Top quark properties measurements at CEPC

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The 2022 International Workshop on the High Energy Circular Electron Positron Collider

2022.10.26

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Motivation

- Top quark properties are fundamental factors in the Standard Model, also a stringent check of internal consistency of SM.
- Top quark properties are measured using top reconstruction at hadron colliders. But it is difficult to further improve the precision given dominant systematic uncertainties at hadron colliders.
- e^+e^- colliders can provide not only the top reconstruction method but also the ttbar threshold scan.

Motivation

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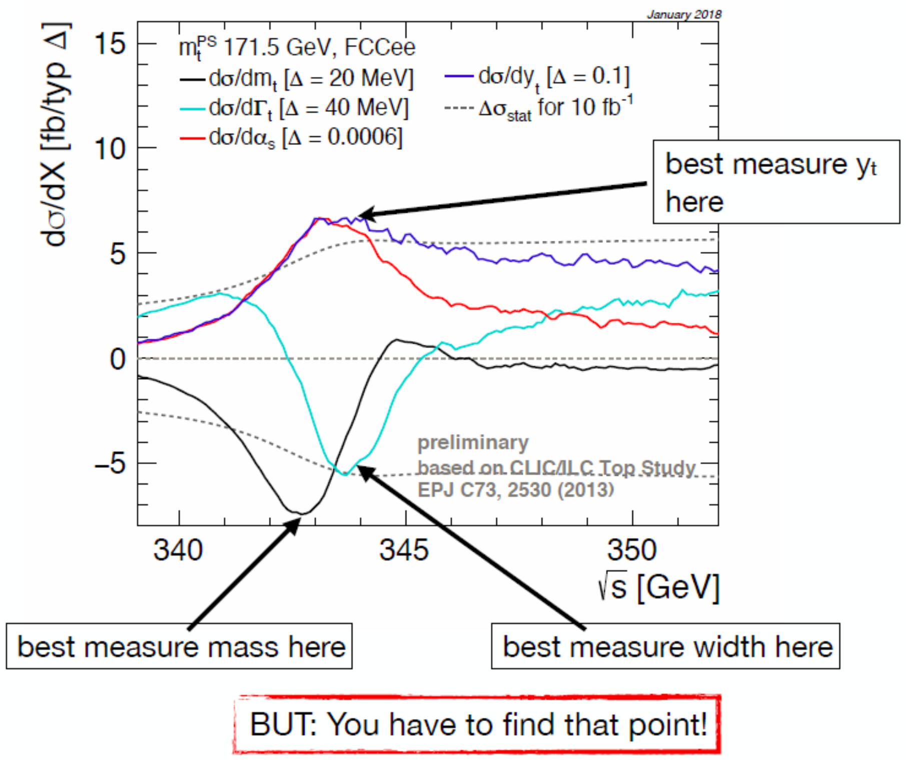
- ttbar threshold scan is made against $\sqrt{s}$ and cross section, which is direct observable.
- It brings measurements of such parameters:
  - Top mass
  - Top width
  - Top Yukawa coupling
  - α_s (strong coupling)



Our setup

- Use the package "QQbar_threshold" to calculate cross section near threshold in ee-colliders at N3LO in resummed non-relativistic perturbation theory
  - *Coulomb interactions between the quark and the antiquark leading to a strong enhancement of the cross section is included*
  - Initial state radiation (ISR) effects are also included in the package
- We incorporate Luminosity Spectrum(LS) by a simple Gaussian function with CEPC LS setup (~0.5GeV) as the energy resolution at the moment.

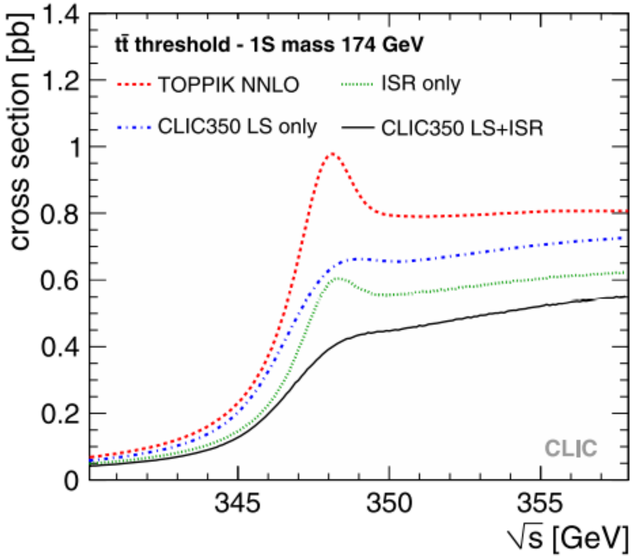


Fig. 4 Top pair production cross section from theory calculations, with the luminosity spectrum (LS) of CLIC at 350 GeV and ISR as well as for all effects combined

Method: $\sqrt{s}$ scan

- Since we are interested in the precise measurement of top properties by using threshold scan, we can try to fit the calculated models to experiment data.
- We can construct our likelihood function with 1 energy point in the following way:

$$L = P\left(D \middle| E(\sigma\left(m_{\mathrm{top}}, \Gamma_{\mathrm{top}}, \alpha_s, \sqrt{s}\right)\right), \mathcal{L}, \theta)$$

