$e^+e^- \rightarrow D^0\overline{D}^0$ Born cross sections measurements

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OUTLINE

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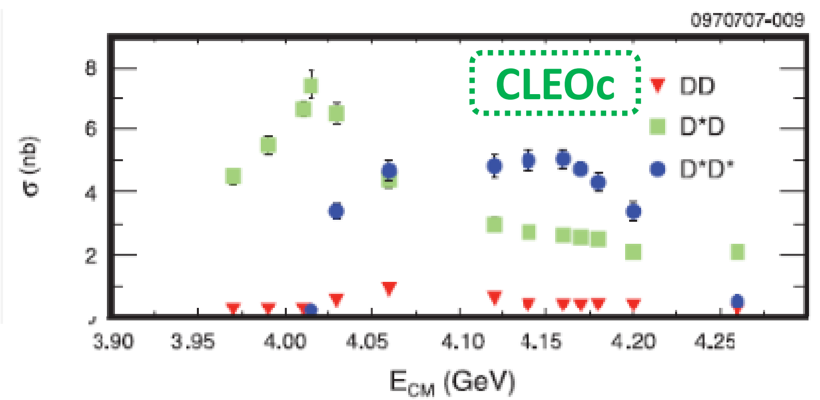
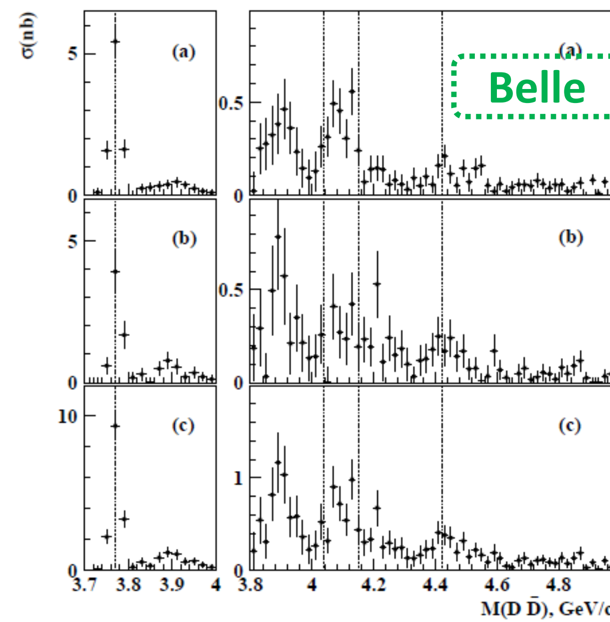
Short motivation

- Searching charmonium(-like) state in electron pairs to exclusive open-charm decays
- dressed cross sections of $e^+e^- \to D^0\bar{D}^0$ measured by Belle with ISR return method
  - low statistics



$E_{\rm cm}$ (MeV)	$\sigma(D^0\bar{D}^0)$ (pb)
3970	$86 \pm 29 \pm 4$
3990	$133 \pm 41 \pm 6$
4010	$76 \pm 25 \pm 3$
4015	< 10 (90%C.L.)
4030	$334 \pm 70 \pm 15$
4060	$410 \pm 72 \pm 18$
4120	$303 \pm 70 \pm 14$
4140	$177 \pm 40 \pm 8$
4160	$167 \pm 28 \pm 8$
4170	$177 \pm 7 \pm 8$
4180	$179 \pm 39 \pm 8$
4200	$180 \pm 55 \pm 8$
4260	$86 \pm 18 \pm 4$



- Using larger data samples collected by BESIII at BEPCII to improve the precision

Dataset and BOSS version

- Data samples
  - XYZ data sample (18 points)
  - R-can data sample(104 points)
    - See BAM-0157
- Analysis in BOSS 700

✓ Generic MC samples in BOSS 664p01

✓ Exclusive MC samples generated in BOSS 700

  ✓ 50K at each point

  ✓ $D^0 \to K^-\pi^+$

  ✓ $\overline{D}^0 \to anything$

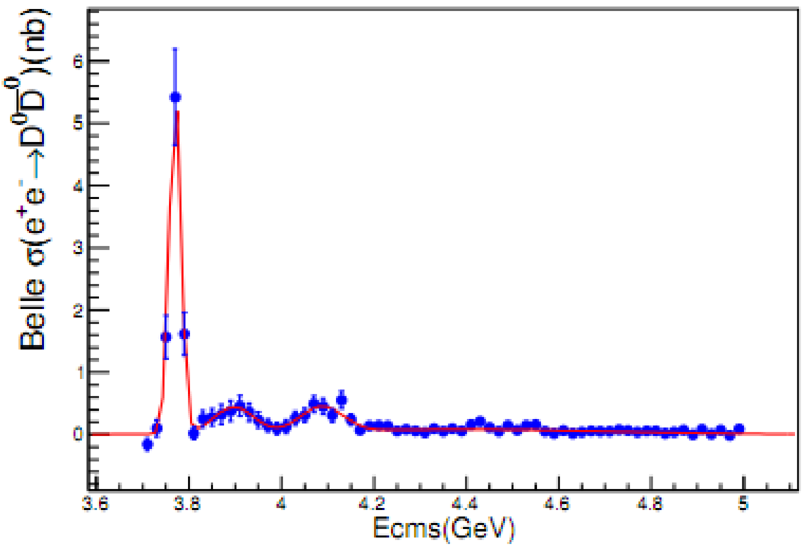
  ✓ KKMC (with ISR)+BesEvtGen

Data sample ID	weighted average E_{cms}(GeV)	$L(\mathrm{pb}^{-1})$	BOSS version
3808	$3807.65 \pm 0.10 \pm 0.58$	50.54 ± 0.03	6.6.4.p01
3896	$3896.24 \pm 0.11 \pm 0.72$	52.61 ± 0.03	6.6.4.p01
4008	$4007.62 \pm 0.05 \pm 0.66$	481.96 ± 0.01	6.6.4
4085	$4085.45 \pm 0.14 \pm 0.66$	52.63 ± 0.03	6.6.4.p01
4189	$4188.59 \pm 0.15 \pm 0.68$	43.09 ± 0.03	6.6.4.p01
4208	$4207.73 \pm 0.14 \pm 0.61$	54.55 ± 0.03	6.6.4.p01
4217	$4217.13 \pm 0.14 \pm 0.67$	54.13 ± 0.03	6.6.4.p01
4226^1	$4226.26 \pm 0.04 \pm 0.65$	44.4 ± 0.03	6.6.4.p01
4226^2		1047.34 ± 0.14	6.6.4.p01
4242	$4241.66 \pm 0.12 \pm 0.73$	55.59 ± 0.04	6.6.4.p01
4258^1	$4257.97 \pm 0.04 \pm 0.66$	523.74 ± 0.1	6.6.4.p01
4258^2		301.93 ± 0.08	6.6.4.p01
4308	$4307.89 \pm 0.17 \pm 0.63$	44.9 ± 0.03	6.6.4.p01
4358	$4358.26 \pm 0.05 \pm 0.62$	539.84 ± 0.1	6.6.4.p01
4387	$4387.40 \pm 0.17 \pm 0.65$	55.18 ± 0.04	6.6.4.p01
4416^1	$4415.58 \pm 0.04 \pm 0.72$	44.67 ± 0.03	6.6.5.p01
4416^2		1028.89 ± 0.13	6.6.5.p01
4467	$4467.06 \pm 0.11 \pm 0.73$	109.94 ± 0.04	6.6.5.p01
4527	$4527.14 \pm 0.11 \pm 0.72$	109.98 ± 0.04	6.6.5.p01
4575	$4574.50 \pm 0.18 \pm 0.70$	47.67 ± 0.03	6.6.5.p01
4600	$4599.53 \pm 0.07 \pm 0.74$	566.93 ± 0.11	6.6.5.p01

- Cross section for inputting exclusive MC productions
  - Use Belle results and fit with multi-Gaussians

$$\sigma(E_{cms}) = \sum_{i=1}^{n} A_i Gaussian(mass_i, width_i)$$

Parameters	A_i	$mass$(MeV)	$width$(MeV)
$D^0\overline{D}^0$ i = 1	5.46	3769.9	12.6
$D^0\overline{D}^0$ i = 2	0.42	3897.0	42.7
$D^0\overline{D}^0$ i = 3	0.41	4087.7	46.1
$D^0\overline{D}^0$ i = 4	0.08	4401.5	311.0



  - Use interpolation approximation (200 points in 3.81-4.6 GeV)

Born cross sections

- The Observed cross section defined as

$$\sigma^{obs} = \frac{N^{obs}}{L \times \epsilon}$$

- The Born cross section defined as

$$\sigma^{obs}(s) = \int_0^{x_{max}} dx \tilde{\sigma}(s(1-x))F(x,s), \quad \tilde{\sigma}(s) = \sigma^B(s)\frac{1}{|1-\Pi(s)|^2}$$

  – F(x,s) is the initial-state radiative factor

- To obtain Born cross sections, define ISR correction factor $(1+\delta) = \sigma_{obs}/\sigma_B$ and then

$$\sigma^{obs}(s) = \tilde{\sigma}(s) \times (1+\delta) = \sigma^B(s)\frac{1}{|1-\Pi(s)|^2}(1+\delta)$$

  – use radiator form in generator ConExc

Event reconstruction

- Single tag method
- Decay channel $D^0 \to K\pi$ to reconstruct D

- Reconstruct **one D^0 only in an event**
  - official good tracks requirement
  - Combined PID of dE/dx and TOF, P(K) > P(pi) for pion and P(pi) > P(K) for kaon
  - Loop all selected $K\pi$ combination
    - Loose requirement mass window $|m_{K\pi} - m_{D^0}| < 0.12$ GeV
    - Kpi recoiling mass > 1.7 GeV
    - choose the one has minimal $\Delta E = E_{K\pi} - E_{beam}$ as tagged D

