Top Threshold Scan Strategy

at FCCee

Frank Simon
Max-Planck-Institute for Physics

given by Patrizia Azzi

FCC Week, Amsterdam, April 2018

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Outline

- Introduction: Measuring top quark properties in a threshold scan
- Optimising energy points
  - The role of systematic uncertainties
- Optimising for mass measurements
- Optimising for multi-parameter measurements: mass & width; mass & Yukawa Coupling
- Summary

Outline

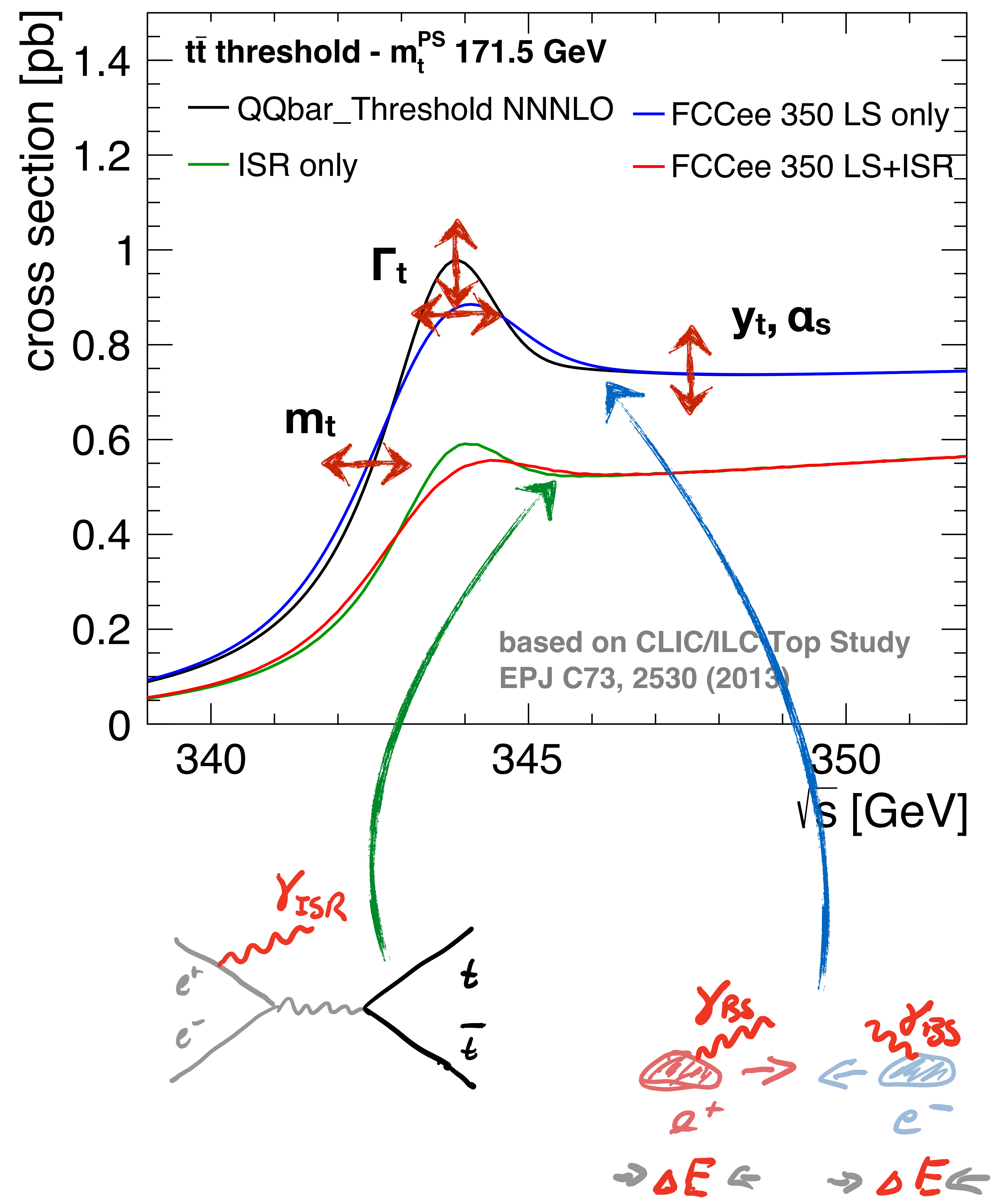
- Introduction: Measuring top quark properties in a threshold scan
- Optimising energy points
  - The role of systematic uncertainties
- Optimising for mass measurements
- Optimising for multi-parameter measurements: mass & width; mass & Yukawa Coupling
- Summary

A word on numbers:
All studies shown here use the ***PS mass scheme*** for the top quark, one of the mass schemes well suited for the threshold problem. Assuming here:
$m_t^{PS} = 171.5$ ***GeV***
this corresponds to a ***top quark pole mass of 173.3 GeV***, consistent with the current WA (assuming this is numerically close to the pole mass, which is a reasonable assumption)

Introduction: Precision Top Physics at the Threshold

- The top quark is the only quark that has so far escaped the scrutiny of e^+e^- colliders - at the same time it may be particularly sensitive to New Physics
- Precise measurements, coupled with precise theoretical calculations, provide excellent discovery potential

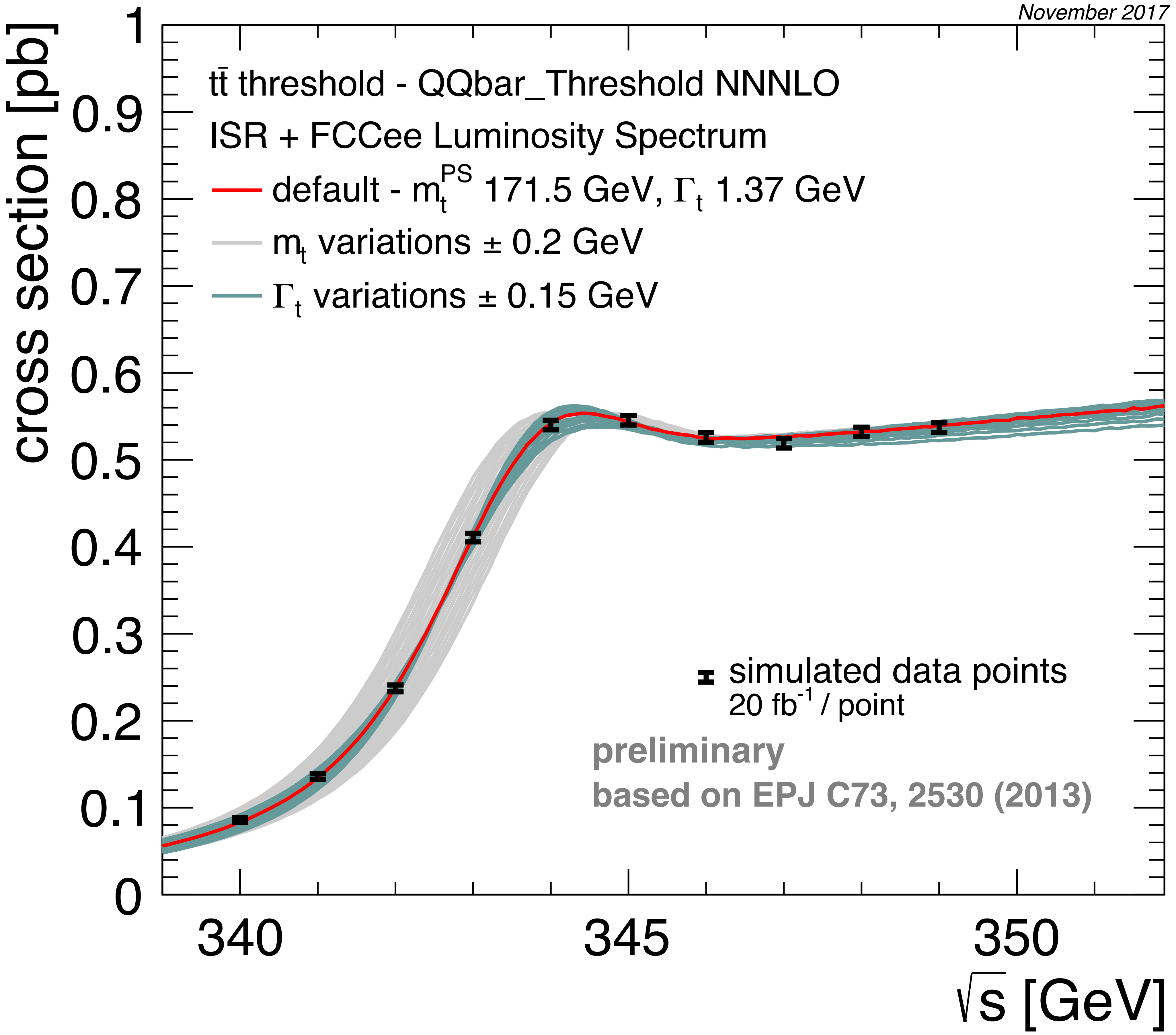
- The cross section for top quark pair production in the threshold region is highly sensitive to the top quark mass and other top quark properties - and can be calculated with high precision
  - also depends on accelerator features
    - For FCCee assuming purely gaussian energy distribution w/o any beamstrahlungs-tail: Only smearing, no reduction in effective cross section



A Top Threshold Scan at e^+e^- Colliders

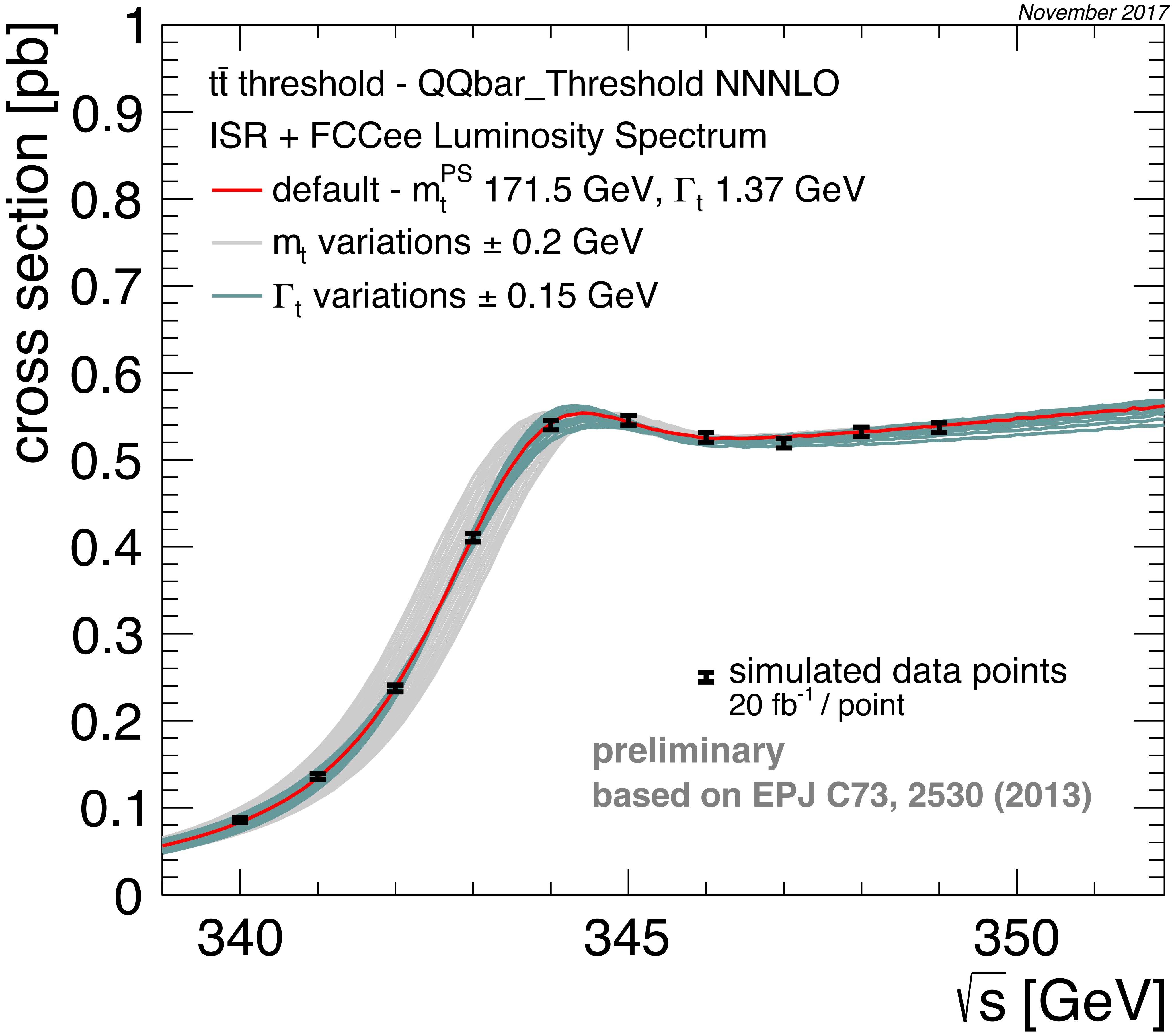
- Measurement of the top pair production cross section at different energy points in the the threshold region
- Extraction of top quark properties by comparing measurements to theory calculations
  - Including other observables (top quark momentum distribution, forward - backward asymmetry, …) may increase sensitivity - not considered here

