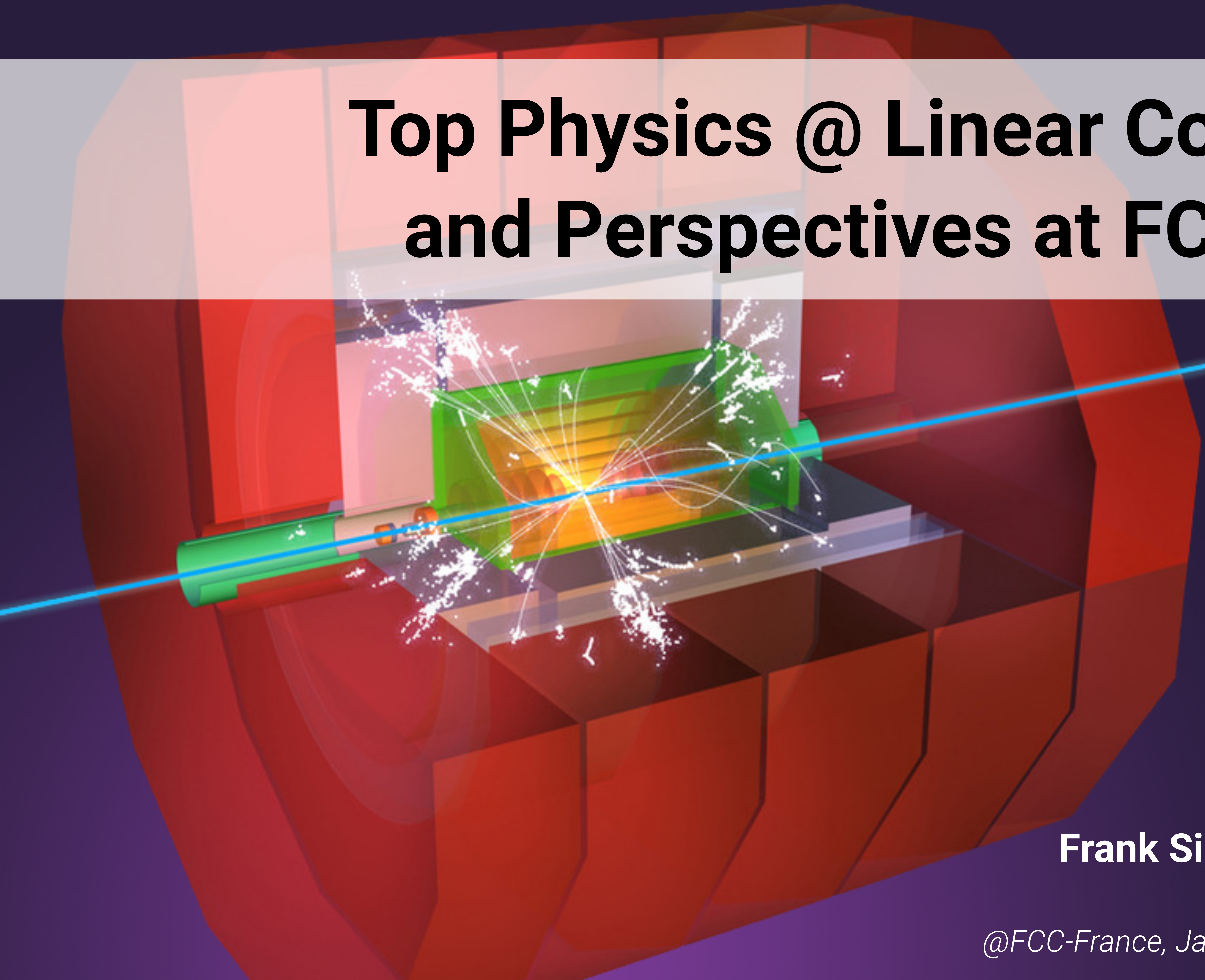
Top Physics @ Linear Colliders and Perspectives at FCC-ee



Frank Simon

@FCC-France, January 2021

MAX-PLANCK-INSTITUT
FÜR PHYSIK

Overview

Top physics: An essential pillar of the program at (higher energy) e^+e^- colliders

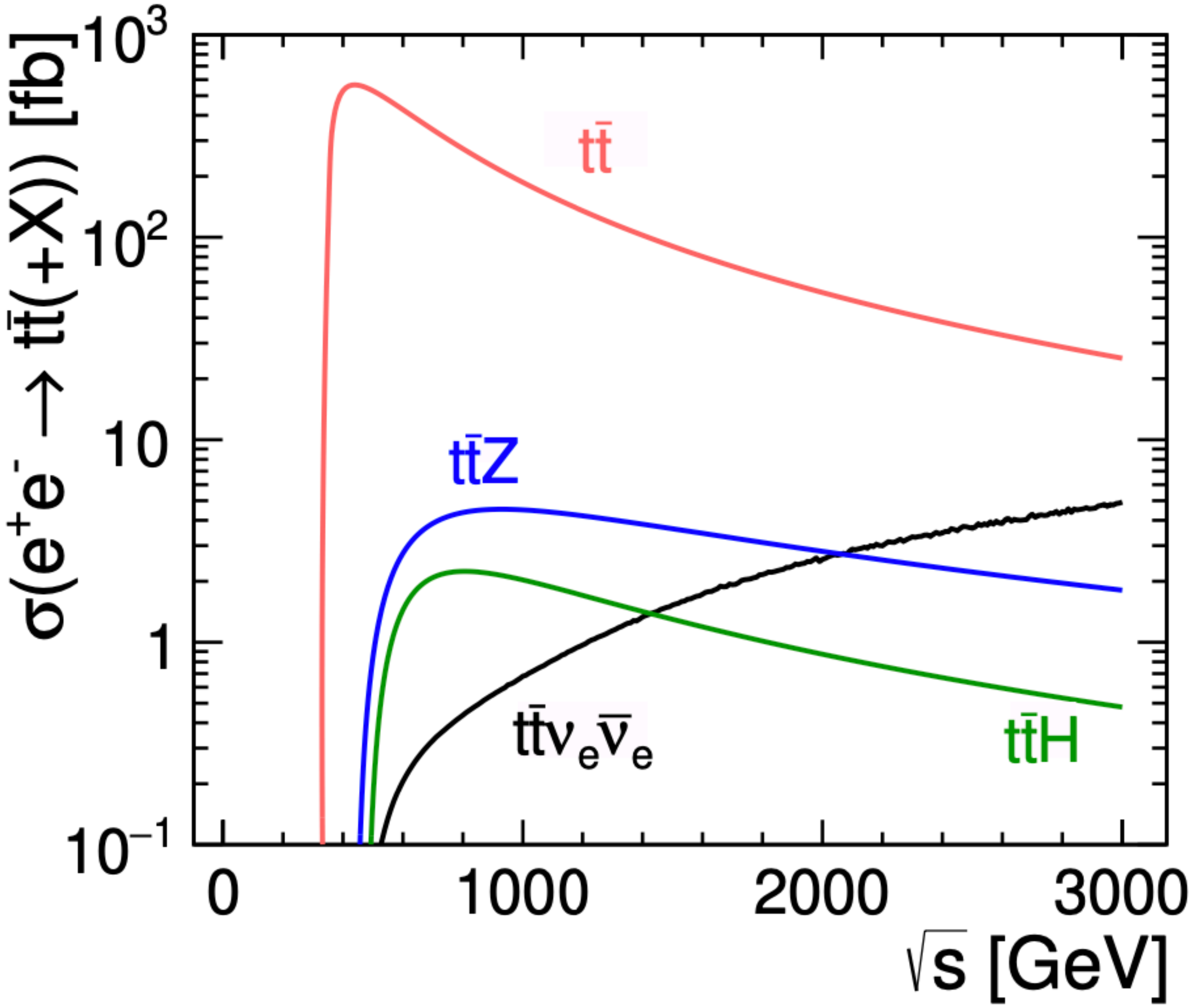
- The mass of the top quark
  - In the continuum and at threshold
- Top quarks as a probe for New Physics
  - Electroweak couplings
  - Global analysis
  - BSM decays
- Top Yukawa via ttH

Focused on linear collider studies, with remarks on FCC-ee potential for selected examples

