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

CEPC DAY (June 21st, 2023)

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on behalf of
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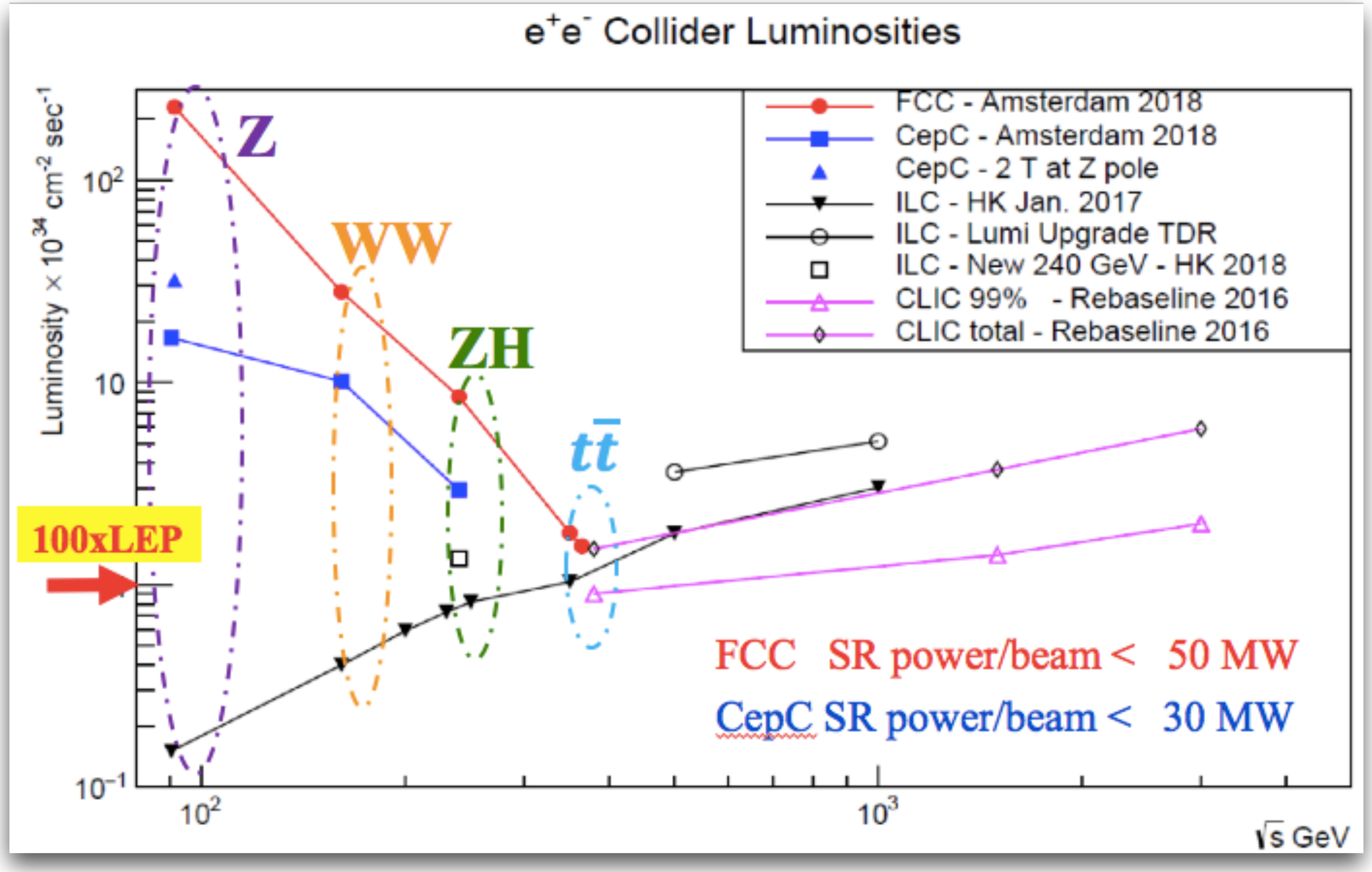
Reference: Eur. Phys. J. C (2023) 83:269

# Introduction

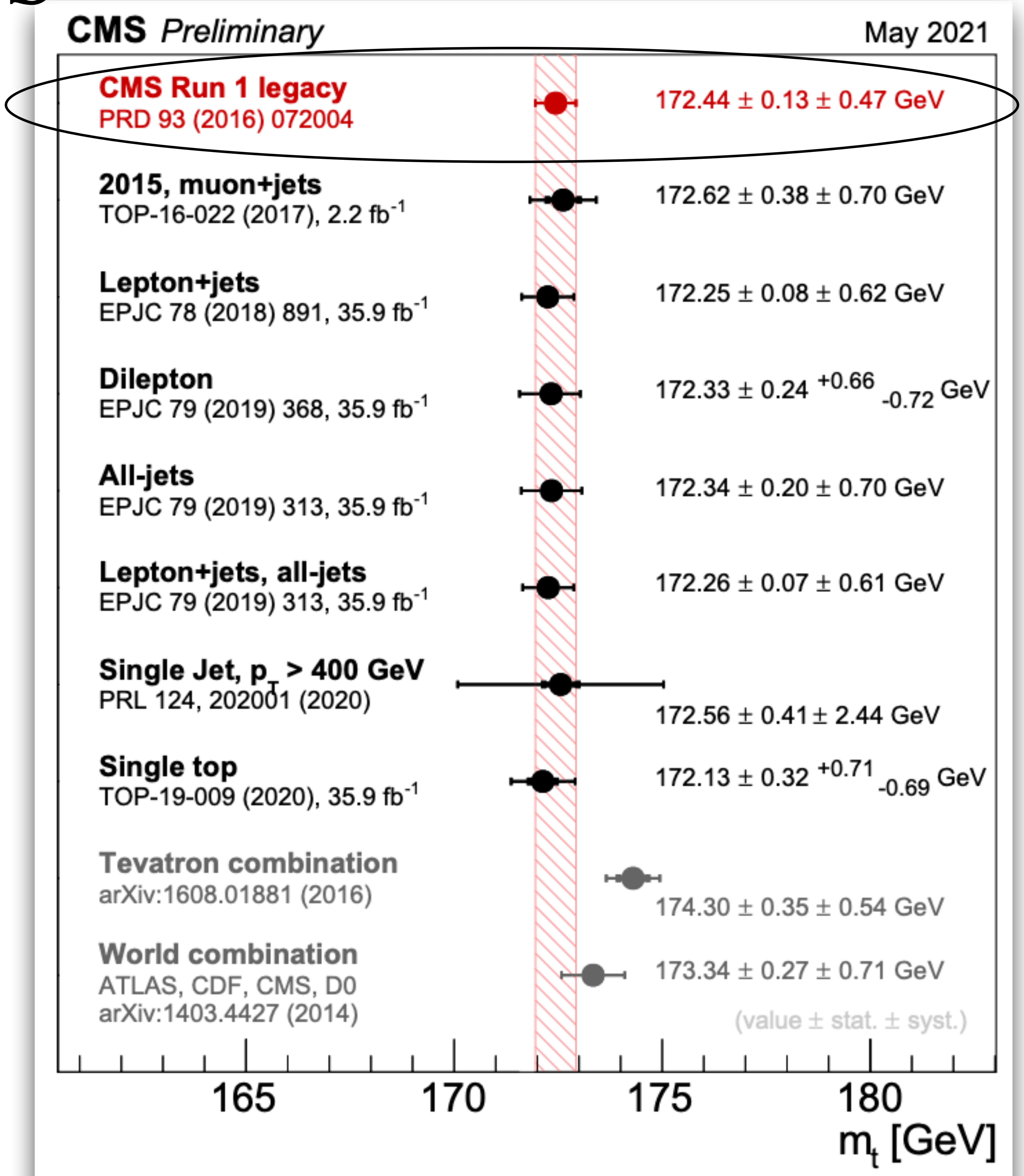
- CEPC will be a versatile machine with many opportunities
  - Higgs factory @~240 GeV
  - Diboson factory @~160 GeV
  - Z factory @~90 GeV
- @~360 GeV it can also be a playground for
  - Top precision measurements
  - Higgs complementary measurements
  - BSM searches



F. Bedeschi

# Top mass measurements

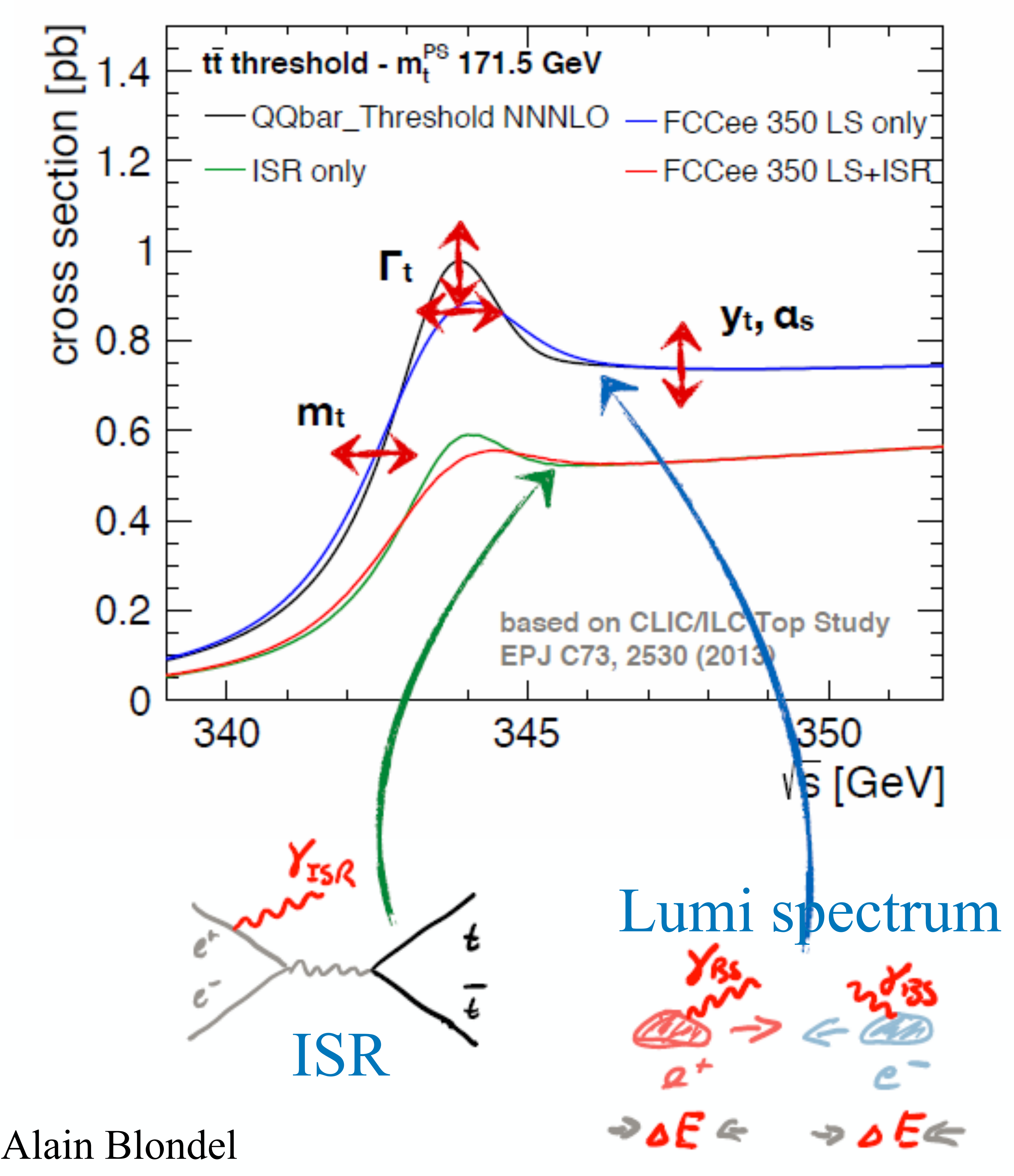
- The top mass is measured using top reconstruction at hadron colliders
  - Heavily relies on the performance of MET (the neutrino) and jet energy scale/resolution uncertainties
- CMS Run1 combined uncertainty reached ~500 MeV dominated by systematic uncertainties
- Very difficult to further improve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



