Top quark properties measurements at CEPC

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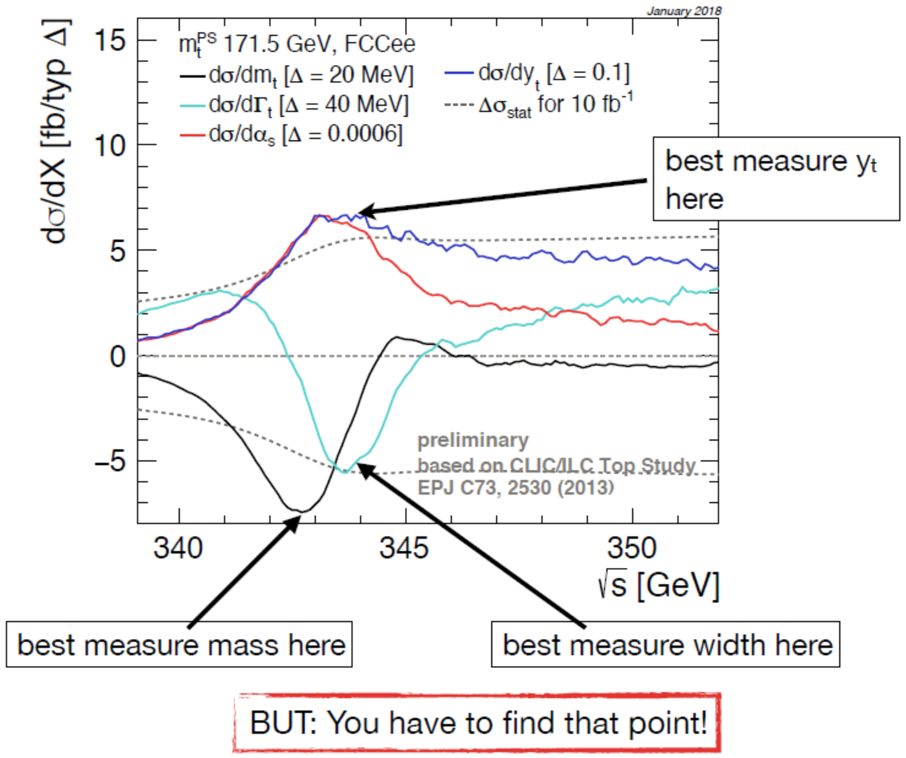
Motivation

- 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

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 setup (~0.5GeV) as the energy resolution at the moment.

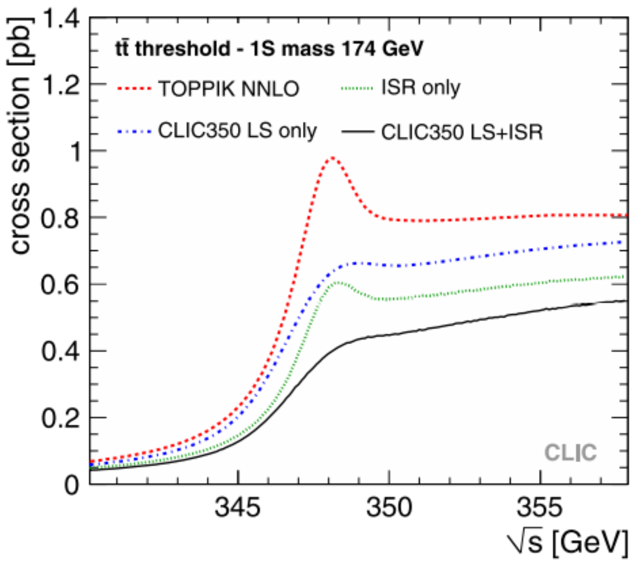


Fig. 4 Top pair production cross section from theory calculations, with the luminosity spectrum (LS) of CLIC at 350 GeV and ISR as well as for all effects combined

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:

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

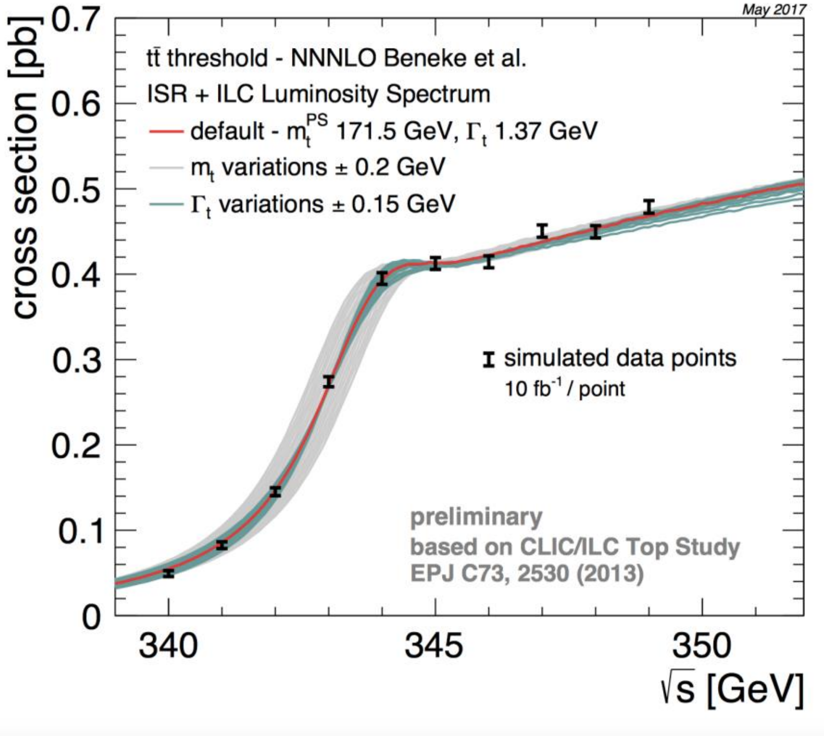
- Since we do not have real experiment data, we use QQbar_threshold to generate pseudo data instead.

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:

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

  - i corresponds to the i-th scan point



Review

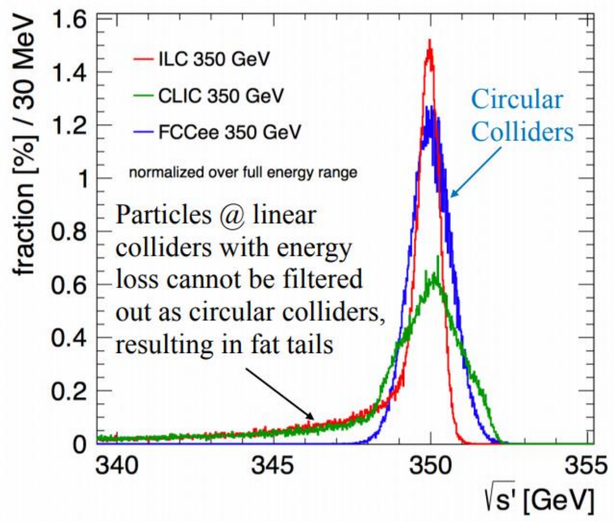
- The uncertainty of this method is tightly related to our points selection scheme.
- 1-point scheme has the best performance at its optimal point.
- At present we use Fisher information to crosscheck the optimal point.
- We proposed to scan the point with low luminosity to identify the optimal point,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