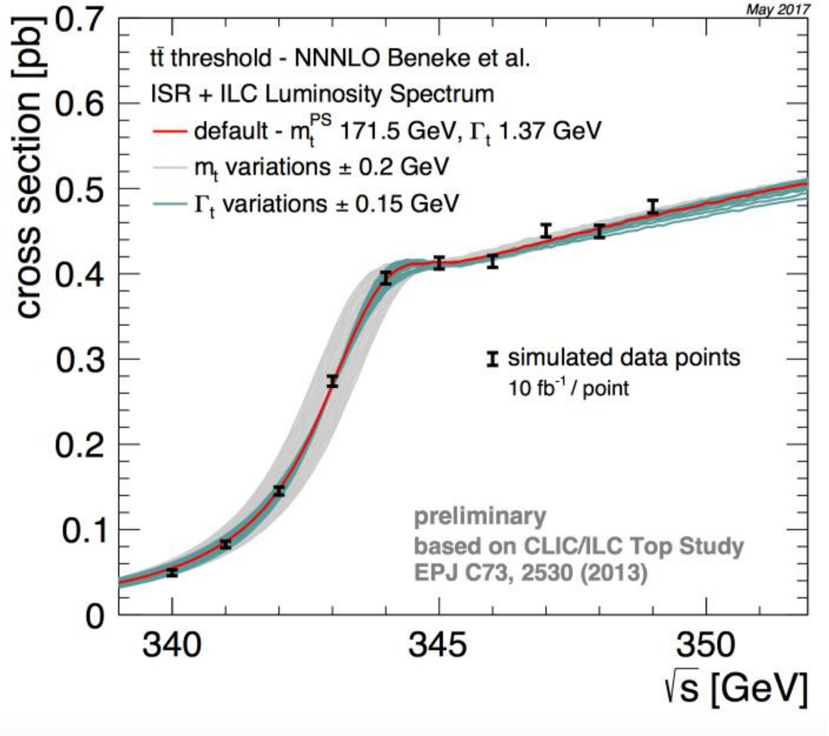
- Since we do not have real experiment data, we use QQbar_threshold to generate pseudo data instead.

Method: $\sqrt{s}$ scan

- For different top masses, we select multiple center mass energy points. To combine the statistical power of all scan points, we can multiply 1-point likelihood functions together:

$$L = \prod_i P\left(D_i \middle| E_i\left(\sigma\left(m_{\text{top}}, \Gamma_{\text{top}}, \alpha_s, \sqrt{s}\right)\right), \mathcal{L}_i, \theta\right)$$

  - i corresponds to the i-th scan point



Review

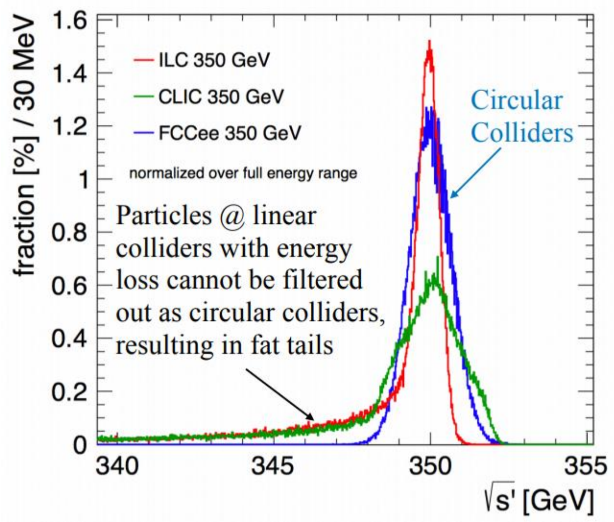
- The uncertainty of this method is tightly related to our points selection scheme.
- 1-point scheme has the best performance at its best point.
- At present we use Fisher information to crosscheck the best point.
- We proposed to scan the point with low luminosity to identify the best point.

Setup

- Top properties:
  - The mass of the top quark is set to be 171.5 GeV.
  - The width of the top quark is set to be 1.33 GeV.
  - The α_s of the top quark is set to be 0.1184.
- Background:
  - It is assumed that the nominal background contribution is well known both from theory and from measurements below threshold, so that the nominal number of background events can be subtracted from the signal.
  - Only signal events included.

Setup

- Channels: Semi-leptonic channel and full-hadronic channel are considered.
- The LS of CEPC compared to others.



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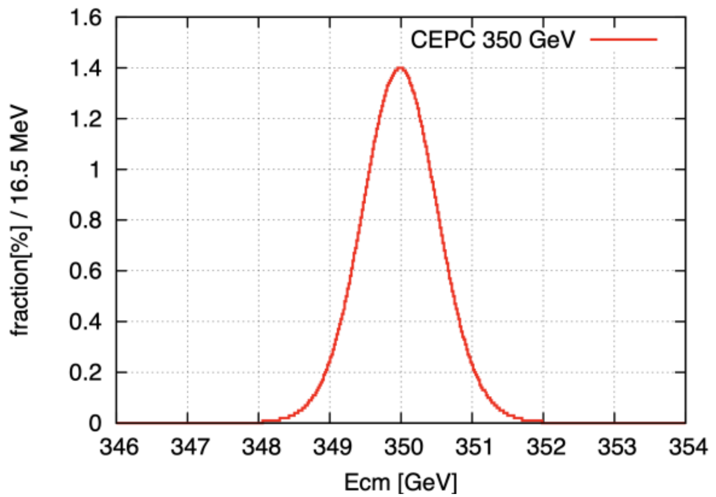
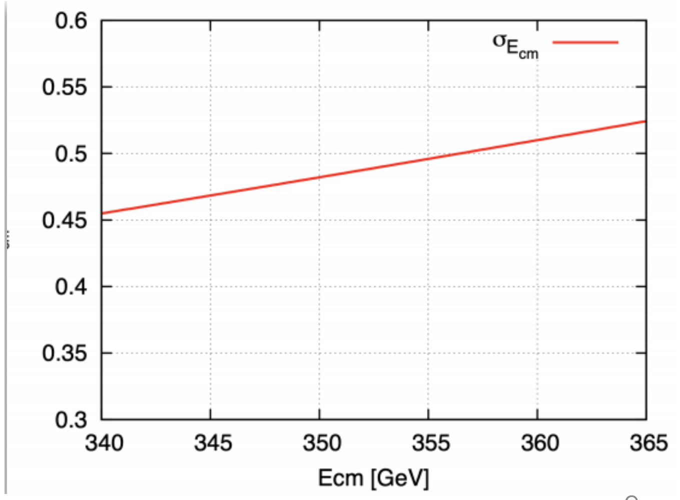




