The top mass at the $t\bar{t}$ threshold with CEPC

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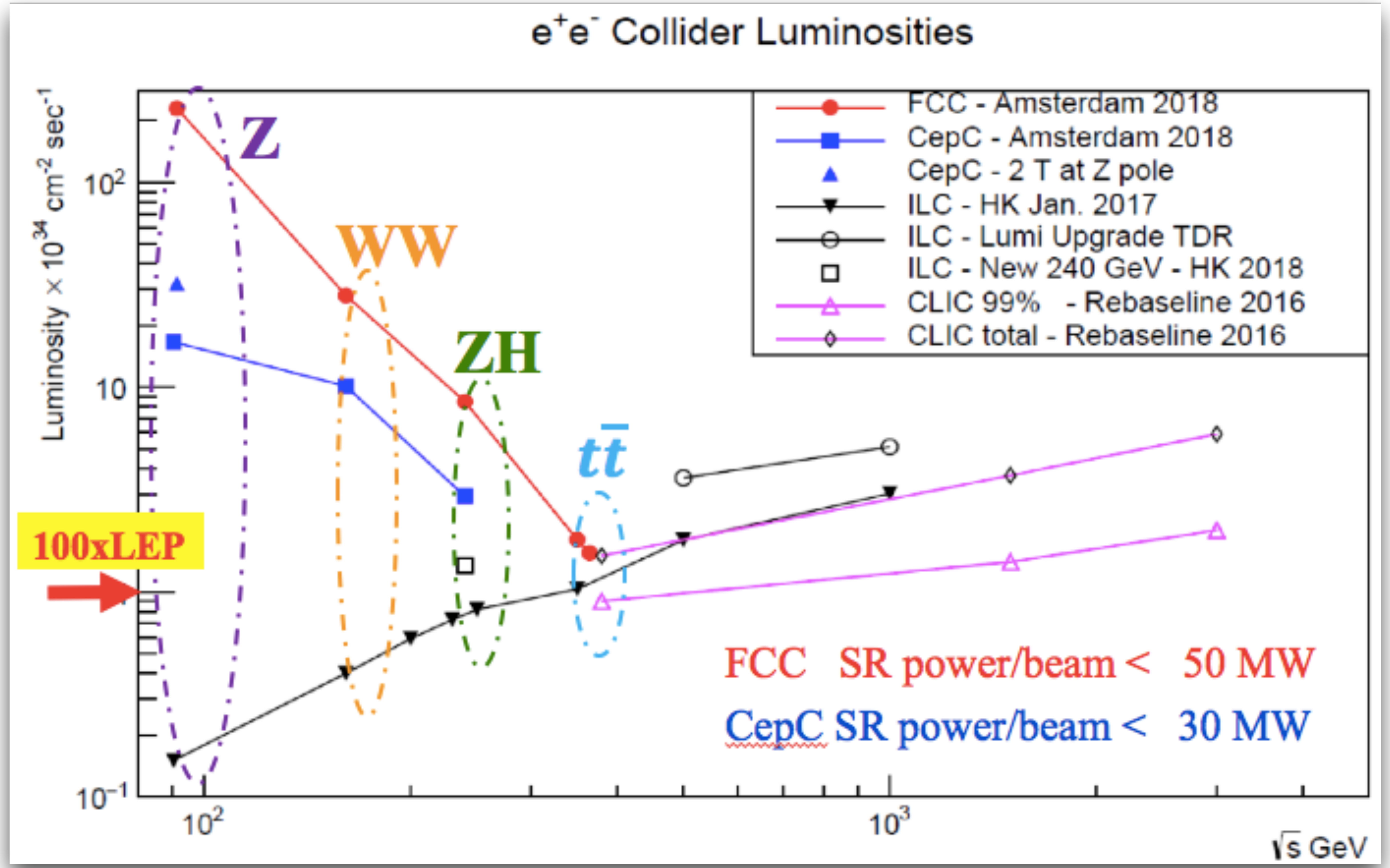
Reference: Eur. Phys. J. C (2023) 83:269, arXiv:2207.12177

Introduction

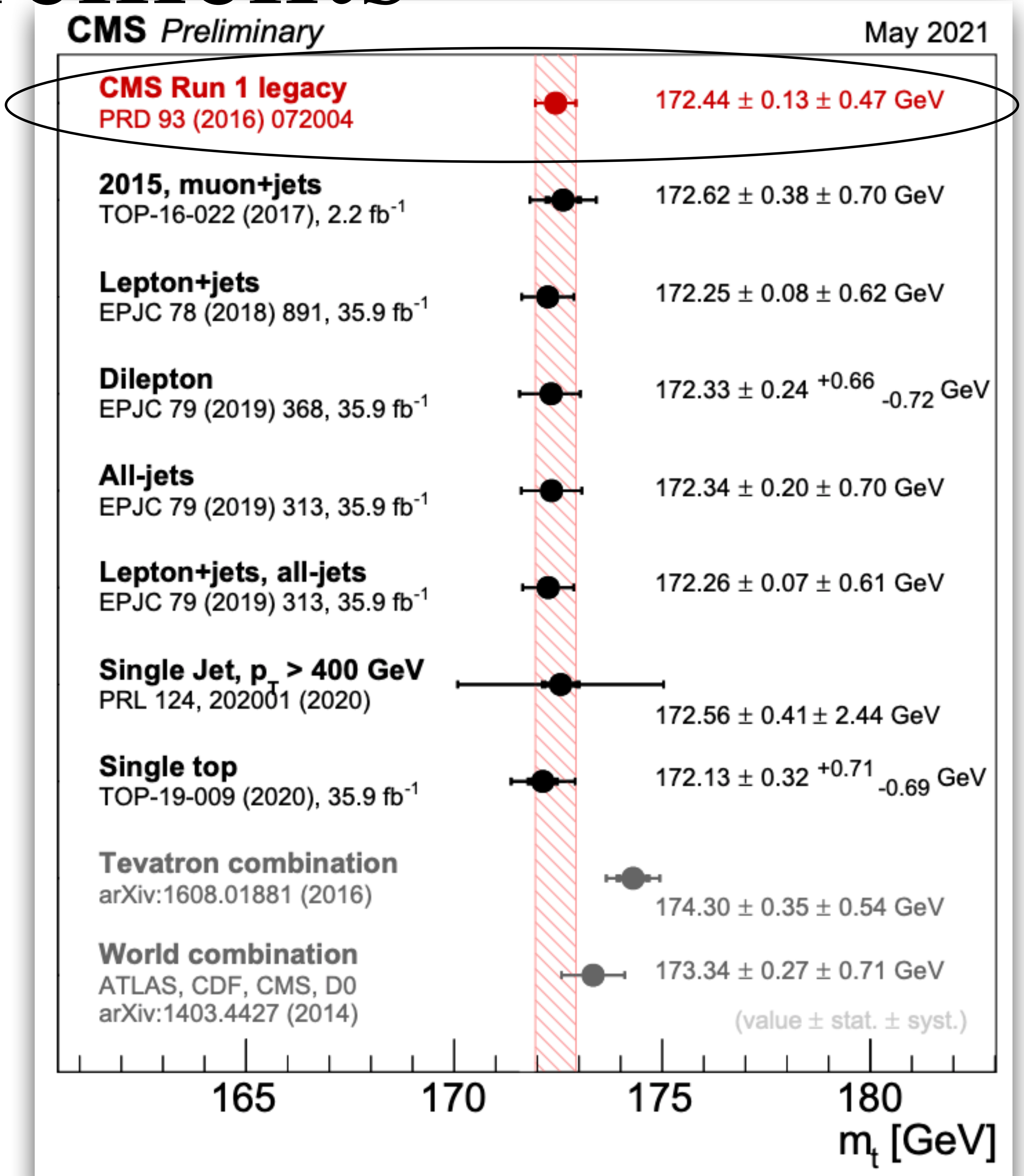
- CEPC will be a versatile machine with many opportunities
  - Higgs factory @~240 GeV
  - Diboson factory @~160 GeV
  - Z factory @~90 GeV
- @~360 GeV it can also be a playground for
  - Top quark precision measurements
  - Higgs complementary measurements
  - BSM searches



F. Bedeschi

Top quark mass measurements

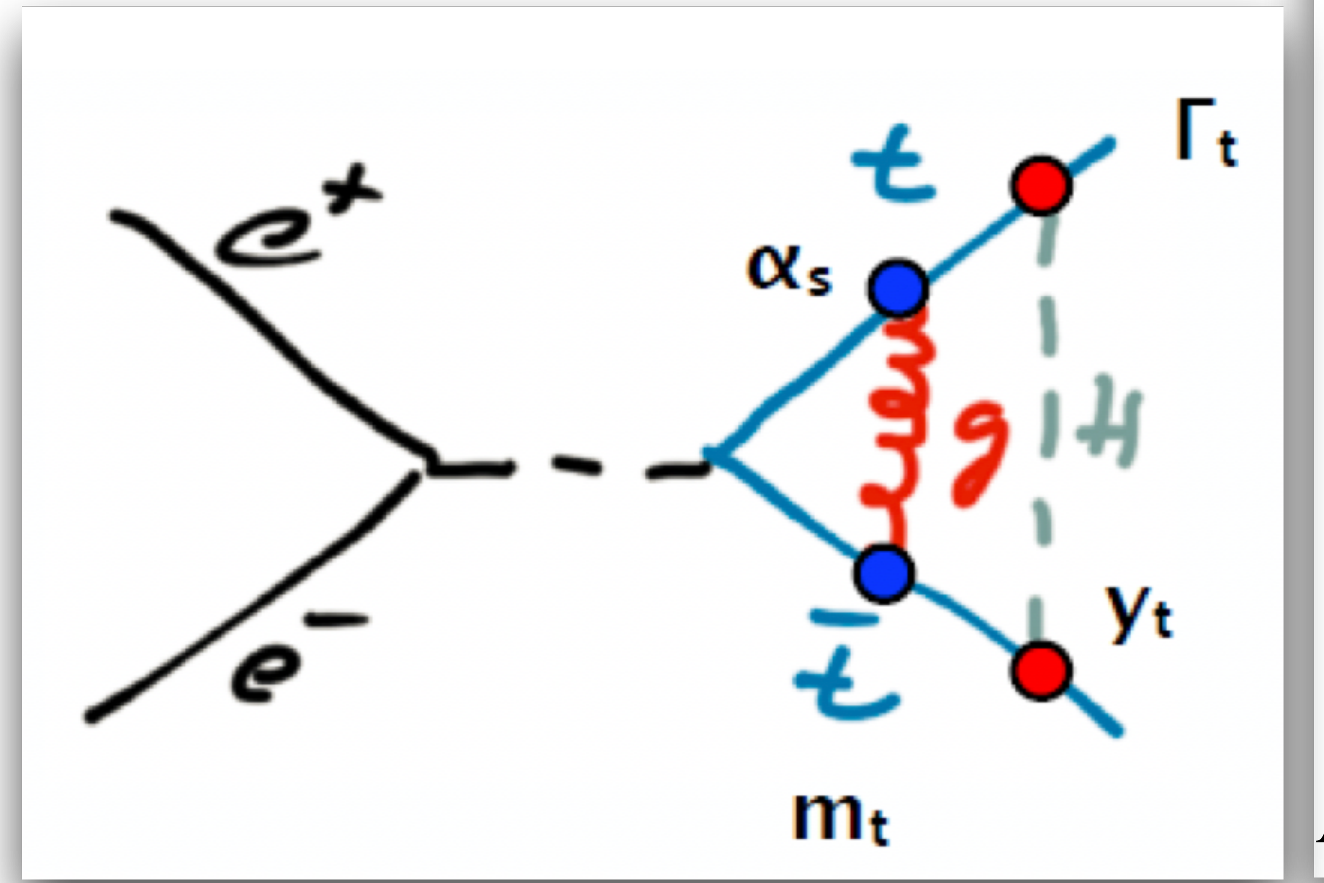
- The top mass is measured using top reconstruction at hadron colliders
  - Heavily relies on the performance of MET (the neutrino) and jet energy scale/resolution uncertainties
- CMS Run1 combined uncertainty reached ~500 MeV dominated by systematic uncertainties
- Very difficult to further improve the precision due to dominant systematic uncertainties at hadron colliders

