IFIC STUDENT SEMINARS

TOP MASS MEASUREMENT IN RADIATIVE EVENTS

PABLO GOMIS LOPEZ

CONTENT

- Top quark mass
- Observable definition
- Theoretical model
- Experimental strategy
- Assessment of the uncertainties
- Summary and the way forward

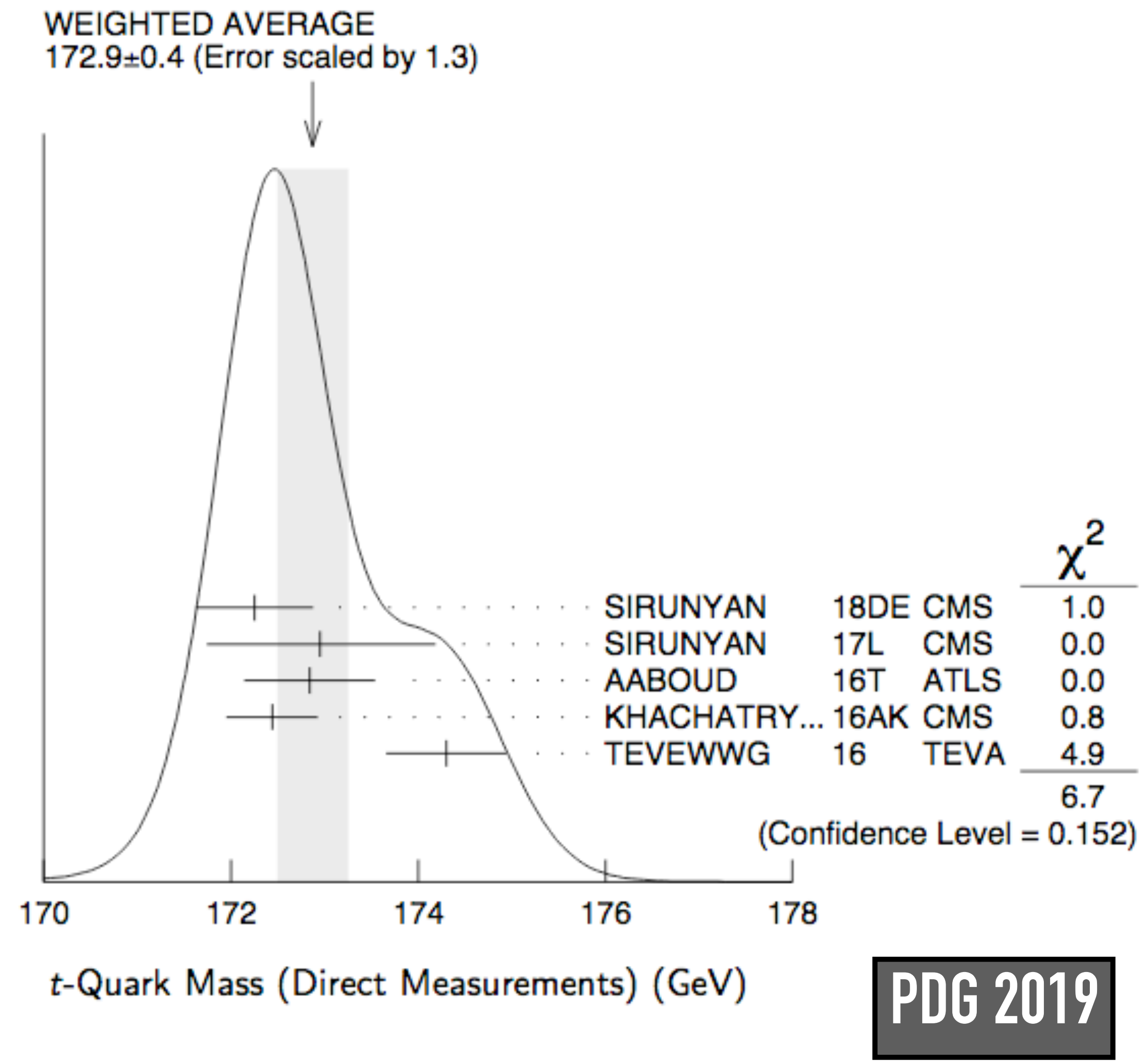
TOP QUARK PERKS

- It carries color charge → color confinement → it cannot be measured freely
- Has a huge mass → tiny lifetime → decays way before hadronization
- As it does not hadronize, it behaves as a quasi-free quark
- Its huge mass influence many QCD calculations, and can be related to high precision predictions in perturbative calculations
  - Great for precise tests of the SM
- As it cannot be spotted freely, its mass has to be measured through its influence on QCD processes
  - Theory dependent measurements → renormalization scheme

STATE OF THE ART MASS MEASUREMENTS

- Direct measurements
  - Kinematic fit
  - MC mass extracted
  - Tricky theoretical interpretation

$$m_t = 172.9 \pm 0.4 \text{ GeV}$$



- Cross section measurements:
  - Pole mass $\qquad m_t^{pole} = 173.1 \pm 0.9 \text{ GeV}$
  - $\overline{\text{MS}}$ mass $\qquad \overline{m}_t \equiv \overline{m}_t(\overline{m}_t) = 160.0^{+4.8}_{-4.3} \text{ GeV}$

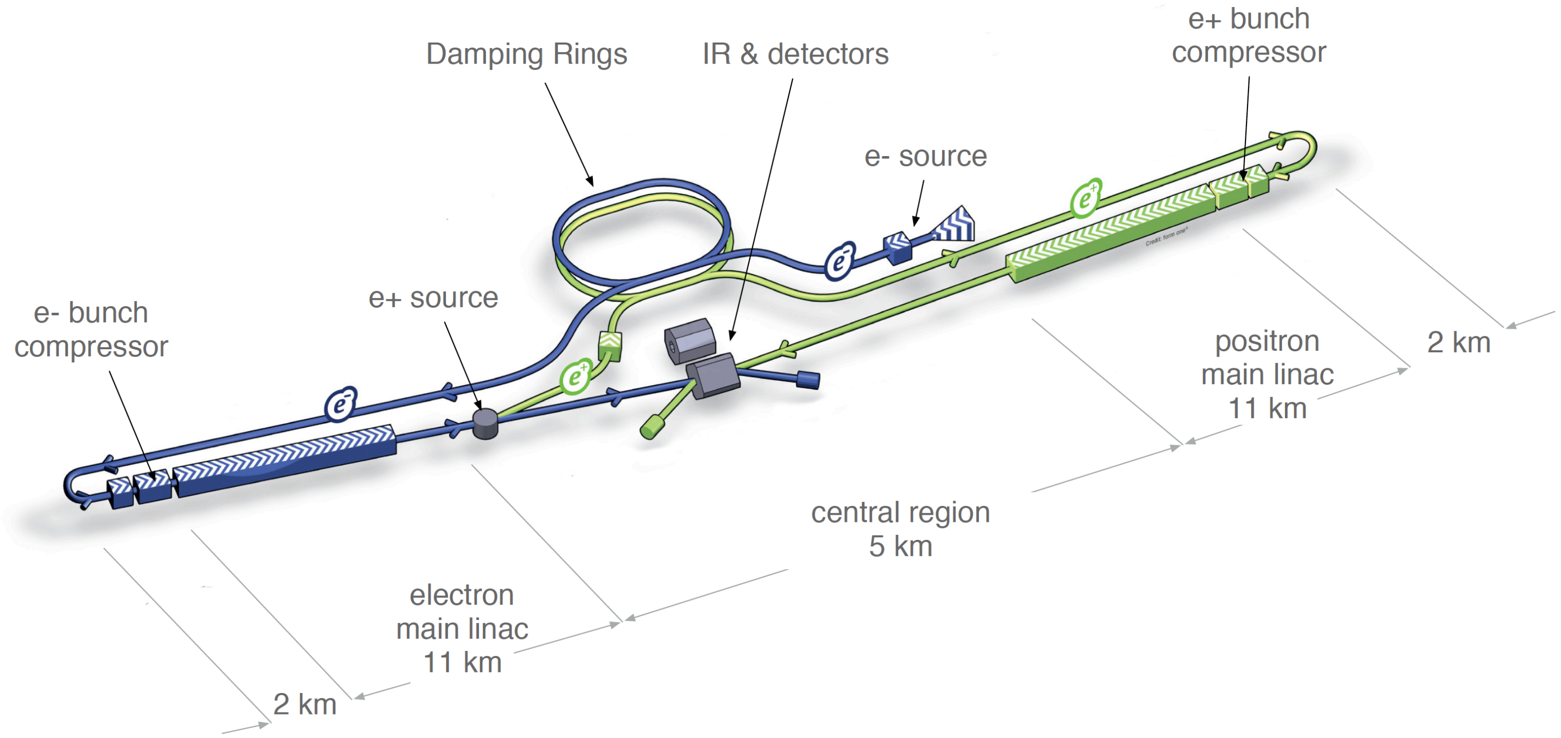
THE WAY FORWARD: e^+e^- LINEAR COLLIDERS

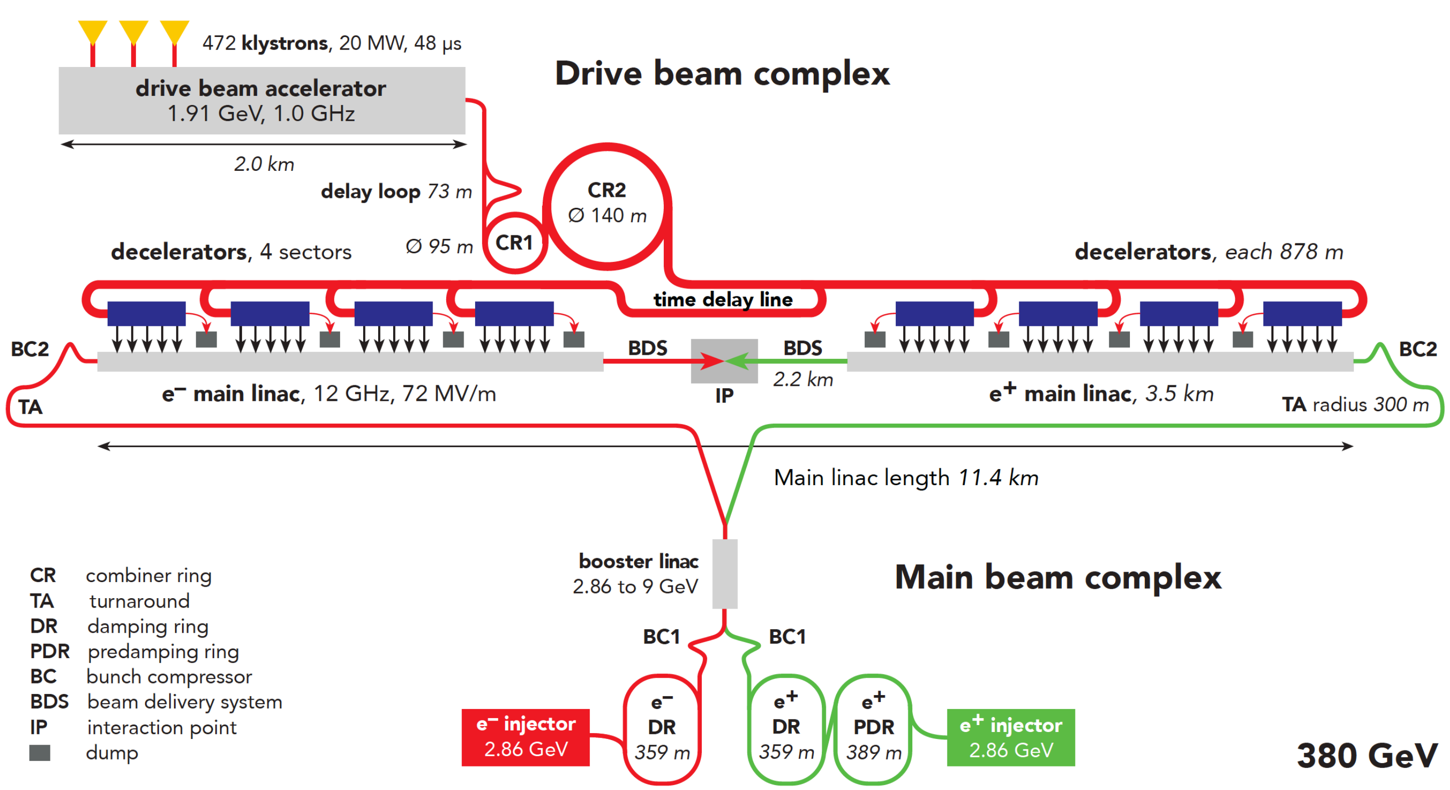
Lepton linear colliders offer the following advantages:

- Knowledge of the initial state e^+e^-
- Point like interactions → known collision energy
- Lower background environments
  - Reduces the experimental complexity (triggering, clustering…)
  - Reducing the requirements about radiation hardness and occupancy allow for the design of more precise detectors
- High flexibility to set the energy staging
  - Collision energy tuned by turning on/off sections in the main linac
- Allows for precision measurements in the TeV scale

e+e- LINEAR COLLIDER PROPOSALS

International Linear Collider	
Stage	Integrated luminosity
Initial @ 250 GeV	2000 fb^{-1}
Upgrade @ 500 GeV	4000 fb^{-1}

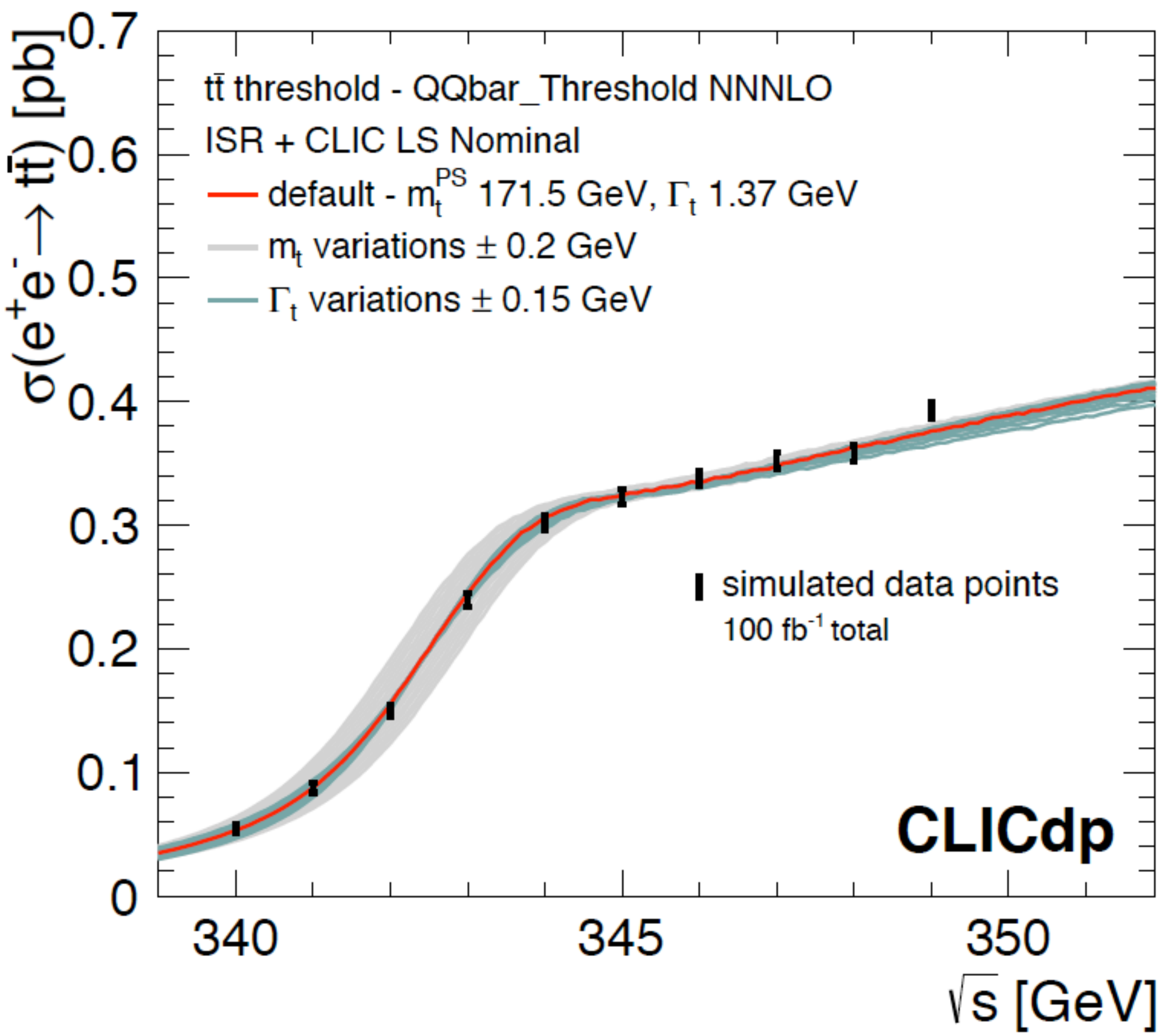




Compact Linear Collider	
Stage	Integrated luminosity
Stage I @ 380 GeV	1000 fb^{-1}
Stage II @ 1500 GeV	3000 fb^{-1}
Stage III @ 3000 GeV	5000 fb^{-1}

LINEAR COLLIDERS: THRESHOLD SCAN

Energy scan of the threshold at steps of 1 GeV, measuring $\sigma_{t\ t\text{-bar}}$



Uncertainties estimation	
Uncertainty	**Δm_t^{PS} (MeV)**
Statistical @ 100 fb^{-1}	± 22
Experimental systematics	± 25 ~ 50
Theoretical systematics	± 30 ~ 50
Overall	± 45 ~ 75

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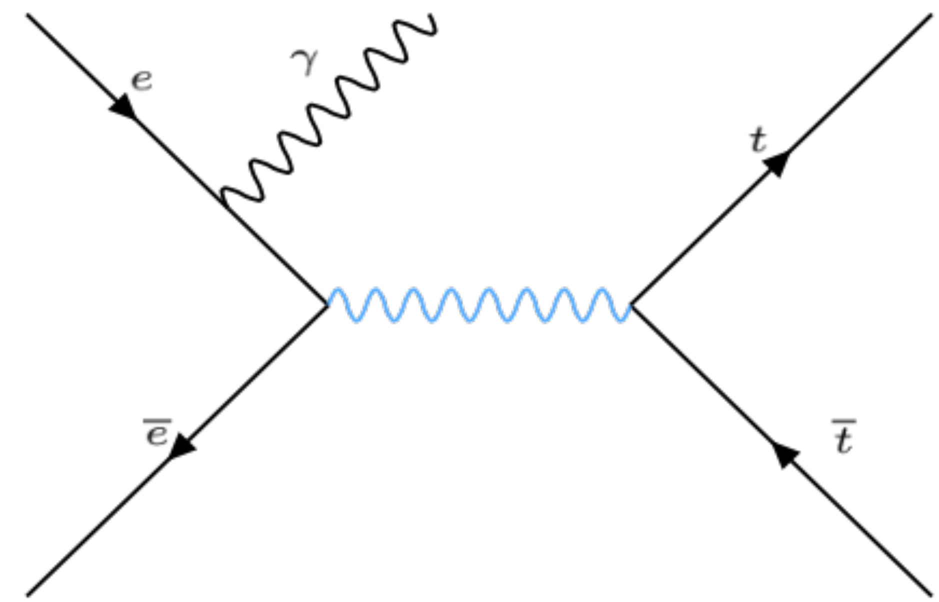
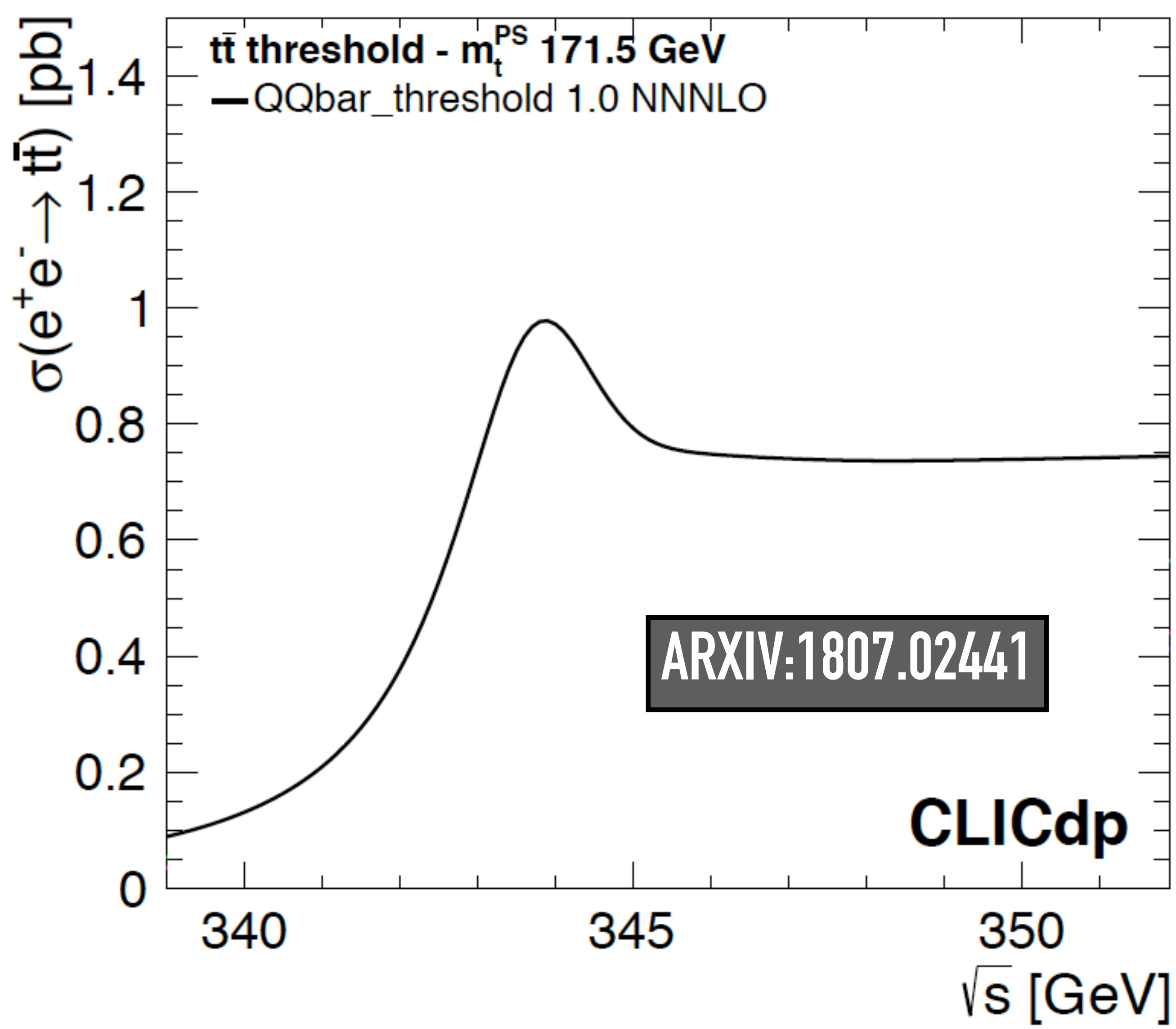
A NEW OBSERVABLE

