The Top Threshold & QCD Precision
at e^+e^- Higgs-Top-Electroweak Factories

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MAX-PLANCK-INSTITUT FÜR PHYSIK

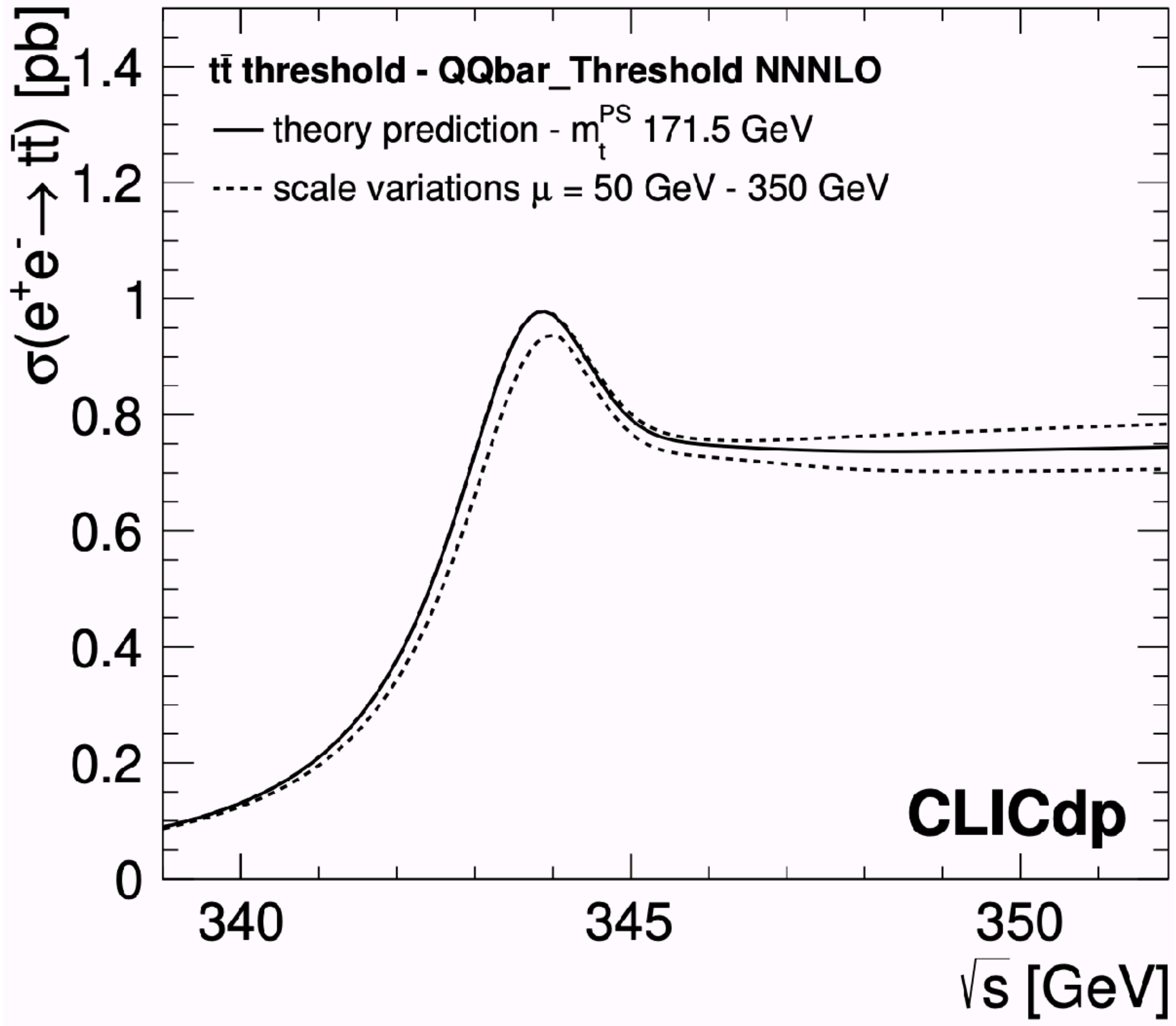
Outline

- The Top quark pair production threshold *[the emphasis of this talk - sorry, personal bias!]*
  - Threshold overview
  - Measuring the mass
  - Threshold beyond mass
- QCD precision measurements
  - The strong coupling constant
  - Gluon jets, colour reconnection

Part I: The Top Threshold

The Top Quark Pair Production Threshold

Sensitivity to Top Quark Properties and Beyond



- The cross section of top quark pair production in the threshold region depends on top quark properties, and on QCD
- 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.

The Top Quark Pair Production Threshold

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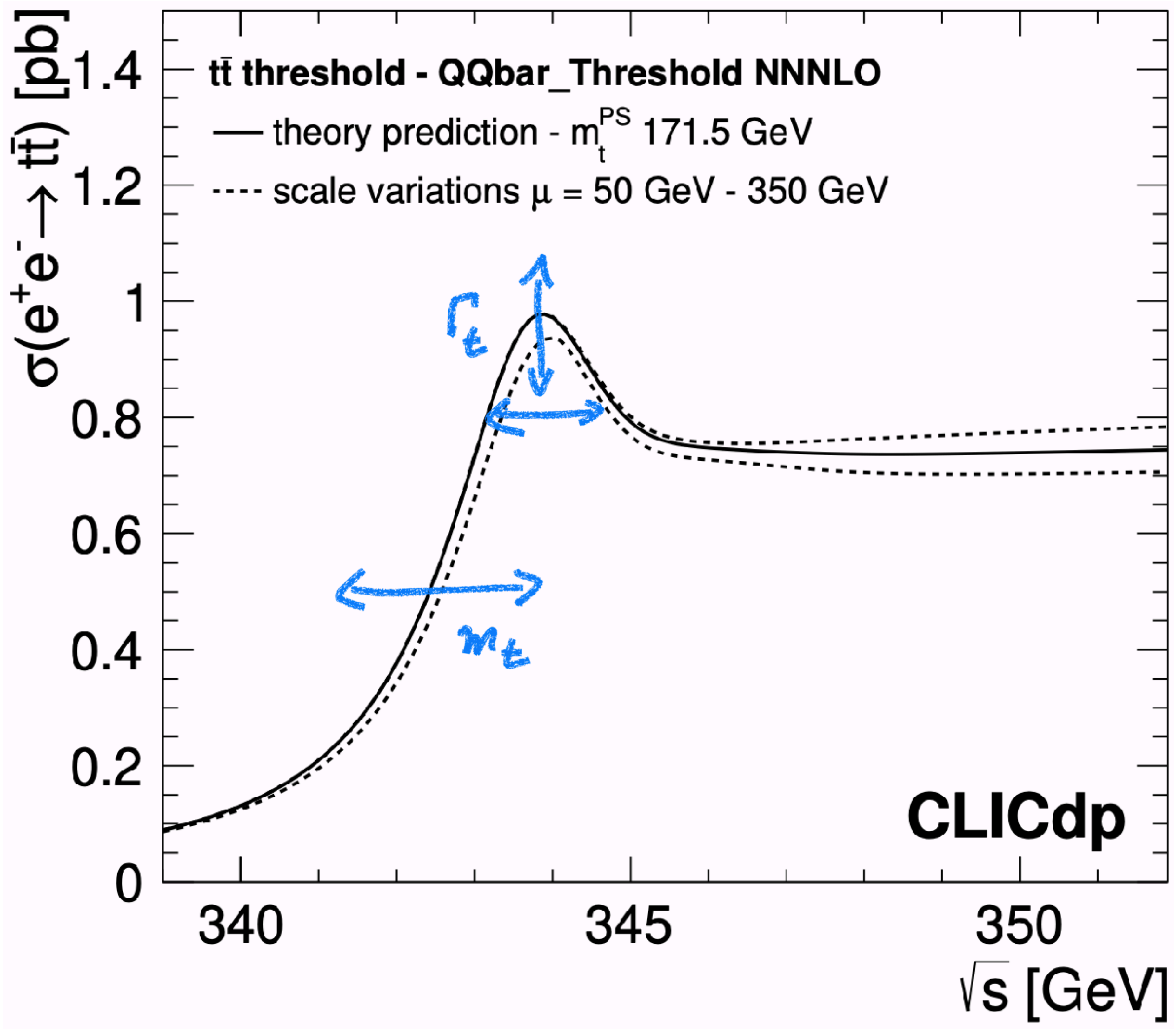

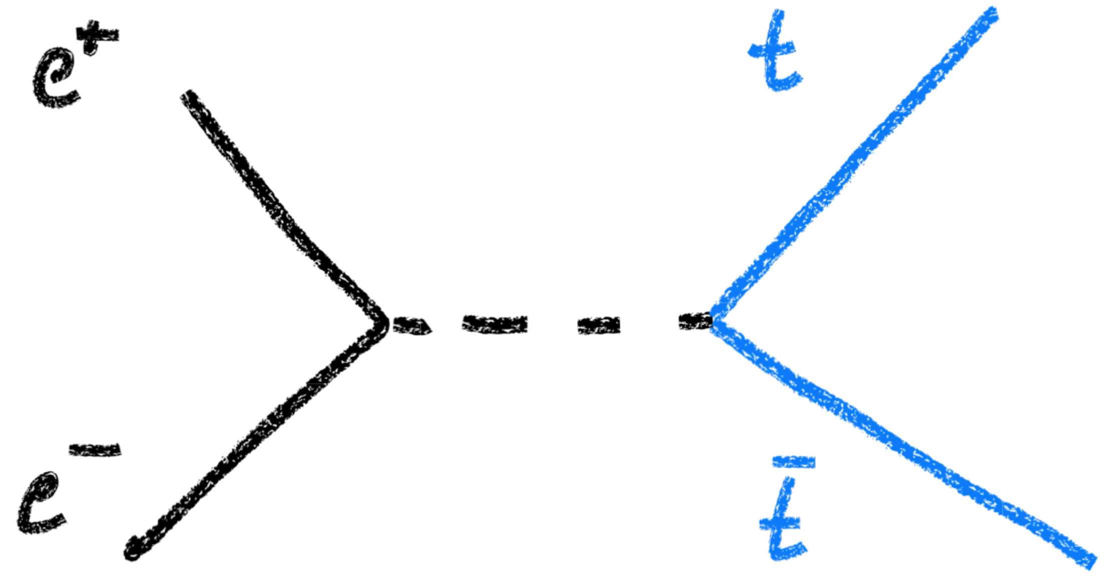

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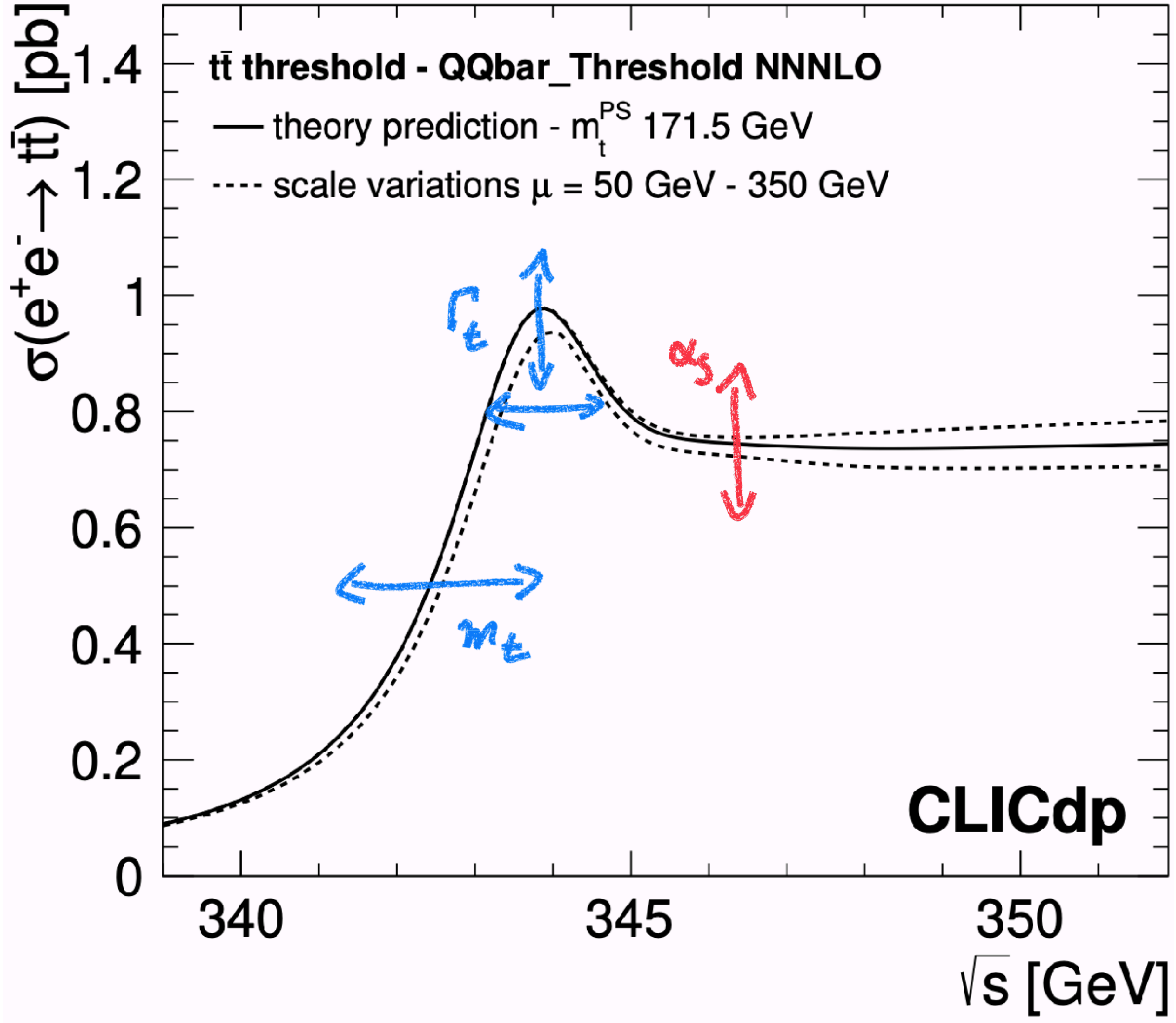

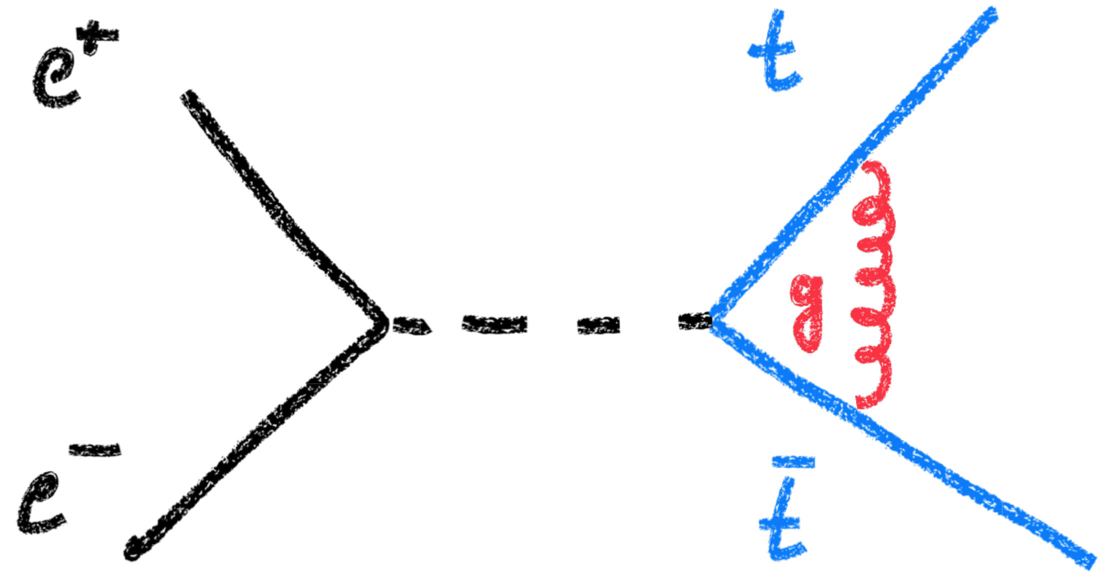

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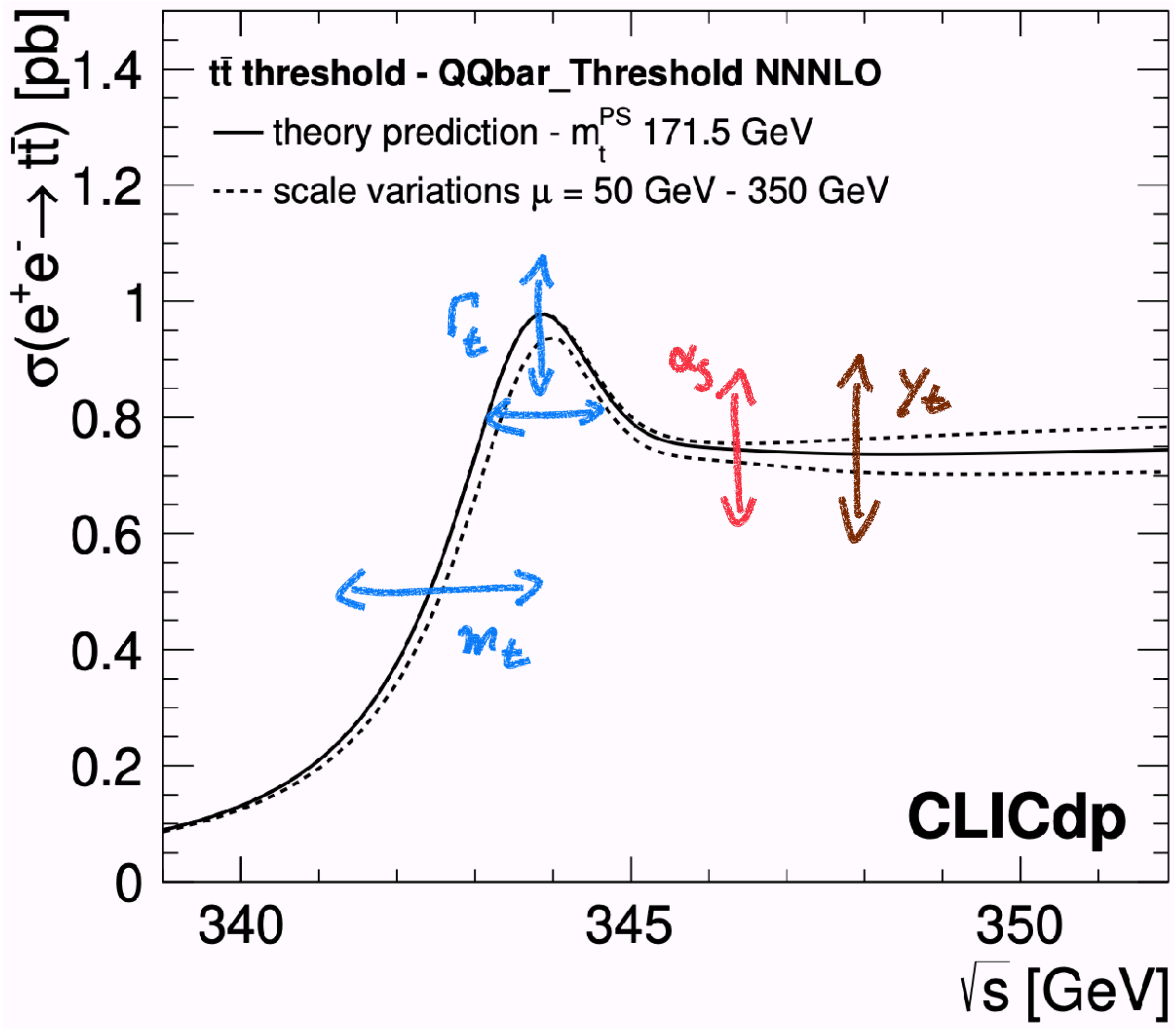