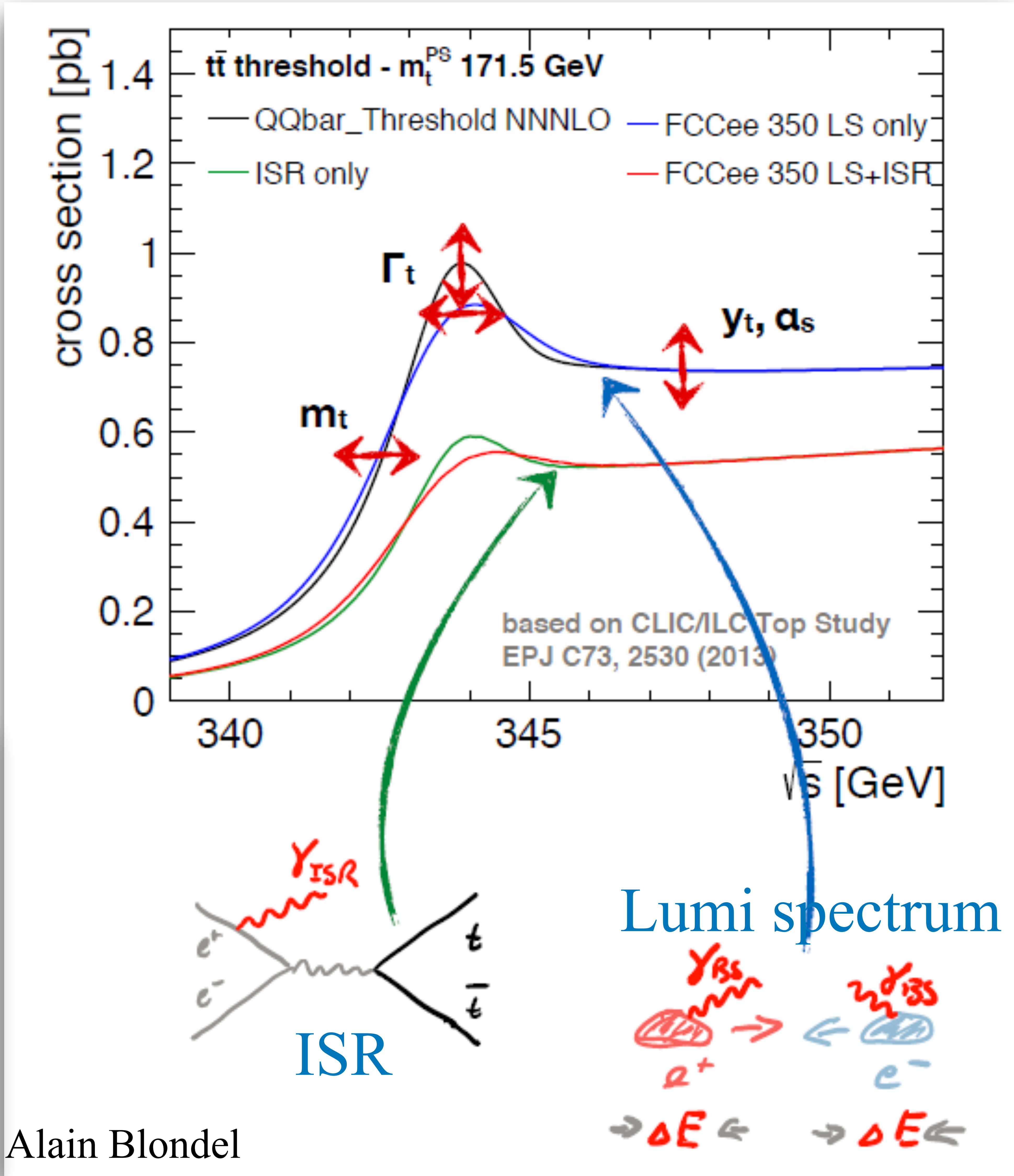


tt threshold scan

- ee-colliders provide not only the top reconstruction method but also the tt threshold scan
- The scan is made against $\sqrt{s}$ and cross-section is the direct observable
- This brings measurements of top mass and a couple of other parameters
  - Top width
  - Top Yukawa coupling
  - α_S

EPJC 73,(2013)2530





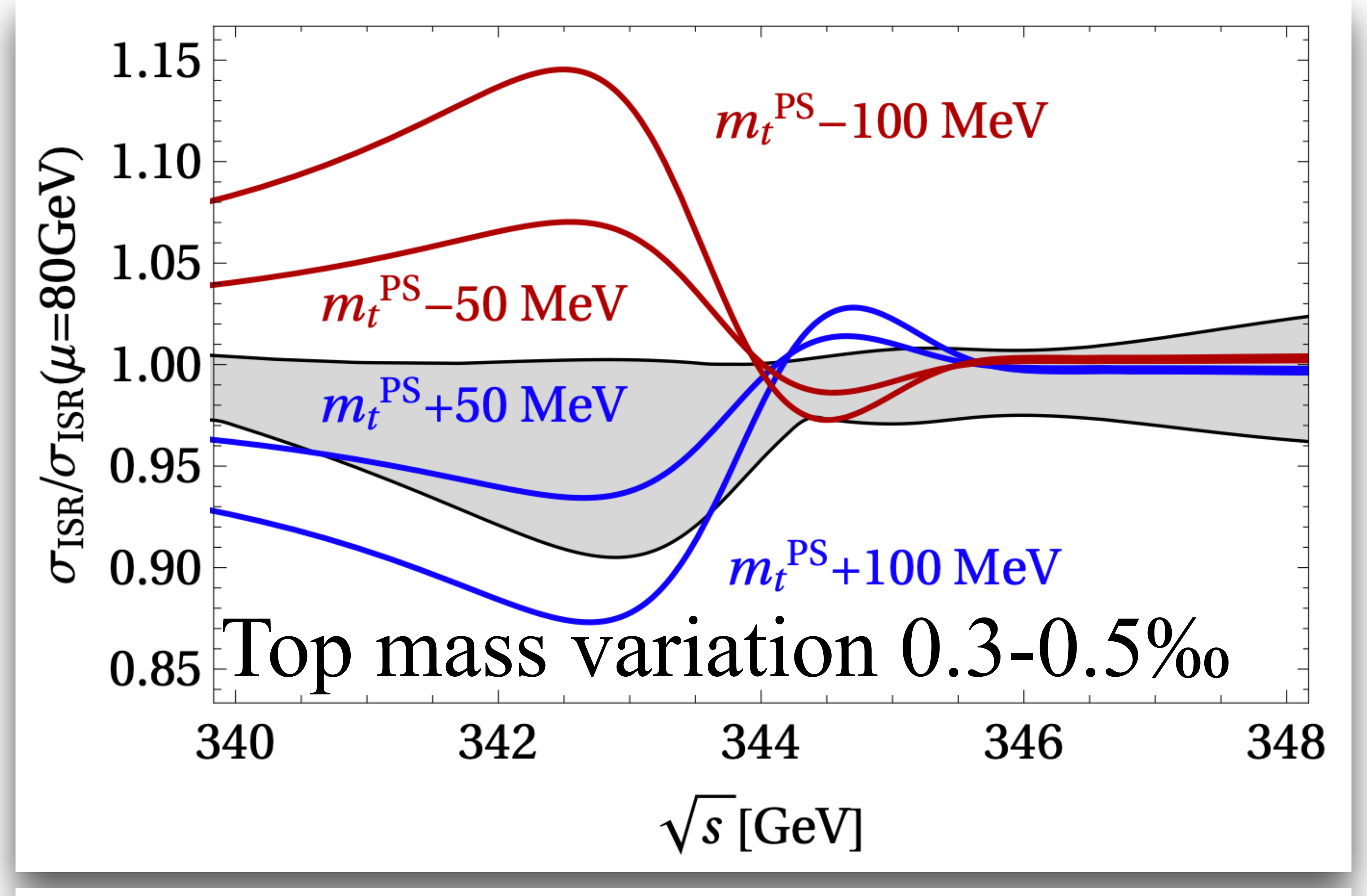
Our setup

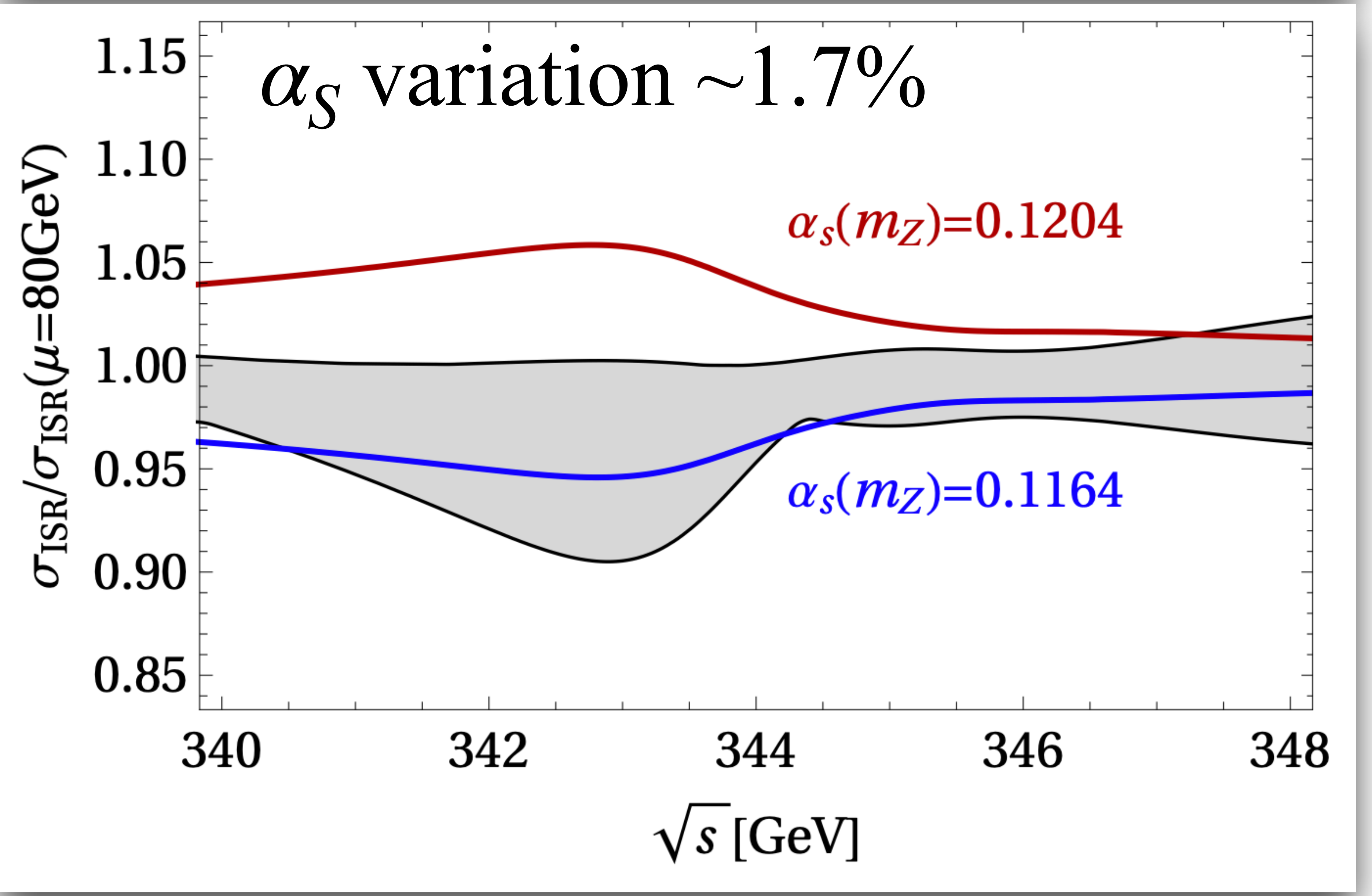
Comput. Phys. Commun. 209 (2016) 96-115
JHEP 1802 (2018) 125

- 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

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

  - ISR effects are also included in the package
- We integrate luminosity spectrum (LS) by a Gaussian function with the CEPC expected beam energy spread (~500 MeV) 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

