TOP MASS AT FUTURE LINEAR COLLIDERS

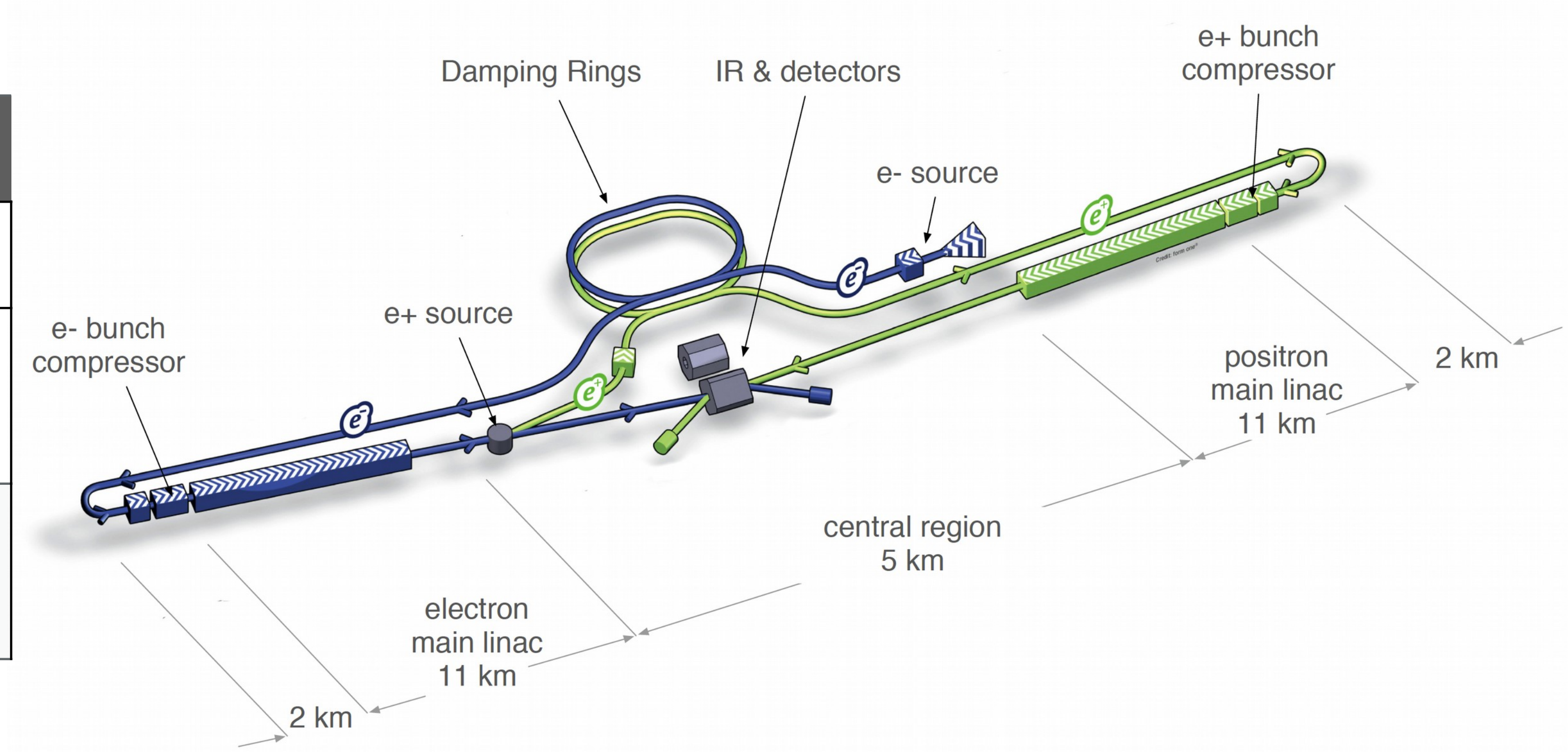
M. BORONAT*, E. FULLANA*, J. FUSTER*, P. GOMIS*,
A. H. HOANGº, V. MATEU+, M. VOS*, A. WIDLº
* IFIC (UNIVERSITAT DE VALÈNCIA/CSIC)
+ UNIVERSIDAD DE SALAMANCA
º UNIVERSITÄT WIEN

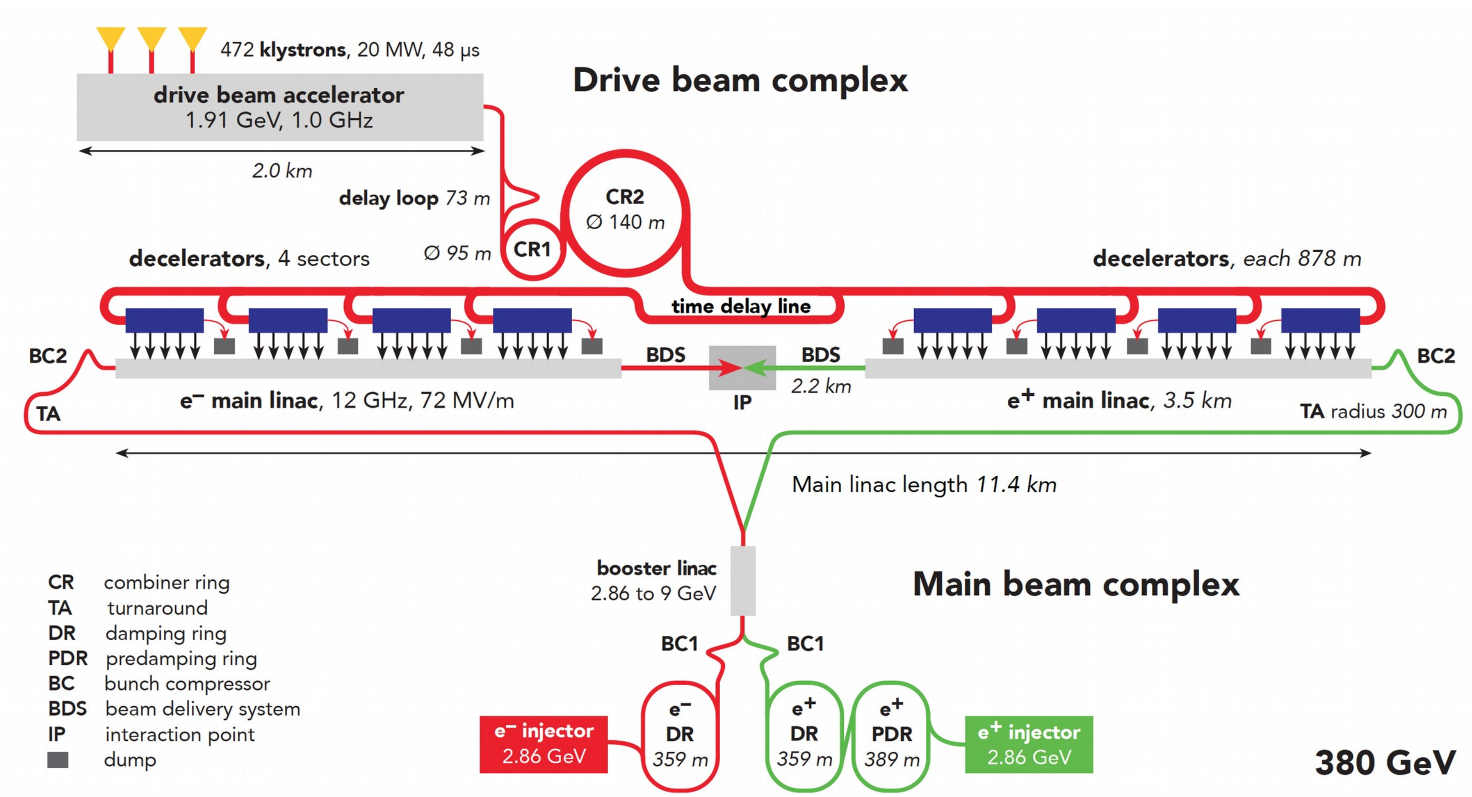
CONTENT

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

e$^+$e$^-$ LINEAR COLLIDER SCENARIOS

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

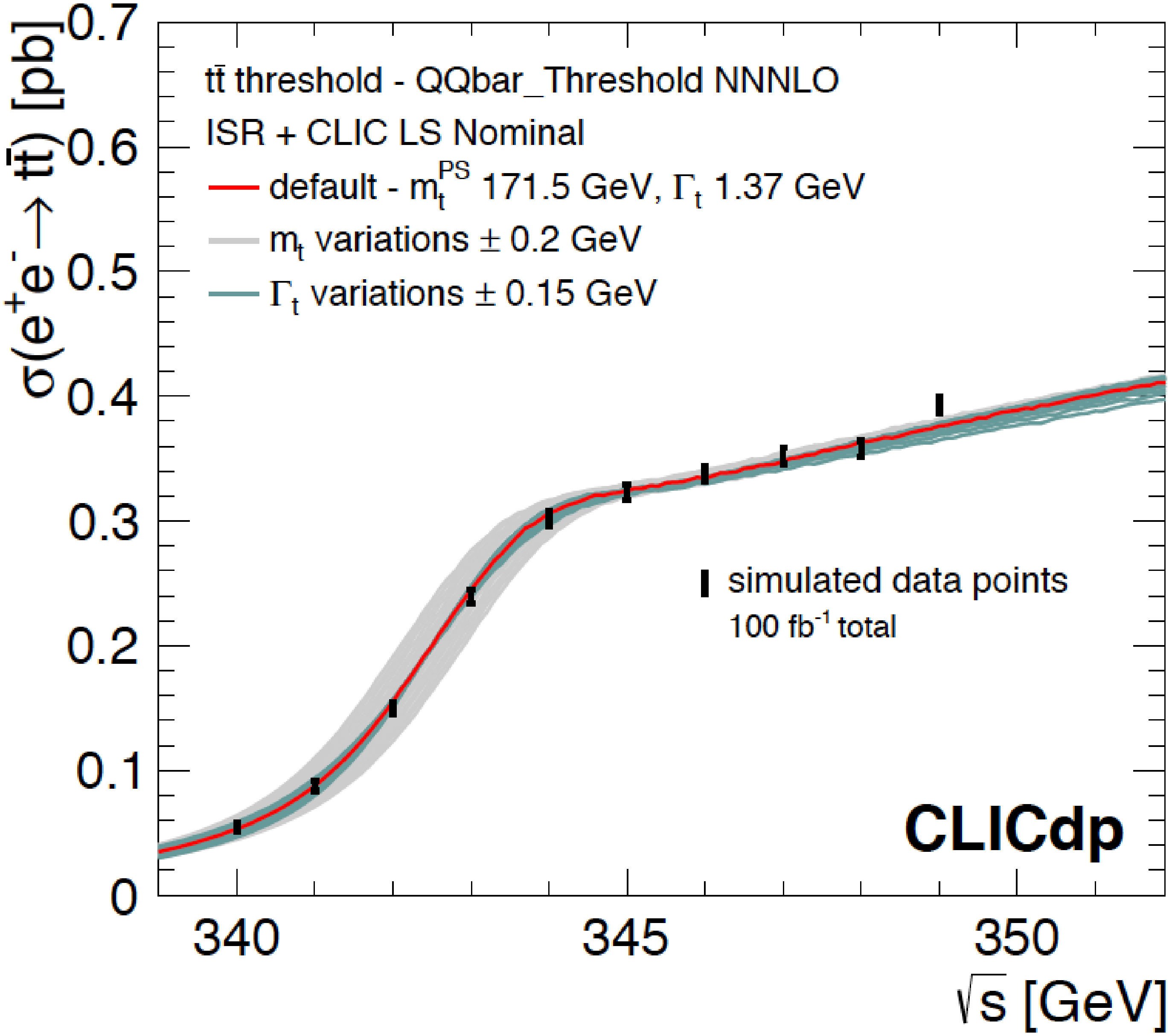




Compact Linear Collider	
Stage	Integrated luminosity
Stage I @ 380 GeV	1000 fb^{-1}
Stage II @ 1500 GeV	3000 fb^{-1}
Stage III @ 3000 GeV	5000 fb^{-1}

