Dark photon search via $D^{*0} \to D^0 A'$ in Belle experiment

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2025/6/23-27
Belle II Summer Workshop 2025

Outline

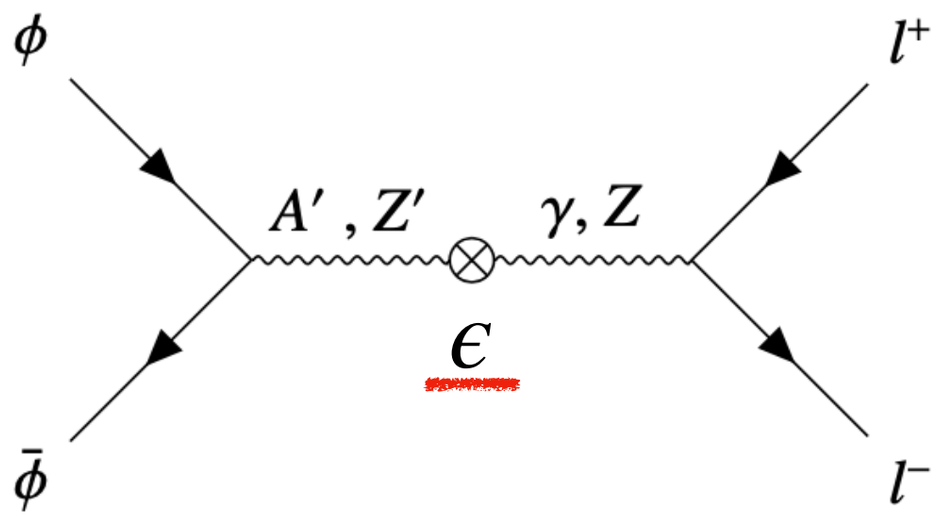
- Introduction - what is Dark Photon
- The previous results of search for Dark Photon A'
- Search for Dark Photon via $D^{*0} \to D^0 A'$ decay

Introduction - Dark Sector

- The particles in the hidden sector do not interact with Standard Model particles directly, but there are "portals" acting as indirect interaction.

- In direct search for Dark particles by collider experiments, they search for a missing momentum and energy or a pair of SM particles into which Dark particle decays.
  - The hottest topic is the vector portal, Dark photon and Dark Z boson.
  - Searching for the decays like $A'/Z' \to l^+l^-$ or invisible.

Portals	SM particle	DS particle
Scalar	Higgs h	Dark Higgs h'
Neutrino	Neutrino ν	Sterile neutrino ν_d
Vector	Photon / Z γ / Z	Dark photon / Z A' / Z'



The annihilation of Dark Sector particle ϕ

Introduction - Dark Photon and Dark Z

- Dark Photon A' and Dark Z boson Z' are Dark particles corresponding photon and Z.

  - There are models in which those dark bosons explain the anomaly of $(g-2)_\mu$.

- Dark photon is a new neutral vector particle couples to EM current.

  - Extension of SM in which a new $U(1)$ symmetry is introduced, so-called "kinetic mixing model".

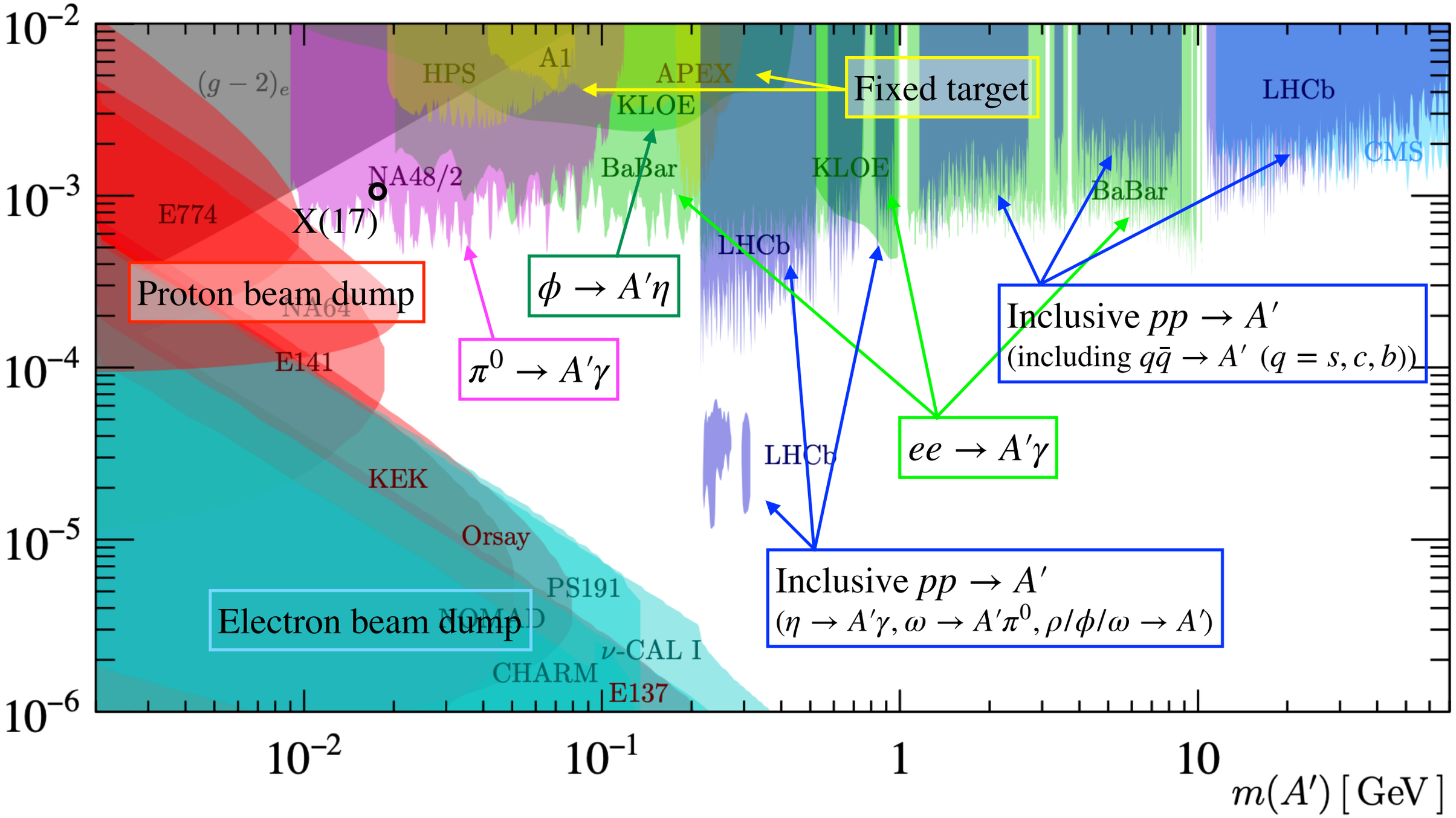
  - It mirrors the hypercharge interactions in the SM and A' can mix with the SM photon.

- Dark Z is a new neutral vector particle, similar to A', but couples to neutral weak current as well as EM current. (In $\epsilon \to 0$ limit, coupling is neutral only.)

  - Z' can, unlike A', couples to each lepton differently.

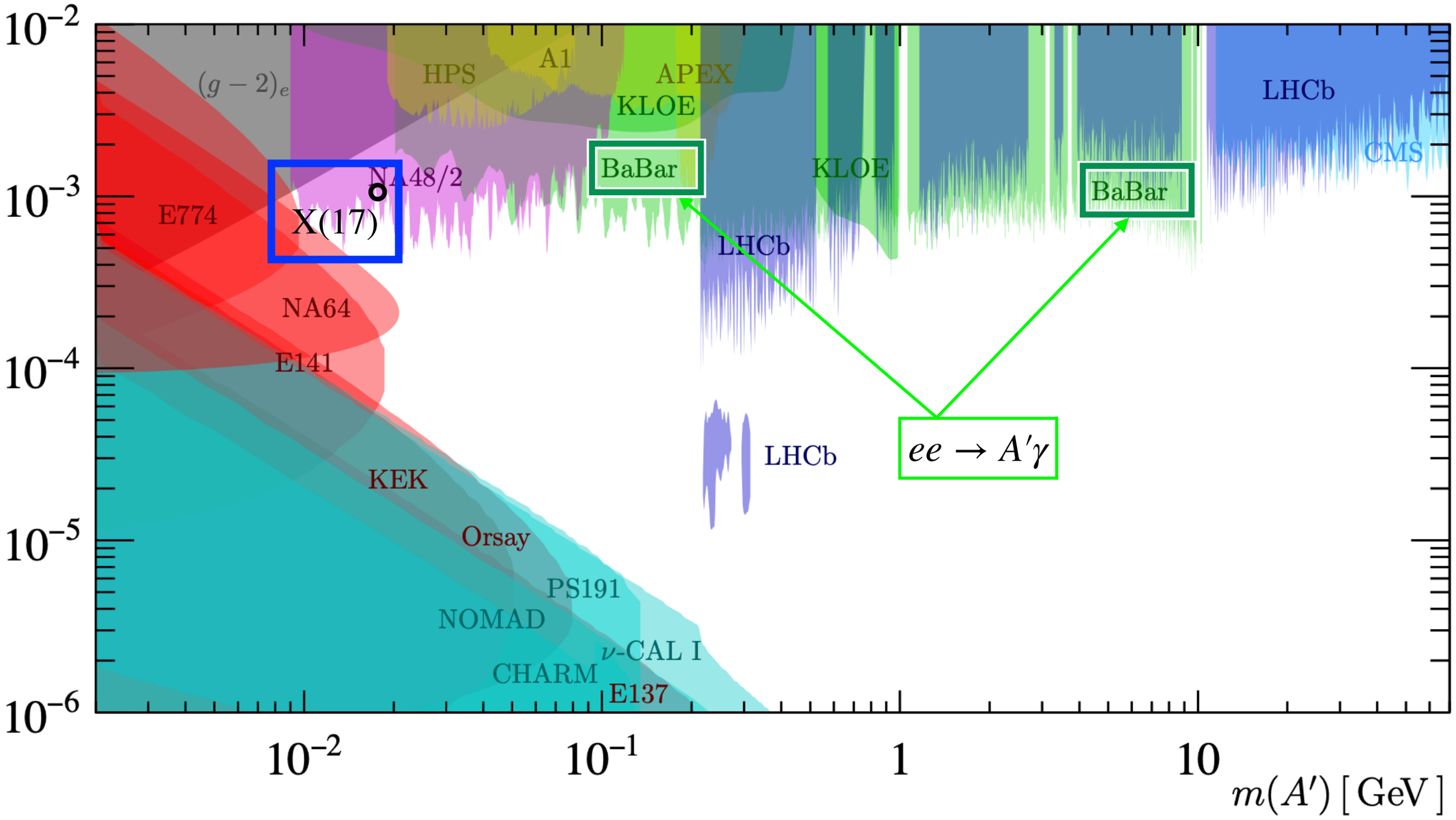
  - Z' couples to electrically neutral particles such as neutrinos.
    There are many neutrino scattering experiments and low mass region is already excluded.

Previous results of search for A'



Phys. Rev. Lett. 124, 041801 (2020)

Previous results of search for A'

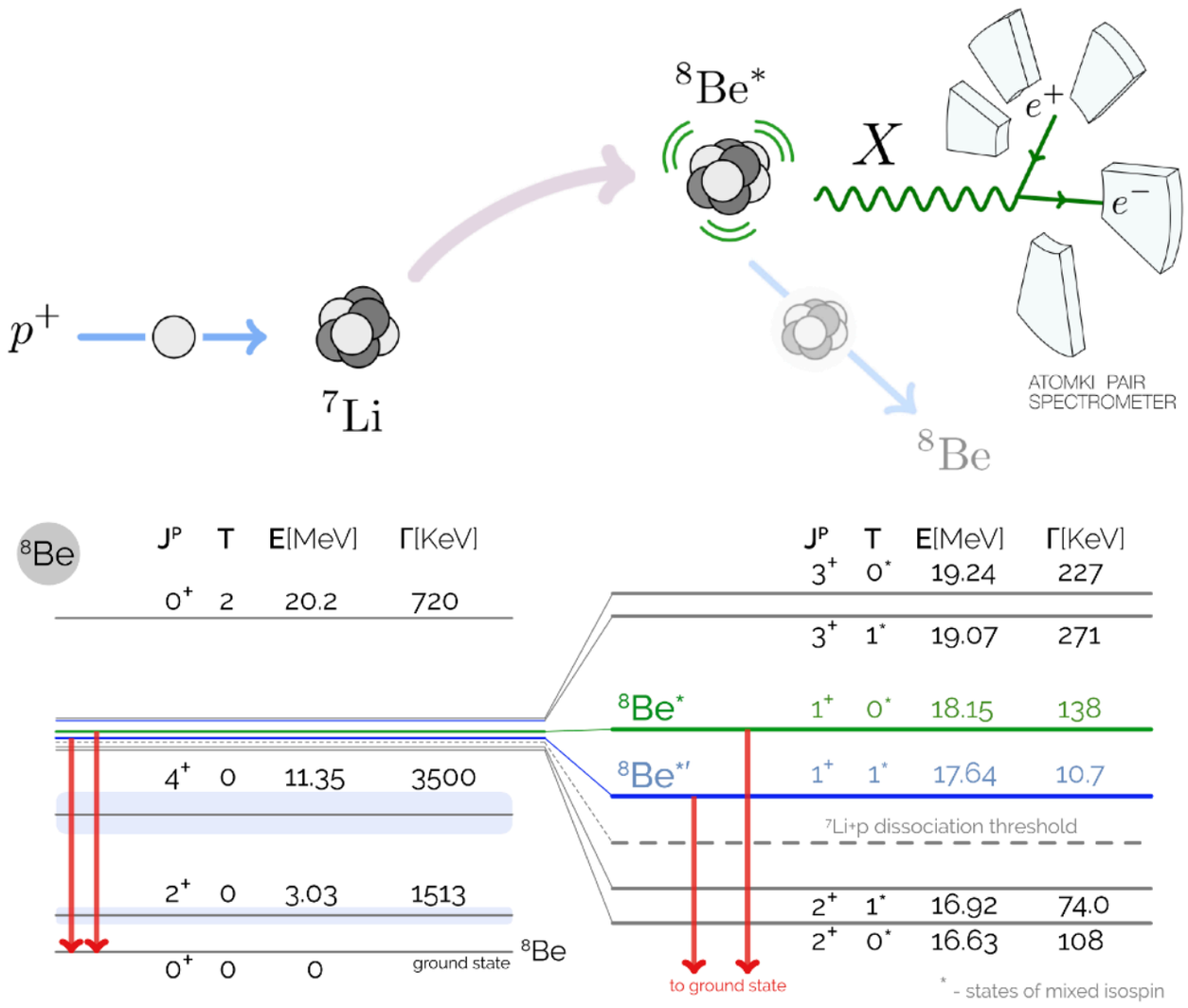


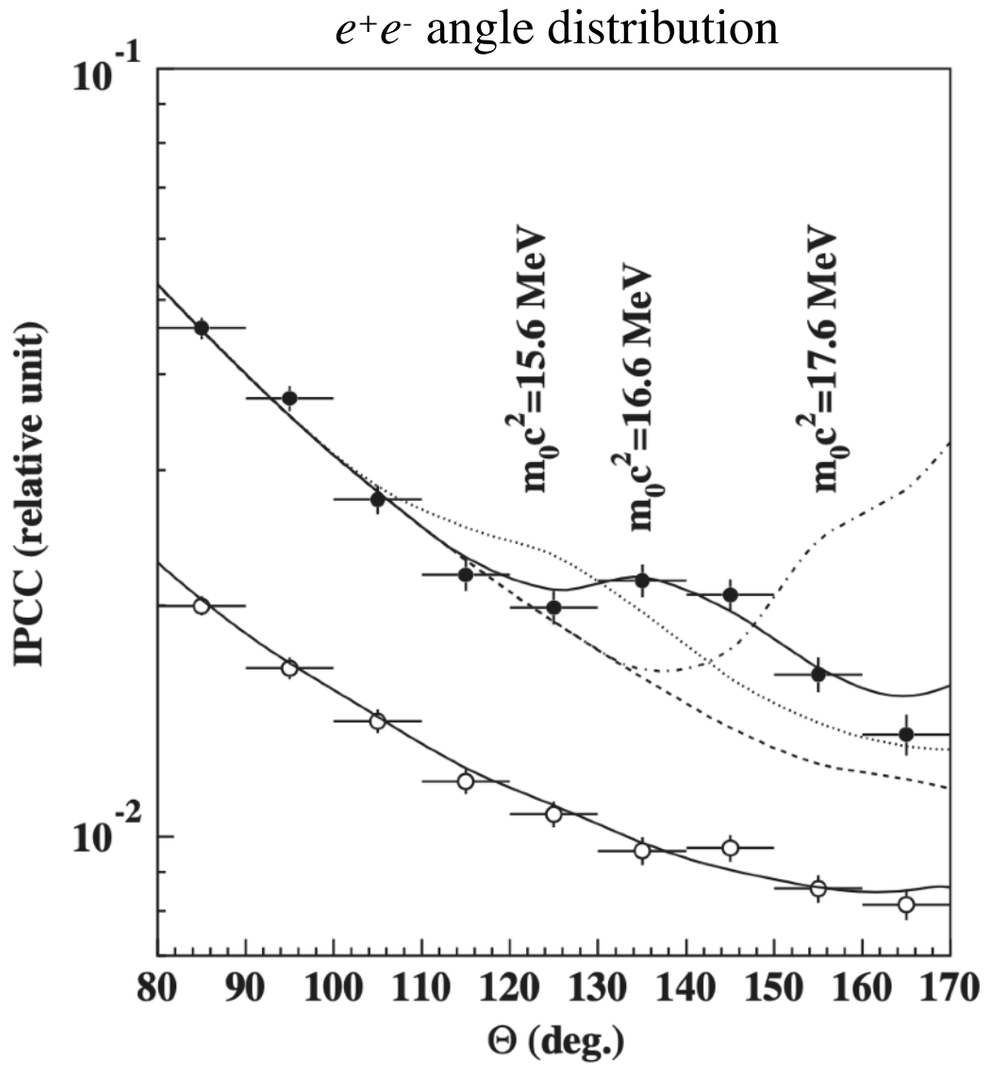
Phys. Rev. Lett. 124, 041801 (2020)

X(17) - Beryllium anomaly

- In 2016, A. J. Krasznahorkay *et al*. reported $X(17)$ in internal pair creation of ^{8}Be* decay.
  Another evidence in the decay of ^{4}He is reported in Oct. 2019. (arXiv:1910.10459)

- The opening angle between e^+ and e^- shows a strange peak ~140°.
  → At best fit, the mass of X is $16.70 \pm 0.35 \pm 0.5$ MeV/c^2, and branching ratio to γ is 5.8×10^{-6} .
  called **X(17)**





A. J. Krasznahorkay *et al*., PRL 116, 042501 (2016)

Outline

- Introduction - what is Dark Sector.
- The previous results of search for Dark Photon A'
- **Search for Dark Photon via $D^{*0} \to D^0 A'$ decay**

Search for A' in $D^{*0} \to D^0 A'$ at Belle

The target: $D^{*0} \to D^0 A'(\to e^+e^-)$

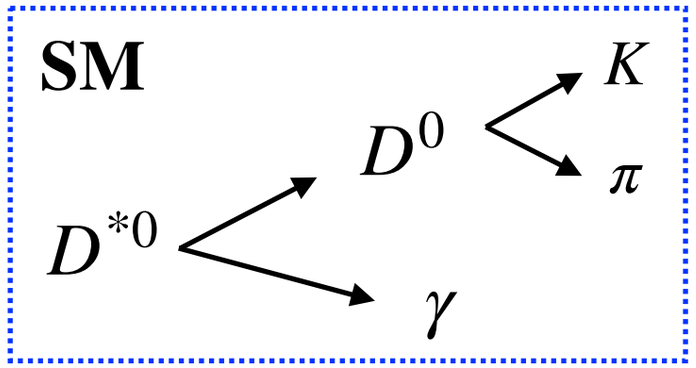
- The first search for Dark Photon in charm-related decay.

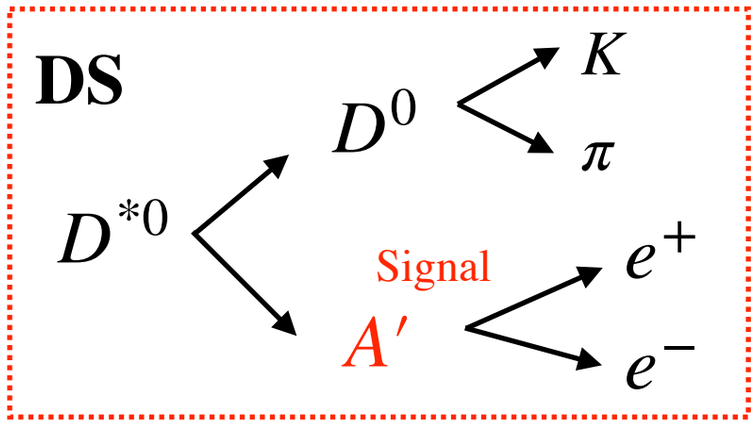
- The dataset is 1 ab^{-1} of Belle experiment including 4.0×10^9 $e^+e^- \to c\bar{c}$ events, i.e. $\sim 1.0 \times 10^8$ of D^{*0} events.