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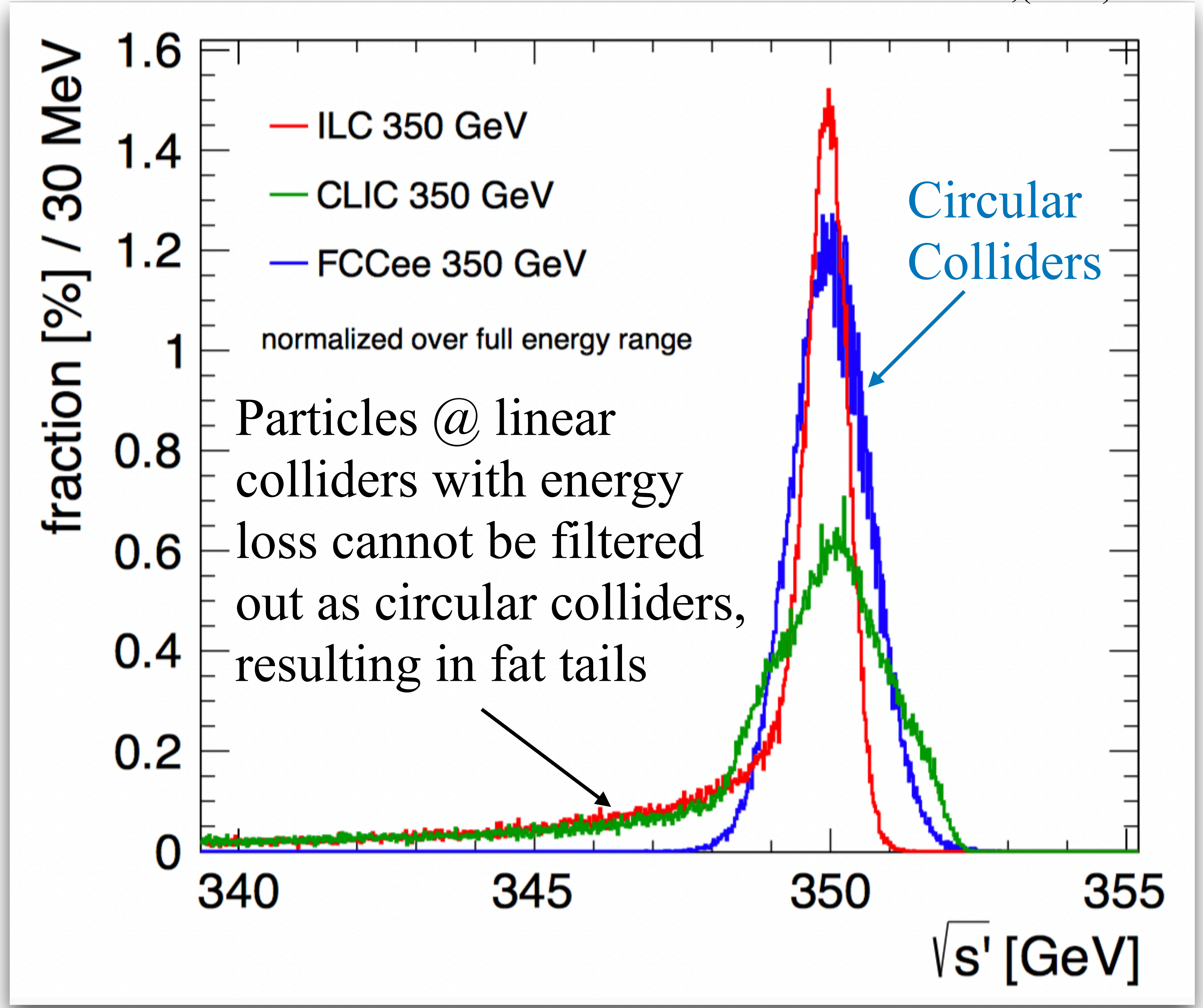
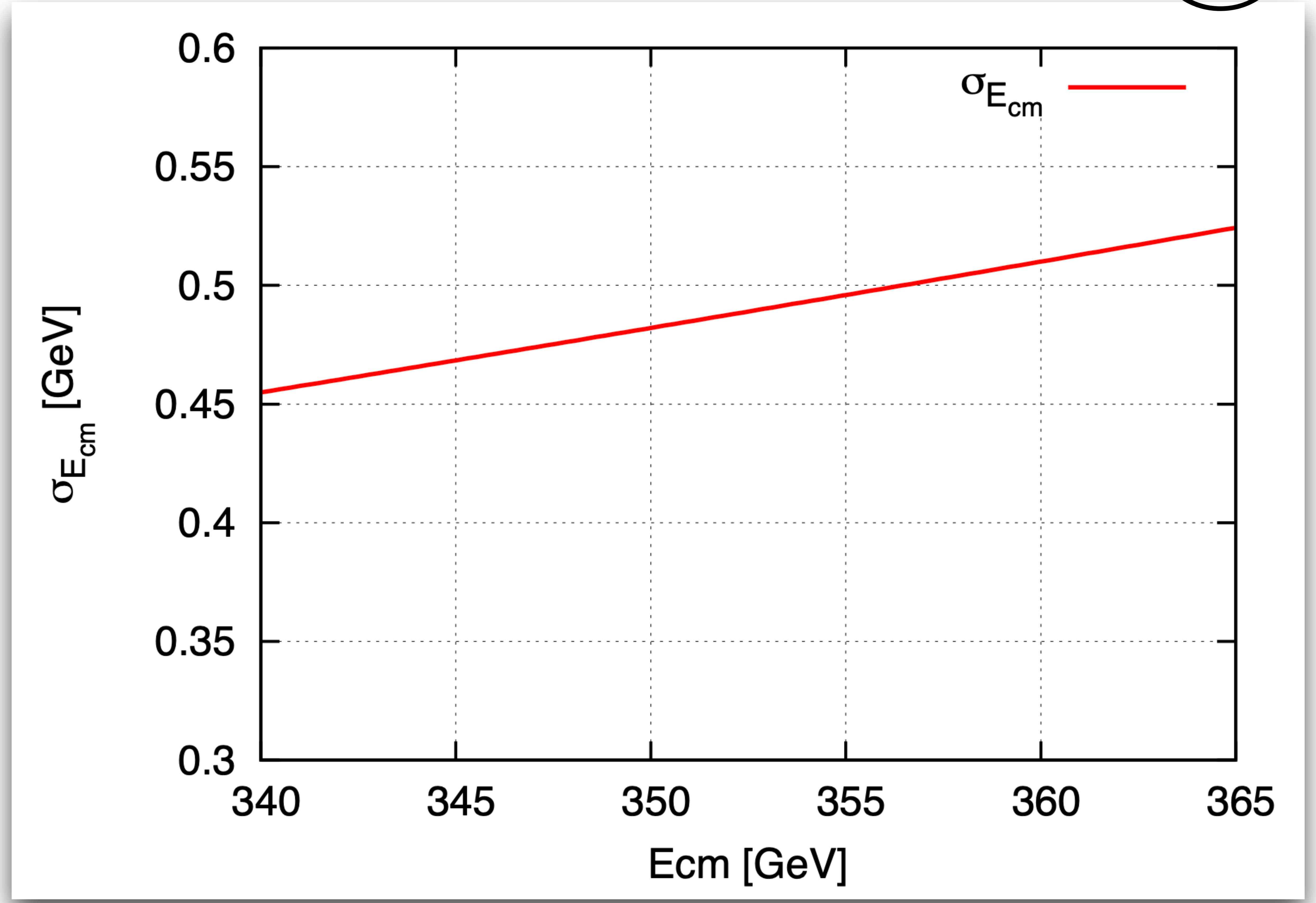
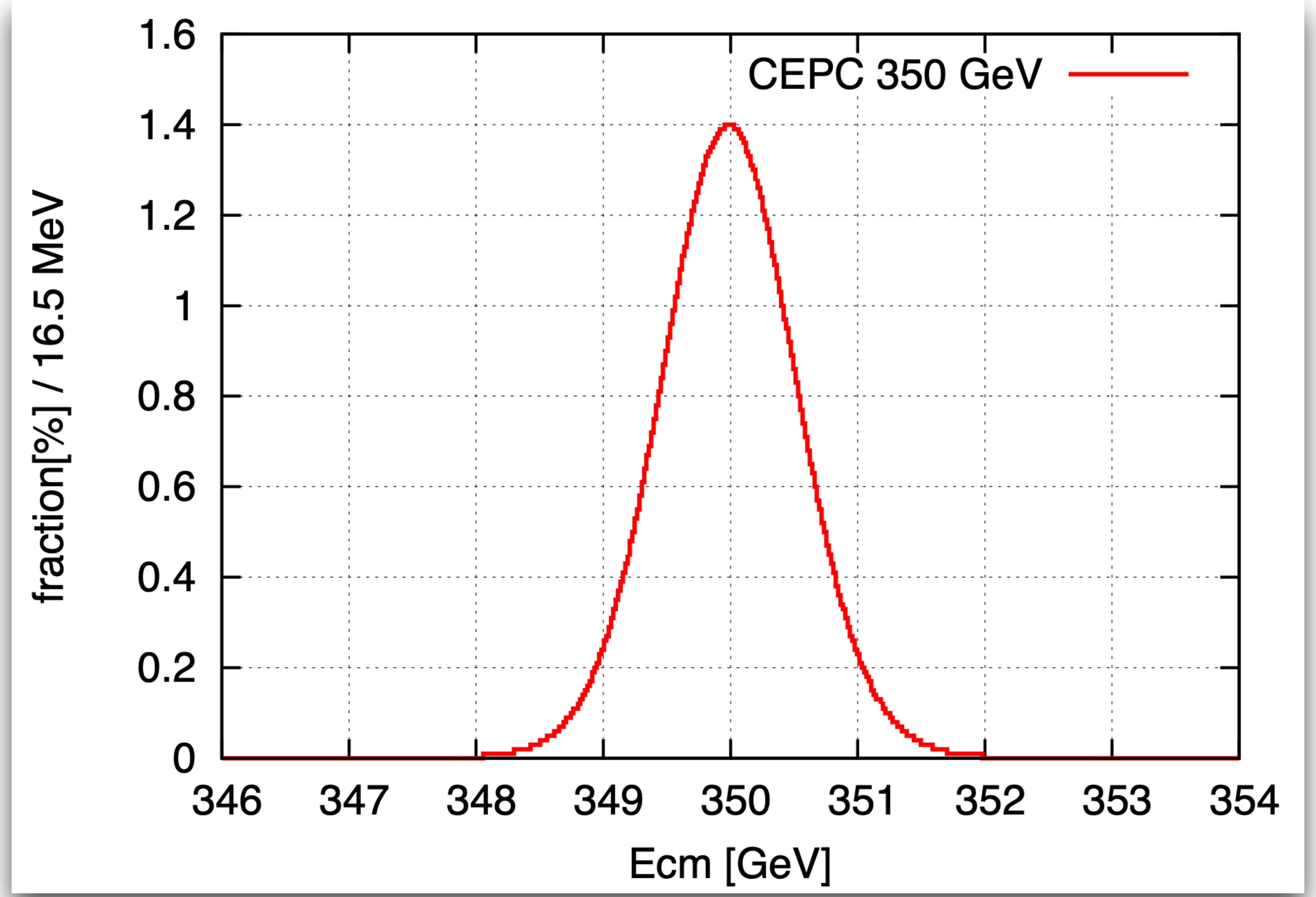