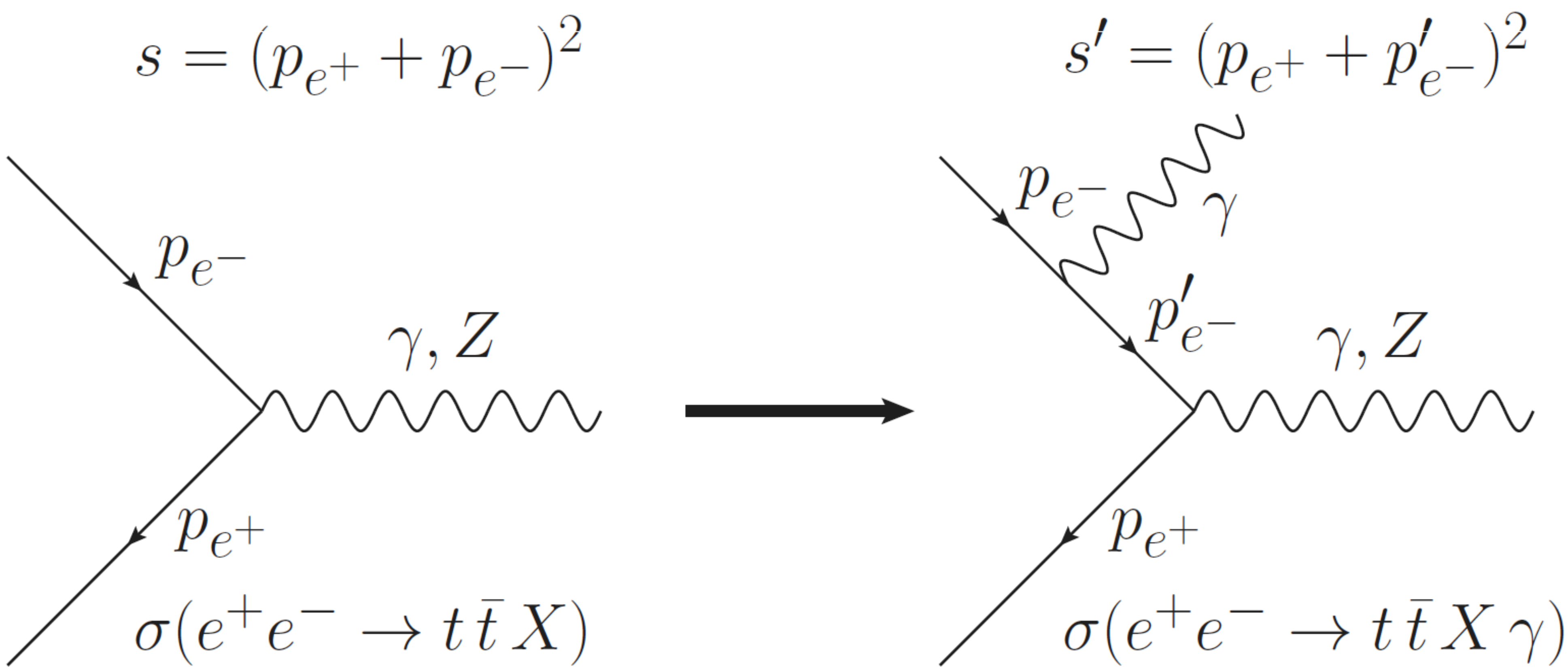
- The idea is to measure the top-quark mass (m_t) in the events $e^+e^- \to t\,\bar{t}\,\gamma_{\mathrm{ISR}}$





- t t-bar pair cross section depends strongly on the on the production energy
- The ISR hard photon carries away energy from the t t-bar production vertex

OBSERVABLE DEFINITION



$$\frac{d\sigma_{t\,\bar{t}\,\gamma}}{d\sqrt{s'}} \quad \xrightarrow{\text{with}} \quad s' = s\left(1 - \frac{2E_\gamma}{\sqrt{s}}\right)$$

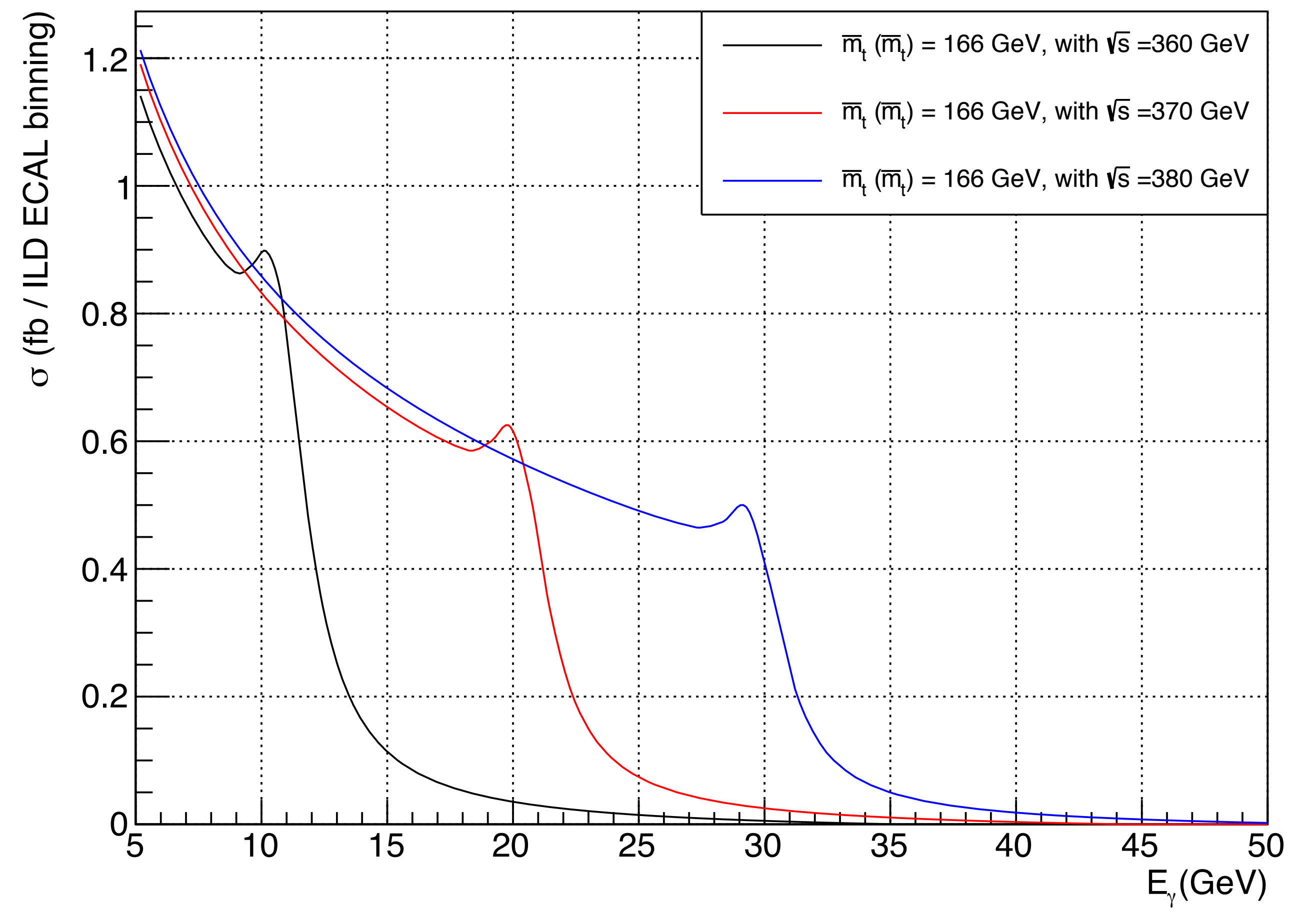
- The observable is defined as the differential cross section of the t t-bar production respect to the remaining energy after the ISR emission

THEORETICAL MODEL

- Factorization theorem by V. Mateu:

$$\sigma_{t\bar{t}\gamma_{ISR}}(\overline{m}_t, s') = \sigma_{ISR}(E_\gamma) * \sigma_{t\bar{t}}(\overline{m}_t, s')$$

- The model convolutes the ISR emission with the t t-bar inclusive cross section.
- State of the art t t-bar calculation, valid in the production threshold and the continuum, by matching:
  - NNLL resummed calculation at the threshold
    - Bound state enhancements included
  - An NNLO calculation in the continuum



- For more information and details on the t t-bar matched calculation:

ANGELIKA WIDL LCWS17 TALK

- The input mass can be chosen to be any short-distance mass scheme, in this case we chose the $\overline{\text{MS}}$ scheme. For the calculation itself the 1S and MSR masses are used.

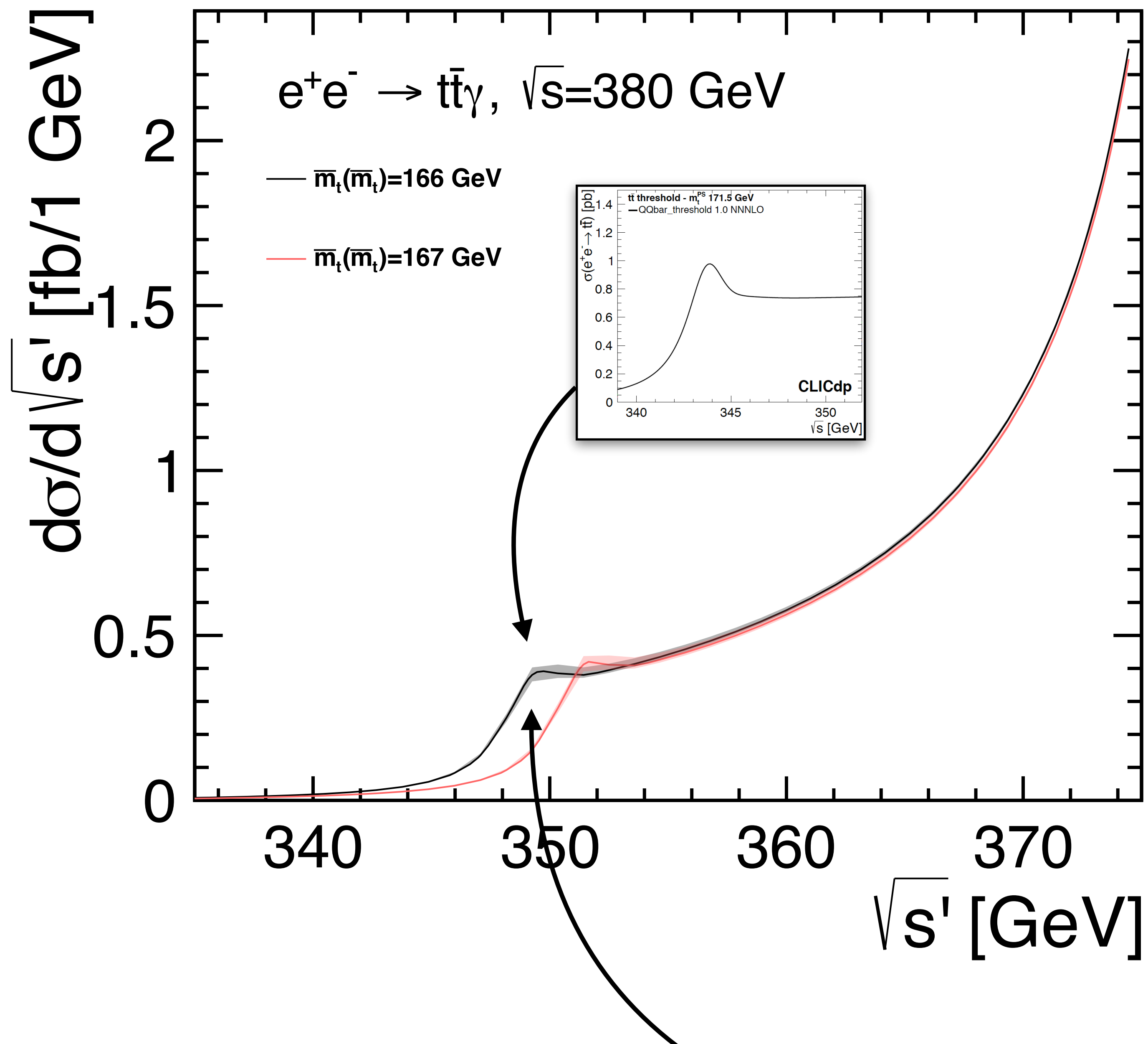
EXPERIMENTAL STRATEGY

- Identify t t-bar events with an ISR photon
- Reconstruct the photon energy
- Translate the photon energy into remaining center of mass energy