XYZ data sample as example in analysis below

Cut flow from MC

Sample	$\|m_{K\pi} - m_{D^0}\| < 0.12$ GeV	best D	$(m_{K\pi\ recoiling} - m_{D^0}) > 1.7$ GeV	$\|m_{K\pi} - m_{D^0}\| < 0.02$ GeV	$\|m_{K\pi\ recoiling} - m_{D^0}\| < 0.075$ GeV
3808	36903/73.81%	35601/96.47%	35543/99.84%	33348/93.82%	33262/99.74%
3896	36157/72.31%	34601/95.70%	34465/99.61%	32244/93.56%	25831/80.11%
4008	35343/70.69%	33689/95.32%	33485/99.39%	31127/92.96%	20907/67.17%
4085	34926/69.85%	33118/94.82%	32900/99.34%	30216/91.84%	26446/87.52%
4189	34959/69.92%	33074/94.61%	32884/99.43%	30148/91.68%	18610/61.73%
4208	35068/70.14%	33137/94.49%	32941/99.41%	30315/92.03%	17663/58.26%
4217	35197/70.39%	33300/94.61%	33079/99.34%	30415/91.95%	17614/57.91%
4226	35204/70.41%	33257/94.47%	33055/99.39%	30269/91.57%	17327/57.24%
4242	35063/70.13%	33145/94.53%	32896/99.25%	30166/91.70%	17377/57.60%
4258	35138/70.28%	33146/94.33%	32971/99.47%	30193/91.57%	17536/58.08%
4308	34958/69.92%	32857/93.99%	32647/99.36%	29779/91.22%	17785/59.72%

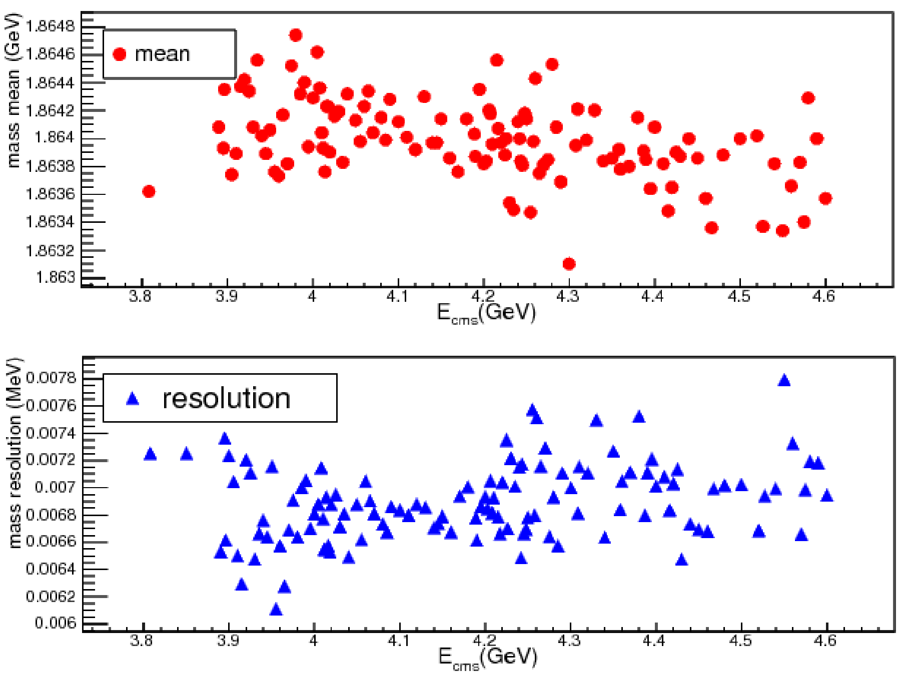
Sample	$\lvert m_{K\pi} - m_{D^0} \rvert$ < 0.12 GeV	best D	$(m_{K\pi\ recoiling} - m_{D^0})$ > 1.7 GeV	$\lvert m_{K\pi} - m_{D^0} \rvert$ < 0.02 GeV	$\lvert m_{K\pi\ recoiling} - m_{D^0} \rvert$ < 0.075 GeV
4358	35027/70.05%	32886/93.89%	32697/99.43%	29806/91.16%	18140/60.86%
4387	35084/70.17%	32947/93.91%	32717/99.30%	29773/91.00%	18428/61.90%
4416	35106/70.21%	32900/93.72%	32704/99.40%	29784/91.07%	18509/62.14%
4467	35444/70.89%	33238/93.78%	33062/99.47%	29960/90.62%	18919/63.15%
4527	34789/69.58%	32572/93.63%	32387/99.43%	29261/90.35%	18621/63.64%
4575	35359/70.72%	33000/93.33%	32837/99.51%	29675/90.37%	18864/63.57%
4600	35351/70.70%	32958/93.23%	32811/99.55%	29664/90.41%	19109/64.42%

- Best D selection efficiency decrease along Ecms

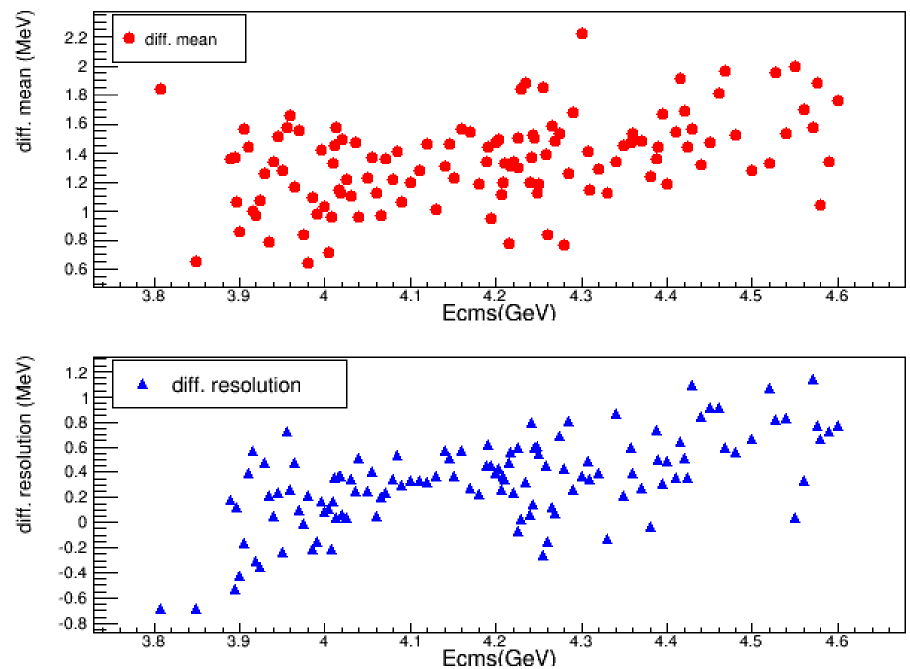
- Fitting with Gaussian and 2nd order polynomial
  - Signal window $3\sigma_{ave}$~20 MeV
  - Sidebands $6\sigma_{ave}$ to $9\sigma_{ave}$ ~40-60 MeV
- Gaussian mean for MC is ~ 1.5 MeV higher than data

