Top quark properties measurements at CEPC

Zhan Li on behalf of

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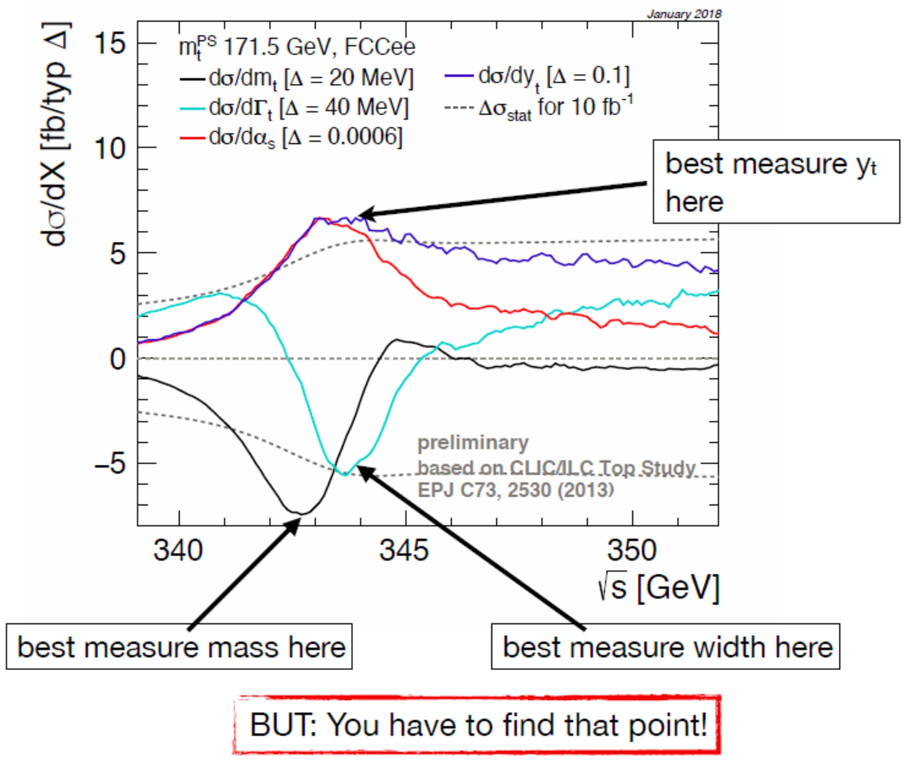
Motivation

- Top properties are fundamental in the Standard Model, also can be stringent check of internal consistency of SM.
- Top 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

Eur. Phys. J. C (2013) 73:2530

- 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 (~0.5GeV, provided by Yiwei Wang) as the energy resolution at the moment.

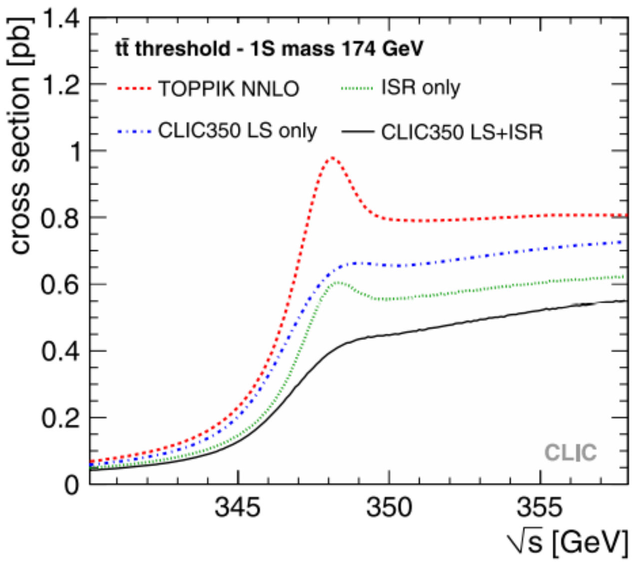


Fig. 4 Top pair production cross section from theory calculations, with the luminosity spectrum (LS) of CLIC at 350 GeV and ISR as well as for all effects combined

Method: $\sqrt{s}$ scan

- Since we are interested in the precise measurement of top mass/width 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:

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

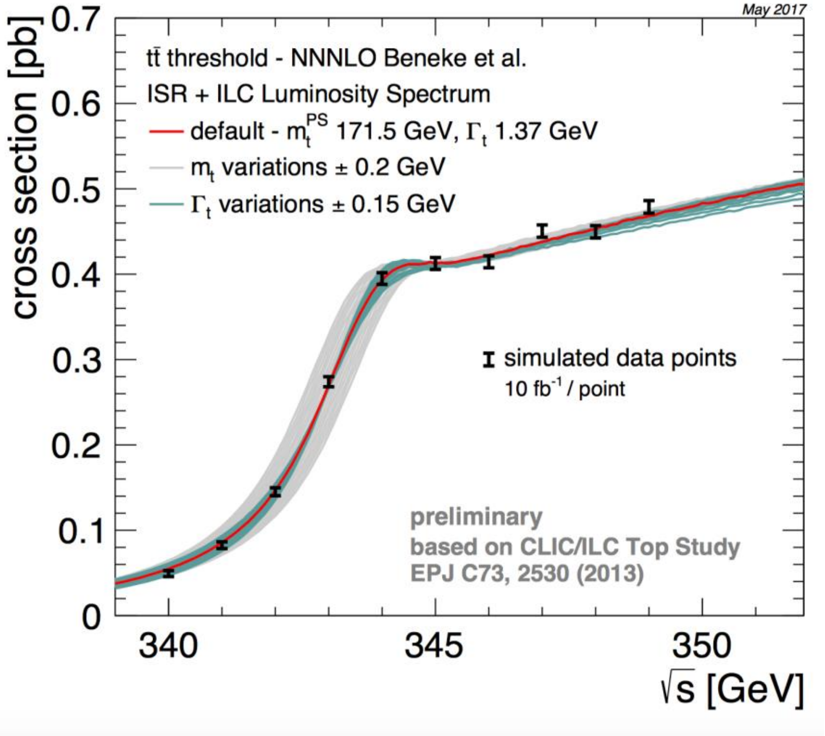
- Since we do not have real experiment data, we use QQbar_threshold to generate pseudo data instead.
    - In this set of pseudo data, top mass is set to be 171.5 GeV, and top width is set to be 1.33 GeV.

Method: $\sqrt{s}$ scan

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

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

  - i corresponds to the i-th scan point



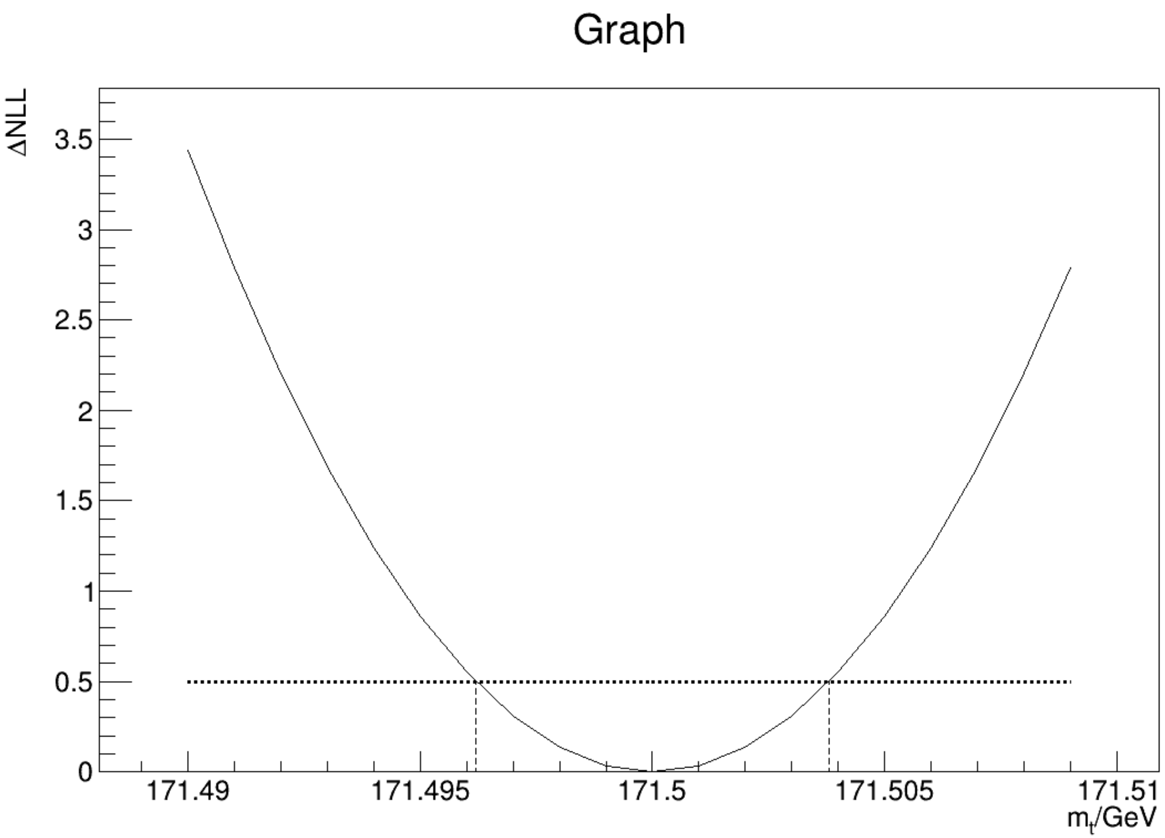
Reminder: last status at Yangzhou Workshop

- We use these setup:
  - The acceptance and selection efficiency are assumed to be 100%.
  - Background events are not considered.
  - ISR is considered, but LS is not included.
  - Luminosity per scan point is assumed to range from 25fb^{-1} to 100fb^{-1}.
  - Systematic uncertainties are not considered.
  - Top mass is set to be 171.5GeV. Top width is set to be 1.33GeV.