The Physics Program at Linear Colliders

Energy Stages as seen from the Top

- The top quark production cross section

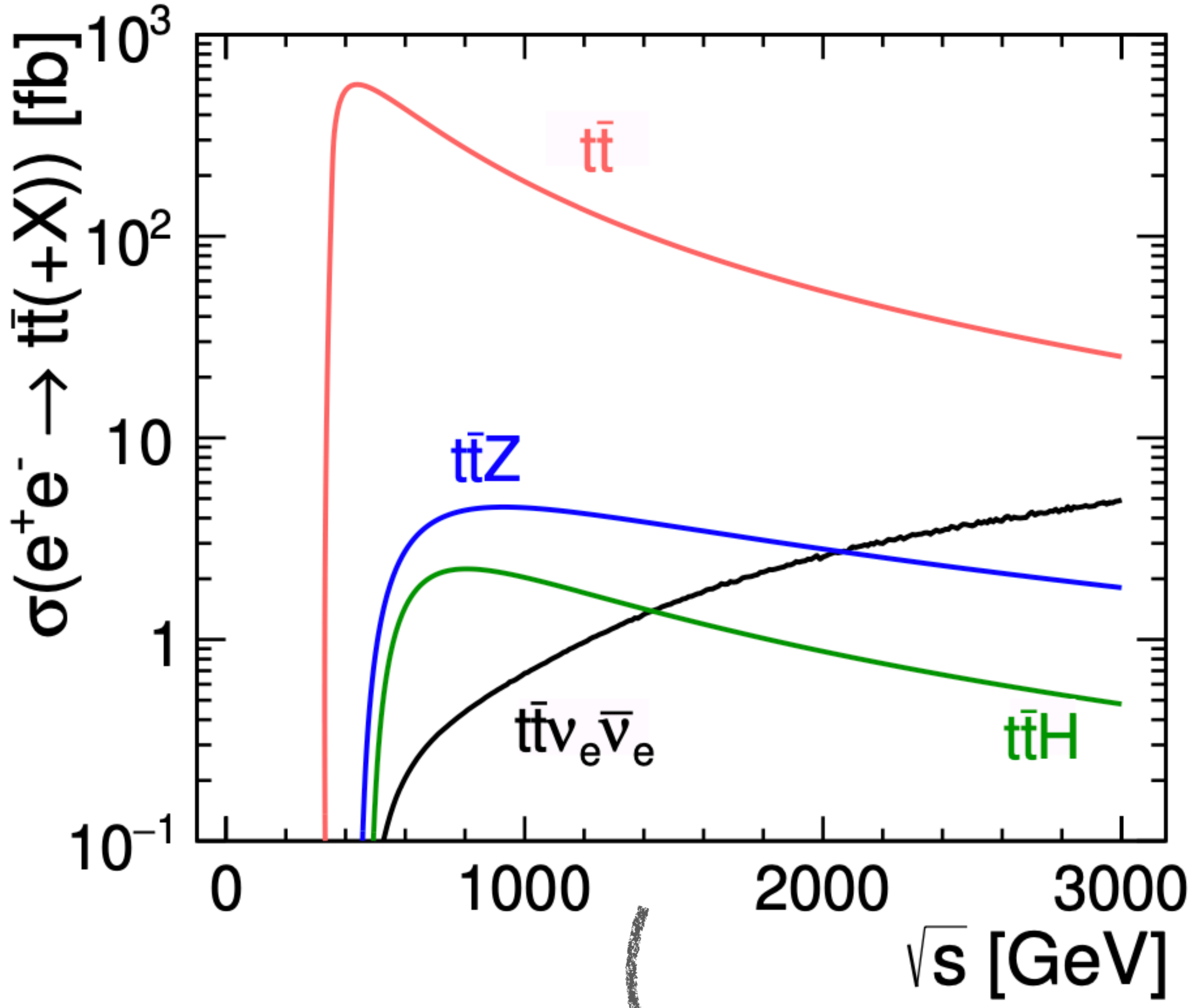


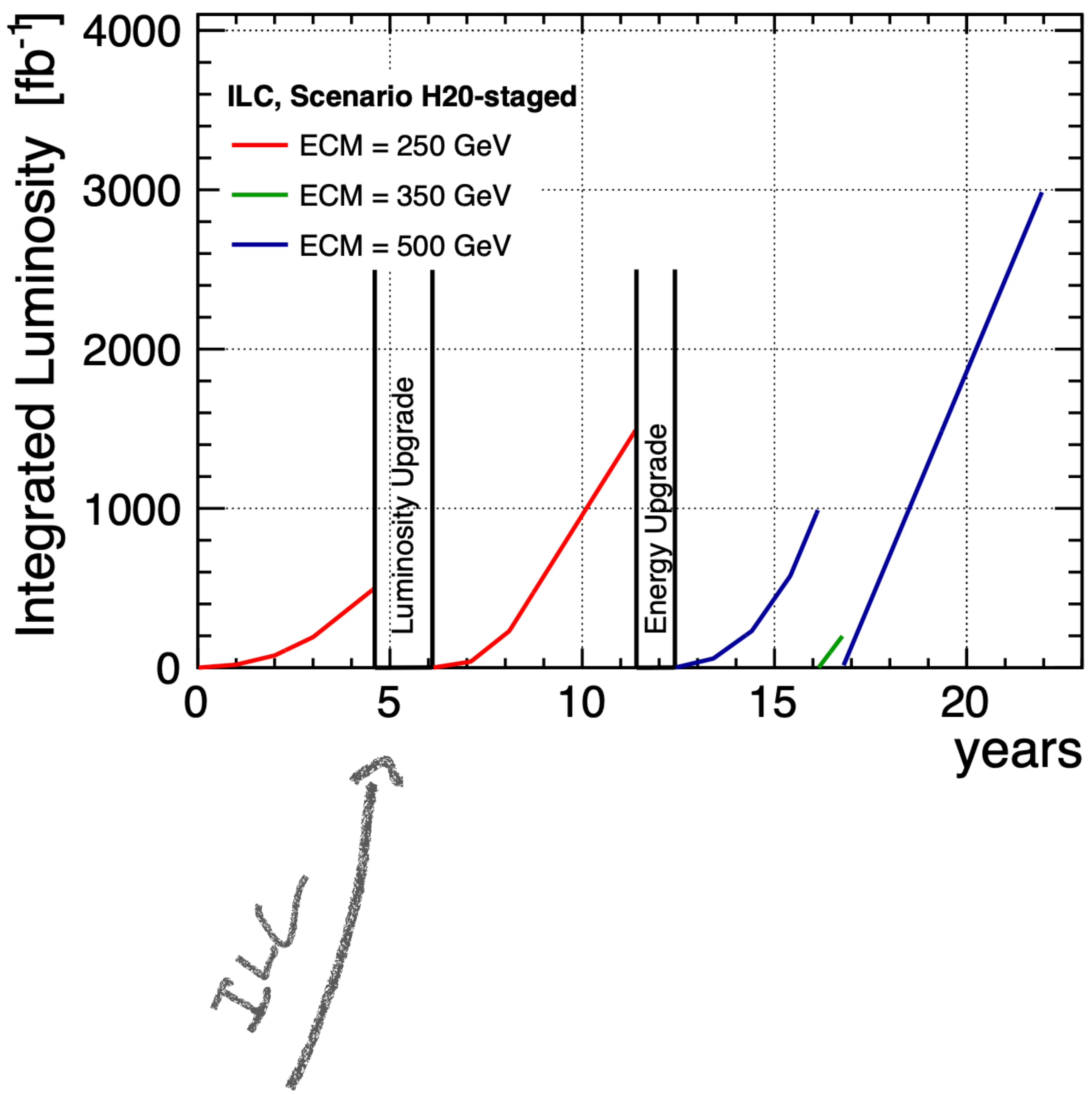
The Physics Program at Linear Colliders

Energy Stages as seen from the Top

MAX-PLANCK-INSTITUT FÜR PHYSIK

- The top quark production cross section



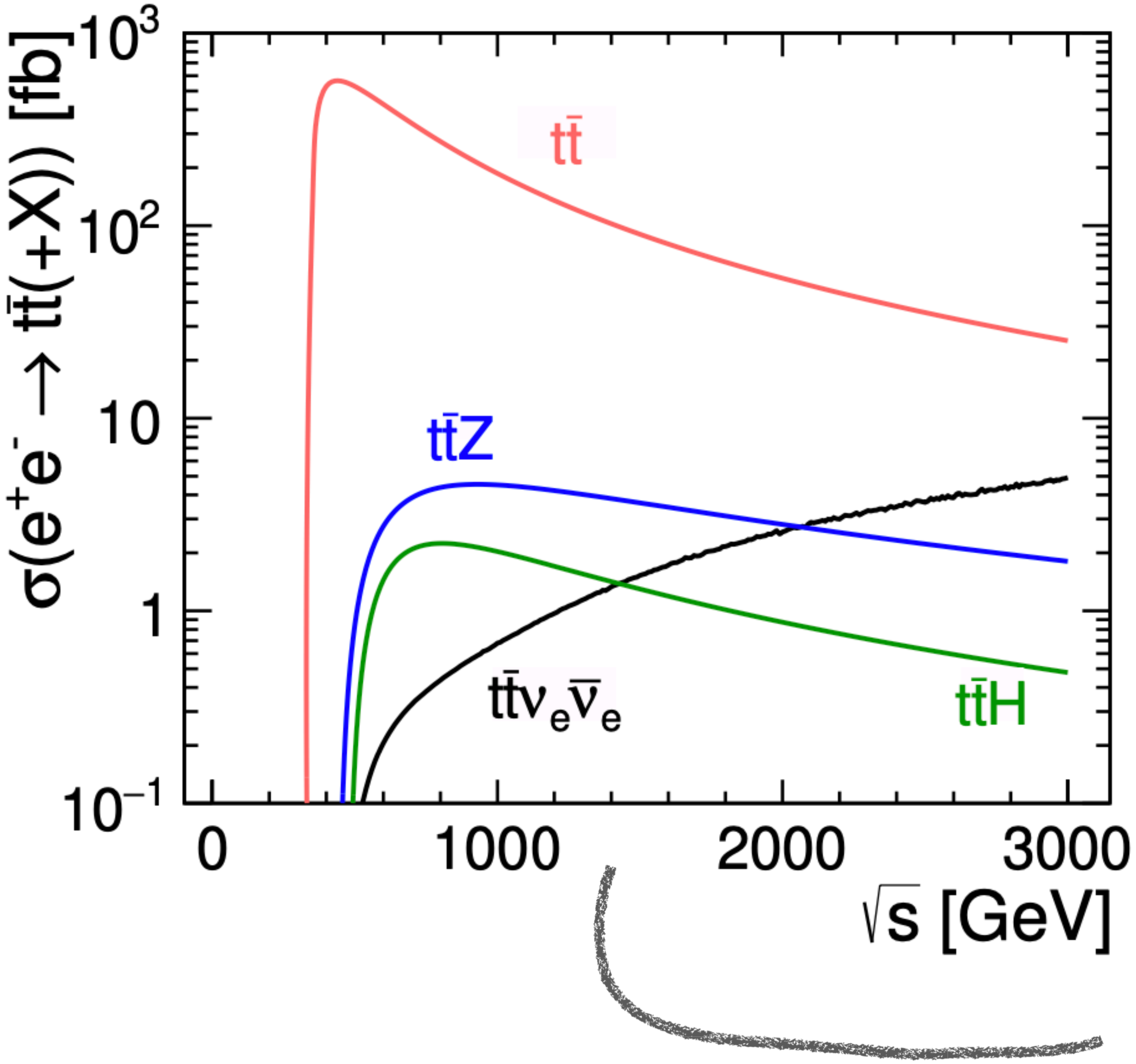


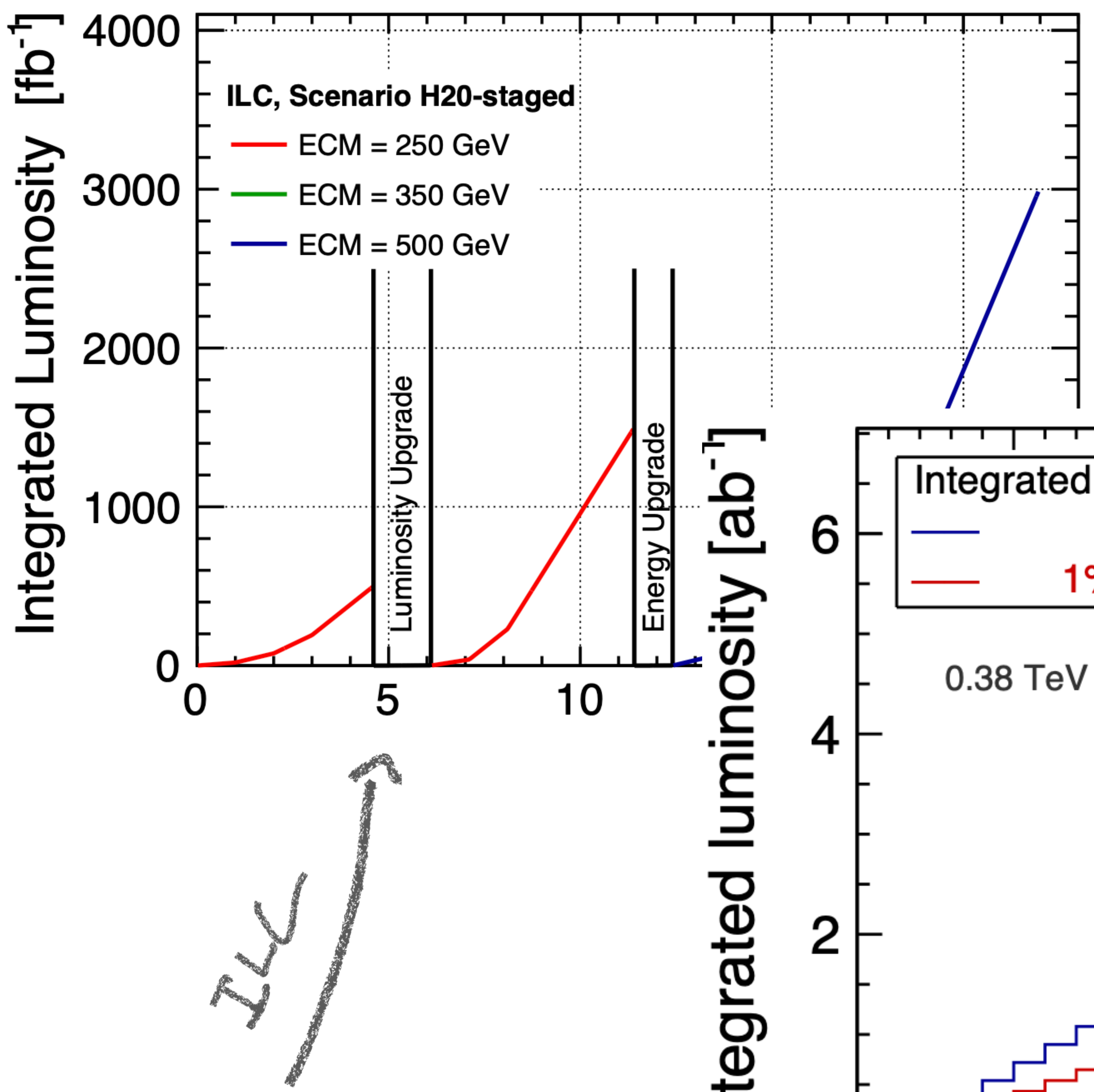
and linear collider running / staging plans

