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

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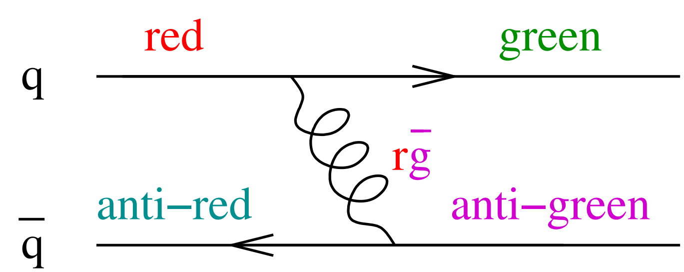
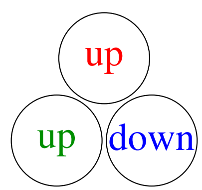
The 3.5 Fundamental Interactions

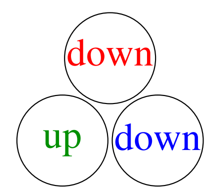
	Electro-	-Weak	Strong Nuclear	Gravity
mediated by	photon (γ)	$W^{\pm}$, Z^0	gluons (g)	curved space
sources	all charged particles	all known particles	quarks, gluons	mass

Strong Nuclear force:

- quarks have red, green, or blue charges
- anti-quarks have anti-colors
- gluons have color/anti-color



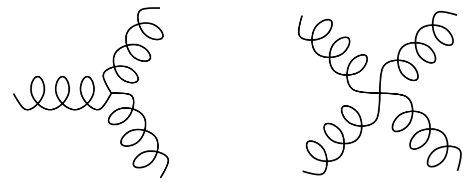
This is the force that holds protons 

and neutrons 

together.

Fringe fields bind protons and neutrons into nuclei

Color-charged gluons can self-interact:



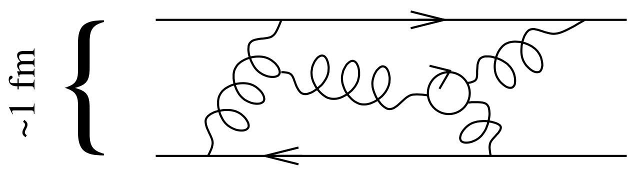
In Quantum Electrodynamics (QED), each graph contributes $\mathcal{O}(\alpha^N)$ to the amplitude

$$\alpha = 1/137 \text{ and } N = \text{number of vertices in graph}$$

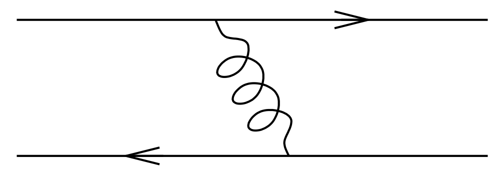
In Quantum Chromodynamics (QCD) at large distances ($\gtrsim$ 0.2 fm $=$ 1 GeV^{-1}),

$$\alpha_s \sim 1$$

Complicated graphs cannot be ignored



is not suppressed relative to



Large-distance QCD is very difficult to calculate

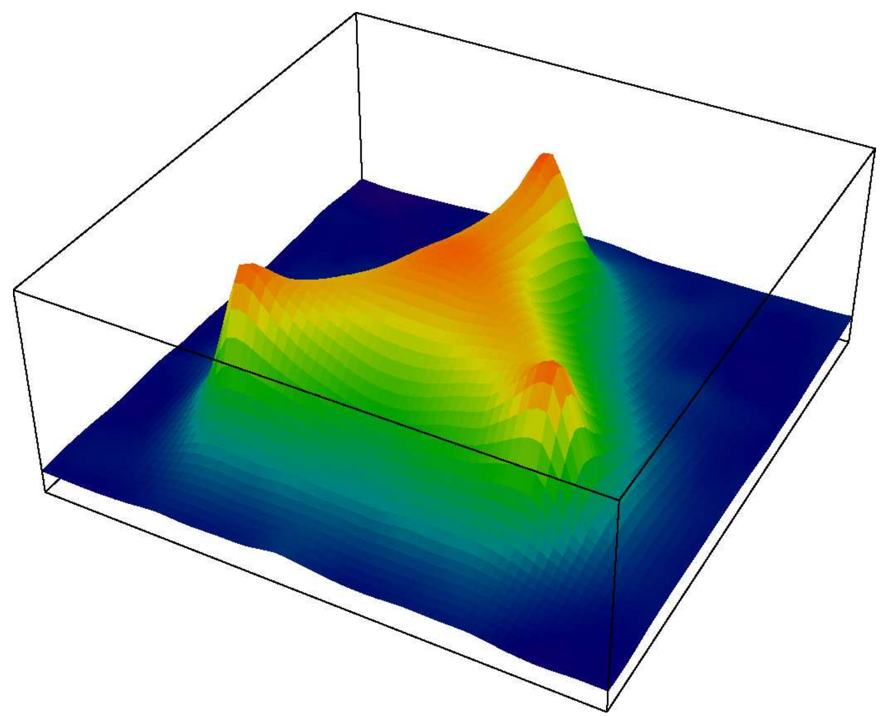
Alternative method: Lattice QCD

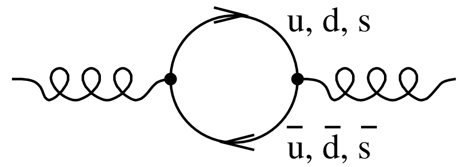
General problem is to compute amplitude $= \sum_f S[f]$

f is a function of quark and gluon field values w.r.t. space-time
S is the action (fundamental theory, in this case QCD)

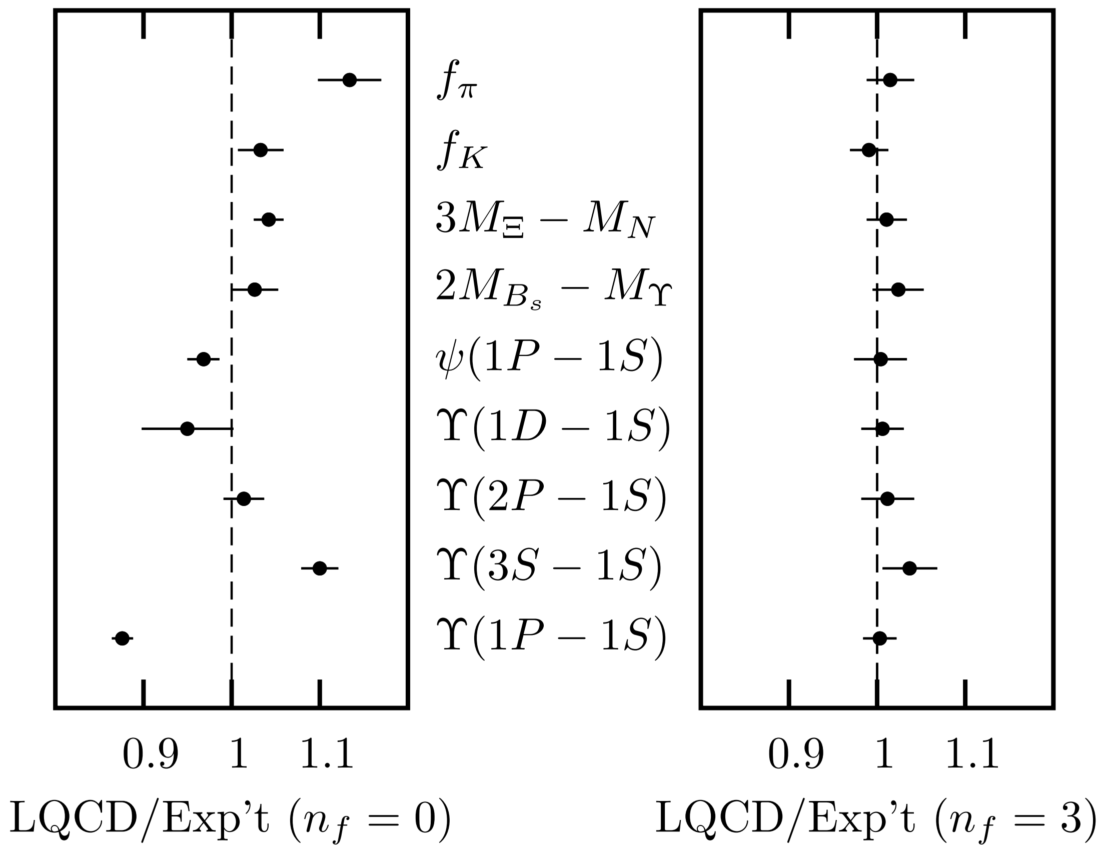
Rather than partitioning $\{f\}$ by topology, simulate random paths with a computer

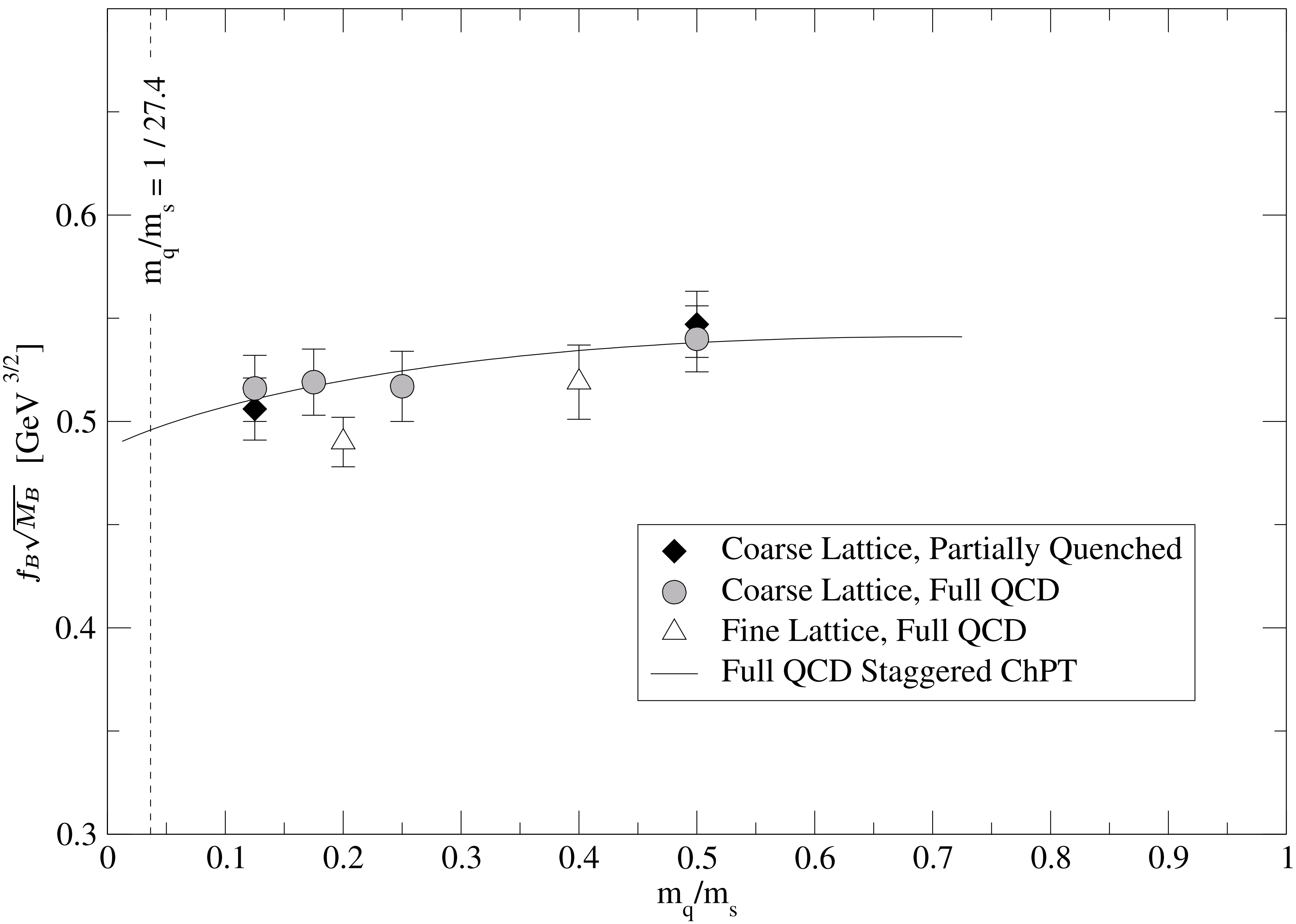
1. Discretize space-time
2. Throw random paths f
3. Interpolate with short-distance QCD
4. Calculate $S(f)$ and integrate
5. Take continuum limit from several simulations



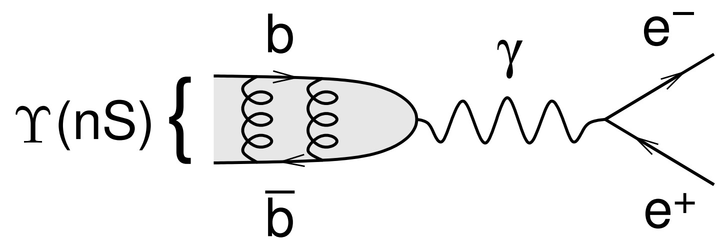
Computationally intensive, particularly because of 

