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

The 2025 International Workshop on the High Energy Circular Electron Positron Collider

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on behalf of the team

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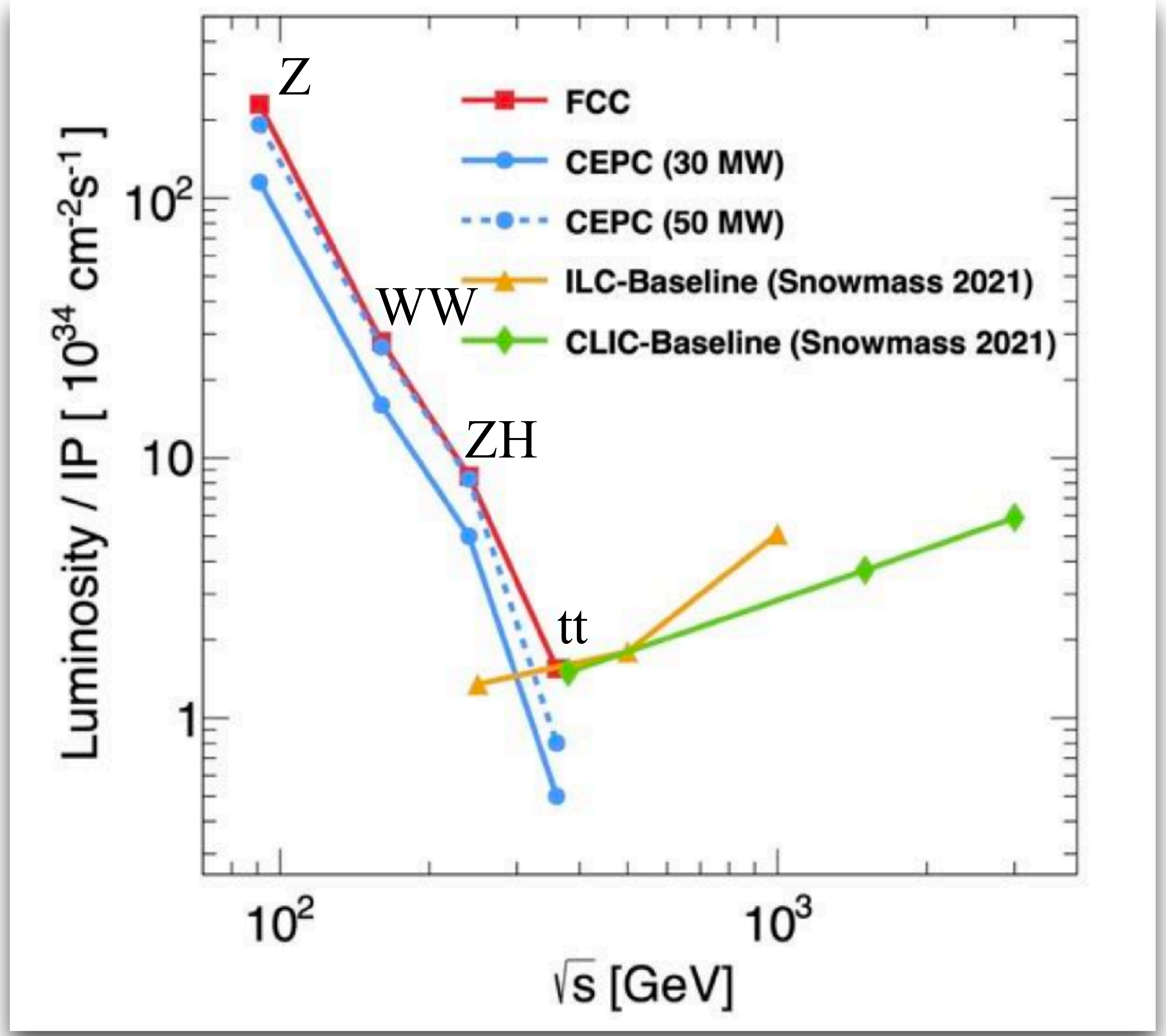
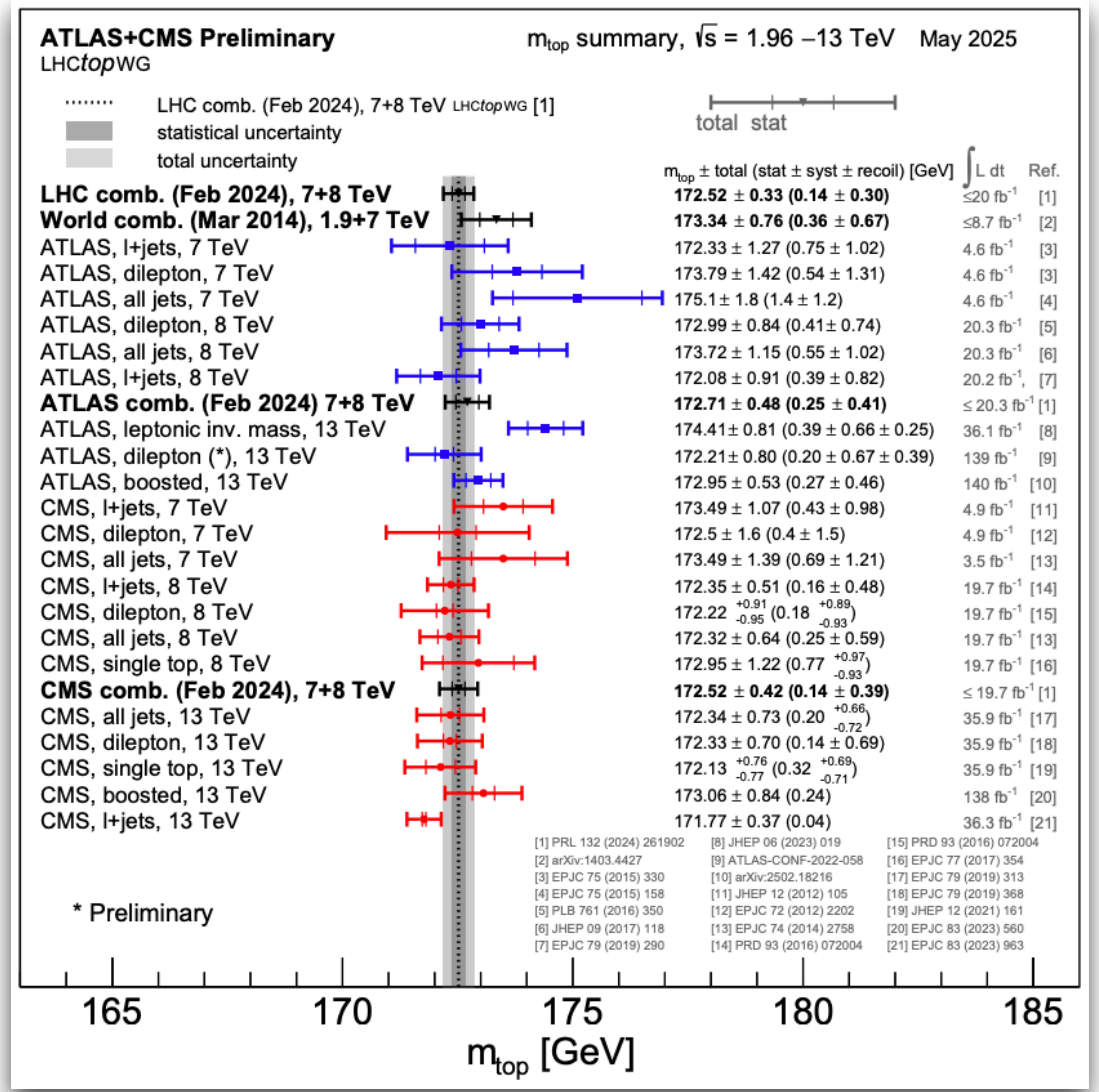
Reference: Eur. Phys. J. C (2023) 83:269, arXiv:2207.12177, RefTDR new in 2025

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
- Plan to have 6×10^5 top pairs with 5 years' data taking