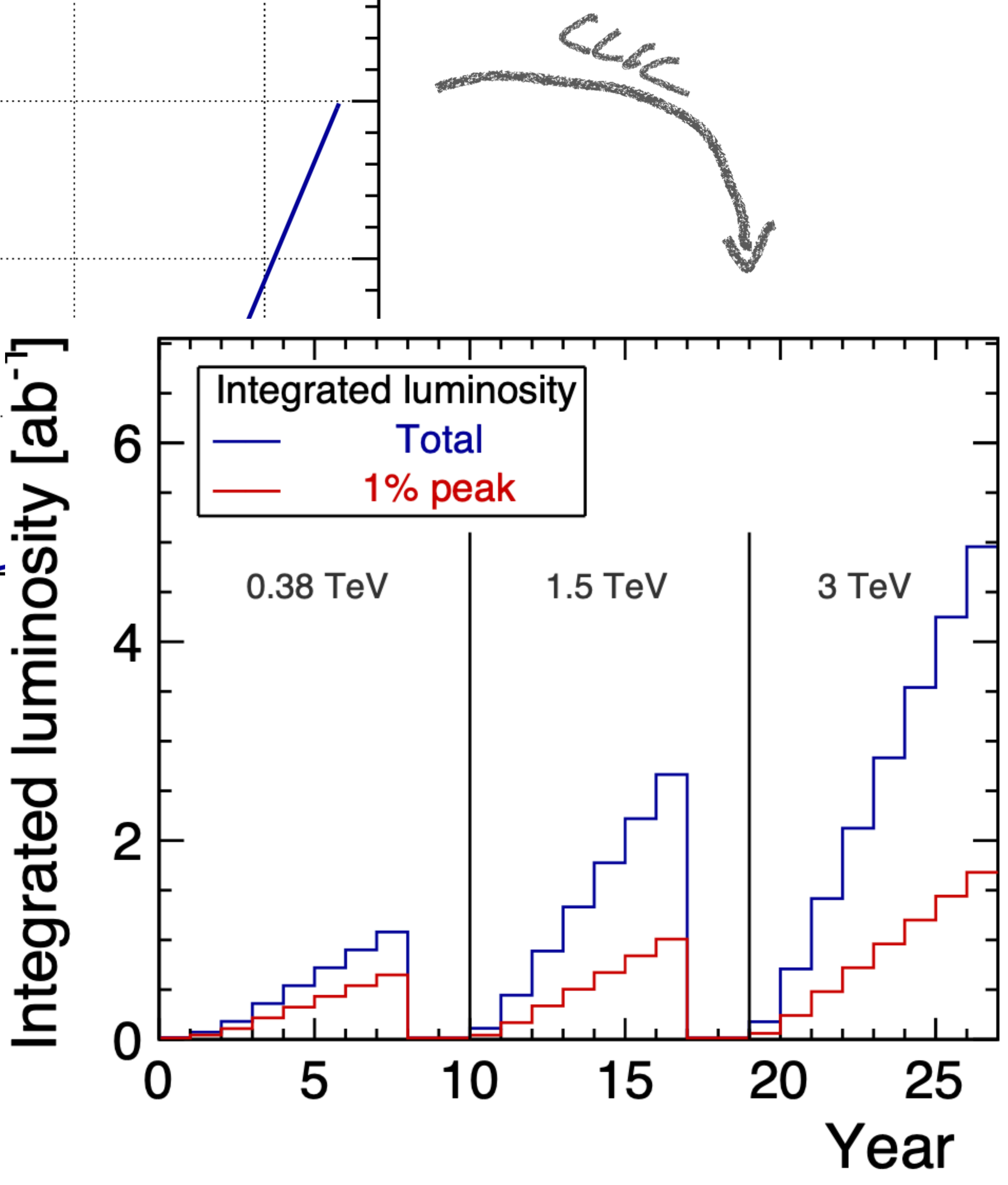
The Physics Program at Linear Colliders

Energy Stages as seen from the Top

- The top quark production cross section





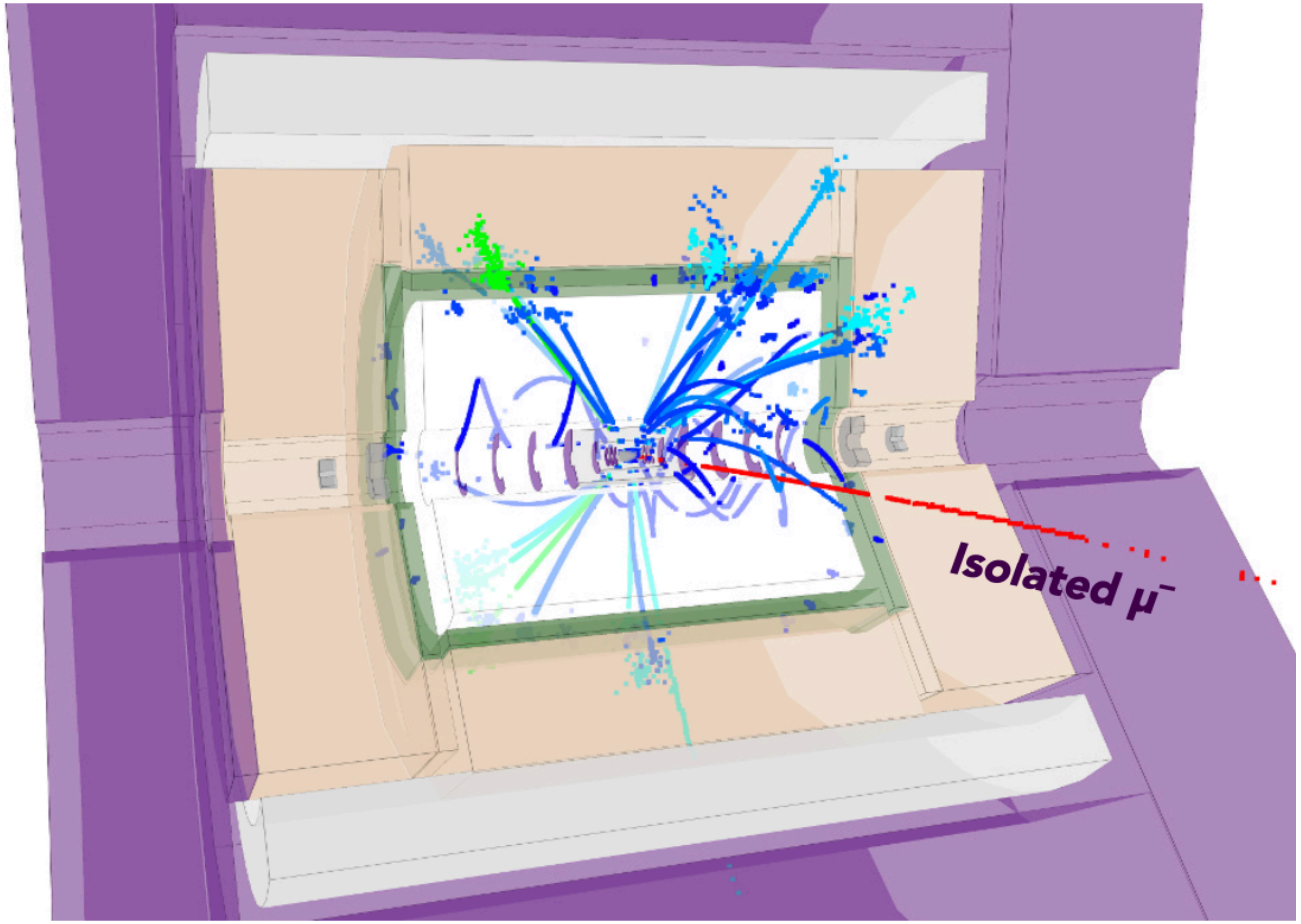


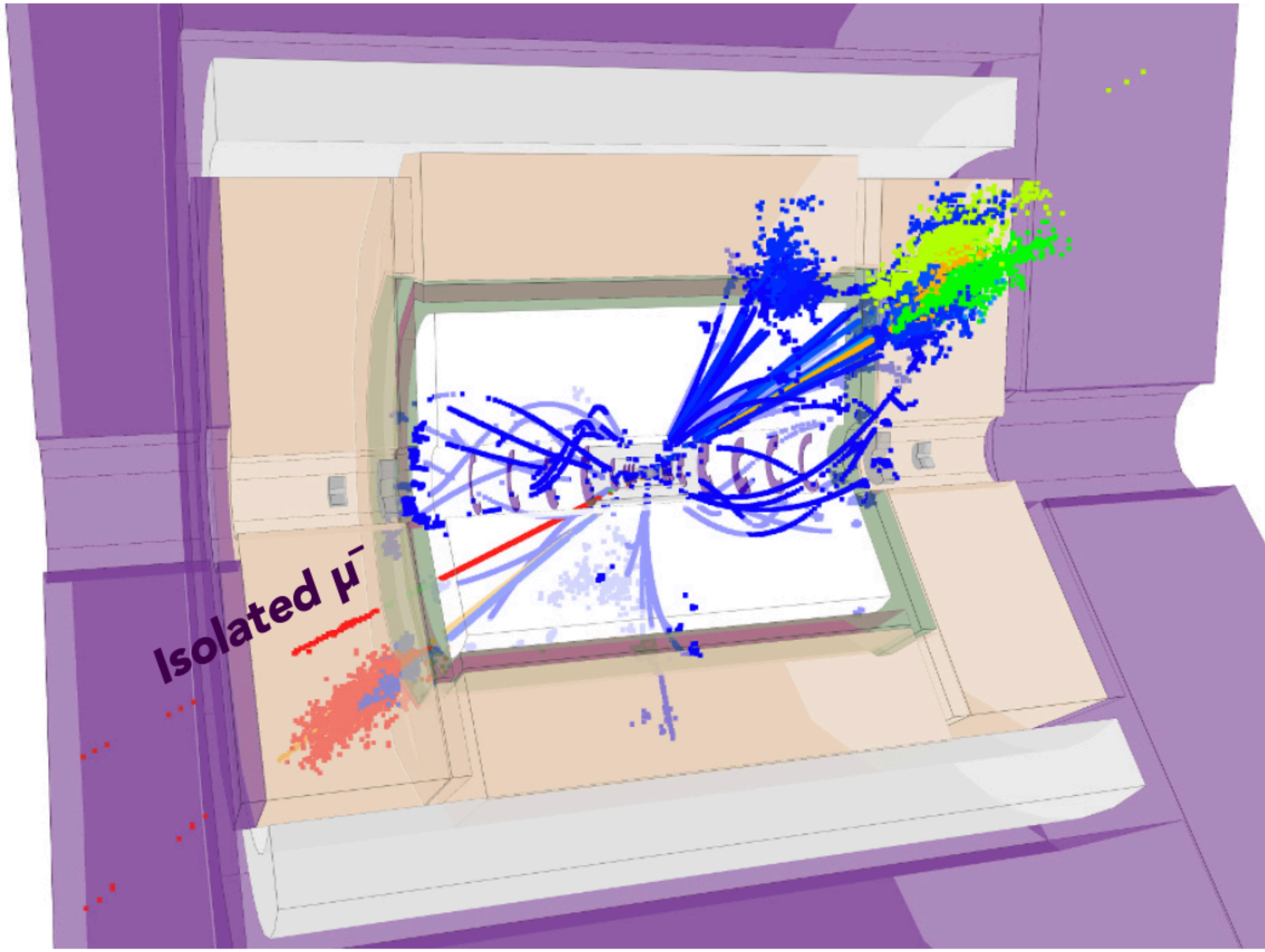
and linear collider running / staging plans

Top Quark Events …

At different Energies

- CLIC 380 GeV and 3 TeV, semi-leptonic top quark pairs

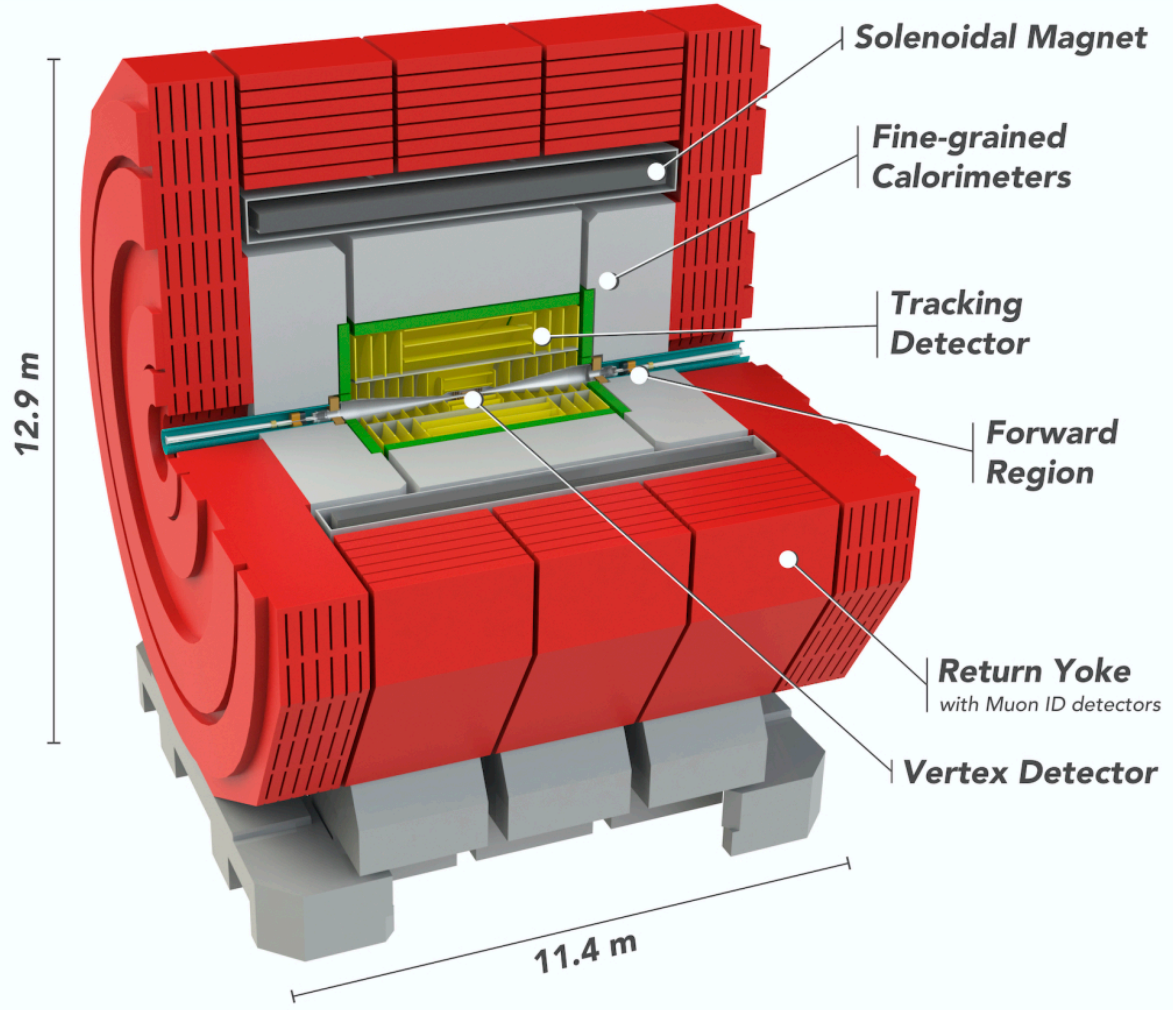




… and their Reconstruction

Key Elements

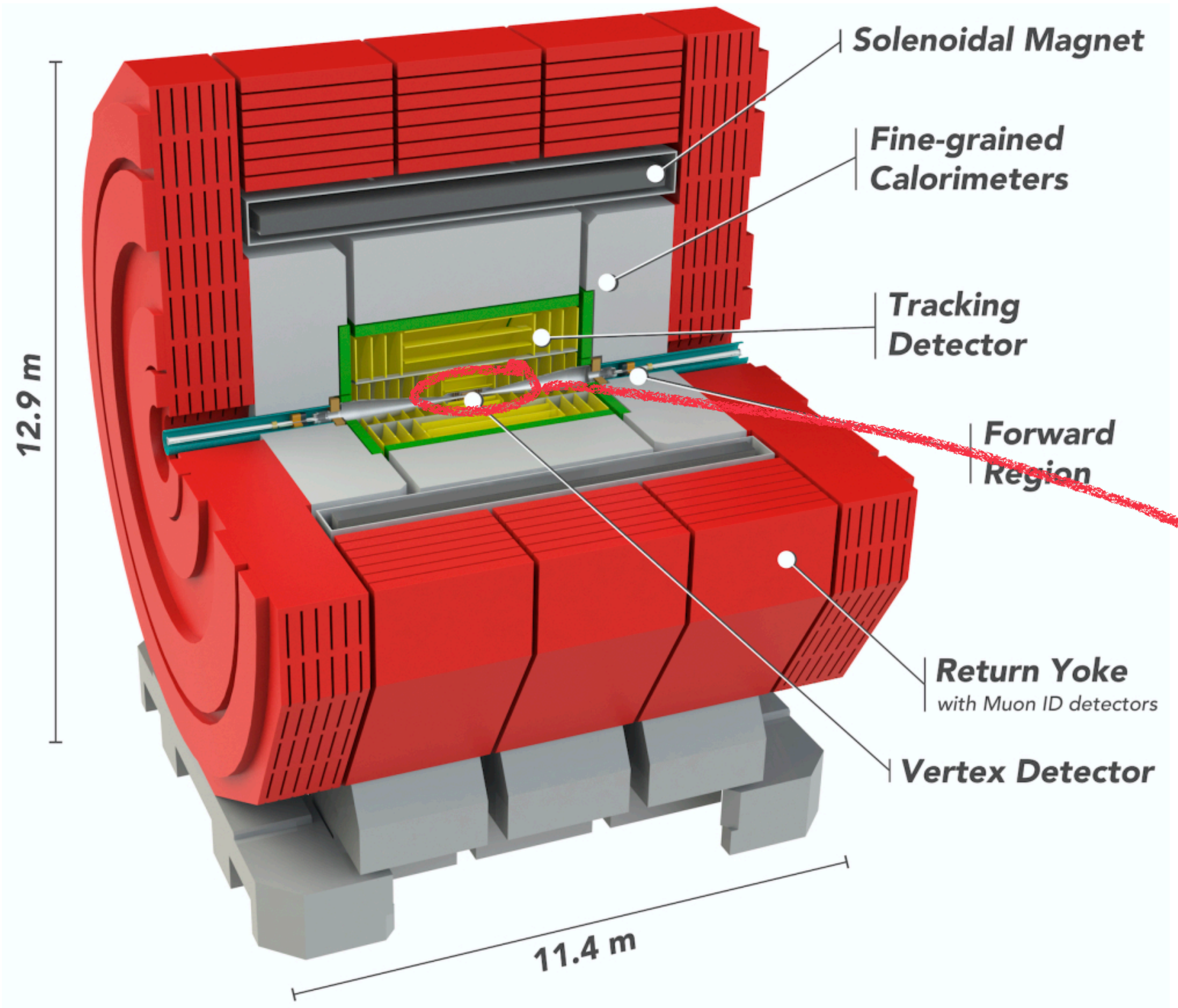
- Top quark physics exercises many of the main detector features of Linear Collider concepts.



