Top Mass Measurements at e^+e^- Colliders

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Max-Planck-Institute for Physics

Snowmass '21 CSS
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Outline

- Different experimental routes
- A detailed look at the threshold
- Snowmass ’21 Systematics summary
- A further look at key uncertainties

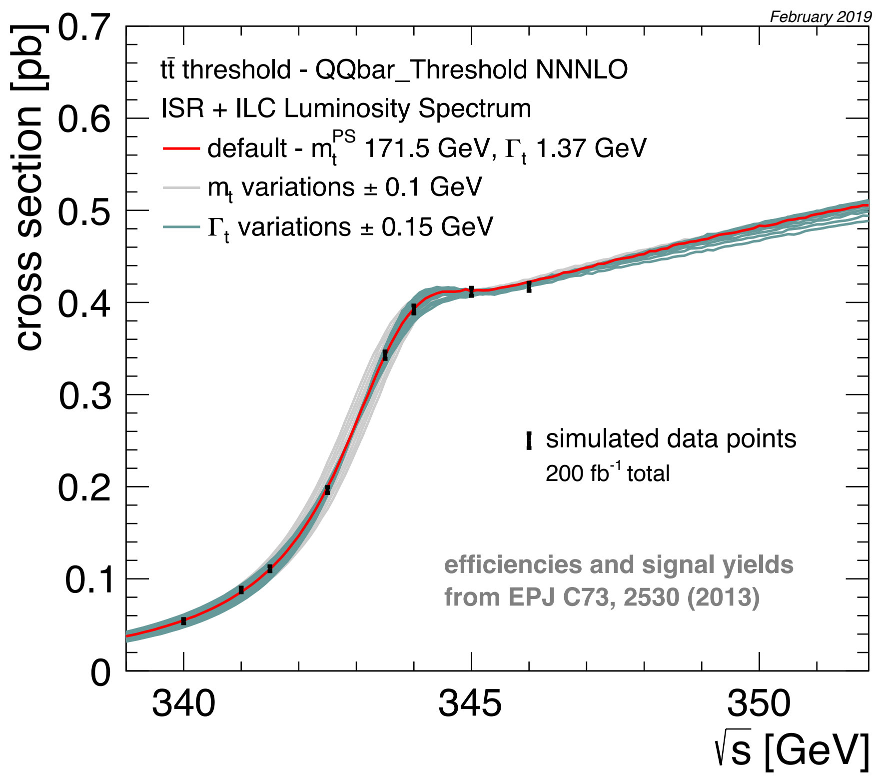
Top Quark Mass: Measurement Strategies

At and above threshold

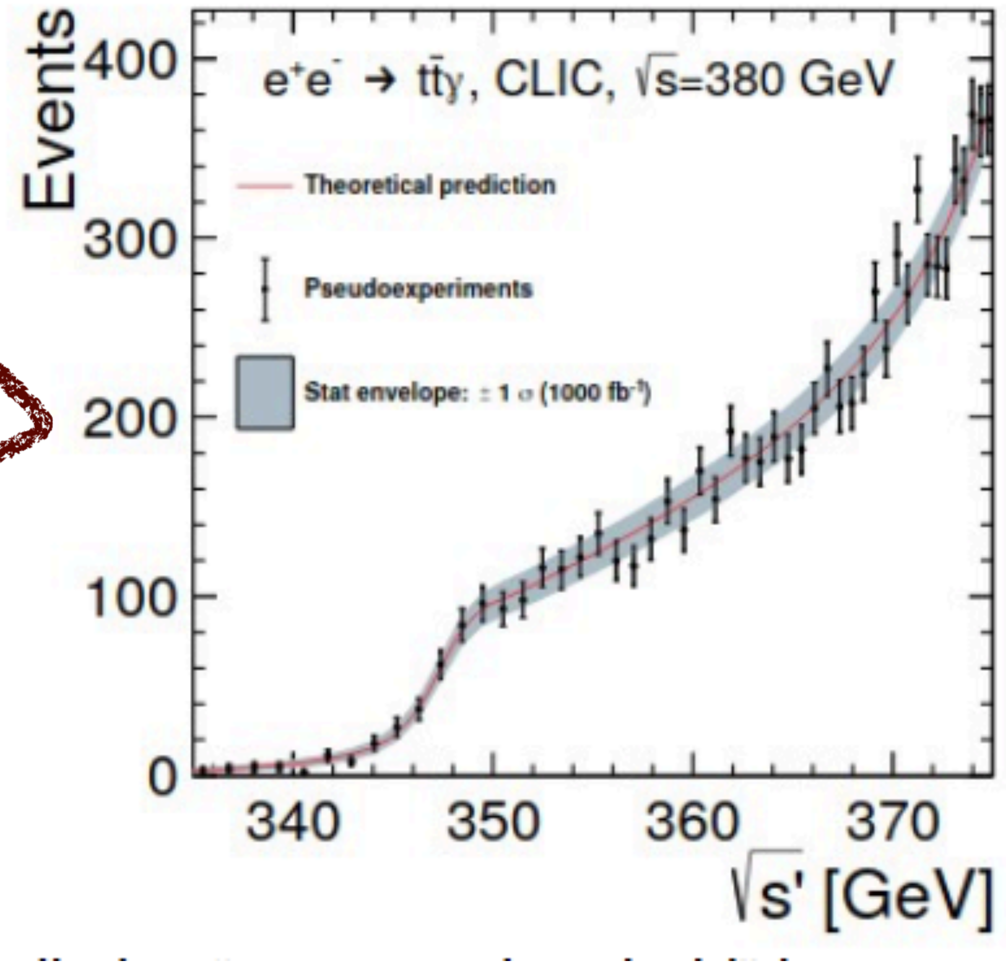
- The accelerator side: Requires sufficient collision energy for top pair production
  - So far thoroughly studied for ILC, CLIC, threshold studies common for CLIC, FCC-ee, ILC

Three approaches to the top mass

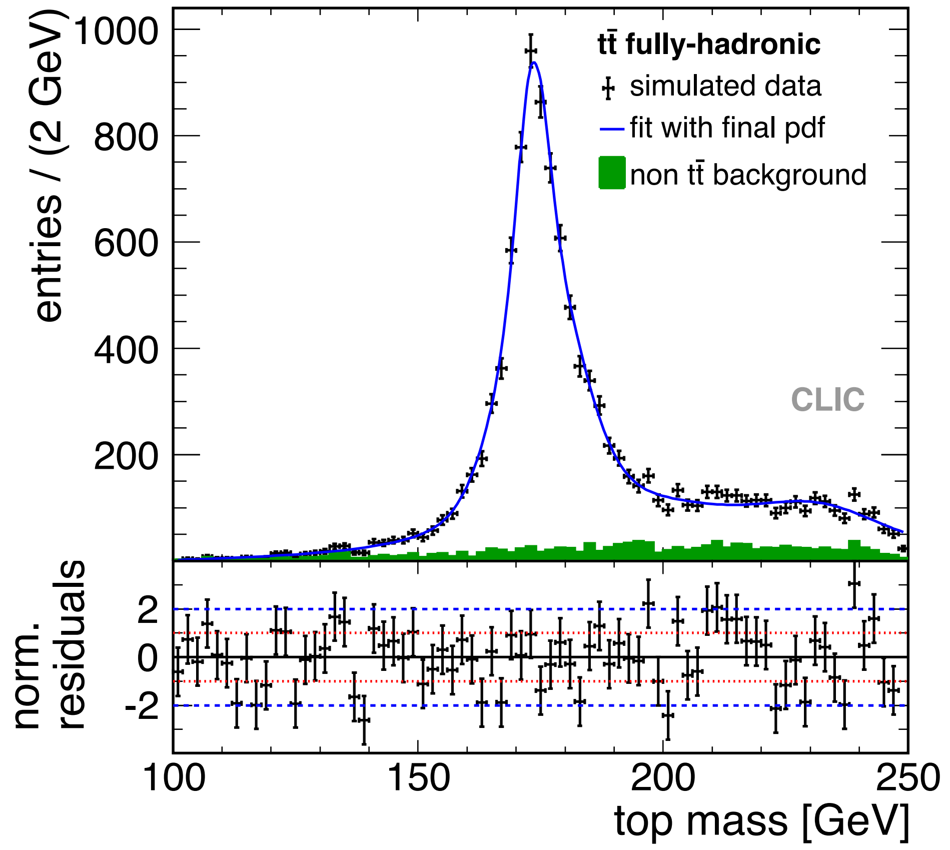
The threshold scan around 350 GeV



The top mass from radiative events



Direct kinematic reconstruction



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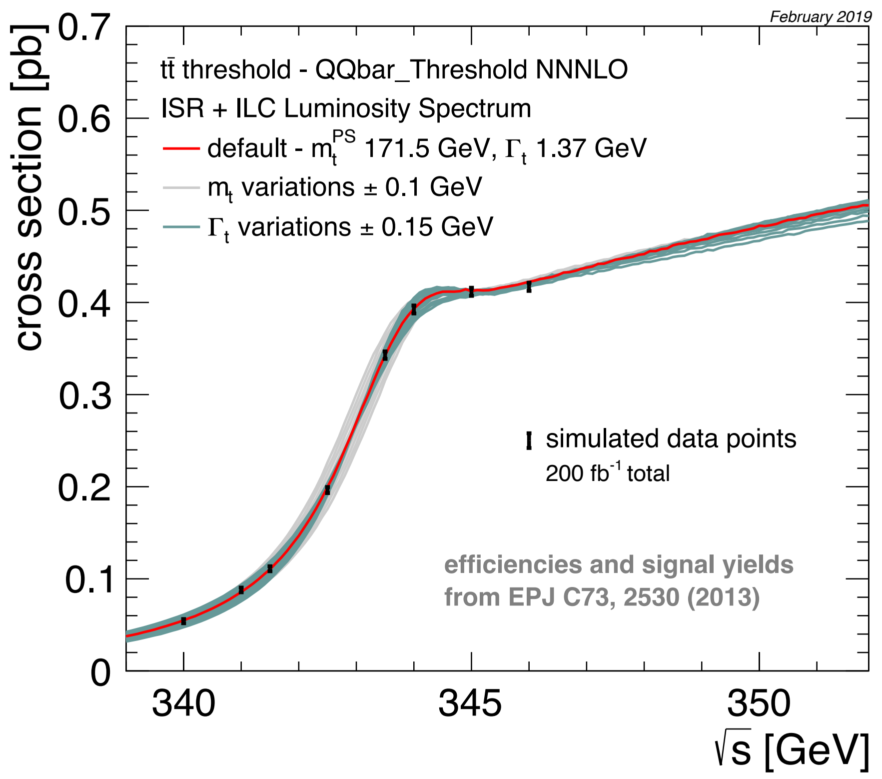

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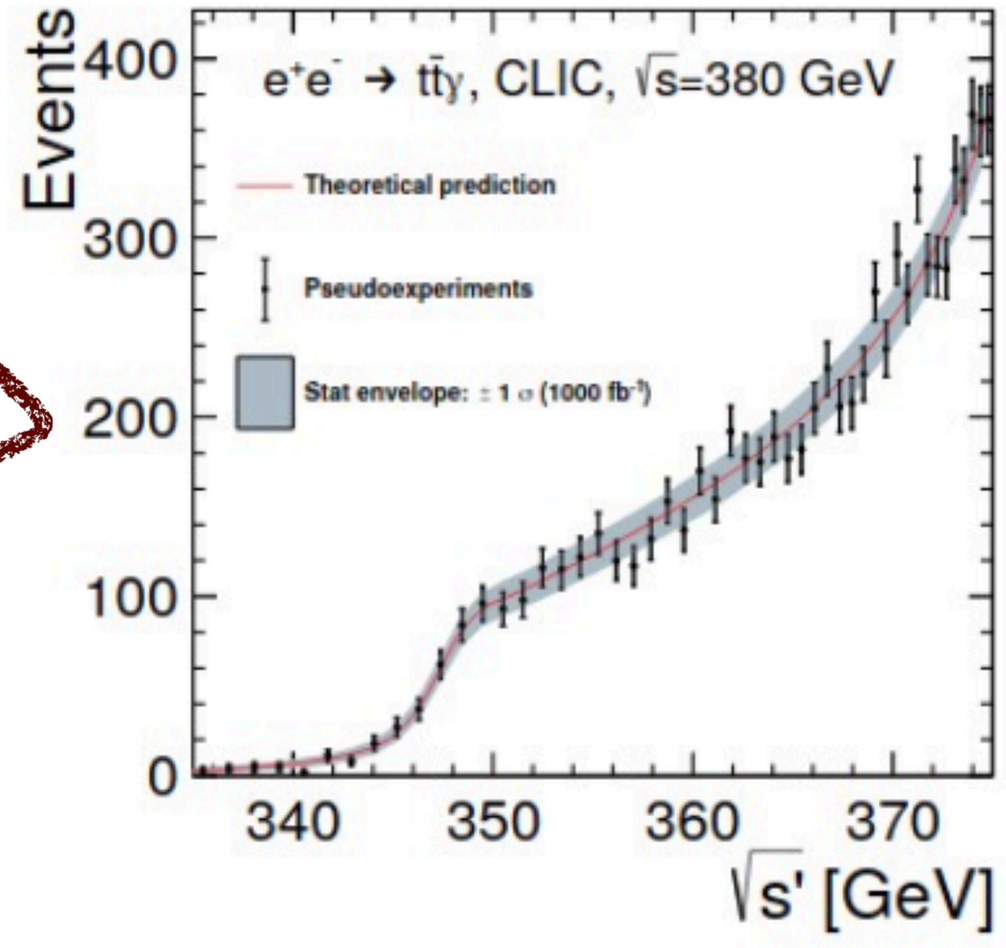

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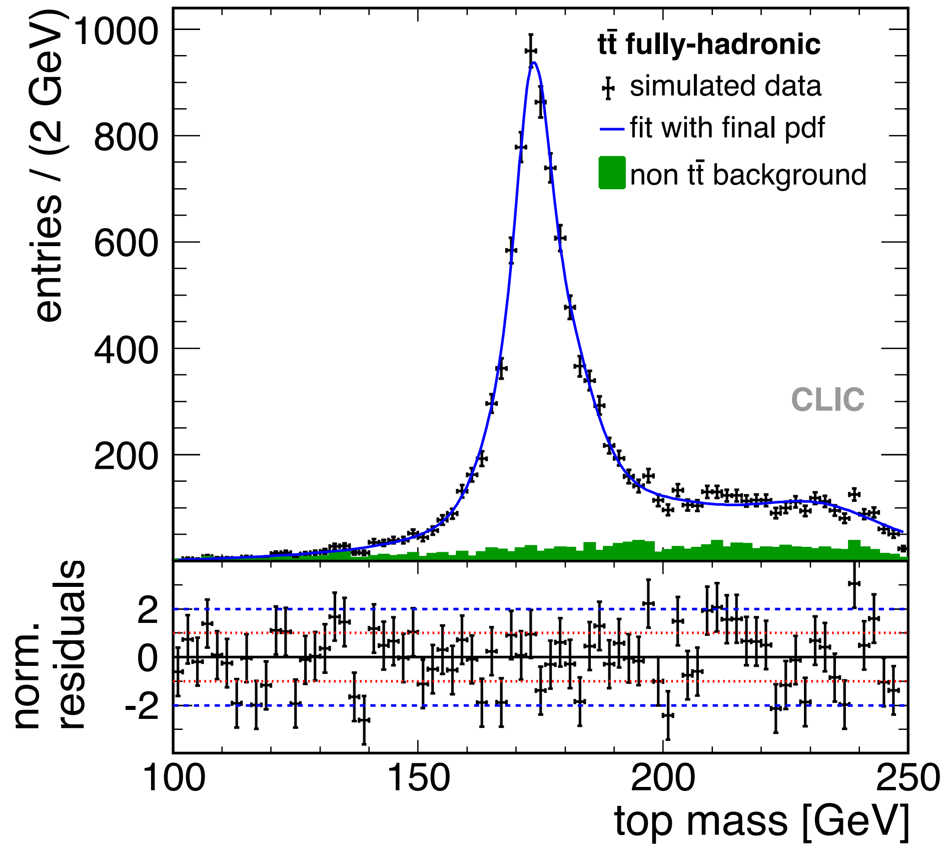


Key references:

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

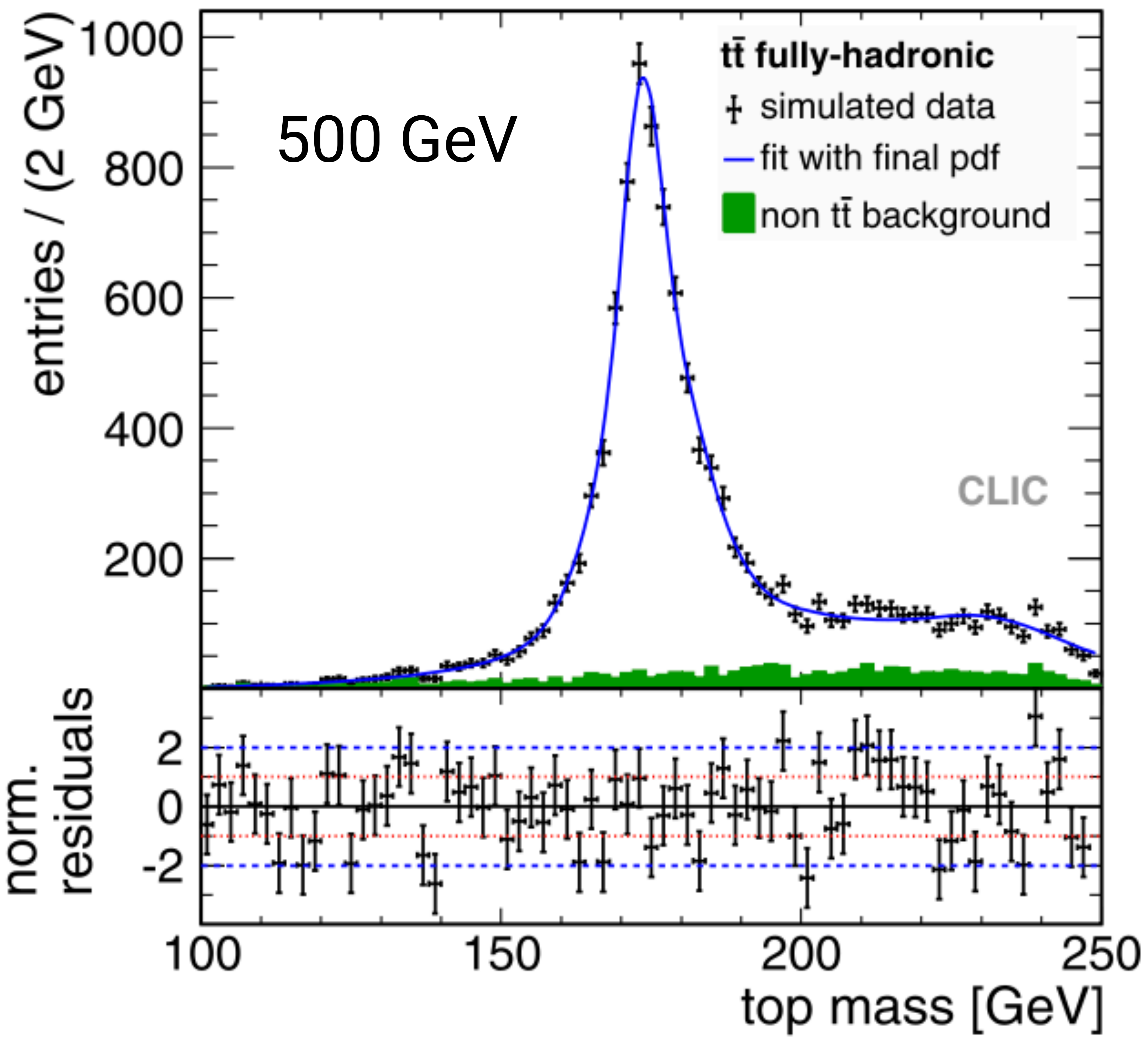
JHEP 11, 003 (2019)
(CLIC: Threshold, radiative, direct)

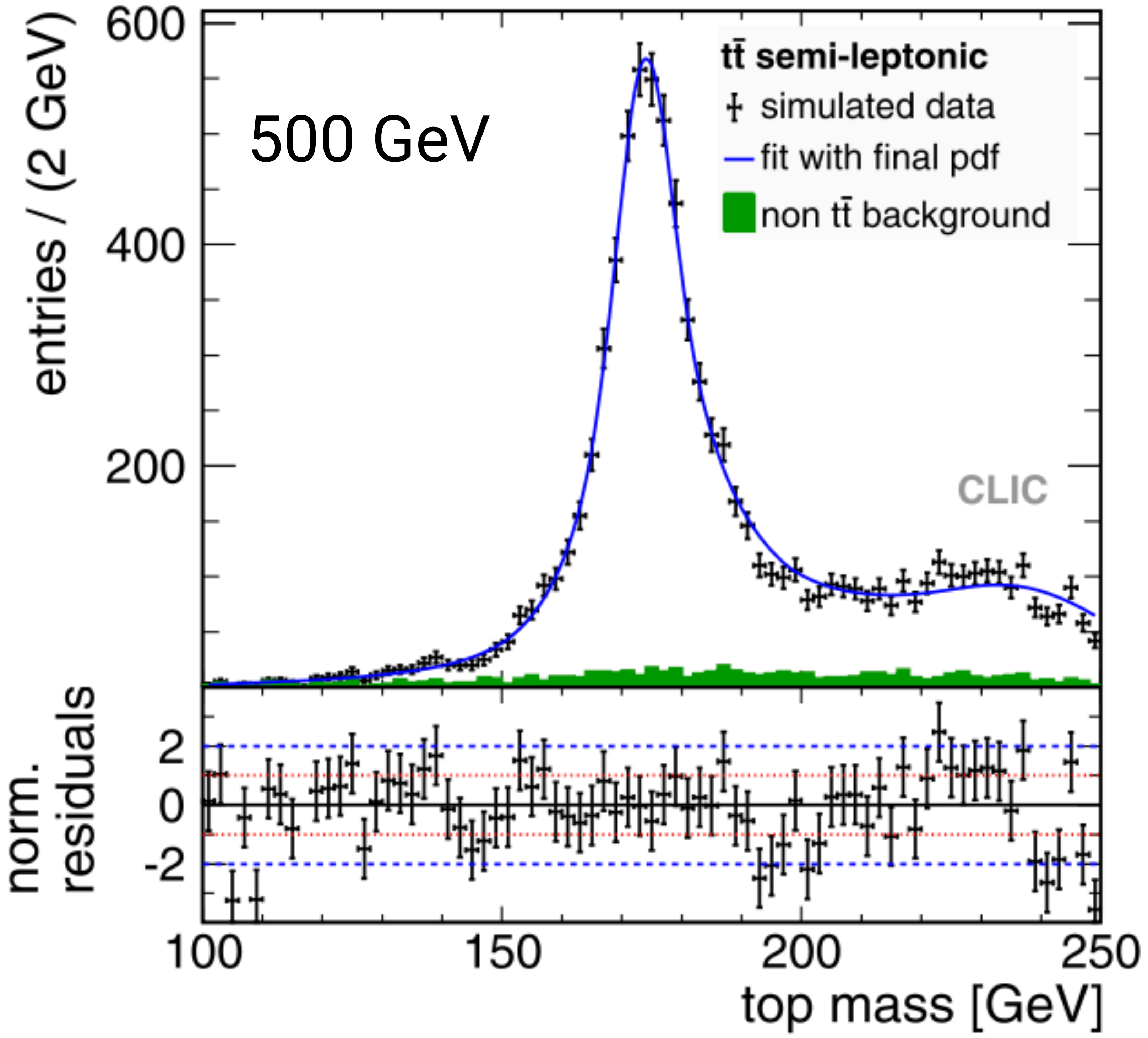
PLB 804,135353 (2020)
(ILC, CLIC: radiative)