Symanzik-improved staggered-quark formalism (1999) makes u, d, s quark loops feasible





$m_q/m_s = 1 / 27.4$
$f_B\sqrt{M_B}$ [GeV $^{3/2}$]
0.3
0.4
0.5
0.6
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
m_q/m_s
Coarse Lattice, Partially Quenched
Coarse Lattice, Full QCD
Fine Lattice, Full QCD
Full QCD Staggered ChPT

Di-electron width ($\boldsymbol{\Gamma_{ee}}$) of $\Upsilon(nS)$ is the rate of 

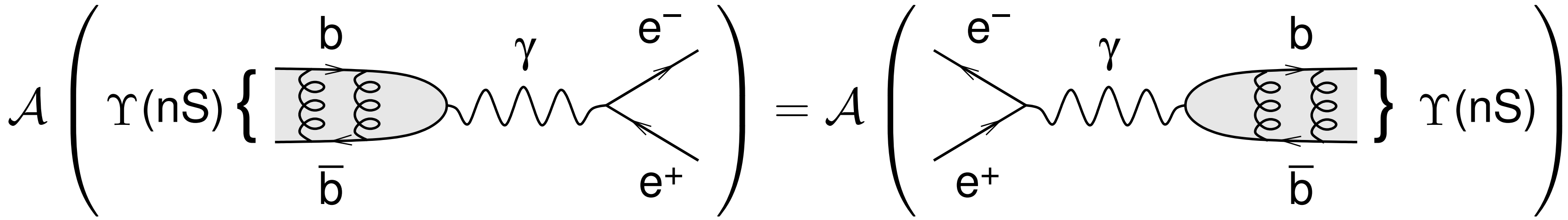
$\boldsymbol{\Gamma_{ee}}$ can be calculated to high-precision using improved Lattice QCD
($\sim$10% for $\boldsymbol{\Gamma_{ee}}(nS)$ and few percent for $\boldsymbol{\Gamma_{ee}}(nS)/\boldsymbol{\Gamma_{ee}}(mS)$)

This calculation shares some aspects of f_B, and is an extremely non-relativistic test case

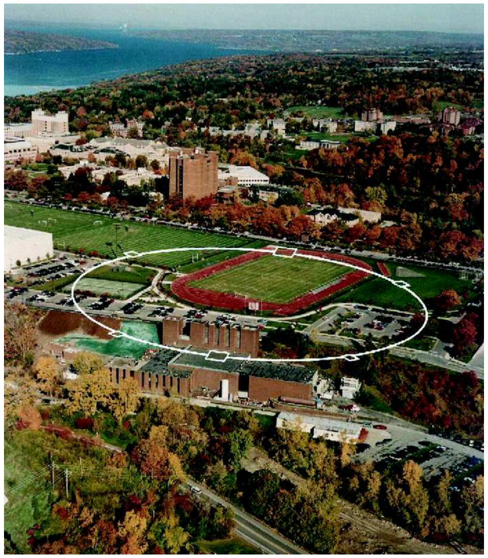
We experimentally measured $\boldsymbol{\Gamma_{ee}}$ for $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$

- 50$\times$ largest previous $\Upsilon(1S)$ dataset, many times more for $\Upsilon(2S)$, $\Upsilon(3S)$
- Total (statistical $+$ systematic) uncertainties of 1.5%, 1.8%, and 1.8%
- Three states in one study allow for significant uncertainty cancellation in ratios

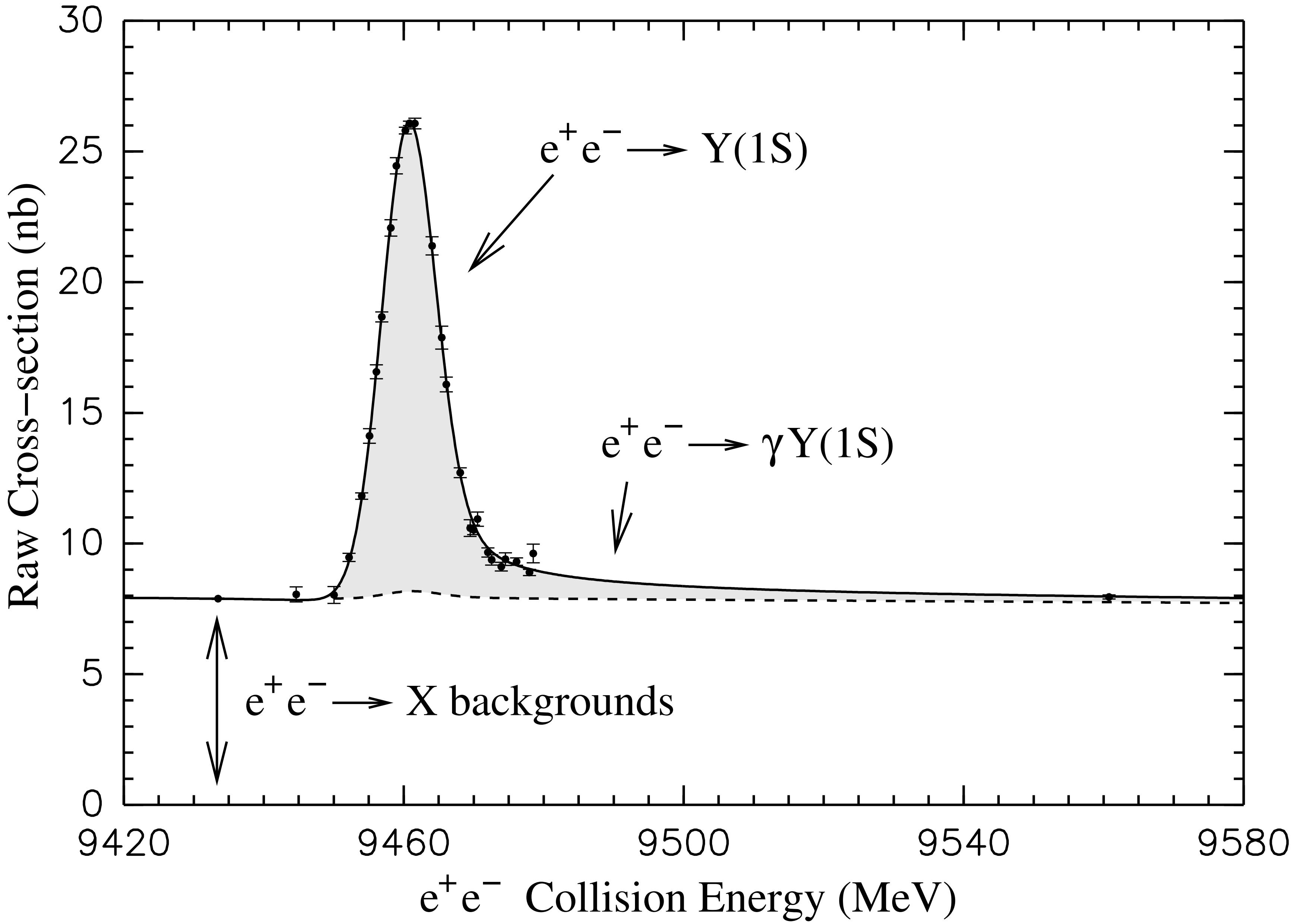
Determine $\Upsilon \to e^+e^-$ decay rate by measuring $e^+e^- \to \Upsilon$ cross-section



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



1. Collide e^+ and e^- at different energies E
2. Measure cross-section $\sigma(e^+e^- \to \Upsilon)$
3. Integrate!

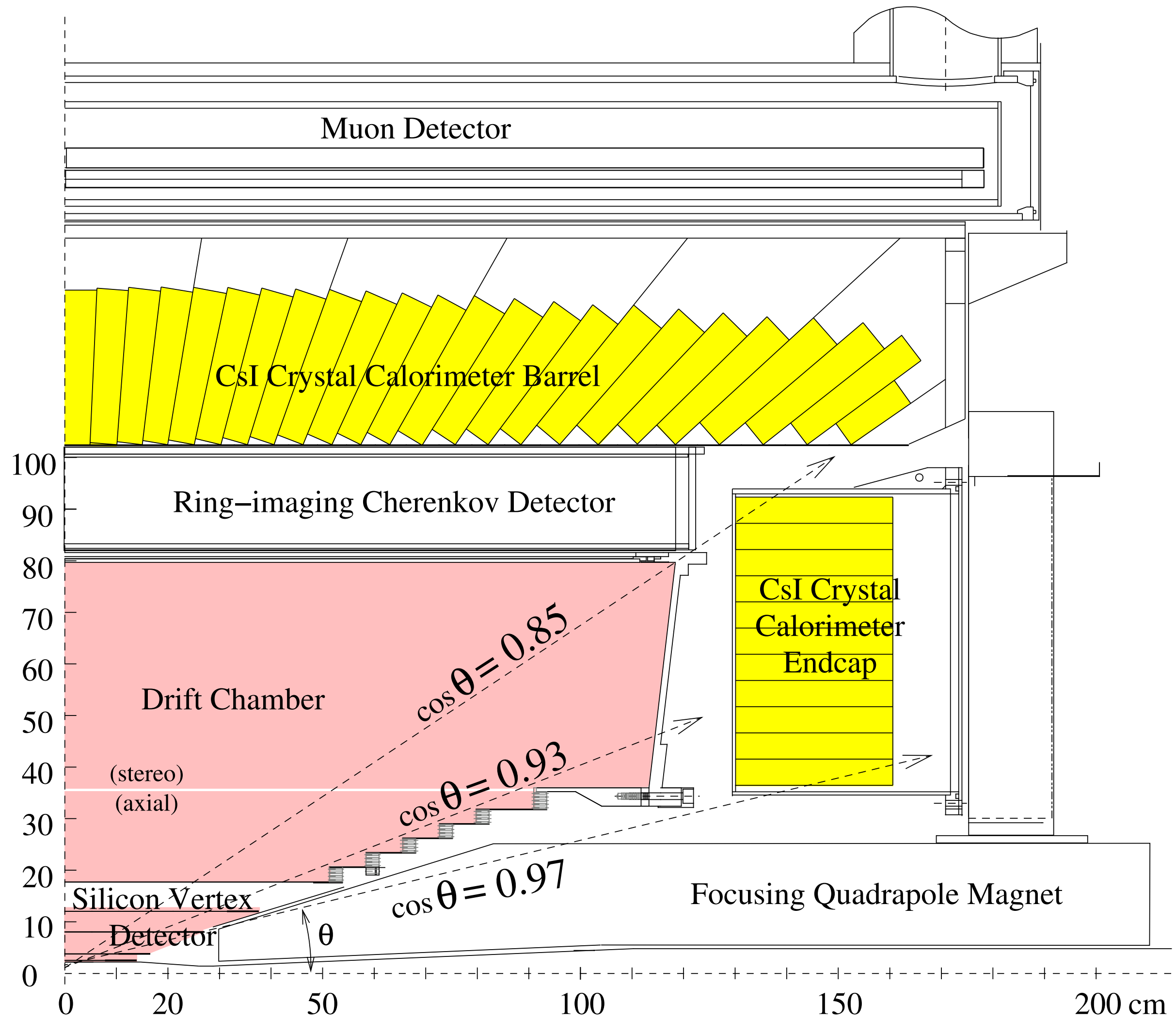

Raw Cross–section (nb)
30
25
20
15
10
5
0
9420
9460
9500
9540
9580
e+e− Collision Energy (MeV)
e+e− → Υ(1S)
e+e− → γΥ(1S)
e+e− → X backgrounds

To measure $\sigma(e^+e^- \to \Upsilon)$,

count Υ events

$$\sigma = \frac{N_{\text{obs}} - N_{\text{back}}}{\epsilon\,\mathcal{L}}$$

$$N_{\text{obs}} = \text{count}$$
$$N_{\text{back}} = \text{backgrounds}$$
$$\epsilon = \text{efficiency}$$
$$\mathcal{L} = \text{luminosity}$$



