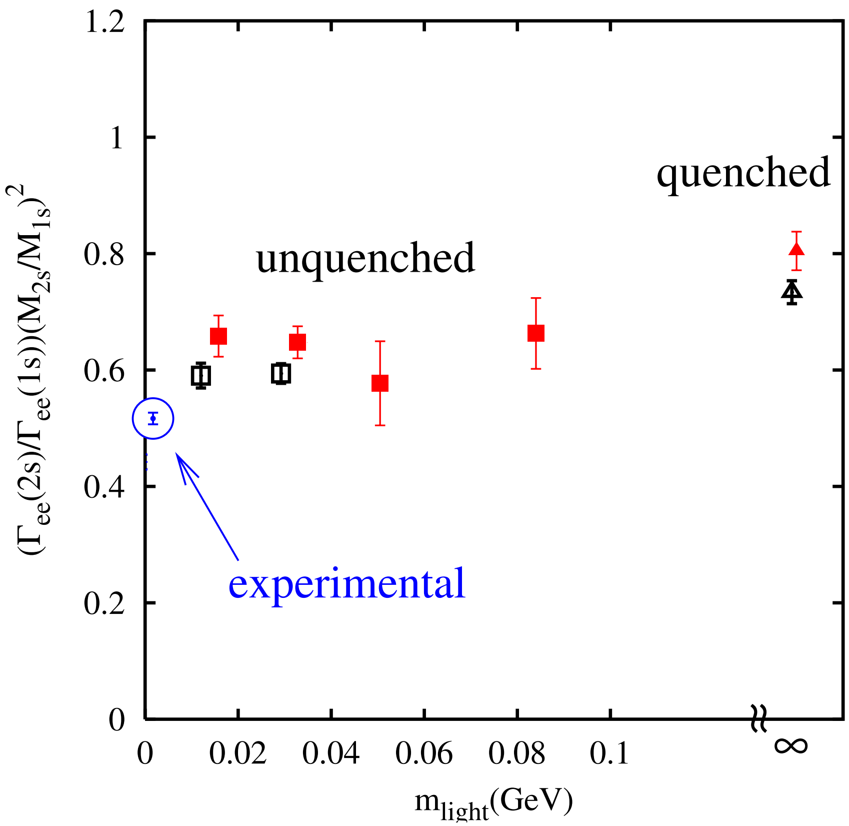
Preliminary Results

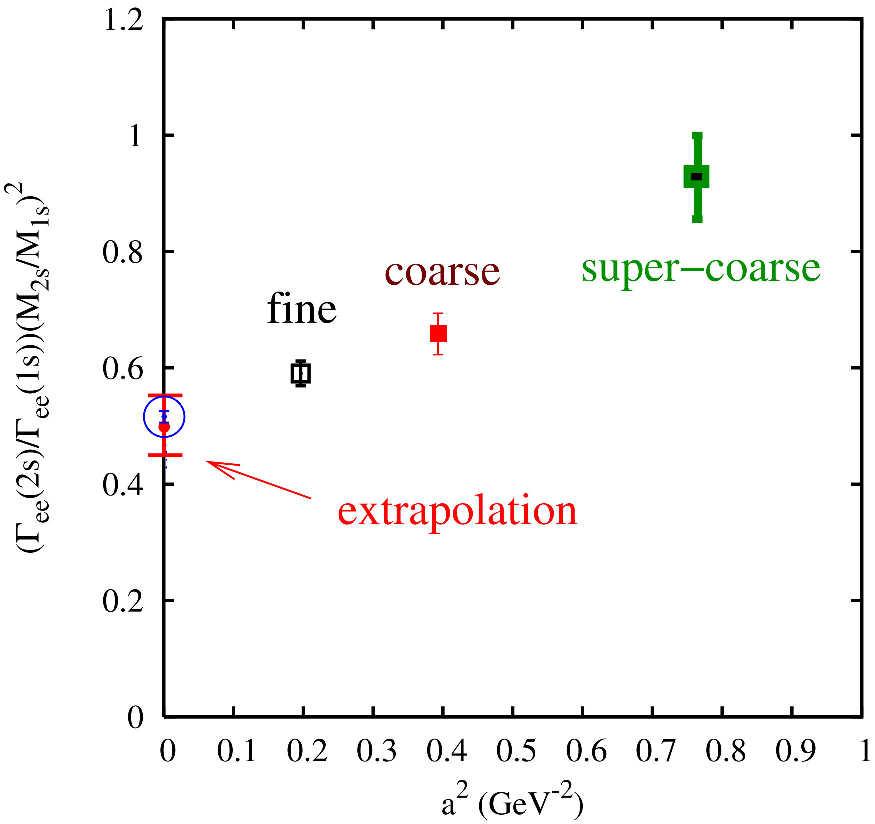
Quantity	Value	Uncertainty
$\Gamma_{ee}(1S)$	$1.336 \pm 0.009 \pm 0.019$ keV	1.6%
$\Gamma_{ee}(2S)$	$0.616 \pm 0.010 \pm 0.009$ keV	2.2%
$\Gamma_{ee}(3S)$	$0.425 \pm 0.009 \pm 0.006$ keV	2.7%
$\Gamma_{ee}(2S)/\Gamma_{ee}(1S)$	$0.461 \pm 0.008 \pm 0.003$	1.8%
$\Gamma_{ee}(3S)/\Gamma_{ee}(1S)$	$0.318 \pm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