Provided by Yiwei Wang

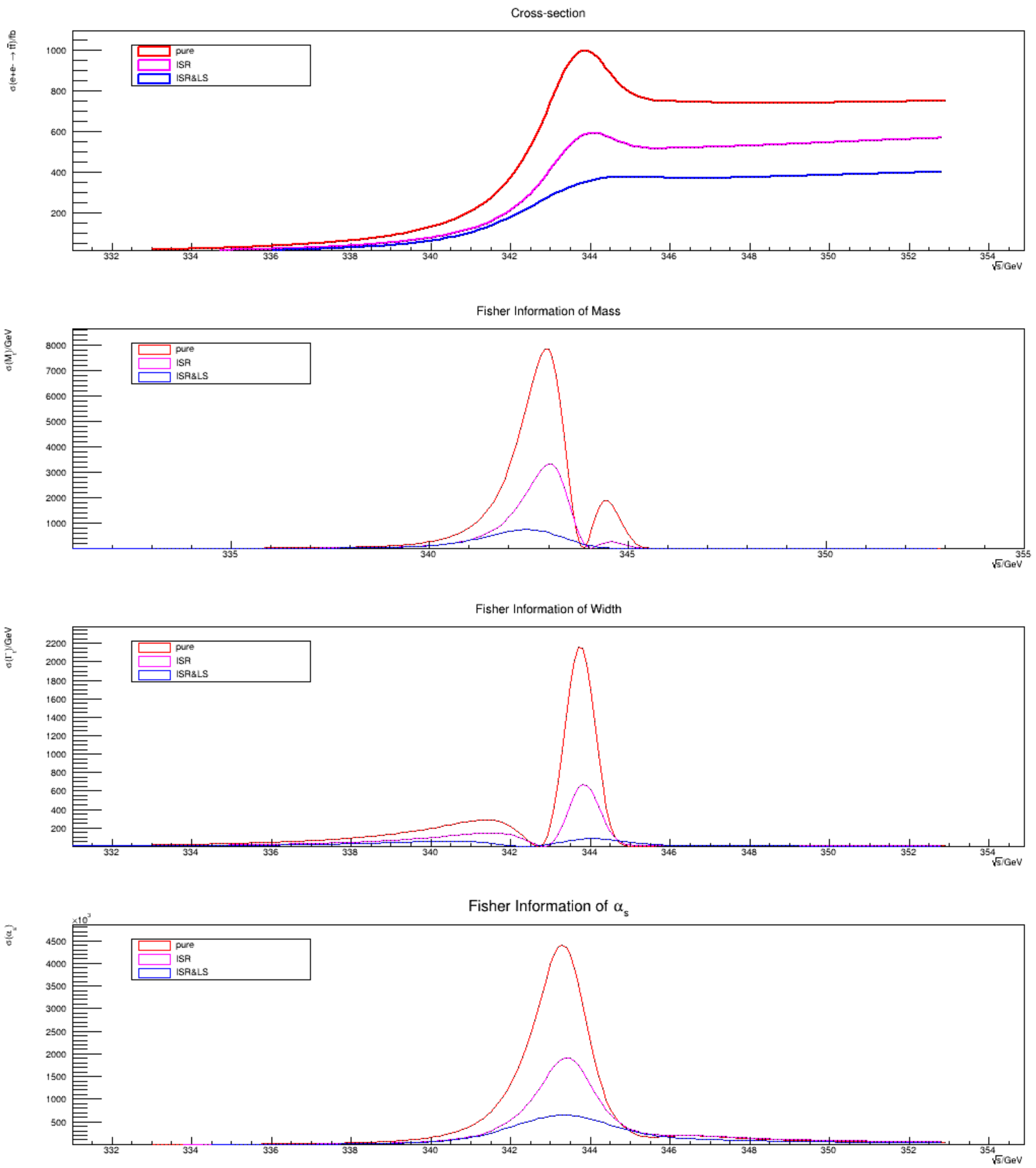
Fisher Information

- At a certain centre-of-mass energy ($\sqrt{s}$), one can consider the measured cross-section (σ) as a random variable which follows a Gaussian distribution (G) with its mean value centered at the true cross-section ($\sigma_0(\sqrt{s}$, θ)), where θ can be top quark properties like top quark mass $\boldsymbol{m_t}$ and width Γ_t as well as the strong coupling α_s).
- Thus the Fisher information reads

$$
I(\sqrt{s}) = \int \left(\frac{\partial log(G(\sigma|\sigma_0(\sqrt{s},\theta),\sqrt{\sigma_0(\sqrt{s},\theta)}))}{\partial\theta}\right)^2
\times G(\sigma|\sigma_0(\sqrt{s},\theta),\sqrt{\sigma_0(\sqrt{s},\theta)})d\sigma
$$

