# Prospects for the Top-quark Mass using Radiative events in an $e^-e^+$ linear collider.

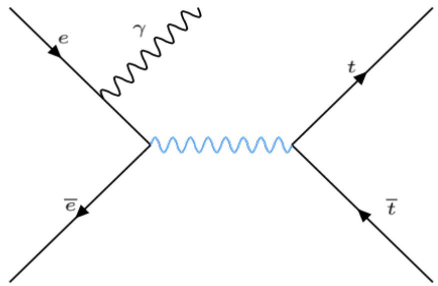
M. Boronat (boronat.arevalo@ific.uv.es), J. Fuster, P. Gomis - IFIC – Valencia (Spain)

# Motivation

- High-precision measurement of the top-quark mass in the continuum of an $e^+e^-$ linear collider.
- Possibility to directly measure the top-quark mass, complementary to the threshold measurement.
- Potential measurement of the running of the top-quark mass.

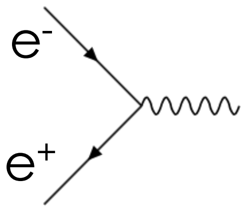
# Initial state radiation: $e^-e^+ \rightarrow t\,t\gamma$

- Measure $m_t$ using the cross section of $e^-e^+ \rightarrow tt\gamma$.



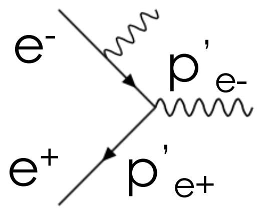

- The cross section is sensitive to the scale of the interaction and the top mass.

$$\sigma(e^+e^- \rightarrow t\bar{t}) = f(s, m_t)$$




$$s = (p_{e^-} + p_{e^+})^2$$

$$\sigma(e^+e^- \rightarrow t\bar{t}\gamma) = f(s', m_t)$$




$$s' = (p'_{e^-} + p'_{e^+})^2$$

# Initial state radiation: $e^-e^+ \to t\,\bar{t}\gamma$

- So, what do we measure?

$$B(m_t, \zeta_{s'}) = \frac{d\sigma_{t\bar{t}\gamma}}{d\zeta_{s'}} \longrightarrow \zeta_{s'} = \sqrt{s'}$$

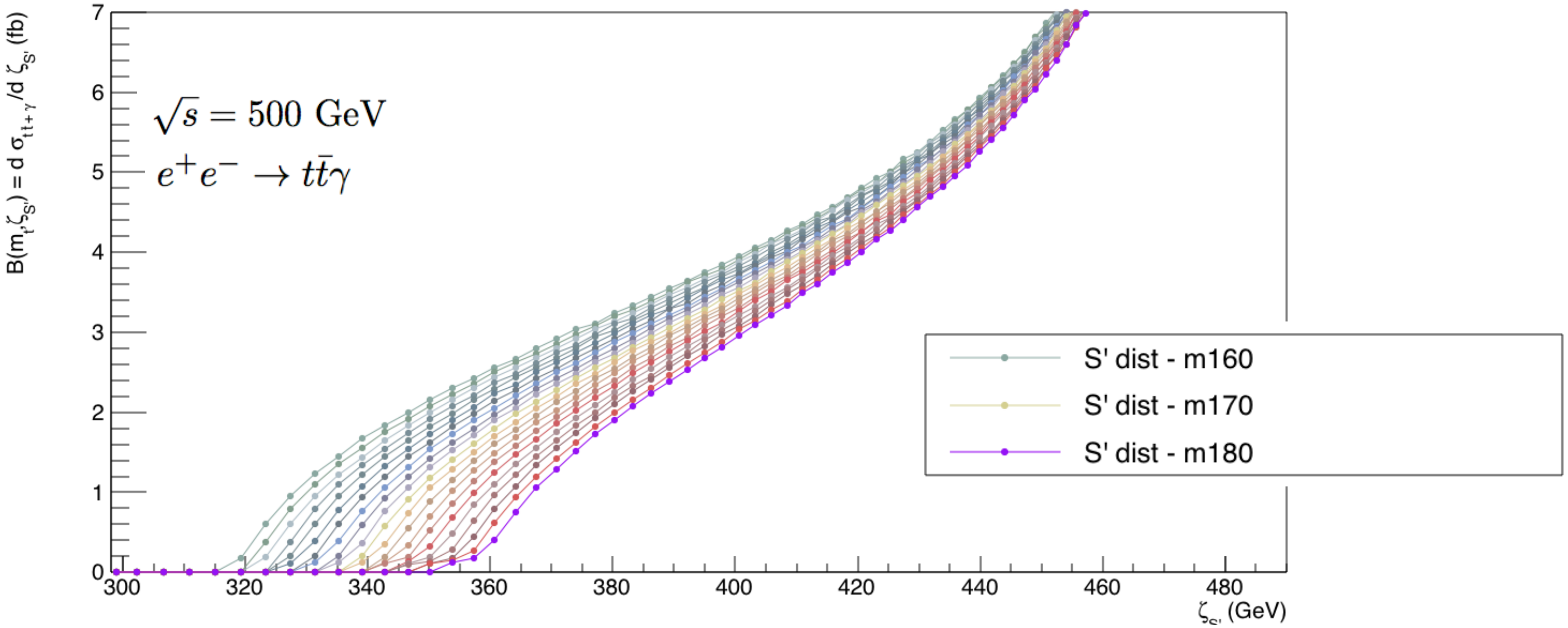
$$s' = s\left(1 - \frac{2E_\gamma}{\sqrt{s}}\right)$$

- $m_t$ can be measured by counting the top production with a certain S', i.e. by using the photon energy, which can be measured with high precision.