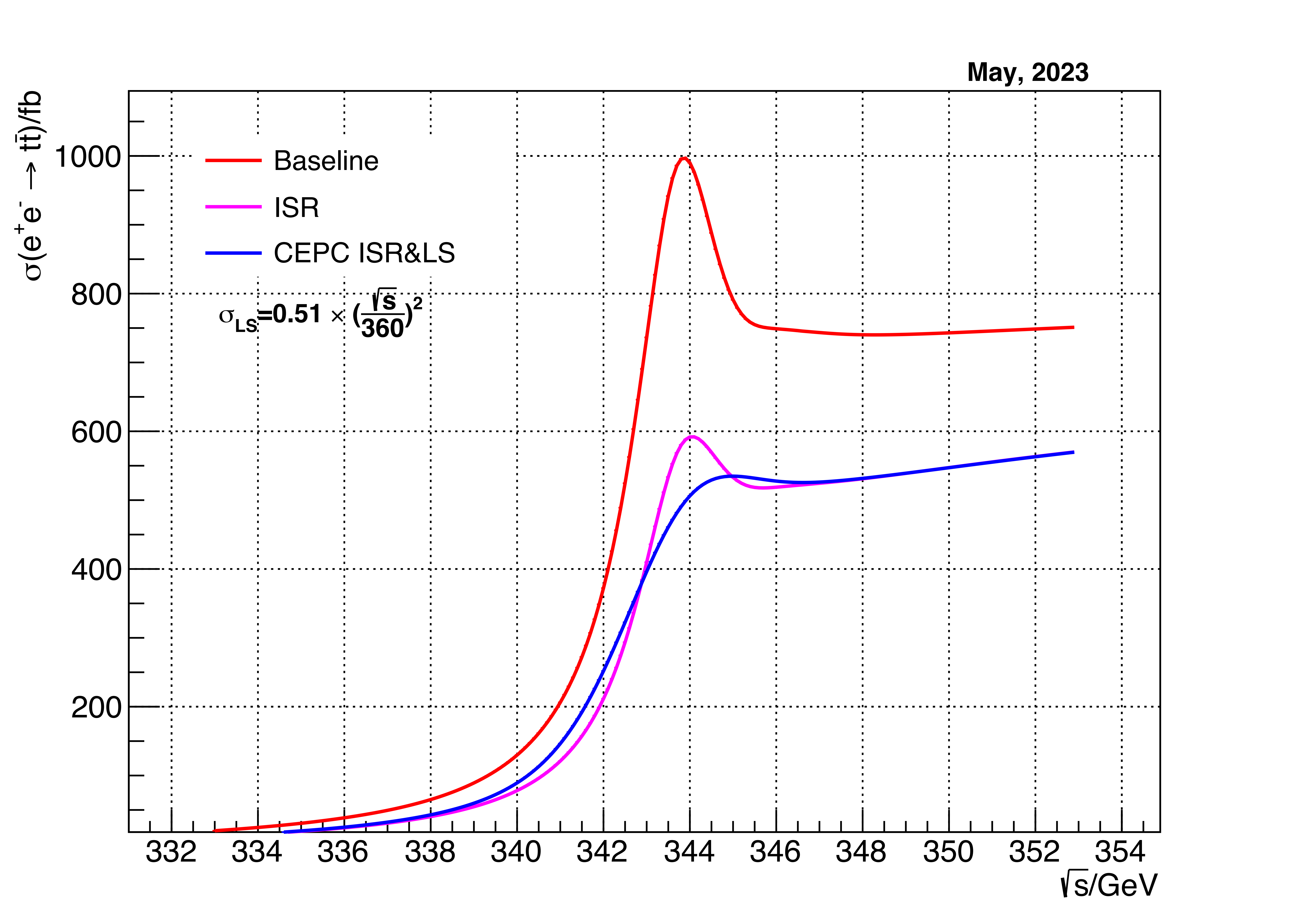
LS @ CEPC



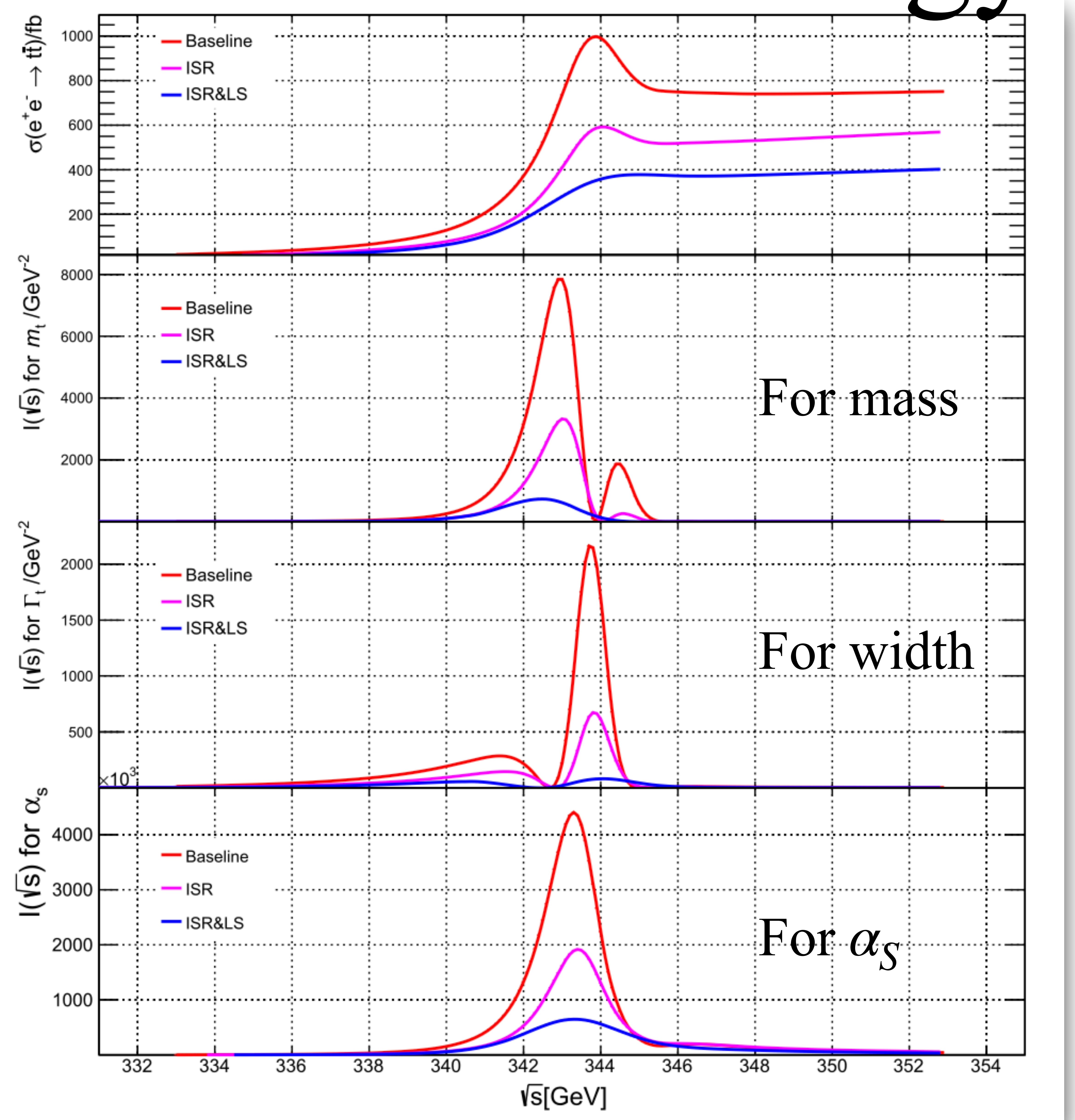


- The beam energy resolution increases as a function of $\sqrt{s}$
- The luminosity spectrum is shown for $\sqrt{s} = 350$ GeV with a width of ~480 MeV
- Similar to the FCC-ee scenario

XS at the $t\bar{t}$ threshold with CEPC



Which energy to collide with?



- Around the $t\bar{t}$ threshold, we need to identify the energy point(s) that contain(s) the most sensitivity
- Construct Fisher information to test the energy point(s)

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

- Larger amplitudes implies richer information and higher sensitivities

The choice of the energy point(s)

- Aiming at measuring one parameter at a time (1D), given limited total luminosity:
  - 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.
- The precision of statistical-only one-parameter measurement using one optimal energy point @CEPC is calculated

$\sqrt{s}$ (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

All are stats-only here

Uncertainties: statistics

	Top mass uncertainties (MeV)	
	Optimistic	Conservative
Statistics	9	9
Theory	8	24
Quick scan	2	2
α_S	17	17
Width	10	10
Experimental efficiency	5	44
Background	2	14
Beam energy	2	2
Luminosity spectrum	3	6
Total	24	57

- Statistical uncertainties are calculated under the total luminosity of $100\ fb^{-1}$
- All luminosity is allocated on one single energy point, i.e. the optimal energy point that can be inferred by Fisher information
- This ends up with a statistical error of 9 MeV, compared to 21 MeV from CLIC where the luminosity is distributed for 10 energy points evenly

Uncertainties: theory

	Top mass uncertainties (MeV)	
	Optimistic	Conservative
Statistics	9	9
Theory	8	24
Quick scan	2	2
α_S	17	17
Width	10	10
Experimental efficiency	5	44
Background	2	14
Beam energy	2	2
Luminosity spectrum	3	6
Total	24	57

- Theoretical uncertainty on the cross section calculation is assumed as
  - 3% based on the current calculations on the market
  - 1% that might be achieved by the time of CEPC, optimistically
- This ends up with theoretical uncertainties of 8 (24) MeV, compared to 18 (56) MeV CLIC where the same assumption is used

Uncertainties: α_S and width

	Top mass uncertainties (MeV)	
	Optimistic	Conservative
Statistics	9	9
Theory	8	24
Quick scan	2	2
α_S	17	17
Width	10	10
Experimental efficiency	5	44
Background	2	14
Beam energy	2	2
Luminosity spectrum	3	6
Total	24	57

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

Uncertainties: experimental efficiency

	Top mass uncertainties (MeV)	
	Optimistic	Conservative
Statistics	9	9
Theory	8	24
Quick scan	2	2
α_S	17	17
Width	10	10
Experimental efficiency	5	44
Background	2	14
Beam energy	2	2
Luminosity spectrum	3	6
Total	24	57

- Experimental efficiency of the future detectors is yet to know
- Assume possible scenarios of uncertainties 0.5%, 1%, 3% and 5% that impacts signal rates directly
- This leads to top mass uncertainties of 5, 10, 27, 44 MeV, respectively

Uncertainties: background

	Top mass uncertainties (MeV)	
	Optimistic	Conservative
Statistics	9	9
Theory	8	24
Quick scan	2	2
α_S	17	17
Width	10	10
Experimental efficiency	5	44
Background	2	14
Beam energy	2	2
Luminosity spectrum	3	6
Total	24	57

- Background is considered to be subtracted cleanly from the observed data. But their uncertainties could affect the measurement
- Assuming background uncertainties of 1% and 5% will give 2 and 14 MeV on top mass measurement
  - This is similar to CLIC that has 18 MeV uncertainty of top mass from 5% background variations, given the low level of background

Uncertainties: luminosity spectrum

	Top mass uncertainties (MeV)	
	Optimistic	Conservative
Statistics	9	9
Theory	8	24
Quick scan	2	2
α_S	17	17
Width	10	10
Experimental efficiency	5	44
Background	2	14
Beam energy	2	2
Luminosity spectrum	3	6
Total	24	57

- LS is varied for 10% and 20% that result in uncertainties of 3 and 6 MeV on top mass

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

Uncertainties: luminosity spectrum

	Top mass uncertainties (MeV)	
	Optimistic	Conservative
Statistics	9	9
Theory	8	24
Quick scan	2	2
α_S	17	17
Width	10	10
Experimental efficiency	5	44
Background	2	14
Beam energy	2	2
Luminosity spectrum	3	6
Total	24	57

- Additionally, we evaluate the prospect of reducing CEPC LS by -20% and -50% of the current LS
  - These give top mass error of 9.0 and 8.4 MeV wrt the nominal one (9.1 MeV)
  - The CEPC LS seems already excellent for this measurement, and large improvements of LS would not sizably improve top mass precision

Uncertainties: total

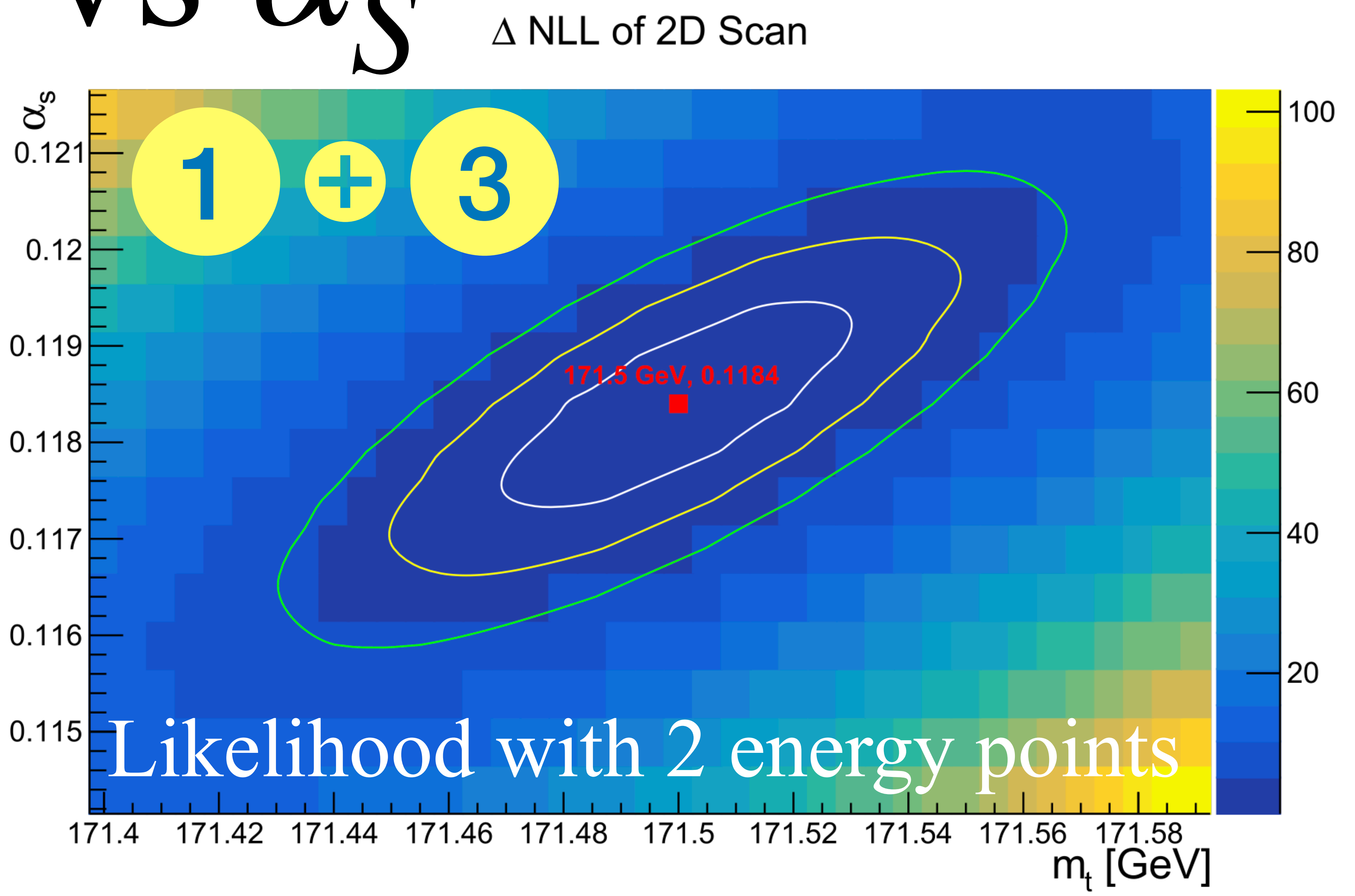
	Top mass uncertainties (MeV)	
	Optimistic	Conservative
Statistics	9	9
Theory	8	24
Quick scan	2	2
α_S	17	17
Width	10	10
Experimental efficiency	5	44
Background	2	14
Beam energy	2	2
Luminosity spectrum	3	6
Total	24	57

- CEPC is expected to measure the top quark mass with the total uncertainties of 24 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)

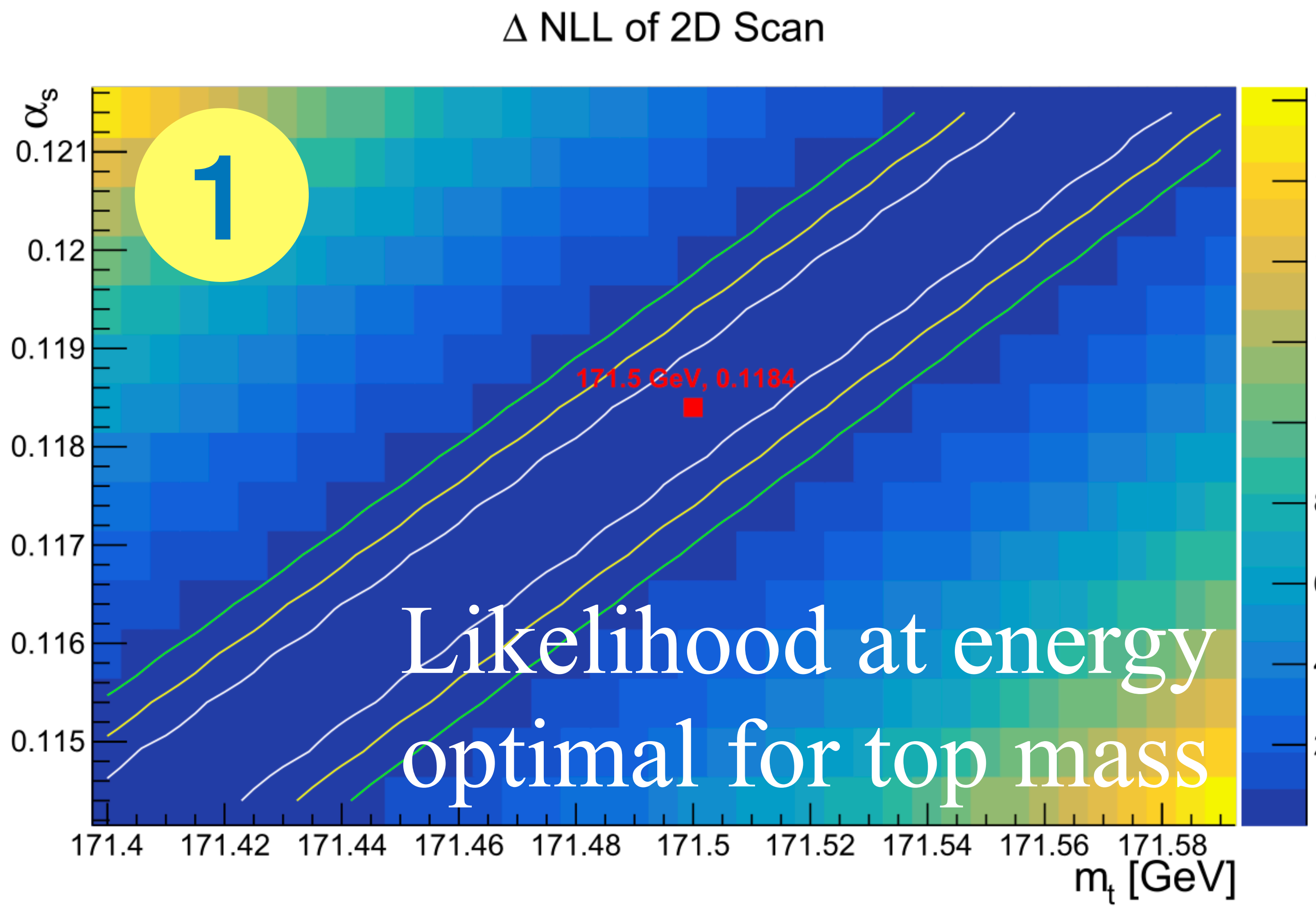
2D scans

- Besides top mass, width and α_S are also of great interests
- We try to extract two parameters at one time with 2D scans
  - 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