- Theoretical result is incomplete— missing lattice renormalization factor
- For now, we can compare *ratio* of $\Gamma_{ee}(2S)/\Gamma_{ee}(1S)$



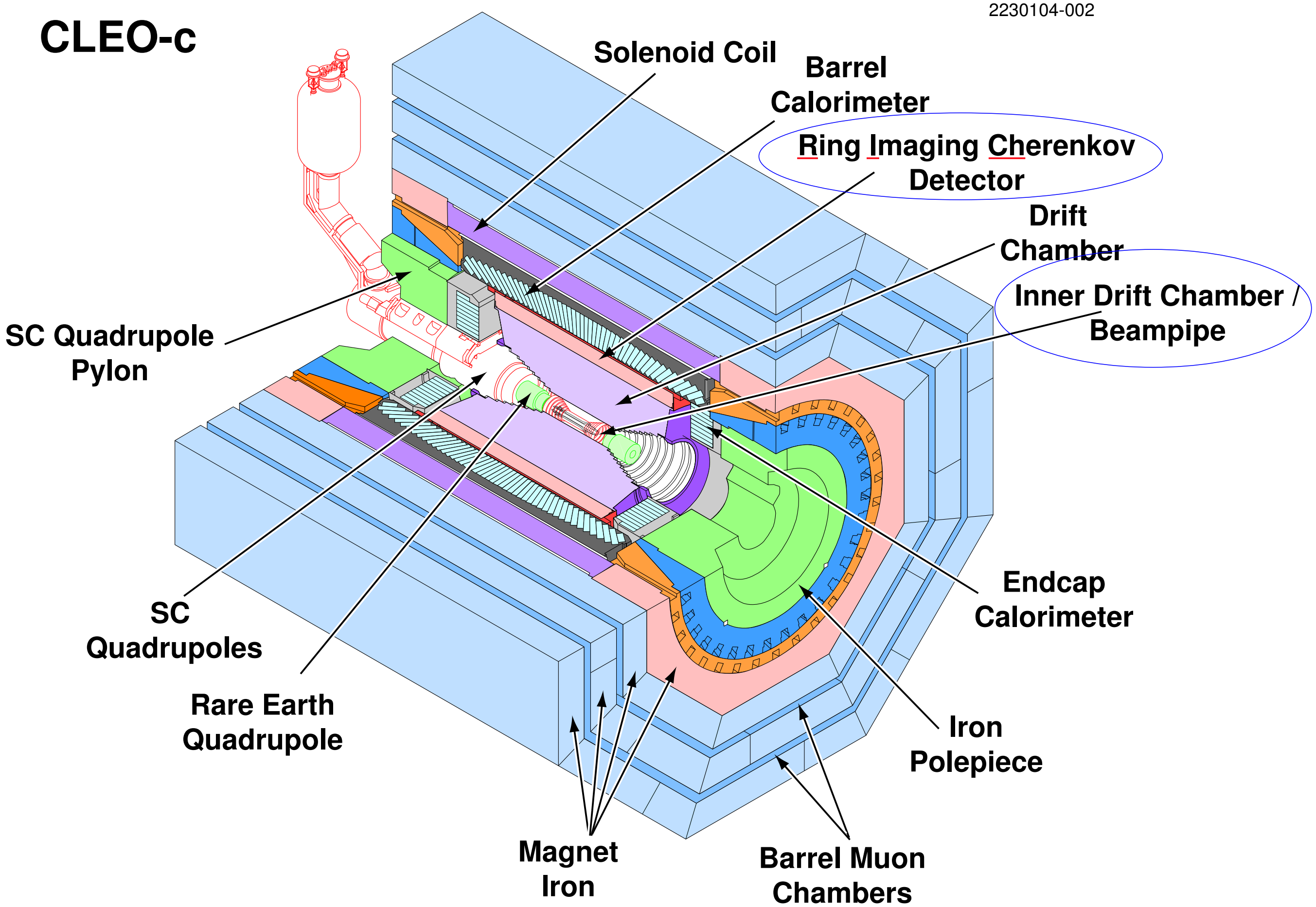