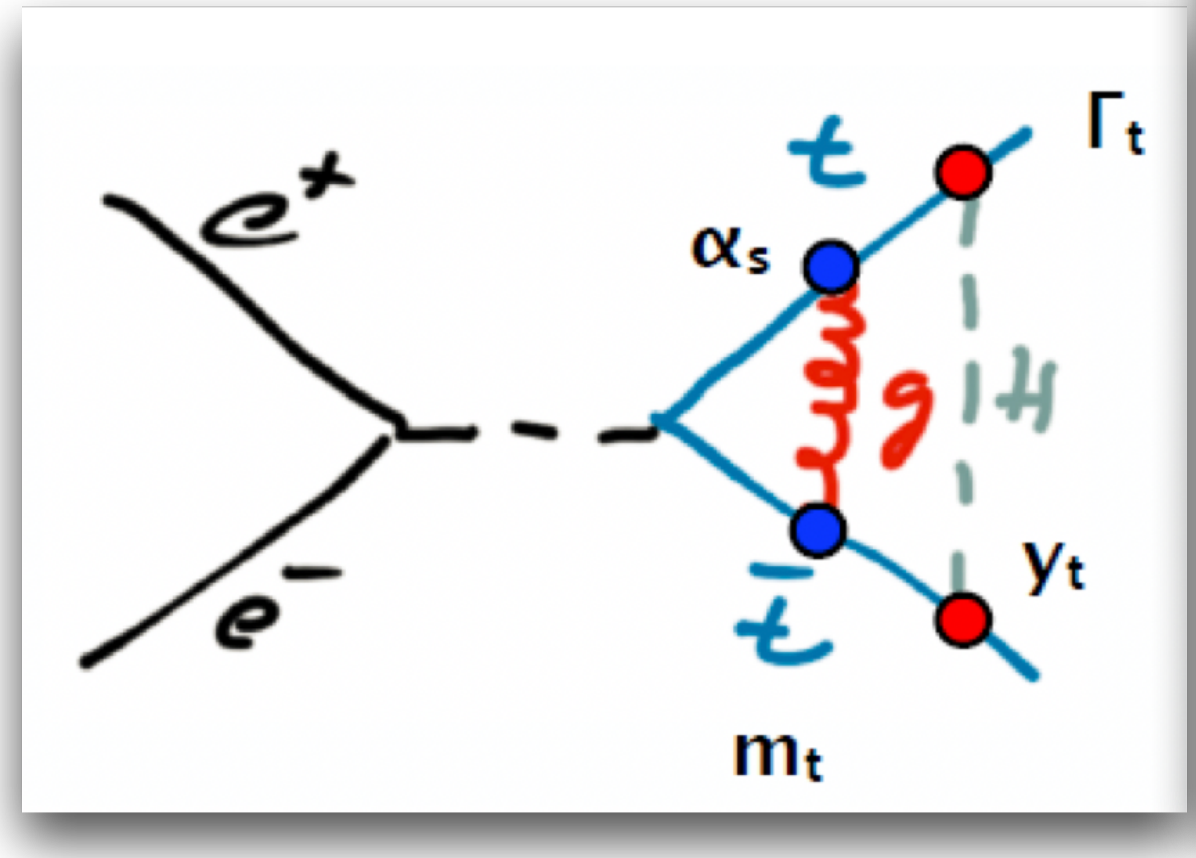
# tt threshold scan

- 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 bunch of other parameters
  - Top width
  - Top Yukawa coupling
  - $\alpha_S$

EPJC 73,(2013)2530



Alain Blondel



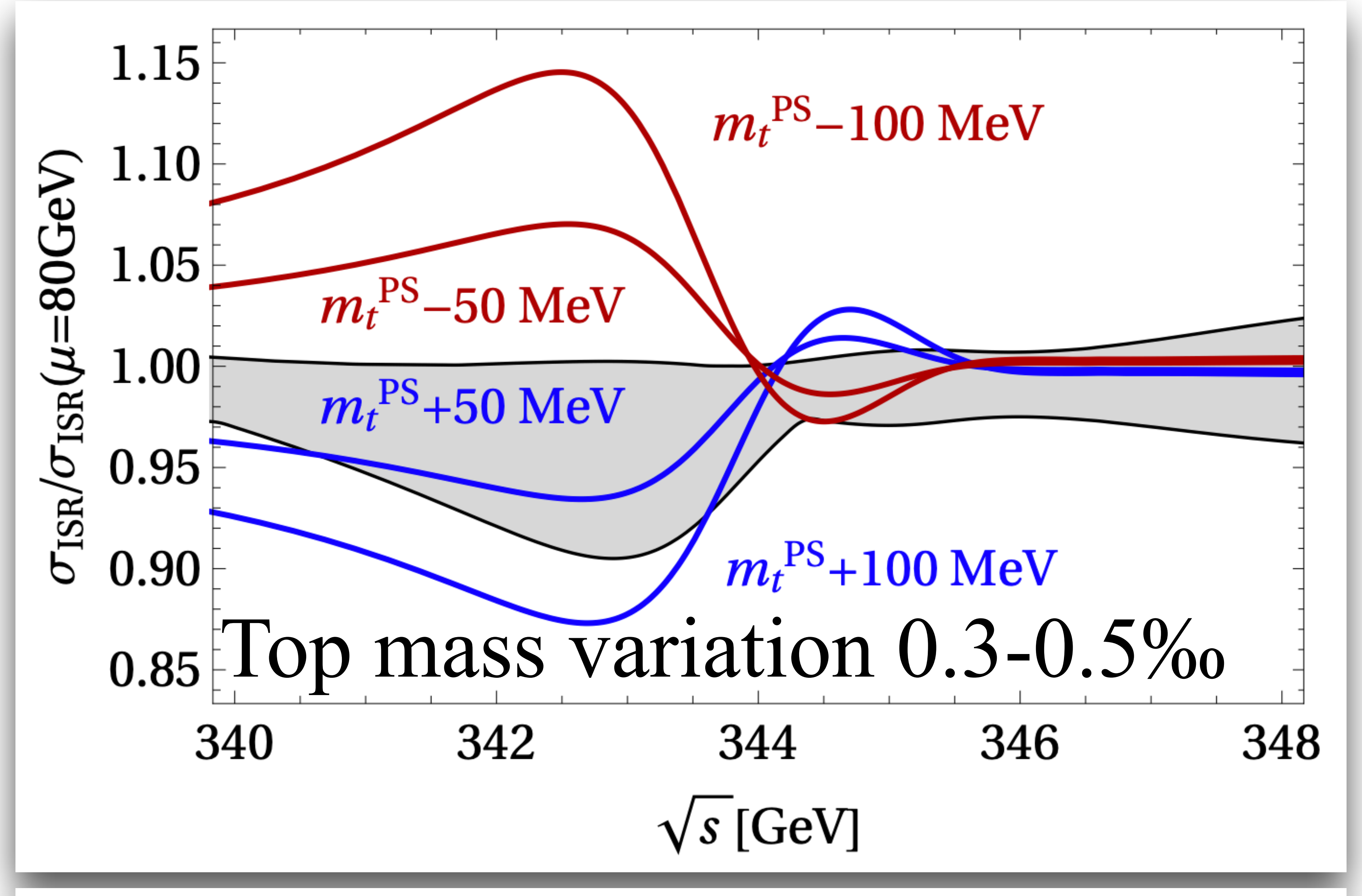
# Our setup

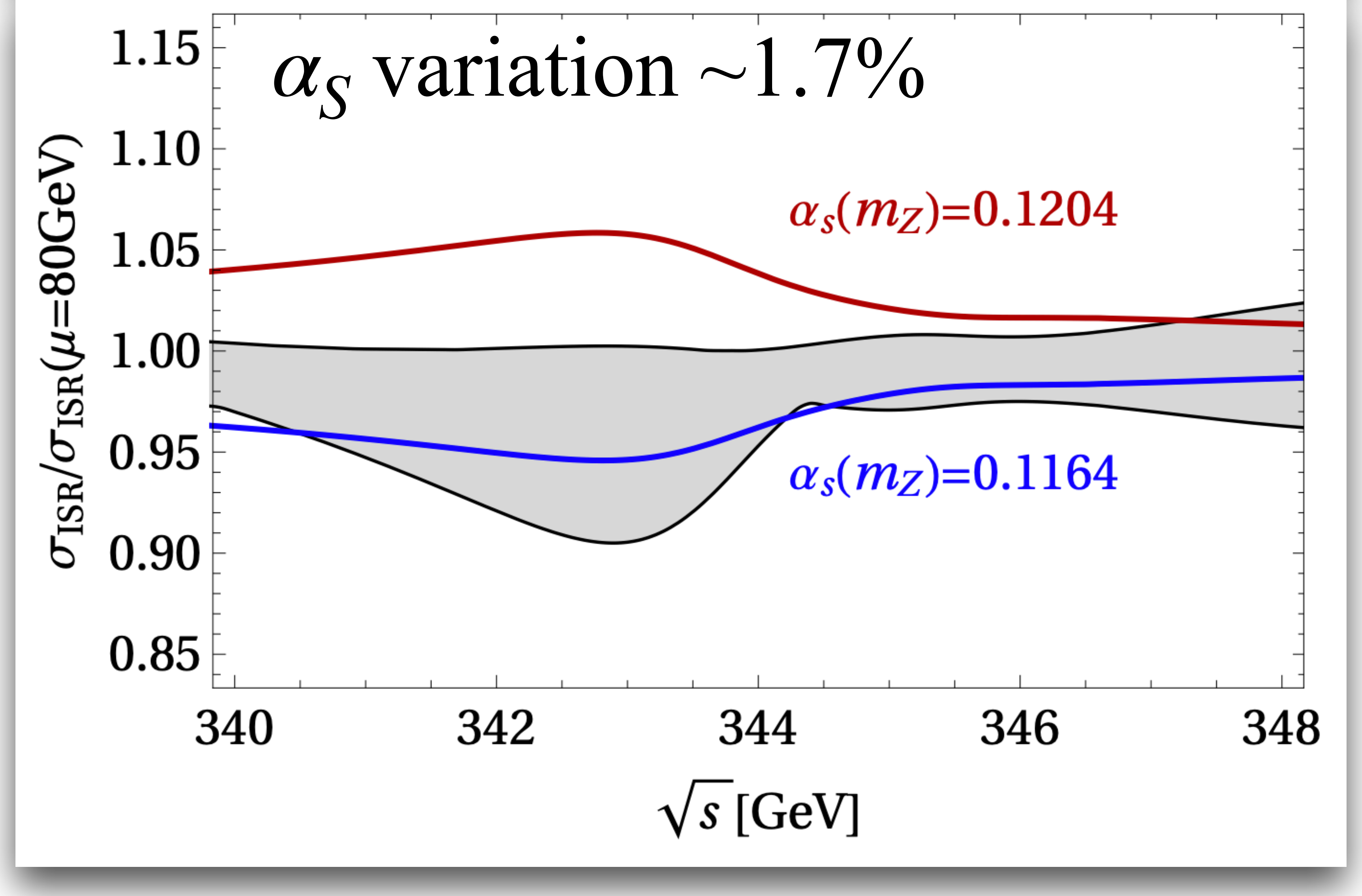
Comput. Phys. Commun. 209 (2016) 96-115
JHEP 1802 (2018) 125