# Initial state radiation: $e^- e^+ \to t\,t\gamma$

- The study is produced using Pythia 8.1 and is limited to its theoretical capabilities and uncertainties.

- Detailed calculations at high theoretical accuracy (NLO, NNLO…) are needed to make the result meaningful. A cooperation with Andre Hoang and Vicent Mateu has started in this line.

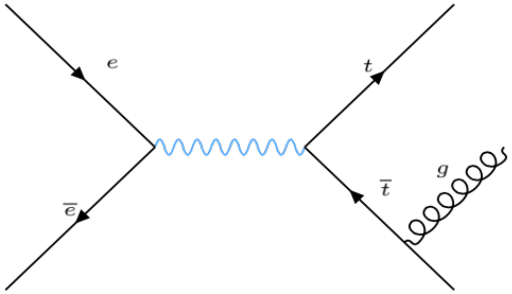



- These curves represent the cross section as a function of $\zeta_{s'}$ at parton level for several $m_t$

- The curve is more sensitive to $m_t$ near the top production threshold, and the dependence diminishes as $\zeta_{s'}$ grows

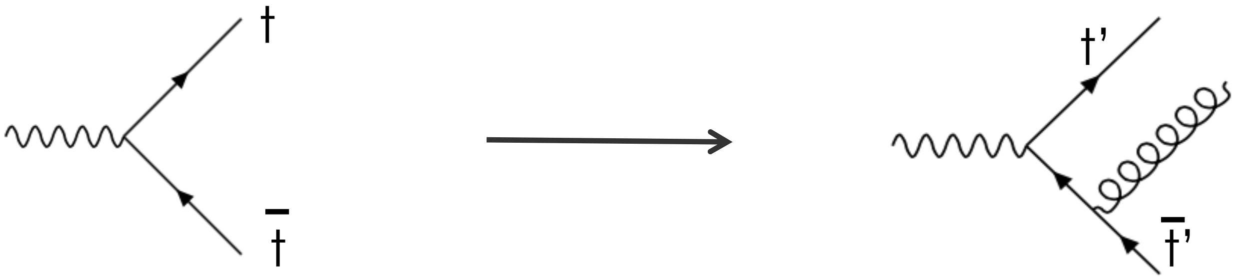
# Final state radiation: $e^-e^+ \to t\,t\,g$

- Measure $m_t$ using the cross section of $e^-e^+ \to t\bar{t}g$.




- The gluon emission depends on the quark to mass.

$$\frac{1}{\sigma_0}\frac{d^2\sigma}{dx_1 dx_2} = C_F\frac{\alpha_s}{2\pi}\left[\frac{x_1^2+x_2^2}{(1-x_1)(1-x_2)} - \frac{4m_q^2}{s}\left(\frac{1}{1-x_1}+\frac{1}{1-x_2}\right) - \frac{2m_q^2}{s}\left(\frac{1}{(1-x_1)^2}+\frac{1}{(1-x_2)^2}\right) - \frac{4m_q^4}{s^2}\left(\frac{1}{1-x_1}+\frac{1}{1-x_2}\right)^2\right]$$