Skip Rscan data 3850

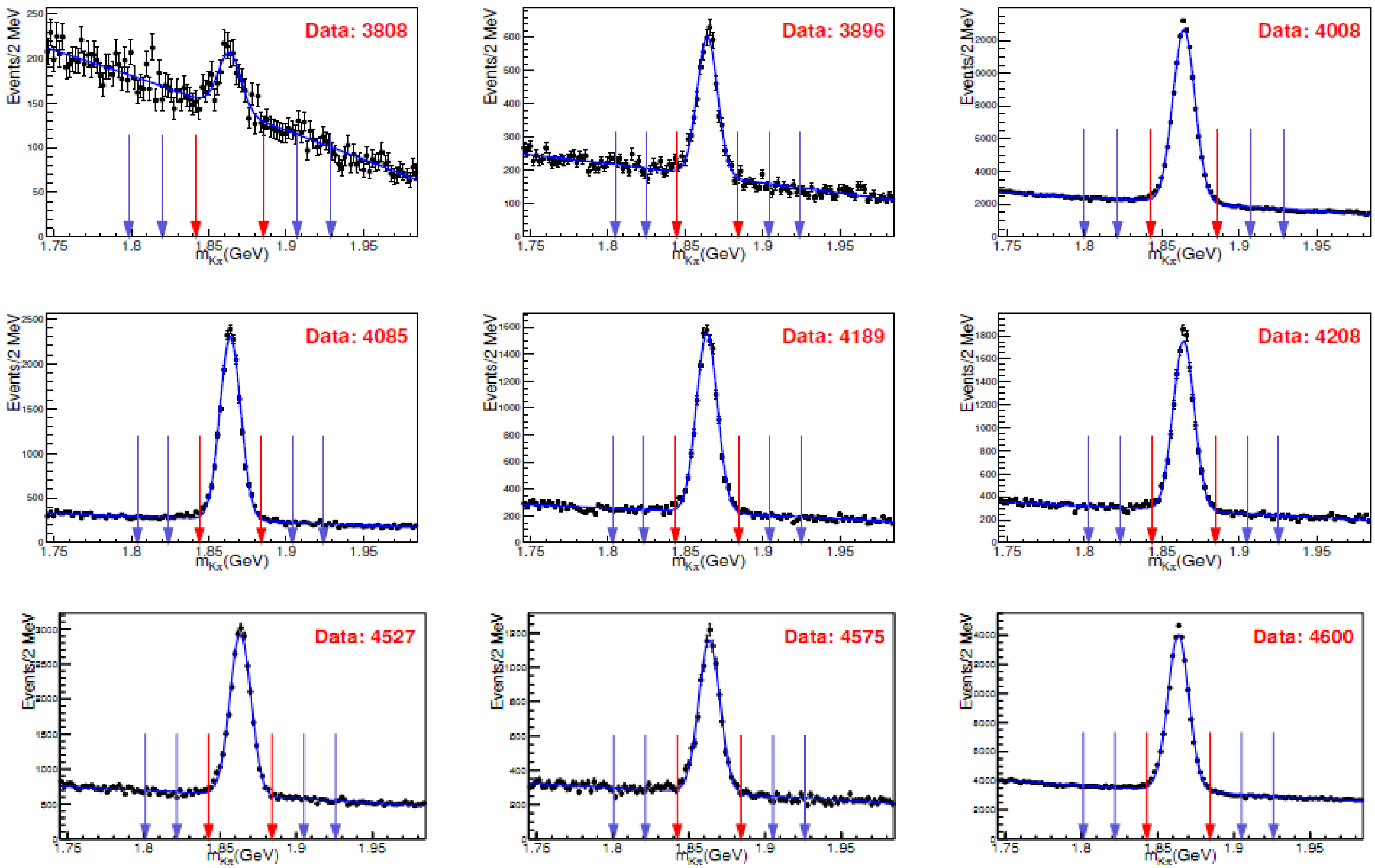
Mean and resolution of data



diff.(MC- data)

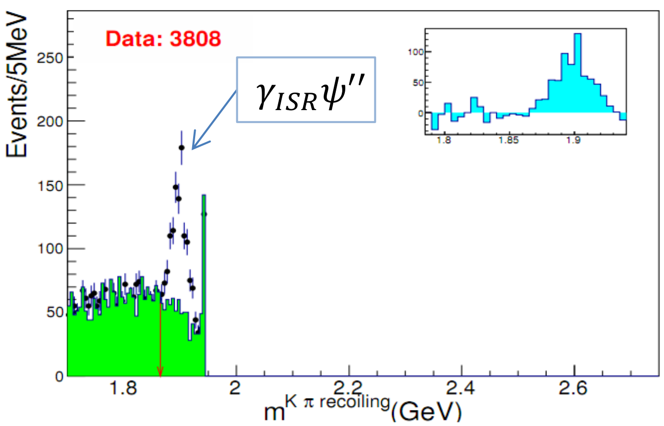


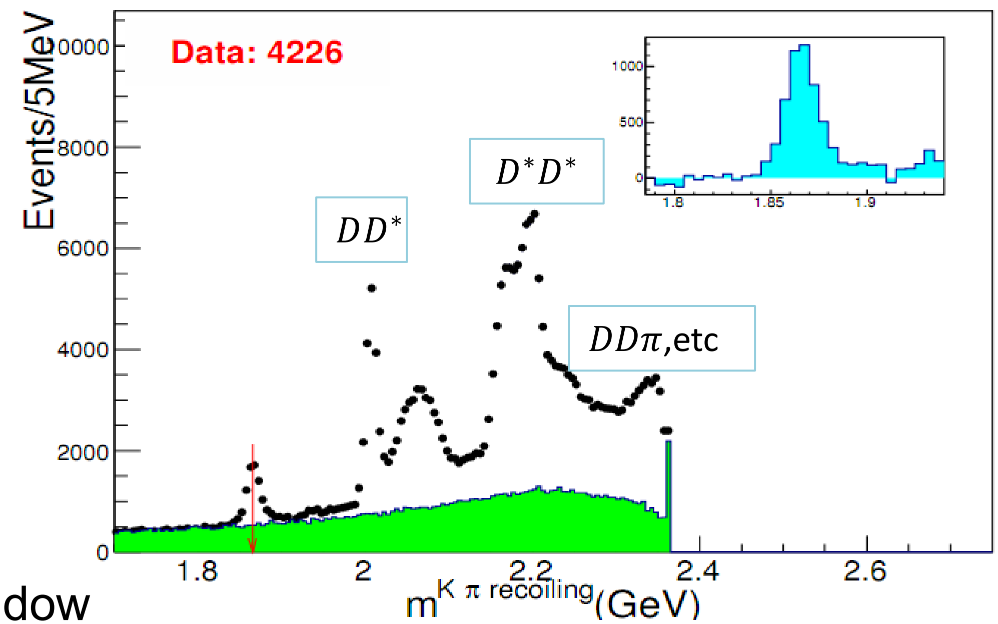
- Mass spectrum of part of XYZ data



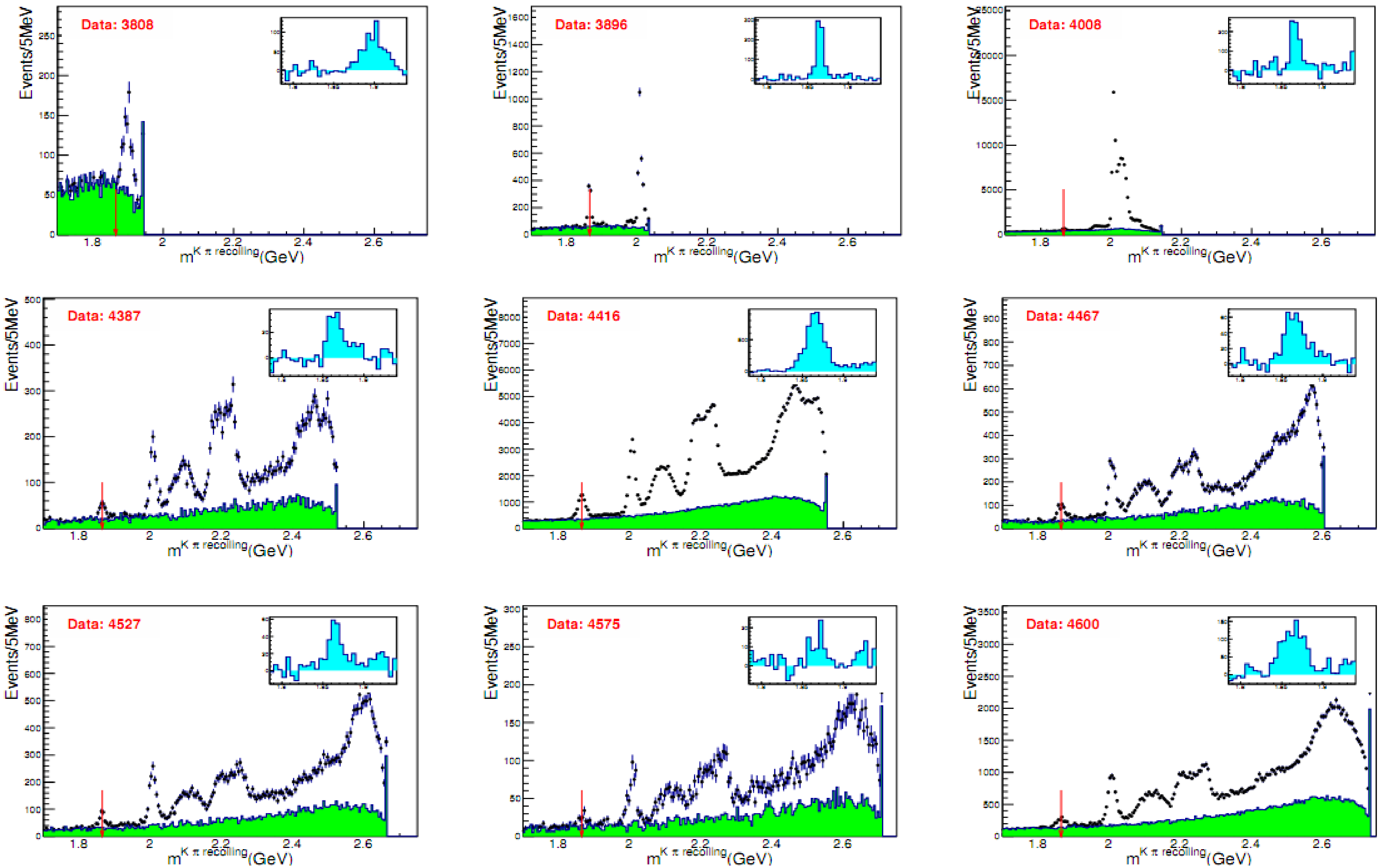
Data recoiling mass spectrum

- With mass window
- Clear peak at D0 mass
- Non peaking from sideband events
- Complicated structures mainly from **other open-charm decays**





- **Black dots**: events in mass window
- **Green histogram**: sideband events
- **Blue histogram:** sideband-subtracted in range $|m_{recoiling} - m_{D^0}| < 0.075$ GeV to make peak clear