- N.B. In principle measurement of α_s also possible (although highly correlated with Yukawa coupling) - assuming here that this will known with high precision (~ 2 x 10^{-4}) from other measurements



A Top Threshold Scan at e^+e^- Colliders

- Measurement of the top pair production cross section at different energy points in the the threshold region
- Extraction of top quark properties by comparing measurements to theory calculations
  - Including other observables (top quark momentum distribution, forward - backward asymmetry, …) may increase sensitivity - not considered here
- N.B. In principle measurement of α_s also possible (although highly correlated with Yukawa coupling) - assuming here that this will known with high precision (~ 2 x 10^{-4}) from other measurements



- Extensively studied in Linear Collider context (TESLA, ILC, CLIC)
  Present study based on EPJ C73, 2530 (2013), using FCCee luminosity spectrum instead of CLIC & ILC spectra

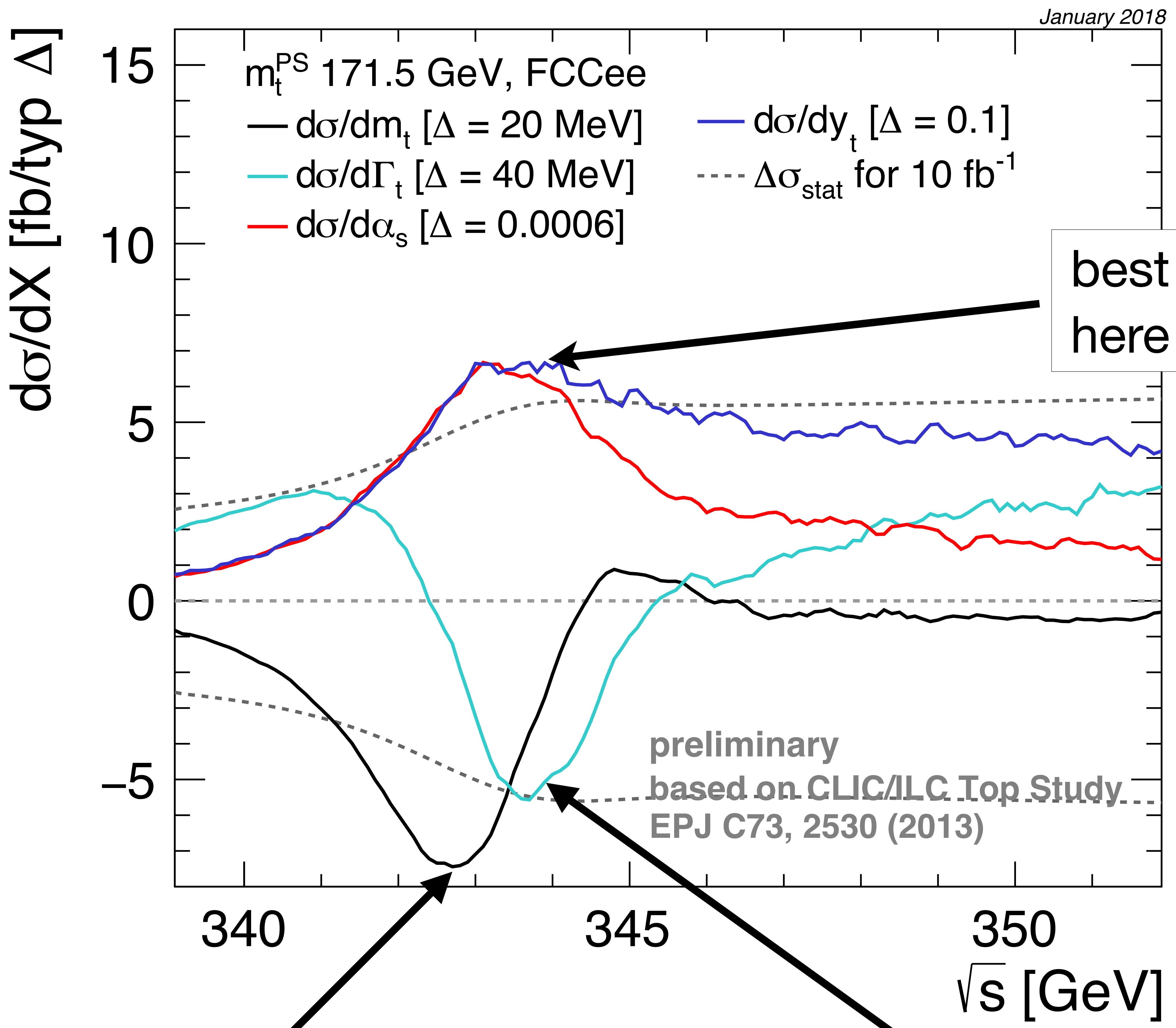
Finding the Optimal Sensitivity

- Default assumption: 10 points spaced by 1 GeV, each with equal integrated luminosity
  Obvious question: **Can we do better?**

➩ The optimal way to distribute the integrated luminosity in the threshold region depends on the quantities you want to measure

Plot shows the derivative of the cross section for various parameters - to make this understandable this is normalised to typical changes of these parameters

For each of the quantities there is an optimum - if you concentrate your integrated lumi there you get the best statistical precision



best measure y_t here

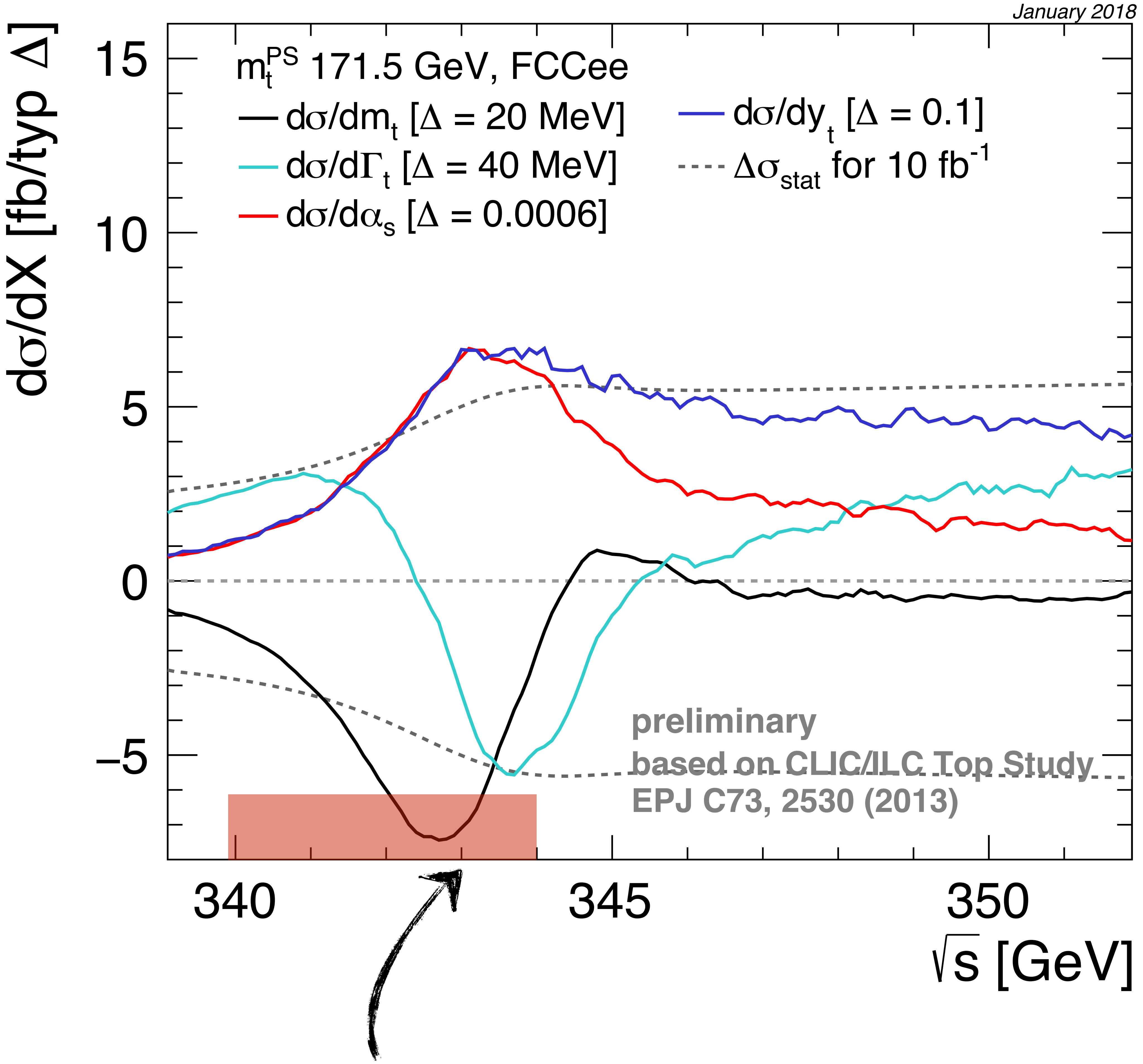
best measure mass here

best measure width here

BUT: You have to find that point!

Pinning Down the Position on the Threshold I

- Assuming you know the PS mass with 1 GeV precision from LHC (N.B. here you have to include all theory uncertainties - so +- 1 GeV is probably realistic):
  The position of the optimum for the mass measurement is uncertain by **+- 2 GeV** (threshold = 2 x m_t)
  - In principle you can determine m_t with a **single measurement of ~ 5 - 10 fb^{-1}** to ~ 100 MeV - you need a 4 GeV wide window where this works to be safe given the LHC input