Top quark mass measurements

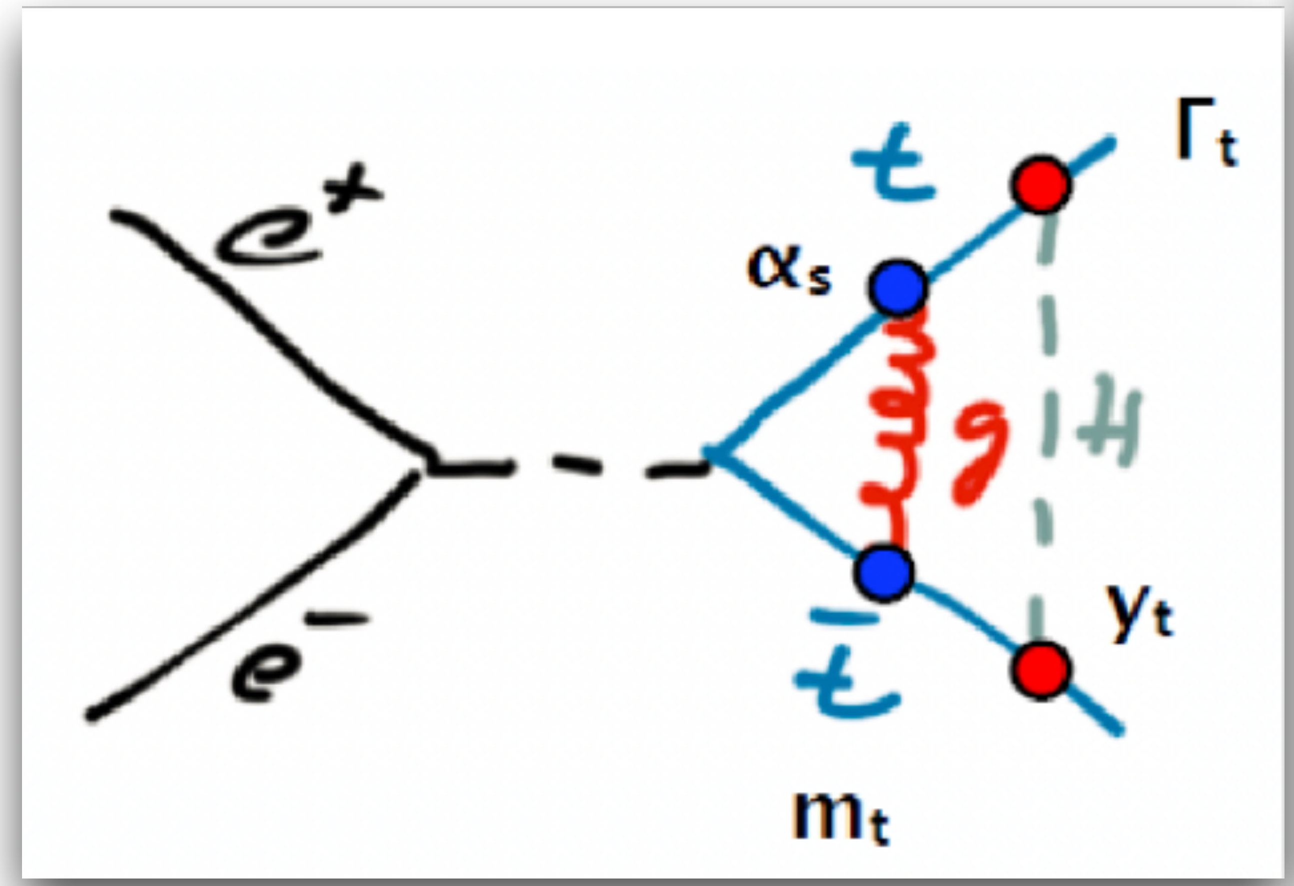


ATL-PHYS-PUB-2025-025

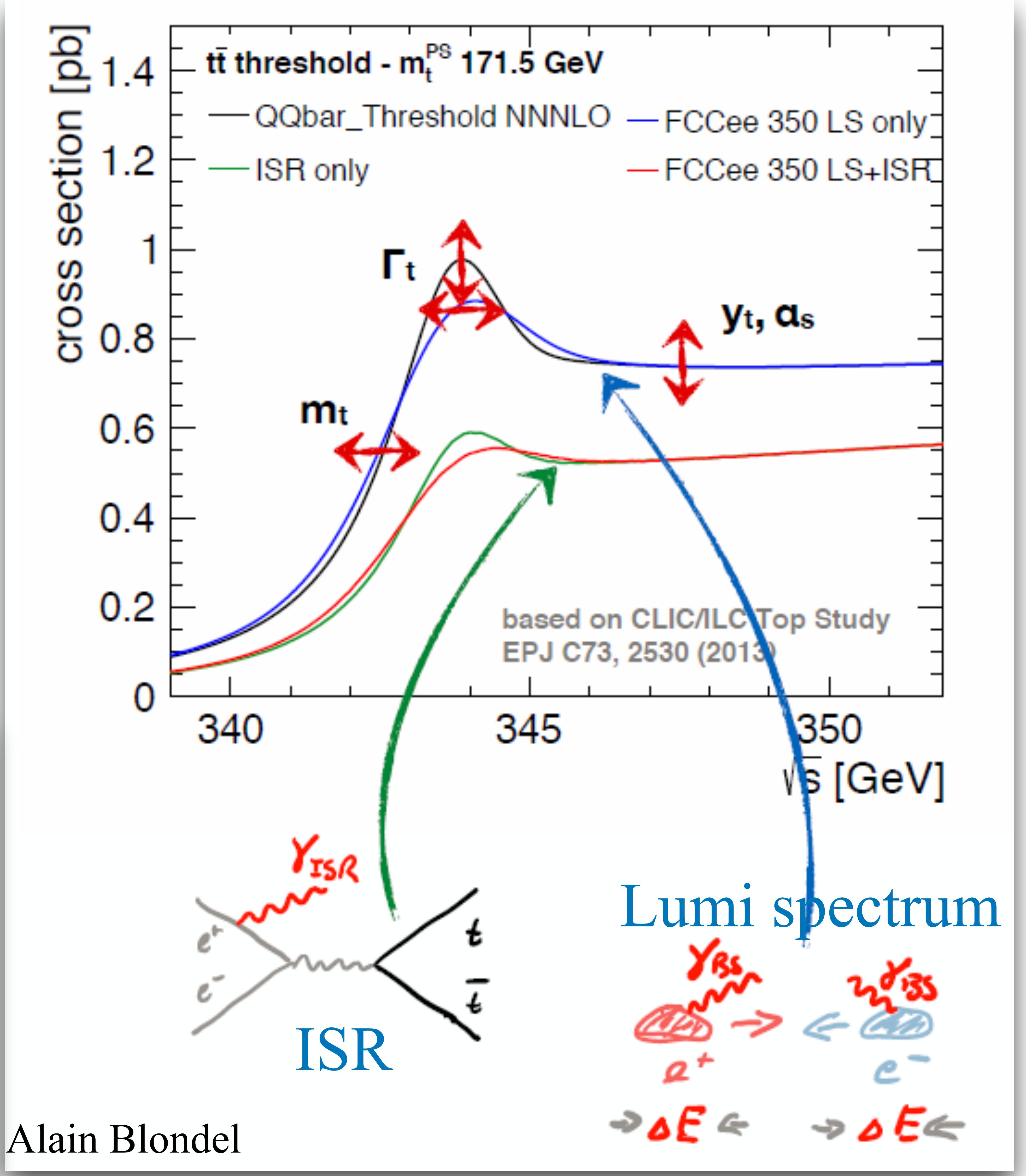
- The top "pole" mass is measured using reconstructed top mass spectrum at hadron colliders
  - Affected by MET (the neutrino), jet energy scale/resolution, btagging etc.
  - Limited by non-perturbative QCD effects
- LHC reached a level of uncertainties of ~300 MeV dominated by systematic uncertainties
- Very challenging to further improve the precision due to dominant systematic uncertainties at hadron colliders

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 serves as 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



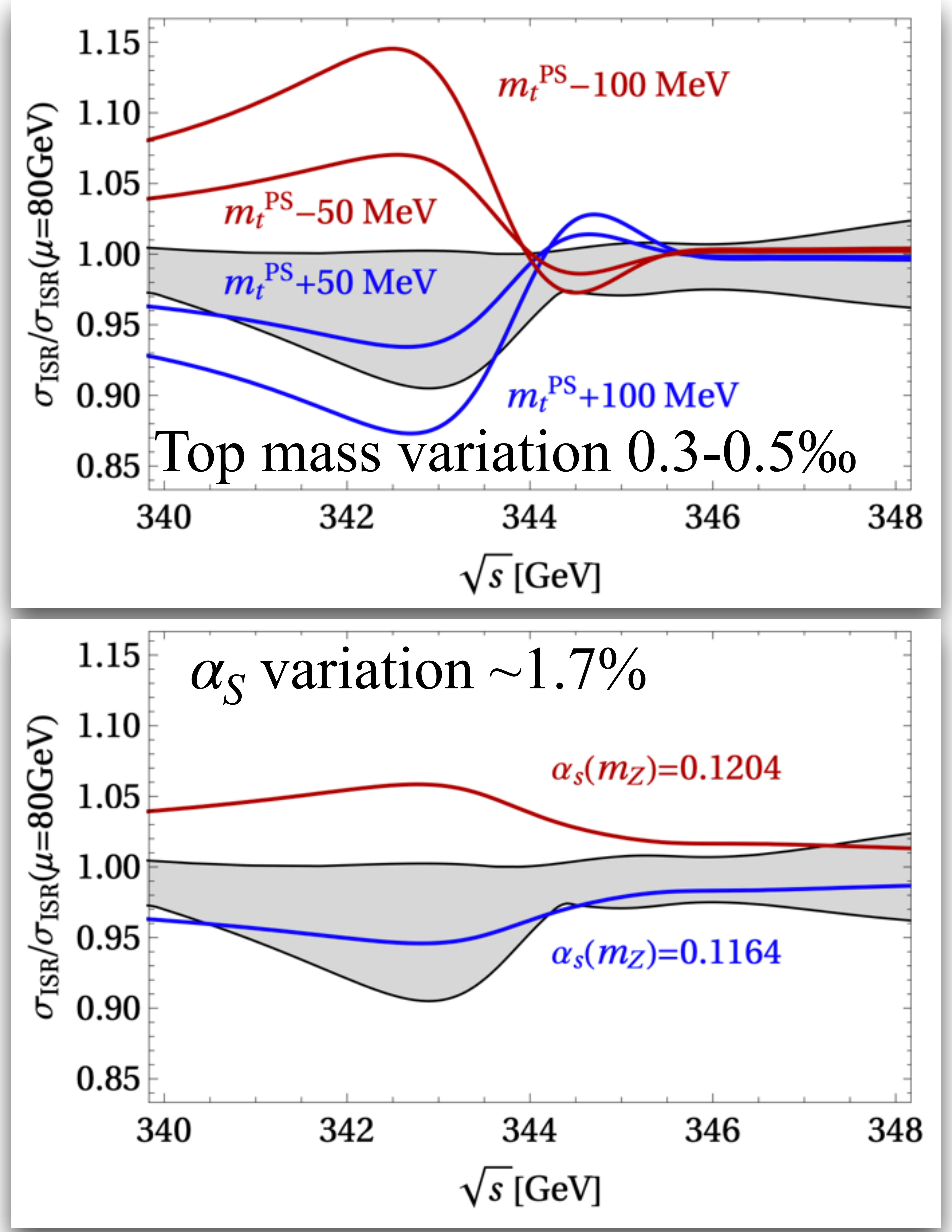
Our setup

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
  - The PS (Potential-Subtracted) Shift (PSS) mass scheme is applied

