Top quark properties measurements at CEPC

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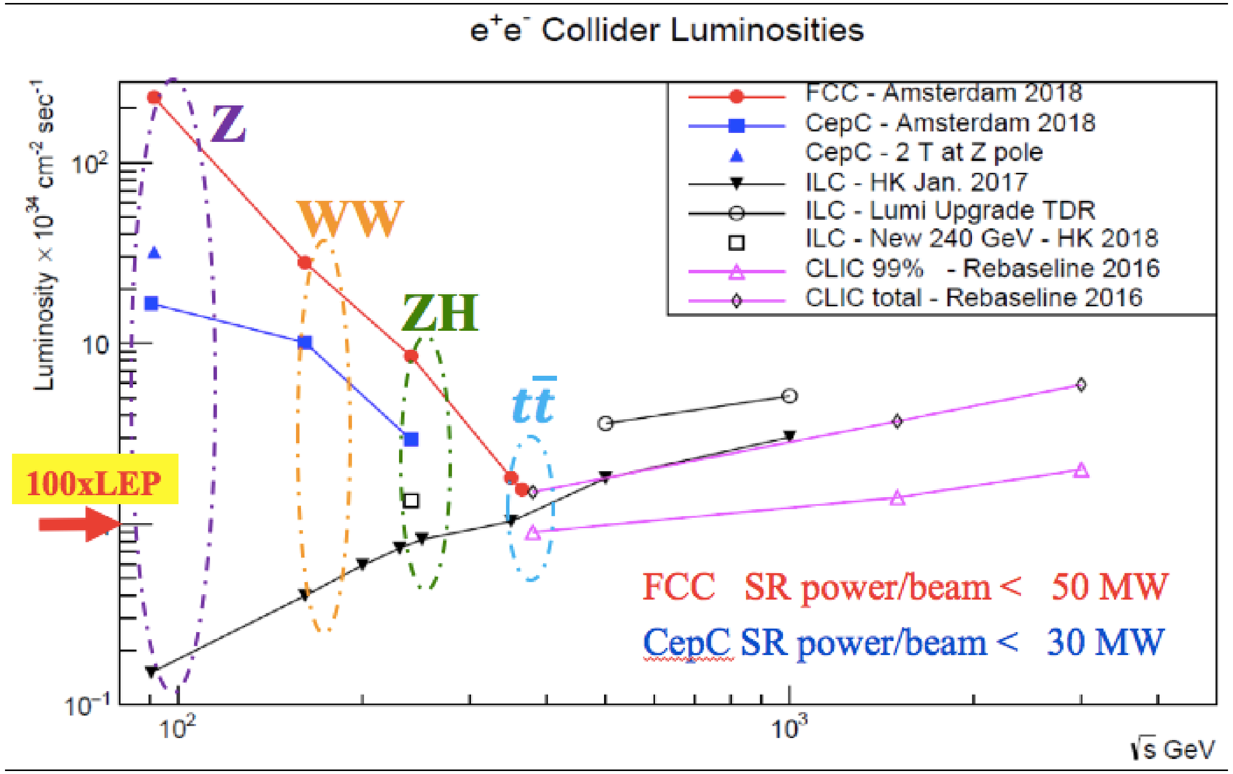
Reference: Eur. Phys. J. C (2023) 83:269, arXiv:2207.12177

Introduction

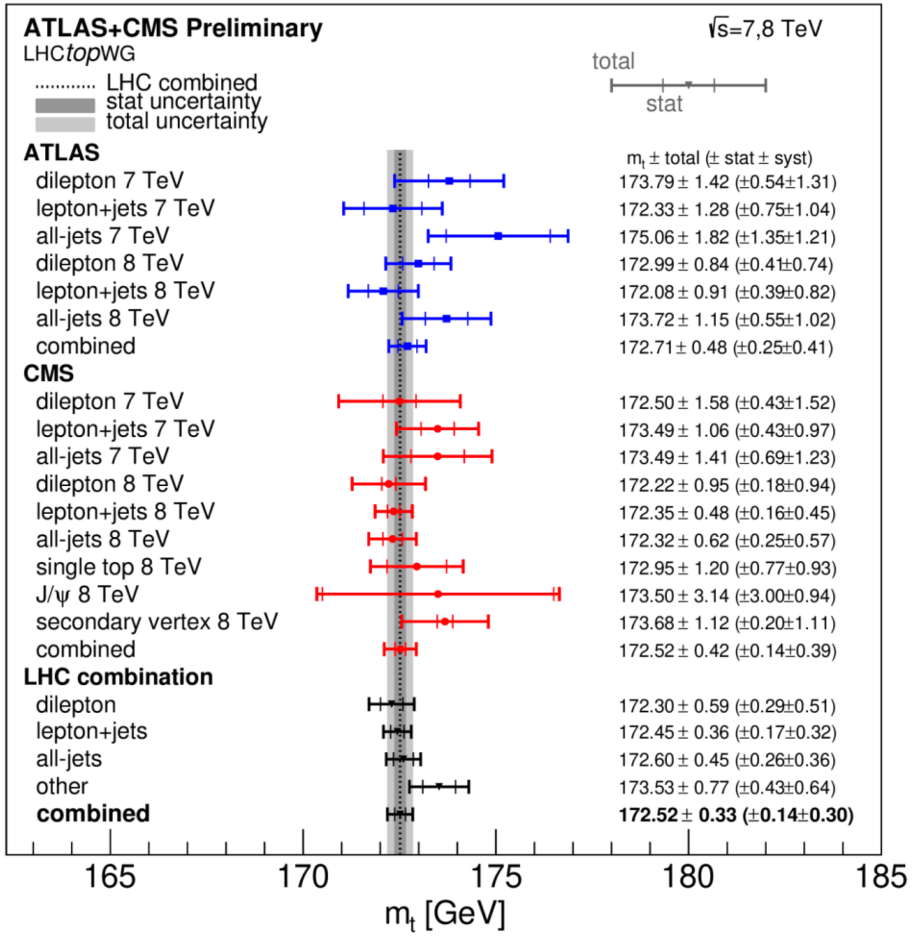
- CEPC is designed to operate in four energy modes:
  - Higgs factory @~240 GeV
  - Super Z factory @~91 GeV
  - W factory @~160 GeV
  - Finally an upgrade will enable CEPC to operate at tt energy ~360GeV
- 360 GeV can be a platform for:
  - Top quark precision measurements
  - Higgs complementary measurements
  - BSM searches



F. Bedeschi

Top mass measurements

- Importance:
  - Fundamental factors in the Standard Model
  - Stringent check of internal consistency of SM.
- Measured using top reconstruction at hadron colliders
  - ATLAS+CMS combined measurements results: 330 MeV dominated by systematic uncertainties
- But difficult to further improve the precision due to dominant systematic uncertainties at hadron colliders.