+ a rich set of reports and conference proceedings on arXiv

Direct Kinematic Reconstruction above Threshold

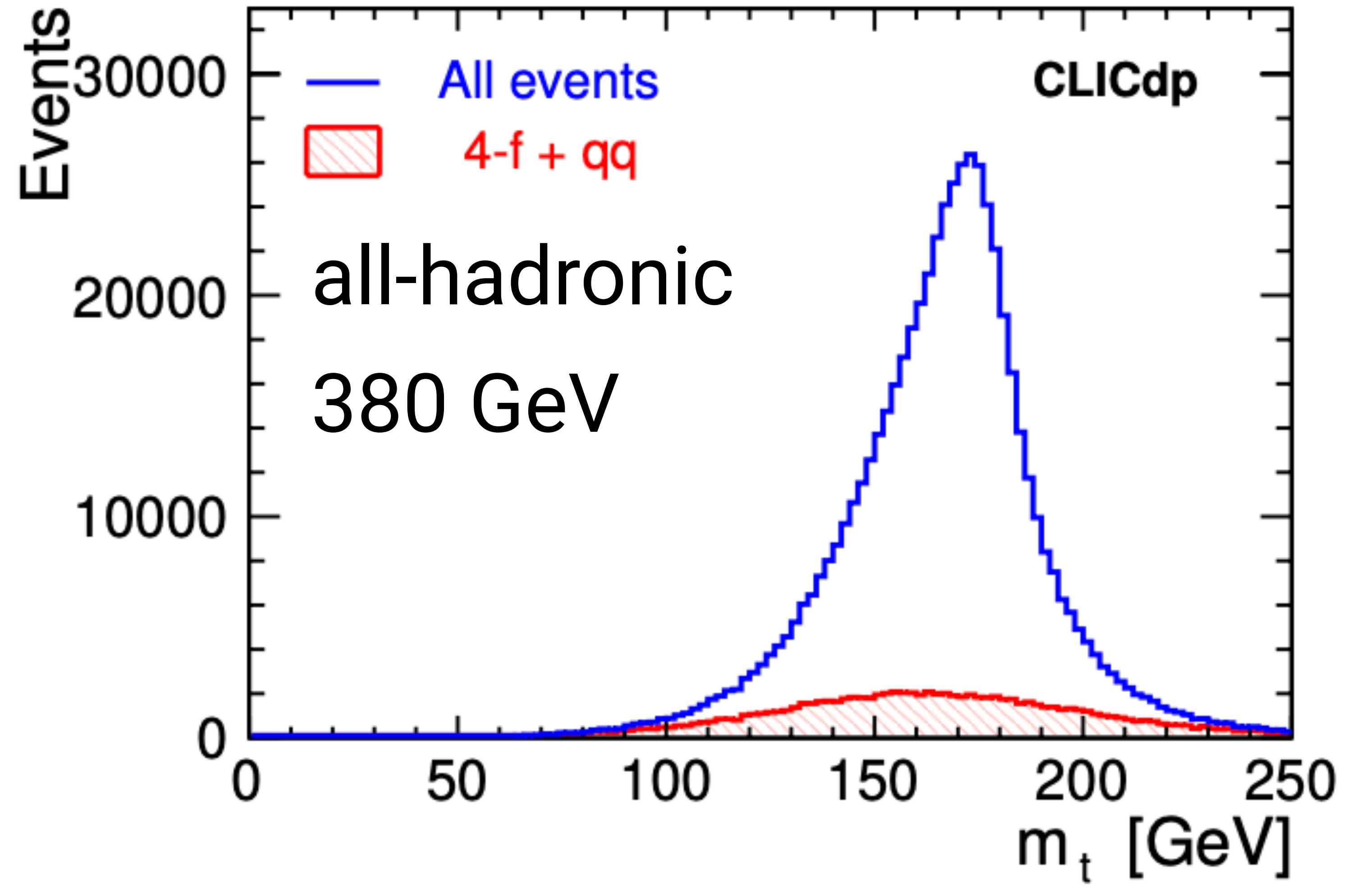
Interpretation challenges





[EPJ C73, 2530 (2013)]

[JHEP 11, 03 (2019)]

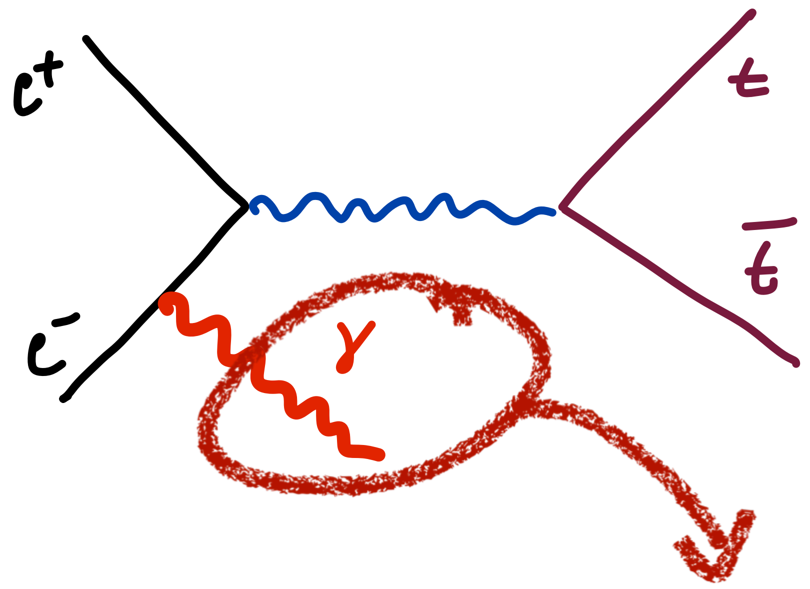


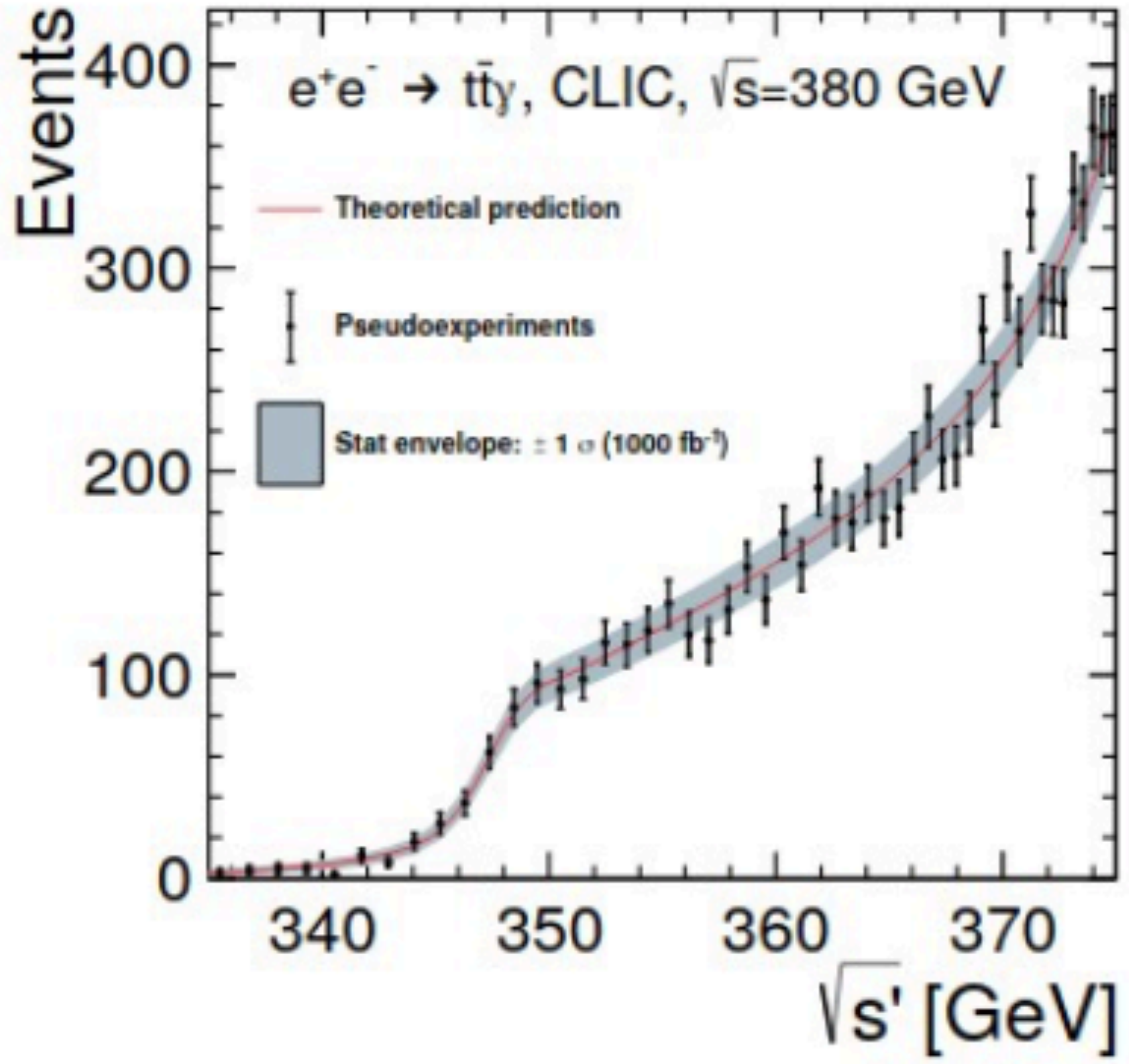
- 80 MeV statistical precision for 100 fb^{-1} at 500 GeV (extracted via template fits) in invariant mass of Wb final state.
  Newer study: 30 MeV at 380 GeV, 1 ab^{-1} at CLIC
- Experimental systematics, in particular b-JES a clear challenge
- On the theory side: interpretation of the measured mass, other corrections

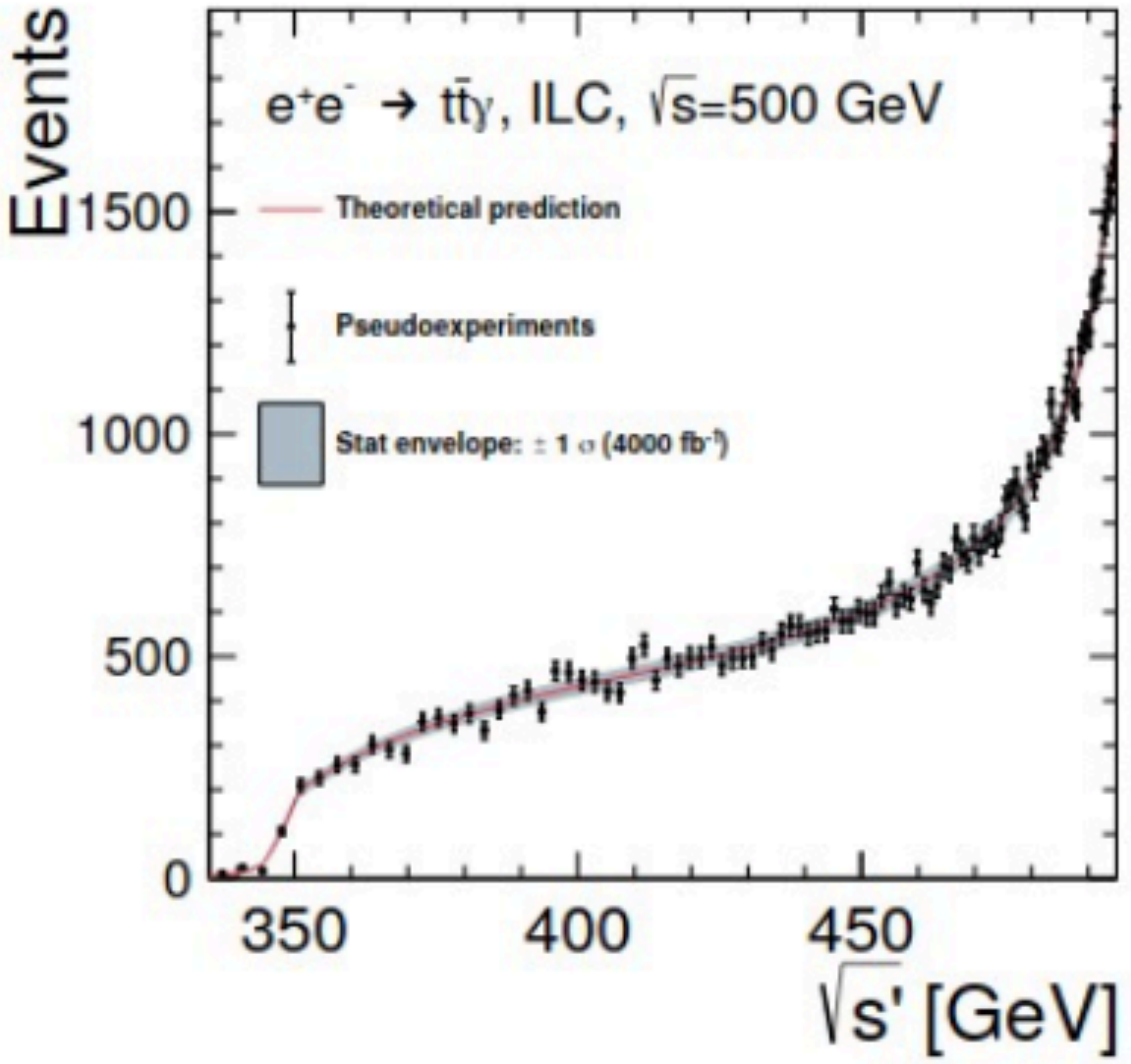
Top Mass in Radiative Events

A threshold scan at higher collision energies

- A new(er) idea to measure the top mass in a theoretically well-defined scheme in high-energy running above the threshold







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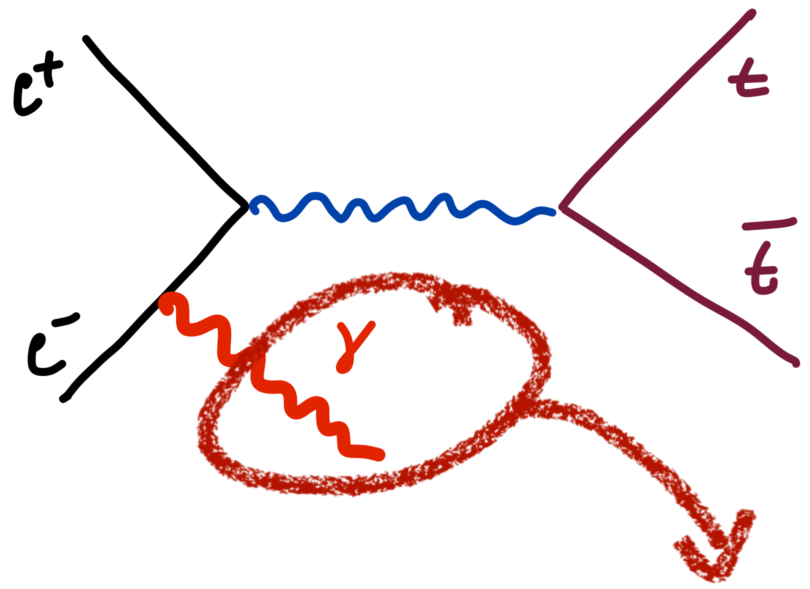
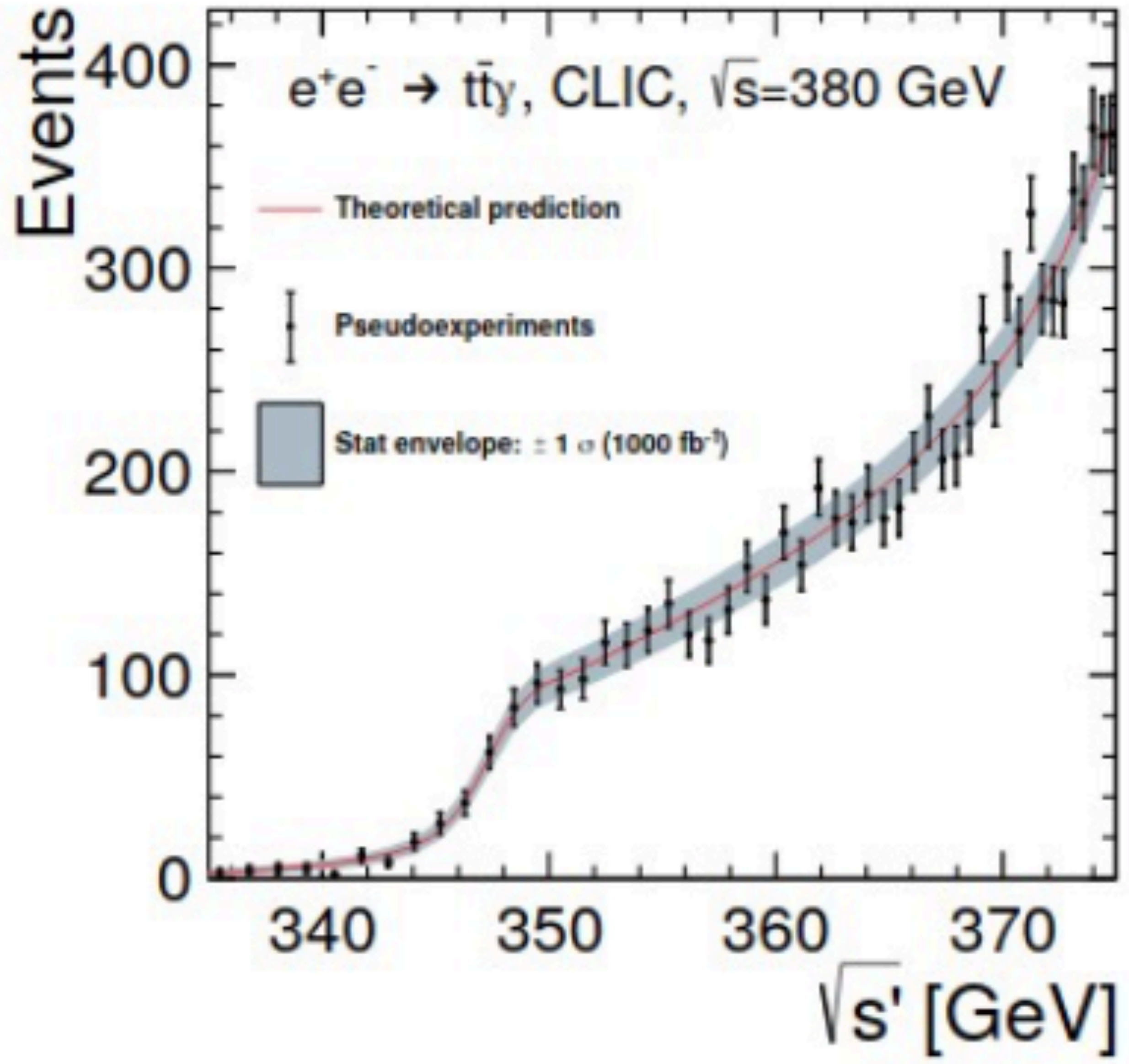
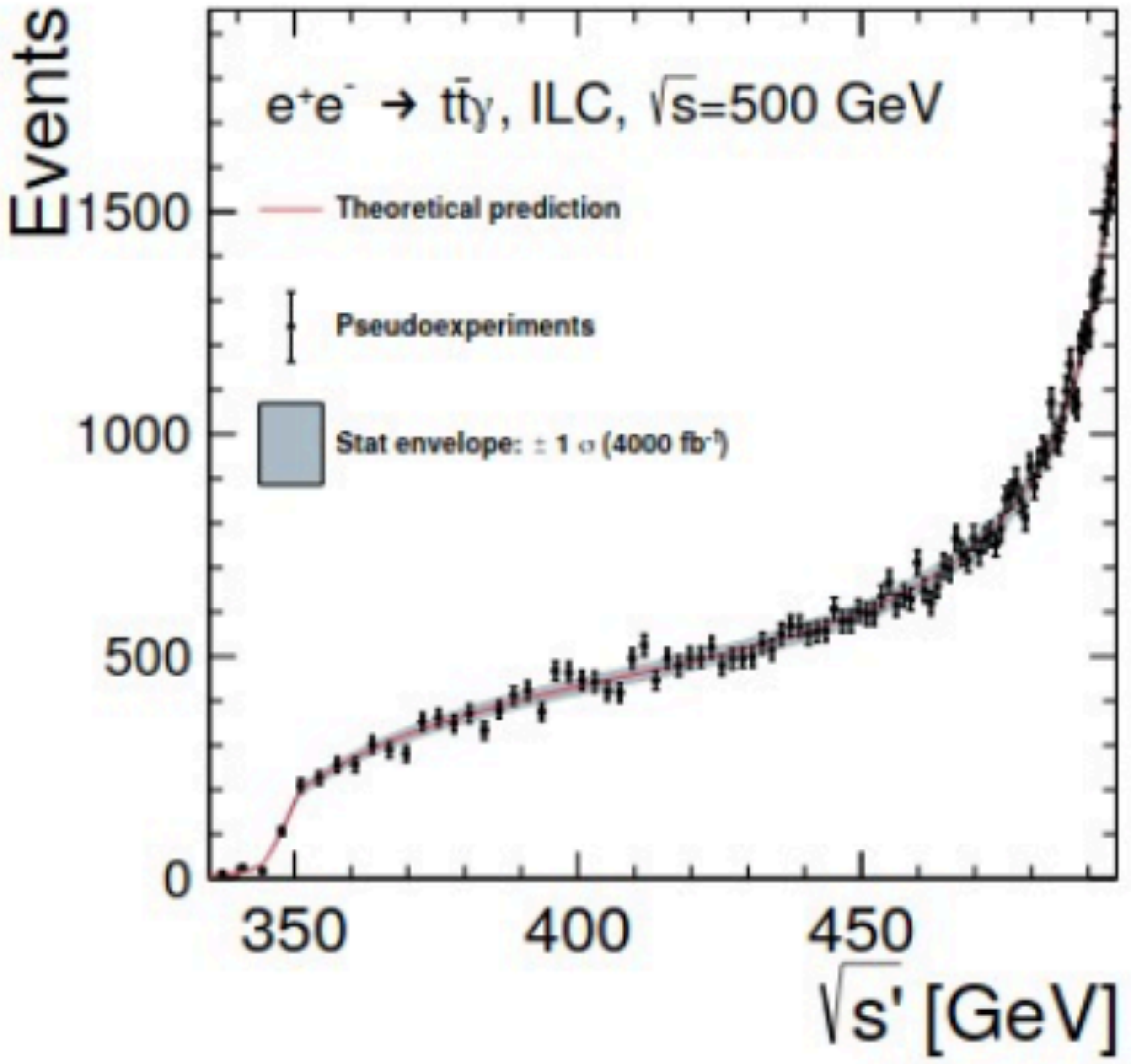


matched NNLO + NNLL calculation, luminosity spectrum folded in explicitly; Extraction of short distance MSR mass

cms energy	CLIC, $\sqrt{s} = 380$ GeV		ILC, $\sqrt{s} = 500$ GeV	
luminosity [fb^{-1}]	500	1000	500	4000
statistical	140 MeV	90 MeV	350 MeV	110 MeV
theory	46 MeV		55 MeV	
lum. spectrum	20 MeV		20 MeV	
photon response	16 MeV		85 MeV	
total	150 MeV	110 MeV	360 MeV	150 MeV