TOP QUARK THRESHOLD SCAN

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

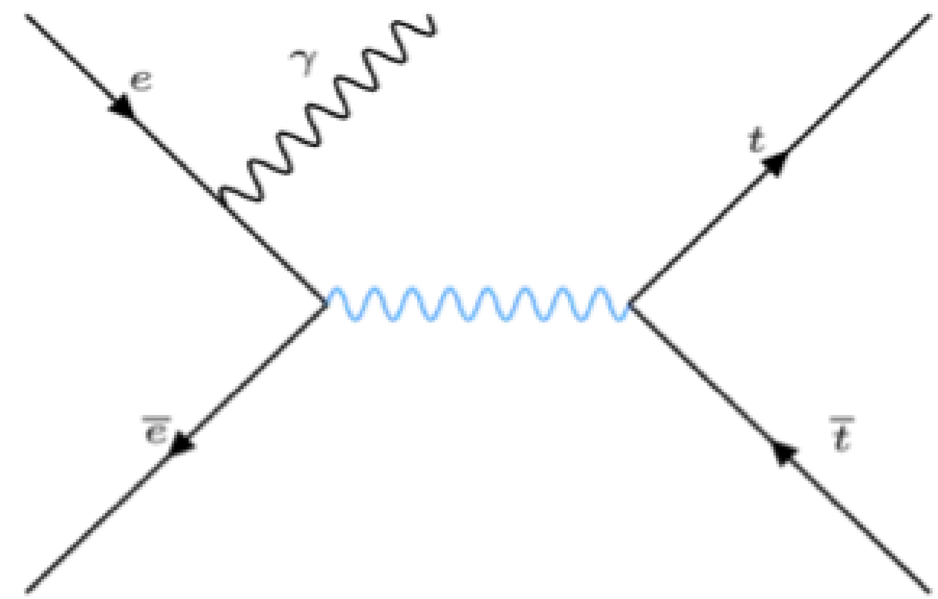


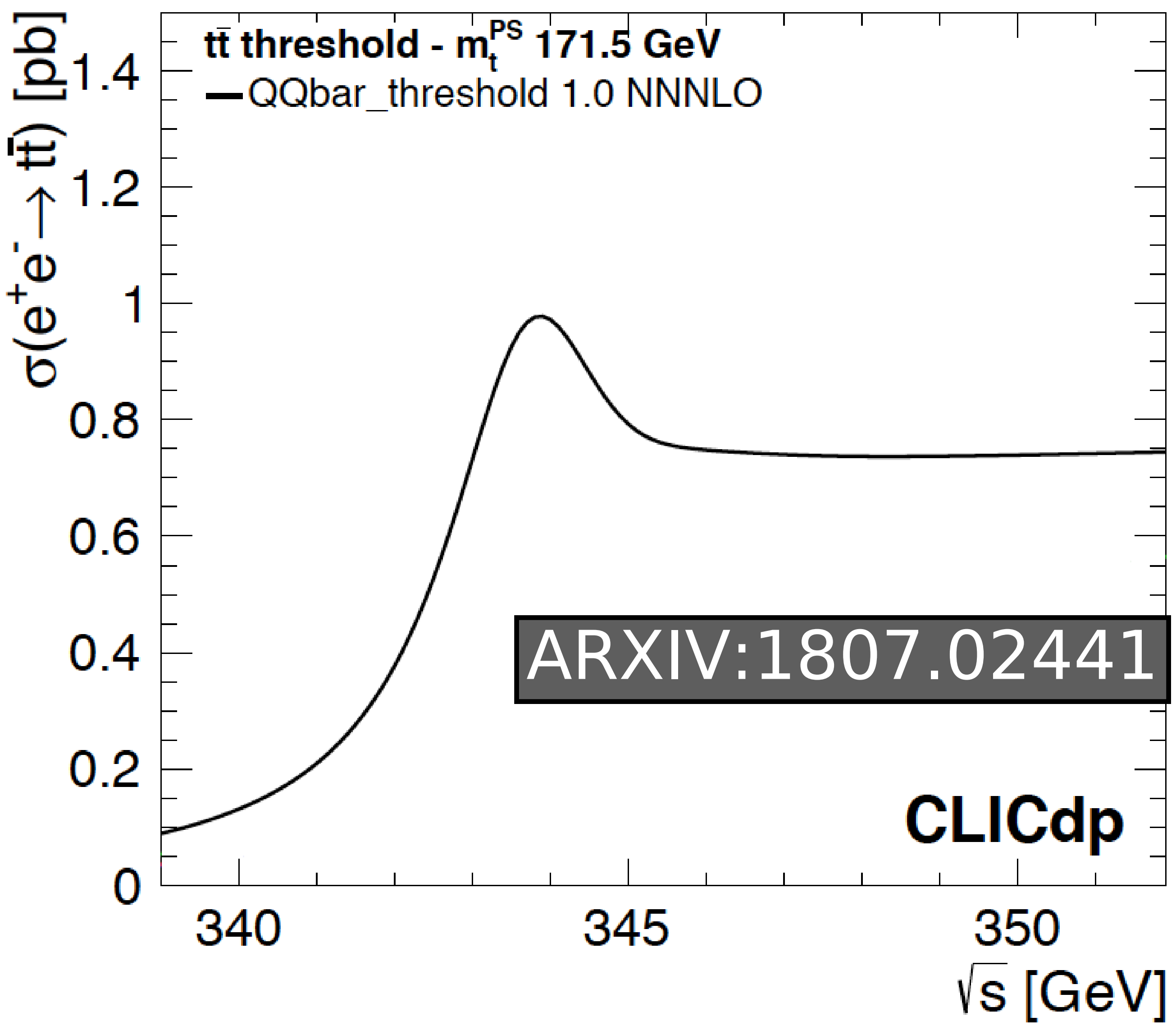
Uncertainties estimation	
Uncertainty	Δm_t^{PS} (MeV)
Statistical @ 100 fb^{-1}	± 22
Experimental systematics	± 25 ~ 50
Theoretical systematics	± 30 ~ 50
Overall	± 45 ~ 75

ARXIV:1807,02441

A NEW OBSERVABLE

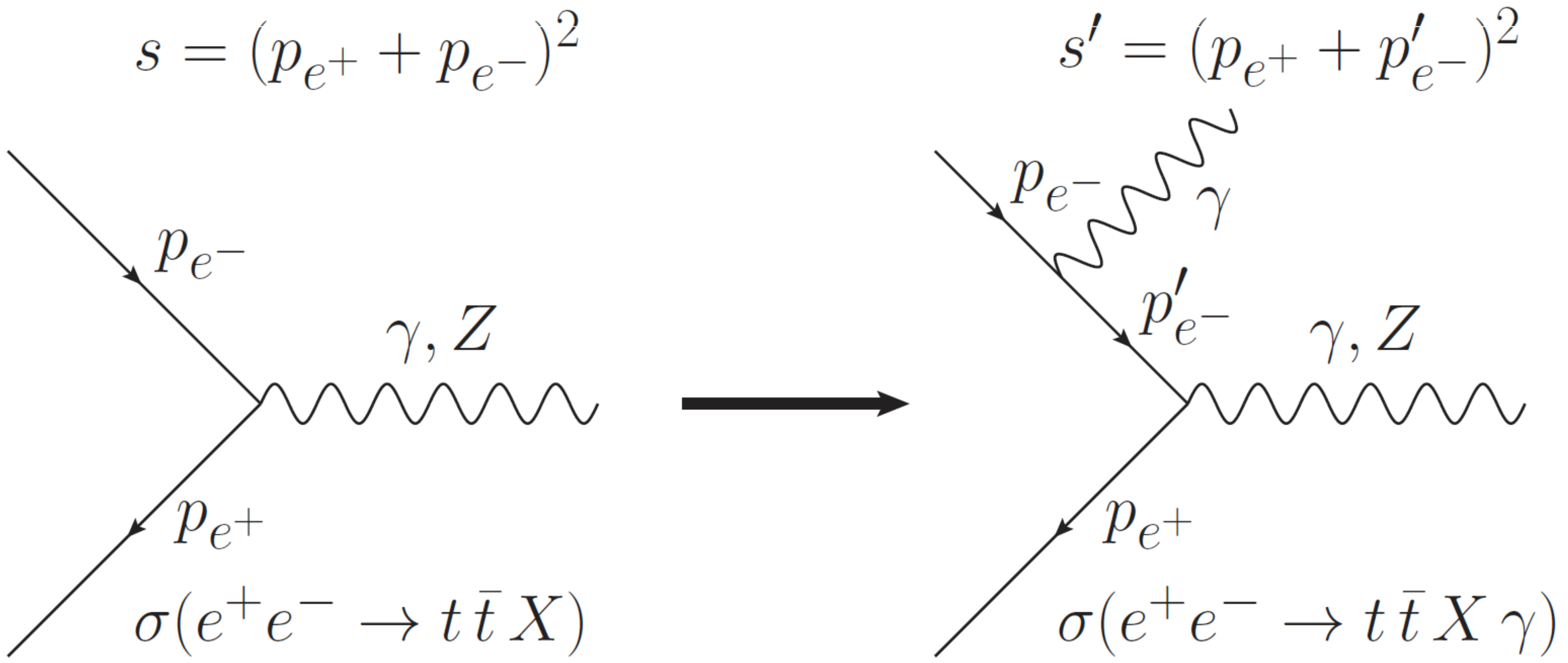
- Measure the top-quark mass in $e^+e^- \to t\bar{t}\gamma_{\rm ISR}$ events





- Pair production x-section depends strongly on the production energy
- A hard ISR hard photon carries away energy (return-to-the-threshold)