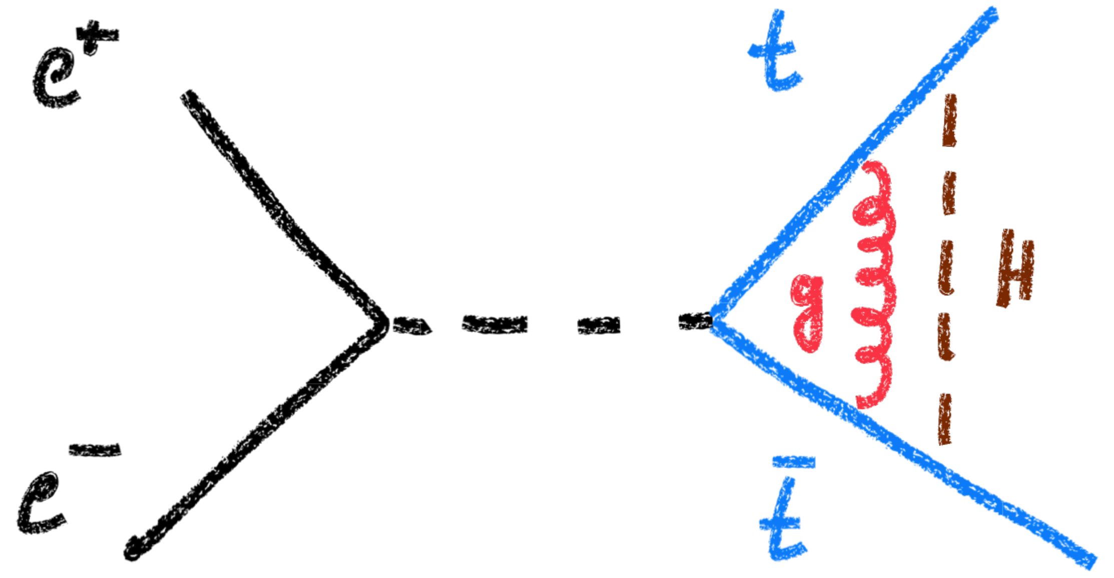

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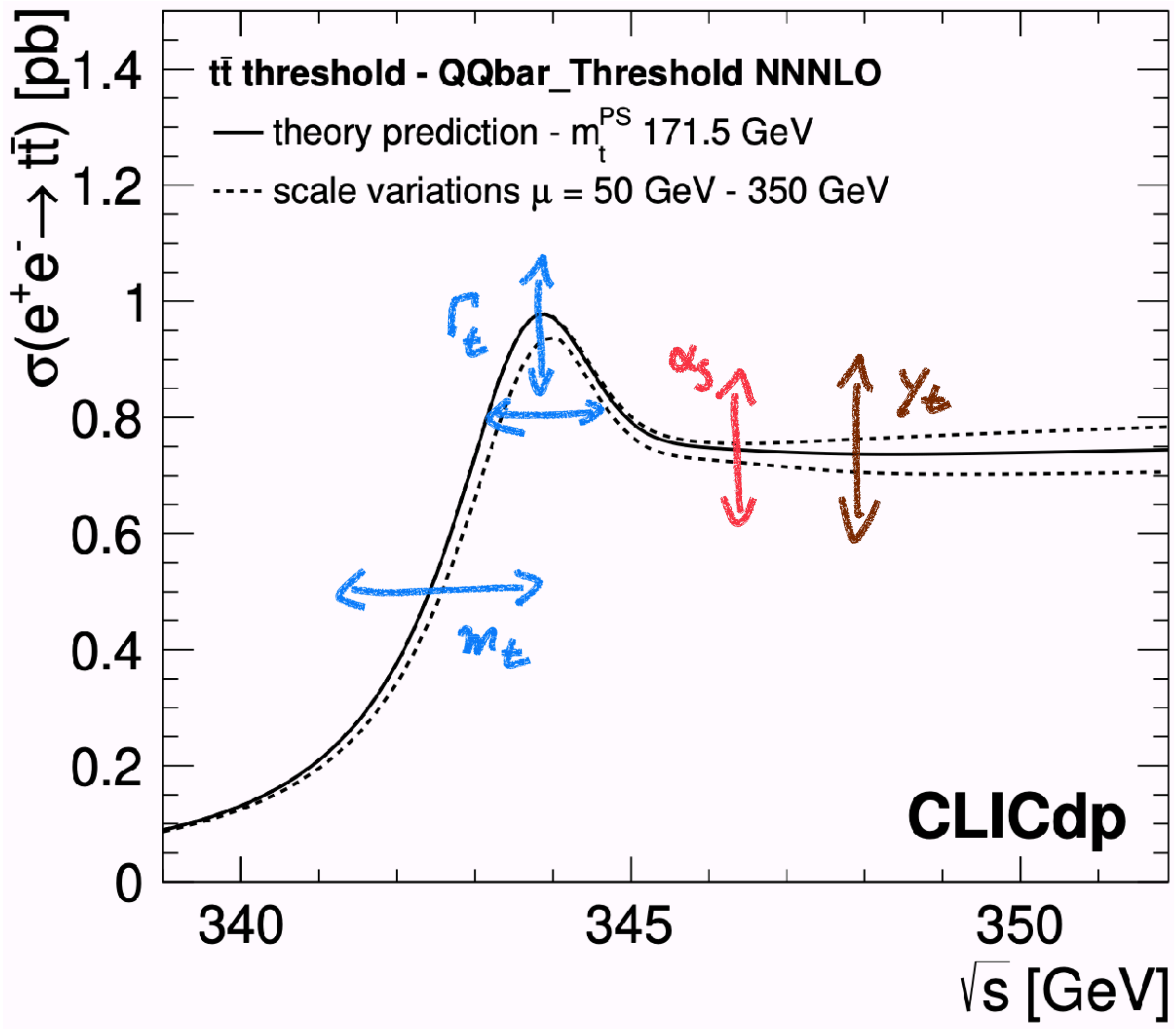

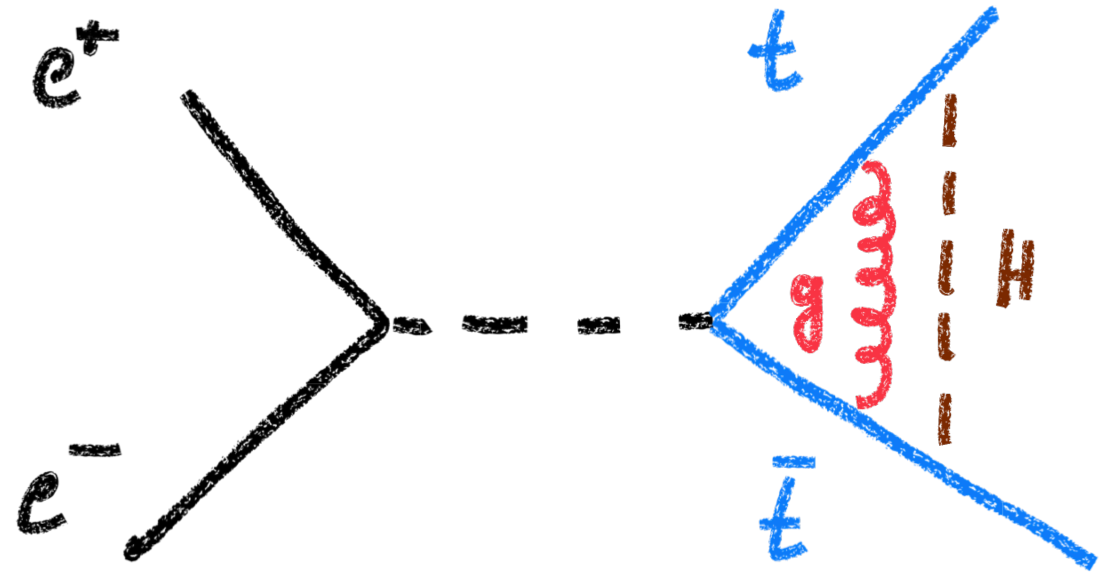

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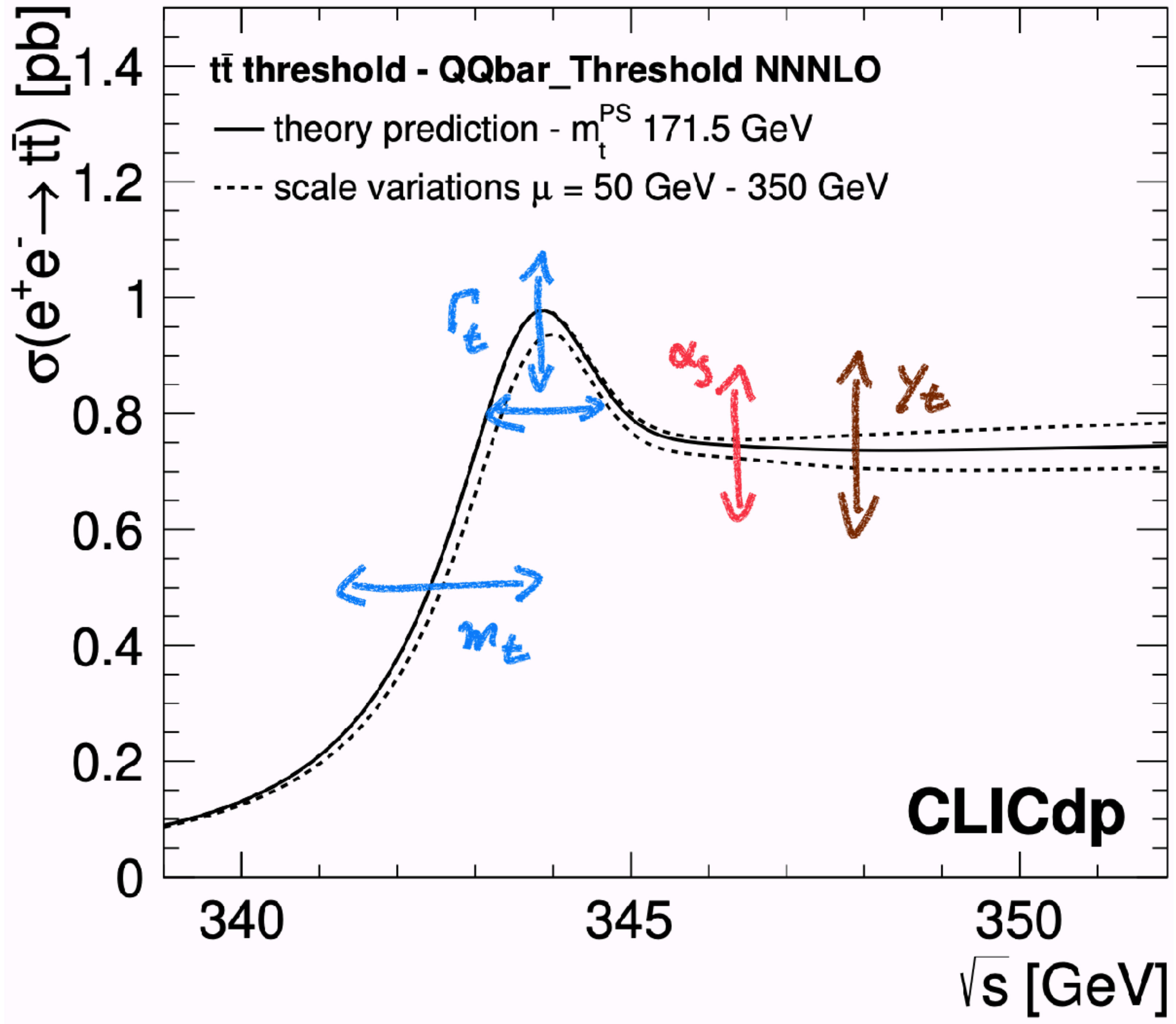
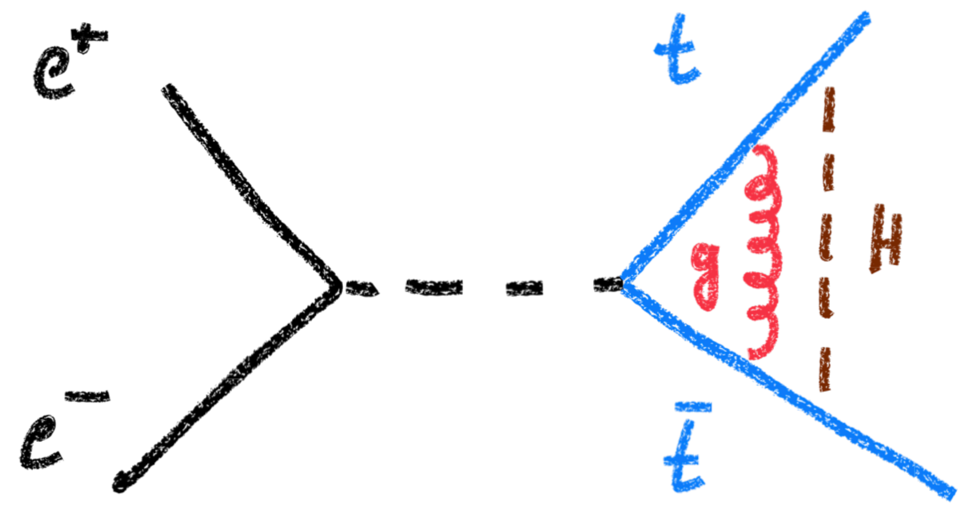
- Precise theoretical calculations of cross section in the threshold region, in well-defined mass schemes (m_t^{PS}, m_t^{1S}…) -> Can be converted directly into MSbar mass.
- In principle, α_s can be extracted from the threshold, but the precision is typically less than the current world average - using external input more efficient.

The Top Quark Pair Production Threshold

From Theory to Experiment

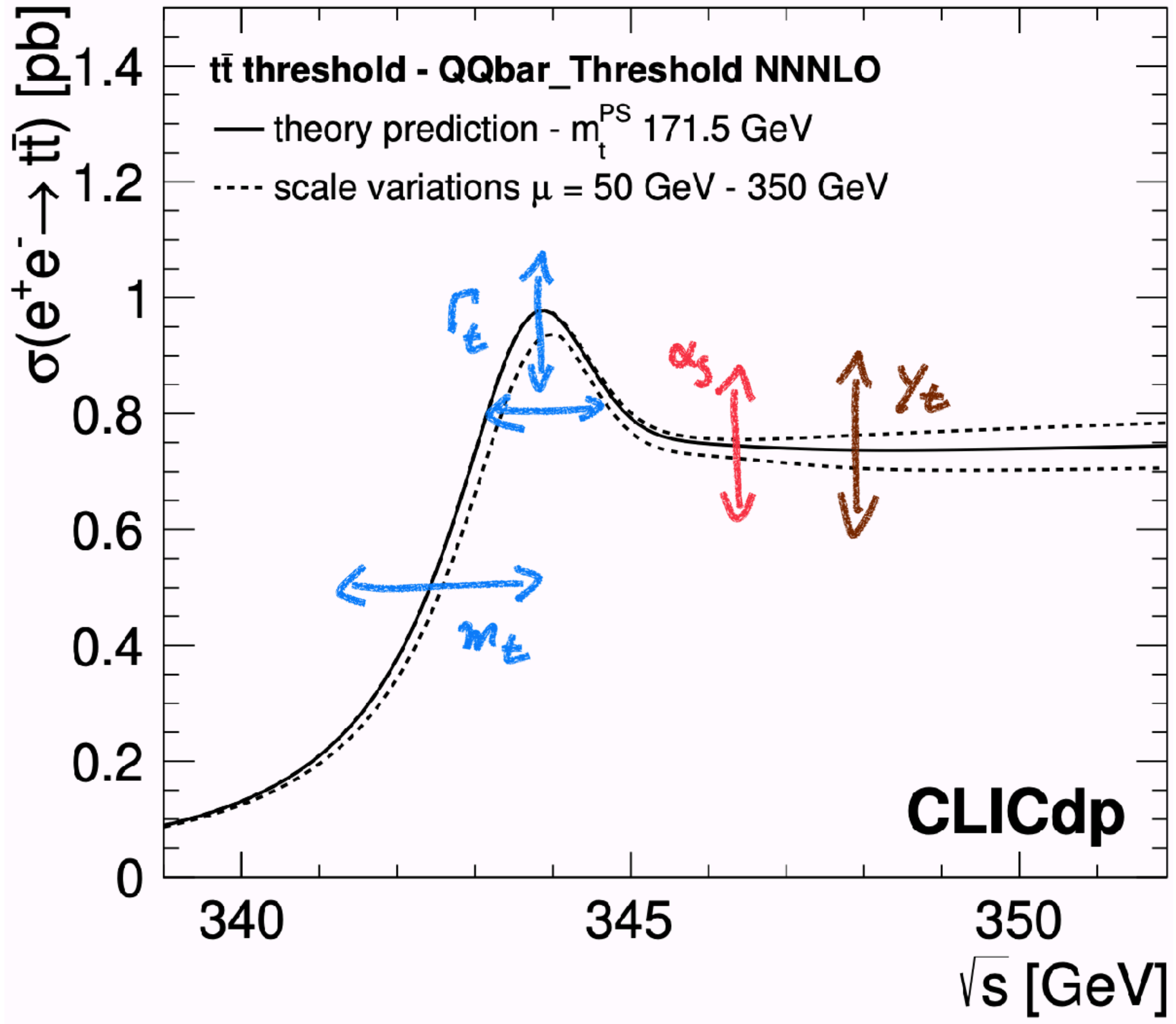


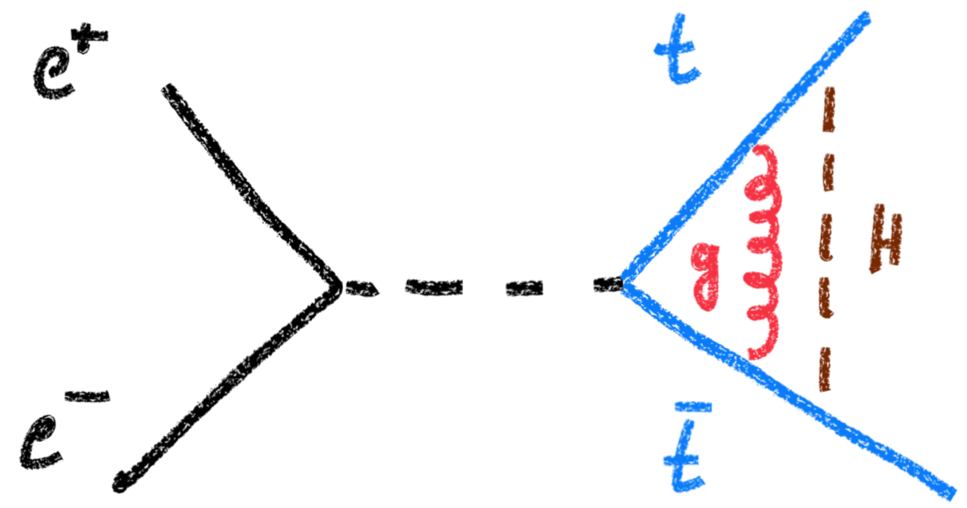


- The threshold shape is modified by
  - initial state radiation
  - collider luminosity spectrum