Top Mass in Radiative Events

A threshold scan at higher collision energies

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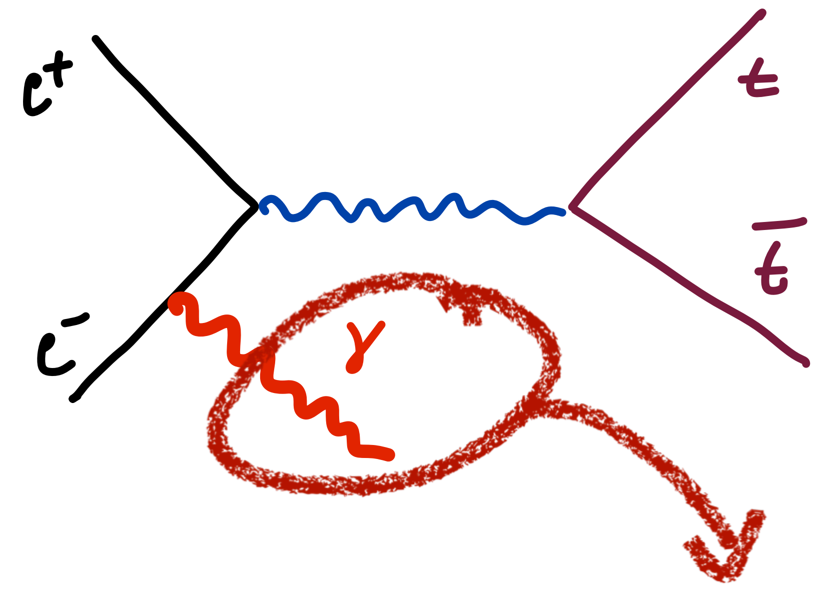

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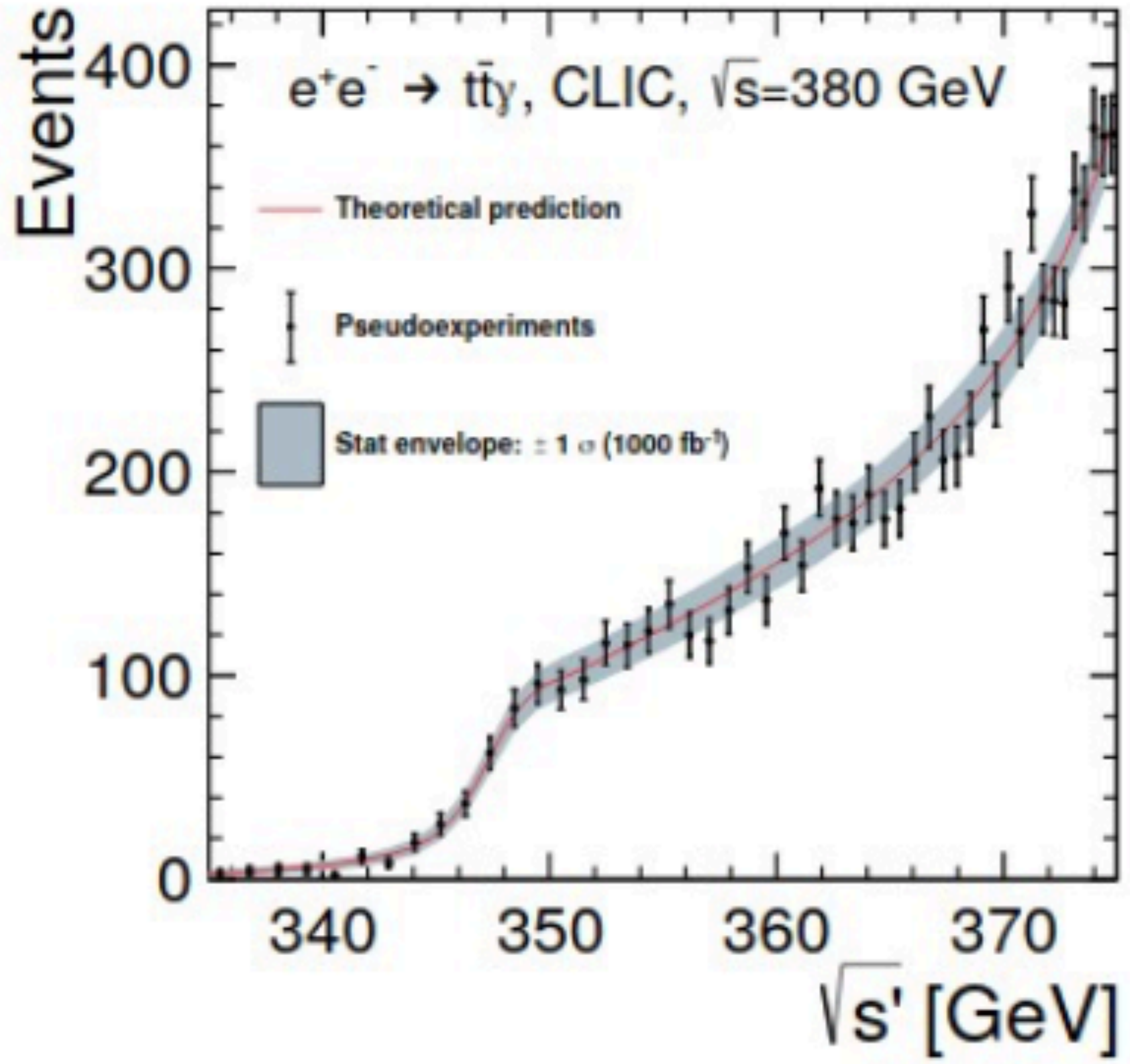
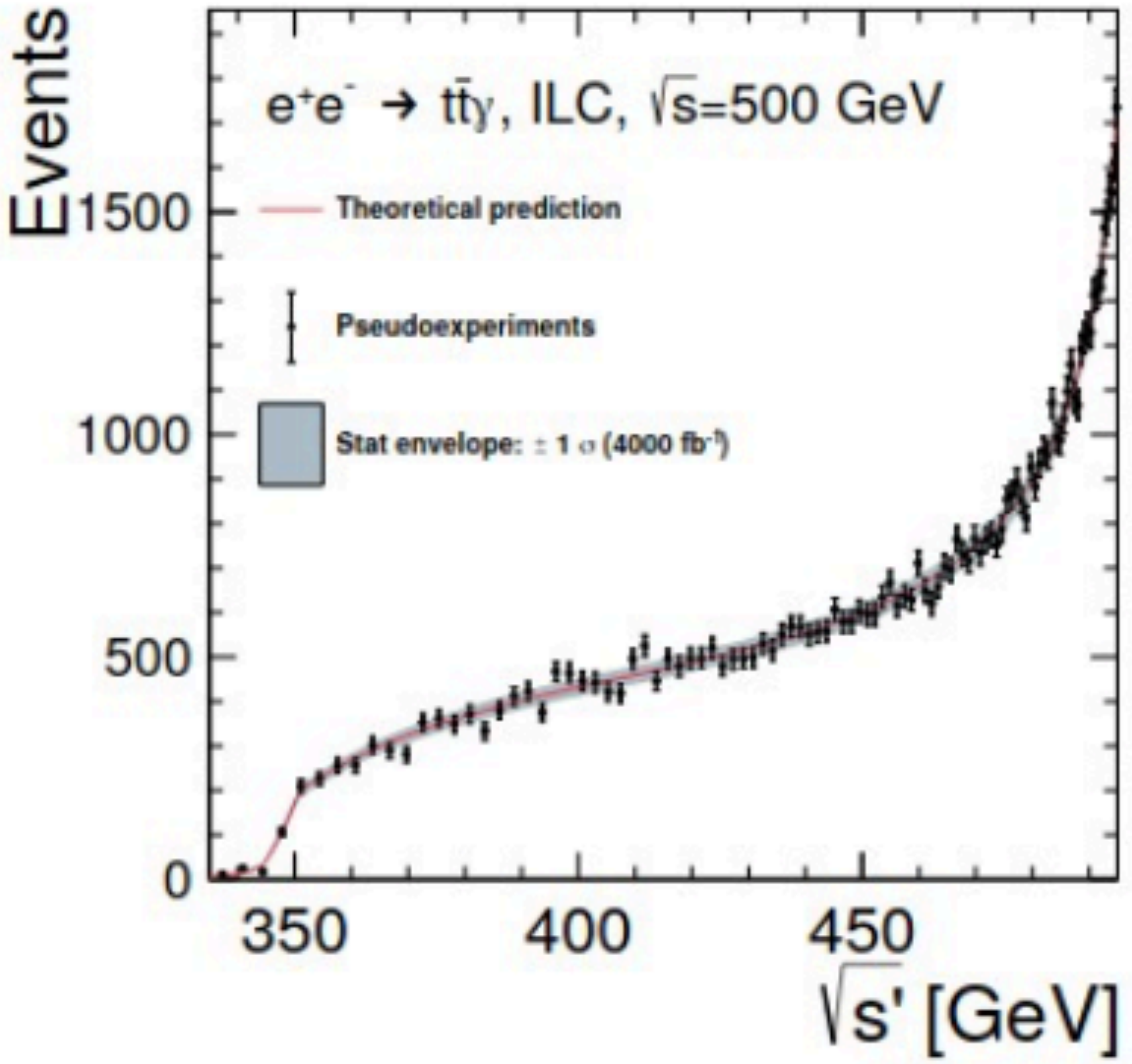
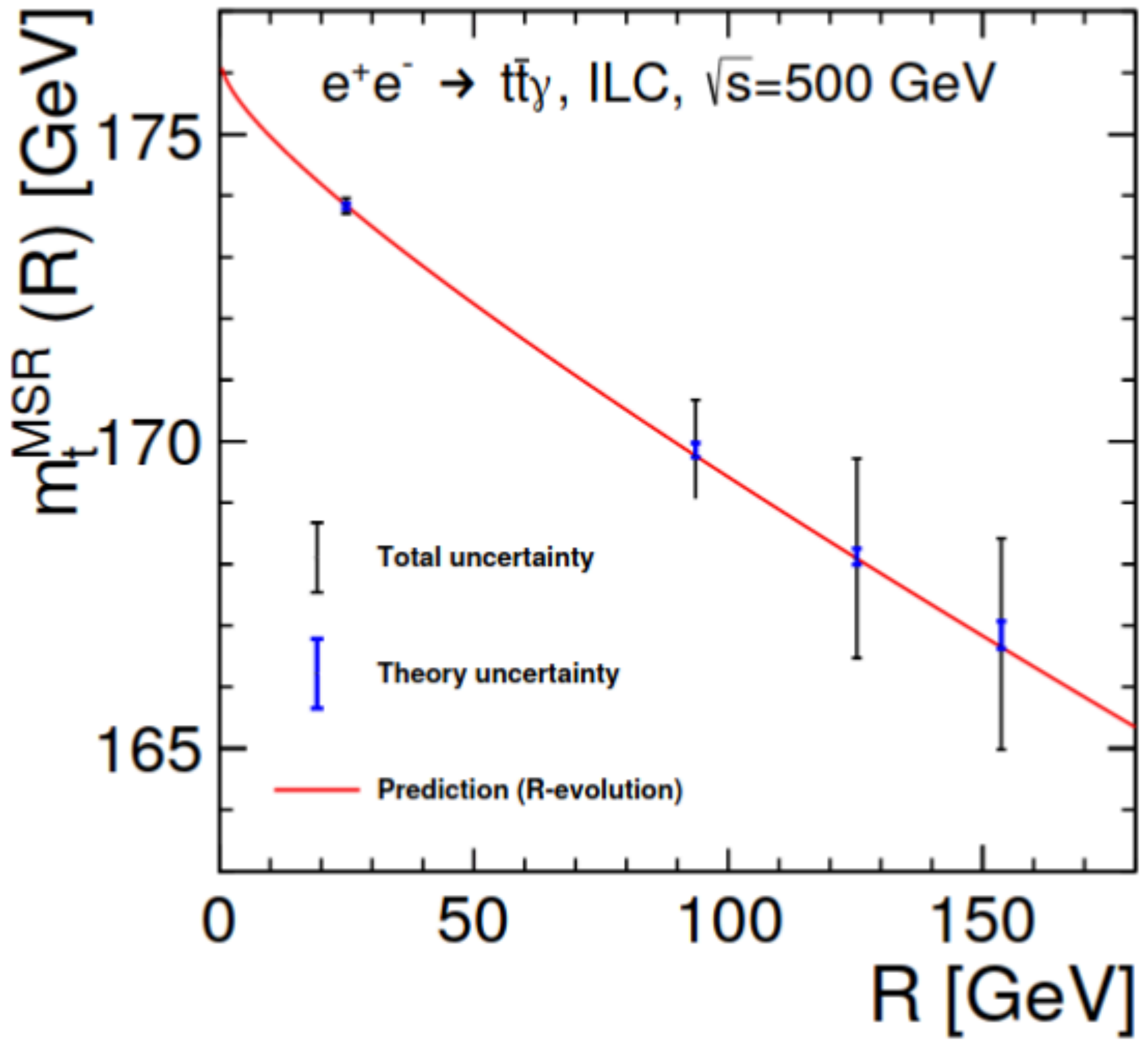


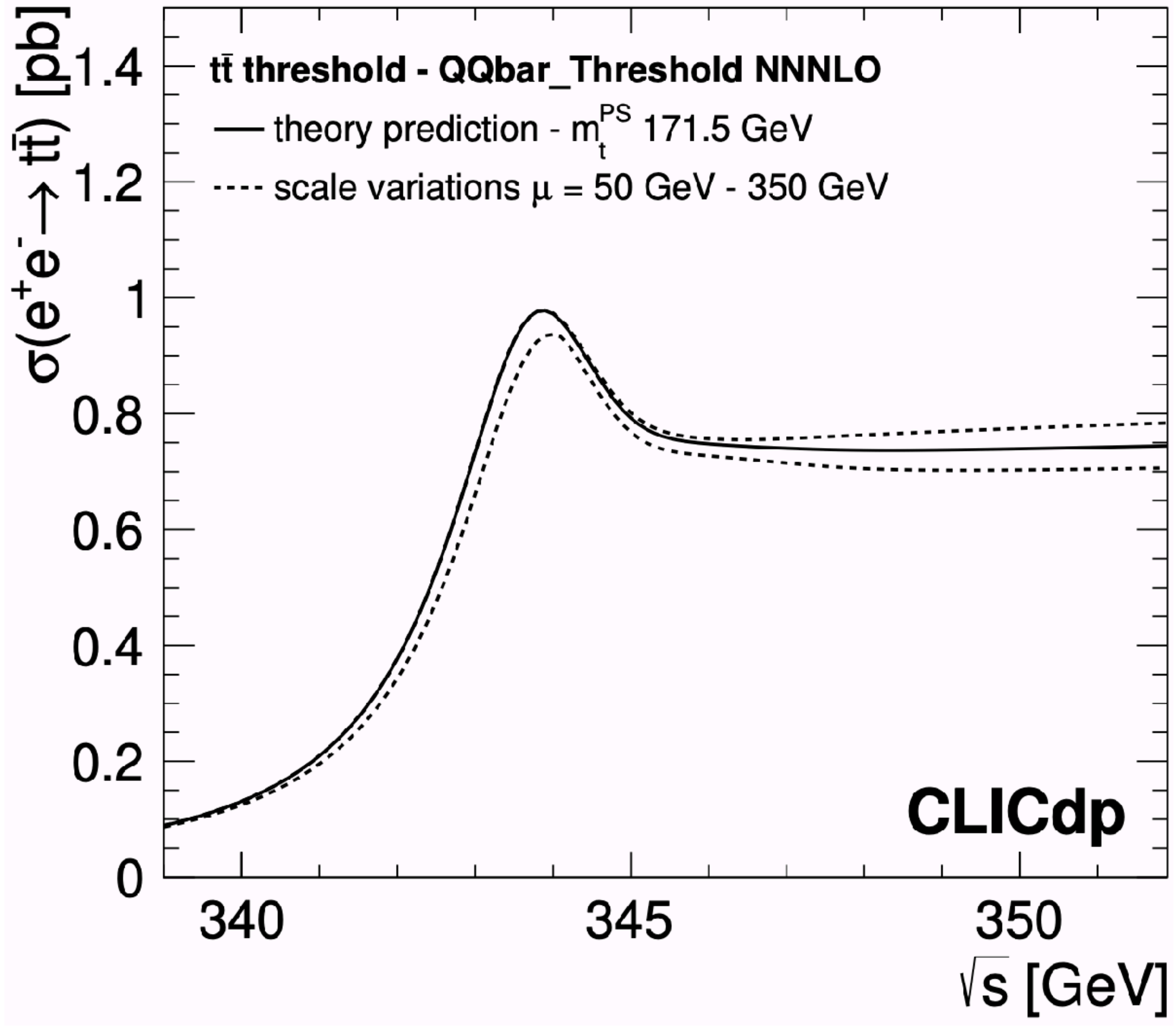


can provide 5σ evidence for scale evolution ("running") of the top quark MSR mass from ILC500 data alone



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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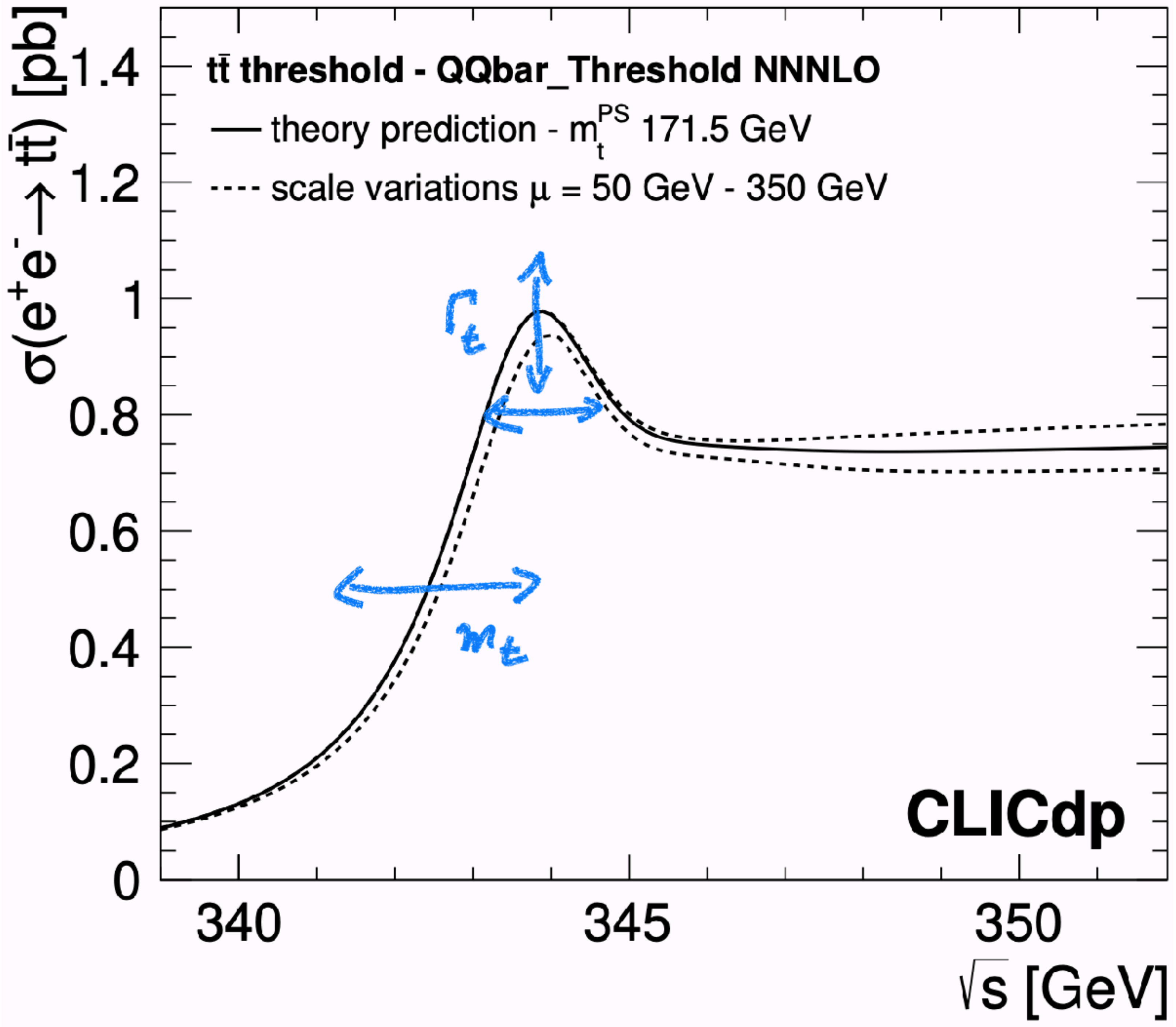

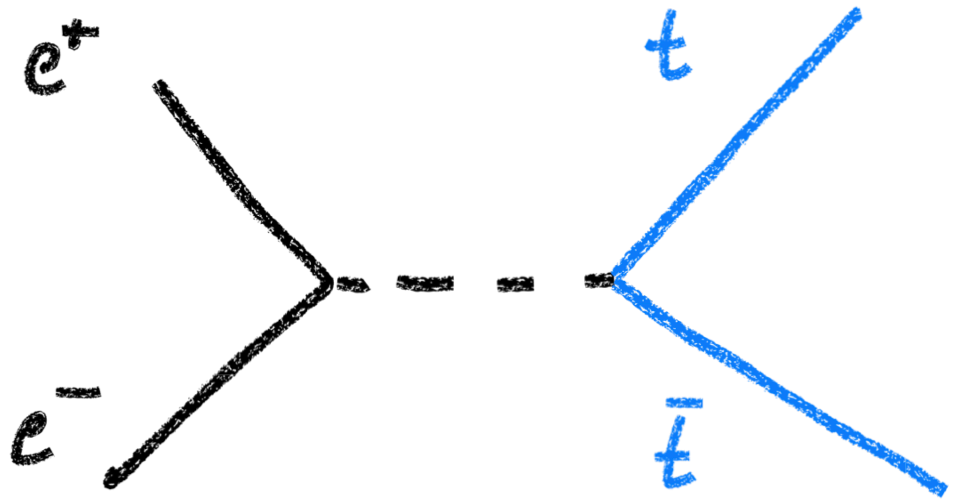

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The threshold is sensitive to top quark properties