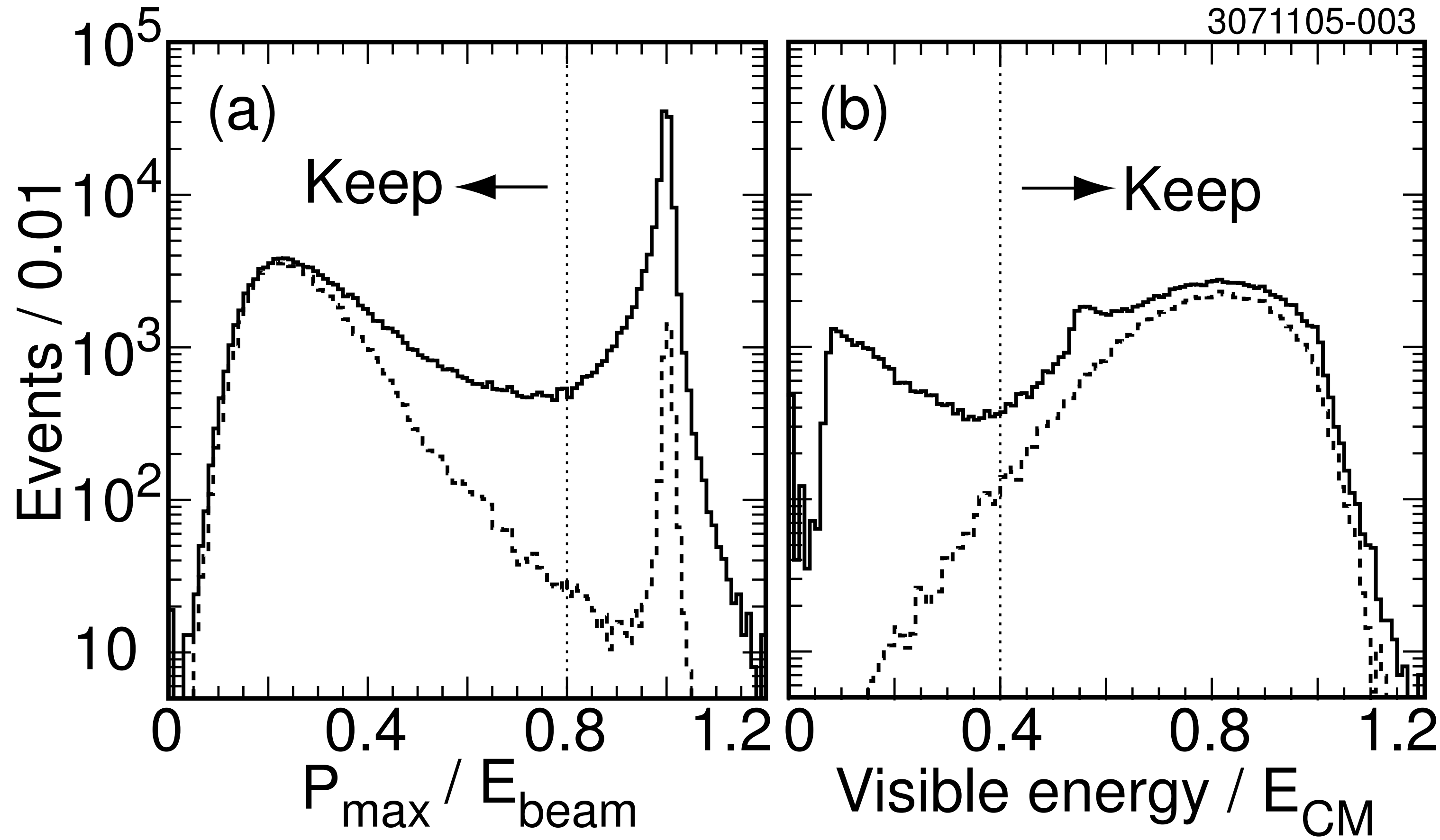
Υ decay modes

- leptonic: total of $3\mathcal{B}_{\mu\mu}$ = 7.5%, well-measured
  - e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$: hard to distinguish from background, easy to simulate
- hadronic: total of $1 - 3\mathcal{B}_{\mu\mu}$, hard to simulate
  - ggg, $gg\gamma$, $q\bar{q} \longrightarrow$ lots of particles
  - $\Upsilon(2S)$ and $\Upsilon(3S)$ decay into lower-energy $b\bar{b}$ states, e.g. $\Upsilon(2S) \longrightarrow \pi^+\pi^-\Upsilon(1S)$
  - unknown modes?

backgrounds

- $e^+e^- \longrightarrow X$
  - e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $q\bar{q}$
  - two-photon fusion: $e^+e^- \longrightarrow e^+e^-X$
  - $e^+e^- \longrightarrow \gamma\Upsilon((n-1)S)$
- beam-gas, beam-wall
- cosmic rays