The Top Quark Pair Production Threshold

From Theory to Experiment





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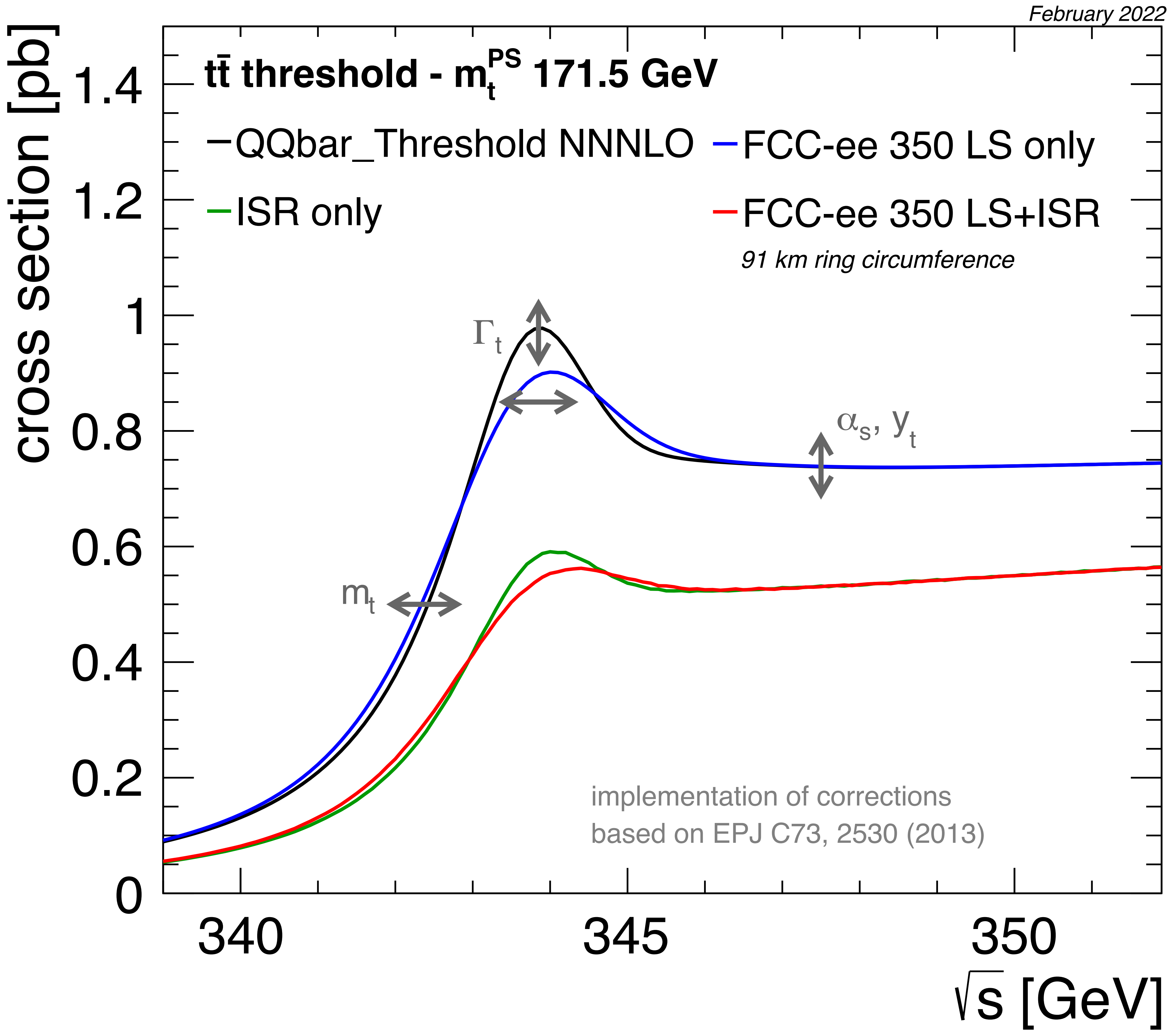
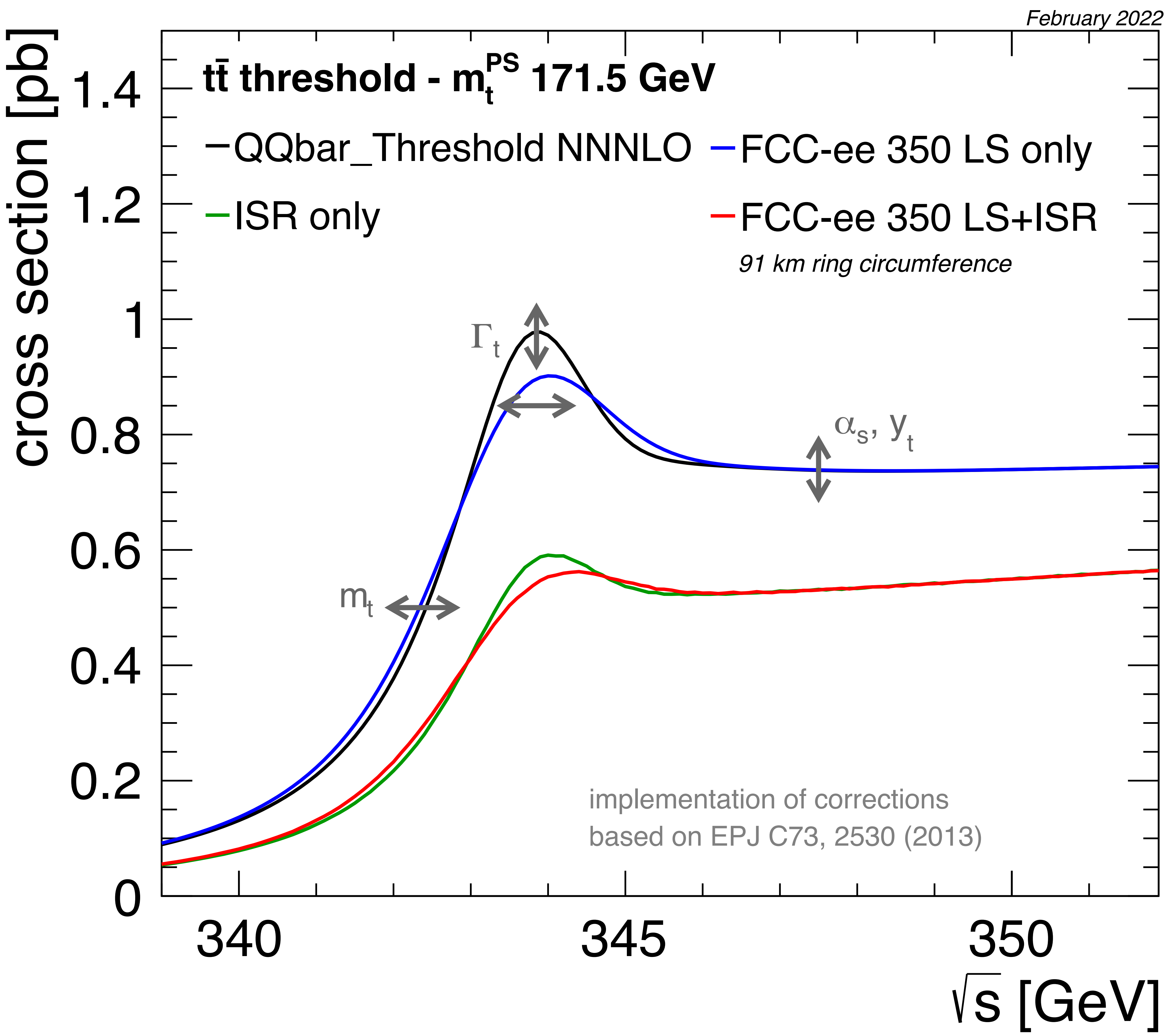
ISR, luminosity spectrum



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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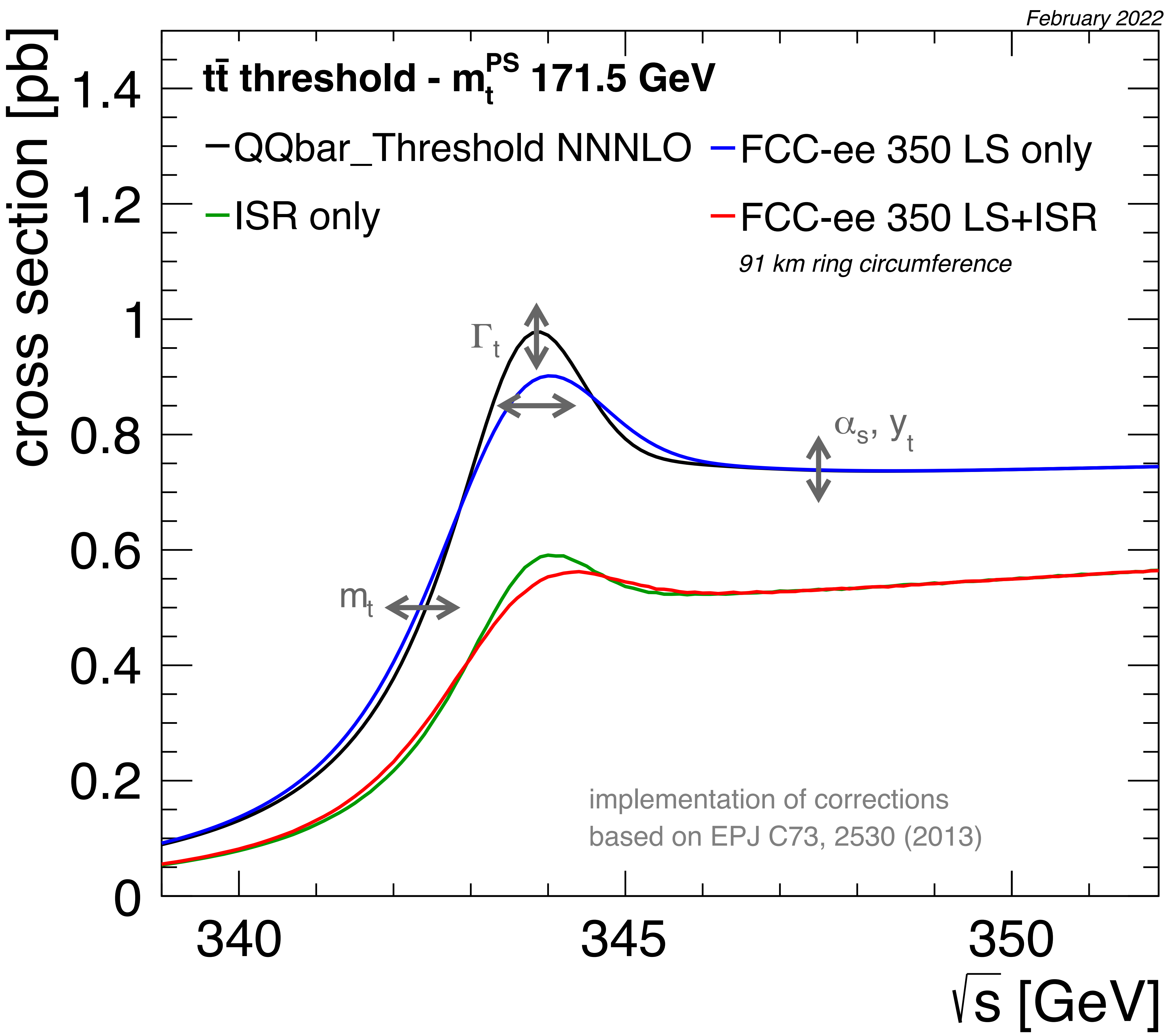
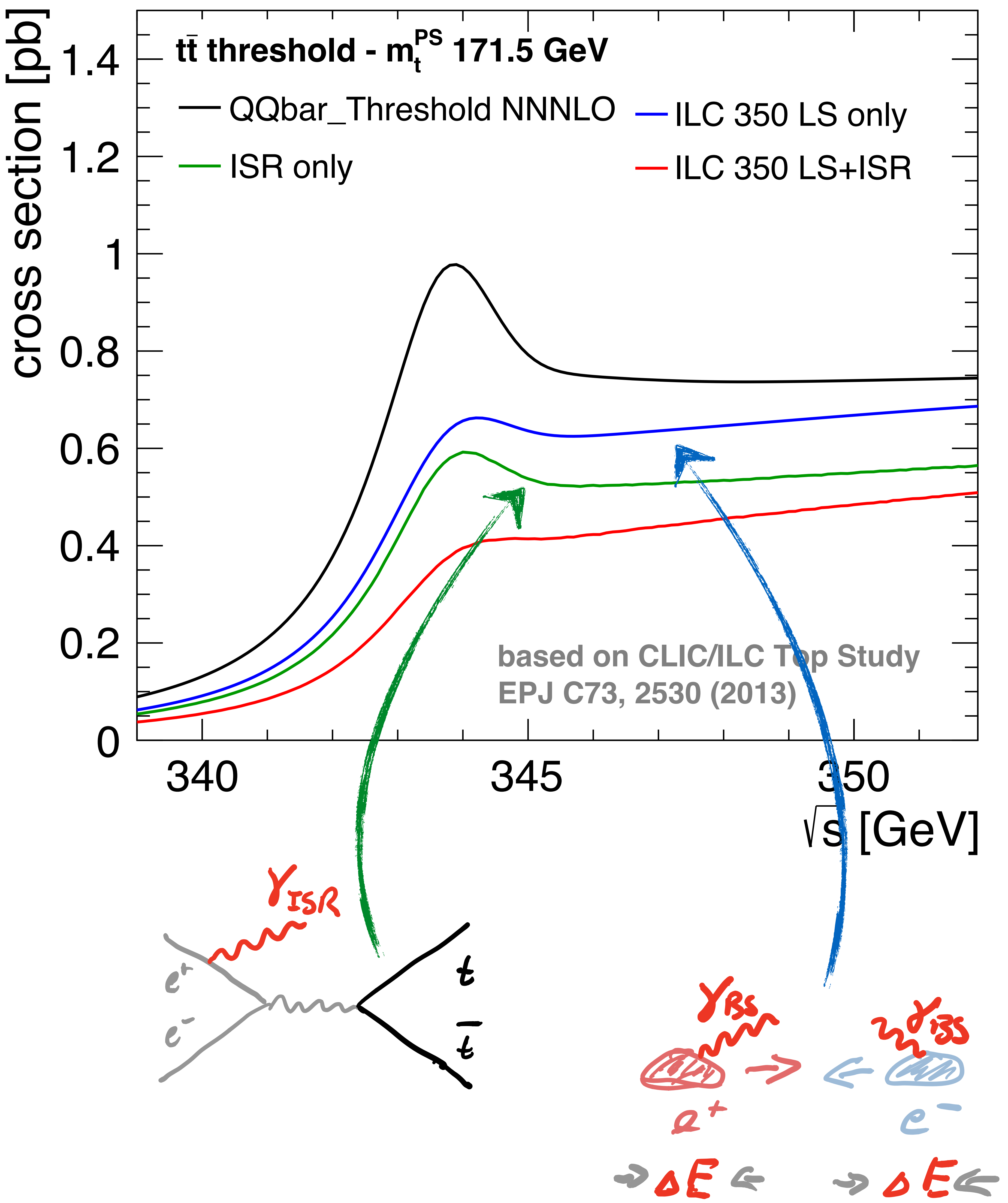


FCC vs

ILC



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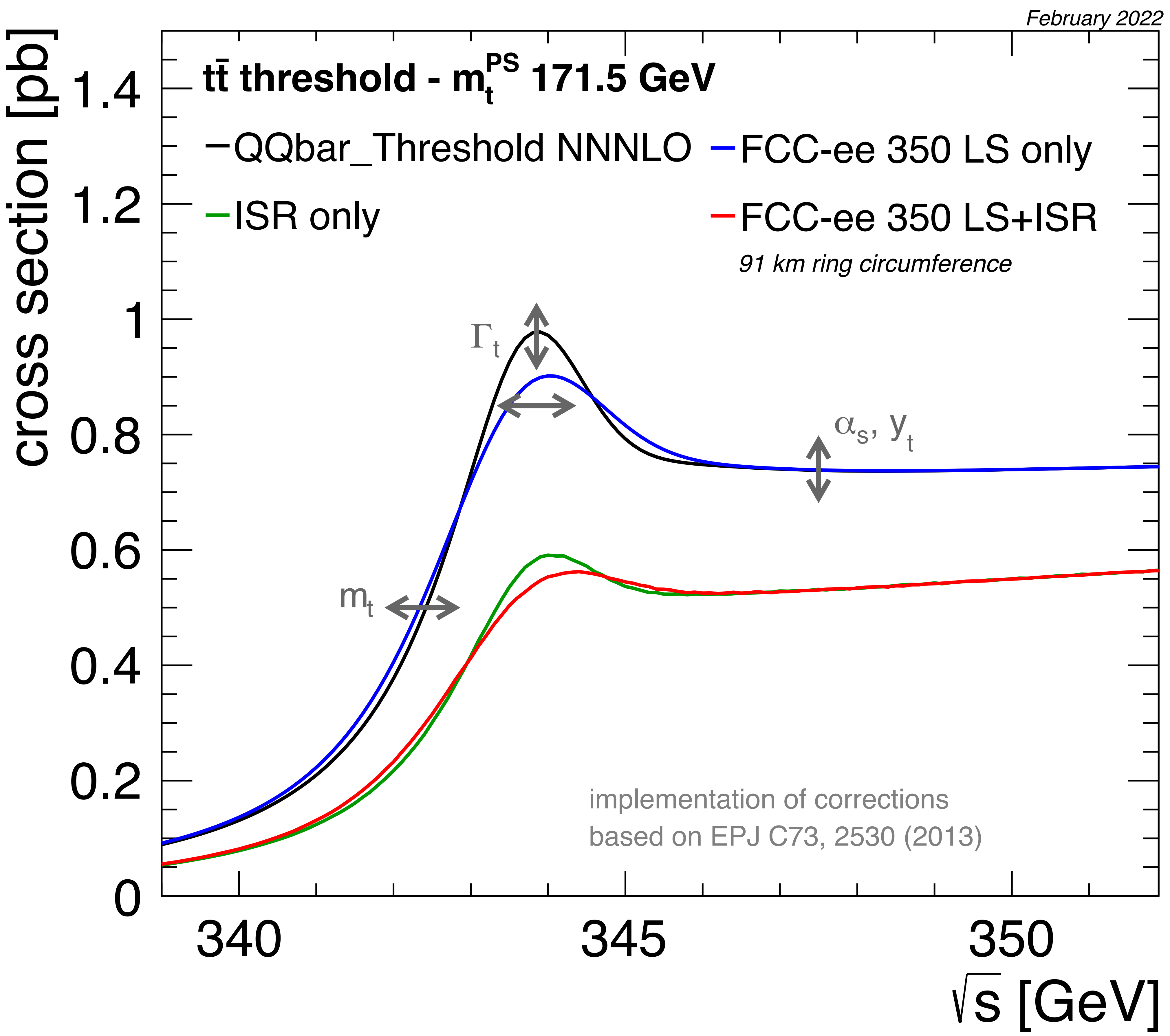