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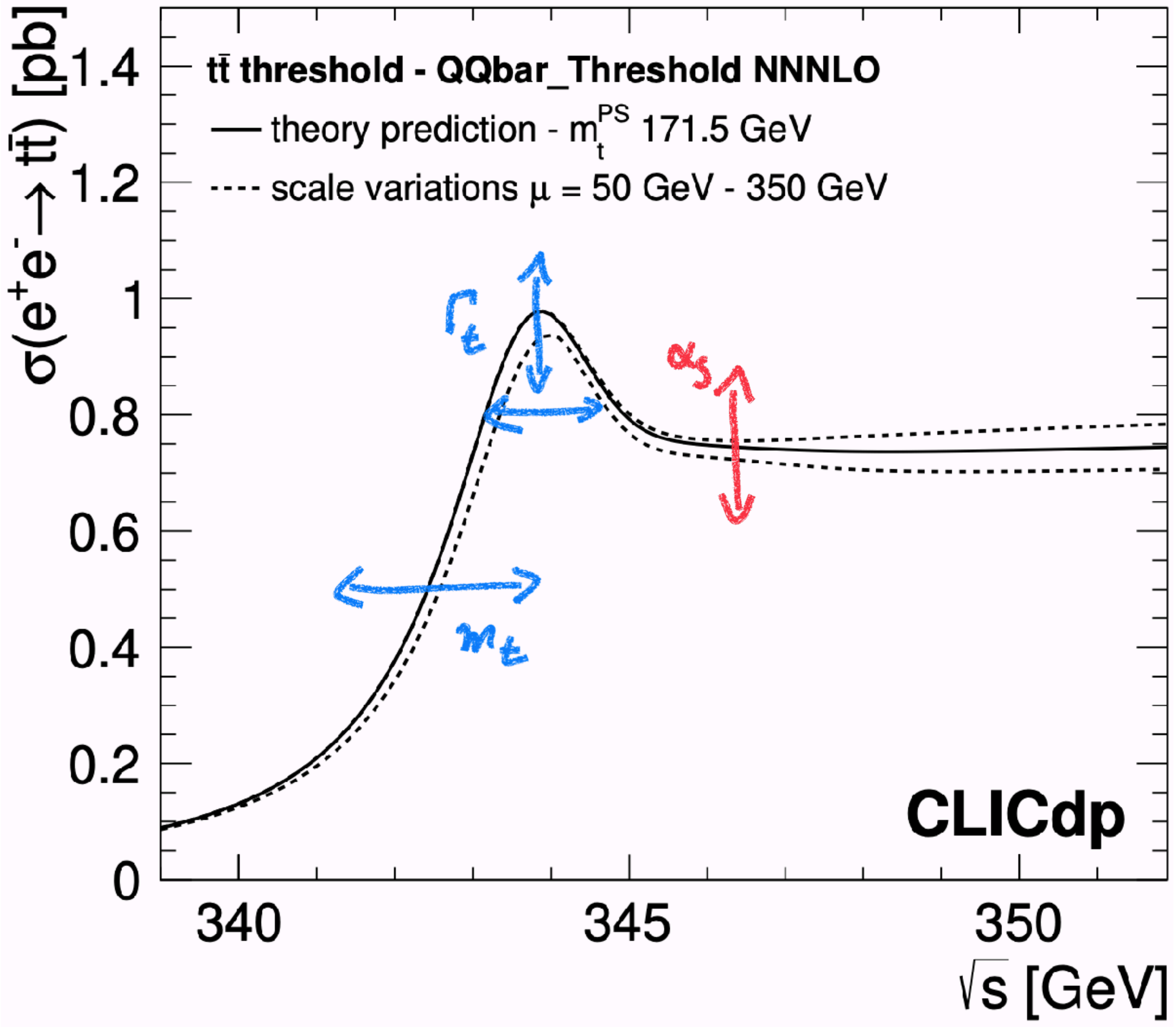

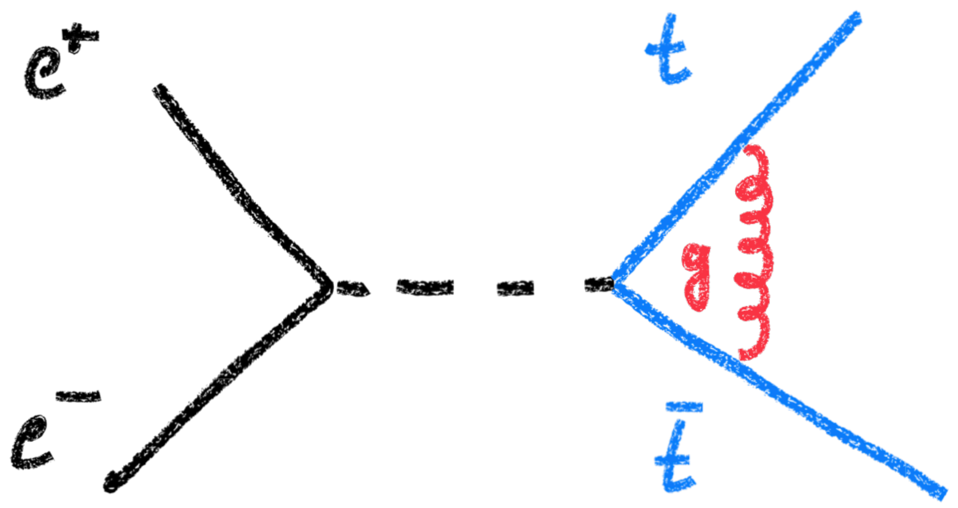

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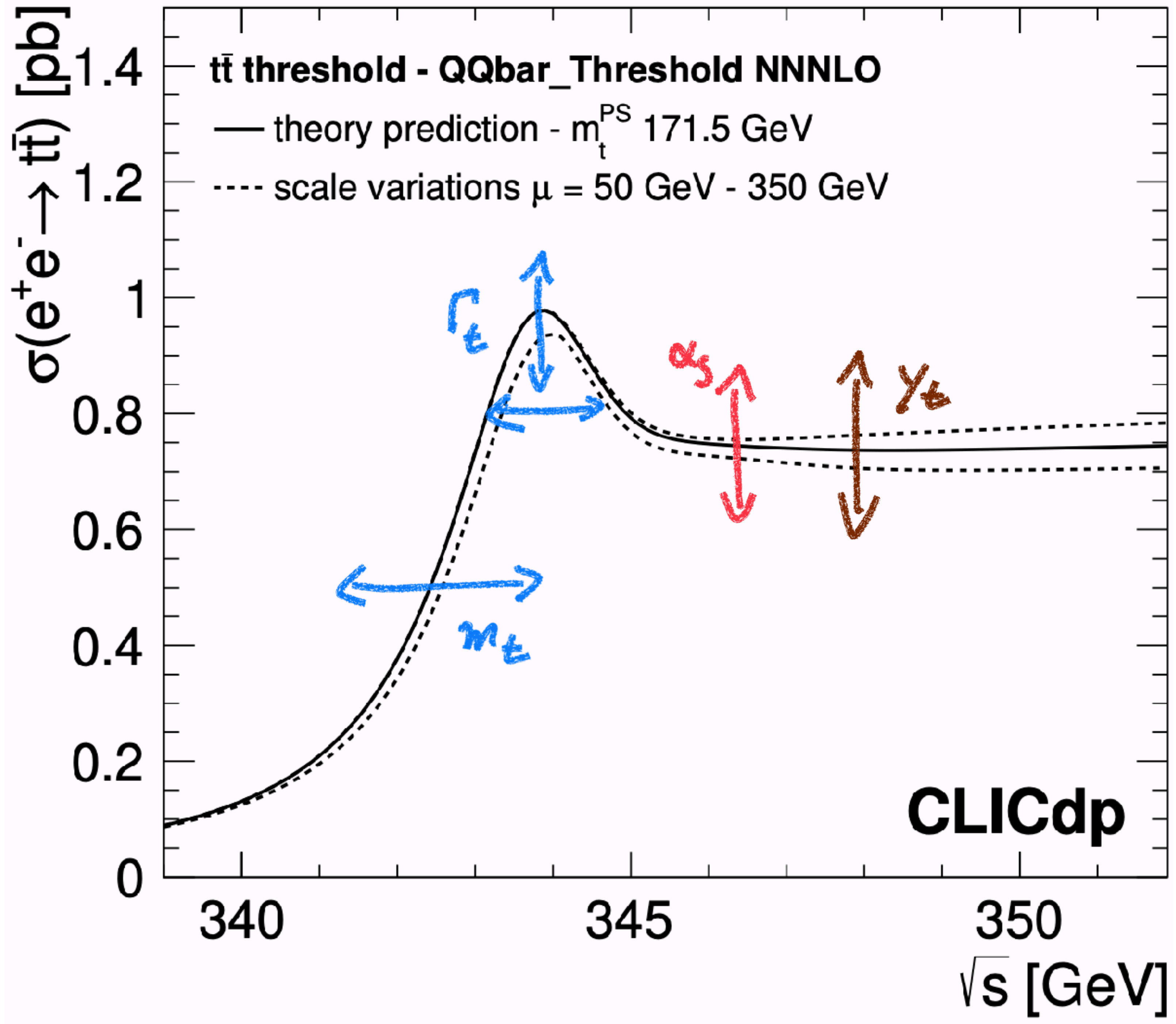

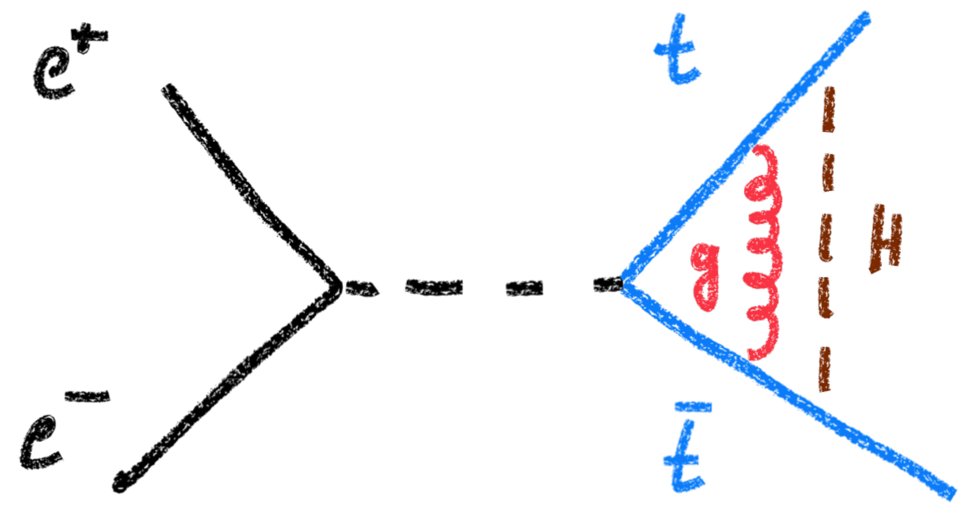

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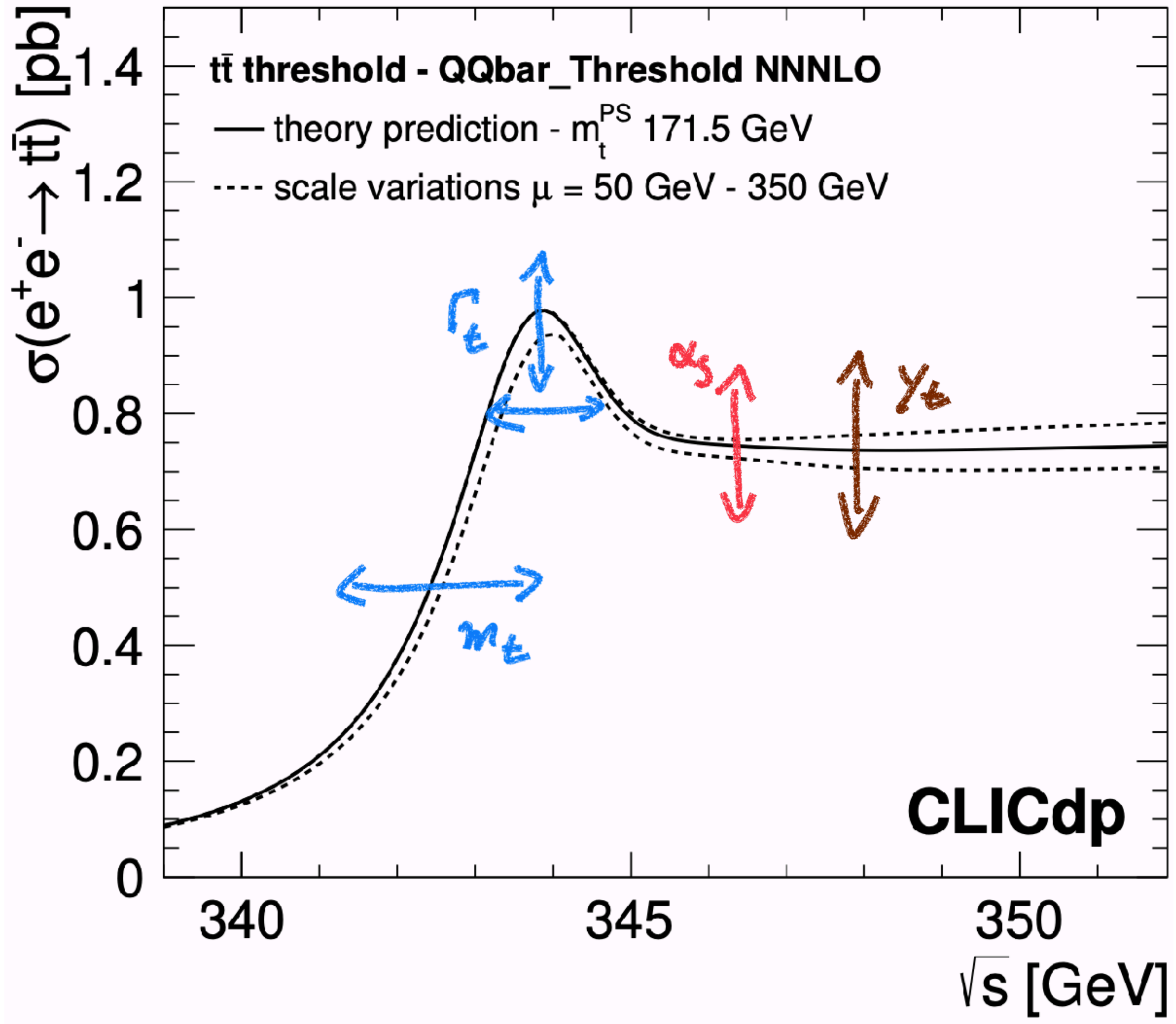

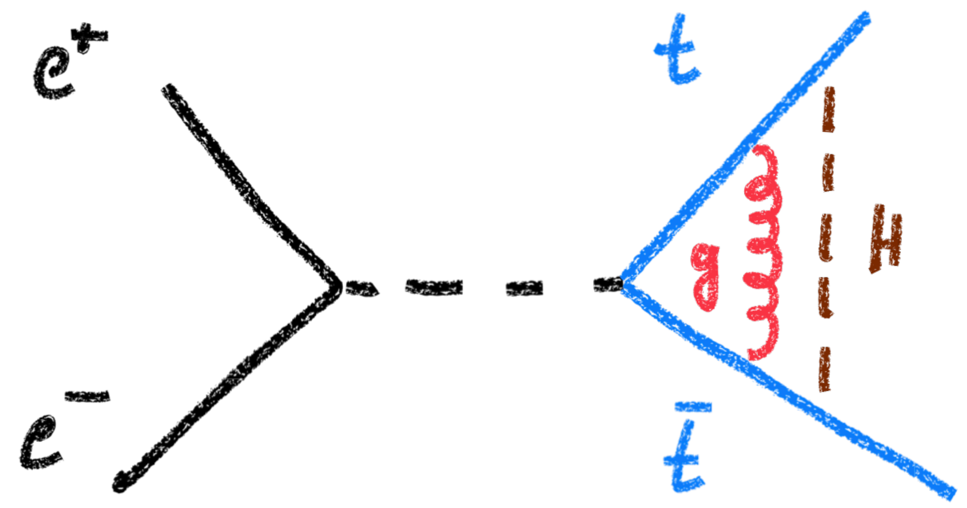

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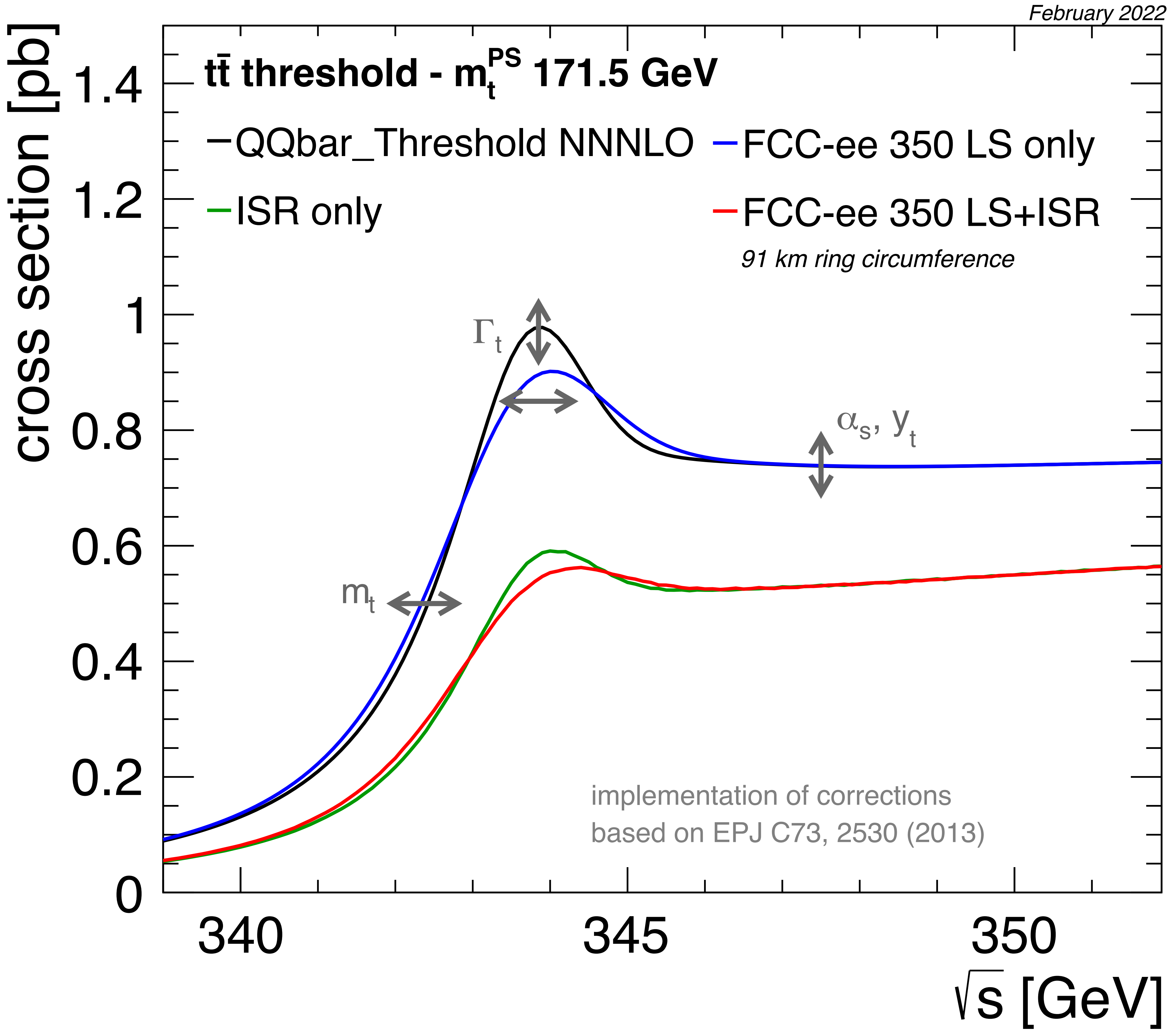
ISR, luminosity spectrum