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

  - 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 $\sqrt{s}$

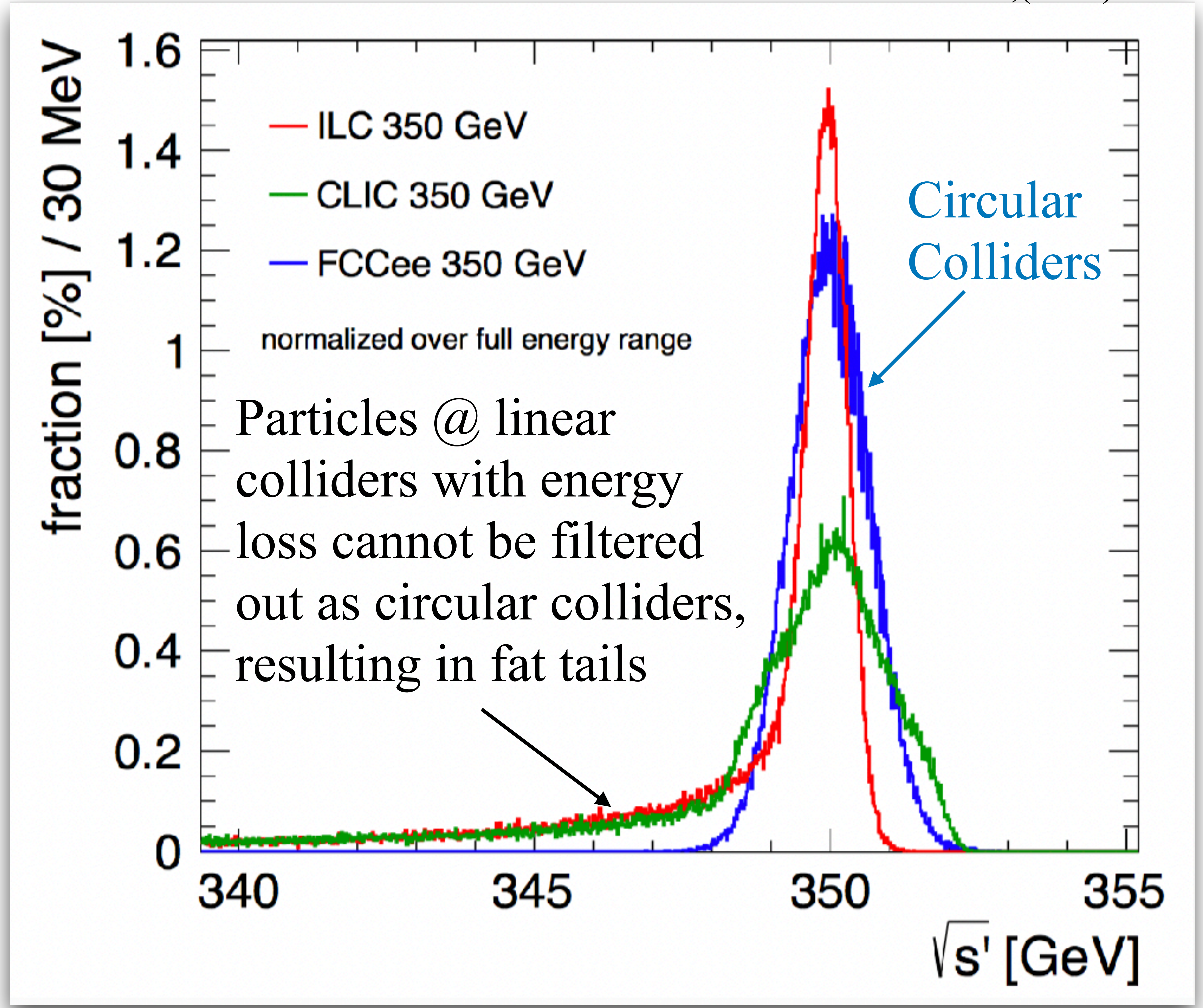


LS in linear/circular colliders

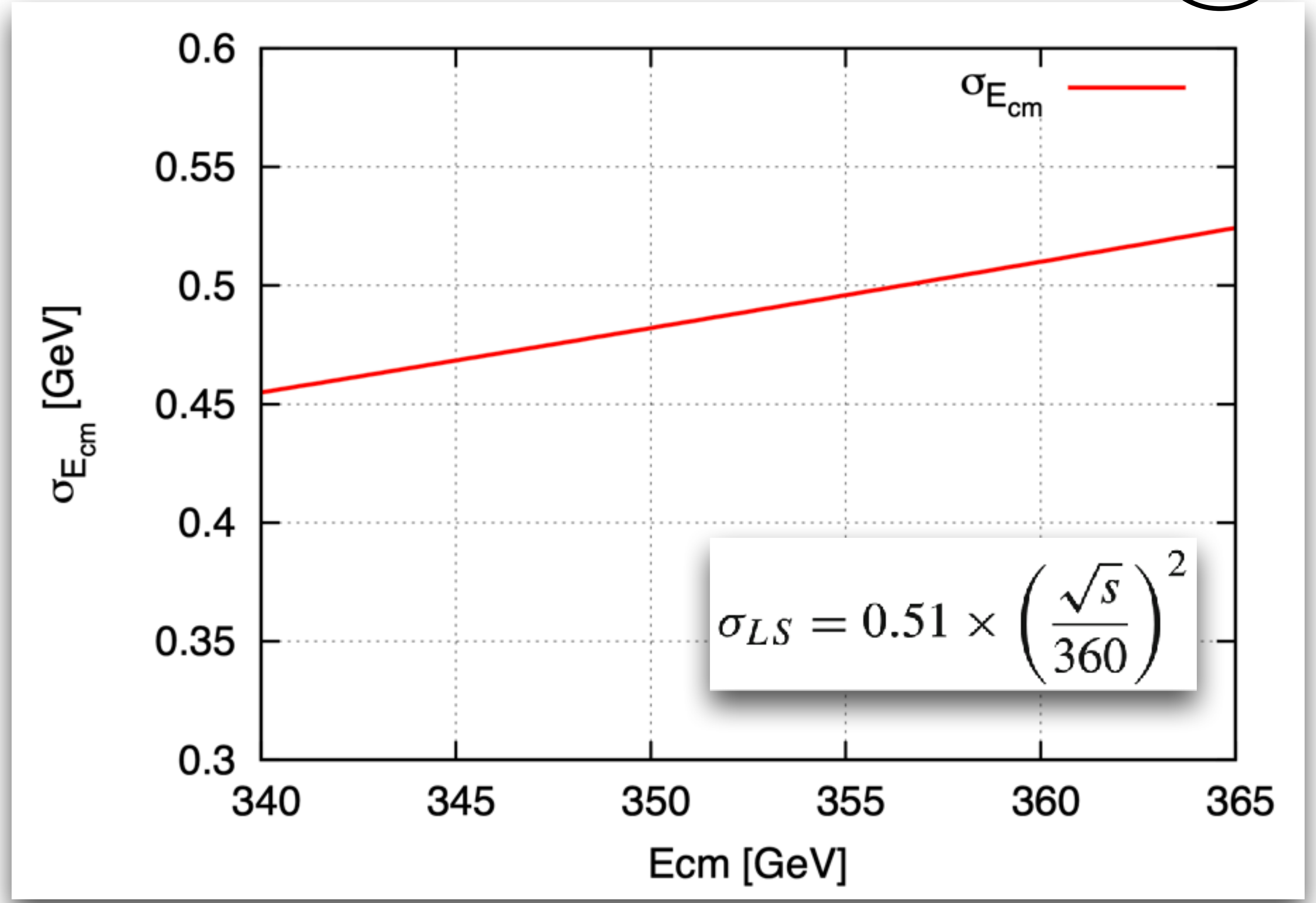
- The luminosity spectrum at linear colliders is obviously worse than circular colliders given that the particles with energy loss are not removed by the bending magnets

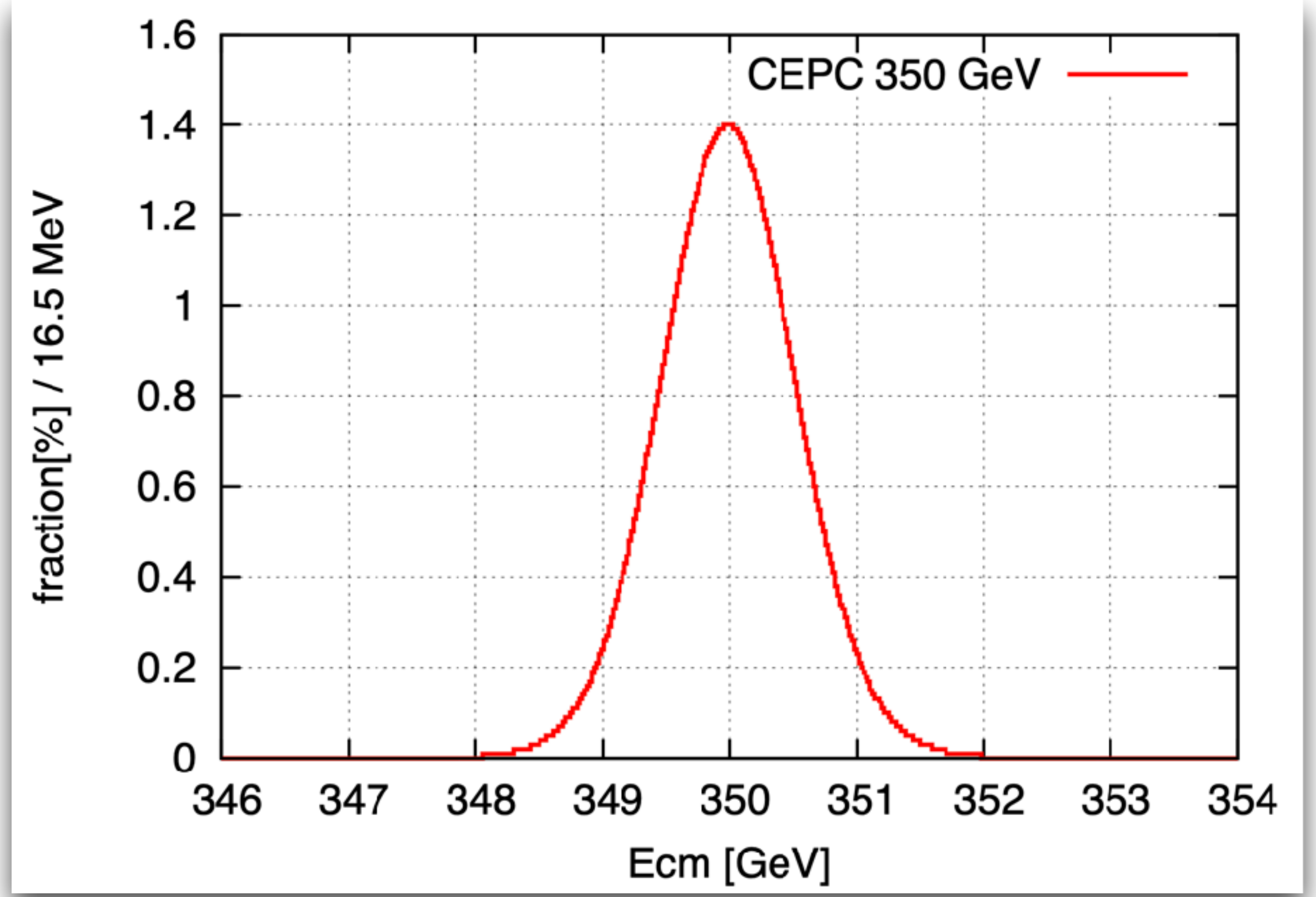
- This can substantially change the cross-section curve at around the tt threshold

