Karlsruher Institut für Technologie

Institute for Data Processing and Electronics

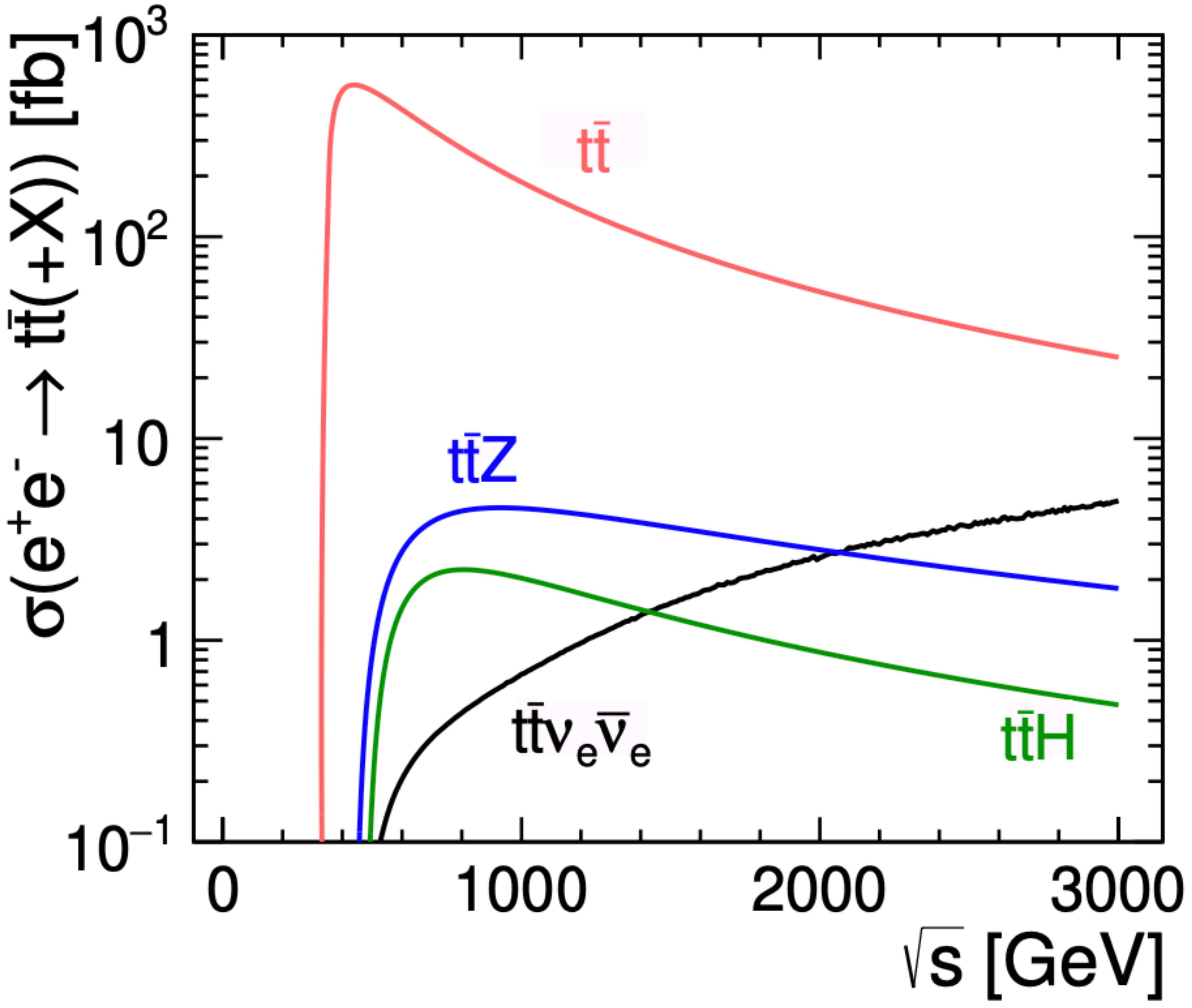
State-of-the-art and open questions on the top quark properties from threshold data

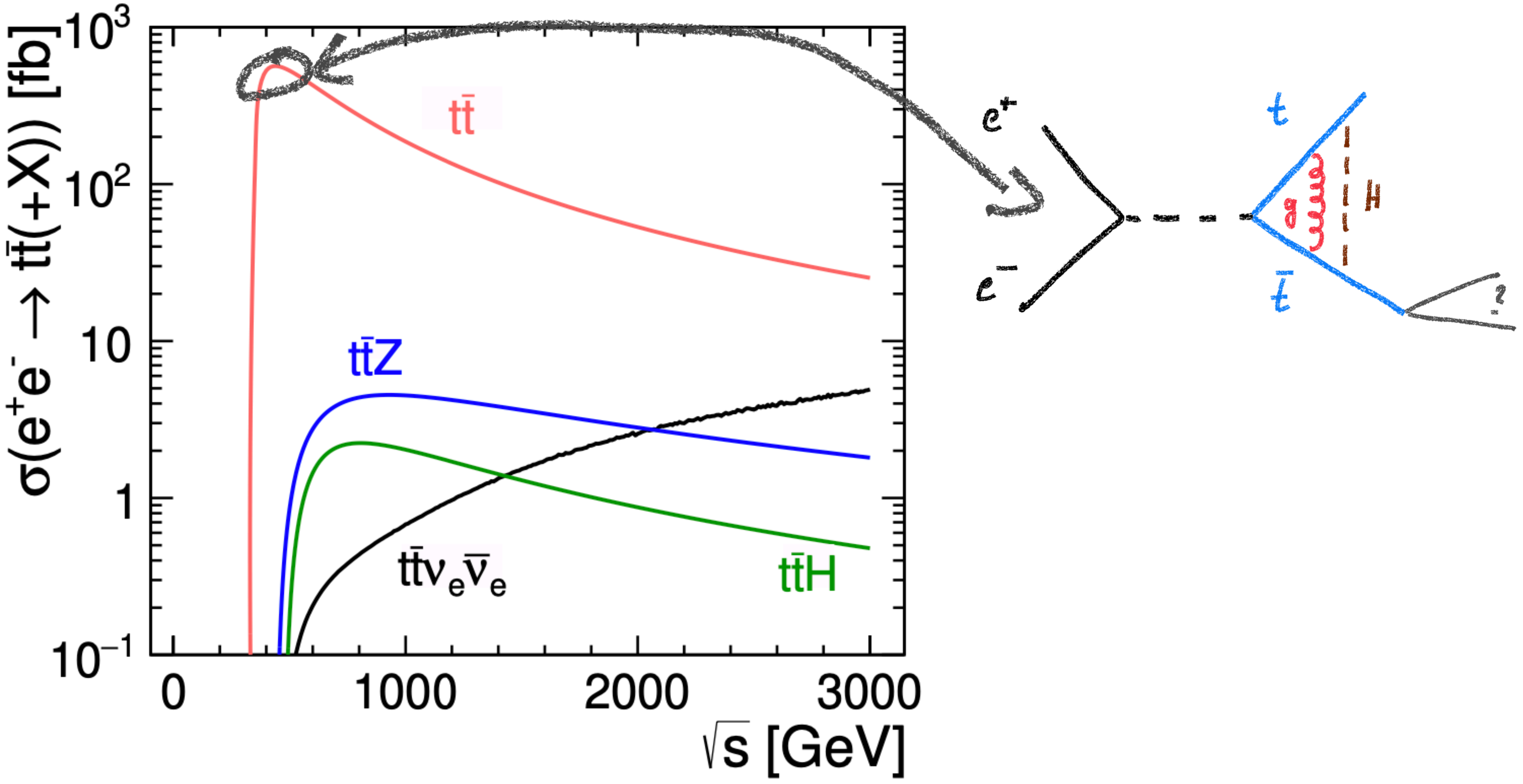
Frank Simon

ECFA Higgs Factory WG1 Seminar, January 2023

Overview: Top Physics at e^+e^- Colliders

Understanding the Top, using the Top





- Measuring the top quark mass (and other parameters) in theoretically well-defined frameworks
- Search for BSM decays in clean environment

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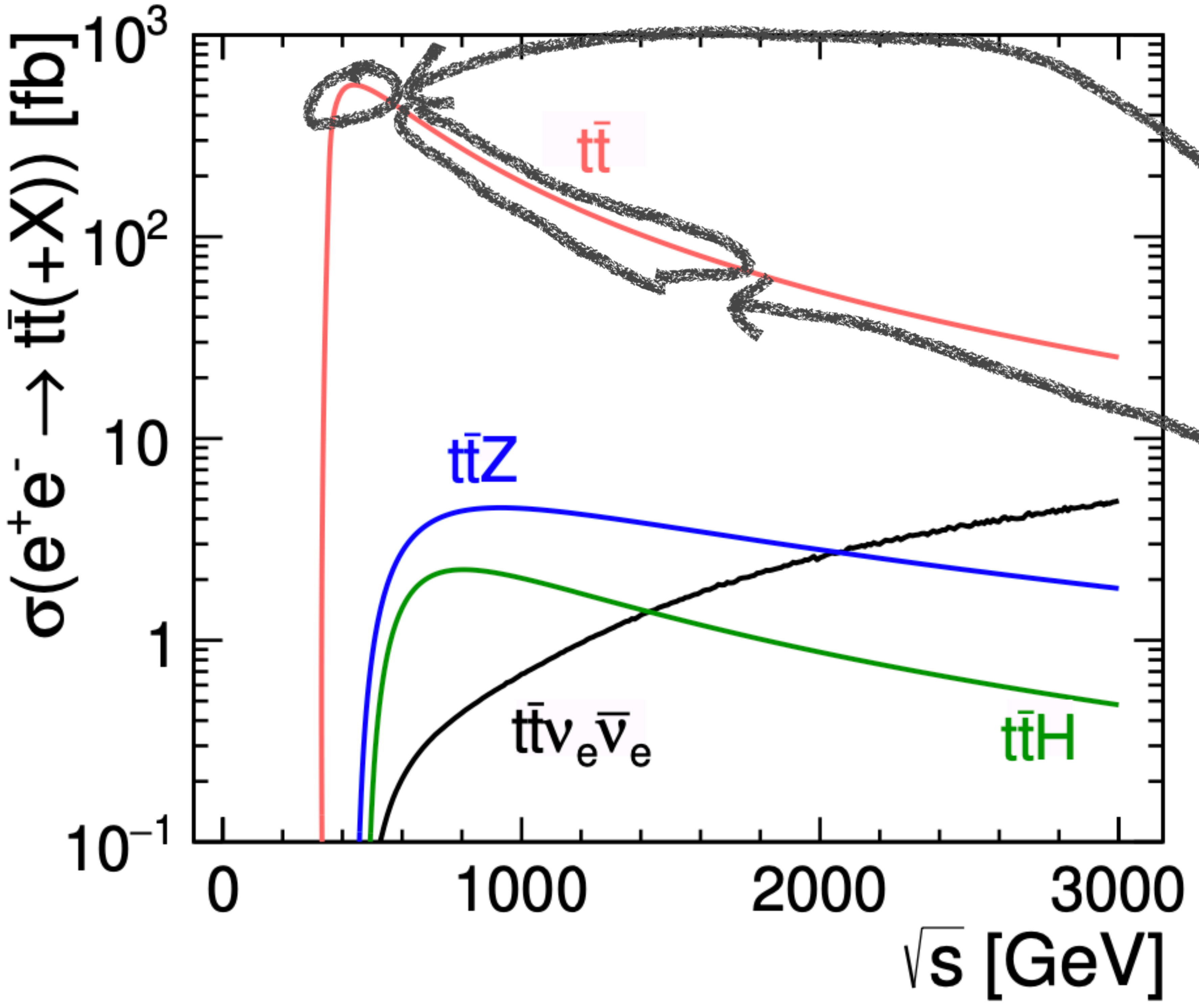

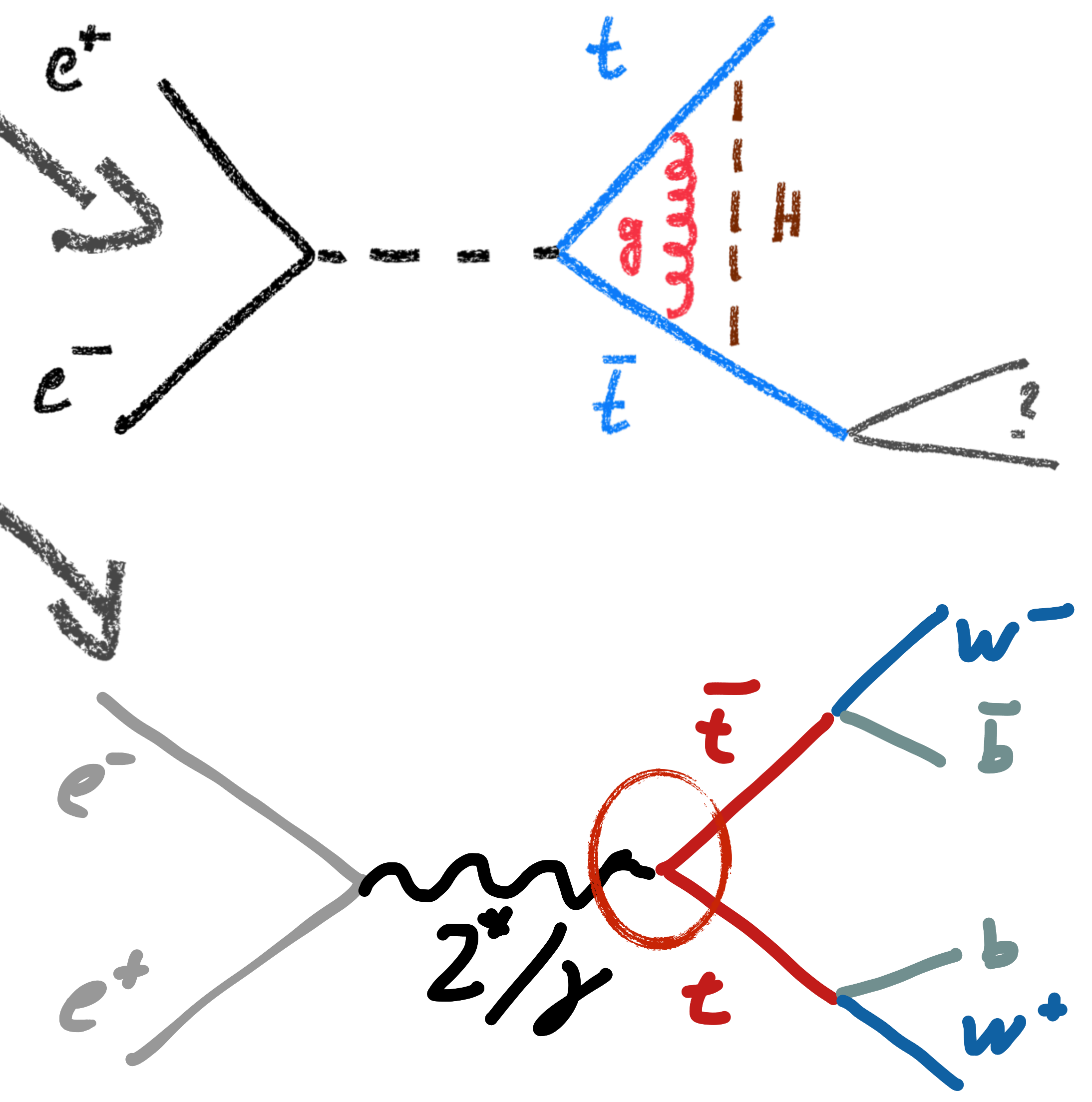

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- Electroweak couplings of the top quark as a probe for New Physics

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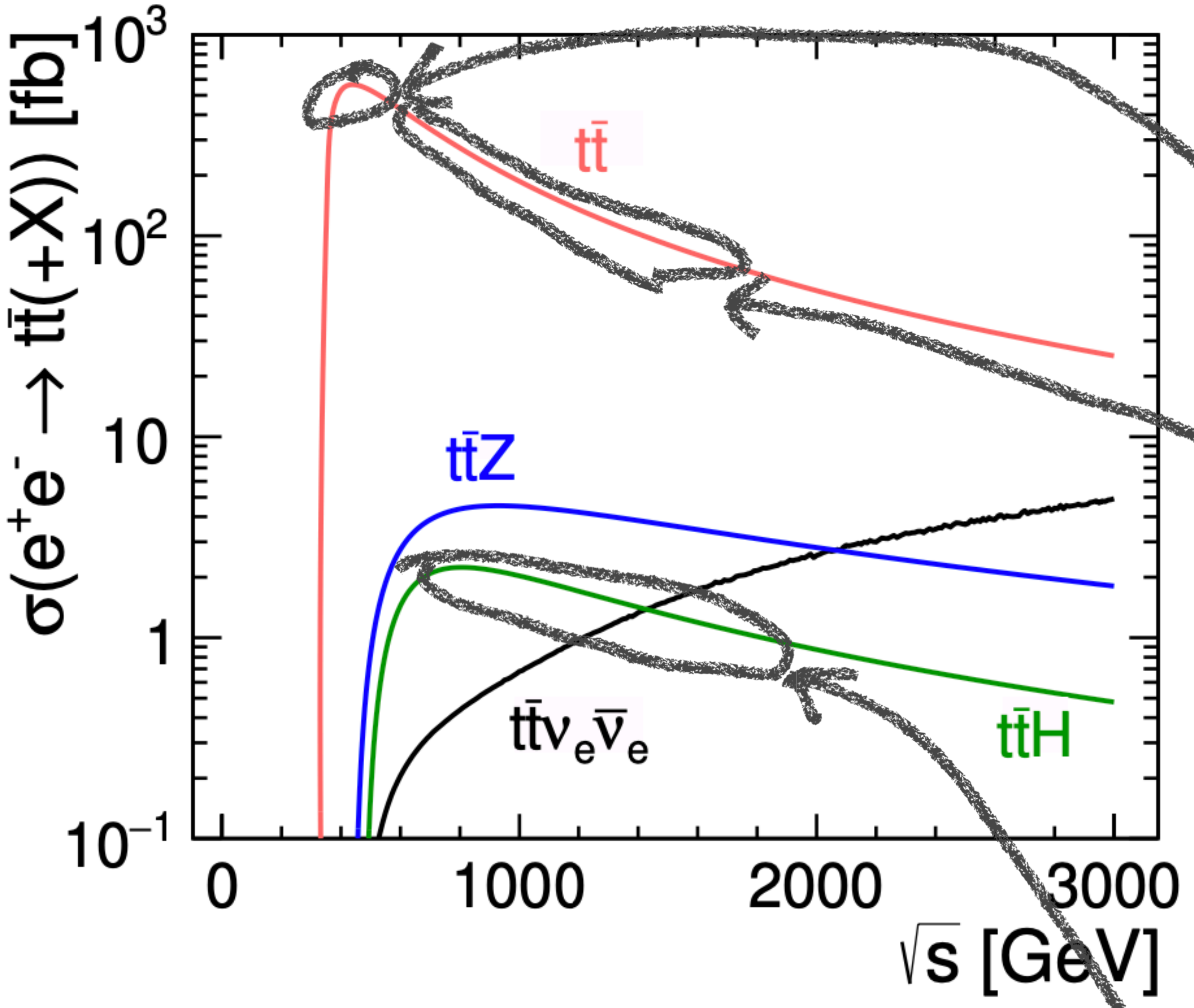

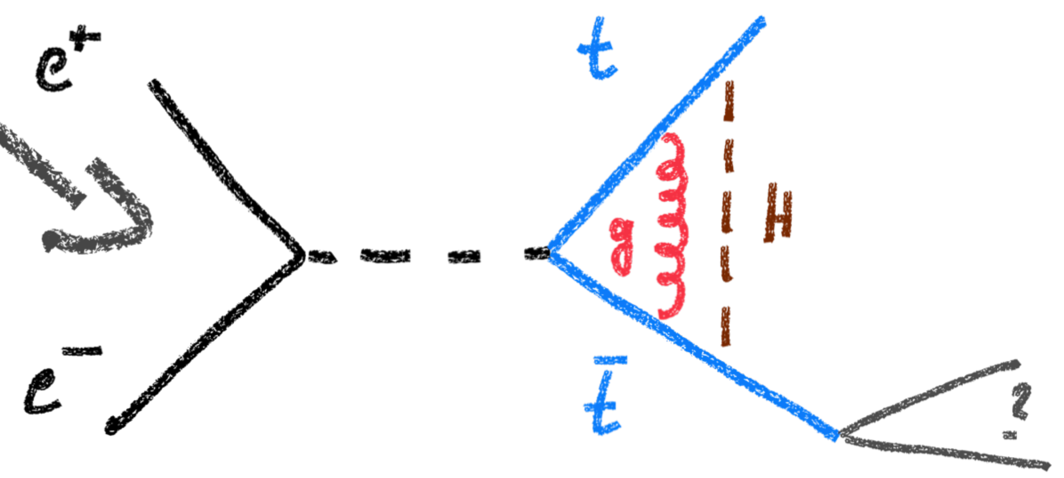

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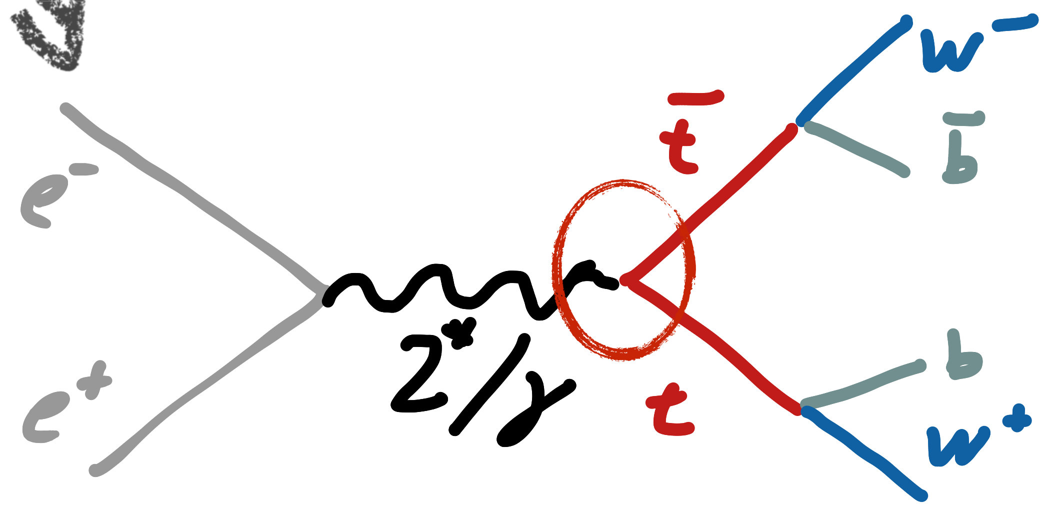

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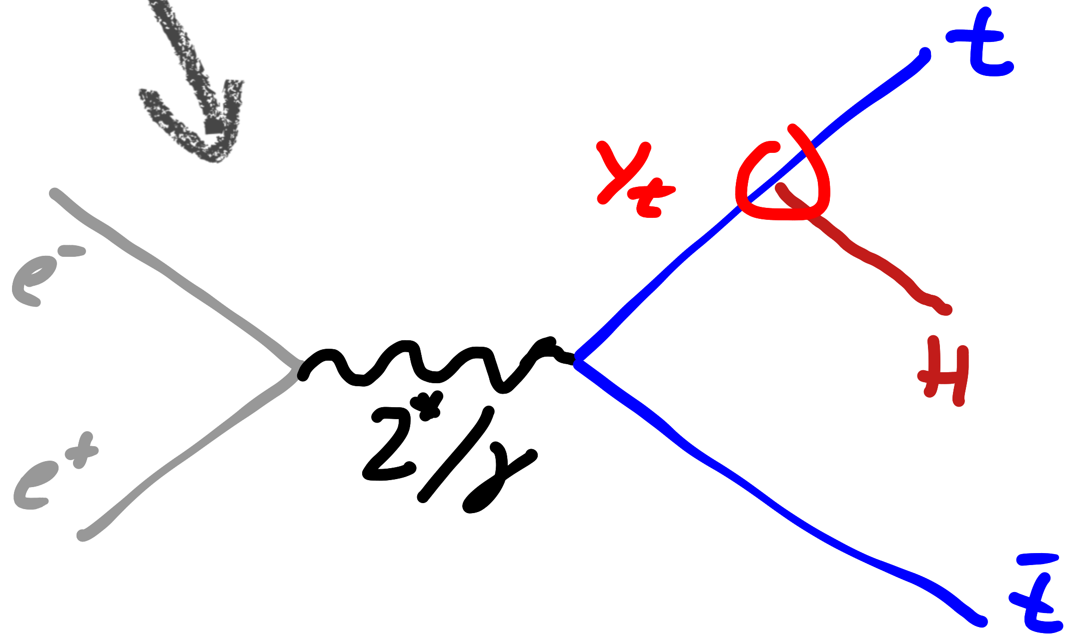