OBSERVABLE DEFINITION



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

with

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

- Measure differential cross section as a function of invariant mass of the tt system (after the ISR emission)

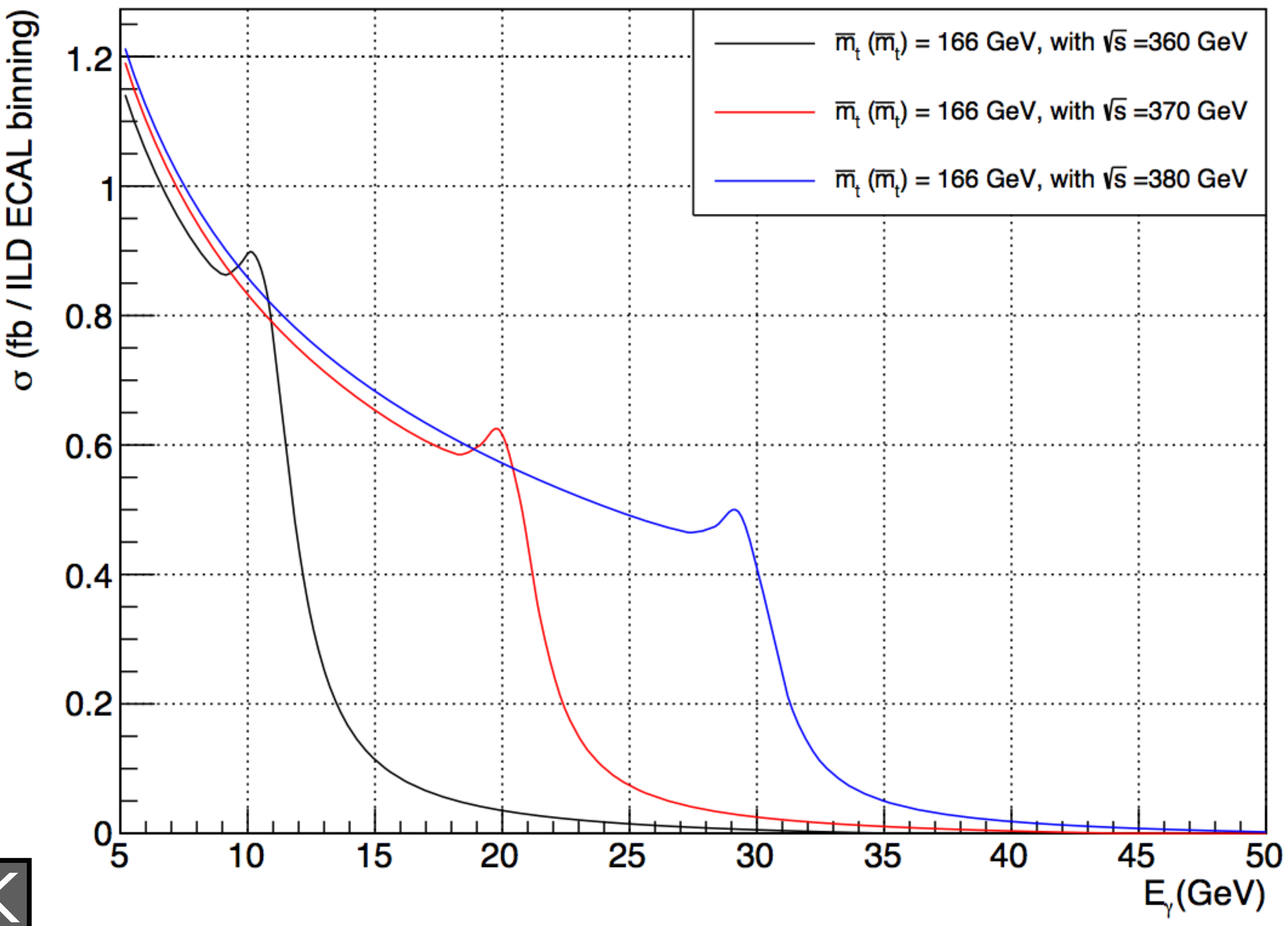
THEORETICAL MODEL

- Factorization theorem by V. Mateu:

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

- convolute the ISR emission with the tt inclusive cross section.
- Matched calculation for $e^+e^- \rightarrow$ tt:
  - NNLL resummation at threshold
  - Fixed-order NNLO in the continuum

ANGELIKA WIDL's LCWS17 TALK



- Mass is specified in the $\overline{\text{MS}}$ scheme. Internally, the 1S and MSR mass are used.
- $m_t = m_t^{\overline{MS}}(m_t^{\overline{MS}})$ [high energy],
- m_t^{1S} [threshold region],
- m_t^{MSR}(10 GeV < R< $\overline{m}_t$) [intermediate region]

EXPERIMENTAL STRATEGY

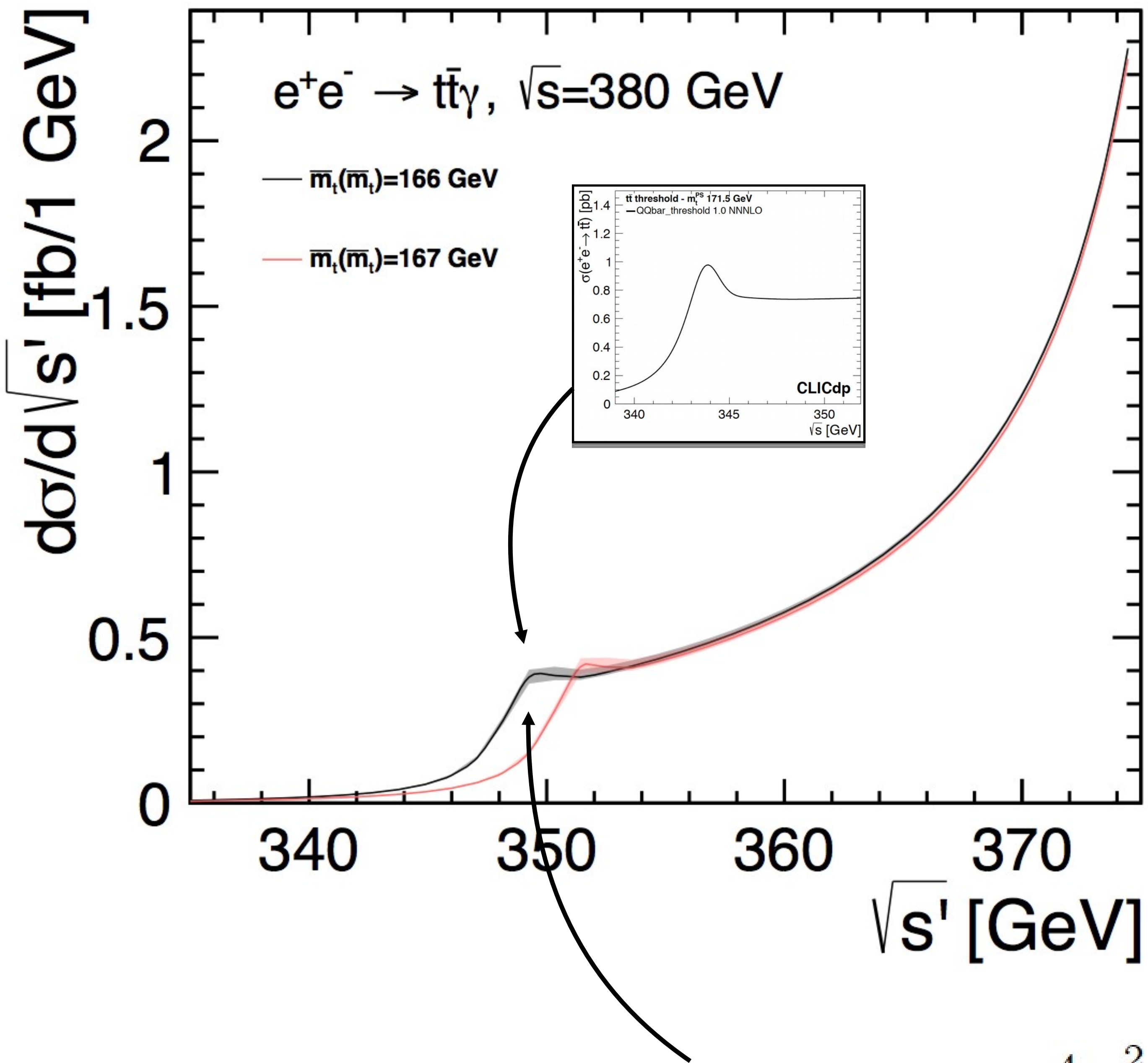
- Select tt events with a hard ISR photon
- Reconstruct the photon energy
- Calculate inv. mass of tt system

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

- Measure differential x-section:

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

- Maximum sensitivity at threshold



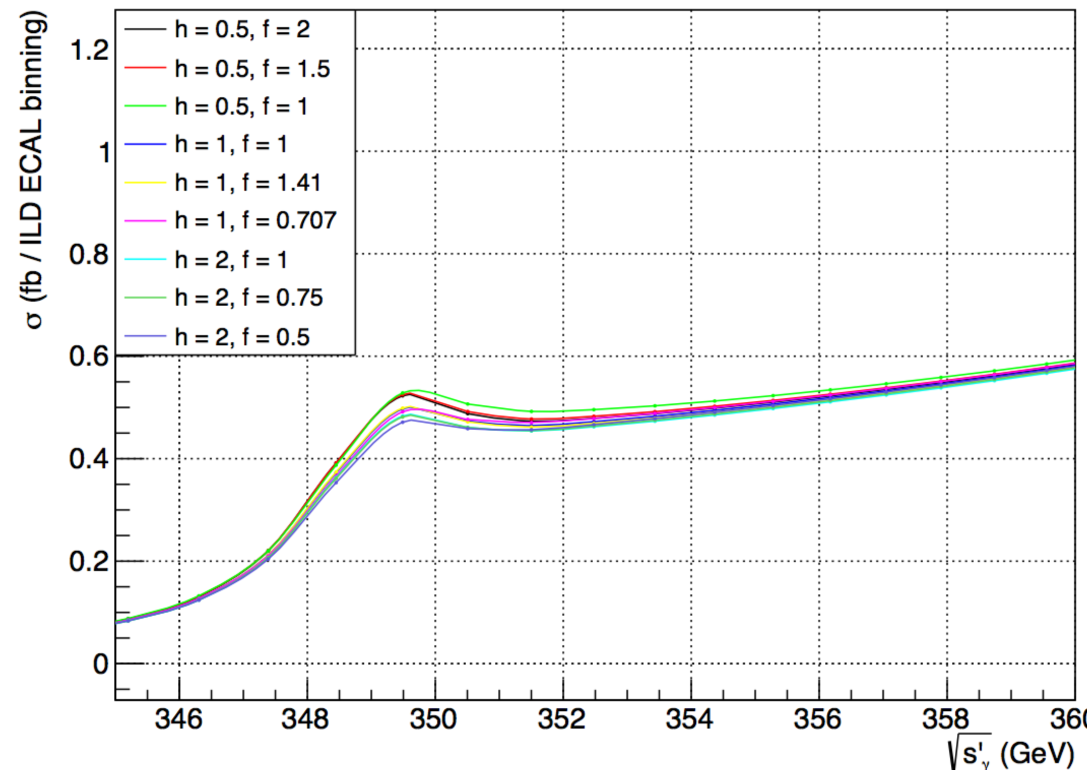
$$E_{\gamma,\max} \simeq \frac{s - 4m_t^2}{2\sqrt{s}}$$