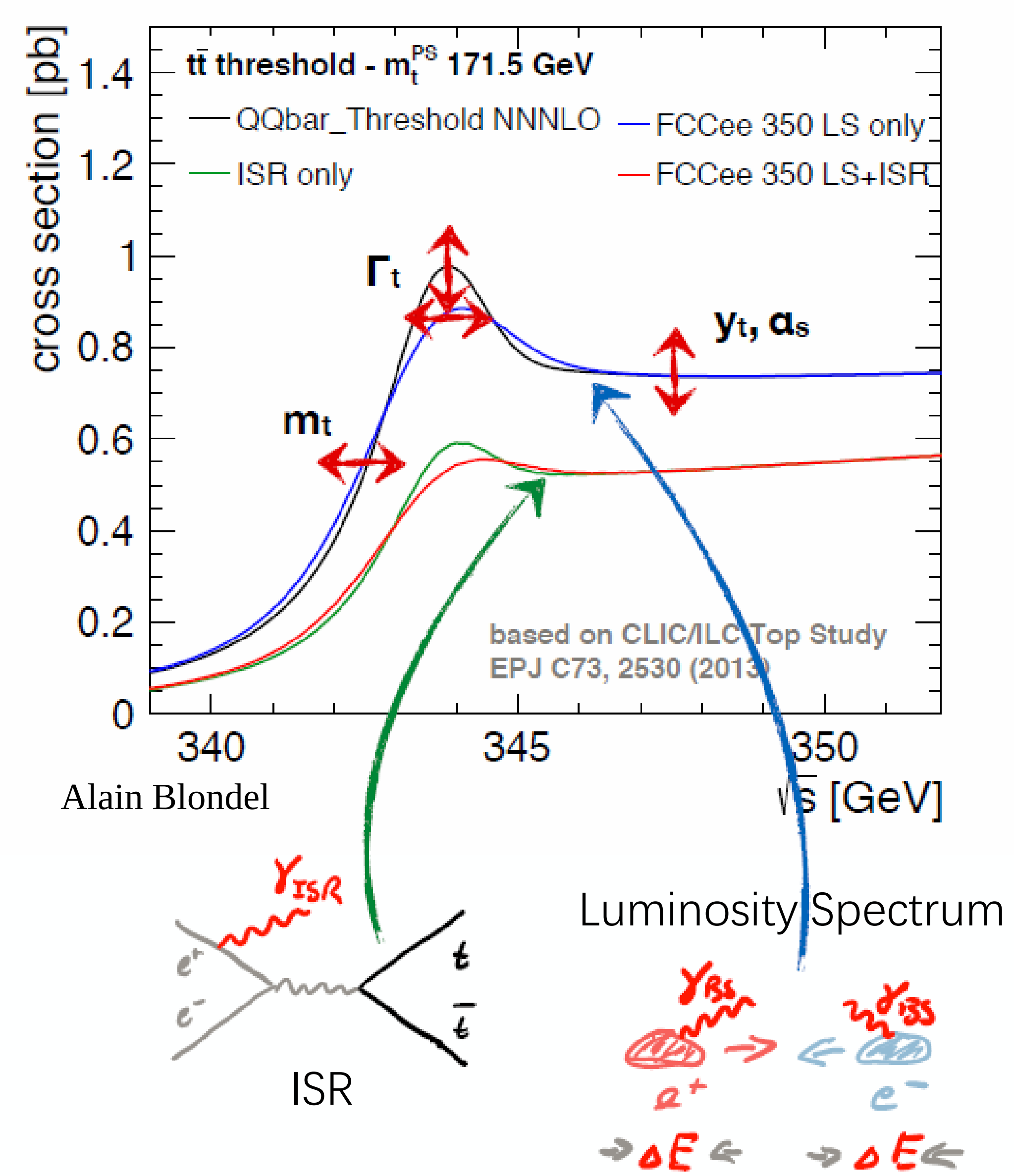


ATLAS-CONF-2023-066, CMS-PAS-TOP-22-001 for Run1

New results such as CMS Eur. Phys. J. C 83 (2023) 963 with 370 MeV using Run2

tt threshold scan

- e^+e^- colliders can provide not only the top reconstruction method but also the tt threshold scan.
- Made against $\sqrt{s}$ and cross section, direct observable.
- It brings measurements of such parameters:
    - Top mass
    - Top width
    - Top Yukawa coupling
    - α_s (strong coupling)



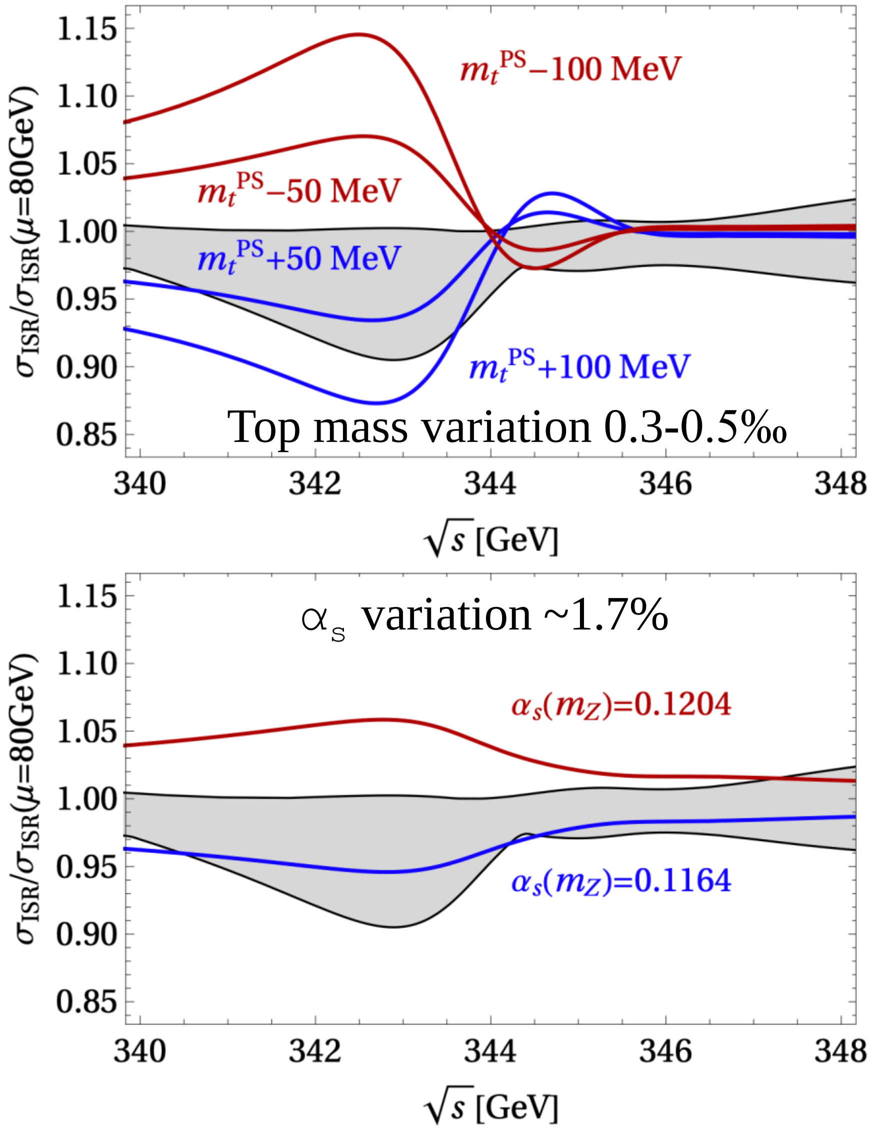
Alain Blondel

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
    - To avoid IR renormalon ambiguities, the PS shift (PSS) mass scheme is applied by default in the package

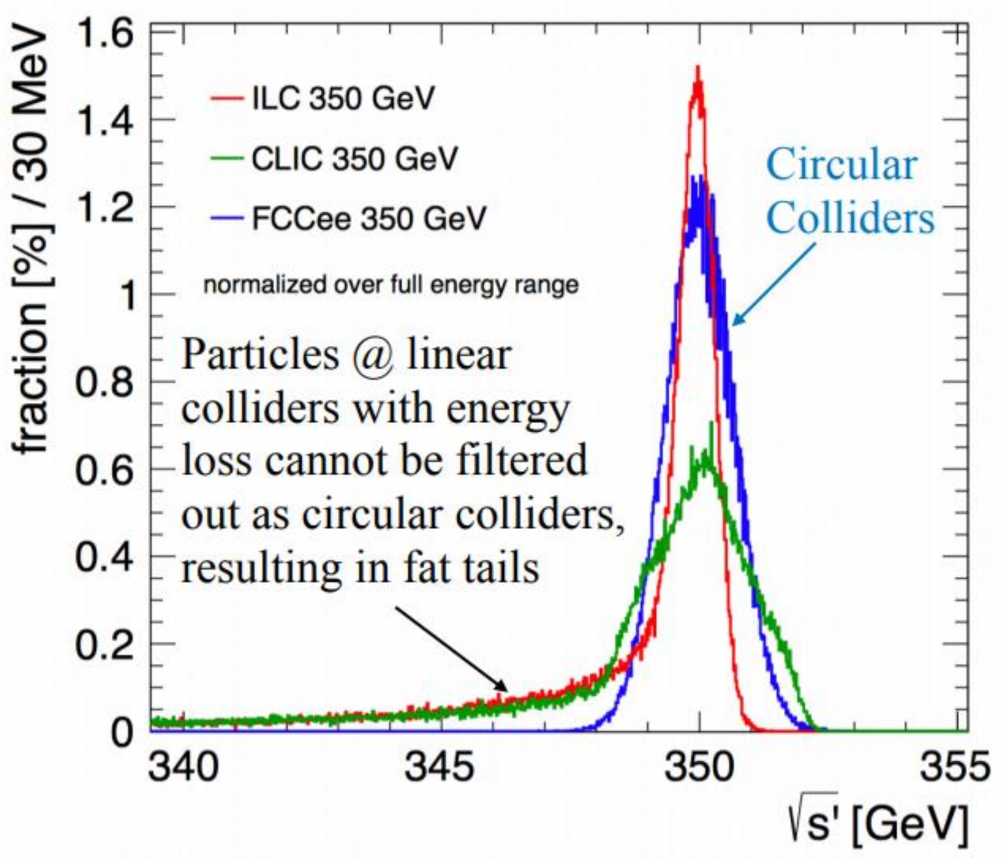
$$m_t^{\mathrm{PS}} = 171.5\,\mathrm{GeV}, \qquad \alpha_s(m_Z) = 0.1184$$

    - Initial state radiation (ISR) effects are also included in the package
- We integrate Luminosity Spectrum(LS) by a Gaussian function with CEPC expected beam energy spread (~0.5GeV) as a function of $\sqrt{s}$.