$$s' = s\left(1 - \frac{2E_\gamma}{\sqrt{s}}\right)$$

- Count the t t-bar pairs for a given s' binning, measuring

$$\frac{d\sigma_{t\bar{t}\gamma}}{d\sqrt{s'}}$$

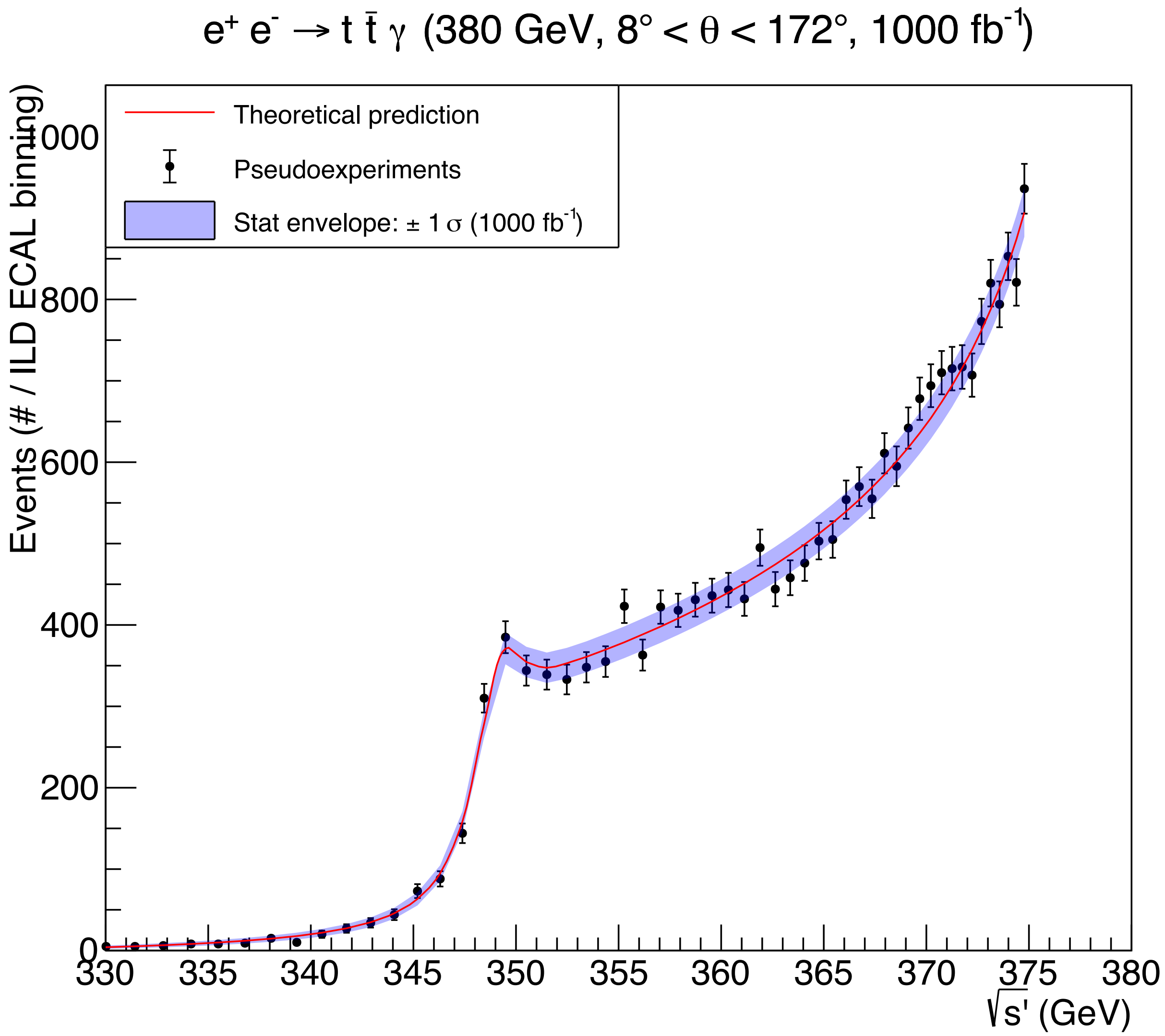


$$E_{\gamma,\max} \simeq \frac{s - 4\overline{m}_t^2}{2\sqrt{s}}$$

- The maximal sensitivity to the mass is reached at the t t-bar production threshold (*radiative return* to the threshold)

POTENTIAL SENSITIVITY TO THE TOP MASS

- Generation of pseudo-experiments by applying poissonian fluctuations around the expected number of events
- ~10000 datasets generated
- Fitting of the pseudo-experiments to the theoretical model with the mass as a free parameter
- The precision is estimated as the mean of the TMinuit uncertainty estimation
  - Which is in good agreement with the fitted mass distribution



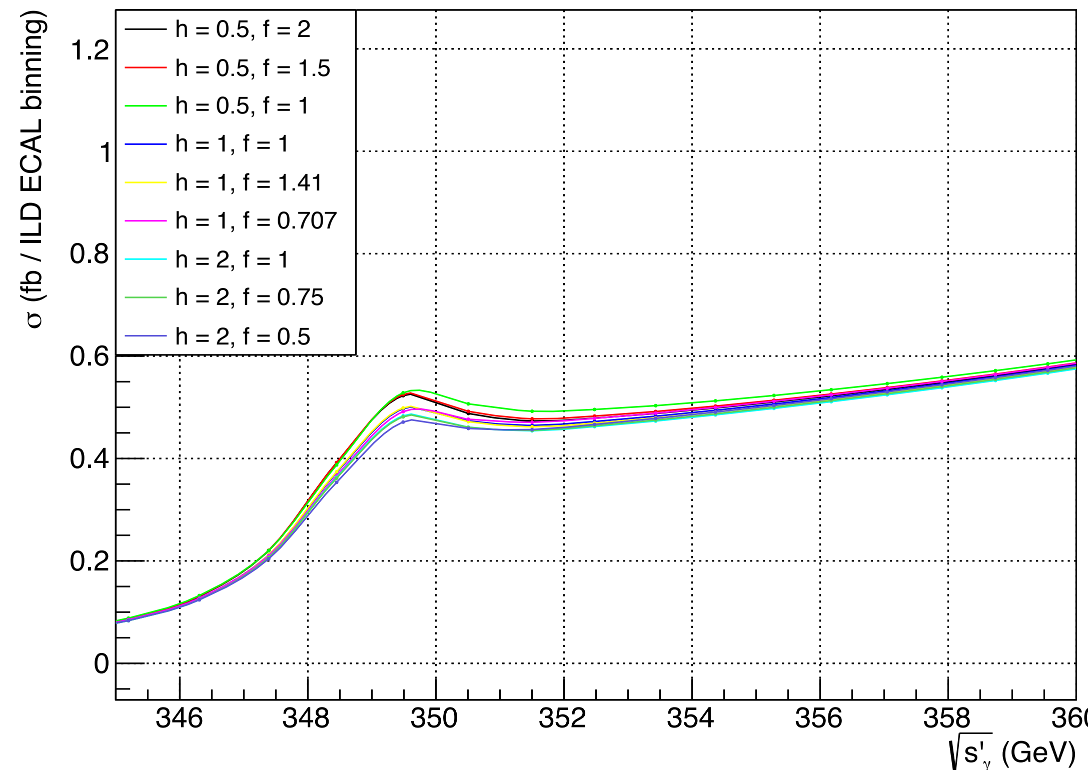
Naive statistical uncertainty estimation		
Nominal energy	**Integrated luminosity**	**Statistical uncertainty**
380 GeV	1000 fb^{-1}	41 MeV
500 GeV	4000 fb^{-1}	64 MeV

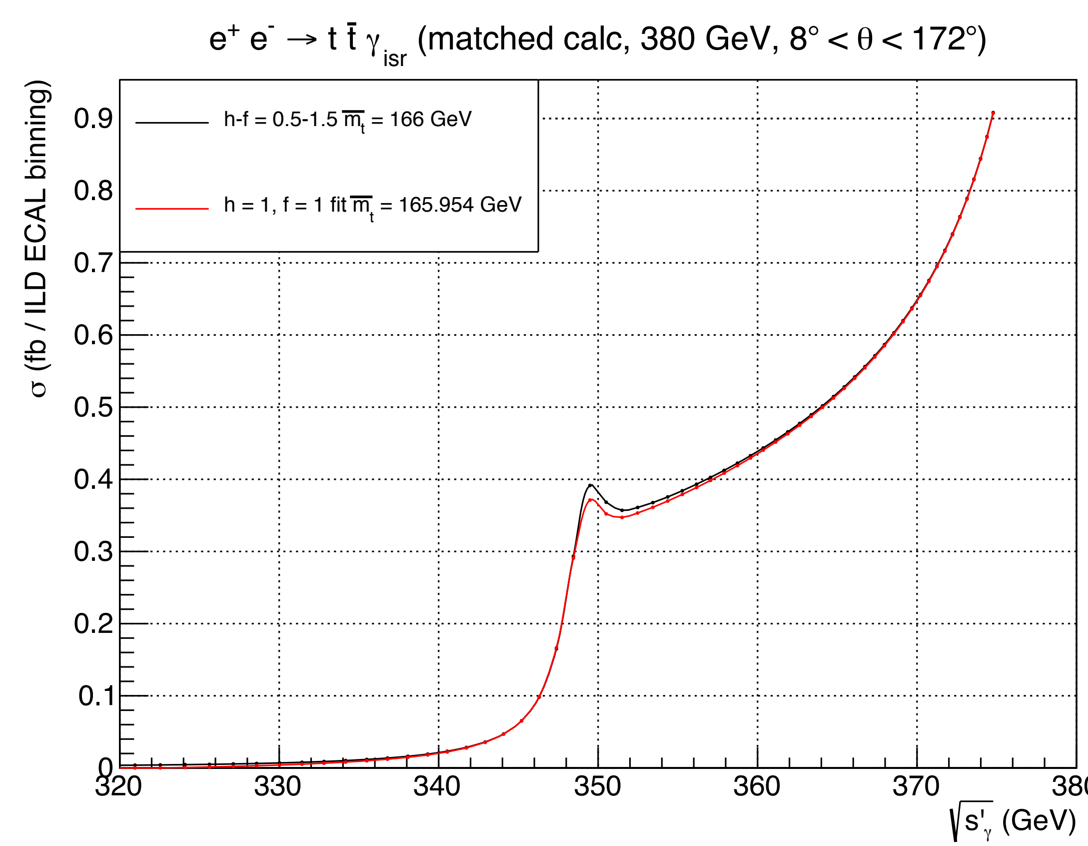
THEORY UNCERTAINTY

- Assess uncertainty due to missing orders via scale variation in the t t-bar matched calculation
- Scales parametrized in *h* and *f* parameters:
  - *h* correspond to the top mass
  - *h f* to the top momentum
  - *h* f^2 to the kinetic energy of the t t-bar pair

Proposed scale parameters variations (A. Hoang , M. Stahlhofen)									
h	1/2	1/2	1/2	1	1	1	2	2	2
f	2	3/2	1	1	√2	√(1/2)	1	3/4	1/2
$\Delta\overline{m}_t$ (MeV) @380 GeV	-44	-46	-43	0	-0.3	8	29	30	45
$\Delta\overline{m}_t$ (MeV) @500 GeV	-55	-58	-54	0	-1.5	12	32	34	51

- Scale variated observables are fitted to the model with nominal (*h* = *f* = 1) scale values, and m_t as a free parameter
- The resulting theory uncertainty is of ± 46 MeV at 380 GeV, and ± 55 MeV at 500 GeV





EXPERIMENTAL UNCERTAINTY

Identification of the t t-bar + ISR events

Reconstruction of the ISR photon

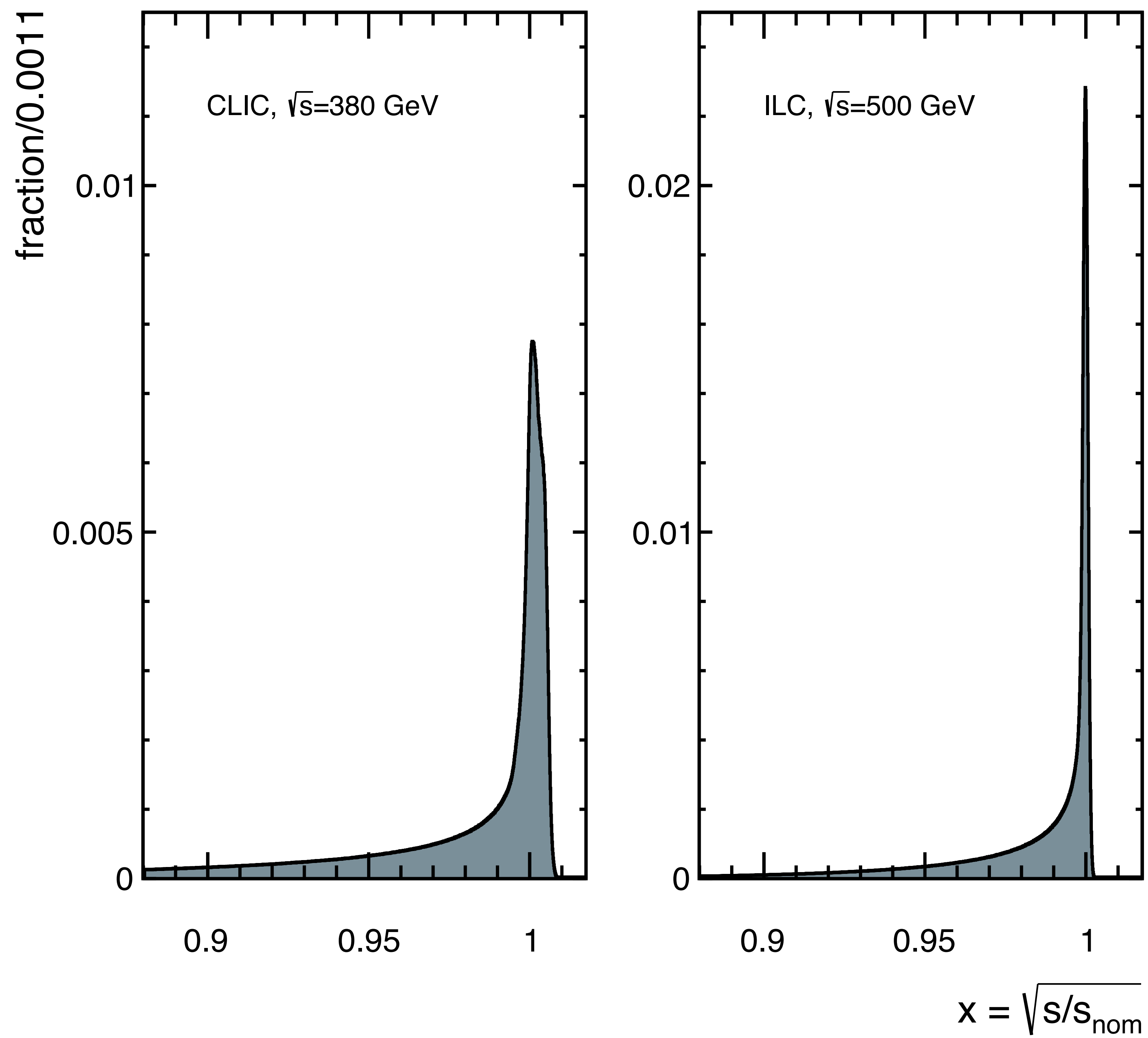
$$\frac{d\sigma_{t\bar{t}\gamma}}{d\sqrt{s'}} \quad \xrightarrow{\text{with}} \quad s' = s\left(1 - \frac{2E_\gamma}{\sqrt{s}}\right)$$