Select $hadronic$ Υ decays, later correct with $(1 - 3\mathcal{B}_{\mu\mu})$

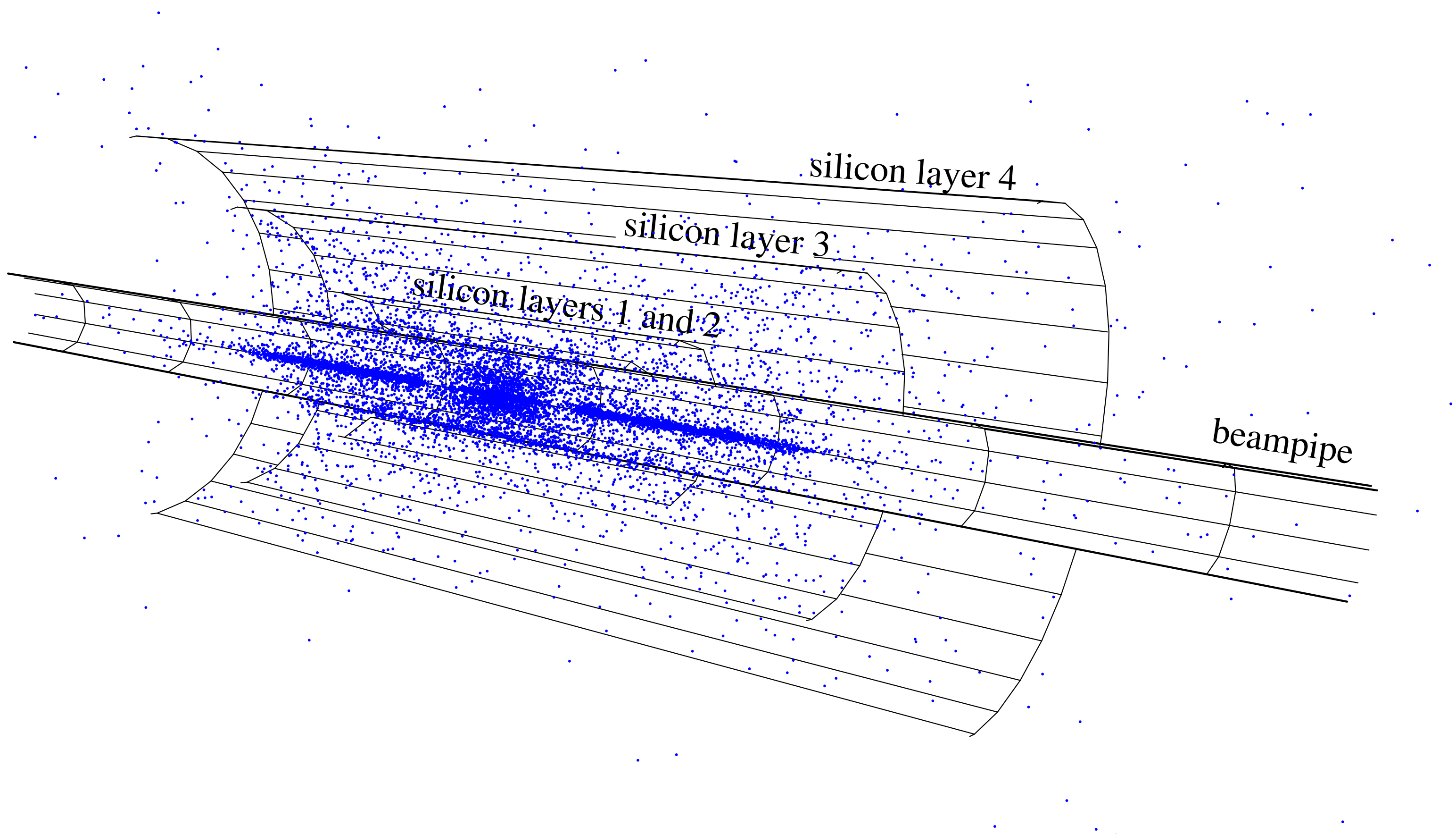


solid are data

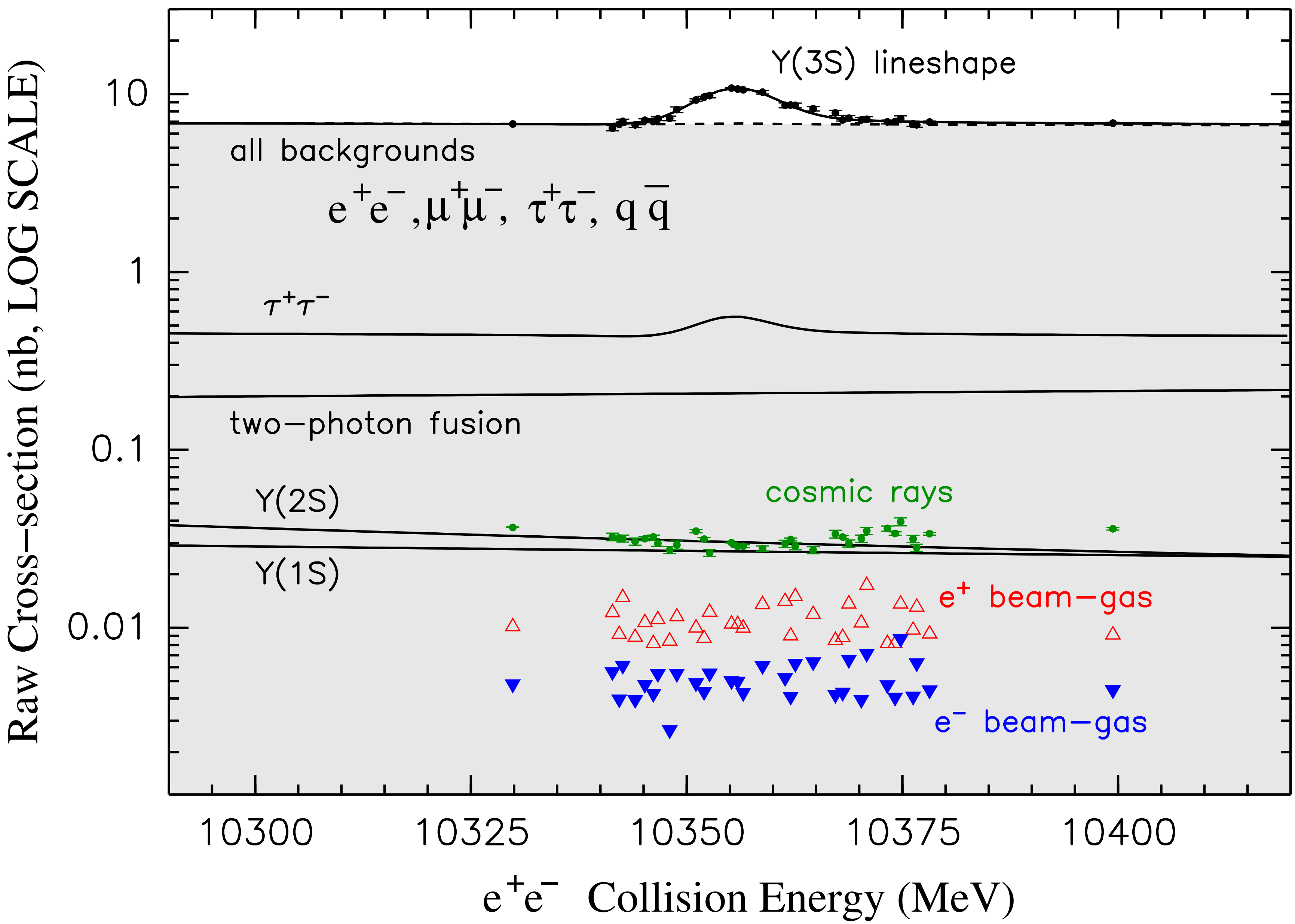
dashed are simulated Υ decays

all cuts applied except the one shown

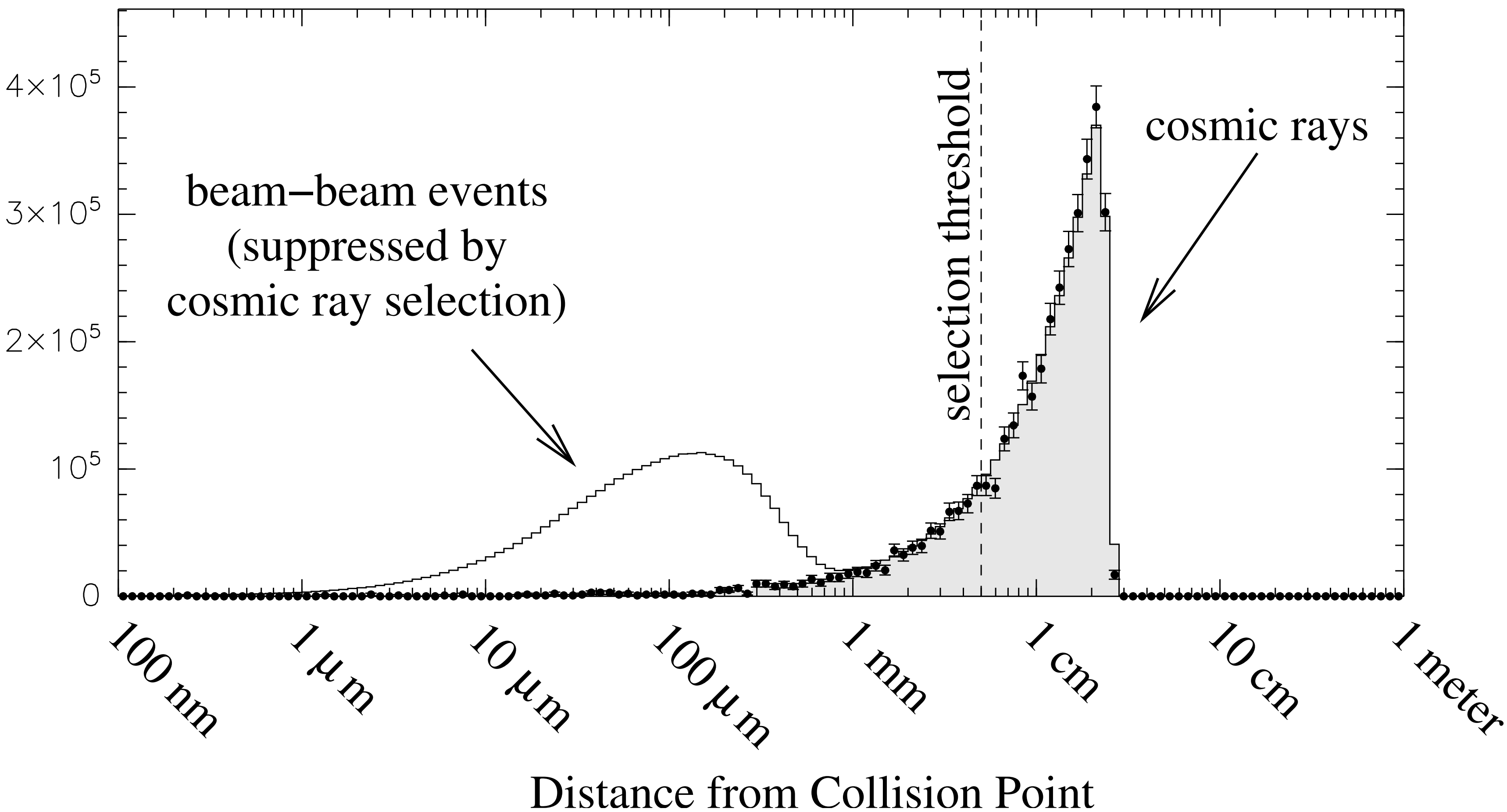
Select events near collision point ($<$ 7.5 cm along beam axis, $<$ 5 mm perpendicular)



blue points are event vertices (determined from track intersections)
beam-beam collision region is suppressed


Υ(3S) lineshape
all backgrounds
e+e−, μ+μ−, τ+τ−, q q̄
τ+τ−
two−photon fusion
cosmic rays
Υ(2S)
Υ(1S)
e+ beam−gas
e− beam−gas
10
1
0.1
0.01
10300
10325
10350
10375
10400
Raw Cross−section (nb, LOG SCALE)
e+e− Collision Energy (MeV)

Subtracting Cosmic Rays

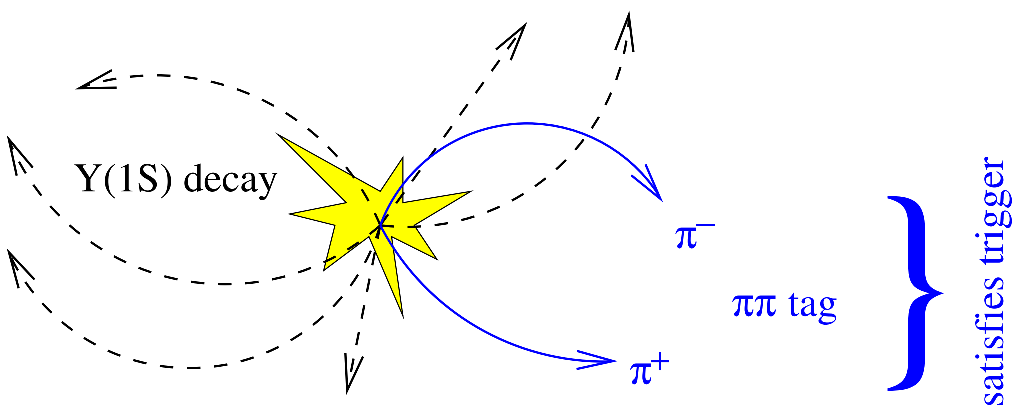


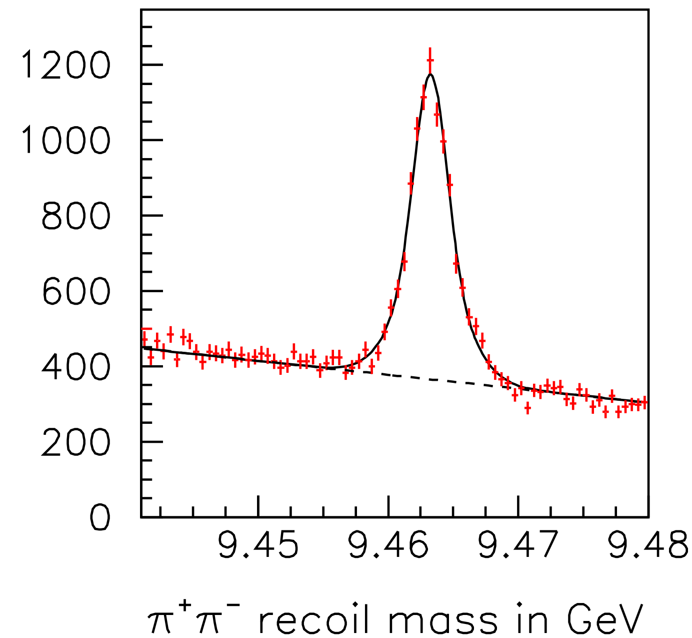
solid histogram are beam-beam data
points with errorbars are no-beam data

Efficiency: what fraction of hadronic Υ decays are *missing* from our count?

Hadronic modes are difficult to simulate, and our definition includes unknown modes

- We have a large sample (1.3 fb^{-1}) of $\Upsilon(2S)$ decays
- Select $\Upsilon(2S) \to \pi^+\pi^-\ \Upsilon(1S)$ by $\pi^+\pi^-$ recoil mass





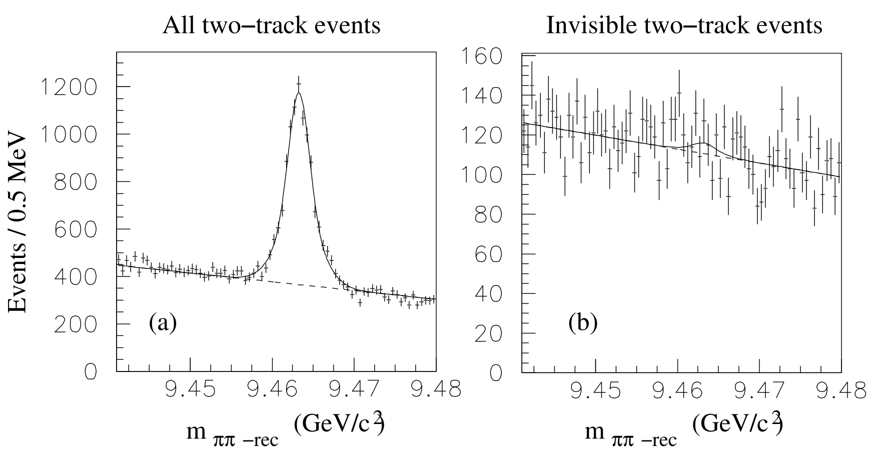
- Set of $\Upsilon(1S)$ events is unbiased, includes all decays
- $\Upsilon(1S)$ efficiency = #pass/#total = $(97.8 \pm 0.5)\%$

Technical detail: `two-track` trigger satisfied by $\pi^+\pi^-$ is prescaled by a factor of 19

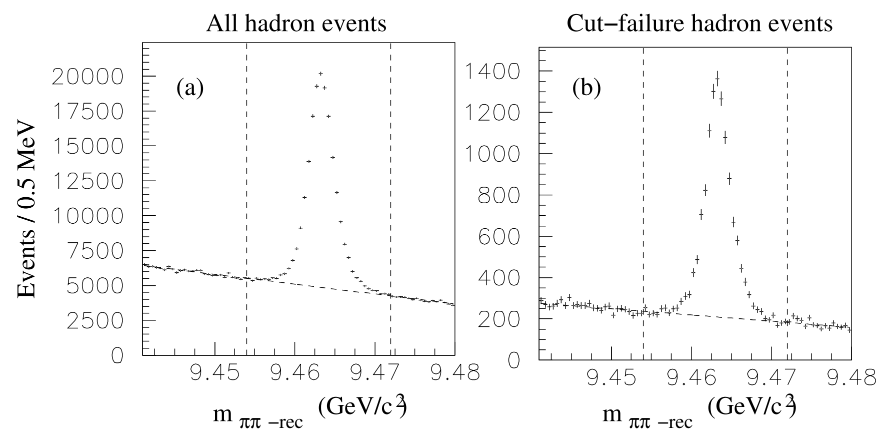
To get a statistically-precise result, we divide problem into two parts:

- define $\Upsilon(1S)$ decay to be visible if it generates one `AXIAL` track and maybe one `CBLO` cluster in the trigger (the `CBLO` may be due to $\pi^+\pi^-$)
- define ϵ_{vis} = probability that $\Upsilon(1S)$ is visible
- define ϵ_{cuts} = probability that a visible $\Upsilon(1S)$ decay passes cuts

determine ϵ_{vis} with a fit yield from `two-track` trigger



determine ϵ_{cuts} with a background-subtracted count from `hadron` trigger

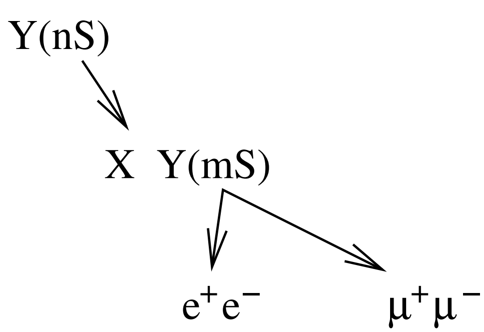


Our efficiency study only applies to $\Upsilon(1S)$

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

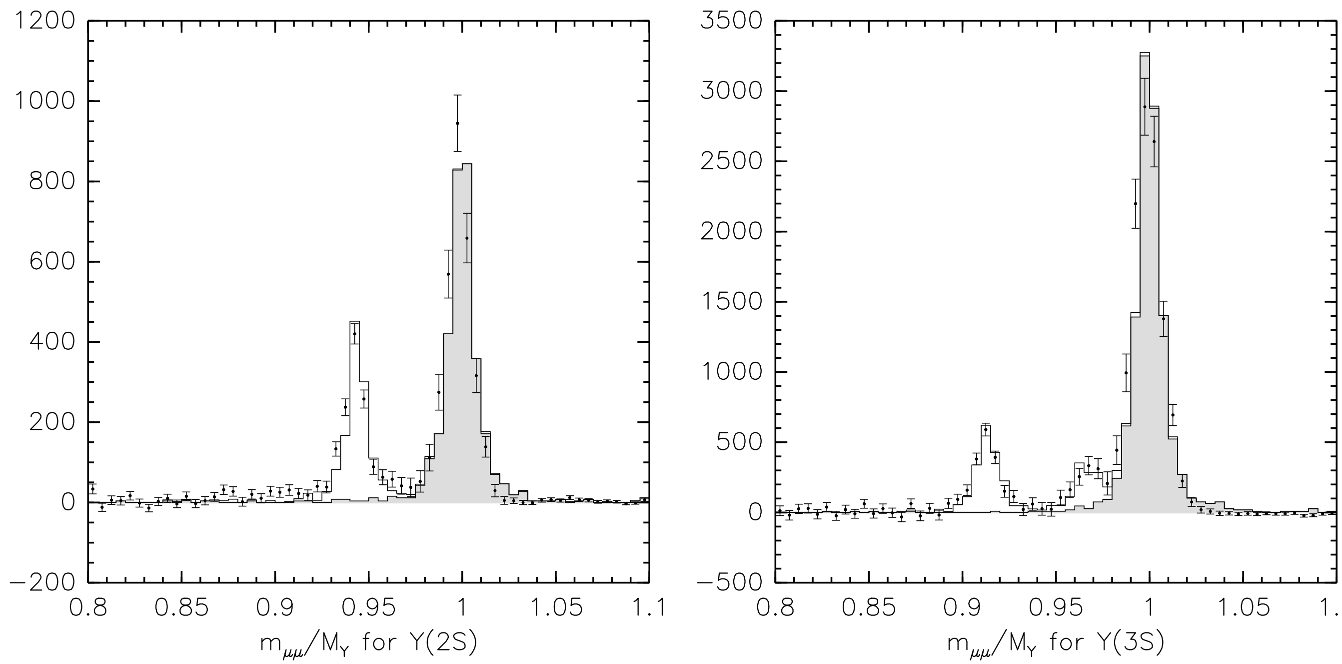
We assume that $\Upsilon(2S)$ and $\Upsilon(3S)$ decay like $\Upsilon(1S)$, but at higher energy and with transitions to lower $b\bar{b}$ states

Primary efficiency correction:



$$\Upsilon(nS) \to X\mu^+\mu^-$$

Measuring $\mathcal{B}_{X\mu\mu}$ relative to $\mathcal{B}_{\mu\mu}$



solid is Monte Carlo, shaded is $\mu^+\mu^-$, open is $X\mu^+\mu^-$
points with errorbars are data