LS in linear/circular colliders

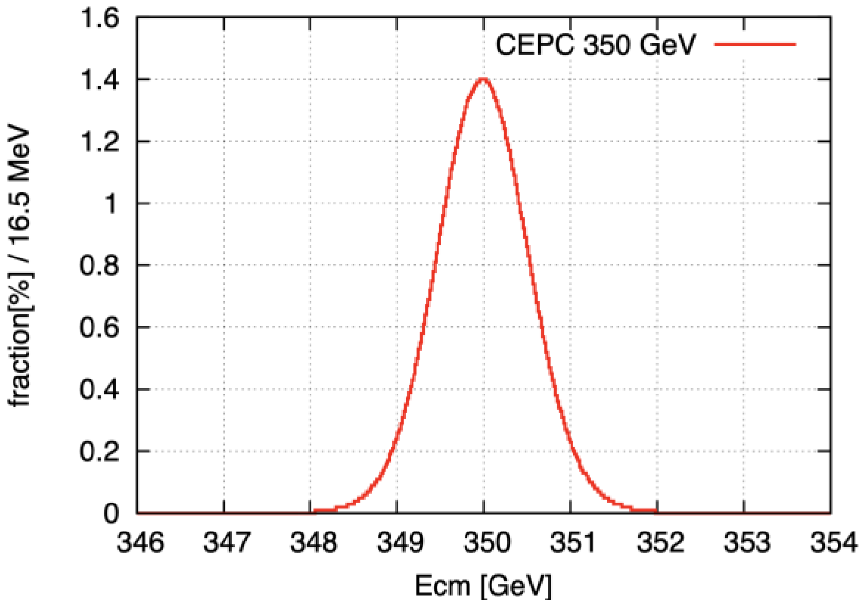
- The luminosity spectrum at linear colliders is obviously worse than circular colliders, given that the particles with energy loss are not removed by the bending magnets.
- This can substantially change the cross-section curve at around the tt threshold

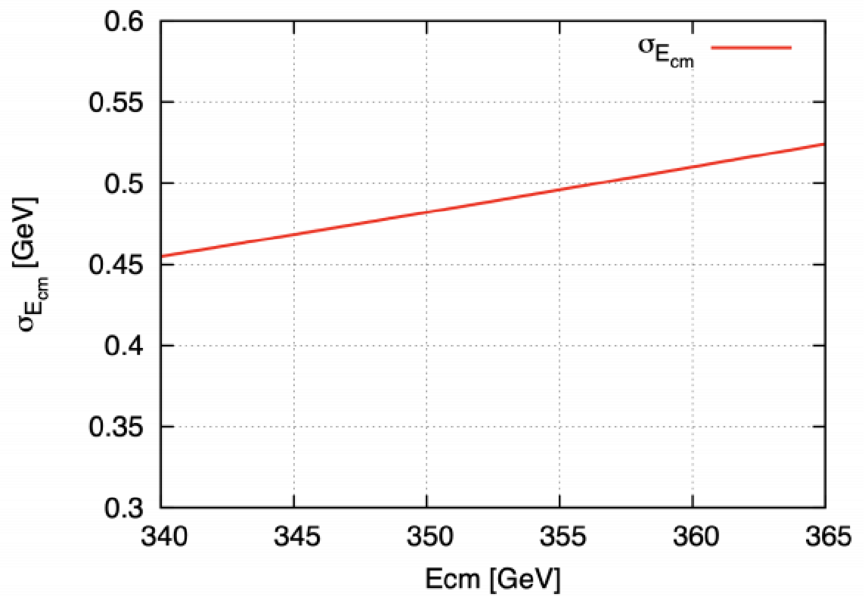


Particles @ linear colliders with energy loss cannot be filtered out as circular colliders, resulting in fat tails

LS in CEPC

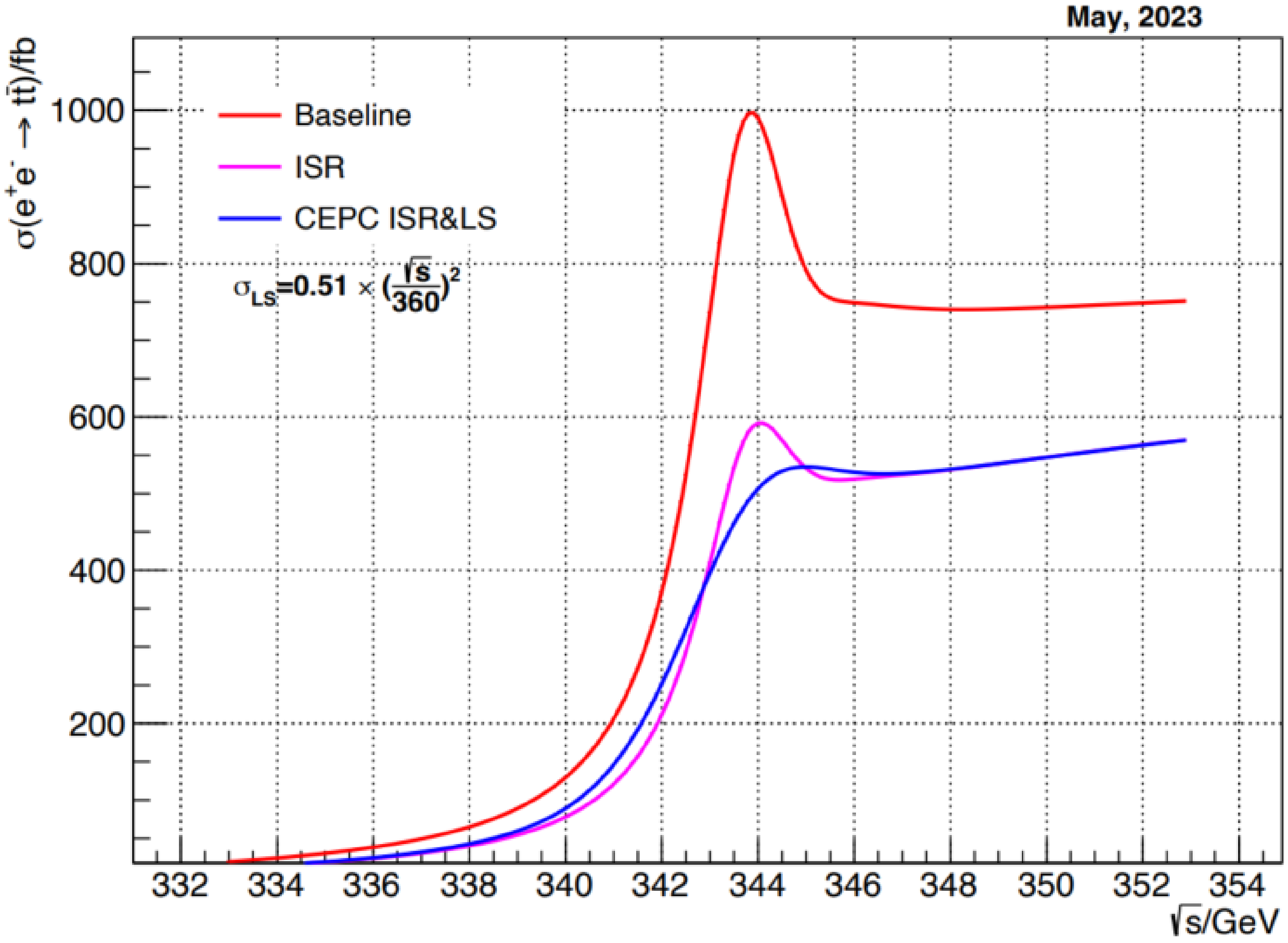
- The luminosity spectrum is shown for $\sqrt{s}$ = 350GeV with a width of ~480 MeV
- Similar to the FCC-ee scenario