- Use the package "QQbar_threshold" to calculate cross-section near threshold in ee-colliders at N$^3$LO 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

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

  - 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 $\sqrt{s}$



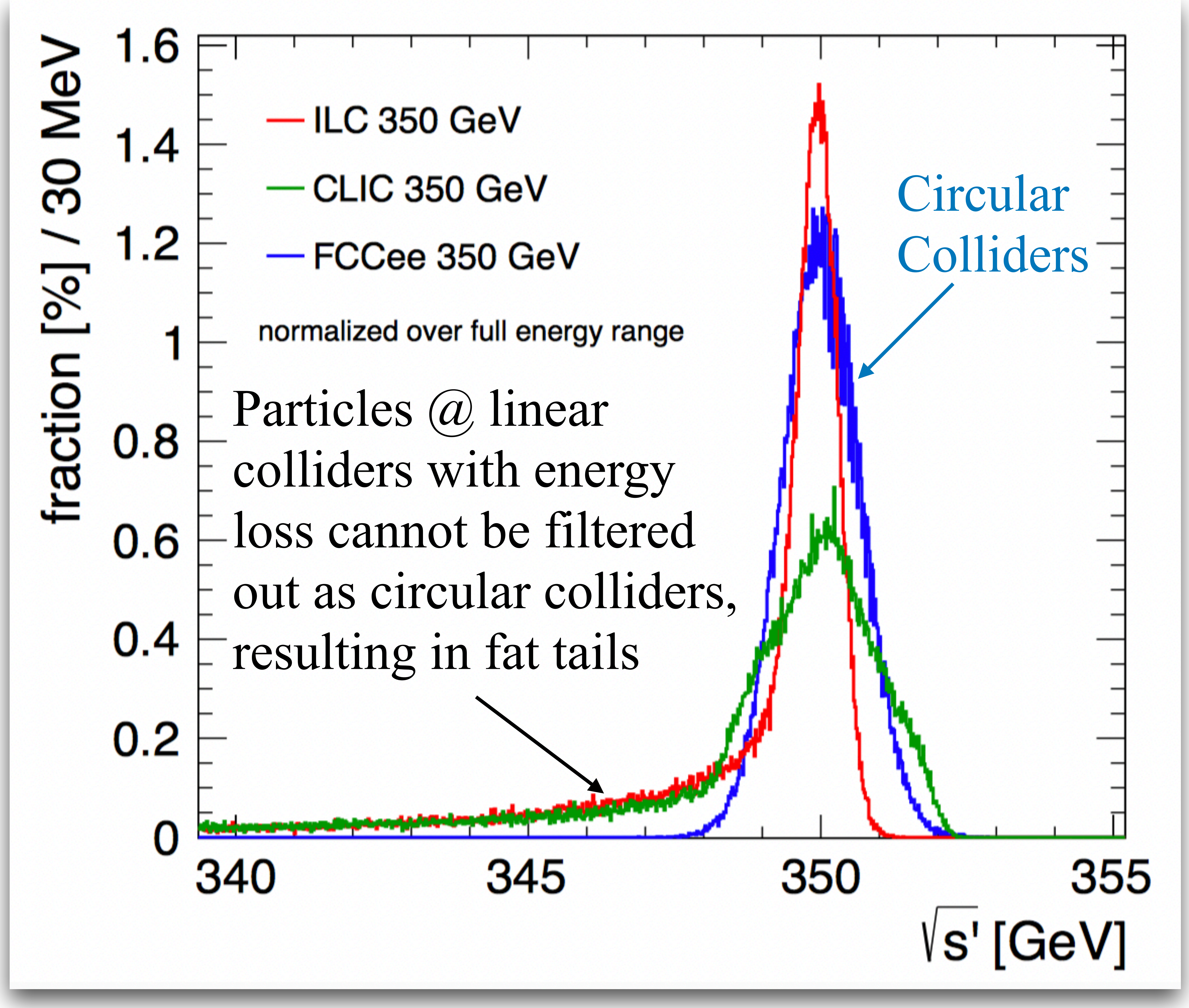


# Advantages from circular colliders

- 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

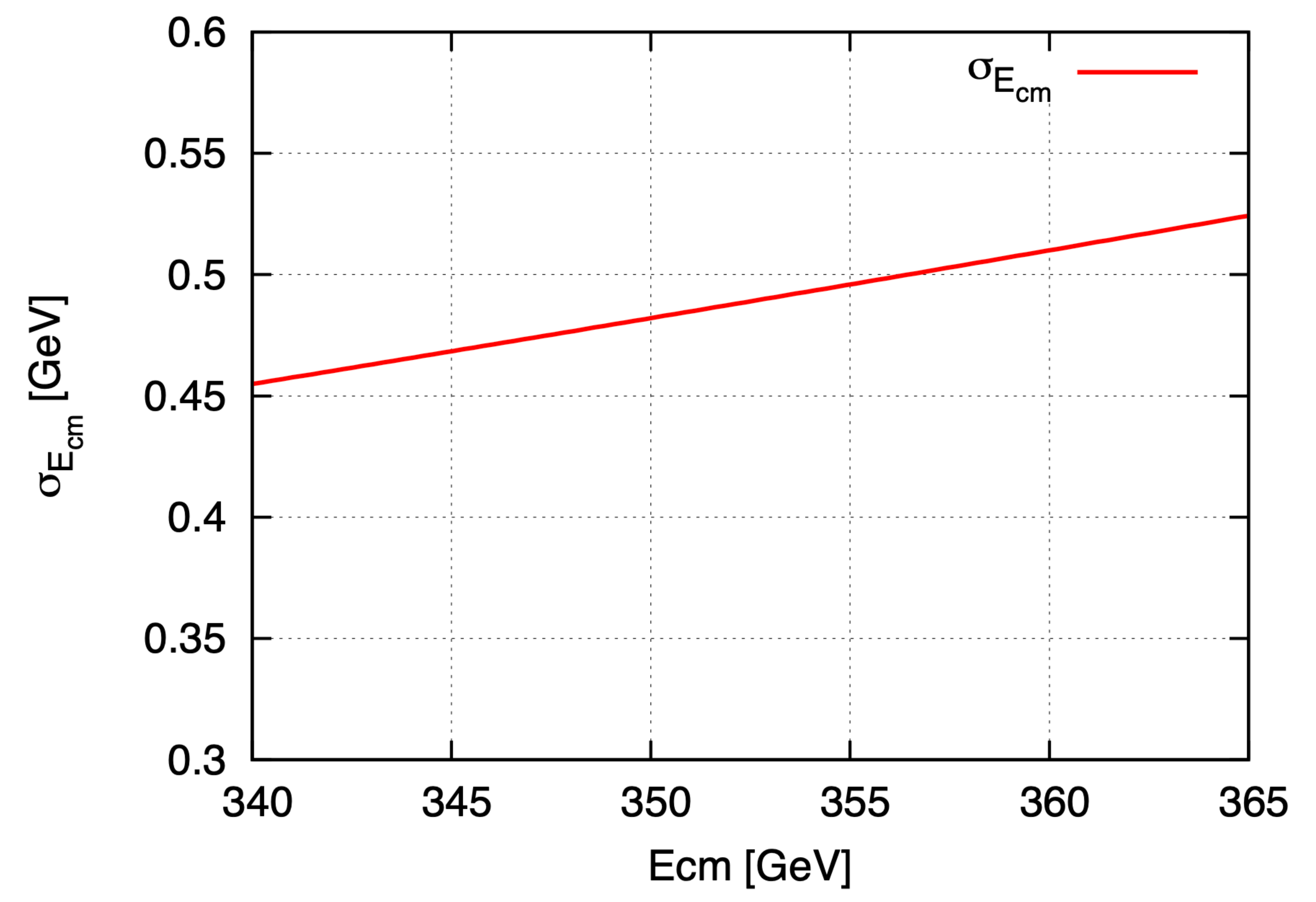
EPJC 73,(2013)2530

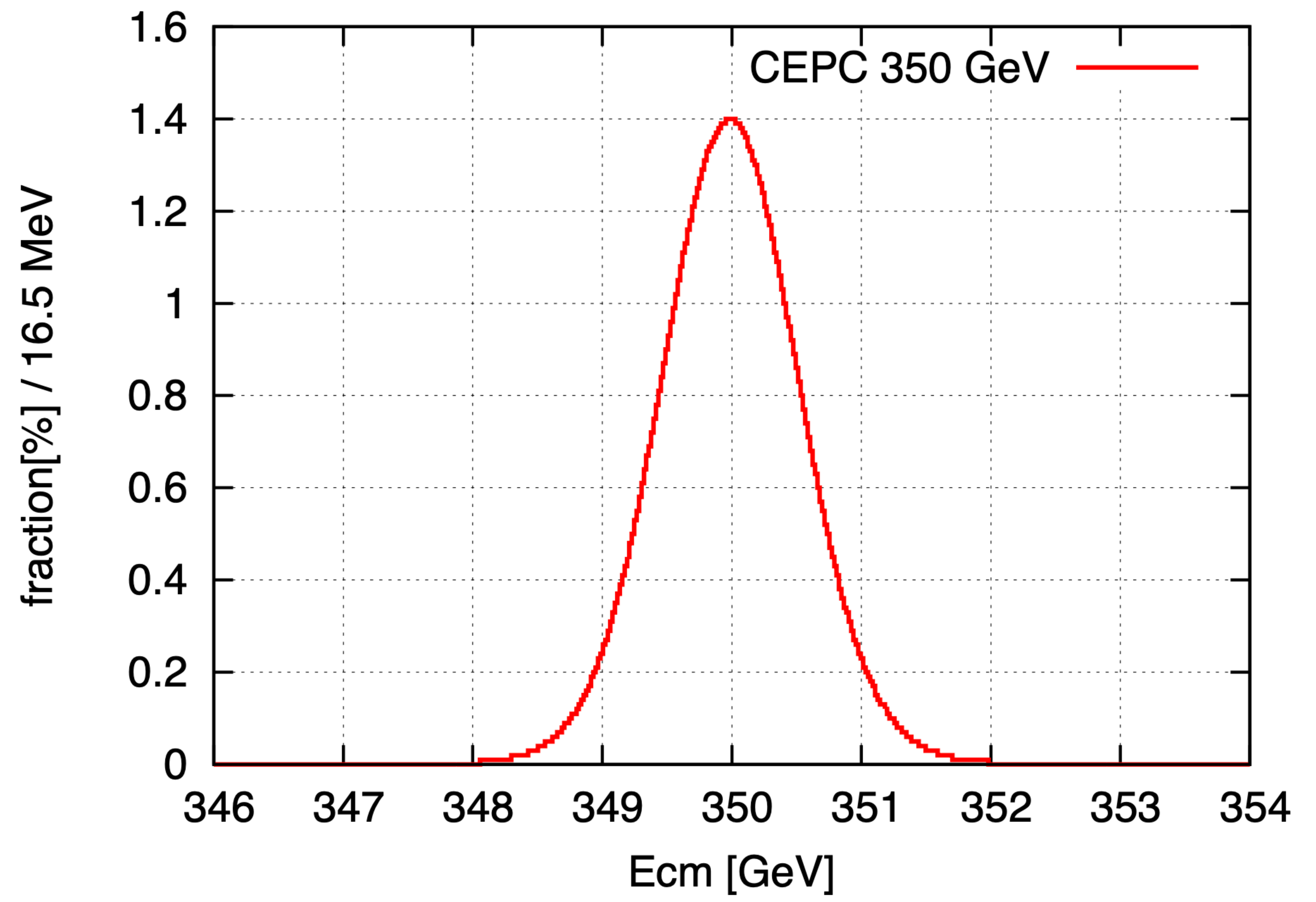


Circular Colliders

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

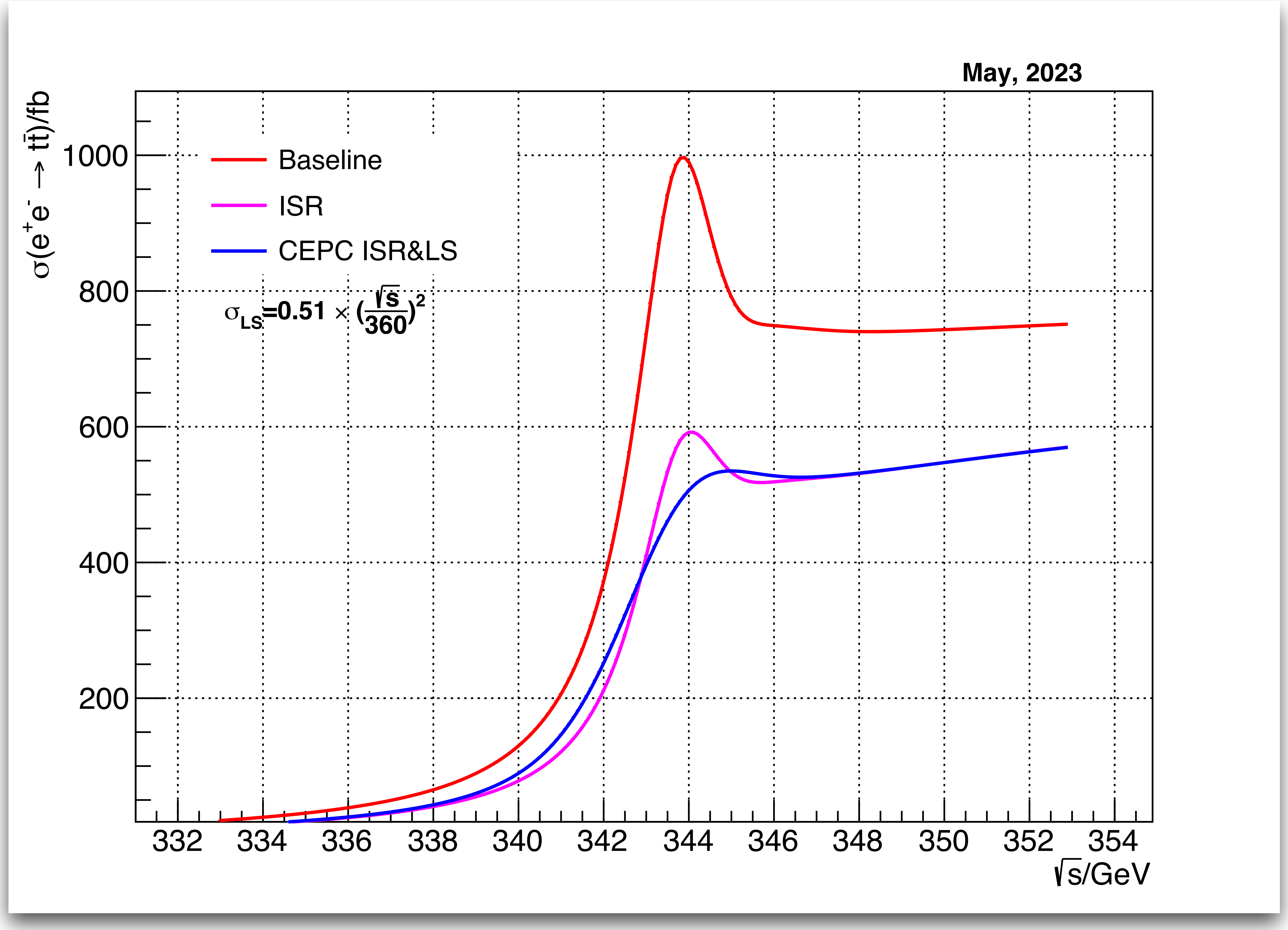
# Luminosity spectrum @ CEPC



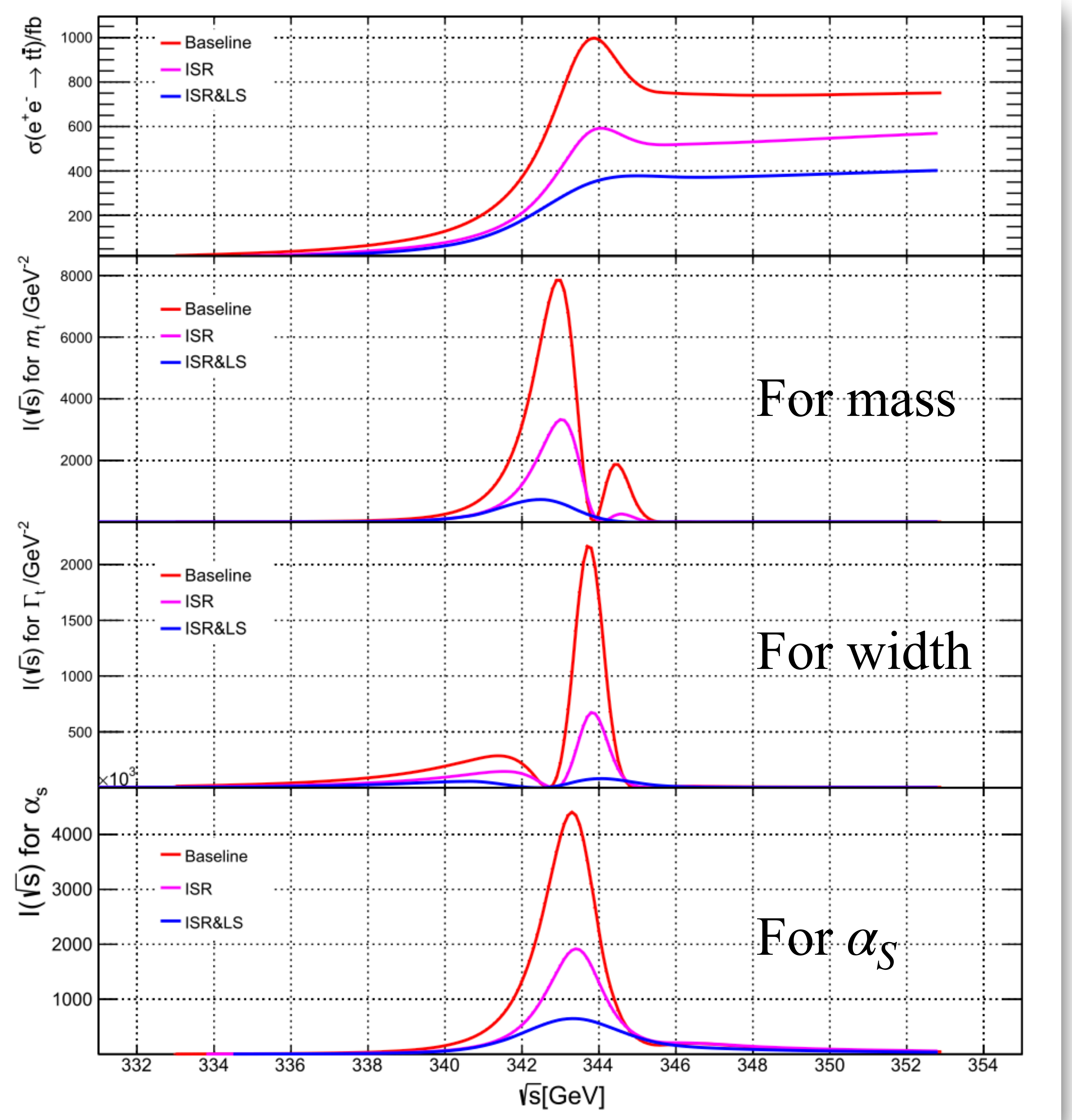