- Direct measurement of the top Yukawa coupling, ultimate potential of 2%
  [requires > 500 GeV, full scope assumes ~ 1 TeV]

Outline

- Intro: The Top Quark Mass - Different experimental routes
- The Top threshold
- Measurements beyond mass

Top Quark Mass: Measurement Strategies

At and above threshold

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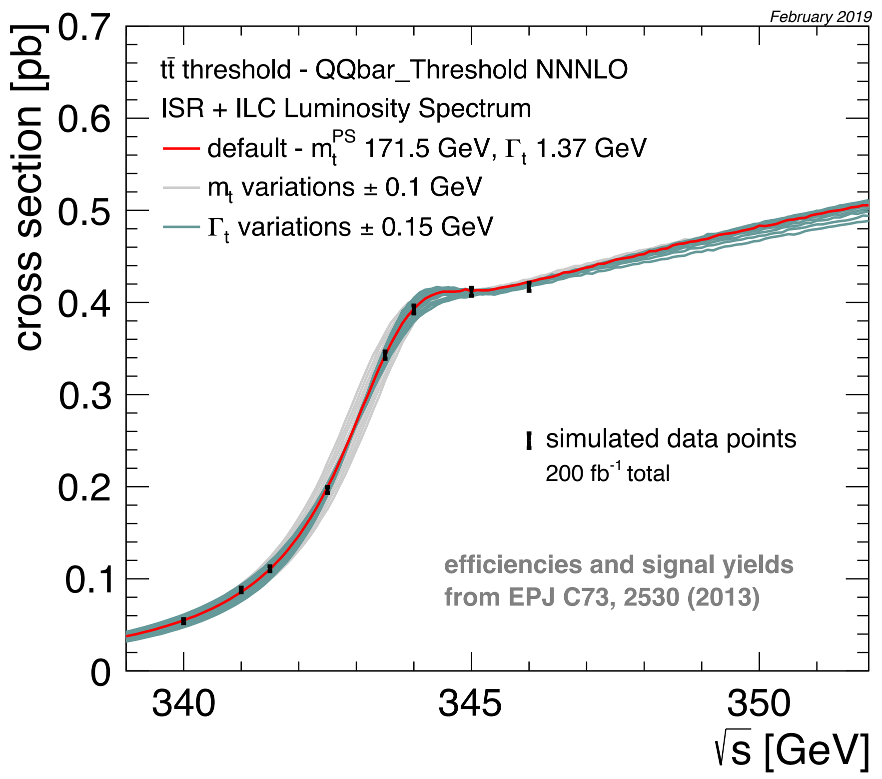
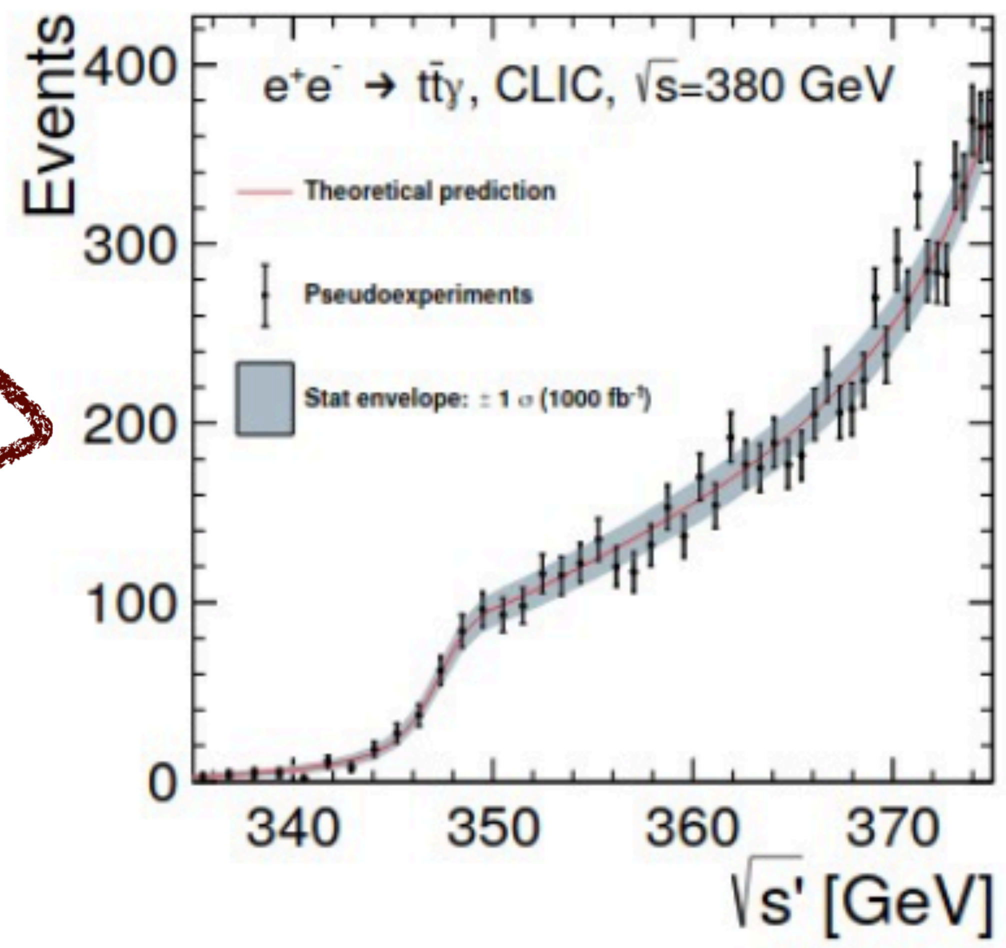
- The accelerator side: Requires sufficient collision energy for top pair production
  - So far thoroughly studied for ILC, CLIC, threshold studies common for CLIC, FCC-ee, ILC

Three approaches to the top mass

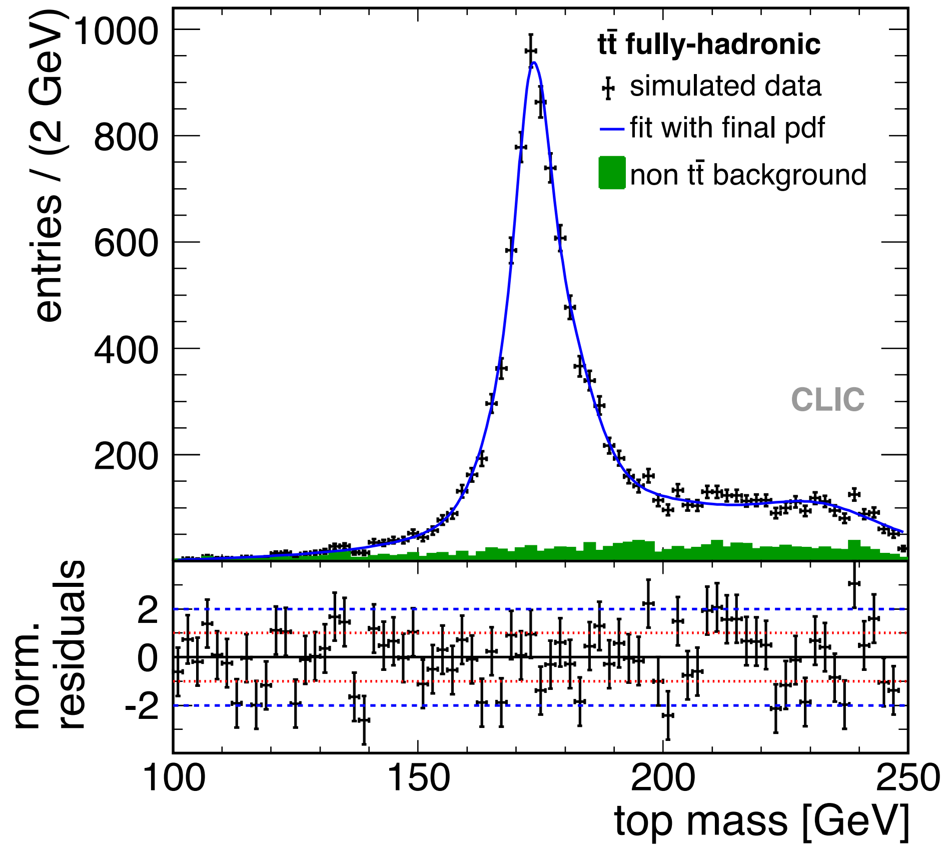
The threshold scan around 350 GeV



The top mass from radiative events



Direct kinematic reconstruction



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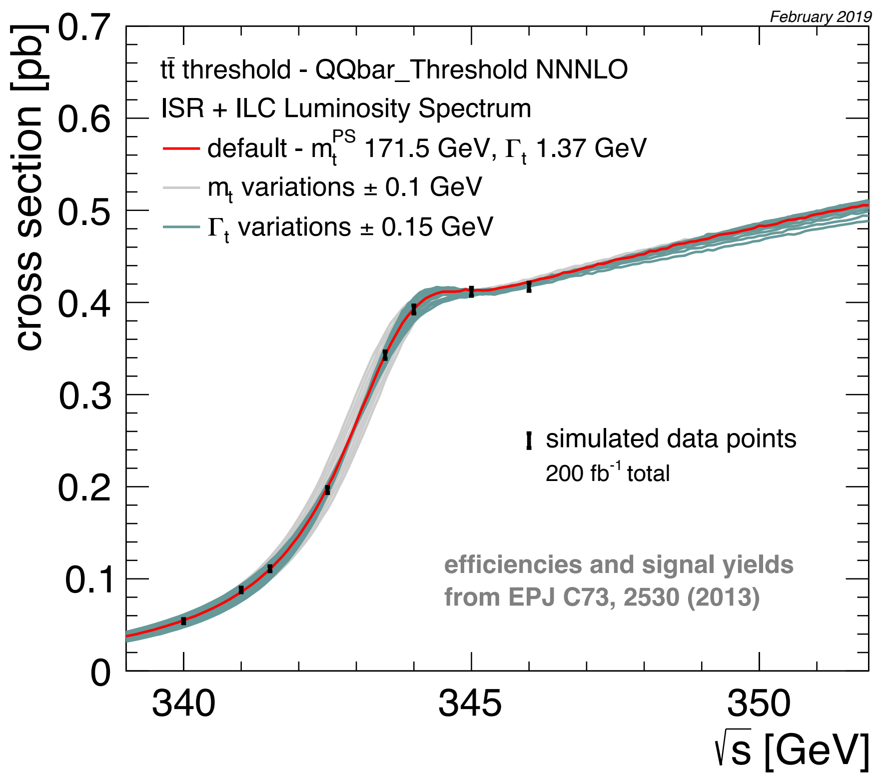

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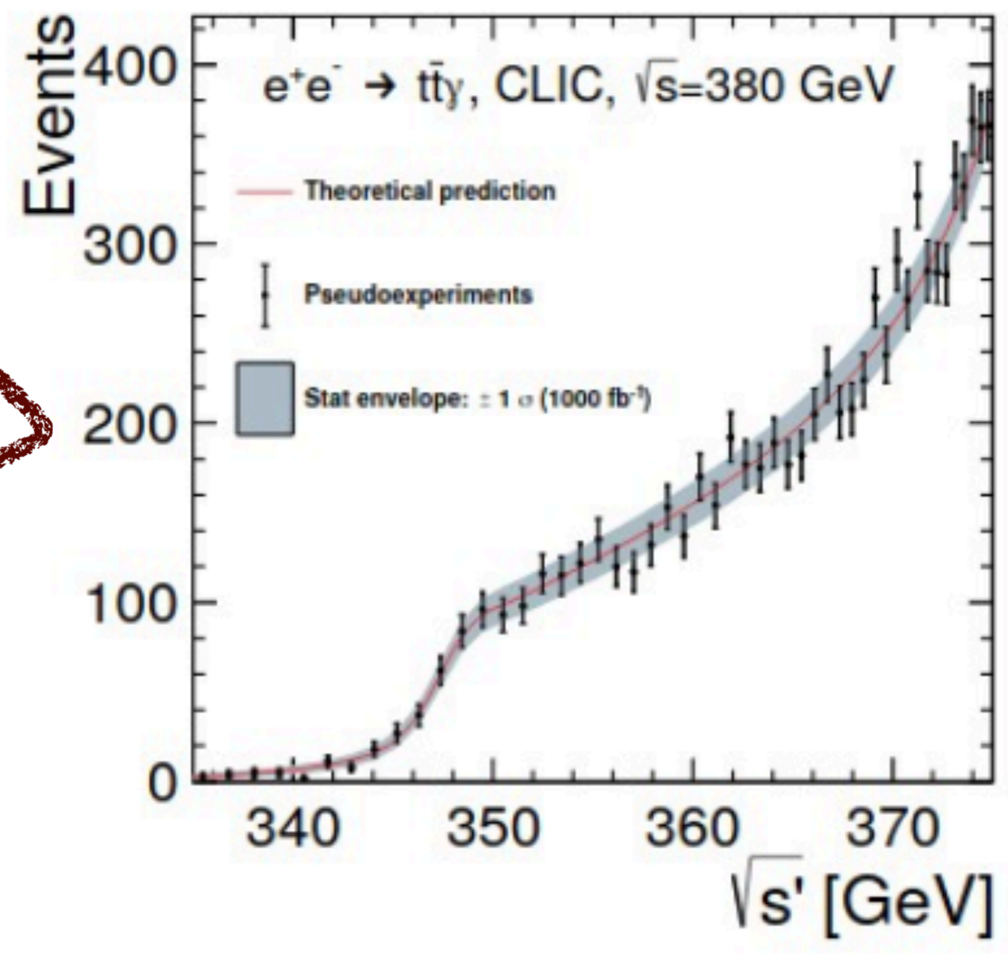

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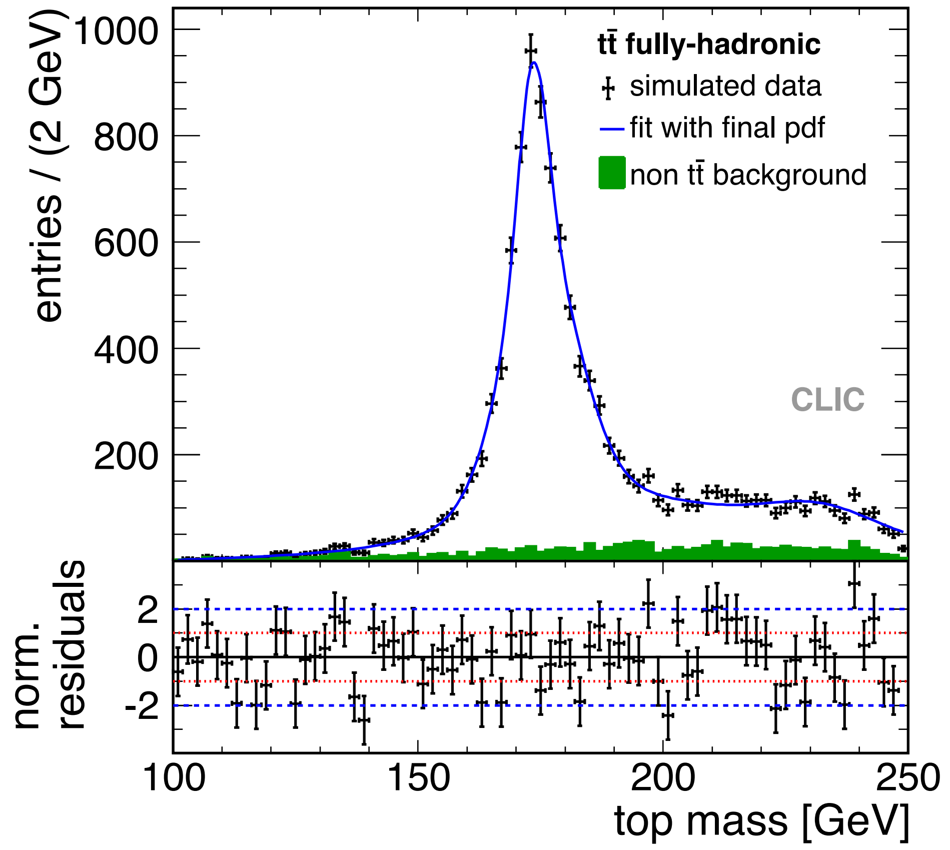


Key references:

EPJ C73, 2530 (2013)
(CLIC, (ILC): Threshold, direct)

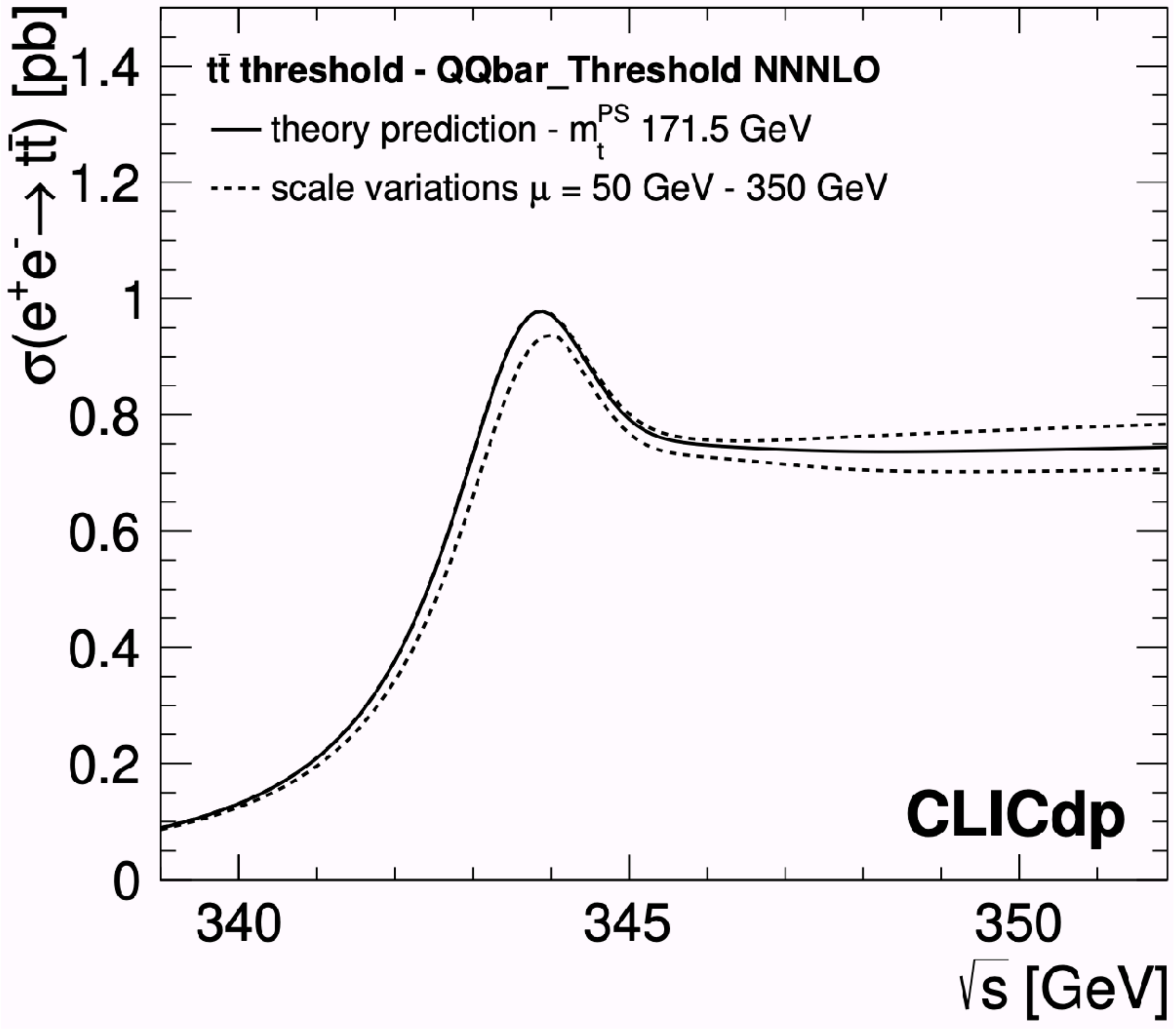
JHEP 11, 003 (2019)
(CLIC: Threshold, radiative, direct)

PLB 804,135353 (2020)
(ILC, CLIC: radiative)

\+ a rich set of reports and conference proceedings on arXiv

The Top Quark Mass

Ultimate precision at the threshold



- Exploit precise theoretical calculations of cross section in the threshold region, in well-defined mass schemes (m_t^{PS}, m_t^{1S}…) -> Can be converted directly into MSbar mass.

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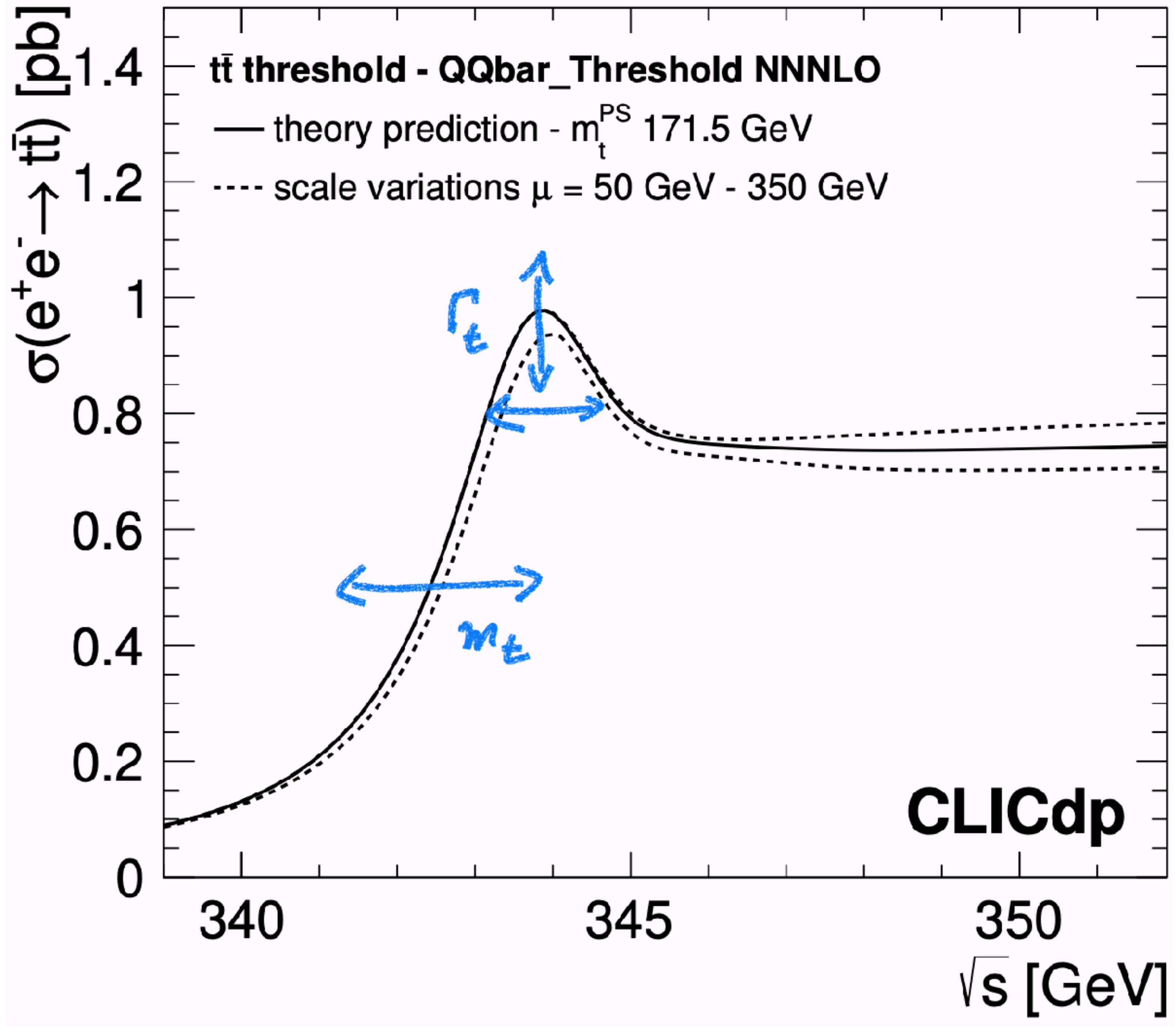