EPJC 73,(2013)2530



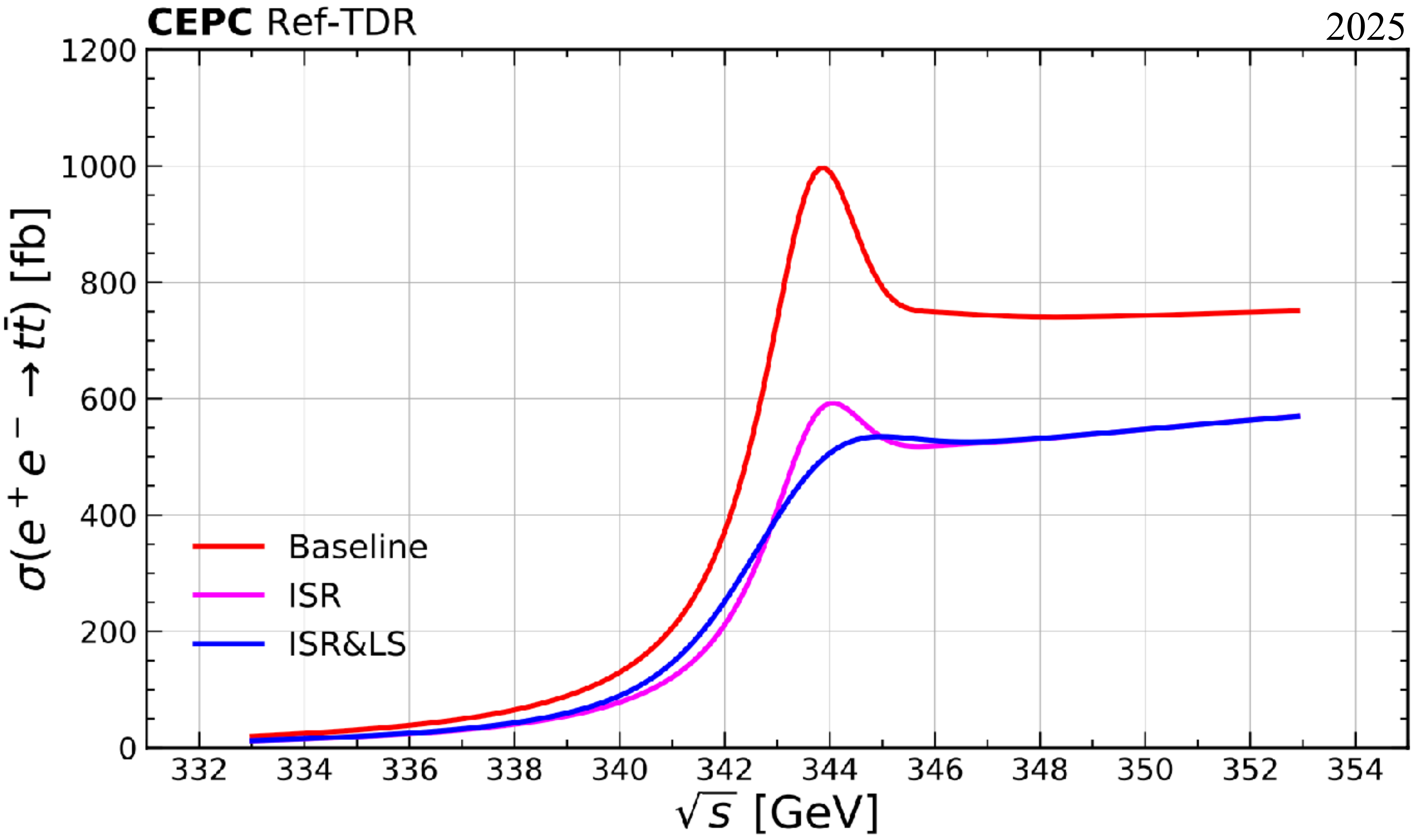
LS @ CEPC



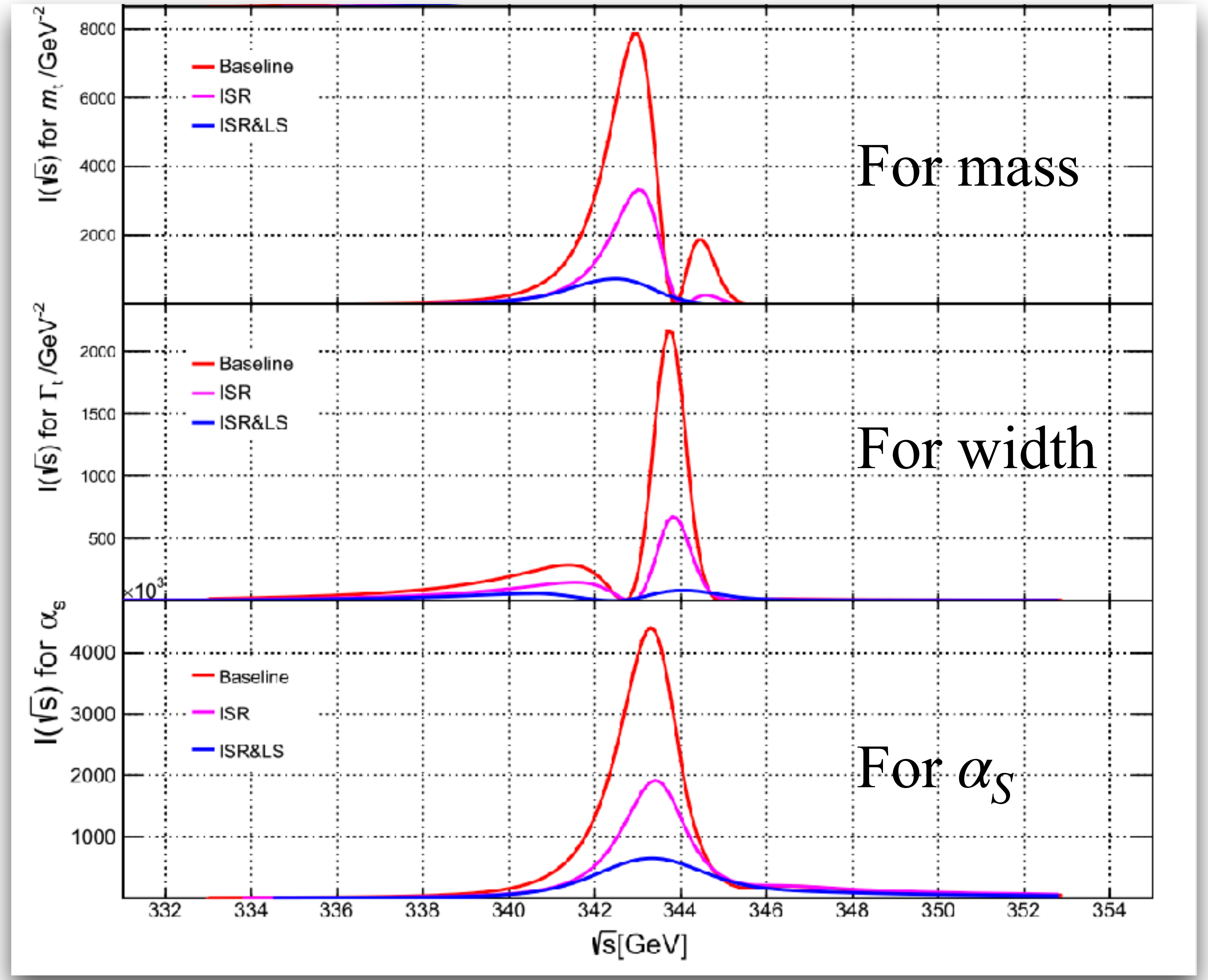


- The beam energy resolution increases as a function of $\sqrt{s}$
- The luminosity spectrum is shown for $\sqrt{s} = 350$ GeV with a width of ~480 MeV
- Similar to the FCC-ee scenario

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



Choice of CME



- 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

Uncertainties: statistics

Source	m_{top} precision (MeV)	
	Optimistic	Conservative
Statistical	7	7
Theory	8	24
Quick scan	2	2
α_S	3	16
Top width	5	5
Experimental efficiency	4	9
Background	1	3
Beam energy	2	2
Luminosity spectrum	3	6
Total (without theory)	11	21
Total	14	32

2025

- 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 7 MeV, compared to 21 MeV from CLIC where the luminosity is distributed for 10 energy points evenly

Uncertainties: theory

Source	m_{top} precision (MeV) Optimistic	Conservative
Statistical	7	7
Theory	8	24
Quick scan	2	2
α_S	3	16
Top width	5	5
Experimental efficiency	4	9
Background	1	3
Beam energy	2	2
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Total (without theory)	11	21
Total	14	32

2025

- 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 future ee colliders, optimistically
- This ends up with theoretical uncertainties of 8 (24) MeV, leading the contribution among all systematics

Uncertainties: α_S and width

Source	m_{top} precision (MeV) Optimistic	Conservative
Statistical	7	7
Theory	8	24
Quick scan	2	2
α_S	3	16
Top width	5	5
Experimental efficiency	4	9
Background	1	3
Beam energy	2	2
Luminosity spectrum	3	6
Total (without theory)	11	21
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2025

- α_S and width are the inputs for this 1D top mass measurement
- α_S uncertainty is taken as 0.0001 (projection from Z boson observables) and 0.0007 (world summary in 2012), while width is varied by 0.14 GeV (CMS constraint 2014)
- α_S uncertainty leads to 3 or 16 MeV on top mass, the latter of which is comparable to CLIC
- Width uncertainty results in 5 MeV on top mass

Uncertainties: experimental efficiency

Source	m_{top} precision (MeV) Optimistic	Conservative
Statistical	7	7
Theory	8	24
Quick scan	2	2
α_S	3	16
Top width	5	5
Experimental efficiency	4	9
Background	1	3
Beam energy	2	2
Luminosity spectrum	3	6
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Total	14	32

2025

- Experimental efficiency of the future detectors is yet to know
- Assume possible scenarios of uncertainties 0.5% and 1% that impacts signal rates directly
- This leads to top mass uncertainties of 4 and 9 MeV, respectively

Uncertainties: background

Source	m_{top} precision (MeV)	
	Optimistic	Conservative
Statistical	7	7
Theory	8	24
Quick scan	2	2
α_S	3	16
Top width	5	5
Experimental efficiency	4	9
Background	1	3
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Total	14	32

2025

- Background contribution is much less than signal. But their uncertainties could affect the measurement
- Assuming background uncertainties of 1% and 5% will give 1 and 3 MeV on top mass measurement
  - Compared to CLIC that has 18 MeV uncertainty of top mass from 5% background variations, given the low level of background

Uncertainties: luminosity spectrum

Source	m_{top} precision (MeV) Optimistic	Conservative
Statistical	7	7
Theory	8	24
Quick scan	2	2
α_S	3	16
Top width	5	5
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2025

- 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

Source	m_{top} precision (MeV) Optimistic	Conservative
Statistical	7	7
Theory	8	24
Quick scan	2	2
α_S	3	16
Top width	5	5
Experimental efficiency	4	9
Background	1	3
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2025

- Additionally, we evaluate the prospect of reducing CEPC LS by -20% and -50% of the current LS
  - These reduce the top mass error less than 10% with respect to the one obtained using the nominal LS
  - The CEPC LS seems already excellent for this measurement, and large improvements of LS would not sizably improve top mass precision

Uncertainties: total

Source	m_{top} precision (MeV) Optimistic	Conservative
Statistical	7	7
Theory	8	24
Quick scan	2	2
α_S	3	16
Top width	5	5
Experimental efficiency	4	9
Background	1	3
Beam energy	2	2
Luminosity spectrum	3	6
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2025

- CEPC is expected to measure the top quark mass with the total uncertainties of 14 and 32 MeV (dominated by the theory/α_S efficiency), considering two different scenarios

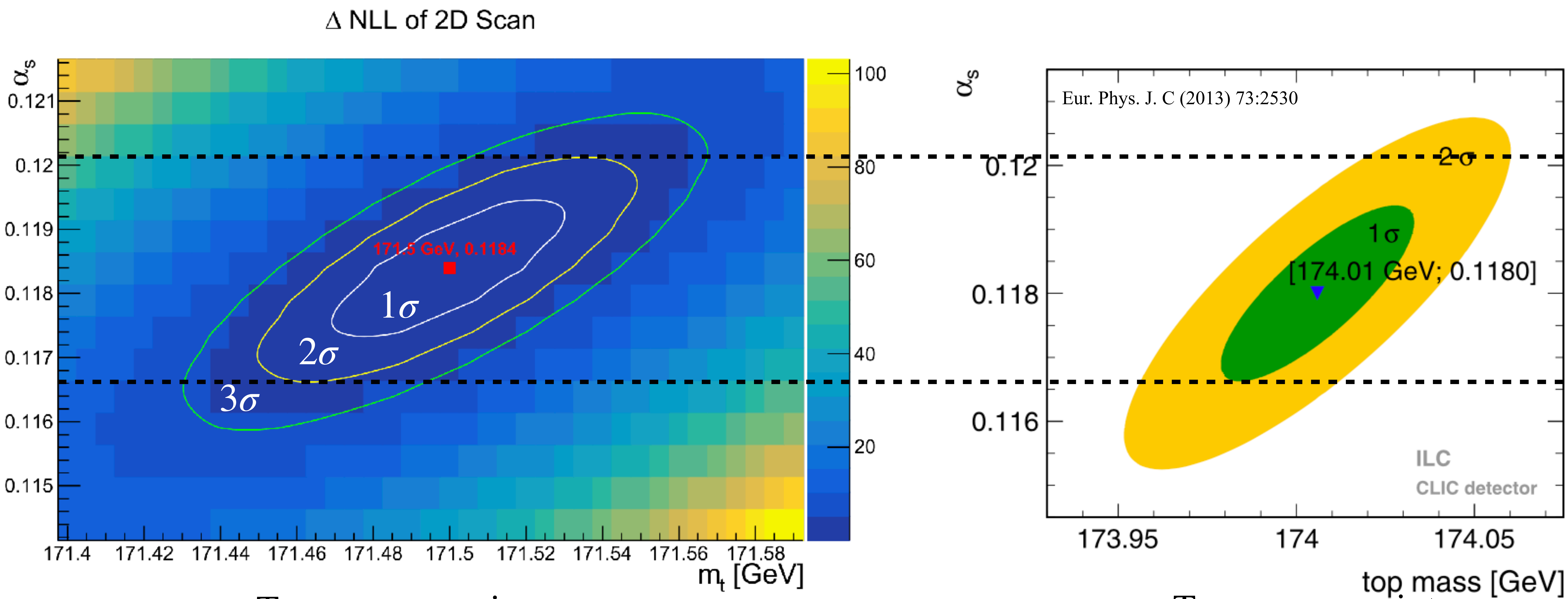
- Compared to ~100 MeV of top mass uncertainty from CLIC (dominated by the LS uncertainty)