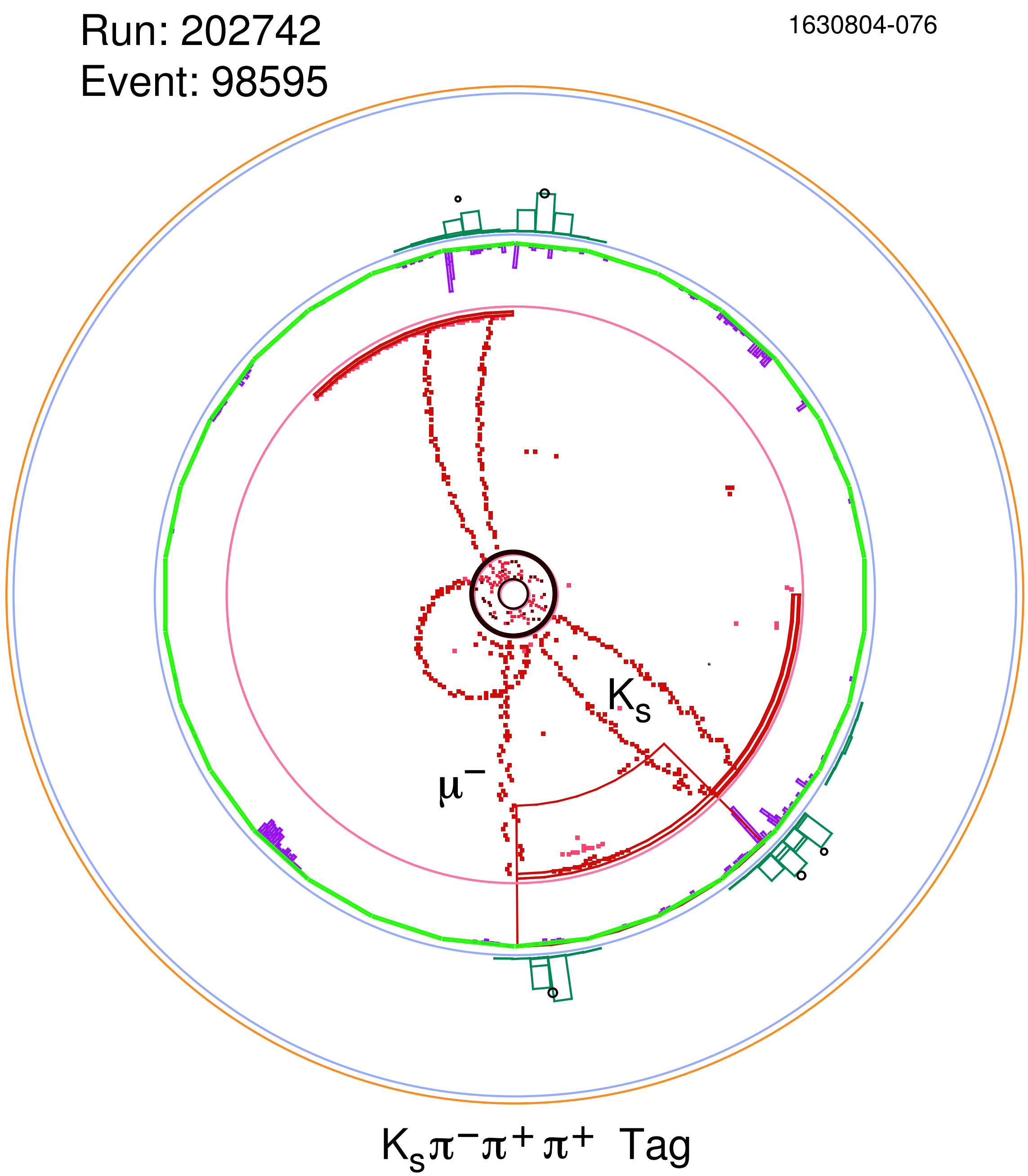
- $\Gamma_{ee}(1S, 2S, 3S)$ calculations will ultimately be $\sim$10% accurate
- Ratios will be a few percent