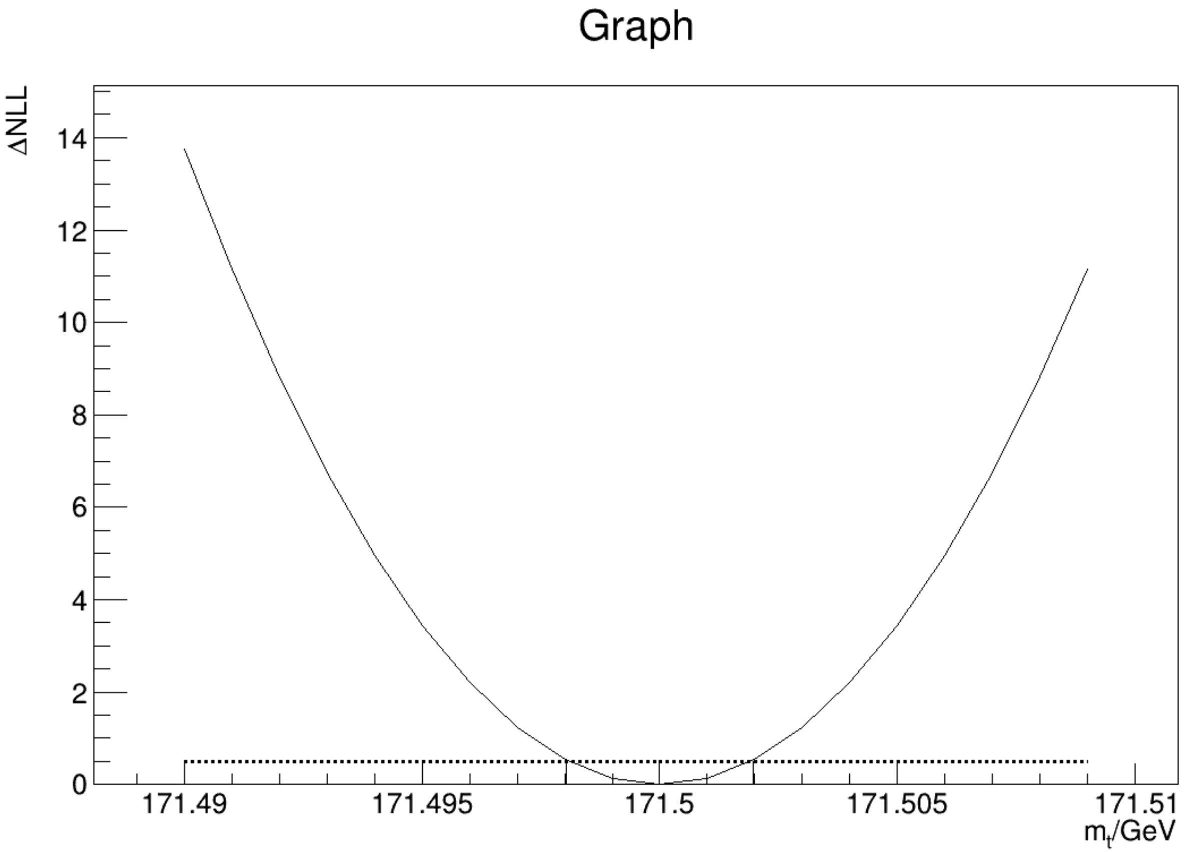
- We use these 3 following schemes:

  4 points scheme, 6 points scheme, and 8 points scheme.

6 $\sqrt{s}$ scheme={341,342,342.5,343,343.5,344.5}



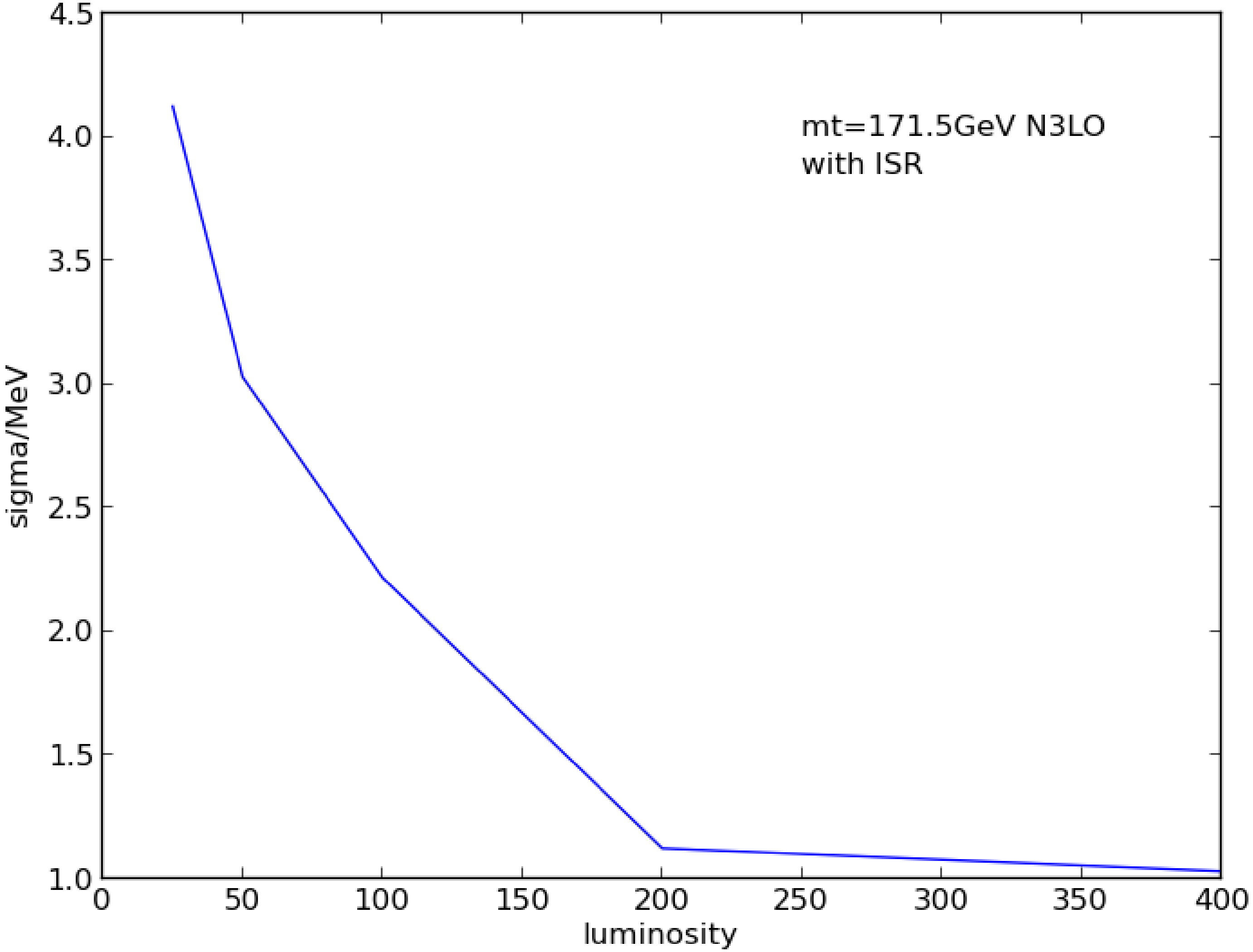
$25 \mathrm{fb}^{-1}$ sigma: -0.004125 +0.004125



$100 \mathrm{fb}^{-1}$ sigma: -0.002189 +0.002189

$\sqrt{s}$ NLL scan

- We pick the 6- $\sqrt{s}$ scheme for its better performance.
- And we tested more luminosity assumptions.
- The curve is consistent with our expectation.

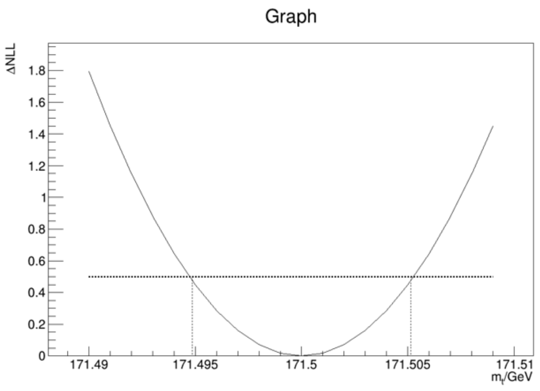


Summary of Previous Results

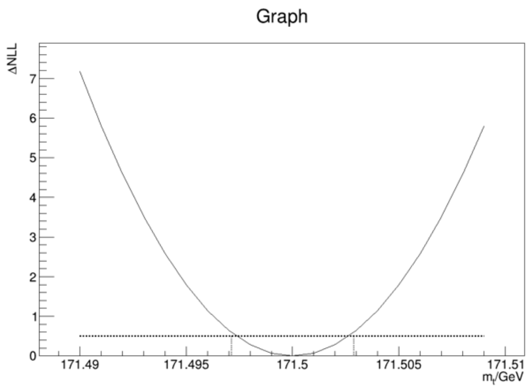
scheme	4 points	6 points	8 points
$\sigma(m_t)$/MeV 100fb^{-1}	2.9	2.2	2.2
$\sigma(m_t)$/MeV 25fb^{-1}	5.1	4.1	4.1

- Build up the machinery of this $\sqrt{s}$ scan to estimate measurement uncertainties.
- Test with a few set of parameters and schemes.
- The way of selecting points is crucial if we want lower error.