Determination of the collision energy

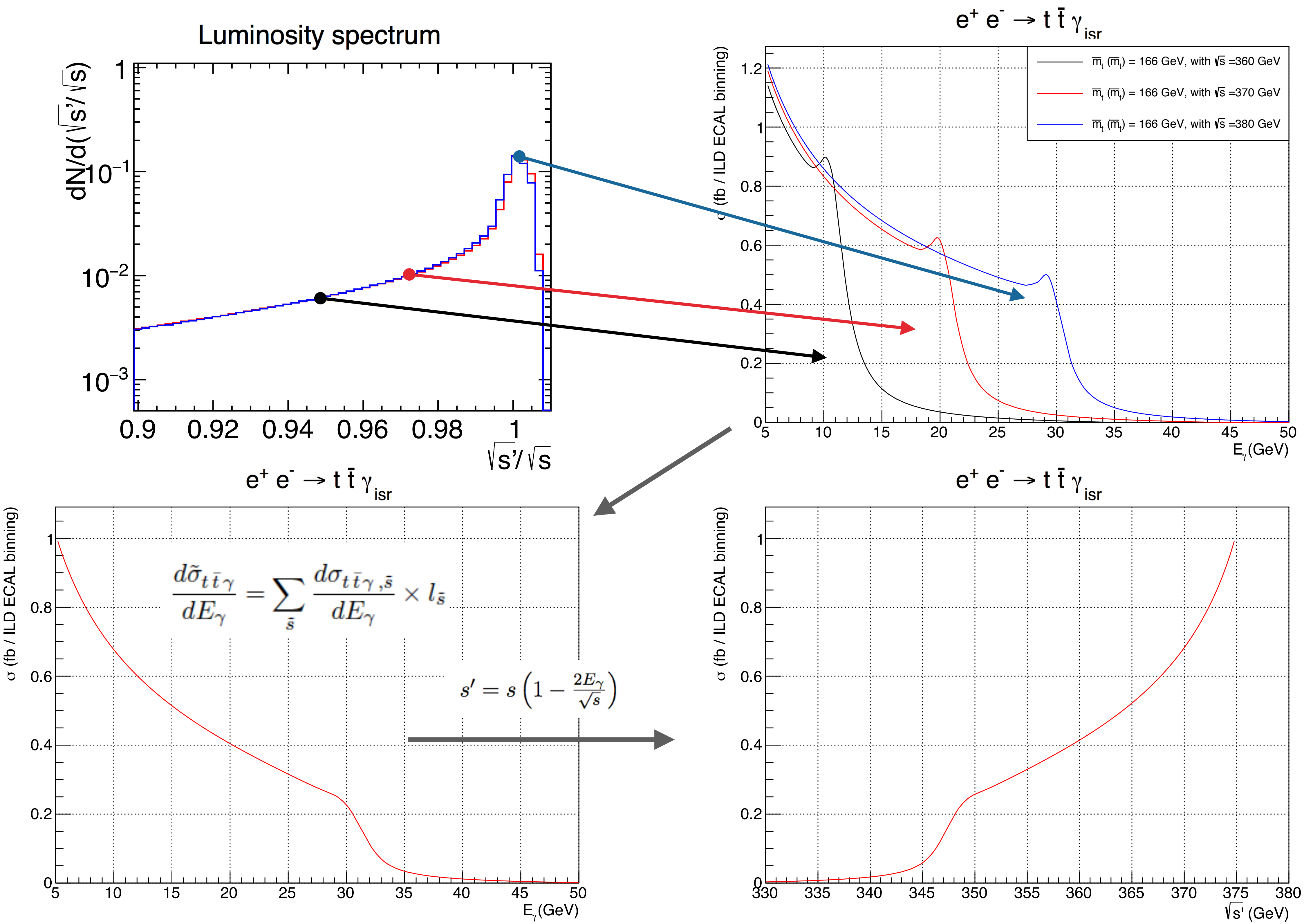
+ statistical uncertainty

LUMINOSITY SPECTRUM

- The centre of mass energy does not correspond to a δ centered at $\sqrt{s}$
- The collision energy is affected by
  - Beam energy spread
  - Beamstrahlung
- The actual collision energy is described by the luminosity spectrum



REDEFINITION OF THE OBSERVABLE



$$\frac{d\tilde{\sigma}_{t\bar{t}\gamma}}{dE_\gamma} = \sum_{\bar{s}} \frac{d\sigma_{t\bar{t}\gamma,\bar{s}}}{dE_\gamma} \times l_{\bar{s}}$$

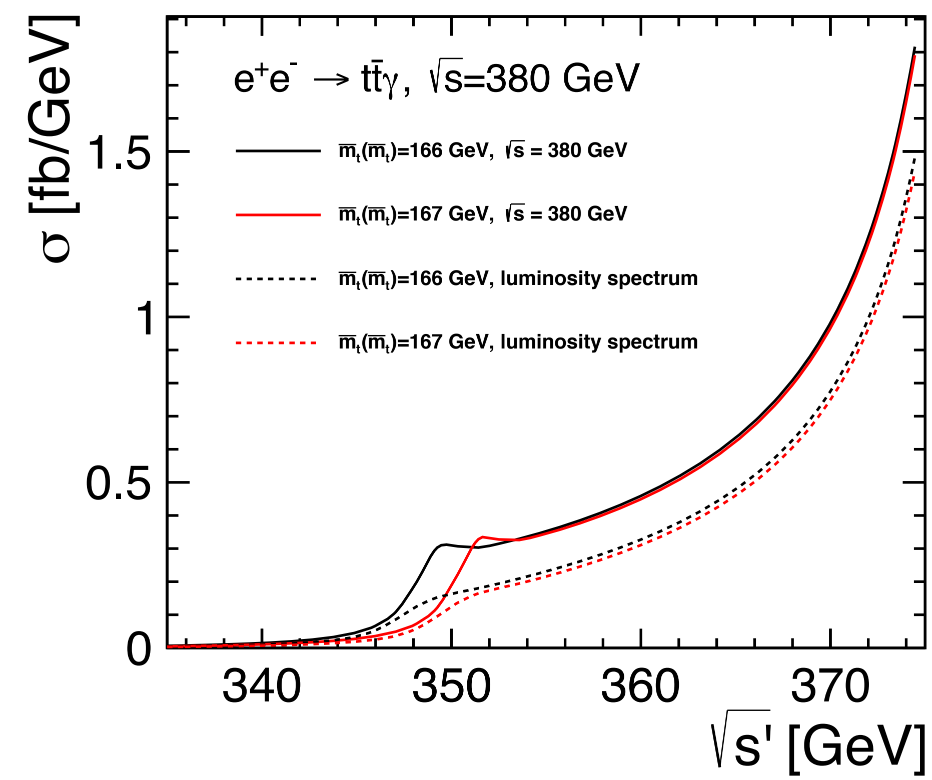
$$s' = s\left(1 - \frac{2E_\gamma}{\sqrt{s}}\right)$$

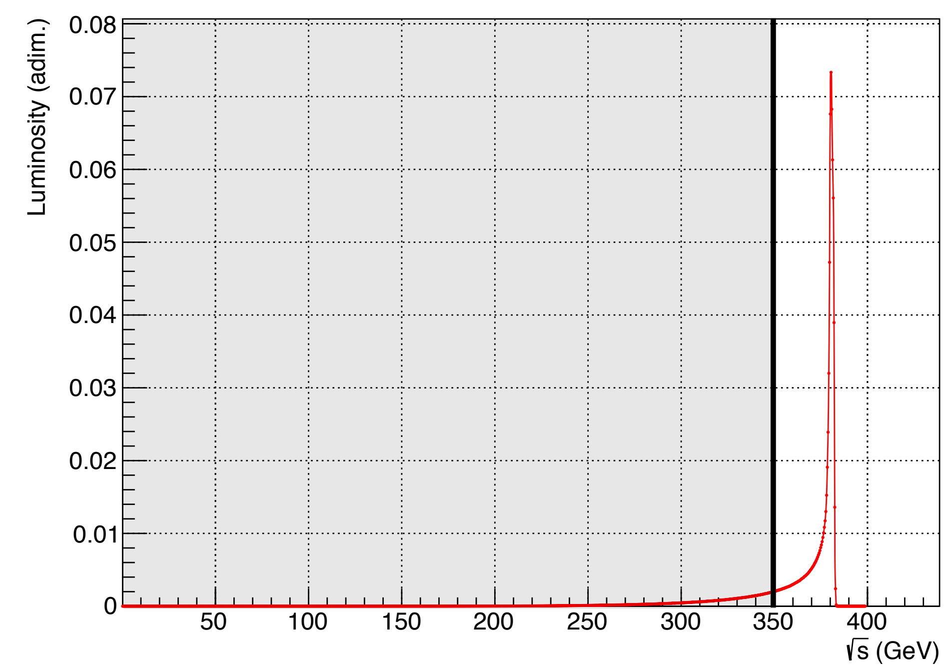
IMPACT OF THE LUMINOSITY SPECTRUM

- When weighting the observable by the luminosity spectrum two things happen:
  - A loss of statistics due to collisions under the t t-bar threshold
  - A change in the shape of the observable that reduces its sensitivity to the top mass
- Repeating the naive statistical estimation, a ~50% deterioration in the sensitivity is found