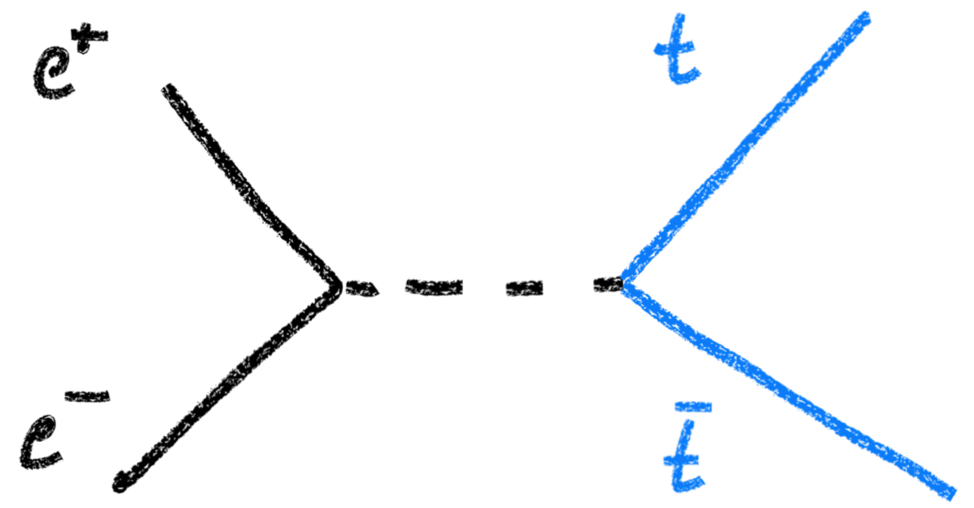

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The threshold is sensitive to top quark properties

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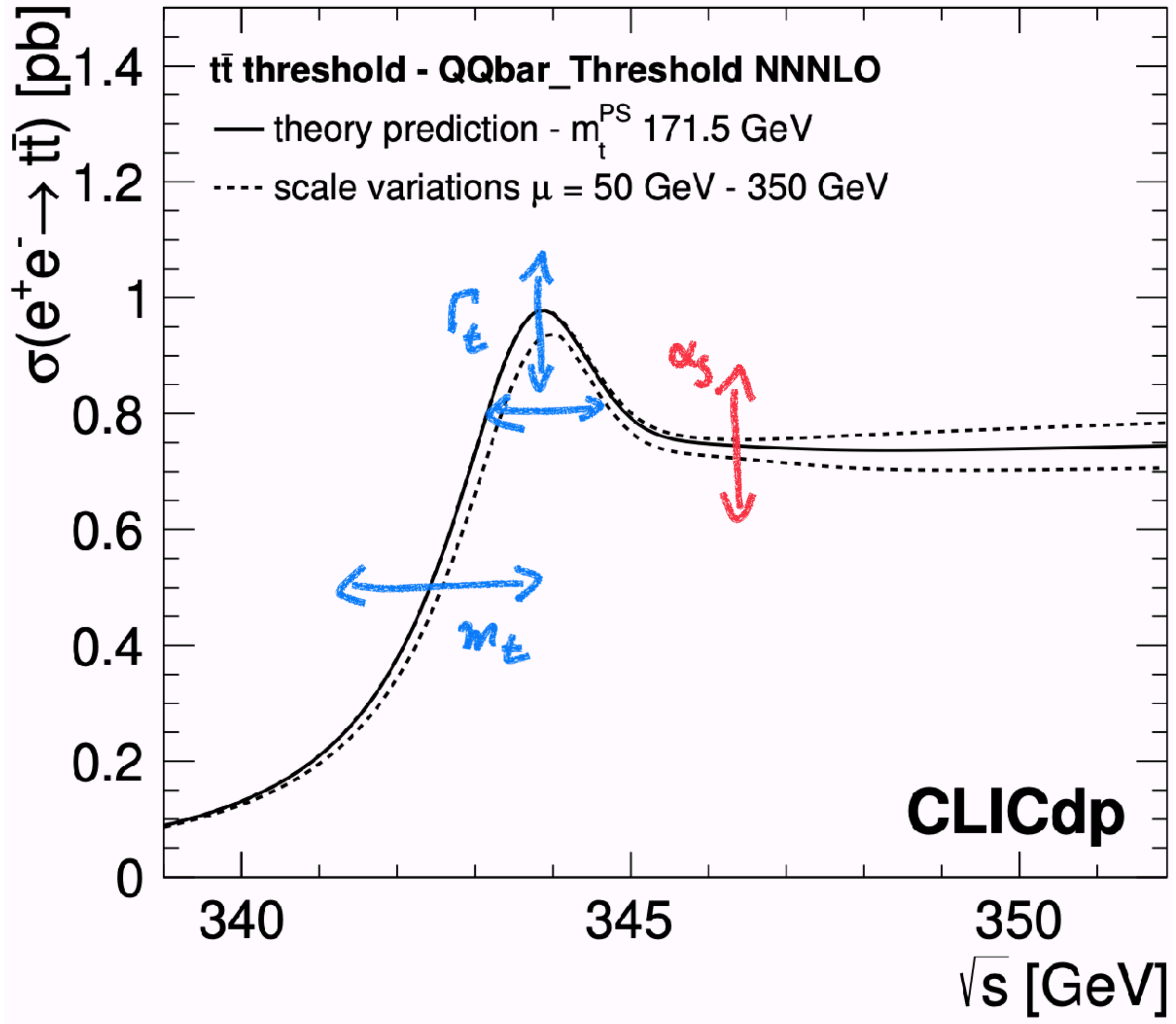

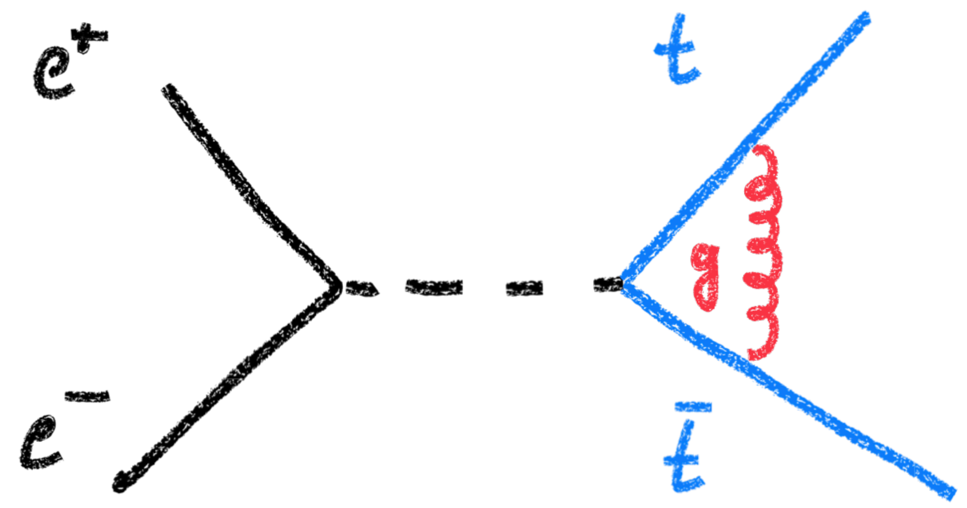

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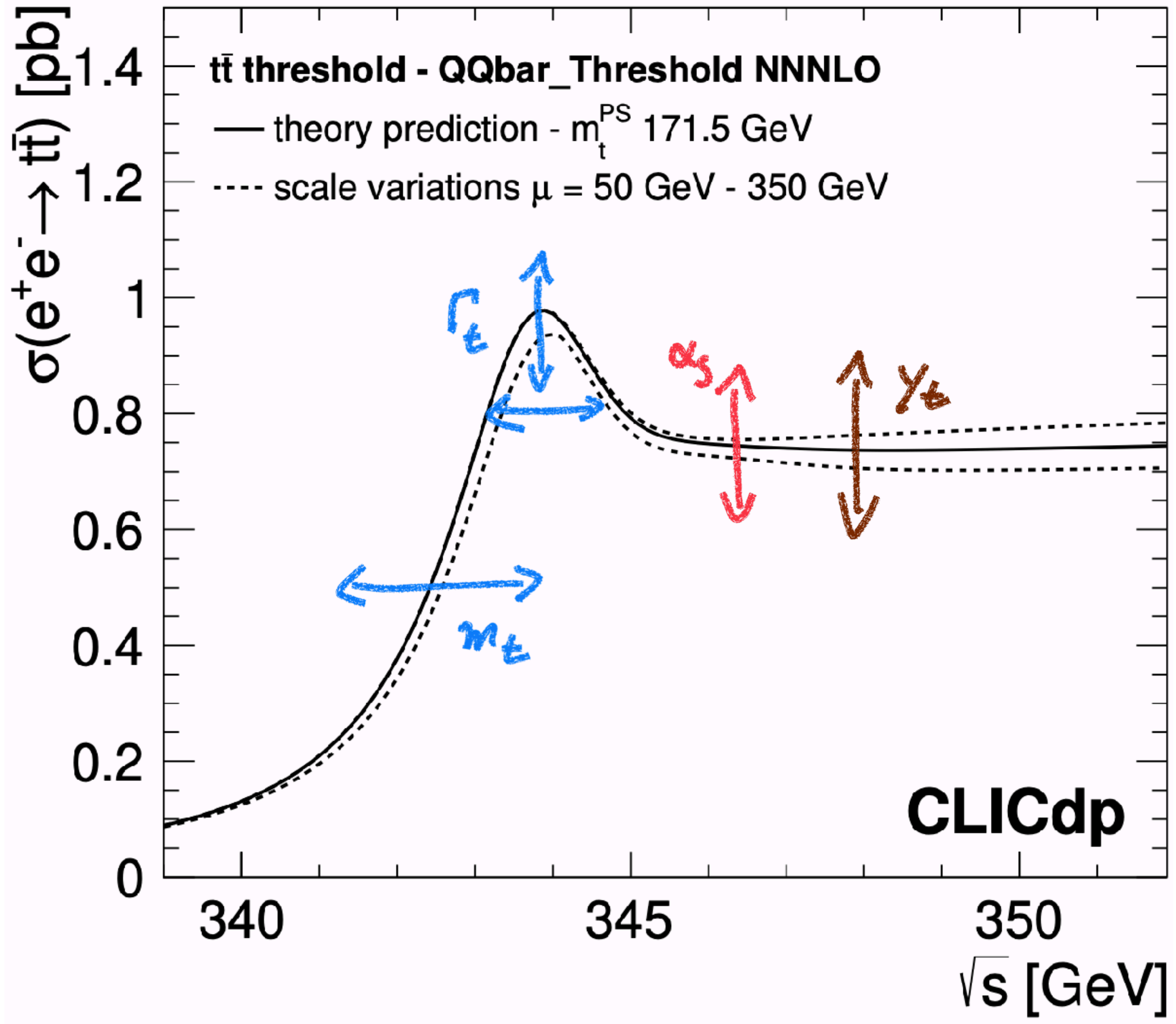

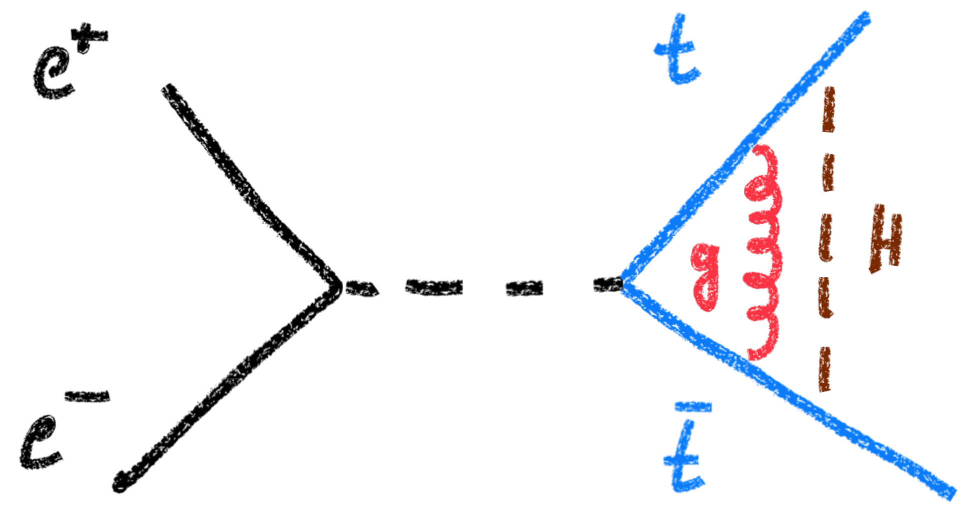

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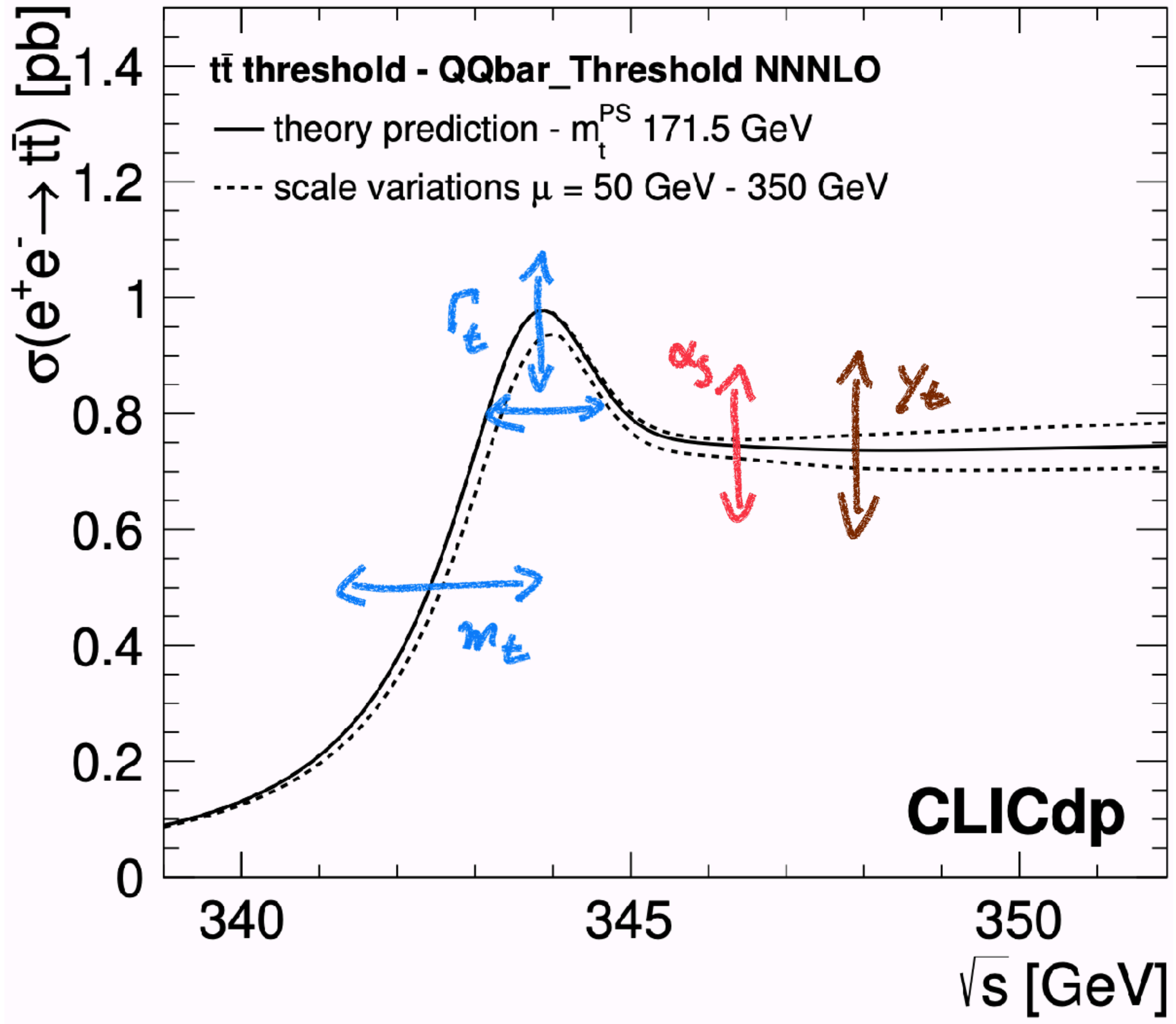

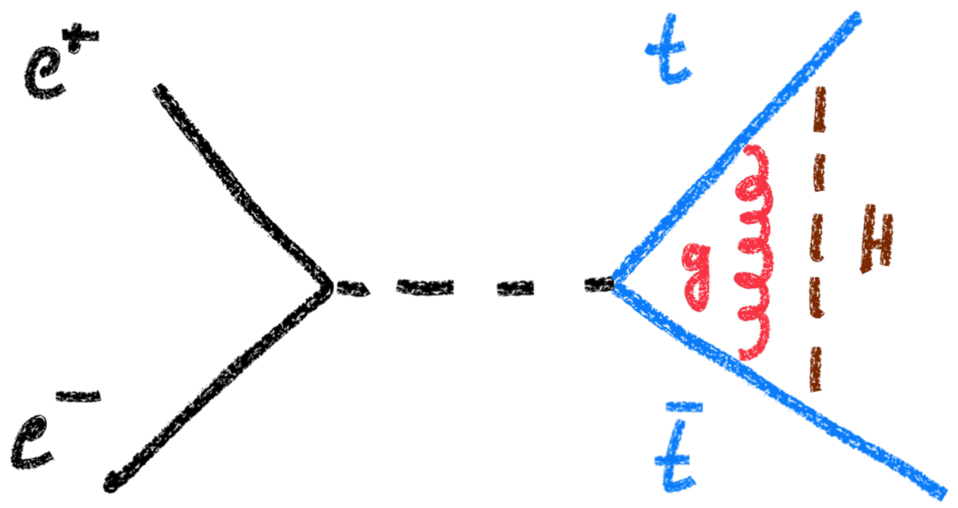

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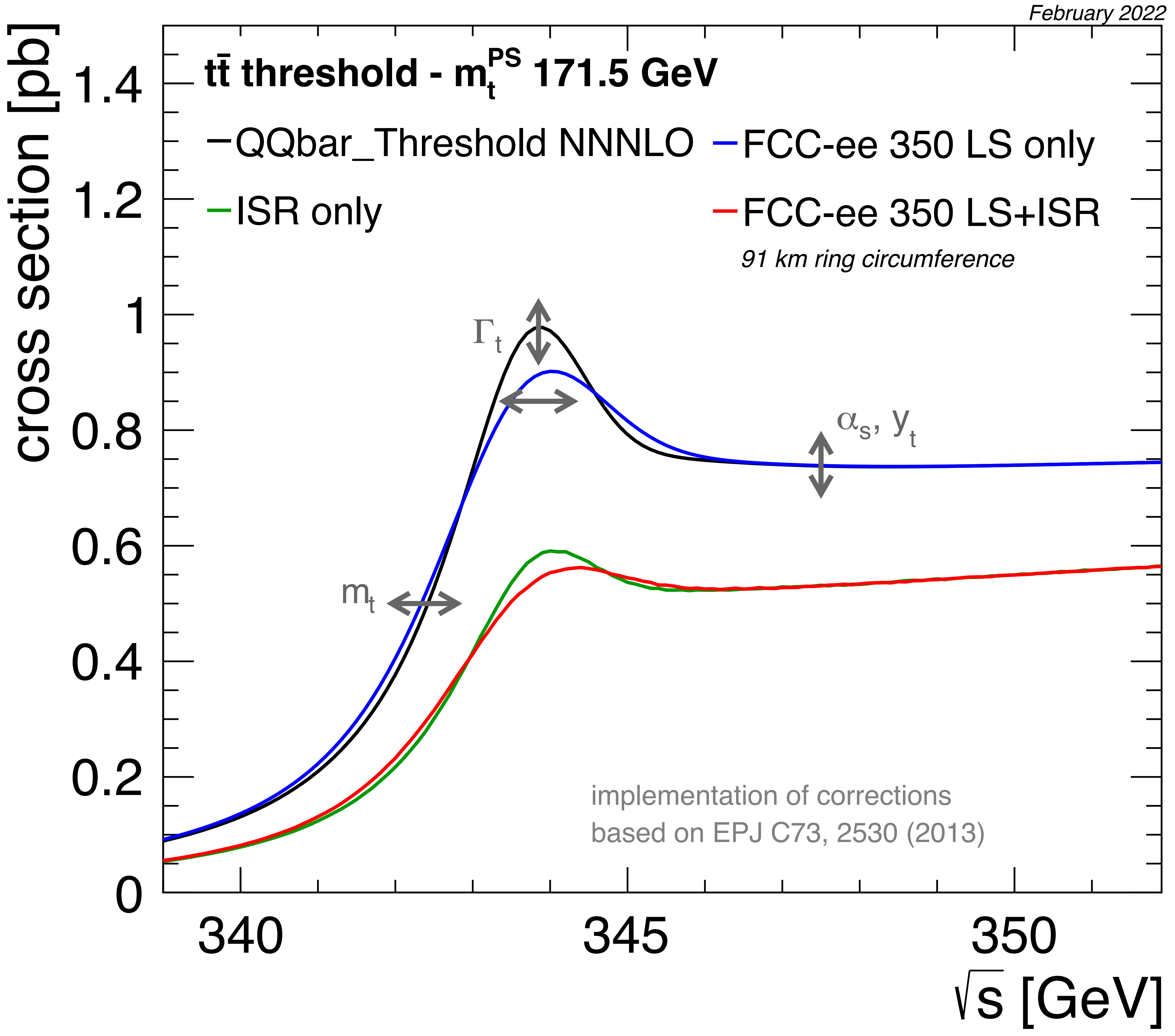
ISR, luminosity spectrum

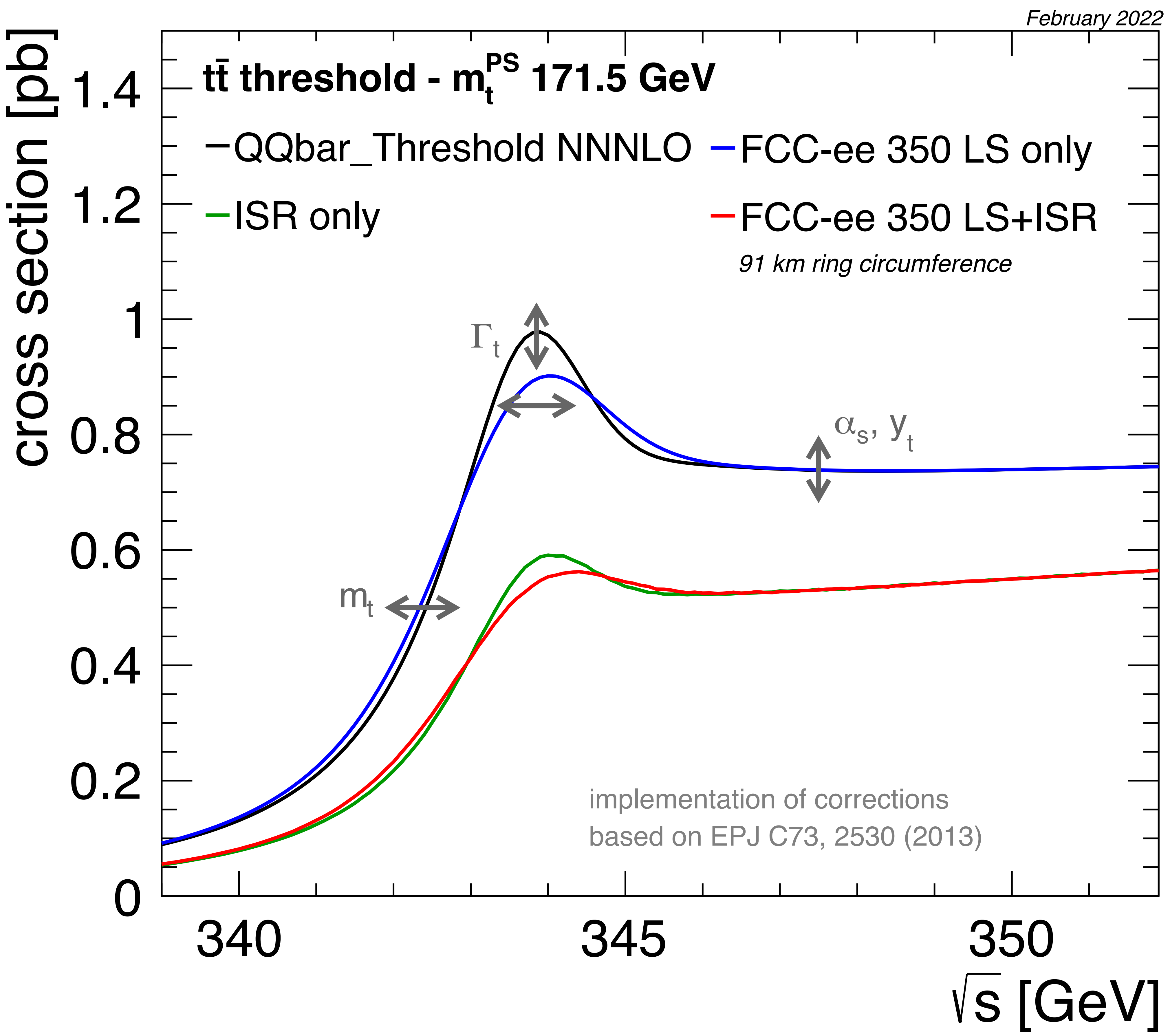


The threshold is sensitive to top quark properties

Differences between Colliders

The Luminosity Spectrum

- Linear collider luminosity spectra are characterized by a beamstrahlung tail, FCC-ee is close to Gaussian