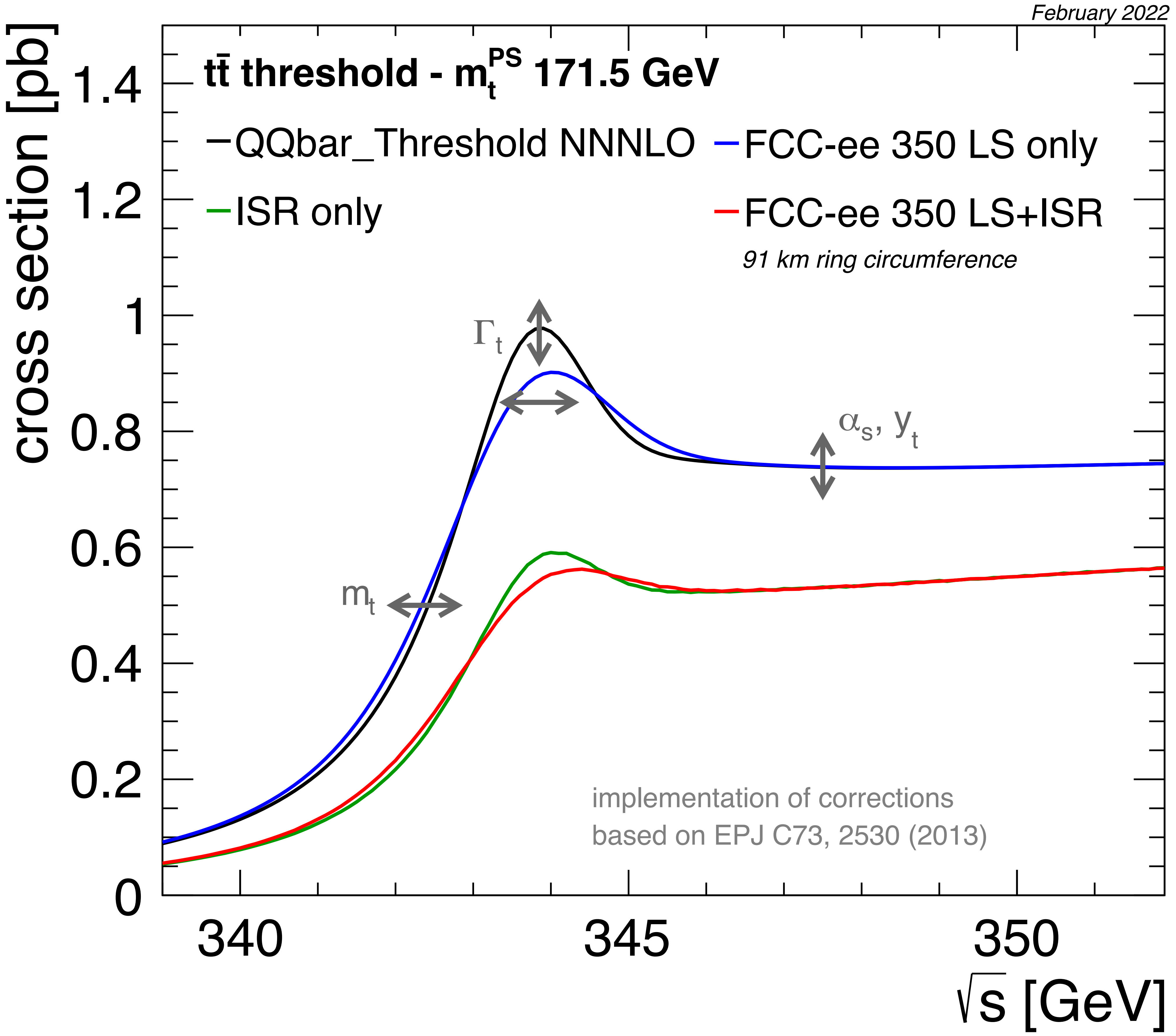


The threshold is sensitive to top quark properties

Differences between Colliders

The Luminosity Spectrum

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



FCC vs

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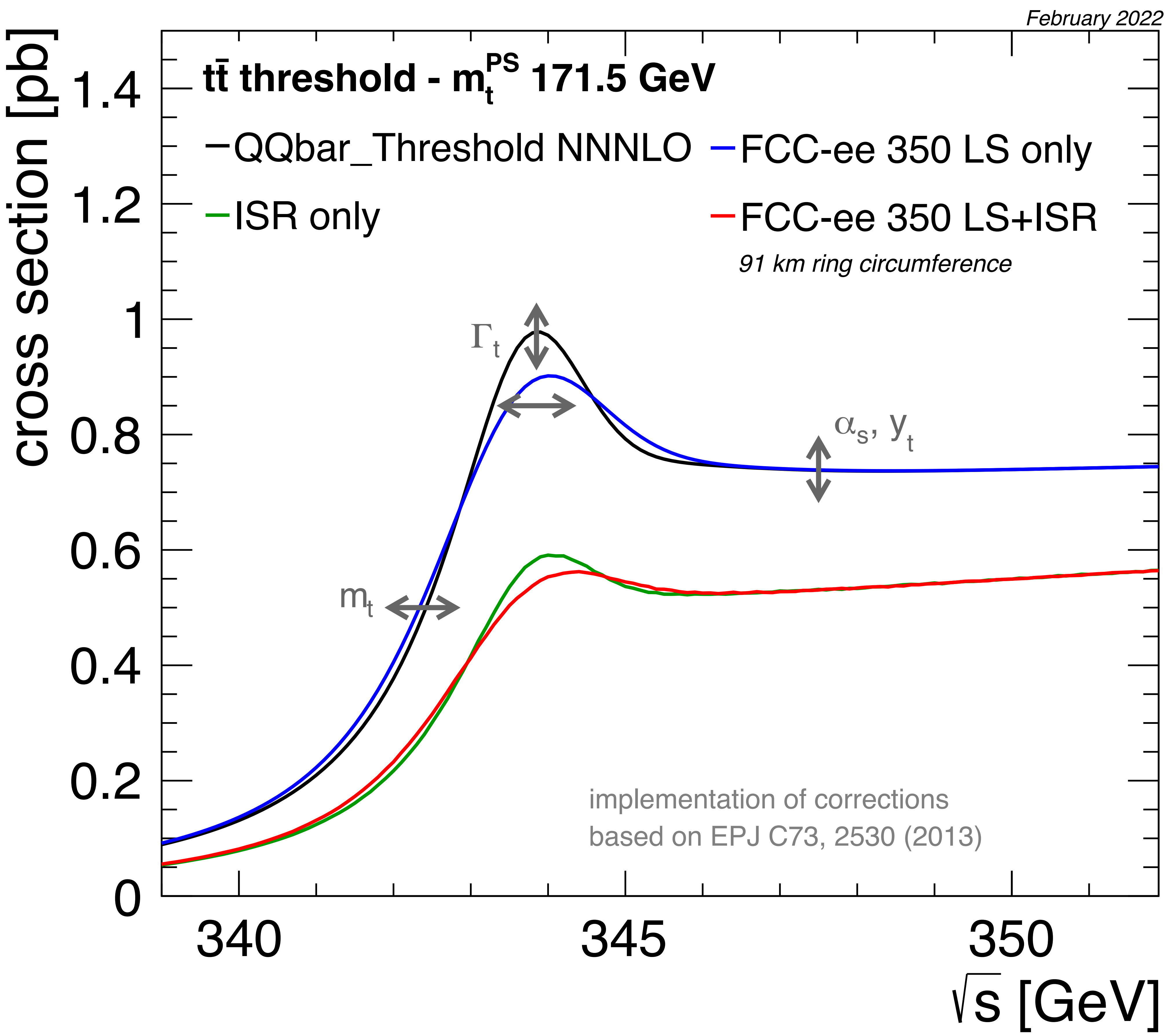
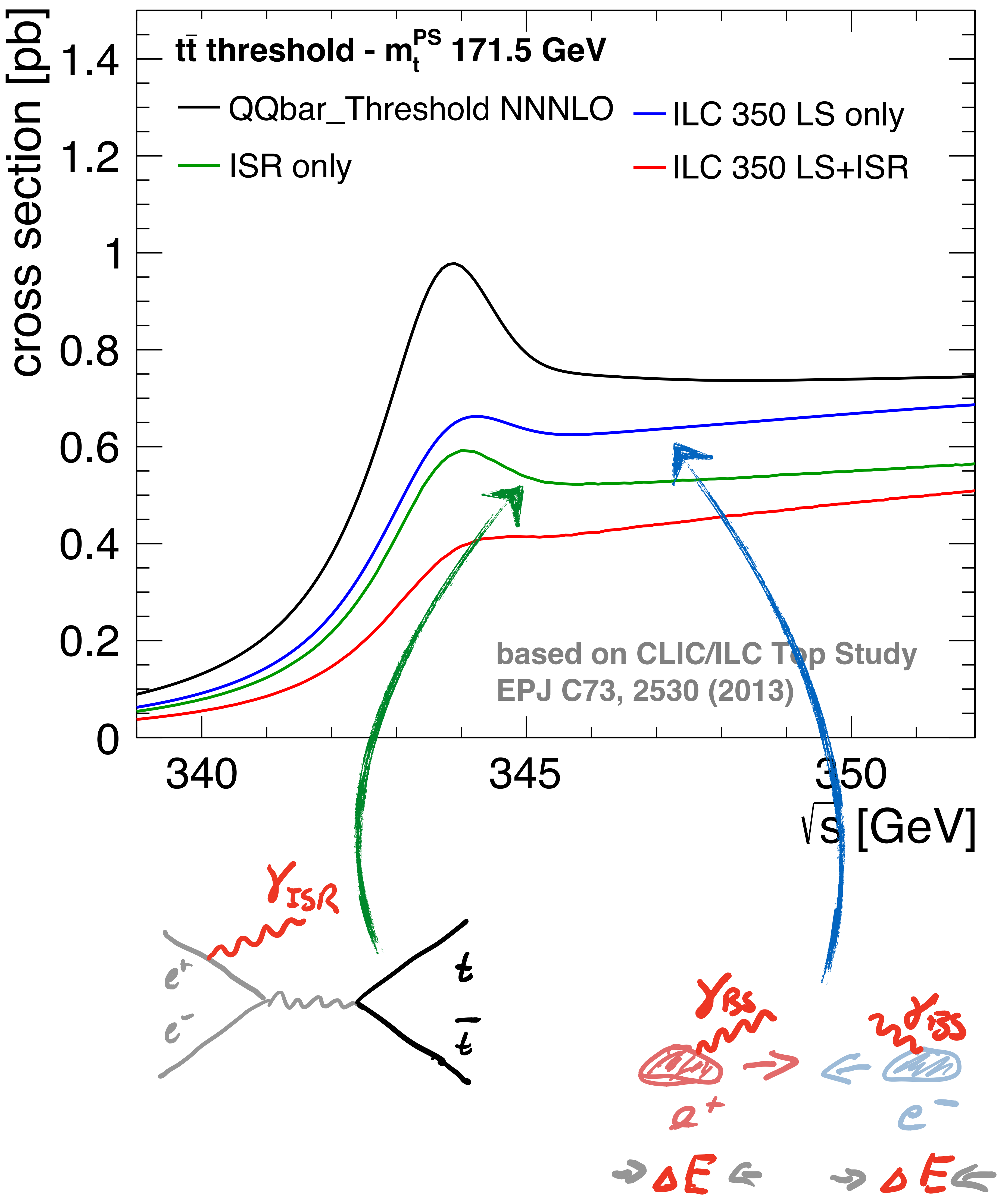


FCC vs ILC



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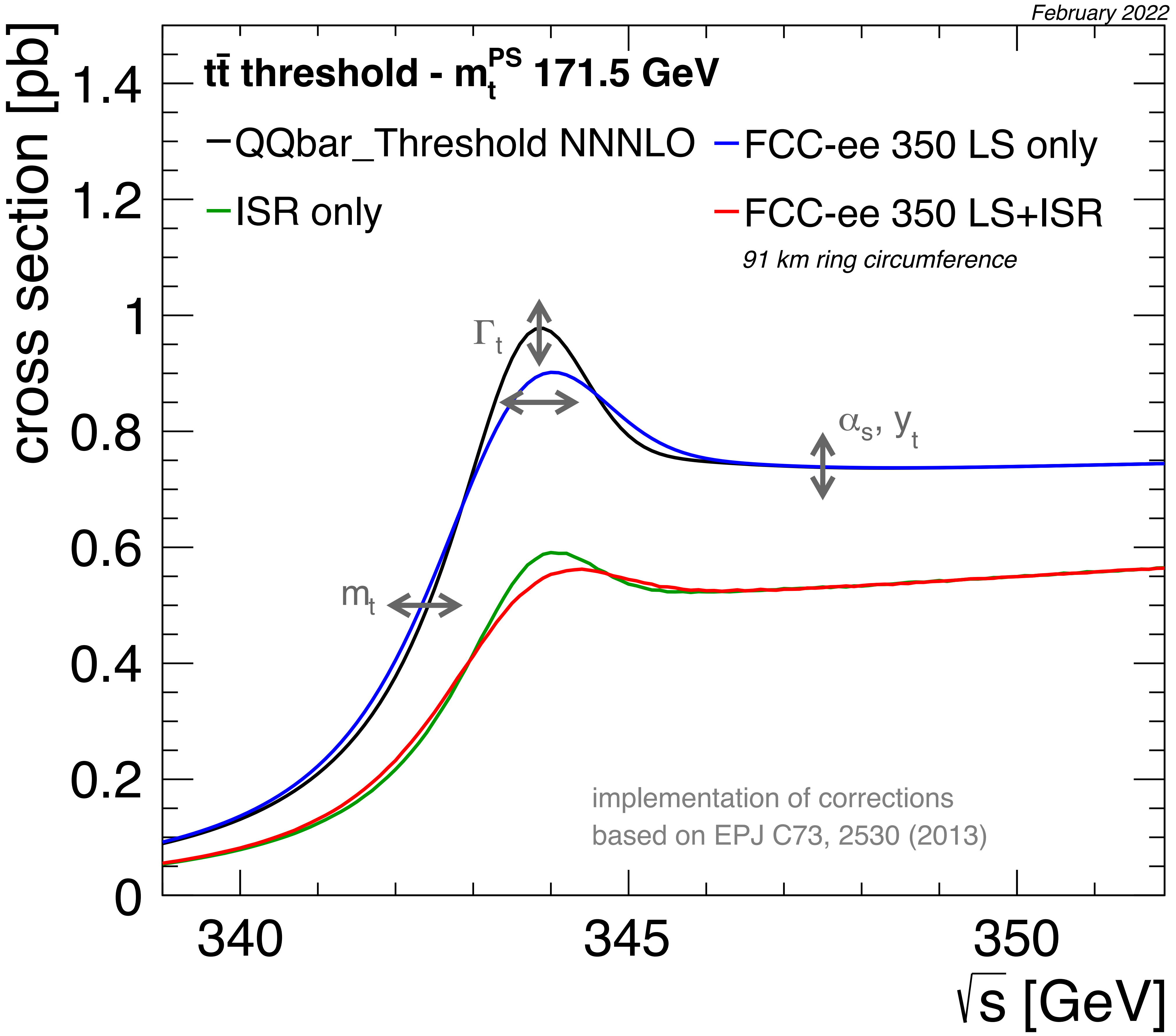


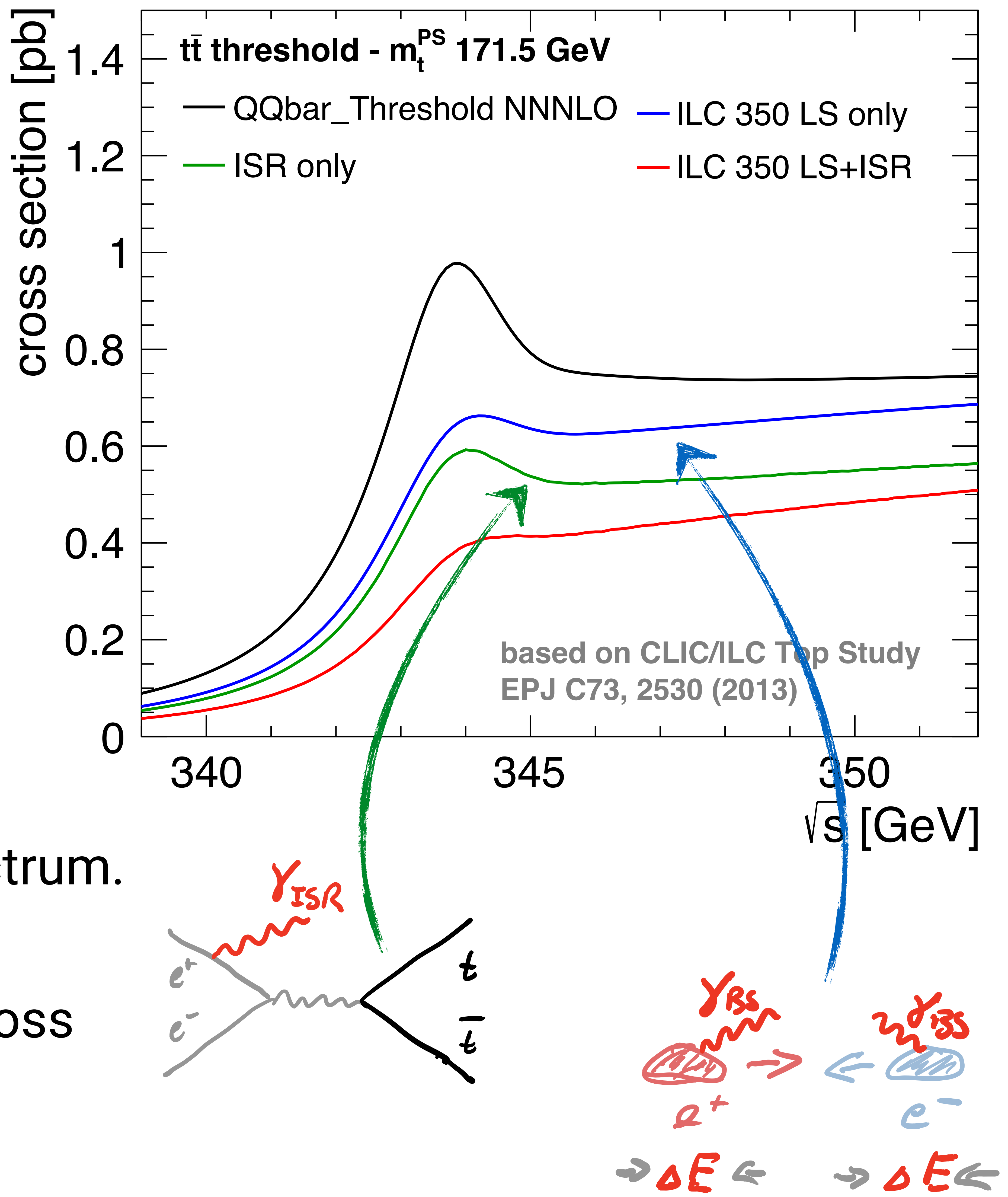
FCC vs

ILC

Requires: Precise understanding and measurement of spectrum.

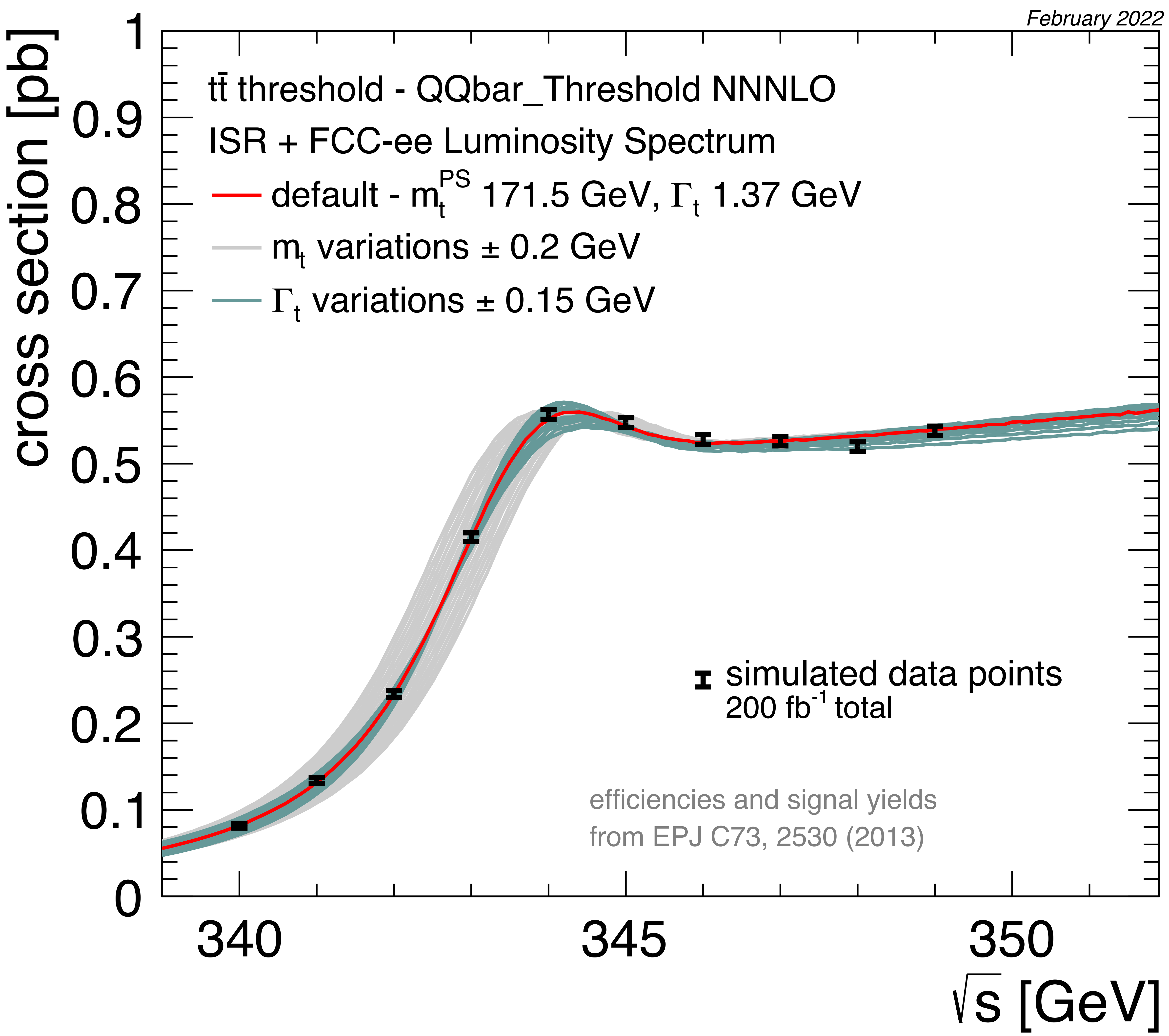
In this case:

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



The Standard Threshold Scan

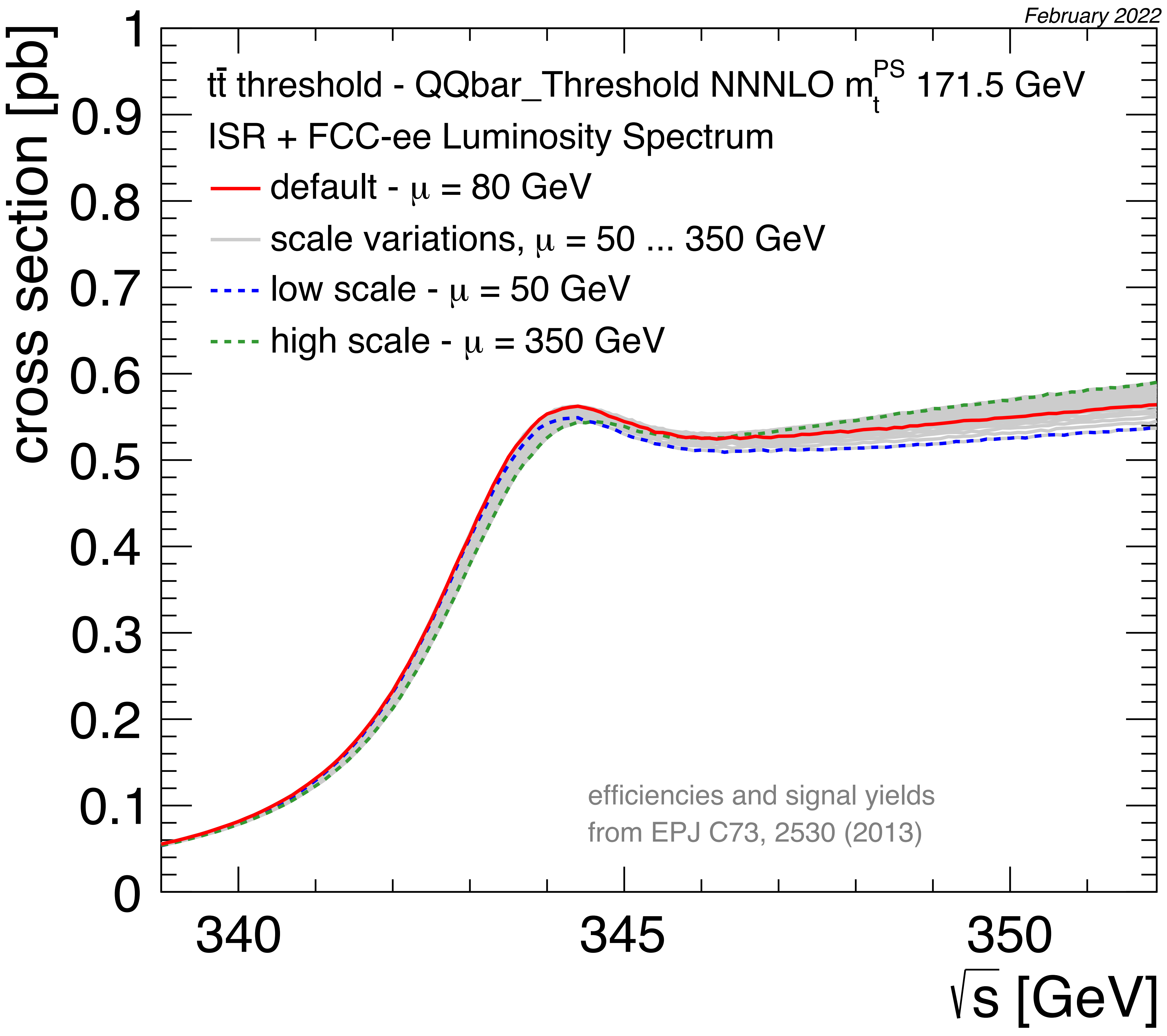
Experimental Assumptions



- 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.