$$s = (p_t + p_{\bar{t}})^2 \qquad s' = (p'_t + p'_{\bar{t}})^2$$

# Final state radiation: $e^- e^+ \rightarrow t\,t\,g$

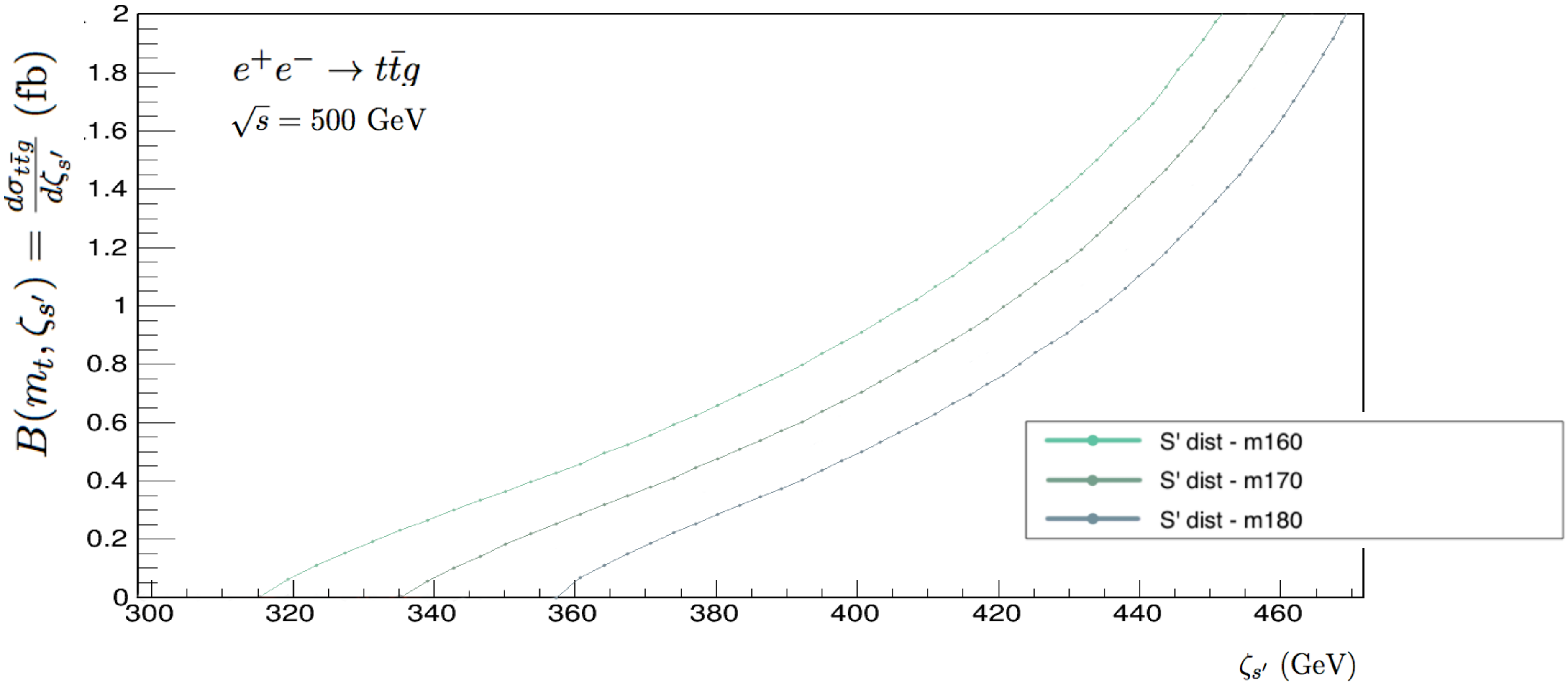
- So, what do we measure?

$$B(m_t, \zeta_{s'}) = \frac{d\sigma_{t\bar{t}g}}{d\zeta_{s'}} \longrightarrow \zeta_{s'} = \sqrt{s'}$$

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

- $m_t$ can be measured by counting the top production with a certain S', i.e. by identifying and reconstructing the gluon-jet energy.
- This method requires jet reconstruction, which complicates the study. However this can be compensated because it has higher cross section.