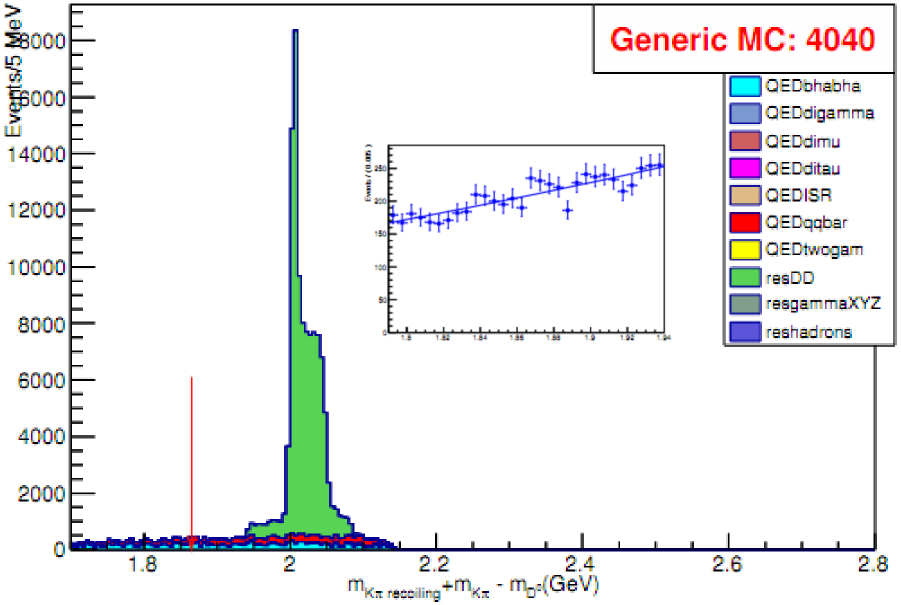


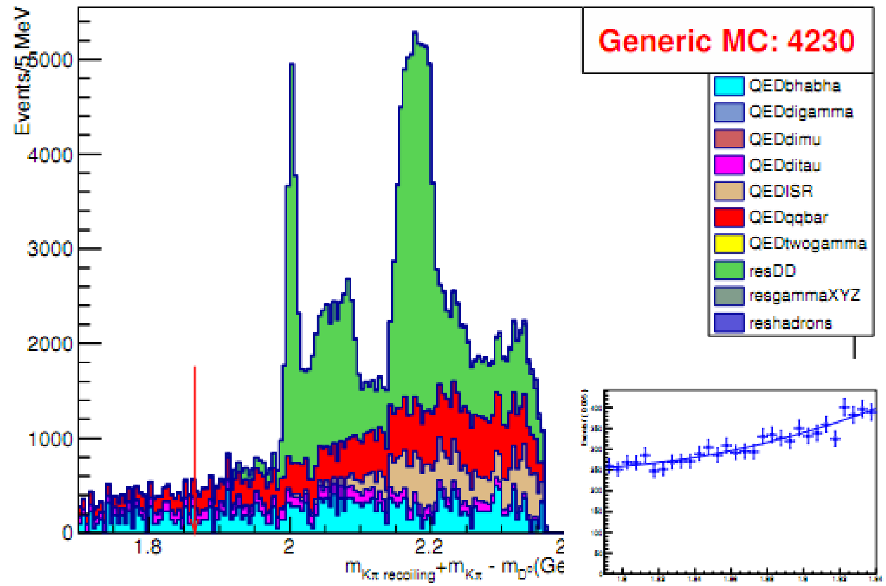
Data: 3808
Data: 3896
Data: 4008
Data: 4387
Data: 4416
Data: 4467
Data: 4527
Data: 4575
Data: 4600
Events/5MeV
m^K π recoiling(GeV)

Background study

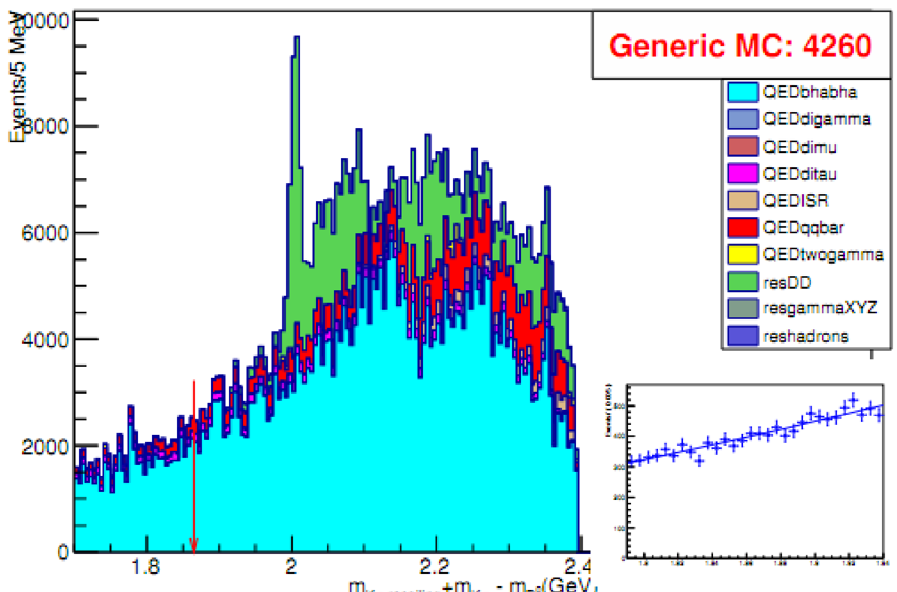
- generic MC samples at 4040, 4230, 4260, 4360
  - signal $e^+e^- \to D^0\overline{D}^0$ is subtract
  - Main background from bhabha and $q\bar{q}$ events
- Fit these backgrounds in recoiling mass
  - range $|m_{recoiling} - m_{D^0}| < 0.075$ GeV
  - Fit with 2nd order polynomial $f(x) = 1 + a_{pol}x + b_{pol}x^2$
  - Parameters of background shape changes slowly along the center-mass energy

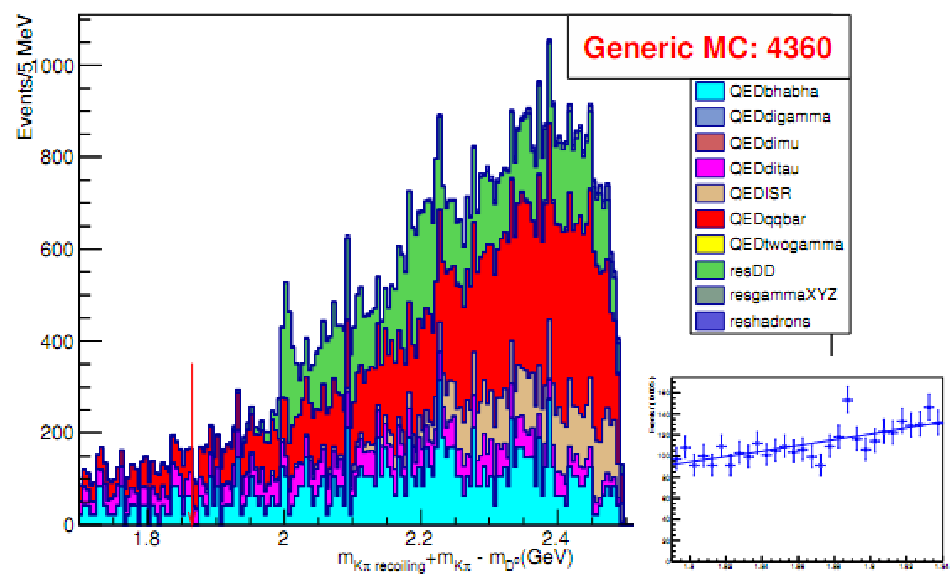
generic MC	mean(MeV)	σ(MeV)	$\chi^2/d.o.f$	a_{pol}	b_{pol}
4040	1865.52	6.27	0.84	-2.08	1.00
4230	1865.48	6.36	0.63	-1.12	0.32
4260	1865.37	6.34	0.75	-2.11	0.98
4360	1865.40	6.44	0.86	-2.04	1.01





- range $|m_{recoiling} - m_{D^0}| < 0.075$ GeV



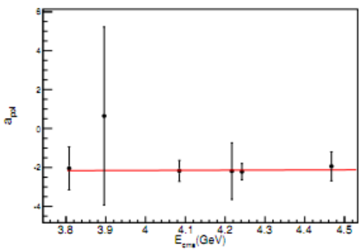


Signal extraction

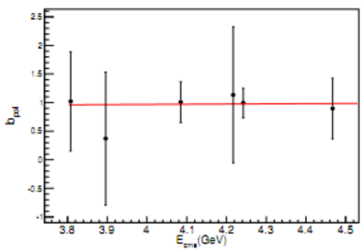
- Fitting on recoiling mass
  - Events in mass window
  - MC shape convoluted with Gaussian function as signal shape
  - 2nd order polynomial as background shape
- Use XYZ data samle to determine the fit parameters