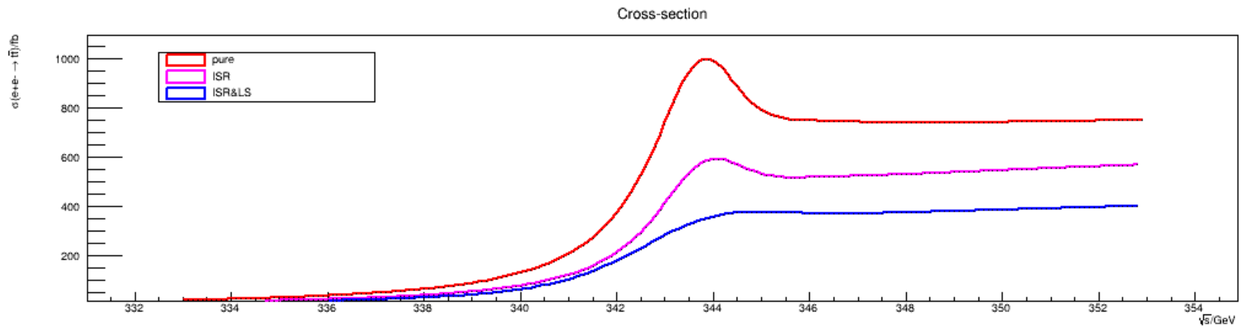
Fisher Information

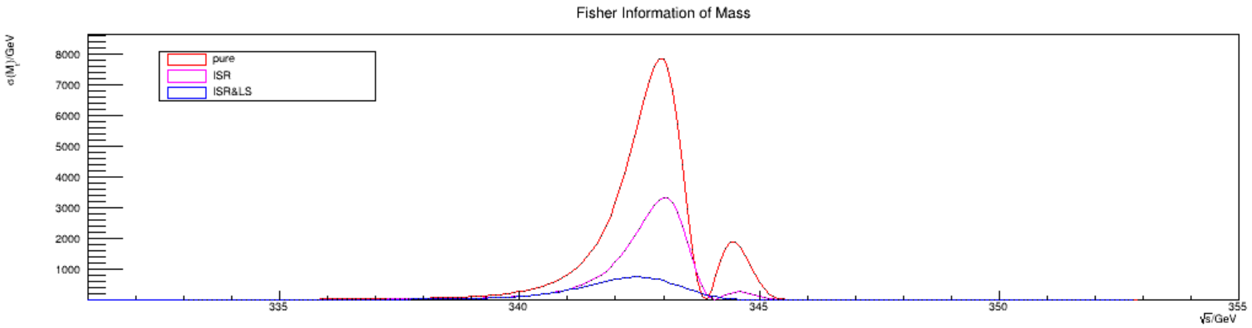
- Calculating fisher information is concerned with its first derivative.
- Larger amplitudes implies richer information and higher sensitivities.

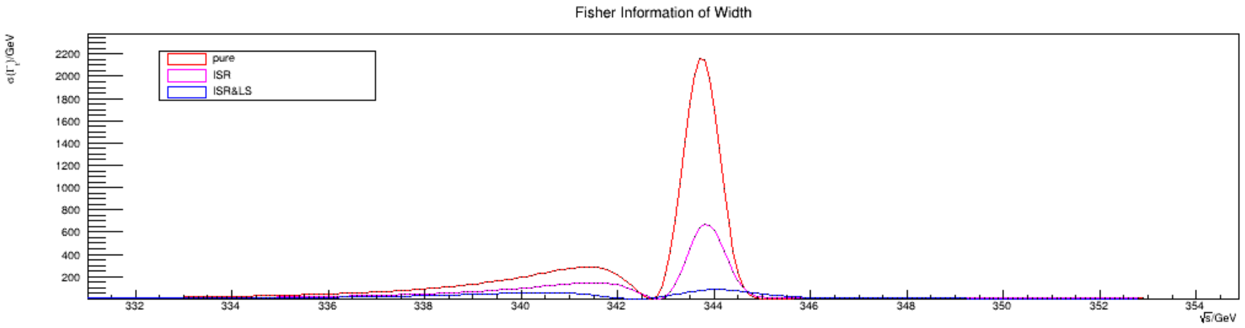


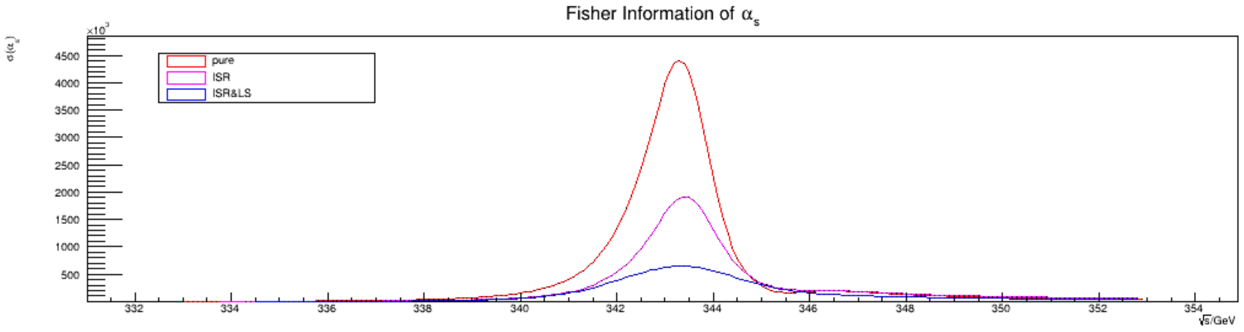
Fisher Information

- Best mass point: 342.75 GeV
- Best width point: 344.00 GeV
- Best α_s point: 343.5 GeV









Expected precision

- With the CEPC setup, limited to the total luminosity of 100 $\mathbf{fb}^{-1}$, top quark mass, width and α_s are measured individually at their optimal energy points.

Parameter of interest	Statistical uncertainty
m_t	9.06 MeV
Γ_t	25.86 MeV
α_s	0.000394

CLIC results:

POI	Stat. uncertainty
m_t	34 MeV
Γ_t	
α_s	0.0009

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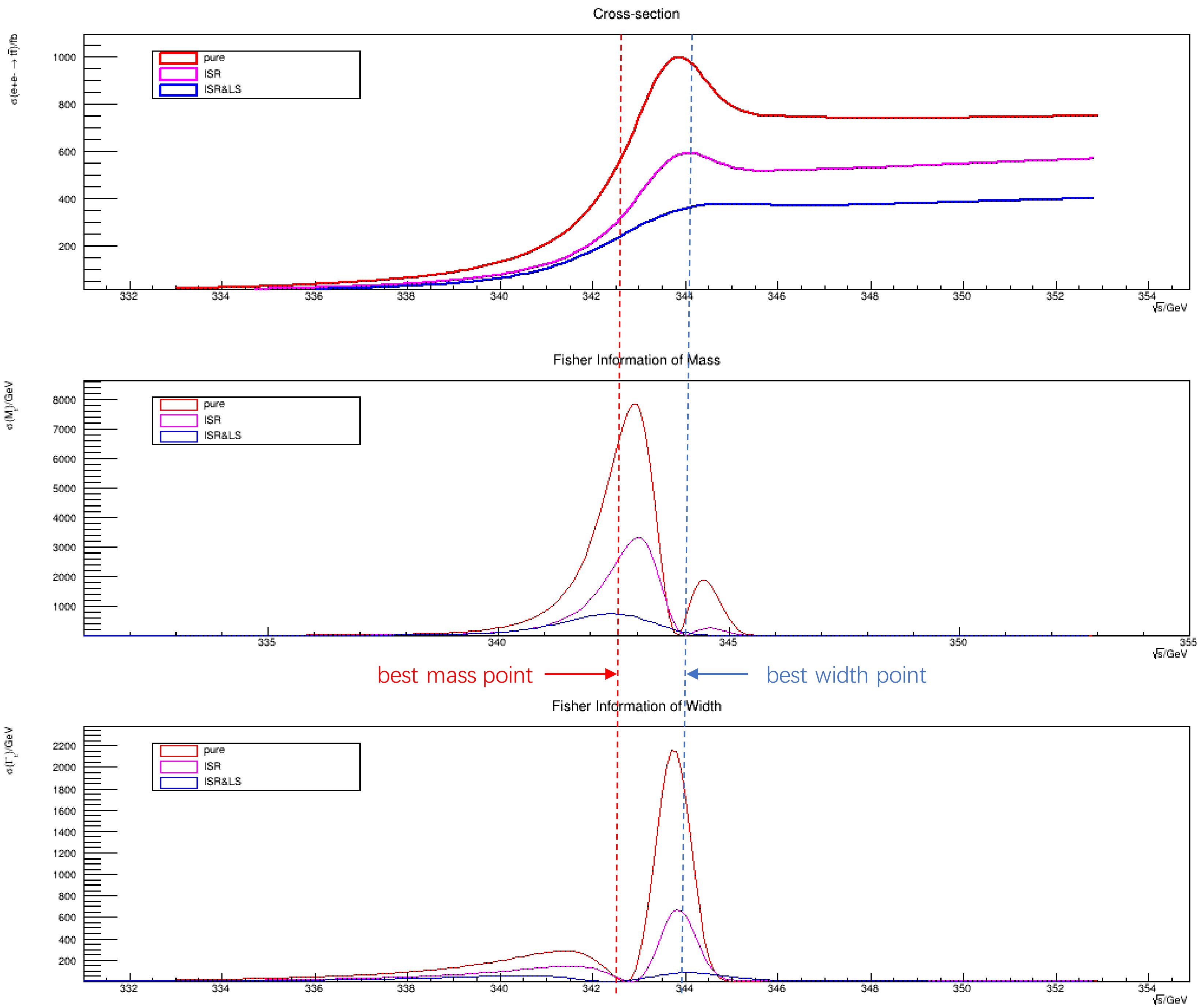
The result on width

- To estimate the expected precision of width, we consider such situation: we give luminosity to both the best mass point and the best width point, {342.75, 344.00}, while keeping the total luminosity unchanged. The results are listed below.

Luminosity/fb^{-1}	Mass precision/MeV	Width precision/MeV
{100, 0}	9.06	342.734
{80, 20}	10.25	57.2656
{50, 50}	12.75	35.918
{20, 80}	19.23	29.6094
{0, 100}	>50	25.8594

- This way we are sacrificing the precision on mass for the precision on width.
- On the FI figure we can see that 344.00 can be the worst point for mass.



The result on α_s

- Then we do the same thing on α_s. The centre-of-mass energies are {342.75, 343.5}.

Luminosity/fb^{-1}	Mass precision/MeV	α_s precision
{100, 0}	9.06	0.000402
{80, 20}	9.94	0.000401
{50, 50}	10.94	0.000399
{20, 80}	12.71	0.000394
{0, 100}	14.32	0.000389

Effect from Luminosity Spectrum

- To improve the precision of top properties measurement, the effect from luminosity spectrum need to be investigated.
- To gain the direct-viewing influence of luminosity spectrum, the energy width is decreased by 20% and 50%. The results are listed below.

	Error/MeV
Keep total CEPC LS	9.06
Reduce 20% of the LS	8.94
Reduce 50% of the LS	8.40

Uncertainty from Theory

- The theory uncertainty of the overall normalization of the cross section is in that case fully absorbed by an uncertainty of the top mass. The results are listed below.

Cross-section uncertainty	Error
1%	9 MeV
3%	26 MeV

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When assuming a 1 % and a 3 % uncertainty, the uncertainty of top mass is 18 MeV and 56 MeV.

Uncertainty of the background

- The background is considered to be subtracted cleanly from the observed data. Therefore, an imperfect background description could also lead to uncertainty.
- Considering the background uncertainty as 1% optimistically and 5% conservatively, a measurement uncertainty of top quark mass of 4 MeV and 18 MeV is reached.

Background uncertainty	Error
1%	4 MeV
5%	18 MeV

Uncertainty from Beam

- In CEPC, the beam can cause the shift in centre-of-mass energy.
- In tt scan, the shift can be 1.8* $\sqrt{2}$=2.55 MeV.
- The shift can contribute to the change of the median value of top mass.

	Higgs mode	Z mode	WW scan	$t\bar{t}$ scan
E_{beam}/GeV	120	45	80	175
X_{edge}/m	6.163 52	9.296 86	7.103 43	5.572 76
X_{beam}/m	1.879 35	5.011 78	2.819 03	1.288 68
δX_{edge}/m		2.6×10^{-5}		
δX_{beam}/m		6×10^{-8}		
δE_{beam}/MeV	1.0	0.3	0.6	1.8

G.Y. Tang et al, Rev. Sci. Instrum. 91, 033109 (2020)

	Median Value	Delta
plus	171.4980 GeV	-2 MeV
minus	171.5010 GeV	+1 MeV

Uncertainty of the Luminosity Spectrum

- Variations on the spread of the luminosity spectrum, i.e. the energy width of the luminosity spectrum 10% and 20% are considered.