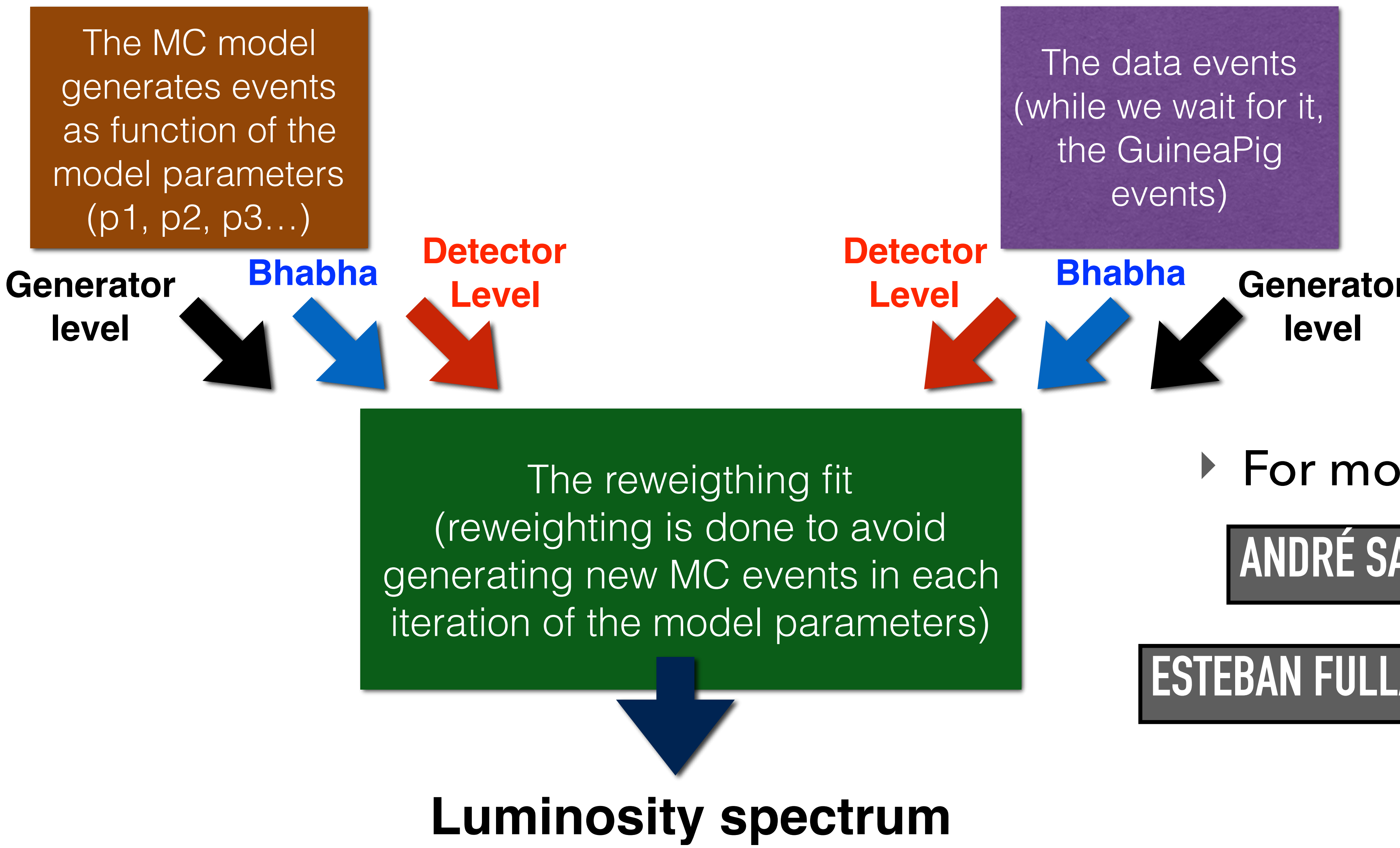
Naive statistical uncertainty estimation	
$1000\ fb^{-1}$	Statistical uncertainty
380 GeV (δ spectrum)	41 MeV
CLIC @ 380 GeV	65 MeV

- Work in progress: a method to recover the shape previous to the luminosity spectrum weighting.





MODELING THE LUMINOSITY SPECTRUM



- For more information:

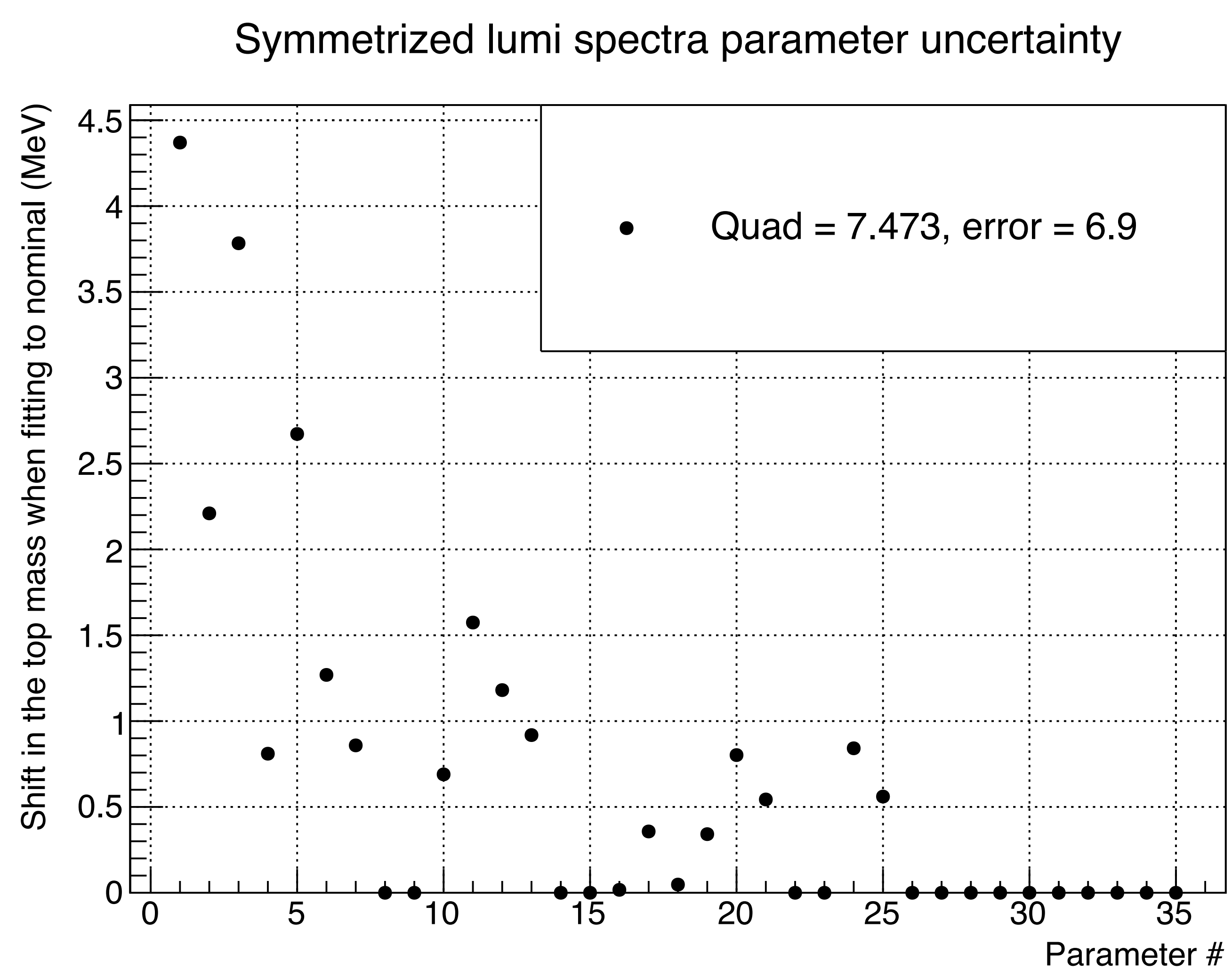
ANDRÉ SAILER'S PHD THESIS

ESTEBAN FULLANA TOP@LC 2017 TALK

- The MC model reproduces the 4-momenta of the $e^+ e^-$ pairs.
- 19 free parameters, optimisation done minimising χ^2 respect to the detector smeared data.
- 3 stages: GuineaPig beam generator, Bhabha scattering simulator and detector simulator.

LUMINOSITY UNCERTAINTY PROPAGATION

- Reconstructing the luminosity spectrum, 19 parameters with their error are obtained (+correlations between them)
- Generating 38 observables within the parameter ± error and fitting them to the *nominal* weighted observable, the error of each parameter is propagated



- The total uncertainty is calculated by performing

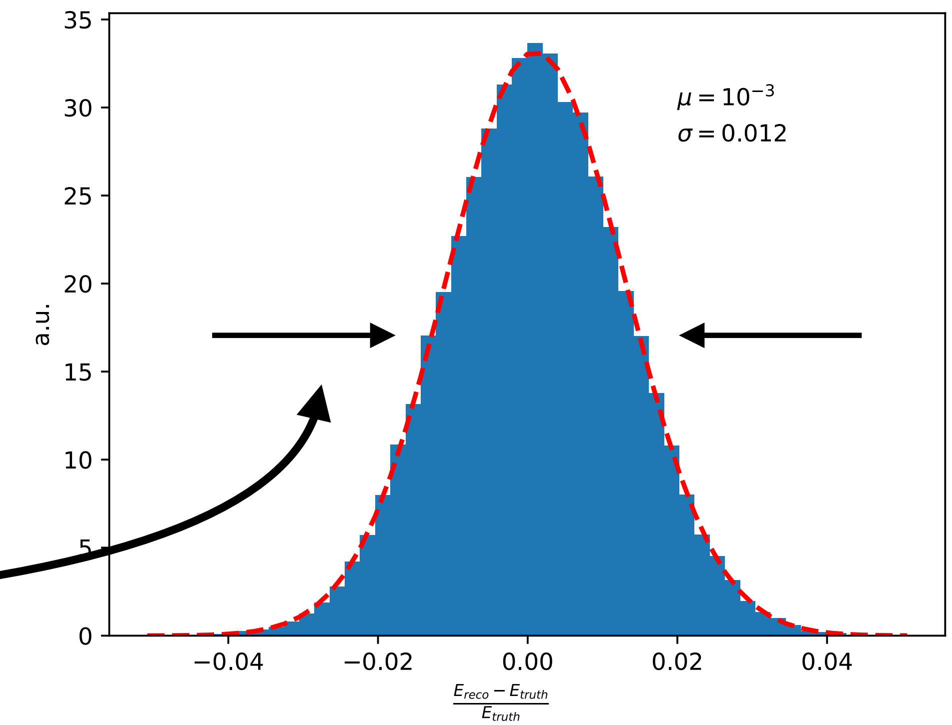
$$E = E_p \, Cov \, E_p^T.$$

- A total propagated uncertainty of ±7 MeV is estimated

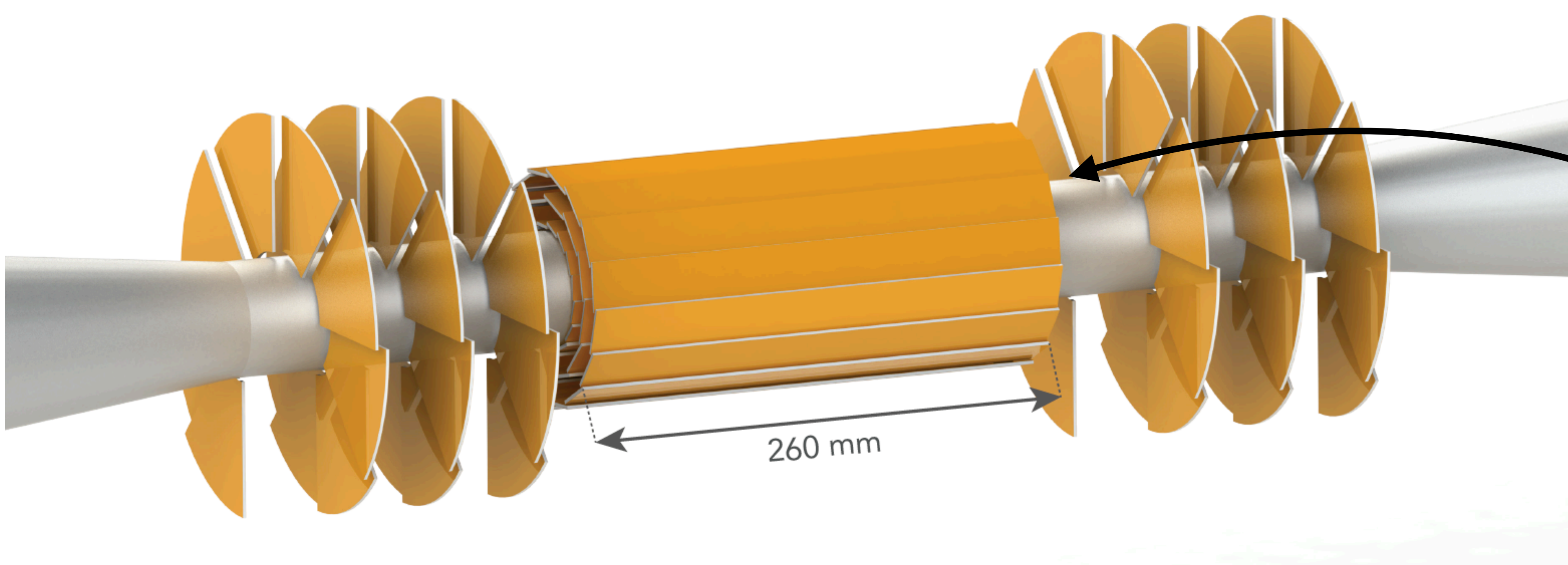
PHOTON RECONSTRUCTION

Two major concerns over photon reconstruction

- Detector coverage → limit acceptance
- Reconstruction of the photon energy
  - Energy resolution → adopt it in the binning
  - Photon energy scale (calibration offset)