Provided by Yiwei Wang

Cross Section at the tt threshold with CEPC



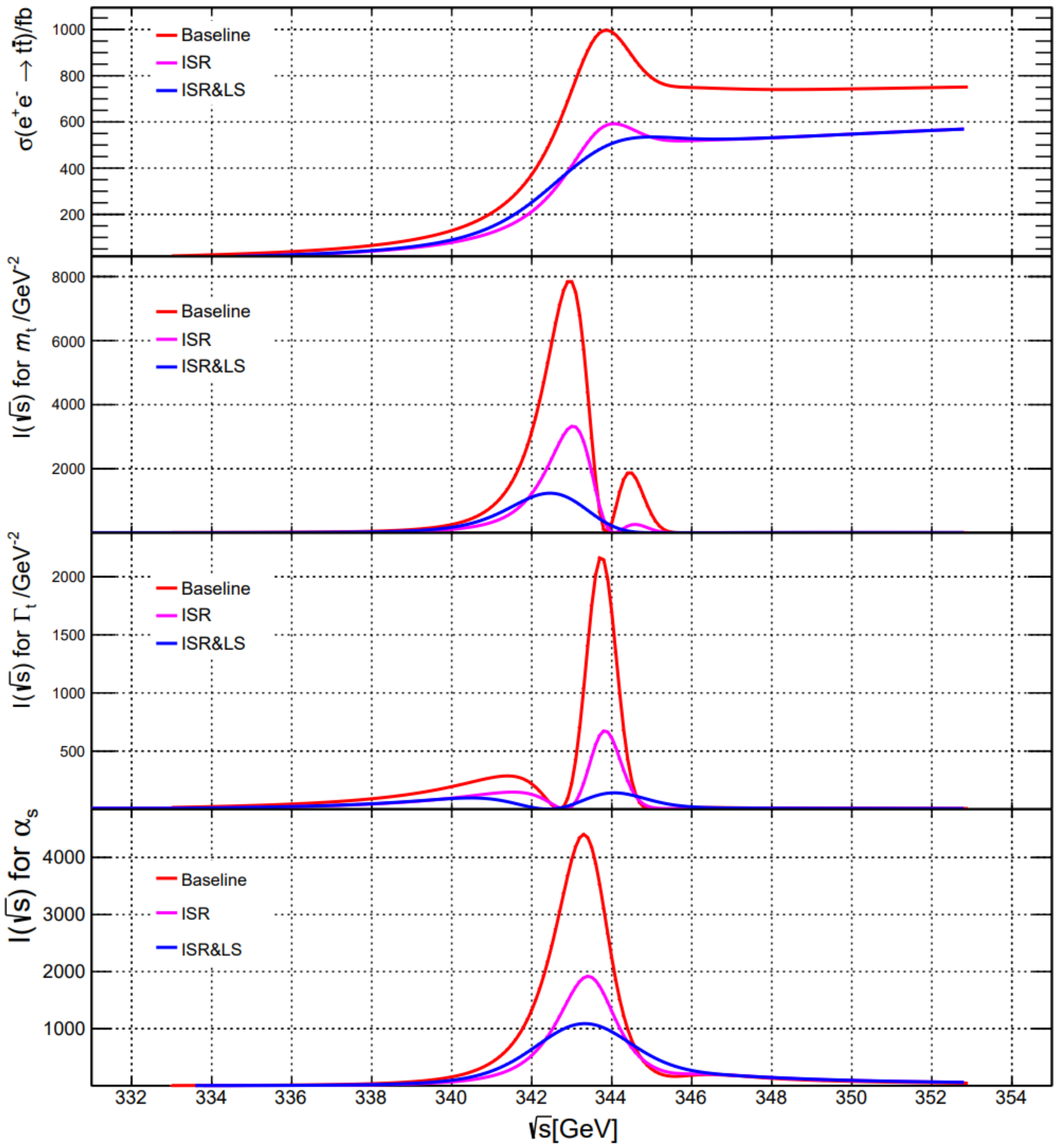
Fisher Information

-Which energy to collide with?

- Around the threshold, we need to identify the energy point(s) that contain(s) the most sensitivity.
- Construct Fisher information to test the energy point(s)

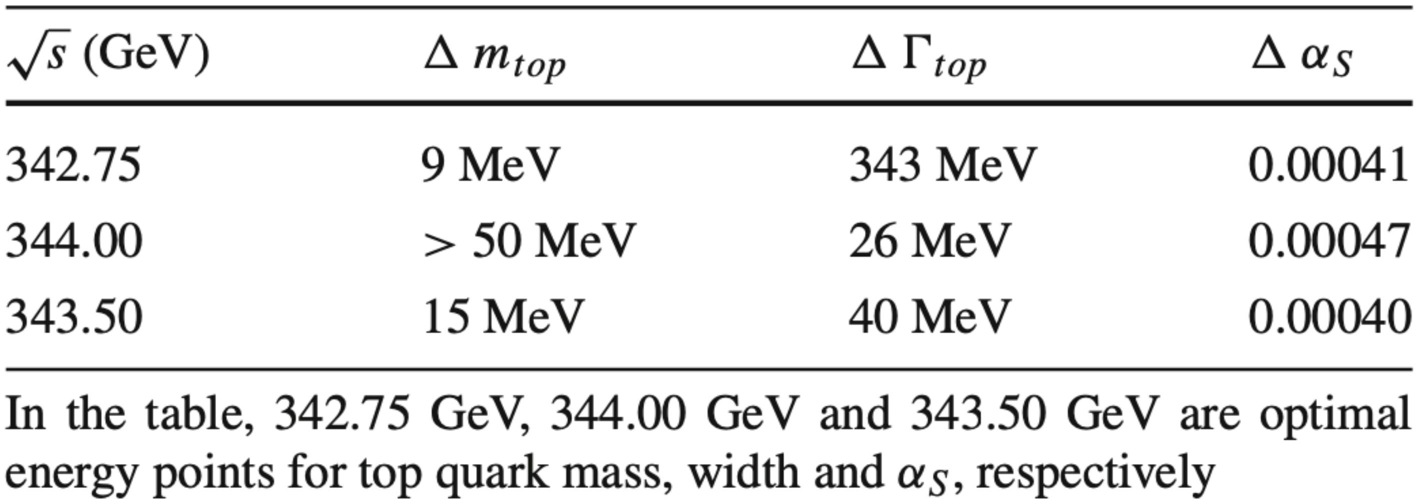
$$I(\sqrt{s}) = \int (\frac{\partial log(G(\sigma|\sigma_0(\sqrt{s},\theta), \sqrt{\sigma_0(\sqrt{s},\theta)}))}{\partial\theta})^2 \times G(\sigma|\sigma_0(\sqrt{s},\theta), \sqrt{\sigma_0(\sqrt{s},\theta)})d\sigma$$

- Larger amplitudes implies richer information and higher sensitivities.



Expected precision

- With the CEPC setup, limited to the total luminosity of 100 fb^{-1} , top quark mass, width and α_s are measured individually at their optimal energy points.
  - Only colliding at one optimal energy point would give the best sensitivity
  - This is tested with many different scenarios: one vs multiples energy points, un-even luminosity allocation etc.



$\sqrt{s}$ (GeV)	$\Delta\ m_{top}$	$\Delta\ \Gamma_{top}$	$\Delta\ \alpha_S$
342.75	9 MeV	343 MeV	0.00041
344.00	$>$ 50 MeV	26 MeV	0.00047
343.50	15 MeV	40 MeV	0.00040

In the table, 342.75 GeV, 344.00 GeV and 343.50 GeV are optimal energy points for top quark mass, width and α_S, respectively

Systematic uncertainty

- Uncertainty from Theory
- Uncertainty of LS
- Uncertainty of width and α_s
- Uncertainty from Experimental efficiency
- Uncertainty of the background
- Uncertainty from Beam
- 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

  - 3% (conservative) based on the current calculations on the market
  - 1% (optimistic) that might be achieved by the time of CEPC, optimistically

Uncertainty of LS

- 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%	6 MeV

- This is very different than CLIC (75 MeV from 20% LS uncertainty), due to the different controls of the luminosity spectrum in circular and linear colliders

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	9.1
Reduce 20% of the LS	9.0
Reduce 50% of the LS	8.4

- The CEPC LS seems already excellent for this measurement, and large improvements of LS would not sizably improve top mass precision.