- The background is fixed by benchmark energy points
  - Fit with a straight line to parameters
  - Use fit above as fixed background shape

$$f(x) = 1 + a_{pol}x + b_{pol}x^2$$



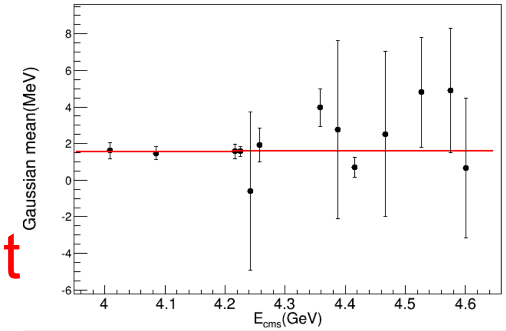
a_{pol}

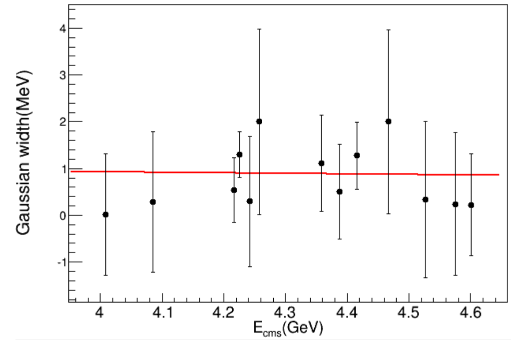


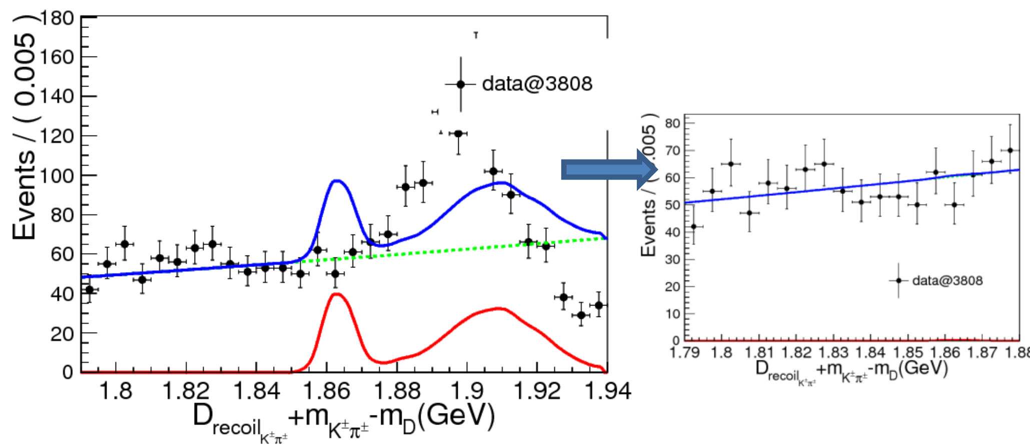
b_{pol}

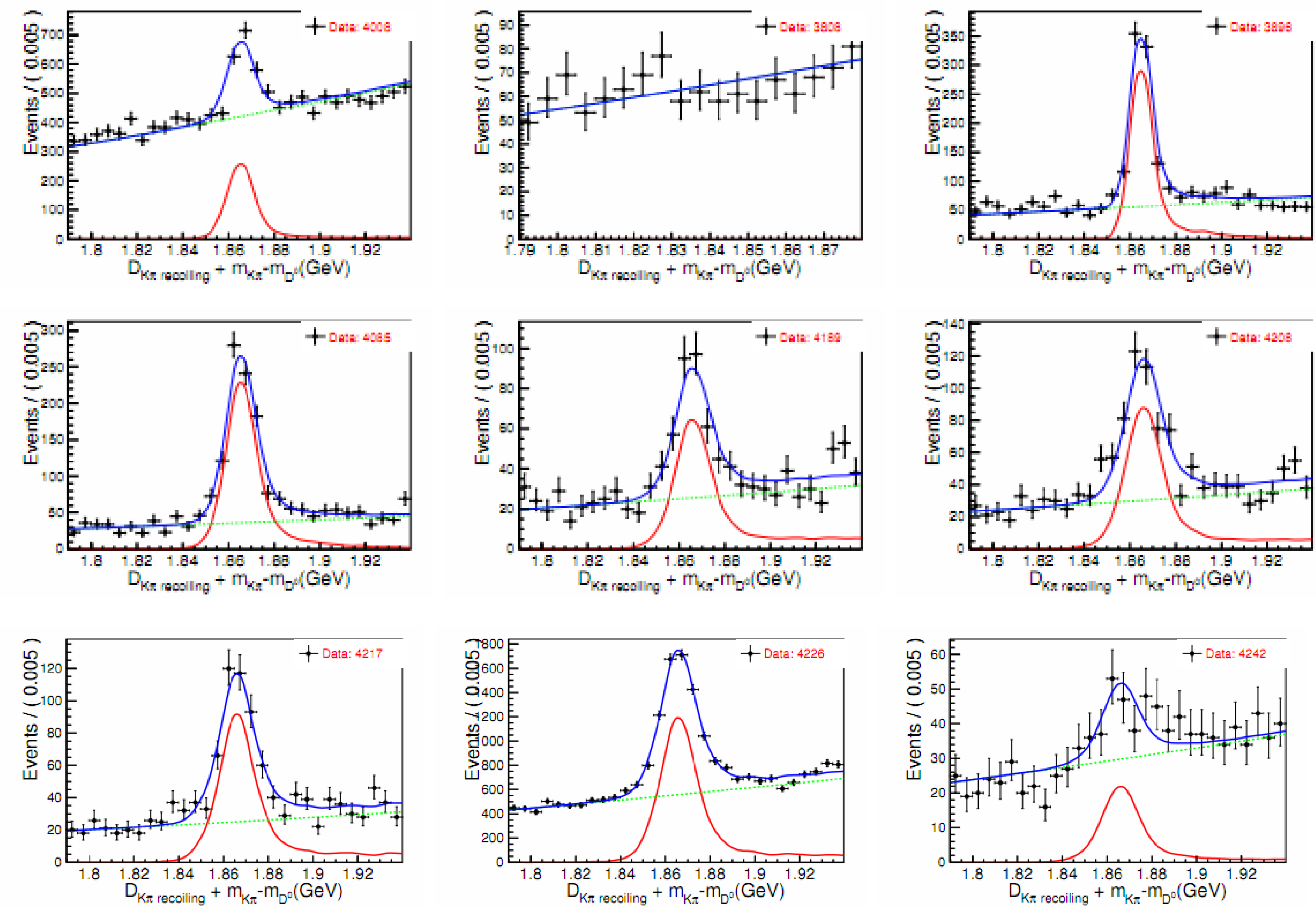
- Then fix the Gaussian
  - Linear assumption

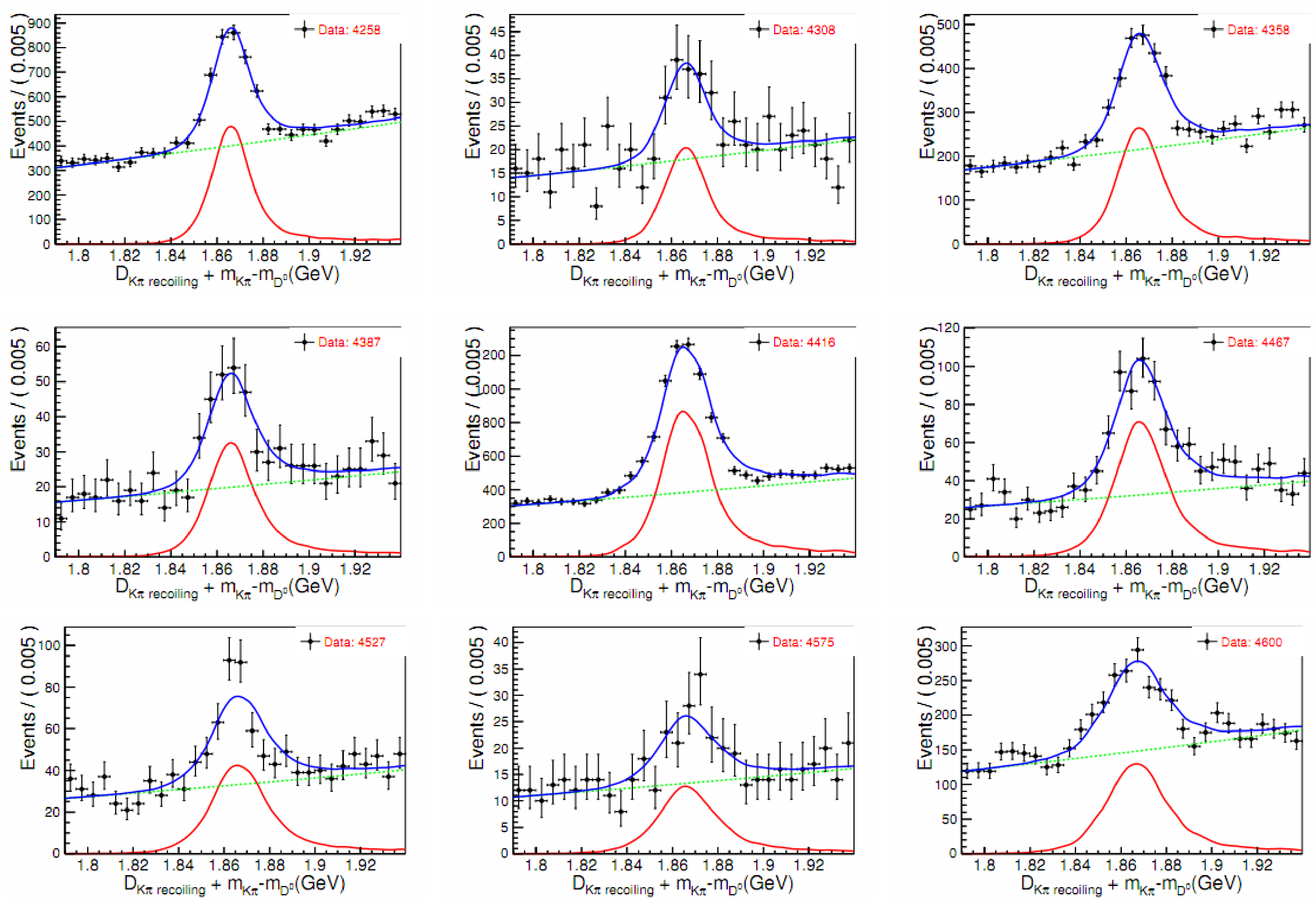
- Special fit range for point 3808 [1.785,1.880] GeV to exclude ISR to ψ''