4 $\sqrt{s}$ scheme={341.5,342.5,343,344.5}

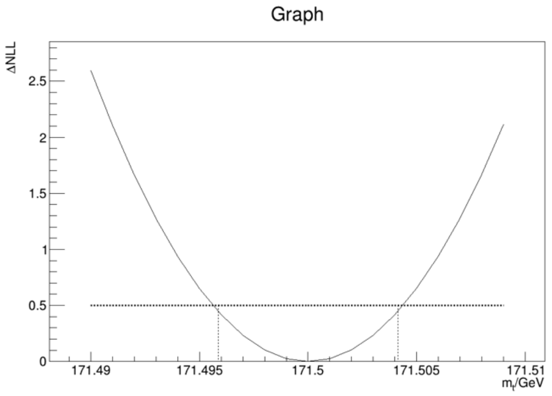


25fb^{-1} sigma: -0.005125 +0.005125

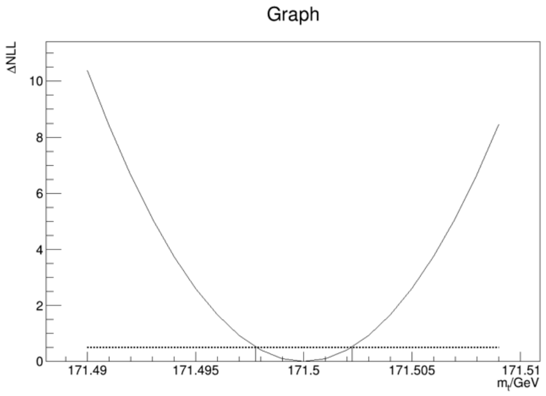


100fb^{-1} sigma: -0.002875 +0.002875

8 $\sqrt{s}$ scheme ={340,341,342,342.5,343,343.5,344.5,345}

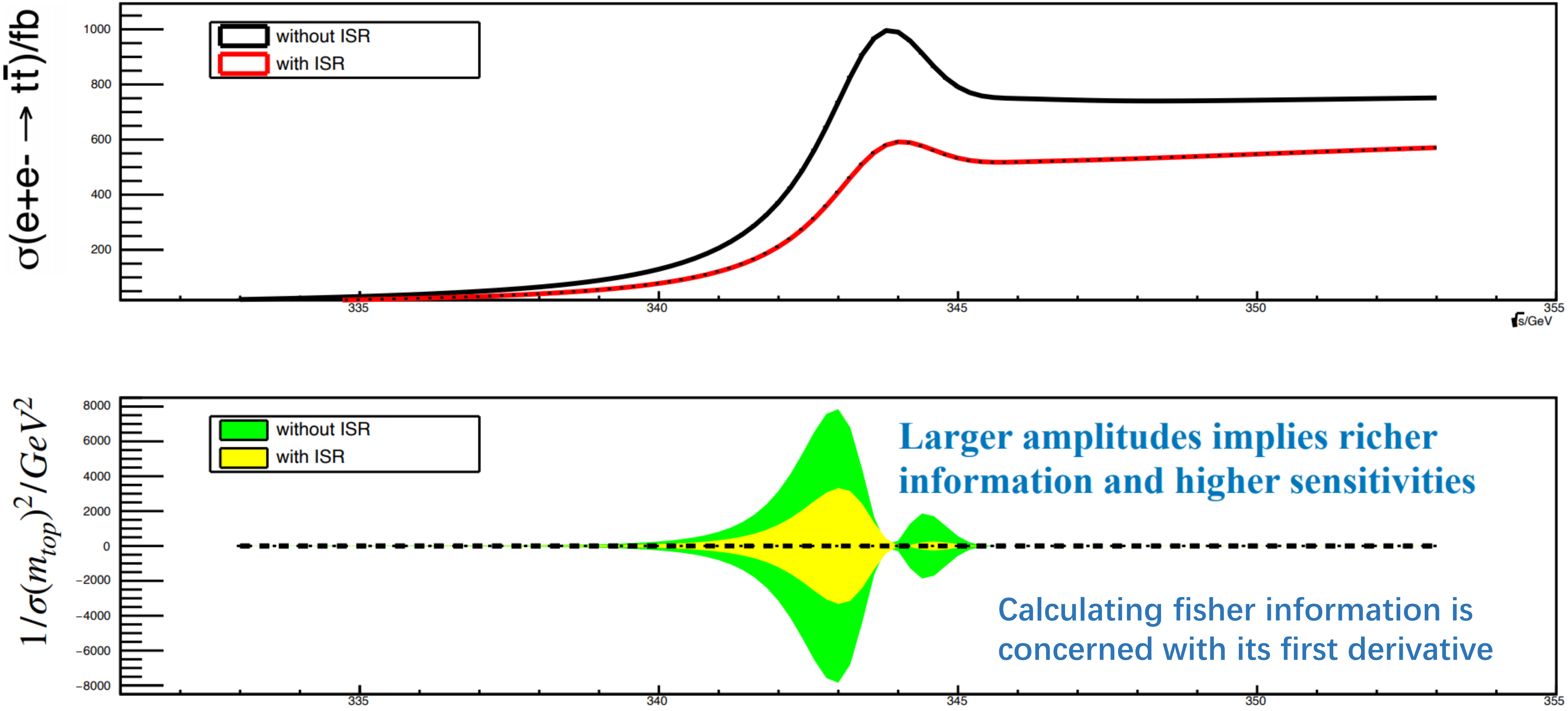


25fb^{-1}sigma: -0.004125 +0.004125



100fb^{-1} sigma: -0.002219 +0.002219

Fisher information



Larger amplitudes implies richer information and higher sensitivities

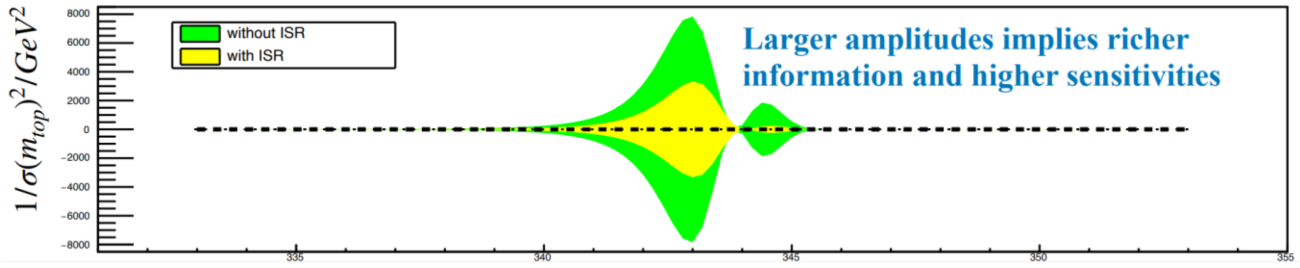
Calculating fisher information is concerned with its first derivative