# Motivation

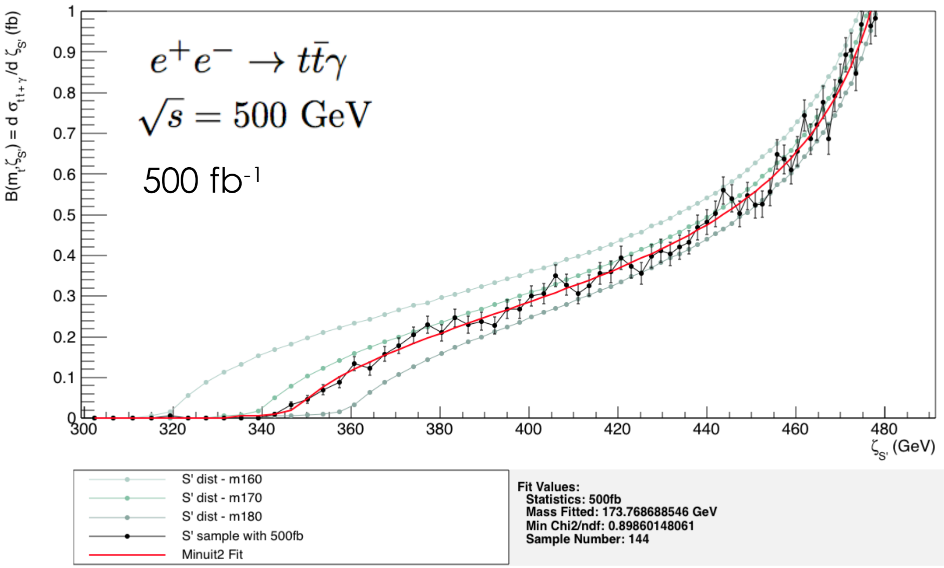


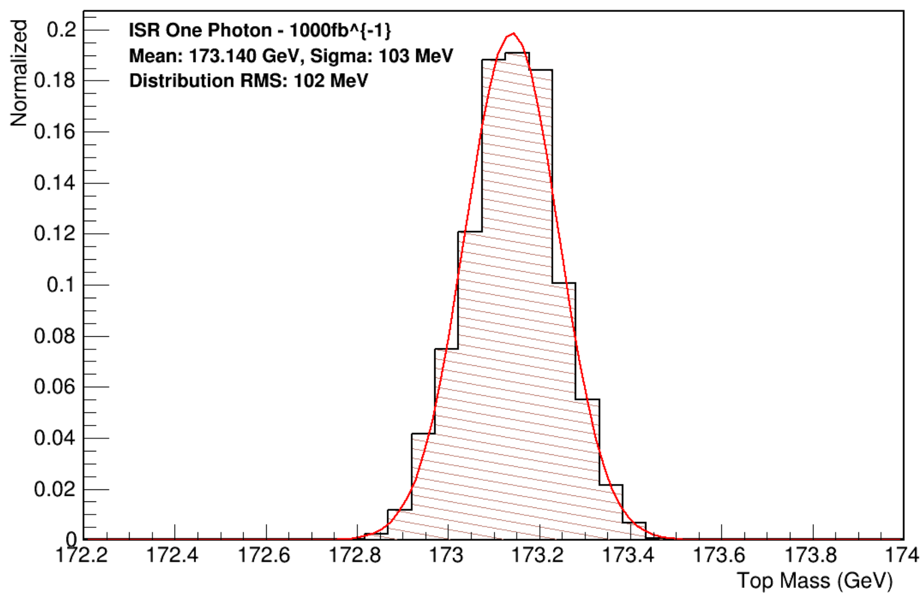

- These curves represent the cross section as a function of $\zeta_{s'}$ at parton level for several $m_t$.
- Experimentally, these events are looked for as $e^-e^+ \to tt$ events with an extra jet from the gluon

# Parton Level study

- Using the reference curves template fits are performed for N (~ 100 - 500) data sets for different integrated luminosities.

- From these fits the top mass is estimated as the median of the distribution and its error as the standard deviation.




Input mass $m_t$ = 173.1 GeV

# Parton Level study

Input mass $m_t$ = 173.1 GeV

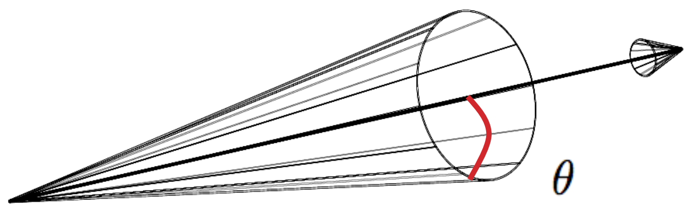
| **500 GeV** | $\mathbf{m_{t\,ISR}}$ **(GeV)** | $\mathbf{m_{t\,FSR}}$ **(GeV)** | $\mathbf{m_{t\,both}}$ **(GeV)** |
|---|---|---|---|
| 500 $fb^{-1}$ | 173.158 ± 0.155 | 173.153 ± 0.130 | 173.158 ± 0.105 |
| 1000 $fb^{-1}$ | 173.140 ± 0.103 | 173.127 ± 0.092 | 173.136 ± 0.069 |
| 2600 $fb^{-1}$ | 173.133 ± 0.061 | 173.114 ± 0.057 | 173.124 ± 0.042 |

# A more realistic approach: particle level without detector simulation - only ISR.

- To increase the realism of the study photons are identified using selection criteria
- Polar angle of the photon needs to be greater than 7° due to detector coverage (ILD based)
- As high-energy ISR emission is usually collinear to the emitter, a good portion of the statistics are lost

| | 380 GeV | 500 GeV | 1000 GeV |
|---|---|---|---|
| ISR lost (%) | 71 | 74 | 79 |

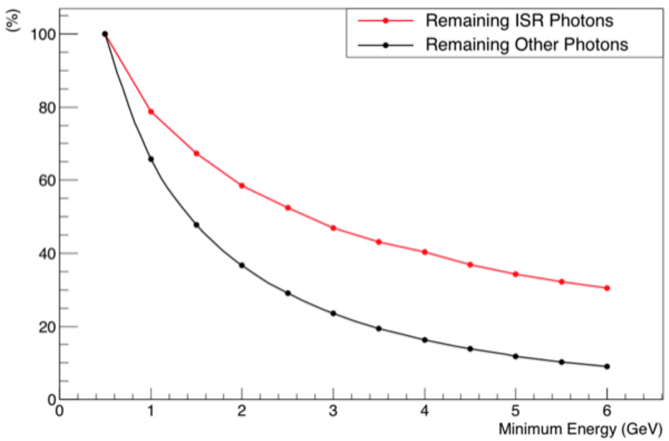
- ISR photons are identified with respect to photons originated in the decay chain of particles by energy cuts ($E_\gamma > E_0$) and isolation angle cuts ($\theta > \theta_0$)



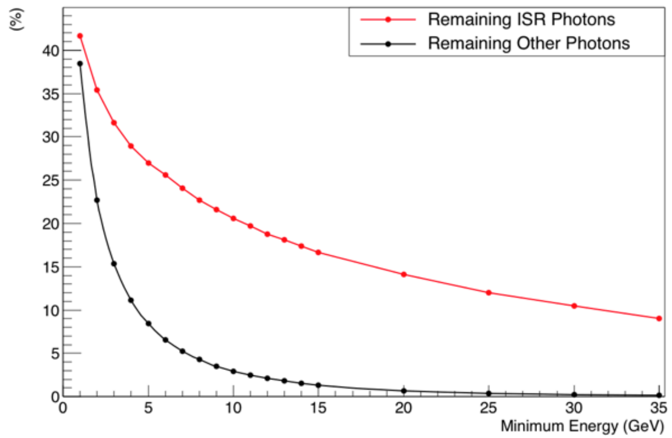
# Event selection: optimizing the cuts (ISR)

- To optimize the selection of ISR photons over decay photons we plot how many photons of each kind (in percentage) survive to different $E_0$ cuts