Reminder: cross-section $\sigma = (N_{\text{obs}} - N_{\text{back}})/(\epsilon\,\mathcal{L})$ where $\mathcal{L}$ is time-integrated luminosity

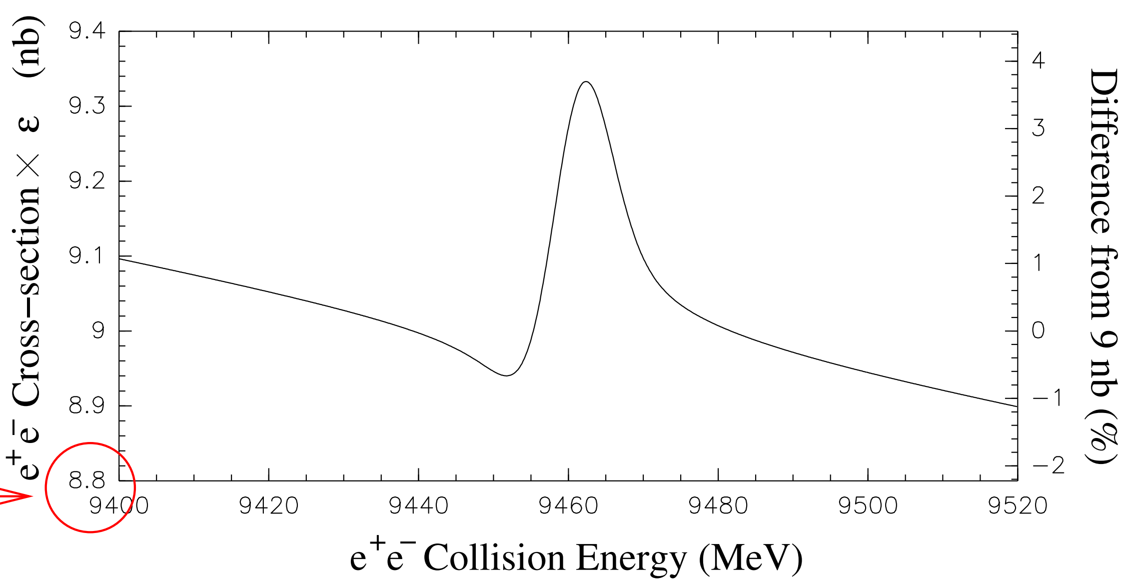
Instantaneous luminosity is the intensity and degree of overlap of e^+e^- beams

Instantaneous luminosity is hard to measure and fluctuates with beam conditions

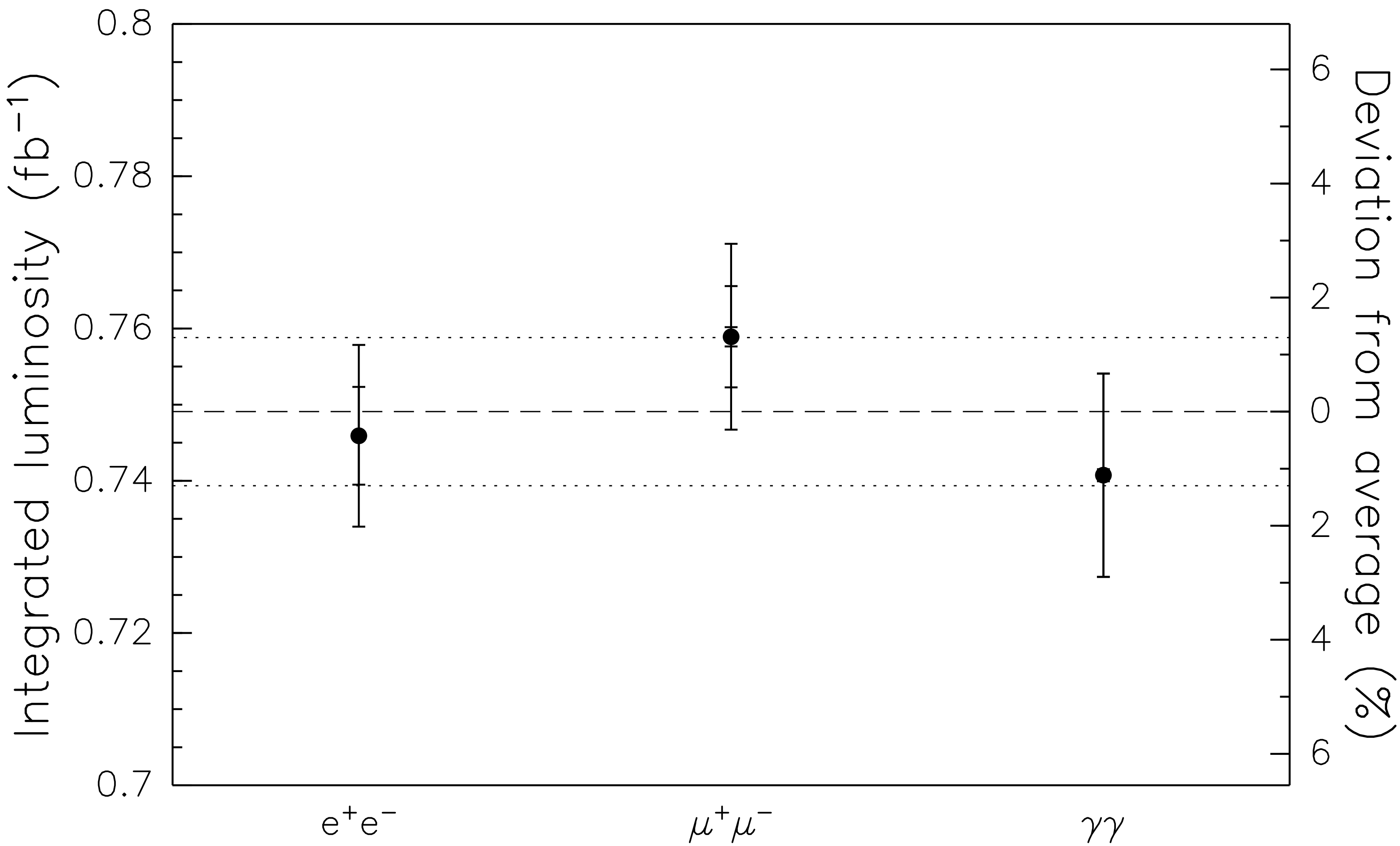
Apply above equation for a process with a known cross-section

$\sigma(e^+e^- \to e^+e^-) \times \epsilon(e^+e^-)$ may be calculated from QED and detector simulations

suppressed zero!

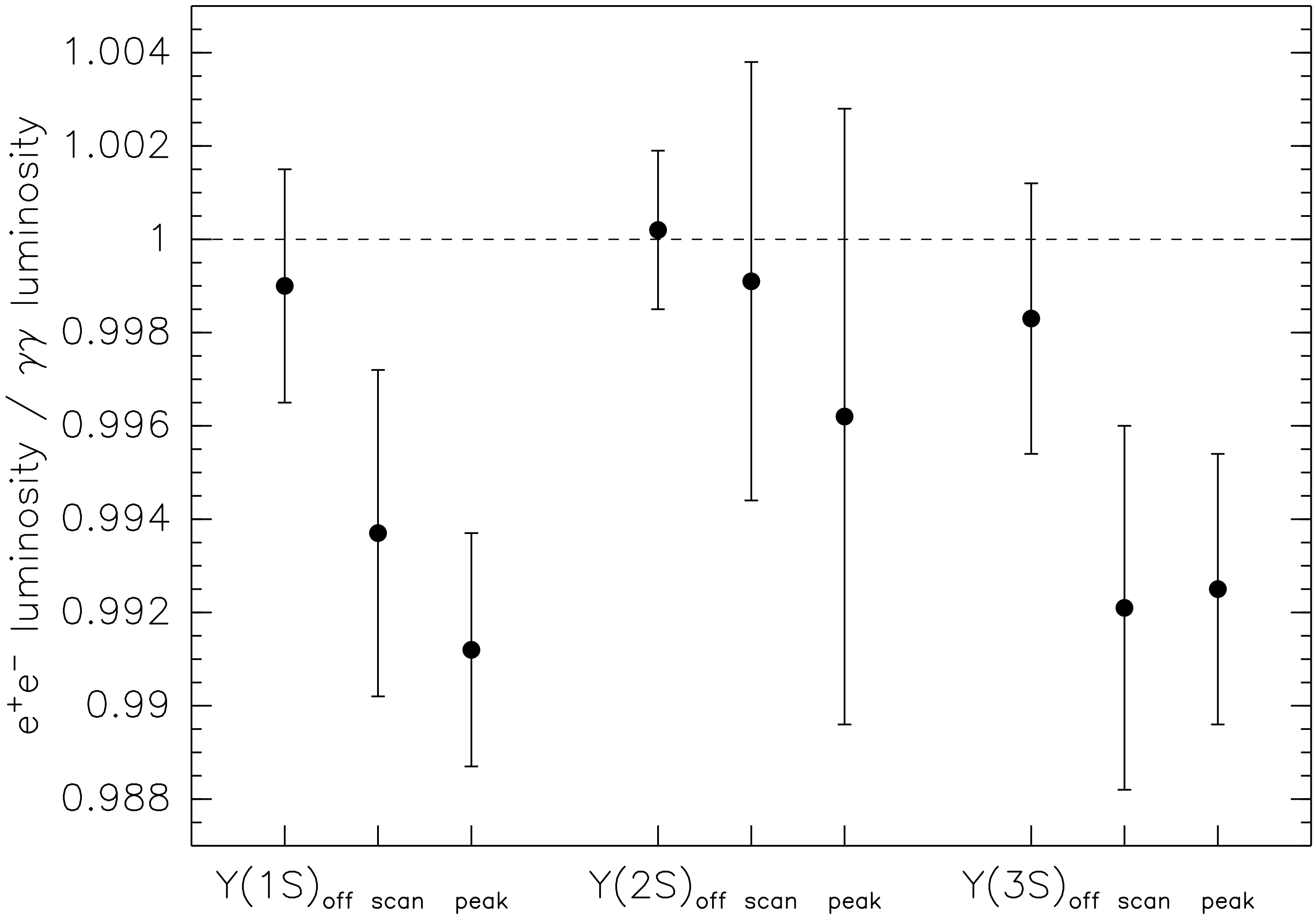


Measure integrated luminosity three ways, consistent overall scale



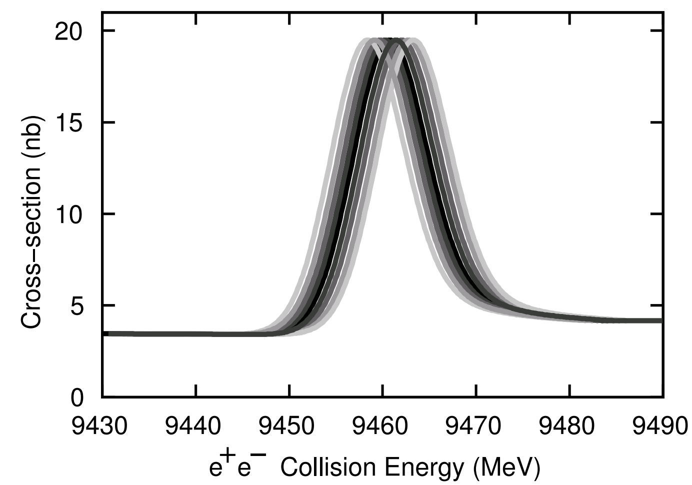
BUT, we observe a difference in $e^+e^- \to \gamma\gamma$ as a function of e^+e^- energy

Unexplained: add to systematic uncertainty



So far, we have only considered vertical uncertainties (uncertainties in cross-section)

Now we turn to the horizontal: beam energy



Beam energy is determined by magnetic field measurements in storage ring magnets

$$E_{\text{beam}} = \text{electron charge} \times \text{magnetic field} \times \text{storage ring radius}$$