FCC vs

Differences between Colliders

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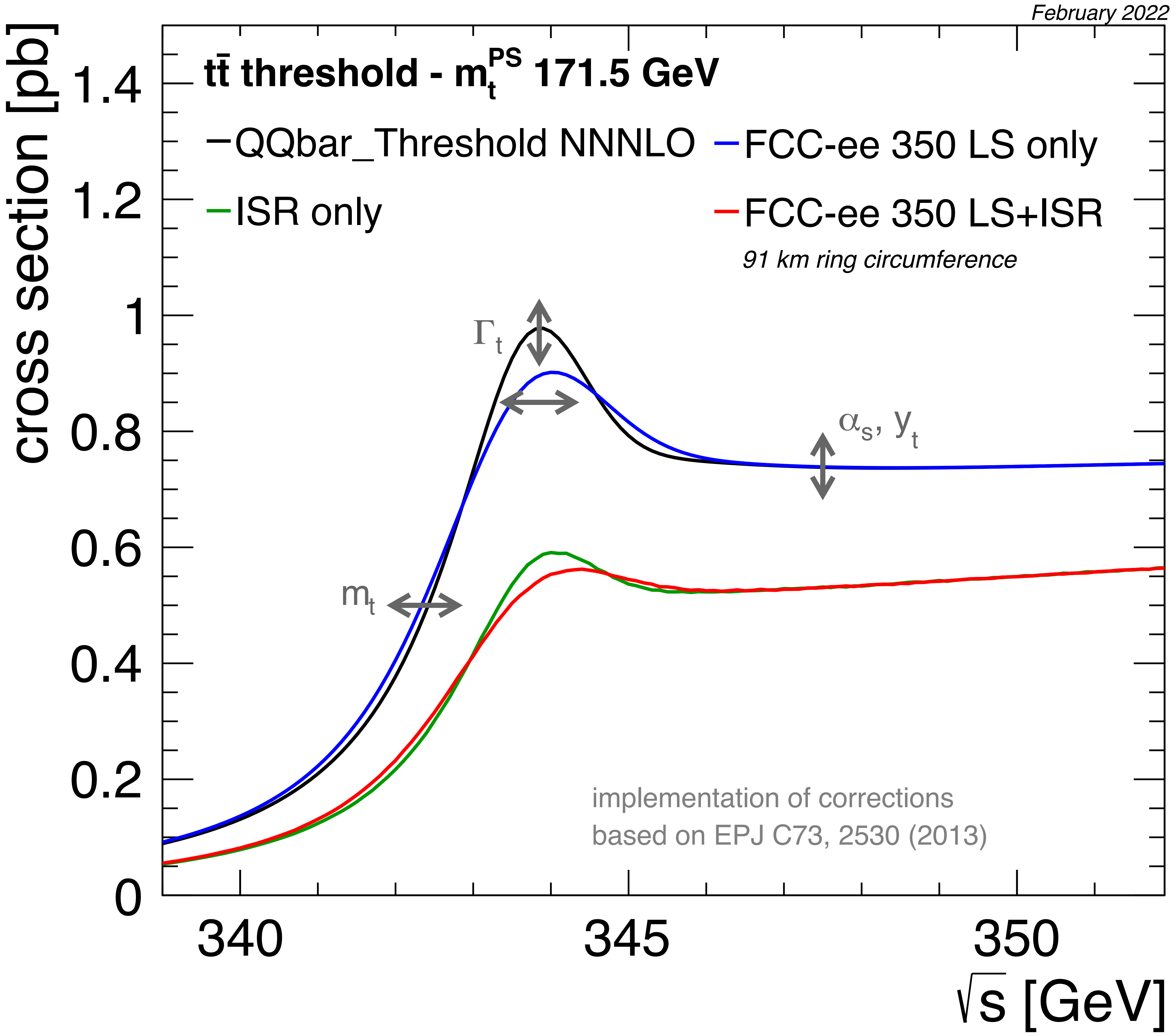
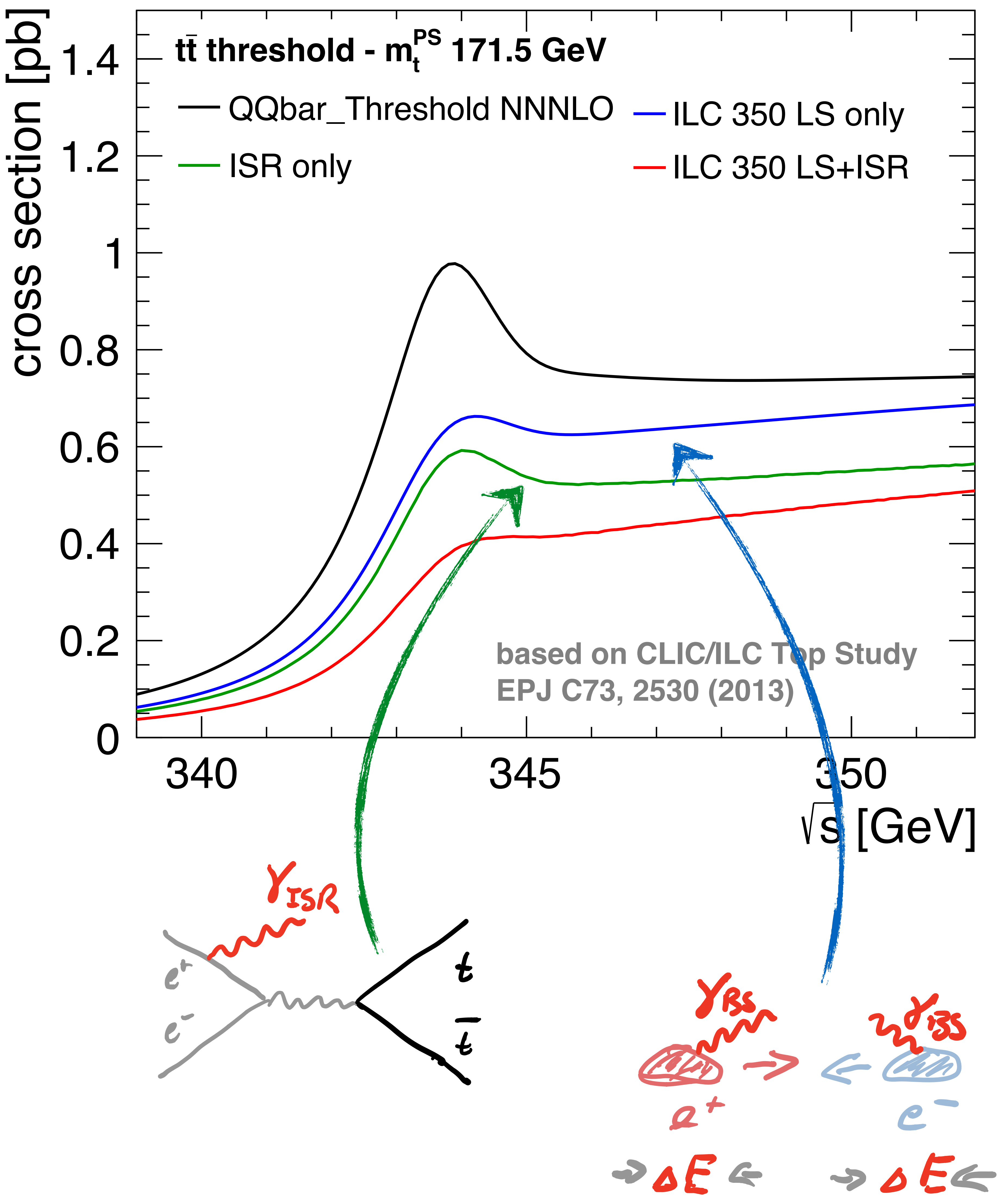


FCC vs

ILC



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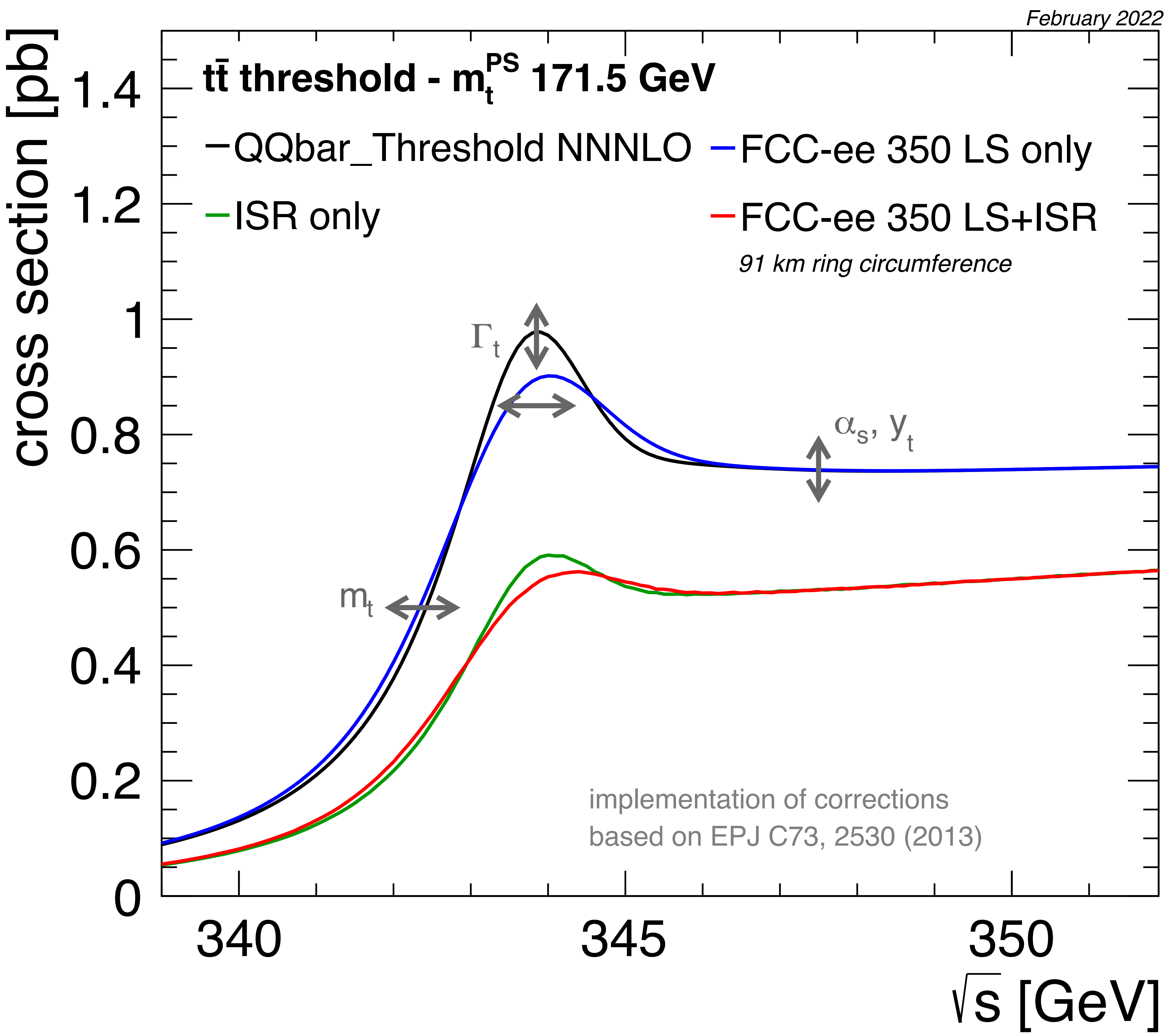

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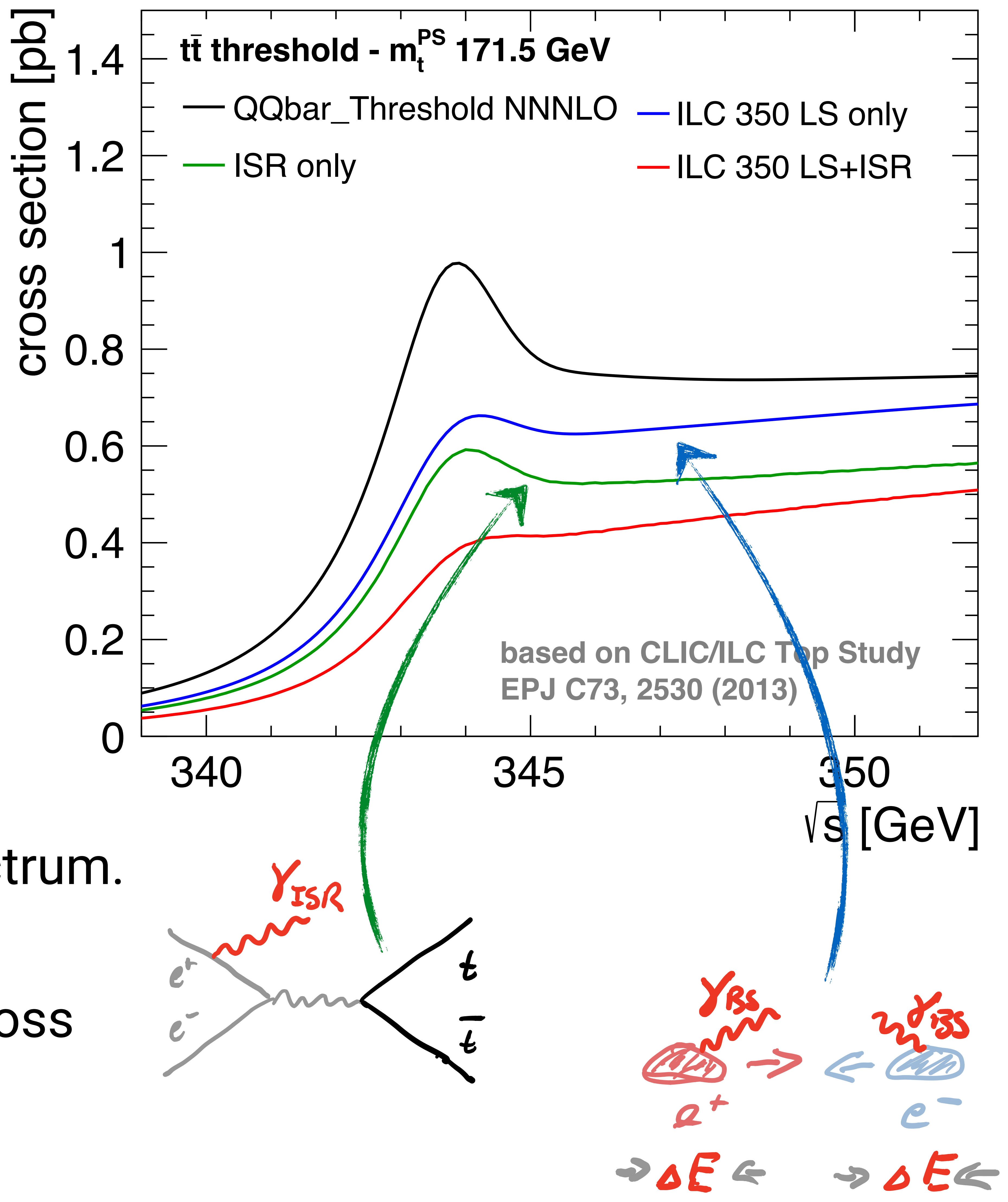


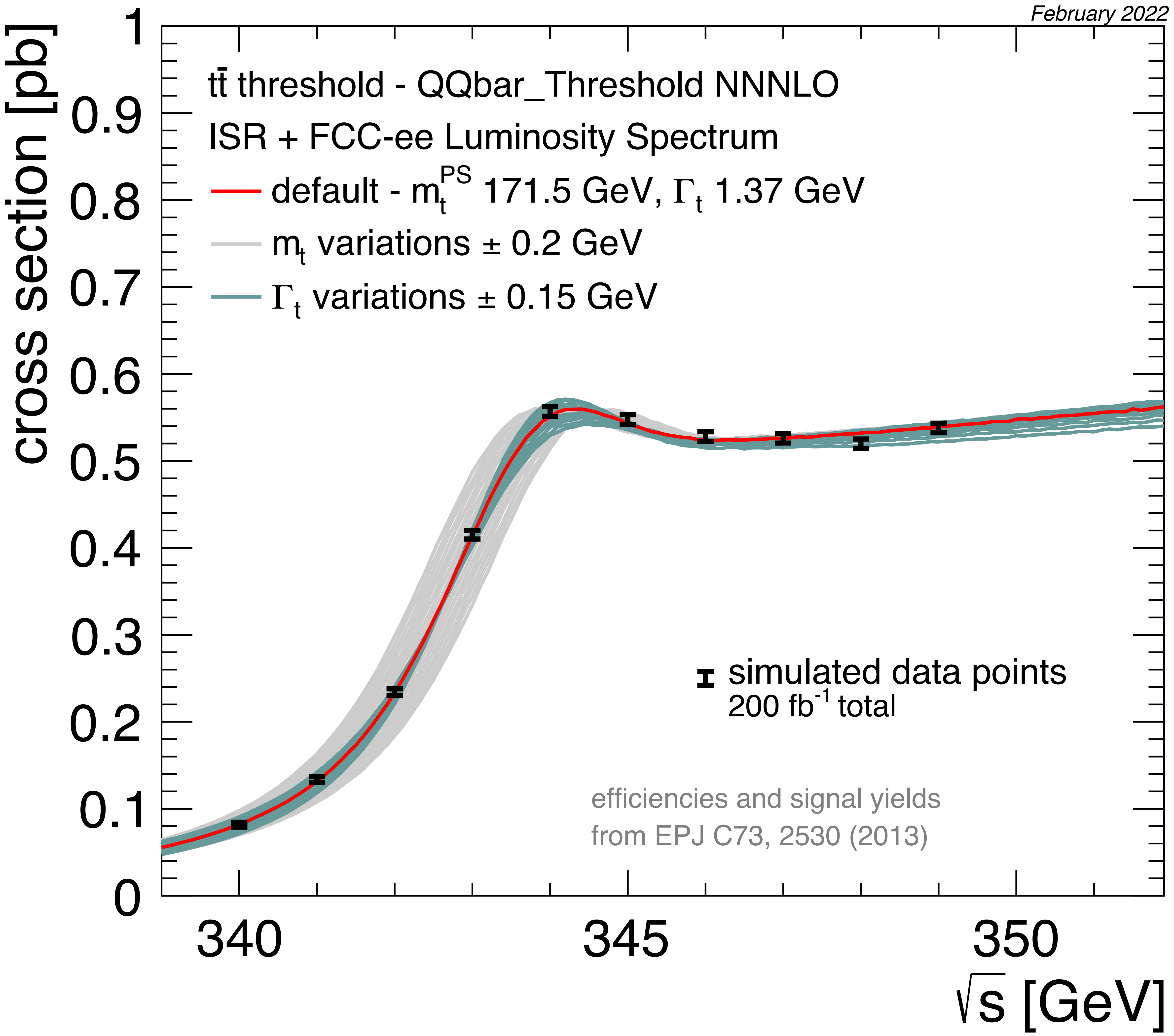
Requires: Precise understanding and measurement of spectrum.

In this case:

~ 30% reduction of cross section -> 15% hit on statistical uncertainty

The Standard Threshold Scan

Experimental Assumptions

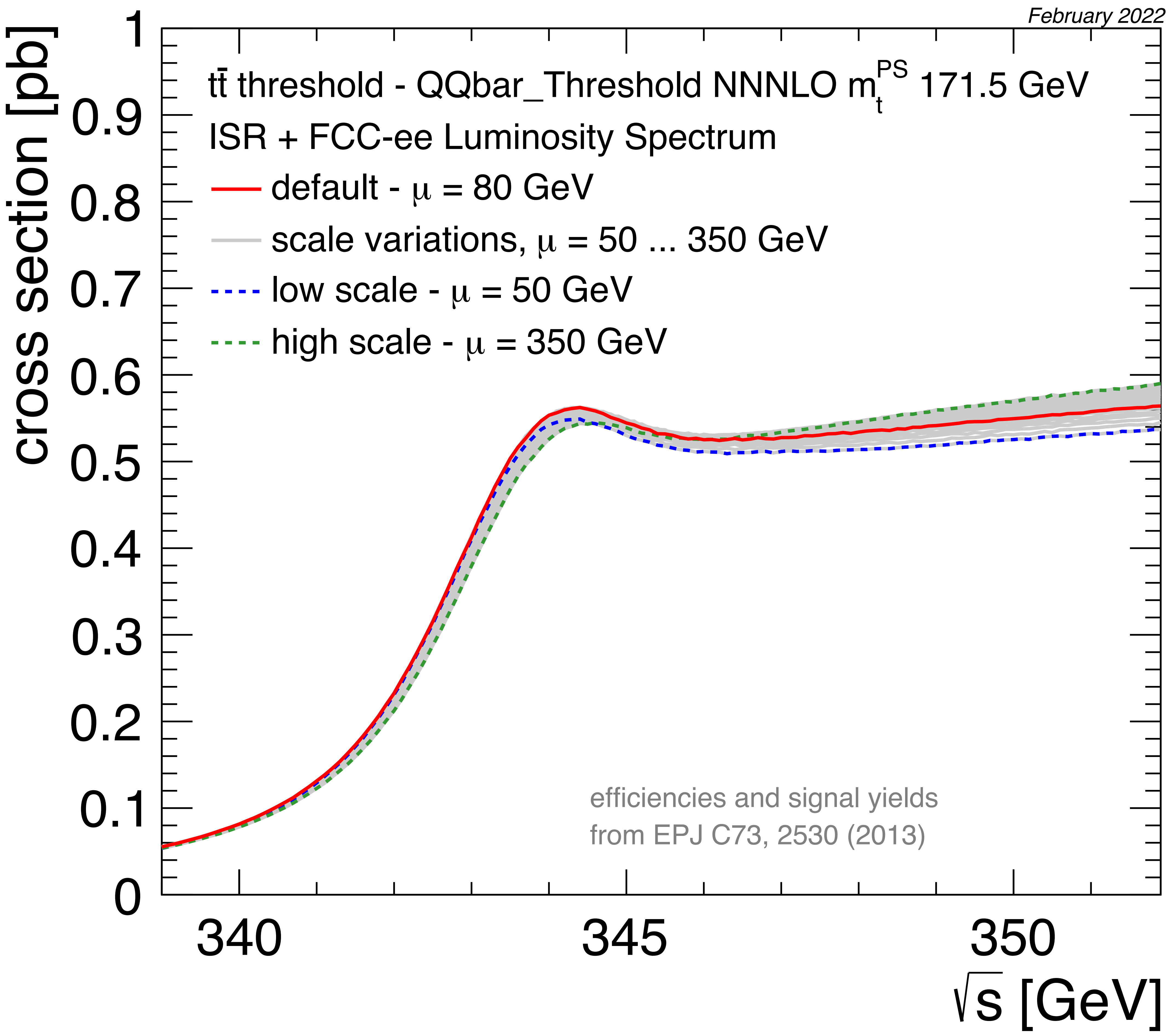


- The standard assumptions:
  Efficiency, signal and background yields taken from EPJ C73, 2530 (2013):
  70.2% signal efficiency, 73 fb effective background cross section after selection
- A 10-point threshold scan, with equal luminosity sharing, spacing by 1 GeV, from 340 - 349 GeV
- ILC, FCC-ee assume 200 fb^{-1} total, CLIC 100 fb^{-1} (for easier comparisons, 200 fb^{-1} numbers are often also quoted for CLIC)

- Top mass (and other parameters, such as Γ_t, y_t, α_s) extracted via template fits of predicted cross sections with different input parameters.
  Theory essential - here NNNLO QCD [Beneke et.al.]

Theory Uncertainties

A key factor



- QCD scale uncertainties highly relevant.