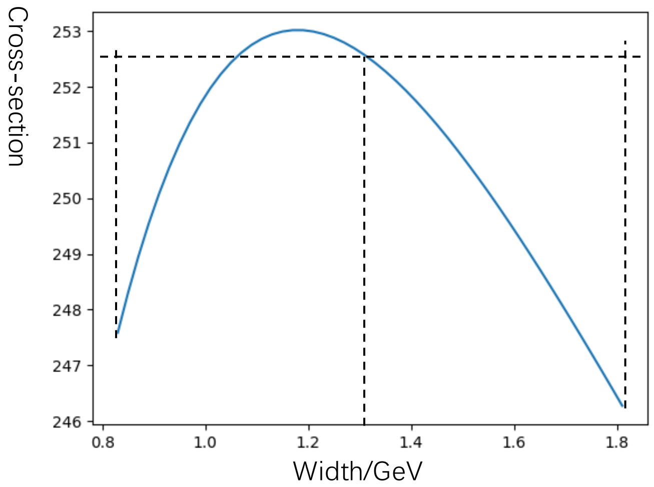
LS uncertainty	Error
10%	3 MeV
20%	5 MeV

Uncertainty caused by width and α_s

- The variation of α_s and width which can also cause the uncertainty on mass, is studied by considering 0.0007 variation on α_s and 0.5 GeV on width.

Fluctuation	Width (0.5 GeV)	α_s (0.0007)
plus	-32 MeV	15.5 MeV
minus	-10.5 MeV	-16.5 MeV

- When we change width, whether larger or smaller, the cross-section becomes smaller. Note that the default width is 1.33 GeV and the variation is 0.5 GeV.



Summary

- The statistic uncertainties of top mass, width and α_s are given.
- The reduction of LS can only do little on improving the performance of top mass precision.
- Beam uncertainty and theoretical uncertainty are considered on top mass.
  - 3% fluctuation on theory can make great contribution to the uncertainty.
- The uncertainty of the background, luminosity spectrum, width and α_s are provided.
- The paper has been uploaded to arXiv and submitted to EPJC.

Source	m_{top} precision (MeV)	
	Optimistic	Conservative
Statistics	9	9
Theory	9	26
Background	4	18
Beam energy	2	2
Luminosity spectrum	3	5
Total	14	34

Thank you!

Back-up

Multiple points or 1 point?

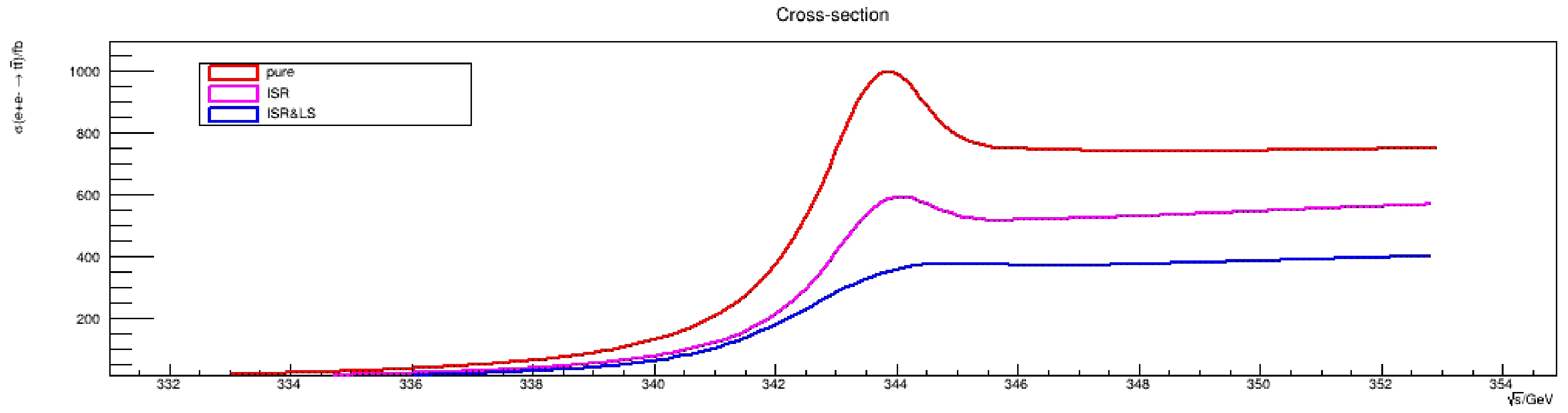
- With the total luminosity limited to 100 fb−1 , we discuss the optimal scan strategy with only statistical uncertainty in this section.
- Firstly, the luminosity is evenly allocated to each centre-of-mass energy scan point. Using the Fisher information as a guide, one can propose various grids of collision energy and evaluate the sensitivities.
- The following grids are tested.
  - 8-point grid: {341, 342, 342.5, 342.75, 343, 343.5, 344.5, 345} GeV
  - 6-point grid: {342, 342.5, 342.75, 343, 343.5, 344.5} GeV
  - 4-point grid: {342.5, 342.75, 343, 343.5} GeV
  - 1-point grid: {342.75} GeV