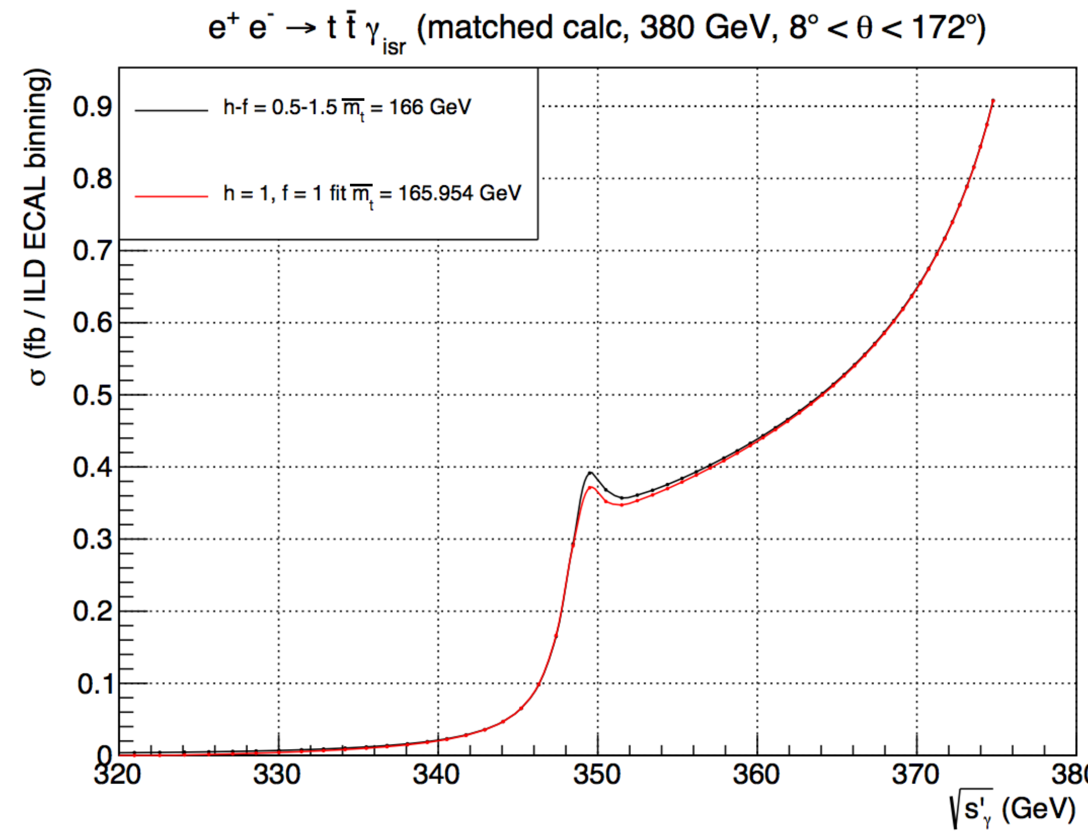
THEORY UNCERTAINTY

- Assess uncertainty due to missing orders by varying hard, soft and ultra-soft scales in the calculation
- Parametrized with 2 parameters: *h* and *f*

arXiv:1309.6323

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
Δm_t (MeV) @380 GeV	-44	-46	-43	0	-0.3	8	29	30	45
Δm_t (MeV) @500 GeV	-55	-58	-54	0	-1.5	12	32	34	51





- Fit to the model with nominal (*h* = *f* = 1) scale values, with 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

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

with

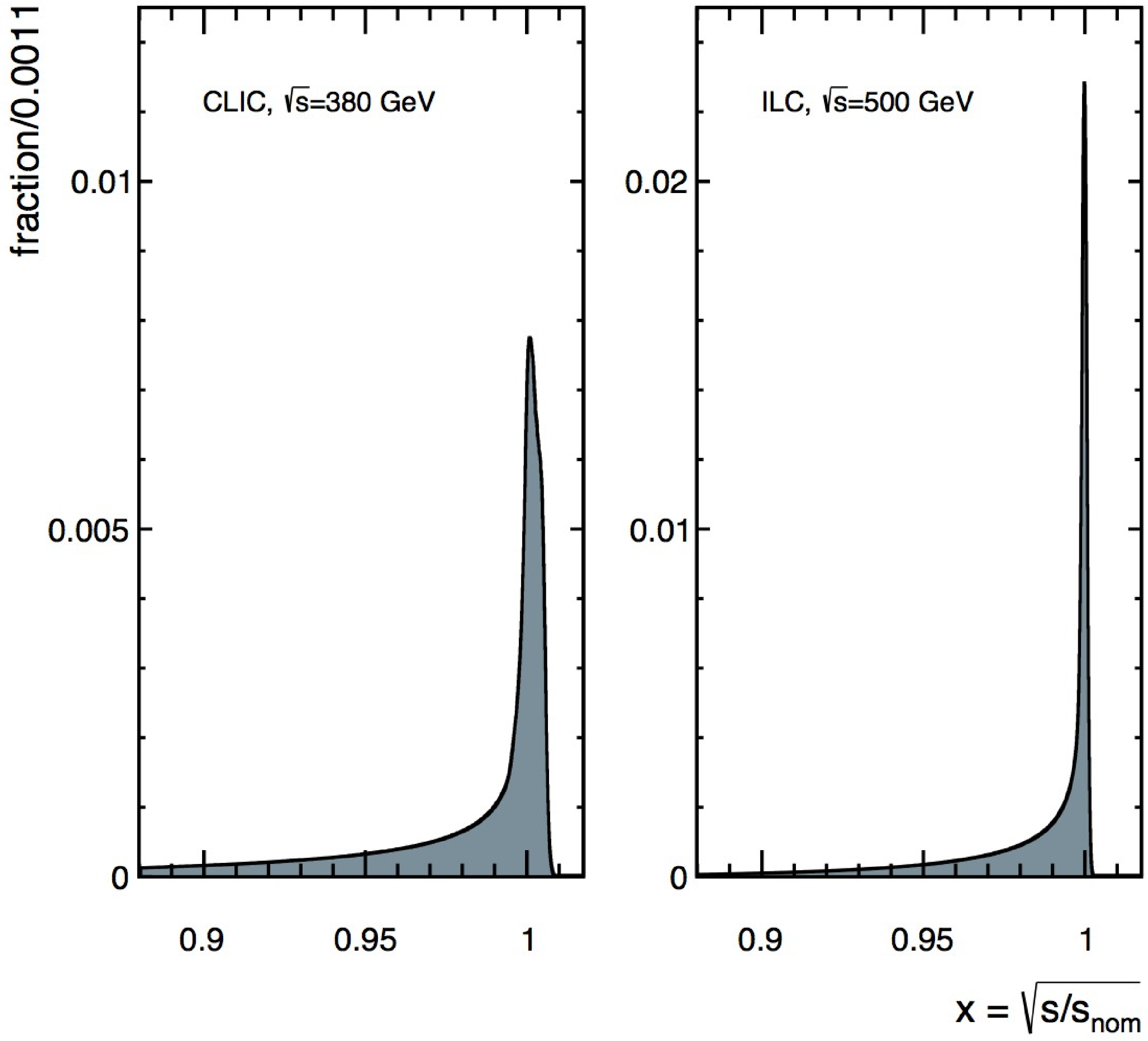
$$s' = s\left(1 - \frac{2E_\gamma}{\sqrt{s}}\right)$$