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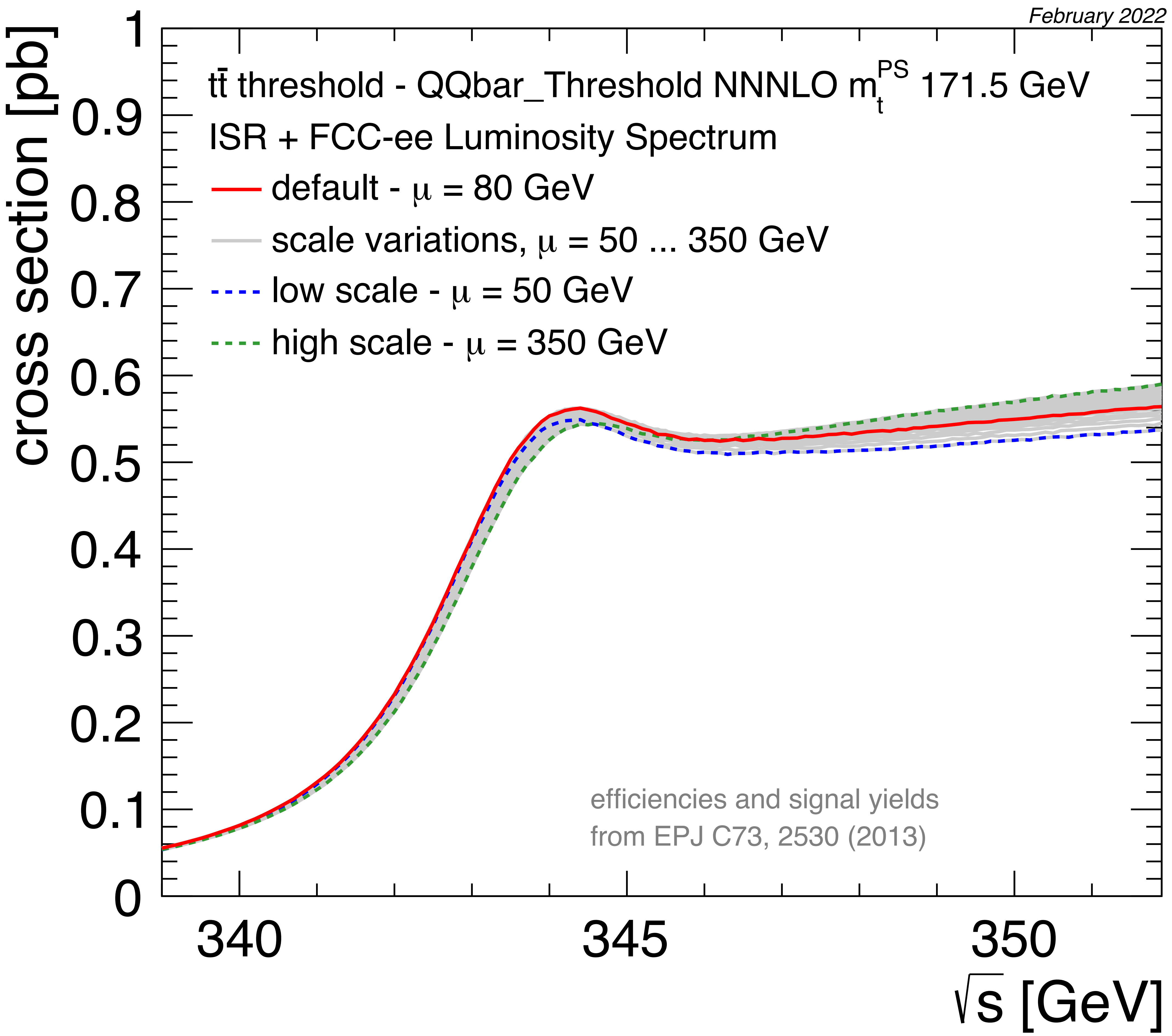
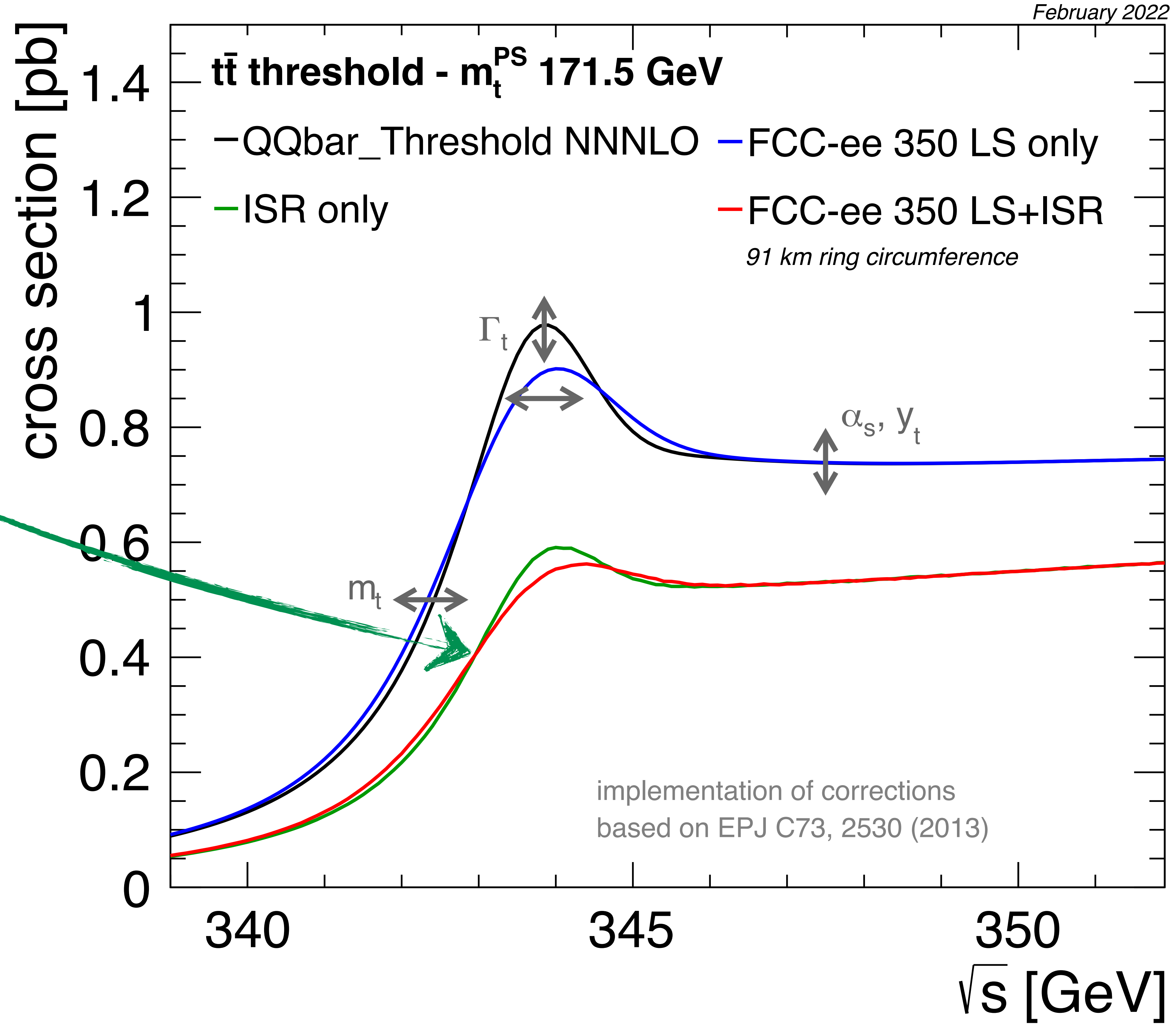


- QCD scale uncertainties highly relevant.
- Also need to calculate other effects, such as ISR, to the required precision!

the step from black to green

[only approximate in current experimental studies]



Theory Status

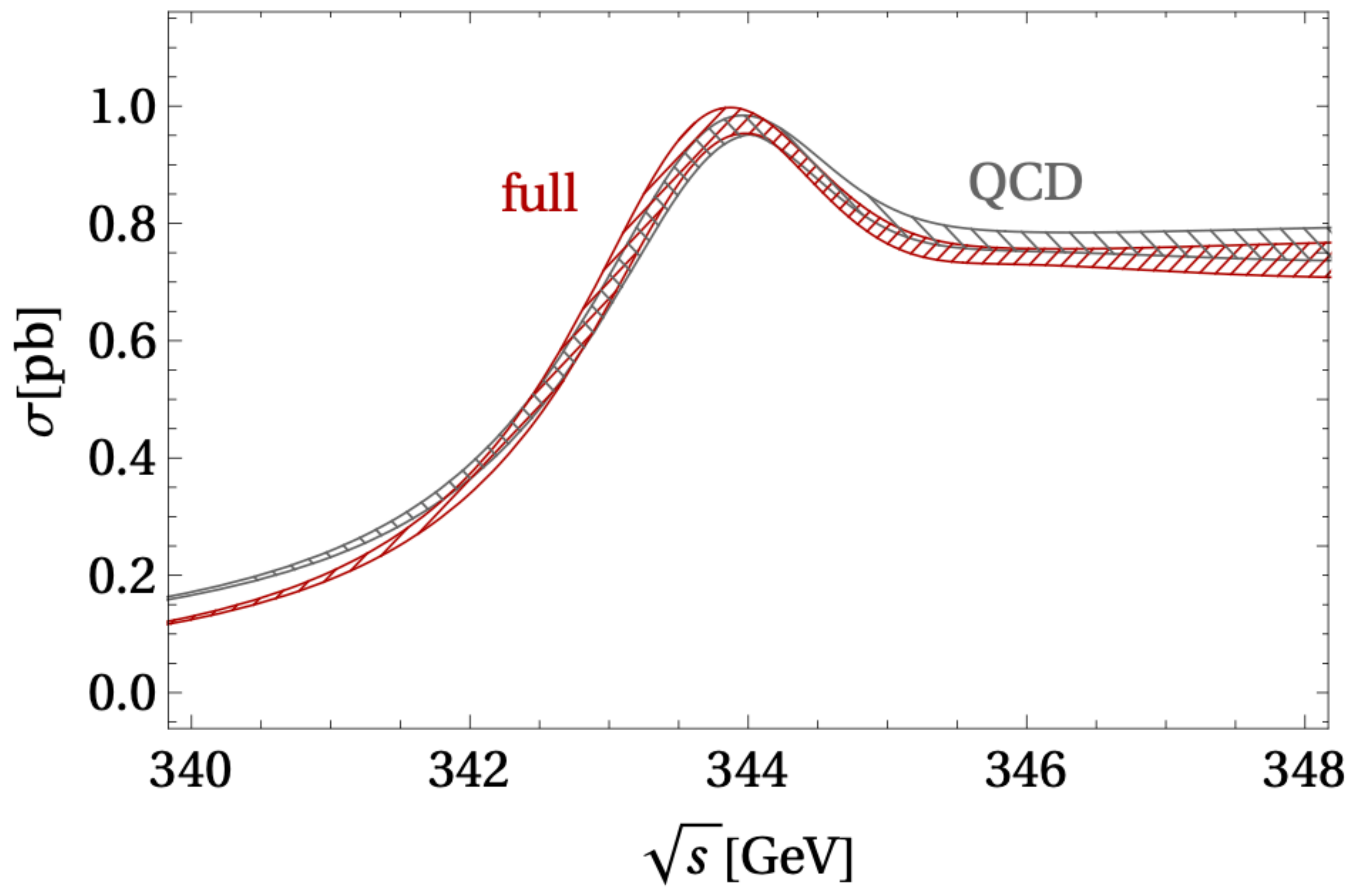
A quick aside

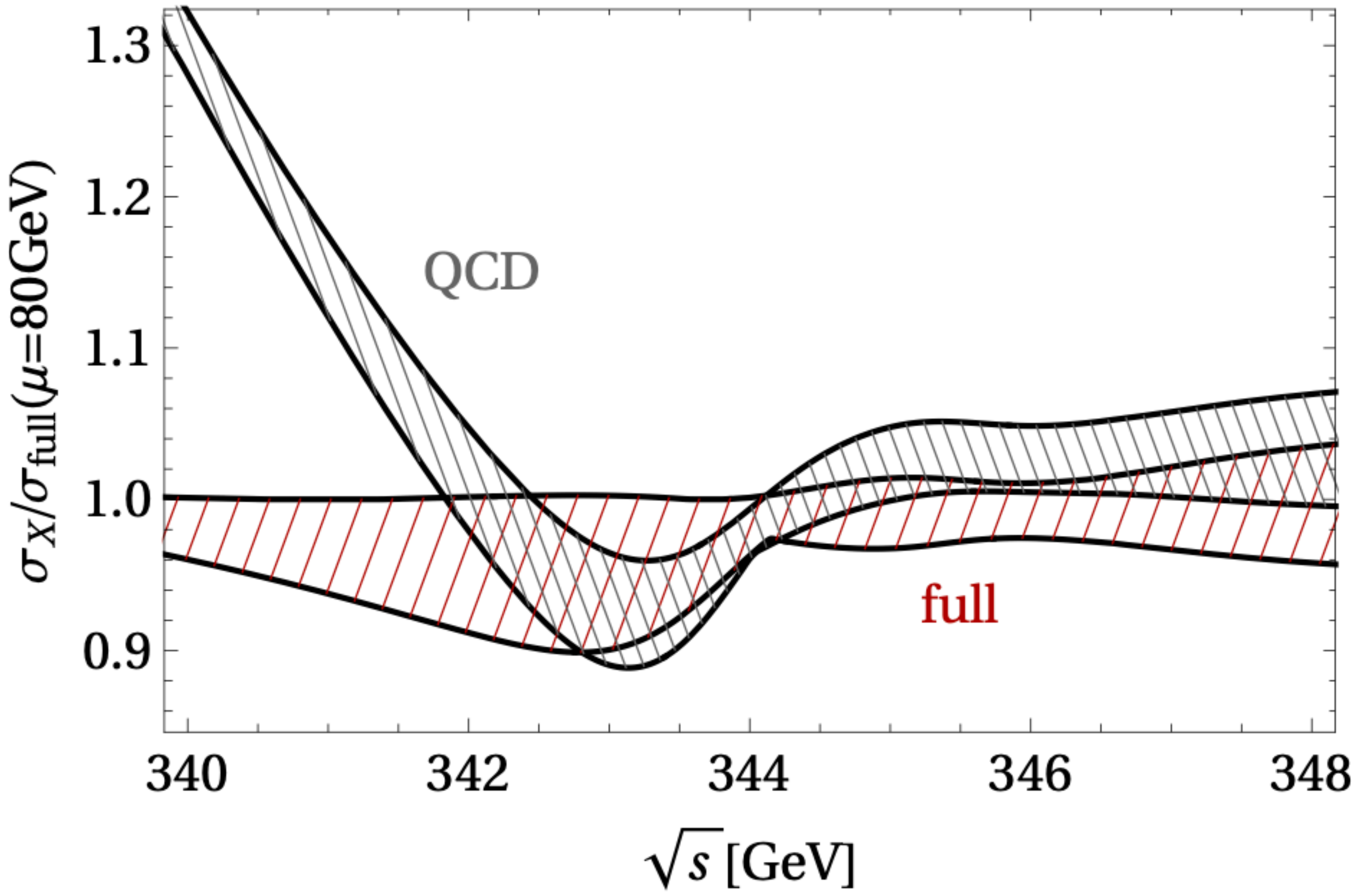
NNNLO (QCD+Higgs) + NNLO (EW+QED+non-resonant)

[MB, Maier, Piclum, Rauh, 2015; MB, Maier, Rauh, Ruiz-Femenia, 1710.10429]

Inclusive $e^+e^- \rightarrow W^+W^- b\bar{b}$ cross section

$m_{t,\mathrm{PS}}(20\,\mathrm{GeV}) = 171.5\,\mathrm{GeV}$, $\Gamma_t = 1.33\,\mathrm{GeV}$, $\alpha_s(m_Z) = 0.1185 \pm 0.006$, $\sin^2\theta_W = 0.2229$,
$\mu = (50\ldots 80\ldots 350)\,\mathrm{GeV}$, $\mu_w = 350\,\mathrm{GeV}$.

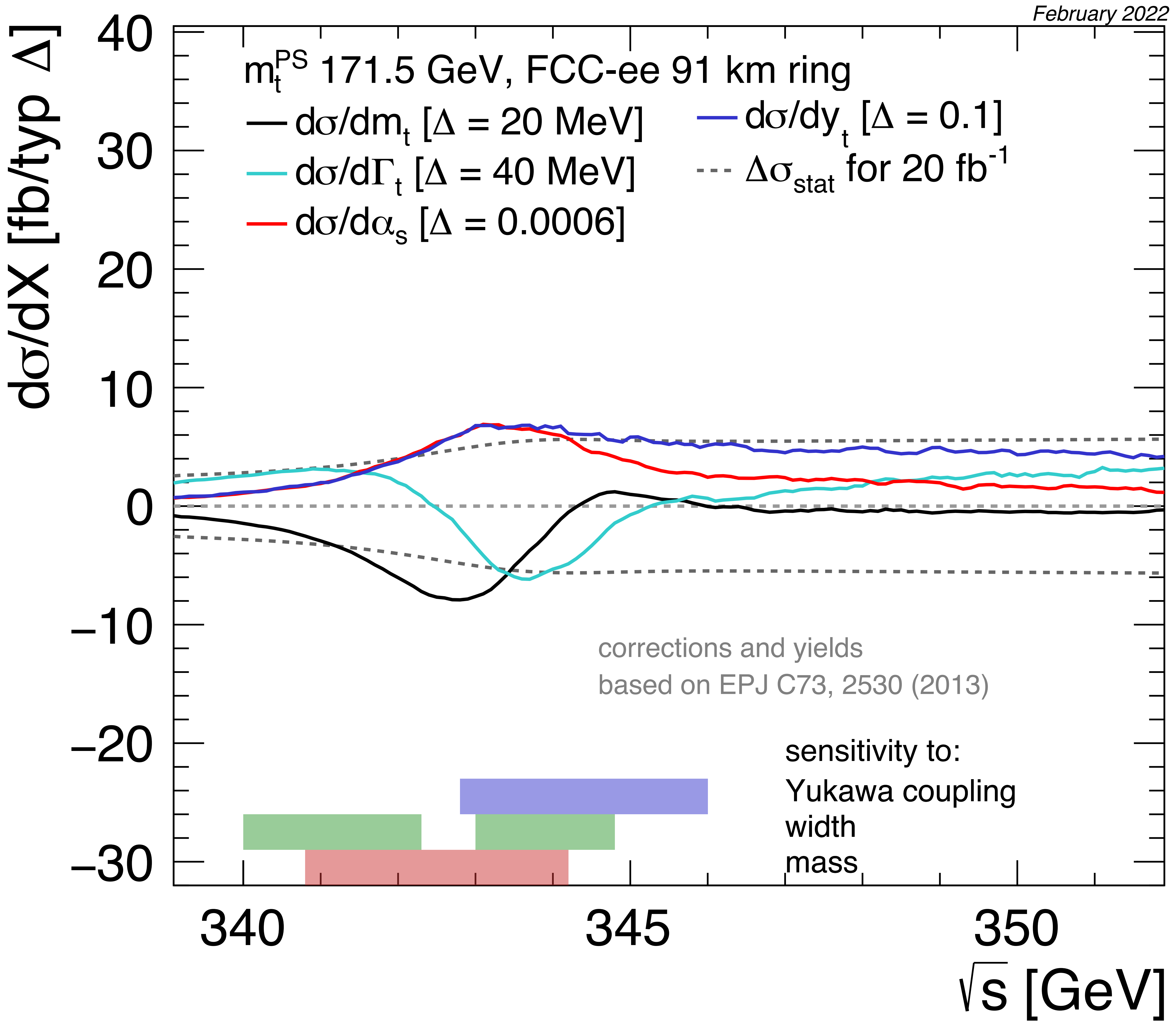




for a thorough discussion:
See presentation by Martin Beneke at CERN workshop “Precision calculations for future e+e− colliders: targets and tools”
https://indico.cern.ch/event/1140580

Choosing the Scan Range

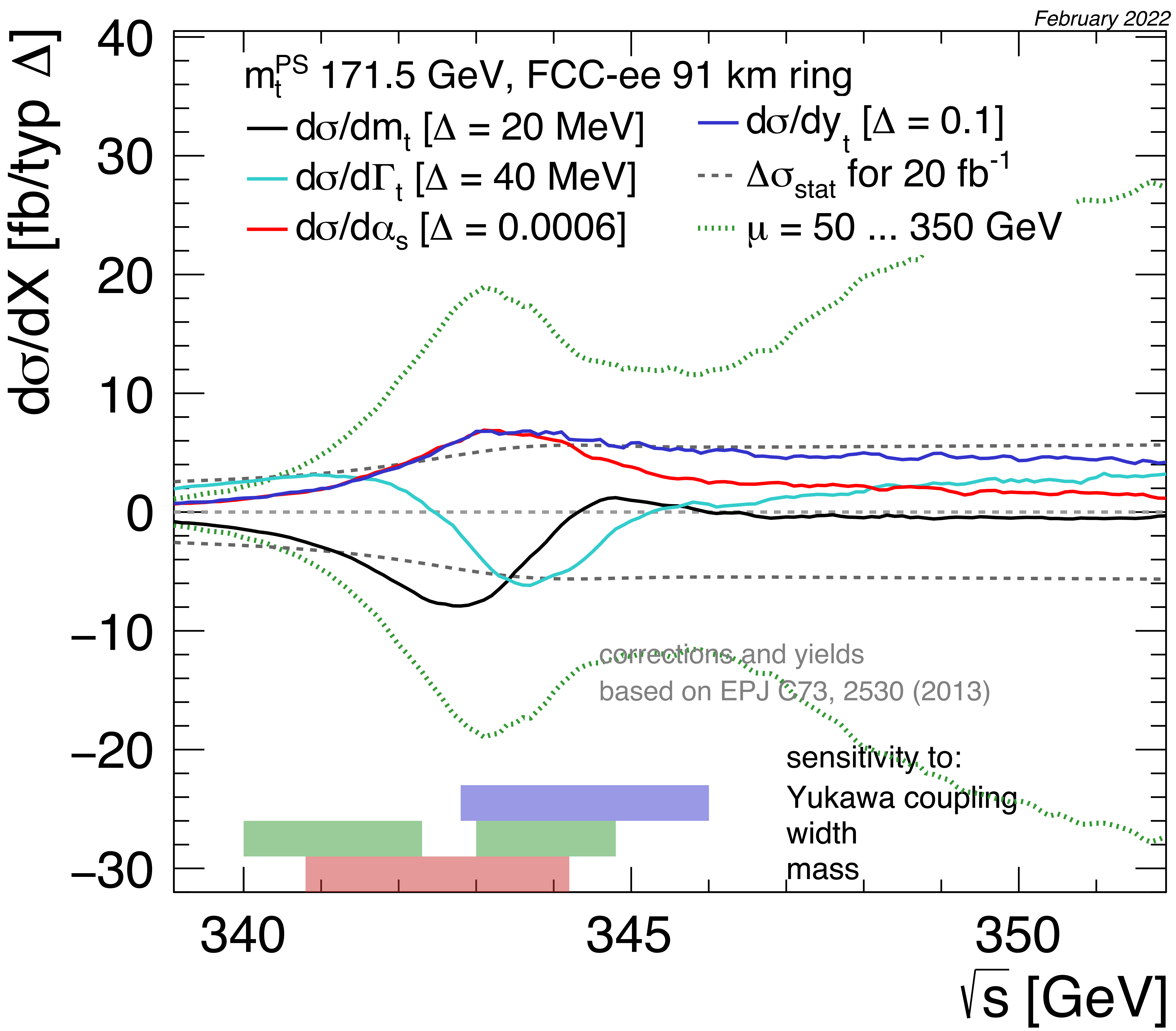
Parameter Sensitivity



- Plot shows the derivative of the cross section for various parameters - to make this understandable this is normalised to typical changes of these parameters
- Full use to optimize scan range requires knowledge of mass to ~ 200 MeV in PS scheme. Can be achieved with 2 x 5 fb^{-1}:
  point 1: $\sqrt{s} = 2 \times m_t^{PS,LHC} - 1.5$ GeV
  point 2: $\sqrt{s} = 2 \times m_t^{PS,LHC} + 0.5$ GeV [arXiv:1902.07246]
  (N.B.: This is safe also when taking theory uncertainties into account)
- Optimizing for particular parameters can reduce the statistical uncertainty by ~ 25% [JHEP 7, 70 (2021)]