$D^+ \to \mu^+\nu$ Table of Contents

- Introduction
- Event selection
- Backgrounds
- Results and comparison with theory

- Very different kind of analysis: discovery, statistics-limited
- 281 pb^{-1} at $\psi(3770) \to D\bar{D}$
- CLEO-III $\to$ CLEO-c: new inner tracker



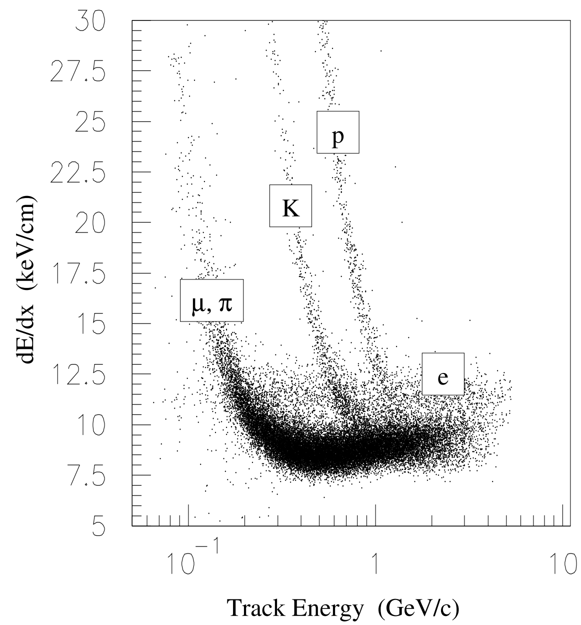


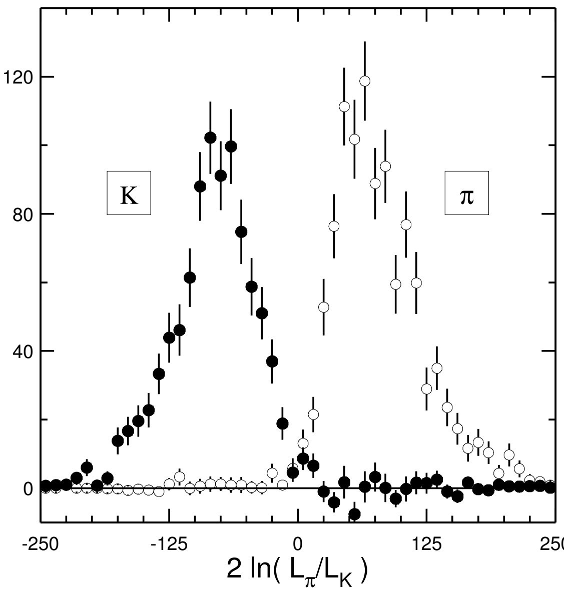
- Follows MARK-III procedure very closely
- Fully reconstruct D^- decay on one side and search for $\mu^+\nu$ signal on the other

Tag Modes
$K^+\pi^-\pi^-$
$K^+\pi^-\pi^-\pi^0$
$K^0_S\pi^-$
$K^0_S\pi^-\pi^-\pi^+$
$K^0_S\pi^-\pi^0$
$K^+K^-\pi^-$