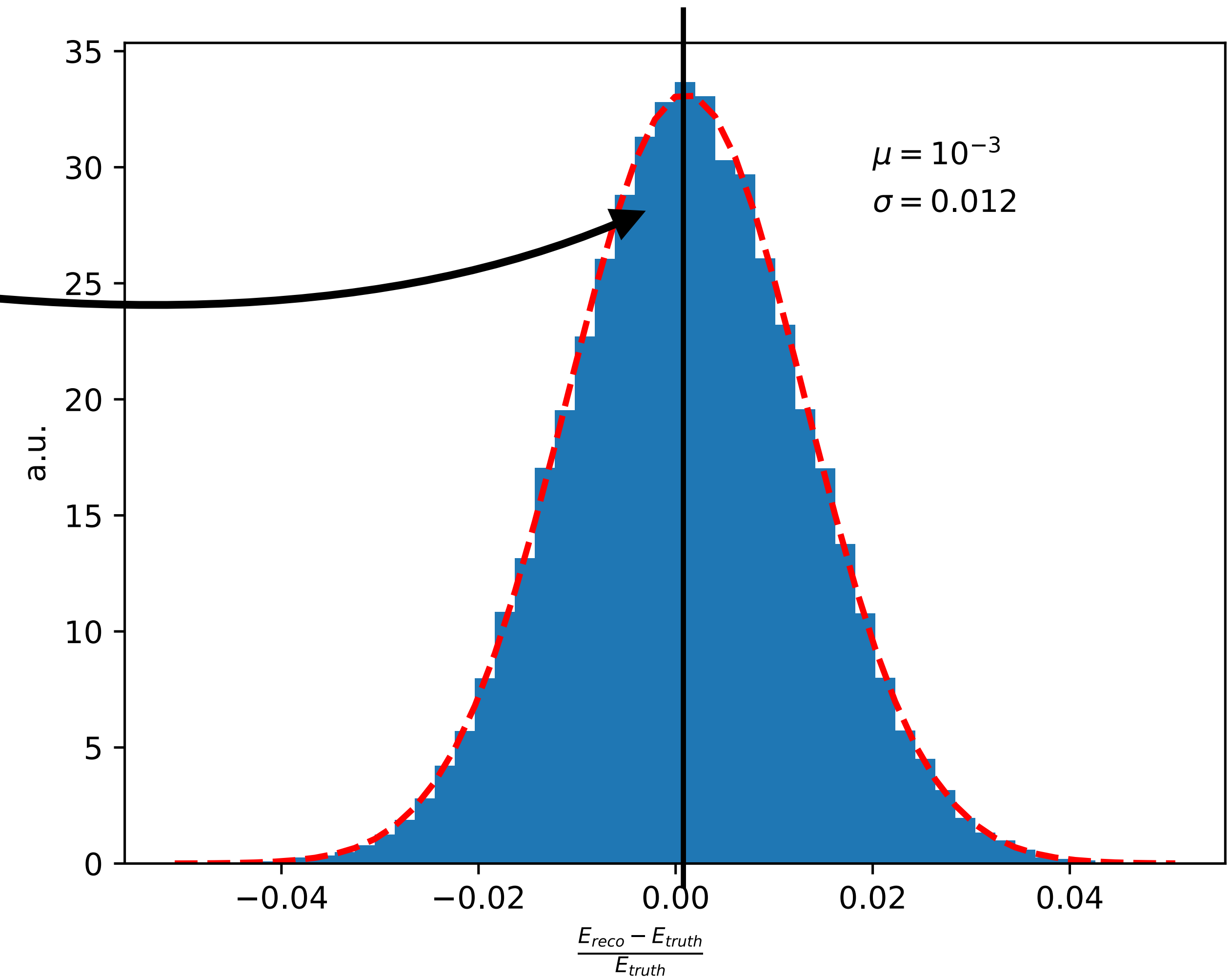
$$\sigma/E = 0.166/\sqrt{E} \oplus 1.1\,\%$$



$$8^\circ < \theta < 172^\circ$$

PHOTON ENERGY SCALE UNCERTAINTY

The calibration is not exact, the reconstructed energy is usually over or underestimated by a tiny amount

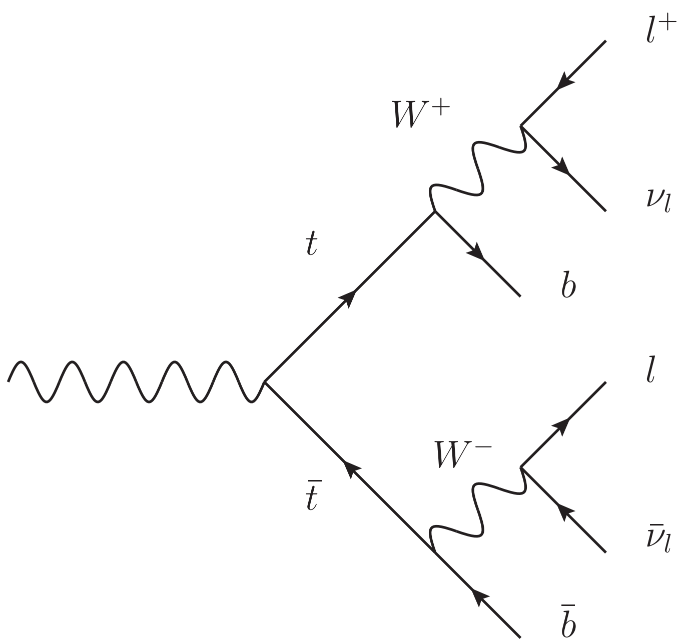


- Propagate the uncertainty by over(under)-estimating the photon energy in the observable
  - Fit to the *nominal* model with m_t as a free parameter

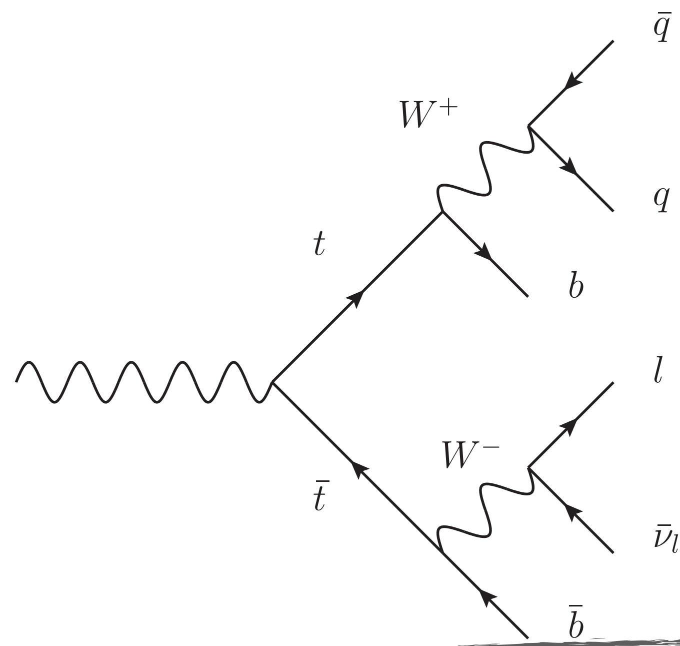
$\overline{m}_t$ shift for different photon energy scale uncertainties			
Nominal energy	**10^{-2} (1%)**	**10^{-3} (0.1%)**	**10^{-4} (0.01%)**
380 GeV	+157 - 160 MeV	± 16 MeV	± 1.6 MeV
500 GeV	+842 - 863 MeV	± 85 MeV	± 9 MeV

feasible today

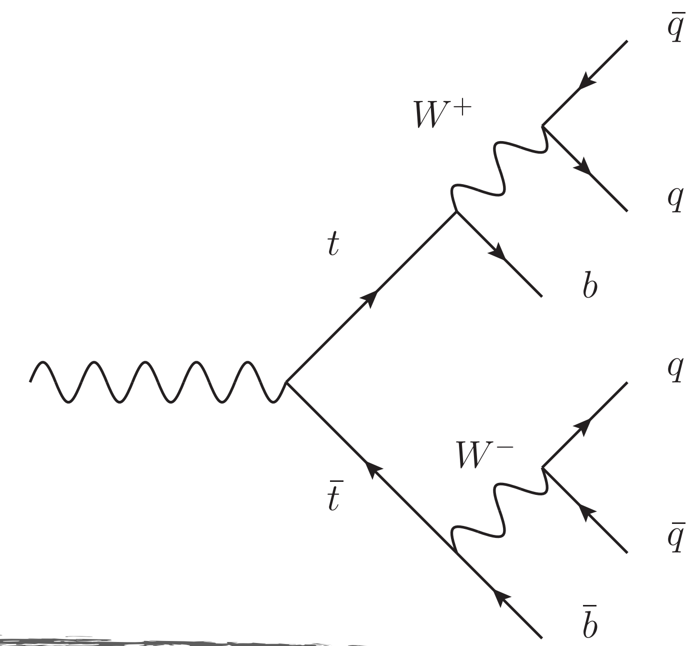
EVENT SELECTION: TOPS



Full leptonic (9%)



Semi-leptonic (45%)



Fully hadronic (46%)

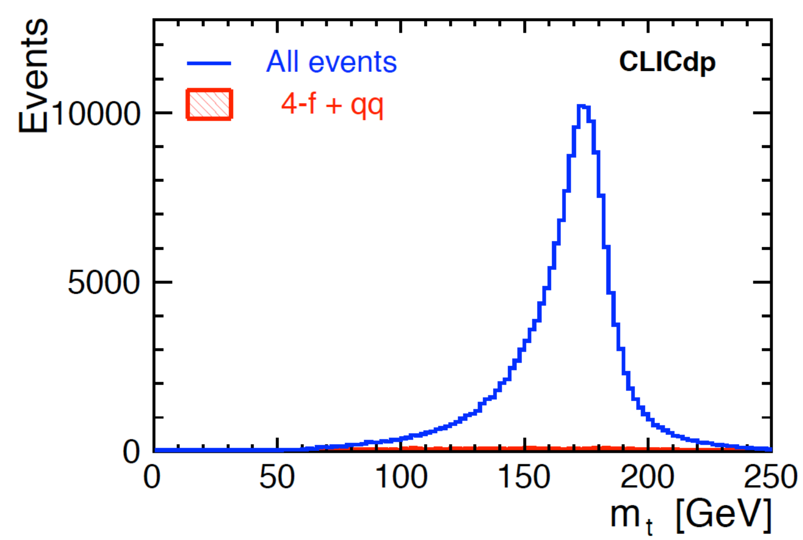
Selection efficiencies estimated at full simulation