Choosing the Scan Range

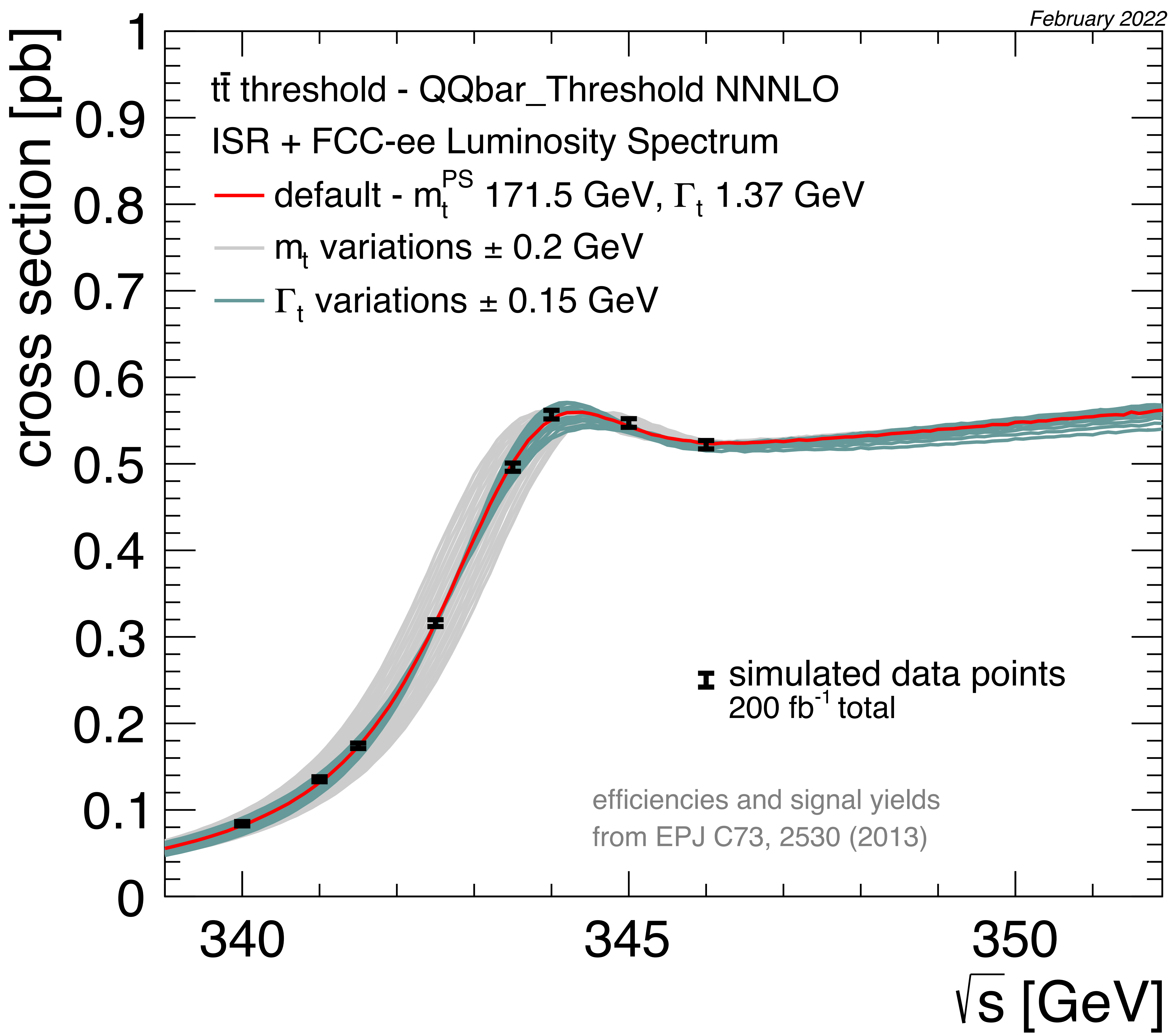
Enter theory uncertainty



- QCD scale uncertainties dominate over point-by-point statistical uncertainties for typical threshold scans: At this point optimising scan strategies to reduce statistical uncertainties does not improve the total uncertainty - in fact concentrating on a very small range may make systematic control more difficult.
- In general: Also to separate contributions from different parameters, the most relevant range is 340 - 346 GeV.
  Higher energy points would primarily benefit a y_t measurement.

Choosing the Scan Range

Bottom line for FCC-ee studies

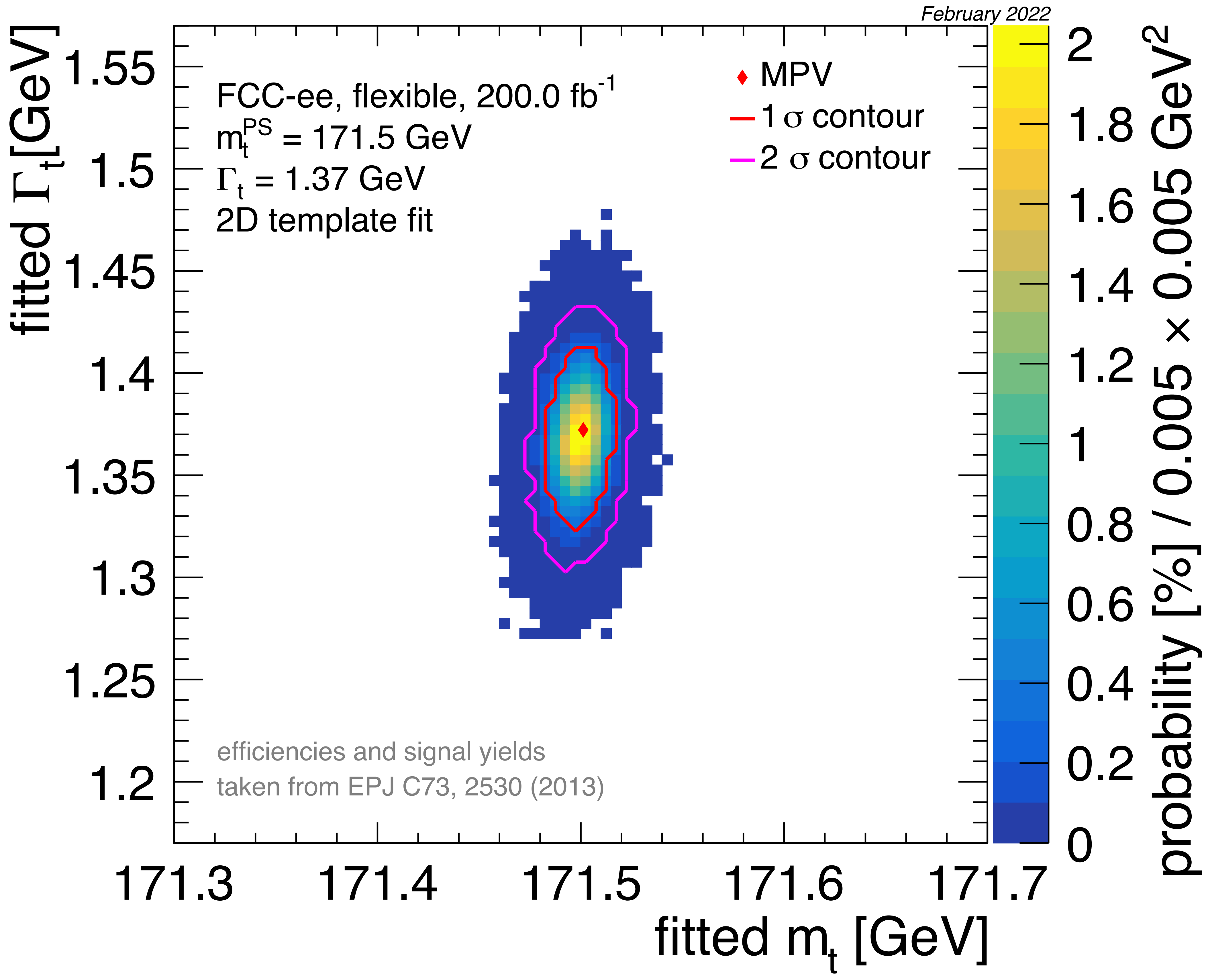


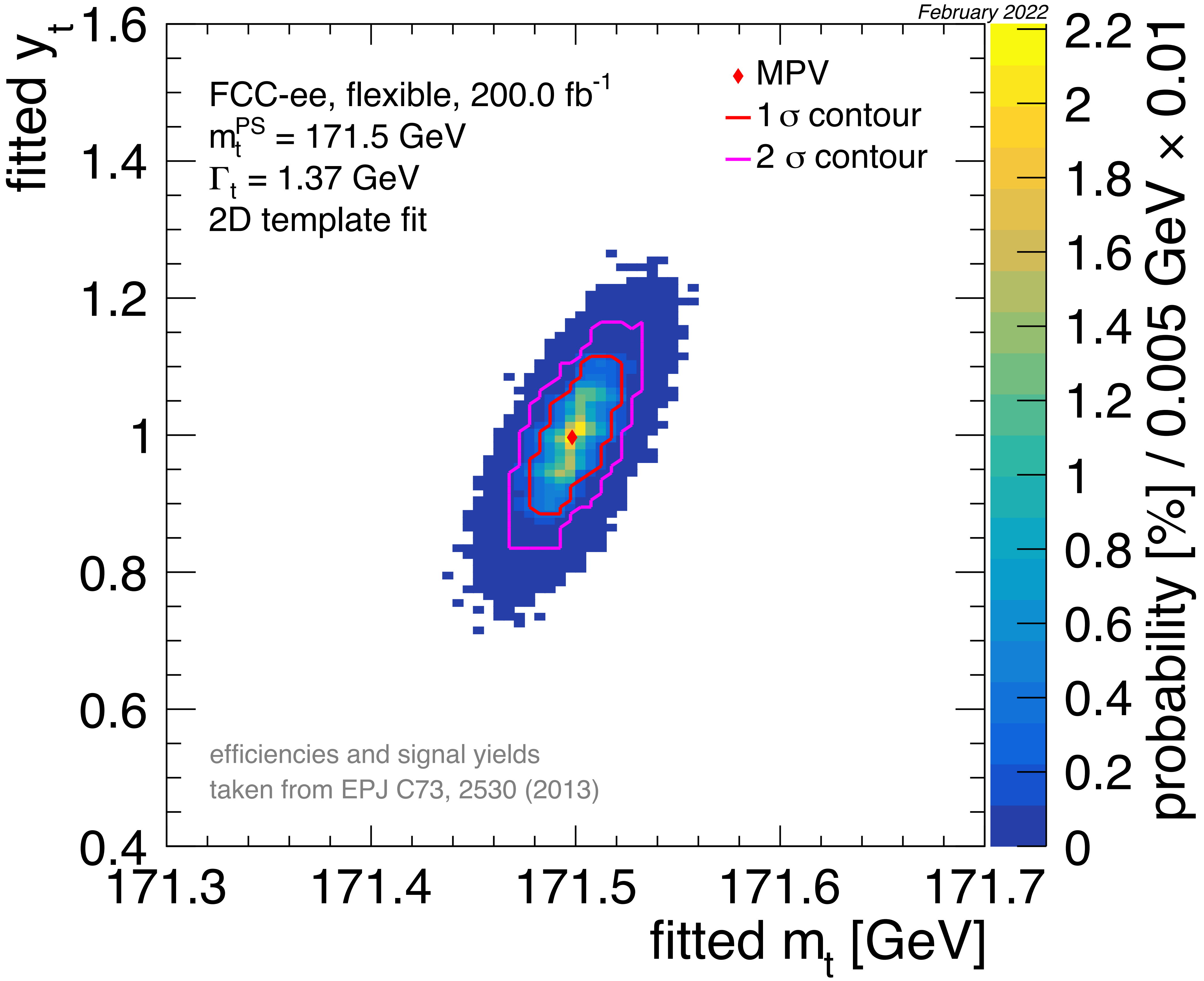
- Mildly optimized scan (mass & width) for FCC-ee as a balance between different sensitivities: 8 points in the range of 340 - 346 GeV

  assumed for most results in the following

Fitting Multiple Parameters

Mass, Width, Yukawa Coupling





- ~ 45 MeV on width
- ~ 11.5% on Yukawa coupling

Uncertainties Overview

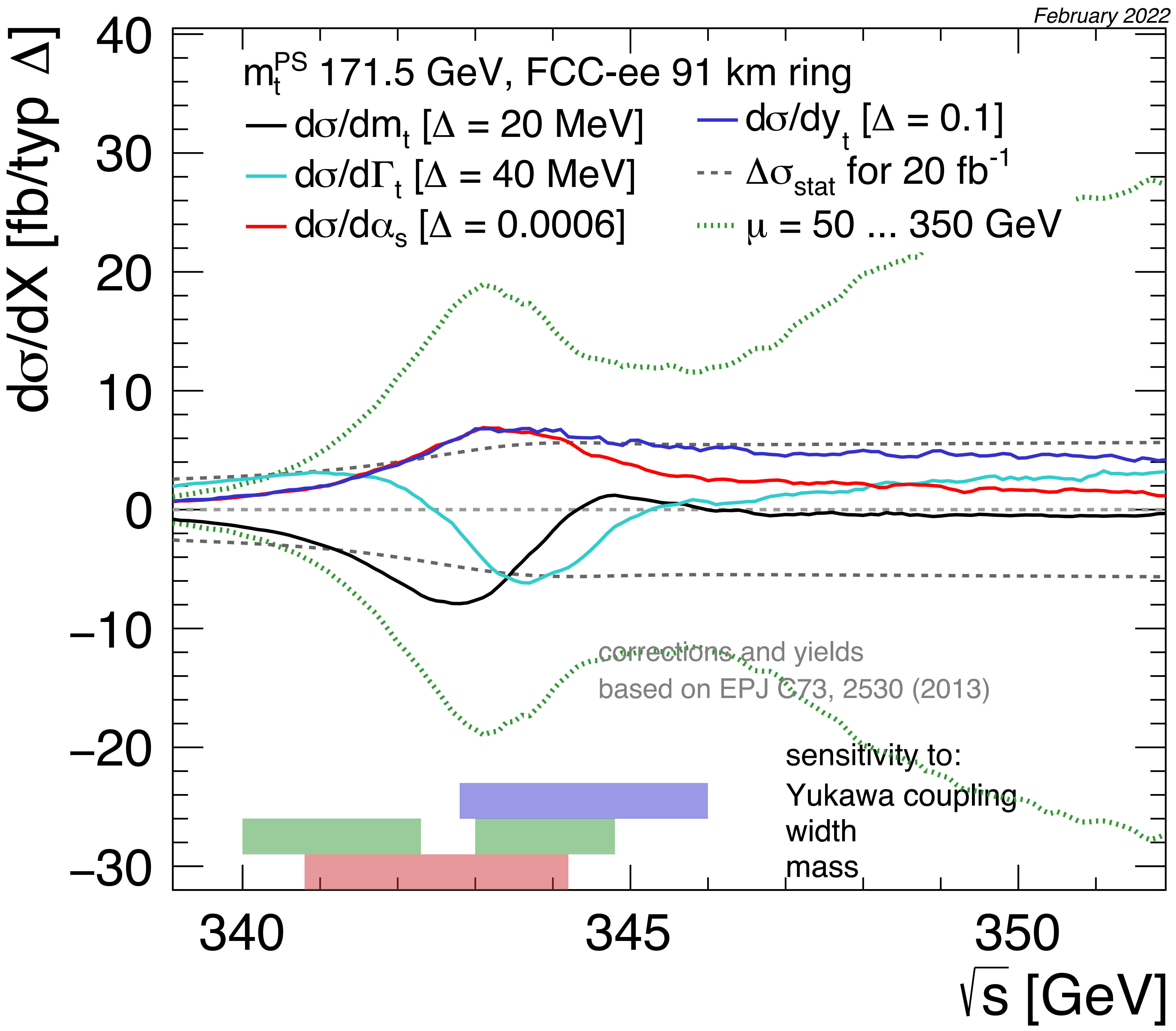
ILC & FCC-ee

- Relatively thorough evaluation for ILC:

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	

Uncertainties - Parametric

A few more details



Correlation of mass with α_s, y_t

Uncertainty scales with input precision:

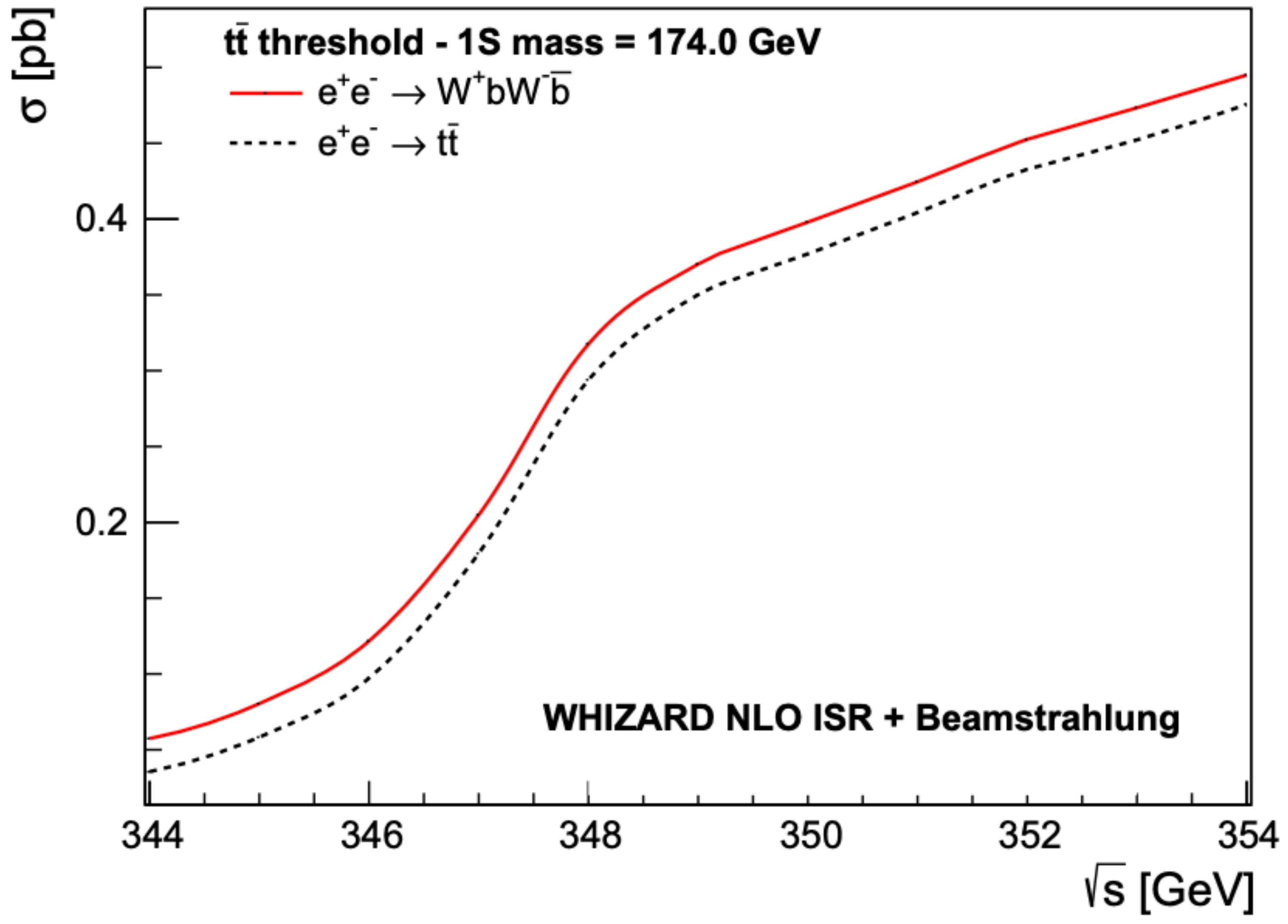
$\Delta m \sim 2.6$ MeV per 10^{-4} in α_s

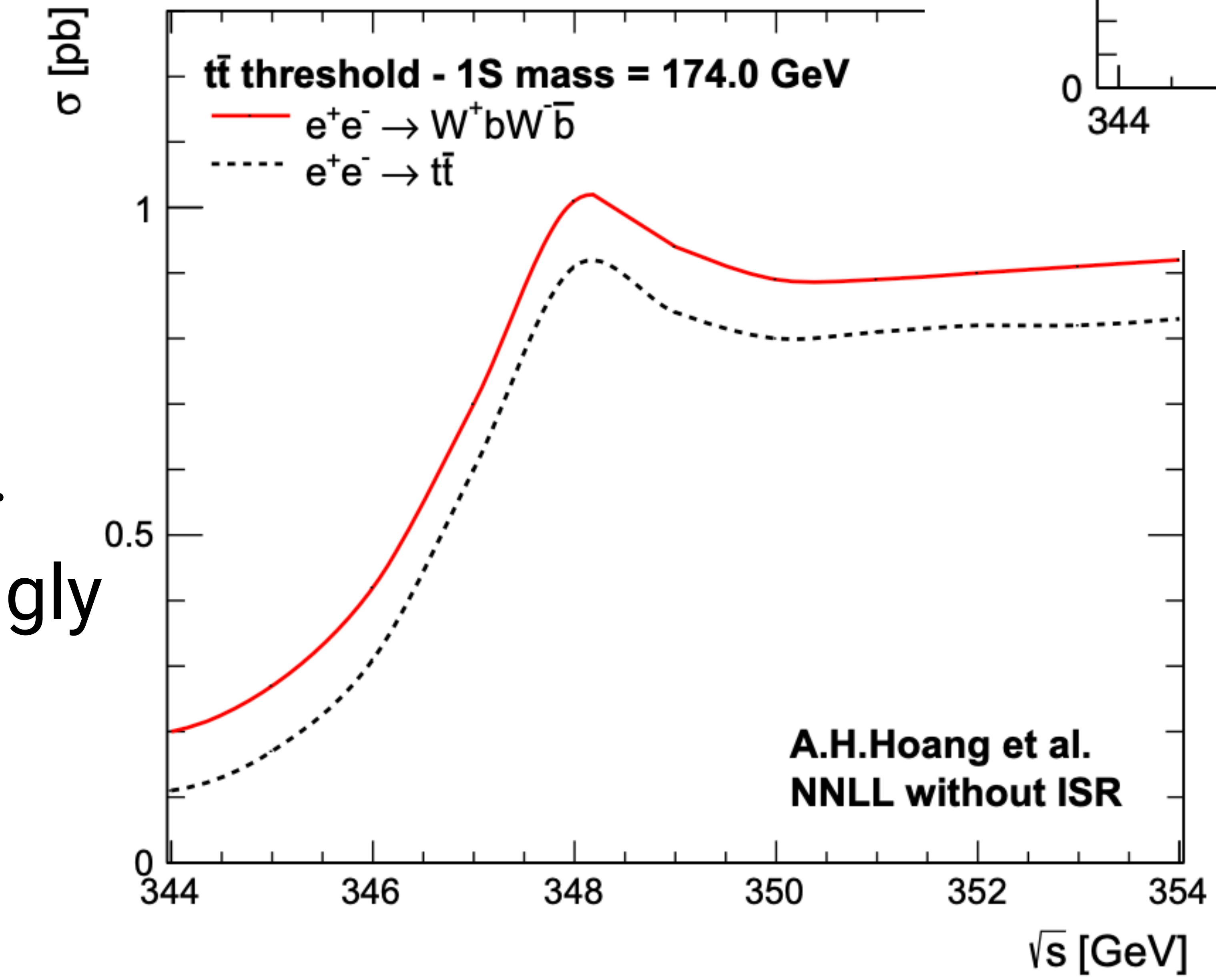
$\Delta m \sim 1.6$ MeV per 1% in y_t: ~ 5 MeV for 3.4% from HL-LHC