Uncertainty of width and α_s

- α_s and width are the inputs for this 1D top mass measurement
- α_s uncertainty is taken as 0.0007, while width is varied by 0.14 GeV (CMS constraint 2014)

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

- α_s uncertainty leads to 17 MeV on top mass, comparable to CLIC
- Width uncertainty results in 10 MeV on top mass

Experimental efficiency

- The experimental efficiency of the future detectors are yet to know.
- 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 the background

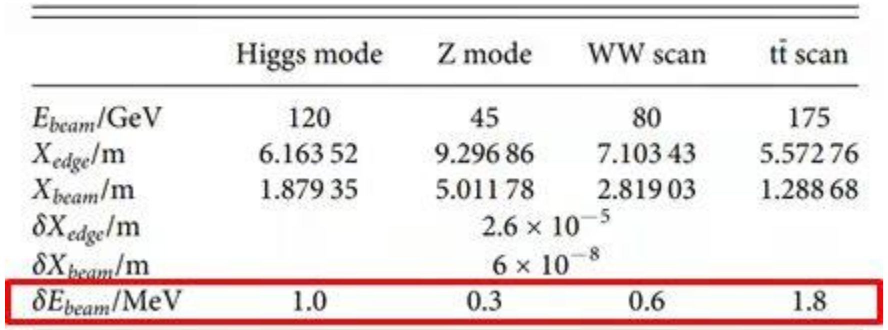
- The background is considered to be subtracted cleanly from the observed data. Therefore, an imperfect background description could also lead to uncertainty.
- Considering the background uncertainty as 1% optimistically and 5% conservatively, a measurement uncertainty of top quark mass of 2 MeV and 14 MeV is reached.

Background uncertainty	Error
1%	2 MeV
5%	14 MeV

- This is similar to CLIC that has 18 MeV uncertainty of top mass from 5% background variations, given the low level of background

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}			
δE_{beam}/MeV	1.0	0.3	0.6	1.8

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

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.

Uncertainties: Total

	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	24	57

- CEPC is expected to measure the top quark mass with the total uncertainties of 24 MeV and 57 MeV (dominated by the experimental efficiency), considering two different scenarios
- Compared to ~100 MeV of top mass uncertainty from CLIC (dominated by the LS uncertainty)

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.

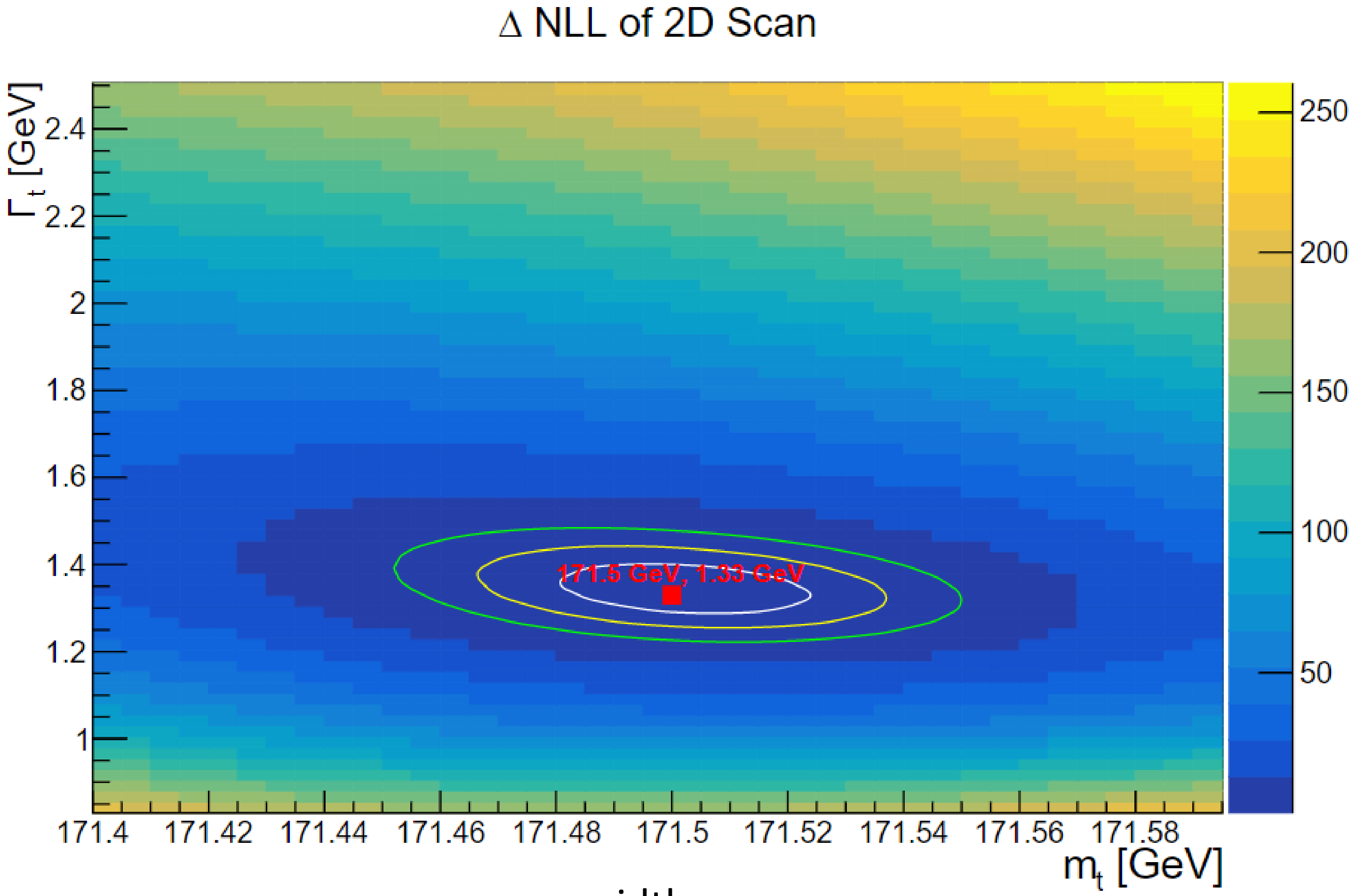
- Besides the optimal energy point for top mass, one additional energy point is needed.

- The energy point that is optimal to top mass will always be included, while the additional energy point to level up the sensitivity for the second parameter to measure will be located

- Statistical-only studies are performed.

Mass vs. Width

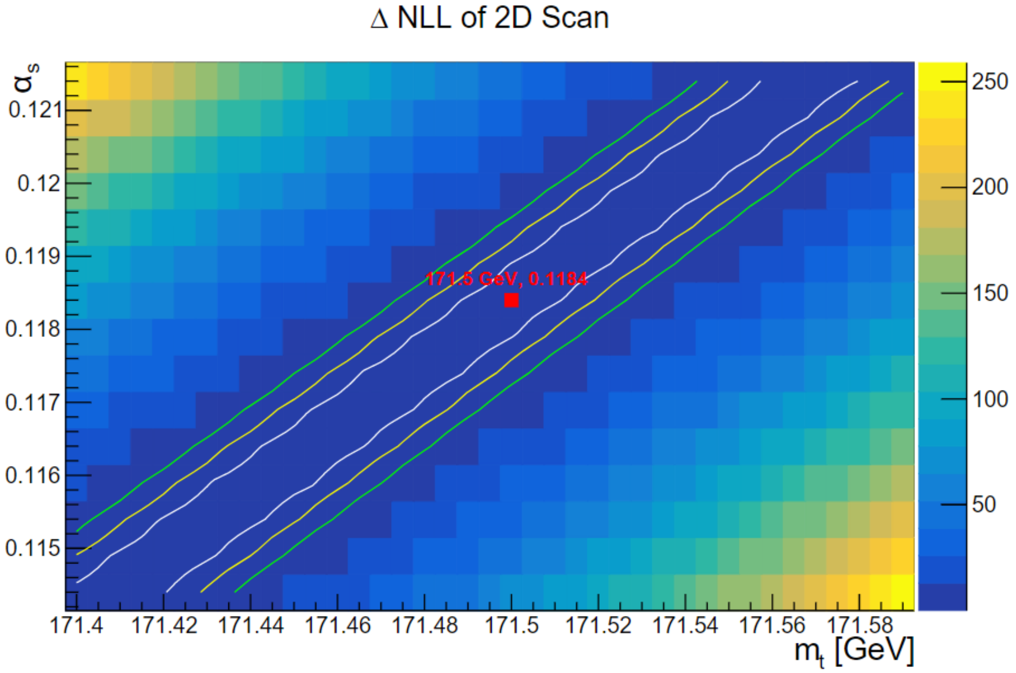
- Following the Fisher Information, note that the optimal mass point is 342.75 GeV and the optimal width point is 344 GeV are selected.
- $50\ \mathrm{fb}^{-1}$ is given to each center-of-mass energy.