Setup

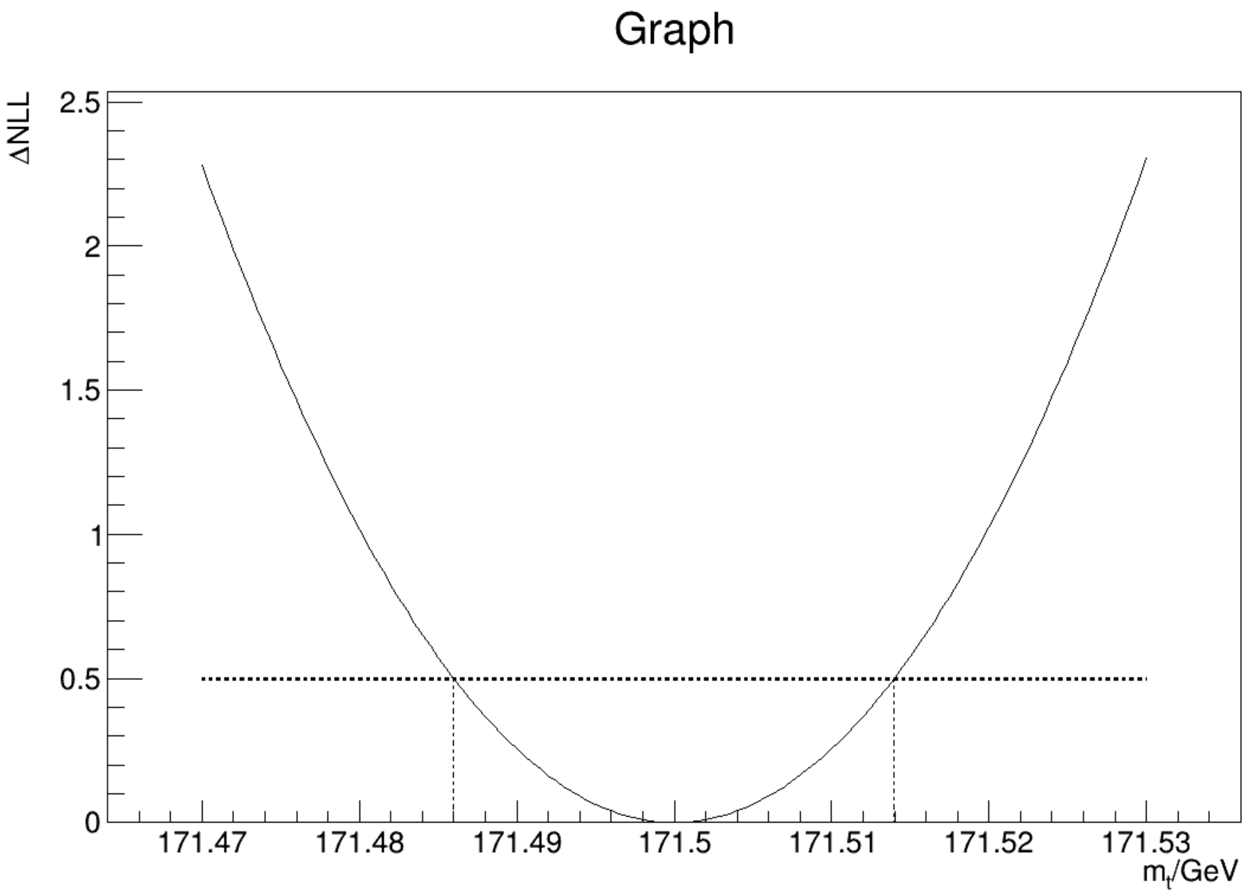
- ISR is considered, but LS is not considered. Systematic uncertainties are not taken into account.
- Acceptance and selection efficiency are added.
- Background events are included.
- We consider these 2 channels: semi-leptonic and fully-hadronic.
  - The selection efficiency and background events obtained from Eur. Phys. J. C (2013) 73:2530

Luminosity and scan $\sqrt{s}$ range

- In reality, the total operation time is limited, so the total luminosity is limited.
- We study the scanning schemes with total lumi fixed.
- Total luminosity will be $100\mathrm{fb}^{-1}$. The luminosity of each point is the same. $\sqrt{s}$ scan ranges from 340GeV to 345GeV.
    - Drop less sensitive points step by step from 8 points to 1 point.



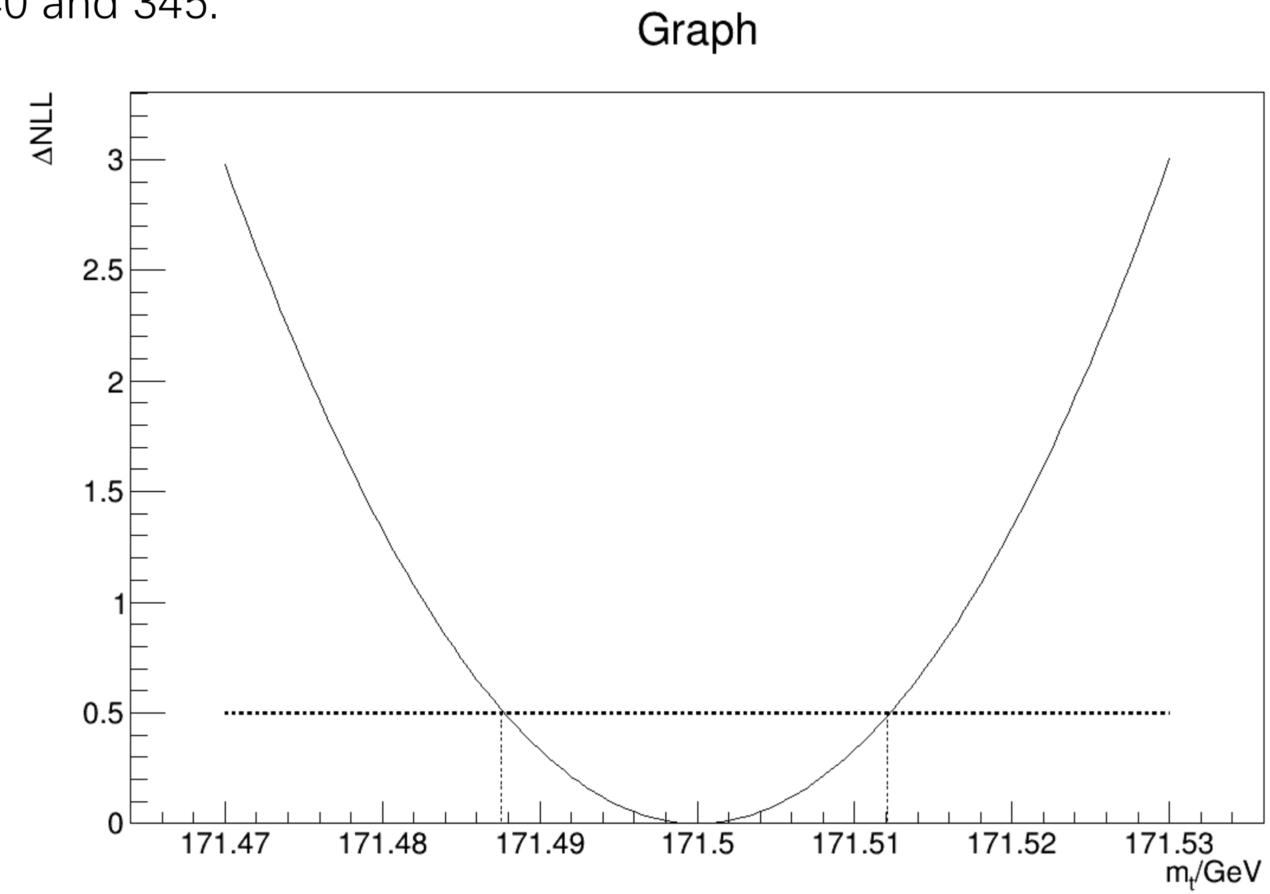
8 $\sqrt{s}$ scheme ={340,341,342,342.5,343,343.5,344.5,345}



12.5fb^{-1} per point $\sigma(m_t)$: -0.0140273 0.0139727

6 $\sqrt{s}$ scheme={341,342,342.5,343,343.5,344.5}

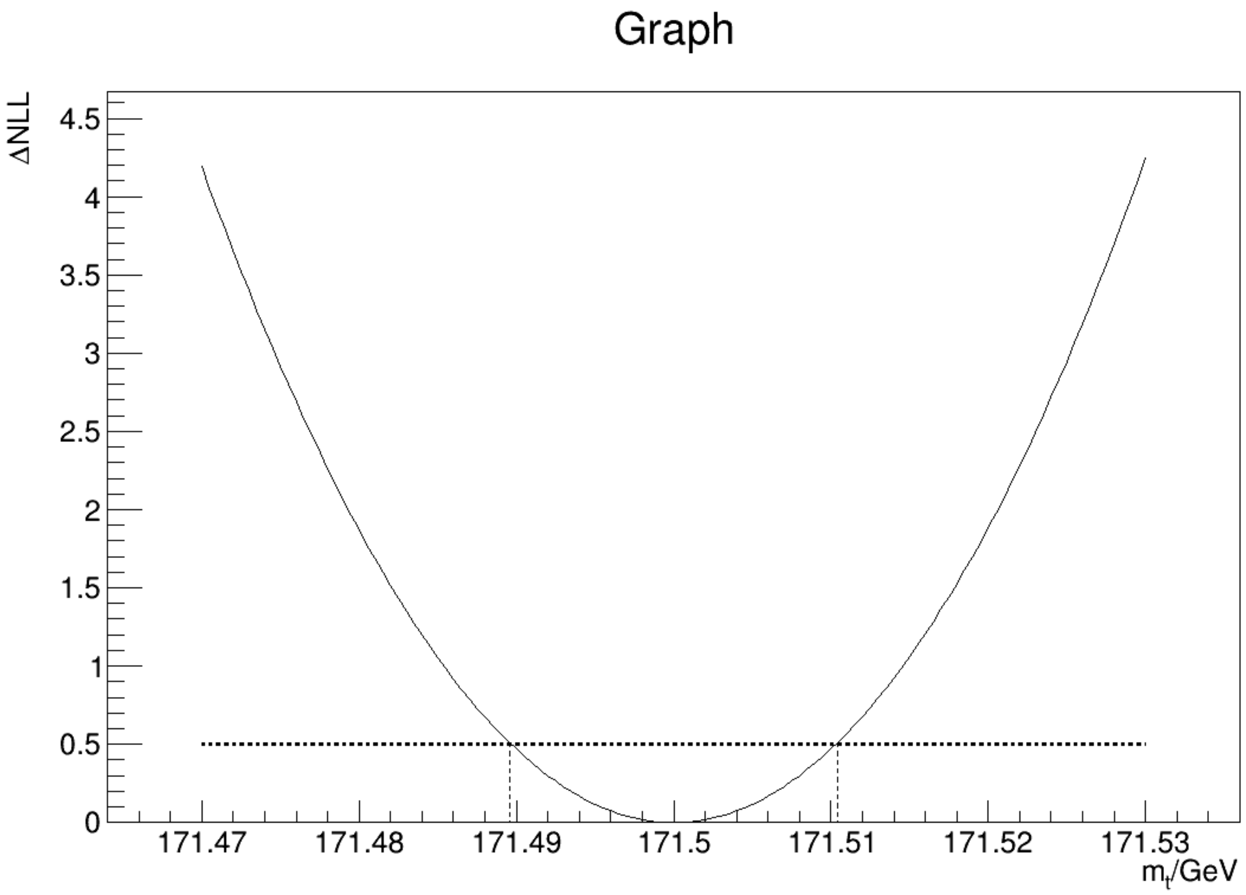
We dropped 340 and 345.