- The beam energy resolution increases as a function of $\sqrt{s}$
- The luminosity spectrum is shown for $\sqrt{s} = 350$ GeV with a width of ~480 MeV
- Similar to the FCC-ee scenario

# tt threshold with CEPC



# Fisher information to get the sensitive energy points



- Around the tt threshold, we need to identify the energy point(s) that contain(s) the most sensitivity
- Construct Fisher information is used to locate the energy point(s)

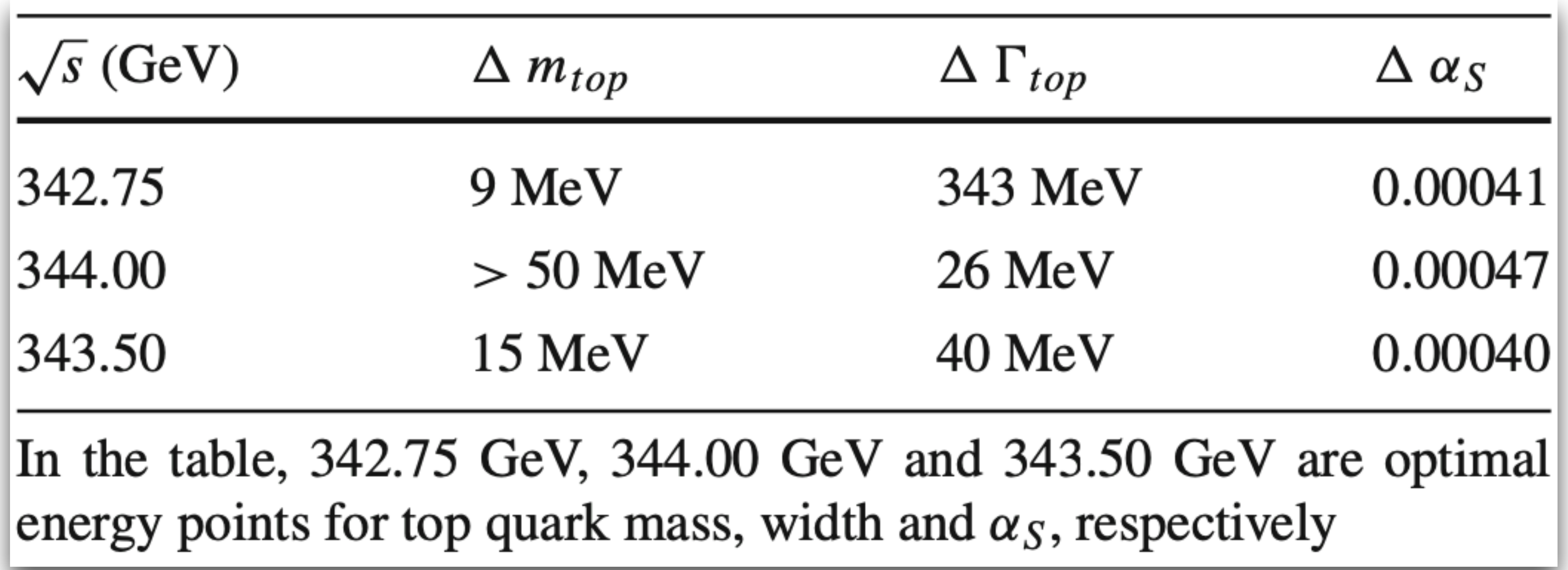
$$I(\sqrt{s}) = \int \left( \frac{\partial log(G(\sigma|\sigma_0(\sqrt{s},\theta), \sqrt{\sigma_0(\sqrt{s},\theta)}))}{\partial\theta} \right)^2$$

$$\times G(\sigma|\sigma_0(\sqrt{s},\theta), \sqrt{\sigma_0(\sqrt{s},\theta)})d\sigma.$$