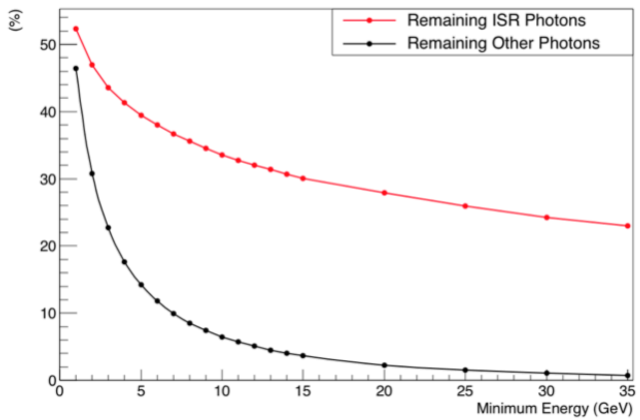
380 GeV




500 GeV




1000 GeV

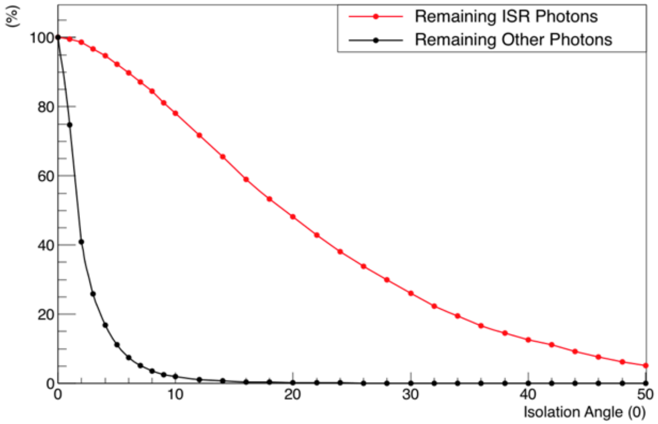



| Cut | 380 GeV | 500 GeV | 1000 GeV |
|---|---|---|---|
| $E_0$ | 3 GeV | 10 GeV | 30 GeV |
| $\theta_0$ | 8° | 8° | 4° |

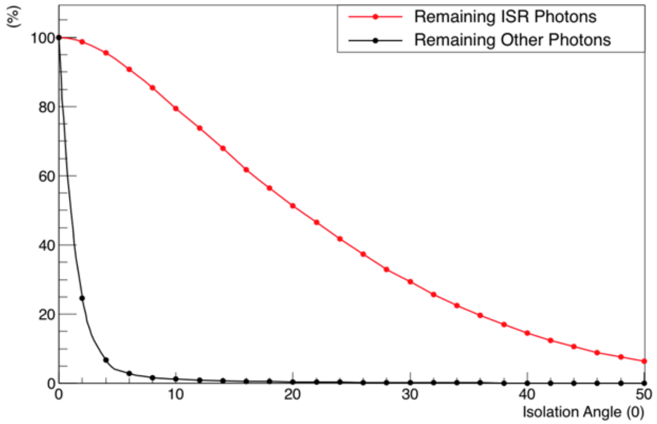
# Event selection: optimizing the cuts (ISR)

- After imposing the $E_0$ cuts, the same proceeding is performed for the $\theta_0$ cuts