μ/K and π/K separation

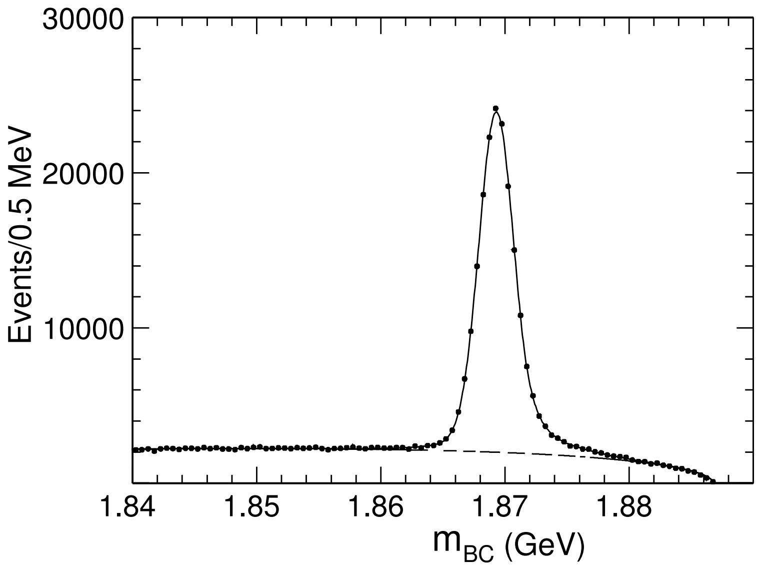
- Energy loss in drift chamber (dE/dx)
- RICH detector above 0.55 GeV