- 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 will 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 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 $\alpha_S$, respectively

# Uncertainties: statistics

| | Top mass uncertainties (MeV) | |
|---|---|---|
| | Optimistic | Conservative |
| Statistics | 9 | 9 |
| Theory | 8 | 24 |
| Quick scan | 2 | 2 |
| $\alpha_S$ | 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 |
| $\alpha_S$ | 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: $\alpha_S$ and width

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

- $\alpha_S$ and width are the inputs for this 1D top mass measurement
- $\alpha_S$ uncertainty is taken as 0.0007, while width is varied by 0.14 GeV (CMS constraint 2014)
- $\alpha_S$ 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 |
| $\alpha_S$ | 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 |
| $\alpha_S$ | 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 |
| $\alpha_S$ | 17 | 17 |
| Width | 10 | 10 |
| Experimental efficiency | 5 | 44 |
| Background | 2 | 14 |
| Beam energy | 2 | 2 |
| Luminosity spectrum | 3 | 6 |
| | | |
| Total | 24 | 57 |

- Luminosity spectrum (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
- 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 |
| $\alpha_S$ | 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 $\alpha_S$ are also of great interests

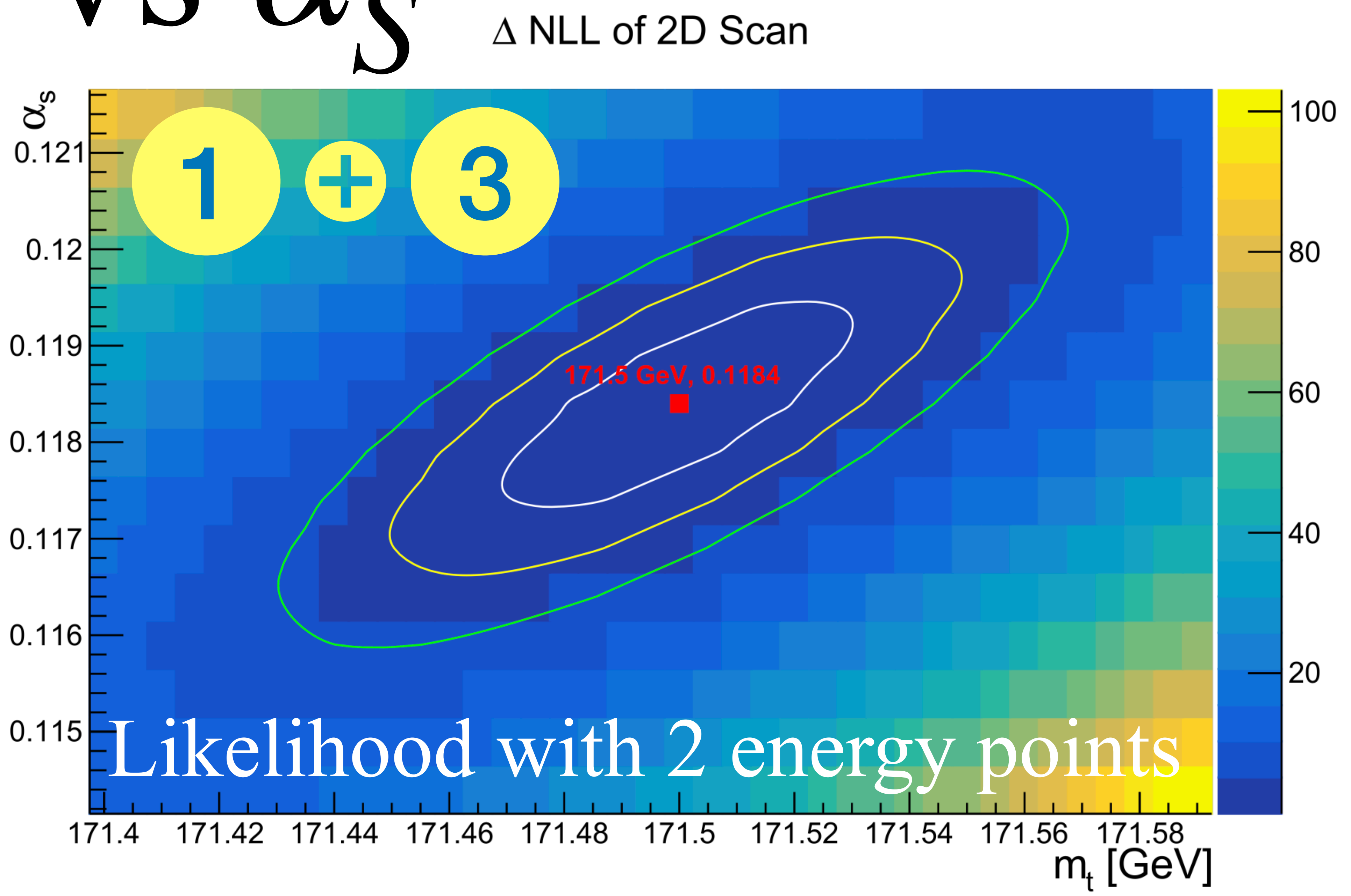
- We try to extract two parameters at a time with 2D scans
  - Besides the optimal energy point for top mass, one additional energy point is needed

- 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

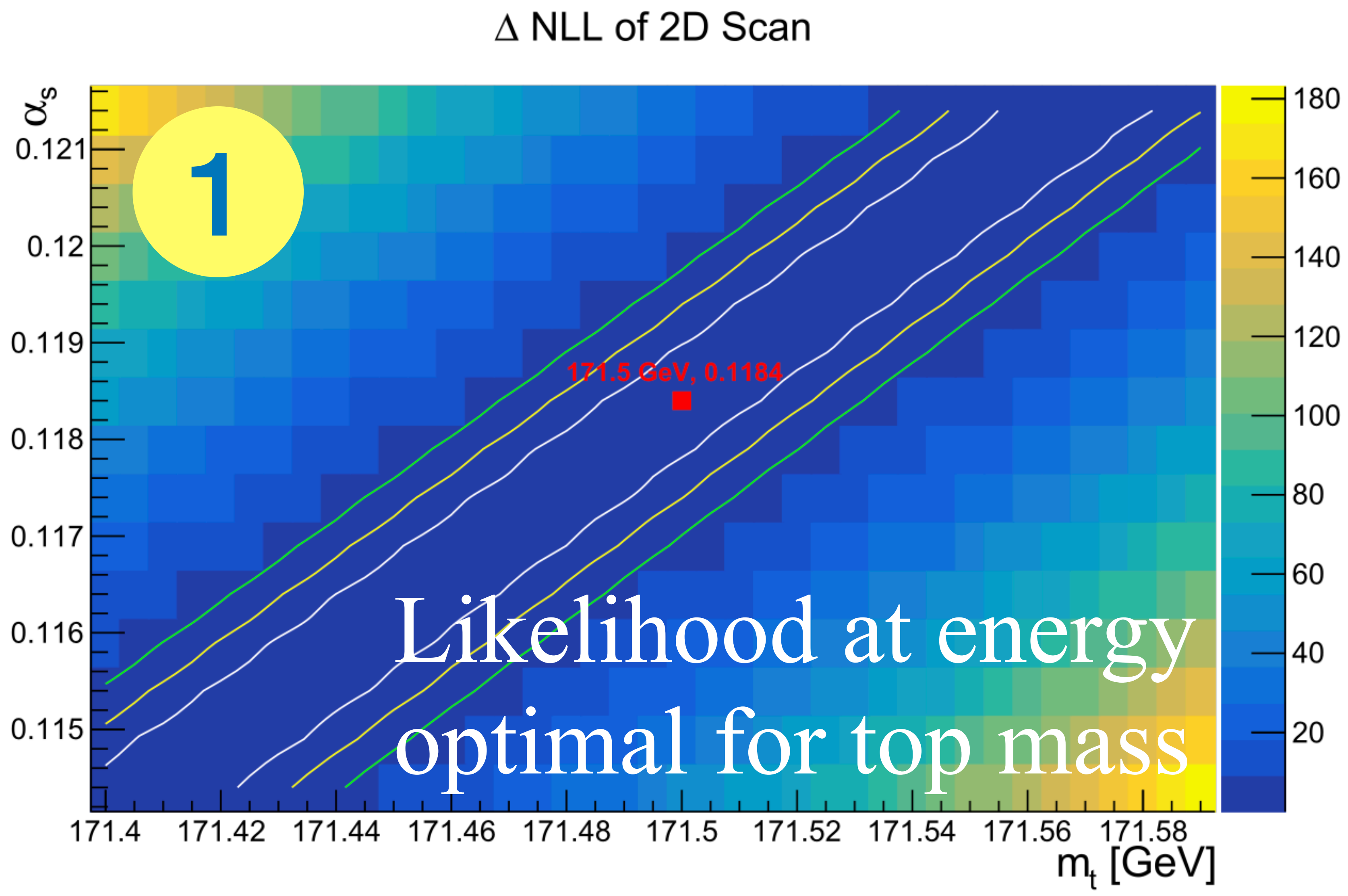
- Statistical-only studies are performed

# 2D scans for $m_{top}$ vs $\alpha_S$

- Ideally taking the two optimal energy points for top mass and $\alpha_S$ 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 $\alpha_S$ is taken. This introduces a different correlation and can close the contour (shown in 3)