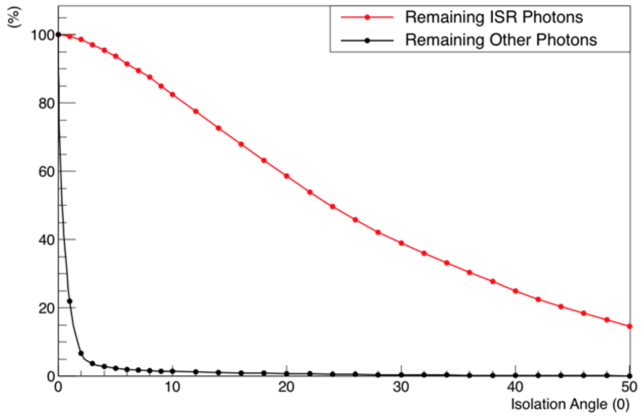
380 GeV




500 GeV




1000 GeV

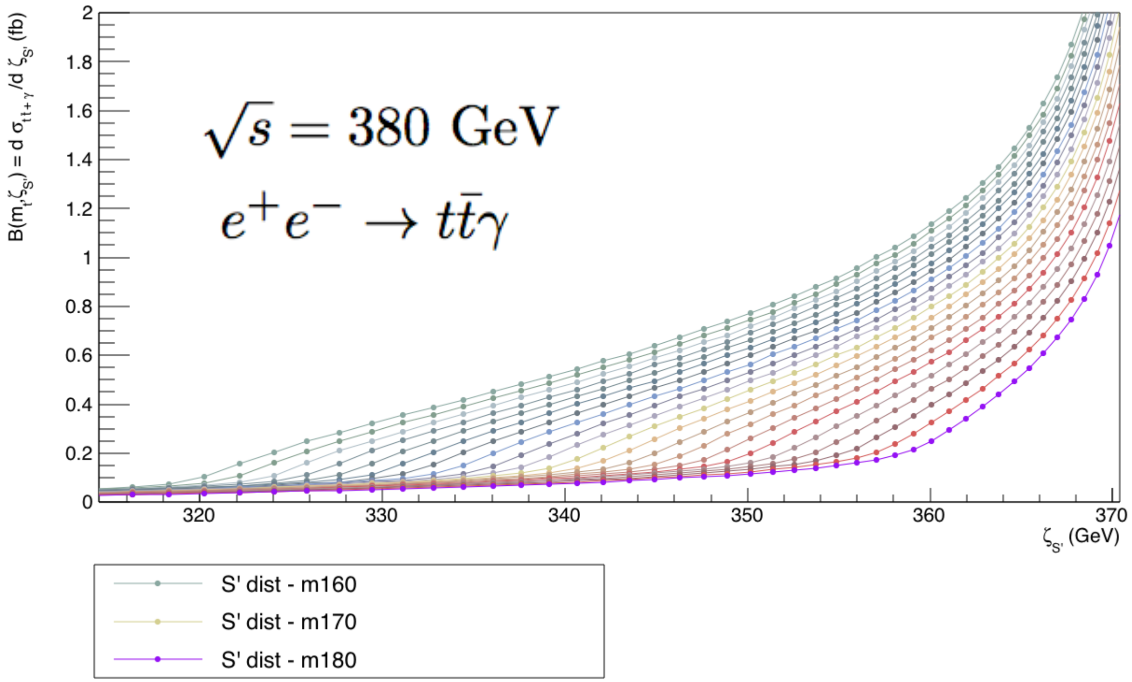


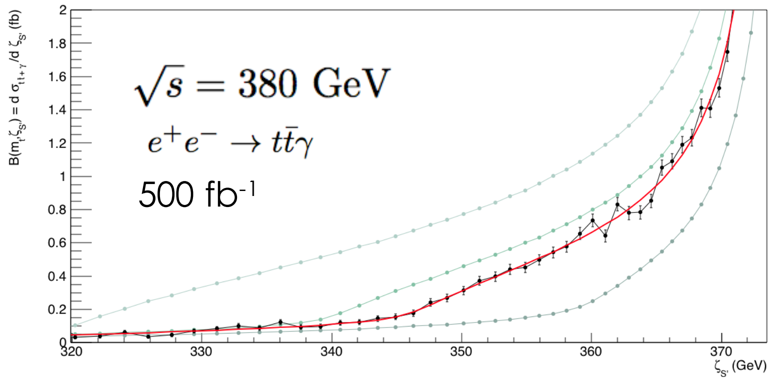

- Final photons entering the analysis satisfy $E_\gamma > E_0$ and $\theta > \theta_0$

| Cut | 380 GeV | 500 GeV | 1000 GeV |
|---|---|---|---|
| $E_0$ | 3 GeV | 10 GeV | 30 GeV |
| $\theta_0$ | 8° | 8° | 4° |

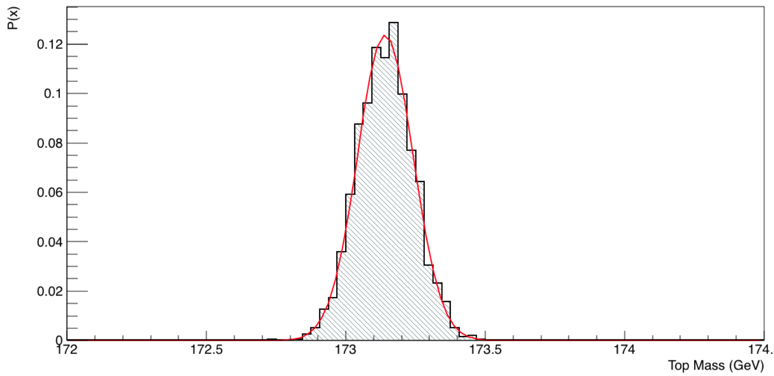
# Reference curves and template fits (ISR)

- Similarly to the parton study, the reference curves are constructed to perform template fits over N (~1000 - 2000) data sets to obtain the estimation of the top quark mass and its error.




Input mass $m_t$ = 173.1 GeV




Fit Values:
Statistics: 500fb
Mean: 173.141474767 GeV
Sensibility (sigma): 99.973305779 MeV
Number of Entries: 1895