Determination of the collision energy

+ statistical uncertainty

LUMINOSITY SPECTRUM

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

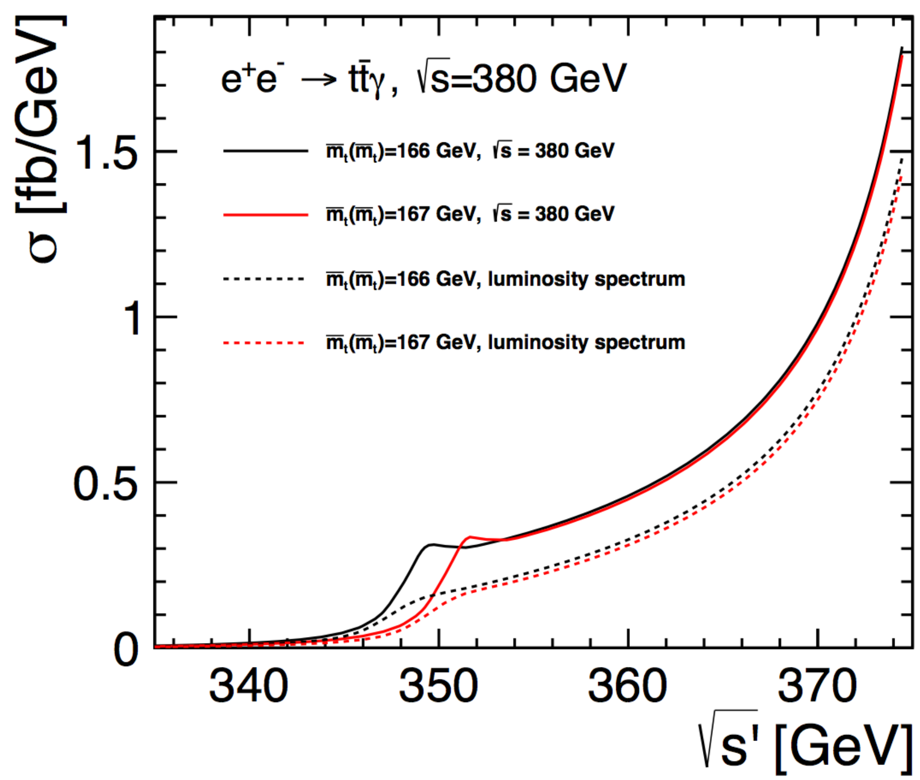


IMPACT OF THE LUMINOSITY SPECTRUM

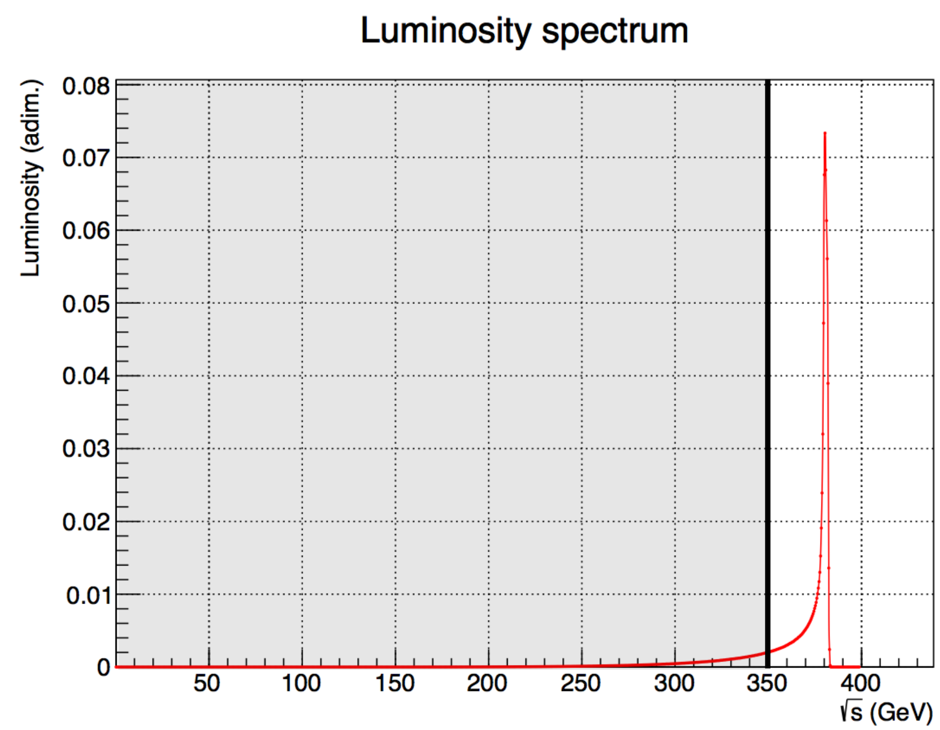
When the observable is reweighted with the luminosity spectrum, 2 things happen:

- collisions below tt threshold cause a loss of statistics
- change in the shape causes reduced sensitivity to the top mass

~50% deterioration in the sensitivity



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.

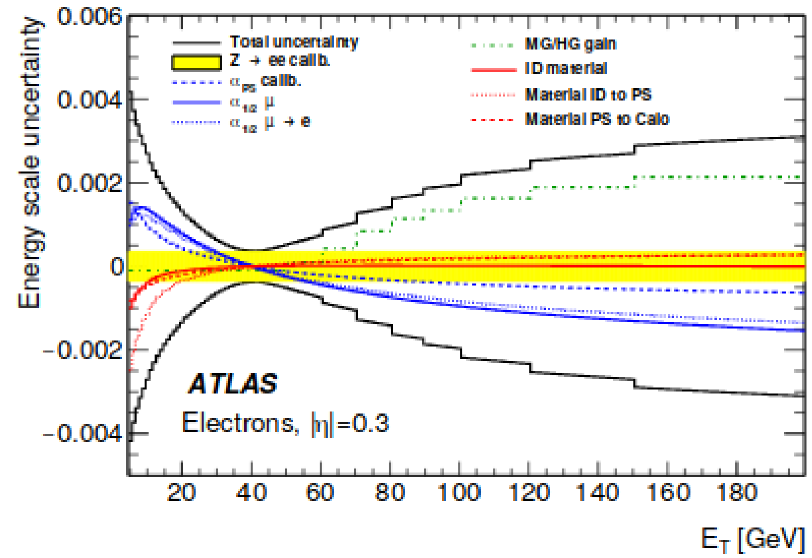
PHOTON ENERGY SCALE UNCERTAINTY

Measurement relies heavily on photon energy response

The photon energy scale, LHC experience: Z → ee gives very good constraint (< 10^{-3})

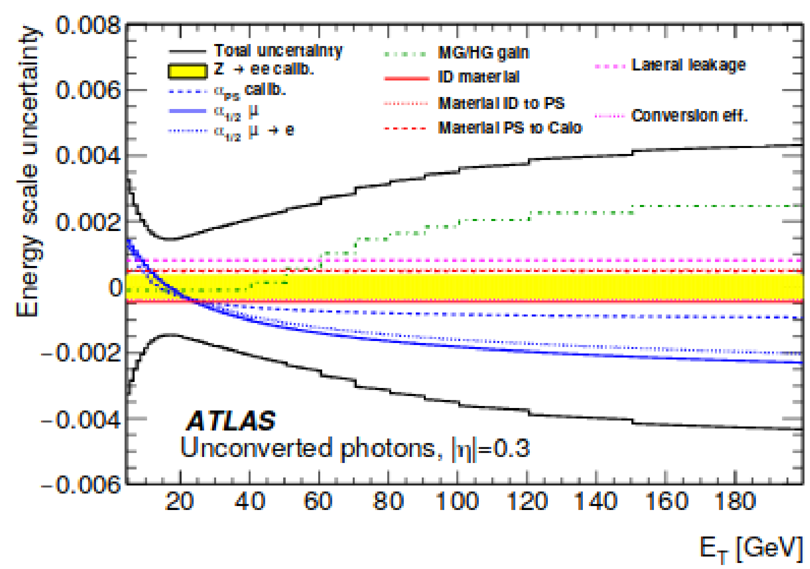
Transfer to different energy non-trivial
(important for ILC at sqrt(s) = 500 GeV)

Transfer to photon energy scale non-trivial
(conversions, leakage → material)

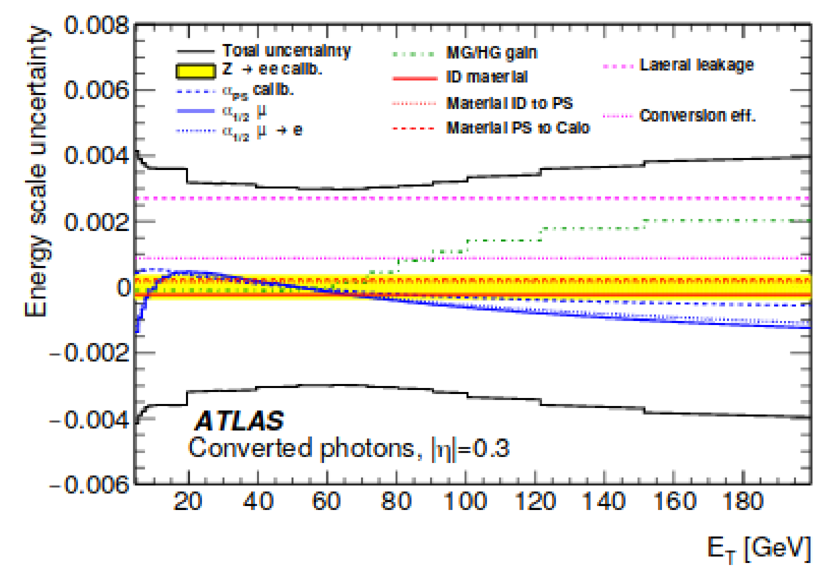


(a)

ATLAS collaboration, 2019
JINST14 P03017



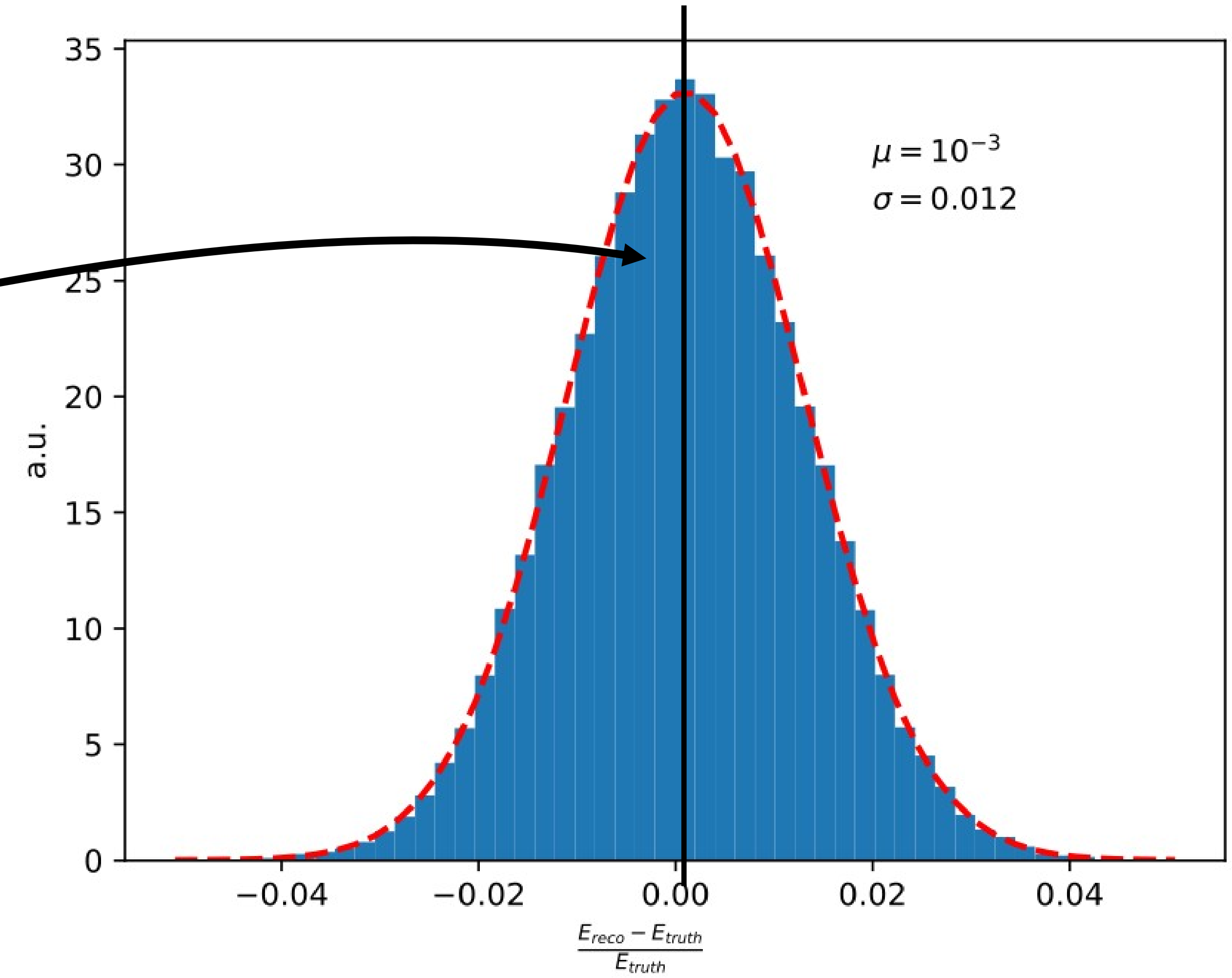
(b)