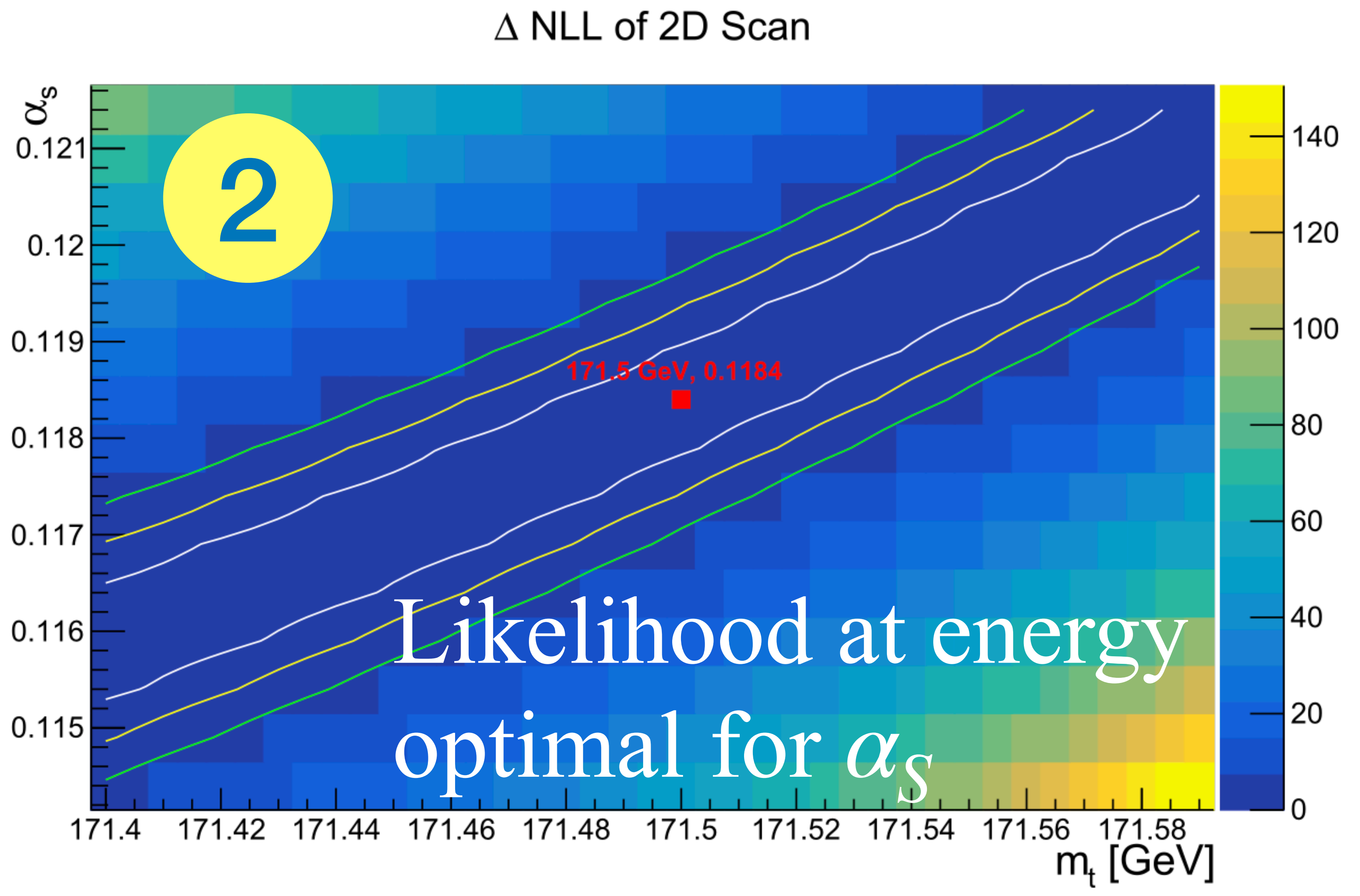


Likelihood with 2 energy points



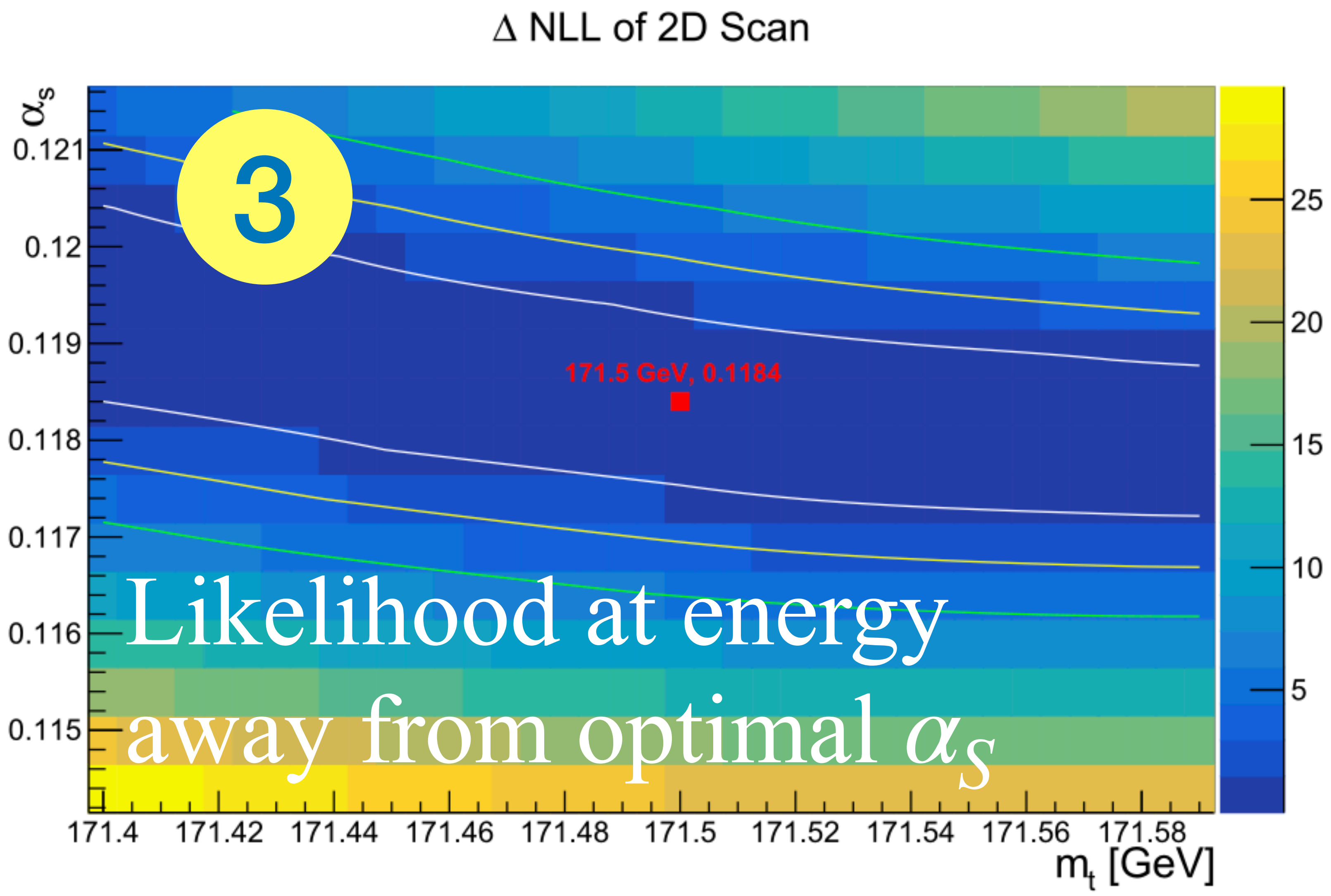
Likelihood at energy optimal for top mass