- SM decay $D^{*0} \to D^0\gamma$ where $\Delta m = 142$ MeV with mixing of γ to A'. The SM decay is used for normalization.

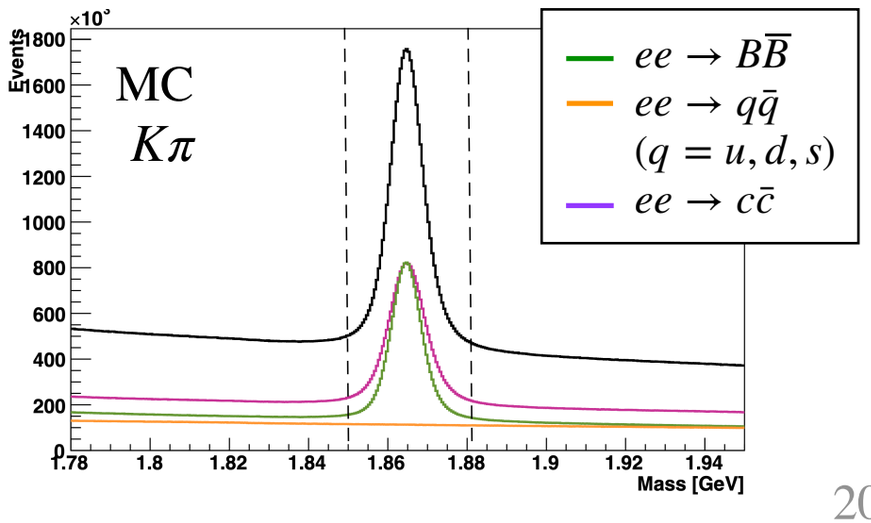
- D^0 is reconstructed by $K^-\pi^+$ (4%), $K^-\pi^+\pi^0$ (14%), and $K^-\pi^+\pi^-\pi^+$ (8%). A' is reconstructed from a pair of an electron and a positron. D^{*0} is reconstructed from D^0 and the pair.

- Selections are based on kinematics.





Reconstructed D^0 mass



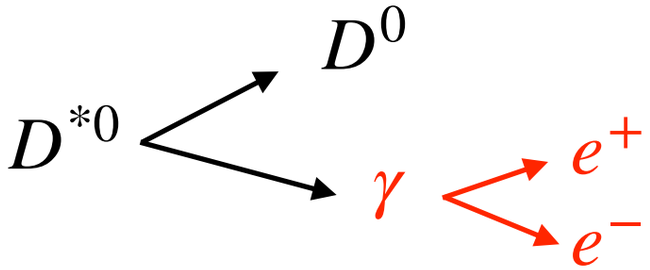
Selection for $K\pi$ mode
$1.857 < m_{D^0} < 1.878$ GeV
$134.6 < \Delta m < 150.9$ MeV
$2.5 < p_{D^{*0}}$ GeV
$dr_{ee} < 0.44$ cm

Major backgrounds

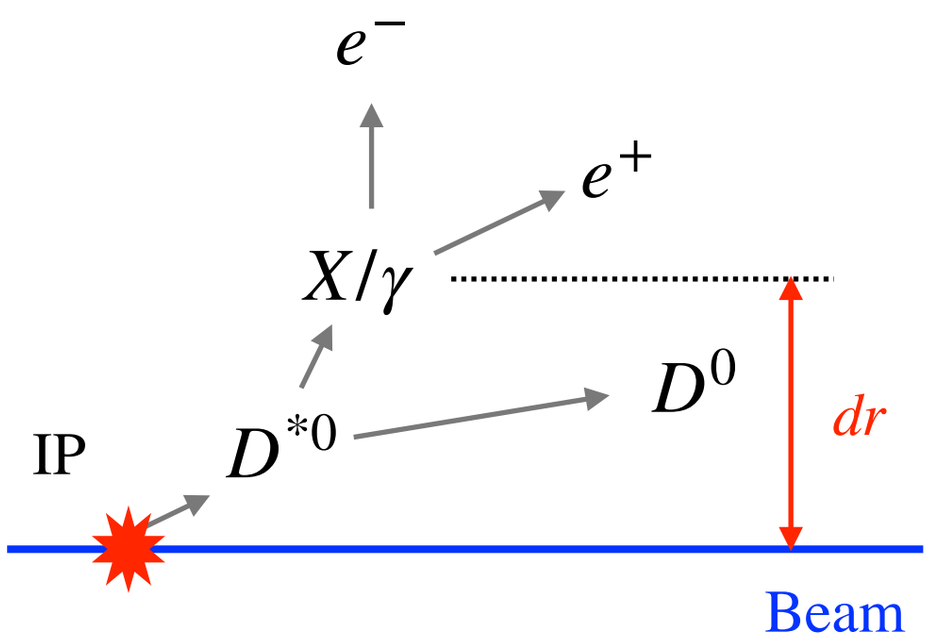
Backgrounds

- Two major backgrounds;

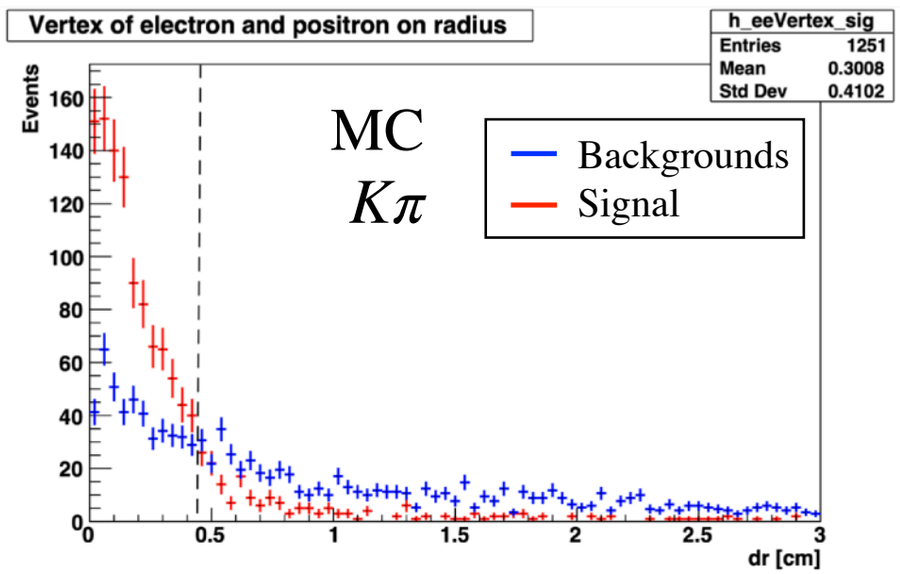
  (1) (Displaced) γ conversion. (2) D^{*+} background.



- $\gamma \to e^+e^-$ occurs in the detector material.
  γ flies finite distance unlike A'. The distributions of reconstructed vertex of e^+ and e^- show larger dr value in backgrounds.
  Events with larger dr than thresholds are excluded.



dr distribution of $K\pi$



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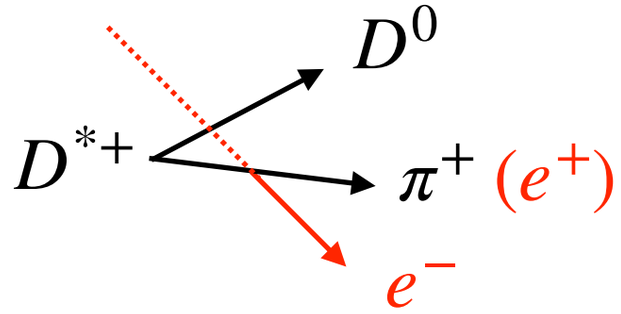
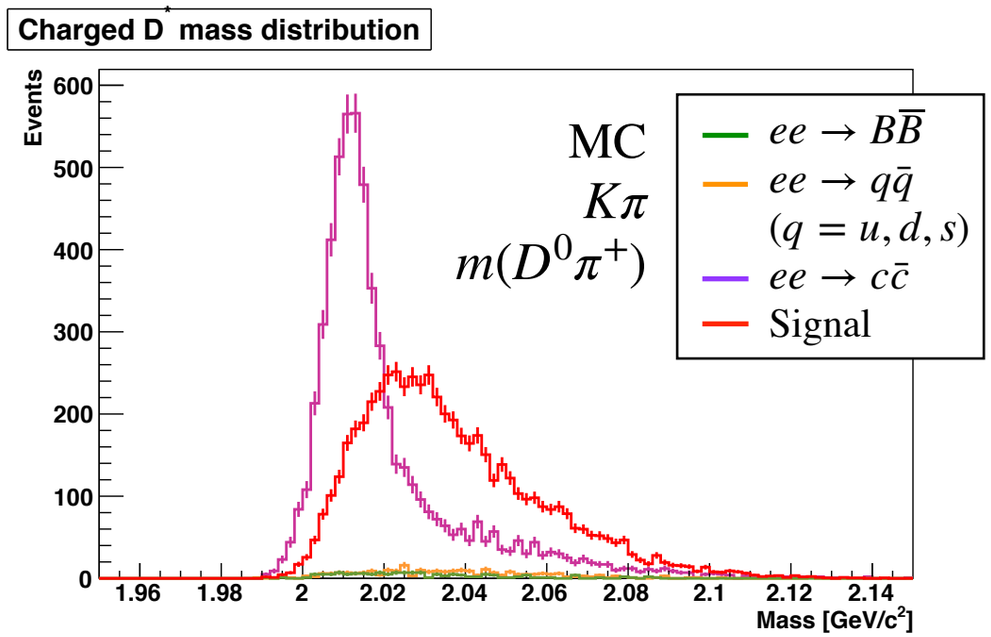
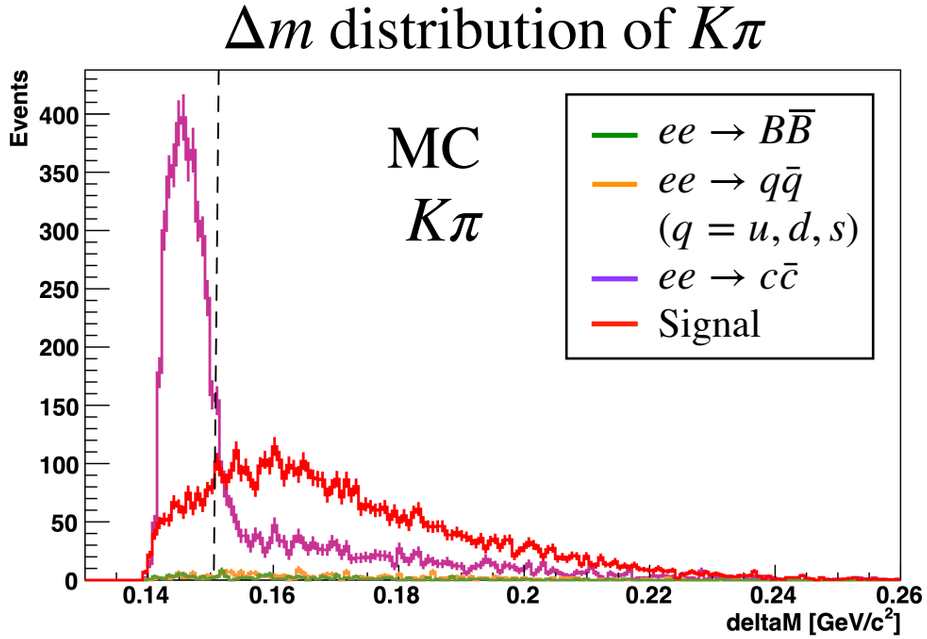


- $m(D^0\pi^+)$ must show a peak at D^{*+} mass.
  $m(D^0\pi^+)$ is calculated assigning pion mass to e^+ track and ignoring e^- track. The distribution shows a peak at 2.01 GeV/c^2.
  For better separation, veto $\Delta m = m(D^0\pi^+) - m_{D^0} < 0.15$ GeV/c^2 is applied.

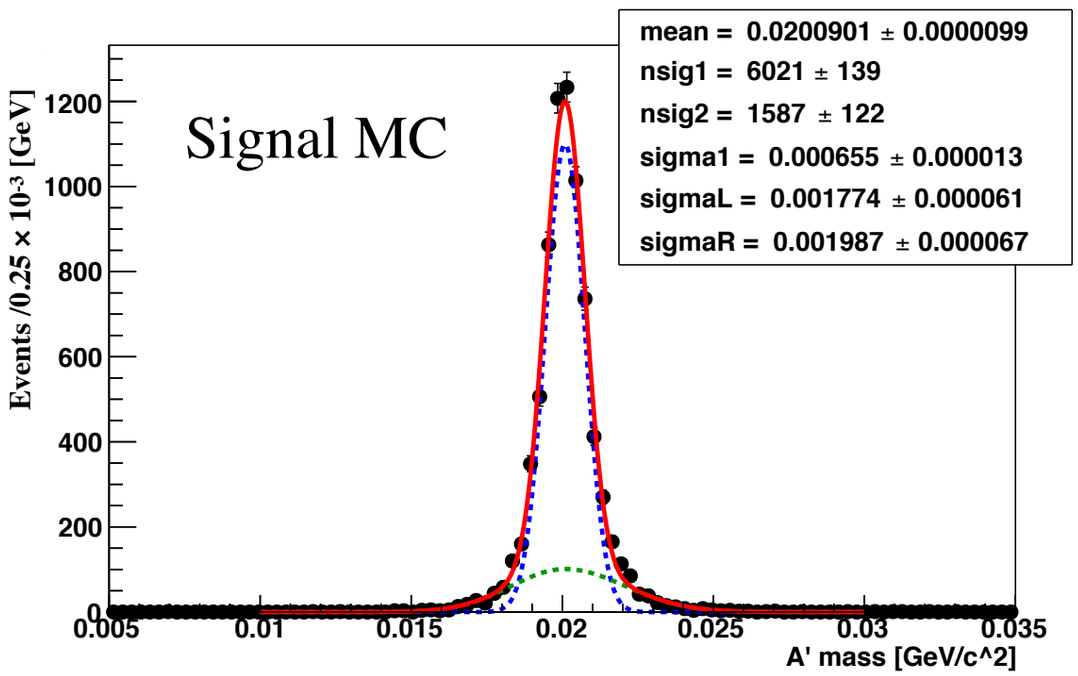




Signal efficiencies after the selections

- After all the selections, the detection efficiencies for the three D^0 decay modes are calculated.
- The efficiencies are calculated from the number of reconstructed events obtained by the fit divided by that of generated events.

Reconstructed A' mass in $K\pi$ mode



The detection efficiencies in each mode

Mode	Signal efficiency
$D^0 \to K^-\pi^+$	$3.12 \pm 0.11\%$
$D^0 \to K^-\pi^+\pi^0$	$1.05 \pm 0.04\%$
$D^0 \to K^-\pi^+\pi^-\pi^+$	$2.09 \pm 0.05\%$

*Not including the sub branching ratio of D^0.

$m_{A'}$ distributions of MC samples

- The signal distribution is modeled by a sum of Gaussian and Bifurcated Gaussian.

$$f_{\mathrm{sig}}(m_{A'}) = C_{\mathrm{sig}} G_{\mathrm{sig}}(m_{A'}|\mu,\sigma) + (1 - C_{\mathrm{sig}}) BG_{\mathrm{sig}}(m_{A'}|\mu,\sigma_L,\sigma_R).$$

- The background distribution is modeled by a sum of exponential and 4th Chebyshev polynomial.

$$f_{\mathrm{bkg}}(m_{A'}) = C_{\mathrm{bkg}}\Big(C_e \exp(m_{A'})\Big) + (1 - C_{\mathrm{bkg}})\Big(\sum_{i=1}^{4} a_i T_i(m_{A'})\Big).$$

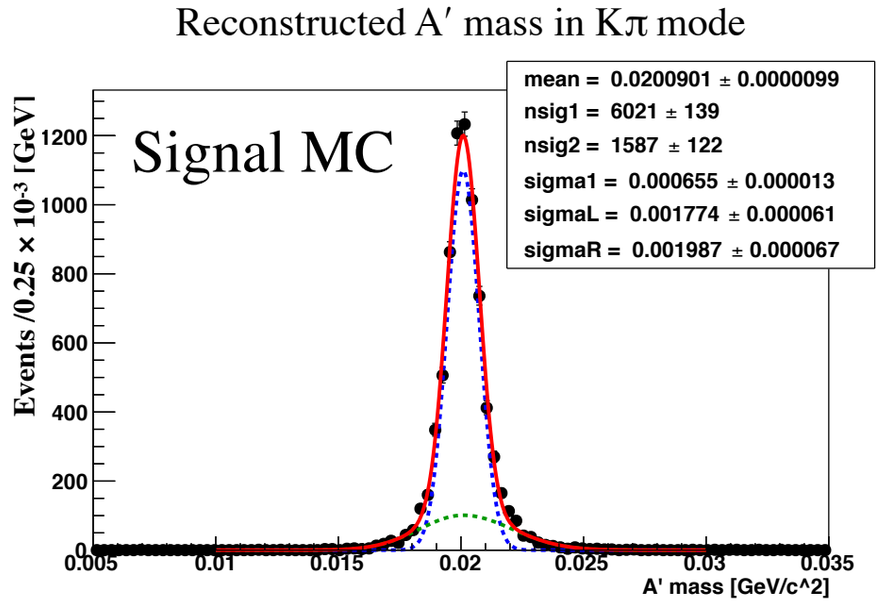
$T_i(x) = \cos(nt)$ where $x = \cos(t)$ (Chebyshev polynomial)

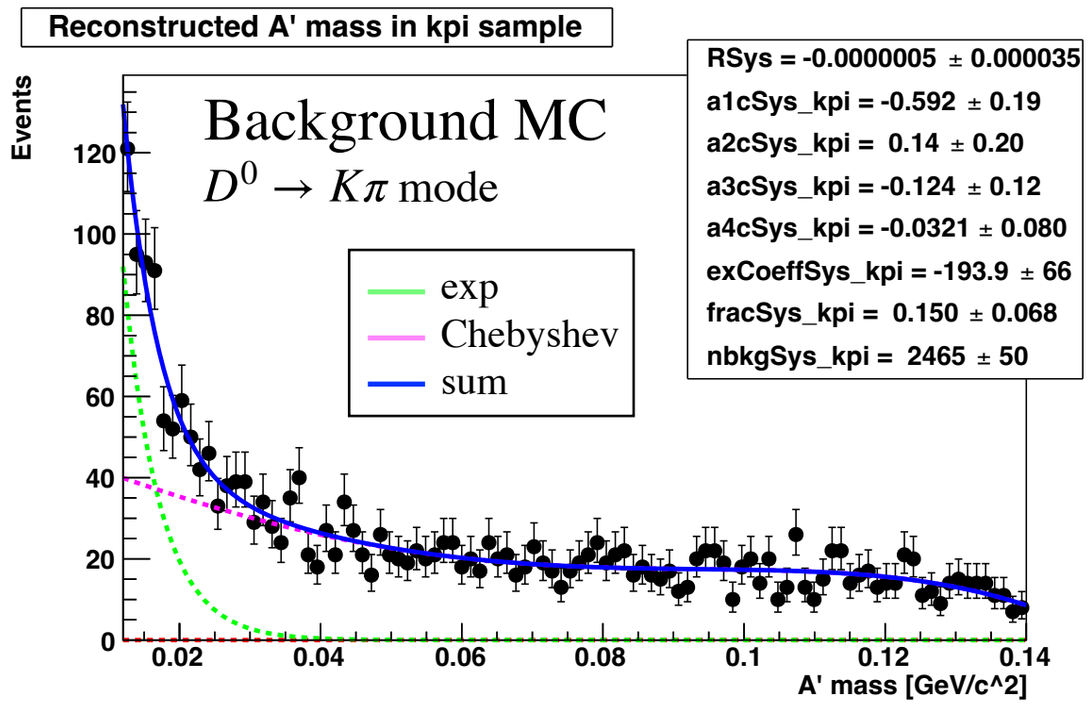
- To verify fit procedure, the background-only sample is fitted by

$N_{\mathrm{sig}} f_{\mathrm{sig}} + N_{\mathrm{bkg}} f_{\mathrm{bkg}}$.

- The result must be 0-consistent, and it is confirmed.

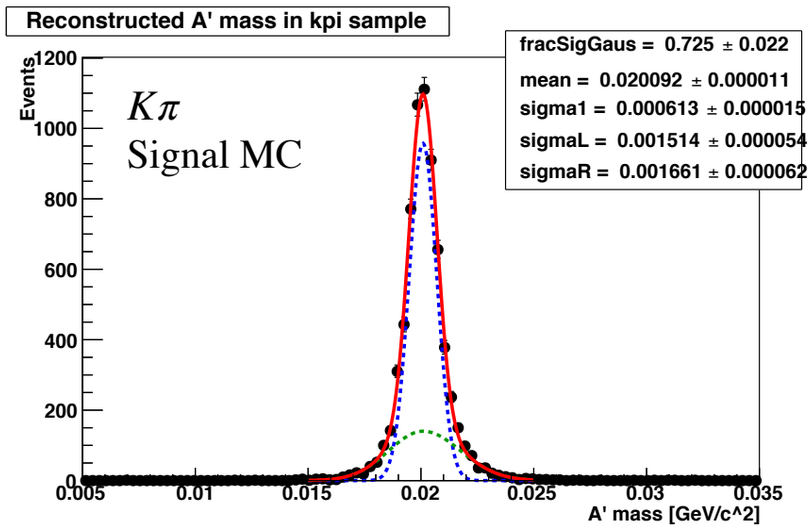
- Linearity is also checked by toyMCs adding a certain signal component.