Setup

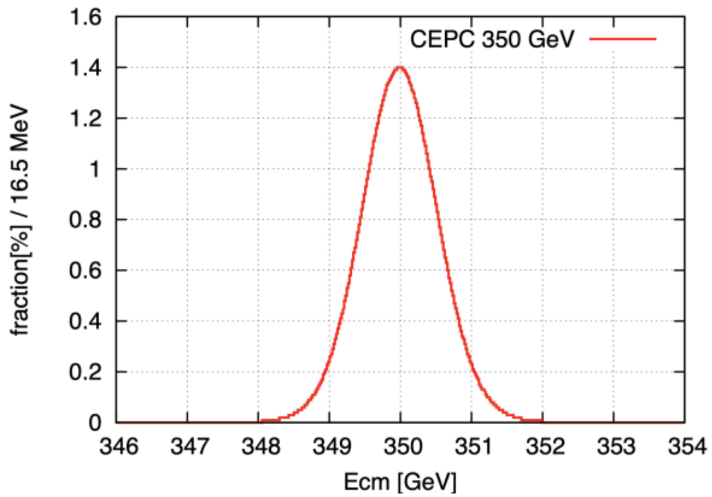
- Top properties:
  - The mass of the top quark is set to be 171.5 GeV.
  - The width of the top quark is set to be 1.33 GeV.
  - The α_s of the top quark is set to be 0.1184.
- Background:
  - It is assumed that the nominal background contribution is well known both from theory and from measurements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