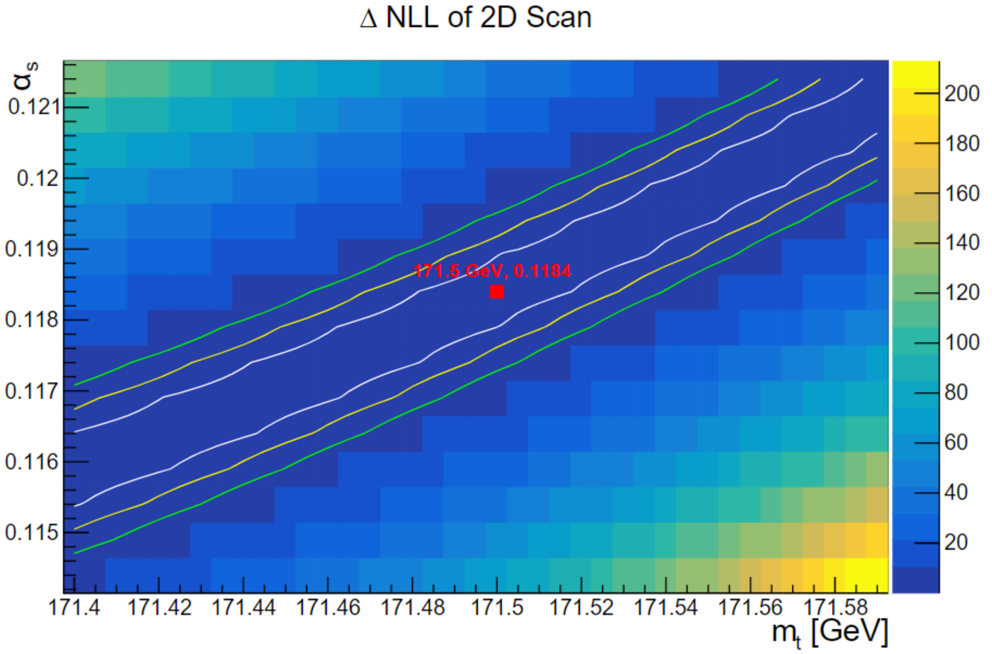
	mass	width
1σ	21MeV	57MeV
2σ	36 MeV	94MeV
3σ	49MeV	131 MeV

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

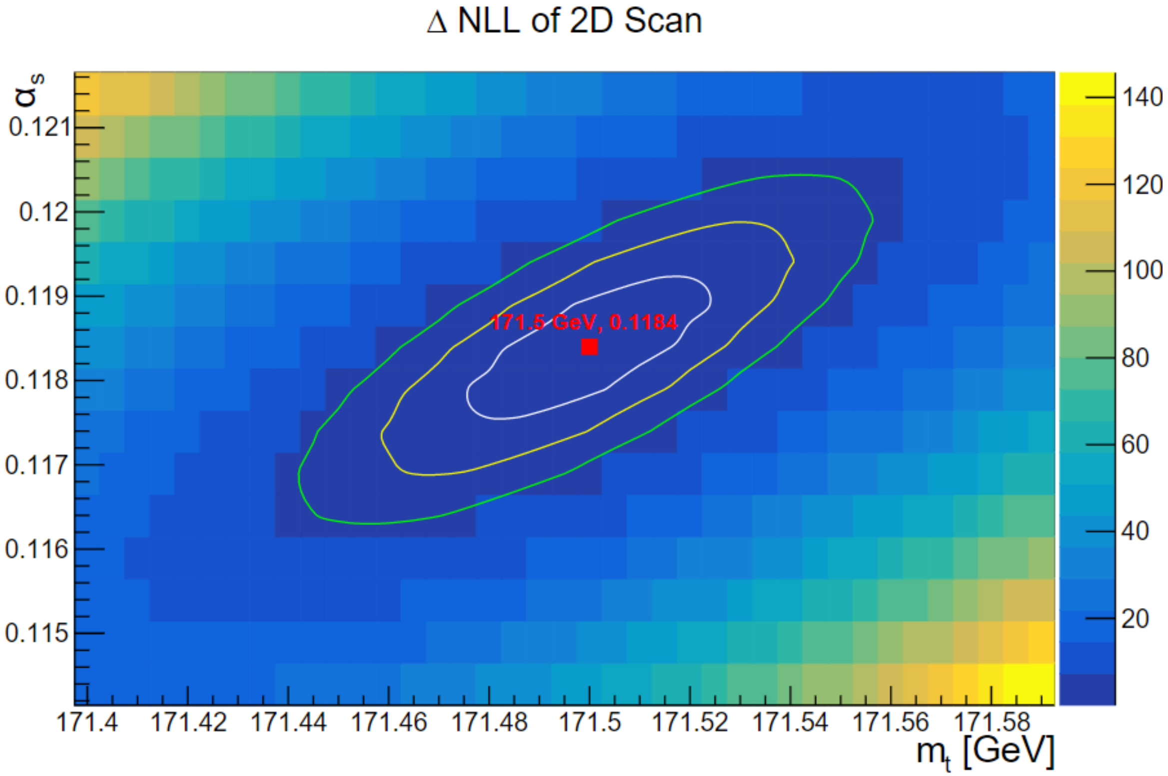


Ecm=343.50GeV

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

- The study shows that CEPC is capable of measuring the top quark mass with a precision below 57 MeV using the single energy point.
    - Its precision is about 1 order of magnitude better than hadron colliders at the moment.

- 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

- Great opportunities for top mass, width and α_s measurements with CEPC at the threshold using the threshold scan method

Thank you!

Back-up

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.

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 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.

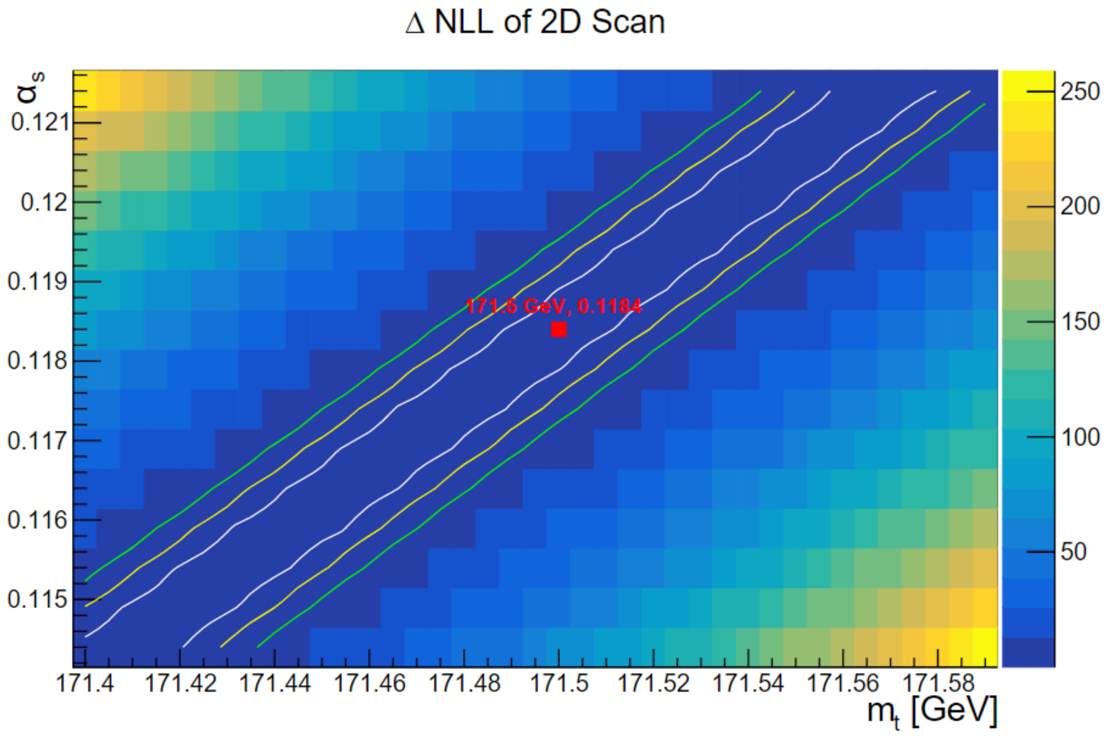
Luminosity/fb^{-1}	**Mass precision/MeV**	**Width precision/MeV**
{100, 0}	9	320
{80, 20}	10	50
{50, 50}	13	31
{20, 80}	19	25
{0, 100}	>50	21