(c)

PHOTON ENERGY SCALE UNCERTAINTY

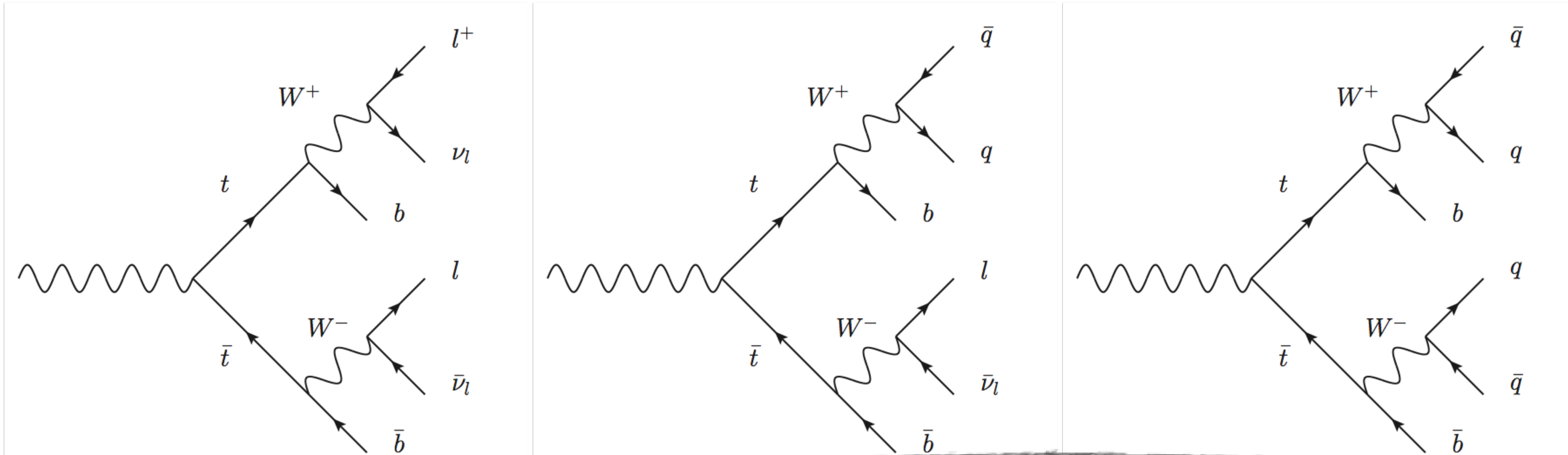
- Propagate the uncertainty from the photon energy
- Fit to the *nominal* model with m_t as a free parameter



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

We take a conservative estimate based on what is feasible at the LHC today

EVENT SELECTION: TOPS



Full leptonic (9%) **Semi-leptonic (45%)** **Fully hadronic (46%)**

Selection efficiency based on full simulation study: 50%

CLIC result for threshold scan: 70.2%, BDT ~90%

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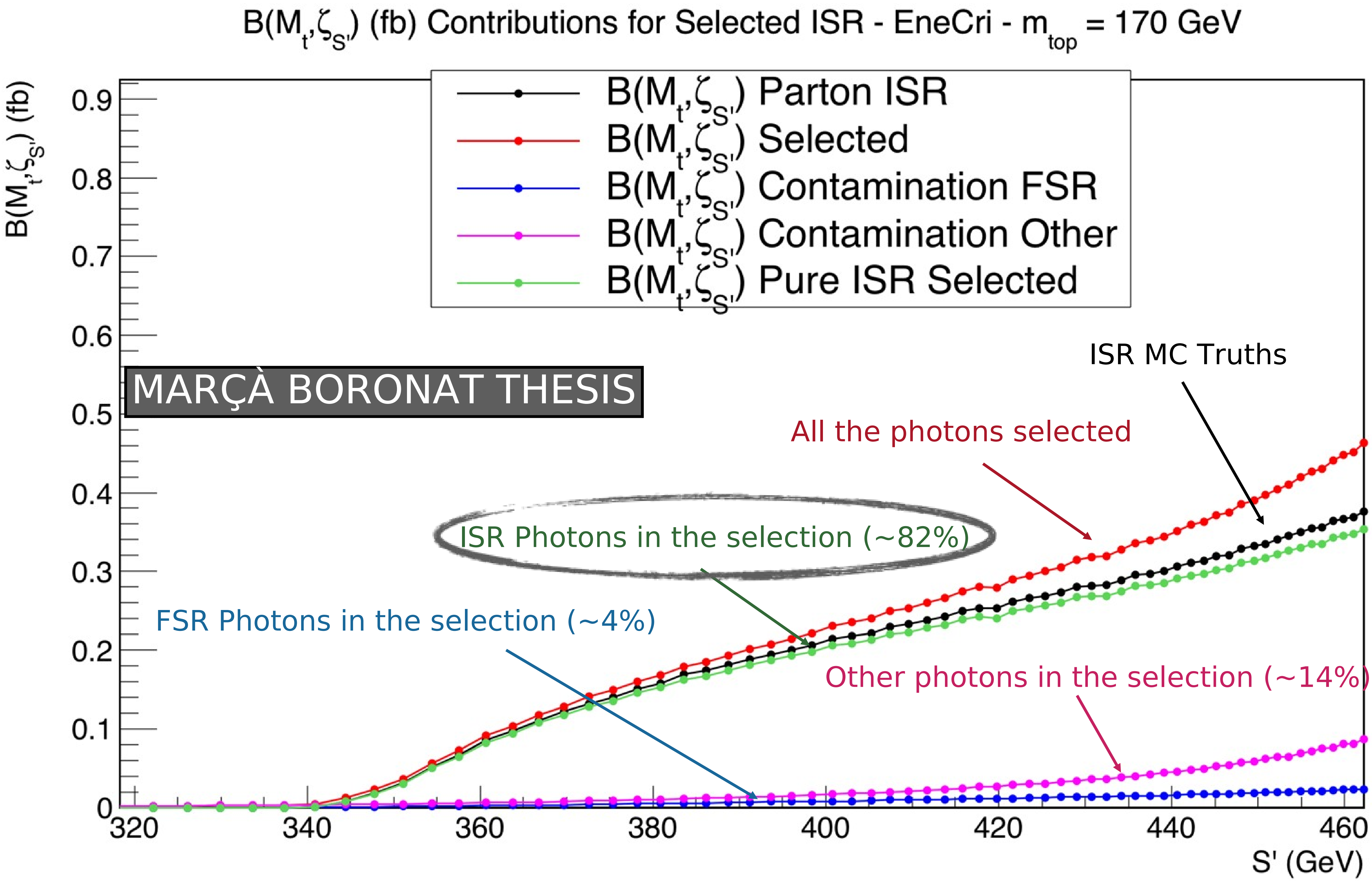
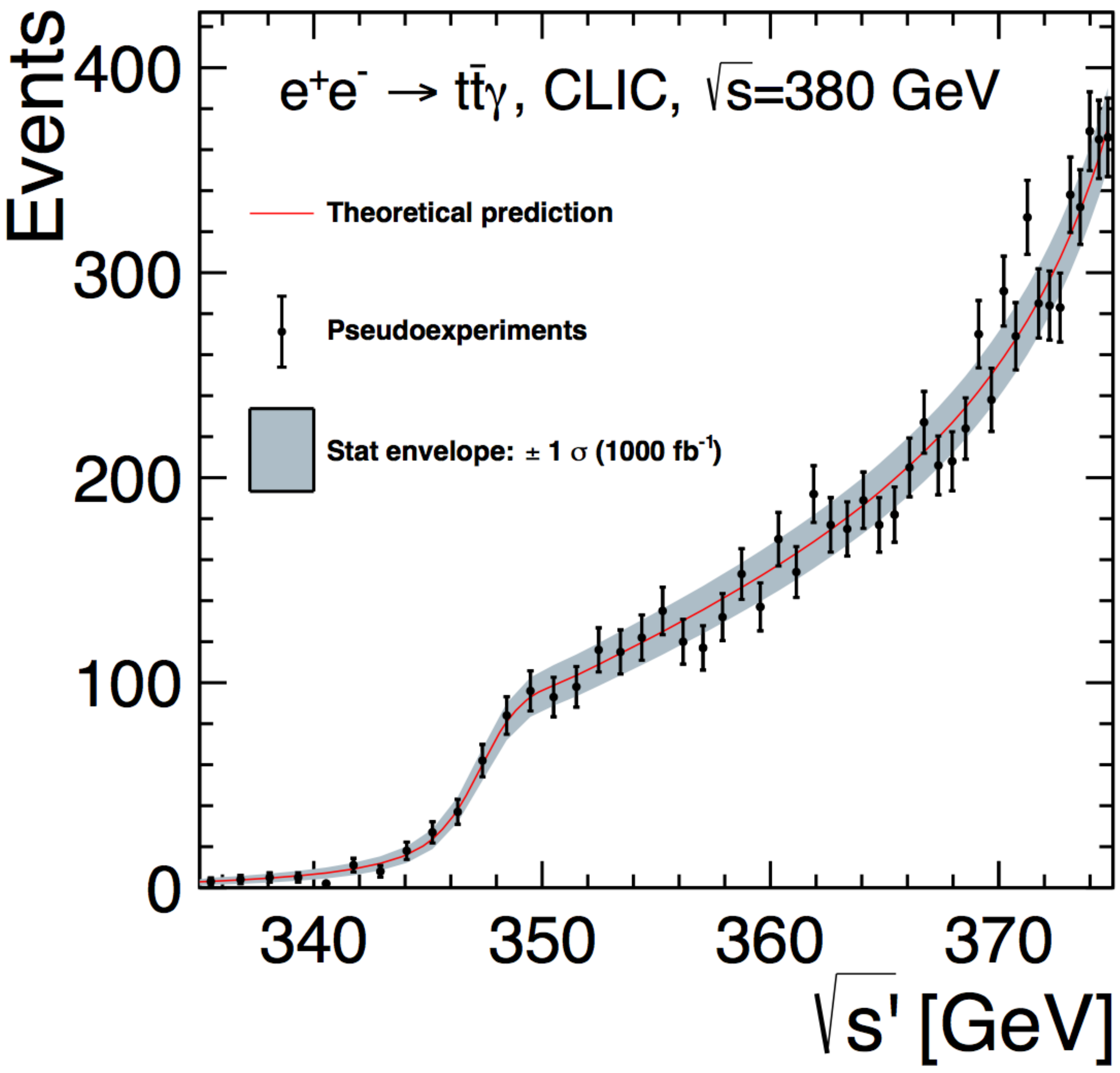
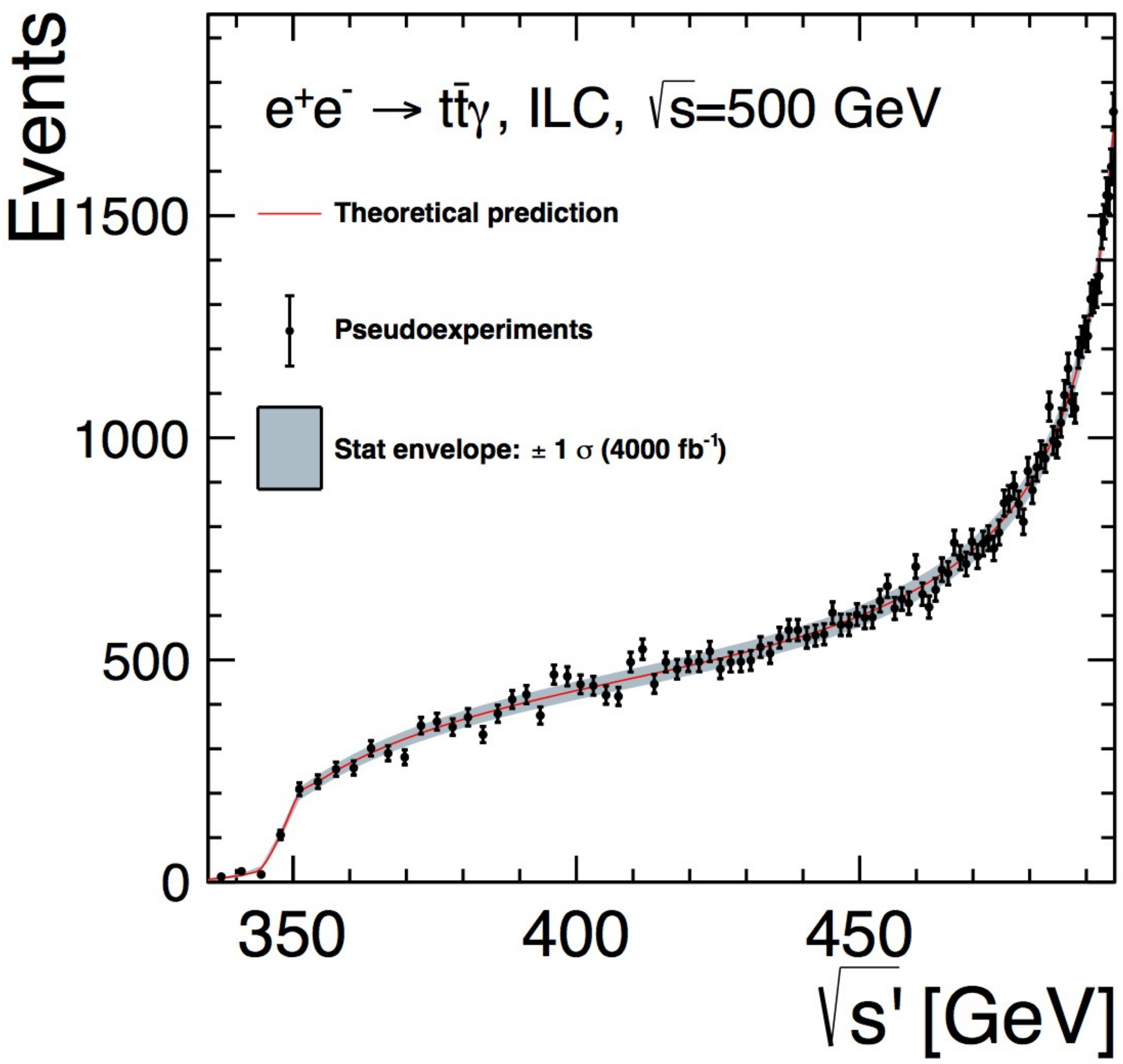
EVENT SELECTION: ISR PHOTONS