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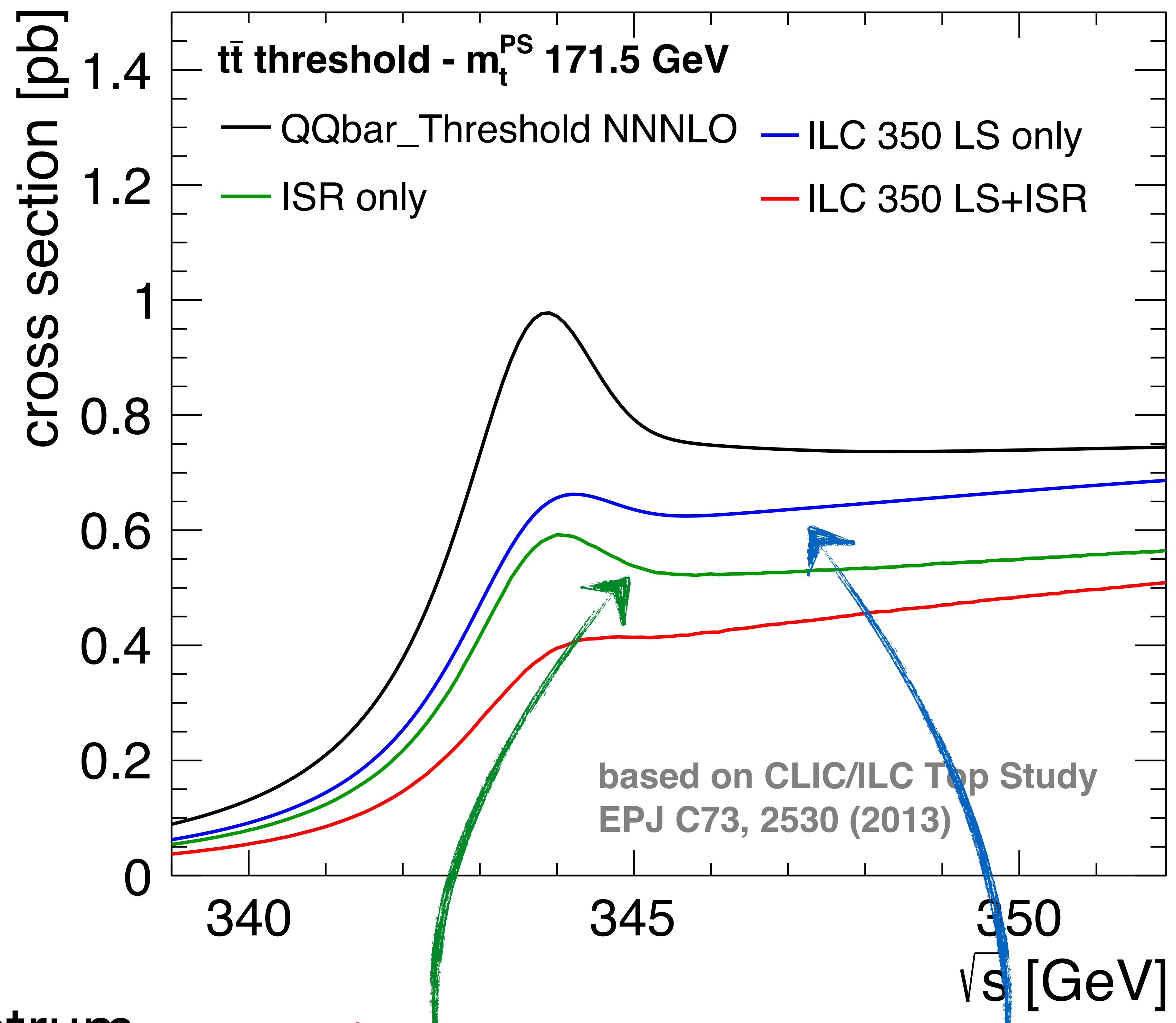
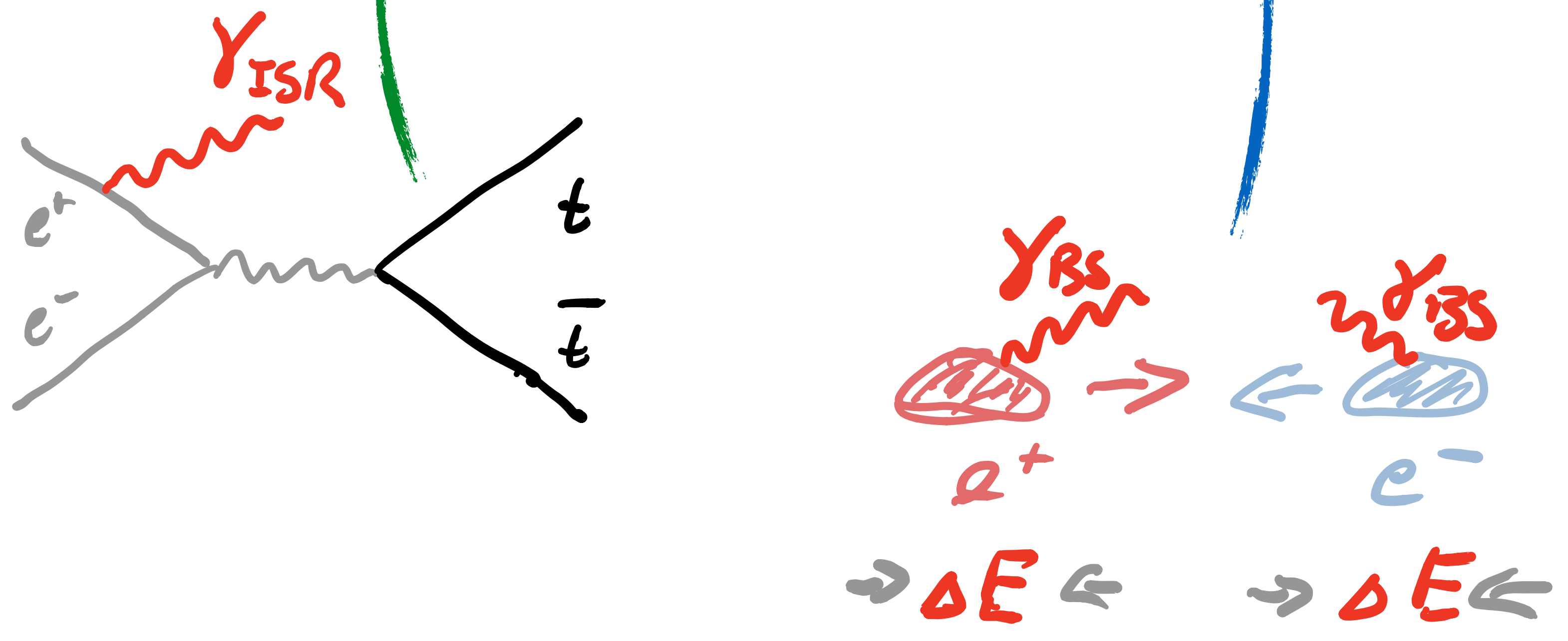




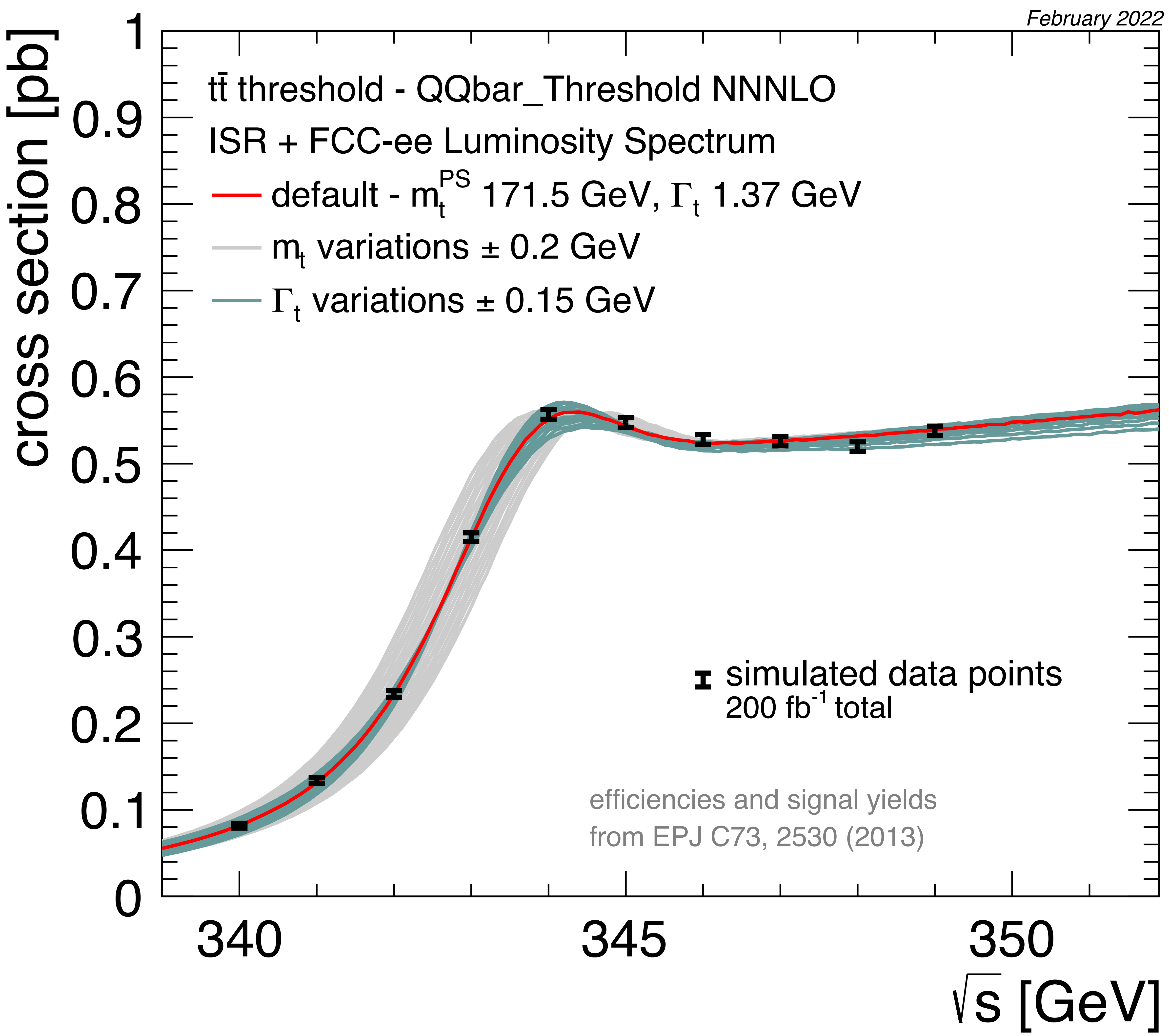
Requires: Precise understanding and measurement of spectrum.

In this case:

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

The Standard Threshold Scan

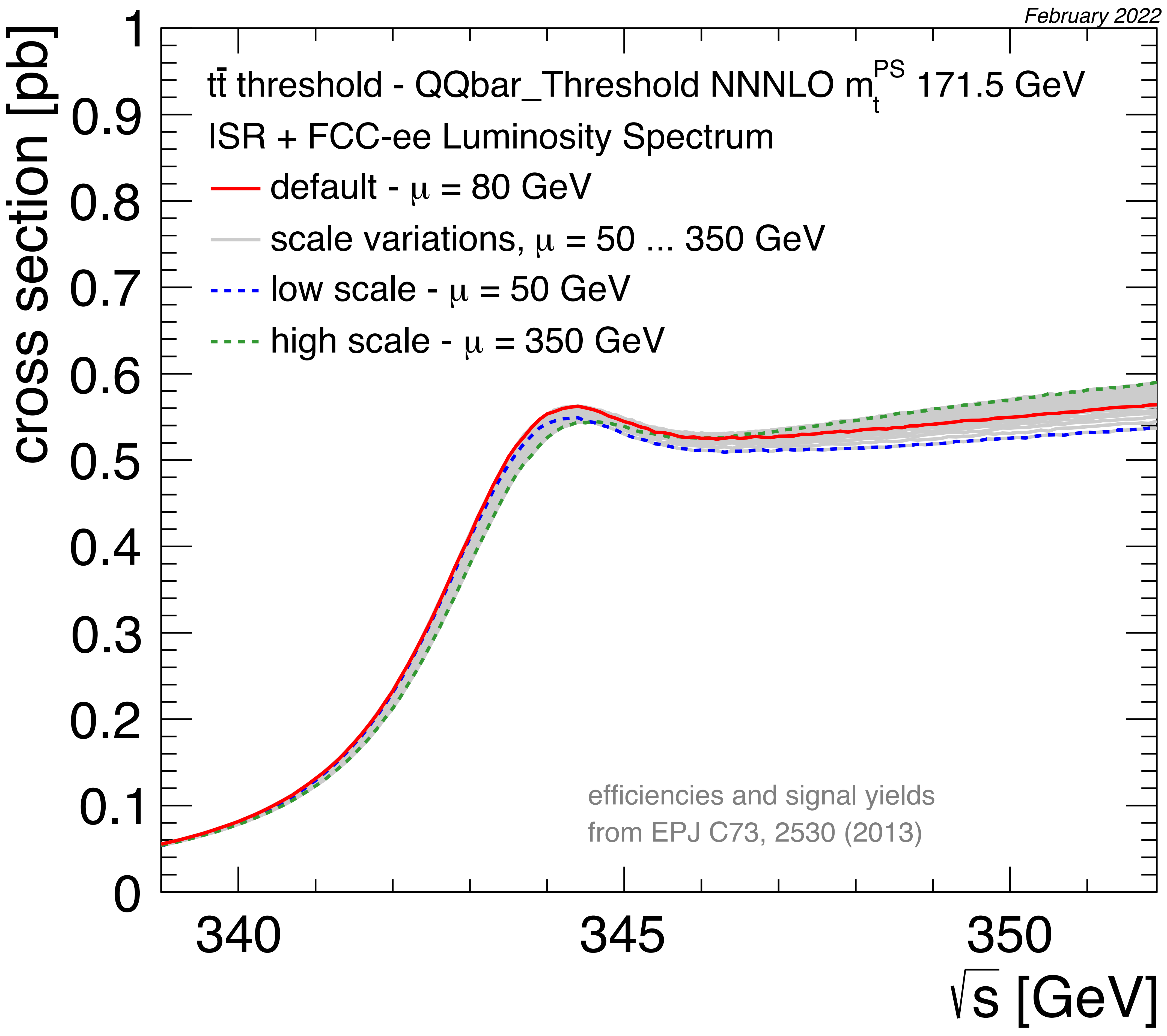
Experimental Assumptions



- 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.

Theory Uncertainties

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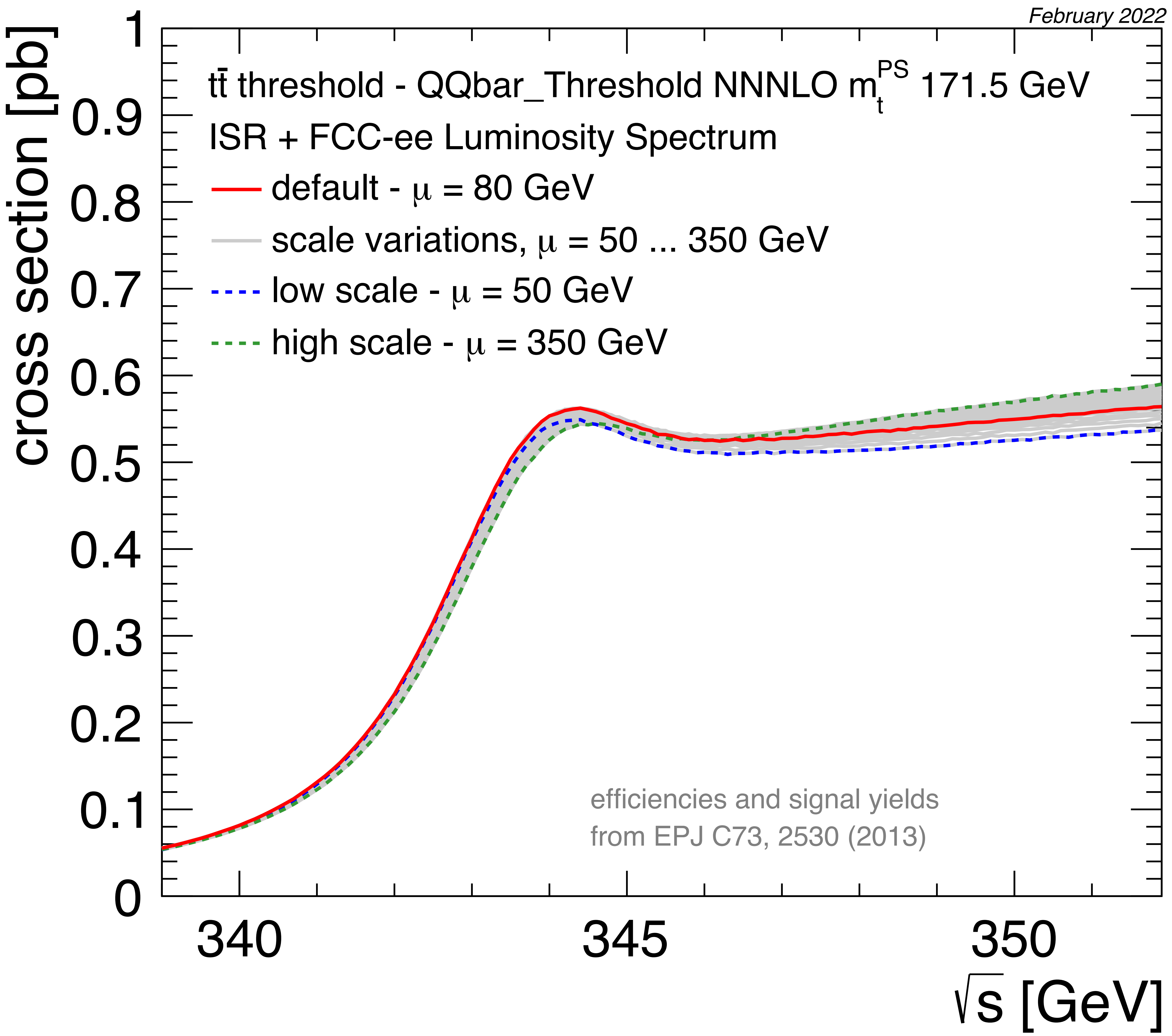
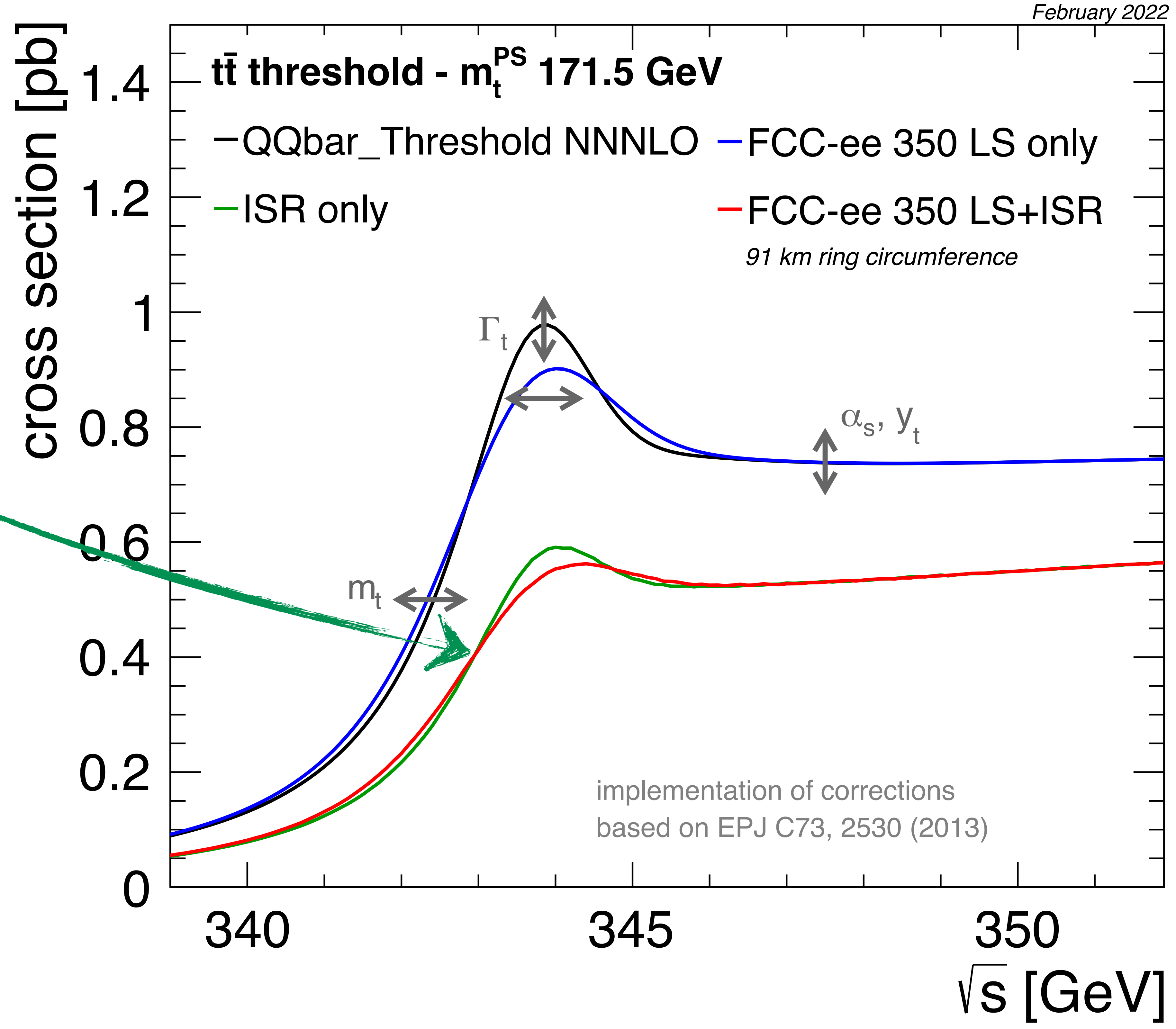


- QCD scale uncertainties highly relevant.
- Also need to calculate other effects, such as ISR, to the required precision!