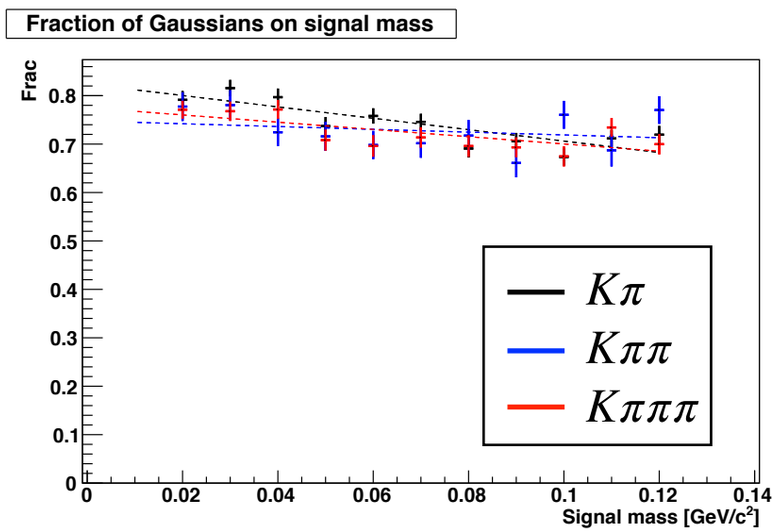


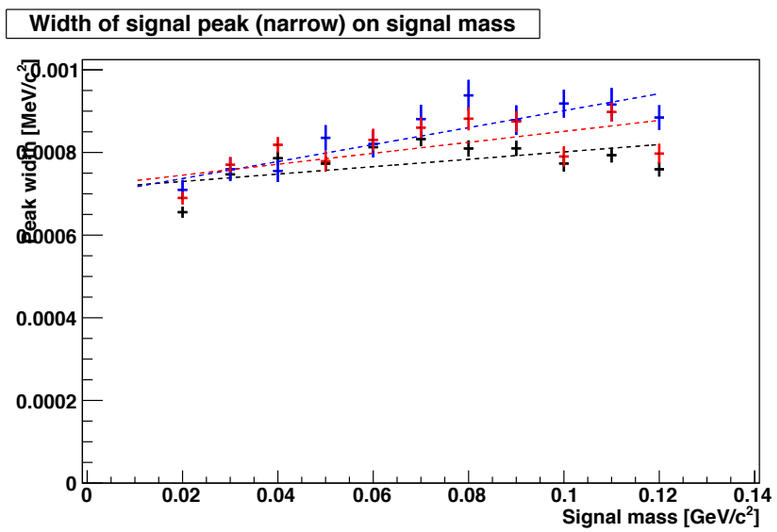


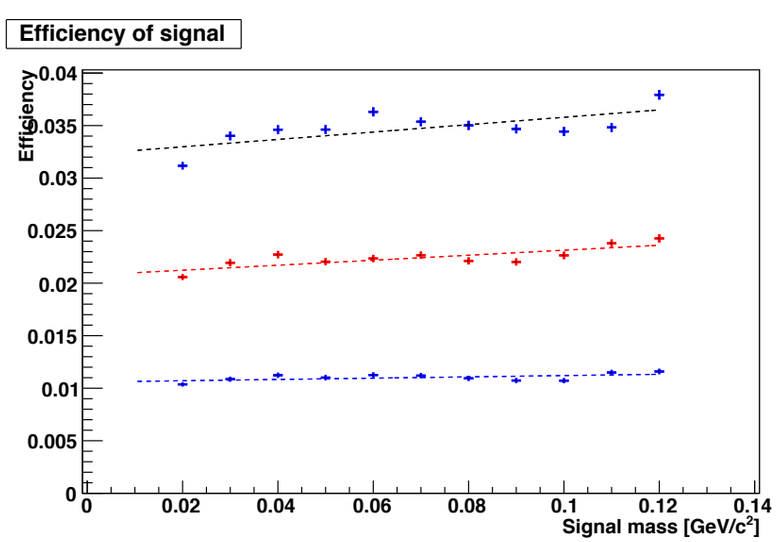
Parameter fixing for each $m_{A'}$

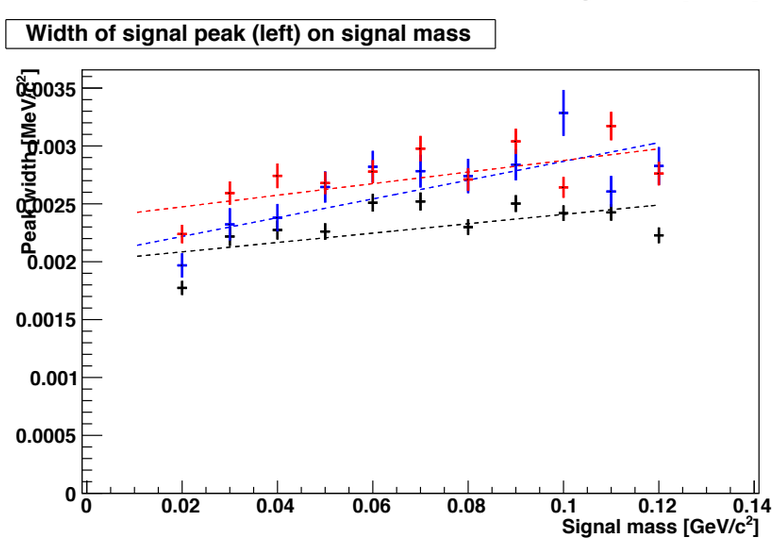
- The fit function for signal is defined by MC ($m_{A'} = 20$ MeV) results. But the mass $m_{A'}$ is unknown.
- In order to scan over $m_{A'}$ from 12 to 120 MeV/c^2, additional signal MCs are prepared for every 10 MeV/c^2 up to 120 MeV/c^2 and fit by the $f_{\rm sig}$.
- Based on the fit results, the signal efficiency and parameters of $f_{\rm sig}$ are fixed as a function of $m_{A'}$.

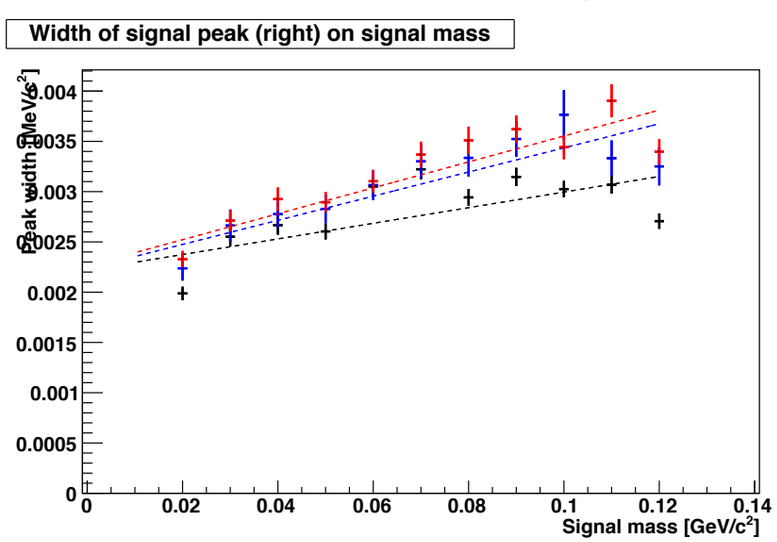








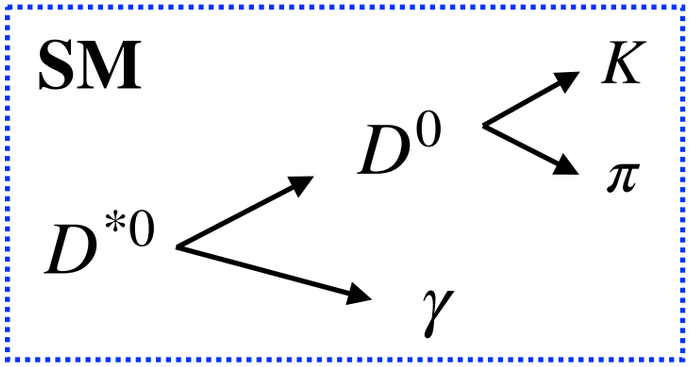




Normalization to cancel systematics

- The Standard Model process $D^{*0} \to D^0\gamma$ is used for the normalization mode as

$$R = \frac{BR(D^{*0} \to D^0 A')}{BR(D^{*0} \to D^0\gamma)}.$$

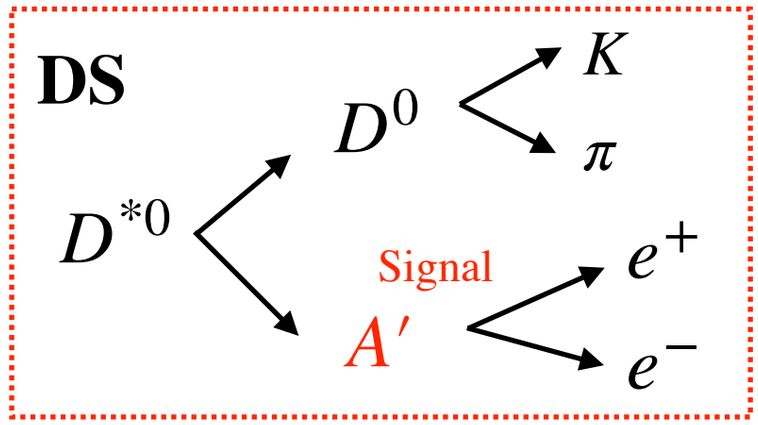


- The branching ratios are

$$\mathrm{BR}(D^{*0} \to D^0 A') = \frac{N_{sig}}{N_{D^{*0}} e_{sig}}, \quad \mathrm{BR}(D^{*0} \to D^0\gamma) = \frac{N_{D^*\gamma}}{N_{D^{*0}} e_{D^*\gamma}},$$

then, for each D^0 decay mode,

$$R^i = \frac{N^i_{sig}}{N^i_{D^*\gamma}} \frac{e^i_{D^*\gamma}}{e^i_{sig}} \; (i = \text{mode}).$$

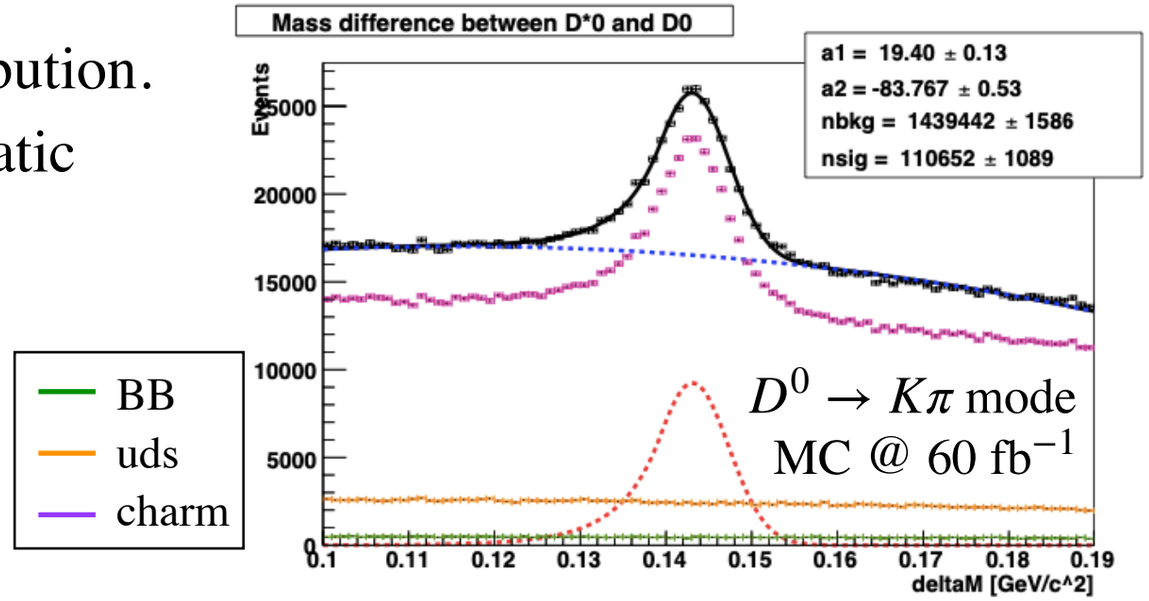


- Using the normalization mode, the measurement of absolute values of BR is not necessary.
  - ✓ $N_{D^{*0}}$ is cancelled.
  - ✓ The systematic uncertainties in D^0 reconstruction are also cancelled.
  - ✓ Only the systematic uncertainties in A' and γ remain.

Fit results of the normalization mode

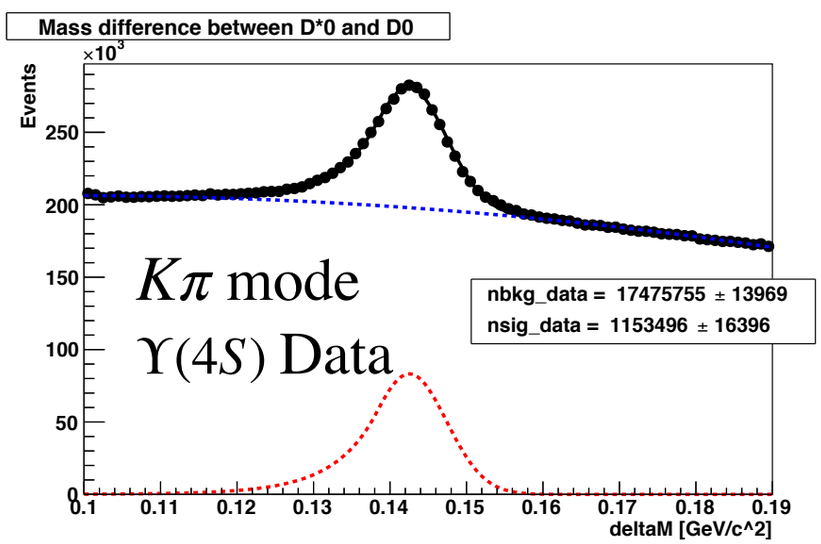
- The yield $N_{D^*\gamma}$ **is derived by the fit on** Δm distribution.
- The fit function is a sum of CrystalBall and quadratic functions.

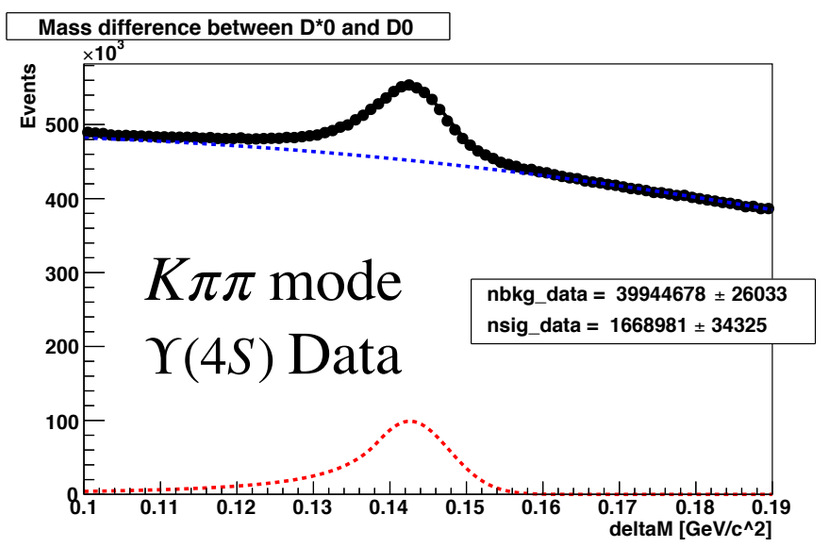
- $e_{D^*\gamma}$ are estimated by MC simulation.

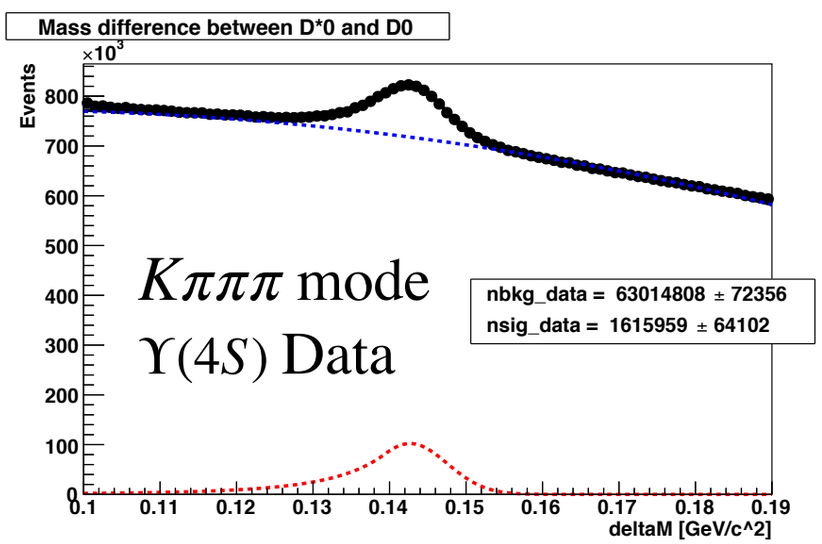


The summary of the numbers of events and efficiencies

D^0 decay mode	$D^0 \to K^-\pi^+$	$D^0 \to K^-\pi^+\pi^0$	$D^0 \to K^-\pi^+\pi^-\pi^+$
$N_{D^*\gamma}$	$(11.5 \pm 0.2) \times 10^5$	$(16.7 \pm 0.03) \times 10^5$	$(16.2 \pm 0.6) \times 10^5$
$e_{D^*\gamma}$ [%]	20.01 ± 0.02	7.51 ± 0.01	13.7 ± 0.01
N_γ/e_γ in total	$(5.76 \pm 0.08) \times 10^6$	$(22.2 \pm 0.5) \times 10^6$	$(11.8 \pm 0.5) \times 10^6$







The systematics studies

- Uncertainties of D^0 are canceled by taking the ratio and e^+e^- pair and γ are still remain.

- The table shows the list of Systematics and the maximum values in 3 sub decay modes.

- The value of systematics uncertainty is

$$\sigma_{\text{sys}} = R \times 7.3\% + \sigma_{\text{fit}}.$$

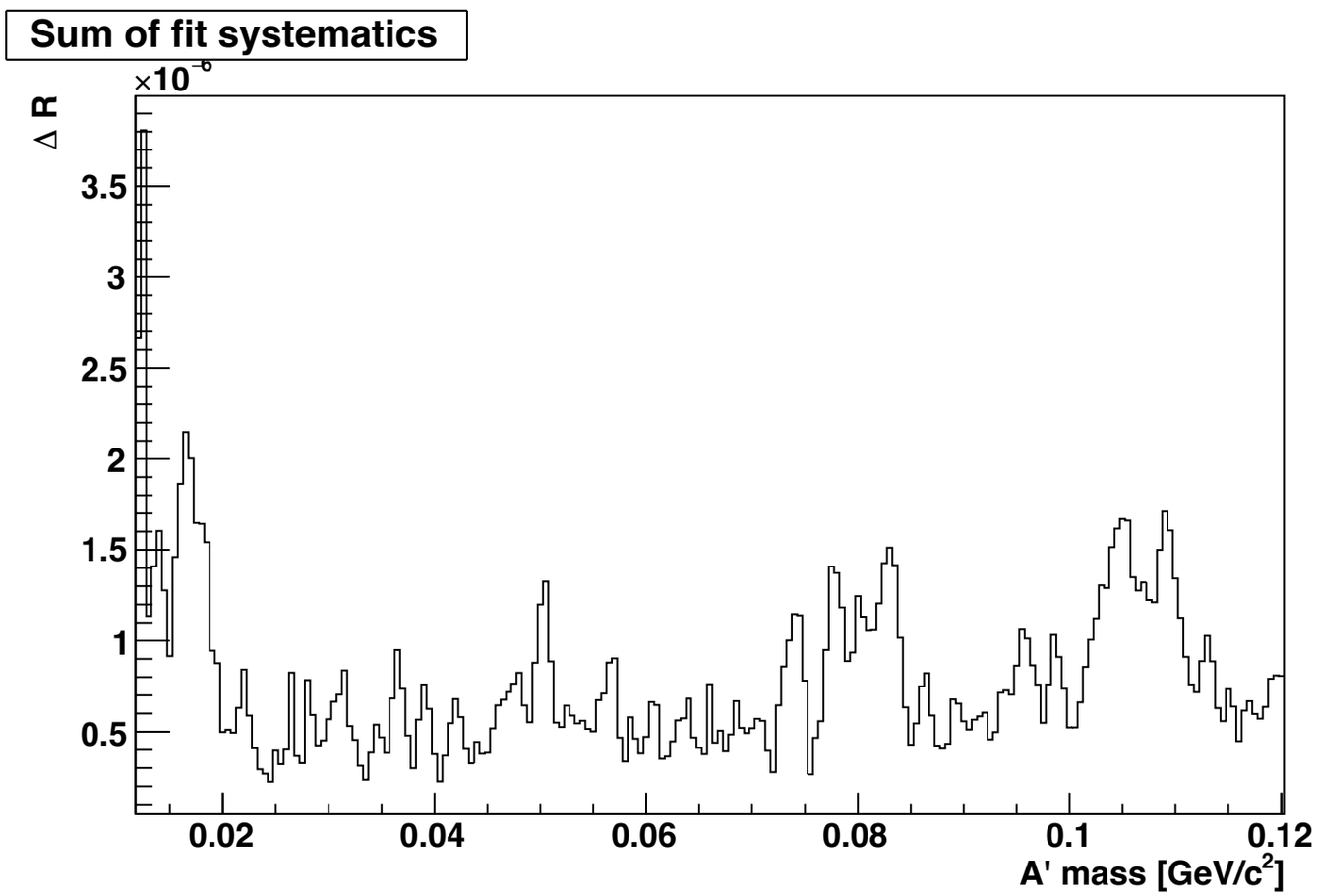
The summary of systematics

	Quantity	Scheme
Electron tracking	3.3%	Belle Official
Electron PID	3.3%	Belle Official
γ finding	2.3%	Belle Official
dr_{ee} efficiency	2.6%	$\psi(2S) \to J/\psi\pi^+\pi^-$
Mass vertex fit efficiency	4.6%	$D^{*+} \to D^0\pi^+$
Total	7.3%	quadratic sum

The fit systematic σ_{fit}

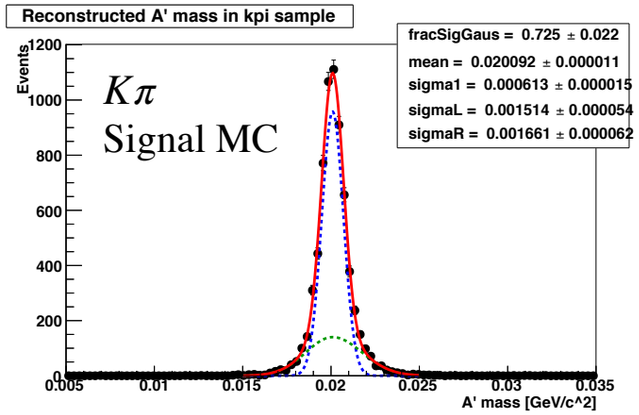
- In the simultaneous fit, the parameters of f_{sig} are fixed at the result of signal MC.
- There are uncertainties in the errors of fit results.