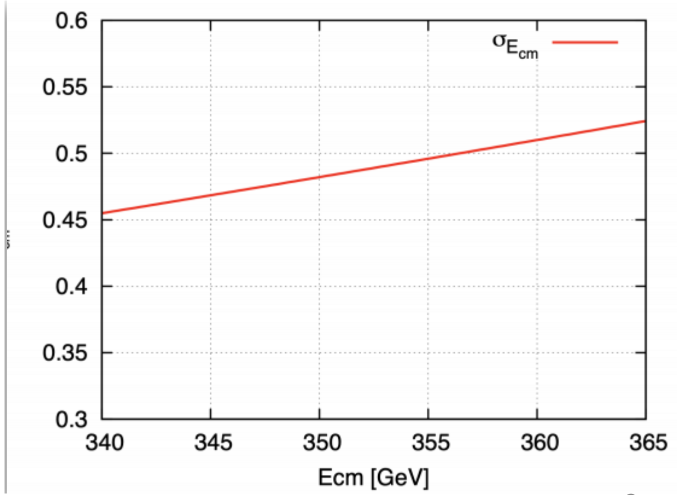
Setup

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



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





Provided by Yiwei Wang

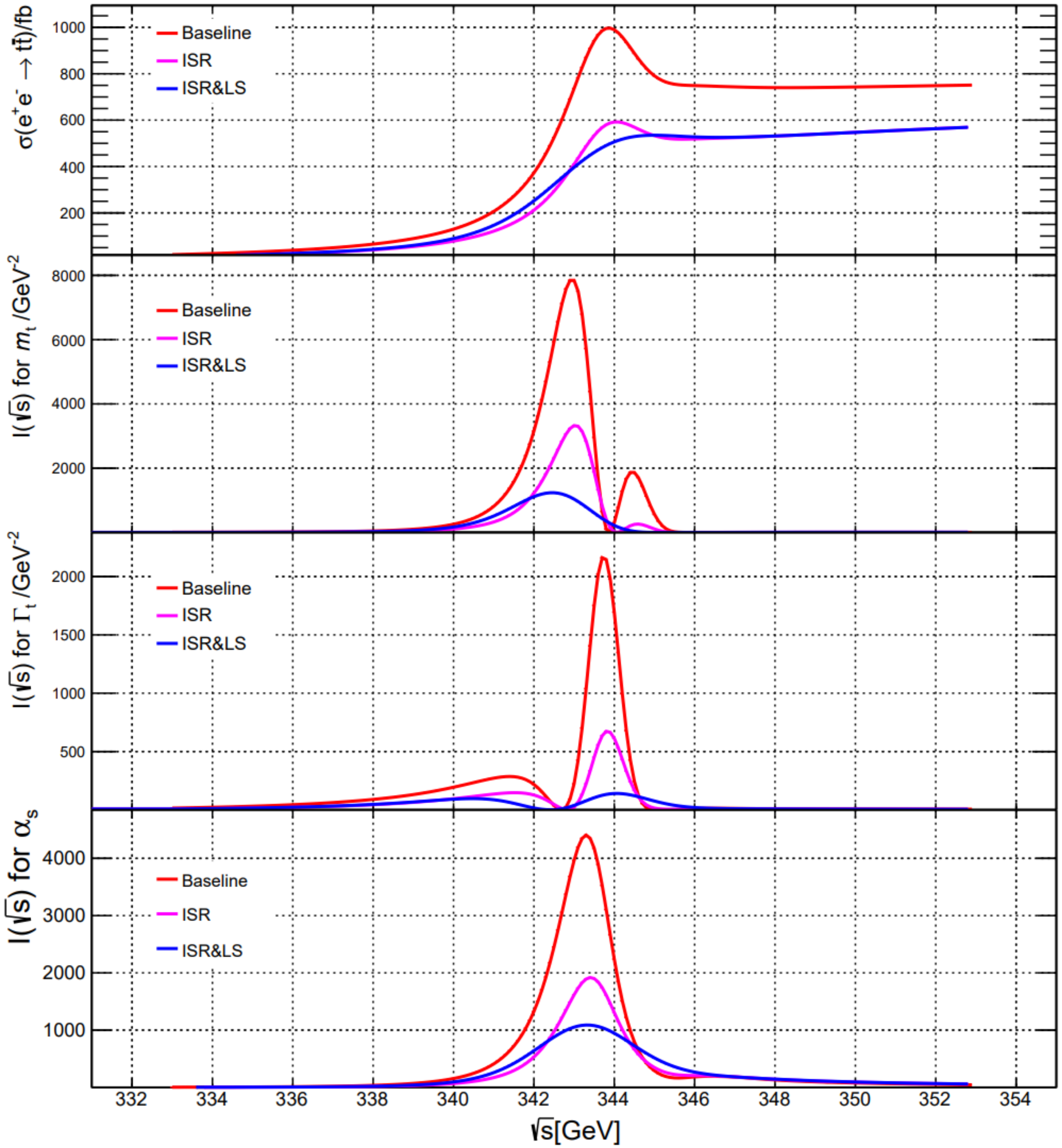
Fisher Information

- 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

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

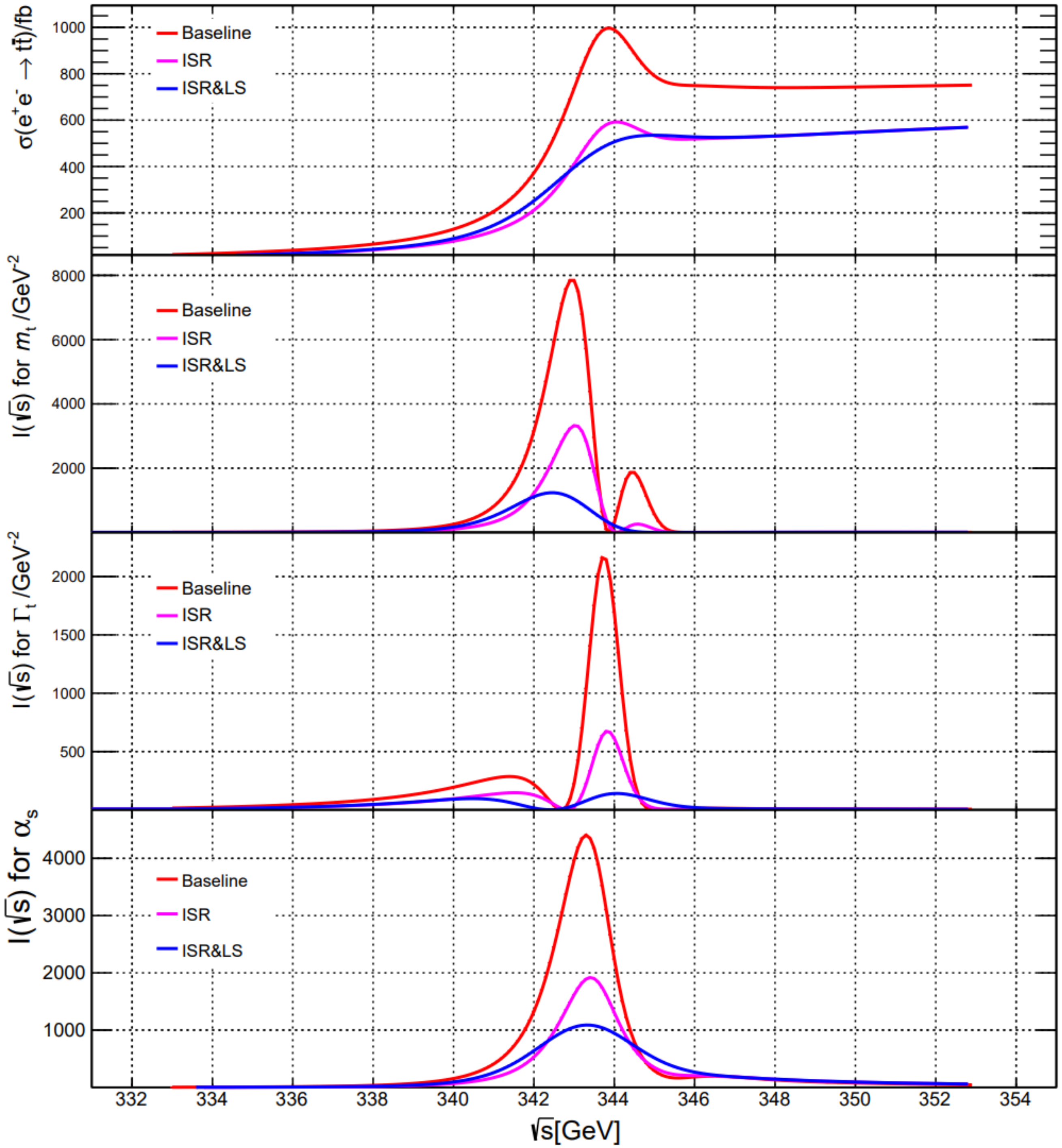
Fisher Information

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



Fisher Information

- Optimal mass point: 342.75 GeV
- Optimal width point: 344.00 GeV
- Optimal 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	CEPC Stat. uncertainty	CLIC Stat. uncertainty
m_t	9 MeV	34 MeV
Γ_t	25 MeV	
α_s	0.000344	0.0009

⋆ The total luminosity of CLIC is 200 $\mathbf{fb^{-1}}$ and uses 10 data points.

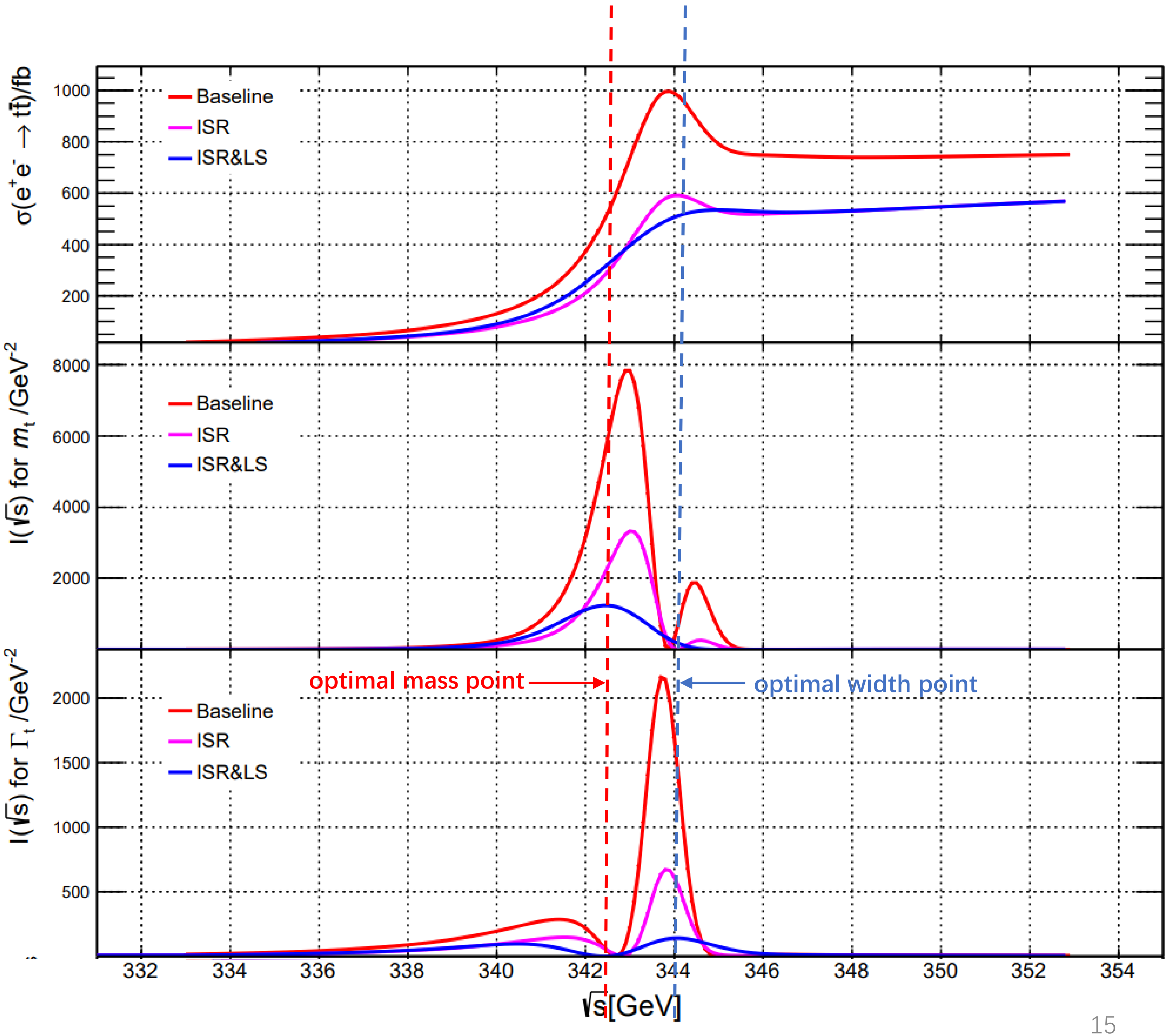
Eur. Phys. J. C (2013) 73:2530

The statistic uncertainties on width

- To estimate the expected precision of width, we consider such situation: we give luminosity to both the optimal mass point and the optimal 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	320
{80, 20}	10	50
{50, 50}	13	31
{20, 80}	19	25
{0, 100}	>50	21

- 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.