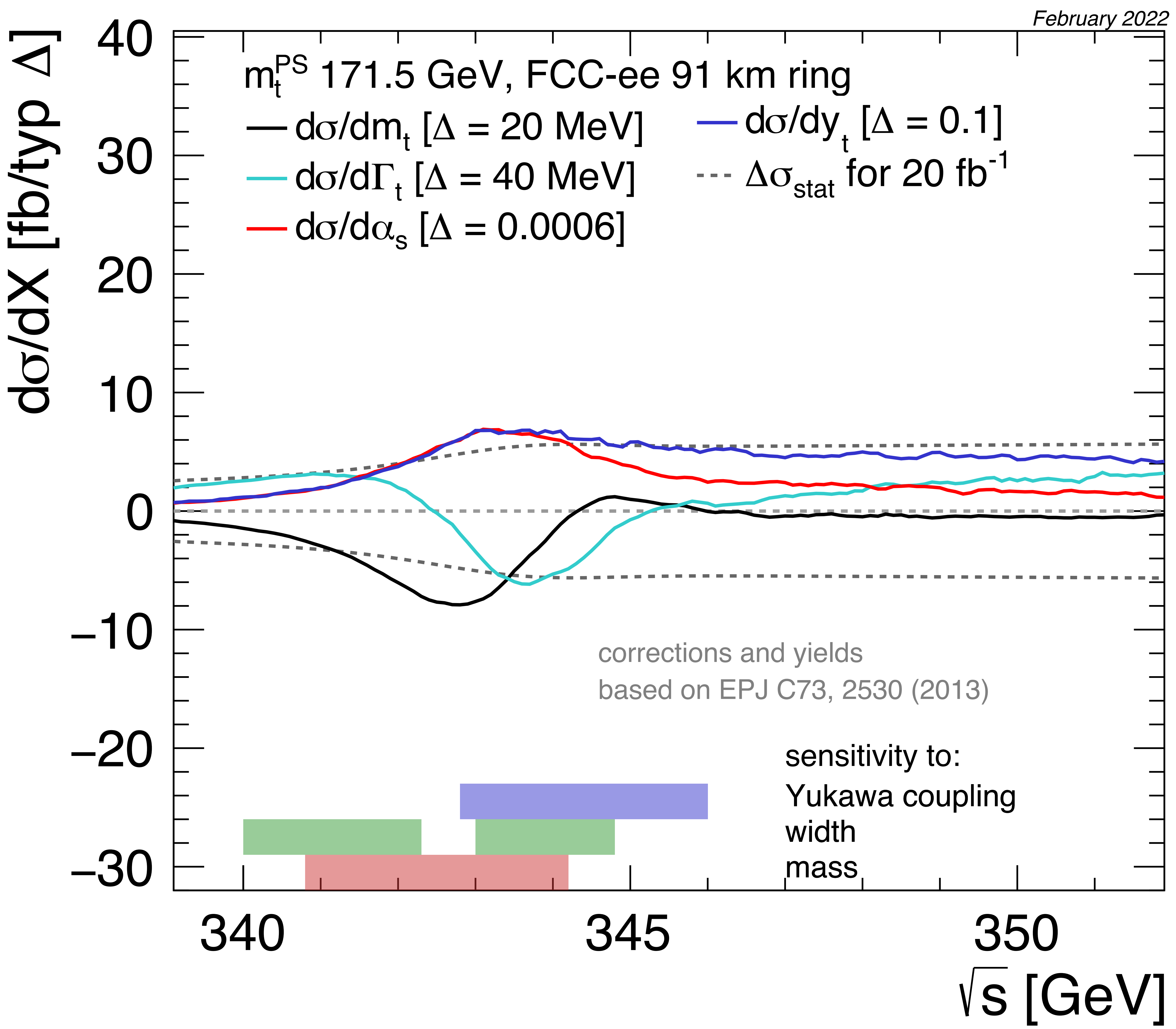
the step from black to green

[only approximate in current experimental studies]



Choosing the Scan Range

Parameter Sensitivity

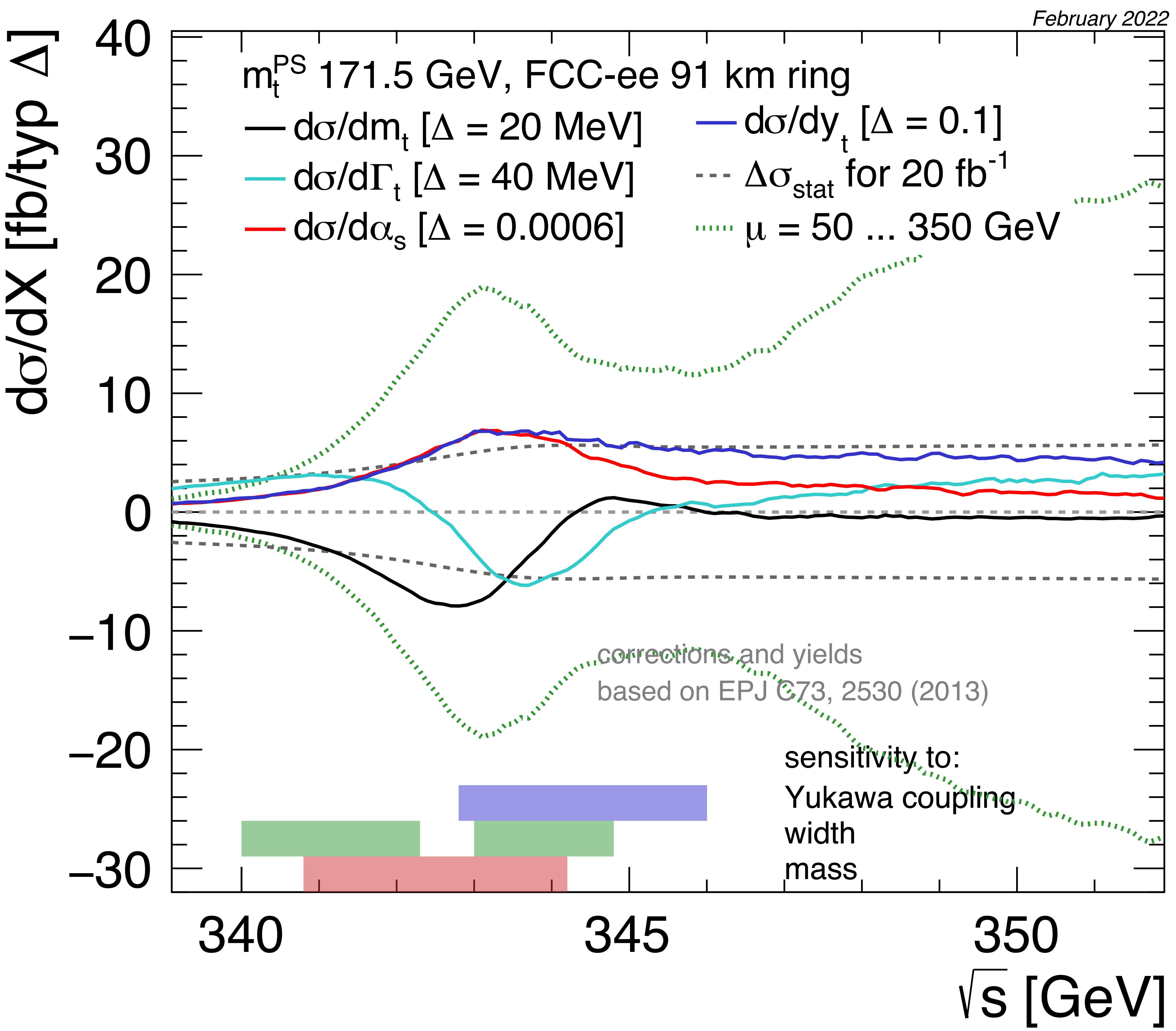


- Plot shows the derivative of the cross section for various parameters - to make this understandable this is normalised to typical changes of these parameters
- Full use to optimize scan range requires knowledge of mass to ~ 200 MeV in PS scheme. Can be achieved with 2 x 5 fb^{-1}:
  point 1: $\sqrt{s}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

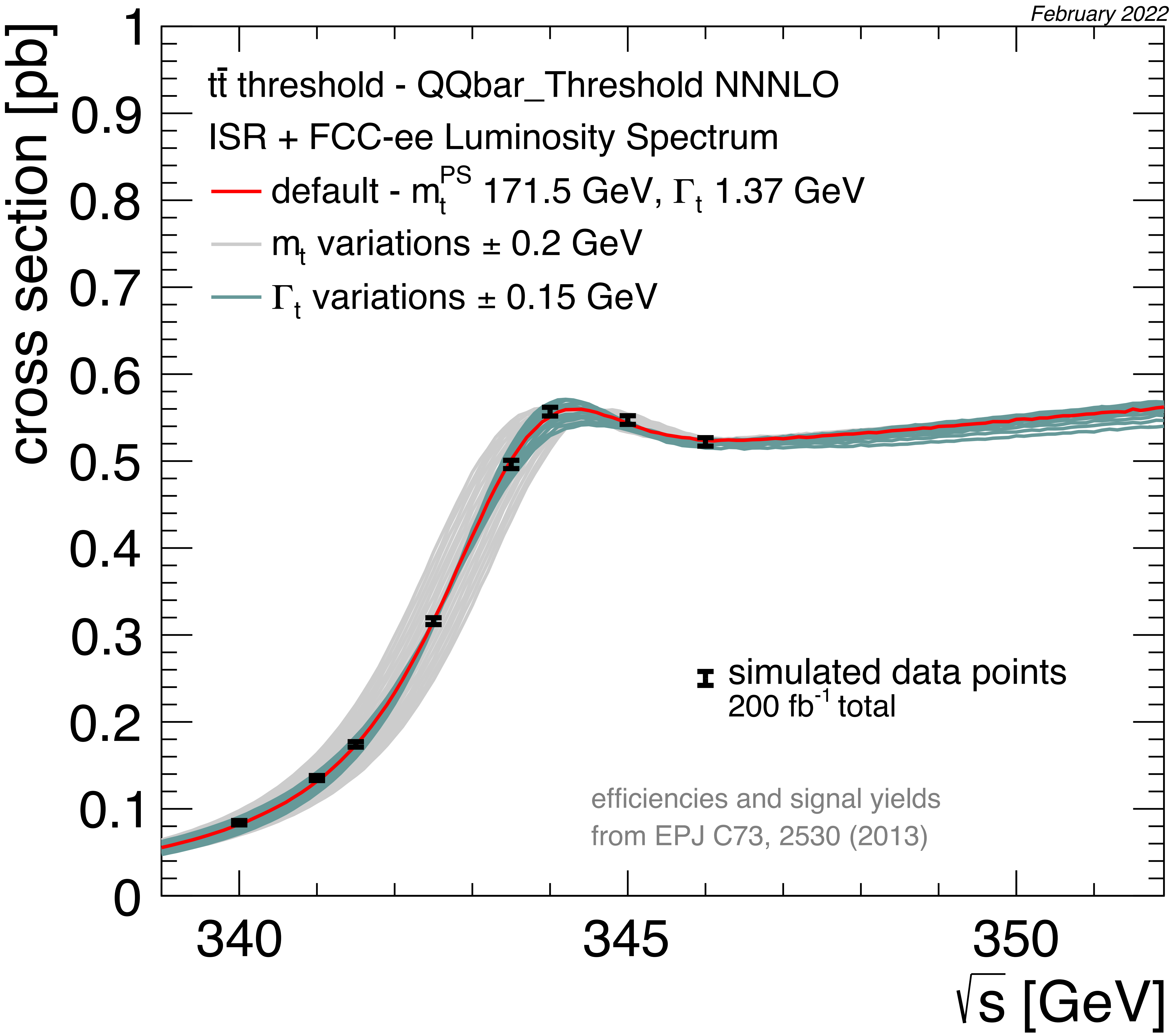


- QCD scale uncertainties dominate over point-by-point statistical uncertainties for typical threshold scans: At this point optimising scan strategies to reduce statistical uncertainties does not improve the total uncertainty - in fact concentrating on a very small range may make systematic control more 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 (very similar for ILC)

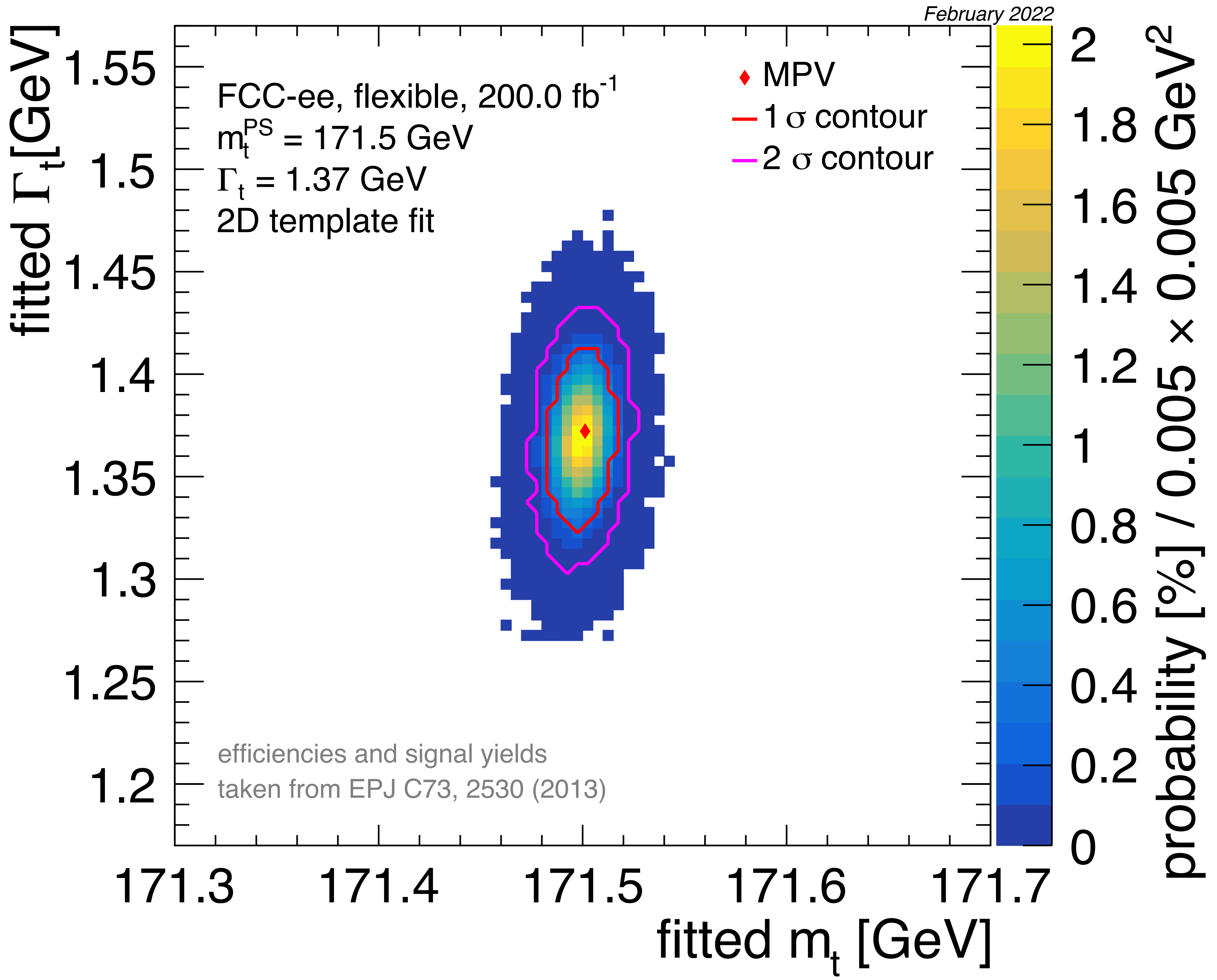


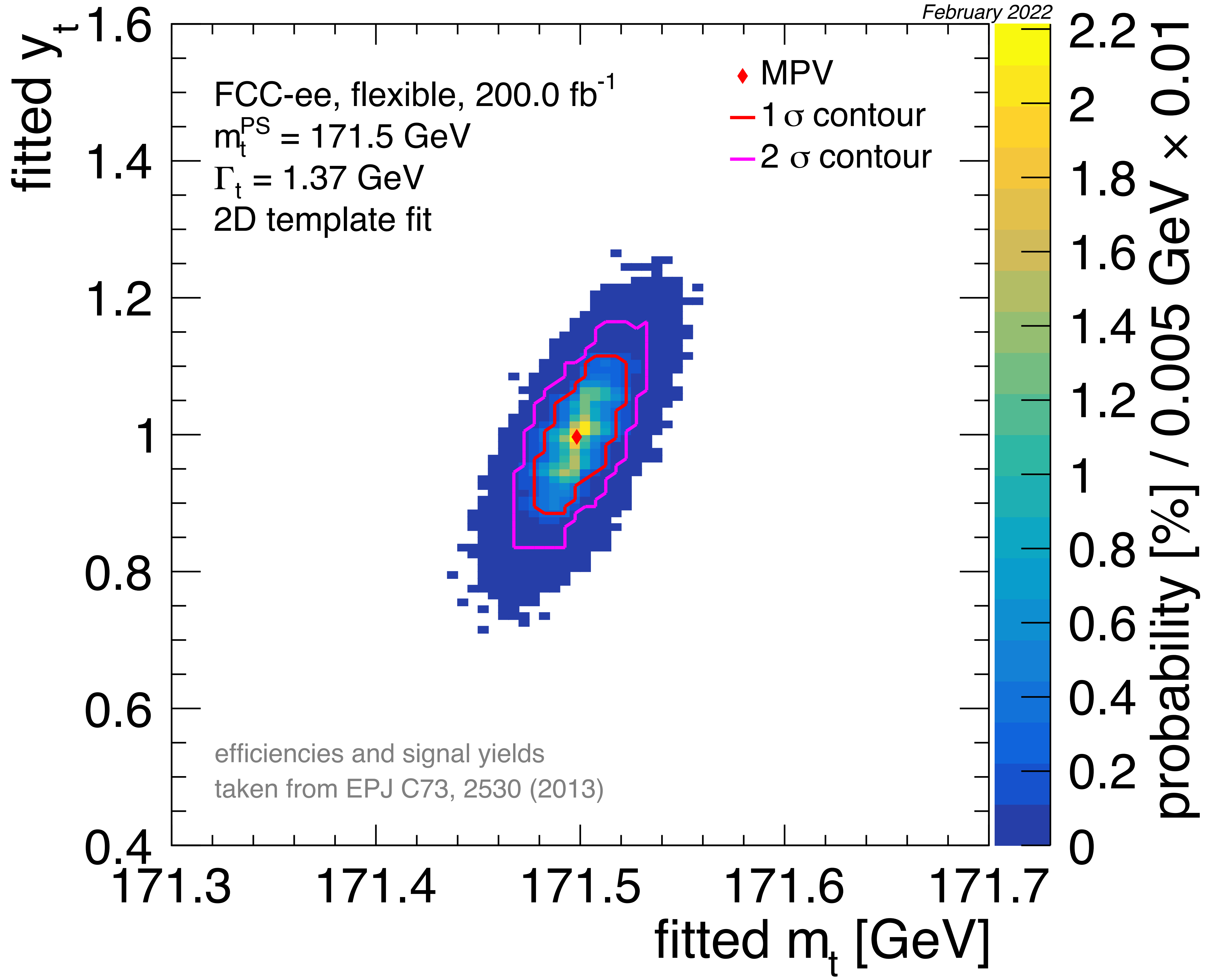
- Mildly optimized scan (mass & width) for FCC-ee as a balance between different sensitivities: 8 points in the range of 340 - 346 GeV