Events / (0.005)
D$_{K\pi\ recoiling}$ + m$_{K\pi}$-m$_{D^0}$(GeV)
Data: 4217
Data: 4226
Data: 4242

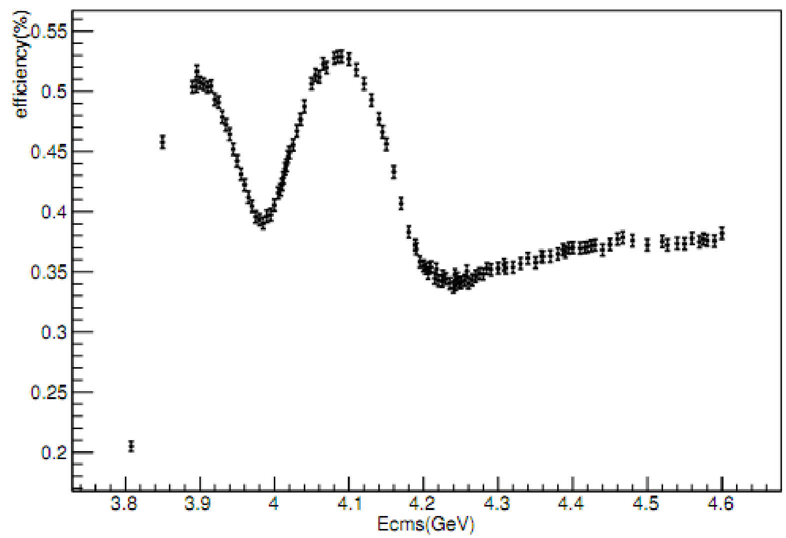

Data: 4258
Data: 4308
Data: 4358
Data: 4387
Data: 4416
Data: 4467
Data: 4527
Data: 4575
Data: 4600
Events / (0.005)
D_{Kπ recoiling} + m_{Kπ}-m_{D^0}(GeV)

Reconstruction efficiency

- efficiency including from exclusive MC sample
  - Tracking, PID efficiency
  - Tagged D mass window, recoiling mass range requirements
  - Signal extraction in fitting
- Performing the same selection criteria of data

- $Br(DX) = 2Br(K\pi) - Br^2(K\pi)$, $Br(K\pi) = Br(D^0 \to K\pi)$

✓ the efficiency is related to the ISR effects of the MC samples, do iterations on Born cross sections



The iteration procedure

- With initial $\boldsymbol{\sigma_B}$ (Belle's as approximation)
  - Generate MC samples with $\boldsymbol{\sigma_B}$ input and get the efficiency $\boldsymbol{\epsilon}$
  - Calculating $\boldsymbol{\sigma_{obs}}$ from formula and get $(\mathbf{1}+\boldsymbol{\delta}) = \boldsymbol{\sigma_{obs}}/\boldsymbol{\sigma_B}$ from formula (from BesEvtGen/ConExc)

$$\sigma^{obs}(s) = \int_0^{x_{max}} dx \tilde{\sigma}(s(1-x))F(x,s), \quad \tilde{\sigma}(s) = \sigma^B(s)\frac{1}{|1-\Pi(s)|^2}$$

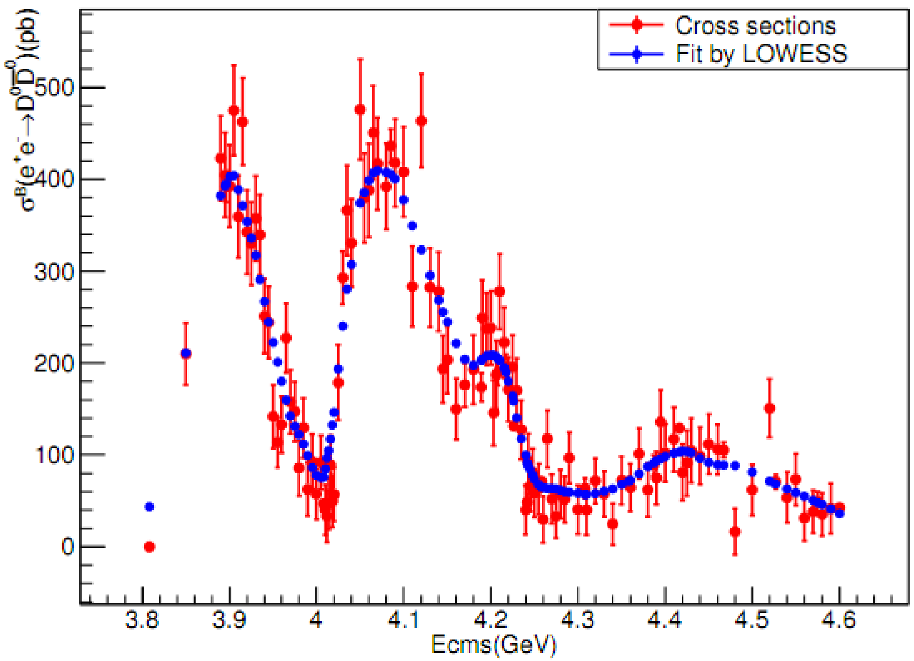
  - Then using data collected, get a new $\boldsymbol{\sigma_B}$ from

$$\sigma^B = \frac{N^{obs}}{L \times \epsilon_{DX} Br_{DX} \times (1+\delta^v) \times (1+\delta)}$$

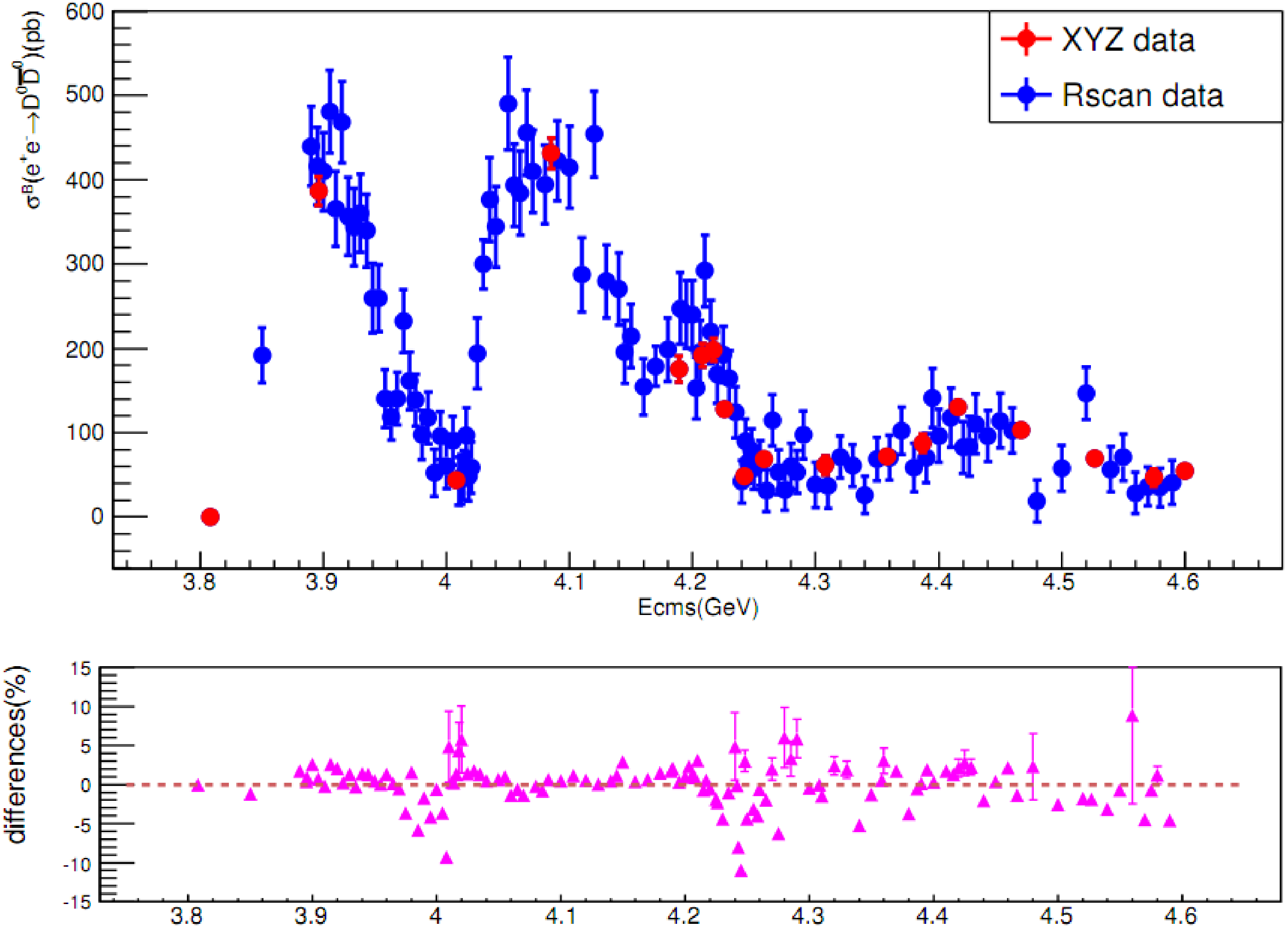
- Do iterations on Born cross sections until the differences are tolerable
  - Notice that the $\sigma_B(s)$ is fit by model-independent method Local Weighted Regression for MC sample generation

- LOWESS fit
  - degree-1 polynomial fit on each point with subset with fraction 0.15 to full set
  - points are cubic-weighted by distance fraction to farest one

$$w(x) = (1 - |x|^3)^3 (\text{for } |x| < 1)$$



- The third iteration and relative difference to last one, error bars statistical only