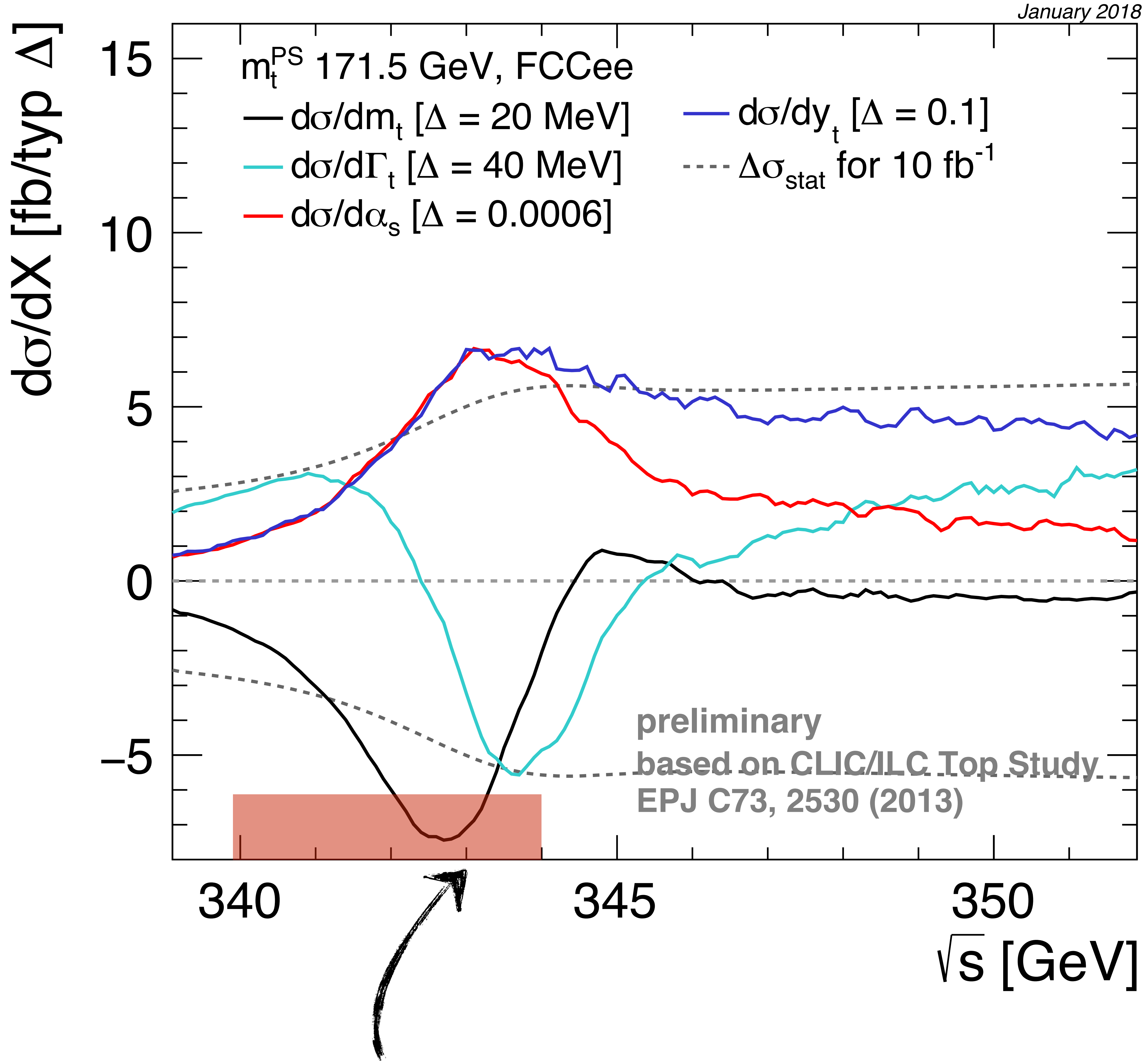


sensitivity to mass provided over whole range

Pinning Down the Position on the Threshold I

- Assuming you know the PS mass with 1 GeV precision from LHC (N.B. here you have to include all theory uncertainties - so +- 1 GeV is probably realistic):
  The position of the optimum for the mass measurement is uncertain by **+- 2 GeV** (threshold = 2 x m_t)
  - In principle you can determine m_t with a **single measurement of ~ 5 - 10 fb^{-1}** to ~ 100 MeV -
    you need a 4 GeV wide window where this works to be safe given the LHC input

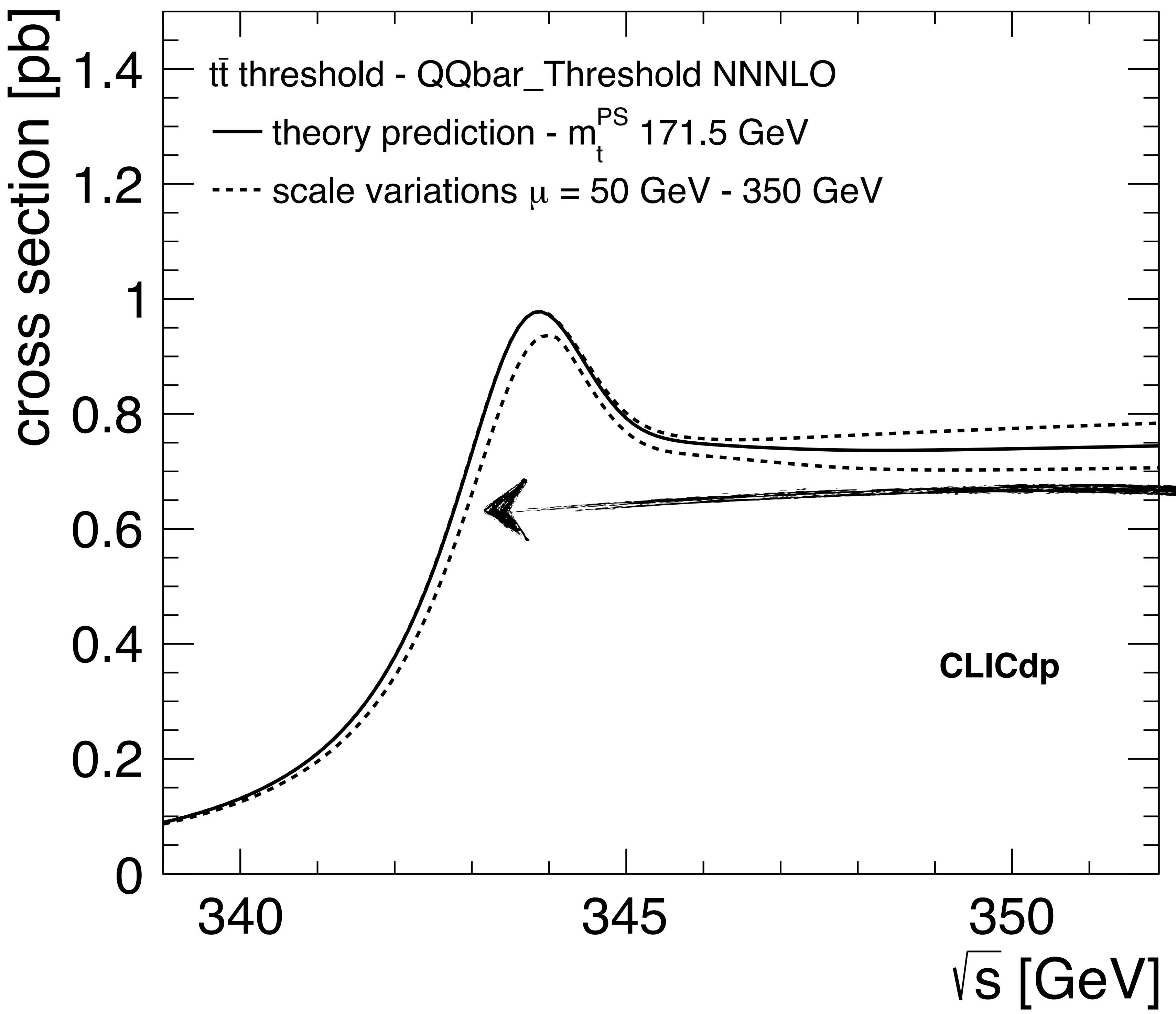
BUT: Here we are ignoring theory uncertainties on the cross section!
With these, a single point does not work!



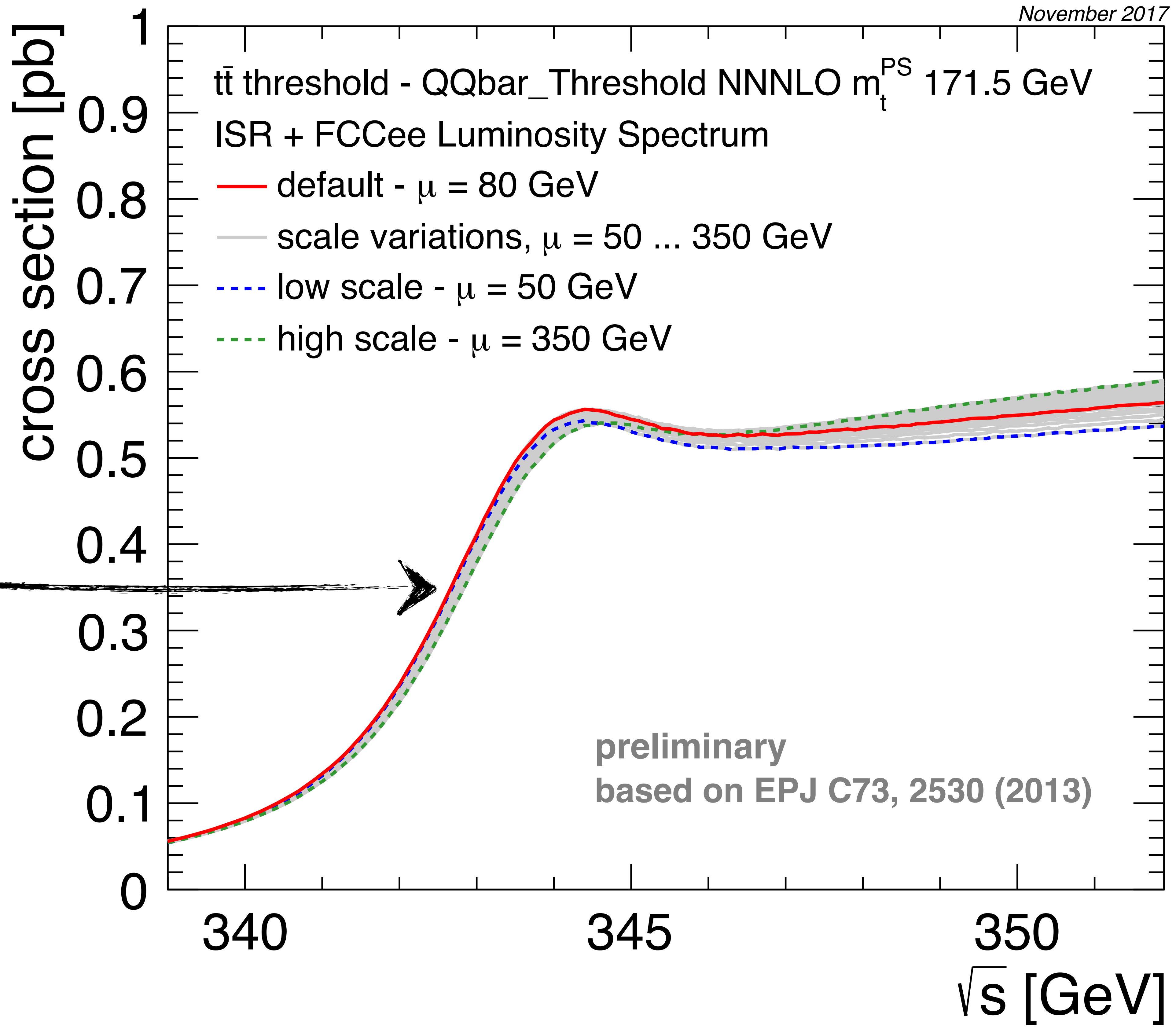
sensitivity to mass provided over whole range

Interlude: Theoretical Uncertainties

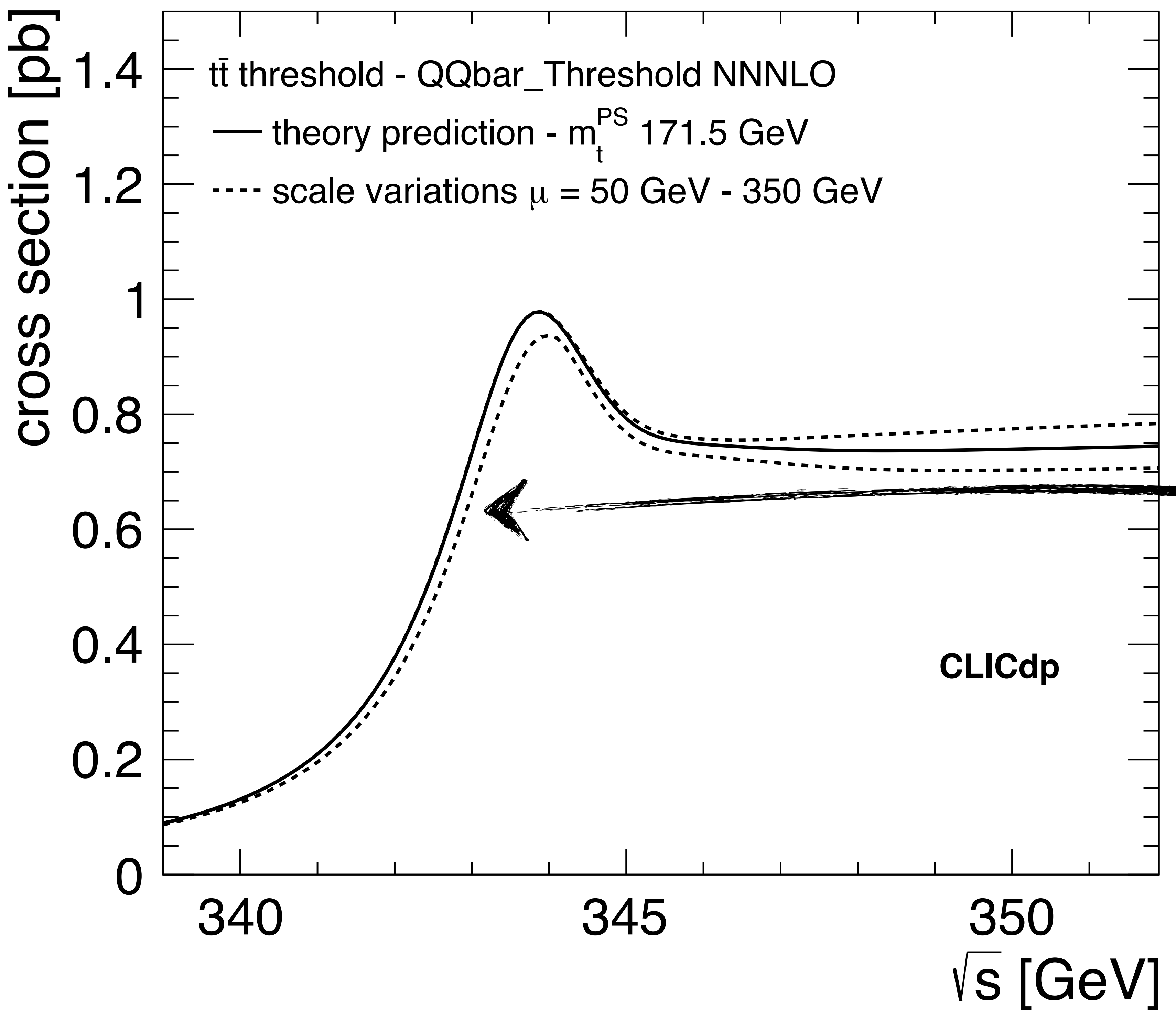
- Theory calculations available at NNNLO / NNLO + NNLL from two different groups: Remaining uncertainty around 3% (but energy - dependent): Given by scale variations



scale uncertainties
(N.B.: not symmetric, default scale results in maximal cross section in threshold region)