Theory Uncertainties

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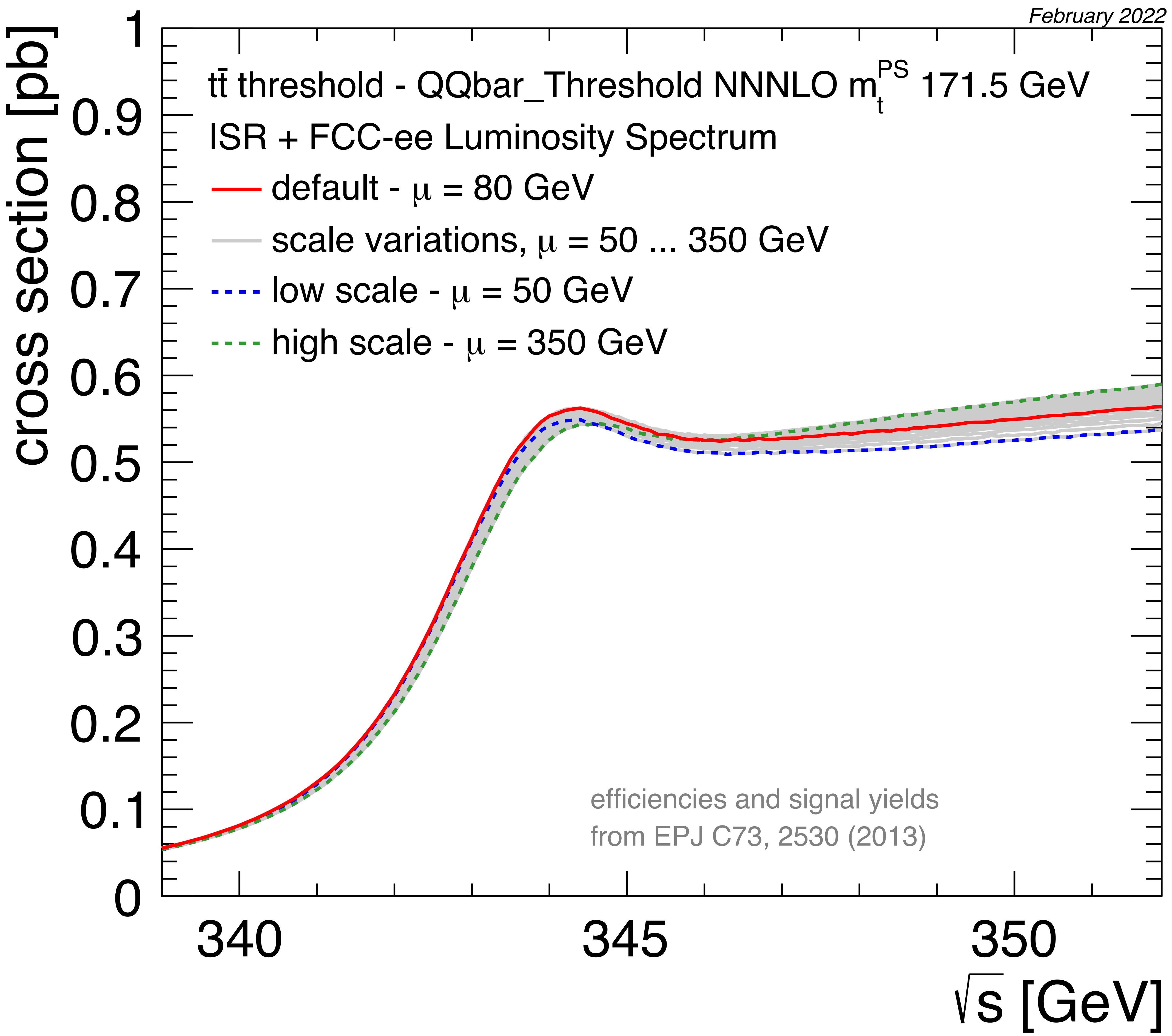
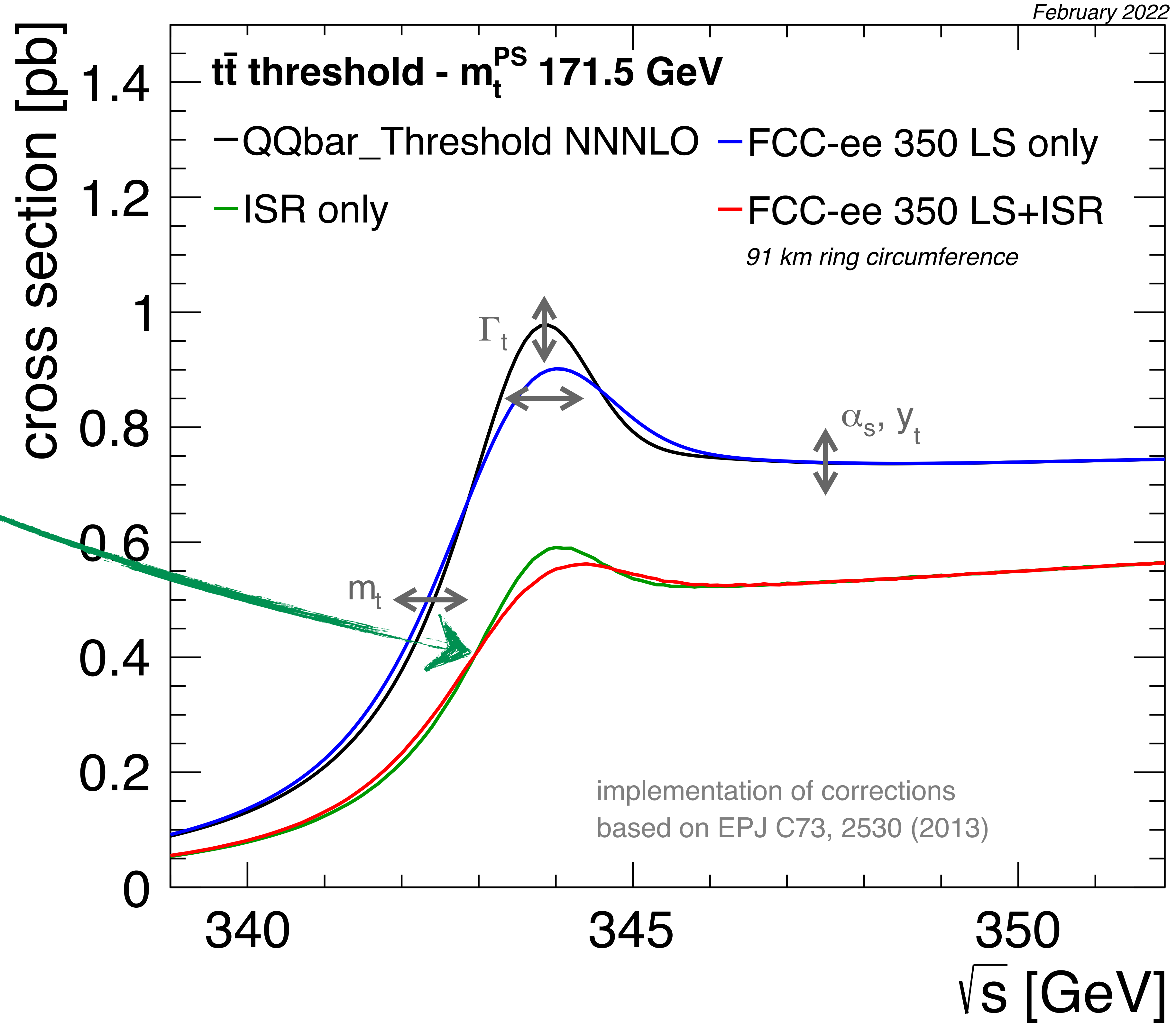


- QCD scale uncertainties highly relevant.
- Also need to calculate other effects, such as ISR, to the required precision!

the step from black to green

[only approximate in current experimental studies]



Choosing the Scan Range

Parameter Sensitivity

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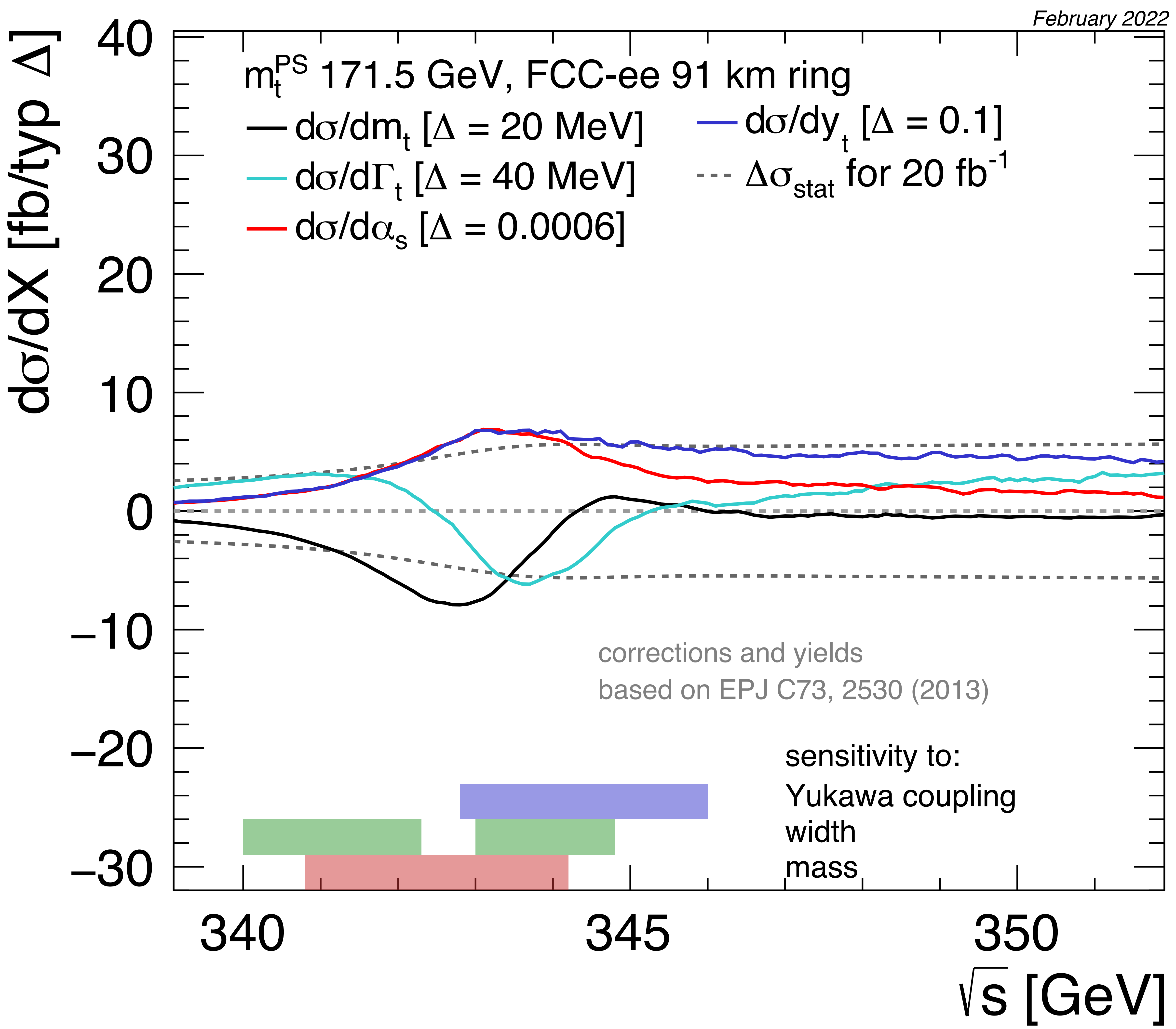
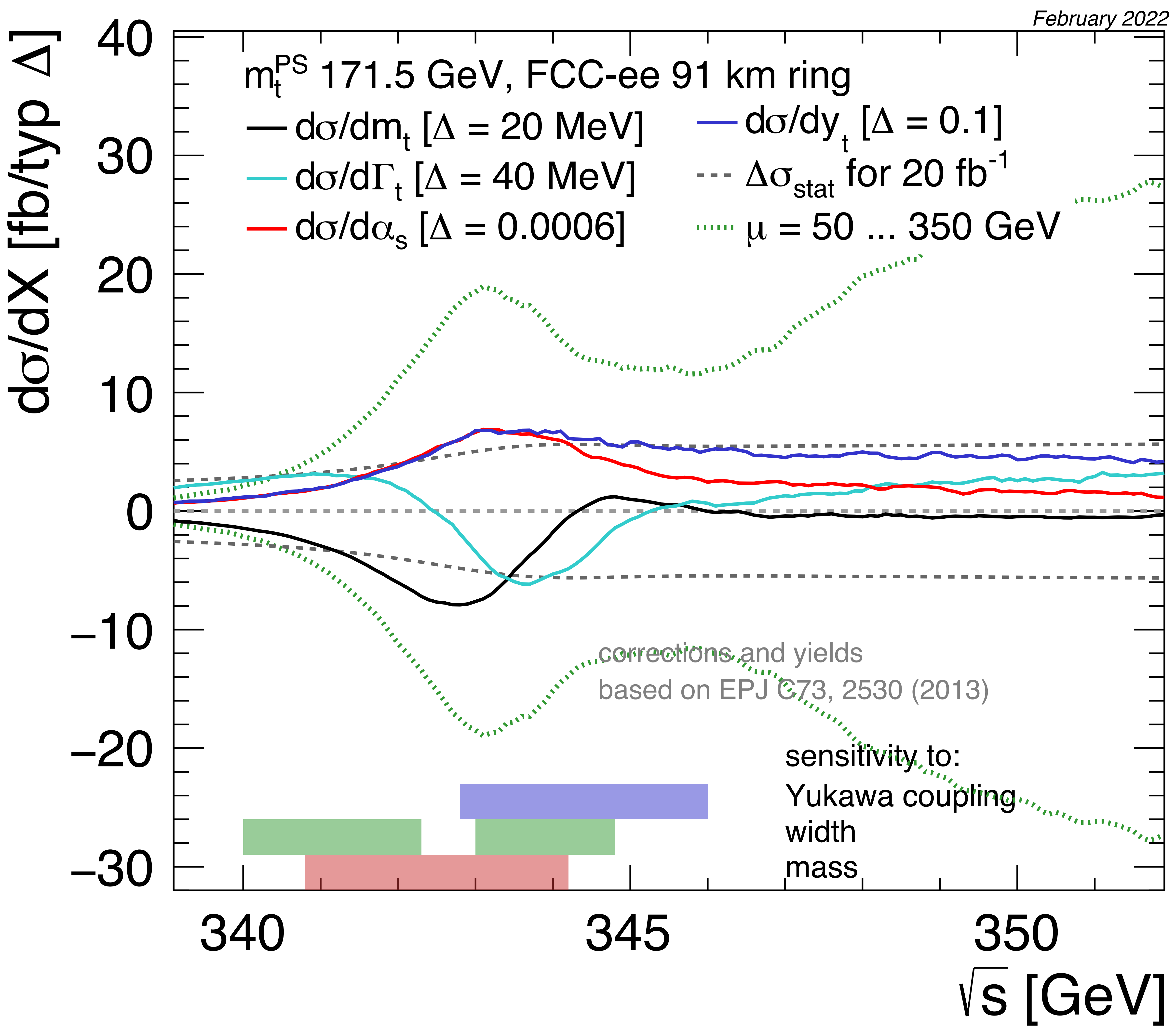


- Plot shows the derivative of the cross section for various parameters - to make this understandable this is normalised to typical changes of these parameters
- Full use to optimize scan range requires knowledge of mass to ~ 200 MeV in PS scheme. Can be achieved with 2 x 5 fb^{-1}:
  point 1: $\sqrt{s}$ = 2 x $m_t^{PS,LHC}$ - 1.5 GeV
  point 2: $\sqrt{s}$ = 2 x $m_t^{PS,LHC}$ + 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