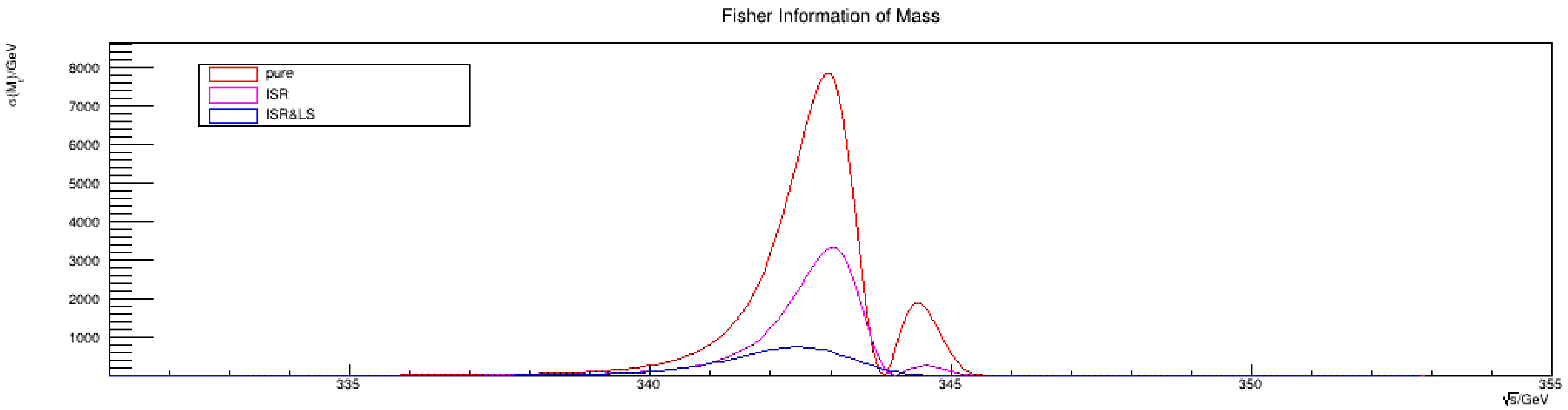
Multiple points or 1 point?

- Among these schemes, the energy point most sensitive to top mass that is indicated by Fisher information is included.
- The likelihood function is calculated for each scan grid and the error at 68% confidence level in the likelihood scan is taken as the statistical uncertainty.

Scheme	Uncertainty
8 points	13 MeV
6 points	12 MeV
4 points	10 MeV
1 points	9 MeV

Fisher Information of mass





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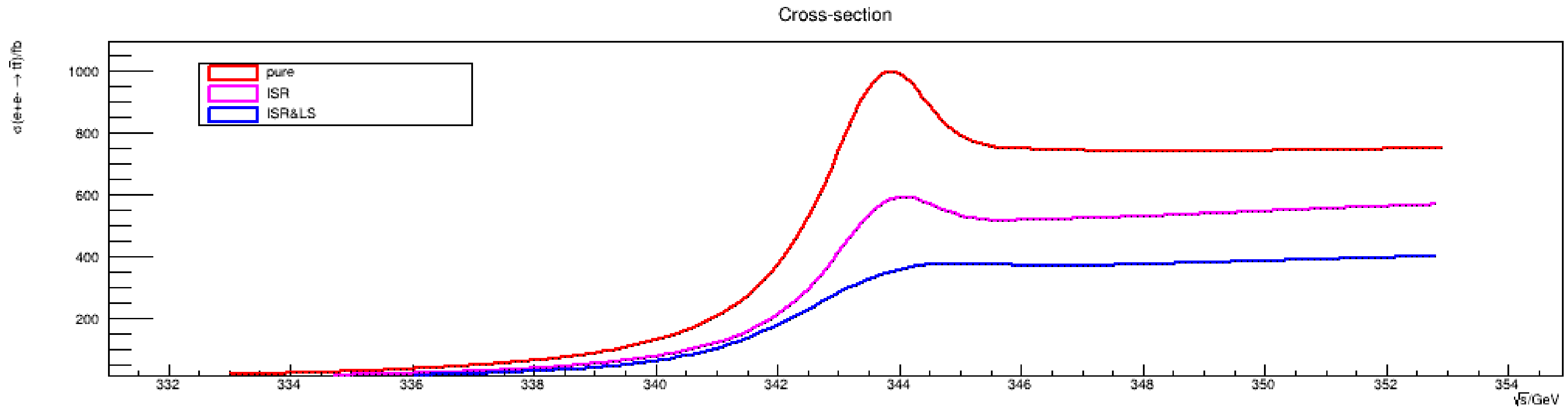
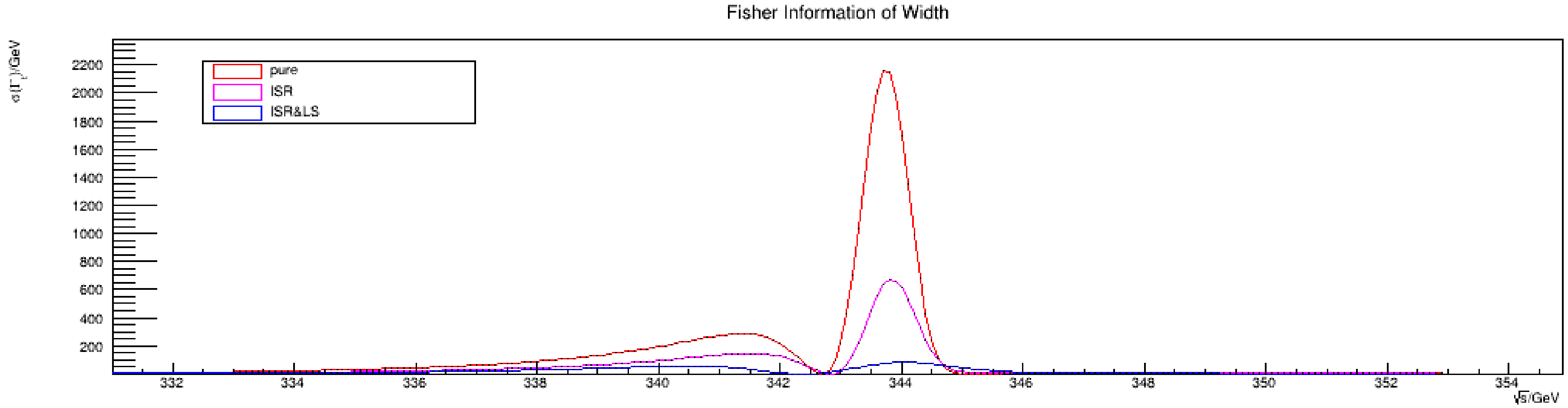
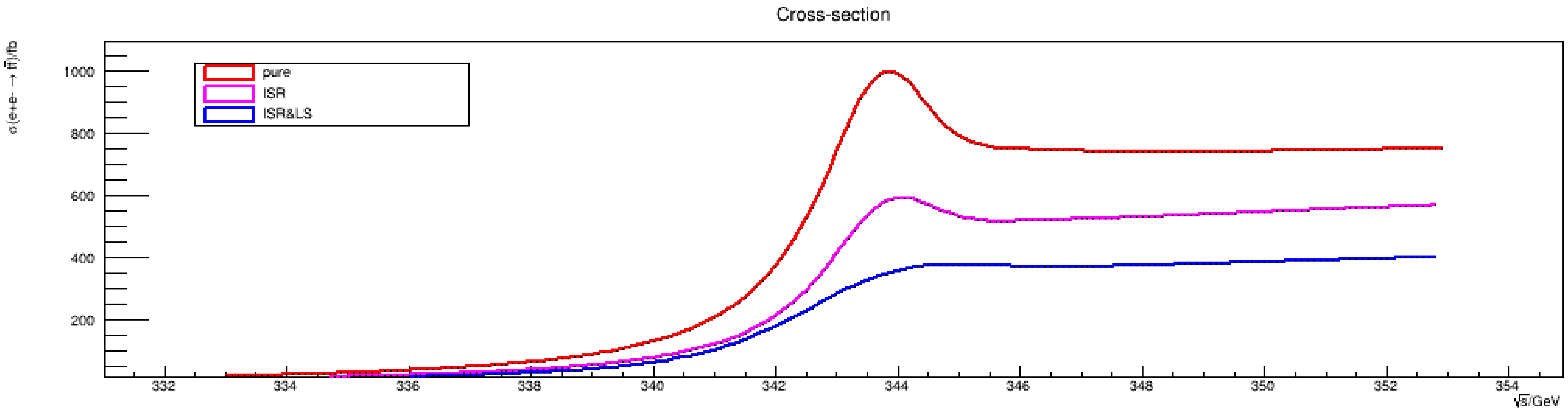