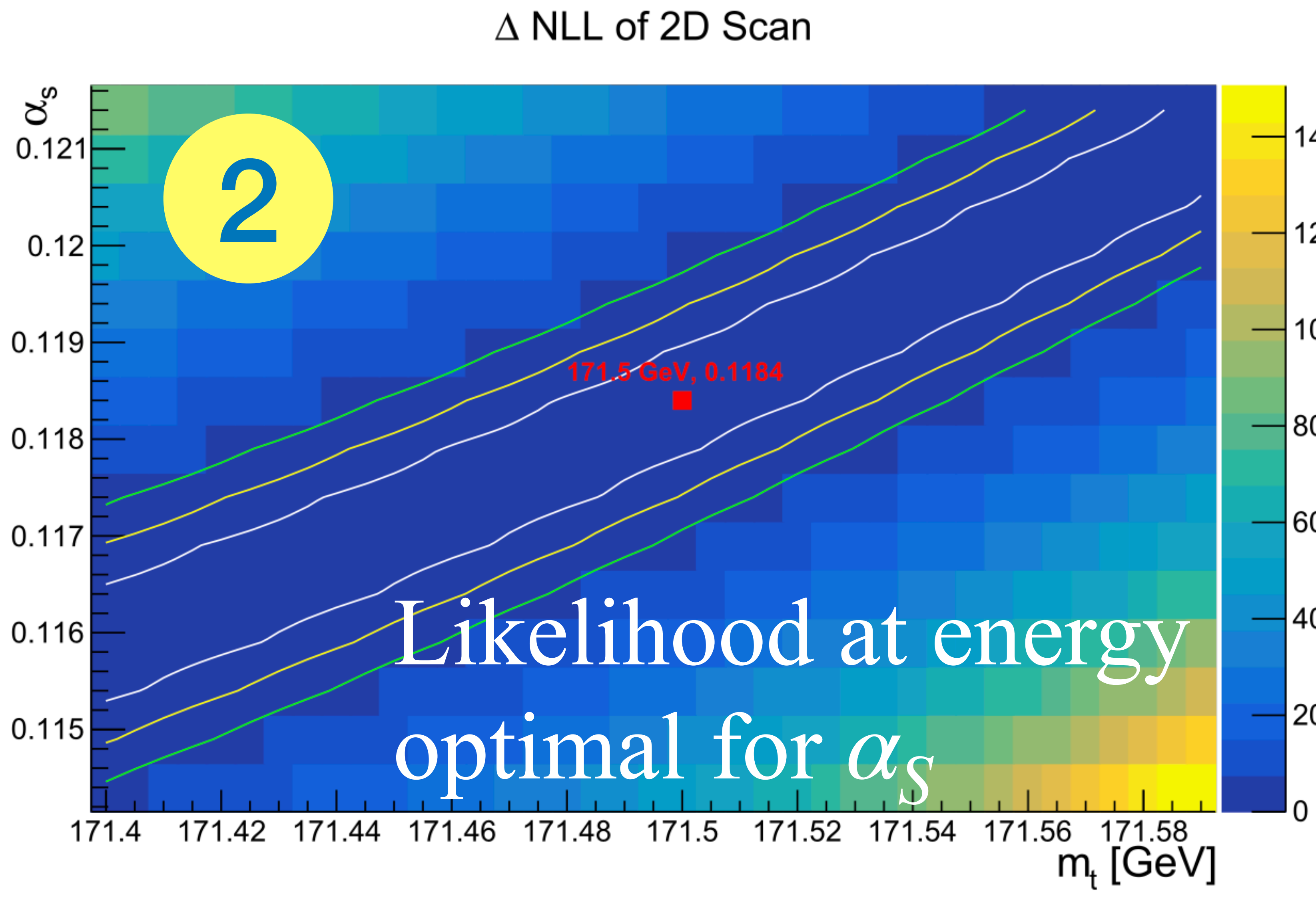
2D scans for m_{top} vs α_S



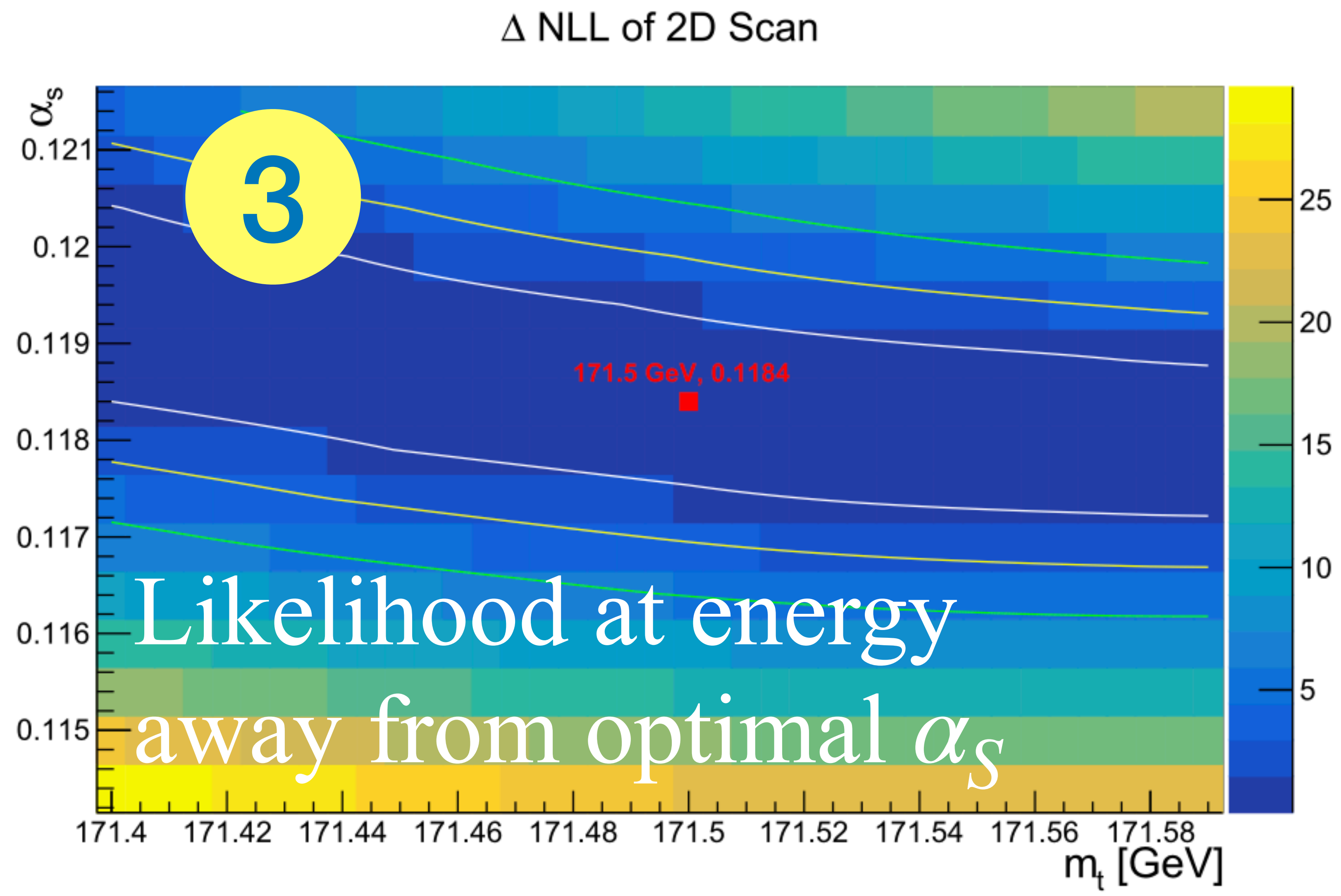
- Ideally taking the two optimal energy points for top mass and α_S would give the best precision on both, but these two energy points are too close, resulting in the same constraint pattern (shown in 1 & 2)
- To close the constraint contour, an energy point away from optimal for α_S is taken. This introduces a different correlation and can close the contour (shown in 3)