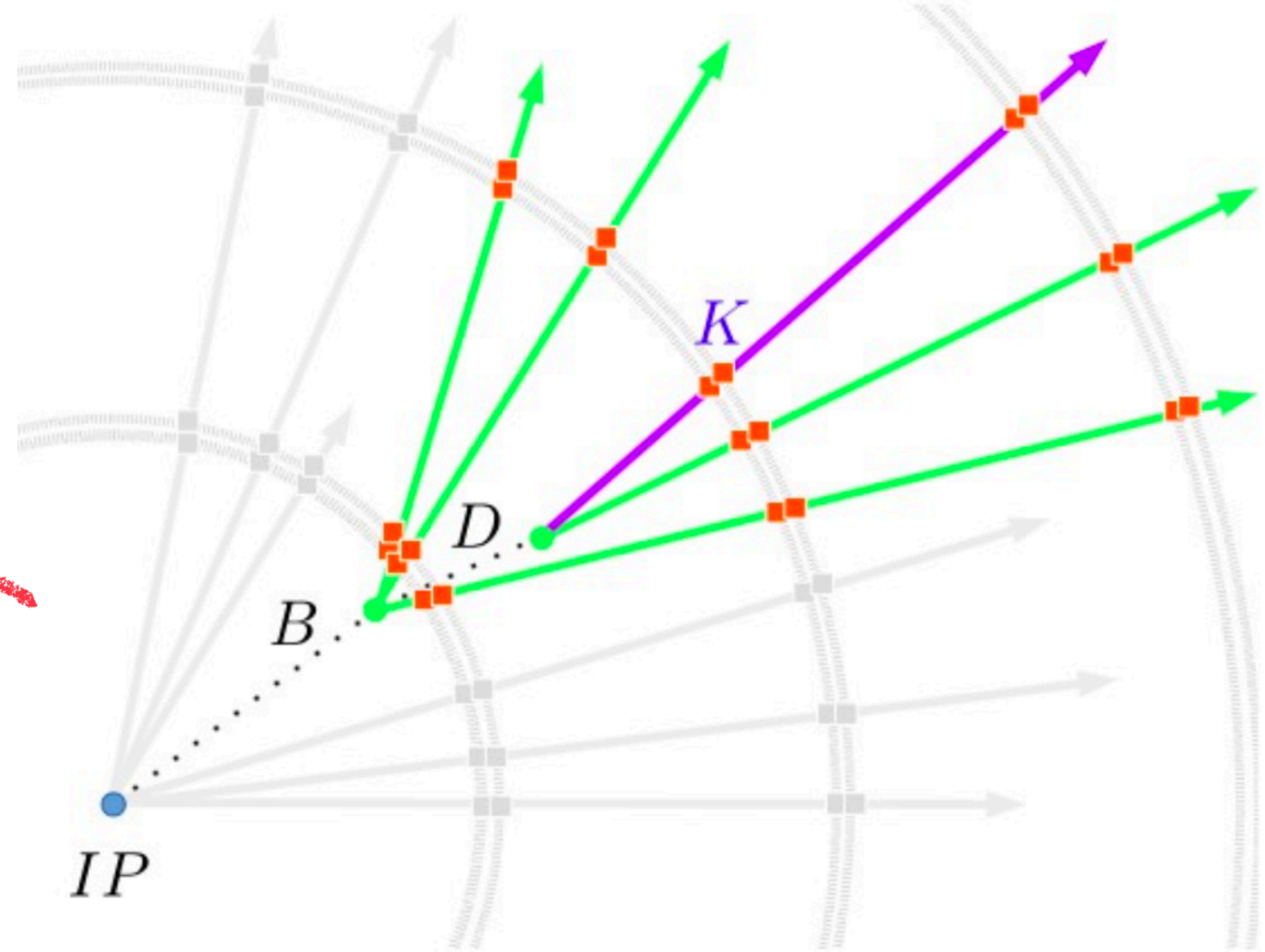
… and their Reconstruction

Key Elements

- Top quark physics exercises many of the main detector features of Linear Collider concepts.



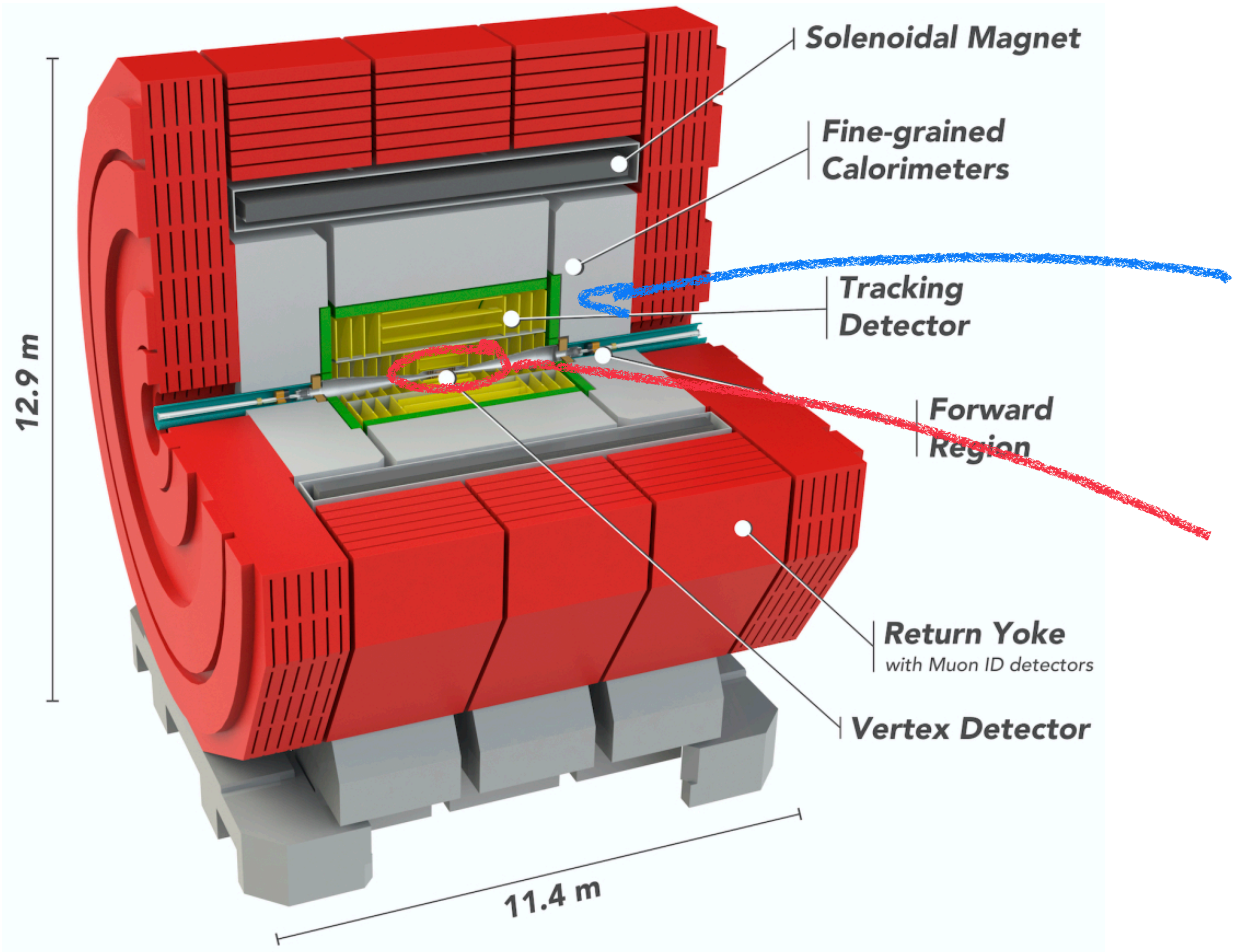
flavor tagging:
b, but also c



… and their Reconstruction

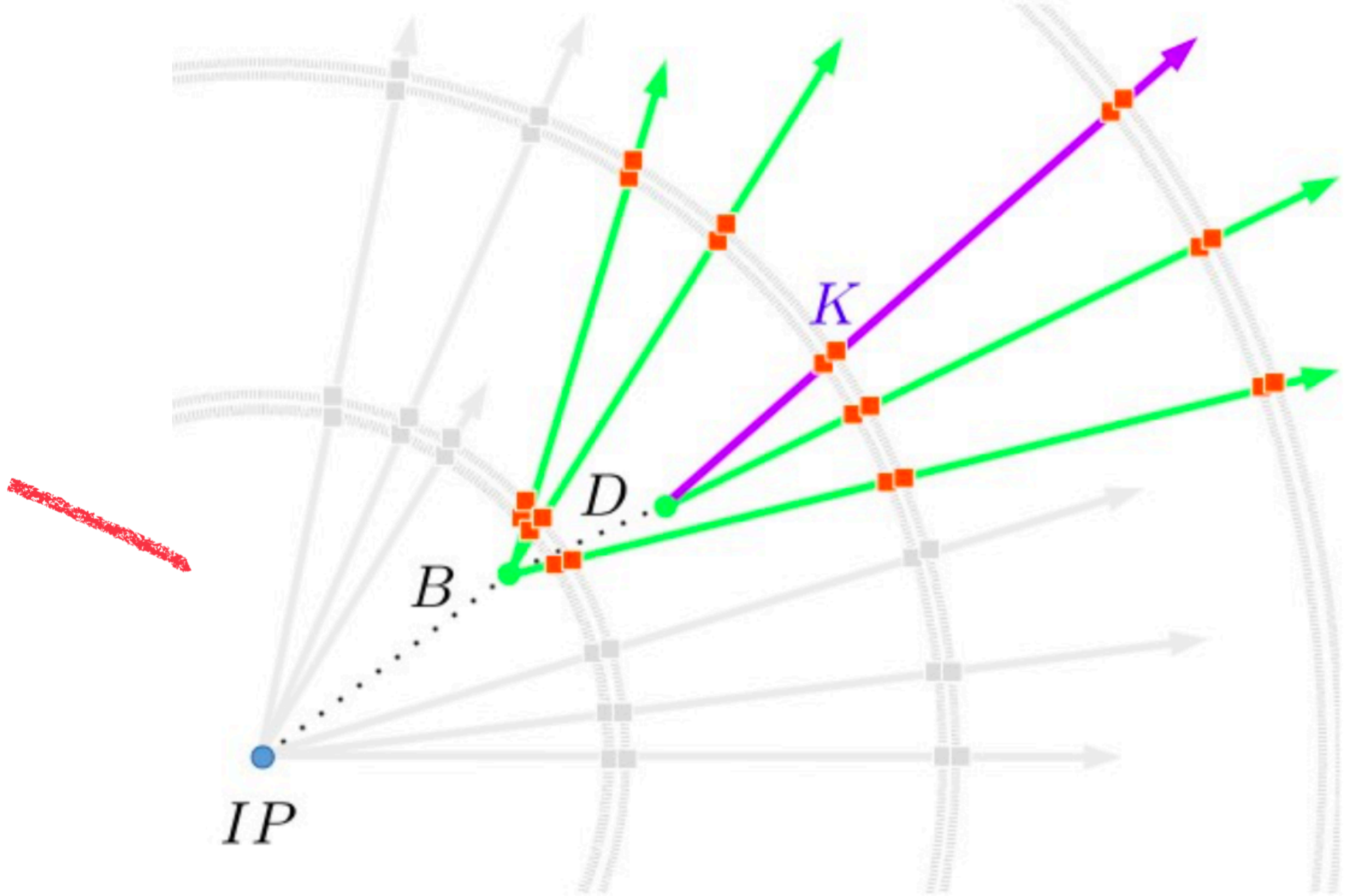
Key Elements

- Top quark physics exercises many of the main detector features of Linear Collider concepts.