16.7fb^{-1} per point $\sigma(m_t)$:-0.0124375 0.0120625

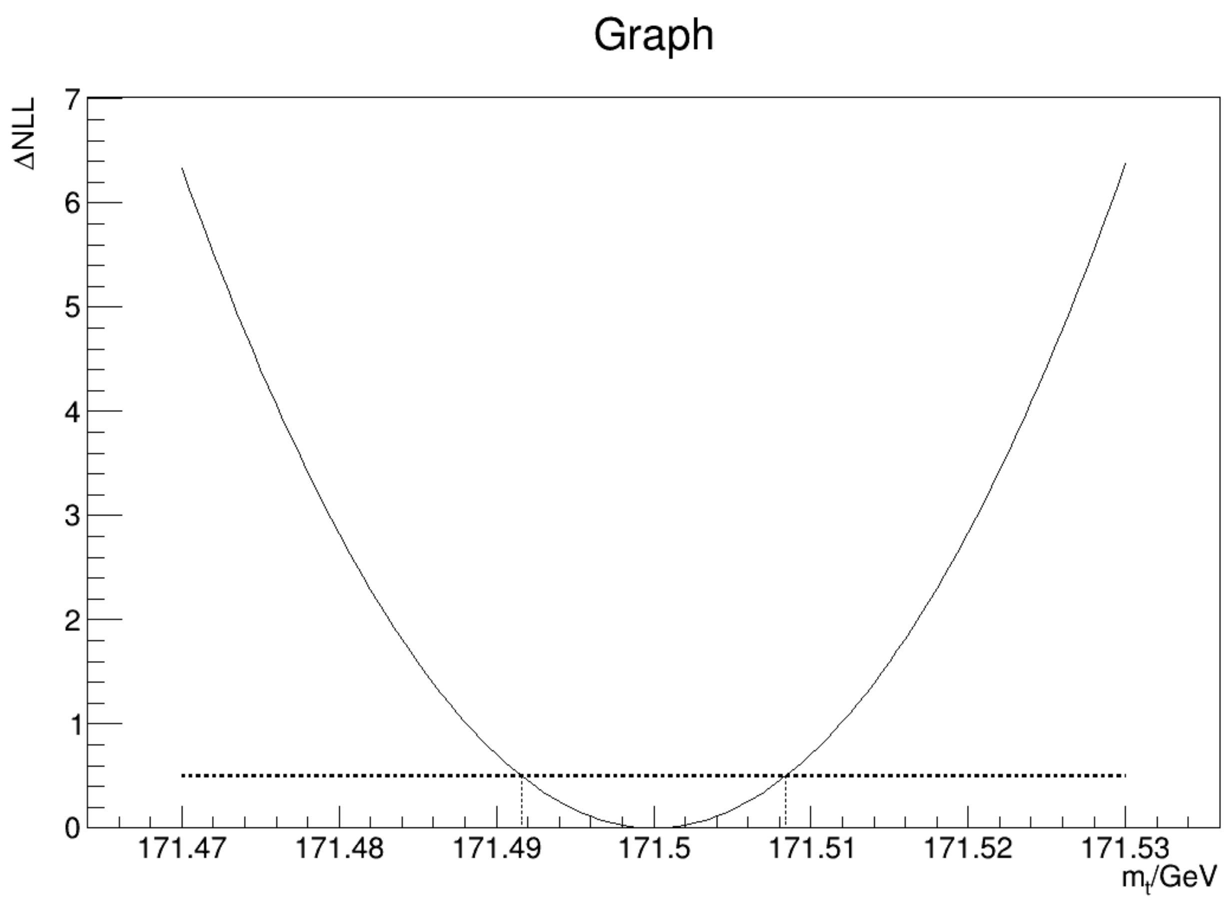
4 $\sqrt{s}$ scheme={342,342.5,343,343.5}

We dropped 341 and 344.5.



25fb^{-1} per point $\sigma(m_t)$:-0.0104375 0.0104375

1 $\sqrt{s}$ scheme={343}

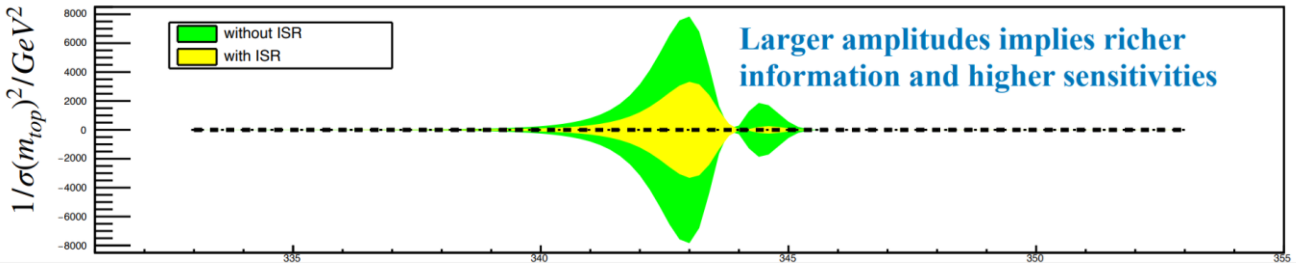


$100fb^{-1}$ per point $\sigma(m_t)$:-0.00840454 0.00840234

Results

scheme	8 points	6 points	4 points	1 point
$\sigma(m_t)$ /MeV	13.97	10.43	12.06	8.40

- For 171.5GeV top mass, 343 GeV center mass energy is the best point, given the total luminosity 100 fb^{-1} .
- Top mass is known as 171.5GeV, so we can get the best point through its known fisher information. But for unknown top mass, we need to first locate a proper range.



1-$\sqrt{s}$ scheme gives the best result

- We use 343GeV as the 1 point scheme.
- We used equal luminosity per point.

- So we have 2 questions:
  - How about unequal luminosity per point?
  - Is 343GeV really the best point?

Exhaustion on 4 sqrts scheme

- Total lumi = 100 fb^{-1}
- $\sqrt{s}$ ={342,342.5,343,343.5}
- Calculate the top mass errors of all schemes with possible lumi fractions while keeping the total lumi fixed.
- 286 lumi combinations in total
  - List from low error to high error
  - Top 30 are listed
- Conclusion: 343GeV is the best point.

$\sqrt{s}$ ={342, 342.5, 343, 343.5}

343GeV

```
lumi ratio= {0, 0, 100, 0},      err= 0.00840344
lumi ratio= {0, 10, 90, 0},      err= 0.00852734
lumi ratio= {0, 10, 80, 10},     err= 0.0085625
lumi ratio= {0, 20, 80, 0},      err= 0.0085625
lumi ratio= {10, 0, 90, 0},      err= 0.0085625
lumi ratio= {0, 0, 90, 10},      err= 0.00861523
lumi ratio= {10, 0, 80, 10},     err= 0.00889108
lumi ratio= {0, 40, 60, 0},      err= 0.00889648
lumi ratio= {0, 0, 80, 20},      err= 0.0089375
lumi ratio= {0, 20, 70, 10},     err= 0.0089375
lumi ratio= {0, 30, 70, 0},      err= 0.0089375
lumi ratio= {10, 10, 80, 0},     err= 0.0089375
lumi ratio= {10, 20, 70, 0},     err= 0.0089375
lumi ratio= {20, 0, 80, 0},      err= 0.00896973
lumi ratio= {0, 10, 70, 20},     err= 0.00897742
lumi ratio= {0, 30, 60, 10},     err= 0.00900123
lumi ratio= {10, 10, 70, 10},    err= 0.00902295
lumi ratio= {0, 10, 60, 30},     err= 0.0090625
lumi ratio= {0, 40, 50, 10},     err= 0.0090625
lumi ratio= {0, 50, 50, 0},      err= 0.0090625
lumi ratio= {0, 60, 40, 0},      err= 0.0090625
lumi ratio= {10, 20, 60, 10},    err= 0.0090625
lumi ratio= {10, 40, 50, 0},     err= 0.0090625
lumi ratio= {20, 0, 70, 10},     err= 0.0090625
lumi ratio= {0, 0, 70, 30},      err= 0.00906836
lumi ratio= {10, 0, 70, 20},     err= 0.0090918
lumi ratio= {0, 20, 60, 20},     err= 0.00910352
lumi ratio= {10, 30, 60, 0},     err= 0.00910937
lumi ratio= {20, 10, 70, 0},     err= 0.00911993
lumi ratio= {0, 30, 50, 20},     err= 0.00925
lumi ratio= {0, 40, 40, 20},     err= 0.00939502
```