(b) $E_{\rm cm}$= 342.75 GeV



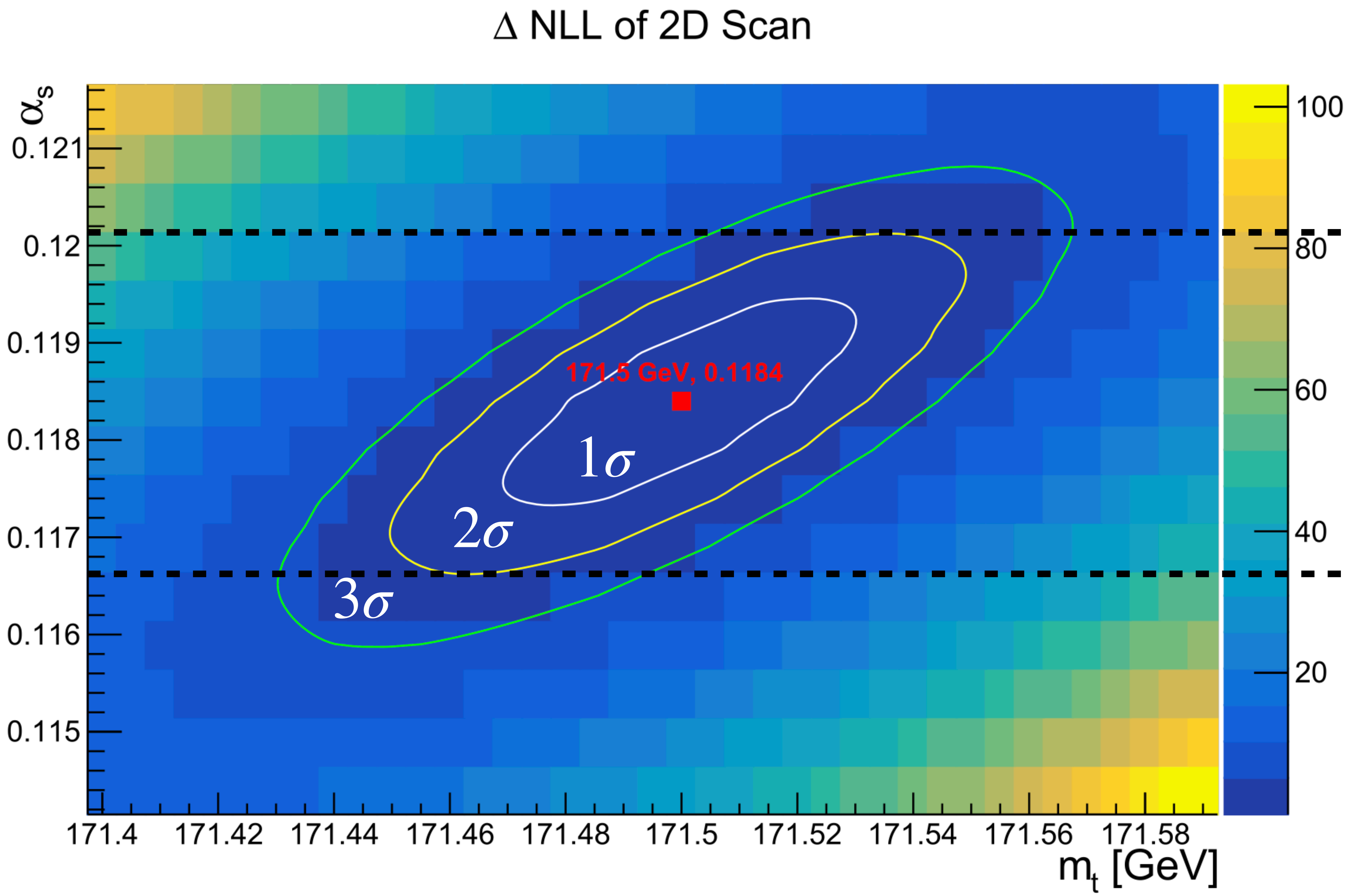
(d) $E_{\rm cm}$= 343.50 GeV



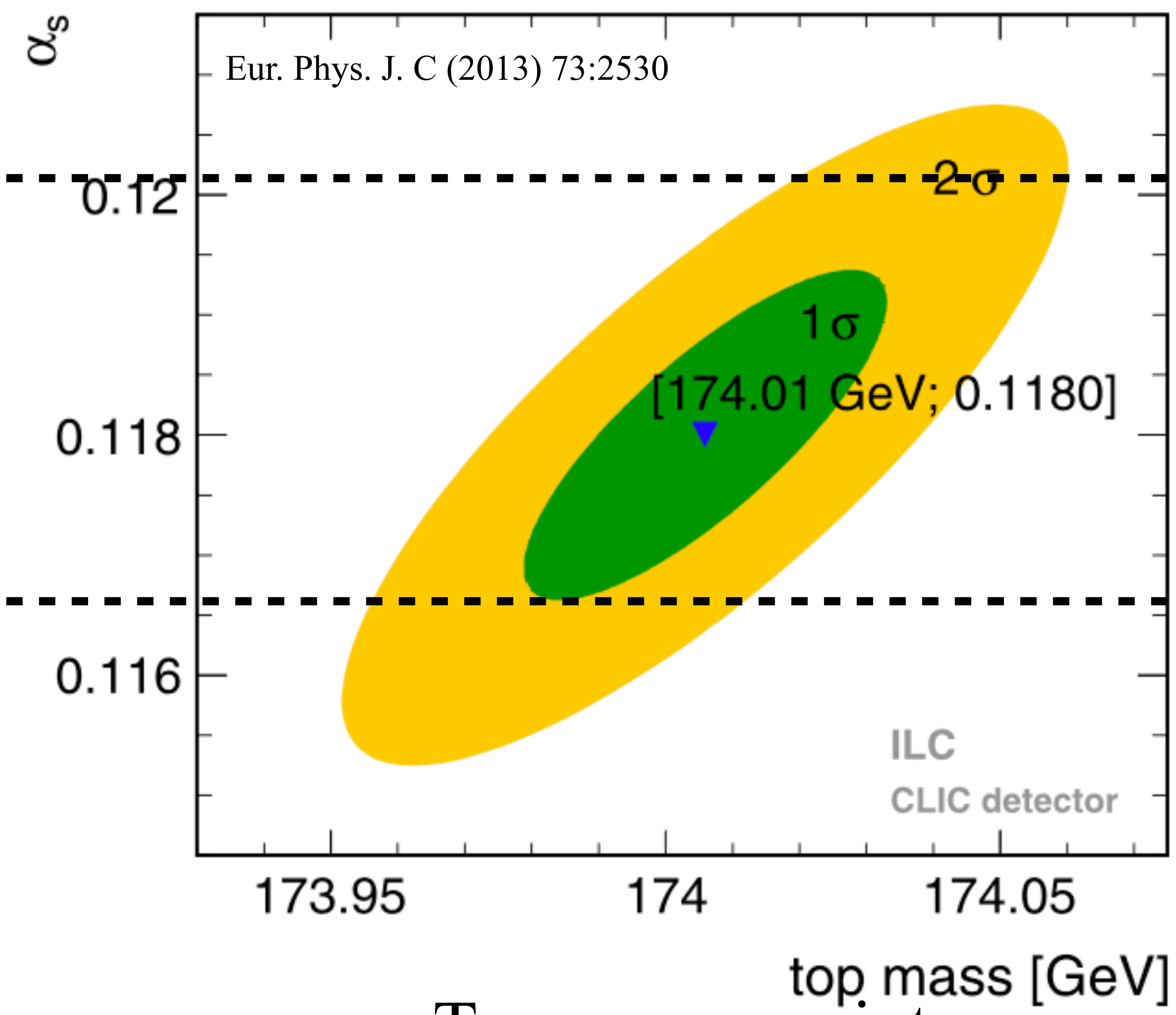
(f) $E_{\rm cm}$= 344.50 GeV

2D scans for m_{top} vs α_S

- A quick comparison to CLIC



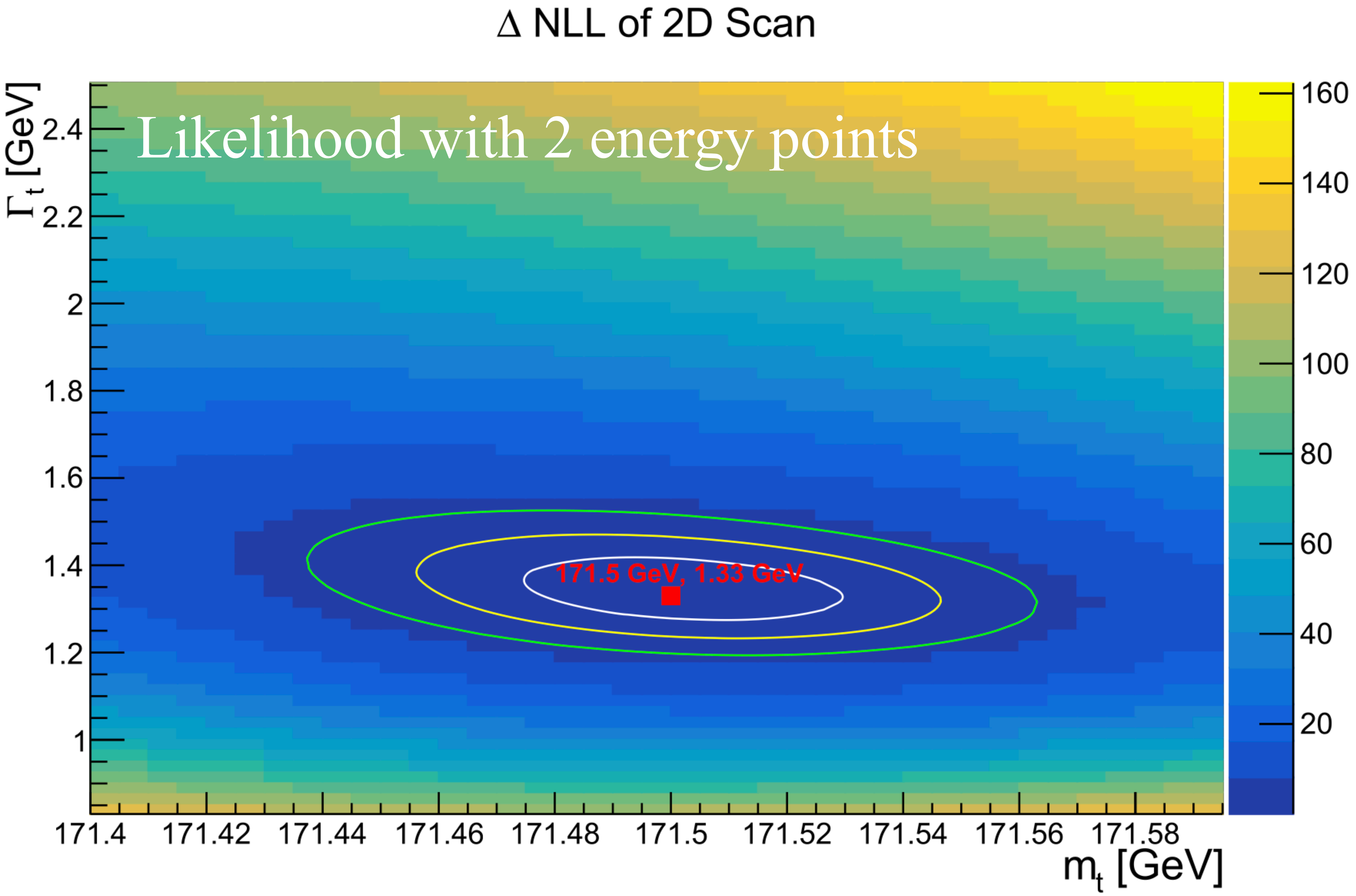
Two energy points

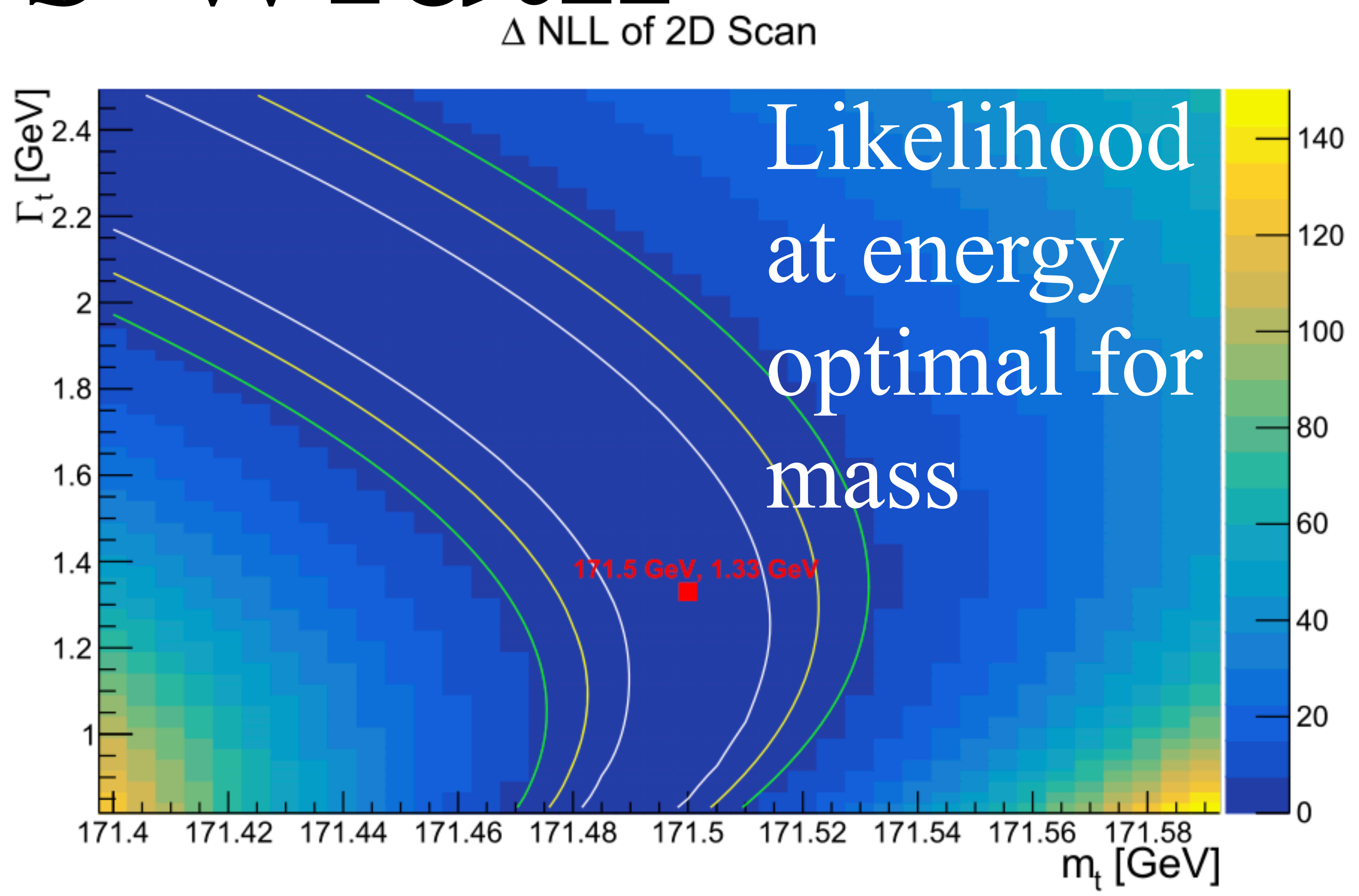


Ten energy points

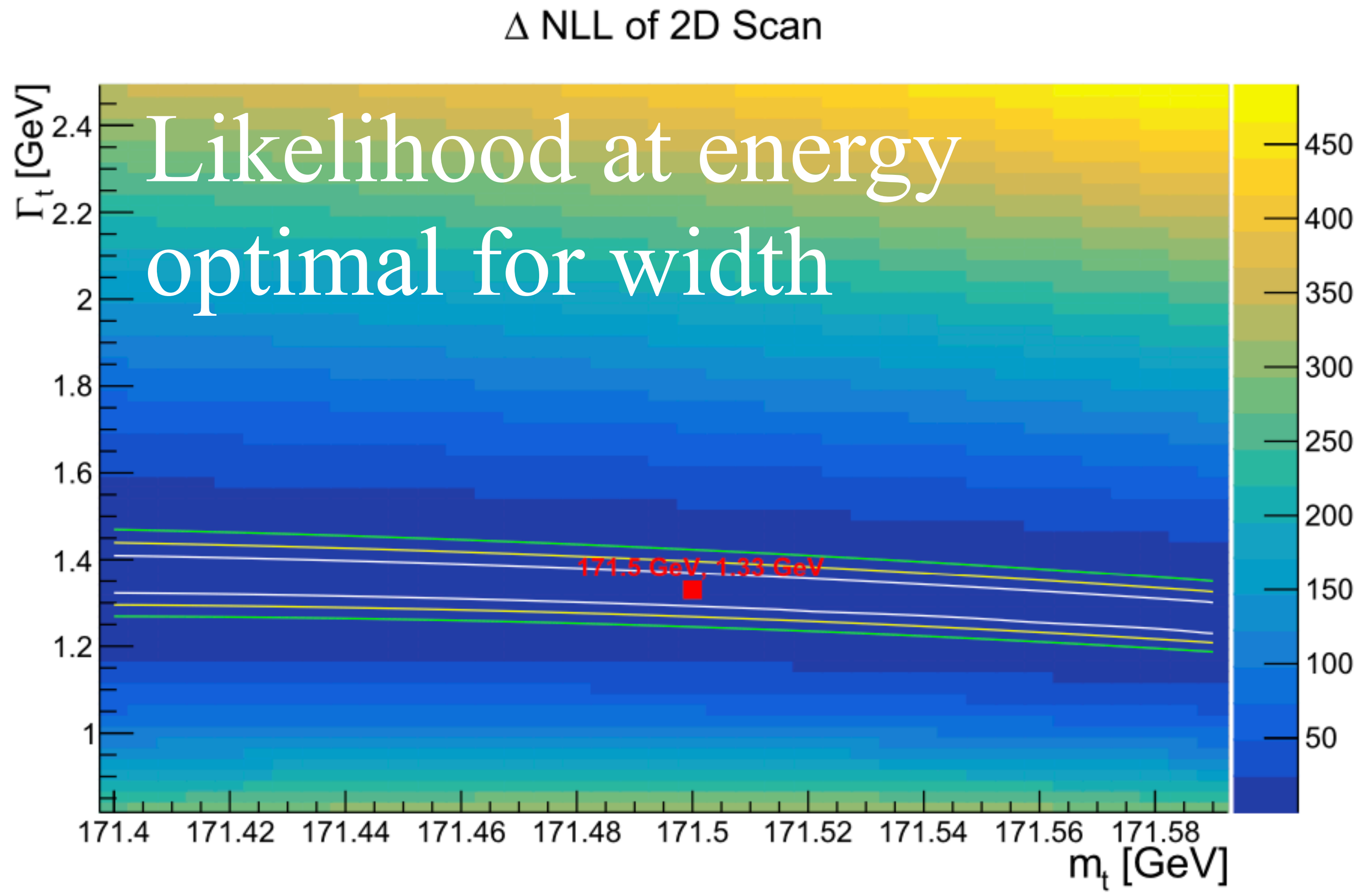
2D scans for m_{top} vs width

- The choice for width is simpler, as its optimal energy point is away from the one for top mass and they have different constraint pattern
- A closed contour can be achieved