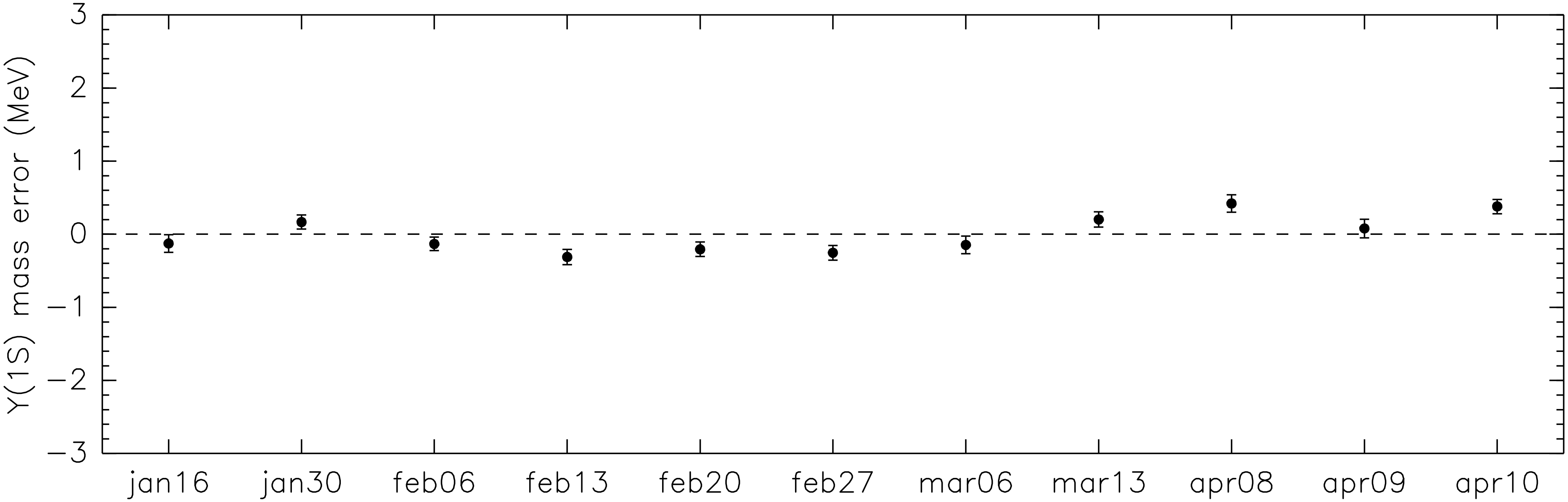
With corrections for

- RF frequency shifts
- steering and focusing magnets
- electrostatic separators

Magnetic field probe is subject to shifts: E_{beam} calibration may shift

M_Υ is known: use Υ peaks as calibrating markers in beam energy

Repeated measurements of $\Upsilon(1S)$ mass

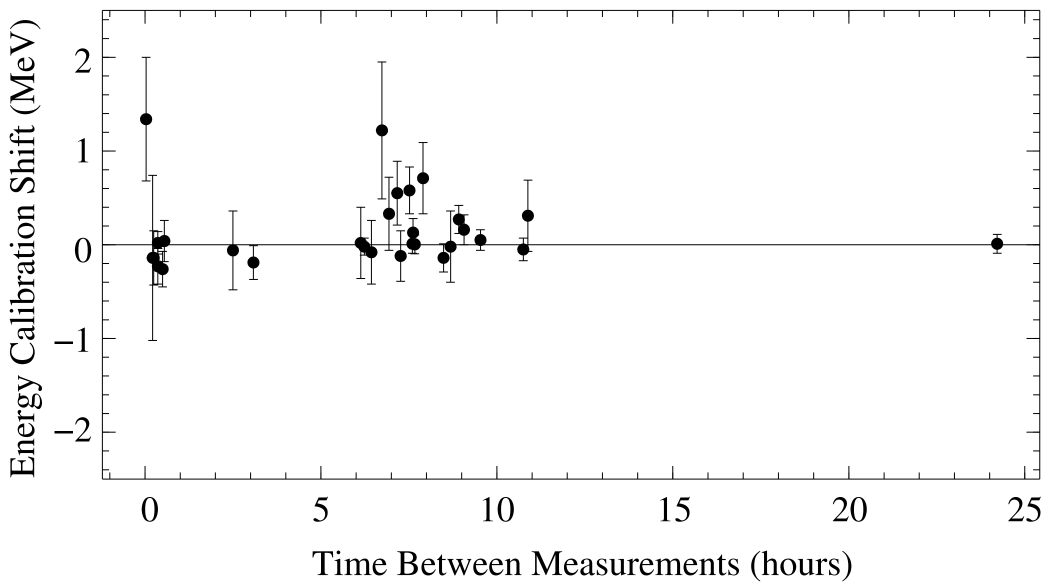


e^+e^- energy measurement drifts about 0.5 MeV/month

We limit acceptable scan data to 48-hour windows

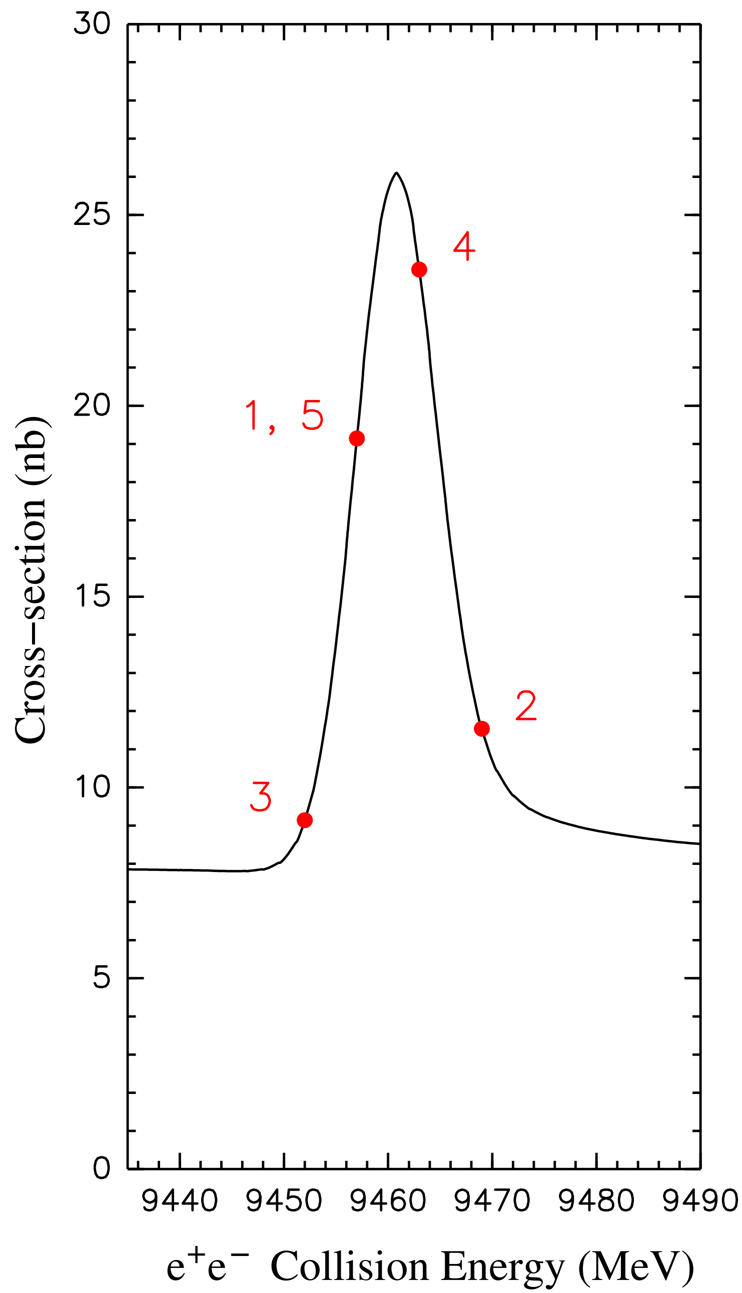
- Measurements alternated above and below resonance peak

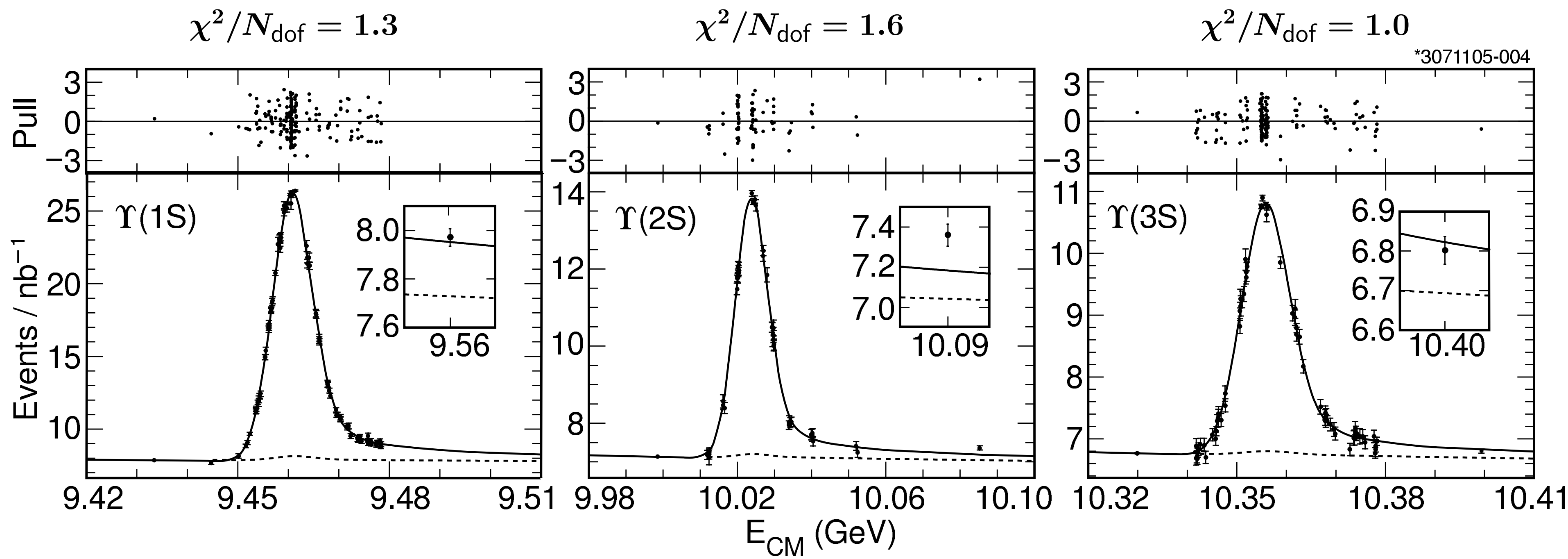
- Point of high slope repeated (1 & 5): convert cross-section reproducibility into beam energy reproducibility



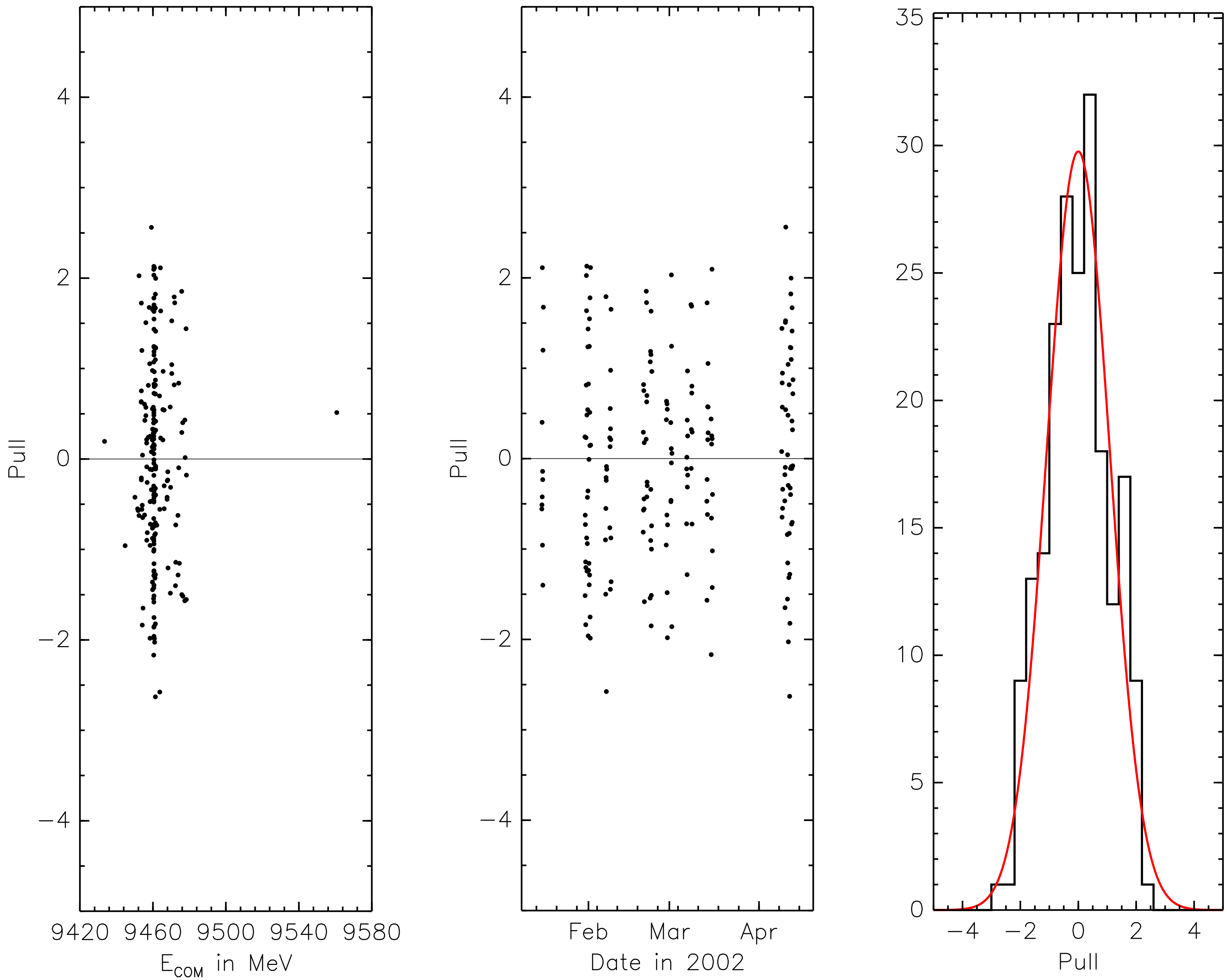
- $\Rightarrow$ 0.07 MeV uncertainty in e^+e^- energy,