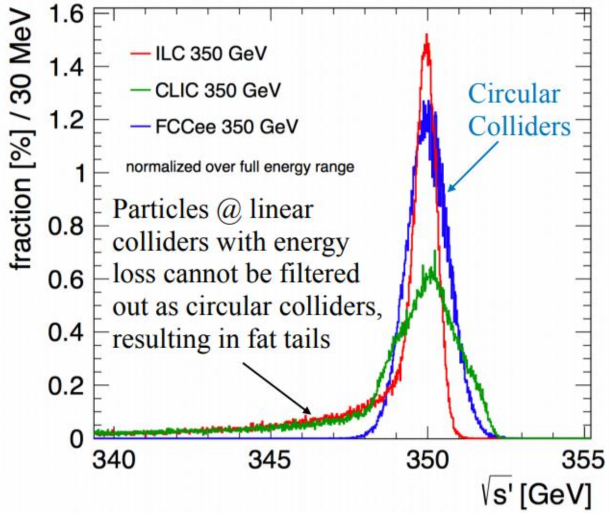
Proposal to Find the Best Point

- Running at a low luminosity ($1 fb^{-1}$) to find out if 343GeV is the best point.
- The discriminant value is much smaller than the one used for deriving $\sigma(m_t)$

```
sqrts = {340, 341, 342, 342.5, 343, 343.5, 344.5, 345}
lum= 1, discriminant value = 1e-4
lumi ratio= {0, 0, 0, 0, 1, 0, 0, 0},   err= 0.0010625
lumi ratio= {0, 0, 0, 1, 0, 0, 0, 0},   err= 0.00138158
lumi ratio= {0, 0, 0, 0, 0, 1, 0, 0},   err= 0.00159912
lumi ratio= {0, 0, 1, 0, 0, 0, 0, 0},   err= 0.00190234
lumi ratio= {0, 1, 0, 0, 0, 0, 0, 0},   err= 0.0039375
lumi ratio= {0, 0, 0, 0, 0, 0, 1, 0},   err= 0.00447998
lumi ratio= {0, 0, 0, 0, 0, 0, 0, 1},   err= 0.00678113
lumi ratio= {1, 0, 0, 0, 0, 0, 0, 0},   err= 0.0069375
```

Adding Luminosity Spectrum

- Total luminosity will be 100fb^{-1}.
  - We would like to compare our results with CLIC, so we are trying to keep these parameters close to CLIC's.
- The luminosity spectrum of CEPC



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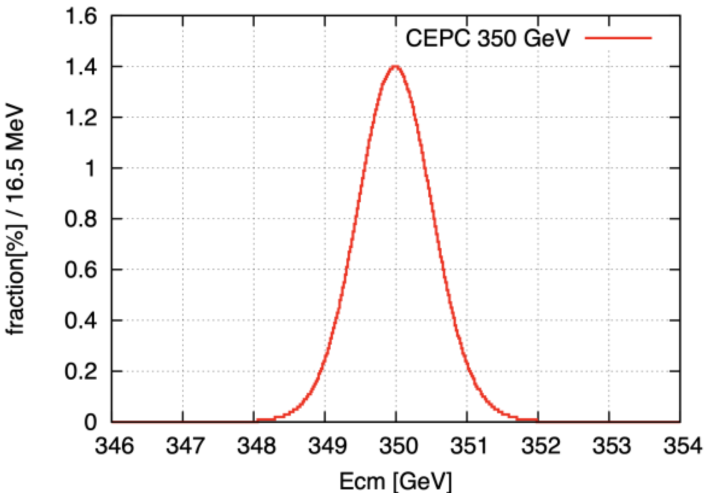
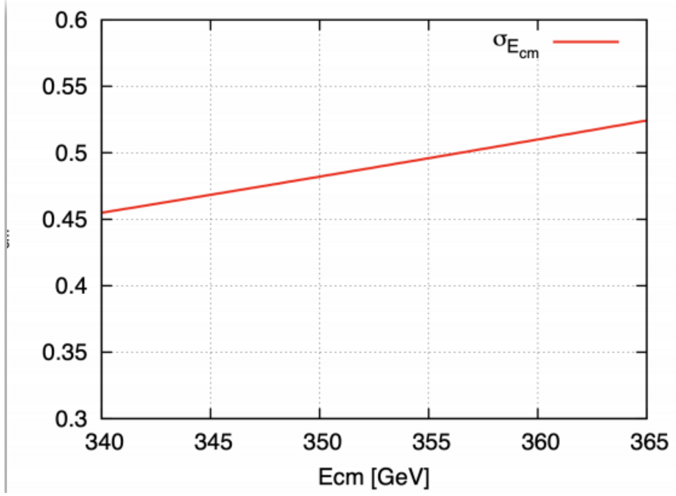




Provided by Yiwei Wang

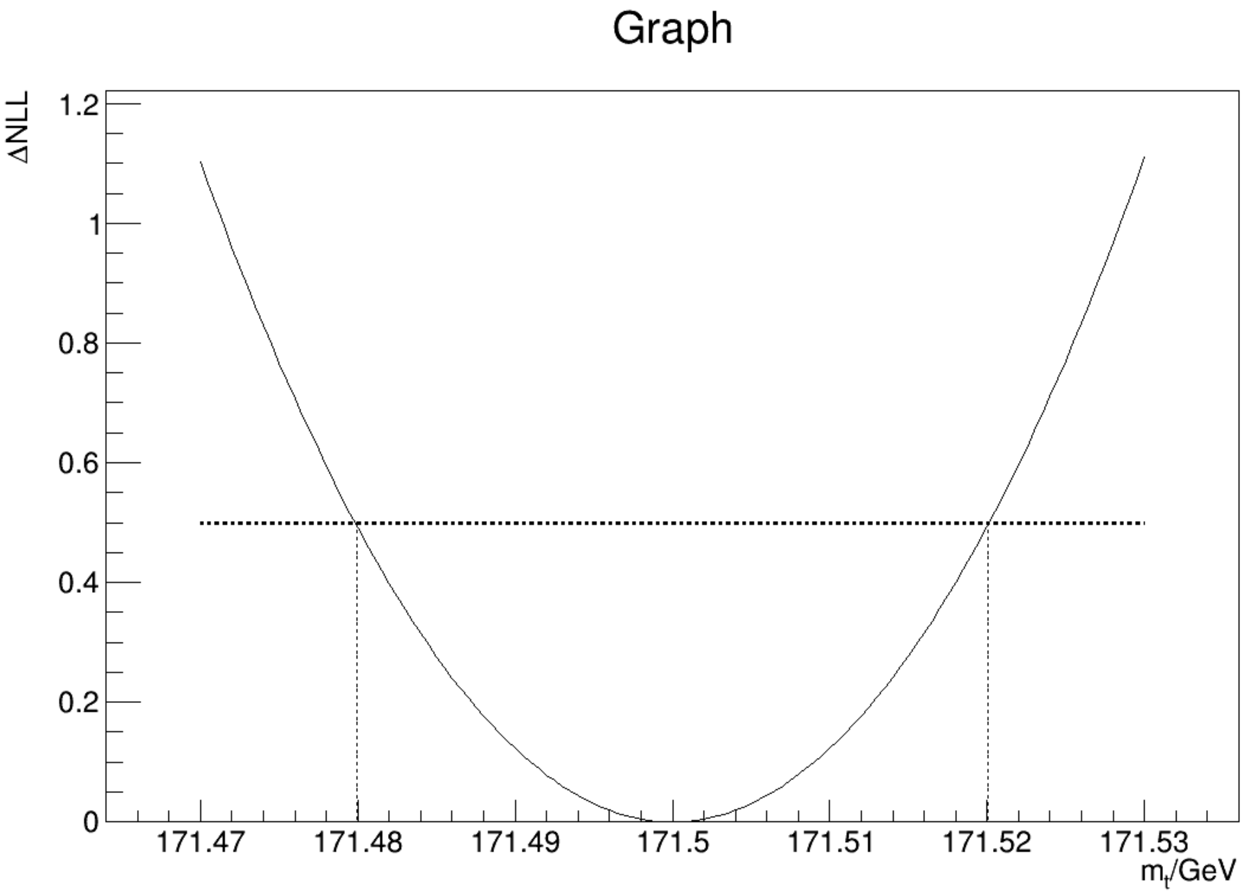
The beam energy resolution increases as a function of $\sqrt{s}$

- The luminosity spectrum is shown for 350 GeV with a width of ~480 MeV

Setup

- ISR and LS are considered. Systematic uncertainties are not taken into account.
- Top mass is set to be 171.5GeV. Top width is set to be 1.33GeV.
- Acceptance and selection efficiency are added.
- Background events are included.
- We consider these 2 channels: semi-leptonic and fully-hadronic.
  - The selection efficiency and background events obtained from Eur. Phys. J. C (2013) 73:2530