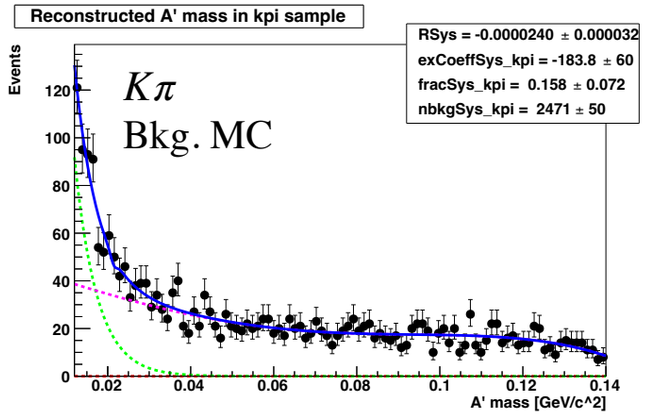
- The fit systematics is estimated by varying each parameter by $\pm 1\sigma$ and fitting to the data again.
- The total systematics is estimated by the quadratic sum of the errors for all the parameters.

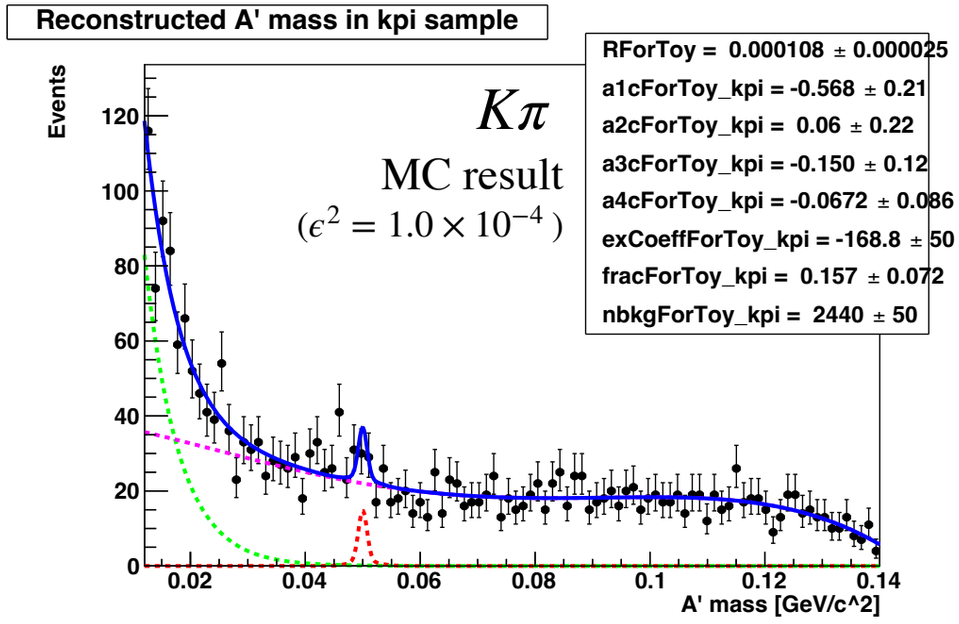


Search for A' in $D^{*0} \to D^0 A'$

- Fit $m_{A'}$ distribution simultaneously to the three D^0modes.

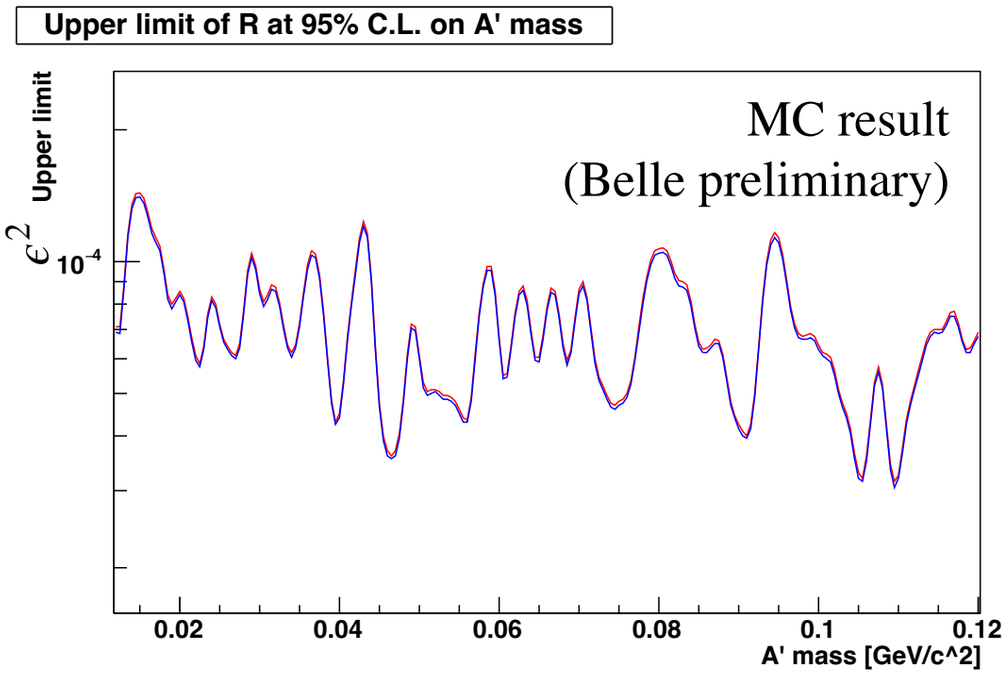






- With full dataset of Belle, the upper limit of ϵ^2 reaches order of 10^{-4}.

- Data unblinding is expected soon.



Upper limit of ϵ at 90% C.L. in MC simulation.
Without and With systematics.

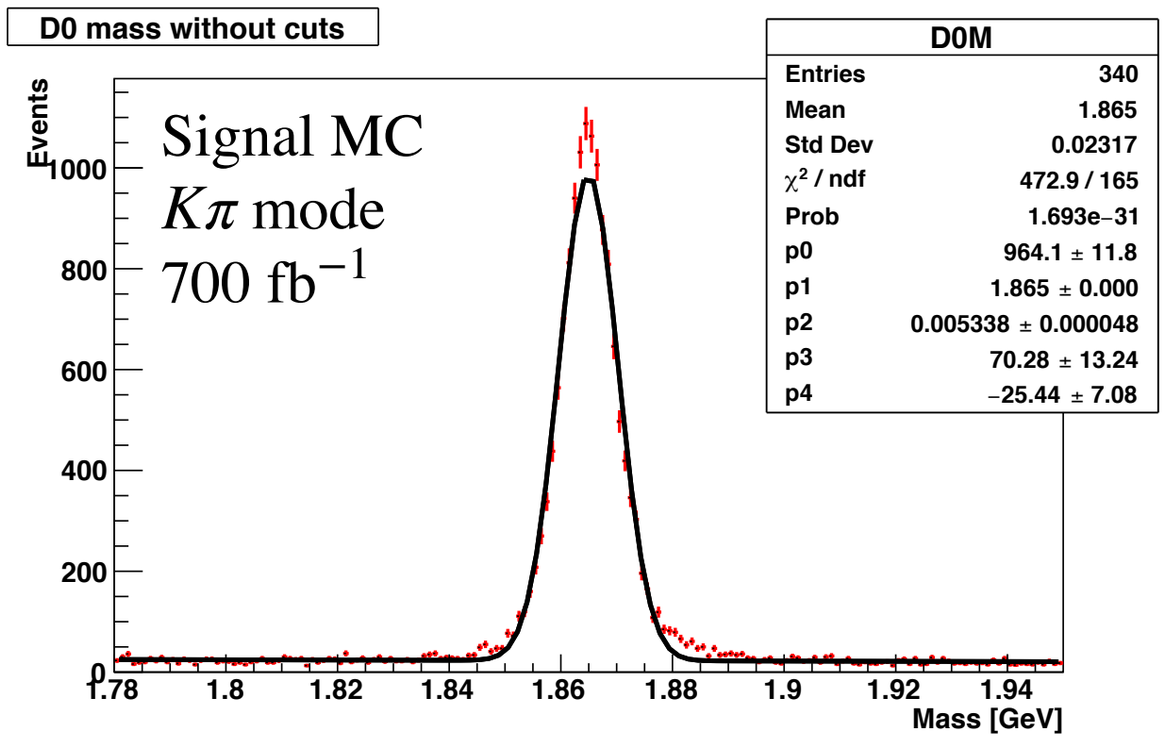
BackUp

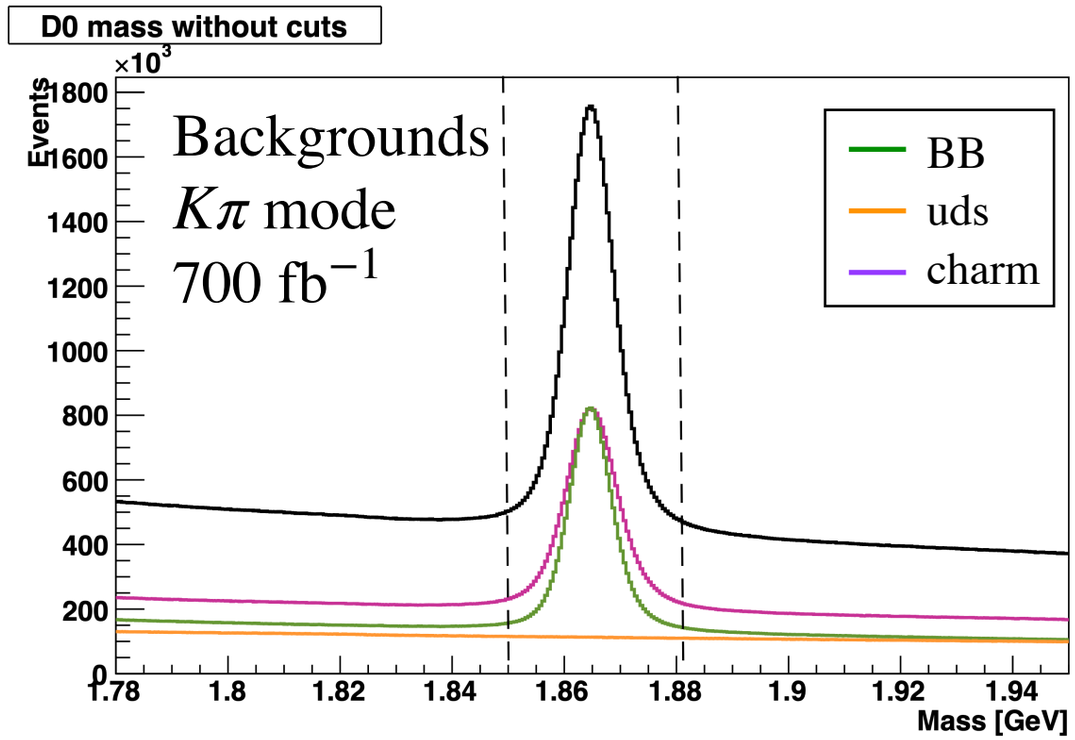
Cuts for the reconstruction

- Track selection :
  - For Kaons and charged Pions : PID > 0.6, dr < 1 cm, |dz| < 5 cm
  - For Electrons and Positrons : PID > 0.1, d0 < 0.1 cm
  - For γ : E > 50 MeV, E9/E25 > 0.9
  - For reconstructed neutral Pions : p > 0.4 GeV/, 0.121 < M < 0.149 GeV

- For the reconstructed D^{*0} and D^0, cut values are :
  - $p_{D^{*0}}$: 2.5 GeV/c for all modes,
  - M_{D0} : 3σ of signal distribution for each mode,
  - ΔM : 3σ of signal distribution for each mode,
  - ee vertex : dr < 0.5 cm,
  - Chi probability of D^{*0},
  - Best candidate selection by $\chi^2(D^{*0})$

D^0 mass criteria



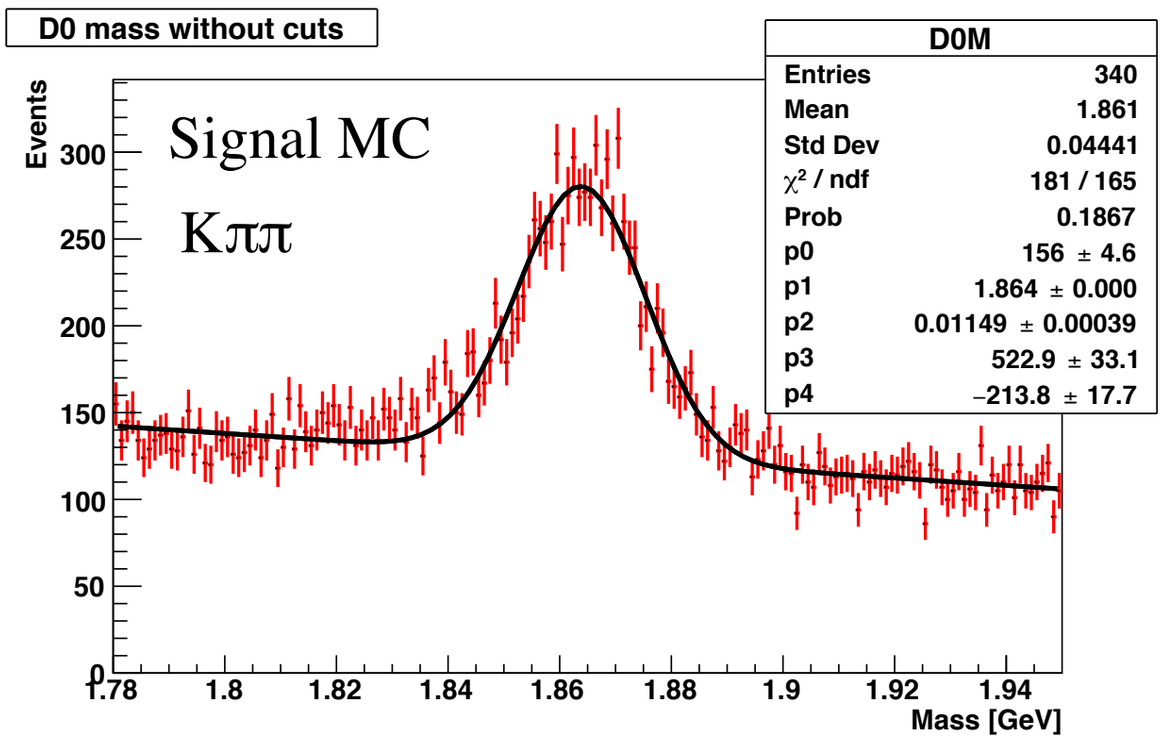


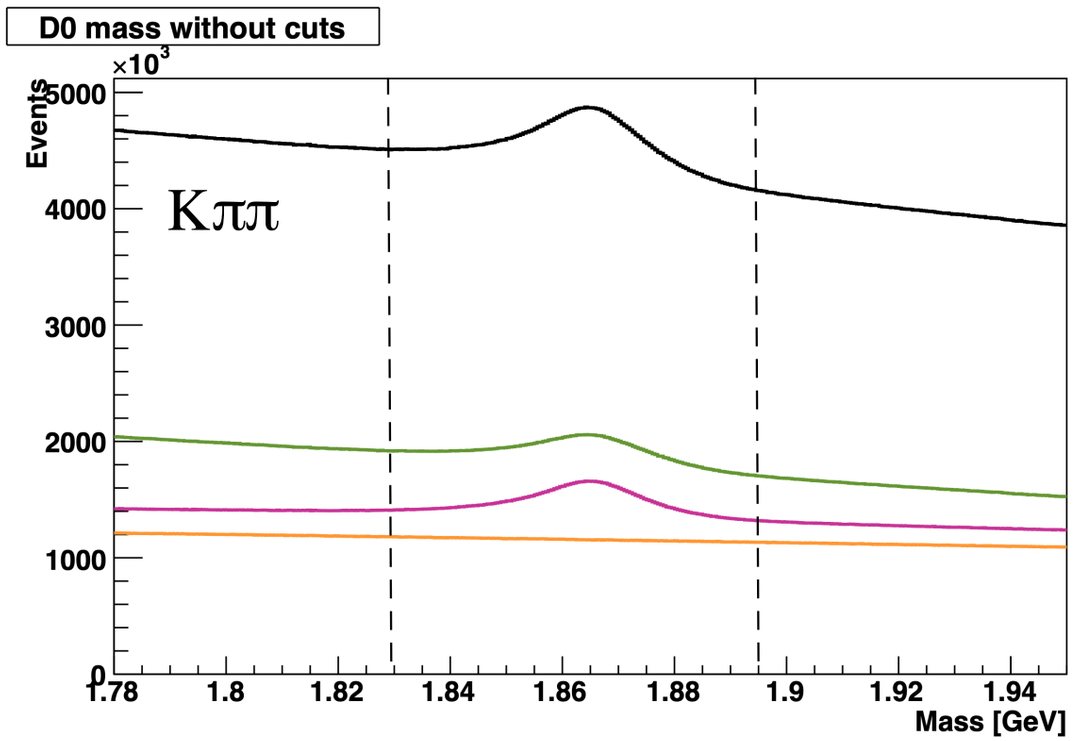
- Reconstruction in $K\pi$ mode is shown.

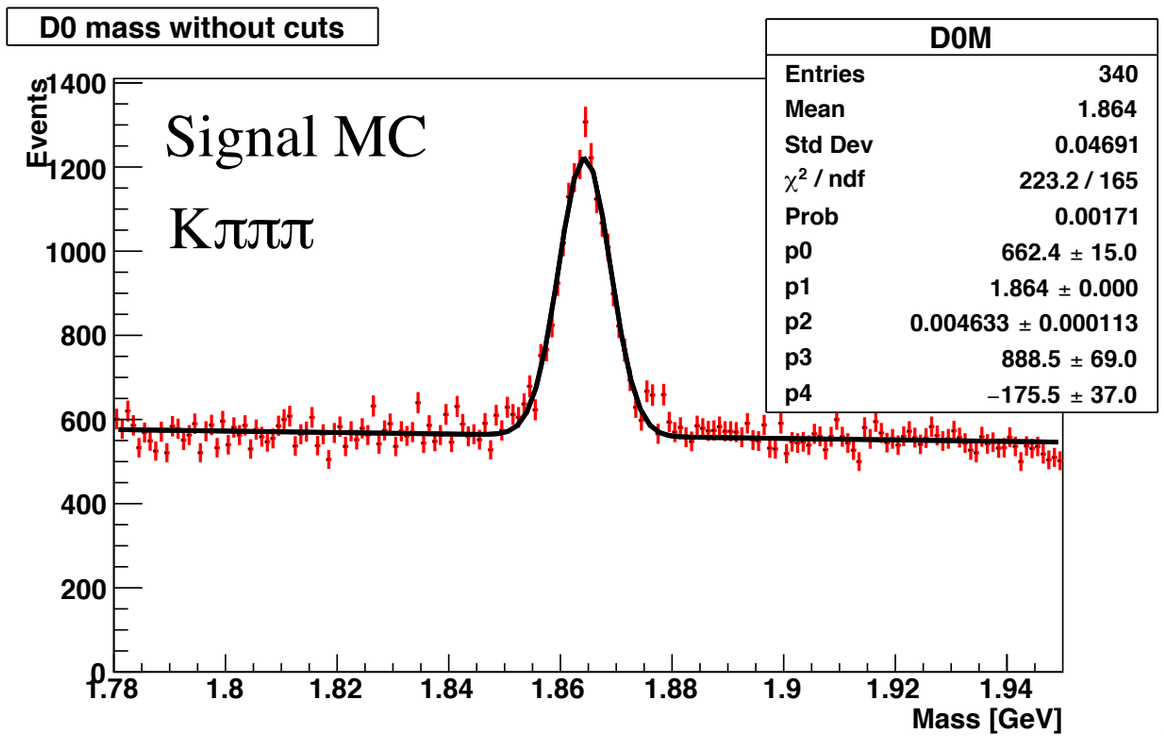
- For the reconstructed D^0, the mass window is set within 3σ from the peak where σ is the width of the signal distribution.