The statistic uncertainties on $\boldsymbol{\alpha_s}$

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

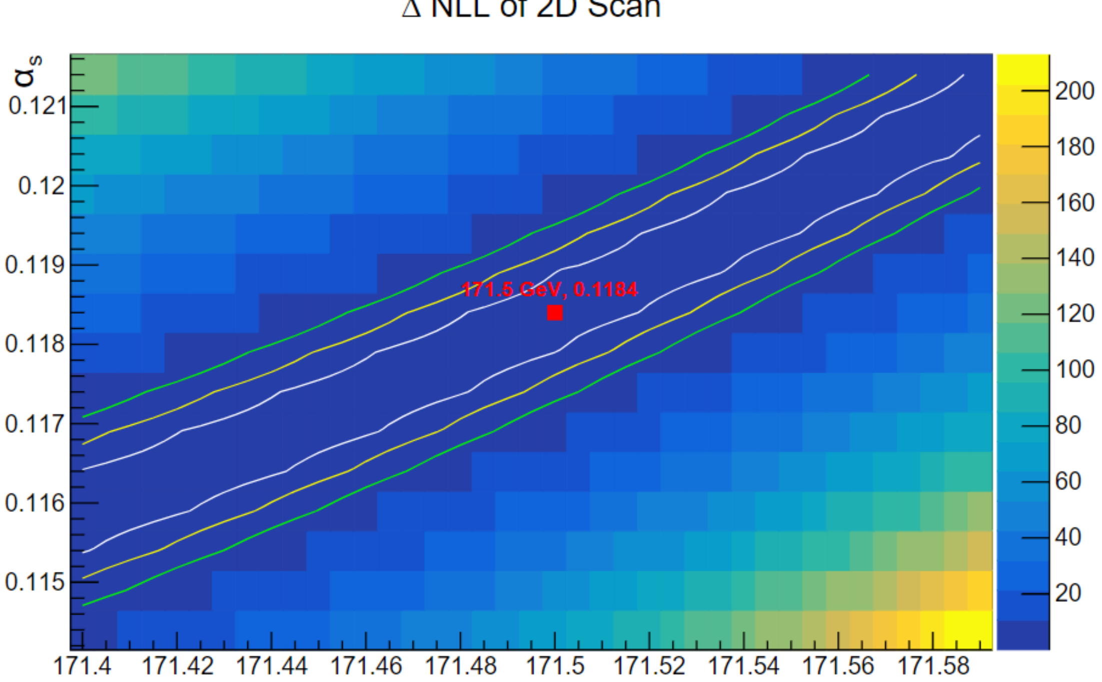
Luminosity/fb^{-1}	Mass precision/MeV	α_s precision
{100, 0}	9	0.00034
{80, 20}	10	0.00034
{50, 50}	11	0.00034
{20, 80}	12	0.00034
{0, 100}	14	0.00034