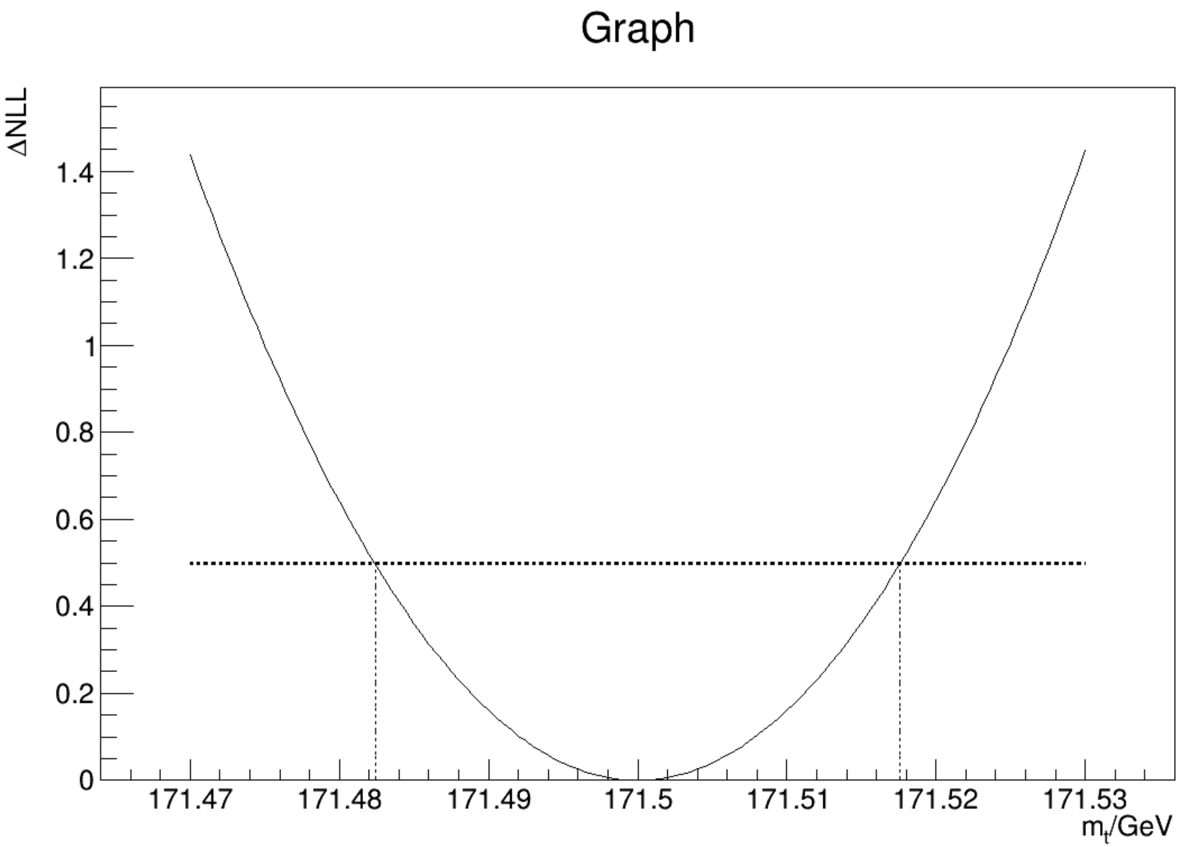
8 $\sqrt{s}$ scheme ={340,341,342,342.5,343,343.5,344.5,345}



12.5 fb^{-1} per point $\sigma(m_t)$:-0.0200625 0.0200625

6 $\sqrt{s}$ scheme={341,342,342.5,343,343.5,344.5}

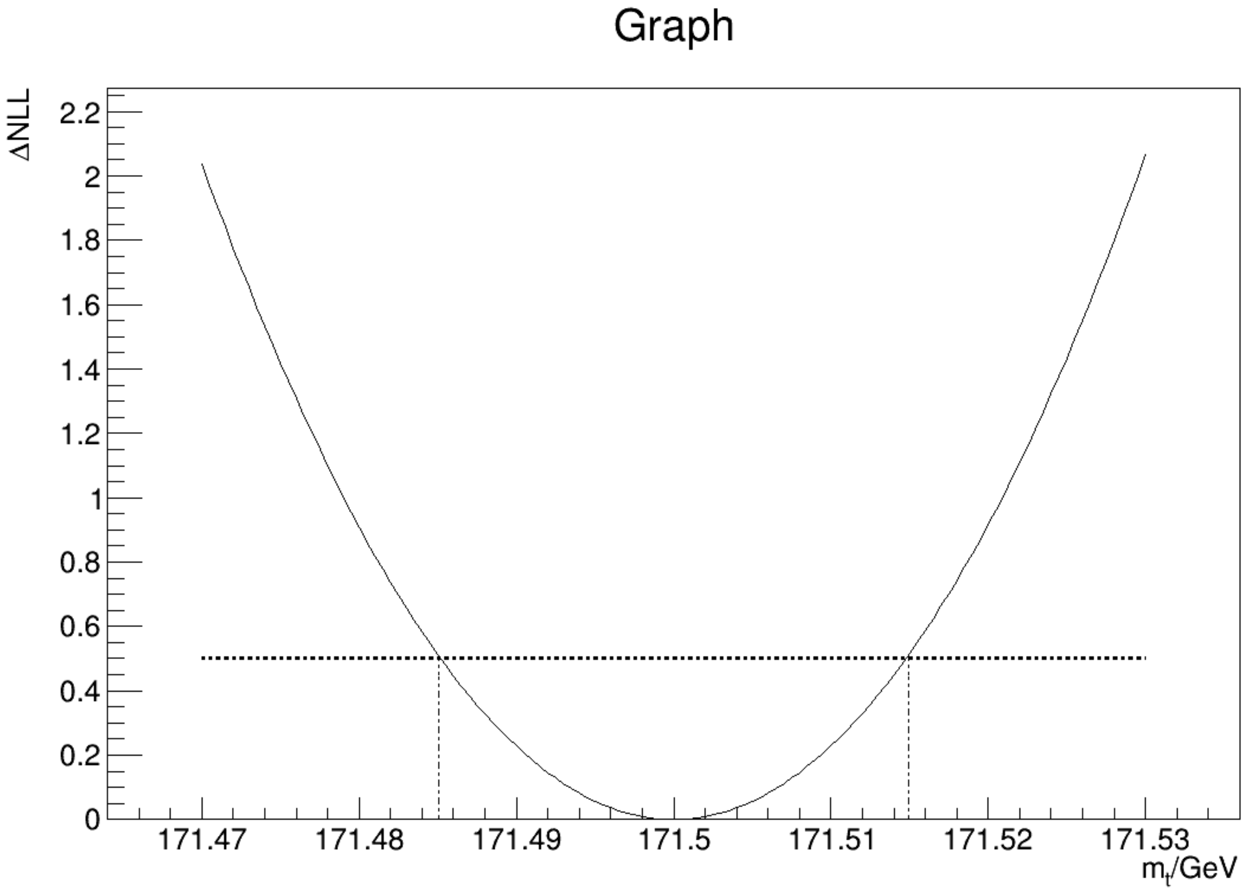
We dropped 340 and 345.



16.7fb^{-1} per point $\sigma(m_t)$: -0.0175625 0.0175625

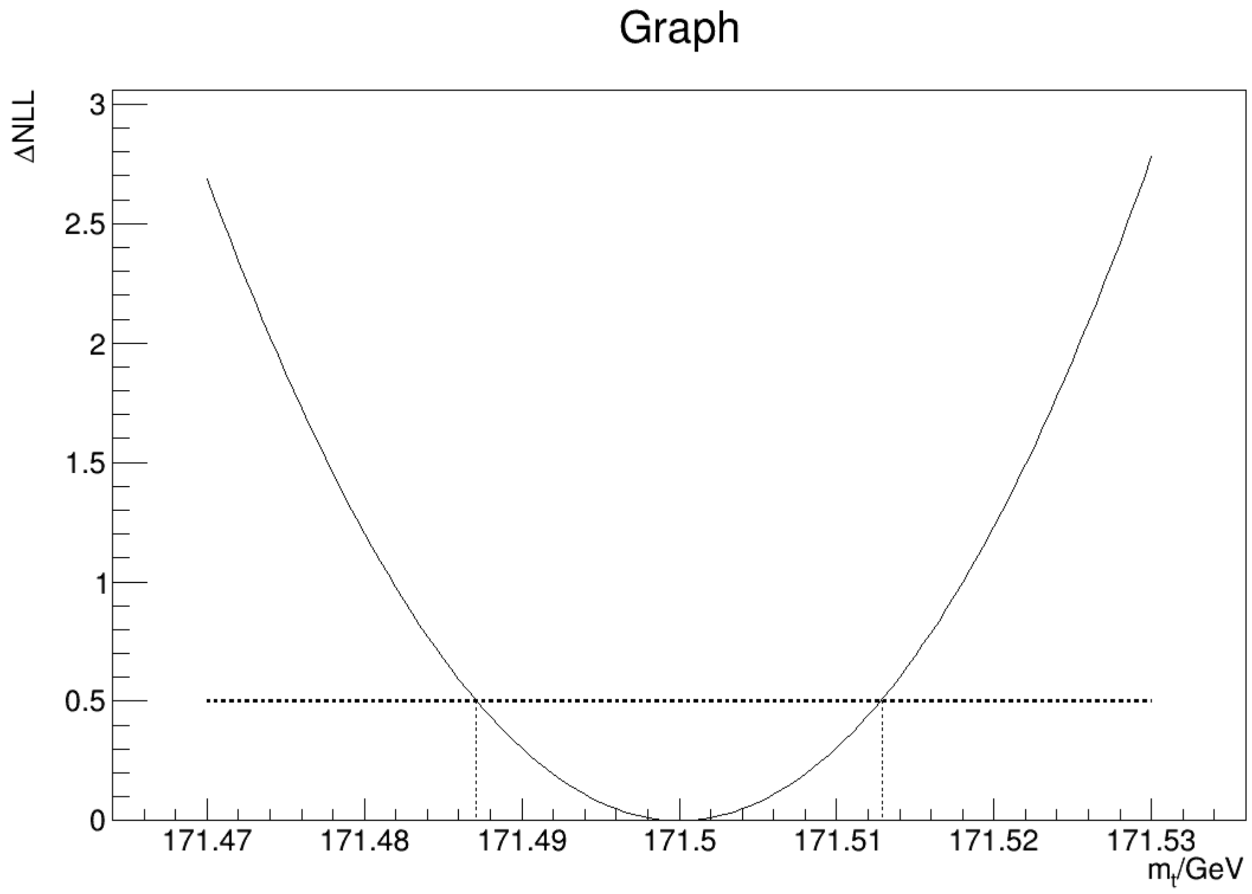
4 $\sqrt{s}$ scheme={342,342.5,343,343.5}

We dropped 341 and 344.5.