jet and overall event reconstruction

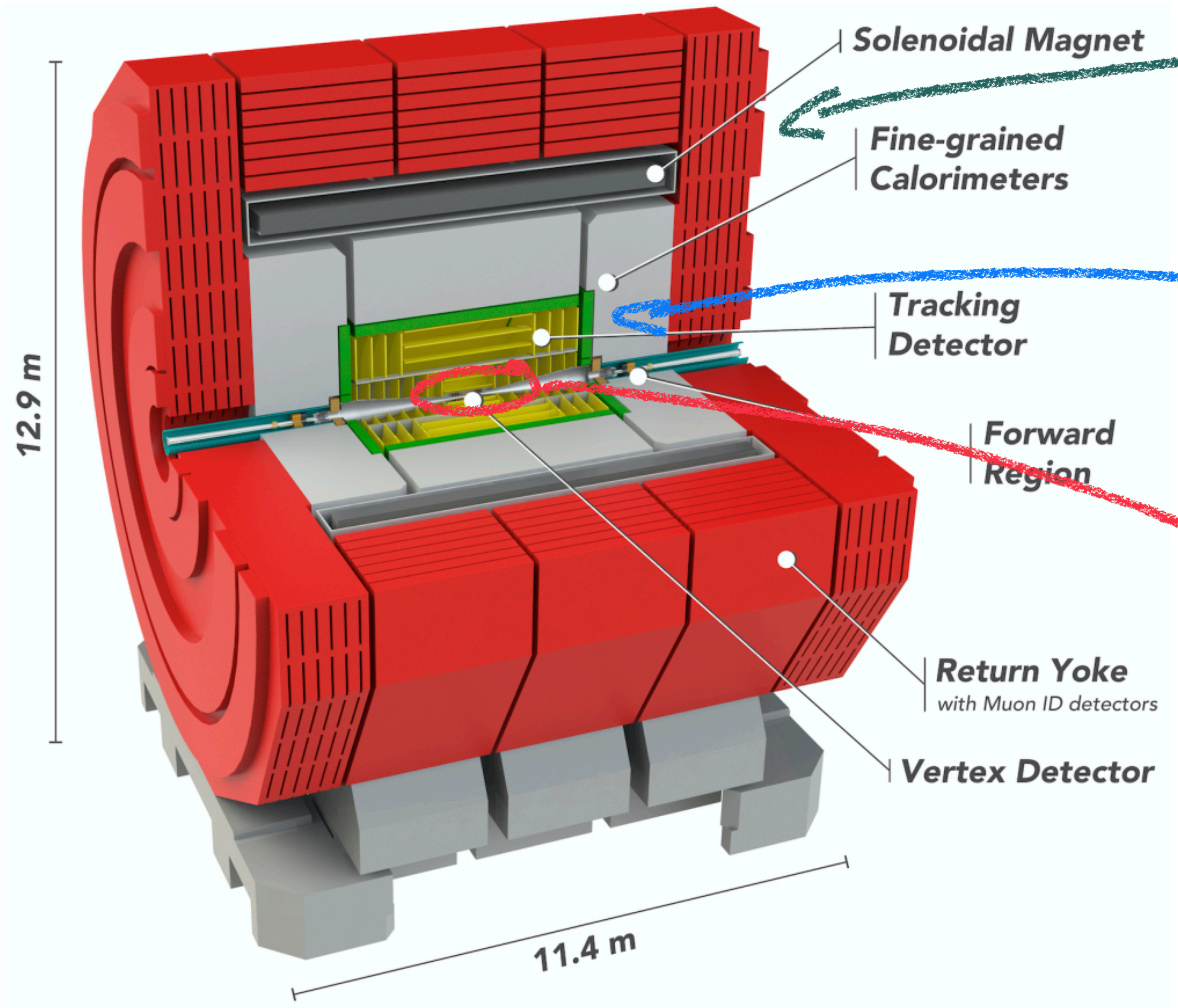
flavor tagging:
b, but also c



… and their Reconstruction

Key Elements

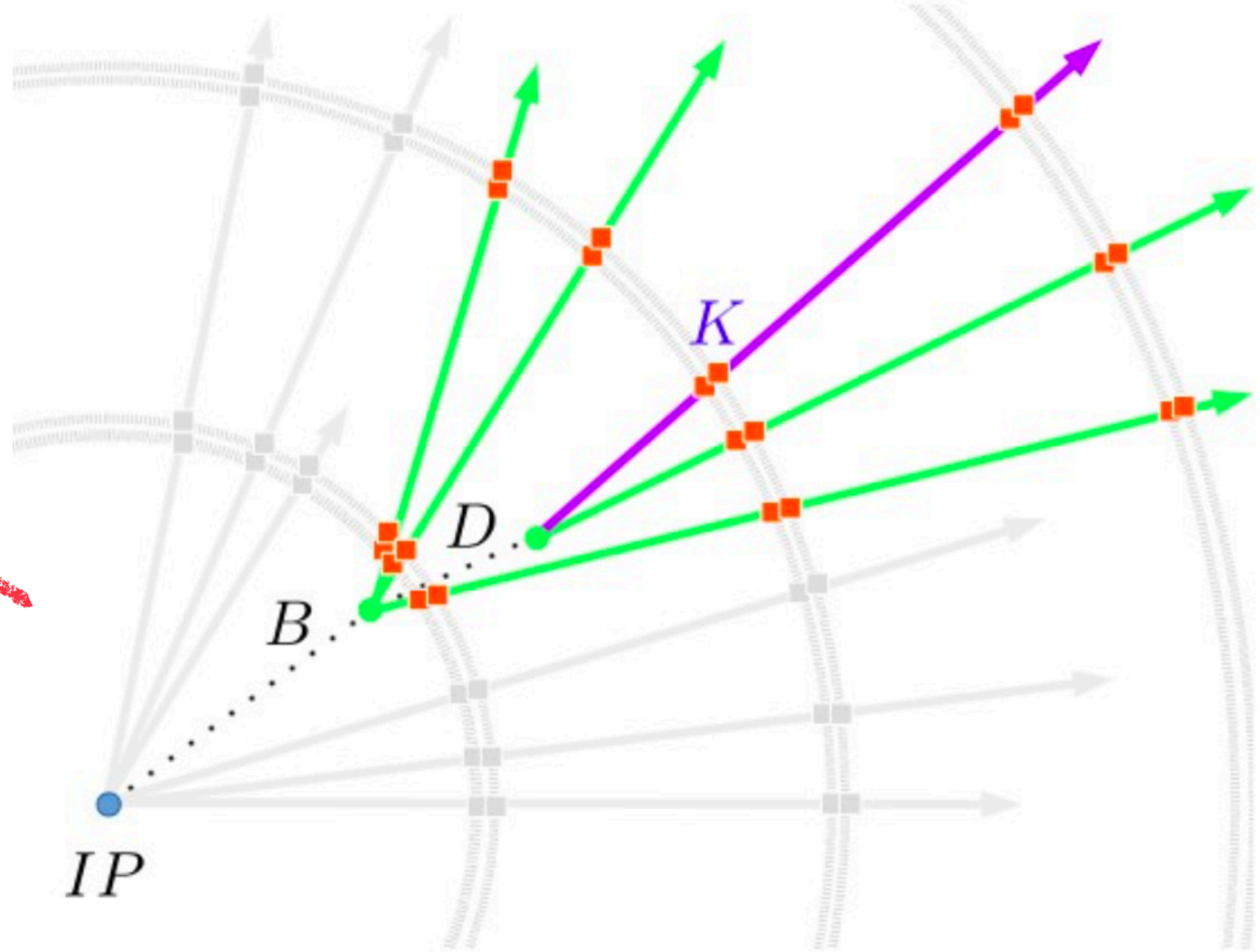
- Top quark physics exercises many of the main detector features of Linear Collider concepts.