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

- A quick comparison to CLIC



Two energy points

Ten energy points

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 14 MeV (32 MeV) optimistically (conservatively)

Reference: Eur. Phys. J. C (2023) 83:269, arXiv:2207.12177, RefTDR new in 2025

Backup

Statistical uncertainty of 1D scan

- 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

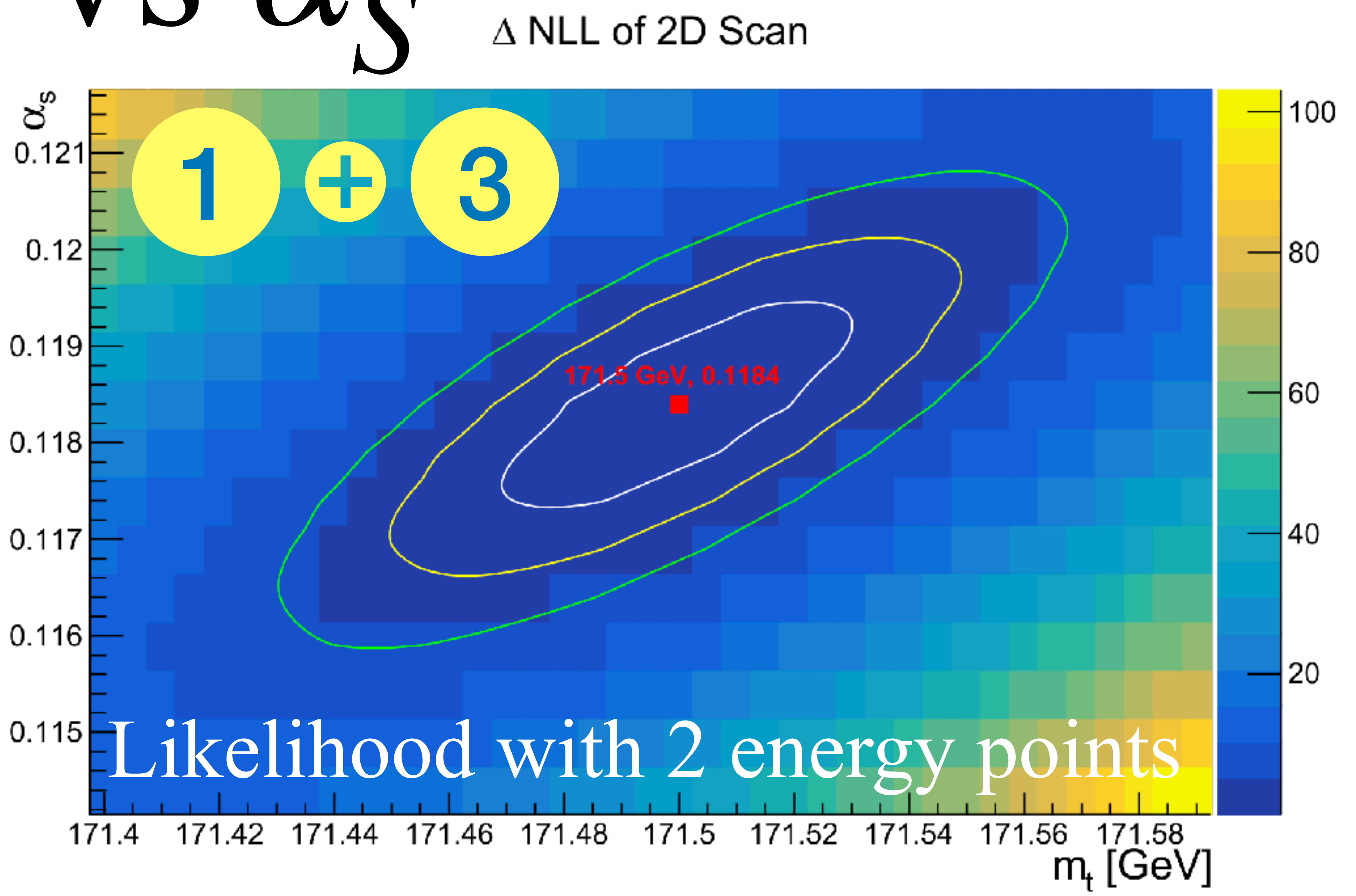
$\sqrt{s}$ (GeV)	$\Delta\, m_{top}$	$\Delta\, \Gamma_{top}$	$\Delta\, \alpha_S$
342.75	9 MeV	343 MeV	0.00041
344.00	$>$ 50 MeV	26 MeV	0.00047
343.50	15 MeV	40 MeV	0.00040

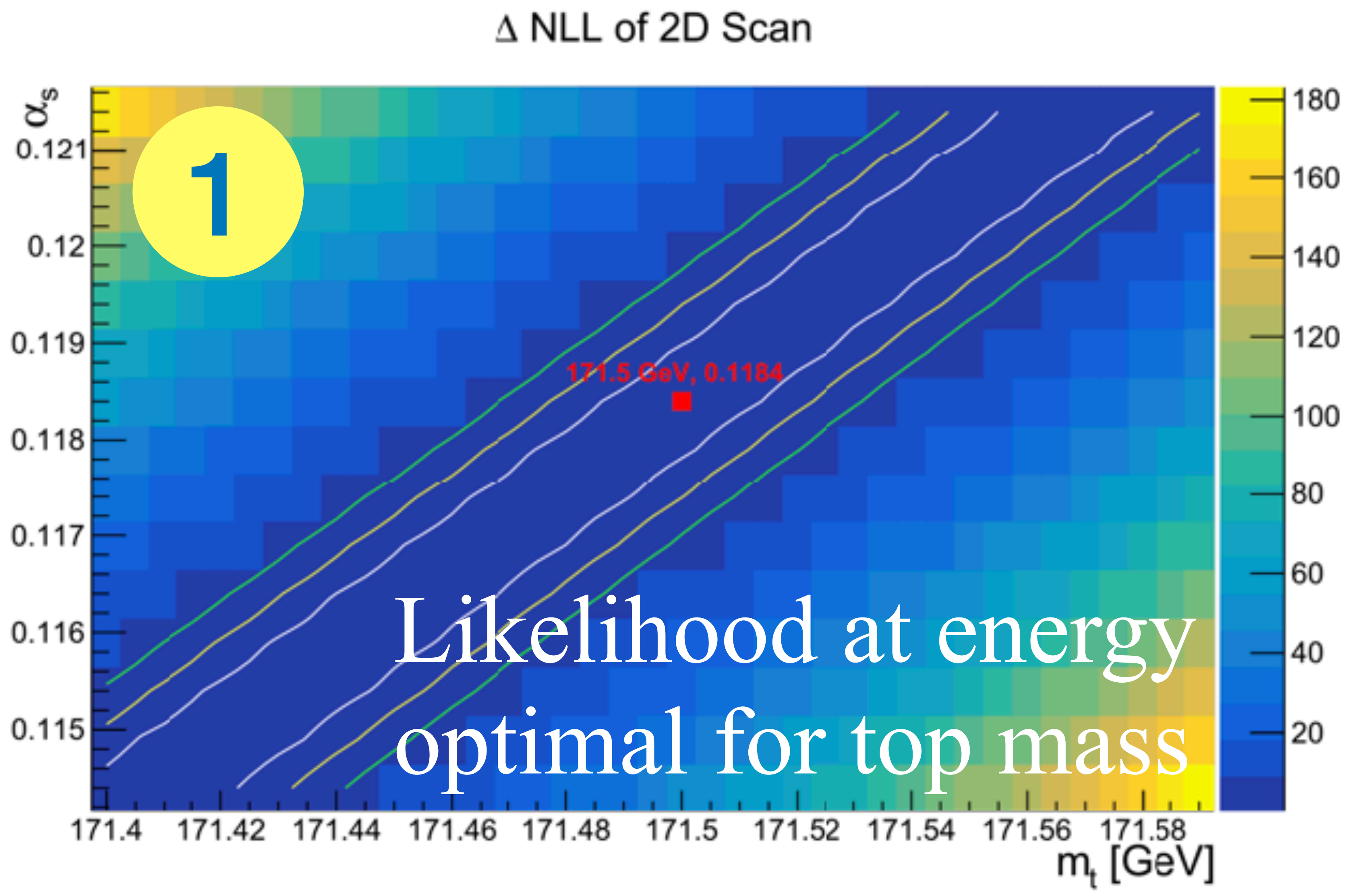
In the table, 342.75 GeV, 344.00 GeV and 343.50 GeV are optimal energy points for top quark mass, width and α_S, respectively

All are stats-only here

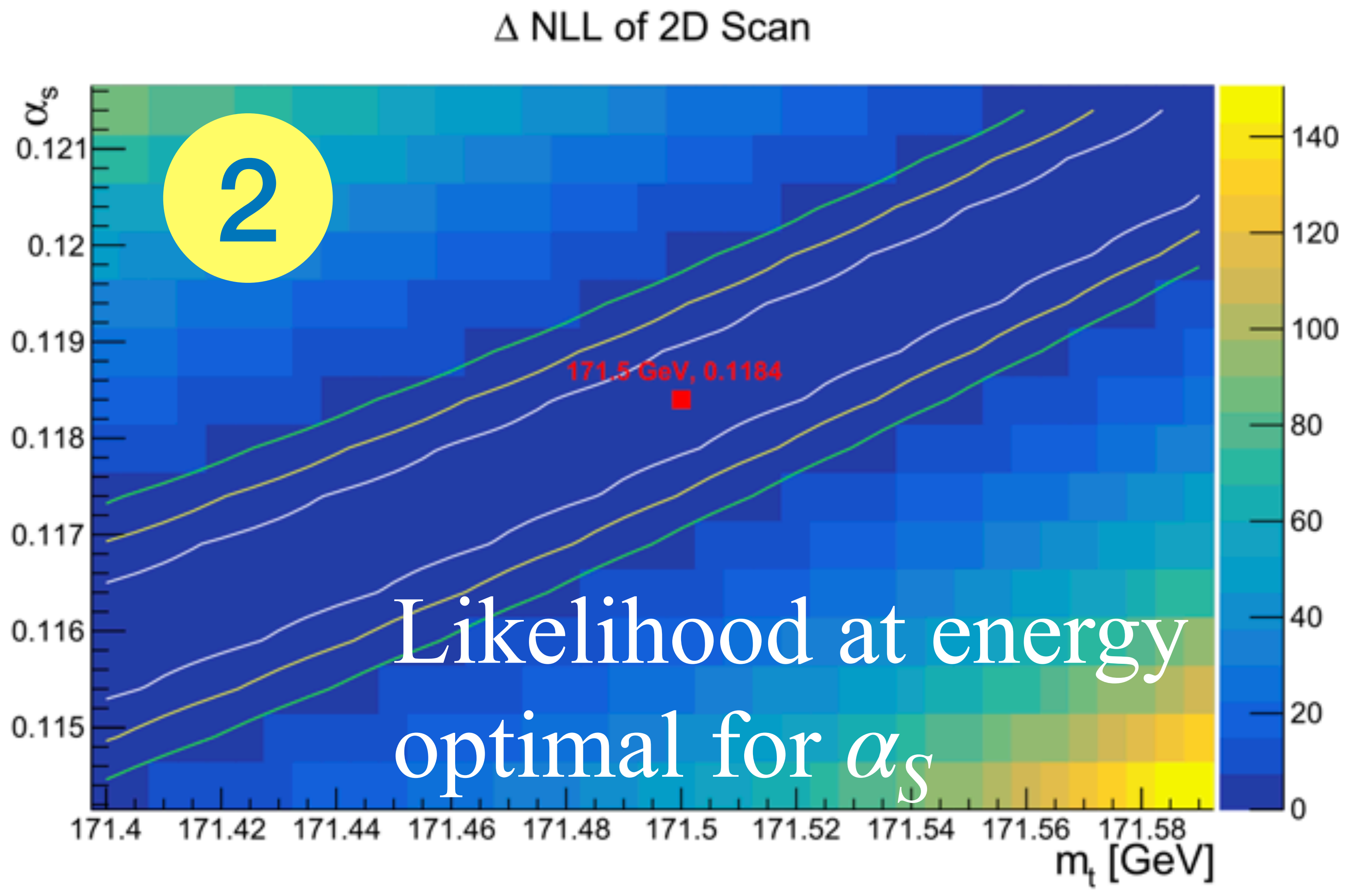
2D scans for m_{top} vs α_S

- 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)