25fb^{-1} per point $\sigma(m_t)$:-0.0149375 0.0149375

1 $\sqrt{s}$ scheme={343}



$100 fb^{-1}$ per point $\sigma(m_t)$:-0.0129375 0.0129375

Results

scheme	8 points	6 points	4 points	1 point
$\sigma(m_t)$/MeV	20.06	17.56	14.93	12.93

- How about unequal lumi per point?
- What is the best point when considering LS added?

Exhaustion on 4 sqrts scheme

- Total lumi = 100
- $\sqrt{s}$ ={342.5,342.75,343,343.5}
- Calculate the top mass error of all possible lumi fraction
- 286 lumi combinations in total
  - List from low error to high error
  - Top 30 are listed
- Conclusion: **with cepc LS**, the best point shift.

L(342.75GeV)=40%
L(343GeV)=60%

342.75GeV

343GeV

```
lumi ratio= {0, 40, 60, 0},      err= 0.0125625
lumi ratio= {0, 50, 50, 0},      err= 0.0125625
lumi ratio= {0, 60, 40, 0},      err= 0.0125625
lumi ratio= {0, 70, 30, 0},      err= 0.0125625
lumi ratio= {0, 80, 20, 0},      err= 0.0125625
lumi ratio= {10, 60, 30, 0},     err= 0.0125625
lumi ratio= {10, 70, 20, 0},     err= 0.0125625
lumi ratio= {10, 80, 10, 0},     err= 0.0125625
lumi ratio= {10, 90, 0, 0},      err= 0.0125625
lumi ratio= {20, 80, 0, 0},      err= 0.0125625
lumi ratio= {0, 100, 0, 0},      err= 0.012605
lumi ratio= {0, 90, 10, 0},      err= 0.0126211
lumi ratio= {0, 20, 80, 0},      err= 0.01275
lumi ratio= {0, 30, 70, 0},      err= 0.01275
lumi ratio= {10, 50, 40, 0},     err= 0.01275
lumi ratio= {20, 70, 10, 0},     err= 0.01275
lumi ratio= {30, 30, 40, 0},     err= 0.0128777
lumi ratio= {20, 0, 80, 0},      err= 0.0128829
lumi ratio= {40, 30, 30, 0},     err= 0.0128906
lumi ratio= {30, 20, 50, 0},     err= 0.0128965
lumi ratio= {40, 40, 20, 0},     err= 0.0128965
lumi ratio= {20, 20, 60, 0},     err= 0.0129067
lumi ratio= {40, 60, 0, 0},      err= 0.0129067
lumi ratio= {20, 10, 70, 0},     err= 0.0129141
lumi ratio= {10, 0, 90, 0},      err= 0.0129181
lumi ratio= {40, 50, 10, 0},     err= 0.0129199
lumi ratio= {50, 40, 10, 0},     err= 0.0129298
lumi ratio= {30, 0, 70, 0},      err= 0.0129331
lumi ratio= {0, 0, 100, 0},      err= 0.0129375
lumi ratio= {0, 10, 90, 0},      err= 0.0129375
lumi ratio= {0, 90, 0, 10},      err= 0.0129375
```

Proposal to find the Best Point

- Running at a low luminosity ($1 fb^{-1}$)
- The discriminant value is much smaller than the one used for deriving $\sigma(m_t)$
- Cannot distinguish 342.5, 342.75 and 343

342.5GeV
342.75GeV
343GeV

```
sqrts = {342, 342.5, 342.75, 343, 343.25, 343.5, 344, 0}
lum= 1, discriminant value = 1e-4
lumi ratio= {0, 1, 0, 0, 0, 0, 0, 0},   err= 0.0019375
lumi ratio= {0, 0, 1, 0, 0, 0, 0, 0},   err= 0.0019375
lumi ratio= {0, 0, 0, 1, 0, 0, 0, 0},   err= 0.0019375
lumi ratio= {0, 0, 0, 0, 1, 0, 0, 0},   err= 0.00202588
lumi ratio= {1, 0, 0, 0, 0, 0, 0, 0},   err= 0.00239062
lumi ratio= {0, 0, 0, 0, 0, 1, 0, 0},   err= 0.0025625
lumi ratio= {0, 0, 0, 0, 0, 0, 1, 0},   err= 0.00846924
lumi ratio= {0, 0, 0, 0, 0, 0, 0, 1},   err= 0.00846924
```

Proposal to find the Best Point

- Running at $10 fb^{-1}$
- The discriminant value is much smaller than the one used for deriving $\sigma(m_t)$

342.75GeV → 343GeV → 342.5GeV →

```
sqrts = {342, 342.5, 342.75, 343, 343.25, 343.5, 344, 0}
lum= 10, discriminant value = 1e-2
lumi ratio= {0, 0, 10, 0, 0, 0, 0, 0},  err= 0.0055625
lumi ratio= {0, 0, 0, 10, 0, 0, 0, 0},  err= 0.0055625
lumi ratio= {0, 10, 0, 0, 0, 0, 0, 0},  err= 0.0059375
lumi ratio= {0, 0, 0, 0, 10, 0, 0, 0},  err= 0.00641406
lumi ratio= {10, 0, 0, 0, 0, 0, 0, 0},  err= 0.00756836
lumi ratio= {0, 0, 0, 0, 0, 10, 0, 0},  err= 0.00803906
lumi ratio= {0, 0, 0, 0, 0, 0, 10, 0},  err= 0.02775
lumi ratio= {0, 0, 0, 0, 0, 0, 0, 10},  err= 0.02775
```

- cannot distinguish 342.75 and 343

Compare with CLIC and FCC-ee

scheme	8 points	6 points	4 points	1 point
$\sigma(m_t)$/MeV	20.06	17.56	14.93	12.93

Comparable with FCC-ee under similar conditions (lumi differ by a factor of 2)

- The estimation of FCC-ee:
  - ~17 MeV for top mass (stat. uncert.)
  - ~45 MeV for top width (stat. uncert.)
  - with 25fb^{-1} taken at each of the 8 centre-of-mass energy points N3LO cross-section calculation brings 40 MeV uncertainty additionally

2d fit results of CLIC Eur. Phys. J. C (2013) 73:2530

Table 4 Summary of the 2D simultaneous top mass and α_s determination with a threshold scan at ILC for 10 points with a total integrated luminosity of 100 fb^{-1}. Event selection and background rejection from CLIC_ILD is used

1S top mass and α_s combined 2D fit	
m_t stat. error	27 MeV
m_t theory syst. (1 %/3 %)	5 MeV/9 MeV
α_s stat. error	0.0008
α_s theory syst. (1 %/3 %)	0.0007/0.0022

Summary

- The uncertainty of this method is tightly related to our points selection scheme.
- 1-point scheme has the best performance, if we have already found the best point.
- We proposed to scan the point with low luminosity to identify the best point.
  - the method should be further investigated, considering the effects of systematics, etc.
- We can scan some points in non-sensitive area (e.g. 320GeV) to do background study.

Next

- We should find the lowest luminosity where we can distinguish similar $\sqrt{s}$.
- LS can cause the shift of the best point. We should find a proper way to deal with it.
- Width study is working in progress.
  - The best points for width and for mass are different.
- 2D-scan should be applied, considering the influence of both mass and width.

Back-up

How do we get the Fisher information

- We assume that the number of events obeys ~N(mu,sigma).
- We believe it is an extreme situation of Poisson distribution, so here mu = sigma.
- Then we construct its likelihood function, but only pick up 1 point in sample space.

$$l(x|\theta) = \log f(x|\theta)$$

$$l'(x|\theta) = \frac{\partial}{\partial\theta}\log f(x|\theta) = \frac{f'(x|\theta)}{f(x|\theta)}$$

$$I(\theta) = E[l'(X|\theta)^2] = \int [l'(X|\theta)^2] f(x|\theta)dx$$

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 4009.14
  - fully hadronic 5236.67

Background events

- Background events are directly scaled from 500GeV to 352GeV, according to their cross section estimated by CLIC paper.
  - For CLIC's 500GeV situation, the luminosity is 100 fb^{-1}
  - Because there is no information about background yields under 352GeV in the paper of CLIC.

Table 1 Signal and considered physics background processes, with their approximate cross section calculated for CLIC at 500 GeV and at 352 GeV

Type	Final state	σ 500 GeV	σ 352 GeV
Signal ($m_{top} = 174$ GeV)	$t\bar{t}$	530 fb	450 fb
Background	WW	7.1 pb	11.5 pb
Background	ZZ	410 fb	865 fb
Background	$q\bar{q}$	2.6 pb	25.2 pb
Background	WWZ	40 fb	10 fb

- Result:
  - semi leptonic bkg event number:2380
  - fully hadronic bkg event number:5156