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



Likelihood at energy optimal for $\alpha_S$

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

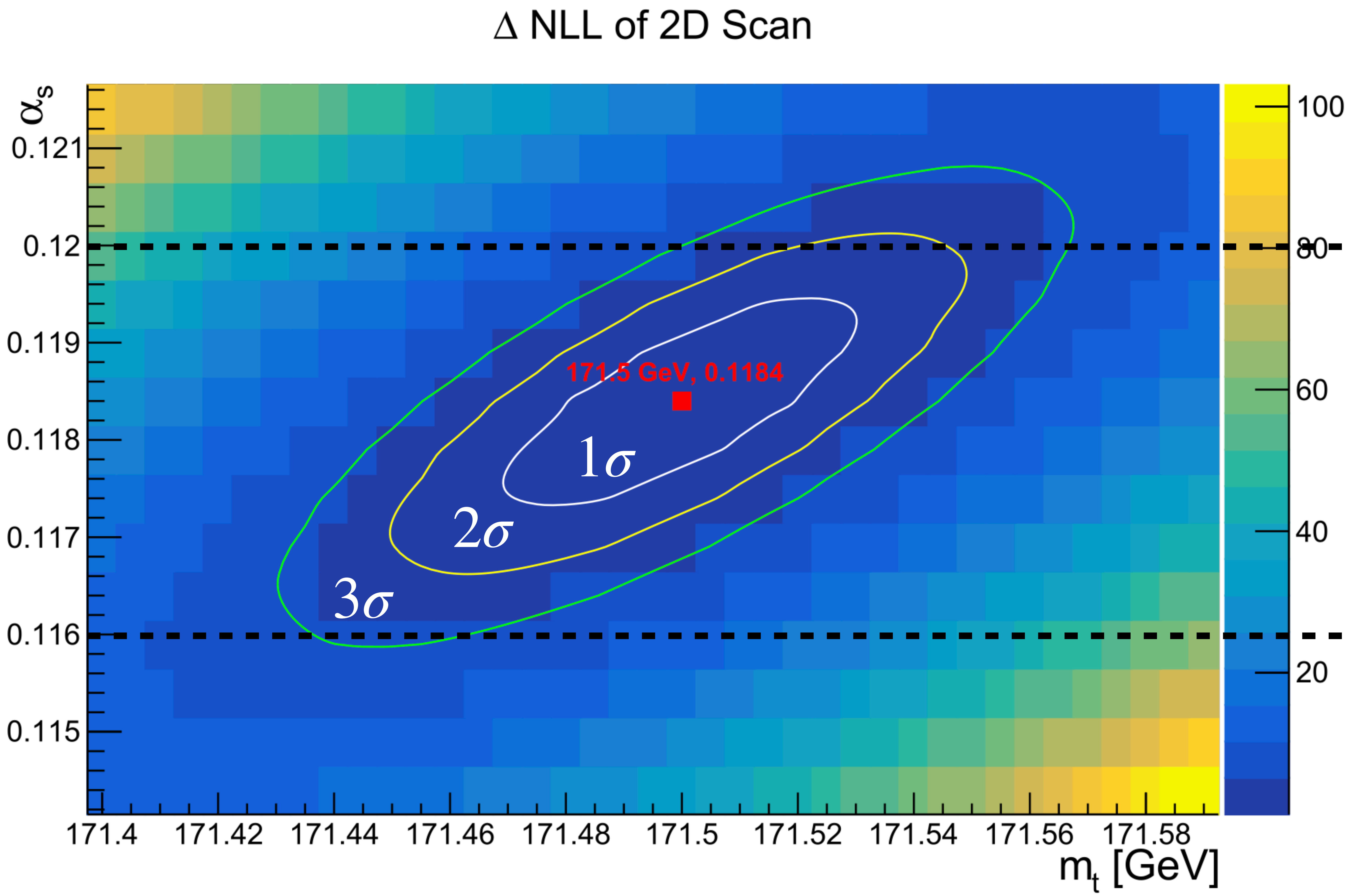


Likelihood at energy away from optimal $\alpha_S$

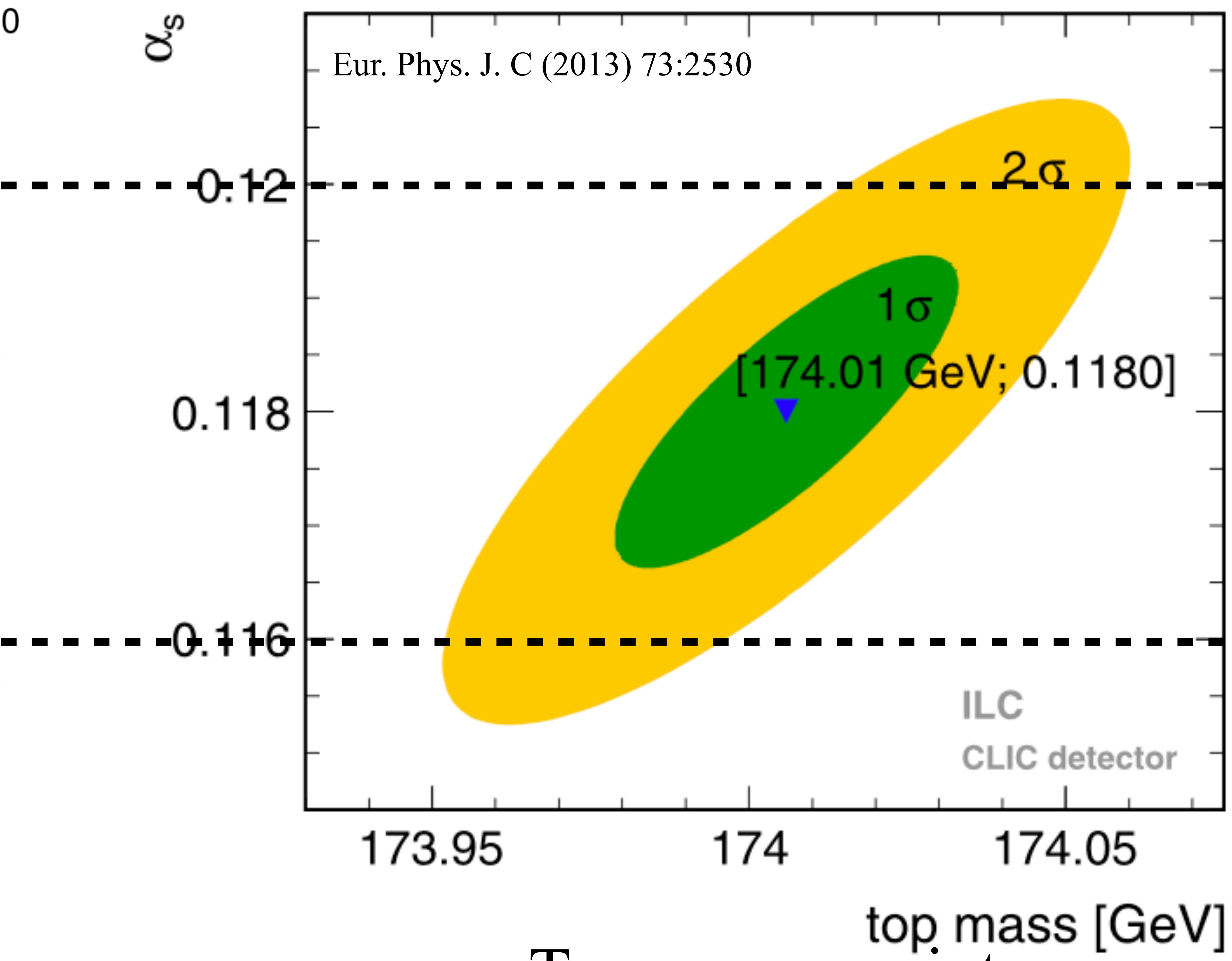
(f) $E_{\rm cm}$= 344.50 GeV

# 2D scans for $m_{top}$ vs $\alpha_S$

- A quick comparison to CLIC



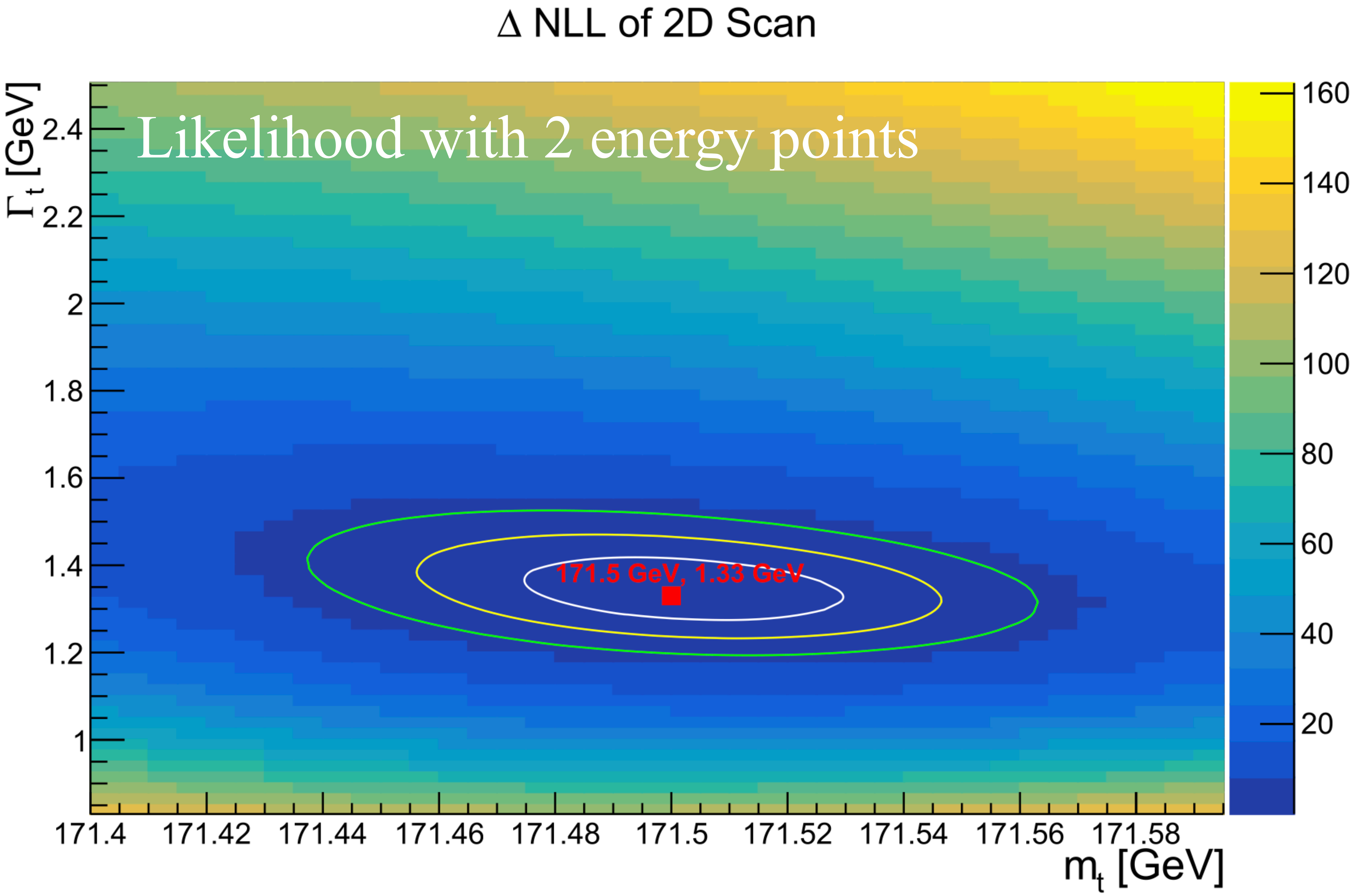
Two energy points



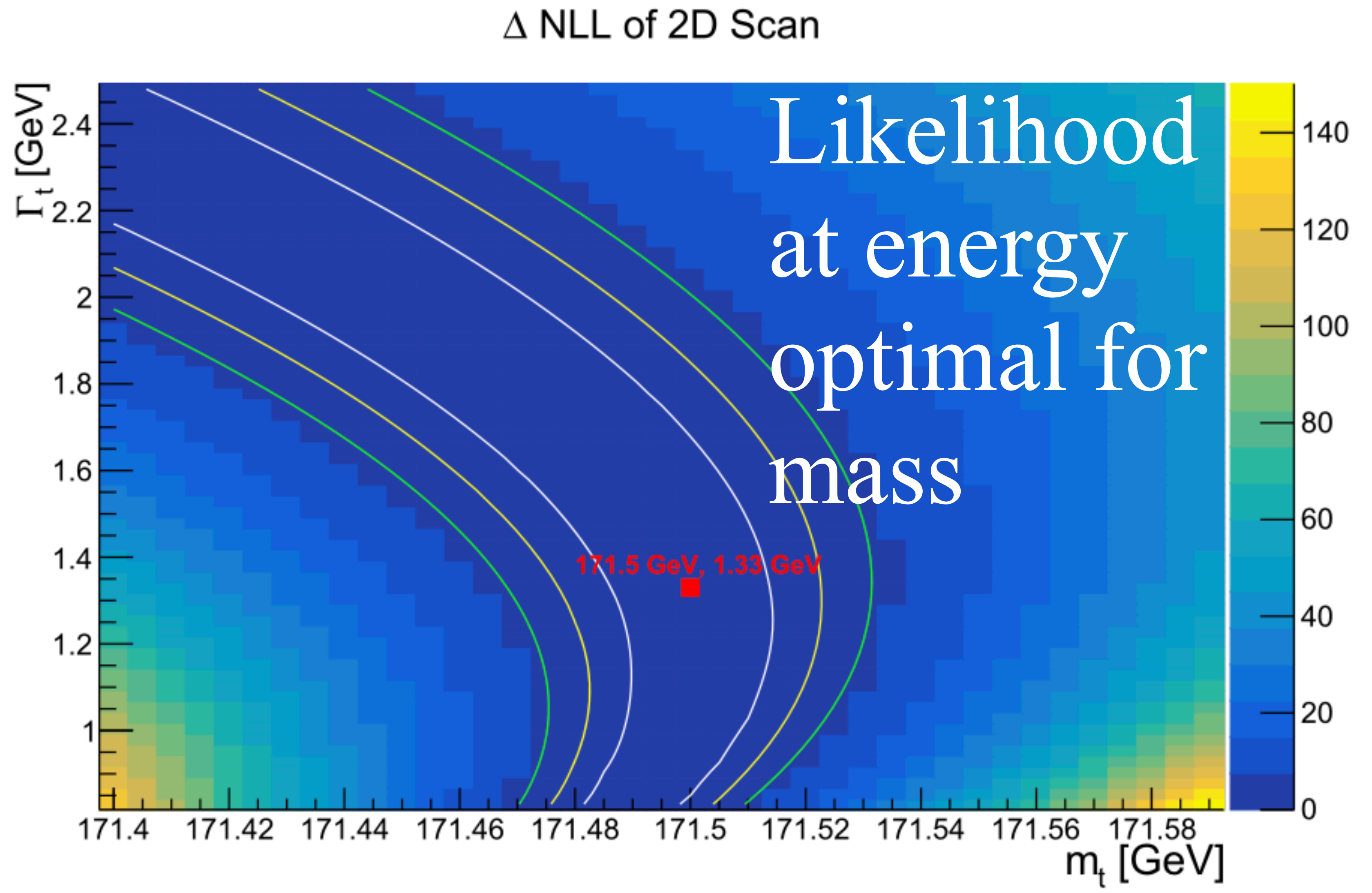
Ten energy points

# 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

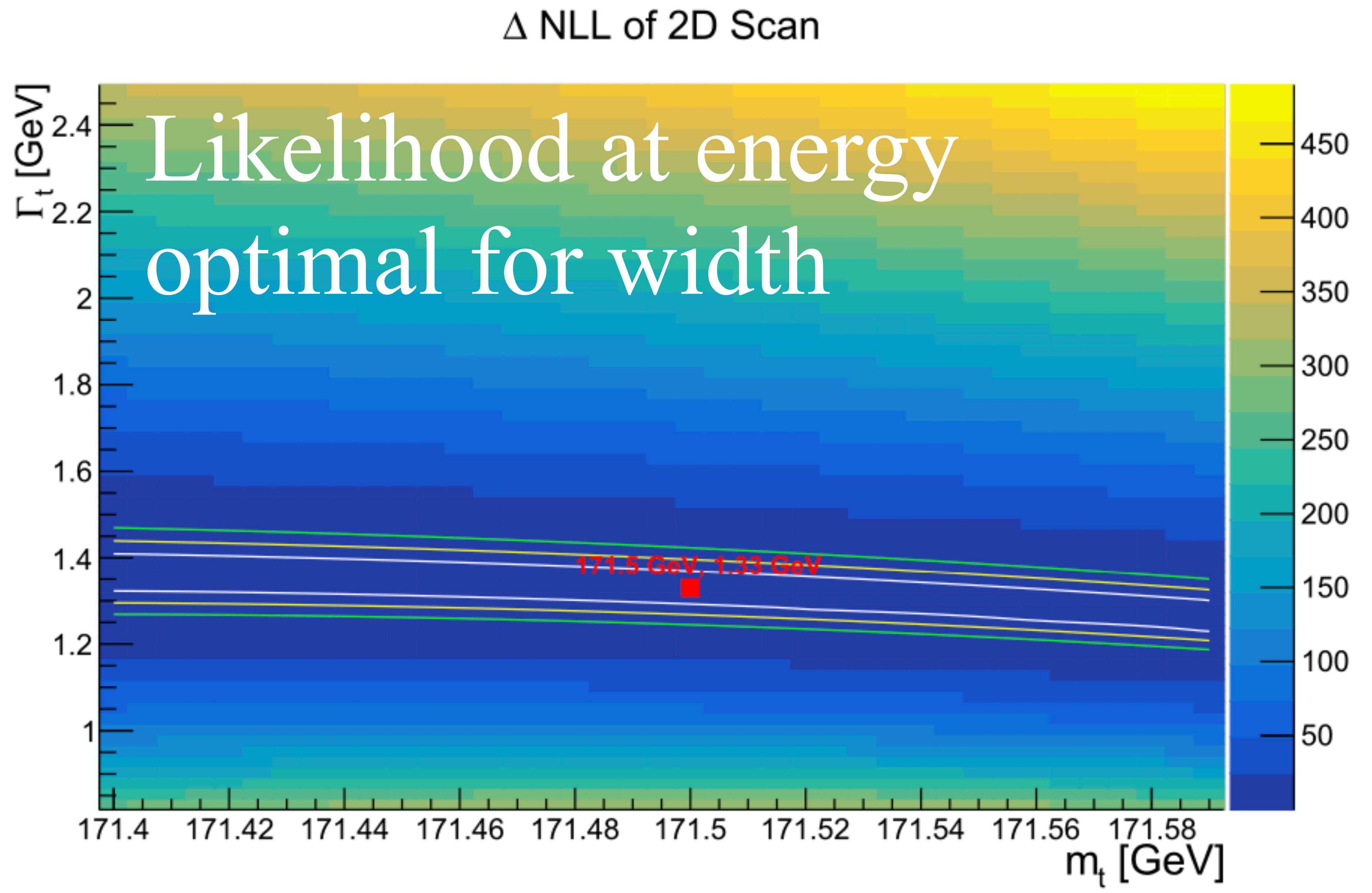


Likelihood with 2 energy points



Likelihood at energy optimal for mass

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



Likelihood at energy optimal for width

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

# Summary

- Great opportunities for top mass, width, $\alpha_S$ measurements with CEPC at the tt threshold

- 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

# Backup

# Uncertainties: quick scan and beam energy

| | Top mass uncertainties (MeV) | |