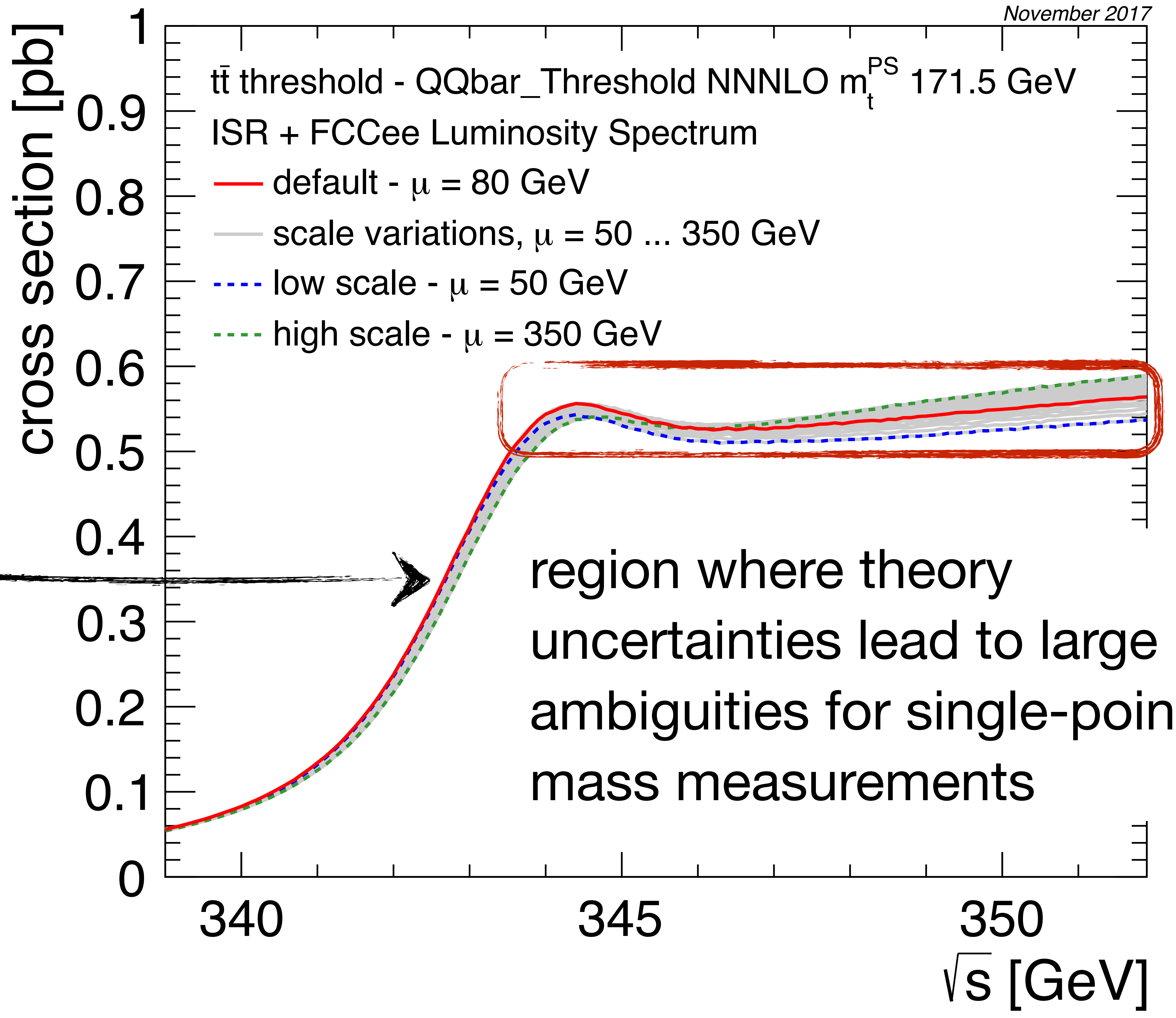


Interlude: Theoretical Uncertainties



- Theory calculations available at NNNLO / NNLO + NNLL from two different groups: Remaining uncertainty around 3% (but energy - dependent): Given by scale variations

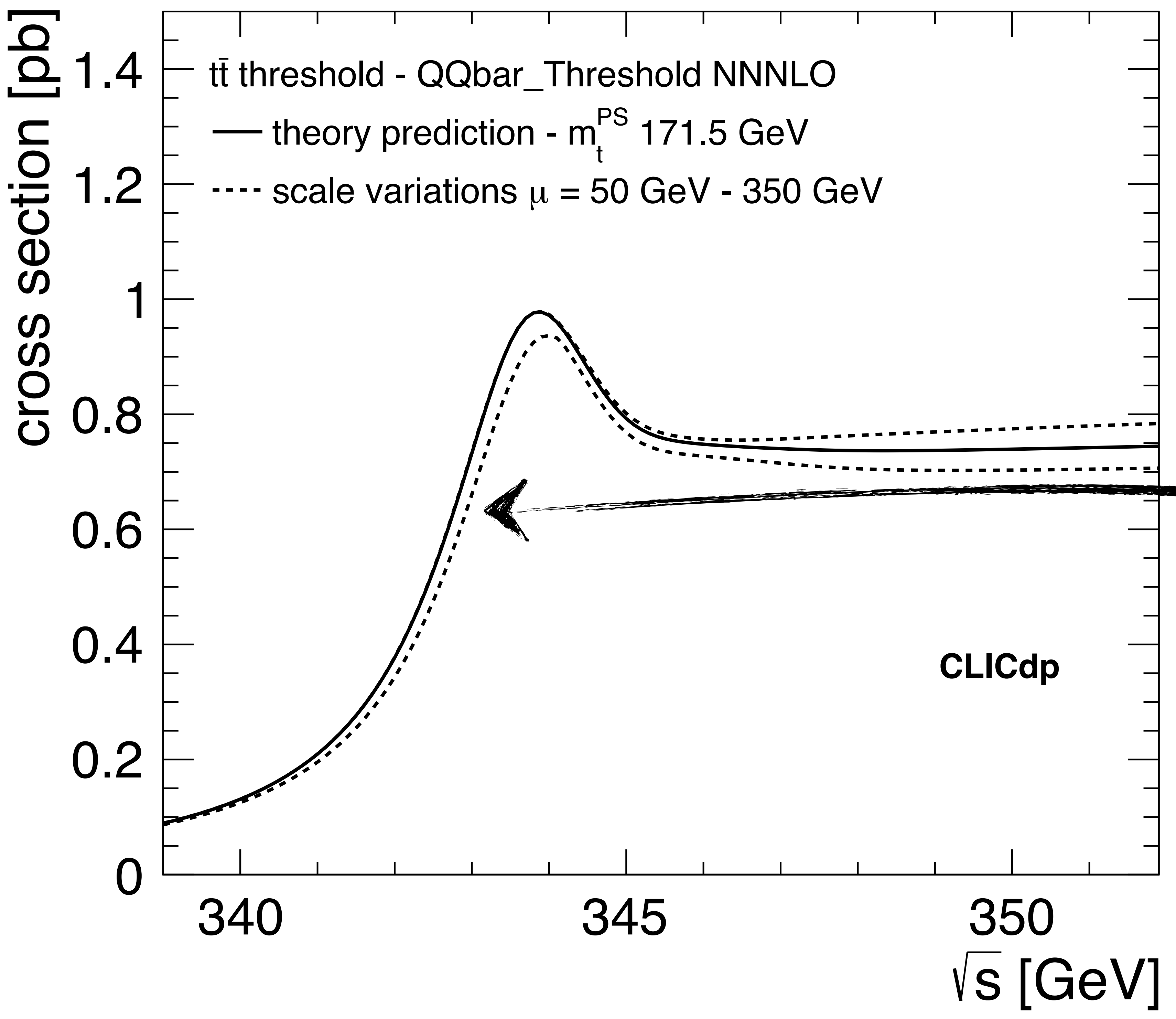
scale uncertainties
(N.B.: not symmetric, default scale results in maximal cross section in threshold region)



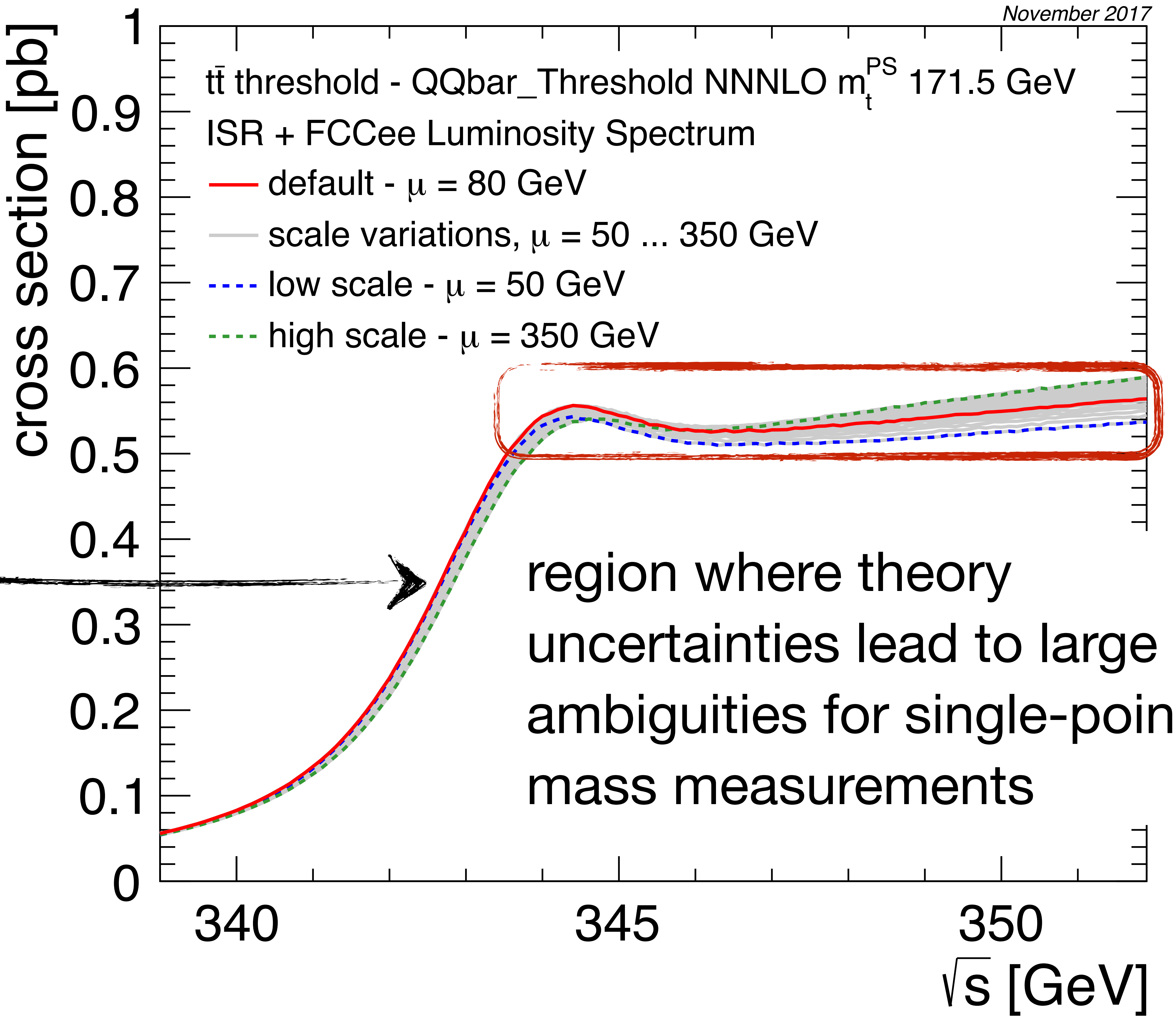
region where theory uncertainties lead to large ambiguities for single-point mass measurements