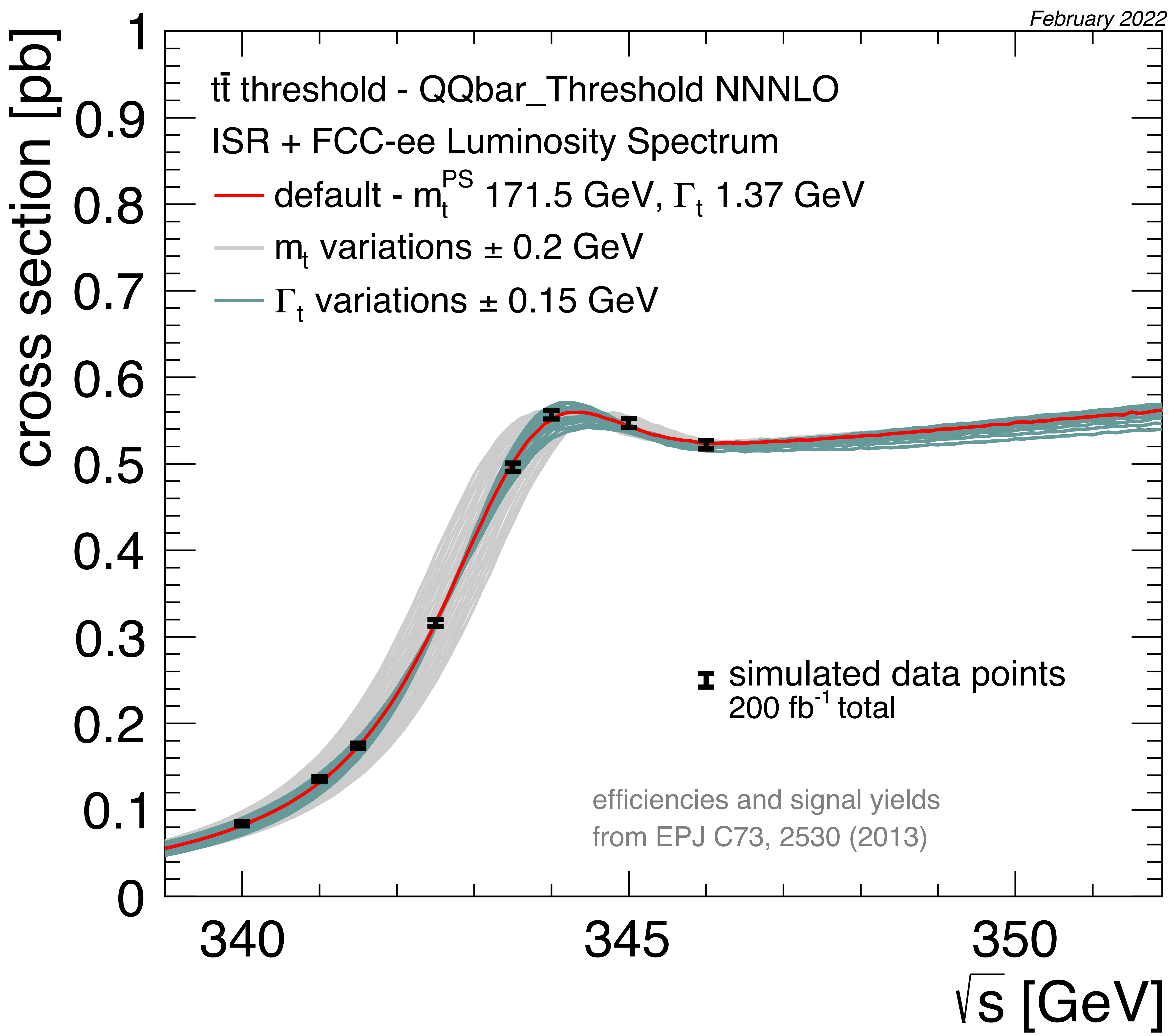
Enter theory uncertainty



- 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

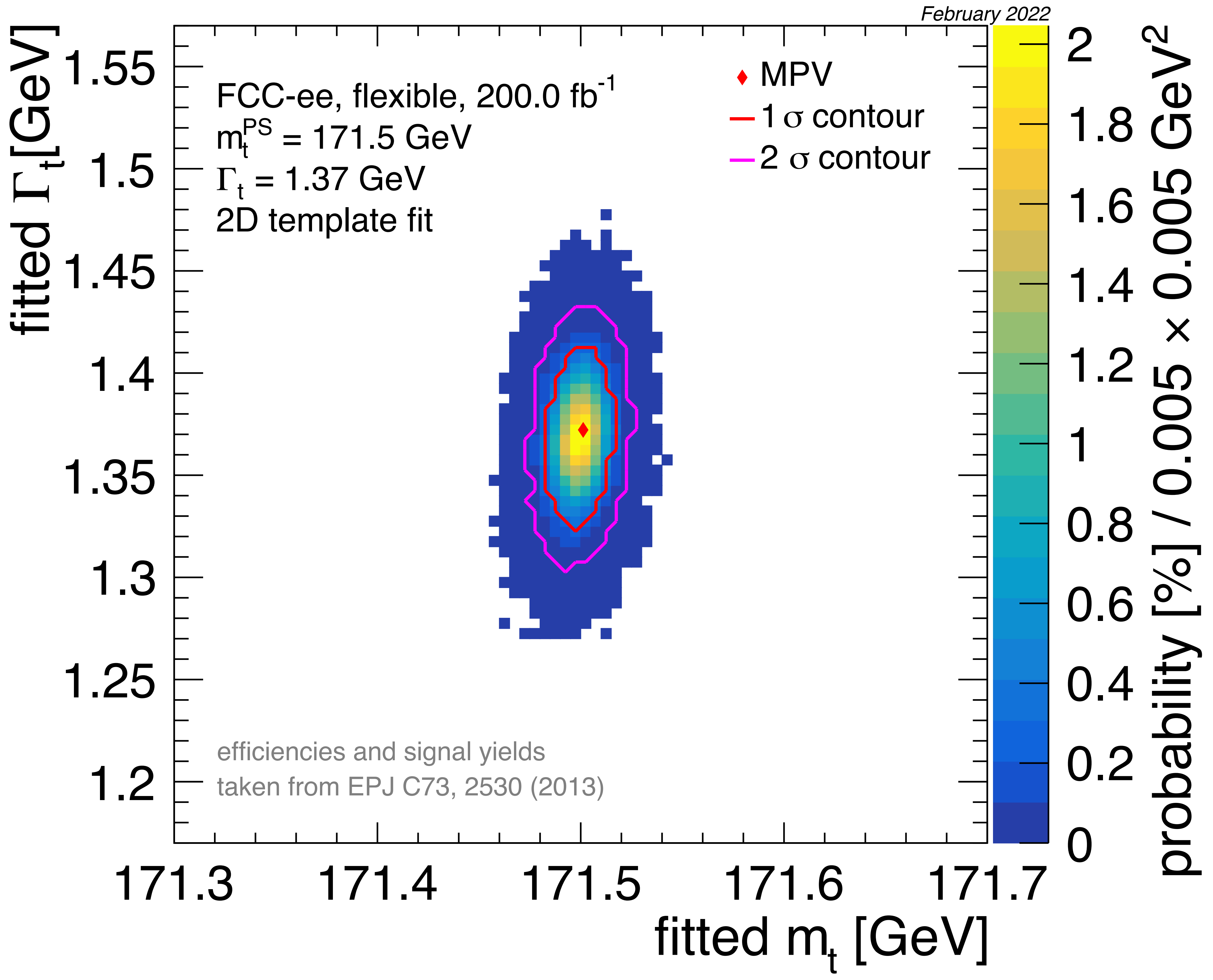


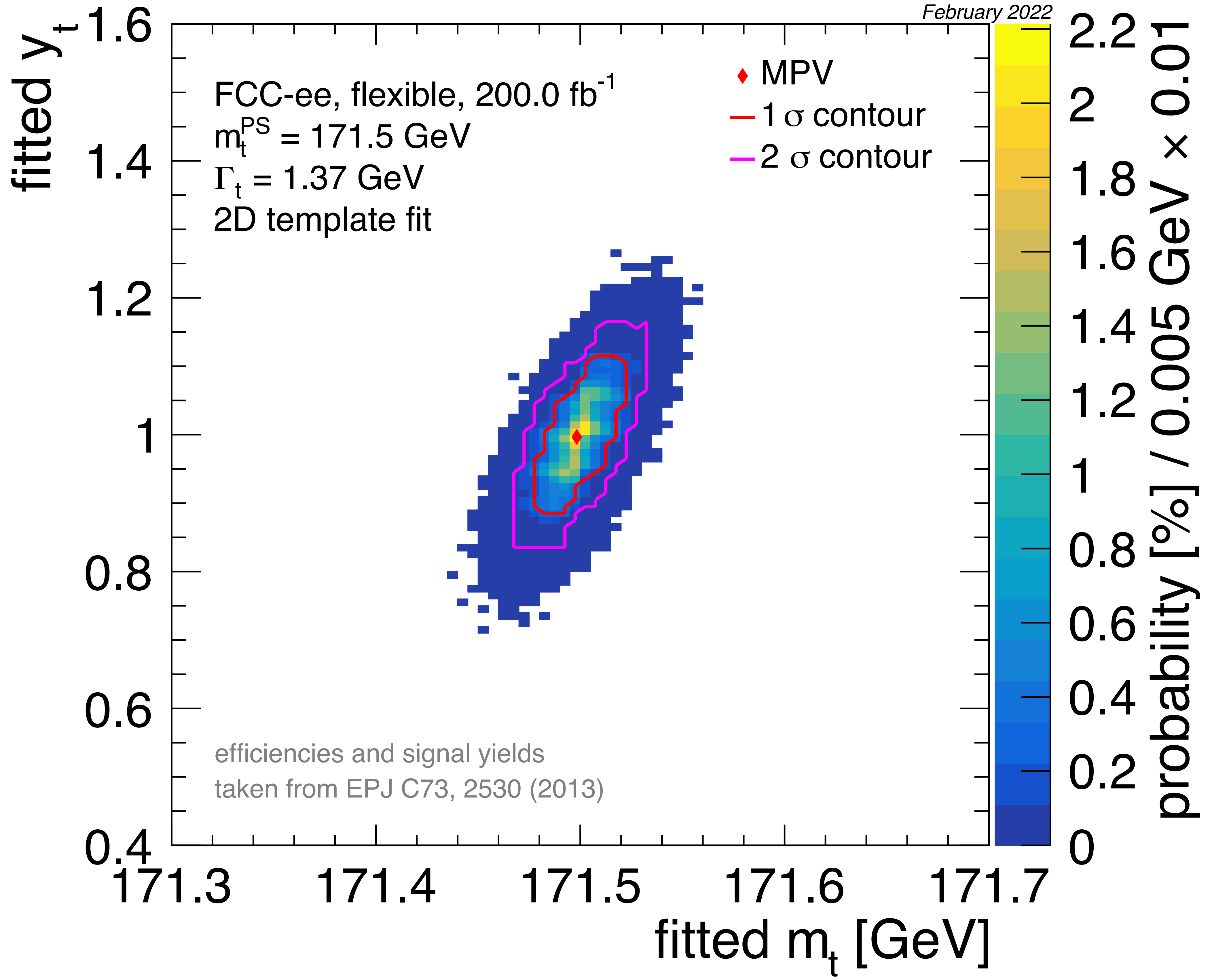
- Mildly optimized scan (mass & width) for FCC-ee as a balance between different sensitivities: 8 points in the range of 340 - 346 GeV

  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 as starting point

- Relatively thorough evaluation for ILC leading up to European Strategy, and adjusted also for CLIC in the framework of the CLIC top physics paper.

error source	Δm_t^{PS} [MeV]	
stat. error (200 fb^{-1})	13	assuming standard 10 point scan
theory (NNNLO scale variations, PS scheme)	40	40 - 45, depending on scan range
parametric (α_s, current WA: 9 x 10^{-4})	26	evaluated with current WA
non-resonant contributions (such as single top)	< 40	2015 study, reduce with theory work
residual background / selection efficiency	10 – 20	2012 study, basis for all newer threshold studies
luminosity spectrum uncertainty	< 10	evaluated for CLIC
beam energy uncertainty	< 17	very conservative estimate - expect to be better
combined theory & parametric	30 – 50	
combined experimental & backgrounds	25 - 50	
total (stat. + syst.)	40 – 75	

Uncertainties Overview

My Snowmass'21 Bottom Line

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δm_t^{PS} [MeV]	ILC	CLIC	FCC-ee
$\mathcal{L}[\mathrm{fb}^{-1}]$	200	100 [200]	200
Statistical uncertainty	10	20 [13]	9
Theoretical uncertainty (QCD)	40 – 45		
Parametric uncertainty α_s	26	26	3.2
Parametric uncertainty y_t (HL-LHC)	5		
Non-resonant contributions	< 40		
Experimental systematic uncertainty	15 – 30		11 – 20
Total uncertainty	40 – 75		

slightly compressed scans for ILC, FCC-ee

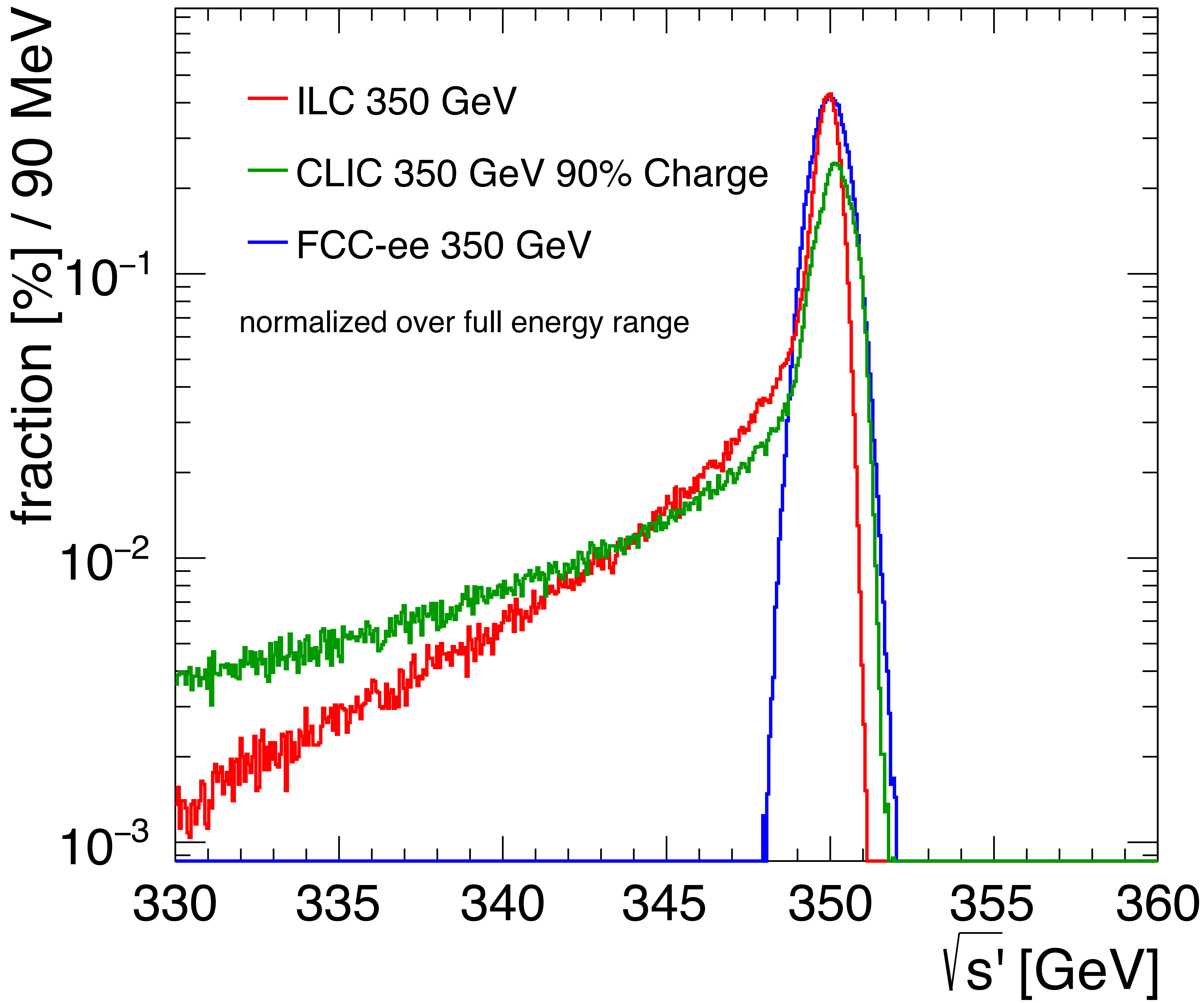
latest evaluation with 8-point scans

ultimate α_s (1.2×10^{-4}) assumed for FCC-ee, current WA for ILC, CLIC (do we have something better?)

- Assumptions on experimental systematics:
  - residual background and selection similar for all
  - very slight advantage for FCC-ee due to absence of luminosity spectrum uncertainty
  - Beam energy uncertainty for FCC-ee 3 MeV (for 5 MeV energy uncertainty) - original conservative estimate for ILC and CLIC can likely be improved to similar range (same energy measurement techniques for linear and circular)

Uncertainties: Luminosity Spectrum

A few more details



- Beamstrahlung tail at linear colliders smears the threshold curve: Requires accurate modeling in analysis
  - Studied with the CLIC spectrum, with full detector simulations for spectrum reconstruction. Effect on top mass controlled to better than 10 MeV

Uncertainties - Parametric

A few more details

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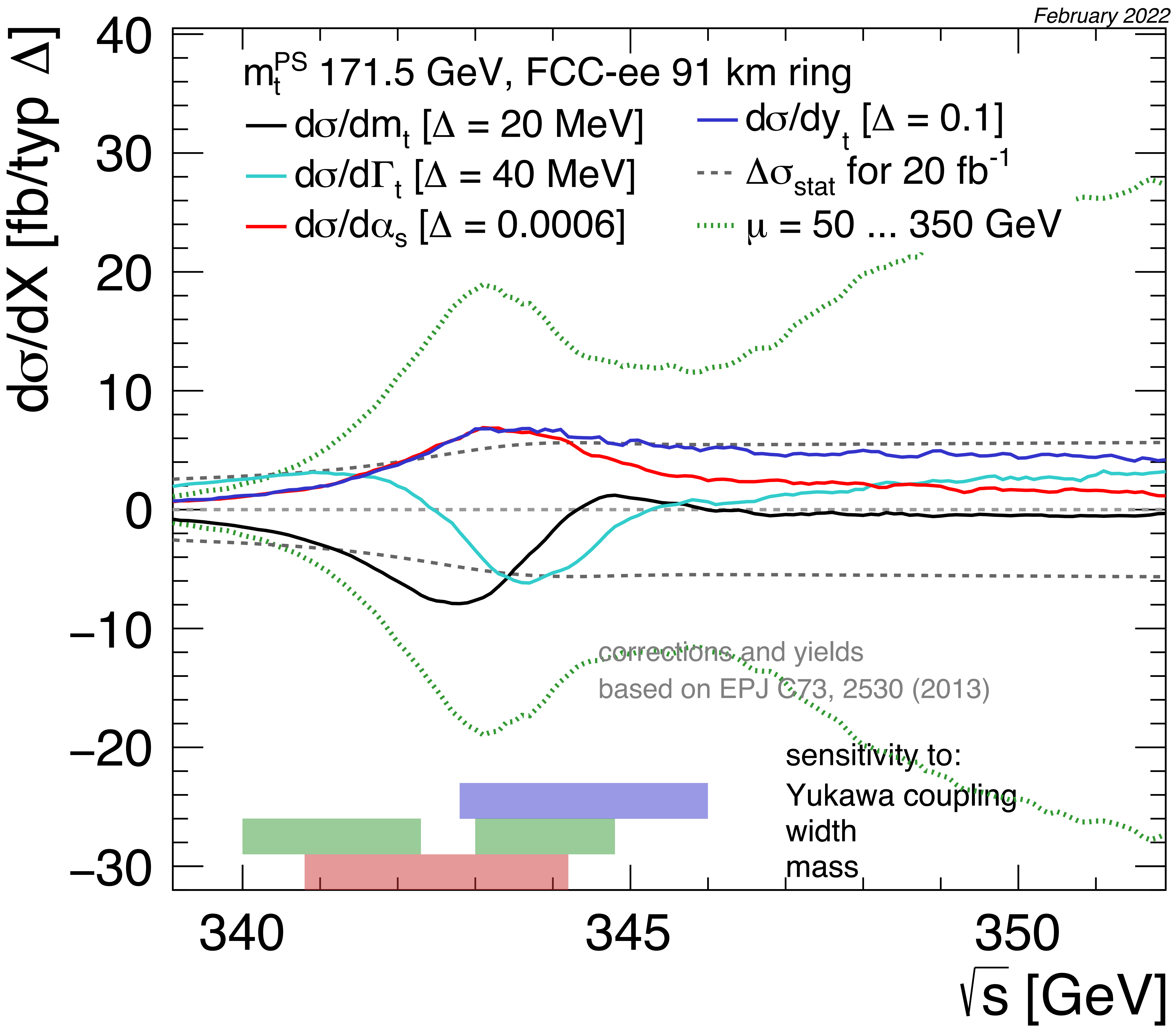


Correlation of mass with α_s, y_t

Uncertainty scales with input precision:

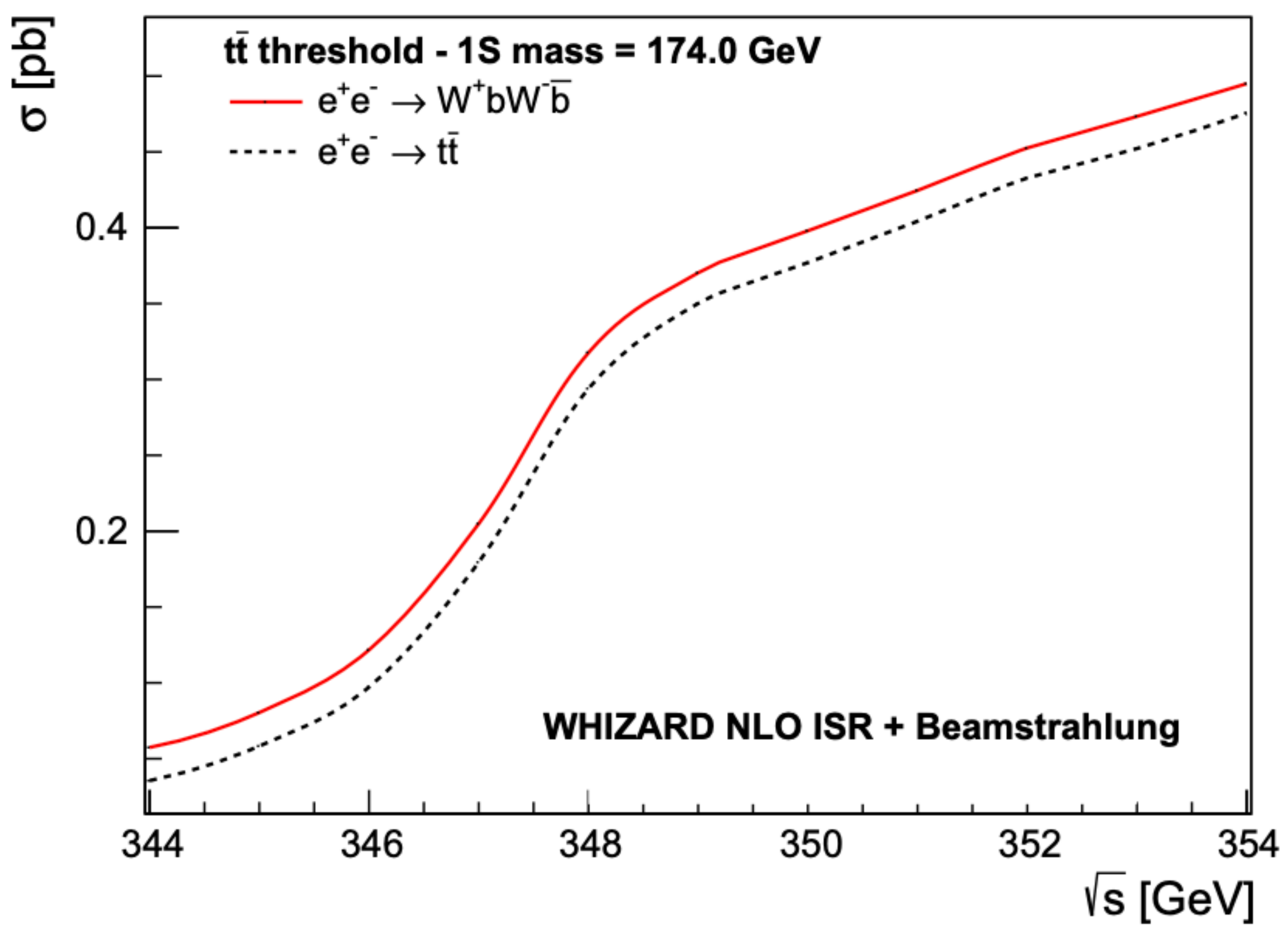
Δm ~ 2.6 MeV per 10^{-4} in α_s

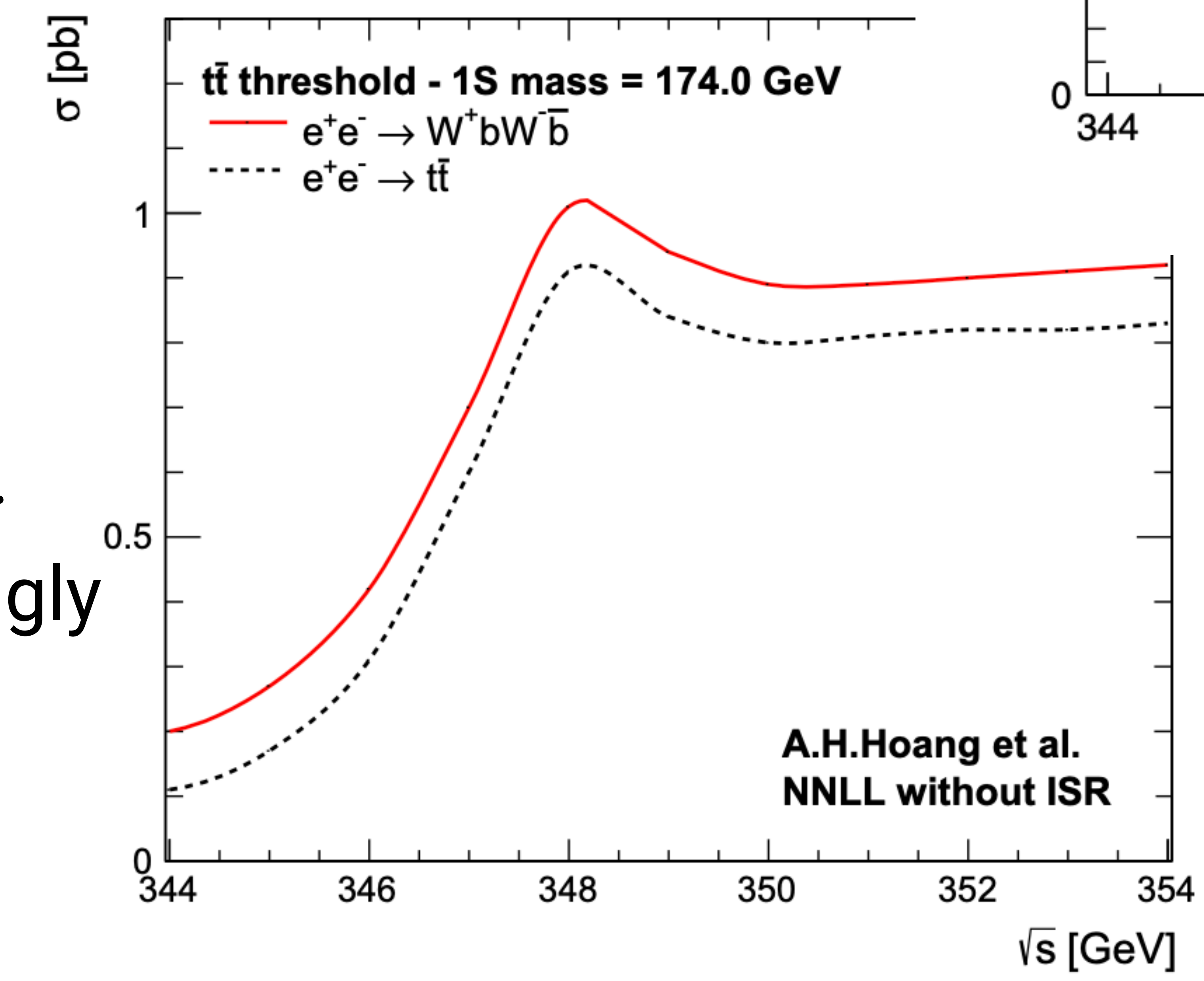
Δm ~ 1.6 MeV per 1% in y_t: ~ 5 MeV for 3.4% from HL-LHC