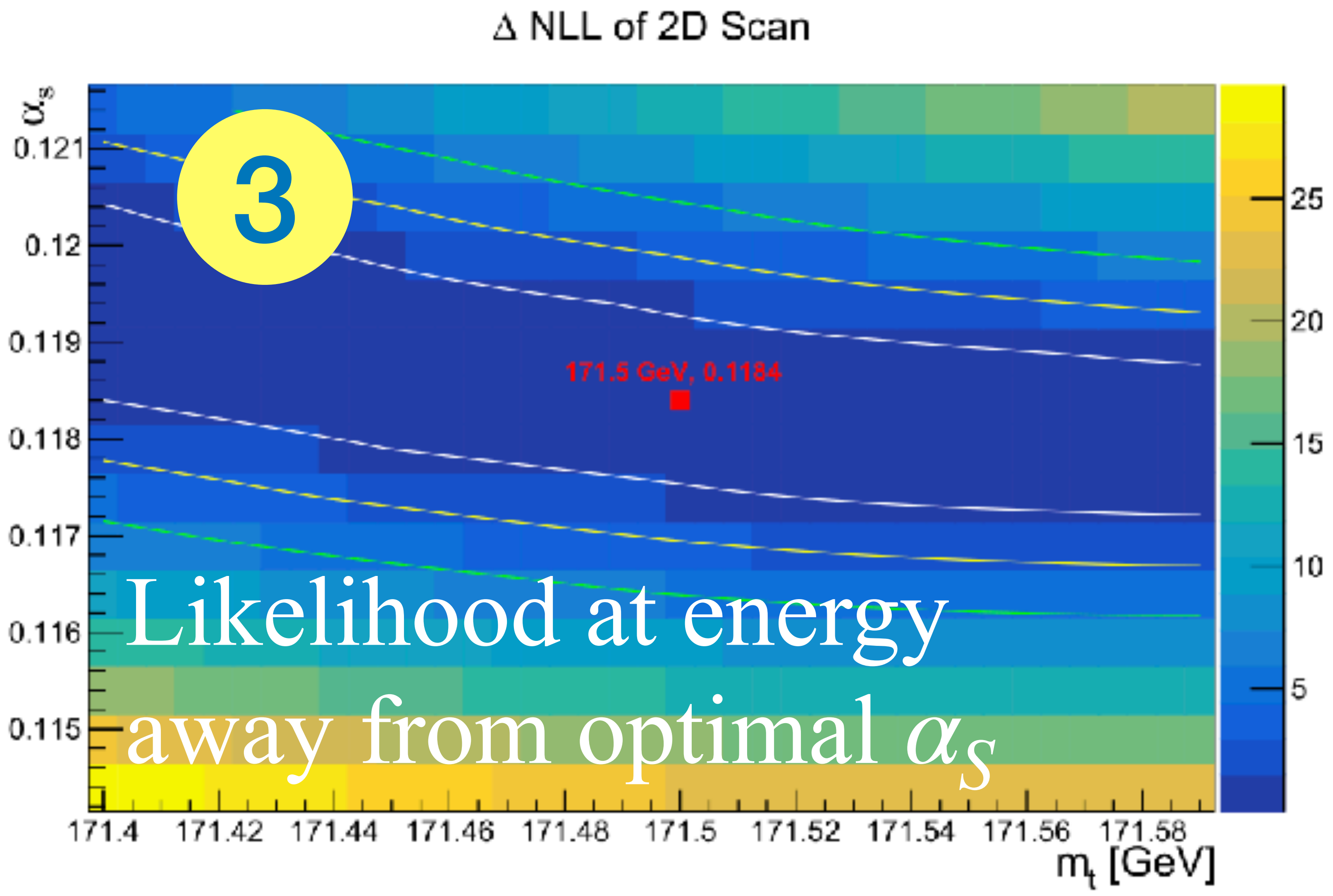




(b) $E_{\rm cm}$= 342.75 GeV



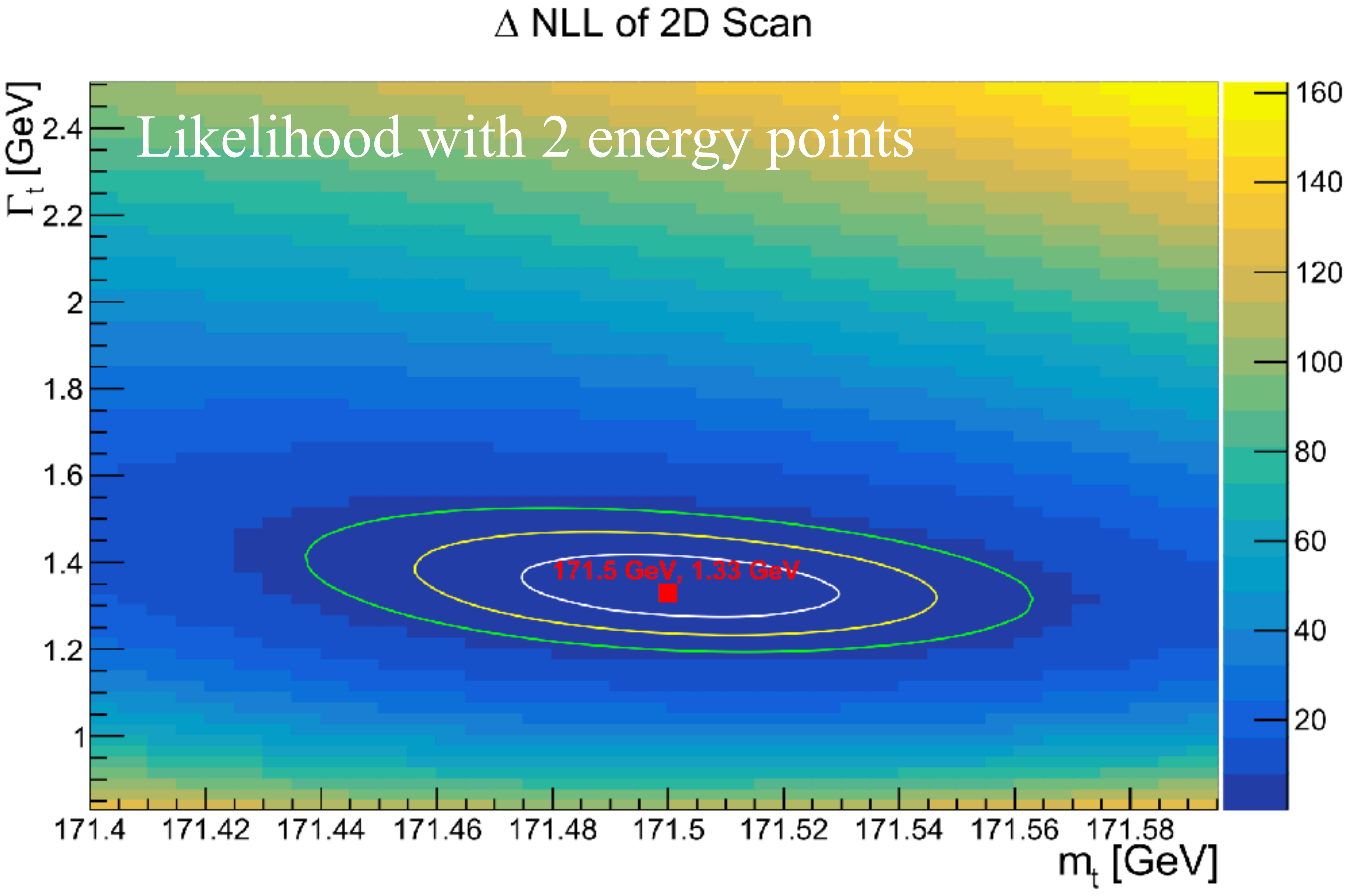
(d) $E_{\rm cm}$= 343.50 GeV

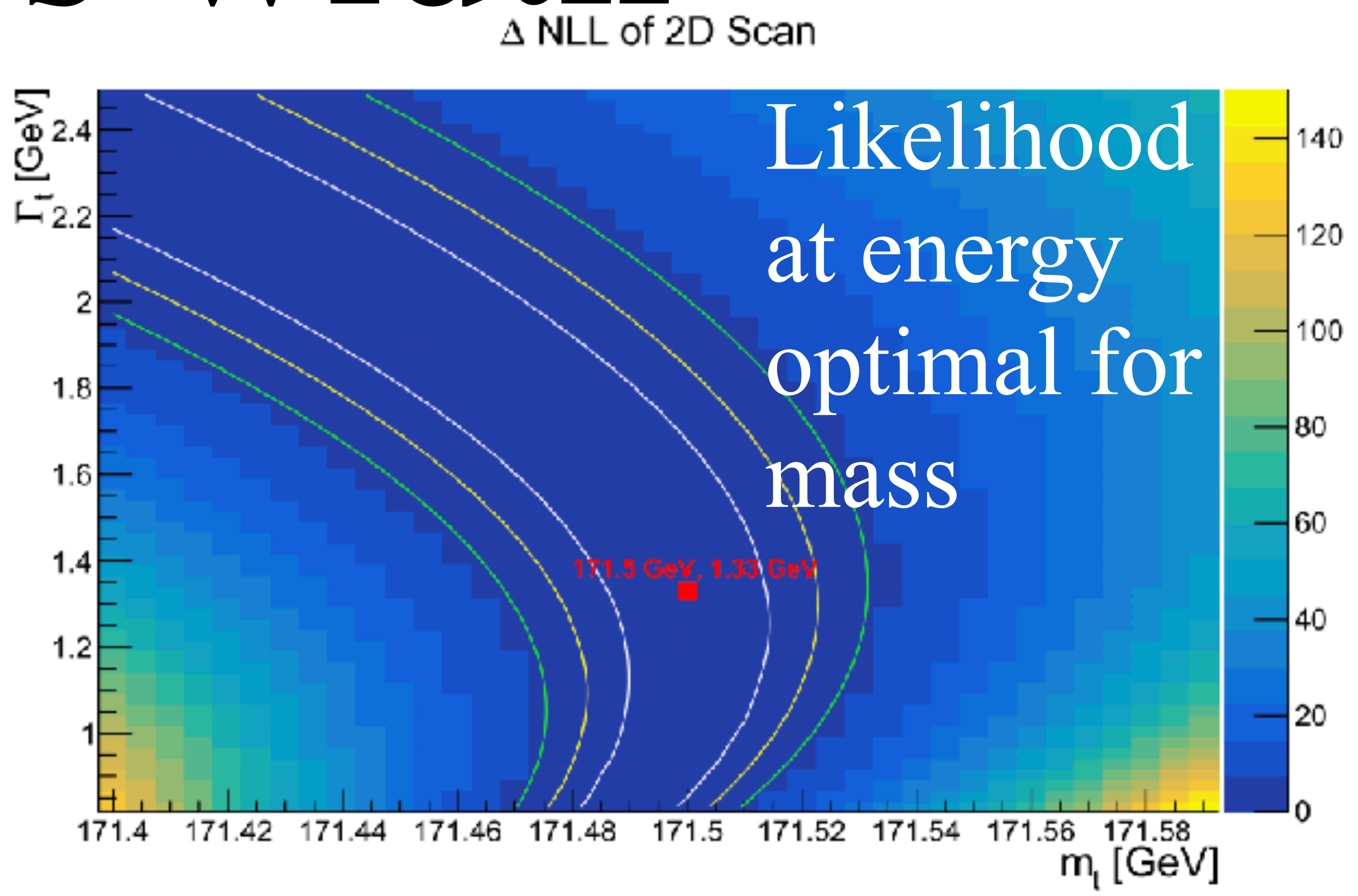


(f) $E_{\rm cm}$= 344.50 GeV

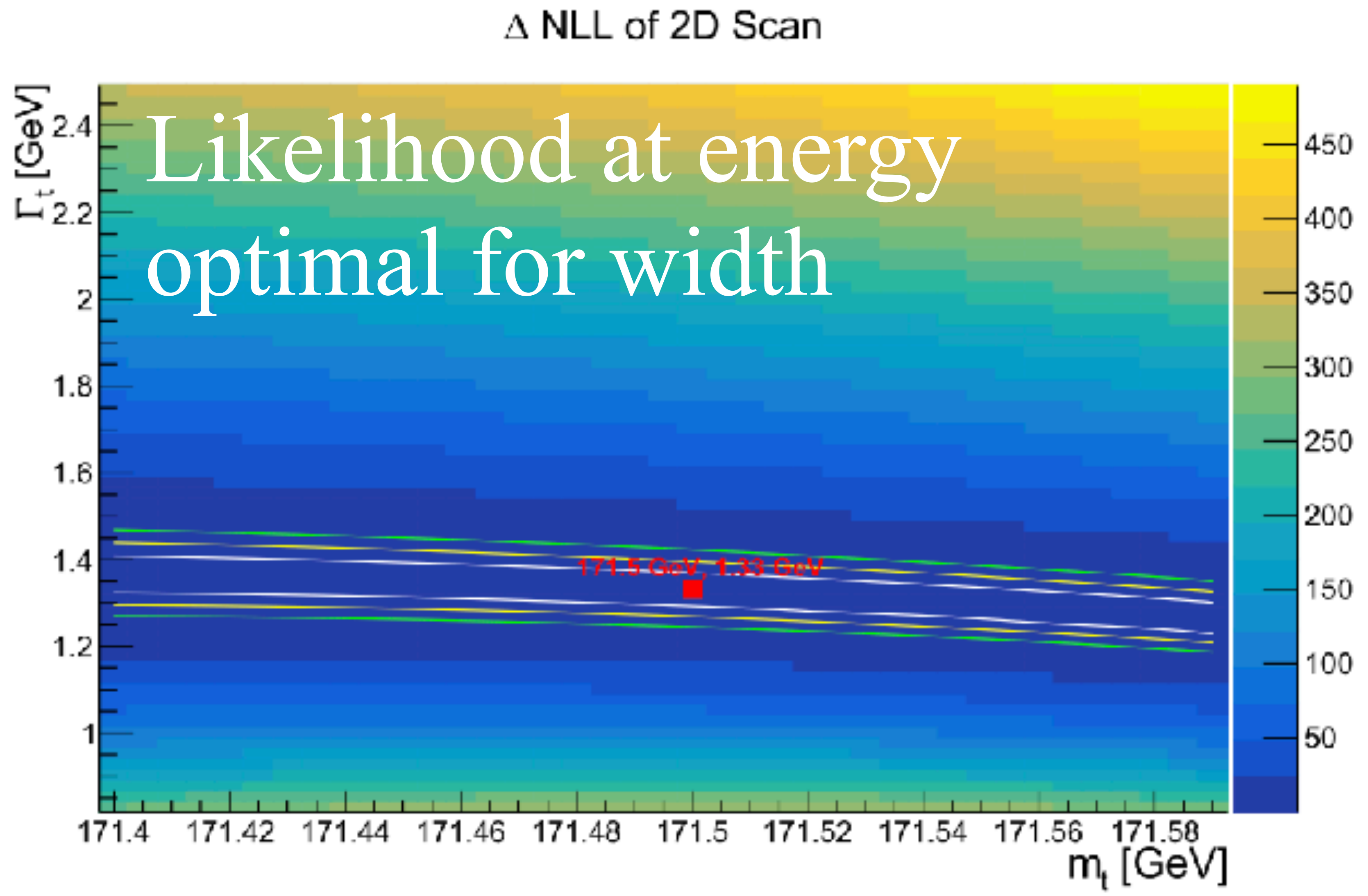
2D scans for m_{top} vs width