STATISTICAL UNCERTAINTY





Account for ECAL resolution, 50% efficiency and luminosity spectrum

RESULTS SUMMARY

Acceptance, 50% efficiency, ECAL resolution, luminosity spectrum accounted for

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

THE WAY FORWARD

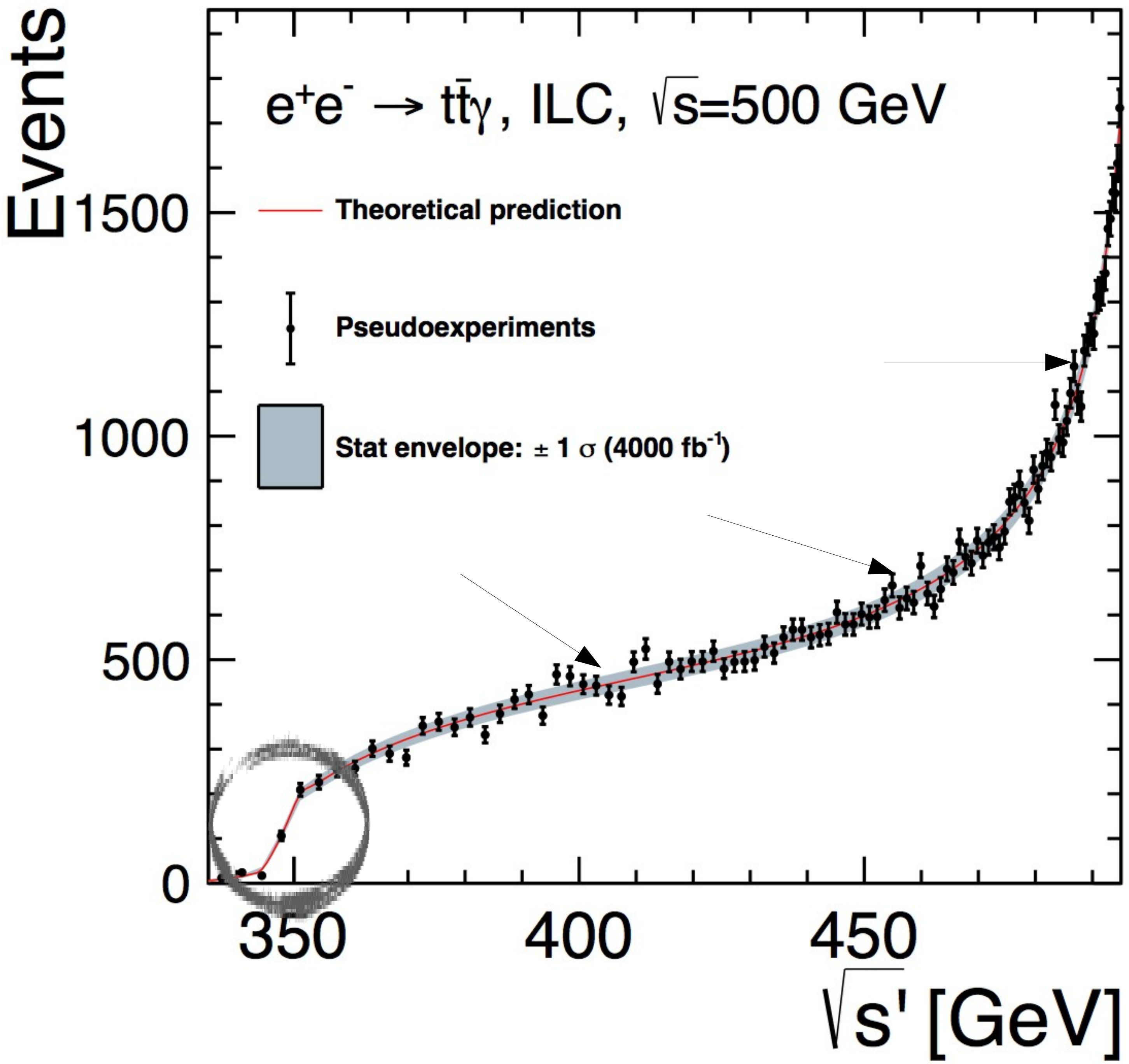
- include forward calorimeters
  - Going down from 8º to 4º would double the statistics
- Inclusion of FSR (gluon)
  - Similar sensitivity to the top quark mass when compared with ISR
- Progress in the theory calculation

MASS EVOLUTION

The method we propose provides access to the threshold in the regular run (at 380 GeV or 500 GeV)

There is non-negligible sensitivity also at higher √s’

Repeat fit in several intervals



Measurement of short-distance mass for several energy scales

MASS EVOLUTION

The top quark mass in short-distance scheme is a running parameter in the QCD Lagrangian

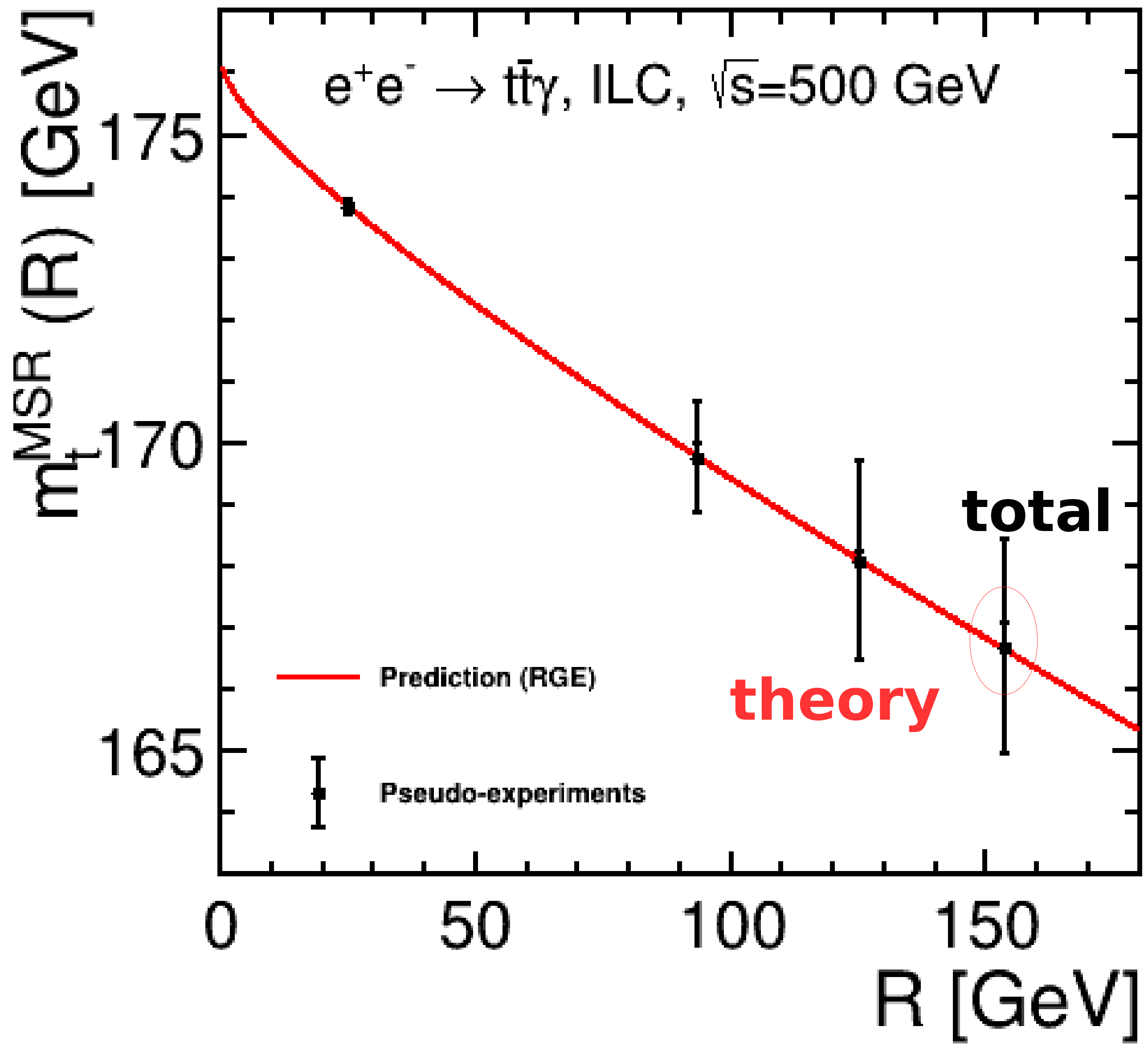
The top quark MSR mass can be measured at different scales $R < m_t$

The 500 GeV run covers R scales in the interval [20 GeV, 160 GeV], where the evolution is significant compared to the measurement uncertainty.