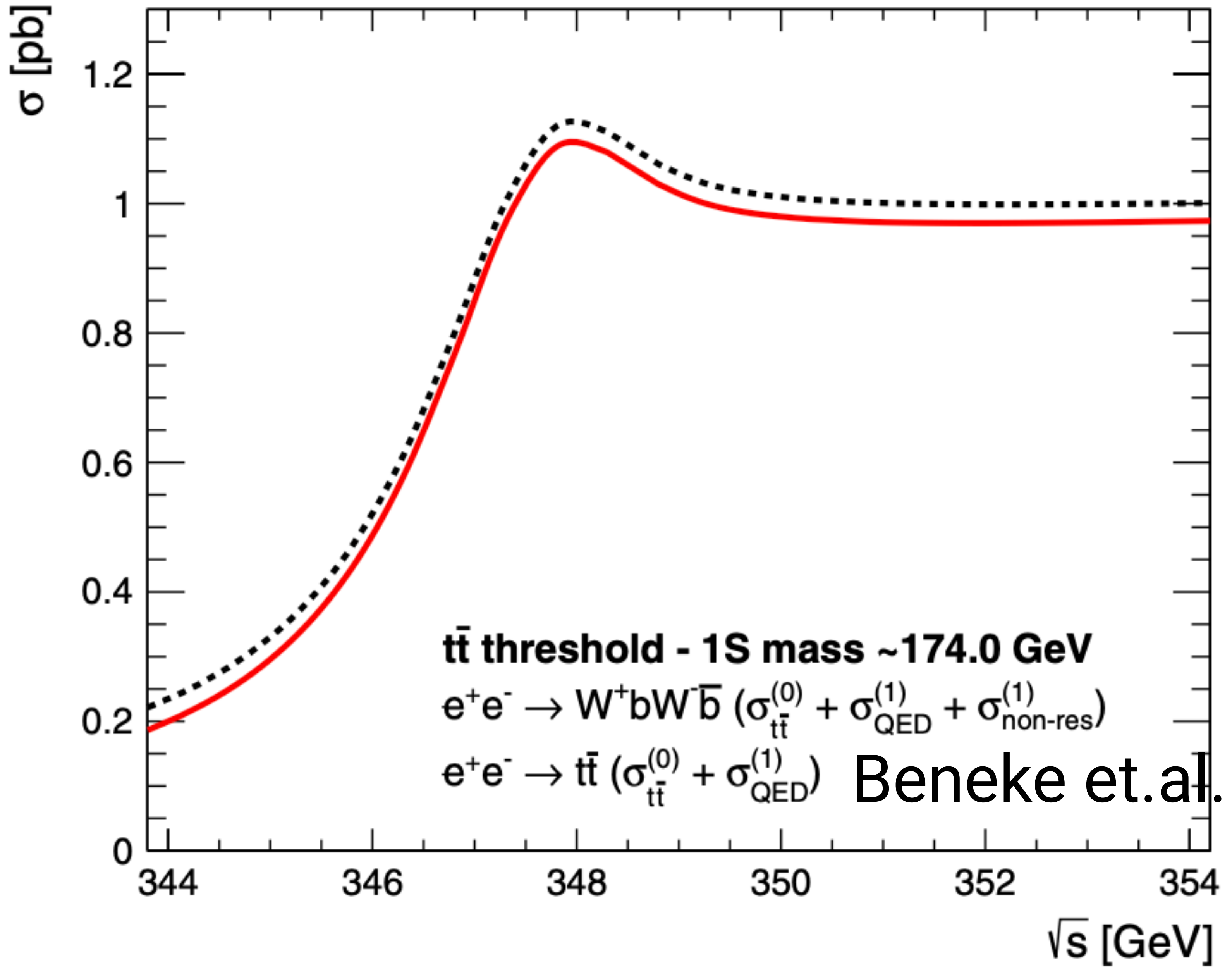
Uncertainties - Non-resonant contributions

A few more details

- Studied in EPJ C75, 223 (2015) (Fuster et al)







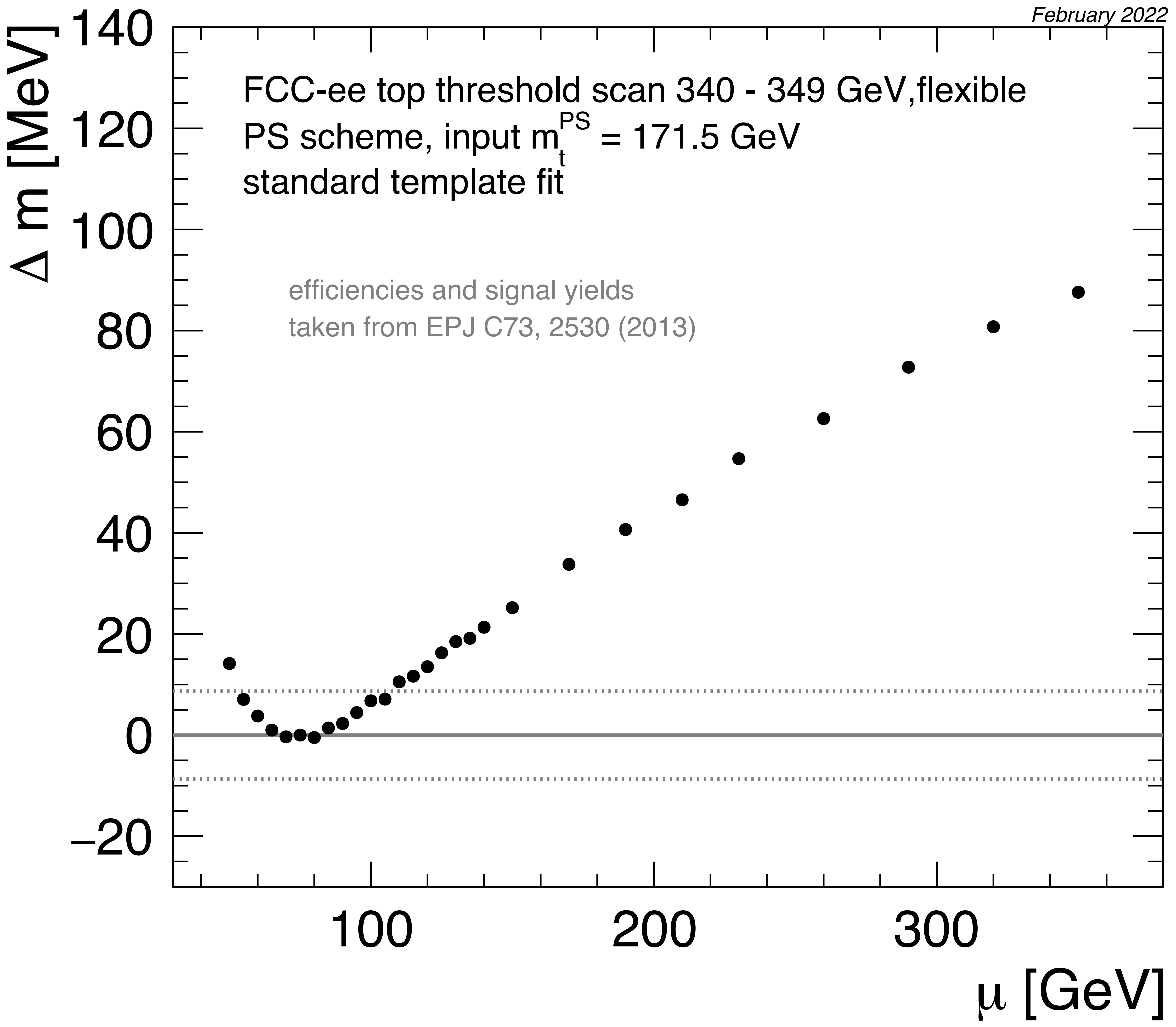
- Non-resonant contributions in the threshold region are non-negligible.
- Contribution to yield depends strongly on cuts.
- Cuts can influence shape

- Precise understanding and control important: need to limit the effect to well below 1% of cross section to make uncertainty smaller than statistics!

Uncertainties - Scale

A few more details

- Impact of QCD scale uncertainties on mass, width, Yukawa extraction



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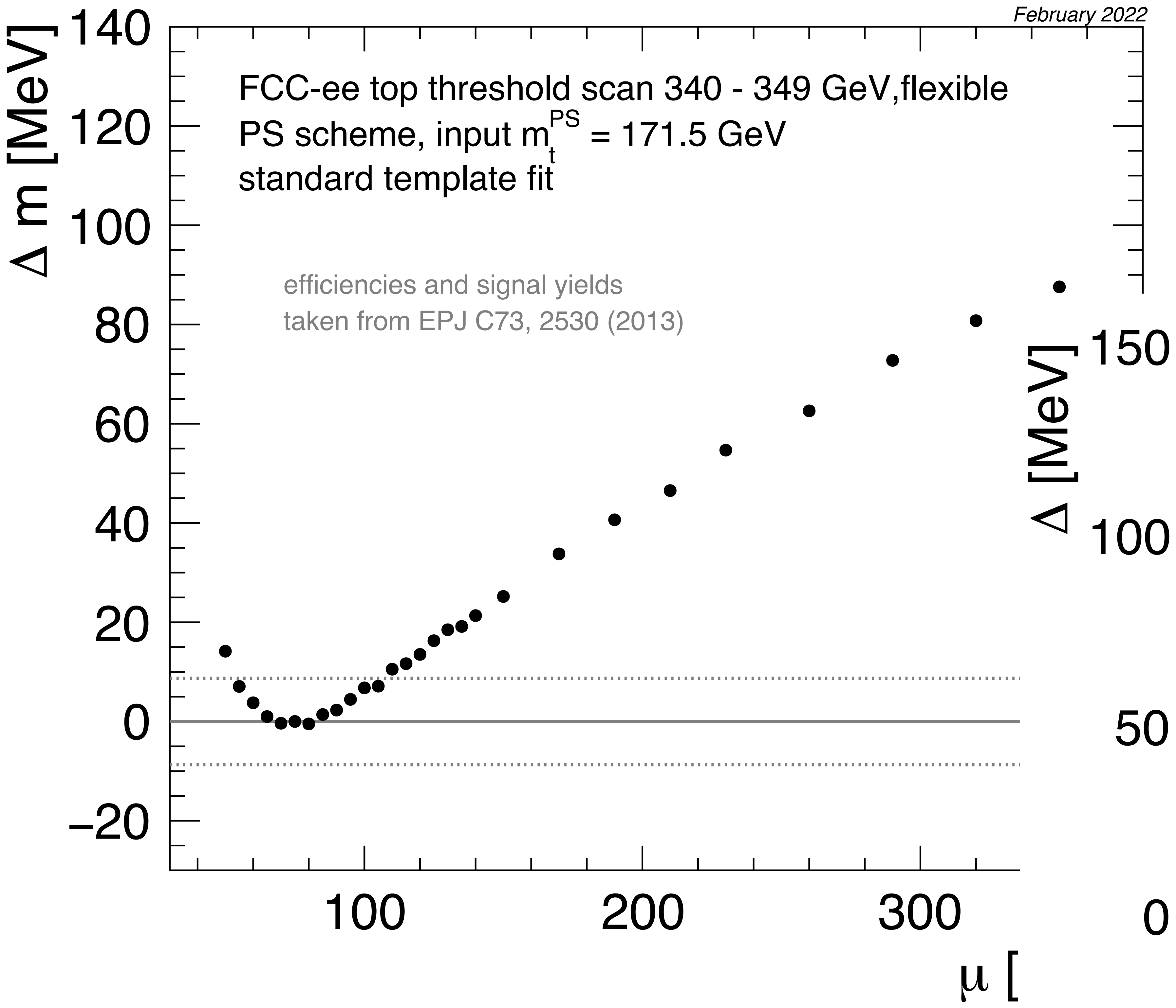

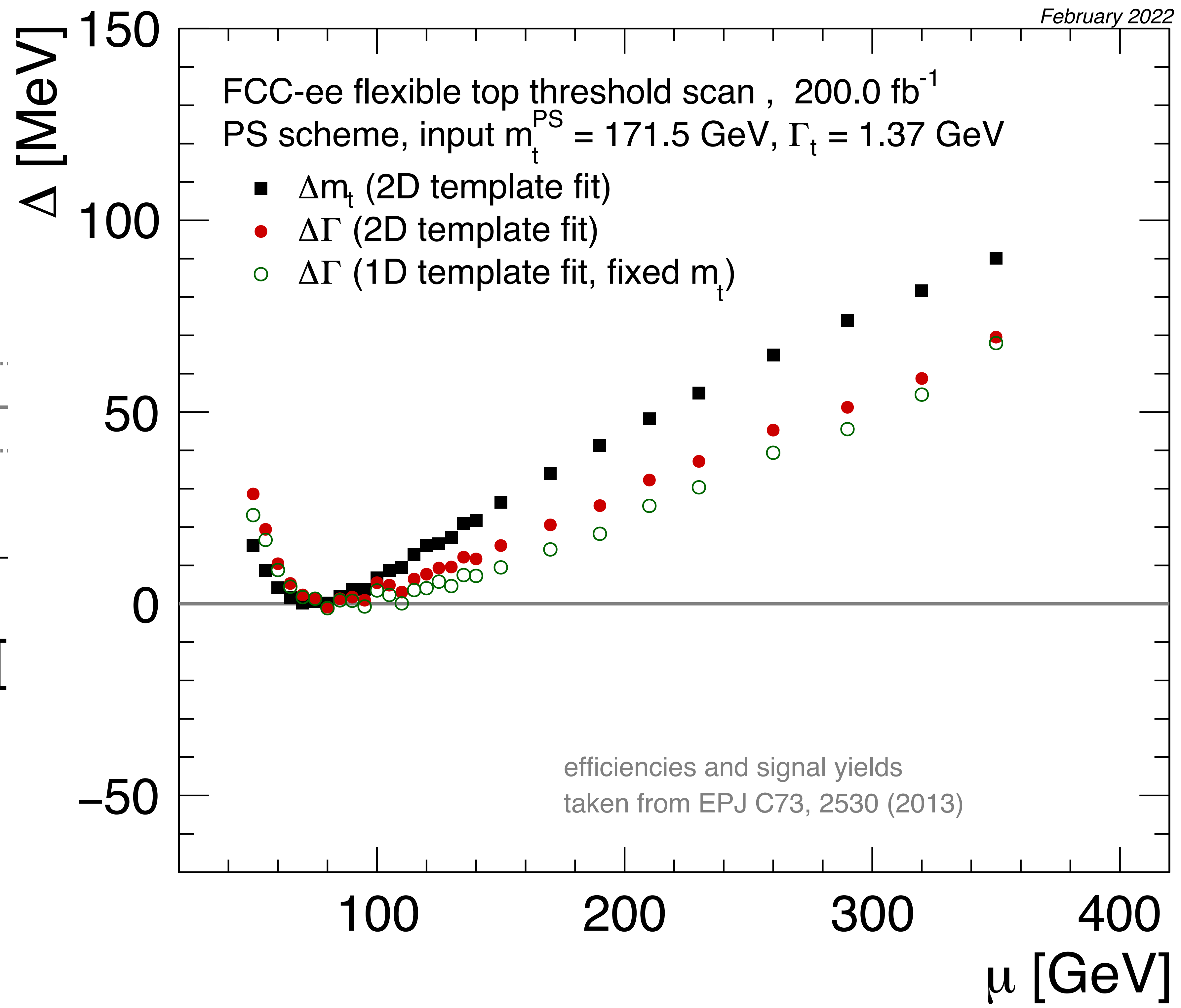

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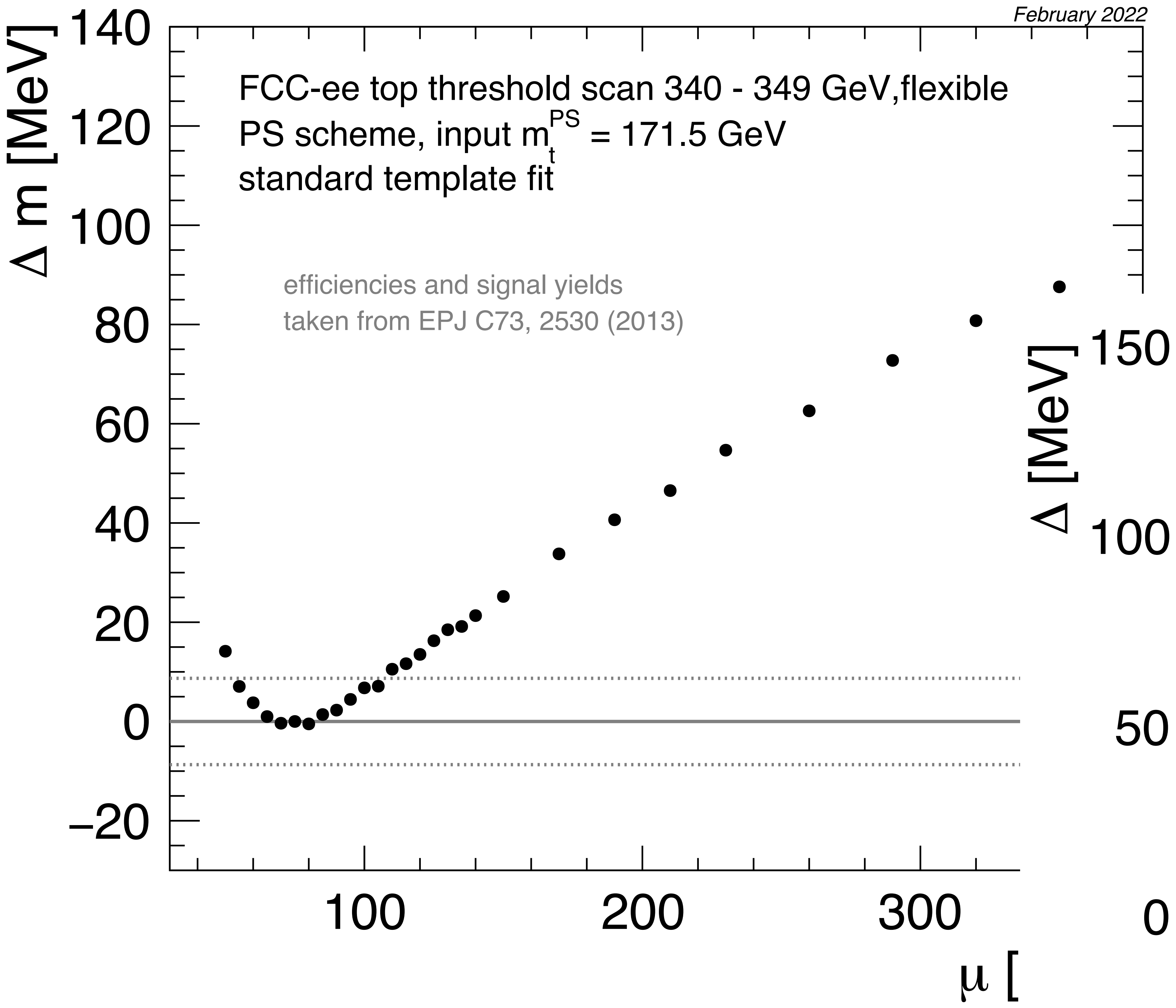