lepton identification and measurement

jet and overall event reconstruction

flavor tagging: b, but also c



The Mass

The Top Quark Mass

Towards ultimate Precision

MAX-PLANCK-INSTITUT FÜR PHYSIK

Conceptually: Three approaches to the top mass

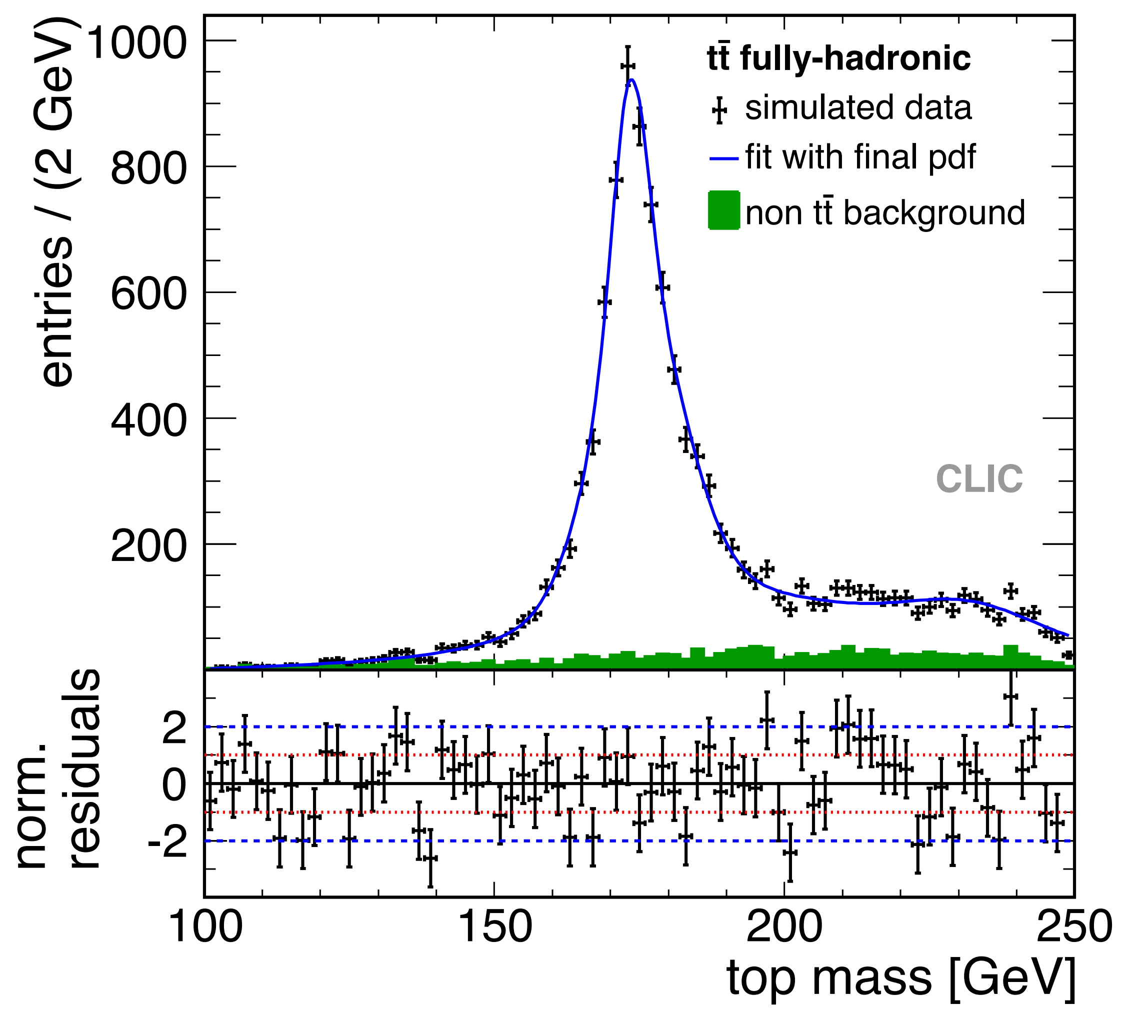
The Top Quark Mass

Towards ultimate Precision

MAX-PLANCK-INSTITUT FÜR PHYSIK

Conceptually: Three approaches to the top mass

Direct kinematic reconstruction



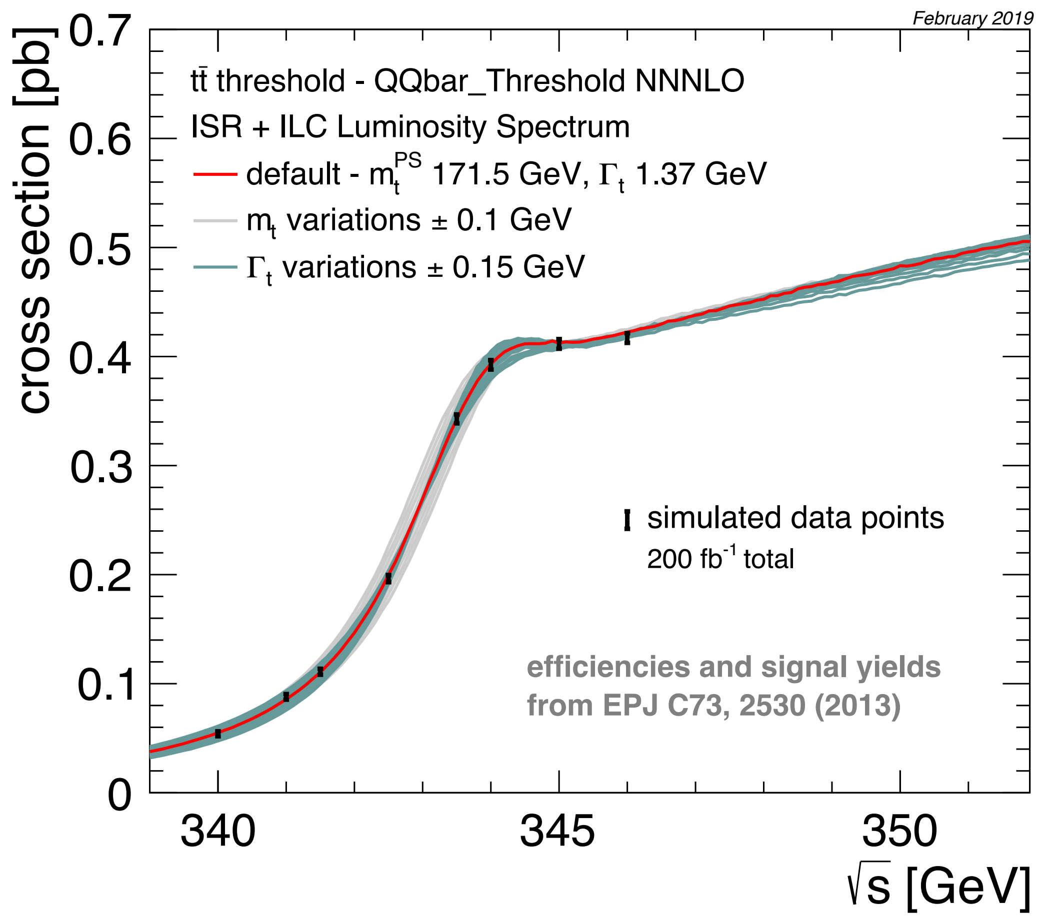
The Top Quark Mass

Towards ultimate Precision

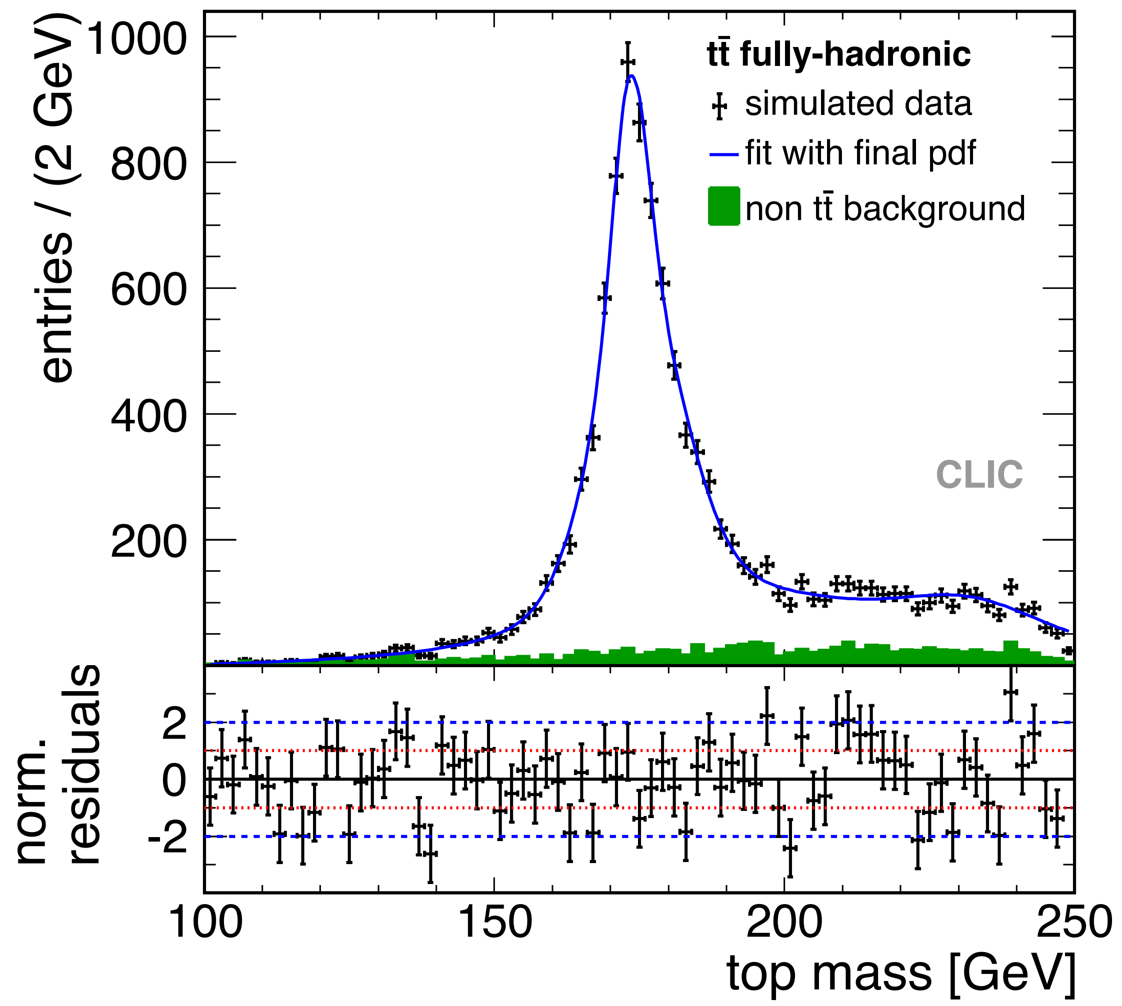
MAX-PLANCK-INSTITUT
FÜR PHYSIK

Conceptually: Three approaches to the top mass

The threshold scan around 350 GeV



Direct kinematic reconstruction

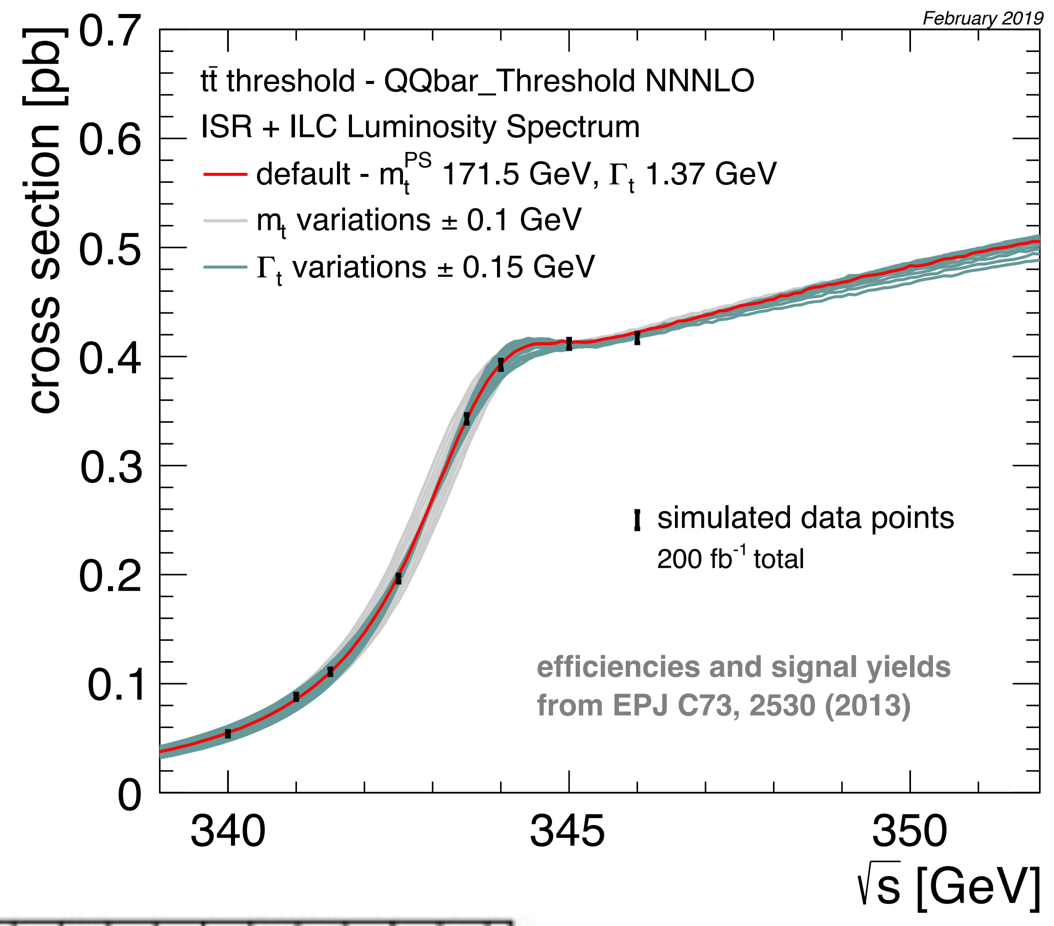


The Top Quark Mass

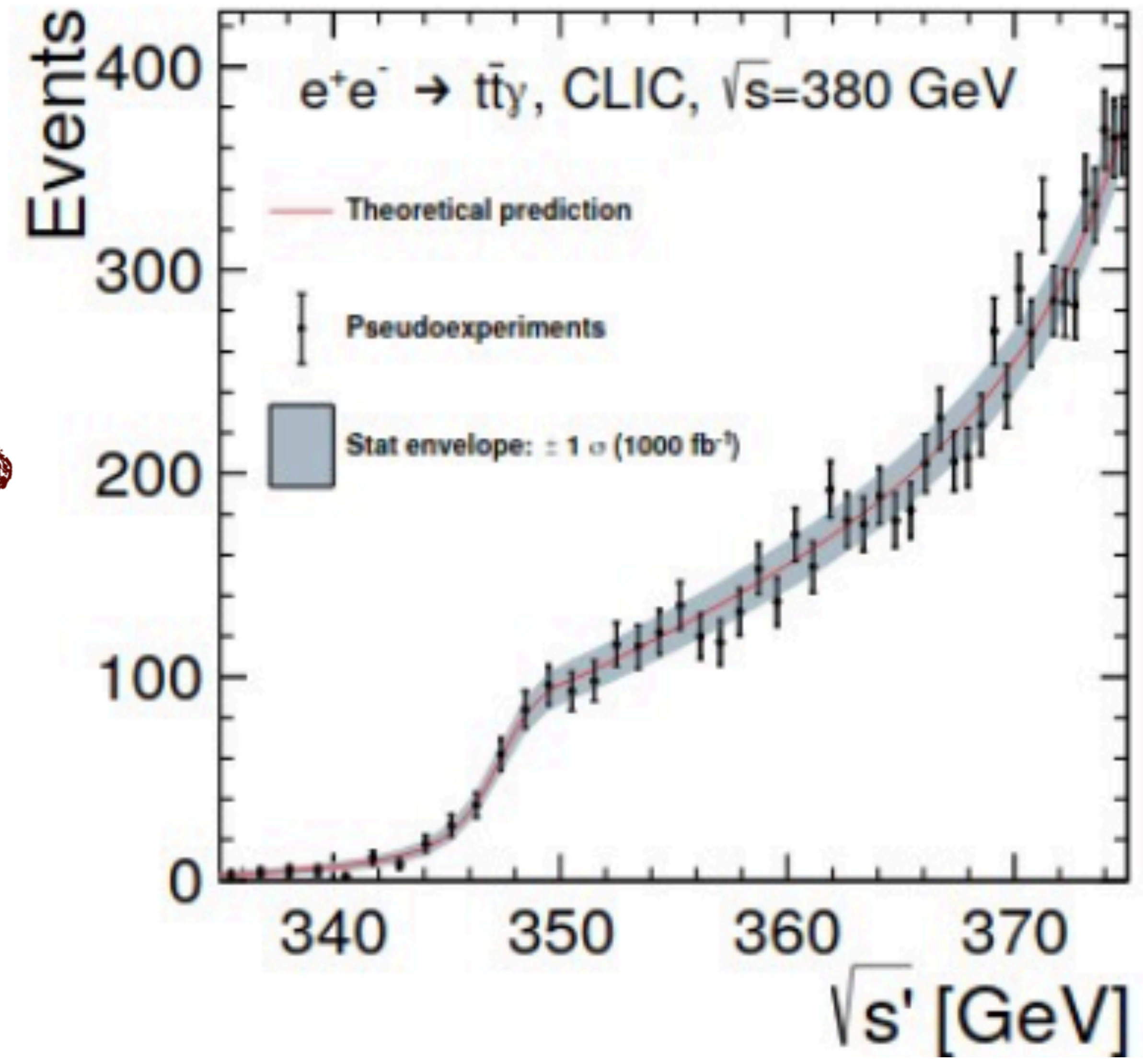
Towards ultimate Precision

Conceptually: Three approaches to the top mass

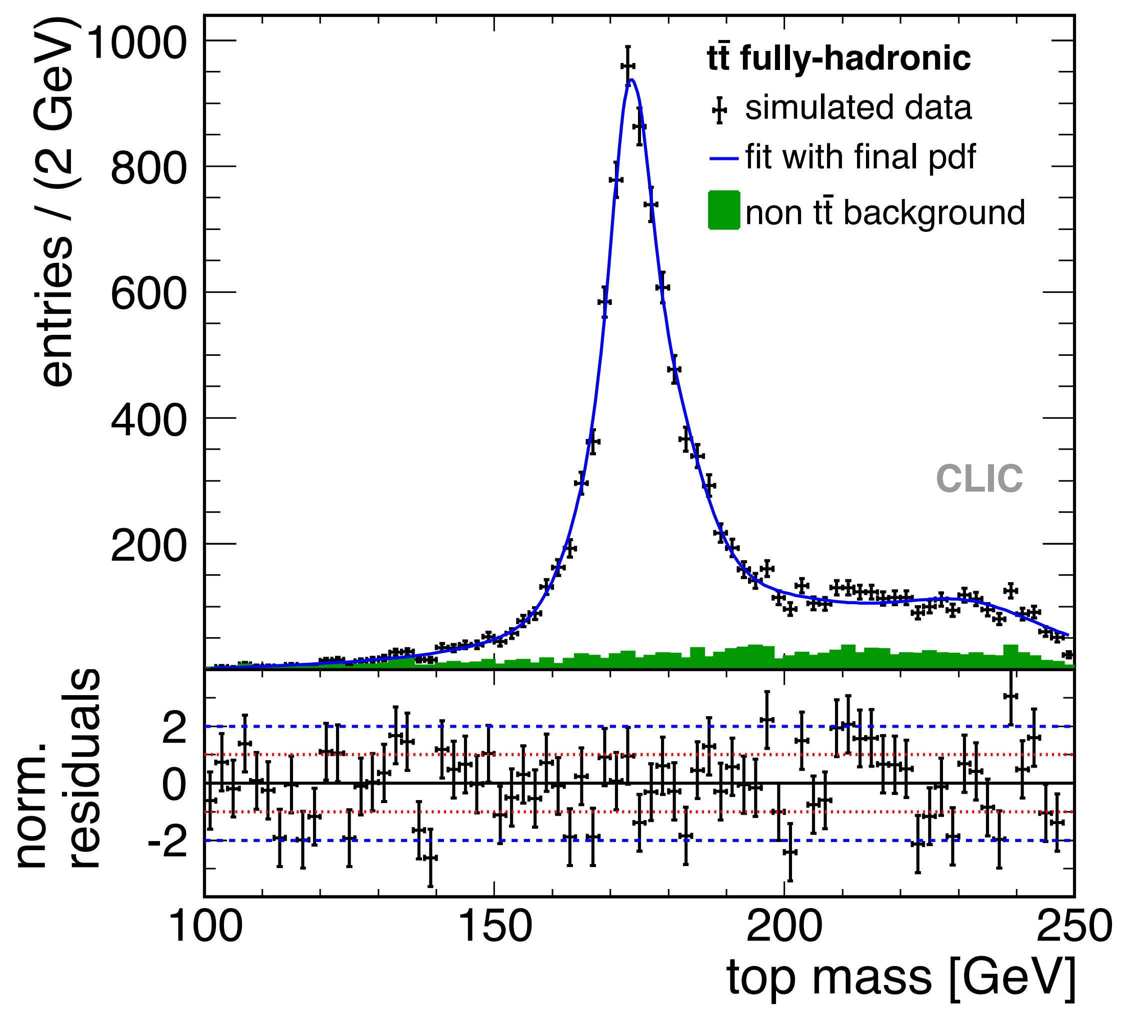