Provides a test of QCD in analogy to measurements of “running” α_s, m_b, m_c

MSR mass: Hoang et al., 0803.4214
Hoang et al., 1704.01580

Running top mass: CMS, arXiv:1909.09193



We can test the evolution of the MSR mass for scales $R < m_t$

SUMMARY

- A new method to measure the top quark mass in e^+e^-
- Matched NNLO+NNLL calculation + ISR
- Complete assessment of uncertainties
  - Stat. uncertainty (incl. acceptance & efficiency, lumi spectrum, E resolution)
  - Theory uncertainty from scale variations
  - Conservative estimate of photon energy scale
  - Luminosity spectrum uncertainty
- Precise measurement of short-distance mass in continuum:

  total uncertainty 100 MeV (CLIC380), 150 MeV (ILC500)
- New (preliminary!): Sensitive to “running” of the top quark:

  ILC500 tests $m^{MSR}(R)$ evolution for $R < m_t$ with over 5σ significance

THANKS FOR YOUR ATTENTION

BACKUP

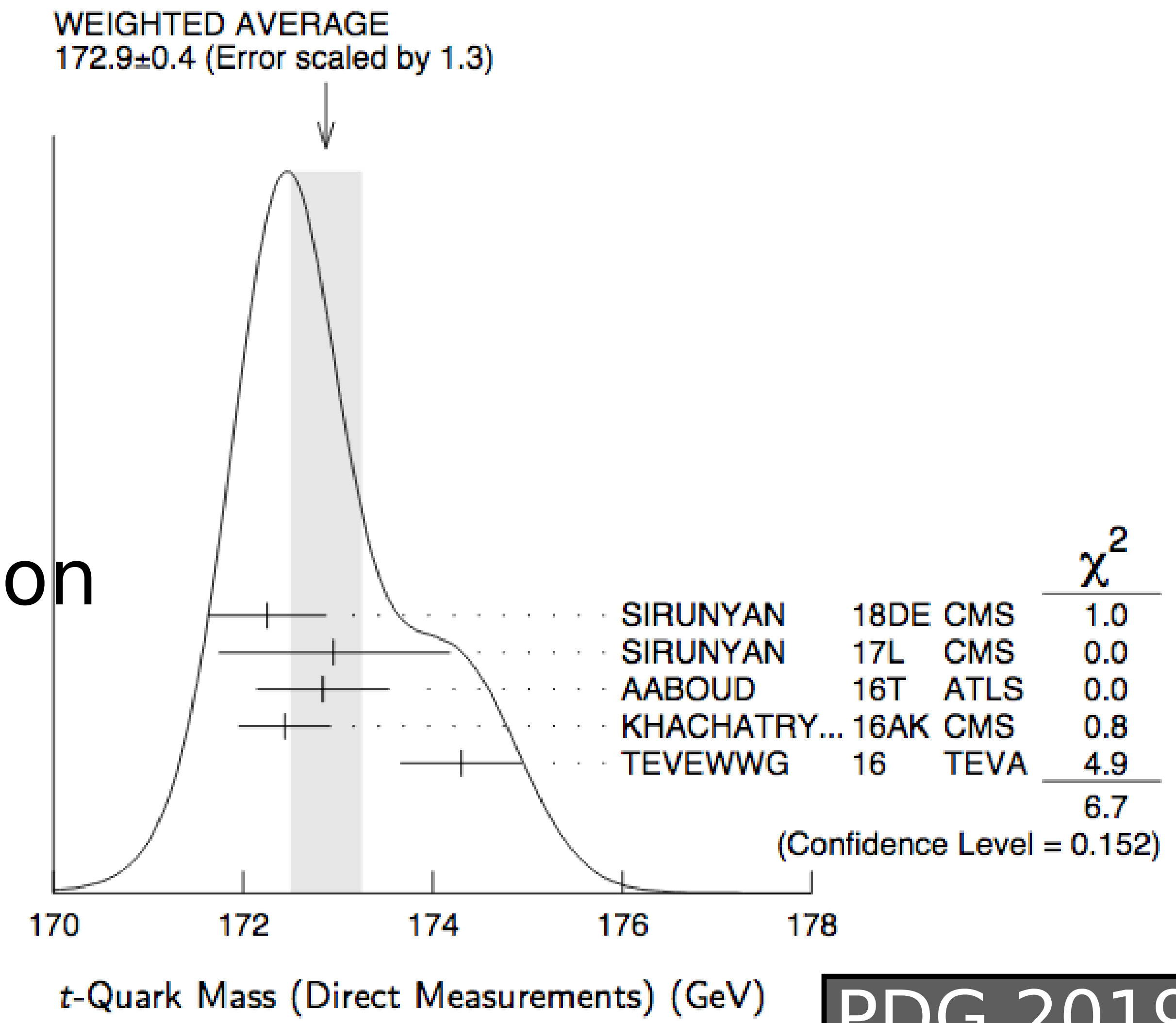
TOP QUARK PERKS

- 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

$m_t = 172.9 \pm 0.4$ GeV

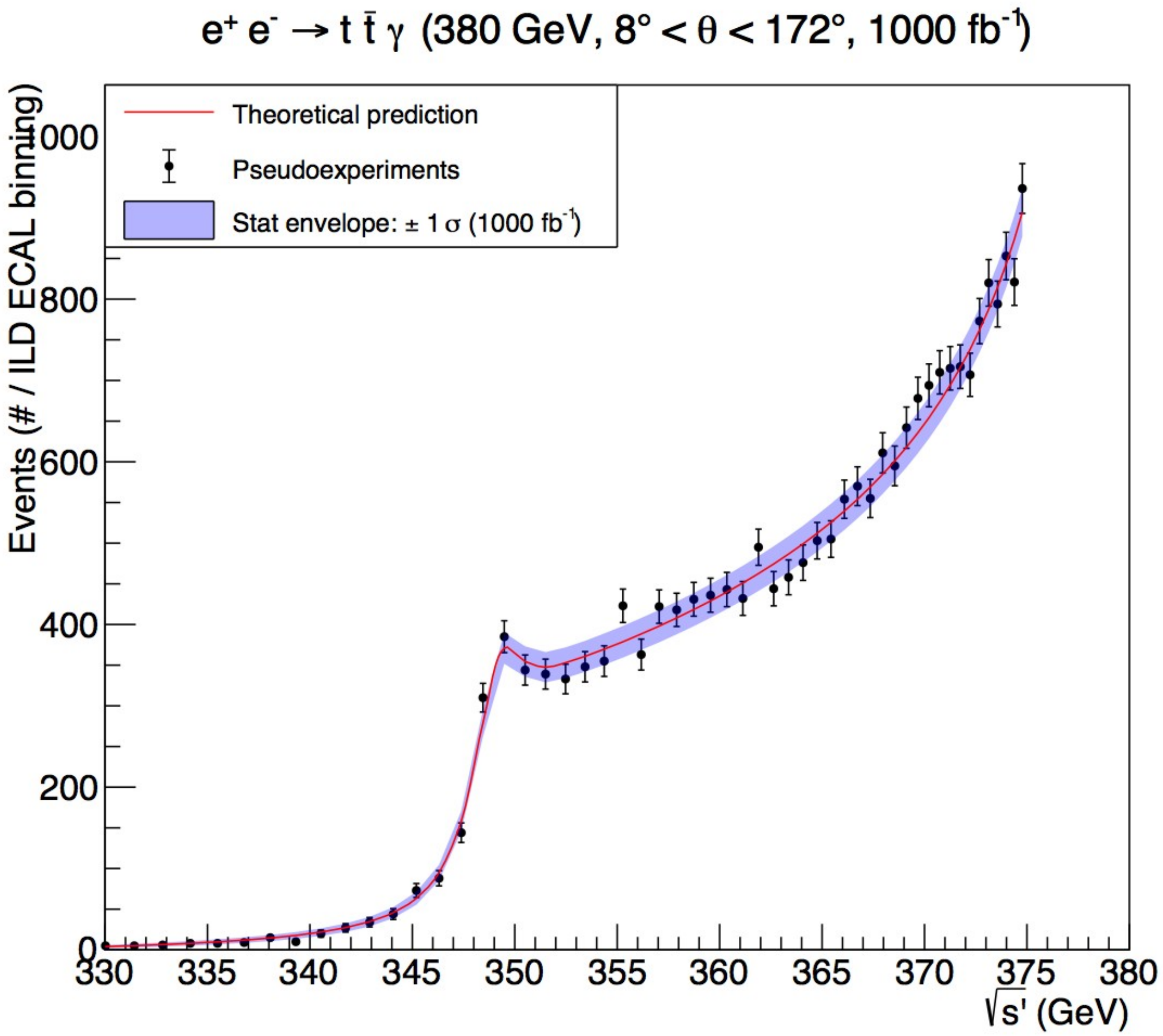


PDG 2019

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

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

MODELING THE LUMINOSITY SPECTRUM

The MC model generates events as function of the model parameters (p1, p2, p3...)

Generator level

Bhabha

Detector Level

The data events (while we wait for it, the GuineaPig events)

Detector Level

Bhabha

Generator level

The reweigthing fit (reweighting is done to avoid generating new MC events in each iteration of the model parameters)

Luminosity spectrum

- For more information:

ANDRÉ SAILER’S PHD THESIS

ESTEBAN FULLANA TOP@LC 2017 T

- 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.