Systematic uncertainty

- Uncertainty from Theory
- Uncertainty of the background
- Uncertainty from Beam
- Uncertainty of LS, width and α_s
- Uncertainty from Experimental efficiency
- Uncertainty of quick scan method

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%	8 MeV
3%	24 MeV

Eur. Phys. J. C (2013) 73:2530
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 2 MeV and 13 MeV is reached.

Background uncertainty	Error
1%	2 MeV
5%	13 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.
- It will bring 2 MeV uncertainty on 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}		
$\boxed{\delta E_{beam}\text{/MeV}}$	1.0	0.3	0.6	1.8

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

Uncertainty of LS, width and α_s

- 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

- 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 0.14 GeV on width.

Width (0.14 GeV)	α_s (0.0007)
10 MeV	17 MeV

Experimental efficiency

- The experimental efficiency of the future detectors are yet to know. We assume several possible scenarios for the level of this uncertainty: 0.5%, 1%, 3% and 5%.

Efficiency Uncertainty	Error
0.5%	5 MeV
1%	10 MeV
3%	27 MeV
5%	44 MeV

Uncertainty of quick scan method

- The quick scan is used to locate the optimal energy point in advance to the high-luminosity measurement.
- Several iterations are needed to approach the truth optimal point, the precision of which is limited by the digital step of the beam energy.
- CEPC has a control on its centre-of-mass energy down to an ultimate digital step of 3.5 MeV at around the threshold, which results in an uncertainty of 2 MeV.

Summary of measurement

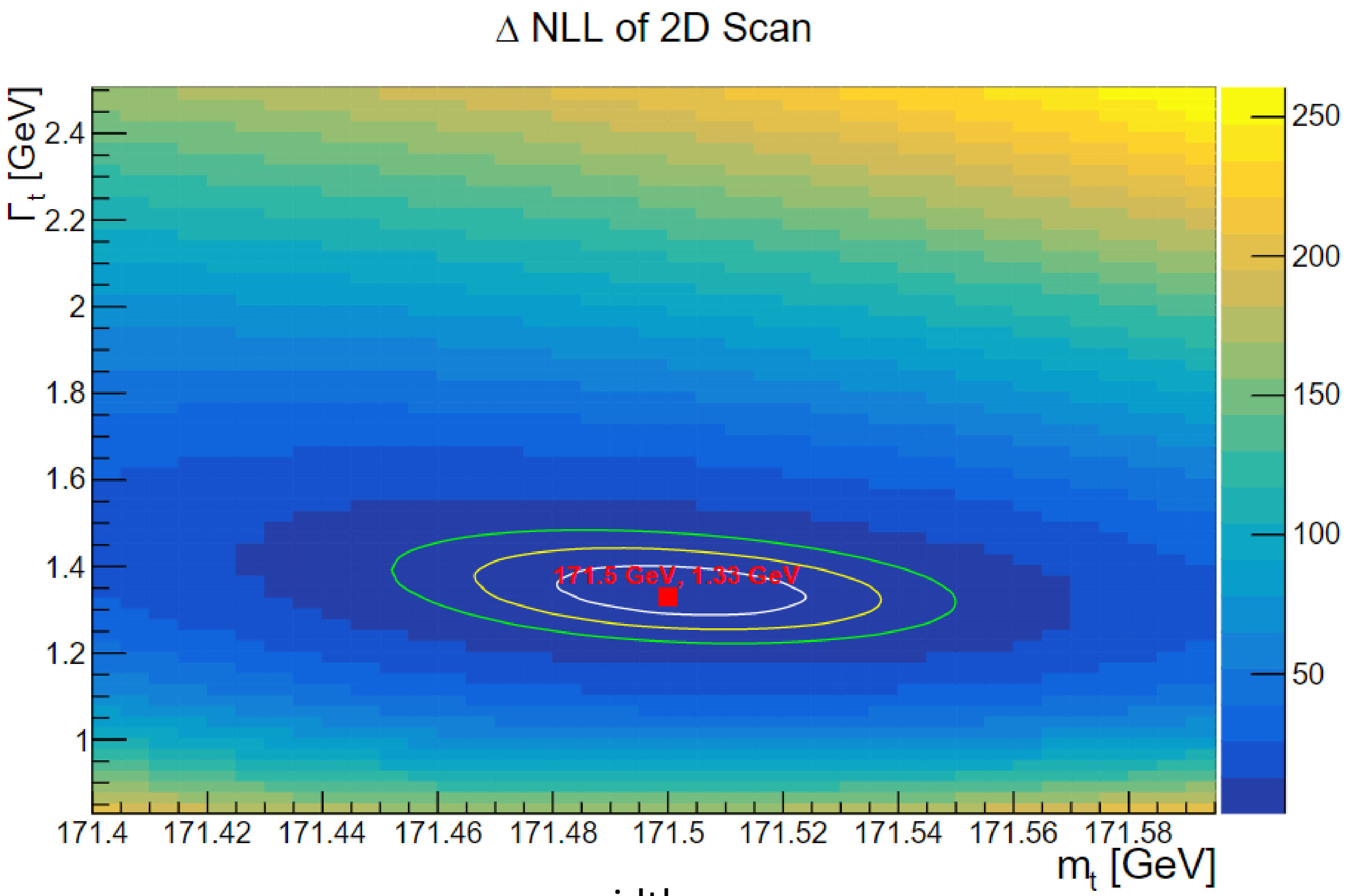
	Optimistic/MeV	Conservative/MeV
Statistics	9	9
Theory	8	24
Background	2	14
α_s	17	17
Width	10	10
Experimental Efficiency	5	44
Quick Scan	2	2
Beam	2	2
LS	3	6
Total	25	57

Extraction of 2 parameters

- Given that top quark mass is of great interests, the studies always include it and are performed on the extractions of top quark mass vs α_s and of top quark mass vs width.
- The energy point that is optimal for top quark mass is taken and to give sufficient constraints on two parameter at a time one more energy point needs to be added.