  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

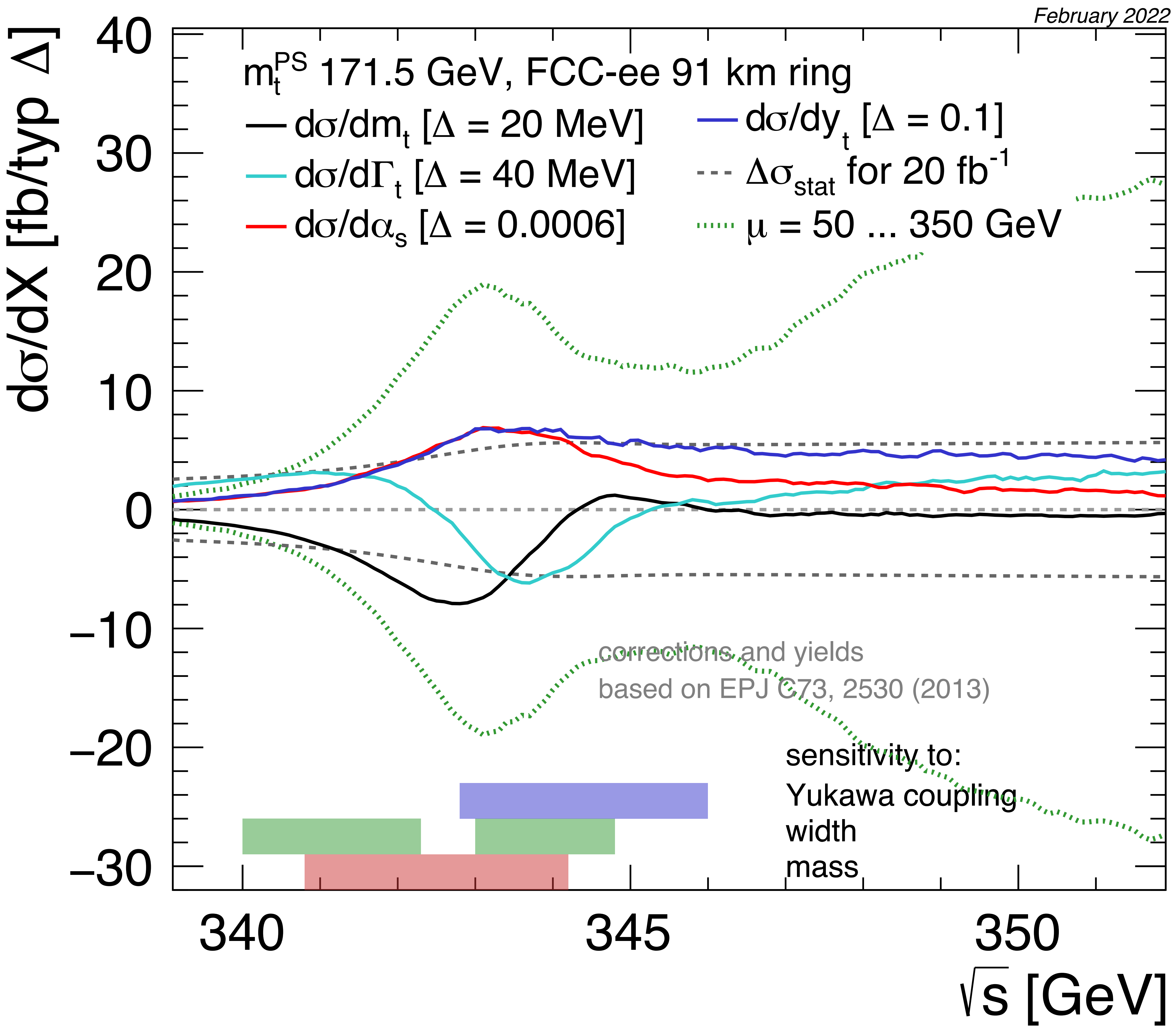
ILC & FCC-ee

- 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:

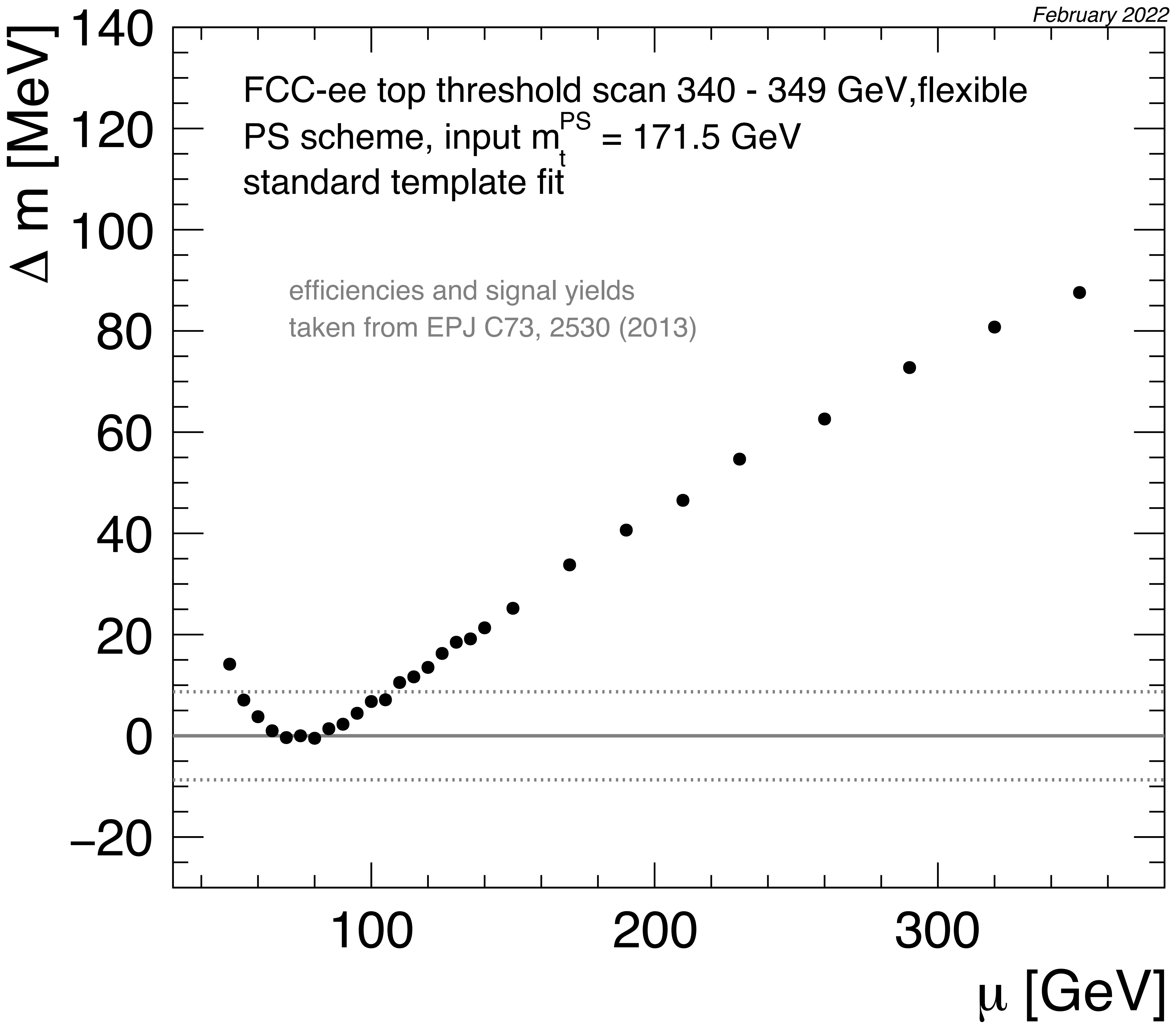
$\Delta m \sim 2.6$ MeV per 10^{-4} in α_s

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

Uncertainties - Scale

A few more details

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



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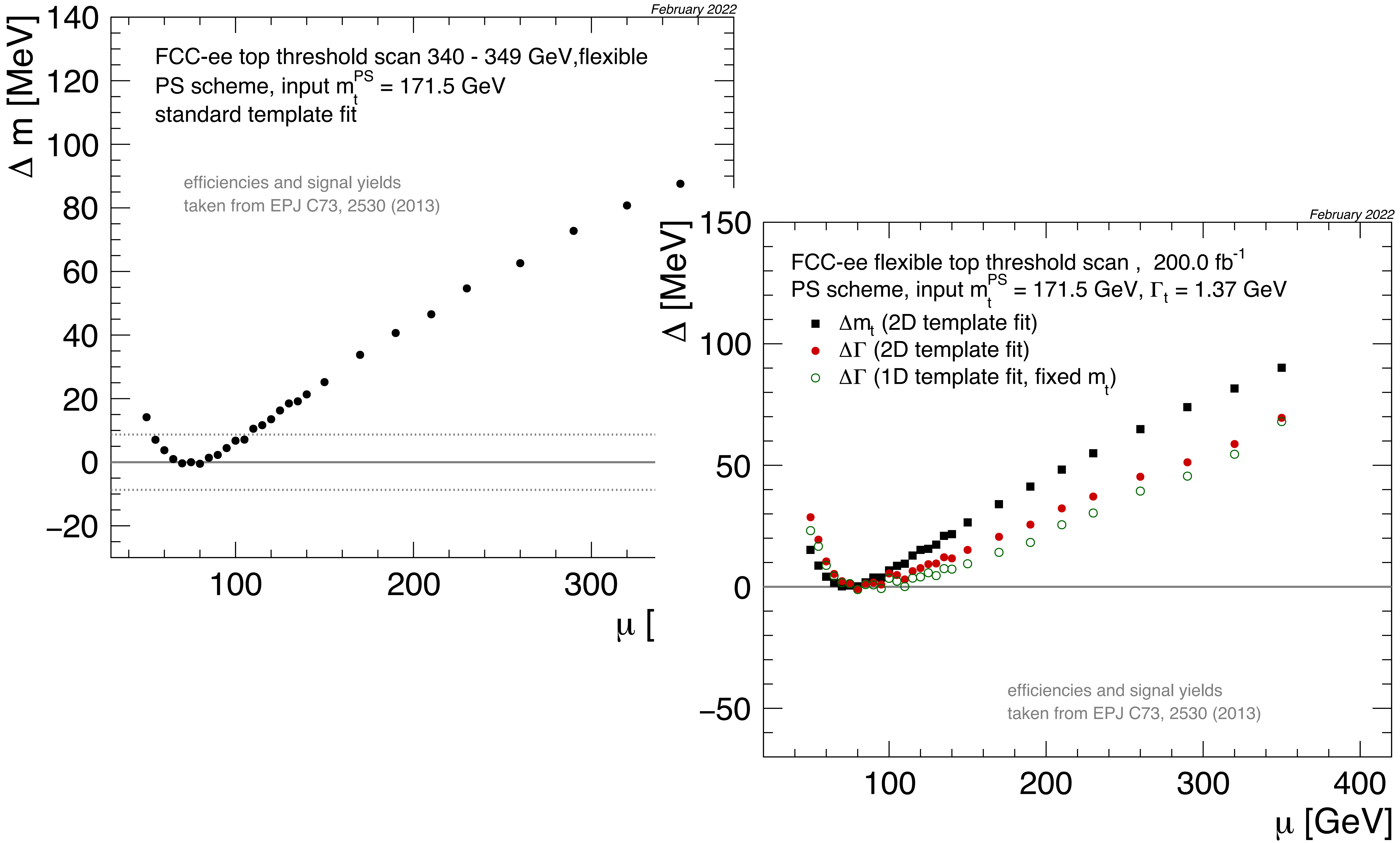

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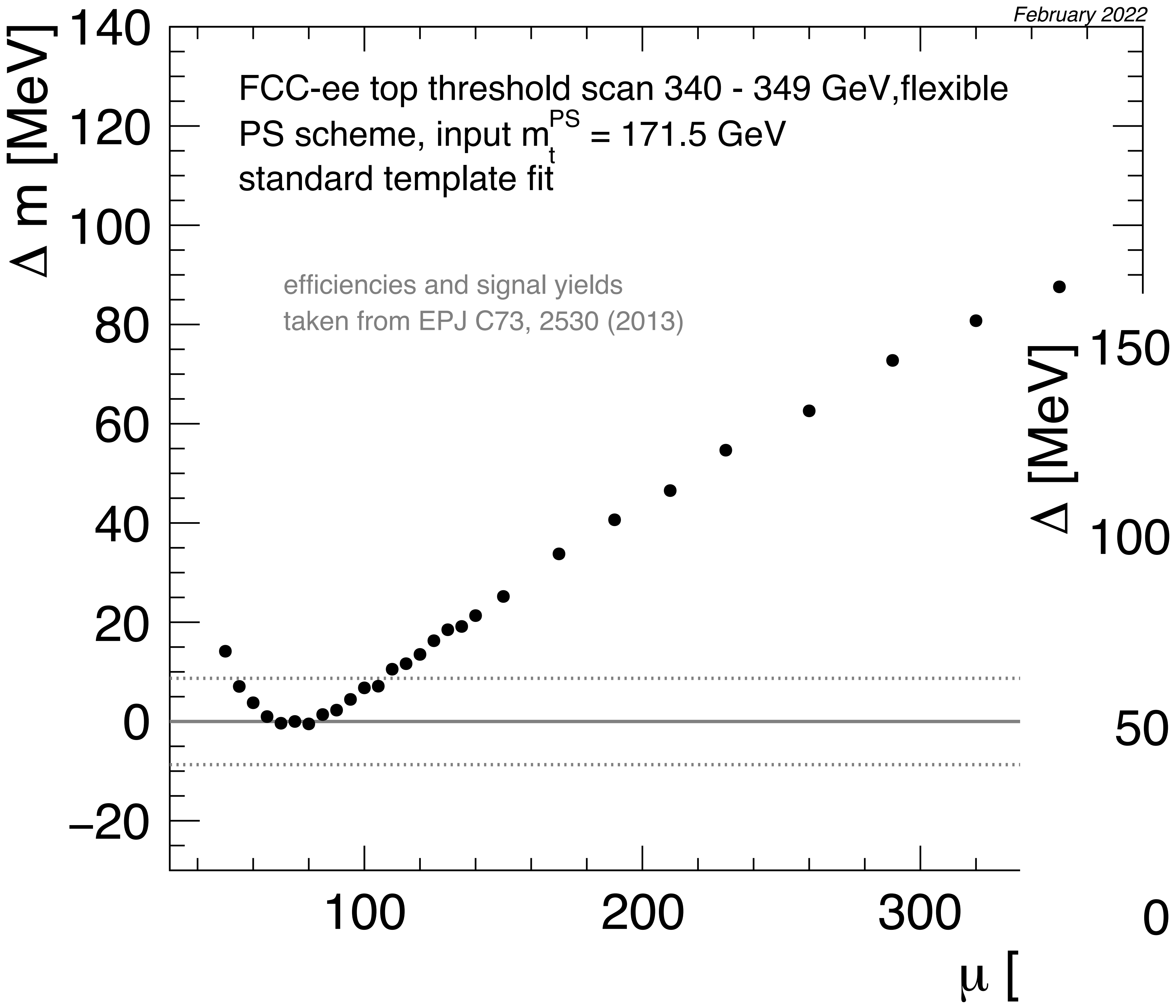
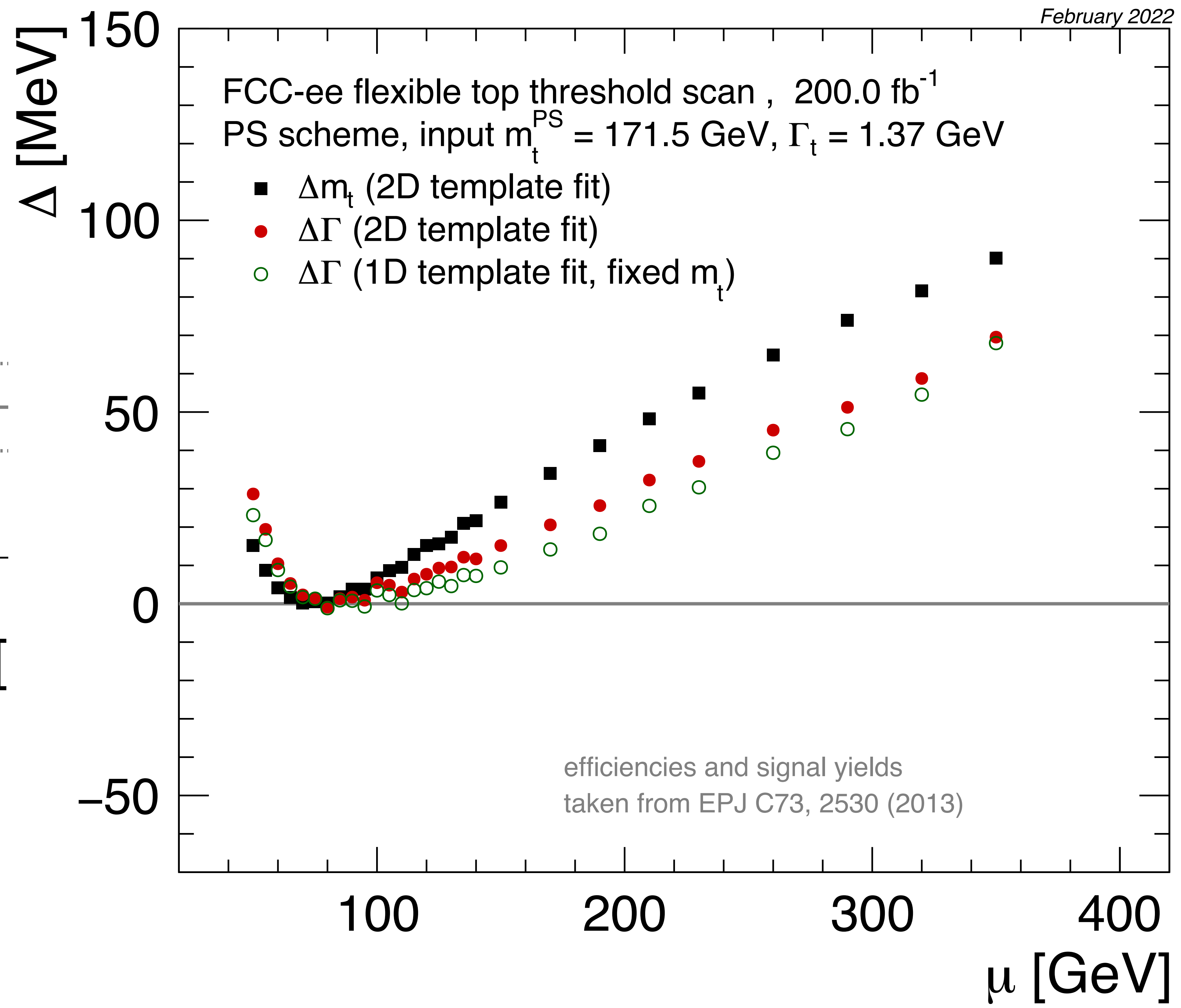
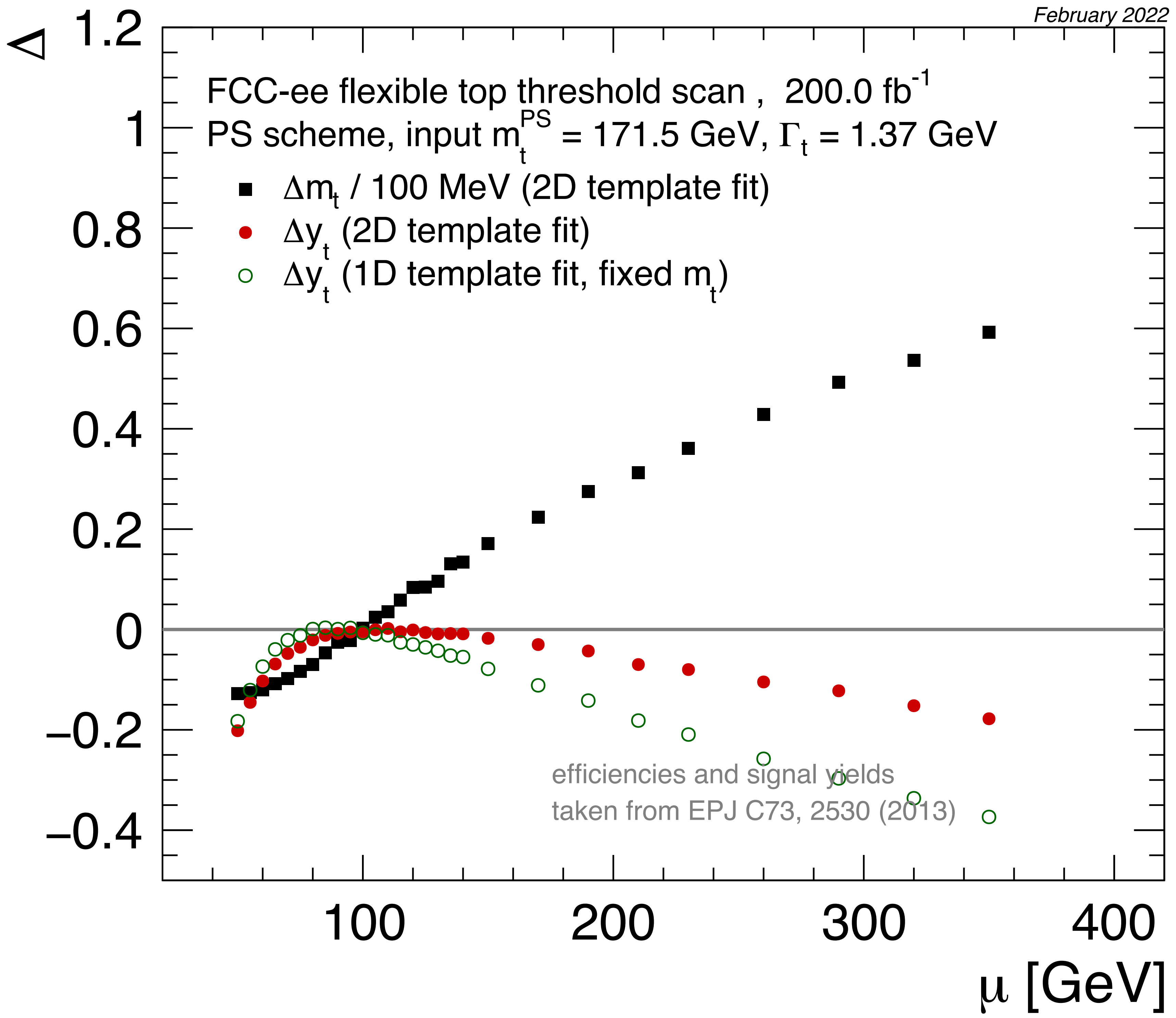