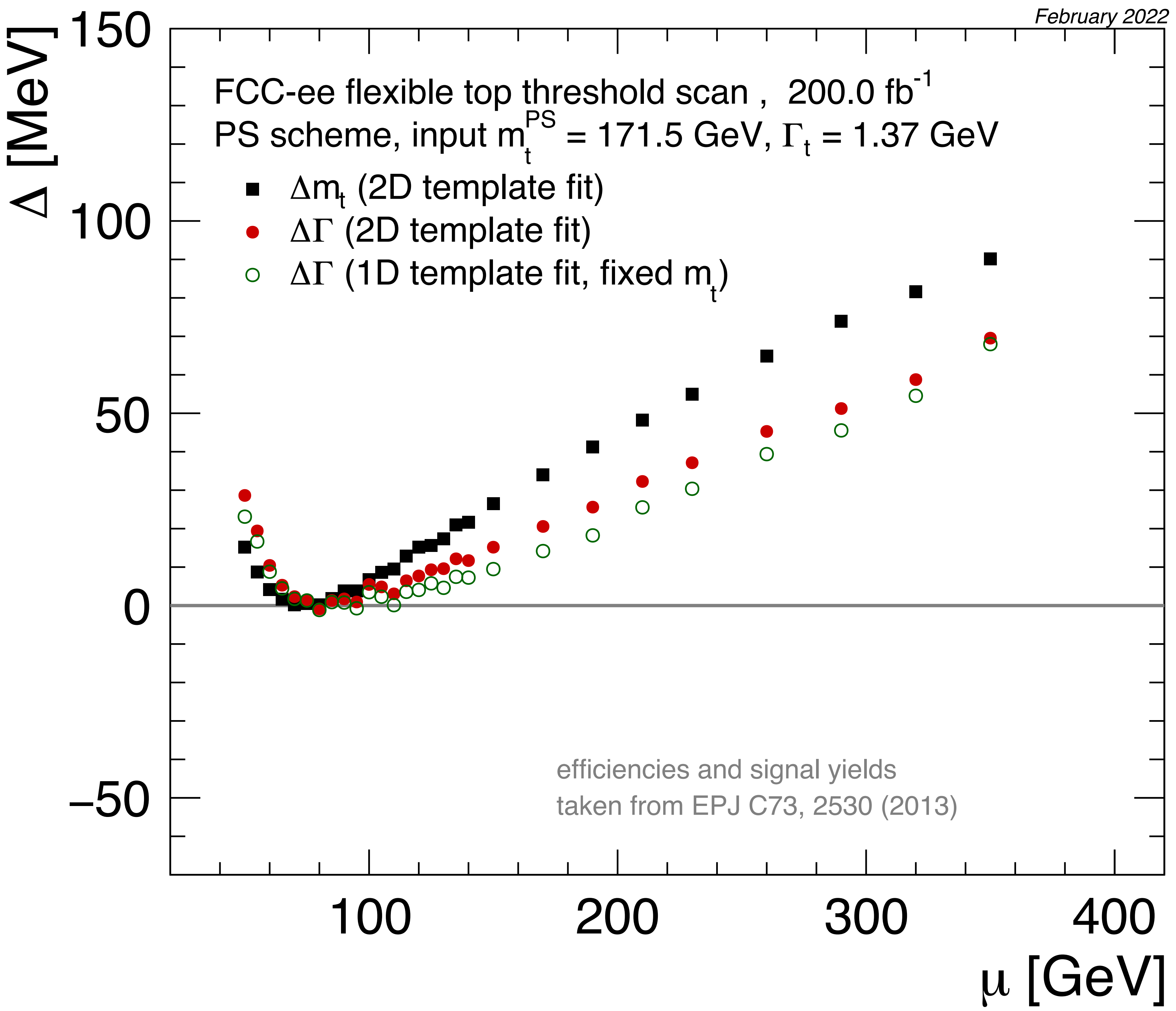

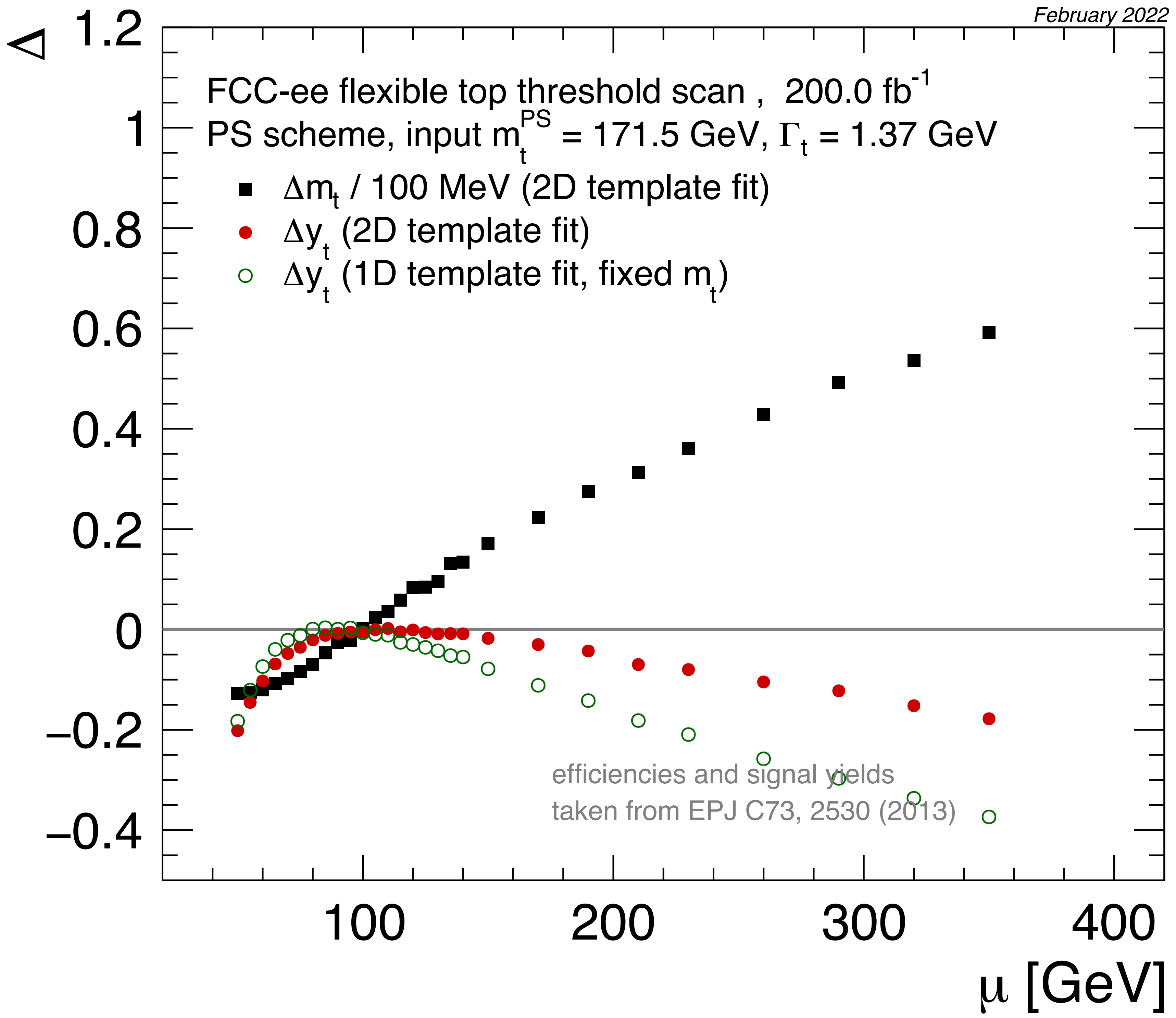

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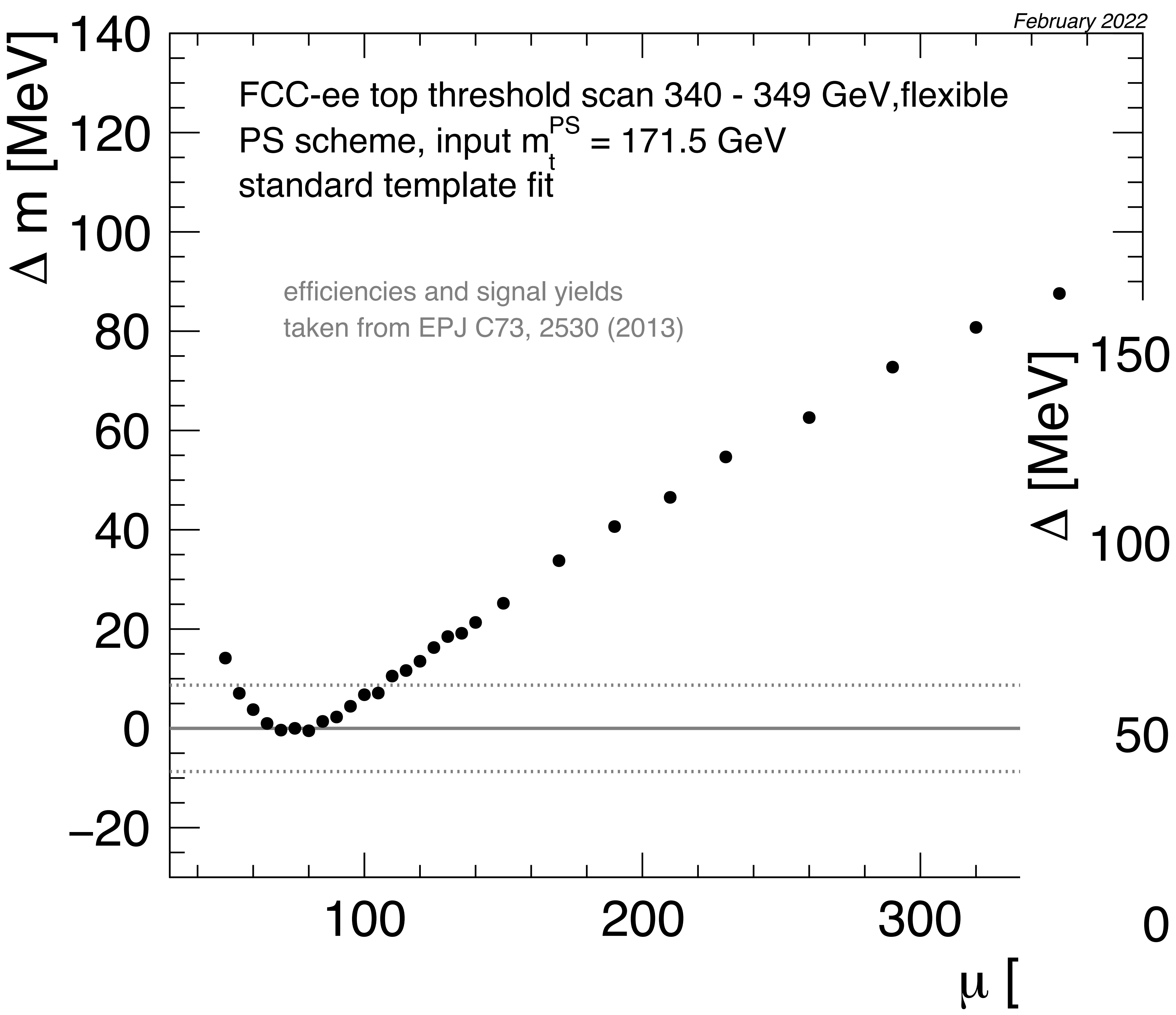
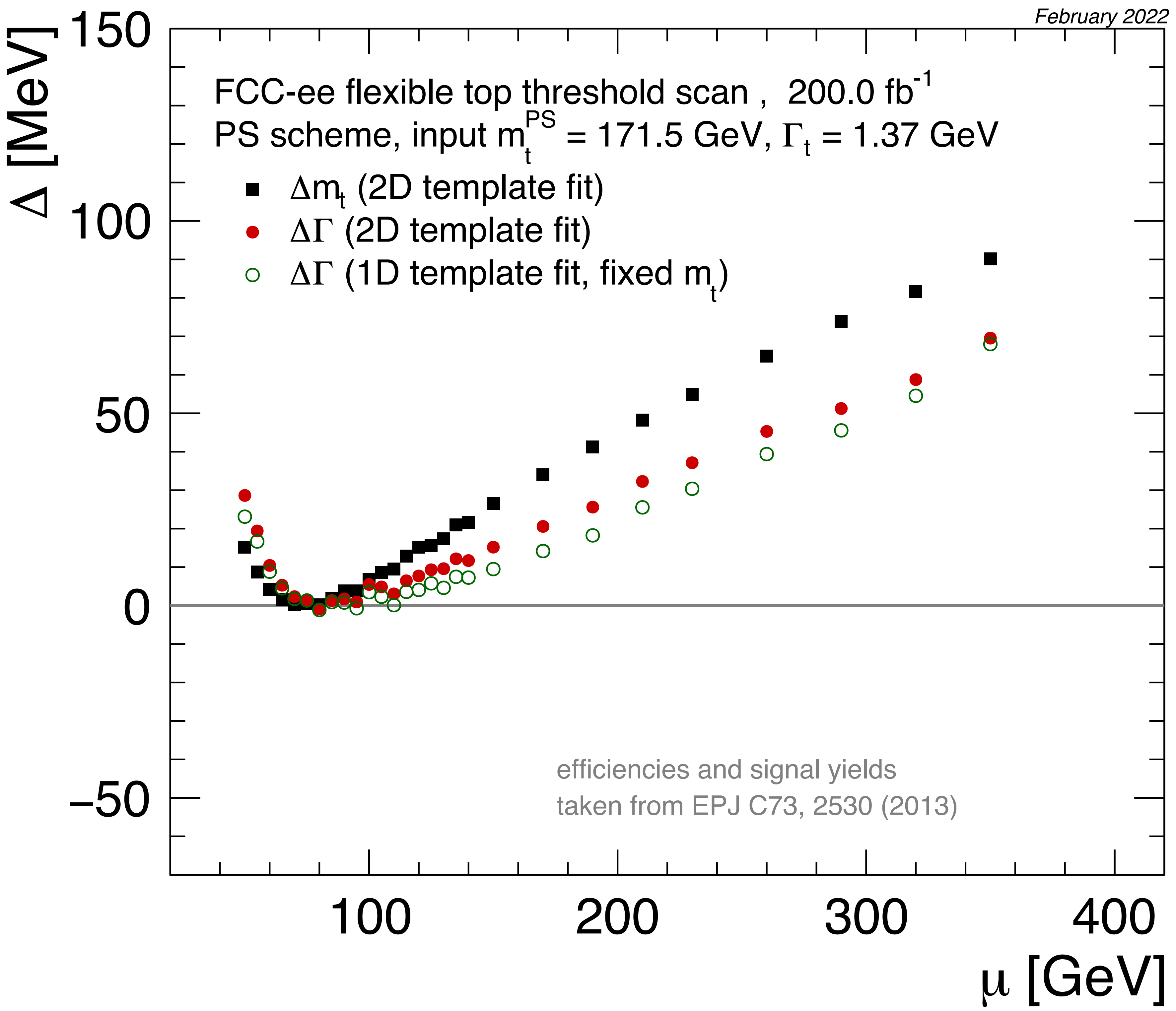
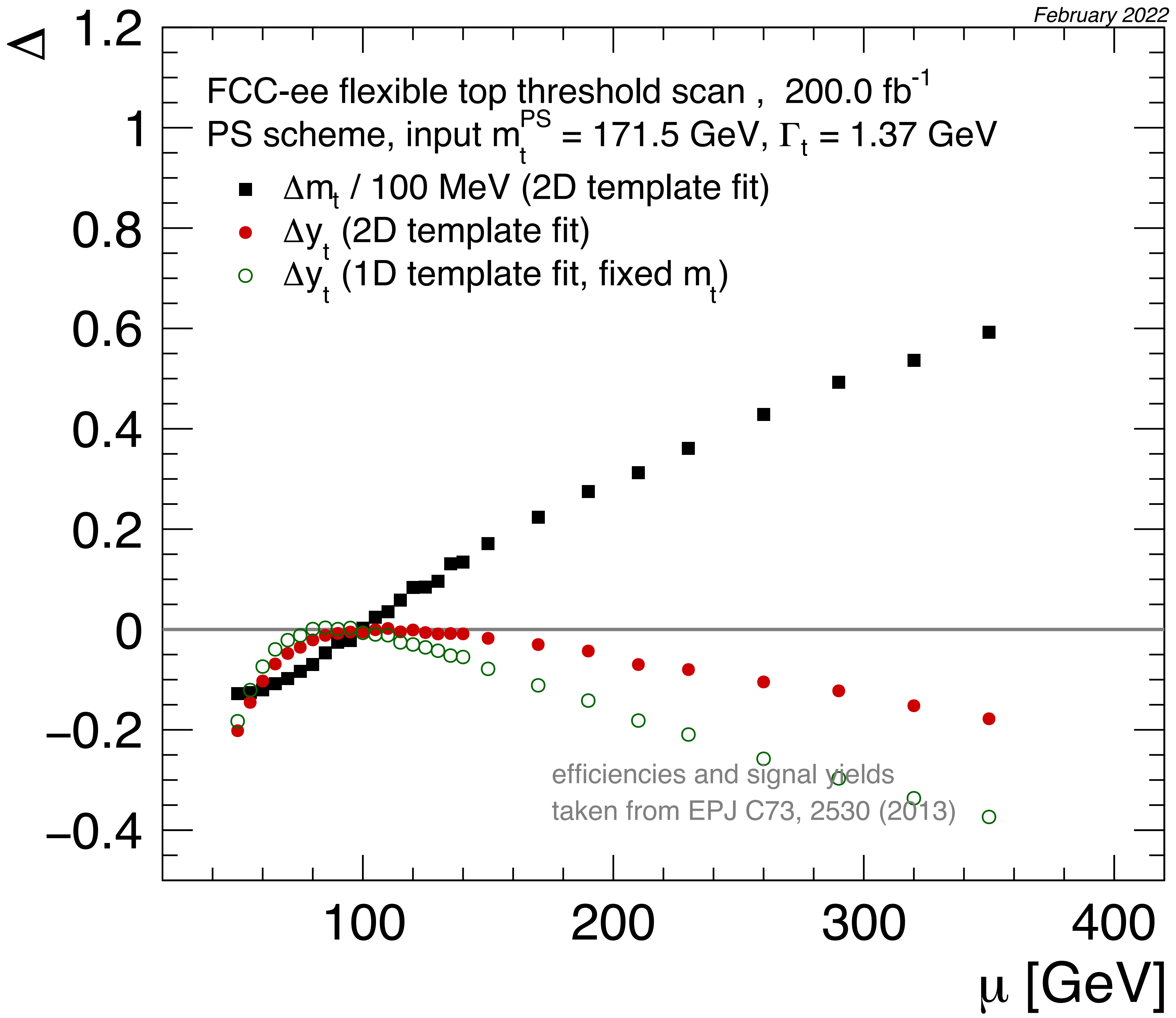






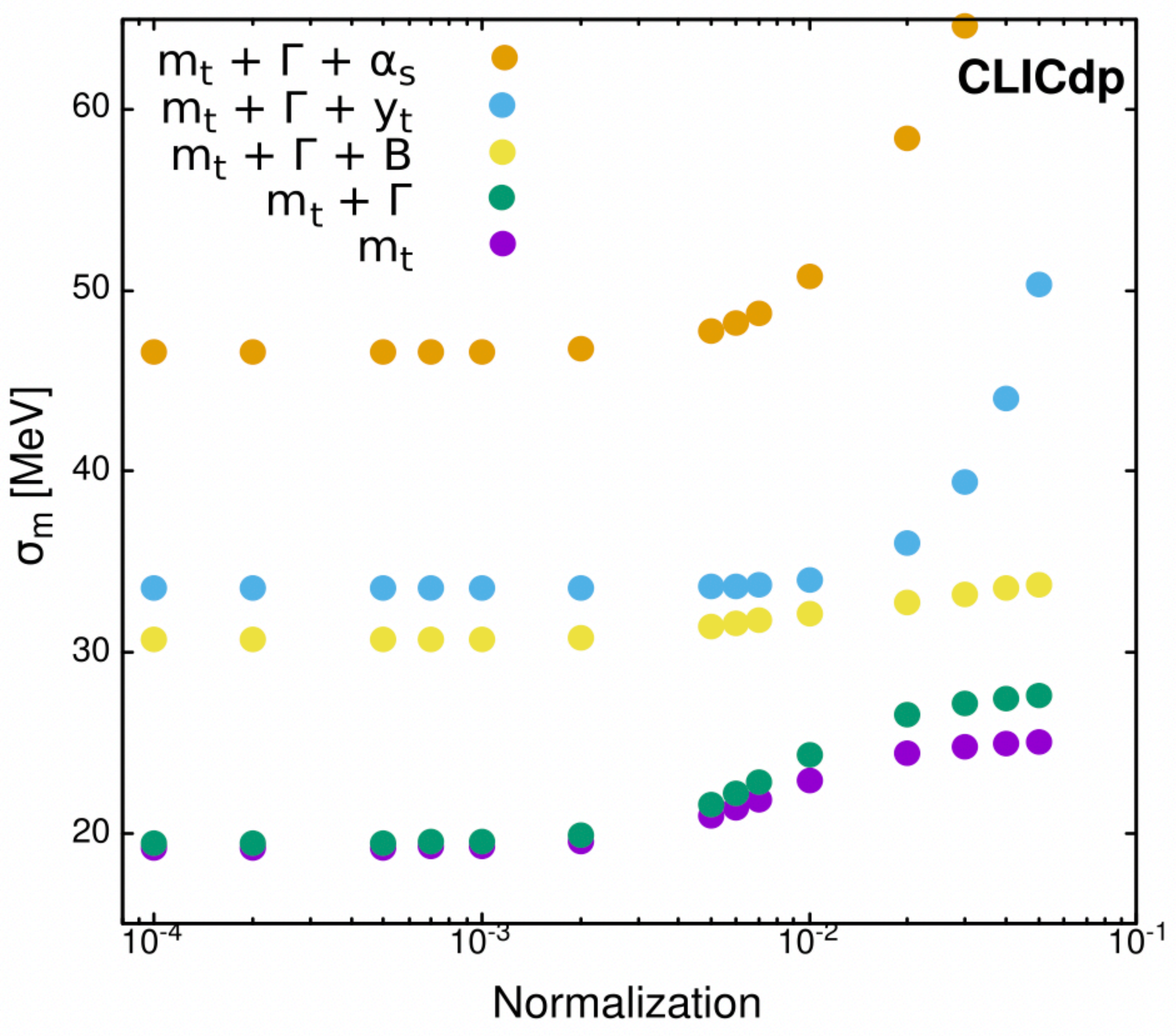
The leading systematic:

Improvements directly propagate to total precision

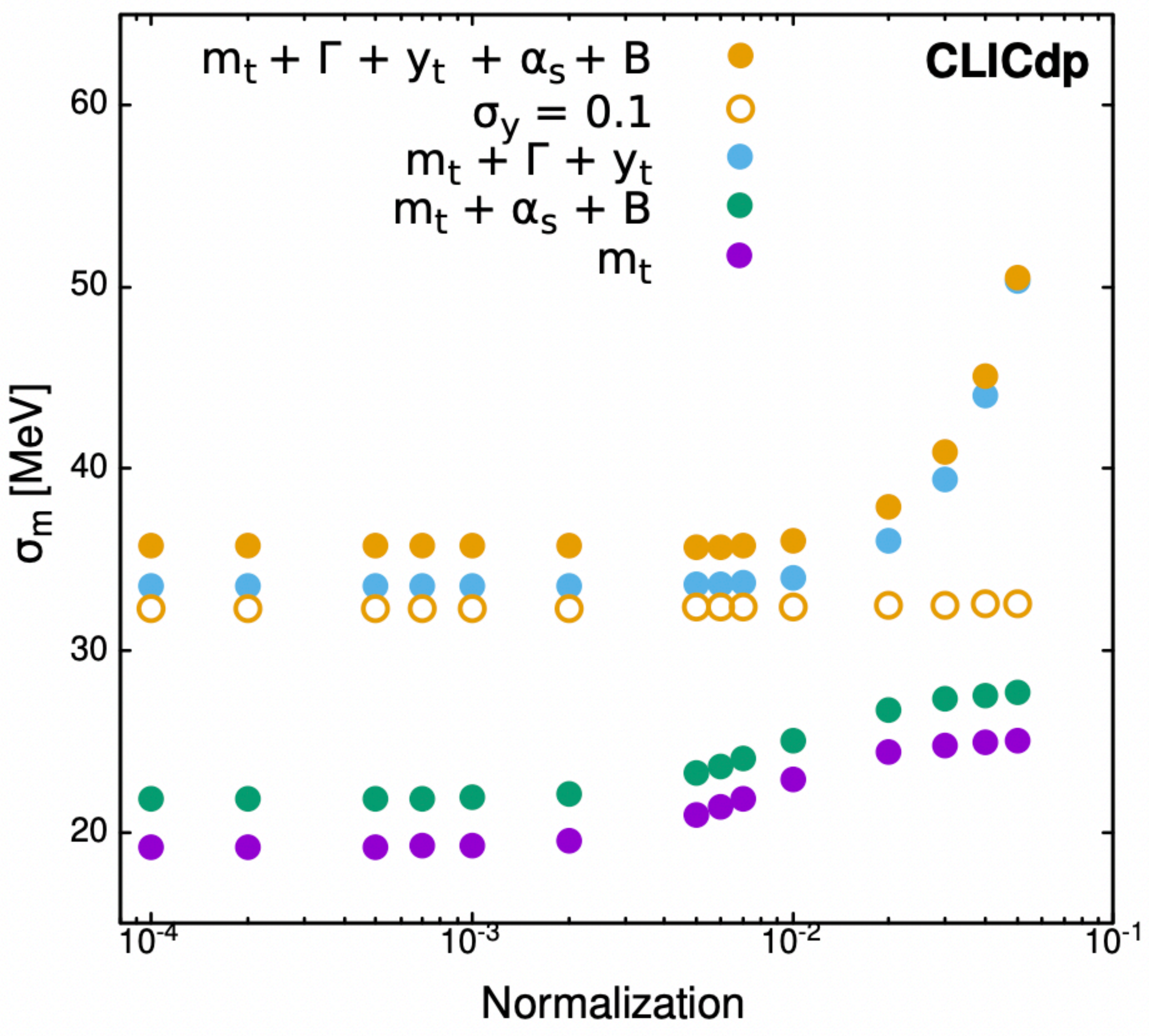
Fitting Multiple Parameters - CLIC

Mass, Width, Yukawa Coupling, Strong Coupling

all parameters free



"SM constrained"



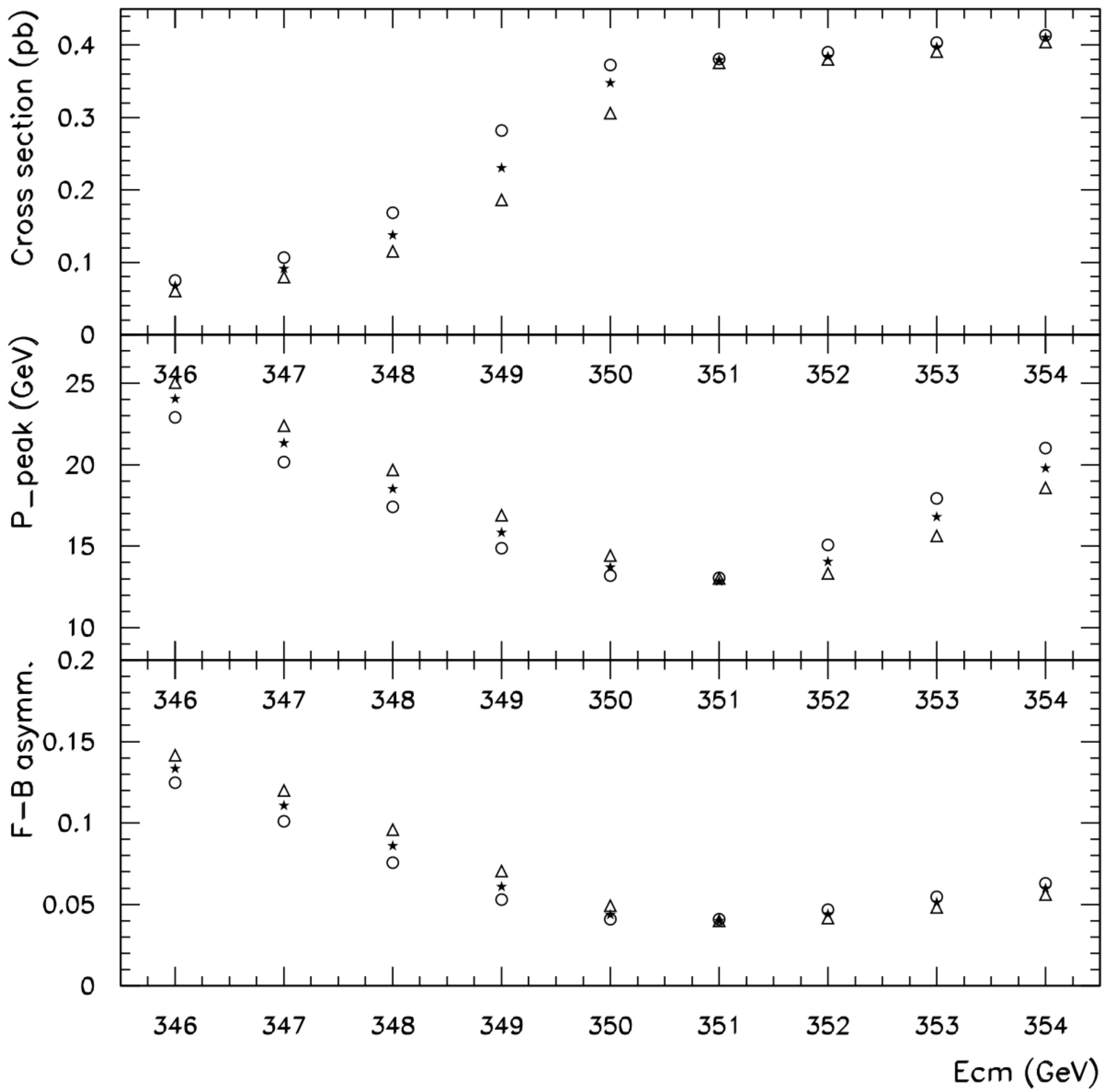
Study by Filip Zarnecki

Beyond Cross Section

Additional observables

- Other observables also provide sensitivity to the mass and other parameters in the threshold region

Sensitivity to top mass



Martinez, Miquel; EPJC 7, 49 (2003):

- Cross section
- Peak of top momentum distribution
- Forward-backward asymmetry

A key challenge when using additional observables beyond the cross section:
Understanding and control of theory systematics.

Bottom Line

- The top quark pair production threshold gives access to top quark properties.
  In particular: Ultimate measurement of the top quark mass.
  - Also width, strong coupling, Yukawa coupling - with the latter two expected to be “done better” in other measurements / at other energies.
- A challenge for theory: Understanding parameters on a level comparable to expected experimental precision. Theory is a / the leading systematic for many measurements - for the mass it is the leading uncertainty overall.

➫ *Advances in theory directly translate into improvements of overall precision.*