Interlude: Theoretical Uncertainties

- Theory calculations available at NNNLO / NNLO + NNLL from two different groups: Remaining uncertainty around 3% (but energy - dependent): Given by scale variations



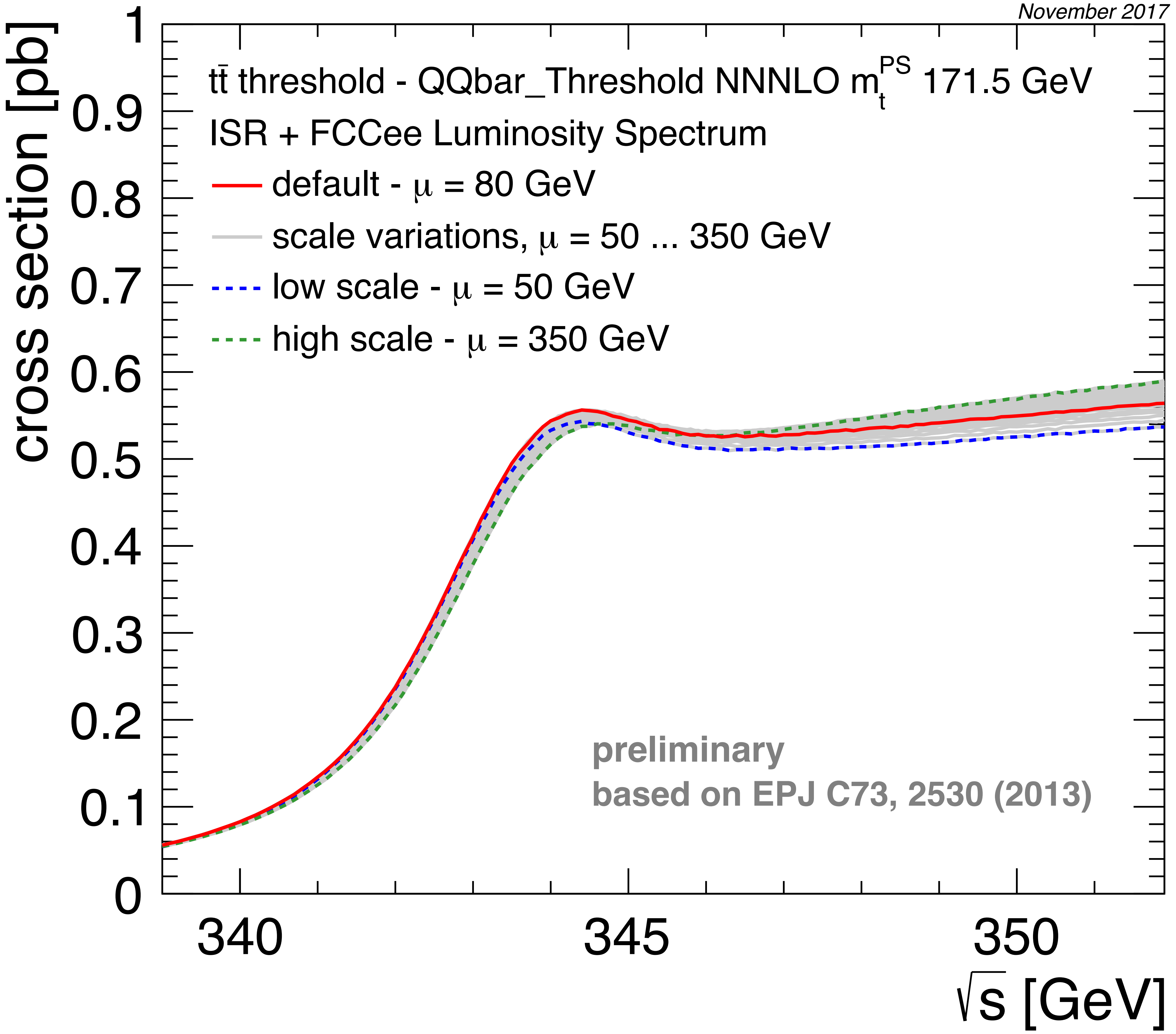
scale uncertainties (N.B.: not symmetric, default scale results in maximal cross section in threshold region)



region where theory uncertainties lead to large ambiguities for single-point mass measurements

- Often ignored in experimental studies, but highly relevant given the small experimental uncertainties
  Preliminary, reasonably thorough studies: arXiv:1603.04764, arXiv:1611.03399 - also considered here

Interlude: Theoretical Uncertainties & Exp. Systematics



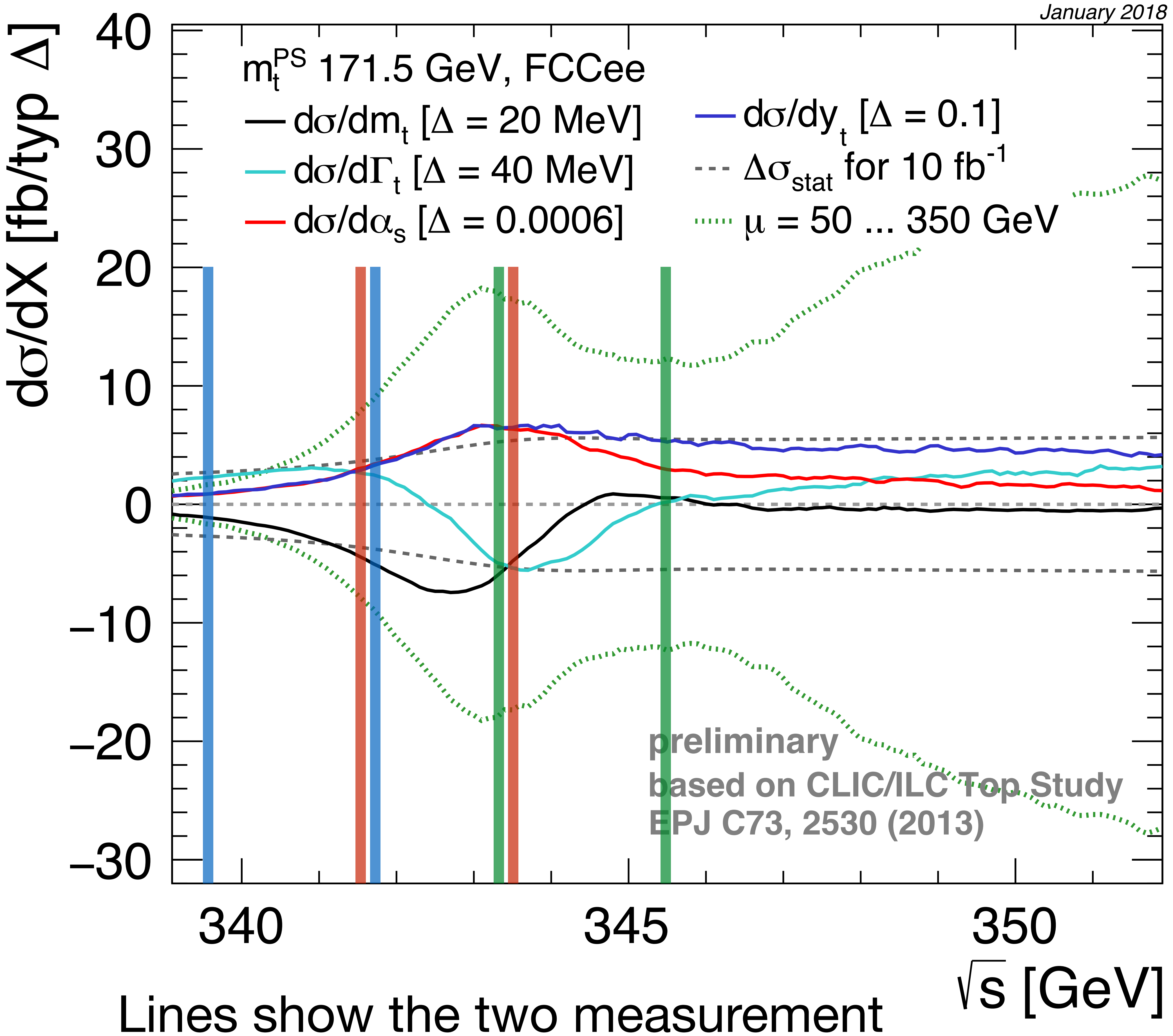
- Theoretical scale uncertainties lead to ~ 40 MeV systematic on the top quark mass

➩ Back of the envelope assessment of a few experimental systematics:

  - Luminosity: Needs to be known on the few per mille level to be completely irrelevant wrt to theory (the scale uncertainties are roughly equivalent to a 3% luminosity uncertainty) - similar arguments apply to selection efficiencies and backgrounds
  - Beam energy: An uncertainty here leads to an effective shift of the curve: directly translates to mass value. Want < ~10 MeV

A note on the theory uncertainties: Scale variations are taken as a measure for the uncertainty, but the scale is not a quantity that can be measured: Uncertainties cannot be eliminated by measurements at higher energies which may appear to be able to constrain the scale (ask your favorite theorists about details…)

Pinning Down the Position on the Threshold II



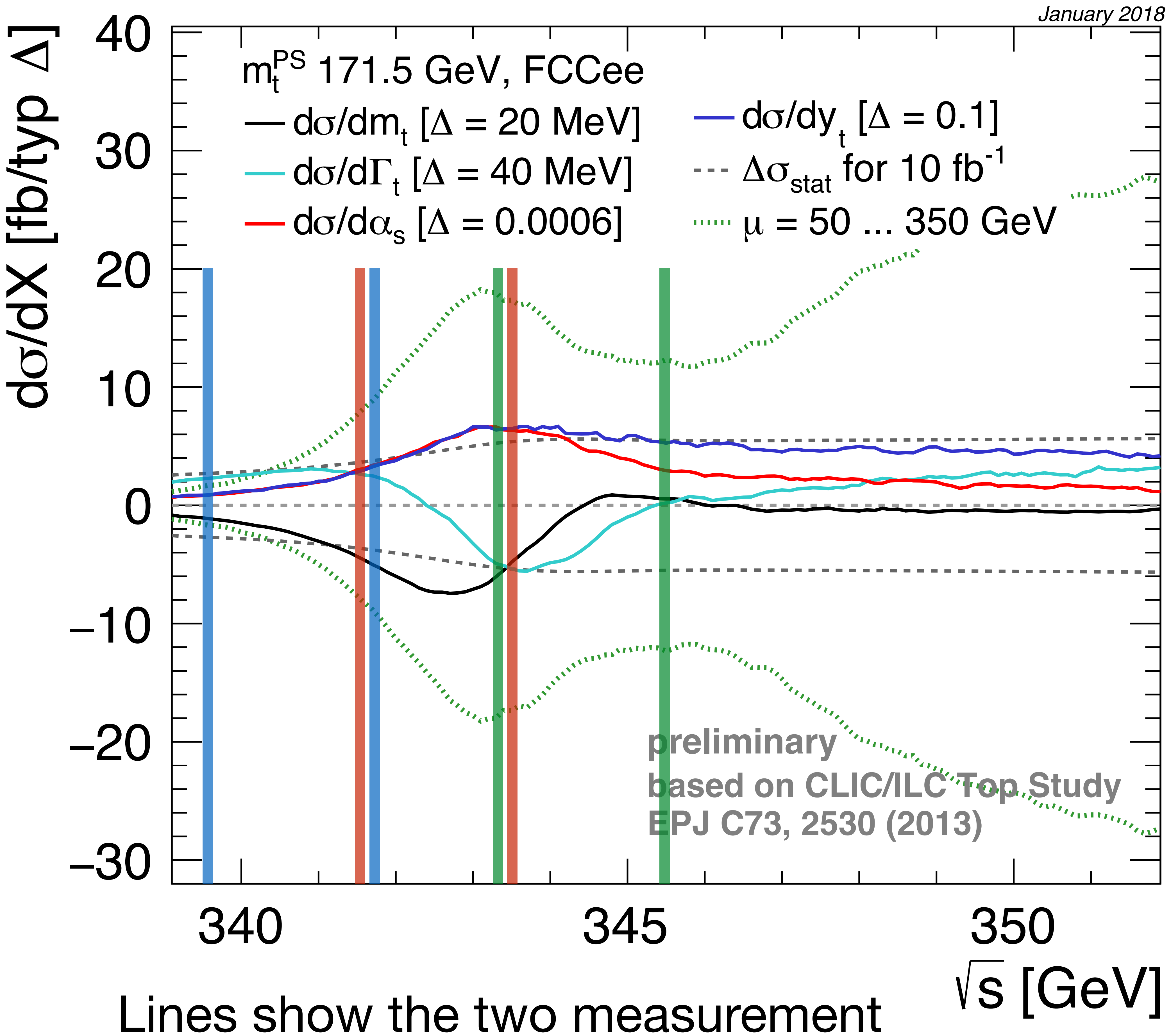
Lines show the two measurement points for three scenarios:

🟥 LHC spot-on
🟦 LHC 1 GeV low
🟩 LHC 1 GeV high

- When considering theory uncertainties, you need two measurement points with 5 fb^{-1} each to get a guaranteed top mass measurement with a precision of ~ 100 MeV (stat+theo - other systematics don't matter here)

The recipe: Measure at
2 x m_t^{PS},LHC - 1.5 GeV
2 x m_t^{PS},LHC + 0.5 GeV

Pinning Down the Position on the Threshold II



Lines show the two measurement points for three scenarios:

🟥 LHC spot-on

🟦 LHC 1 GeV low

🟩 LHC 1 GeV high

- When considering theory uncertainties, you need two measurement points with 5 fb^{-1} each to get a guaranteed top mass measurement with a precision of ~ 100 MeV (stat+theo - other systematics don't matter here)

The recipe: Measure at
2 x m_t^{PS},LHC - 1.5 GeV
2 x m_t^{PS},LHC + 0.5 GeV

The threshold scan strategy:
Exploratory measurement of 2 x 5 fb^{-1}
to define measurement range
then regular threshold scan

First Studies towards Optimised Scan Scenarios

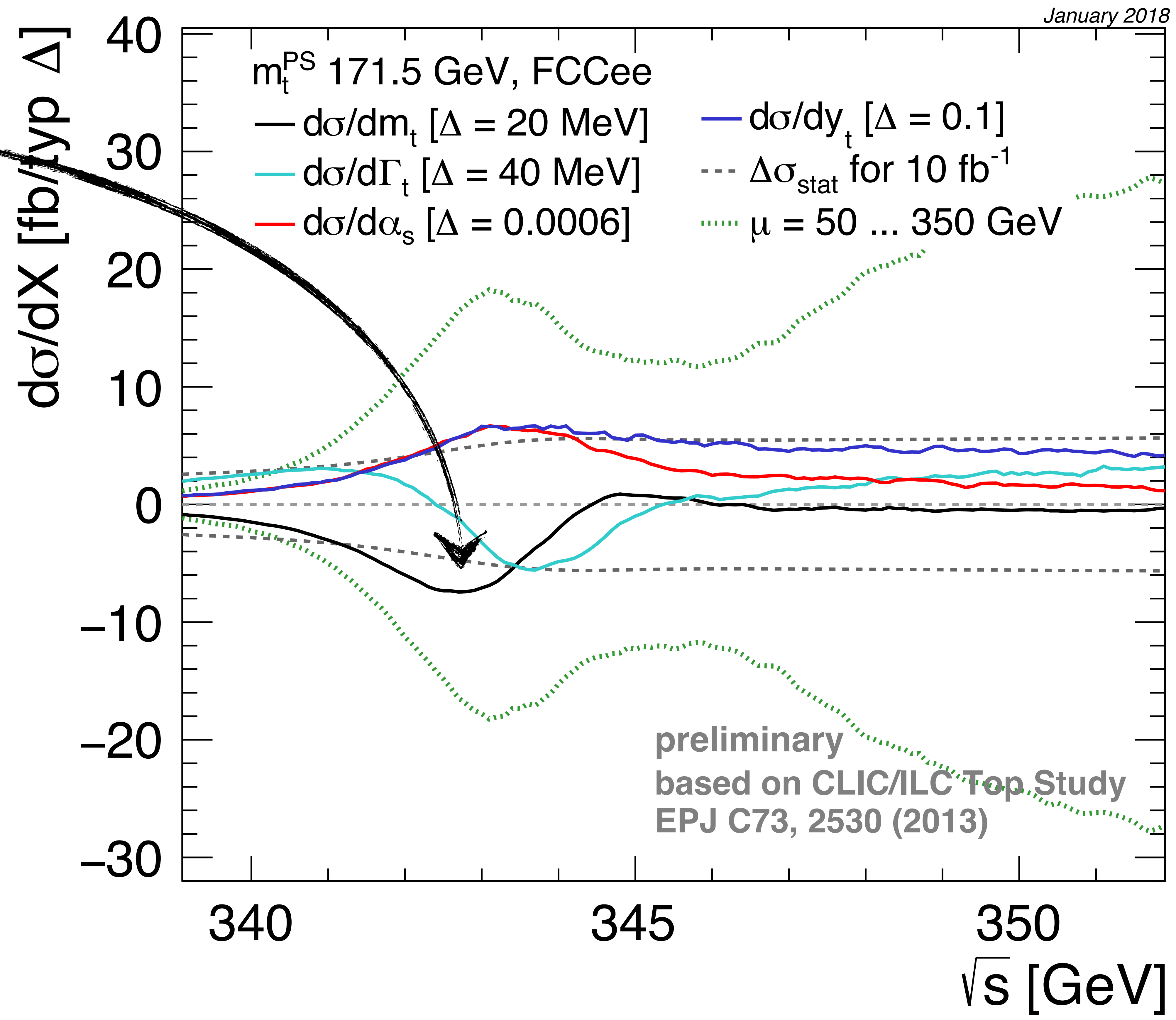
- Performed first rather naive studies towards optimised threshold scan scenarios - more thorough studies coming up

- The general assumption: total integrated luminosity of 200 fb^{-1}
  - 2 x 5 fb^{-1} for the exploratory 2 - point scan
    (assuming LHC is spot on, measuring at 341.5 GeV and 343.5 GeV)
  - 190 fb^{-1} on top distributed along points chosen ad-hoc (but reasonably well motivated), considering energy locations in multiples of 0.5 GeV

- Today: considering two cases
  - Optimising for mass measurement alone
  - Optimising for 2D extractions of mass & width and mass & Yukawa coupling

Measuring just the Mass

- Optimised for statistical uncertainty: 190 fb^{-1} at 343 GeV: **5.3 MeV (stat)**
  - But: **45.3 MeV** theory uncertainty

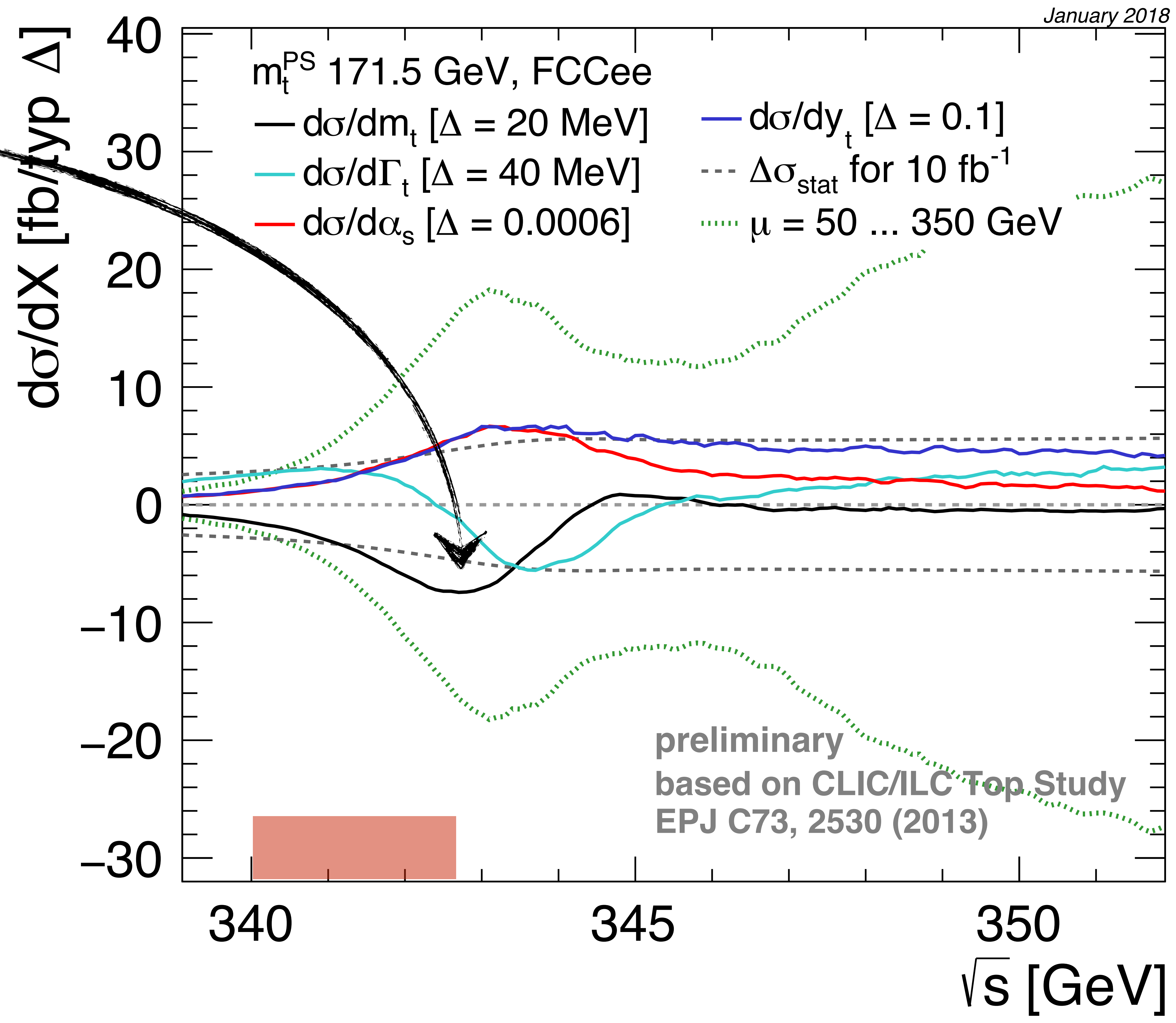


For comparison: default 10 point scan:
10.5 MeV (stat), 42.3 MeV (theo), 5.3 MeV α_s

Measuring just the Mass

- Optimised for statistical uncertainty: 190 fb^{-1} at 343 GeV:
  5.3 MeV (stat)
  - But: **45.3 MeV** theory uncertainty