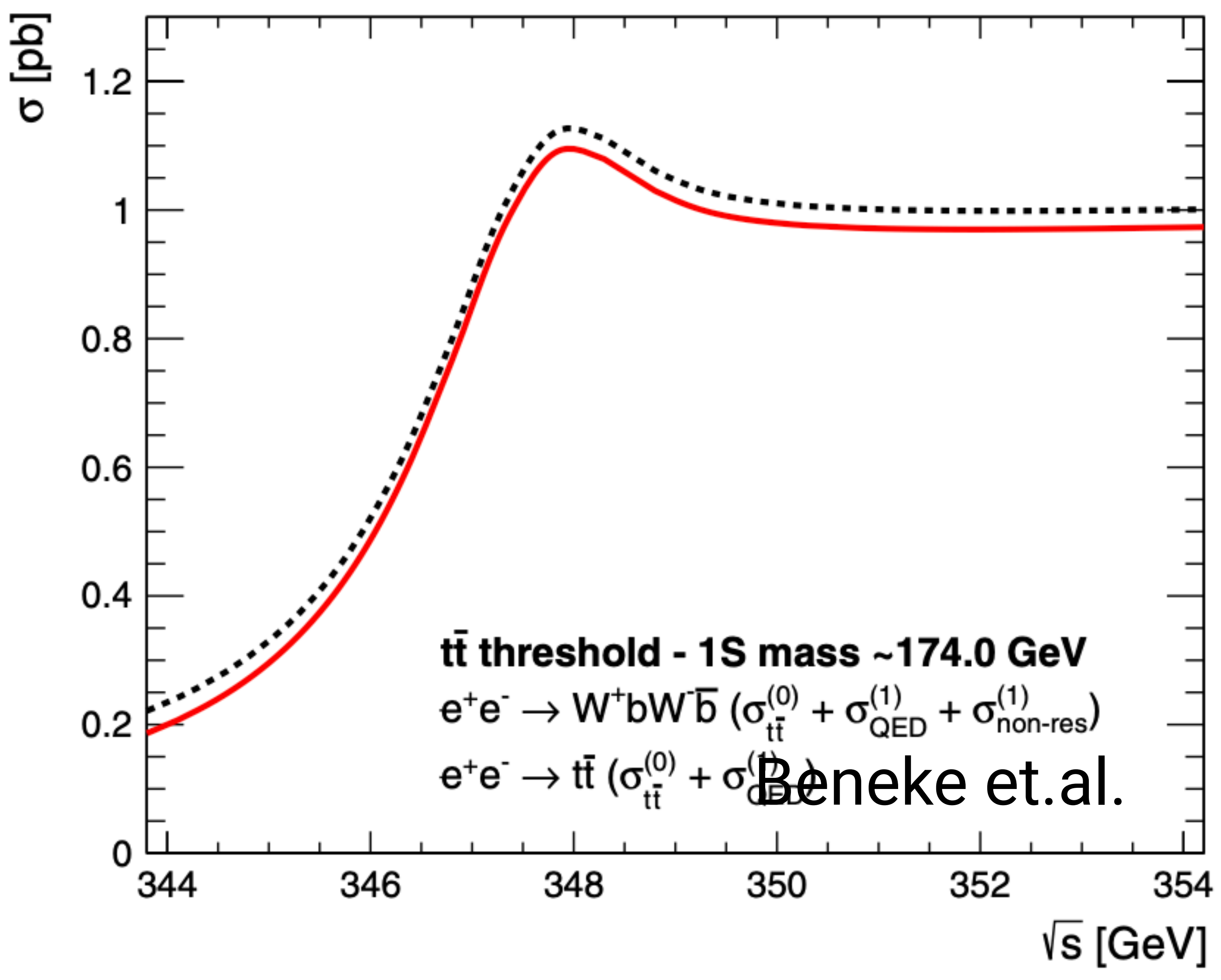
Uncertainties - Non-resonant contributions

A few more details

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







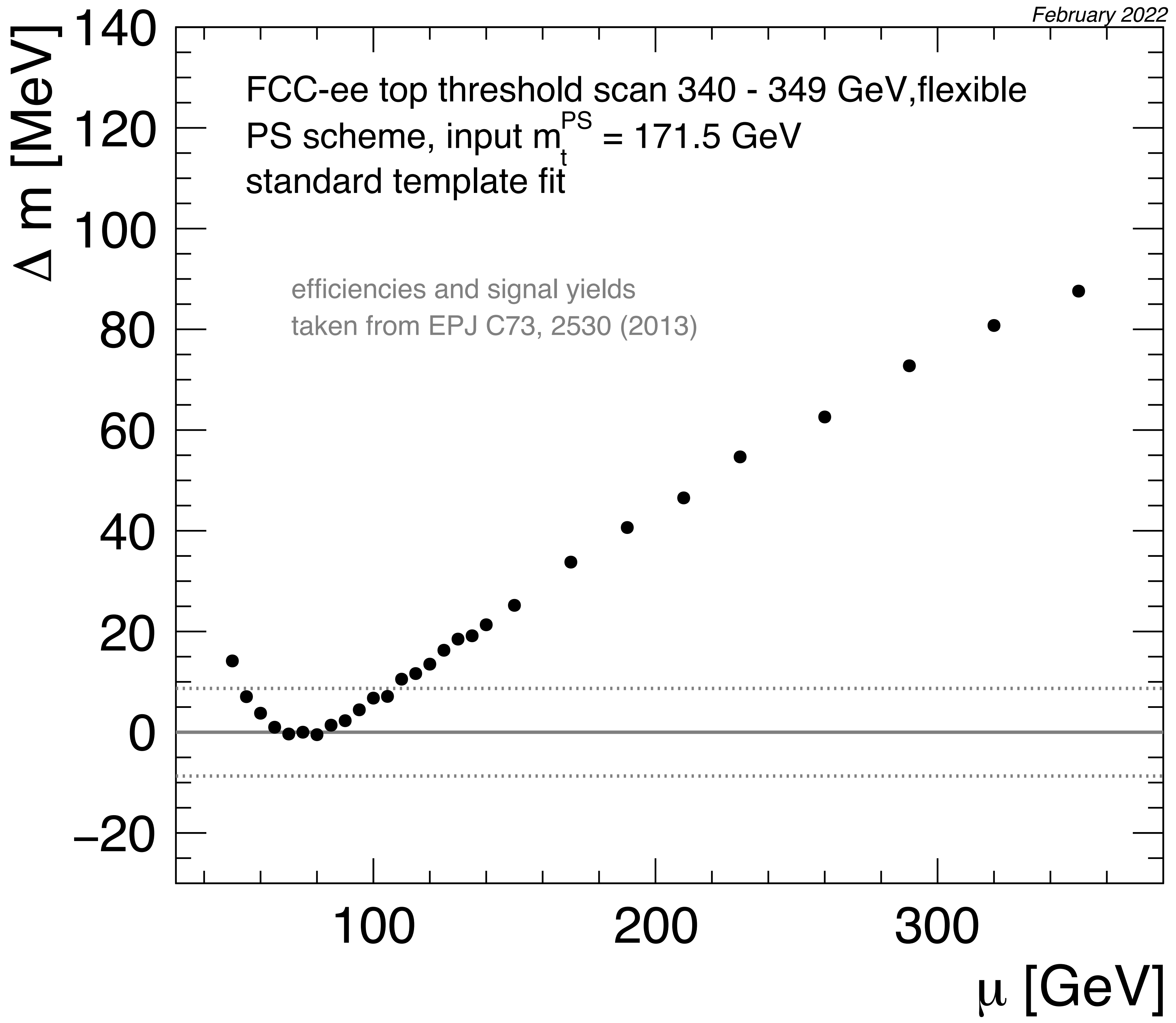
- Non-resonant contributions in the threshold region are non-negligible.
- Contribution to yield depends strongly on cuts.
- Cuts can influence shape

- 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

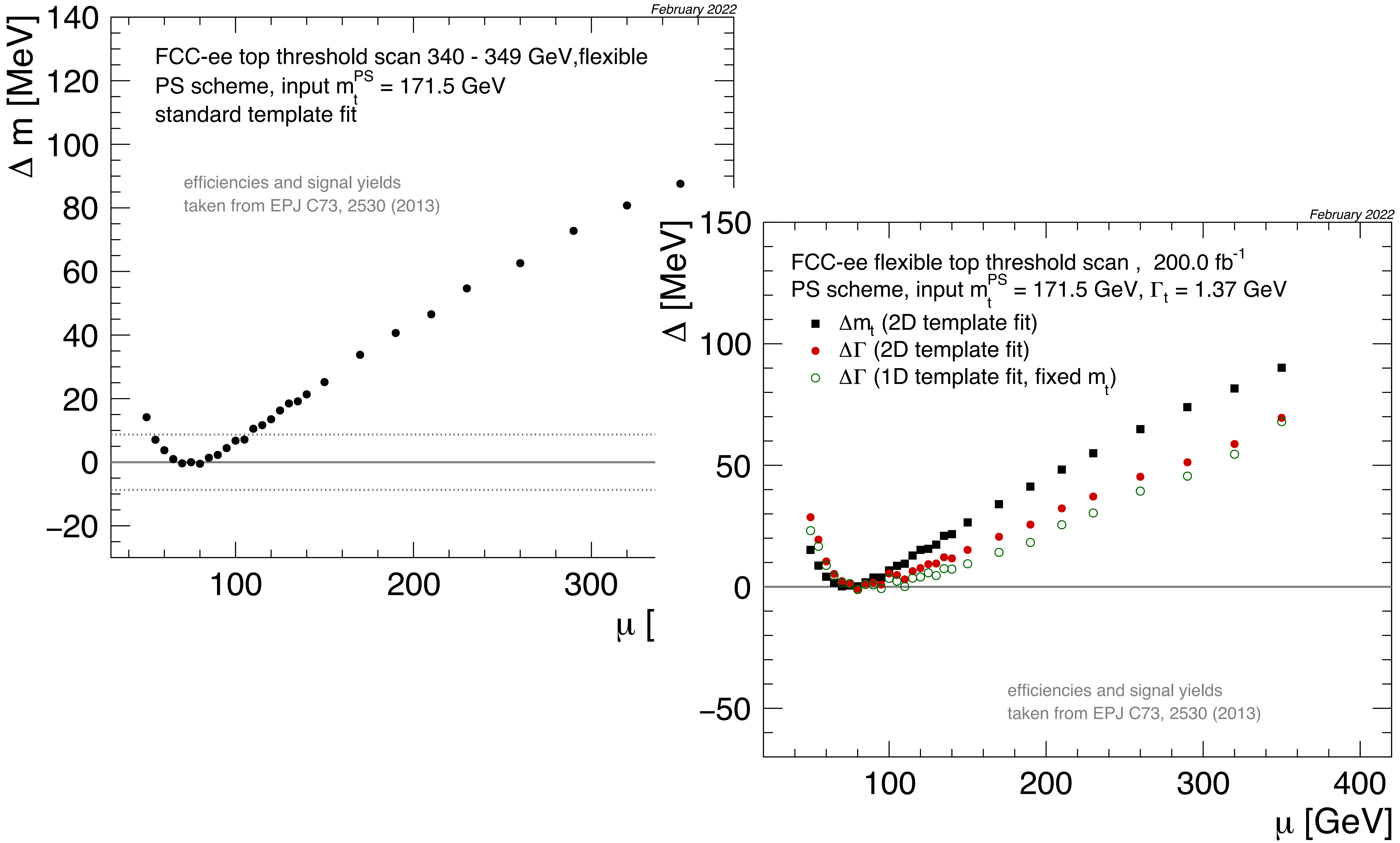
- Impact of QCD scale uncertainties on mass, width, Yukawa extraction



Uncertainties - Scale

A few more details

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



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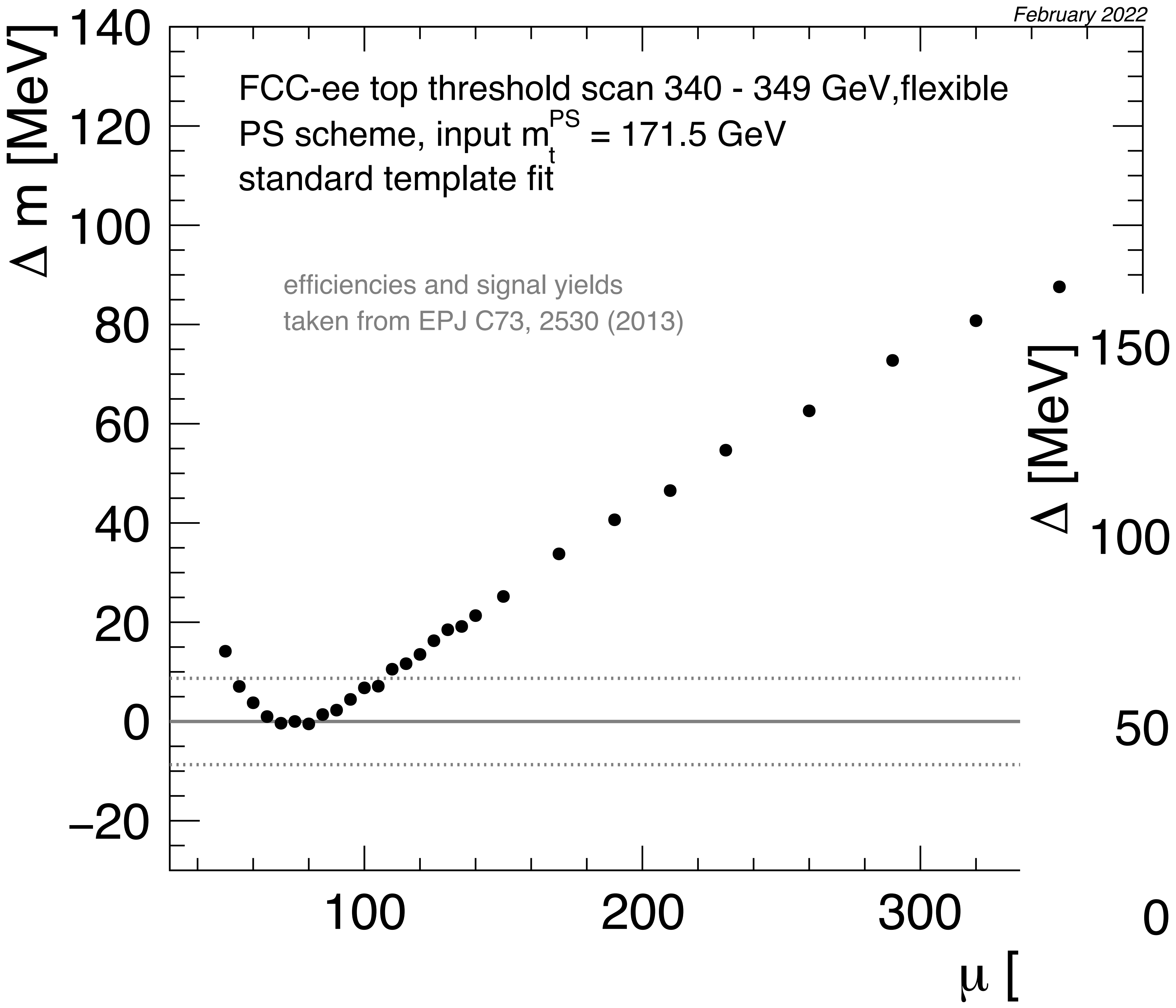
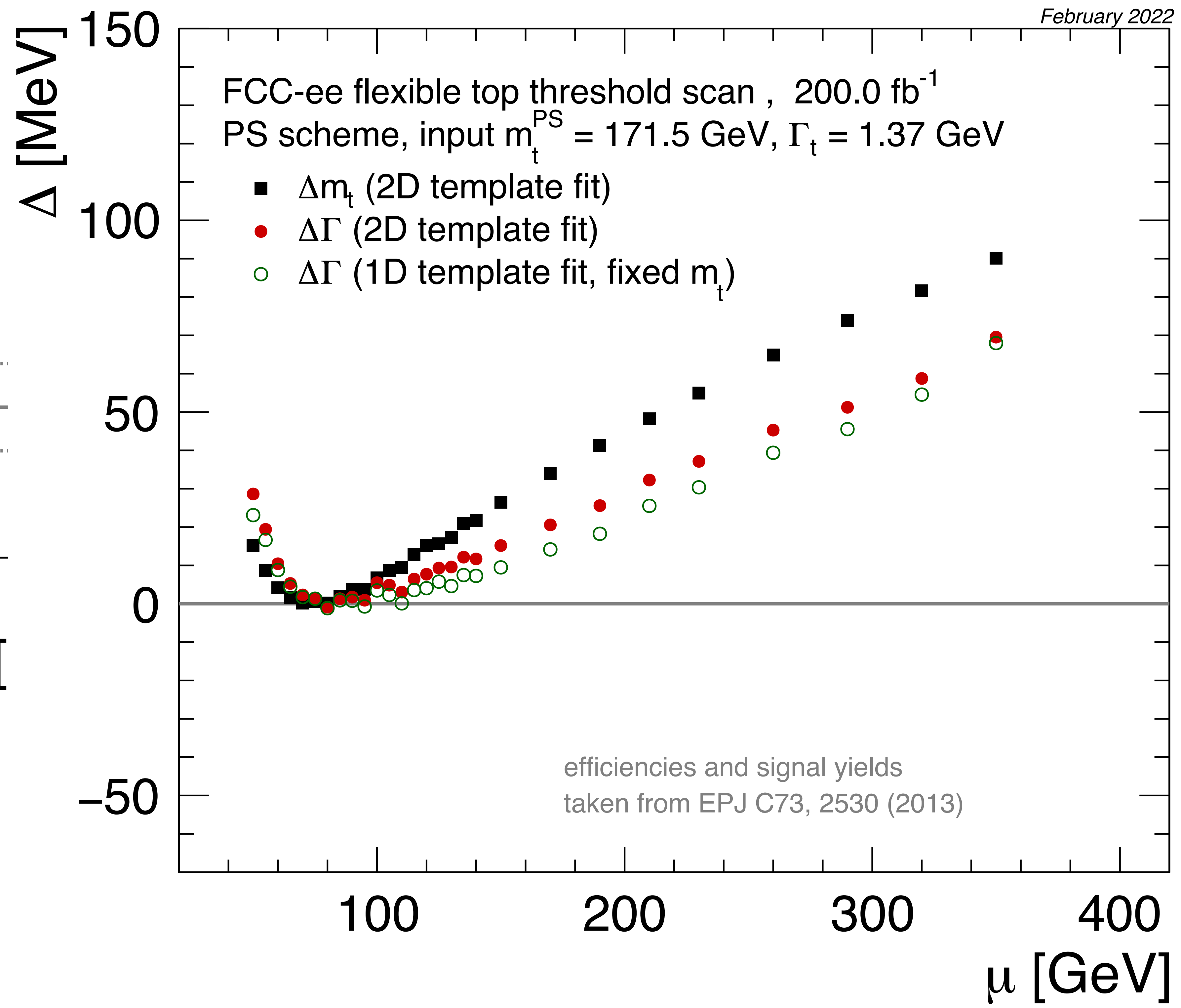
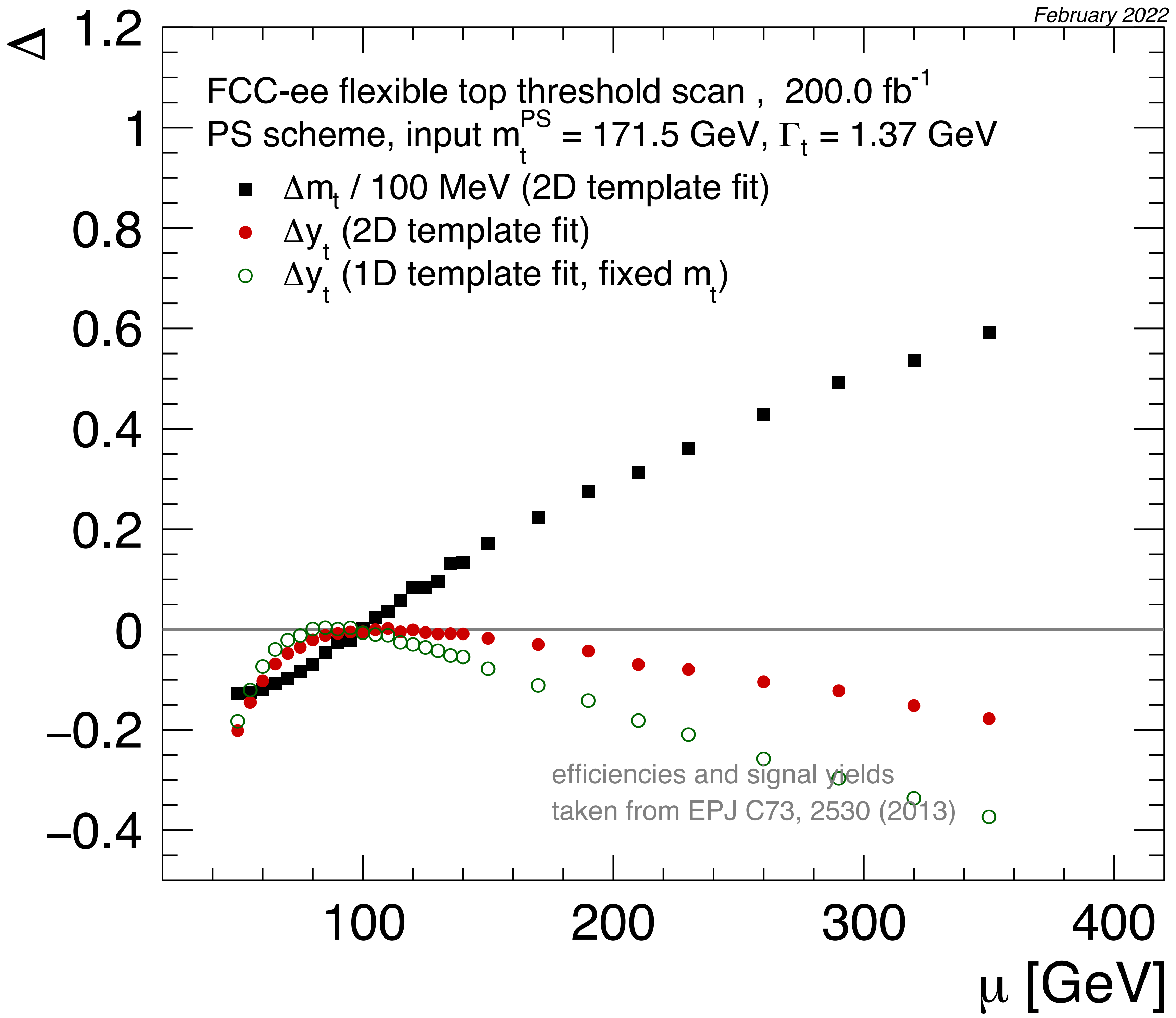
MAX-PLANCK-INSTITUT FÜR PHYSIK

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







The leading systematic:

Improvements directly propagate to total precision

Bottom Line

- e^+e^- Colliders running at the top quark pair production threshold will provide the ultimate precision on the top quark mass

- 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.