Uncertainties - Scale

A few more details

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

The leading systematic:

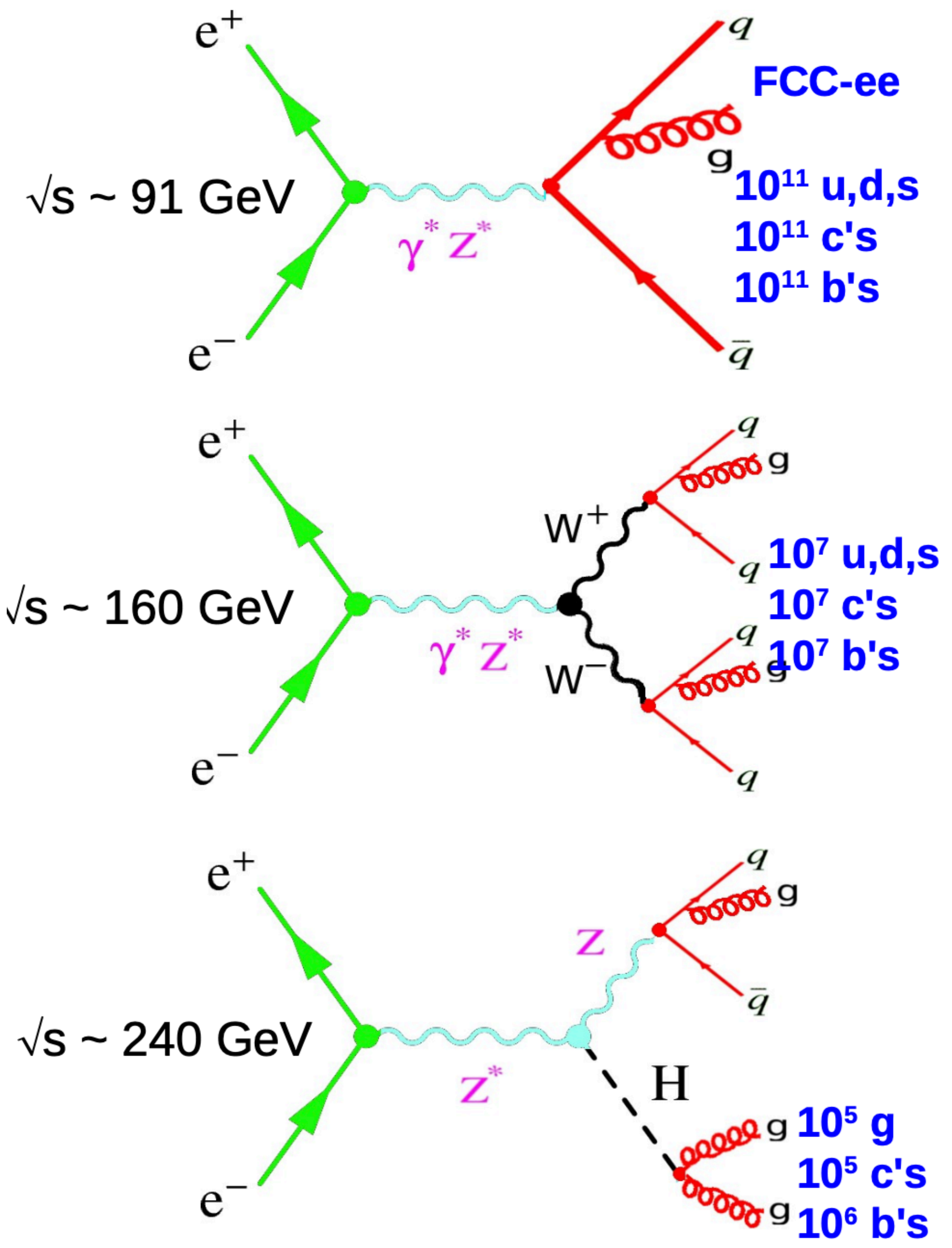
Improvements directly propagate to total precision

Frank Simon (frank.simon@kit.edu)

Part II: QCD

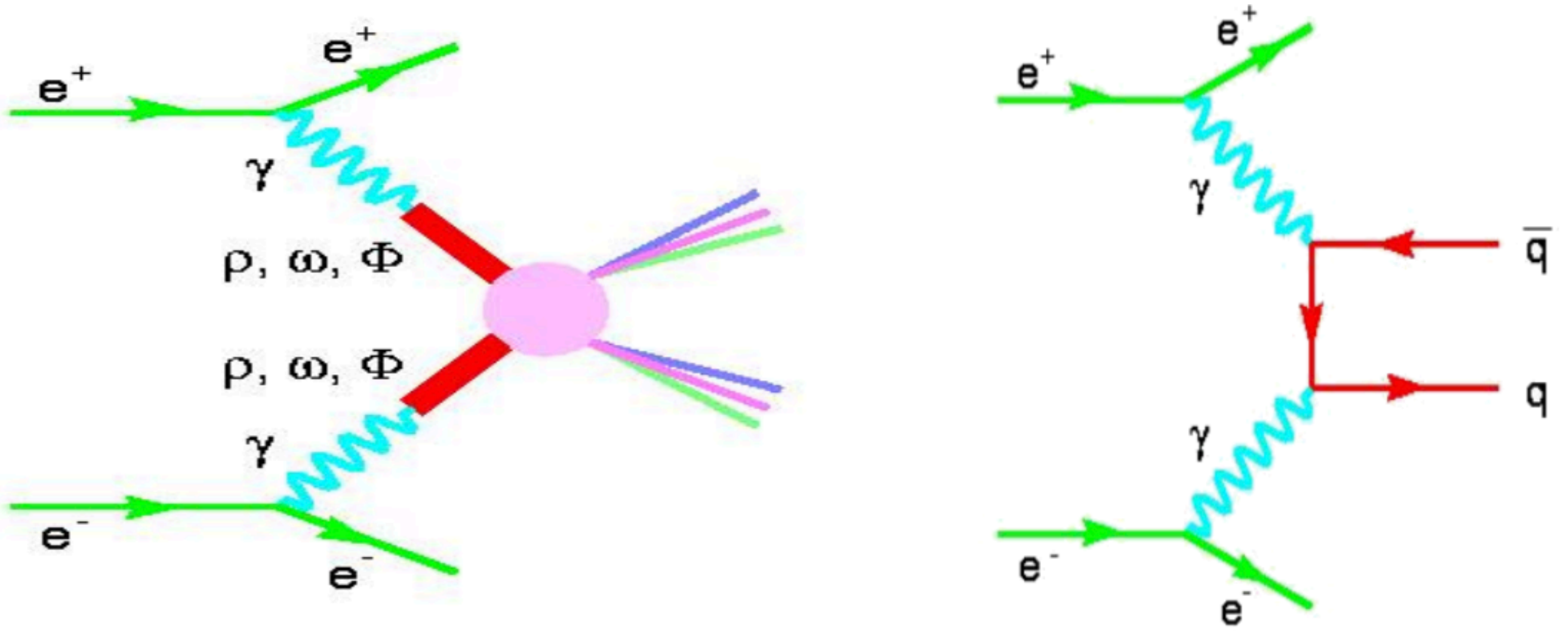
Based on studies in the context of FCC-ee

Material taken from Francesco Giuli , LFC 2022



- Clean environment in e+e- collisions, fully controlled initial state
- High statistics QCD samples at all energy stages

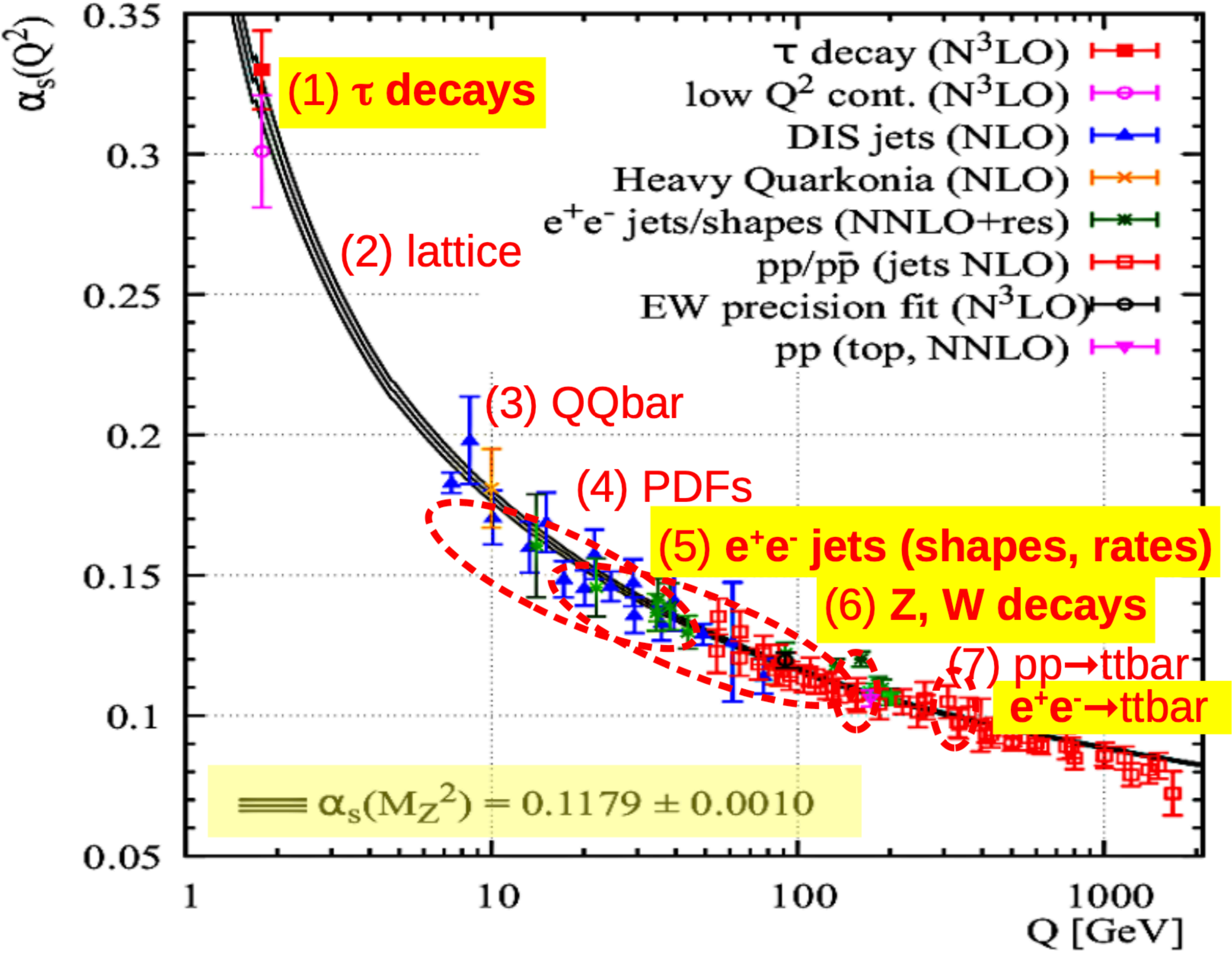
- In addition: access to QCD (and other) processes in γγ collisions



(soft, VDM) (direct)

The Strong Coupling Constant

Precise α_s measurements

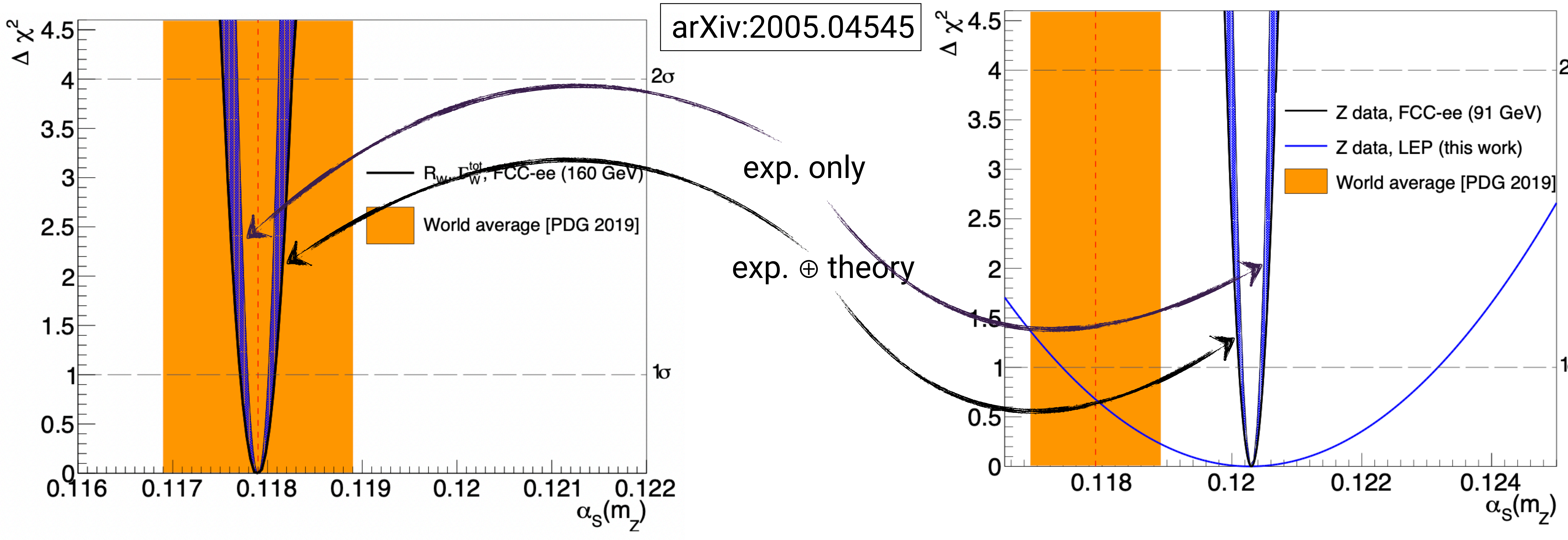


current WA: ~ 0.8% uncertainty

- e^+e^- data contributes in several ways. Significant potential for improvement in particular for:
  - τ decays: extreme statistics (> 10^{11} τ pairs) expect < 1% uncertainty
  - event shapes at lower energies, jet rates at high √s; expect < 1% uncertainty
  - hadronic decays of gauge bosons: Combined fits, expect ~ 0.1% for Z, 0.2% for W experimental uncertainty.
    To fully profit, requires reduction of theory uncertainty by computing missing terms (x10 on W, x4 on Z)

The Strong Coupling Constant

Precise α_s measurements from gauge boson decays

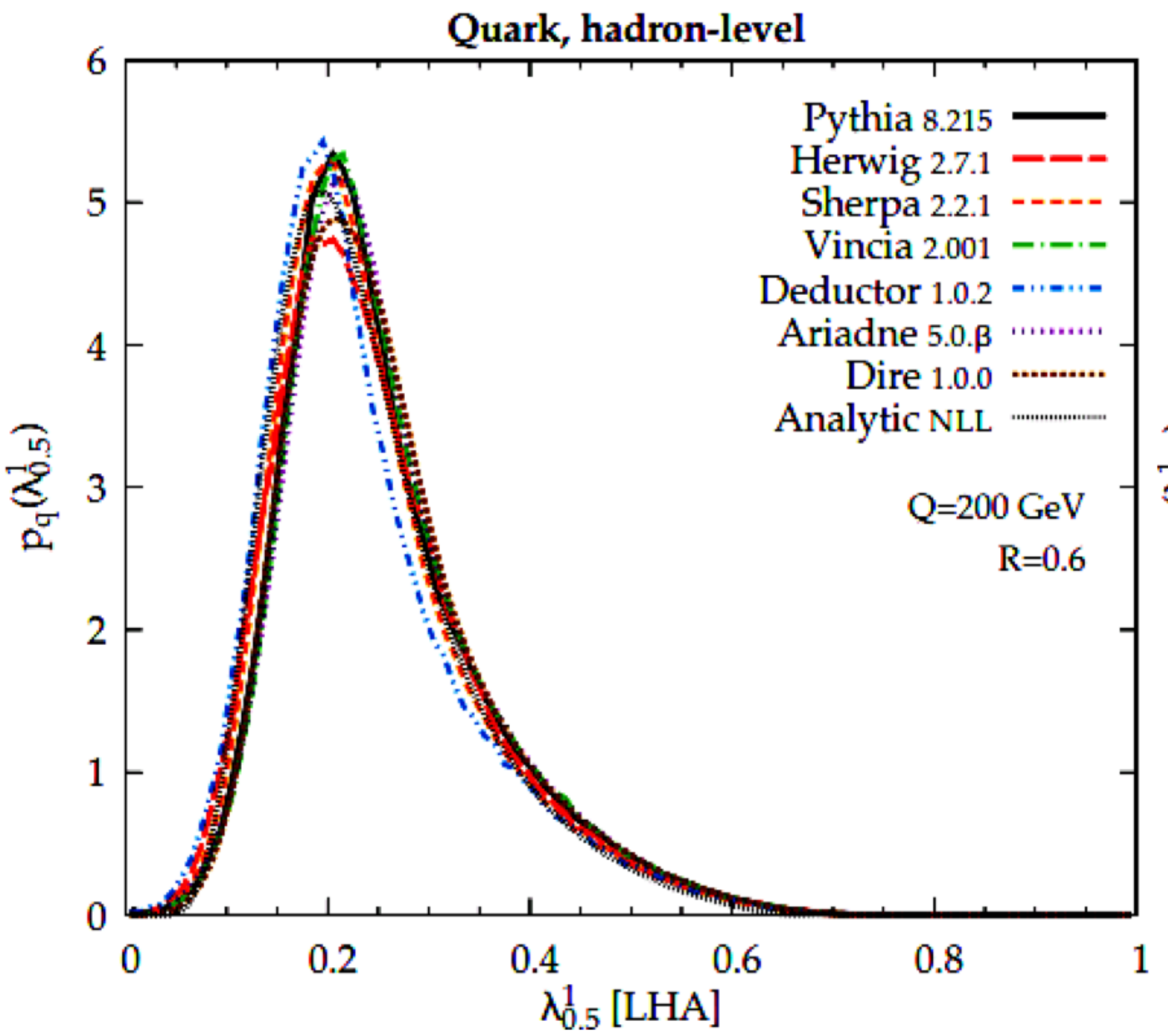


- The highest accuracy: Z (and W) decays:
  ~0.2% with theoretical uncertainties, potential to 0.1% (1.2×10^{-4}) with improved theory
  (NB: similar potential from lattice)