(d) $E_{\rm cm}$= 342.75 GeV



(f) $E_{\rm cm}$= 344.00 GeV

Summary

- Great opportunities for top mass, width, α_S measurements with CEPC at the $t\bar{t}$ threshold using the threshold scan method

- Top mass can be measured with a precision 1 order of magnitude better than hadron colliders at the moment
  - The error including systematic uncertainties is 24 MeV (57 MeV) optimistically (conservatively), competitive among future colliders

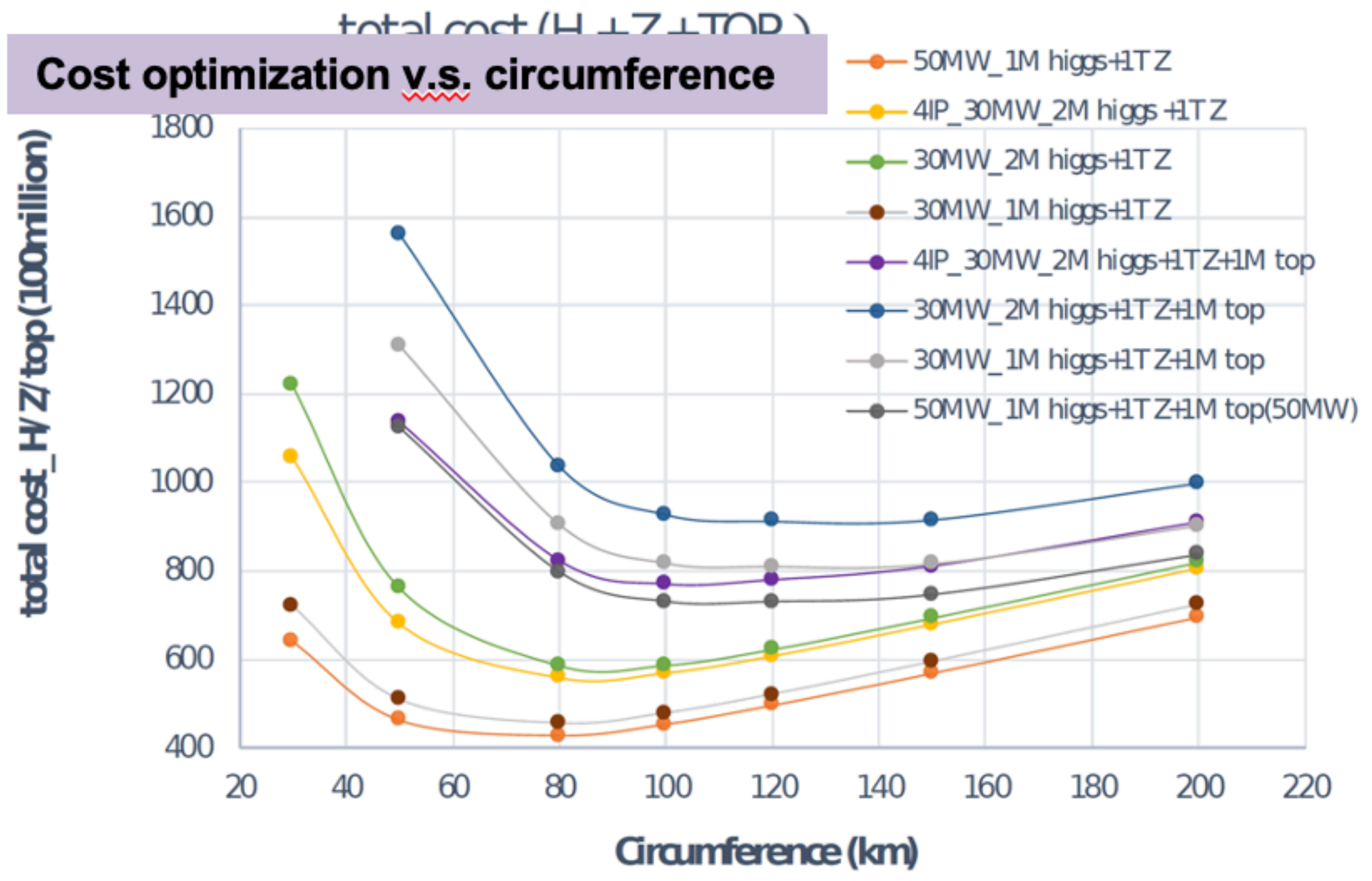
- Reference: Eur. Phys. J. C (2023) 83:269 arXiv:2207.12177

Backup

Yuhui Li@CEPC UK workshop this week

Design of experimental facility

- **Circular collider**: Higher luminosity than a linear collider
- **100km circumference**: Optimum total cost, good also for SppC
- **Shared tunnel**: Accommodate CEPC booster &collider and SppC
- **Switchable operation**: Higgs, W/Z, top



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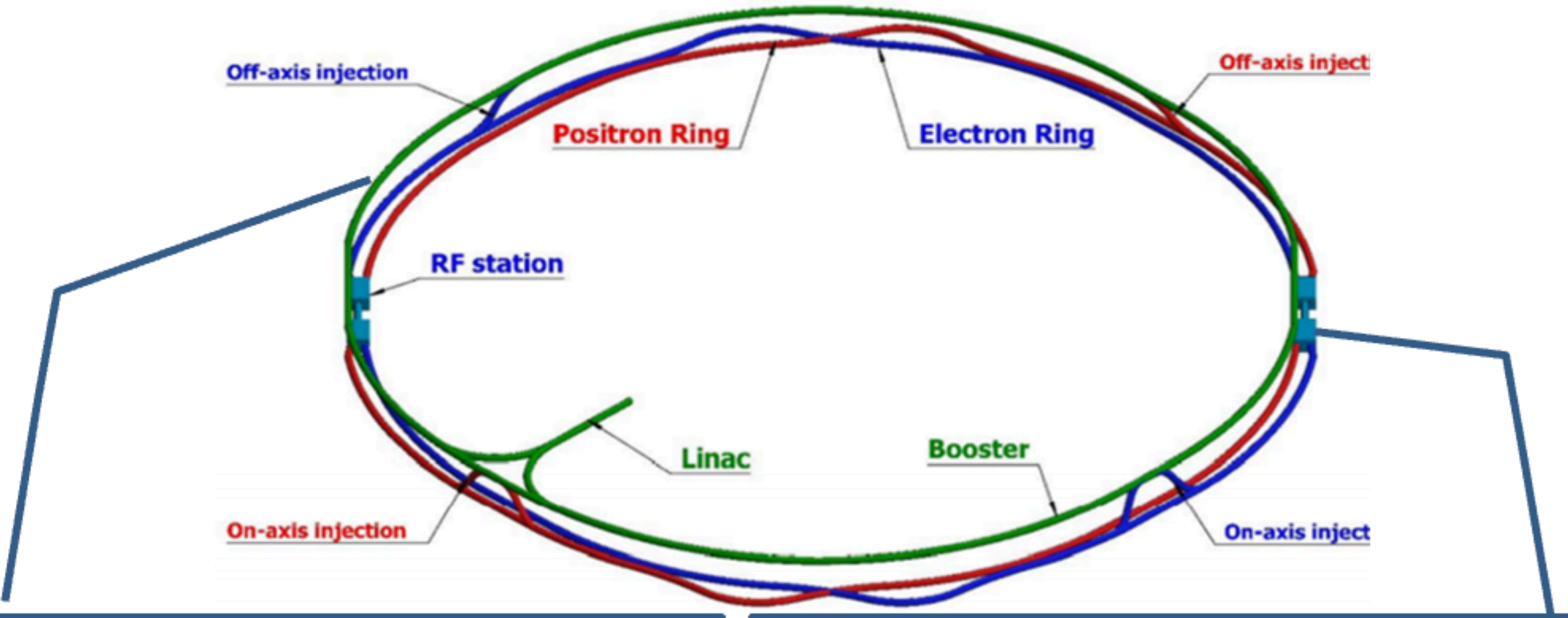
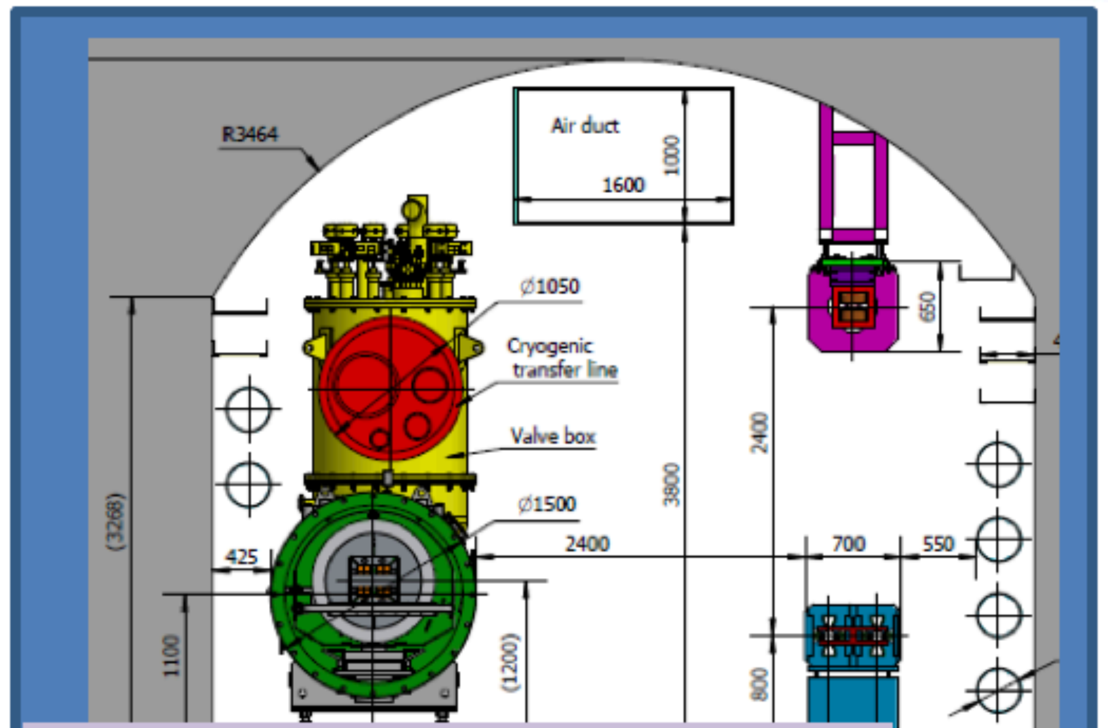
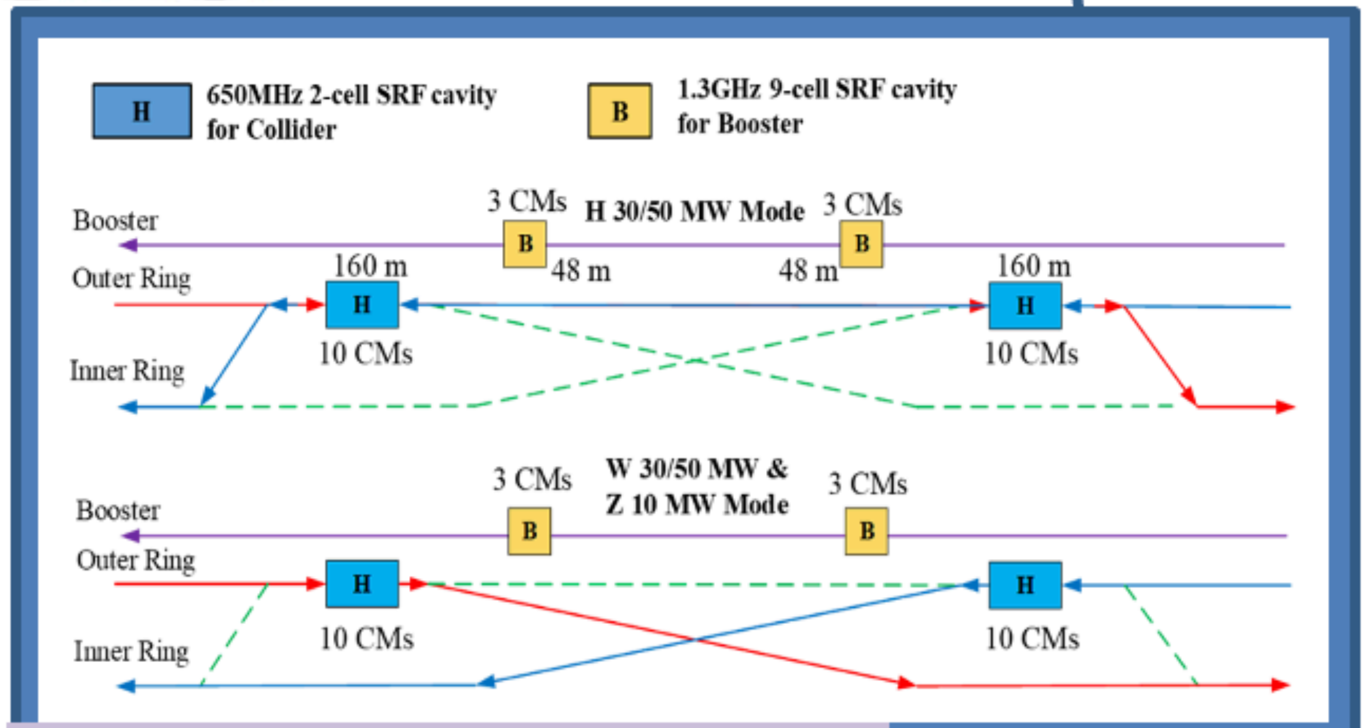