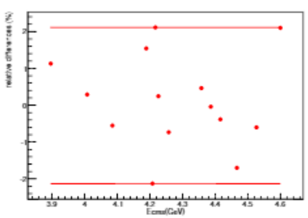
Systematic uncertainty

- **Luminosity** 1% (official)
- **Branching ratios** of $D^0 -> K\pi$ 1.1% (PDG2016)
- **Reconstruction efficiency**
  - Tracking 2% per track
  - PID 1% per track
  - Mass window, change 20 MeV to 18 MeV, use the differences on cross sections
  - Recoiling mass range, change range $|\mathrm{m}_{\mathrm{recoiling}} - \mathrm{m}_{\mathrm{D}^0}| < 0.075$ GeV to 0.070 GeV, use the differences on cross sections
- **Fitting model**
  - For Fixed method: let one parameter a_{pol}/ b_{pol}/mean/width free, use the changes of signal events
- **Iteration of cross sections**
  - Differences between last two iterations for each point

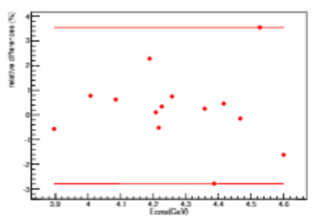
Systematic uncertainty

- For mass window, recoiling mass range, fit model, Use XYZ data samples only with number of signal events >120 and used for R-scan data sample
- Relative differences below

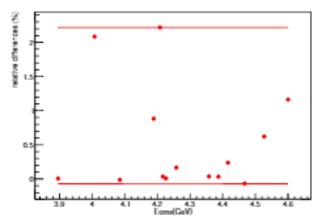
$$\Delta_{a_{pol}} = ^{+1.8\%}_{-0.3\%} \quad \Delta_{b_{pol}} = ^{+1.8\%}_{-0.4\%} \quad \Delta_{mean} = ^{+2.2\%}_{-0.1\%} \quad \Delta_{width} = ^{+1.1\%}_{-0.2\%}$$



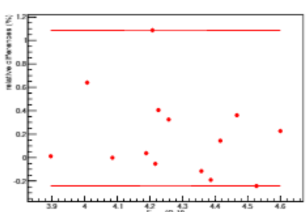
(a)D^0 mass window



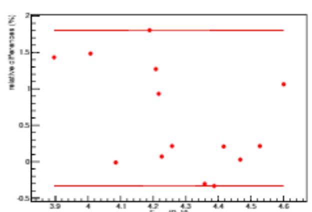
(b)D^0 recoiling mass window



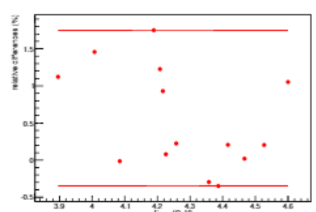
(c)Gaussian *mean*



(d)Gaussian *width*



(e)a_{pol}

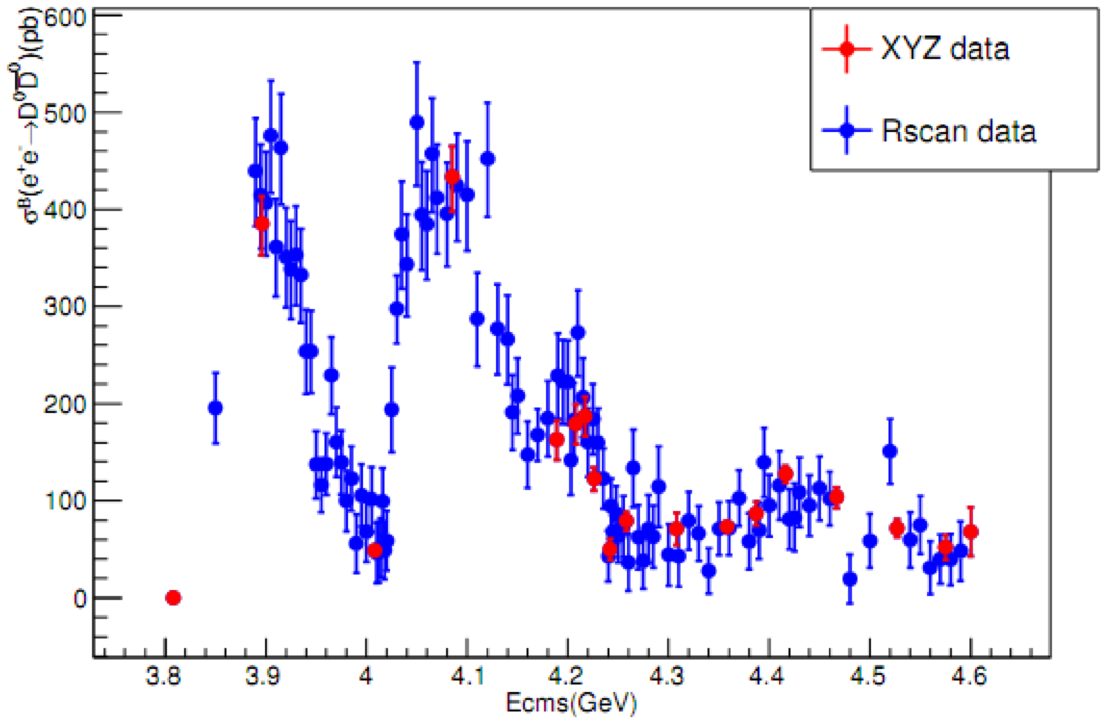


(f)b_{pol}

resources	relative uncertainty(%)
luminosity	1.0
branching ratio	1.1
tracking	4.0
PID	2.0
D^0 mass window	2.1
D^0 recoiling mass window	$^{+3.5}_{-2.8}$
Fixed fit	$^{+3.5}_{-0.6}$
iterations	RMS=3.4
Total	$^{+7.9}_{-6.8}$

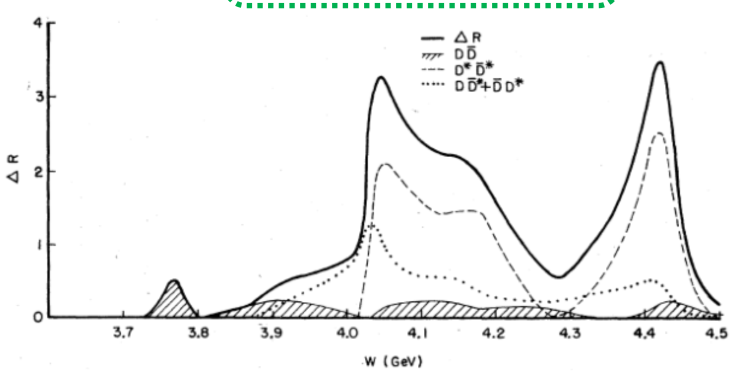
Results

- Lineshape with both statistical and systematic uncertainty combined

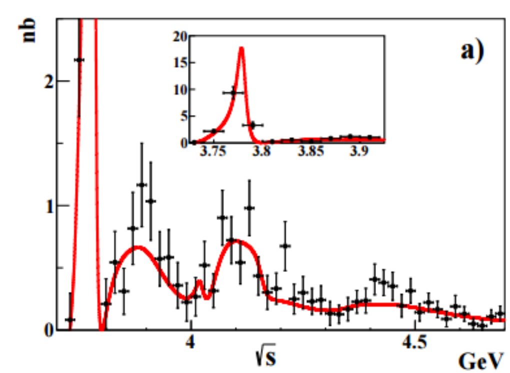


- Coupled-channel model to data of Belle

PRD21,203(1980)



arXiv: 1611.07582v1

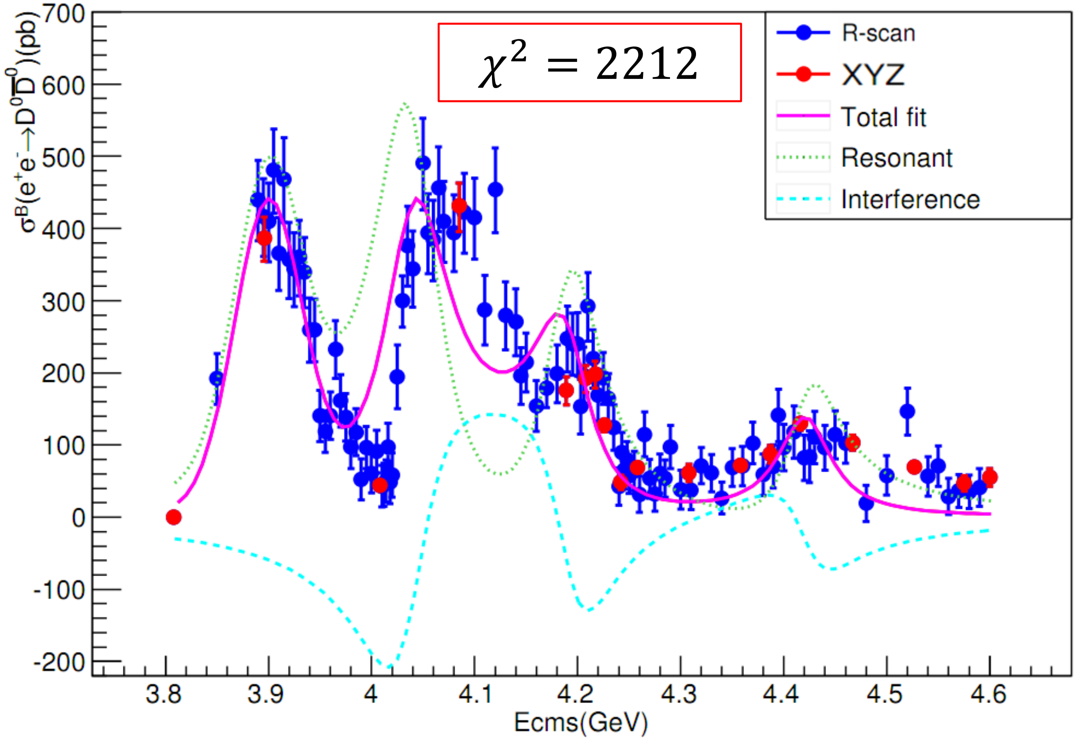


Naïve fits

- Fit with four charmonium states and use Gaussian for 3.9 GeV

$$BW(E_{cms}, M, \Gamma) \propto \frac{1}{E_{cms}^2 - M^2 + iM\Gamma}$$

$$\sigma(E_{cms}) = |\Sigma A_i BW_i e^{i\delta_i}|^2 + A_G Gaussian(mean, width),\ \ i = 1, 2, 3$$