  0.2% in $\mathbf{\Gamma}_{ee}$

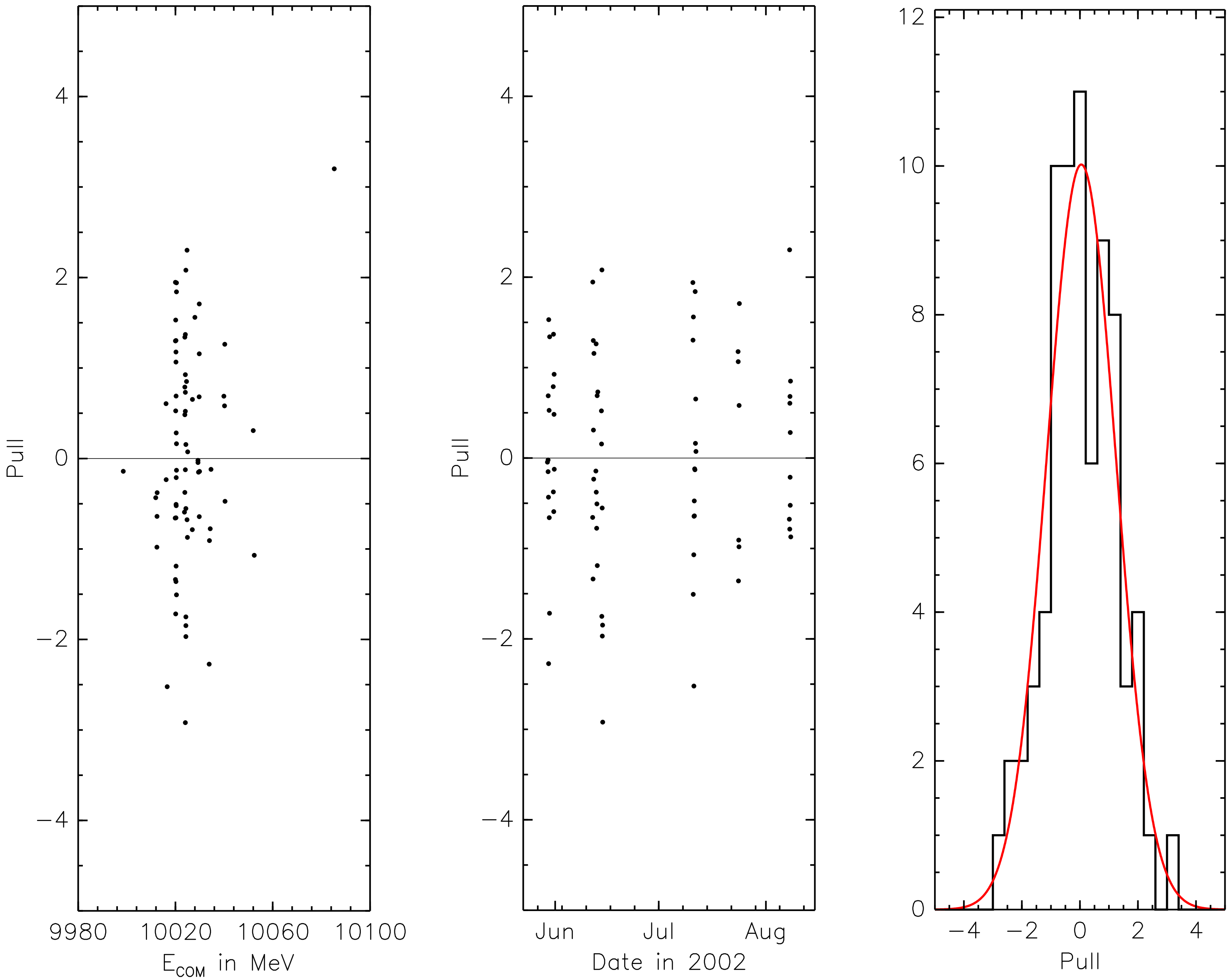




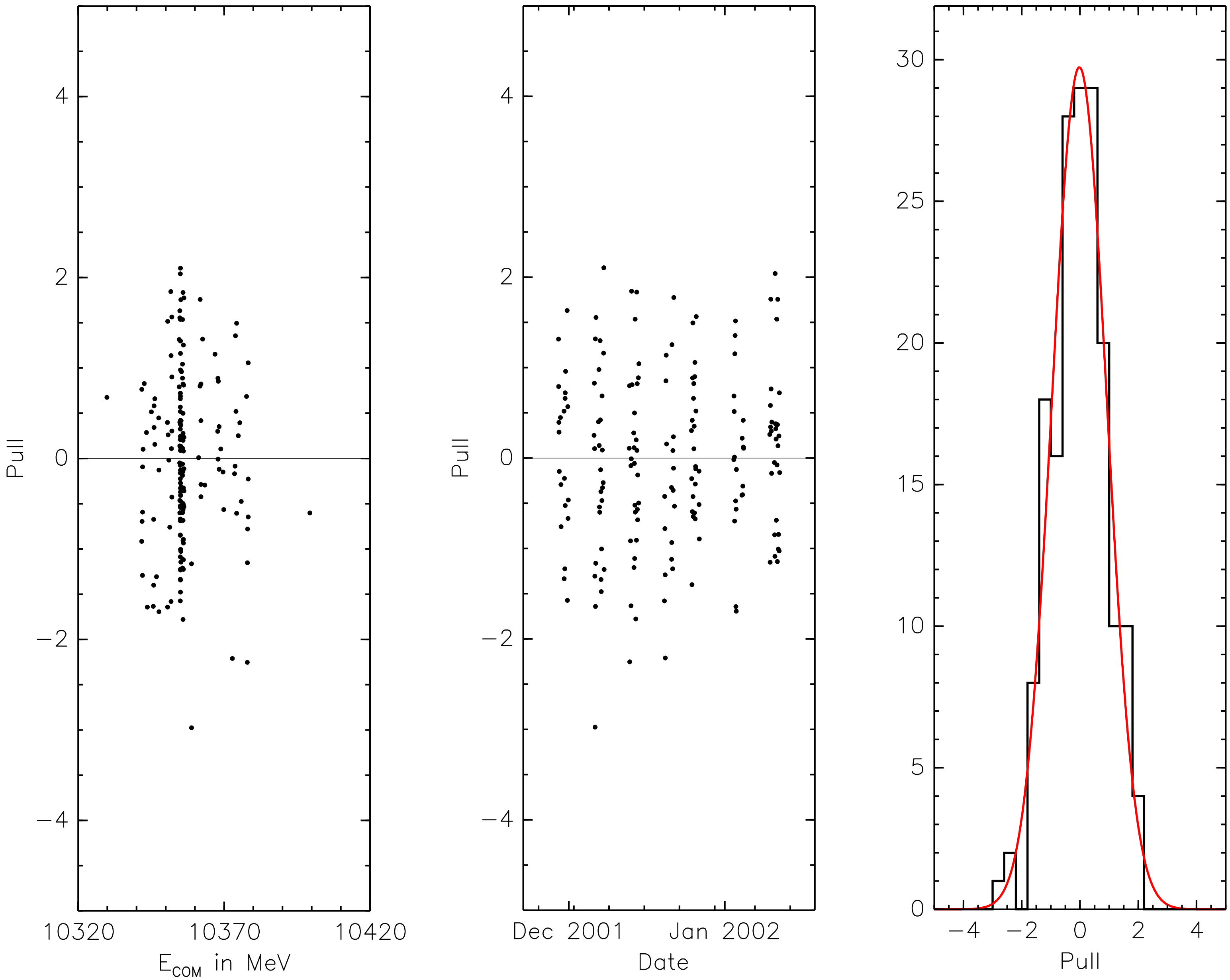
			Statistical	Systematic
$\Gamma_{ee}(1S)$	$=$	$1.354 \pm 0.004 \pm 0.020$ keV	0.3%	1.5%
$\Gamma_{ee}(2S)$	$=$	$0.619 \pm 0.004 \pm 0.010$ keV	0.7%	1.6%
$\Gamma_{ee}(3S)$	$=$	$0.446 \pm \underbrace{0.004}_{\text{stat}} \pm \underbrace{0.007}_{\text{syst}}$ keV	1.0%	1.5%



$\chi^2/N_{\text{dof}} = 240/187 = 1.3$, confidence level $= 0.5\%$



$\chi^2/N_{\text{dof}} = 107/66 = 1.6$, confidence level $= 0.1\%$



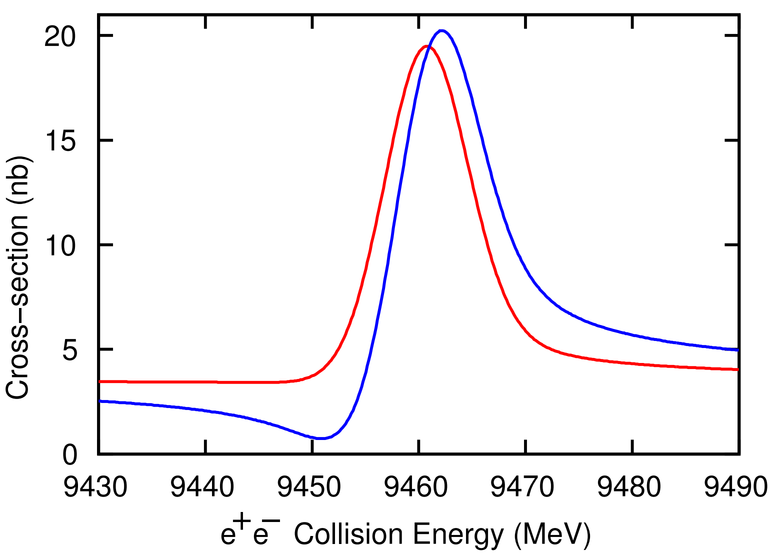
$\chi^2/N_{\text{dof}} = 155/159 = 1.0$, confidence level $= 59\%$

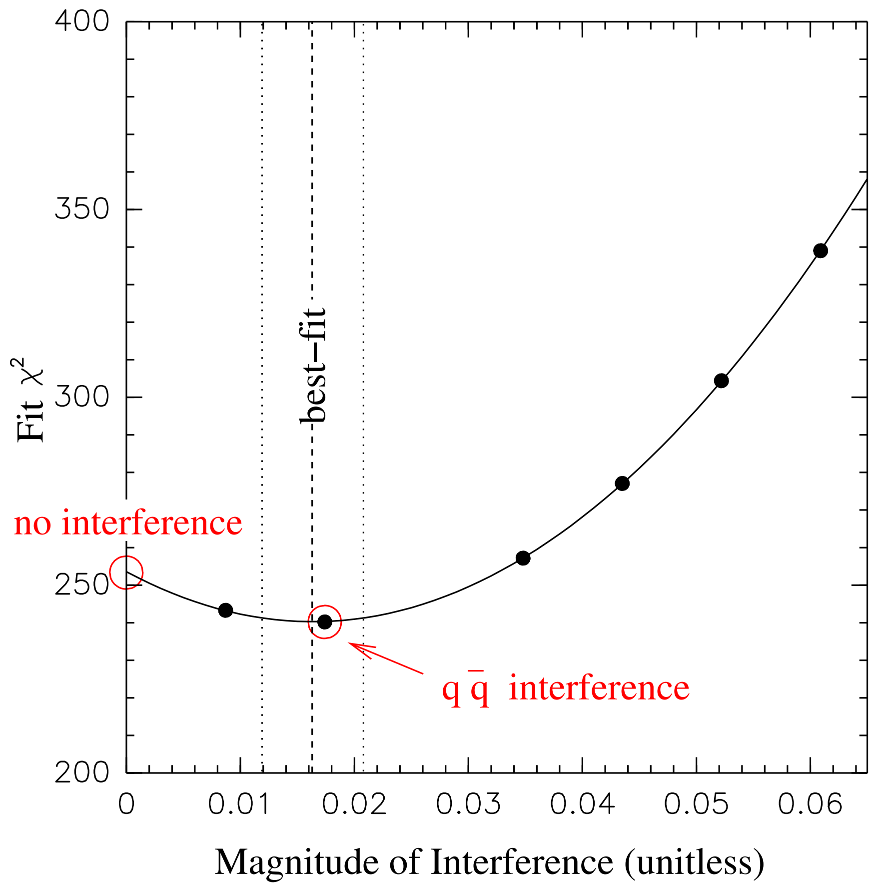
Need to consider interference between $e^+e^- \to \Upsilon \to q\bar{q}$ and $e^+e^- \to q\bar{q}$

Resonance and continuum *amplitudes* add, not cross-sections $(\sigma \propto \mathcal{A}^2)$