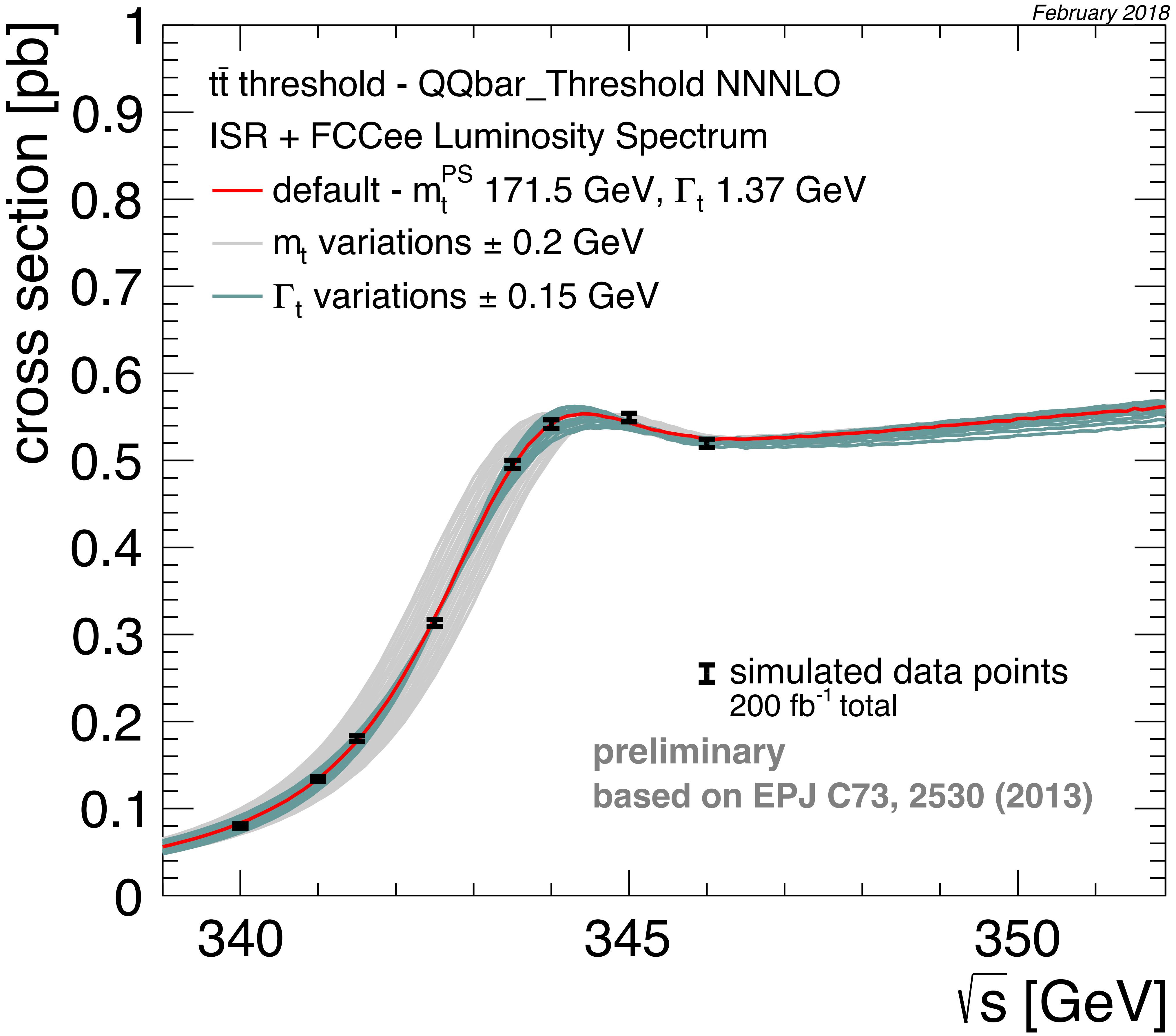
- Optimised for reduced theory uncertainty - concentrate luminosity at low energy
  341.5 GeV: 35/fb; 343.5 GeV: 5/fb; 340 GeV: 40/fb;
  341 GeV: 40/fb; 342 GeV: 40/fb; 342.5 GeV: 40/fb;
  6.7 MeV (stat)
  - **38.7 MeV** theory uncertainty
  - But: Not good if you want to measure other parameters as well



For comparison: default 10 point scan:
10.5 MeV (stat), 42.3 MeV (theo), 5.3 MeV α_s

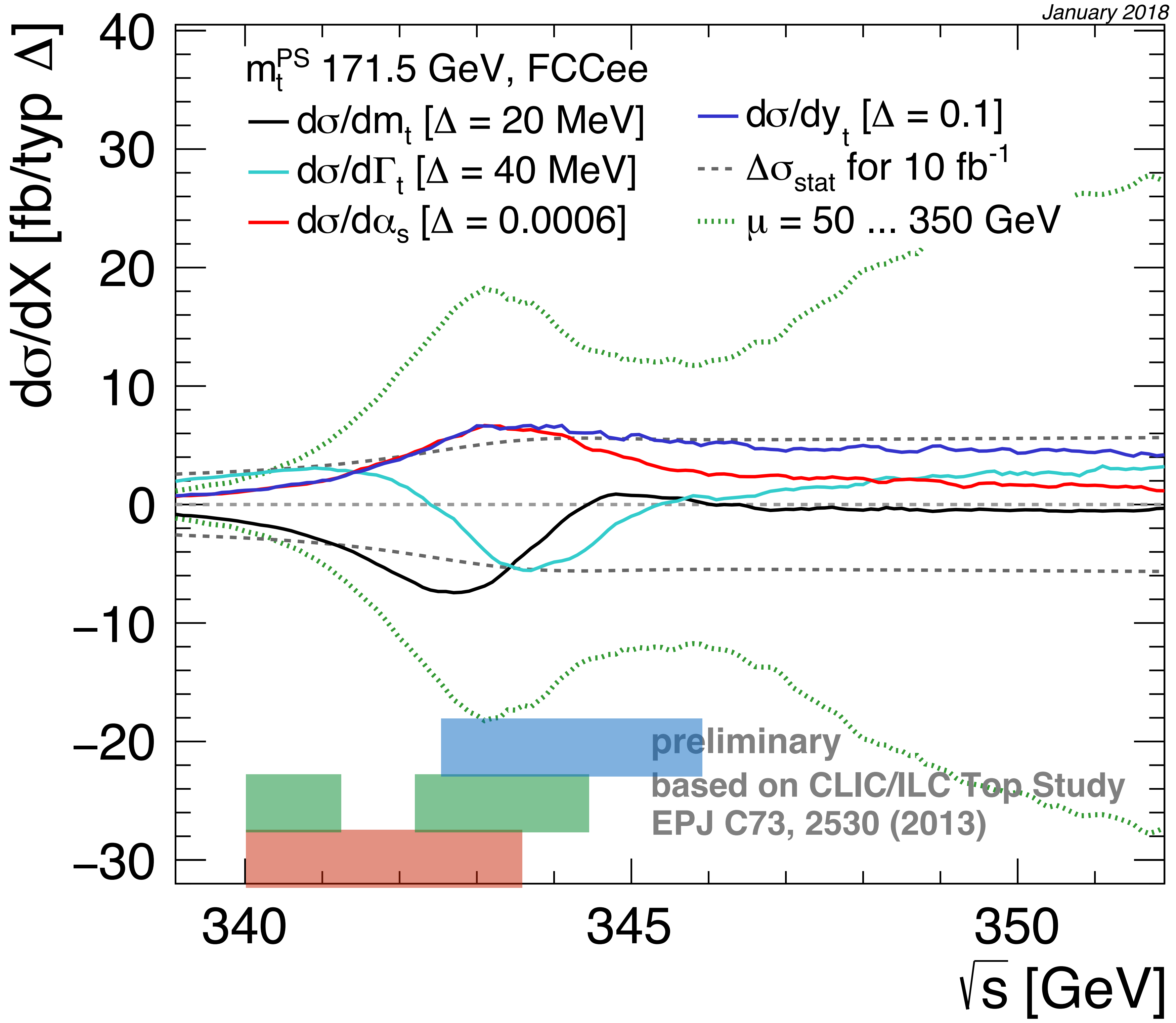
2D: Mass & Width, Mass & Yukawa

- For multi-parameter measurements: somewhat wider range needed to access width and Yukawa coupling



sensitivity to:

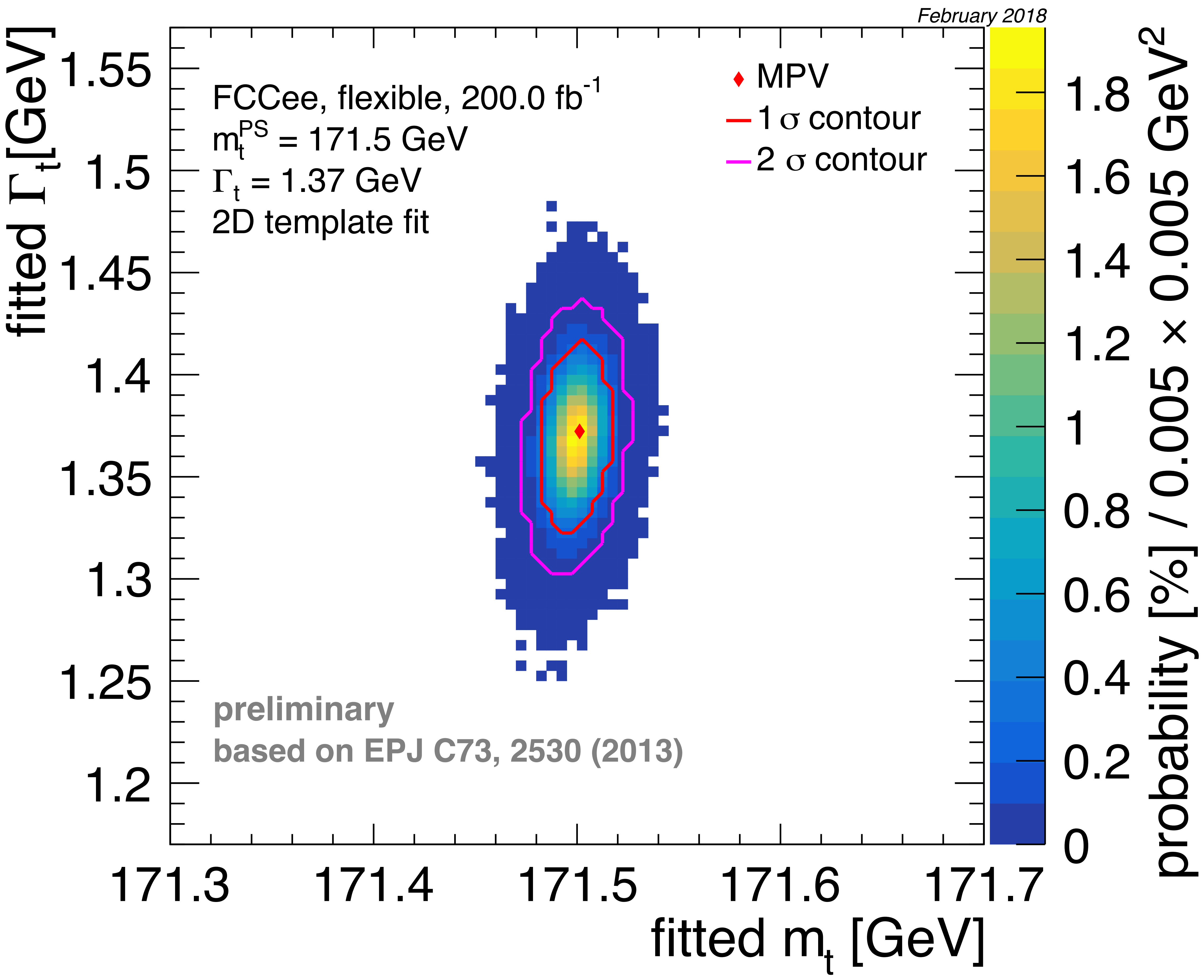
🟥 mass
🟩 width
🟦 Yukawa

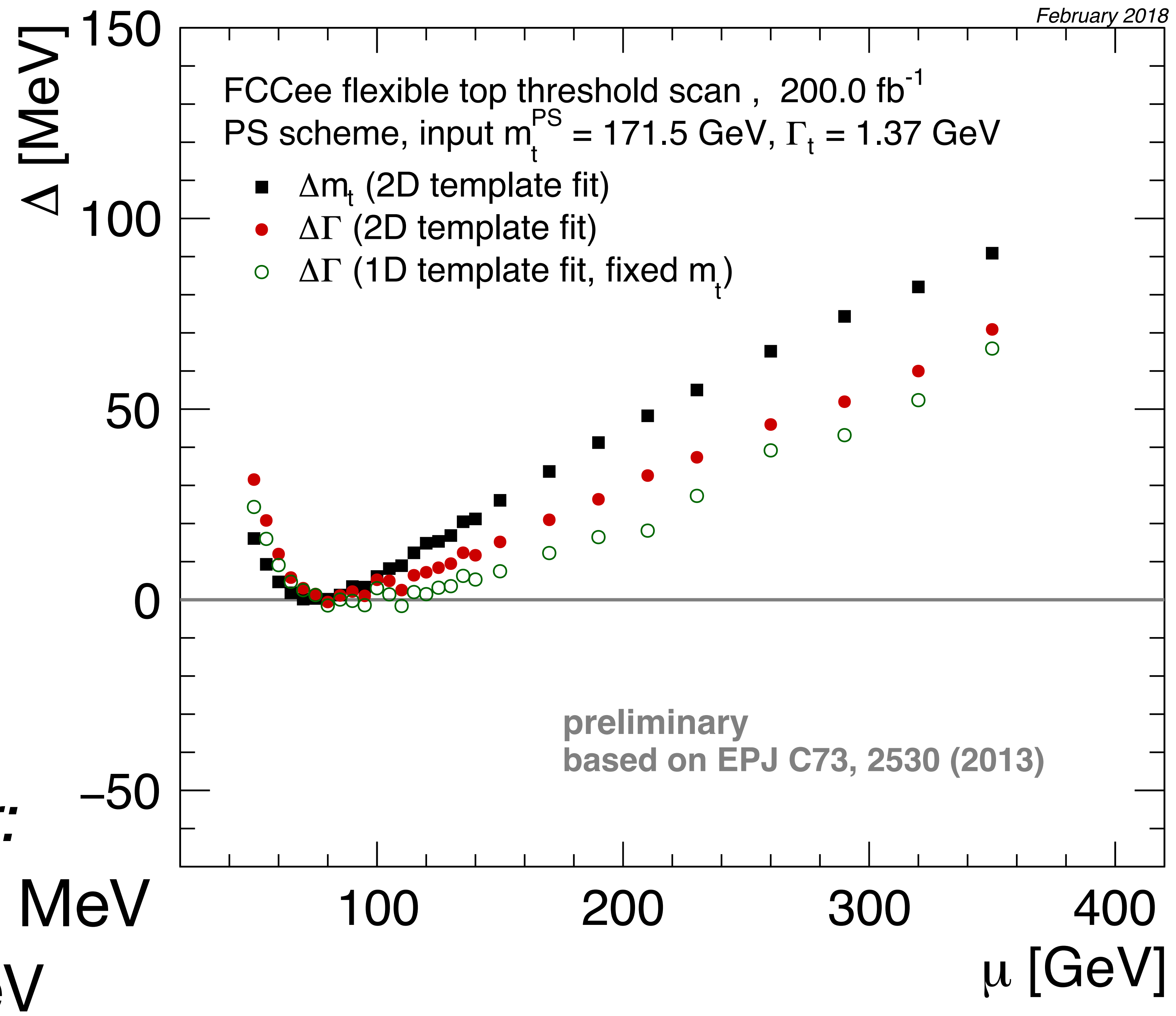


340 GeV: 25/fb; 341 GeV: 25/fb; 341.5 GeV: 25/fb; 342.5 GeV: 25/fb; 343.5 GeV: 25/fb; 344 GeV: 25/fb; 345 GeV: 25/fb; 346 GeV: 25/fb;

Mass alone, and Mass & Width

- Mass only: **8.8 MeV** (stat), **5.4 MeV** (α_s [2 x 10^{-4}]), **44 MeV** (theo)
    - 2D Mass & Width fit



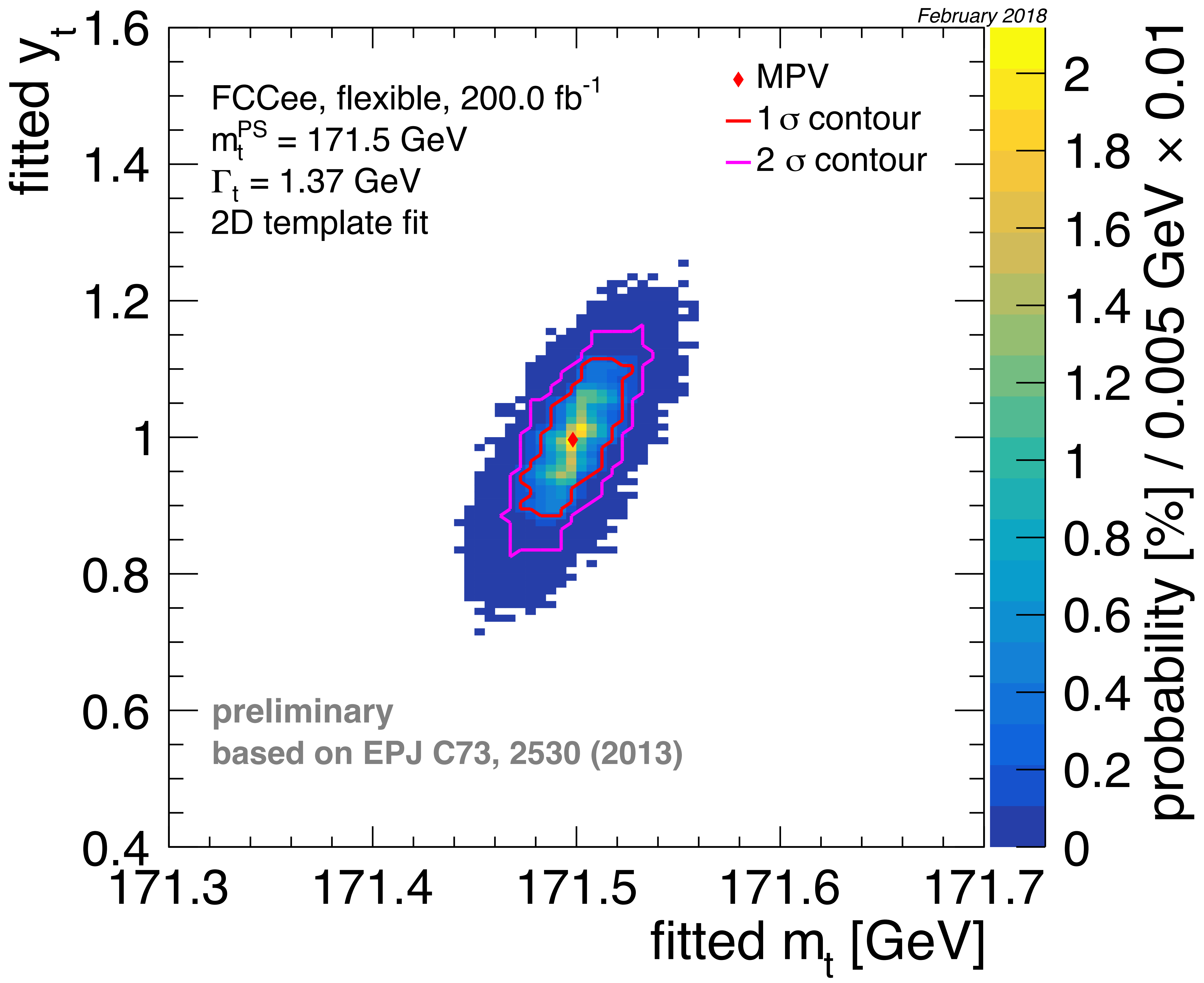


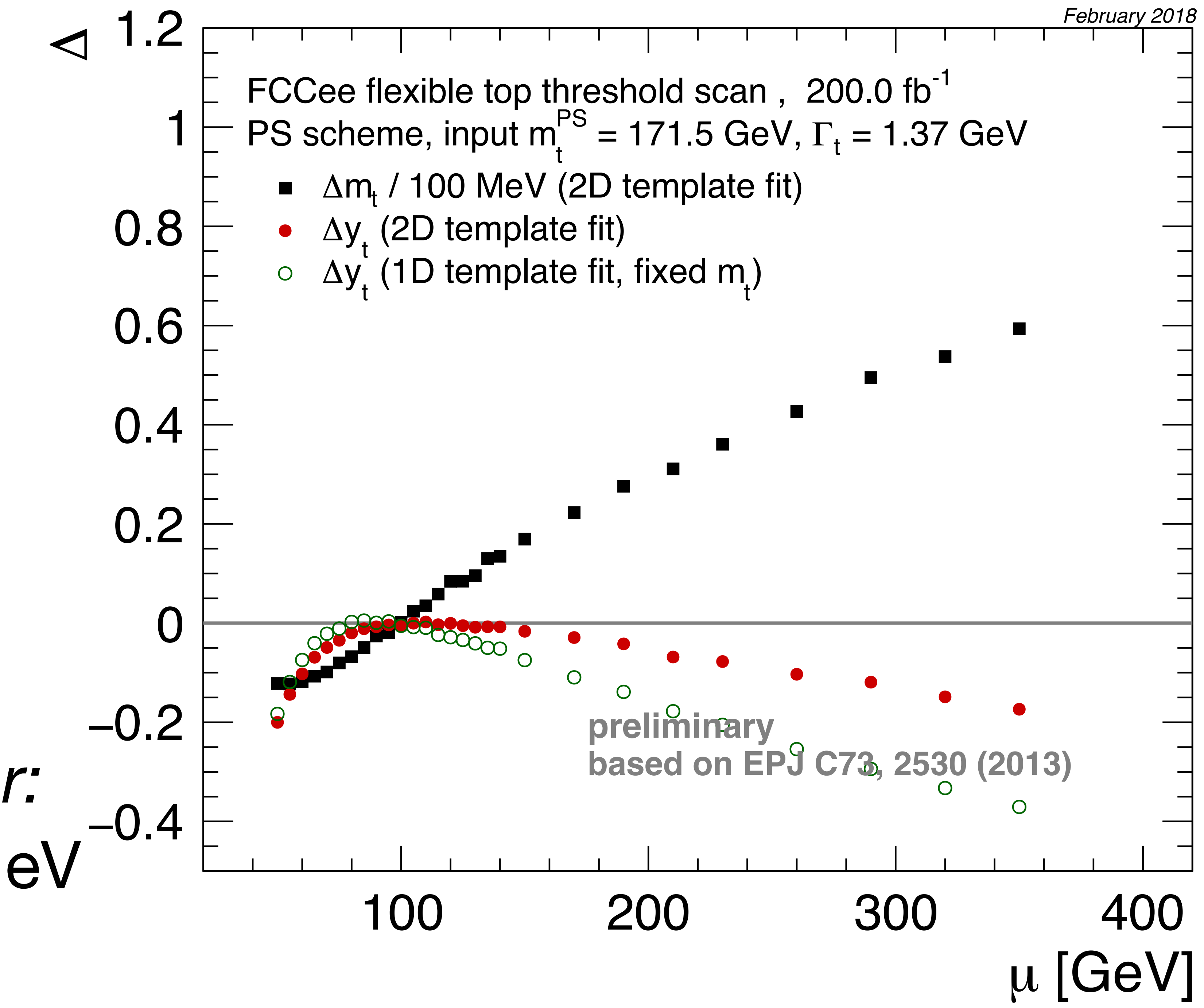
Extension of 1σ contour:
mass: +16.6 MeV, -18.8 MeV
width: +45 MeV, -50 MeV
Theory uncertainty (symm.):
mass: 45 MeV; width: 36 MeV

For comparison: default 10 point scan:
10.5 MeV (stat), 42.3 MeV (theo), 5.3 α_s
2D mass: +24 MeV, - 21 MeV; 44.5 MeV (theo)
2D width: +64.5 MeV, -50.5 MeV; 57 MeV (theo)

Mass & Yukawa Coupling

- 2D Mass & Yukawa fit





Extension of 1σ contour:

mass: +29 MeV, - 26 MeV

y_t: +0.12, -0.11

Theory uncertainty (symm.):

mass: 36 MeV; y_t: 0.11

α_s parametric uncertainty (0.0002)

mass: 3 MeV; y_t: 0.02

For comparison: default 10 point scan:
2D mass: +28.5 MeV, - 26.5 MeV; 47 MeV (theo)
2D Yukawa: +0.08, 0.12 MeV; 0.165 (theo)

Conclusions

- A scan of the top threshold is one of the core measurements at a future e^+e^- collider: Enables the precise exploration of top quark properties, with small theoretical uncertainties
- A top threshold scan can be optimised wrt to the energy points
  - requires an exploratory measurement of 2 x 5 fb^{-1}
- Substantial increase in statistical precision possible for mass alone - but such approaches are not suitable for multi-parameter measurements
- A substantial gain in precision (~ 20% for mass, more for width, and substantial gains in theoretical uncertainty for the Yukawa coupling at a mild expense on statistics) is possible compared to a “standard” 10 point scan over a range of 10 GeV
  - Very naively: **~ *50 MeV mass, 70 MeV width, 15% Yukawa Coupling total uncertainties*** (assuming exp. uncertainties are small)
    - with FCCee α_s precision, the corresponding parametric uncertainty is negligible compared to theory uncertainties, and also compared to the stat. uncertainty in 2D fits