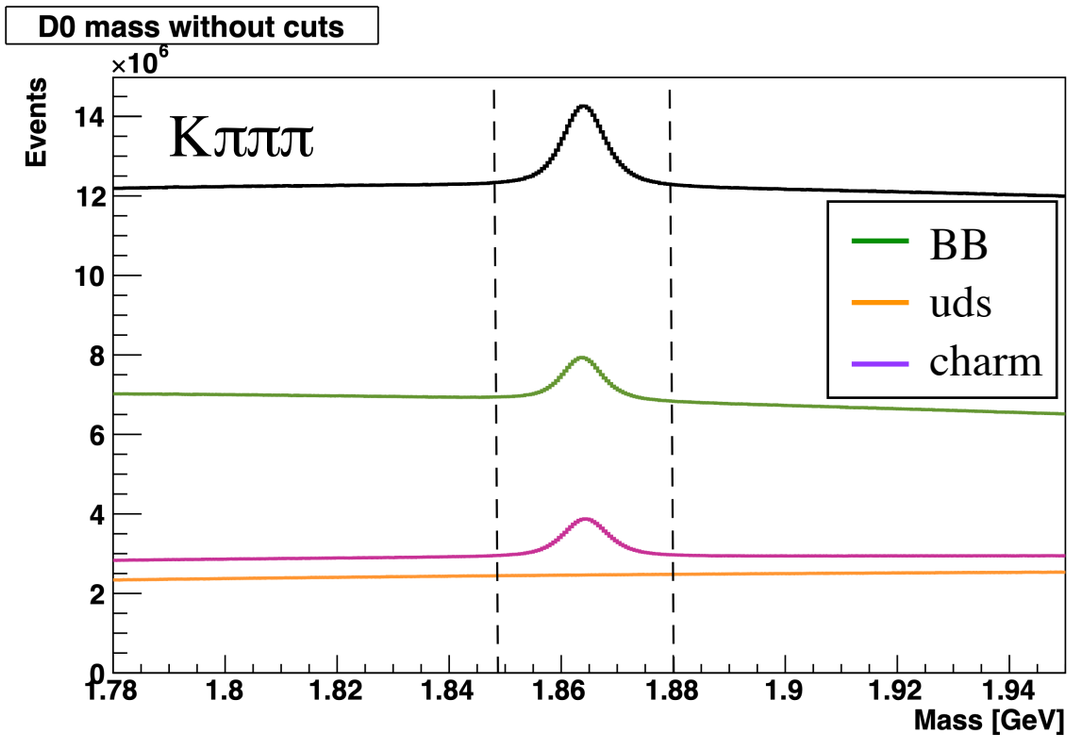
D^0 mass criteria

- **D0 mass criteria are determined by the 3σ of signal.**



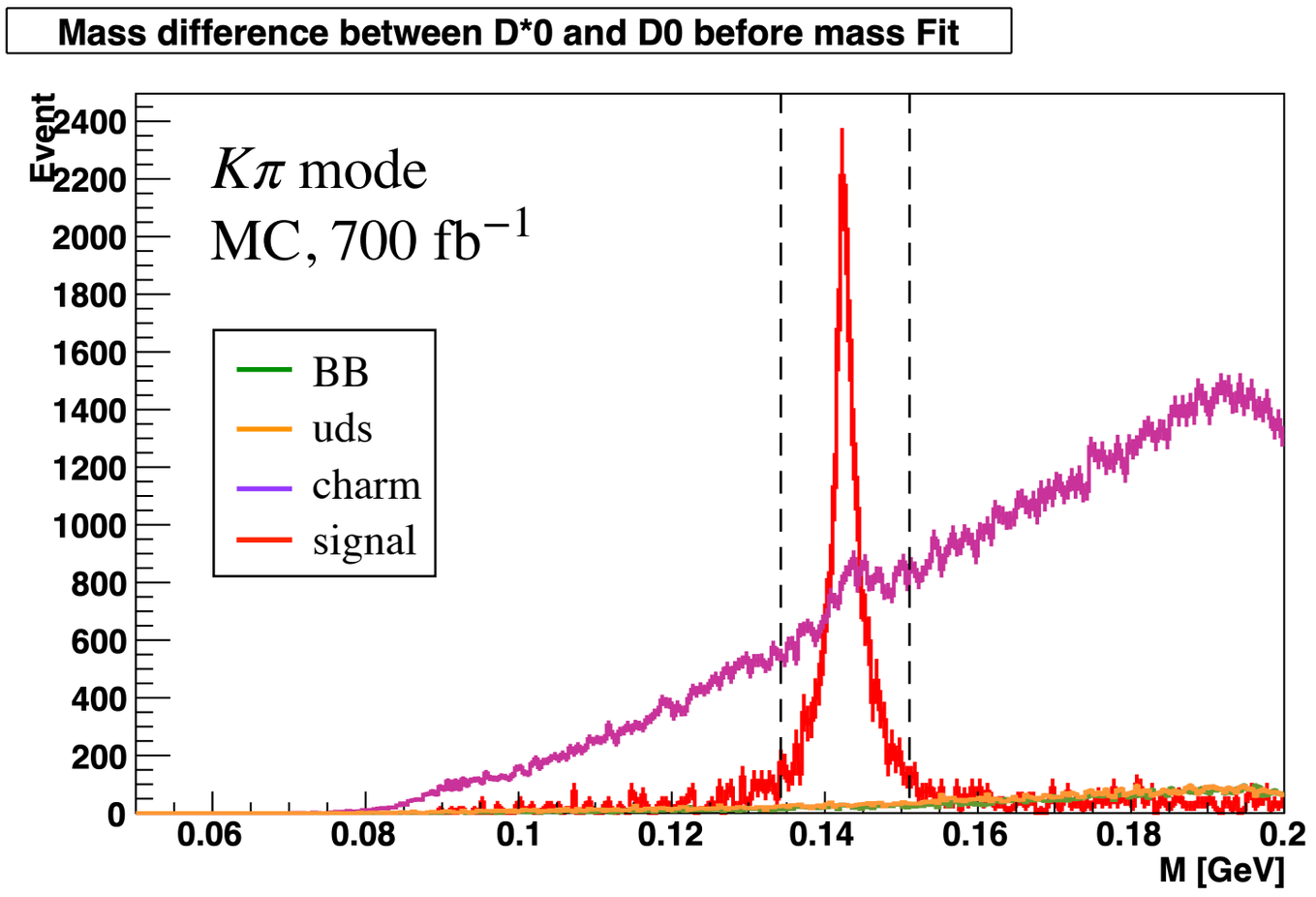






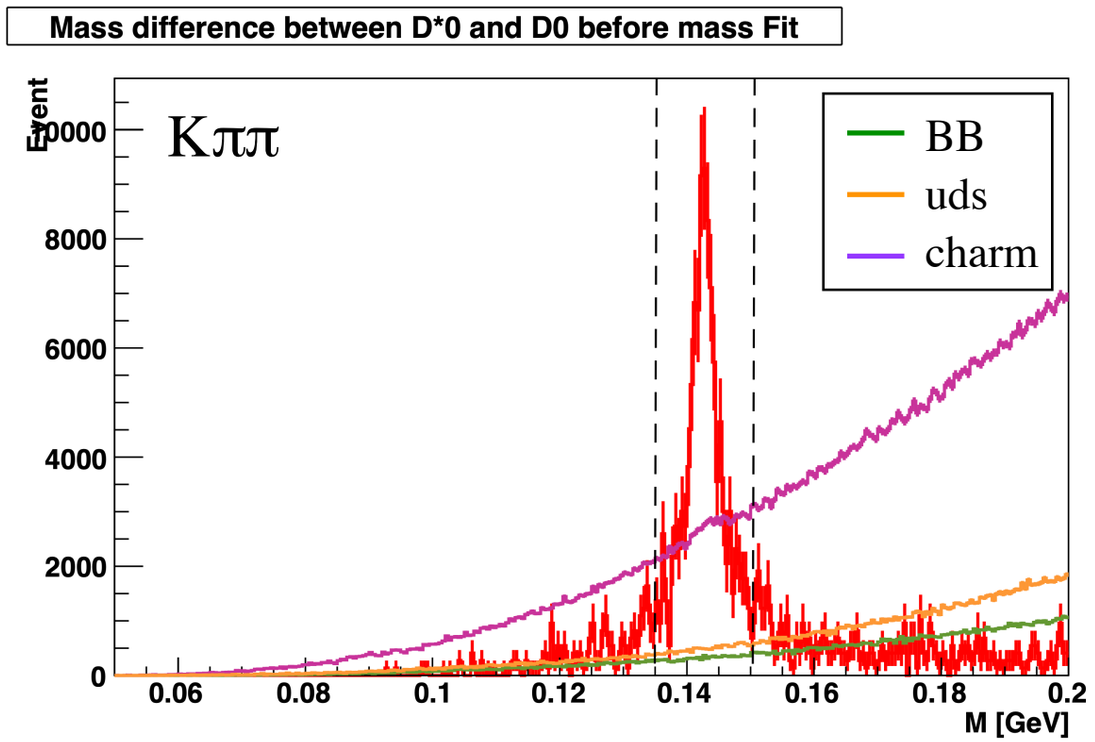
ΔM criteria

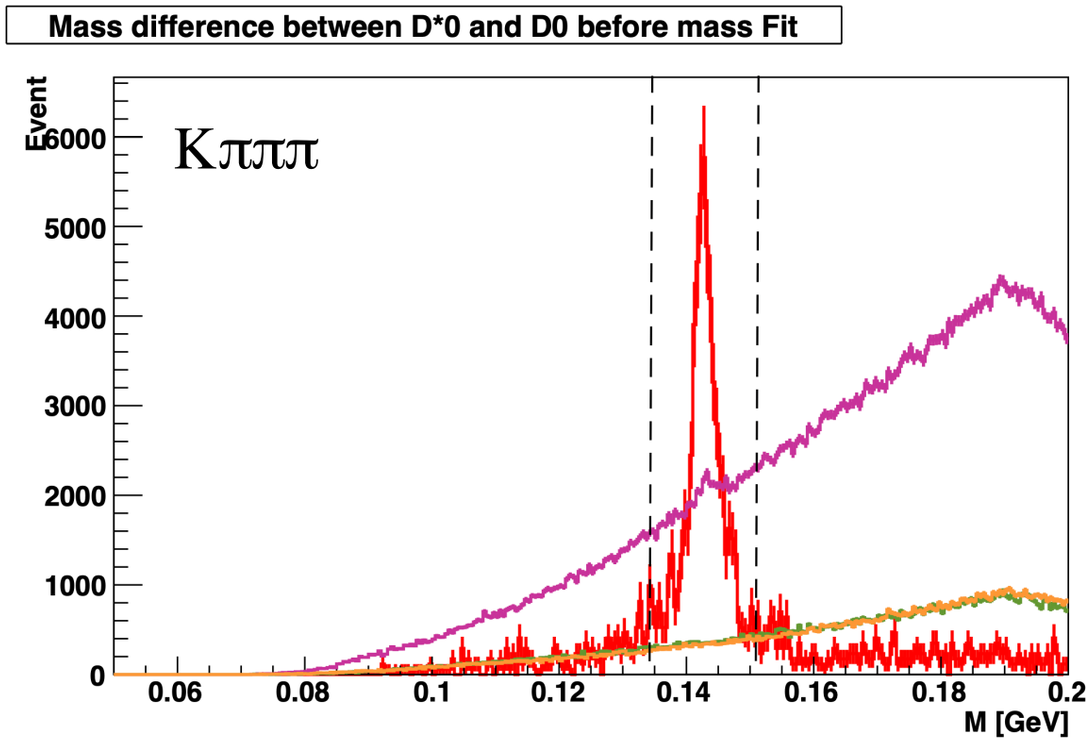
- For D^{*0} reconstruction, the mass difference $\Delta M = m_{D^{*0}} - m_{D^0}$ is used to reject the backgrounds.
- Candidates in 3σ window from the peak are selected.



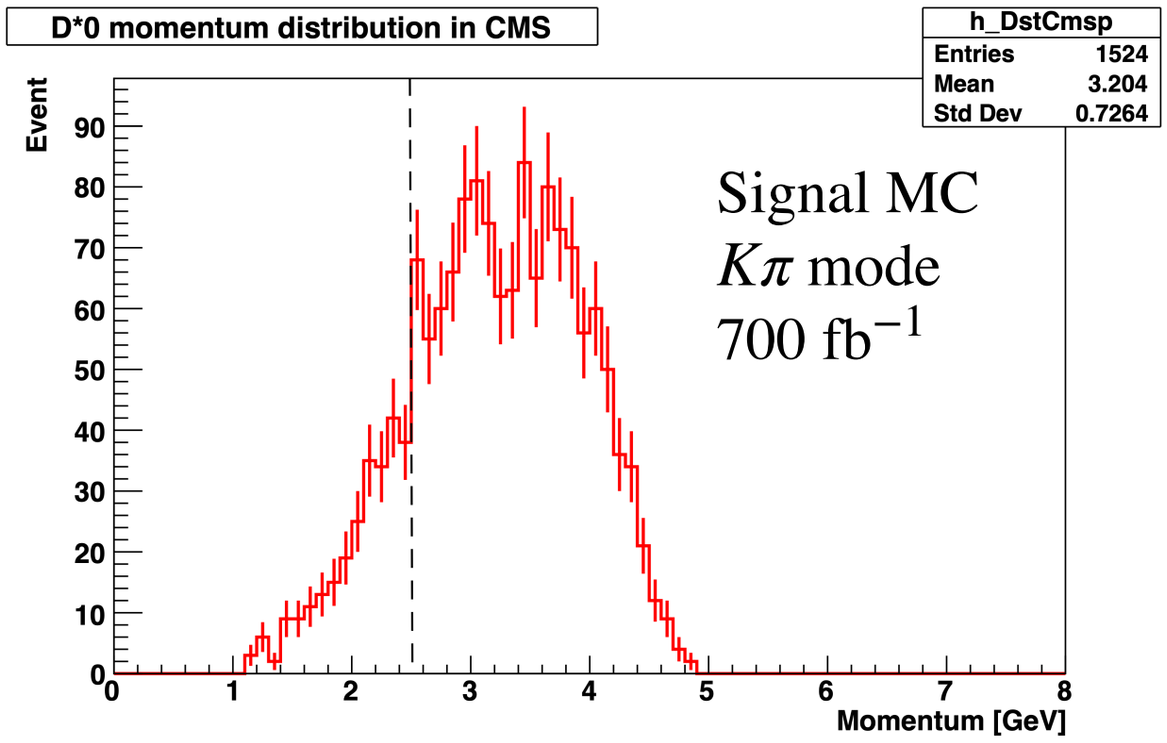
ΔM criteria

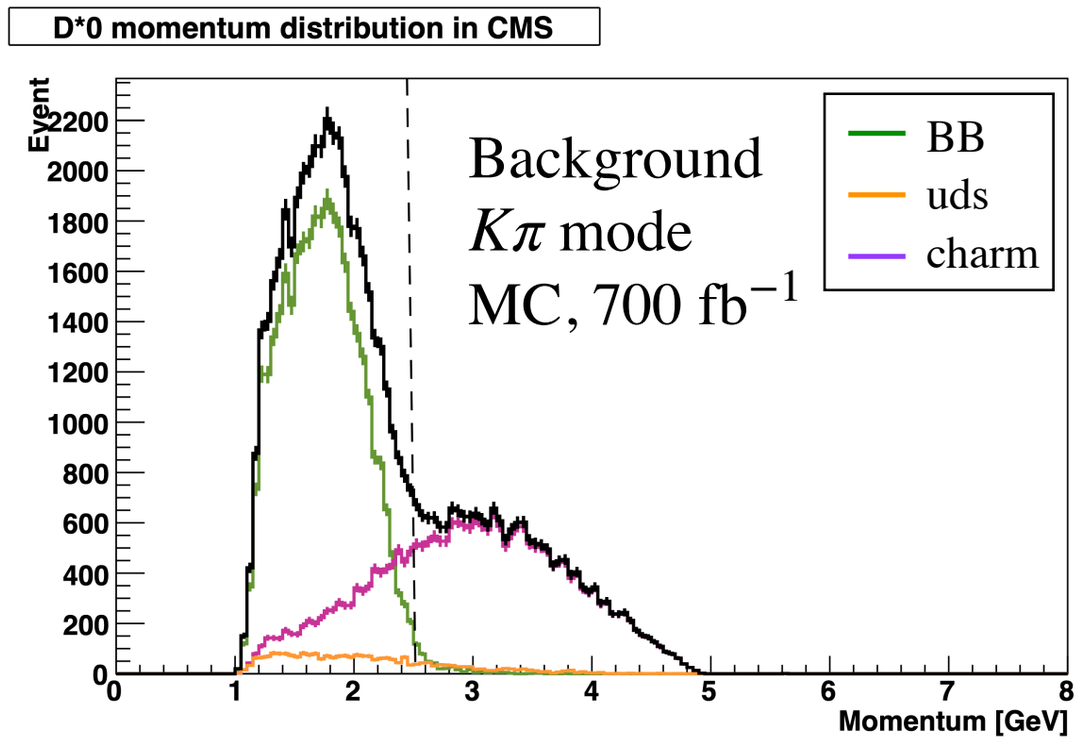
- **ΔM criteria are determined by the 3σ of signal.**