Common tunnel for booster/collider & SppC



Compatible Operation for Higgs W and Z

Main Parameters: High luminosity as a Higgs Factory

	Higgs	W	Z	ttbar
Number of IPs	2			
Circumference [km]	100.0			
SR power per beam [MW]	**50**			
Energy [GeV]	**120**	**80**	**45.5**	**180**
Bunch number	415	2161	19918	59
Emittance (εx/εy) [nm/pm]	0.64/1.3	0.87/1.7	0.27/1.4	1.4/4.7
Beam size at IP (σx/σy) [um/nm]	15/36	13/42	6/35	39/113
Bunch length (SR/total) [mm]	2.3/3.9	2.5/4.9	2.5/8.7	2.2/2.9
Beam-beam parameters (ξx/ξy)	0.015/0.11	0.012/0.113	0.004/0.127	0.071/0.1
RF frequency [MHz]	650			
Luminosity per IP[10^{34}/cm^2/s]	**8.3**	**27**	**192**	**0.83**

CEPC TDR Parameters (upgrade)

	Higgs	Z	W	$t\bar{t}$
Number of IPs	2			
Circumference (km)	100.0			
SR power per beam (MW)	**50**			
Half crossing angle at IP (mrad)	16.5			
Bending radius (km)	10.7			
Energy (GeV)	120	45.5	80	180
Energy loss per turn (GeV)	1.8	0.037	0.357	9.1
Damping time $\tau_x/\tau_y/\tau_z$ (ms)	44.6/44.6/22.3	816/816/408	150/150/75	13.2/13.2/6.6
Piwinski angle	4.88	29.52	5.98	1.23
Bunch number	446	13104	2162	58
Bunch spacing (ns)	355 (53% gap)	23 (10% gap)	154	2714 (53% gap)
Bunch population (10^{11})	1.3	2.14	1.35	2.0
Beam current (mA)	27.8	1340.9	140.2	5.5
Momentum compaction (10^{-5})	0.71	1.43	1.43	0.71
Beta functions at IP β_x^*/β_y^* (m/mm)	0.3/1	0.13/0.9	0.21/1	1.04/2.7
Emittance $\varepsilon_x/\varepsilon_y$ (nm/pm)	0.64/1.3	0.27/1.4	0.87/1.7	1.4/4.7
Betatron tune ν_x/ν_y	445/445	266/267	266/266	445/445
Beam size at IP σ_x/σ_y (um/nm)	14/36	6/35	13/42	39/113
Bunch length (natural/total) (mm)	2.3/4.1	2.7/10.6	2.5/4.9	2.2/2.9
Energy spread (natural/total) (%)	0.10/0.17	0.04/0.15	0.07/0.14	0.15/0.20
Energy acceptance (DA/RF) (%)	1.6/2.2	1.3/1.5	1.2/2.5	2.0/2.6
Beam-beam parameters ξ_x/ξ_y	0.015/0.11	0.0045/0.13	0.012/0.113	0.071/0.1
RF voltage (GV)	2.2	0.1	0.7	10
RF frequency (MHz)	650			
Longitudinal tune ν_s	0.049	0.032	0.062	0.078
Beam lifetime (Bhabha/beamstrahlung) (min)	39/40	86/400	60/700	81/23
Beam lifetime (min)	20	71	55	18
Hourglass Factor	0.9	0.97	0.9	0.89
Luminosity per IP (10^{34} cm^{-2} s^{-1})	**8.3**	**192**	**26.7**	**0.8**

Jie Gao@CEPC UK workshop this week

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CEPC Operation Plan

Particle	$E_{c.m.}$ (GeV)	Years	SR Power (MW)	Lumi. per IP ($10^{34}cm^{-2}s^{-1}$)	Integrated Lumi. per year (ab^{-1}, 2 IPs)	Total Integrated L (ab^{-1}, 2 IPs)	Total no. of events
H*	240	10	50	8.3	2.2	21.6	4.3×10^6
			30	5	1.3	13	2.6×10^6
Z	91	2	50	192**	50	100	4.1×10^{12}
			30	115**	30	60	2.5×10^{12}
W	160	1	50	26.7	6.9	6.9	2.1×10^8
			30	16	4.2	4.2	1.3×10^8
$t\bar{t}$	360	5	50	0.8	0.2	1.0	0.6×10^6
			30	0.5	0.13	0.65	0.4×10^6

* Higgs is the top priority. The CEPC will commence its operation with a focus on Higgs.

** Detector solenoid field is 2 Tesla during Z operation, 3Tesla for all other energies.

*** Calculated using 3,600 hours per year for data collection.

Uncertainties: quick scan and beam energy

	Top mass uncertainties (MeV)	
	Optimistic	Conservative
Statistics	9	9
Theory	8	24
Quick scan	2	2
α_S	17	17
Width	10	10
Experimental efficiency	5	44
Background	2	14
Beam energy	2	2
Luminosity spectrum	3	6
Total	24	57

- The quick scans of CEPC beam energy are used to locate the optimal energy point before the high-luminosity runs
- CEPC can control the beam energy with a precision down to 10^{-5} corresponding to ~O(1) MeV at tt threshold
- This leads to an uncertainty of 2 MeV, as a small contribution to the total
- CLIC has a control of 10^{-4} on the beam energy, but still gives an impact on top mass less than the statistical uncertainty

Uncertainties Overview

ILC & FCC-ee

MAX-PLANCK-INSTITUT FÜR PHYSIK

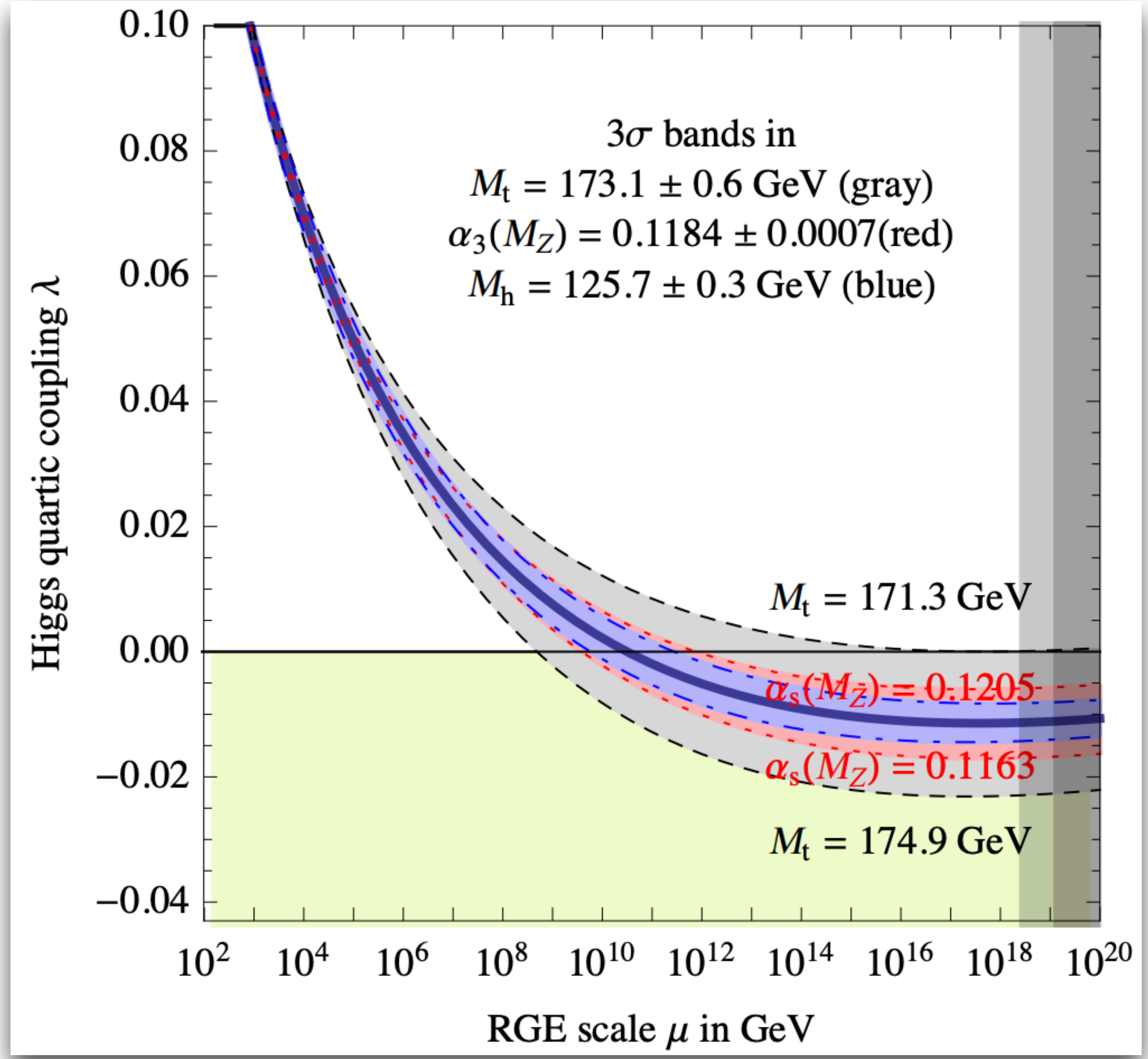
- Relatively thorough evaluation for ILC:

For FCC-ee $200 fb^{-1}$

error source	Δm_t^{PS} [MeV]	For FCC-ee $200 fb^{-1}$
stat. error (200 fb^{-1})	13	9 (compressed scan)
theory (NNLO scale variations, PS scheme)	40	40 - 45, depending on scan range
parametric (α_s, current WA: 9 x 10^{-4})	26	3.2 with ultimate α_s (1.2 x 10^{-4})
non-resonant contributions (such as single top)	< 40	< 40 (no new evaluation)
residual background / selection efficiency	10 – 20	10 - 20 (no new evaluation, ~ % level on selection)
luminosity spectrum uncertainty	< 10	negligible
beam energy uncertainty	< 17	3 (for 5 MeV energy uncertainty)
combined theory & parametric	30 – 50	
combined experimental & backgrounds	25 - 50	
total (stat. + syst.)	40 – 75	

Why top mass?

- A fundamental parameter in SM
- A stringent check of the internal consistency of SM
- Required in the evolution of Higgs quartic coupling affecting the Higgs potential stability at high energy scale
- Of course, the top mass is the heaviest particle "so far", why?



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	δm_t^{hyb} [GeV]		
	all-jets	ℓ+jets	combination
Experimental uncertainties			
Method calibration	0.06	0.05	0.03
JEC (quad. sum)	0.15	0.18	0.17
– Intercalibration	−0.04	+0.04	+0.04
– MPFInSitu	+0.08	+0.07	+0.07
– Uncorrelated	+0.12	+0.16	+0.15
Jet energy resolution	−0.04	−0.12	−0.10
b tagging	0.02	0.03	0.02
Pileup	−0.04	−0.05	−0.05
All-jets background	0.07	–	0.01
All-jets trigger	+0.02	–	+0.01
ℓ+jets background	–	+0.02	−0.01
Modeling uncertainties			
JEC flavor (linear sum)	−0.34	−0.39	−0.37
– light quarks (uds)	+0.07	+0.06	+0.07
– charm	+0.02	+0.01	+0.02
– bottom	−0.29	−0.32	−0.31
– gluon	−0.13	−0.15	−0.15
b jet modeling (quad. sum)	0.09	0.12	0.06
– b frag. Bowler–Lund	−0.07	−0.05	−0.05
– b frag. Peterson	−0.05	+0.04	−0.02
– semileptonic b hadron decays	−0.03	+0.10	−0.04
PDF	0.01	0.02	0.01
Ren. and fact. scales	0.04	0.01	0.01
ME/PS matching	+0.24	−0.07	+0.07
ME generator	–	+0.20	+0.21
ISR PS scale	+0.14	+0.07	+0.07
FSR PS scale	+0.18	+0.13	+0.12
Top quark p_T	+0.03	−0.01	−0.01
Underlying event	+0.17	−0.07	−0.06
Early resonance decays	+0.24	−0.07	−0.07
CR modeling (max. shift)	−0.36	+0.31	+0.33
– "gluon move" (ERD on)	+0.32	+0.31	+0.33
– "QCD inspired" (ERD on)	−0.36	−0.13	−0.14
Total systematic	0.70	0.62	0.61
Statistical (expected)	0.20	0.08	0.07
Total (expected)	0.72	0.63	0.61

CMS top mass
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