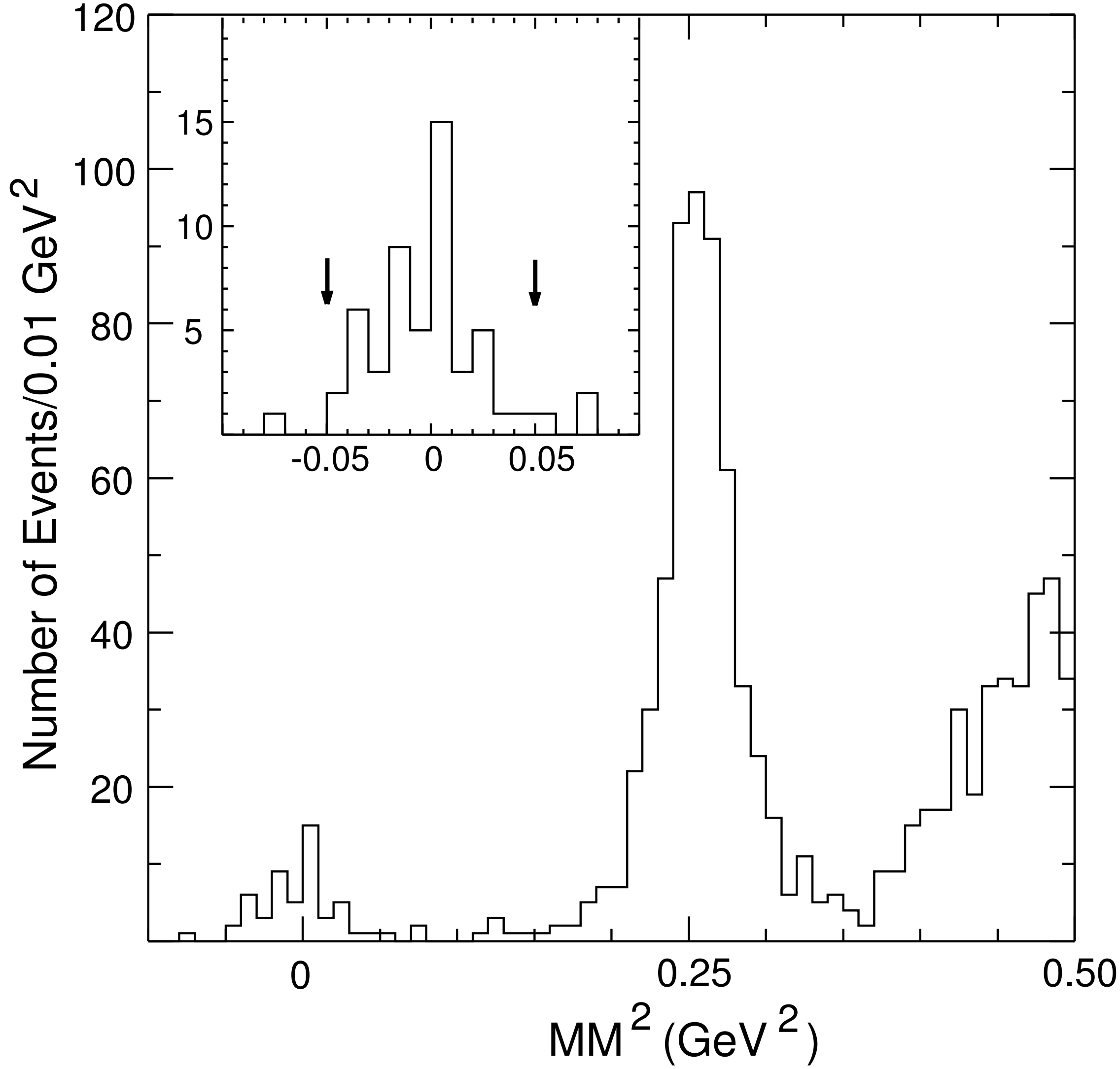


Beam-constrained mass $m_{BC} = \sqrt{{E_{beam}}^2 - |\sum_i \vec{p_i}|^2}$

- Background: 3^{rd}-order polynomial or ARGUS function
- Signal: Gaussian for most modes, double-Gaussian for $K^+\pi^-\pi^-$ and $K^0_S\pi^-$



- μ^+: track within $|\cos\theta| < 0.81$ pointing to event vertex ($\pm$ 5 mm in XY, 5 cm in Z) matched to less than 300 MeV in CsI calorimeter
- ν: missing mass^2 within 0.05 GeV^2 of zero
- 50 events in signal region