# Top mass sensitivity – only ISR

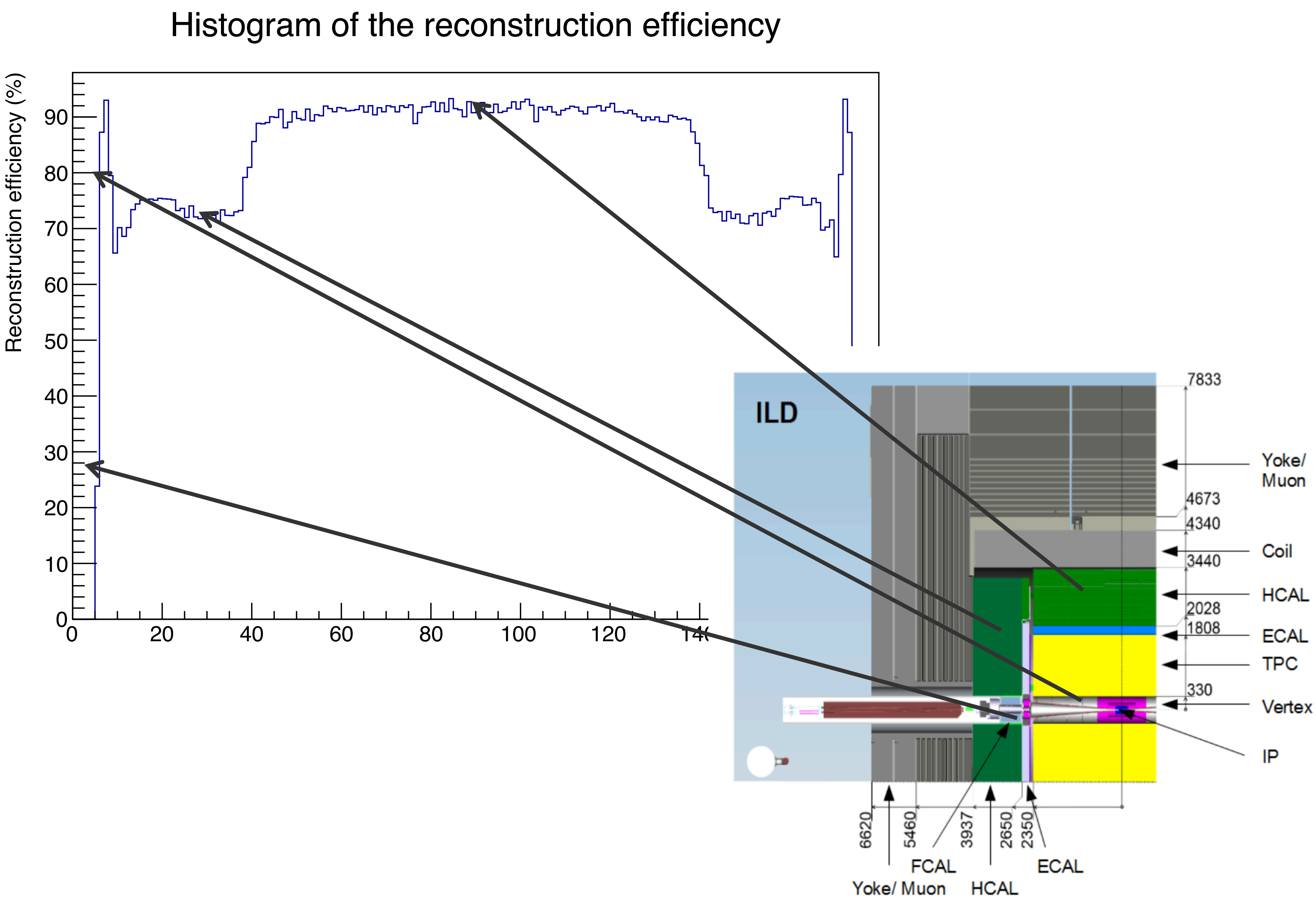
Input mass $m_t$ = 173.1 GeV

| Energy (GeV) | Luminosity ($fb^{-1}$) | $m_t$(GeV) | $\Delta m_t$ (MeV) |
|---|---|---|---|
| 380 | 500 | 173.141 | 100 |
| 500 | 500 | 173.327 | 294 |
| 500 | 4000 | 173.122 | 100 |
| 1000 | 1000 | 173.381 | 639 |
| 1000 | 3500 | 173.197 | 388 |