Mass vs. Width

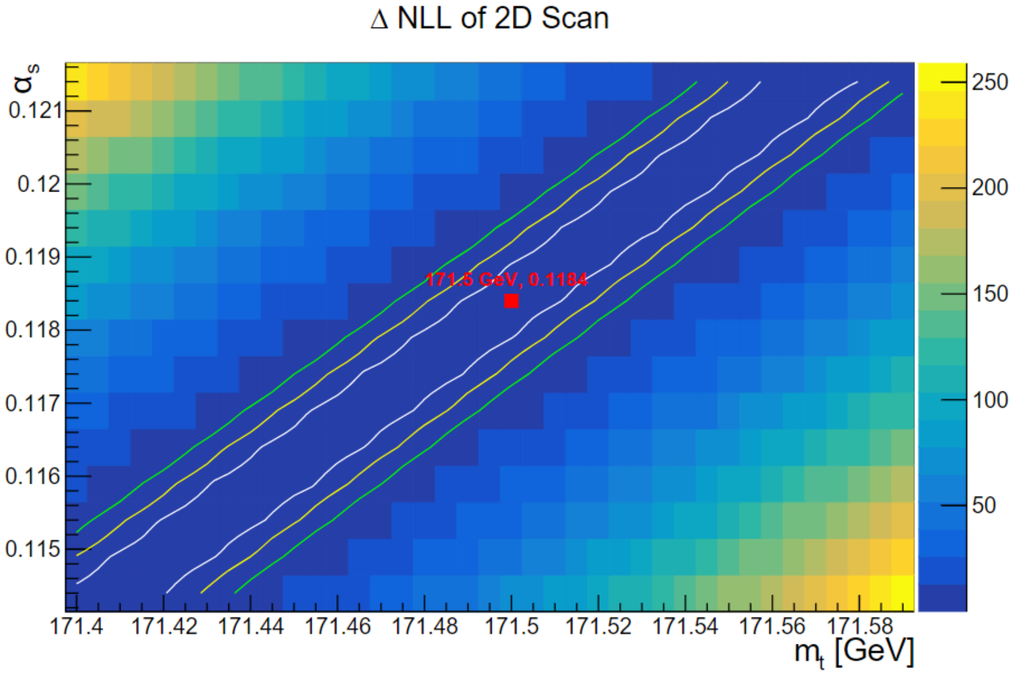
- Following the Fisher Information, note that the optimal mass point is 342.75 GeV and the optimal width point is 344 GeV are selected.
- 50 $\mathbf{fb}^{-1}$ is given to each center-of-mass energy.



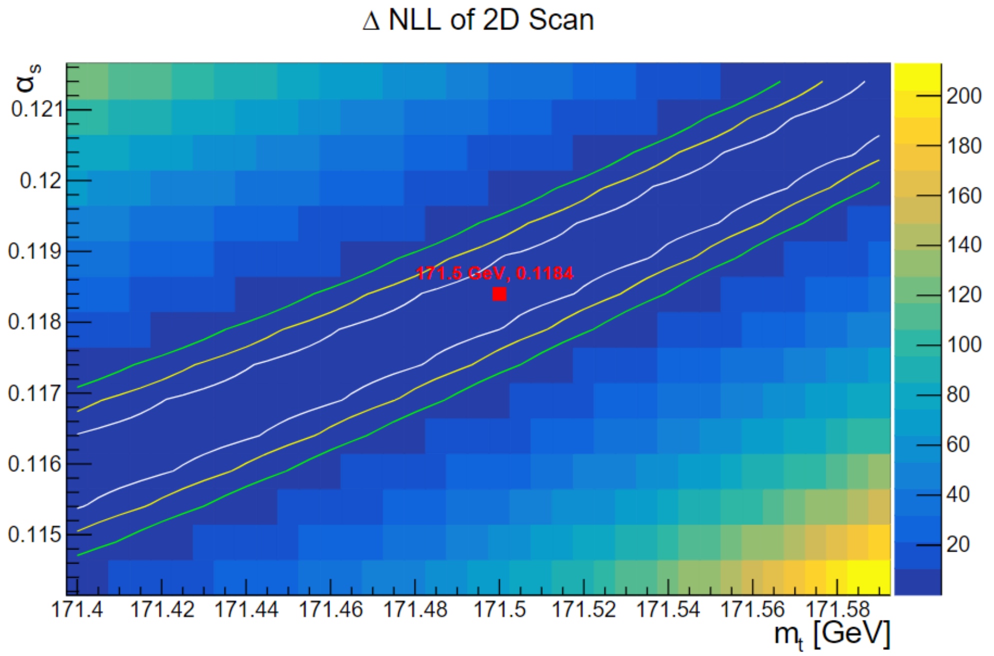
	mass	width
1σ	21MeV	57MeV
2σ	36 MeV	94MeV
3σ	49MeV	131 MeV

Mass vs. α_s

- Following the Fisher Information, note that the optimal mass point is 342.75 GeV and the optimal α_s point is 343.5 GeV are selected.
- But it is too close to the optimal point for top quark mass 342.75 GeV. This makes the crosssection curve highly sensitive to both parameters, leading to both variations dominating the cross-section uncertainty.



Ecm=342.75GeV

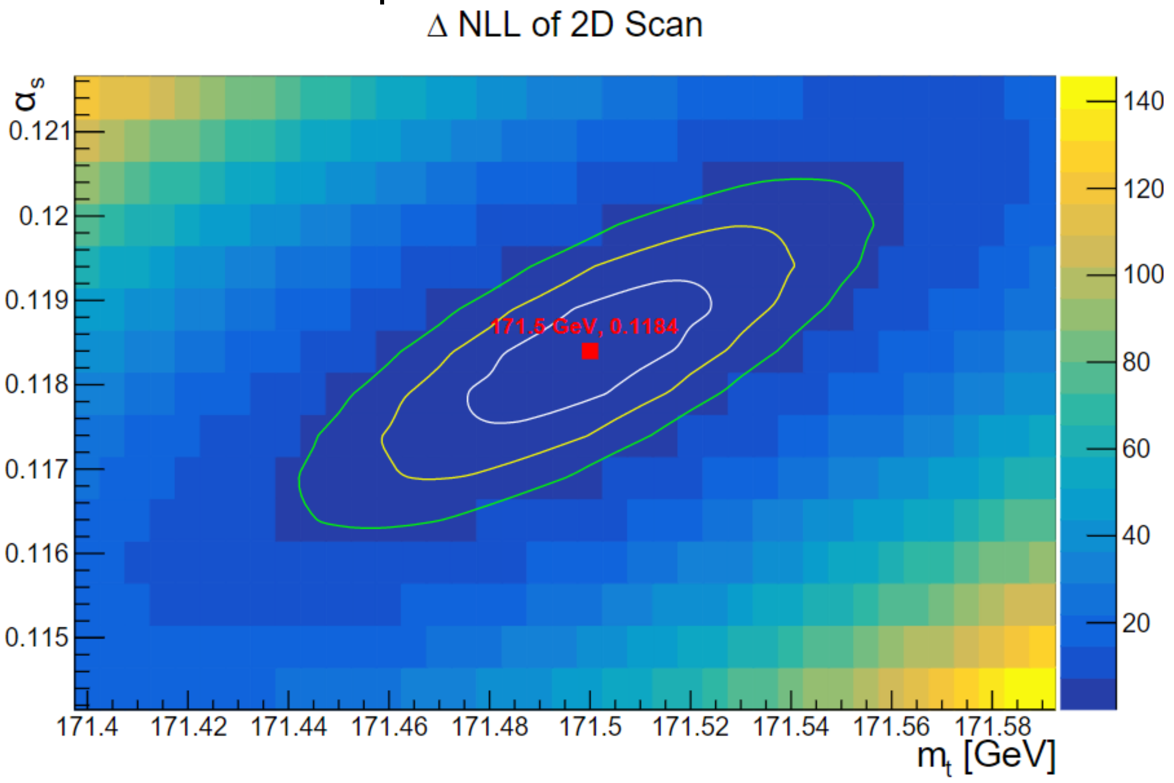


Ecm=343.50GeV

Mass vs. α_s

- Therefore, one has to drop the optimal point for α_s and move higher to somewhere the cross-section curve still keep some sensitivity to it but leaves much less constraint power on top quark mass.
- The energy point 344.50 GeV is one of these points in tests and shows the best performance.

	mass	α_s
1σ	24MeV	0.00086
2σ	44MeV	0.00153
3σ	61MeV	0.00210



Summary

- In the one energy point method, measuring one parameter at a time while keeping others to their SM predictions, the precision are given.
- The study shows that CEPC is capable of measuring the top quark mass with a precision below 57 MeV using the single energy point.
- The method requires a good understanding of theory, experimental efficiency and background estimations, and also requires a low-luminosity scan to locate the optimal energy point
- It is also suggested to use other observables which can also provide sensitivity to top mass and other properties in the threshold region, including peak of momentum distribution and forward-backward asymmetry.