Failed

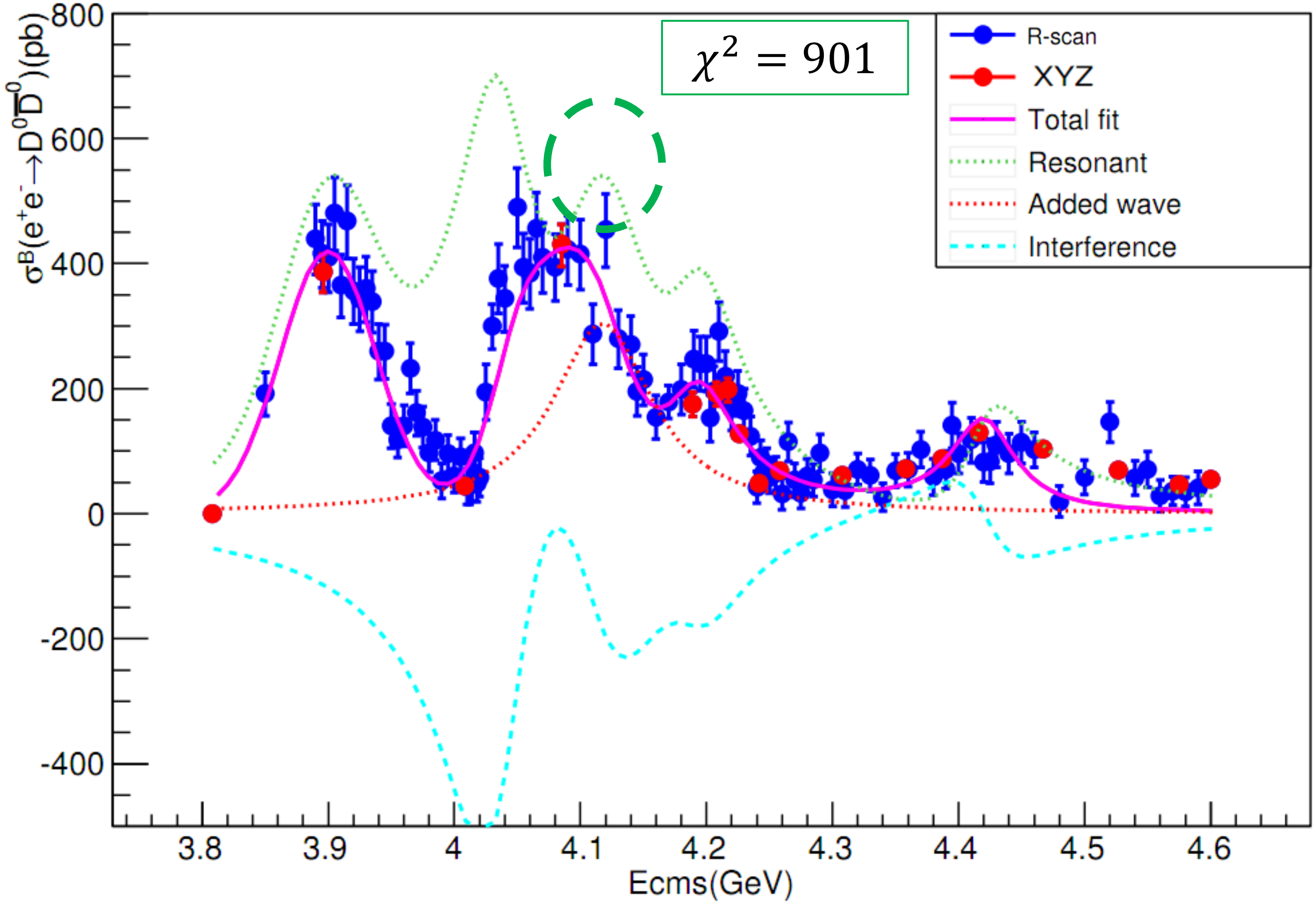
Try to add a resonant

$$\sigma(E_{cms}) = |\Sigma A_i BW_i e^{i\delta_i}|^2 + A_G Gaussian(mean, width),\ i = 1,2,3,4$$

- Fix Gaussian mean to be 3.9 GeV and width 38 MeV from fit above

$$\delta_1 = -5^\circ \pm 20^\circ,\ \delta_2 = 38^\circ \pm 27^\circ,\ \delta_3 = 158^\circ \pm 30^\circ,\ \delta_4 = 0^\circ,$$

$$M_4 = 4117.7 \pm 6.0\ \mathrm{MeV},\ \Gamma_4 = 96 \pm 10\ \mathrm{MeV}.$$

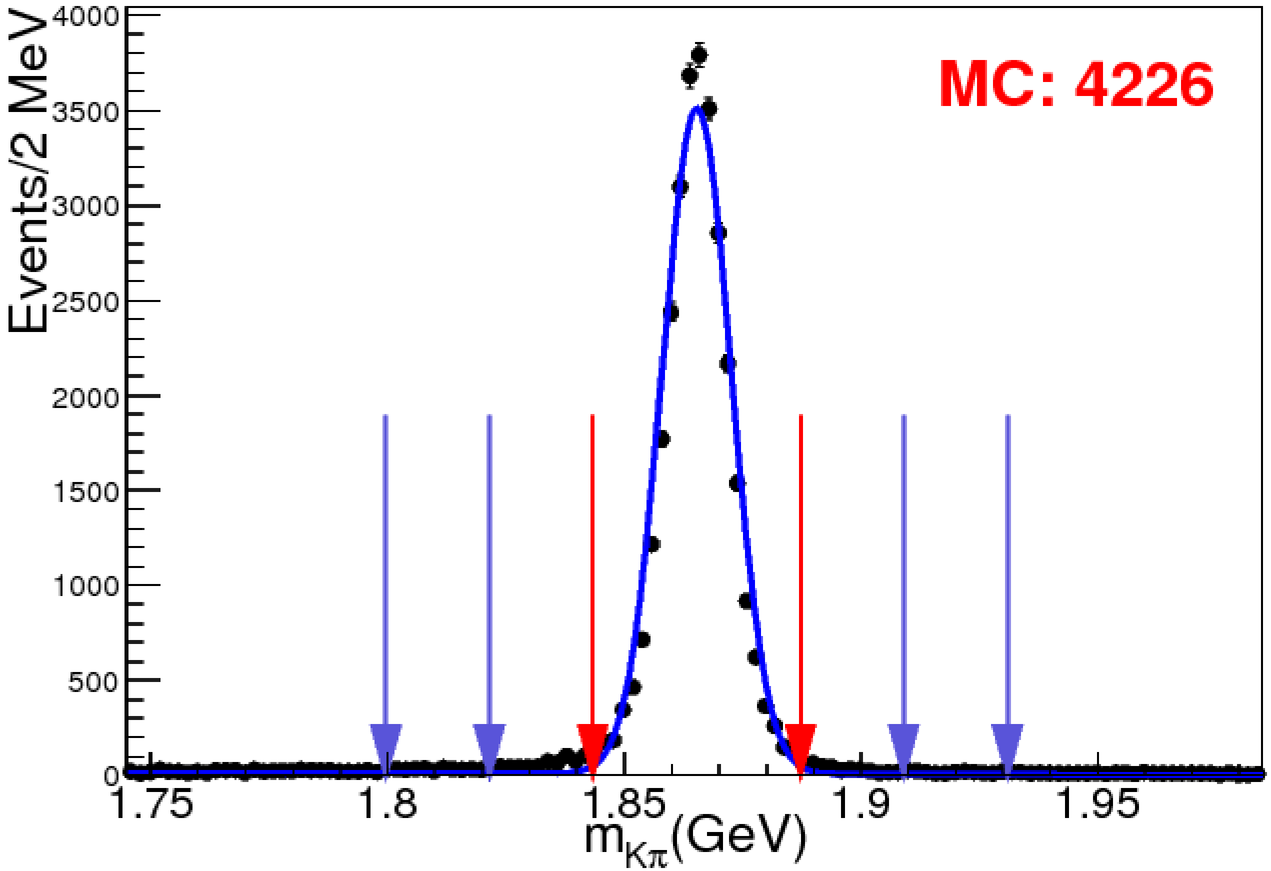


Next to do

- Measure lineshape of $e^+e^- \to D^+D^-$
- Estimate the systematic uncertainties from signal shape and background shape

Back-up

MC mass spectrum



LOWESS fitting

- Local Weighted Regression(LOWESS) fitting
  - Model independent
  - For every fit point, Use $f \times N_{total}(f < 1)$ data points instead of all points around fitted points
  - F=0.15, Cubic weighted 1st order fitting in this analysis