D^{*0} momentum criteria



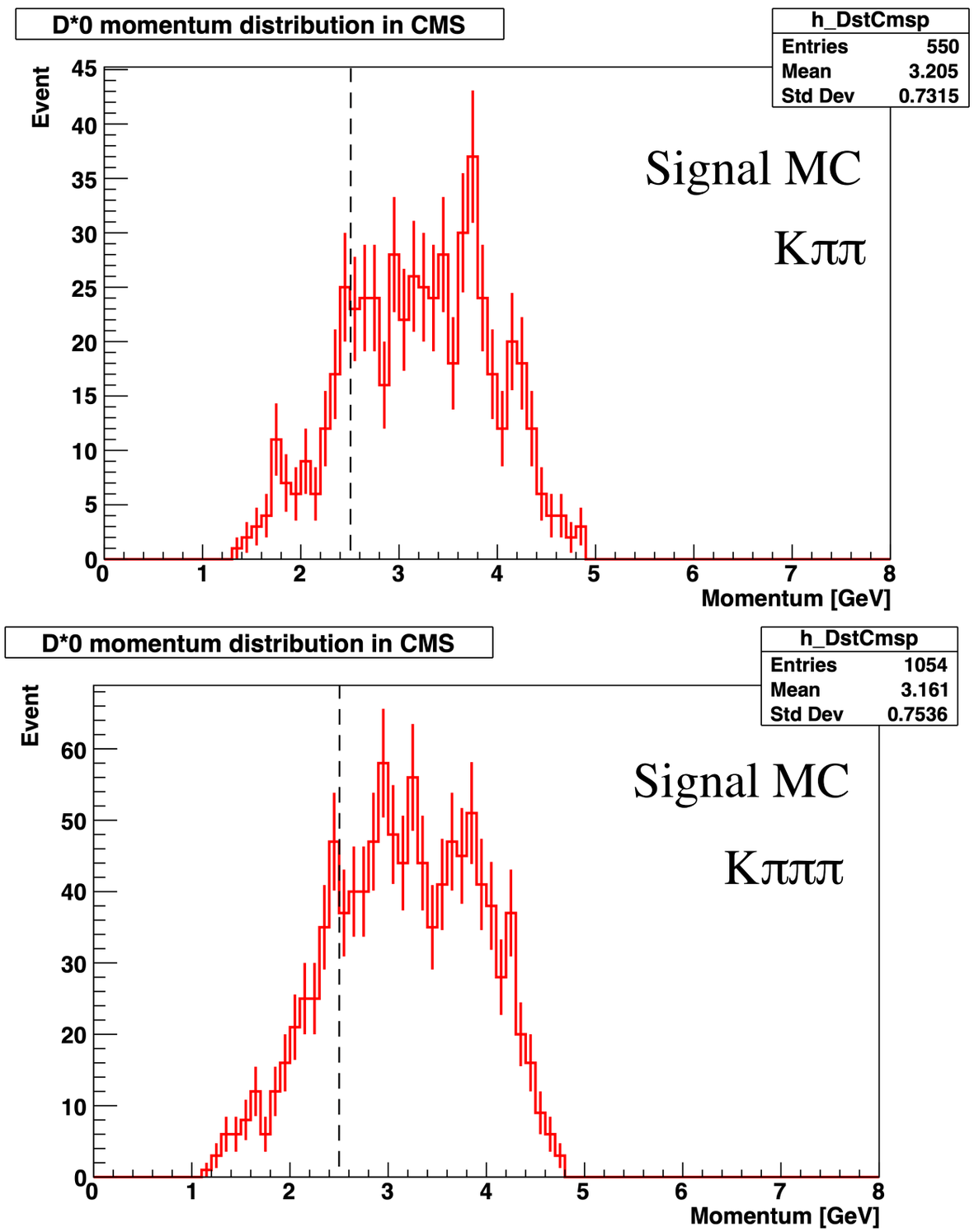


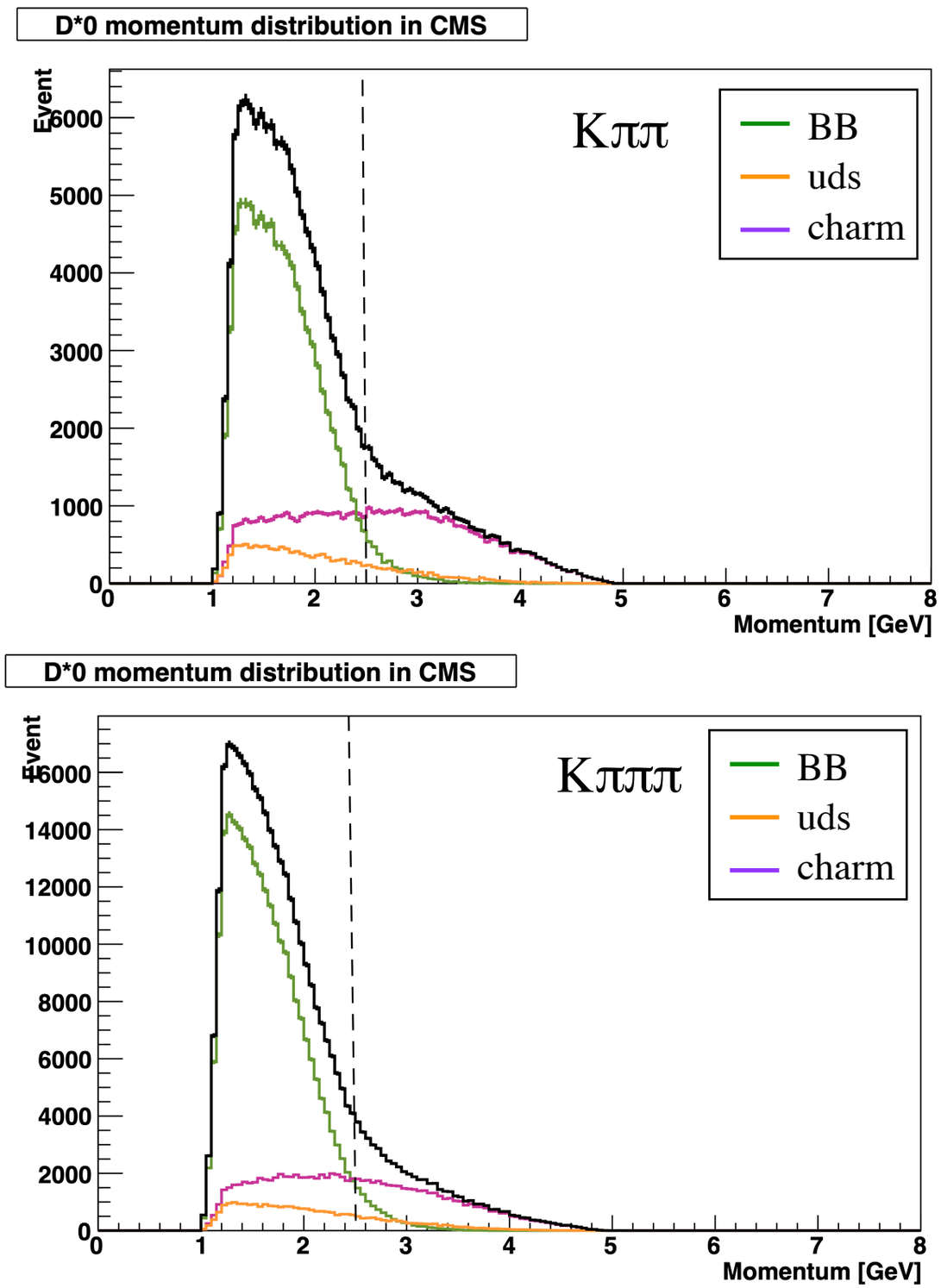
- To reduce the background, the momentum of D^{*0} is required to be $p_{D^{*0}} > 2.5$ GeV/c.

- D^{*0} from B meson decays are also excluded by this selection.

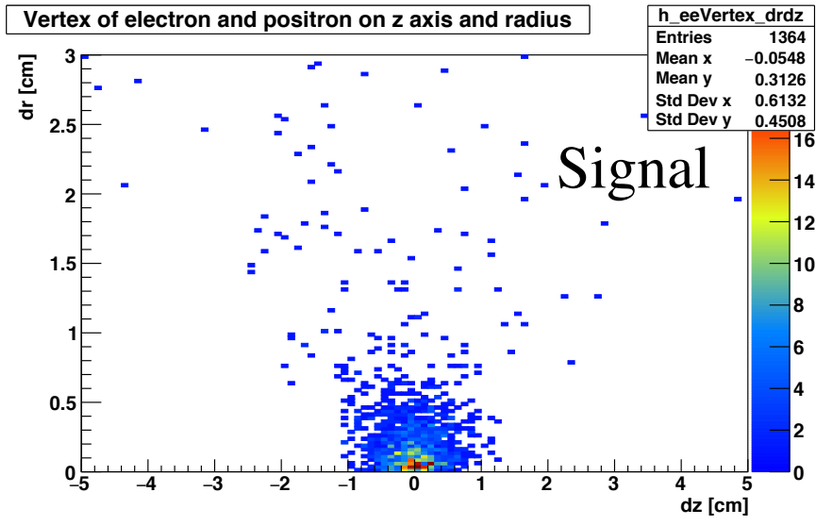
D^{*0} momentum criteria

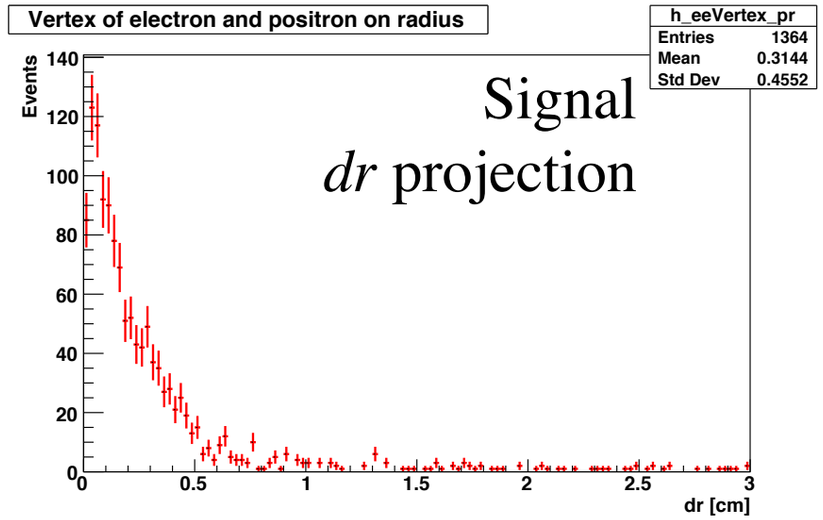
- **D^{*0} momentum criteria are set at 2.5 GeV/c for all modes.**

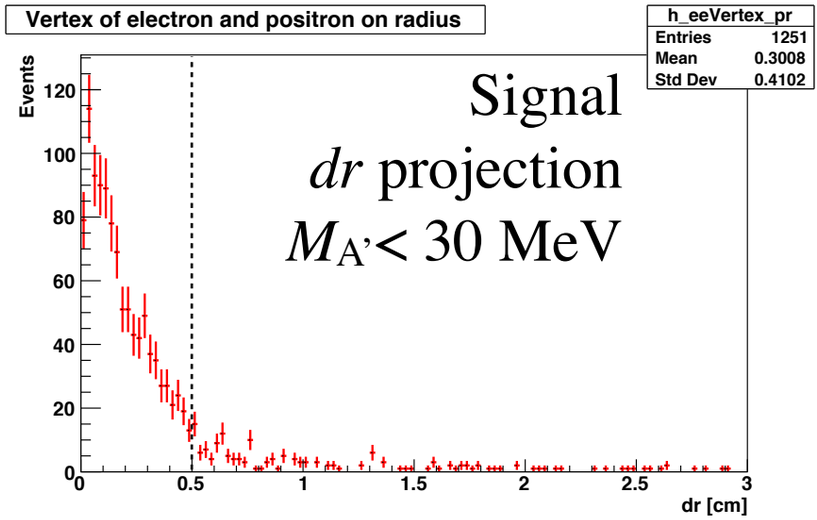


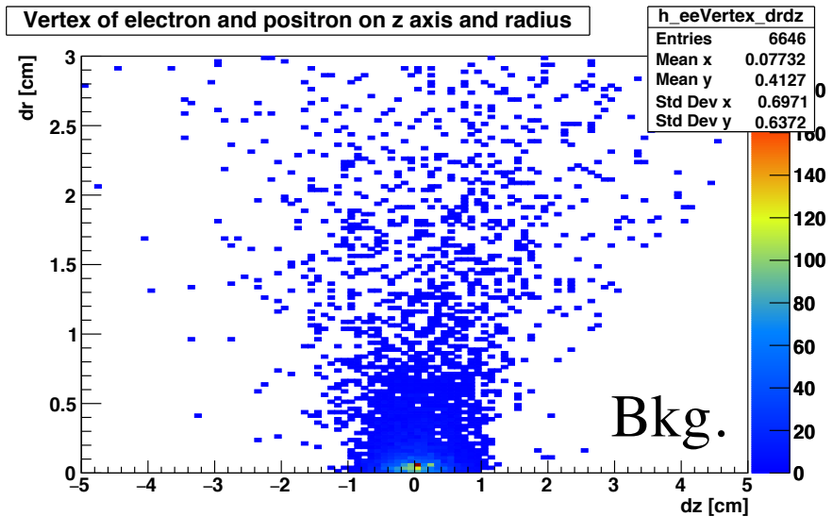


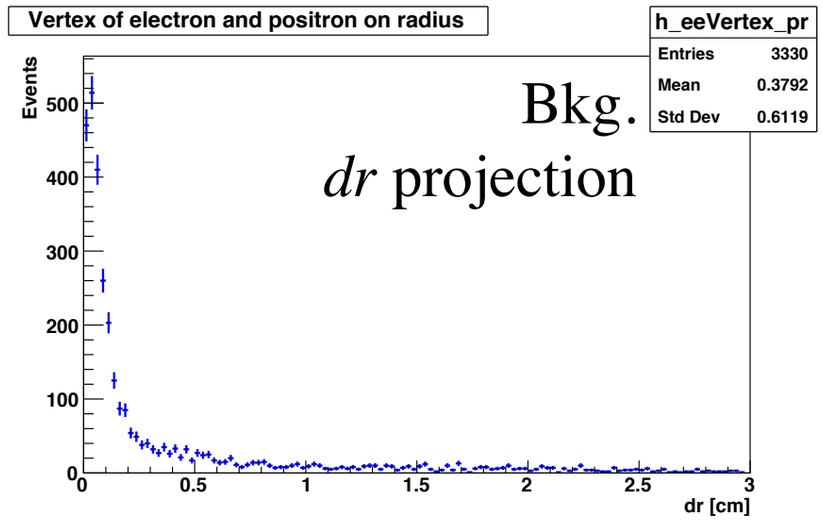
Criterion on ee vertex

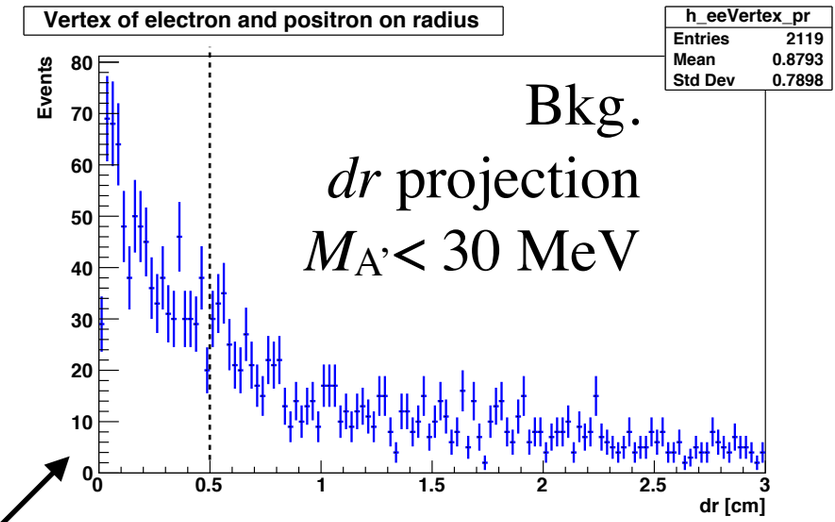


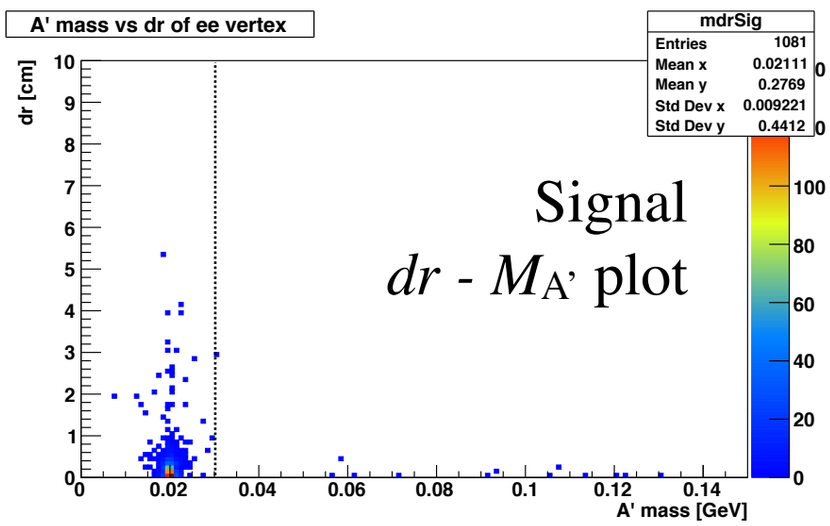


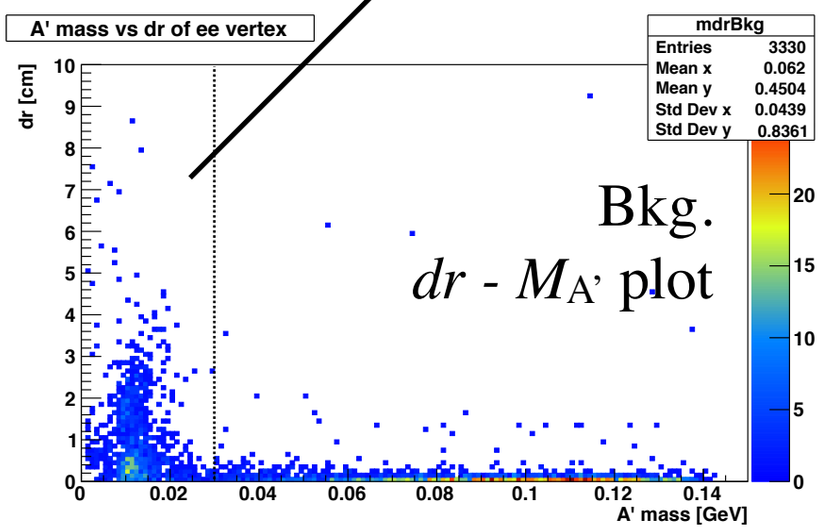












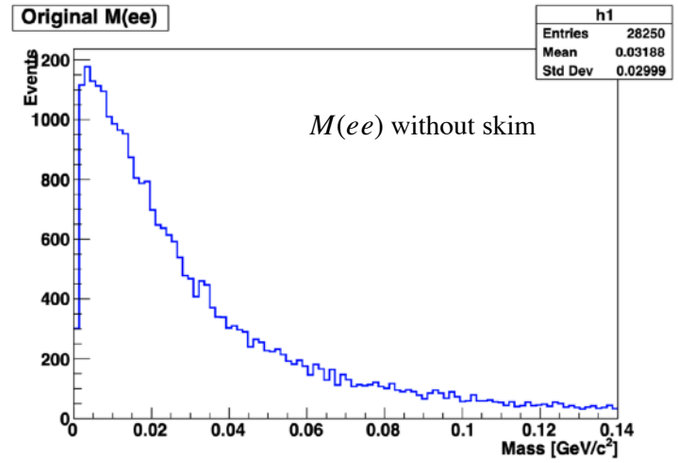
The background of $D^{*0} \to D^0 e^+ e^-$

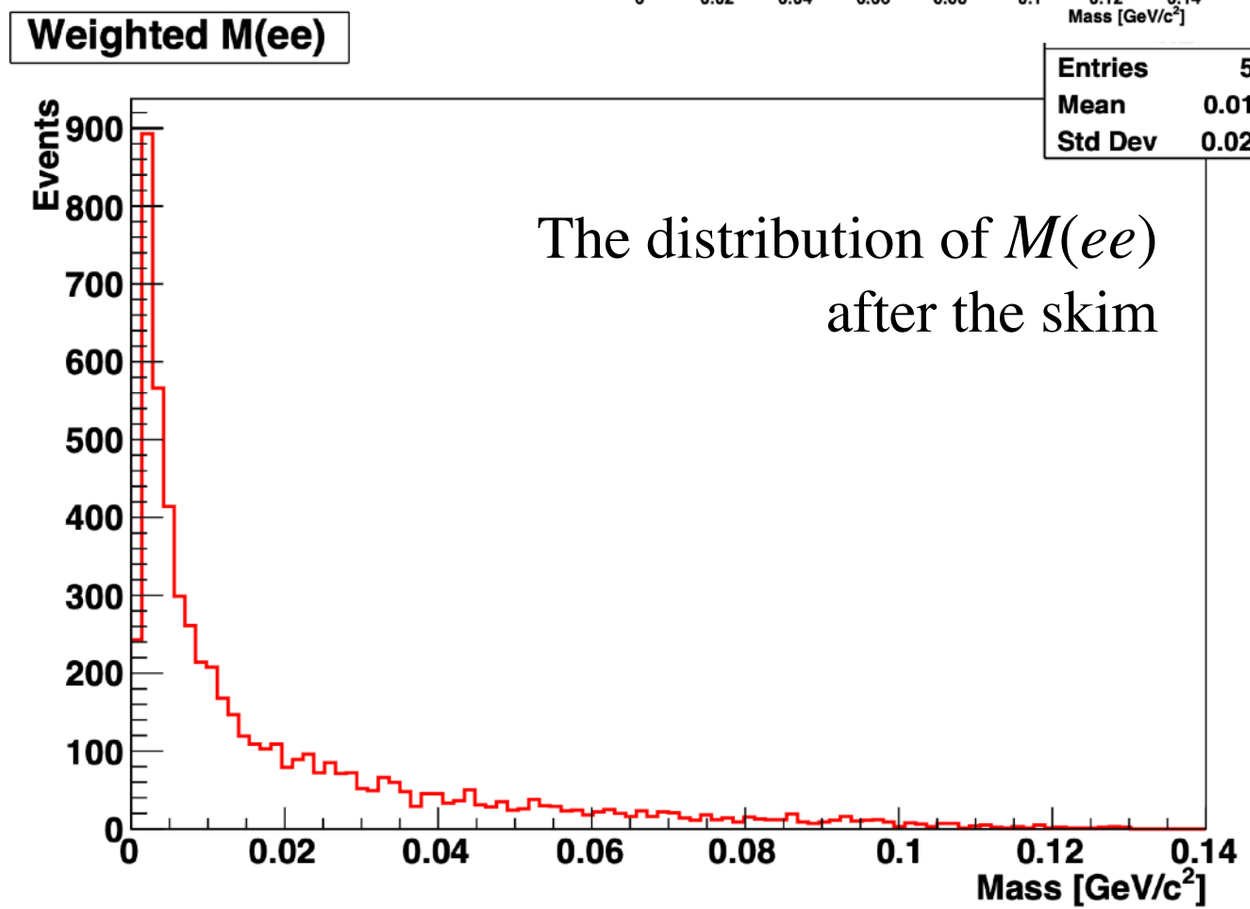
- This process is not forbidden in SM, but whose BR is not measured.