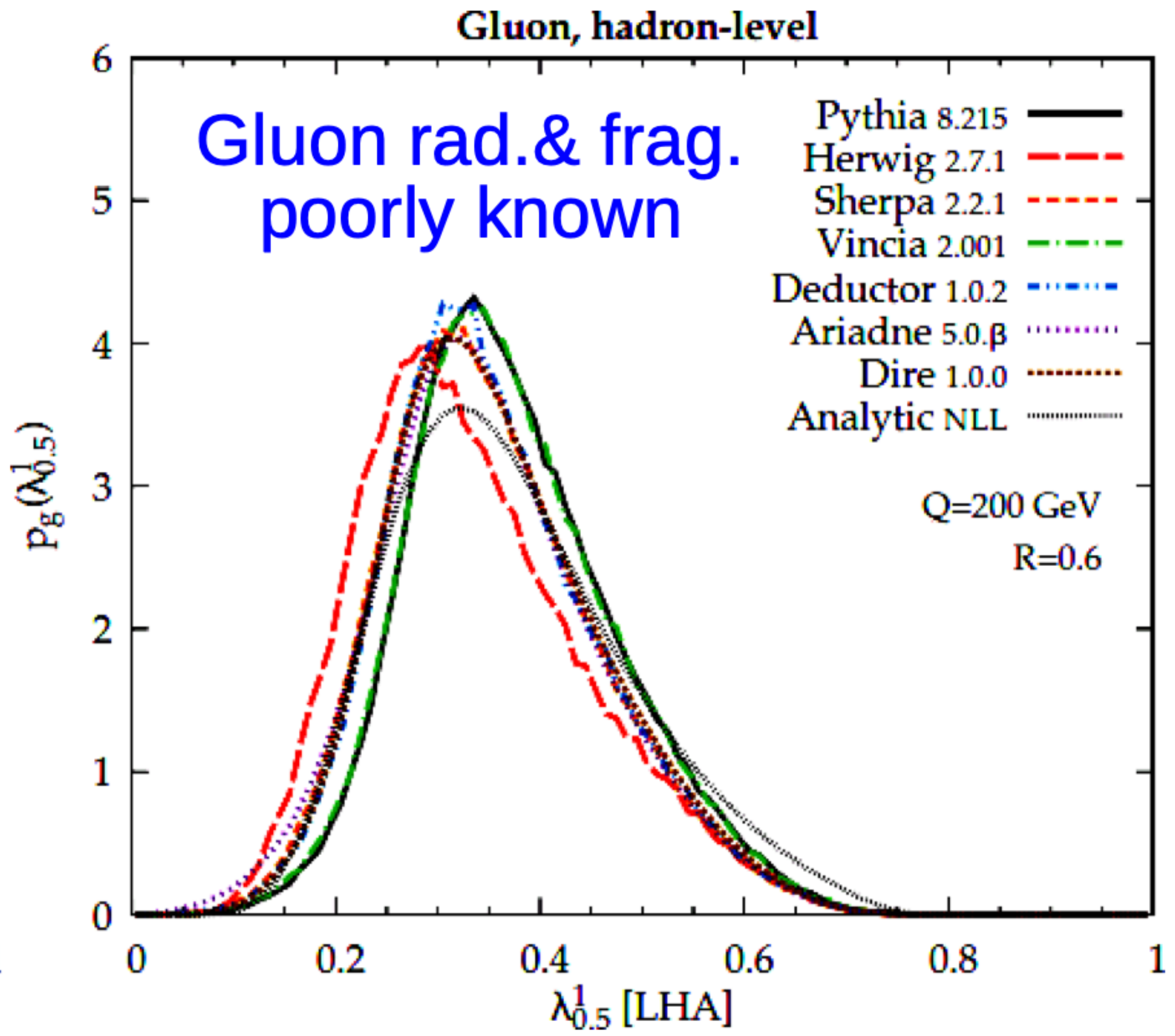
Gluon Jets, Colour Reconnection, …

Examples for non-perturbative effects

- Understanding gluon jets: Currently sizable uncertainties



$e^+e^- \to Z \to uu$



$e^+e^- \to H \to gg$

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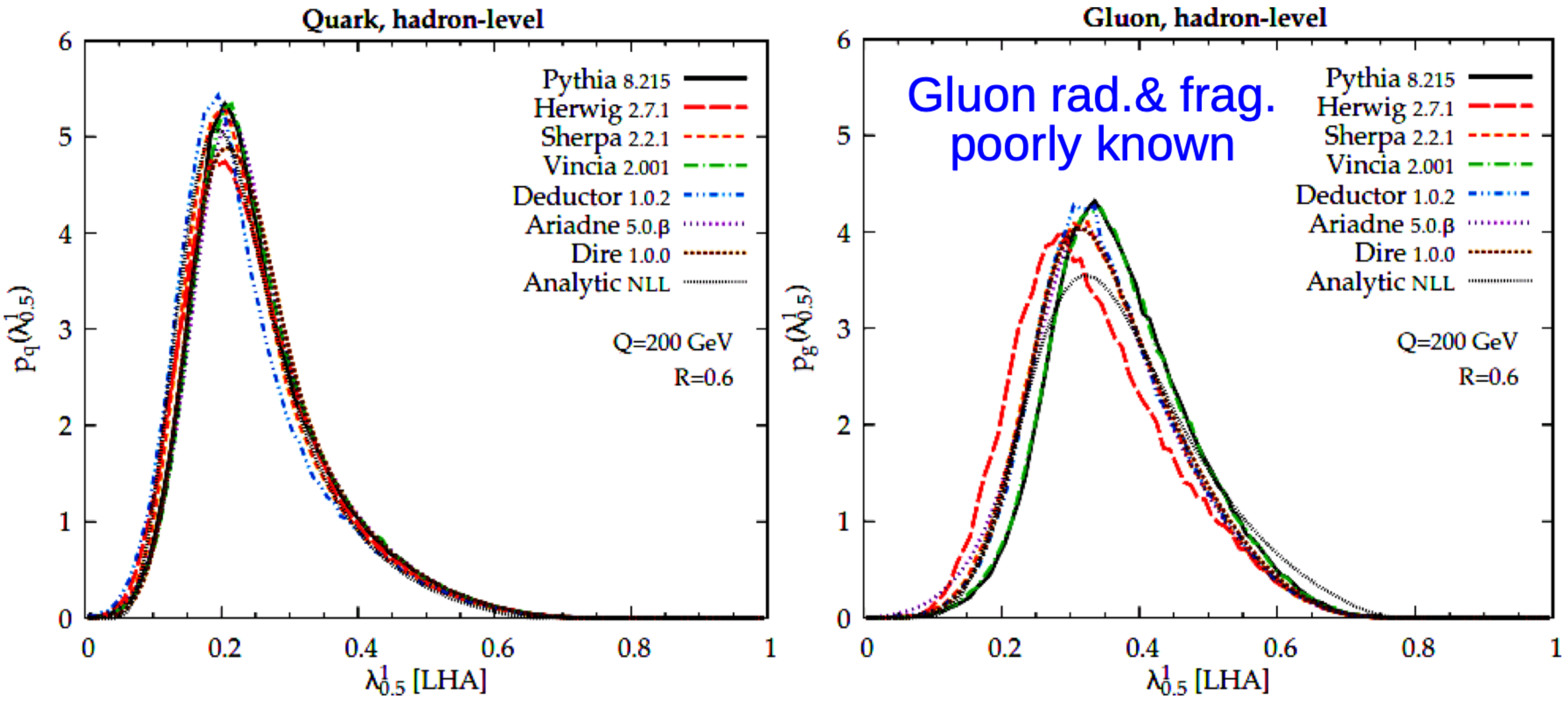
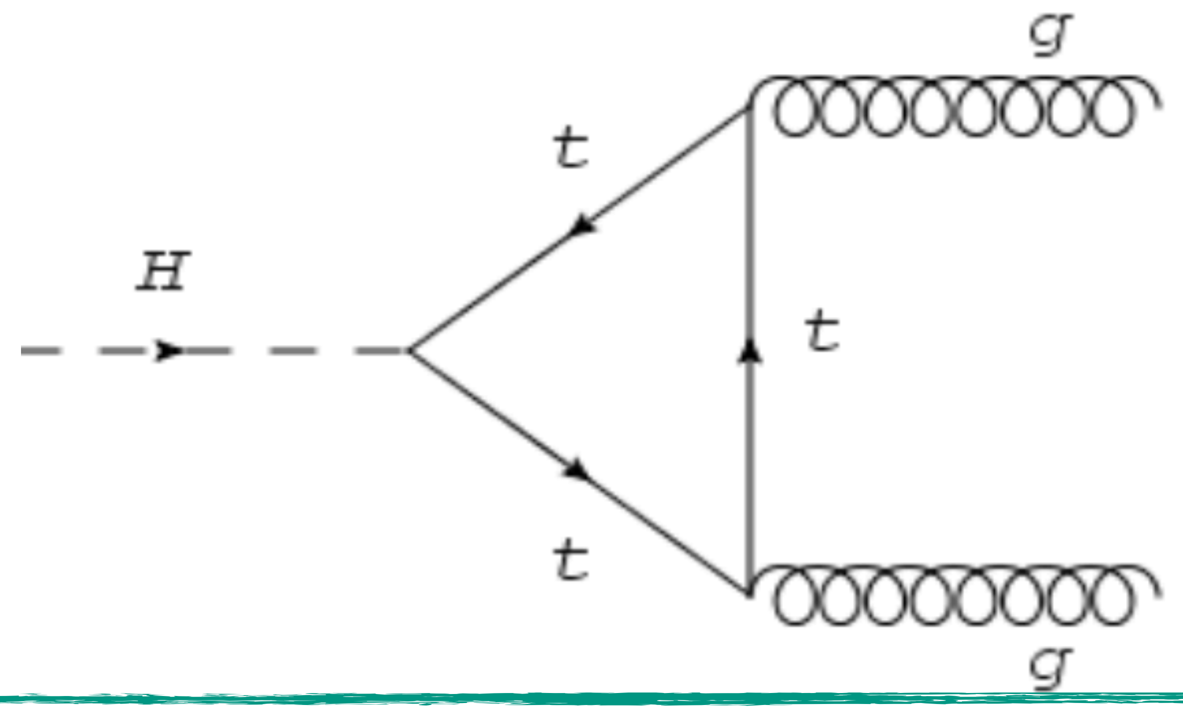


$e^+e^- \to Z \to uu$

$e^+e^- \to H \to gg$

- A clean sample of gluon jets to study gluon jet properties with high precision: ZH, H->gg



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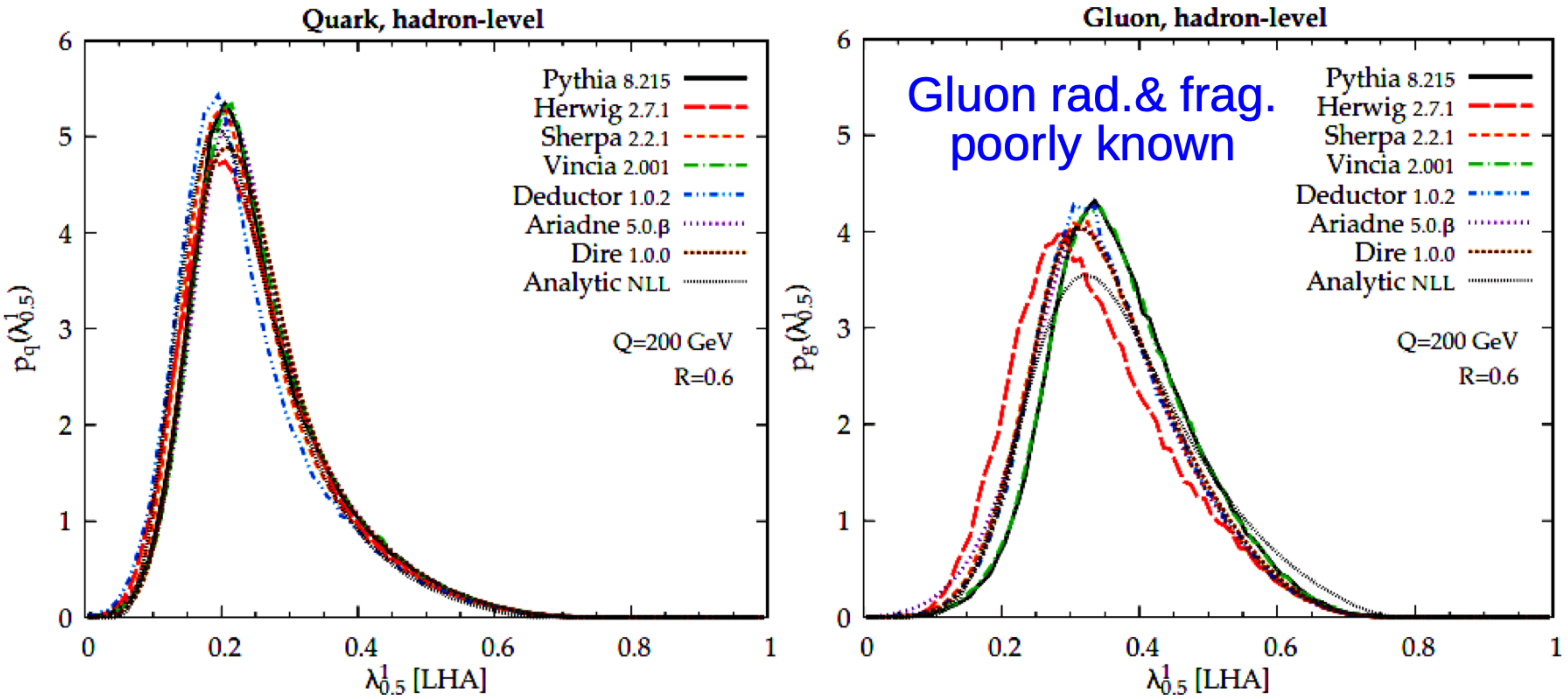
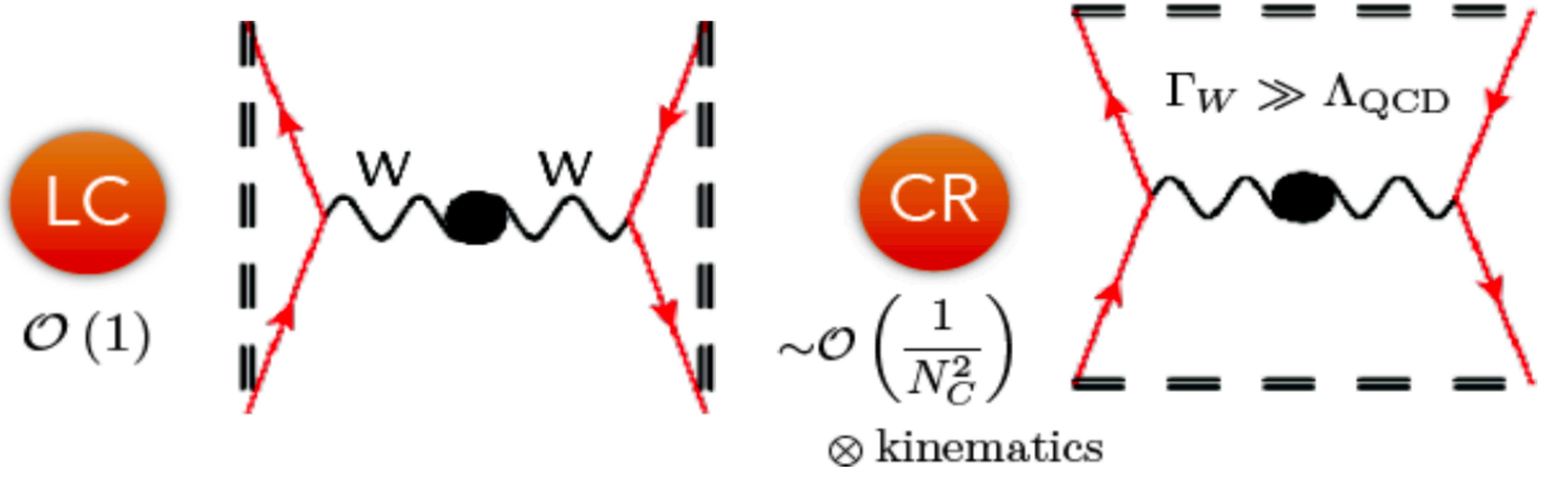


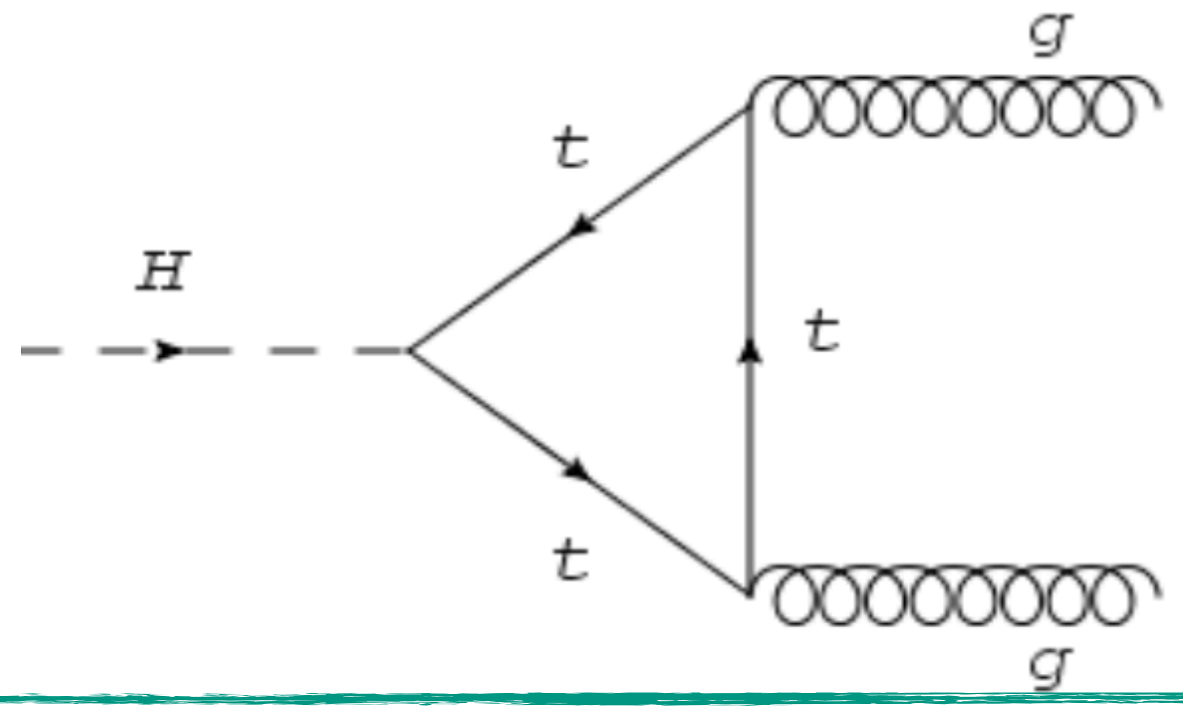
$e^+e^- \rightarrow Z \rightarrow uu$ $e^+e^- \rightarrow H \rightarrow gg$

- Colour reconnection: Impacts all FCC-ee multi-jet final states, highly relevant for a wide range of observables also at LHC, FCC-hh, …



"leading colour" "colour reconnection"

- A clean sample of gluon jets to study gluon jet properties with high precision: ZH, H->gg



- Exploit the large W sample to constrain CR experimentally: Compare W mass measured in leptonic and hadronic final states.

Bottom Line

- e^+e^- Colliders from 91 to 350 GeV are precision tools for top quark physics and QCD measurements
  Ultimate precision on top quark mass and other properties, on the strong coupling constant
  [and much more!]

- 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 top quark mass it is the leading uncertainty overall

➪ Advances in theory directly translate into improvements of overall precision.