|---|---|---|
| | Optimistic | Conservative |
| Statistics | 9 | 9 |
| Theory | 8 | 24 |
| Quick scan | 2 | 2 |
| $\alpha_S$ | 17 | 17 |
| Width | 10 | 10 |
| Experimental efficiency | 5 | 44 |
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| 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*

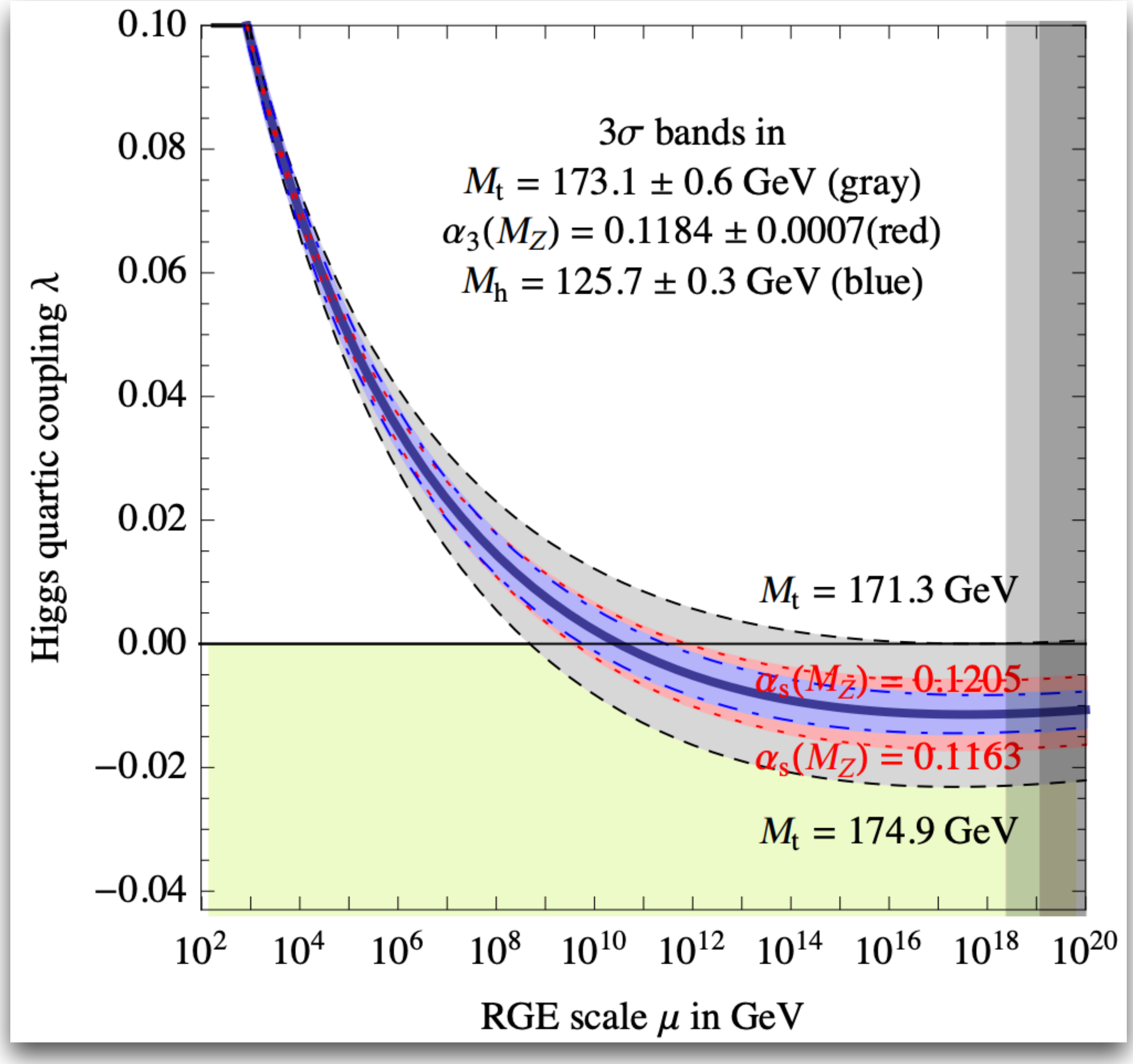
MAX-PLANCK-INSTITUT FÜR PHYSIK

- Relatively thorough evaluation for ILC:

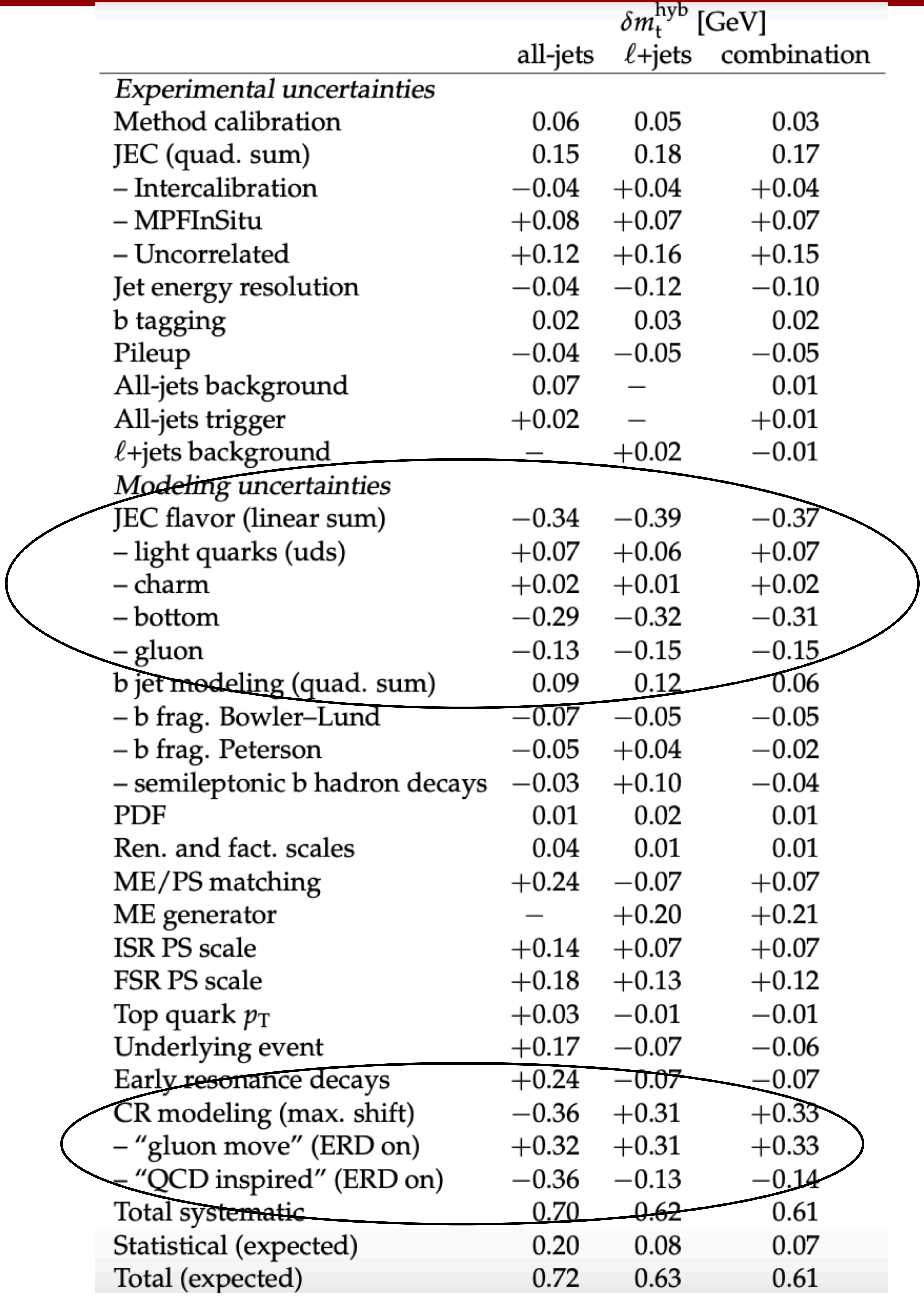
| error source | $\Delta m_t^{\mathrm{PS}}$ [MeV] | For FCC-ee $200 fb^{-1}$ |
|---|---|---|
| stat. error (200 $\mathrm{fb}^{-1}$) | 13 | 9 (compressed scan) |
| theory (NNNLO scale variations, PS scheme) | 40 | 40 - 45, depending on scan range |
| parametric ($\alpha_s$, current WA: 9 x $10^{-4}$) | 26 | 3.2 with ultimate $\alpha_s$ (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?



JHEP08(2012)098



| | $\delta m_t^{hyb}$ [GeV] | | |
|---|---|---|---|
| | all-jets | $\ell$+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 |
| $\ell$+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
Eur. Phys. J. C 79 (2019) 313