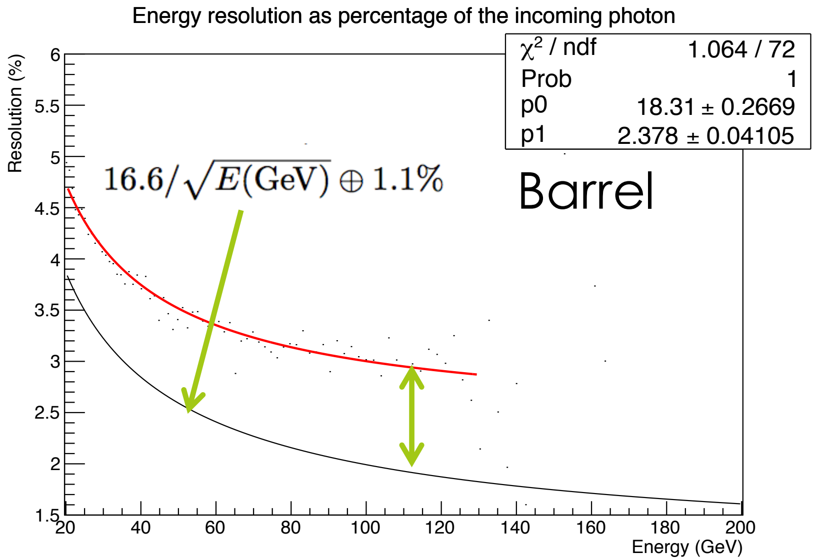
# Current Status and Plans

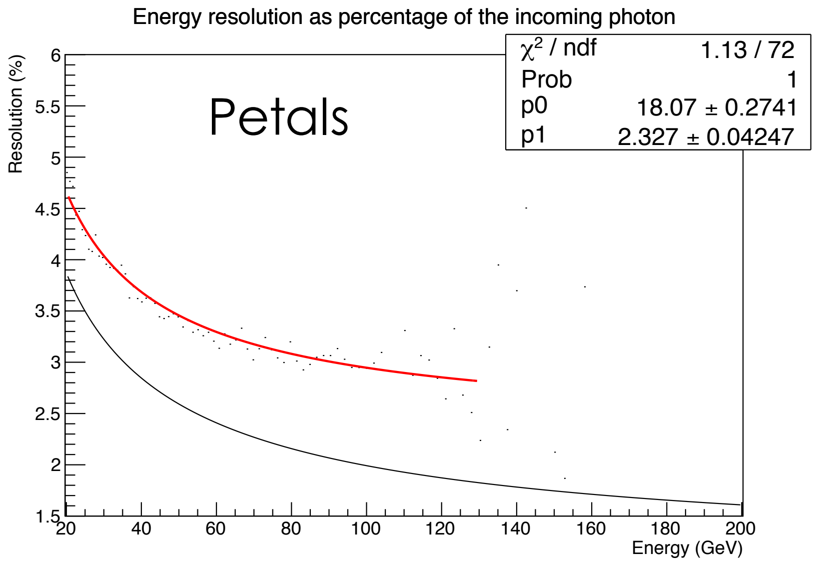
- Reconstructing the extra jets to extend the FSR parton study to particle level, due to the complexity of this topology, the observable may be changed
- Performing the QED and QCD calculations to obtain the reference curves and estimate the systematic uncertainties, which we expect to be similar or lower than experimental. A cooperation with Andre Hoang and Vicent Mateu has started in this line.
- Full simulation: Including detector effects in the ISR study.

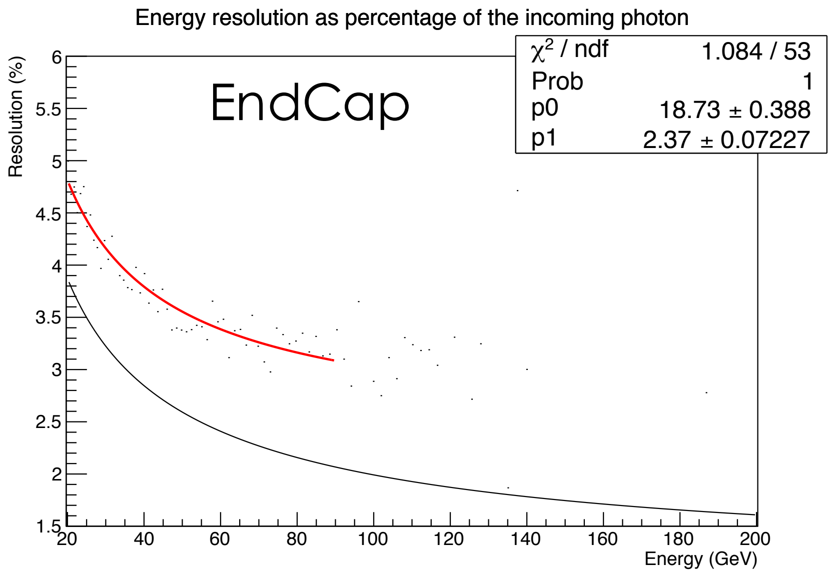
# Angular efficiency



# Energy Resolution



# Summary

- A study on the potential to use radiative events (γ and g) has been produced to evaluate their potential to measure the top-quark mass with high precision.
- The study has been performed at parton level for both ISR and FSR.
- A preliminary study **using ISR events** at particle level show that a statistical precision **of 100 MeV** is within reach for this topology.
- A combined analysis including ISR (γ) and FSR(g) events has the potential to significantly improve the precision well bellow 100MeV.
- These analysis can be part of the physics program at higher energies than the top production threshold, complementing the measurement at threshold.

# Thank you

THANK YOU

# Backup

BACKUP

# Backup

| $E_{CM}$ | ISR $E_{min}$ | ~$ISR_{lost}$ | ~ General $\gamma$ Reduction |
|---|---|---|---|
| 380 GeV | 3 GeV | 53 % | 76 % |
| 500 GeV | 10 GeV | 79 % | 97 % |
| 1000 GeV | 30 GeV | 75 % | 99 % |

| $E_{CM}$ | $ISO_{ang}$ | ~$ISR_{lost}$ | ~ General $\gamma$ Reduction |
|---|---|---|---|
| 380 GeV | 8° | 15 % | 95 % |
| 500 GeV | 8° | 15 % | 98 % |
| 1000 GeV | 4° | 5 % | 98 % |

# Backup

| Stage | Nickname | $L_a\ (fb^{-1})$ | $m_t$ (GeV) ISR (Final Particles) |
|---|---|---|---|
| 2 | ILC(500) | 500 | 173.327 |
| 3 | ILC(LumUp) | 4000 | 173.122 |

| Stage | Nickname | $L_a\ (fb^{-1})$ | $\Delta m_t$ (MeV) ISR (Final Particles) |
|---|---|---|---|
| 2 | ILC(500) | 500 | 294 |
| 3 | ILC(LumUp) | 4000 | 100 |

J. Brau - PAC Meeting (Osay, Japan 13 April 2015)

| Stage | Nickname | $L_a\ (fb^{-1})$ | $m_t$ (GeV) ISR (Final Particles) |
|---|---|---|---|
| 3 | ILC(1000) | 1000 | 173.381 |
| 4 | ILC(LumUp) | 3500 | 173.197 |

| Stage | Nickname | $L_a\ (fb^{-1})$ | $\Delta m_t$ (MeV) ISR (Final Particles) |
|---|---|---|---|
| 3 | ILC(1000) | 1000 | 639 |
| 4 | ILC(LumUp) | 3500 | 388 |

Howard E. Haber - LCWS13 (Tokyo, Japan 15 November 2013)