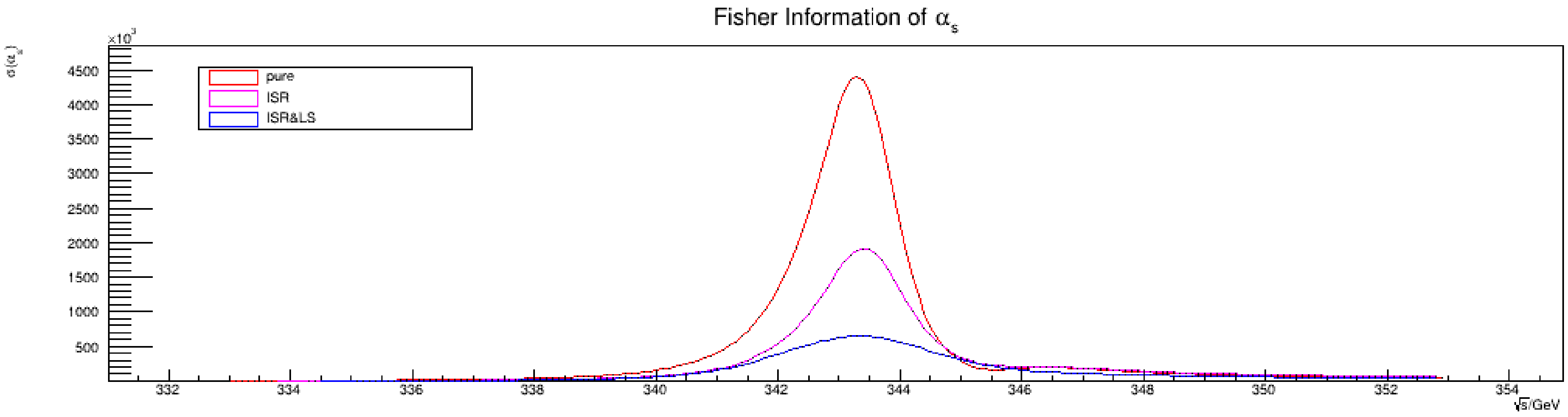
Cross-section
σ(e+e- → tt̄)/fb
pure
ISR
ISR&LS
1000
800
600
400
200
332
334
336
338
340
342
344
346
348
350
352
354
√s/GeV



Fisher Information of Width
σ(Γt)/GeV
pure
ISR
ISR&LS
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
332
334
336
338
340
342
344
346
348
350
352
354
√s/GeV



Cross-section
pure
ISR
ISR&LS
1000
800
600
400
200
332
334
336
338
340
342
344
346
348
350
352
354
√s/GeV



Fisher Information of α_s
×10³
pure
ISR
ISR&LS
4500
4000
3500
3000
2500
2000
1500
1000
500
332
334
336
338
340
342
344
346
348
350
352
354
√s/GeV

Acceptance and selection efficiency for signal

- The number read from CLIC Eur. Phys. J. C (2013) 73:2530
- semi-leptonic :
  - Data: 8296, Bkg: 643, extracted signal: 7653, acceptance*selection efficiency = 48.13%, Branch ratio=30%
- Full-hadronic
  - Data: 11396, Bkg: 1393, extracted signal: 10003, acceptance*selection efficiency = 41.0%, Branch ratio=46%
- These parameters are under 500 GeV situation. At the moment we assume that acceptance and selection efficiency will not change under 352 GeV situation.
- The signal yields of our pseudo data: at 343GeV, 100 fb^{-1}
  - semi leptonic 1201.1
  - fully hadronic 2602.1