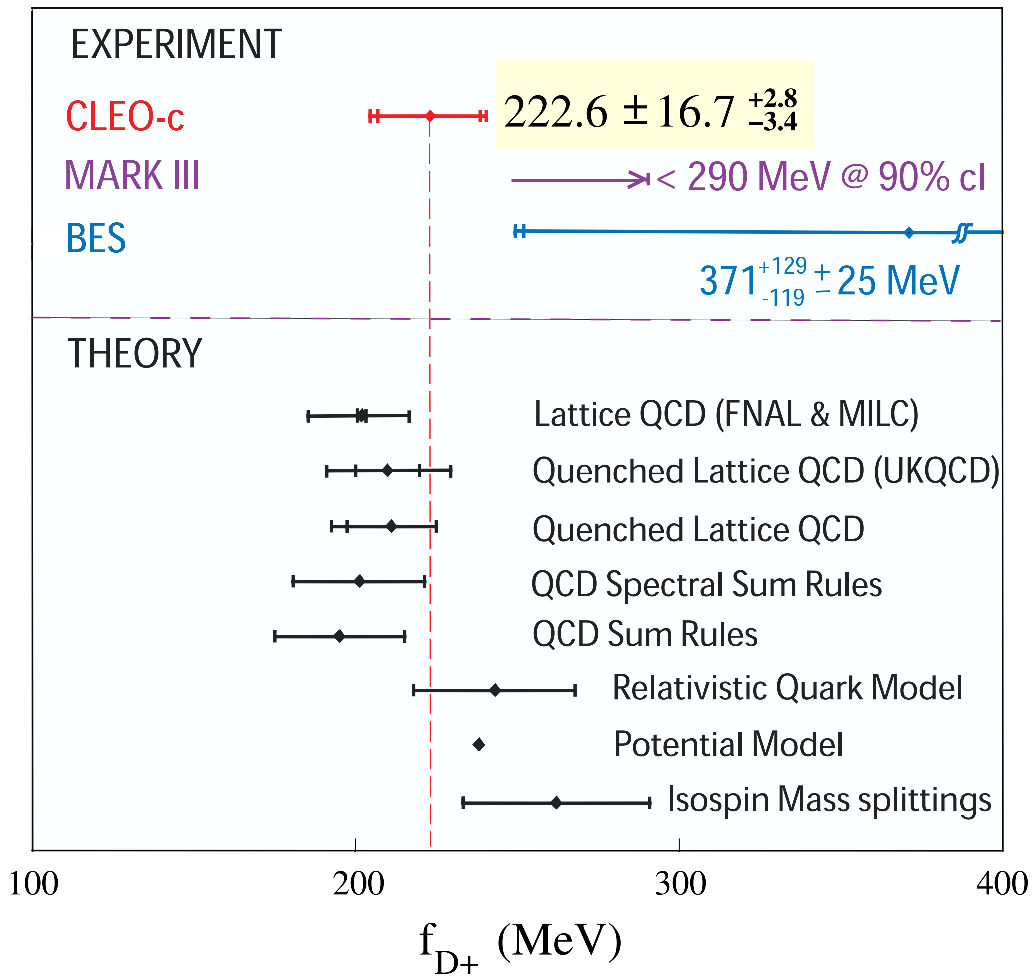
- K_L^0 mass^2 is 0.25 GeV^2

$$MM^2 = (E_{beam} - E_{\mu^+})^2 - |-\vec{p}_{D^-} - \vec{p}_{\mu^+}|^2$$

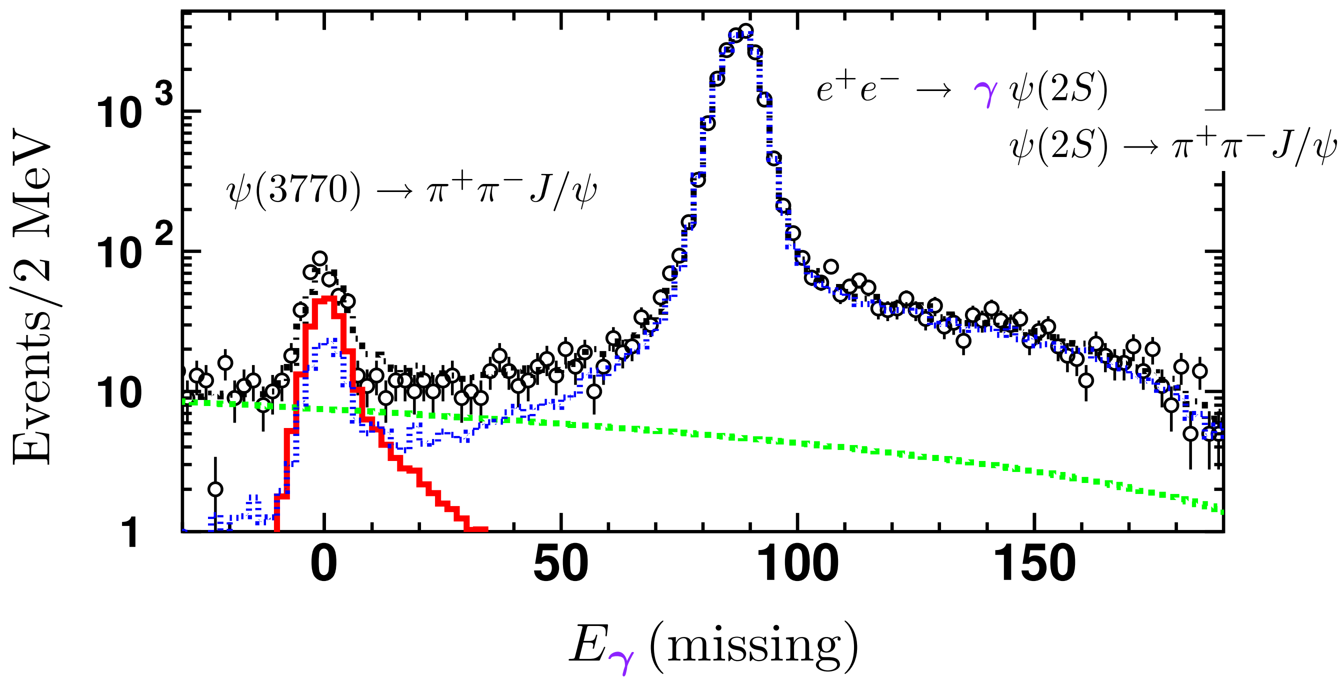
- $D^+ \to K_L^0 \pi^+$:
  - Identify $D^0 \to K^- \pi^+$ in $D^0 \bar{D}^0$ sample
  - Ignore kaon, and compute missing mass^2
  - Background is 0.3 ± 0.2 events
- $D^+ \to \pi^+ \pi^0$:
  - Monte Carlo + branching fractions $\Rightarrow$ background is 1.4 ± 0.3 events
- $D^+ \to \tau^+ \nu$:
  - Related to signal
  - Monte Carlo + branching fractions $\Rightarrow$ background is 1.1 ± 0.2 events
- $D^+ \to$ anything else, $D^0 \bar{D}^0$ and continuum backgrounds
  - 2.3 fb^{-1} of Monte Carlo ($8\times$ signal) $\Rightarrow$ no events

Total background is 2.8 ± 0.4 events $\Rightarrow$ yield of $47.2 \pm 7.1\ ^{+0.3}_{-0.8}$ signal events