	Optimistic/MeV	Conservative/MeV
Statistics	9	9
Theory	8	24
Background	2	14
α_s	17	17
Width	10	10
Experimental Efficiency	5	44
Quick Scan	2	2
Beam	2	2
LS	3	6
Total	25	57

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

Acceptance and selection efficiency for signal

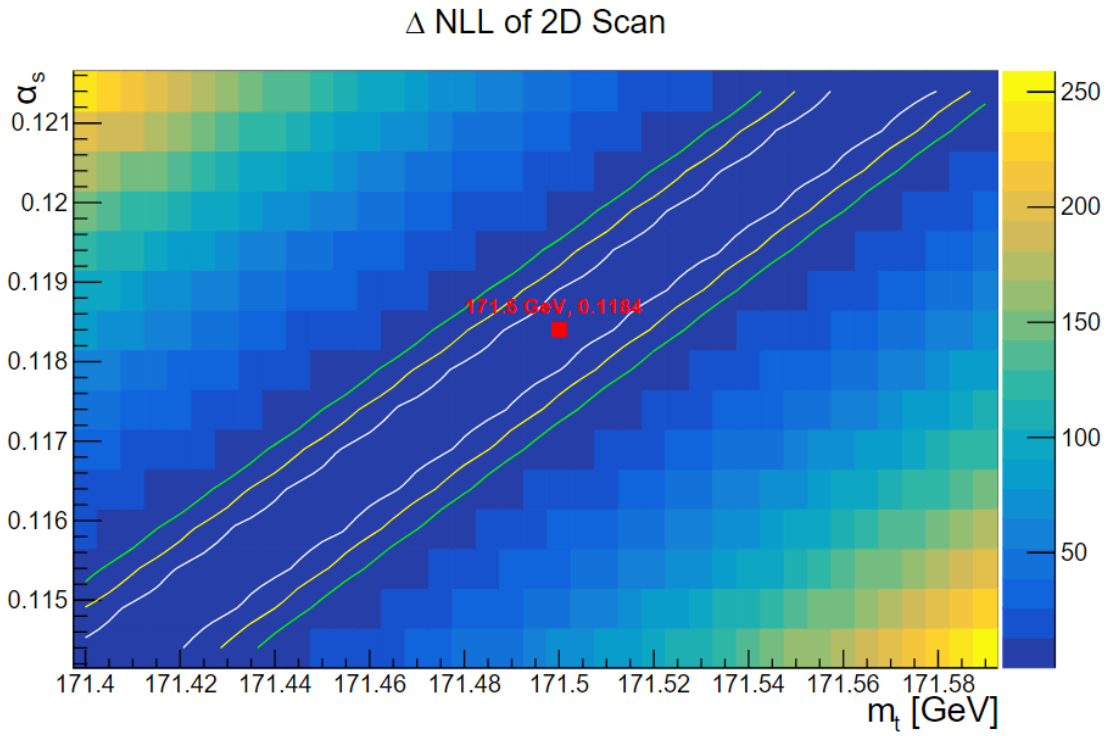
- The number read from CLIC Eur. Phys. J. C (2013) 73:2530
- semi-leptonic :
  - Data: 8296, Bkg: 643, extracted signal: 7653, acceptance*selection efficiency = 48.13%, Branch ratio=30%
- Full-hadronic
  - Data: 11396, Bkg: 1393, extracted signal: 10003, acceptance*selection efficiency = 41.0%, Branch 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

The statistic uncertainties on α_s

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

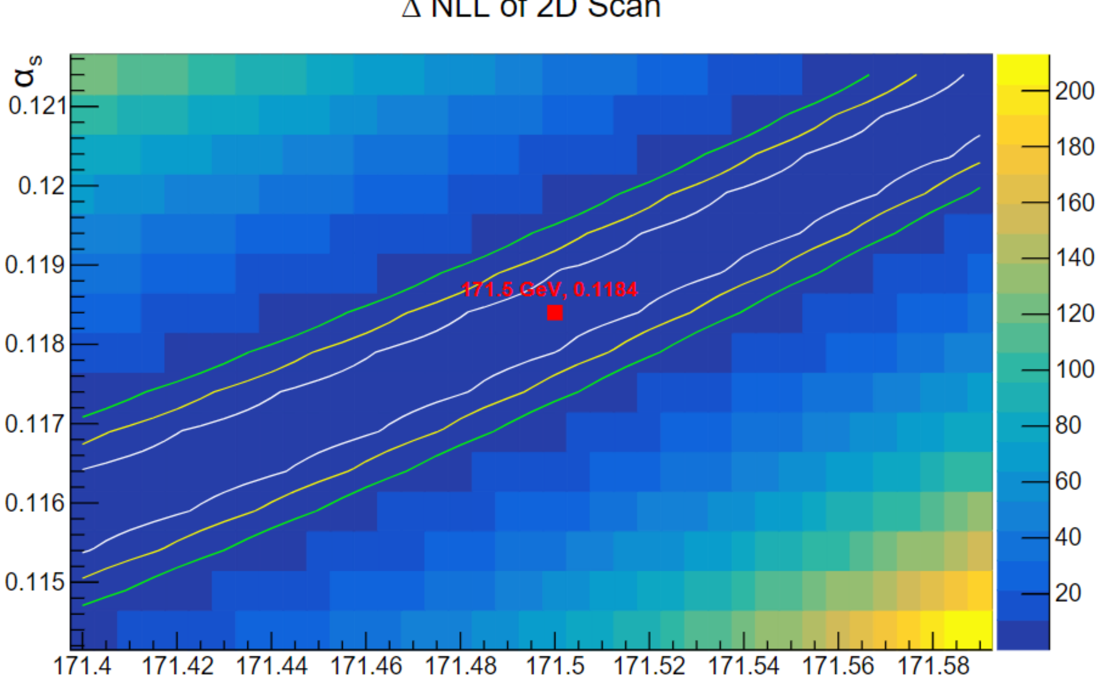
Luminosity/fb^{-1}	Mass precision/MeV	α_s precision
{100, 0}	9	0.00034
{80, 20}	10	0.00034
{50, 50}	11	0.00034
{20, 80}	12	0.00034
{0, 100}	14	0.00034