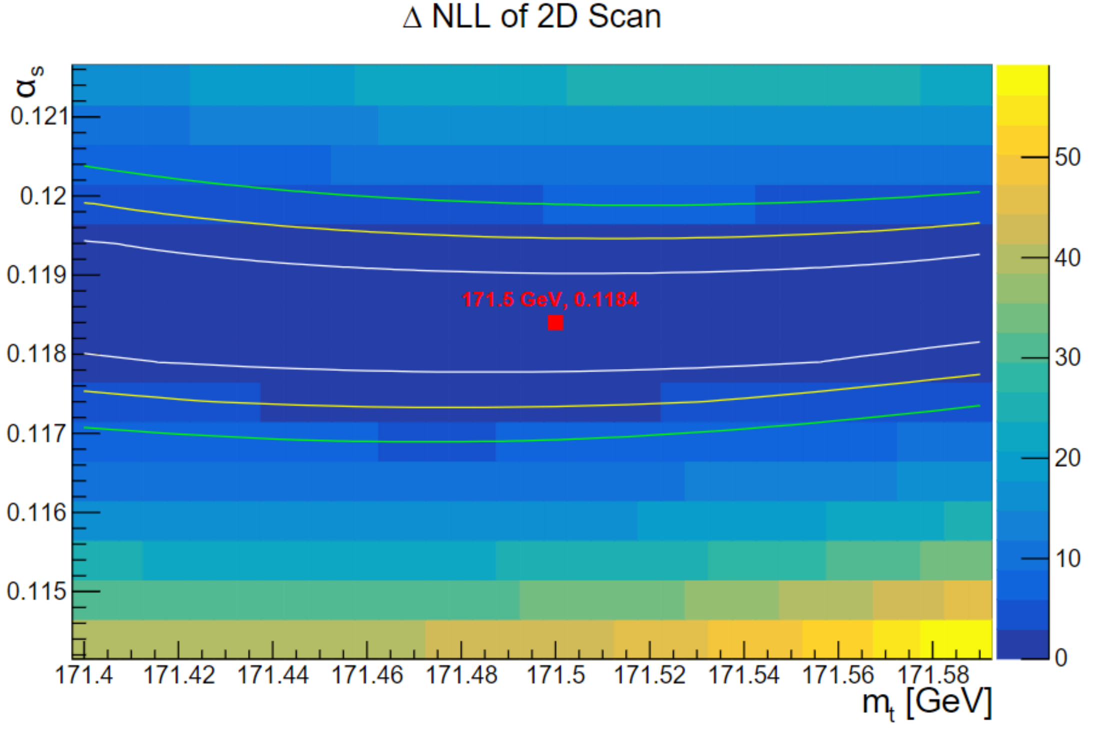
Mass vs α_s in single Ecm



342.75 GeV

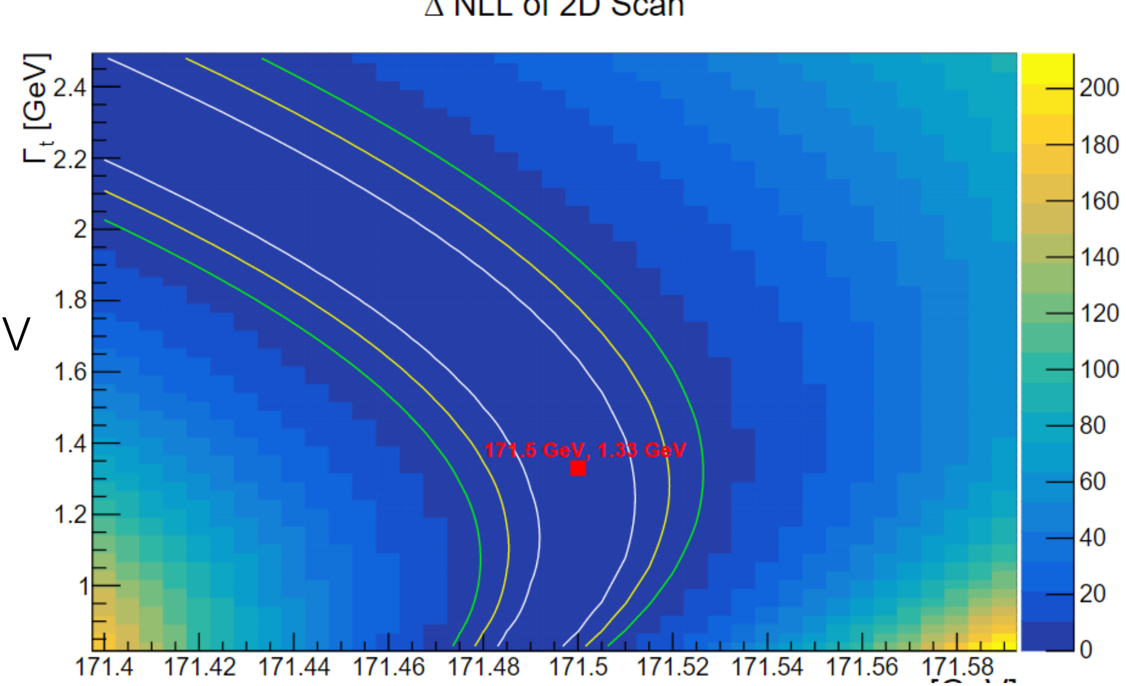
343.5 GeV



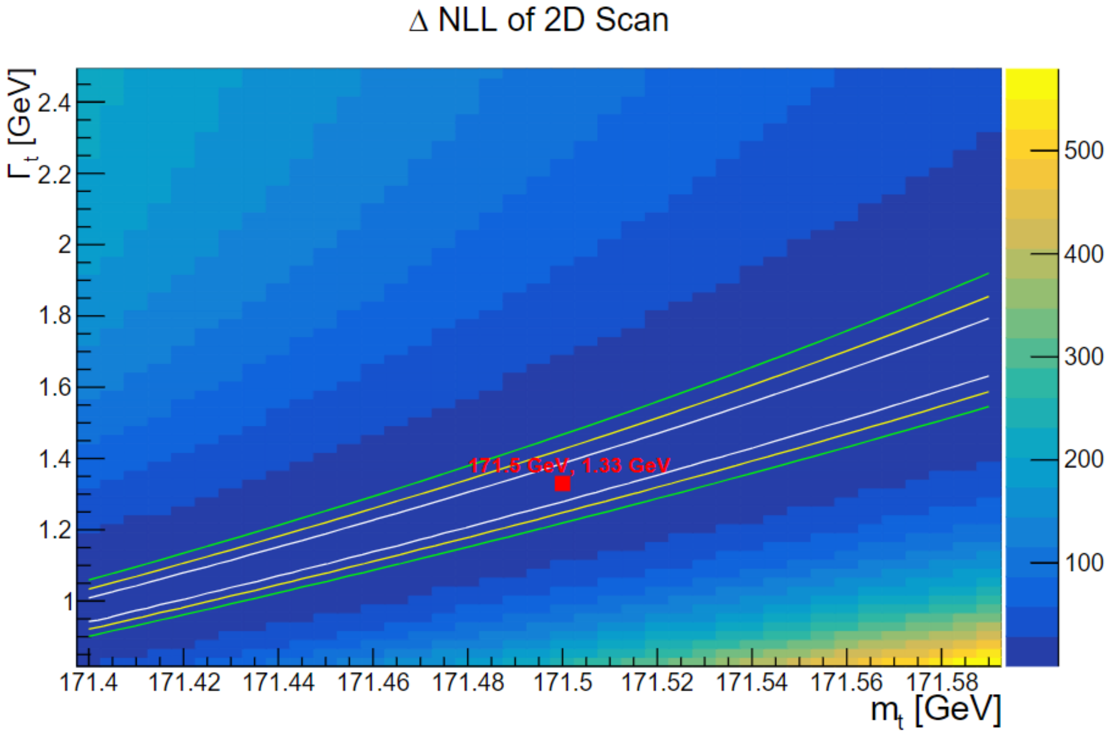


344.25 GeV

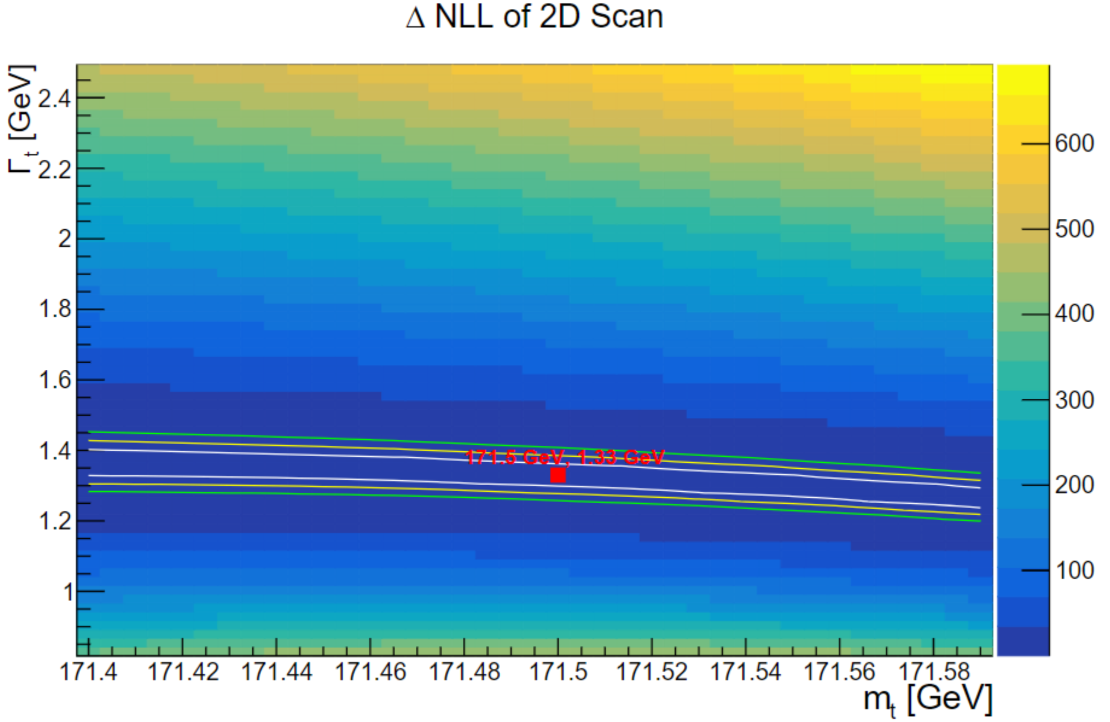
Mass vs width in single Ecm



342.75 GeV



342.00 GeV



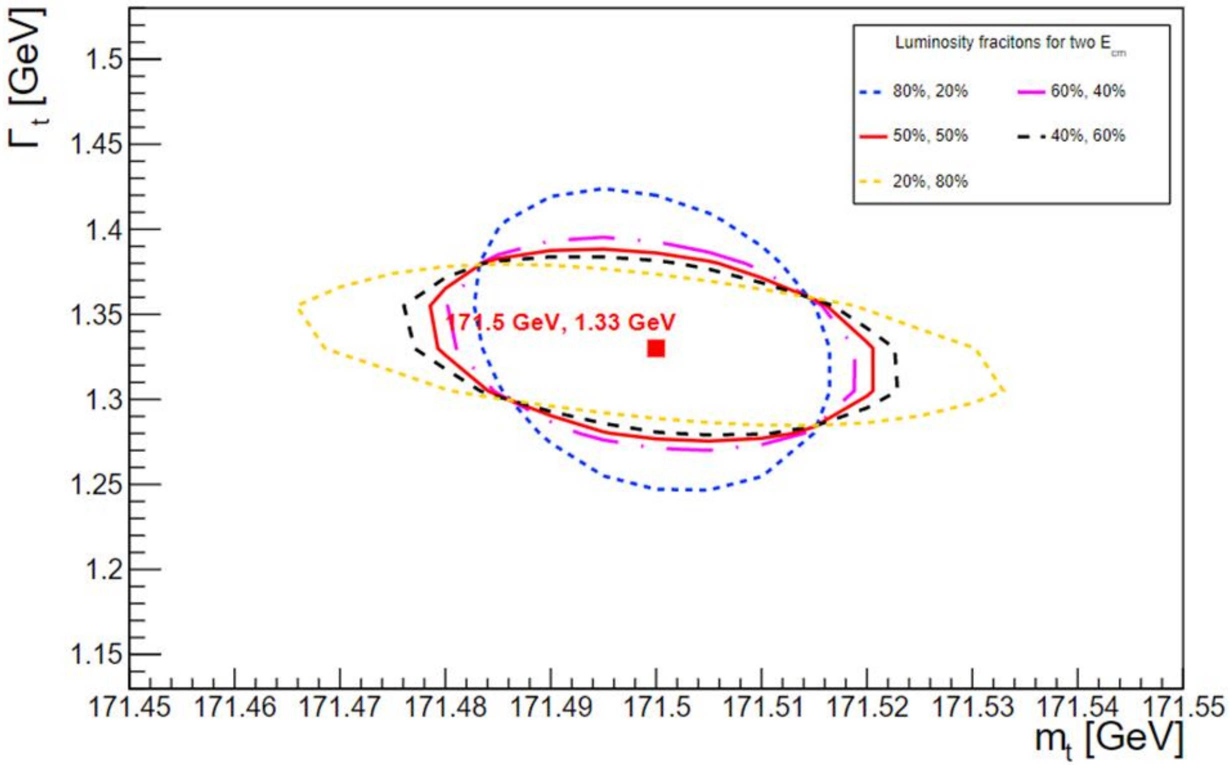
344.00 GeV

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 .