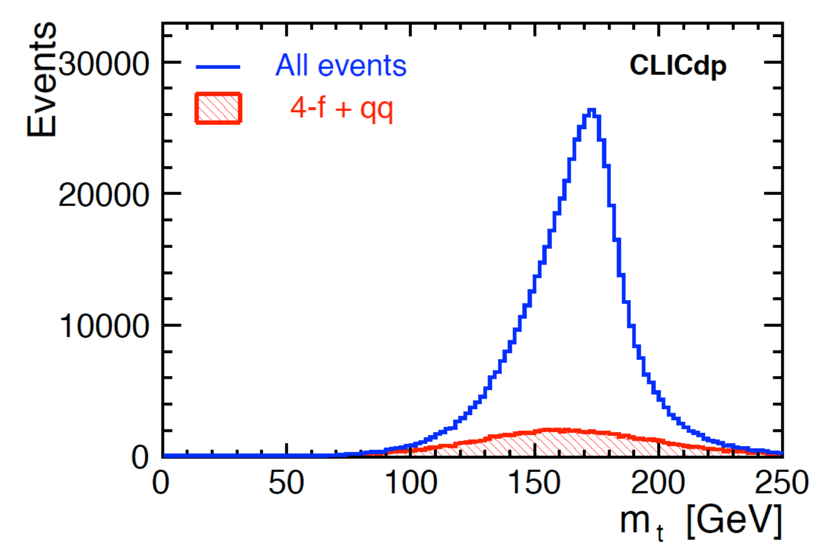
- Threshold scan study

  70.2%

- Boosted decision tree

  ~90%





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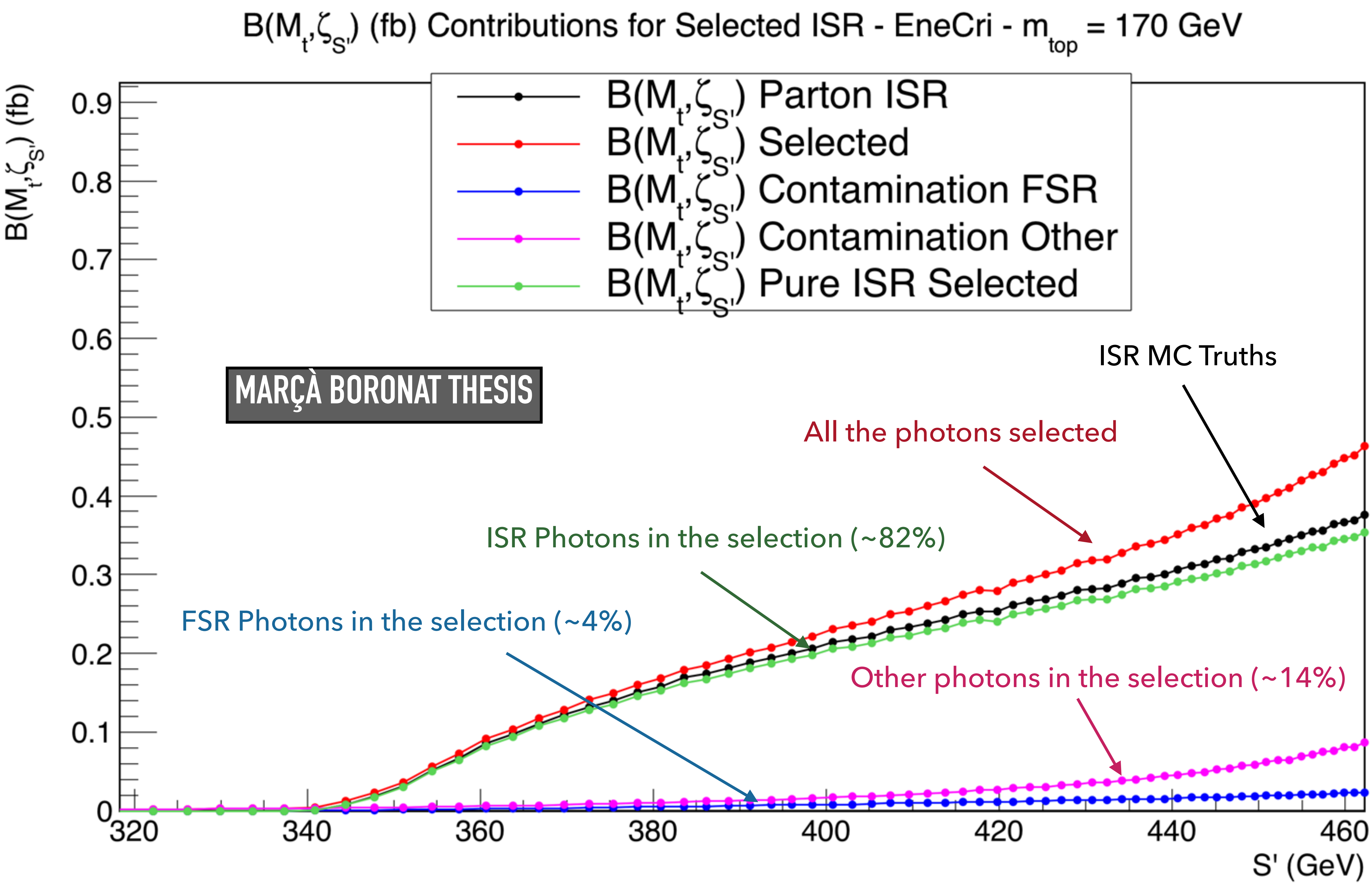
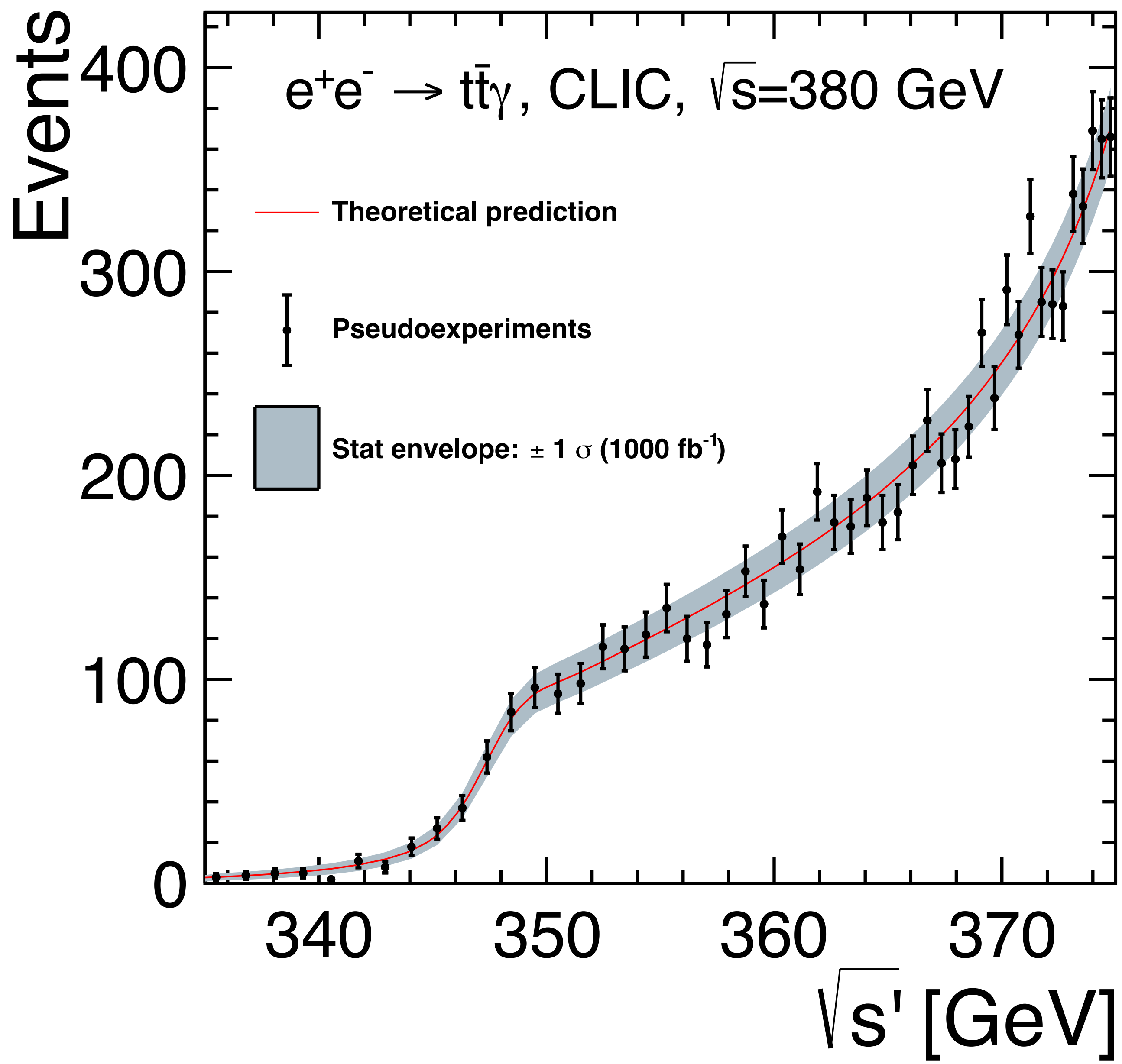
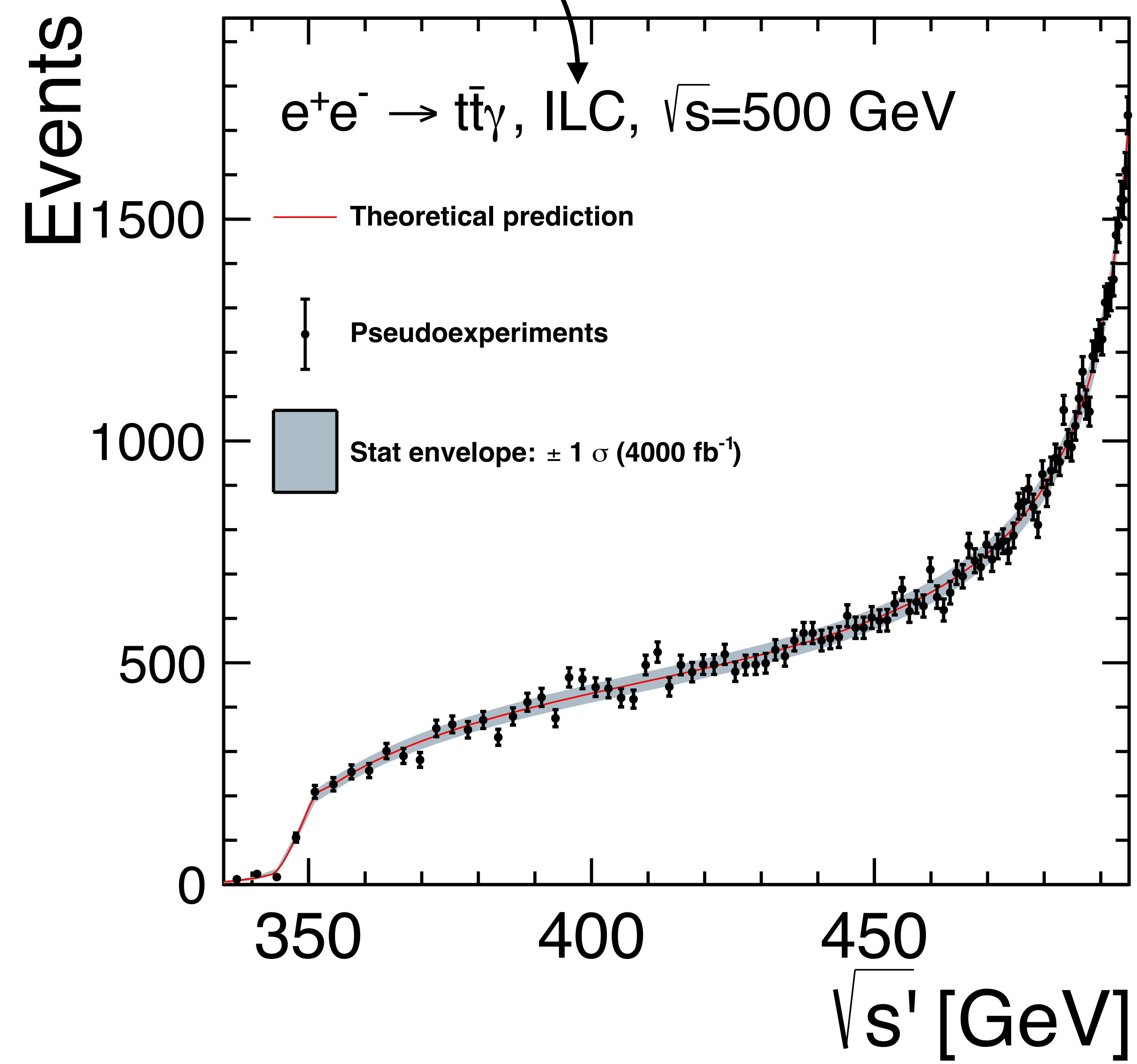
EVENT SELECTION: ISR PHOTONS



STATISTICAL UNCERTAINTY

24% bump in the statistics
due to beam polarisation





ECAL binning, 50% efficiency and luminosity spectrum accounted for

RESULTS SUMMARY

50% efficiency, ECAL resolution, luminosity spectrum and beam polarisation accounted

Experiment	CLIC, $\sqrt{s} = 380$ GeV		ILC, $\sqrt{s} = 500$ GeV	
L_{int} (fb^{-1})	500	1000	500	4000
Statistical	138 MeV	93 MeV	348 MeV	109 MeV
Theory	46 MeV		55 MeV	
Luminosity spectrum	7 MeV		7 MeV*	
Photon energy scale	16 MeV		85 MeV	
Total	147 MeV	105 MeV	363 MeV	149 MeV

Potential to measure $\overline{m}_t$ with 100-150 MeV precision for the nominal luminosities at CLIC and ILC

SUMMARY

- A new observable to measure the top quark mass with high precision in the continuum of a e^+e^- collider has been introduced
- A state of the art theoretical calculation was performed to assess the potential of the observable in a well defined theoretical framework
- The major sources of uncertainties were explored, including
  - Theory uncertainty
  - Photon reconstruction
  - Event selection
  - Luminosity spectrum
- Measurements in the order of 100 to 150 MeV are achievable for CLIC and ILC respectively for their 380 GeV and 500 GeV runs.

THE WAY FORWARD

- The ISR emission is usually collinear to the emitter → extend the polar angle range of the analysis by including forward calorimeters
  - Going down from 8° to 6° increases statistics by a 33%
  - Going down from 8° to 4° would double the statistics
- Inclusion of the FSR from the top anti-top pair
  - Similar sensitivity to the top quark mass when compared with ISR
- Progress in the theory calculation to bring the uncertainty down
- Potential to measure the running of $\overline{m}_t$, as the measurement can be performed at different scales

THANKS FOR YOUR ATTENTION

¿Dudas? ¿Comentarios?