Mass vs aS in single Ecm

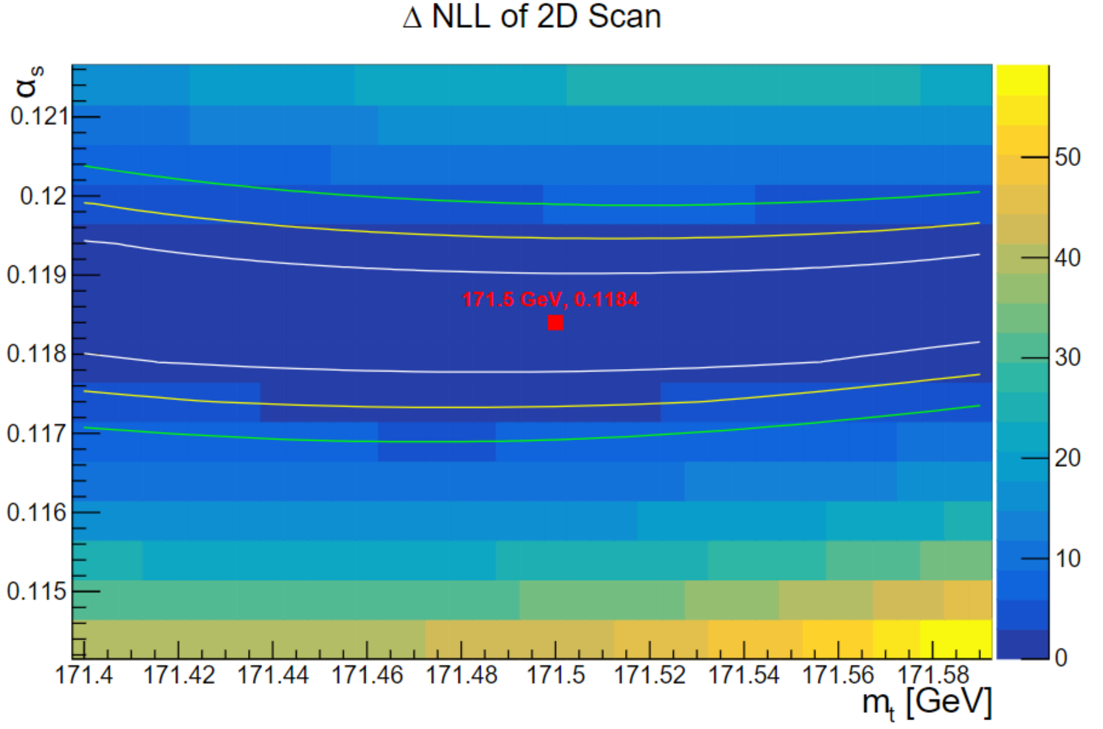


342.75 GeV

343.5 GeV

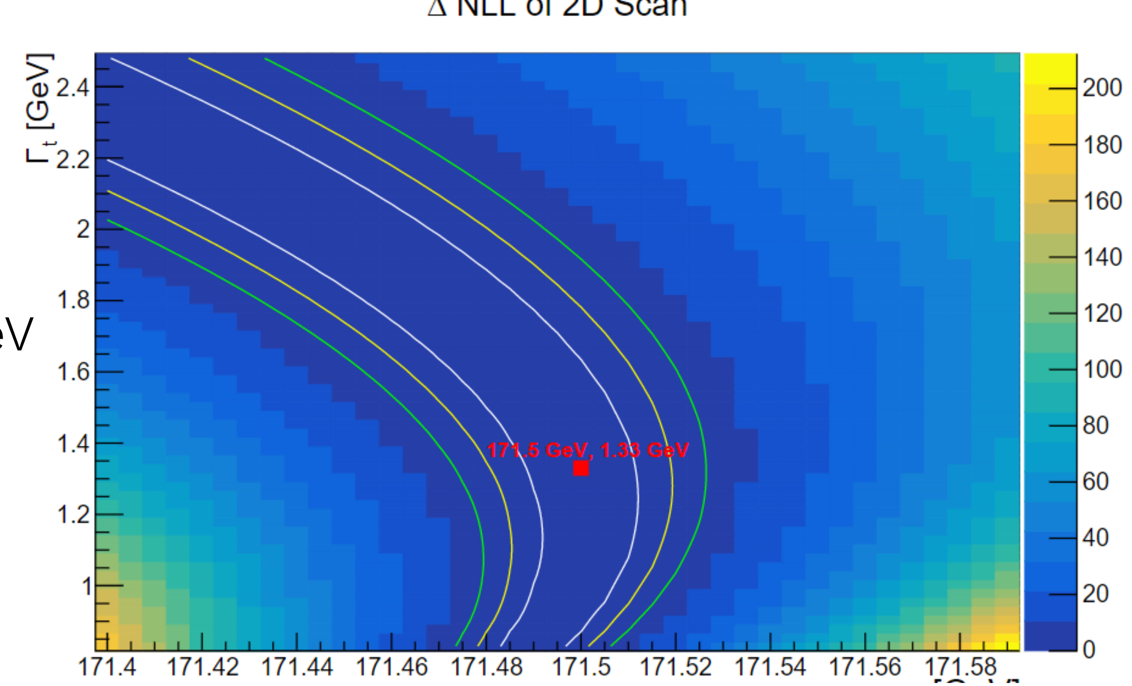


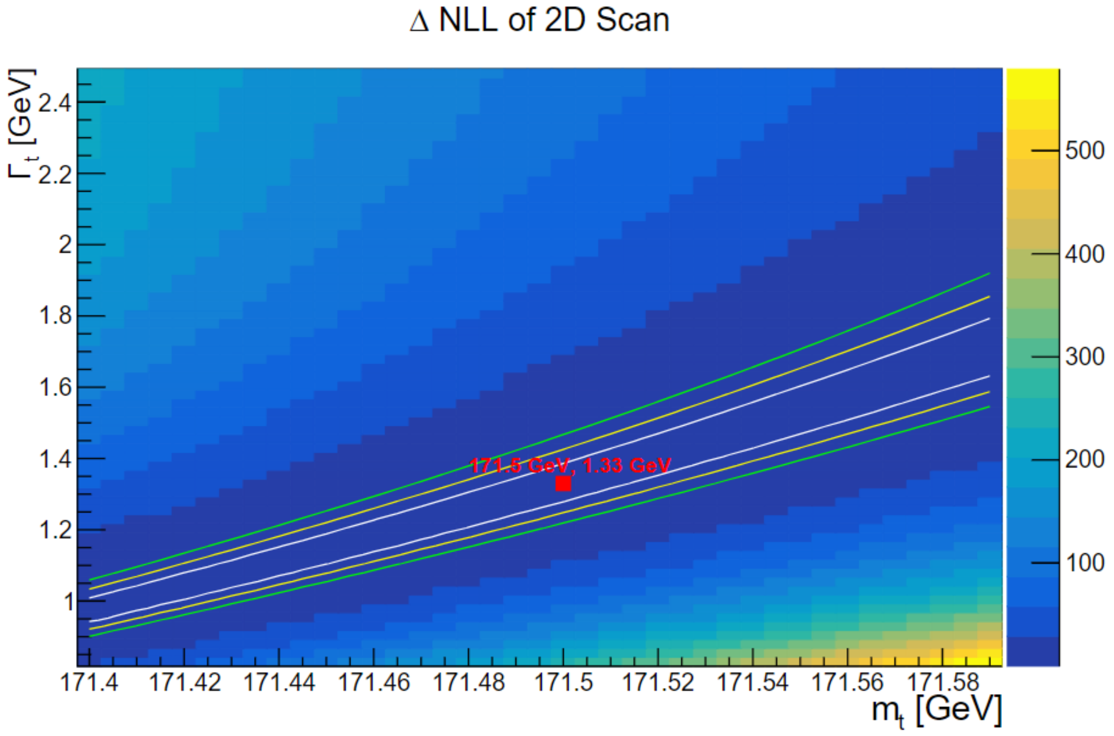
344.25 GeV



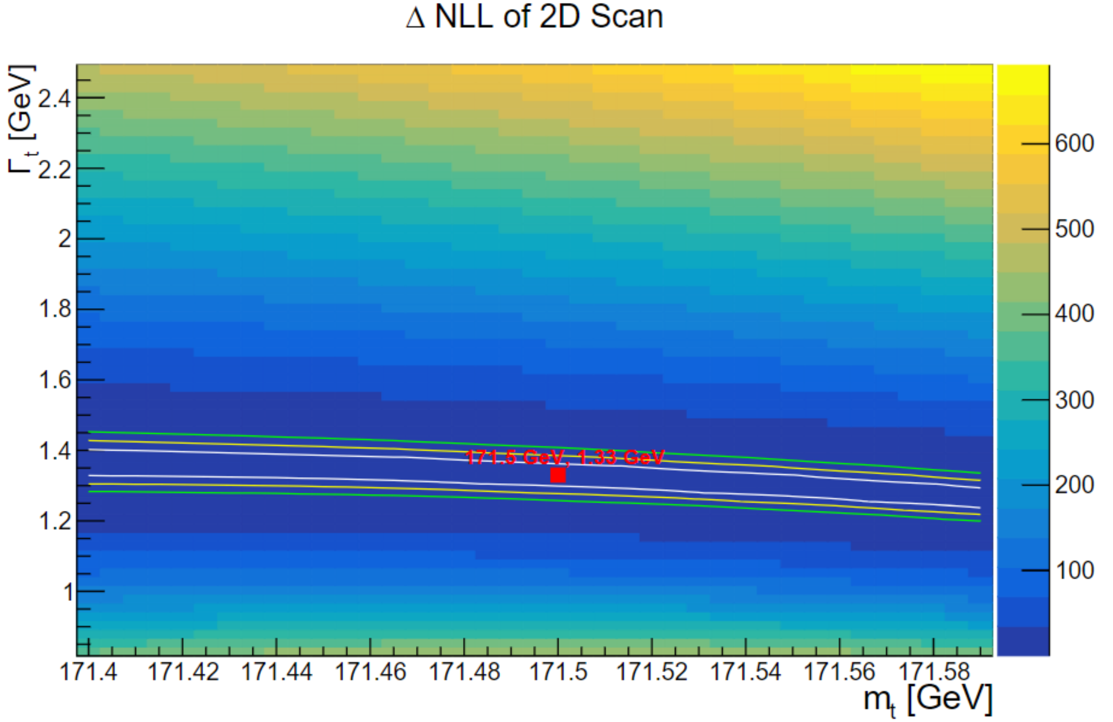
Mass vs width in single Ecm

342.75 GeV





342.00 GeV



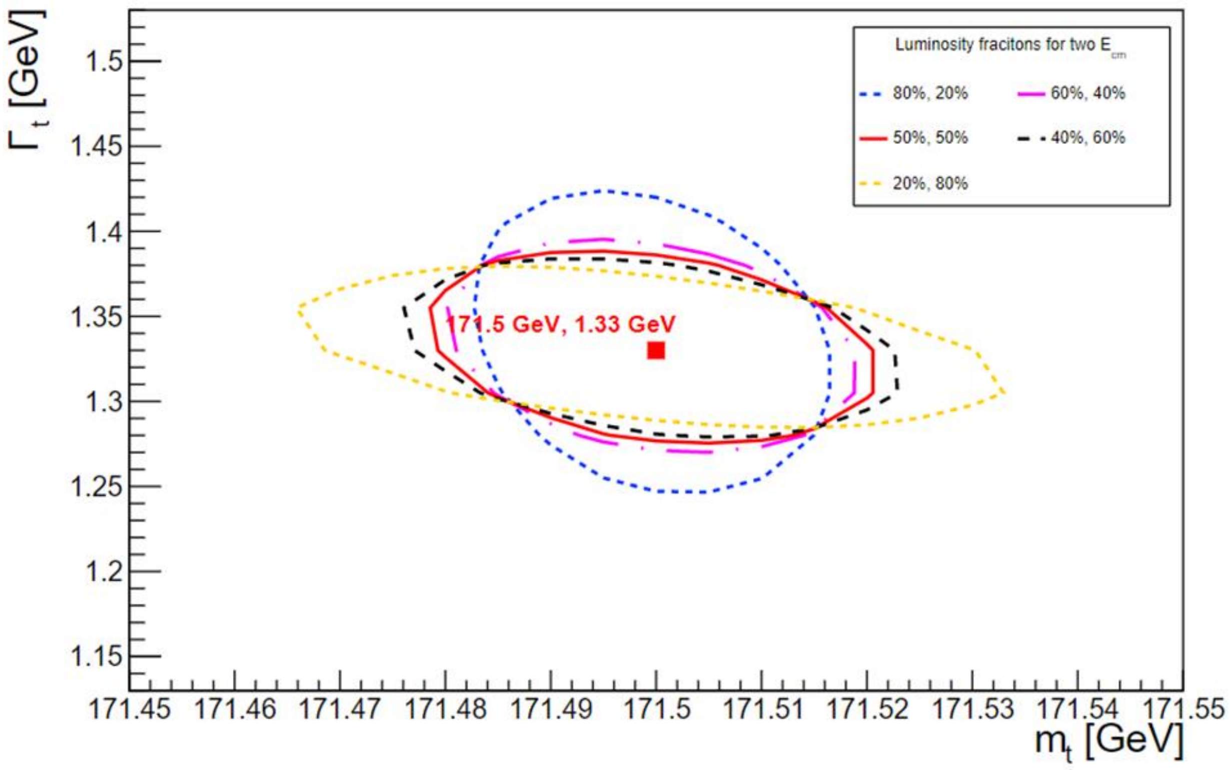
344.00 GeV

Uneven lumi test

- So far, the two energy points split the total luminosity evenly, i.e. 50% vs 50%. Thus, an additional check on the uneven split of the luminosity is performed.
- Here presents the sensitivities by varying luminosity fractions of 80% vs 20%, 60% vs 40%, 50% vs 50%, 40% vs 60% and 20% vs 80%

Uneven lumi test

- Mass vs. Width
- From 50% vs 50% to 80% vs 20% there is a sizeable improvement in top quark mass, but it degrades the width precision too much.
- The split of 50% vs 50% can a pragmatic choice for both.



Uneven lumi test

- Mass vs. α_s
- 50%-50% split is optimal for top quark mass and sub-optimal for α_s.
- Moving more luminosities from 342.75 to 344.50 GeV (such as the split of 20% vs 80%) can slightly improve the precision on α_s but will lose a lot in top quark mass .