The threshold scan around 350 GeV



The top mass from radiative events



Direct kinematic reconstruction

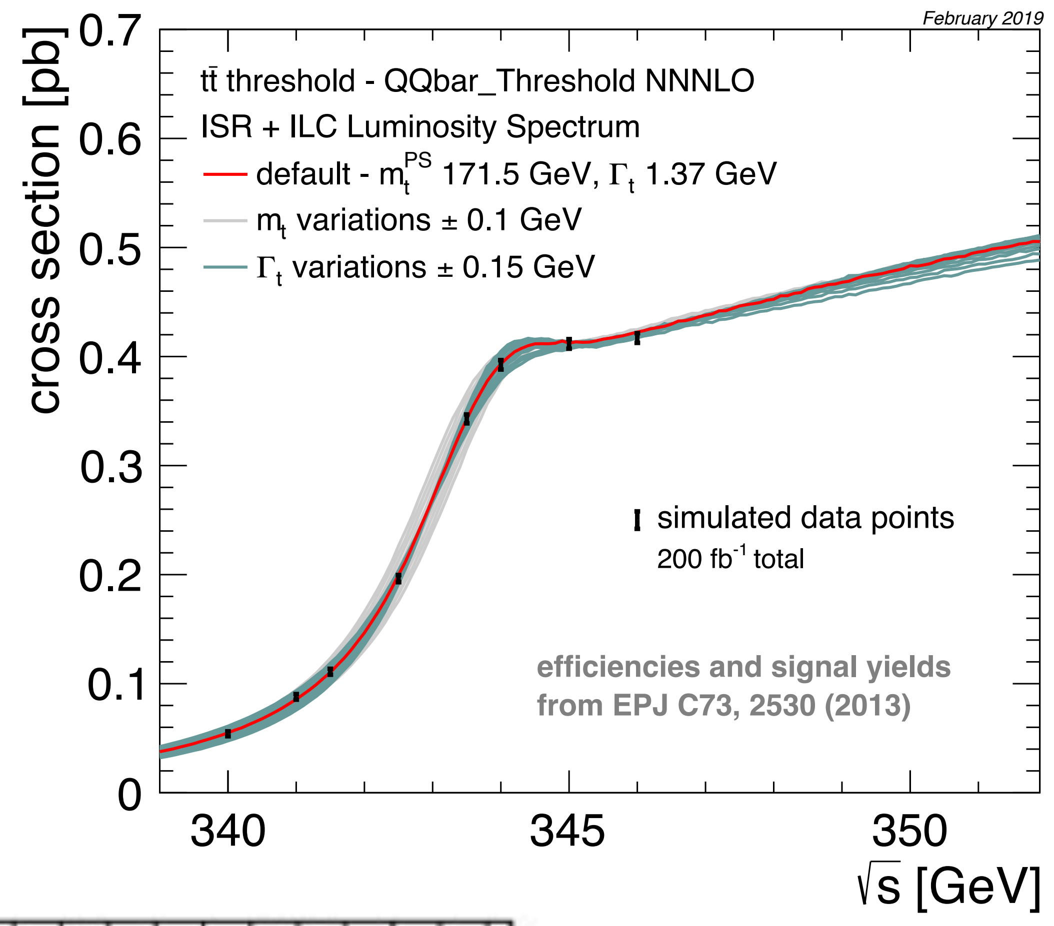


The Top Quark Mass

Towards ultimate Precision

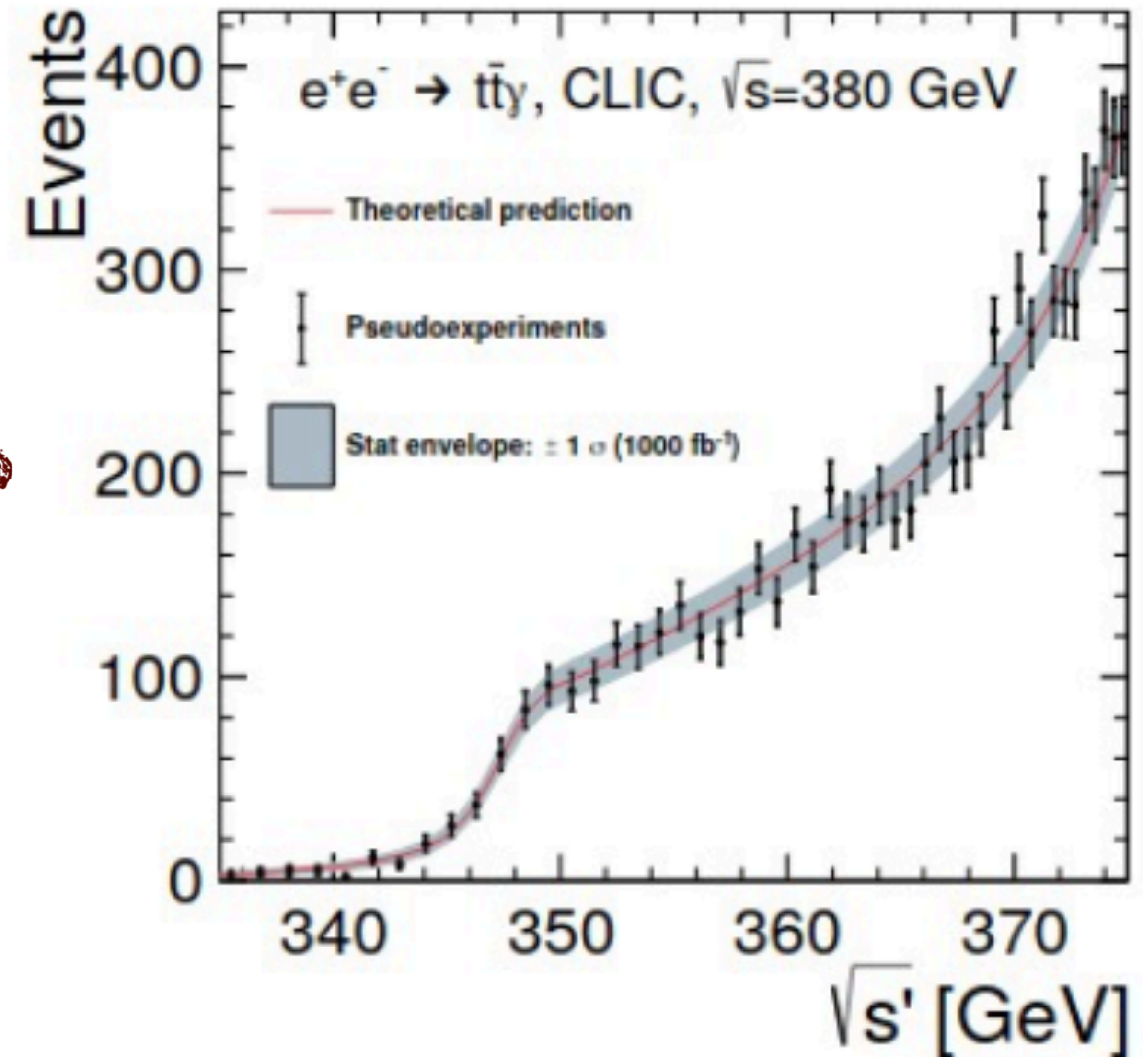
Conceptually: Three approaches to the top mass

The threshold scan around 350 GeV

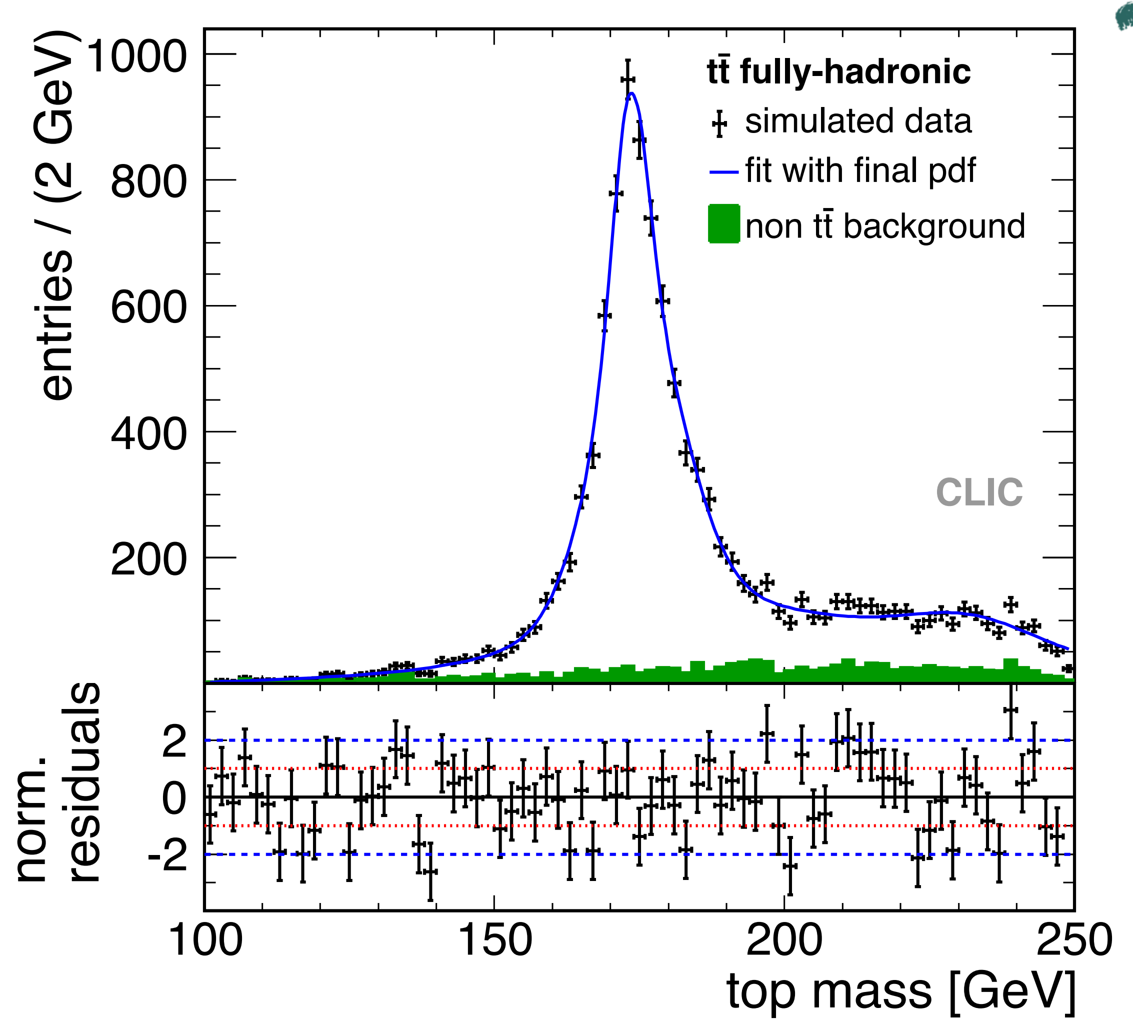


theoretically well-defined

The top mass from radiative events



Direct kinematic reconstruction

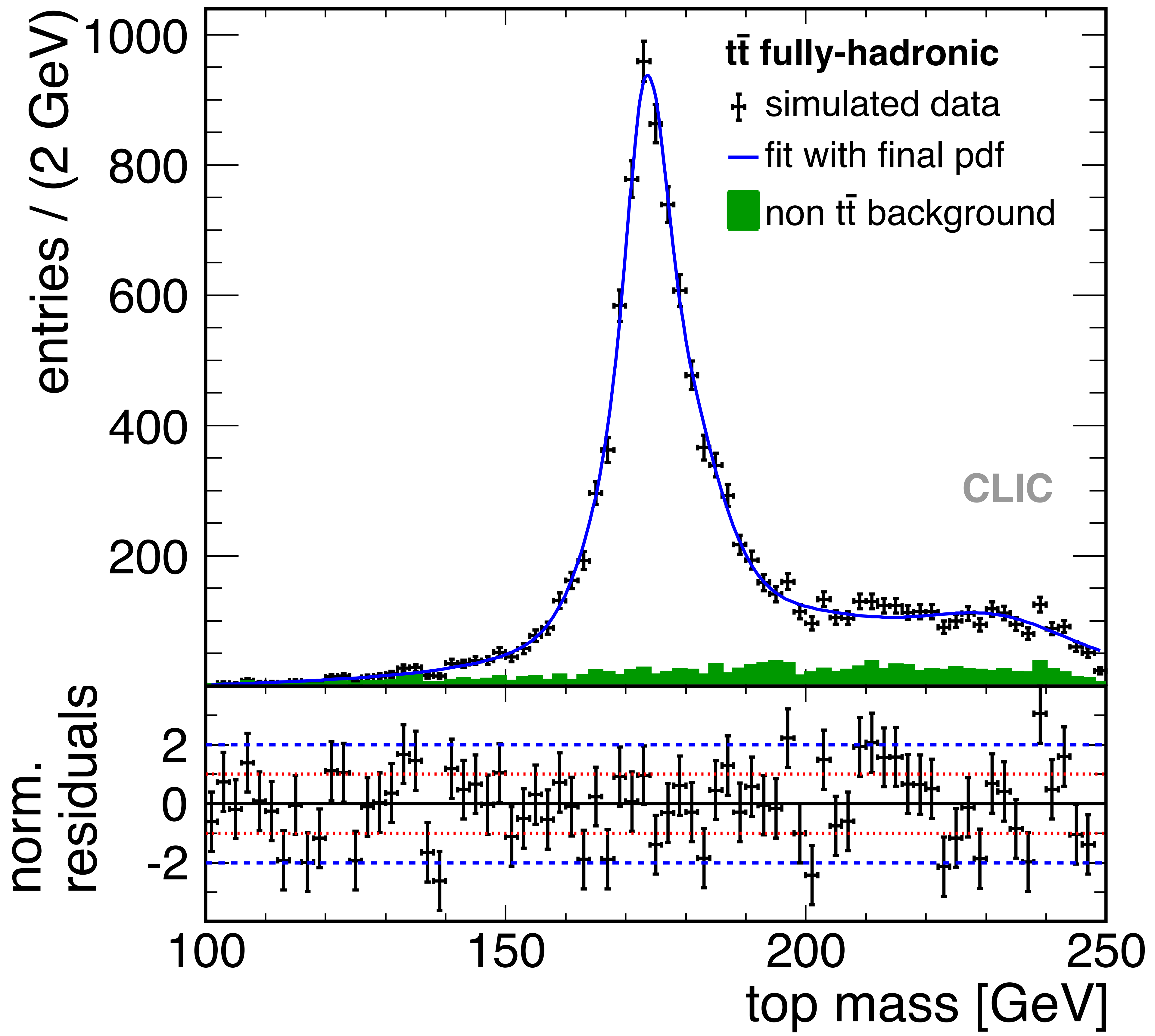


interpretation challenge

Kinematic Mass Reconstruction

Measuring the Mass "a la LHC"

- Kinematic reconstruction of decay products
  - Profits from kinematic fits exploiting constraints: overall energy, W mass



- For 1 ab^{-1} statistical uncertainties of 20 - 40 MeV
  - key challenge: controlling jet energy scales, in particular b-JES

- Main conceptual problem: Interpretation of mass value - with significant uncertainties