- We generated the background MC by the pdf : $\frac{p_{ee}^2}{q^4}\left(\left(\frac{q^2}{4}+m_e^2\right)+\left(\frac{q^2}{4}-m_e^2\right)\cos^2\theta\right)$

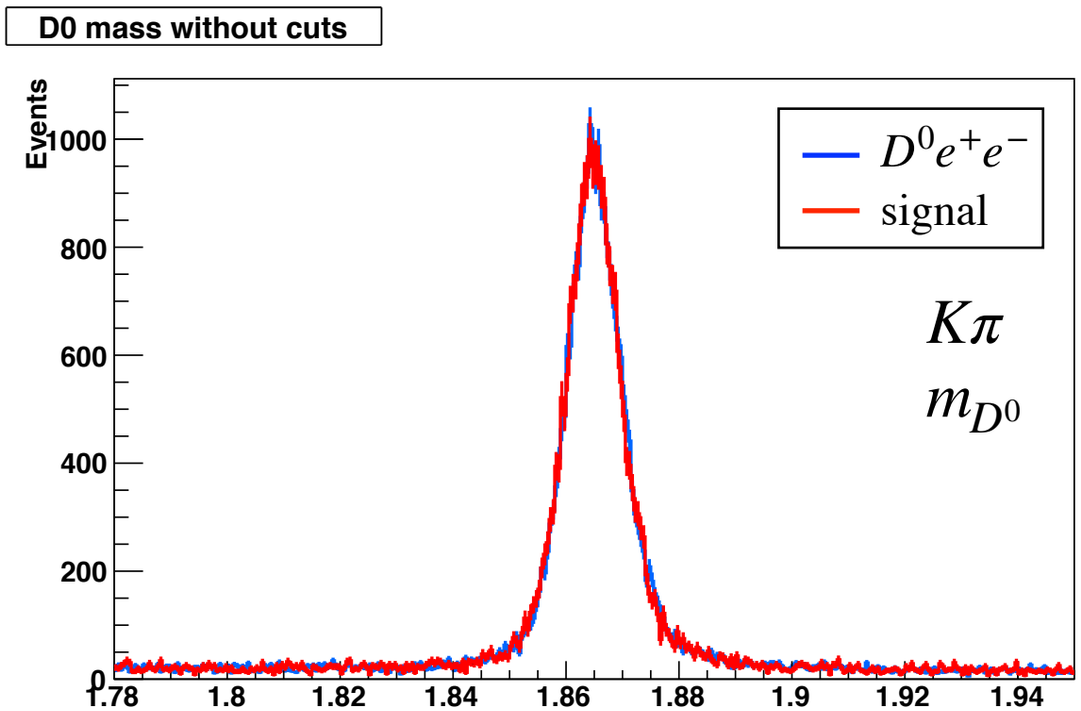
  which is based on matrix element of $D^{*0} \to D^0\gamma$.

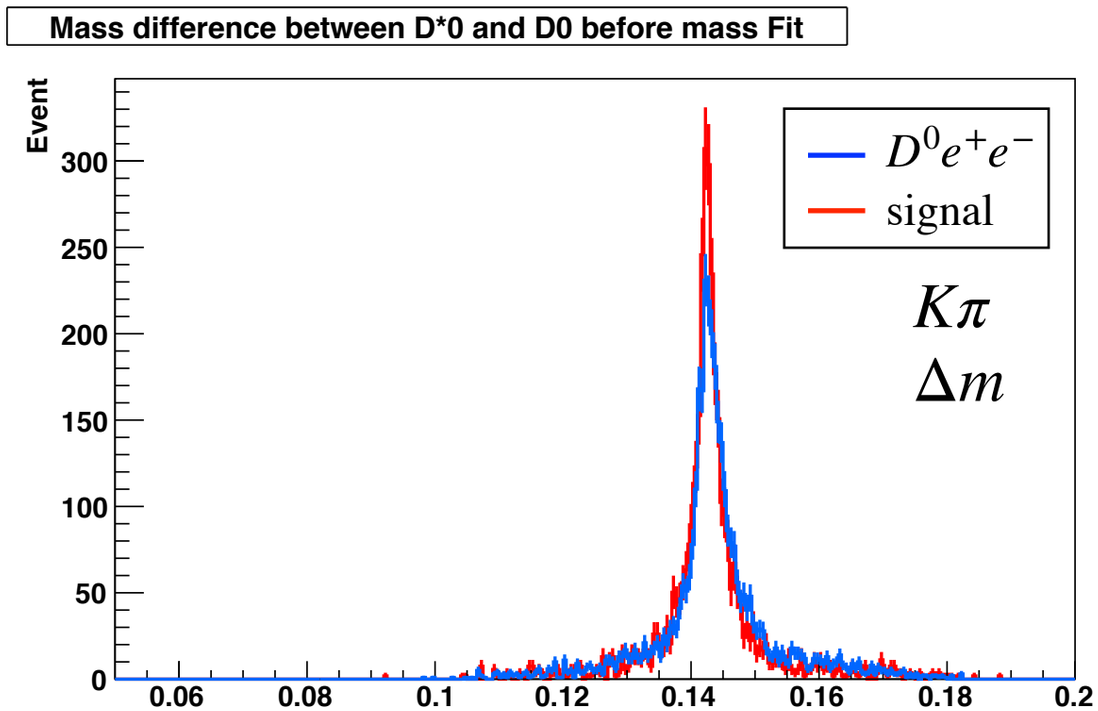
  - The generation is done by EvtGen using a Breit-Wigner distribution.
  - And then, events are skimmed to fit the pdf.

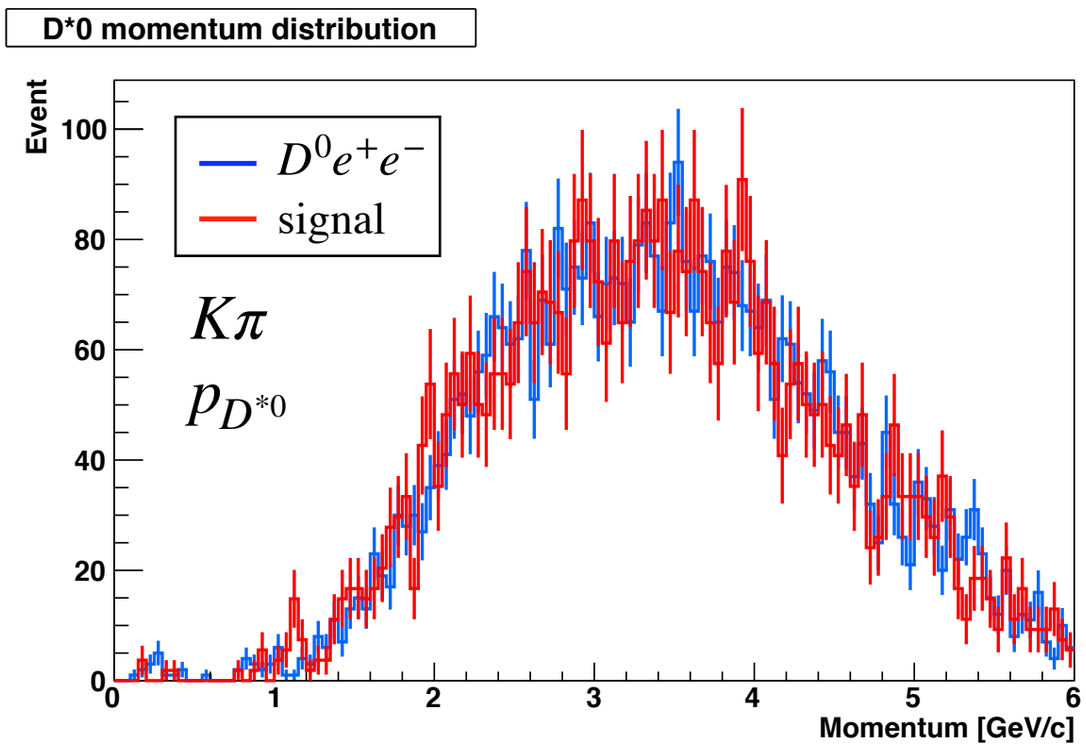


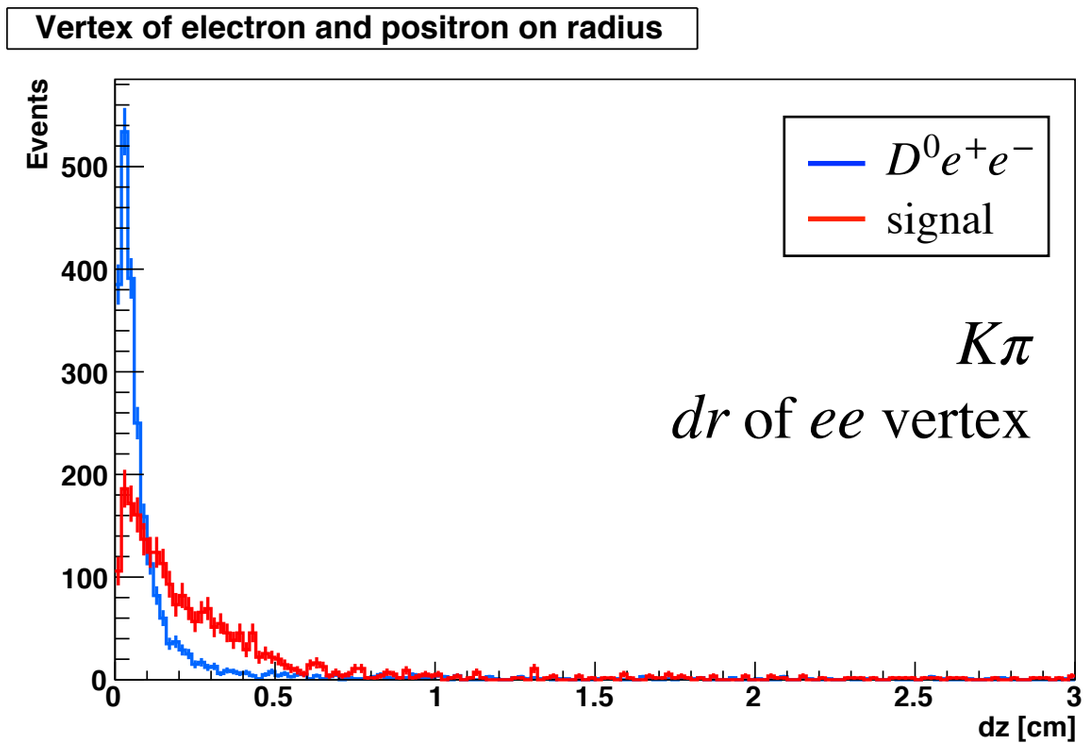


The background of $D^{*0} \to D^0 e^+ e^-$





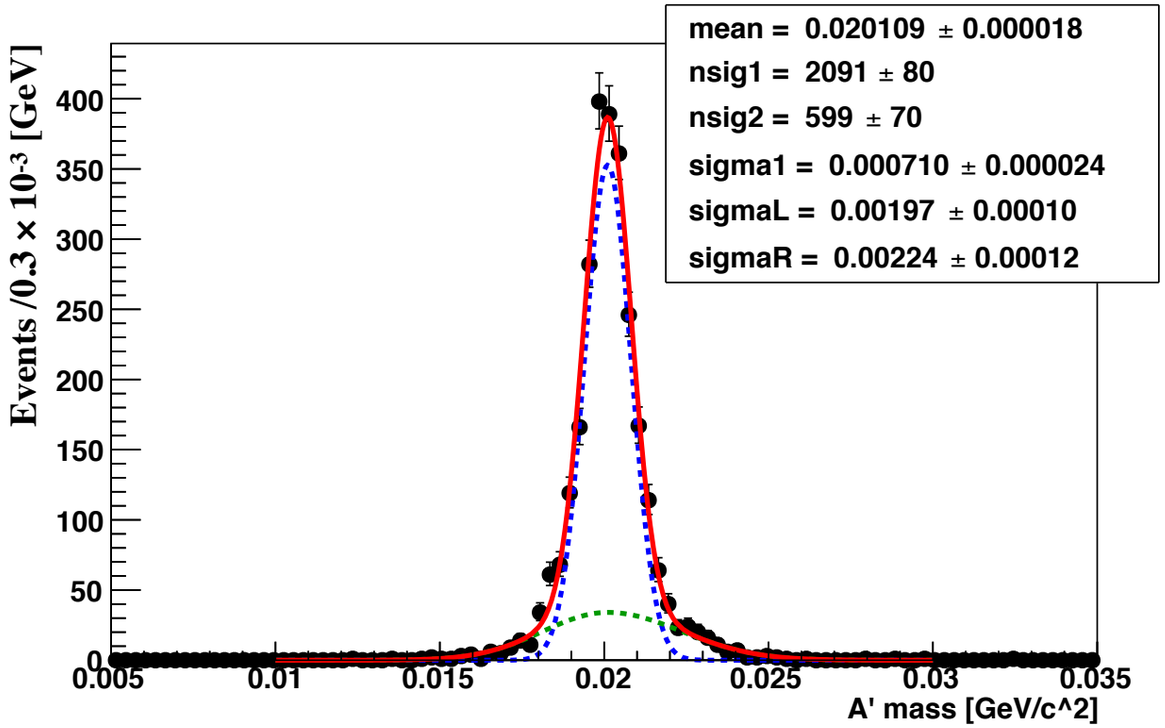




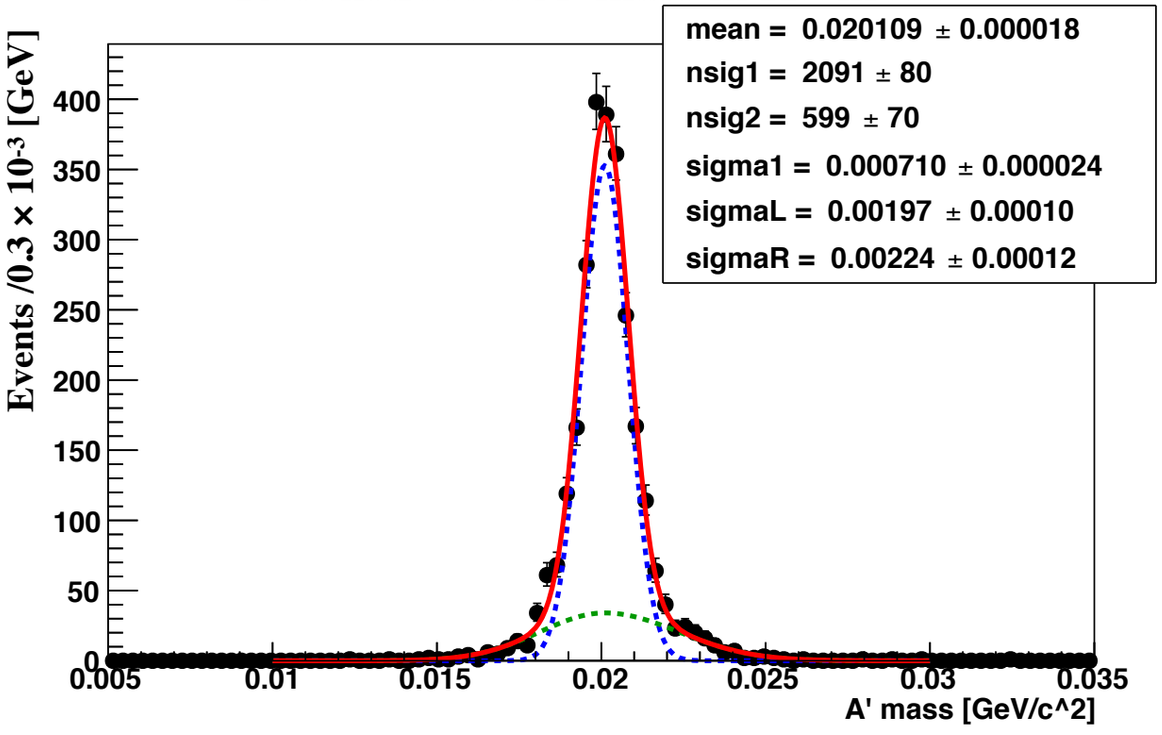
A′ mass distribution of signal MCs

Mode	Fitted yield	Generated events	Signal efficiency
$D^0 \to K^-\pi^+$	7,608 ±261	244,036	$3.12 \pm 0.11\%$
$D^0 \to K^-\pi^+\pi^0$	2,721 ±100	259,417	$1.05 \pm 0.04\%$
$D^0 \to K^-\pi^+\pi^-\pi^+$	5,492 ±133	262,707	$2.09 \pm 0.05\%$

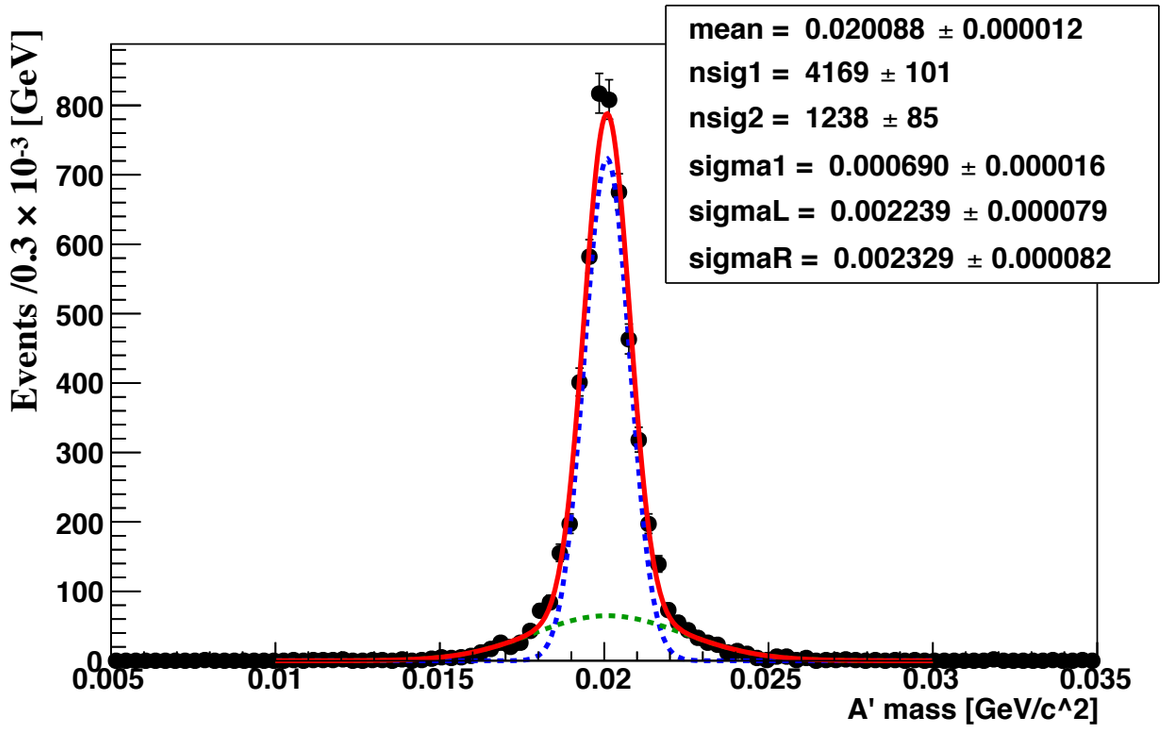
Reconstructed A′ mass in $K\pi\pi$ mode



Reconstructed A′ mass in Kπ mode



Reconstructed A′ mass in $K\pi\pi\pi$ mode



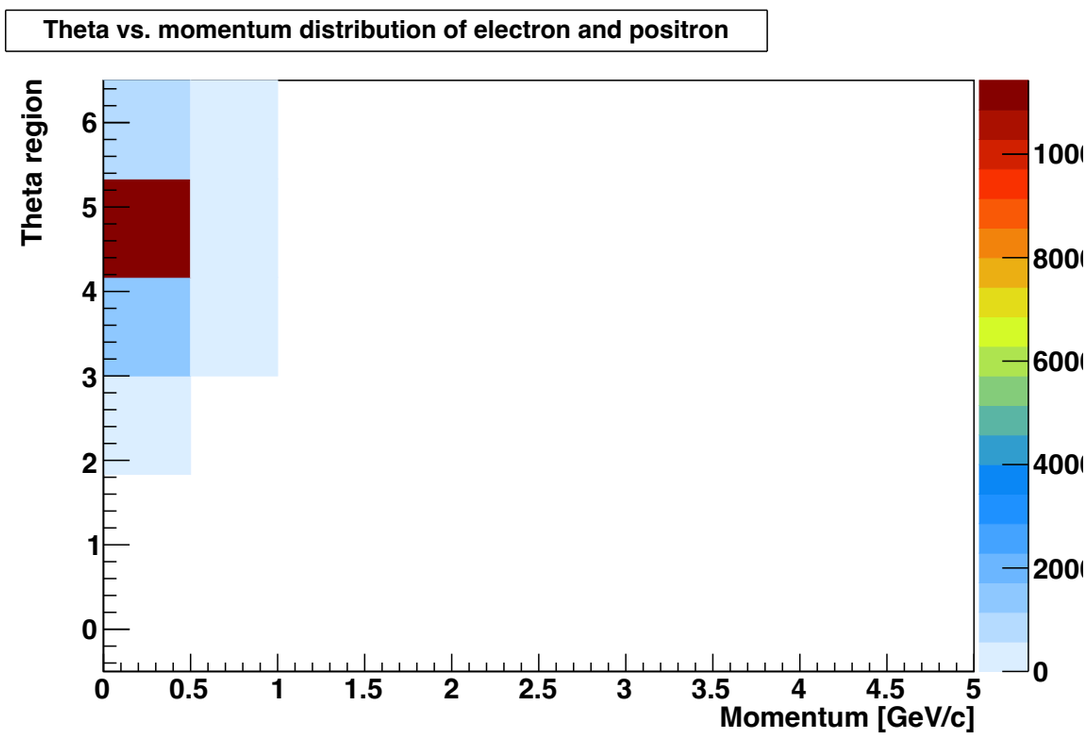
Systematics - tracking, PID, and γ finding