Phase difference cycles through resonance: destructive interference below resonance, constructive above

red: no interference
blue: exaggerated interference



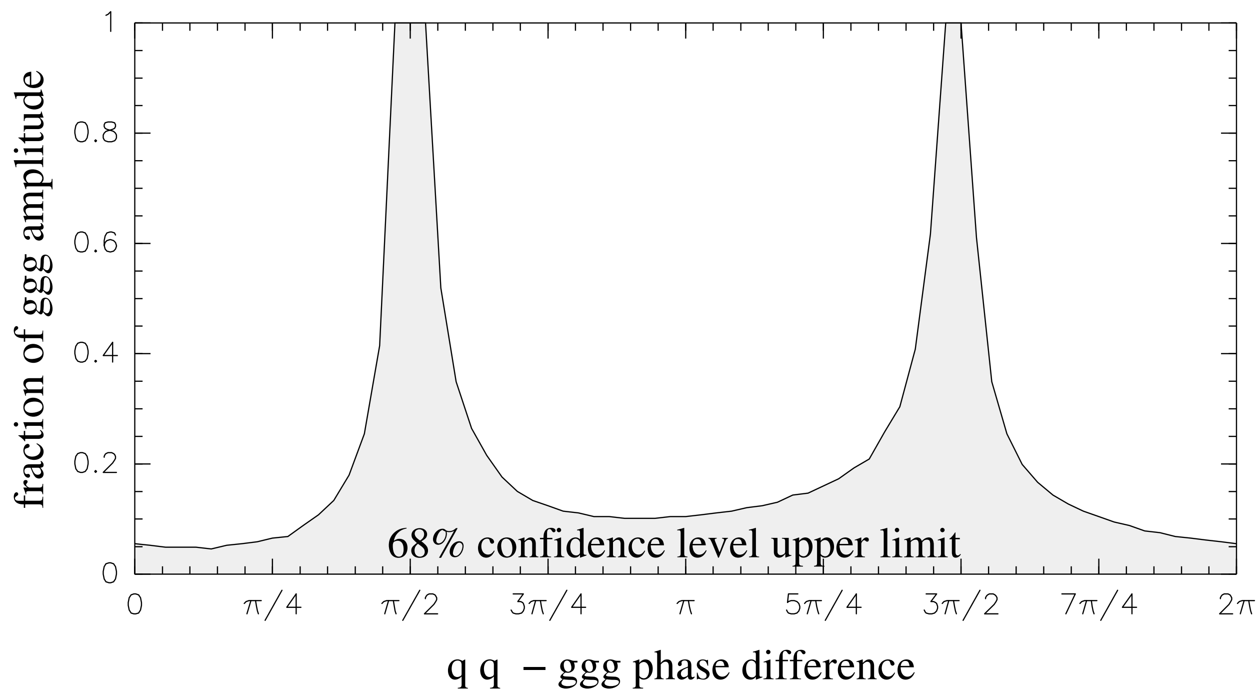


Does $q\bar{q} \longrightarrow$ hadronic interfere with $ggg \longrightarrow$ hadronic?

Exclusive final states known to interfere ("hadronic" $= \pi^+\pi^-$, K^+K^-)

Do they interfere inclusively (sum over all final states)? or do phases wash out?

Our fits provide first constraints, as a function of $q\bar{q} - ggg$ phase difference



We assume no $q\bar{q}/ggg$ interference in our $\mathbf{\Gamma}_{ee}$ fits

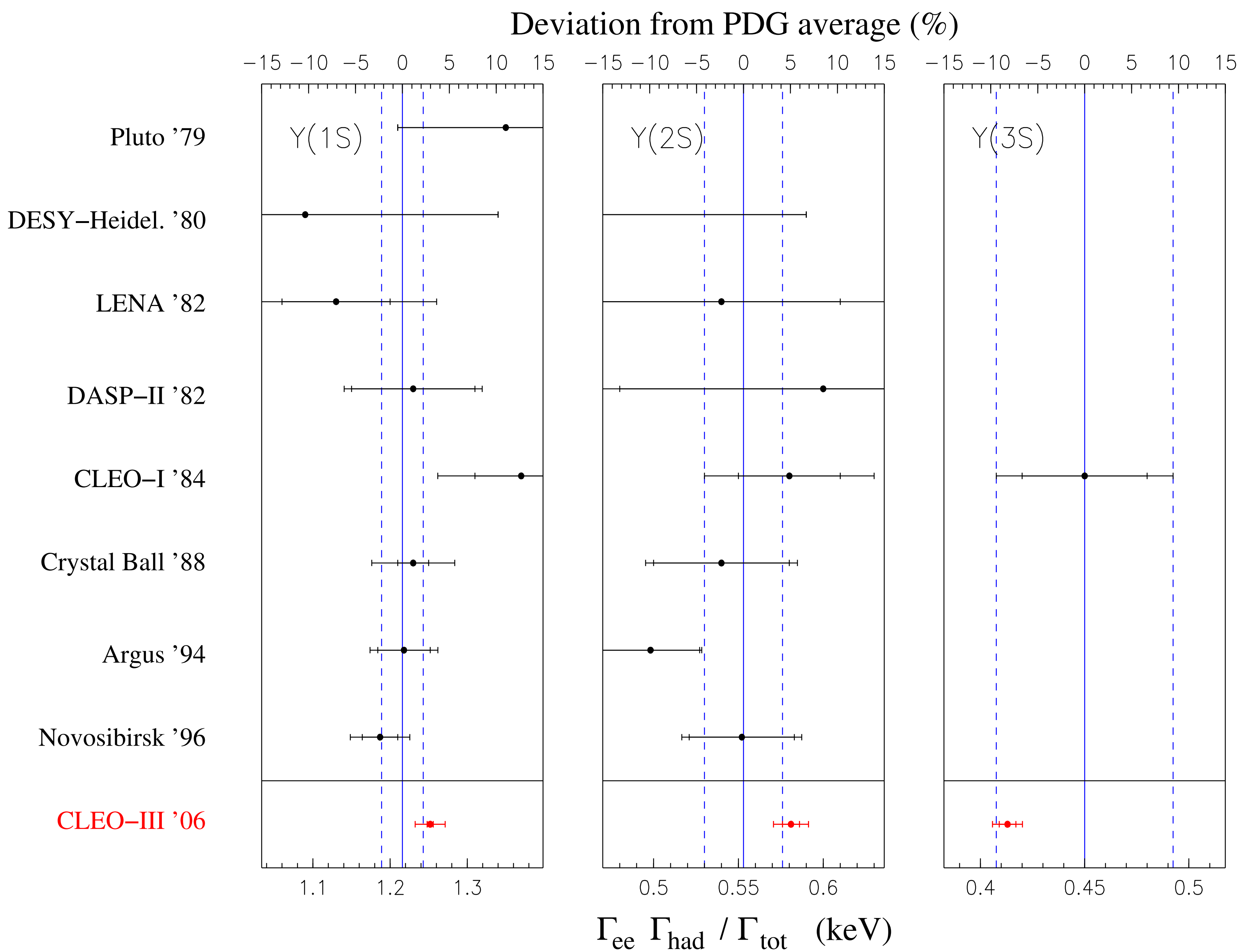
Summary of All Uncertainties

*Common to all resonances

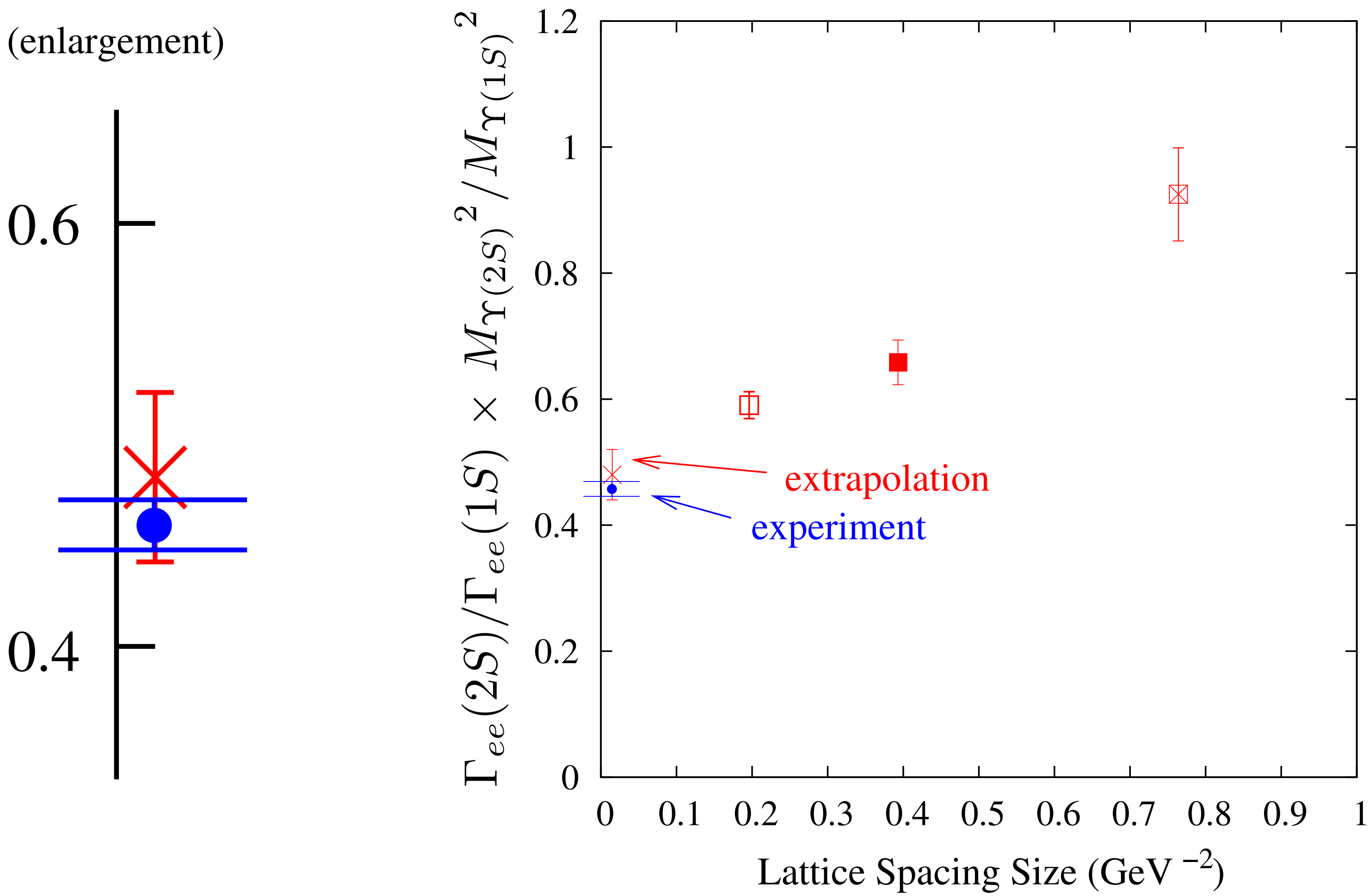
Contribution to $\mathbf{\Gamma}_{ee}$	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
Correction for leptonic modes	0.2%	0.2%	0.3%
Hadronic efficiency*	0.5%	0.5%	0.5%
Xe^+e^-, $X\mu^+\mu^-$ correction	0	0.15%	0.13%
Overall luminosity scale*	1.3%	1.3%	1.3%
Bhabha/$\gamma\gamma$ inconsistency	0.4%	0.4%	0.4%
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%

Results!

$\boldsymbol{\Gamma_{ee}(1S)}$	=	1.354 $\pm$ 0.004 $\pm$ 0.020 keV	1.5%
$\boldsymbol{\Gamma_{ee}(2S)}$	=	0.619 $\pm$ 0.004 $\pm$ 0.010 keV	1.8%
$\boldsymbol{\Gamma_{ee}(3S)}$	=	0.446 $\pm$ 0.004 $\pm$ 0.007 keV	1.8%
$\boldsymbol{\Gamma_{ee}(2S)/\Gamma_{ee}(1S)}$	=	0.457 $\pm$ 0.004 $\pm$ 0.004 keV	1.2%
$\boldsymbol{\Gamma_{ee}(3S)/\Gamma_{ee}(1S)}$	=	0.329 $\pm$ 0.003 $\pm$ 0.003 keV	1.3%
$\boldsymbol{\Gamma_{ee}(3S)/\Gamma_{ee}(2S)}$	=	0.720 $\pm$ 0.009 $\pm$ 0.007 keV	1.6%
$\boldsymbol{\Gamma(1S)}$	=	54.4 $\pm$ 0.2 $\pm$ 0.8 $\pm$ 1.6 keV	3.3%
$\boldsymbol{\Gamma(2S)}$	=	30.5 $\pm$ 0.2 $\pm$ 0.5 $\pm$ 1.3 keV	4.6%
$\boldsymbol{\Gamma(3S)}$	=	18.6 $\pm$ 0.2 $\pm$ 0.3 $\pm$ $\underbrace{0.9}_{\mathcal{B}_{\mu\mu}}$ keV	5.2%


Deviation from PDG average (%)
−15 −10 −5 0 5 10 15
Υ(1S)
Υ(2S)
Υ(3S)
Pluto '79
DESY−Heidel. '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
$\Gamma_{ee}\ \Gamma_{had}\ /\ \Gamma_{tot}$ (keV)

- Lattice QCD results are preliminary
- Final results will have few percent precision in $\Gamma_{ee}(nS)/\Gamma_{ee}(mS)$ and ~10% in $\Gamma_{ee}(nS)$



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