- Clean environment, well-understood detector $\rightarrow$ 2% systematic uncertainty
- Statistical uncertainty is 15%
- $\mathcal{B}(D^+ \rightarrow \mu^+\nu) = (4.40 \pm 0.66\ ^{+0.09}_{-0.12}) \times 10^{-4}$ and $f_{D^+} = (222.6 \pm 16.7\ ^{+2.8}_{-3.4})$ MeV



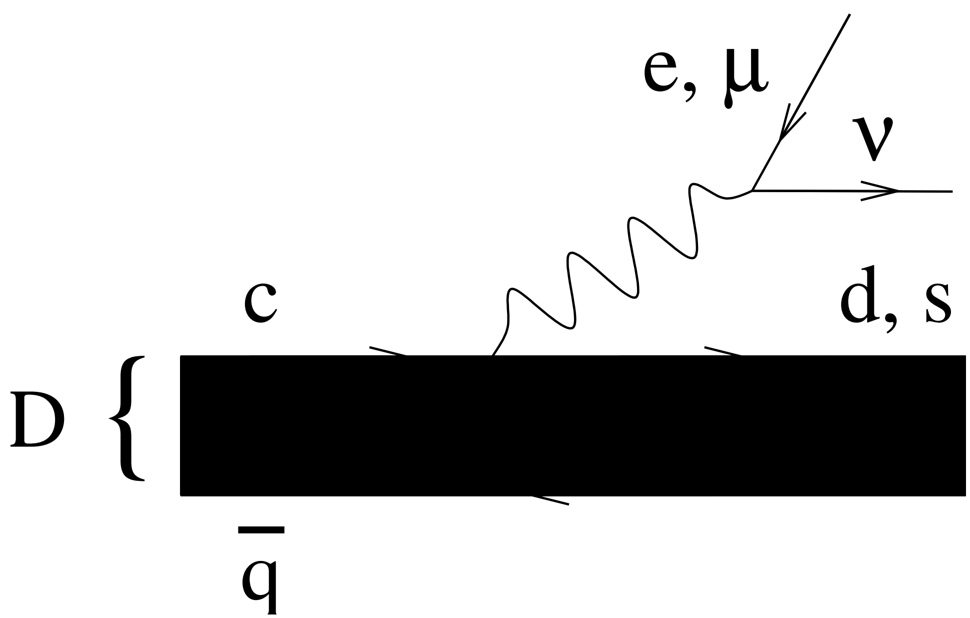
Γ_{ee} without a scan



- $e^+e^-(3770\ \mathrm{MeV}) \to \gamma\ \psi(2S)$ is the primary background to $\psi(3770) \to \pi^+\pi^- J/\psi$
- ISR photon is not reconstructed, but inferred from missing momentum
- Equivalent to a scan with exactly one energy point, far above resonance mass
  - ISR lineshape is convoluted with $\psi(2S)$ BW, so it is normalized by BW area
  - $\pi^+\pi^- J/\psi$ is a particularly sensitive channel for $\psi(2S)$
  - $\Gamma_{ee}(\psi(2S)) = 2.13 \pm 0.03 \pm 0.08$ keV (4% measurement)
  - Limited by branching fraction uncertainties

Future confrontations between LQCD and experiment at CLEO-c

- LQCD uncertainties cancel in ratios such as $\dfrac{f_{B_s}B_{B_s}}{f_B B_B}$
- Compare experiment and theory for f_{D_s} as well: $D_s \to \mu\nu$
- CLEO-c is already optimizing an energy point for D_s production
- Optimal use of LQCD and data: $\dfrac{f_{B_s}}{f_B} = \left(\dfrac{f_{B_s}f_D}{f_B f_{D_s}}\right)_{\text{LQCD}} \left(\dfrac{f_{D_s}}{f_D}\right)_{\text{experiment}}$



Future confrontations between LQCD and experiment at CLEO-c

stuff about semileptonics

Summary (I haven't proofread this)

- Precision LQCD is a breakthrough in its own right
- As a tool, it can extract fundumental parameters from decay rate measurements
- Some contacts with experiment, such as Γ_{ee}, f_D, f_{Ds}, $f(q^2)$ Can use these to
  - Check the validity the calculations in different quark pair settings
  - Extrapolate experimental measurements, such as f_D and f_{Ds}/f_D, to higher quark masses