- 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

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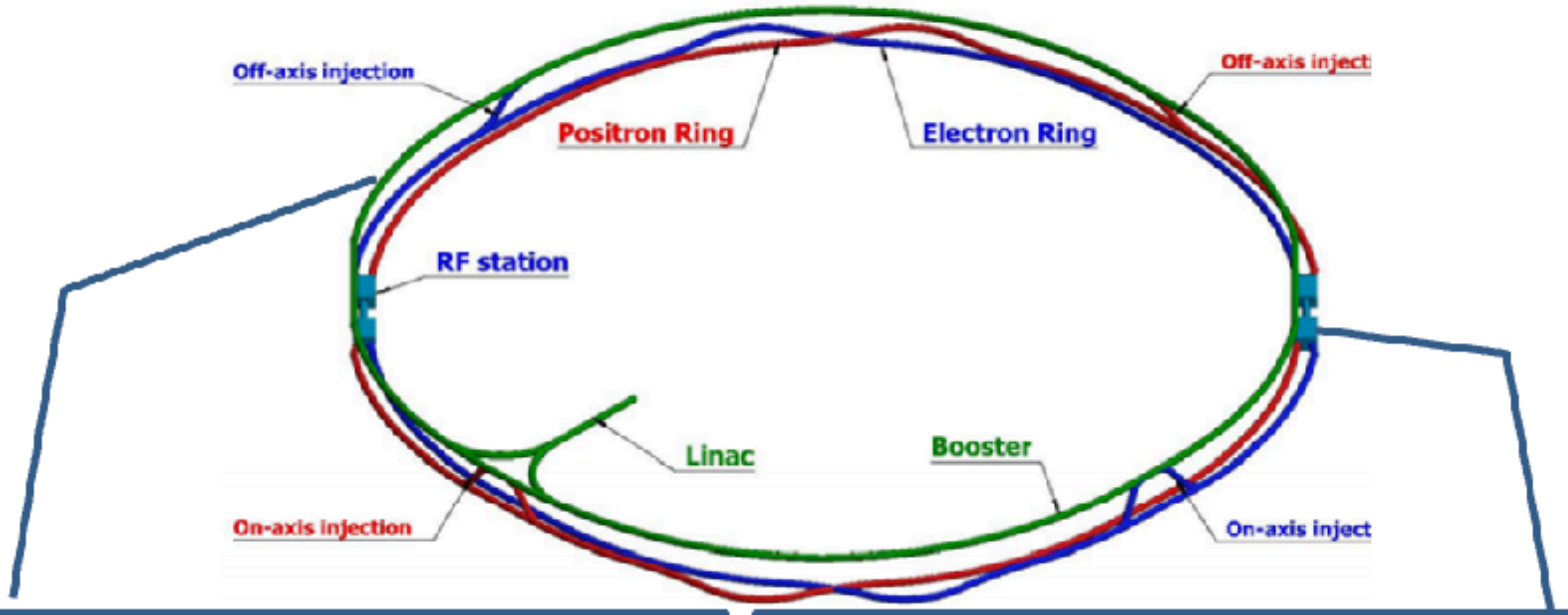
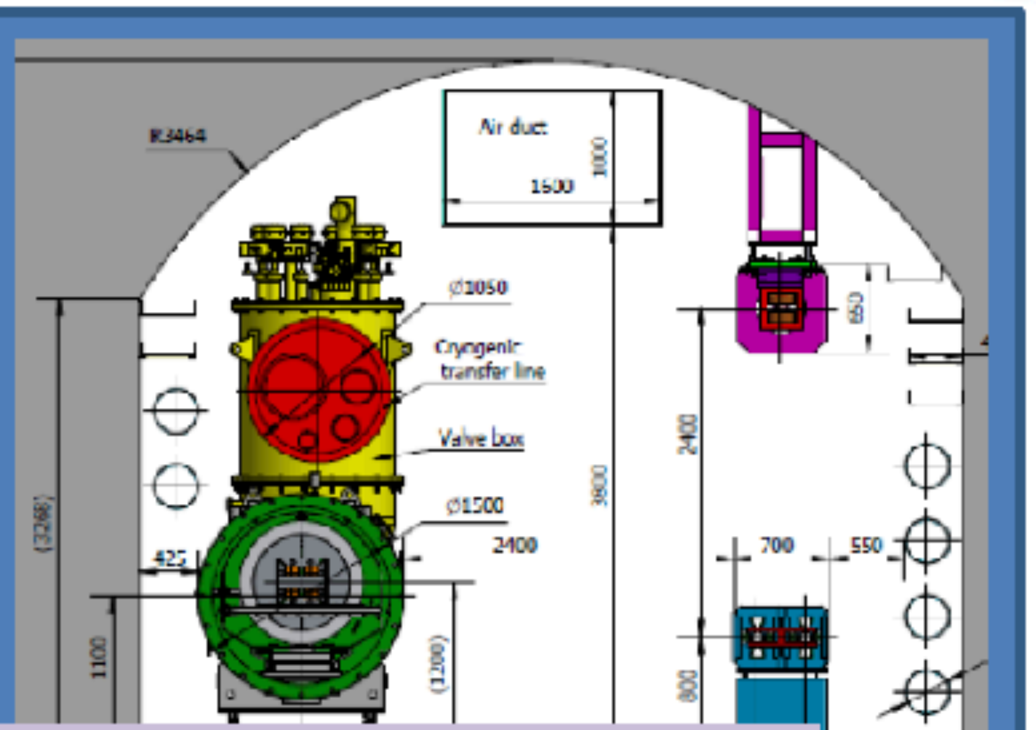
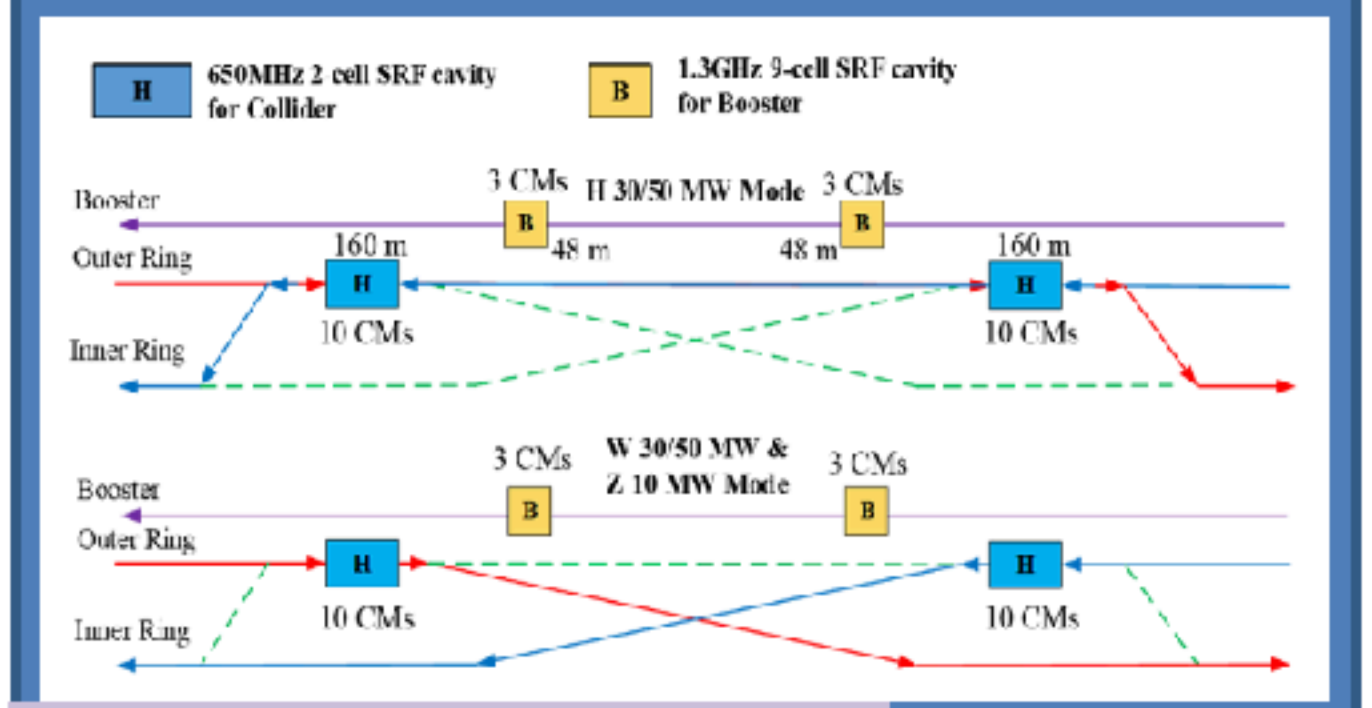
Design of experimental facility