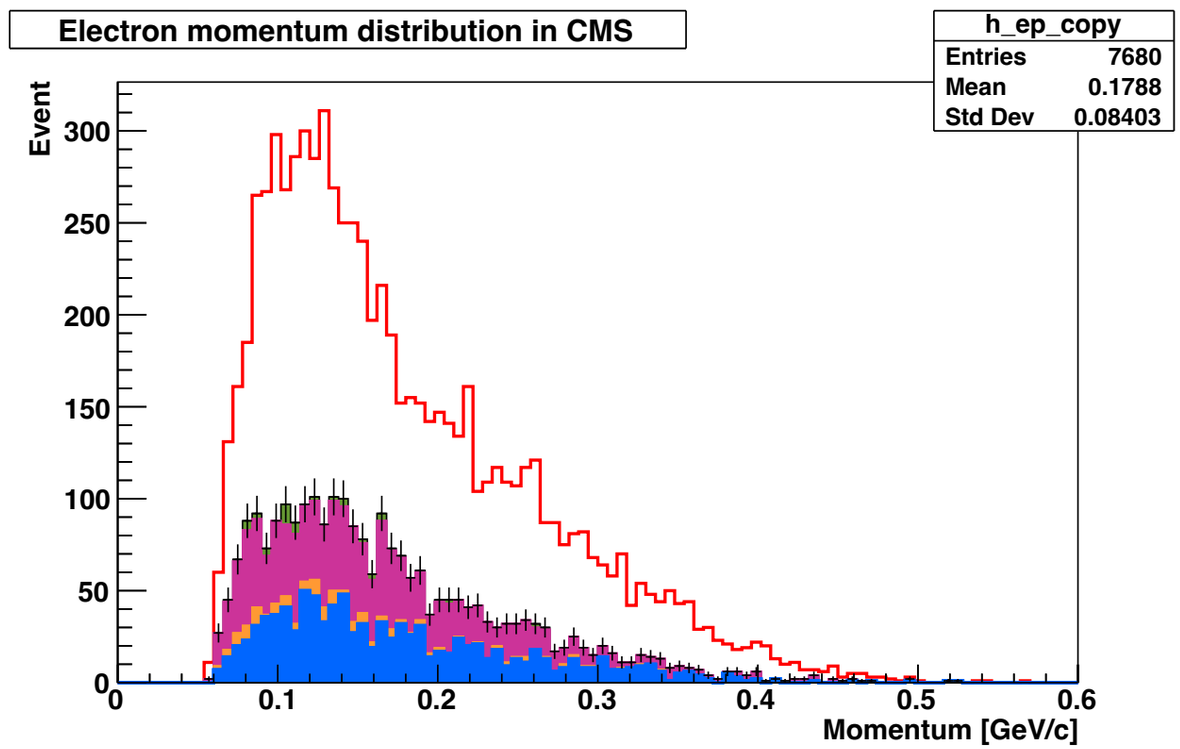
- The systematics concerning the electrons, positrons and γ are estimated by Belle official table.

- The table for tracking and PID of electrons shows the discrepancies between data and MC for each momentum and polar angle.

  -> The systematics are estimated from the weighted average of the discrepancies.

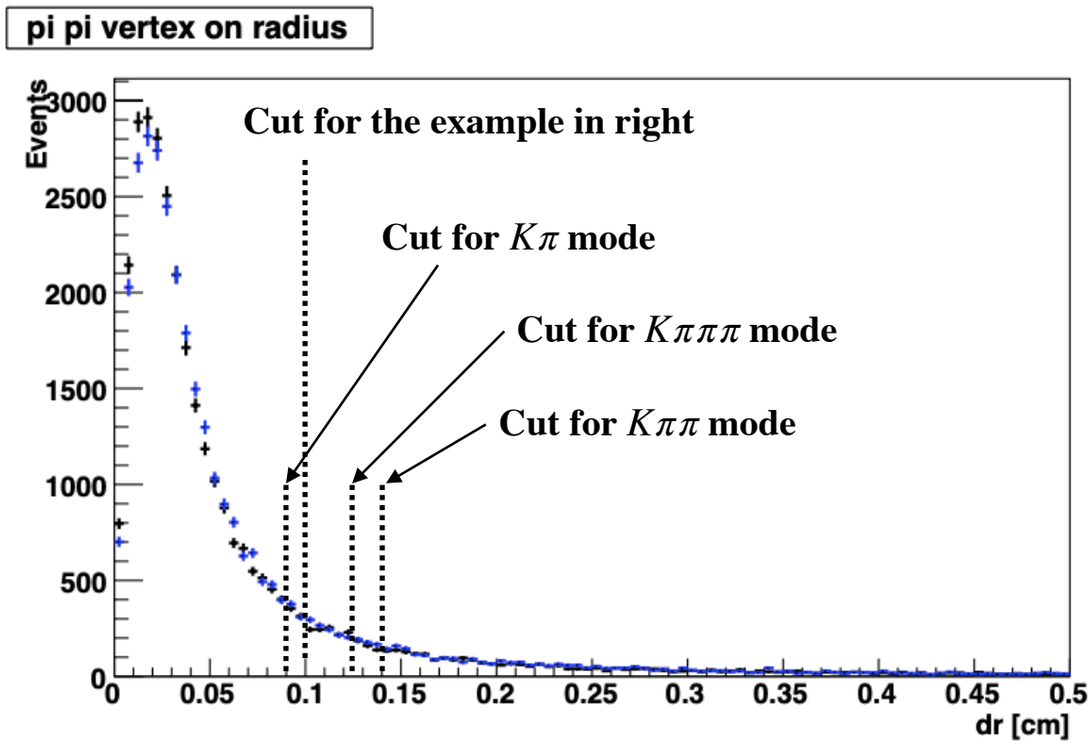
- The systematics in γ finding is also calculated by weighted average of each energy and angle.

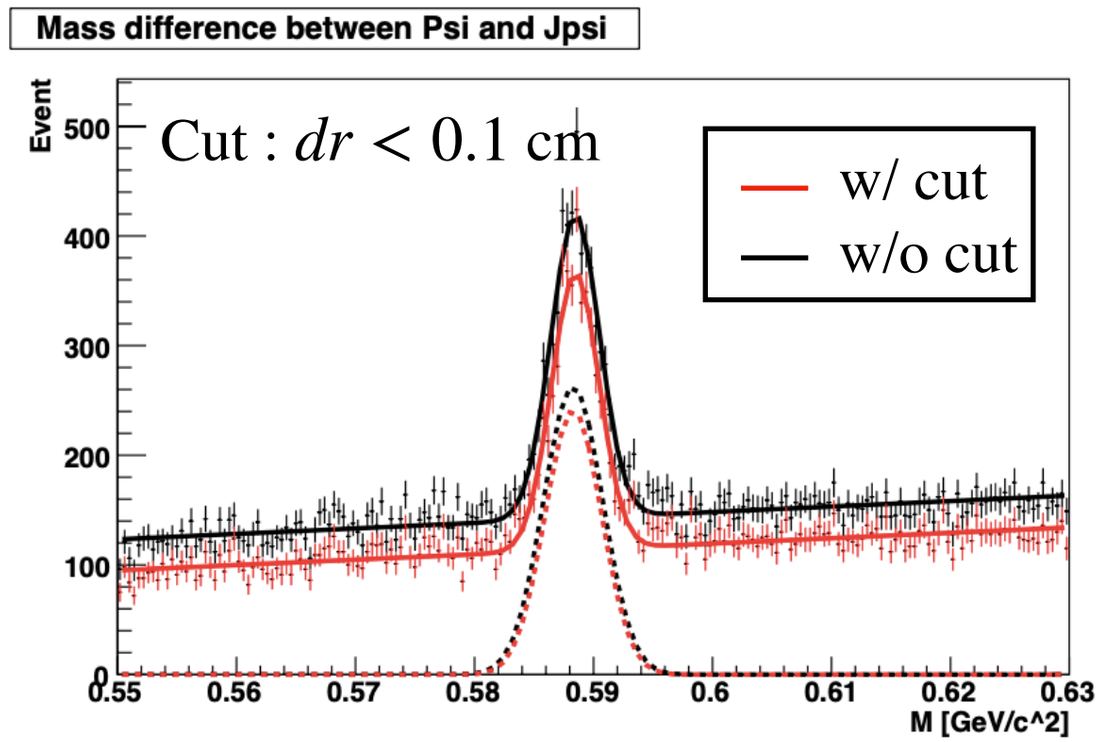




Systematics - ee vertex

- The systematics in e^+e^- vertex selection is estimated by the $\pi^+\pi^-$vertex of the control mode $\psi(2S) \to J/\psi\pi^+\pi^-$.
- The selection efficiencies of the control mode are estimated by the ratio of yields with and without cut for both of MC and Data.



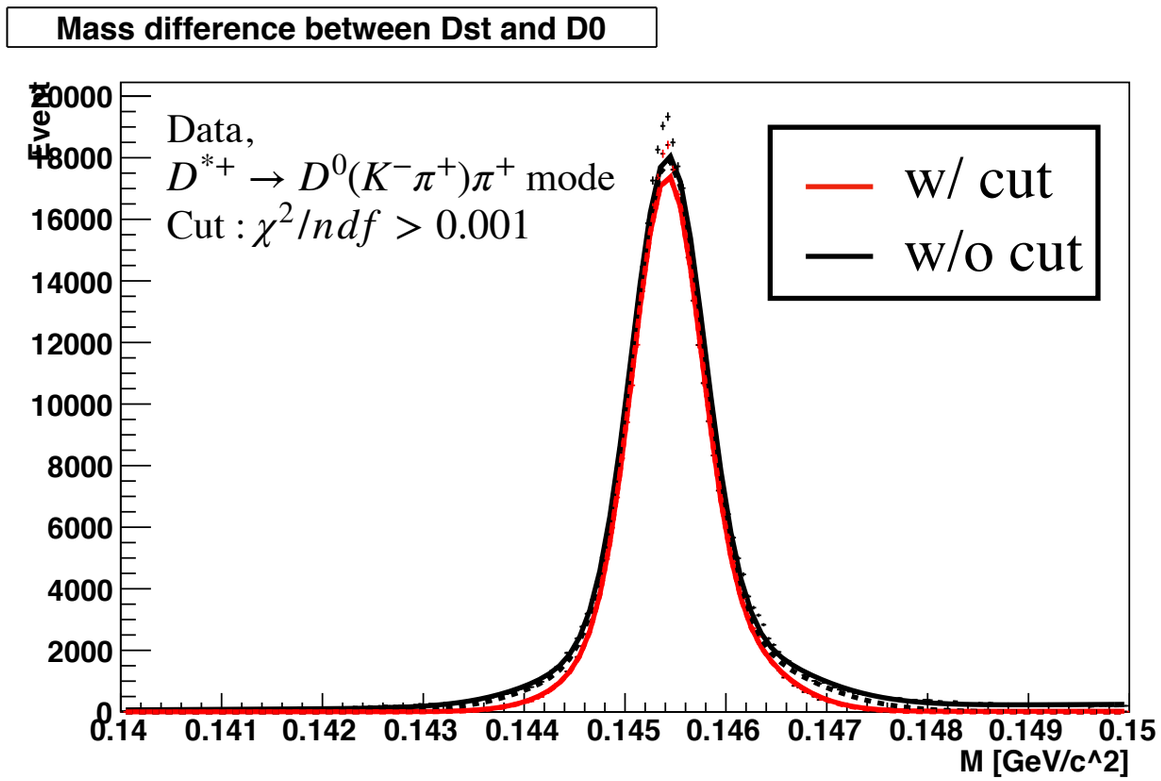


Mode	Cut value for signal mode	Efficiency of signal mode e^+e^- vertex in MC [%]	Cut value for control mode	Efficiency of control mode $\pi^+\pi^-$ vertex in MC [%]	Efficiency of control mode $\pi^+\pi^-$ vertex in data [%]	Δe [%]
$K^-\pi^+$	0.44	88.03 ± 0.99	0.092	88.15 ± 0.54	86.32 ± 0.54	-1.83 ± 0.76
$K^-\pi^+\pi^0$	0.64	93.27 ± 1.25	0.139	93.30 ± 0.42	93.05 ± 0.43	-0.25 ± 0.60
$K^-\pi^+\pi^-\pi^+$	0.66	92.35 ± 1.02	0.124	92.39 ± 0.44	90.97 ± 0.45	-1.42 ± 0.63

Systematics - χ^2/ndf of vertex fit to D^{*0}

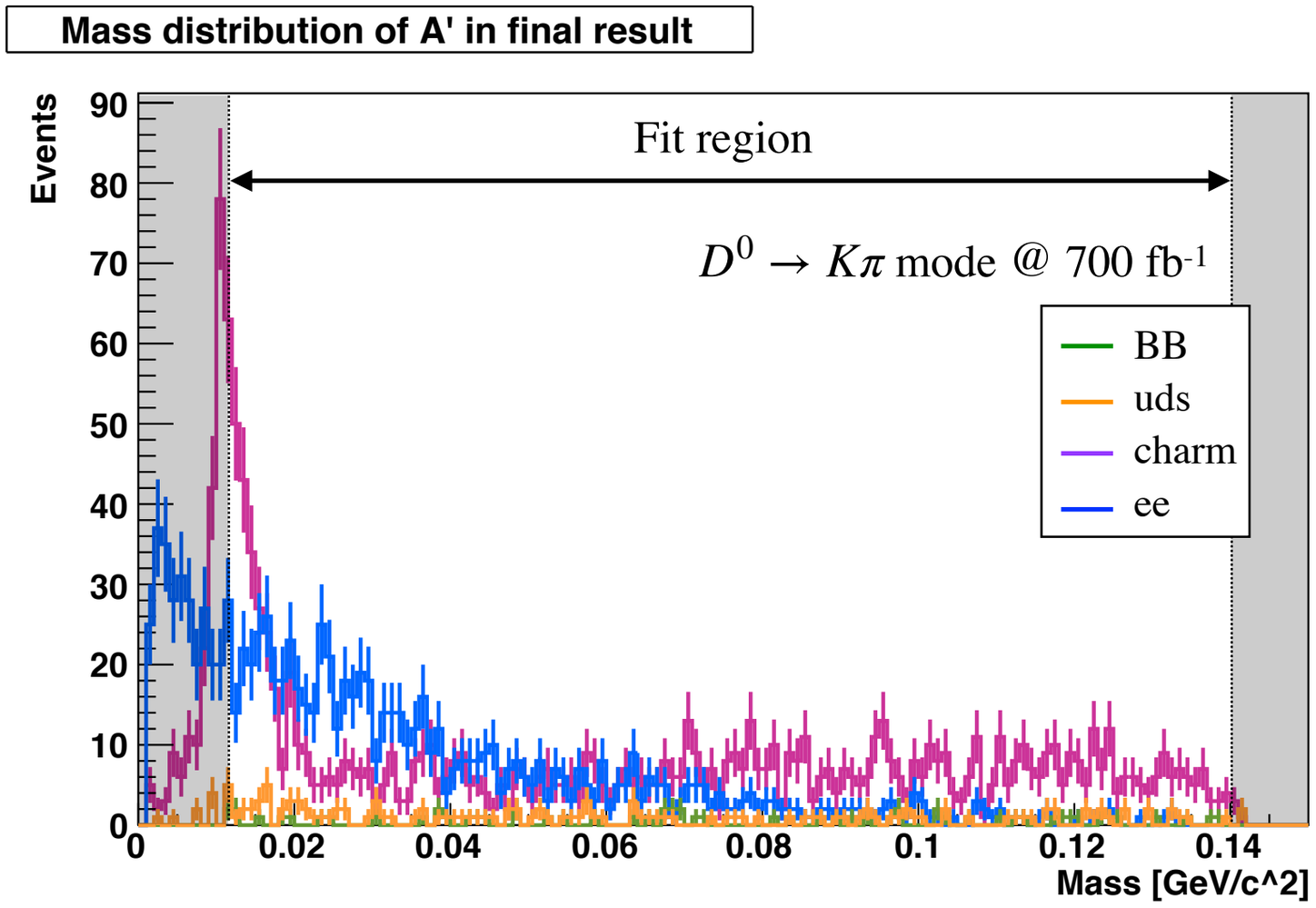
- The systematics in the vertex fit to D^{*0} is estimated by the vertex fit to D^{*+} of the control mode $D^{*+} \to D^0\pi^+$.

- The selection efficiencies of the control mode are estimated by the ratio of yields with and without cut of χ^2/ndf for both of MC and Data.



Mode	Efficiency in the signal mode $D^{*0} \to D^0 A'$ MC [%]	The threshold for the control mode $D^{*+} \to D^0\pi^+$	Efficiency in the control mode $D^{*+} \to D^0\pi^+$ MC [%]	Efficiency in the control mode $D^{*+} \to D^0\pi^+$ data [%]	Δe [%]
$K^-\pi^+$	88 ± 1	0.0178	88.0 ± 0.1	85.1 ± 0.1	-2.8 ± 0.1
$K^-\pi^+\pi^0$	85 ± 2	0.0182	85.0 ± 0.1	80.9 ± 0.1	-4.1 ± 0.1
$K^-\pi^+\pi^-\pi^+$	83 ± 1	0.0196	83.0 ± 0.1	78.5 ± 0.1	-4.5 ± 0.1

A′ mass distribution of background MCs



- There is low energy cutoff in $m_{A'} < 10$ MeV region.
- The cutoff comes from the resolution limit of Belle spectrometer.
- So, the fit region is set 0.012 - 0.14 GeV.

Decay length

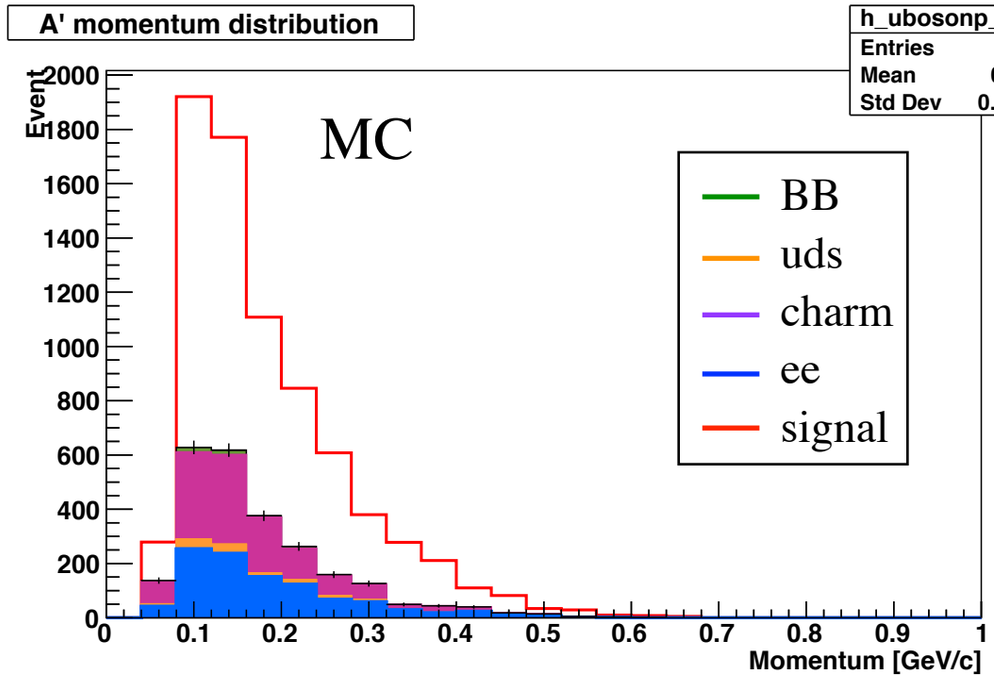
- Assuming the kinetic mixing, the decay rate of $A' \to e^+e^-$ is given as

$$\Gamma_{A'} = \frac{1}{3}\alpha\epsilon^2\left(1-\frac{4m_e^2}{m_{A'}^2}\right)^{\frac{1}{2}}\left(1+\frac{2m_e^2}{m_{A'}^2}\right)\frac{m_{A'}}{E_{A'}}$$

where α is the fine-structure constant.

- The lifetime is, using the relation of $m_e^2 \ll m_{A'}^2$,

$$c\tau = \frac{3}{\alpha}\frac{1}{\epsilon^2}\frac{E_{A'}}{m_{A'}^2}\ \text{cm}$$



- Assuming $\epsilon^2 = 10^{-4}$, $m_{A'} = 20\ \text{MeV}/c^2$ and $E_{A'} = 200\ \text{MeV}/c^2$, $c\tau \sim 0.4\ \mu\text{m}$.