- **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



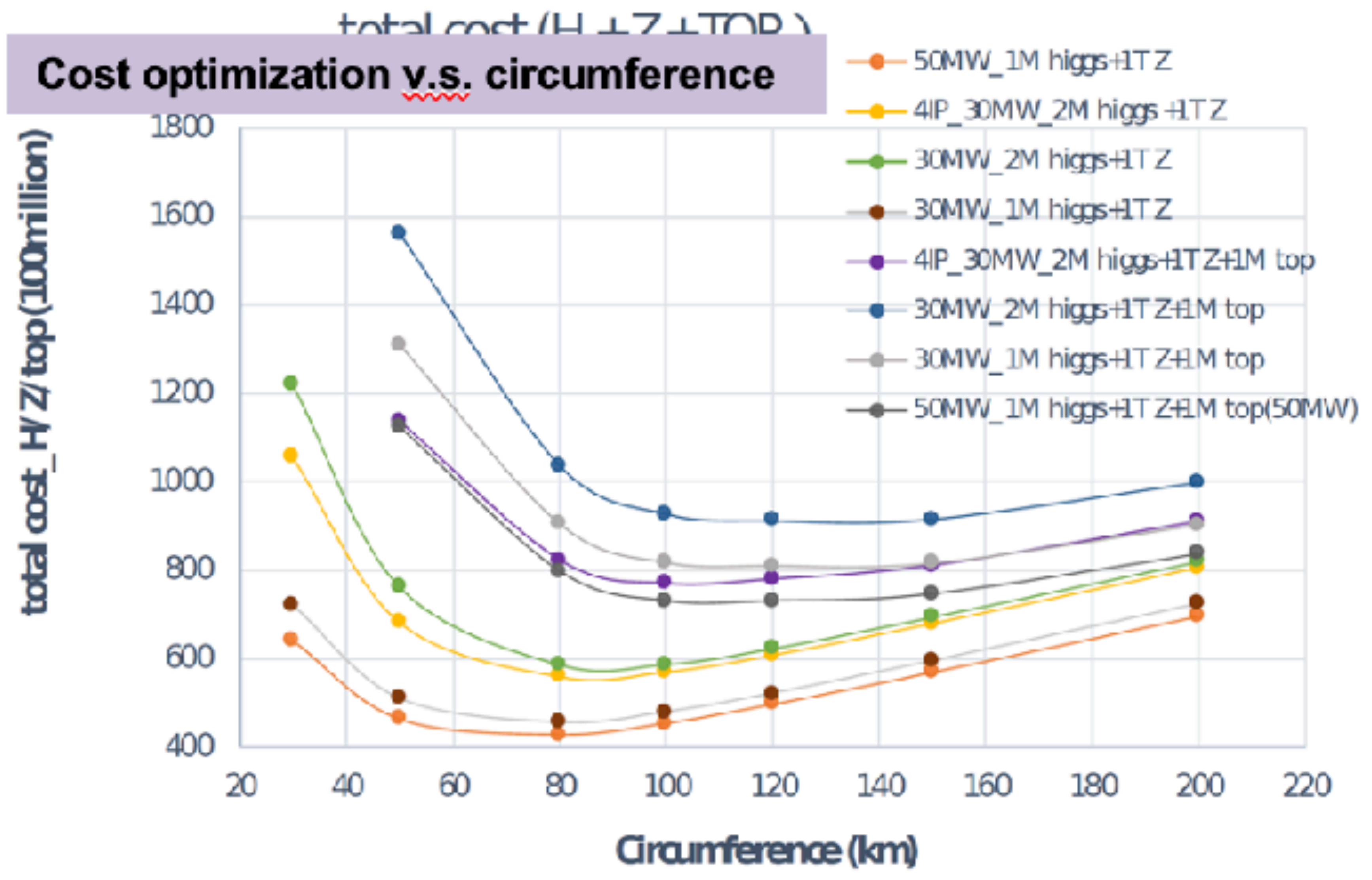


Common tunnel for booster/collider & SppC



Compatible Operation for Higgs W and Z

Cost optimization v.s. circumference



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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}/cm²/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**

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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

Source	m_{top} precision (MeV) Optimistic	Conservative
Statistical	7	7
Theory	8	24
Quick scan	2	2
α_S	3	16
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- 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 also 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 $200fb^{-1}$

error source	Δm_t^{PS} [MeV]	For FCC-ee
stat. error (200 fb^{-1})	13	9 (compressed scan)
theory (NNNLO 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	

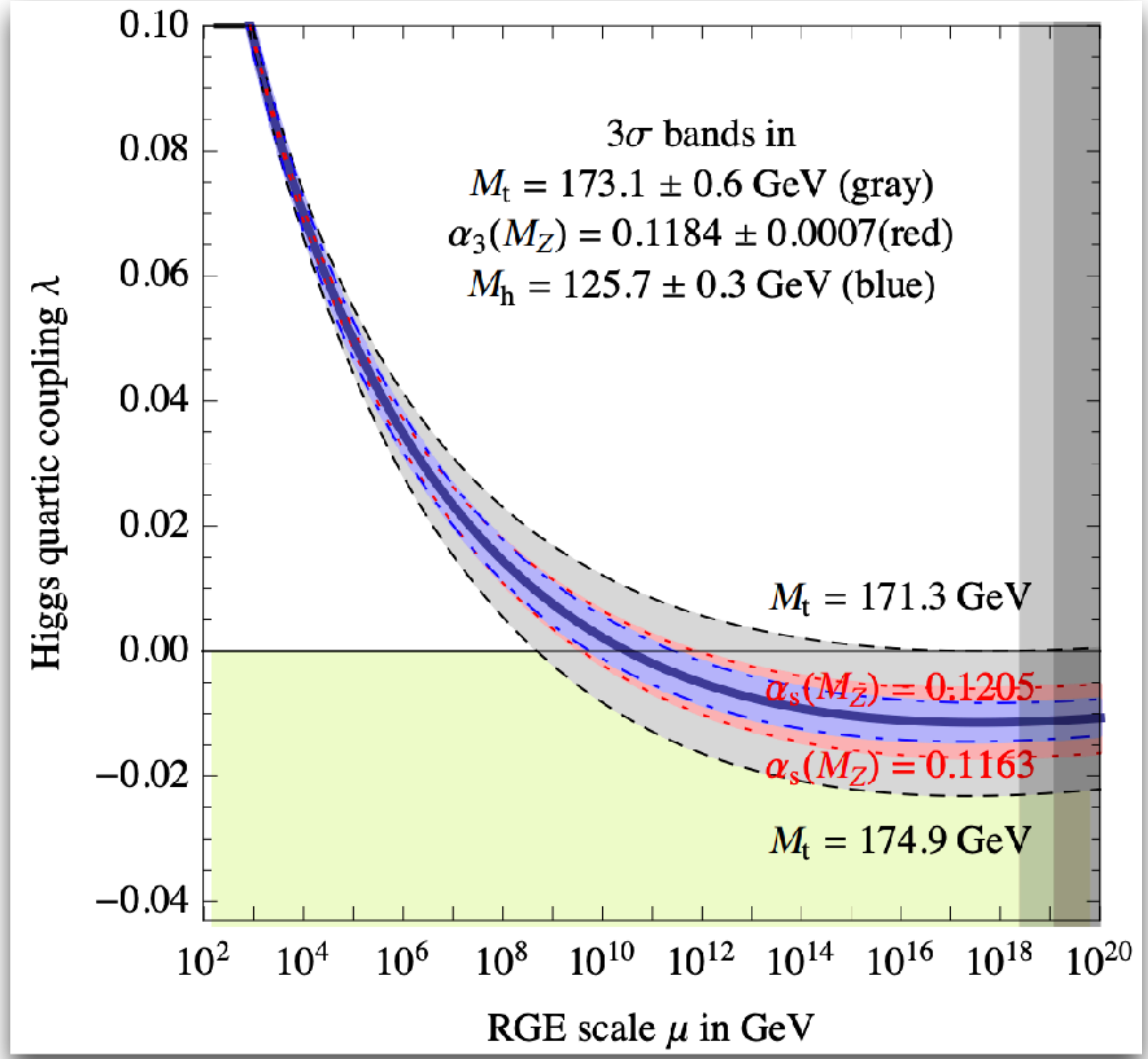
FCC-ee 2025

Uncertainty source	m_t^{PS} [MeV]	Γ_t [MeV]	Input values	CEPC studies
Experimental (stat. ×1.2)	4.3	10.4	$L = 410\,fb^{-1}$ (FCC-ee)	100/fb
Parametric y_t	4.2	3.6	$\delta y_t = 3\%$	
Parametric α_S	2.2	1.7	$\delta\alpha_S(m_Z^2) = 10^{-4}$	Similar 0.0001, 0.0007
Luminosity calibration (uncorr.)	0.5	1.0	$\delta L/L = 0.1\%$	
Luminosity calibration (corr.)	0.4	0.4	$\delta L/L = 0.05\%$	
Beam energy calibration (uncorr.)	1.2	1.8	$\delta\sqrt{s} = 5\,MeV$ [36, 37]	Similar
Beam energy calibration (corr.)	1.2	0.1	$\delta\sqrt{s} = 2.5\,MeV$	
Beam energy spread (uncorr.)	0.3	0.8	$\delta\Delta E = 1\%$ [36]	
Beam energy spread (corr.)	0.1	1.1	$\delta\Delta E = 0.5\%$	
Total profiled	6.8	11.5		
Theory, unprofiled (scale)	35	25	N^3LO NR-QCD [11]	1%, 3%

2503.18713

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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