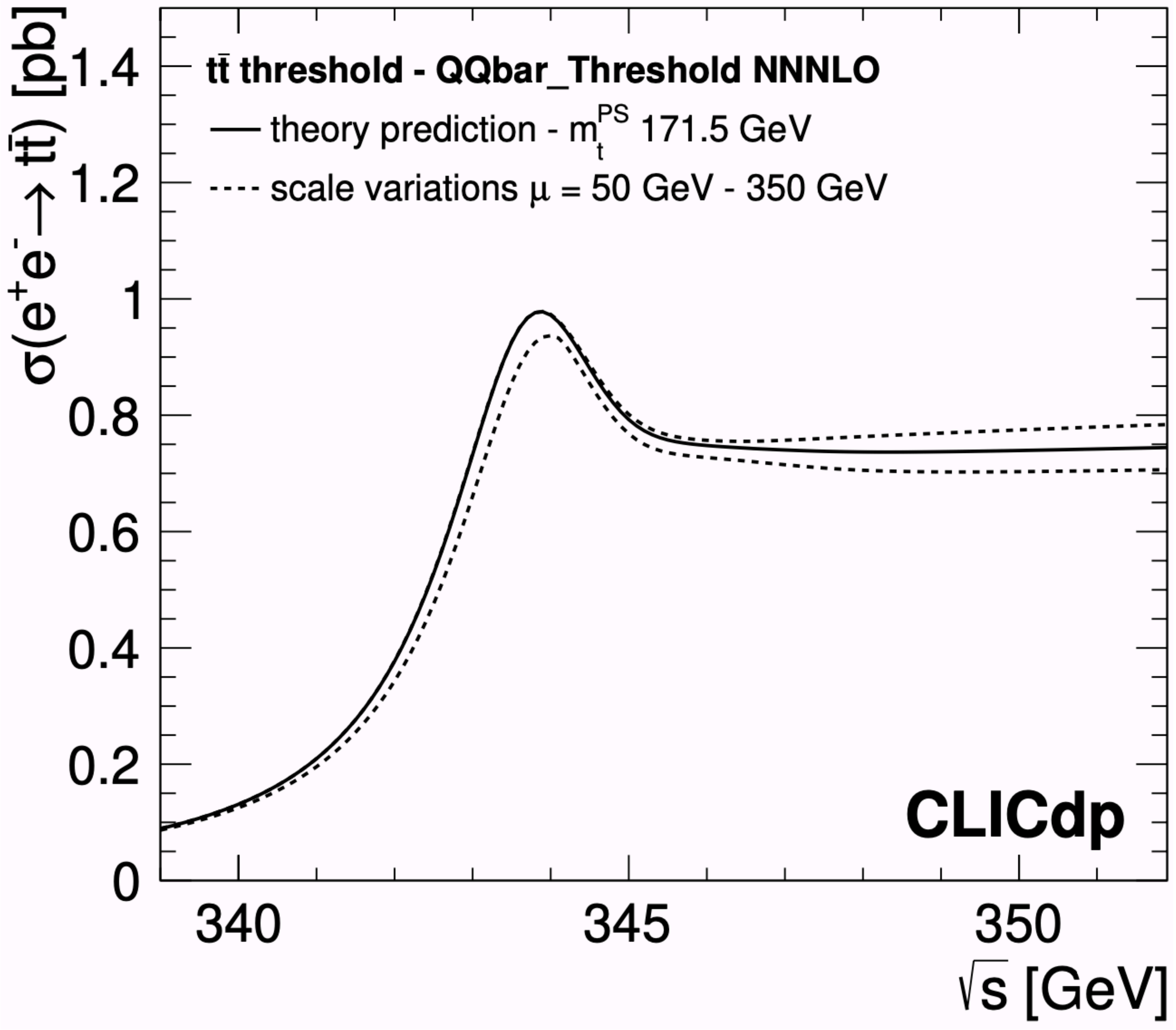
"old" study, 100 fb^{-1} @ 500 GeV

newer (simpler) studies at 380 GeV consistent

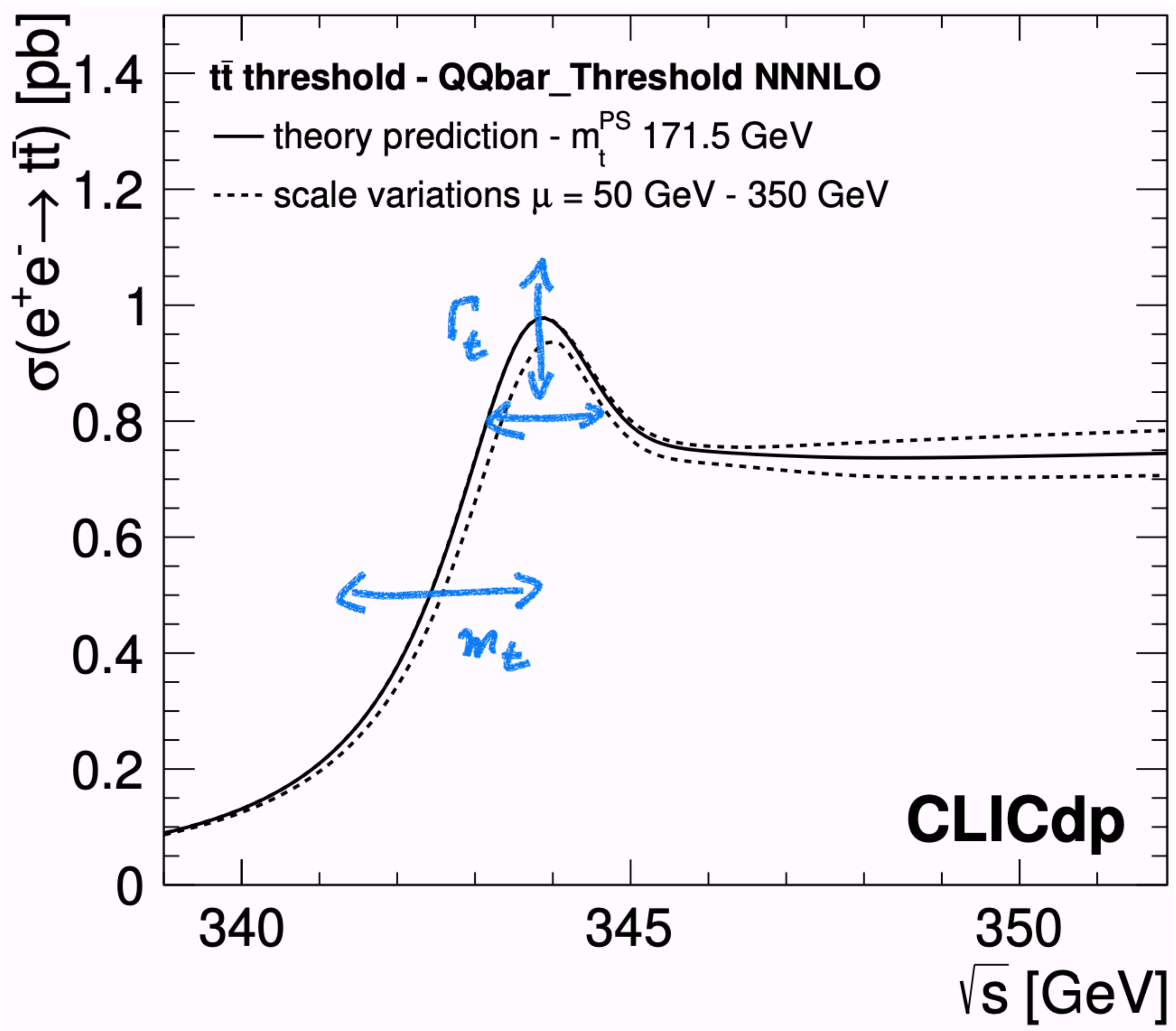
EPJ C73, 2530 (2013)

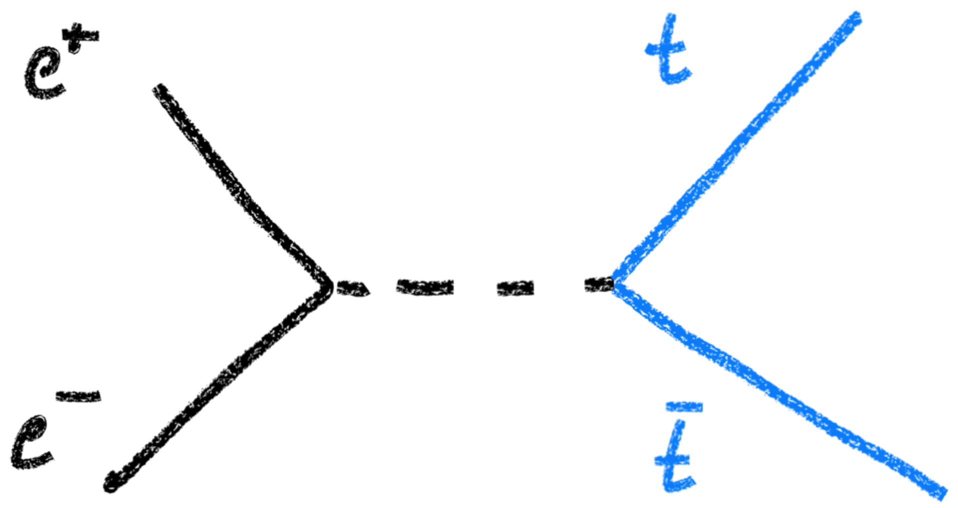
The Top Pair Threshold

Sensitivity to Top Quark Parameters



- Exploit 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.





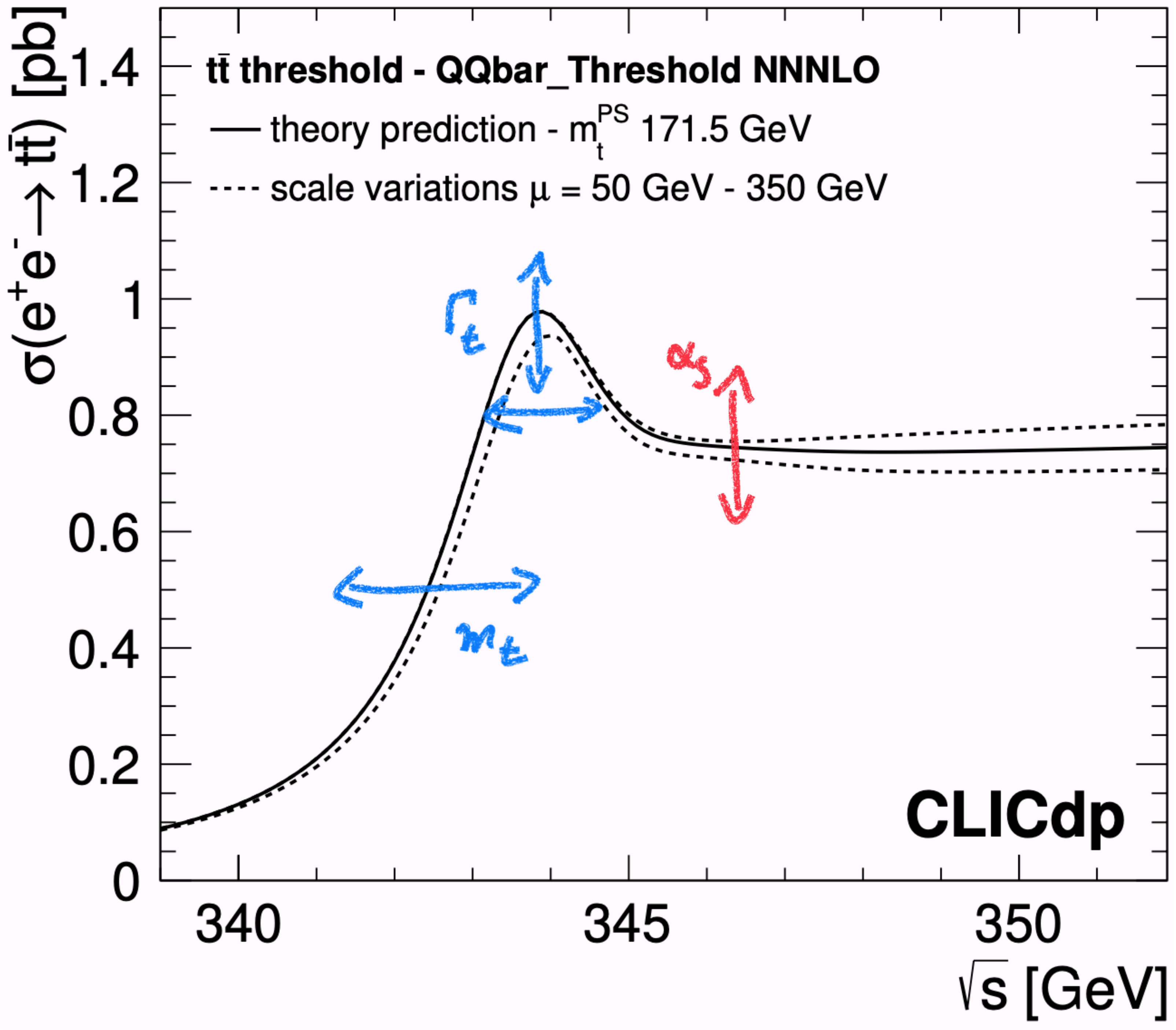
- Exploit precise theoretical calculations of cross section in the threshold region, in well-defined mass schemes (m_t^{PS}, m_t^{1S}…) -> Can be converted directly into MSbar mass.

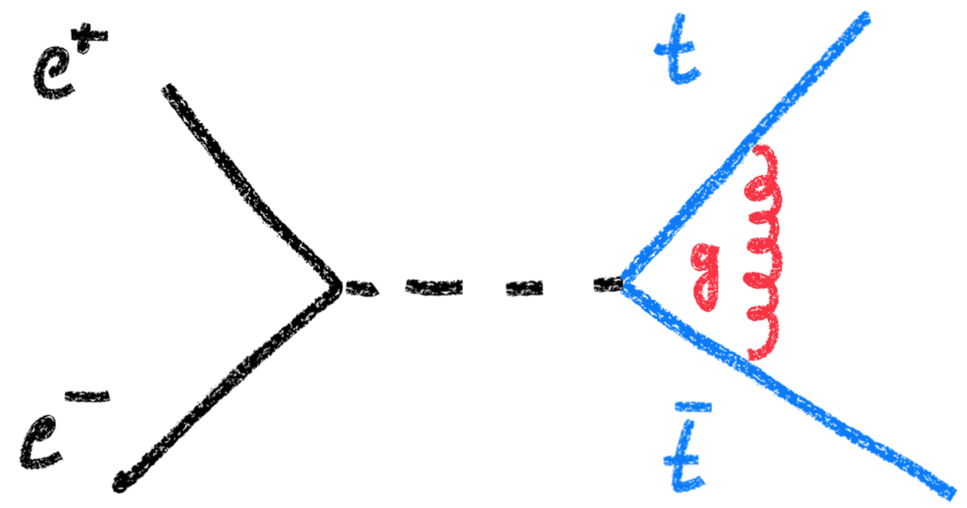
The threshold is sensitive to top quark properties

The Top Pair Threshold

Sensitivity to Top Quark Parameters

MAX-PLANCK-INSTITUT FÜR PHYSIK



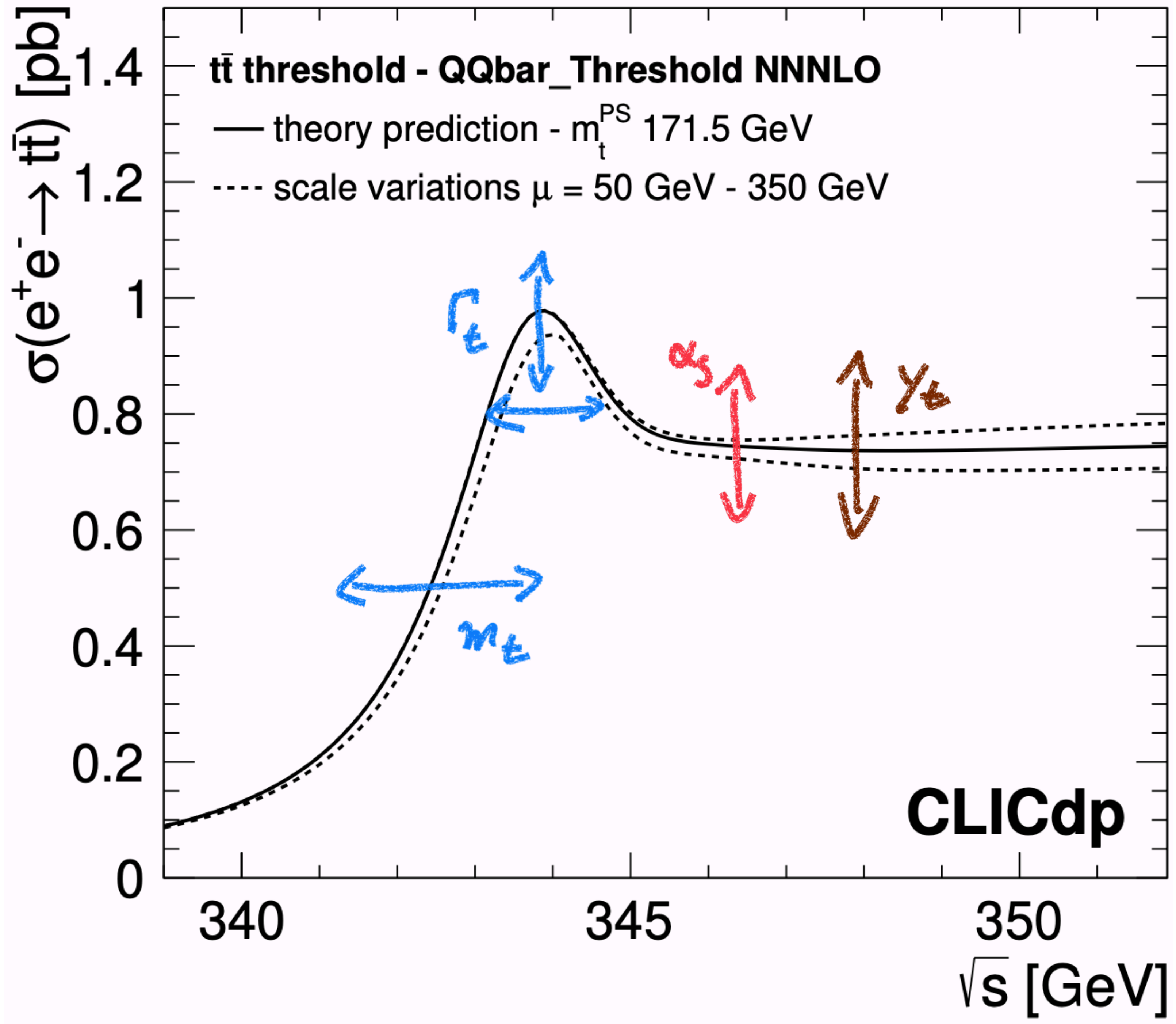


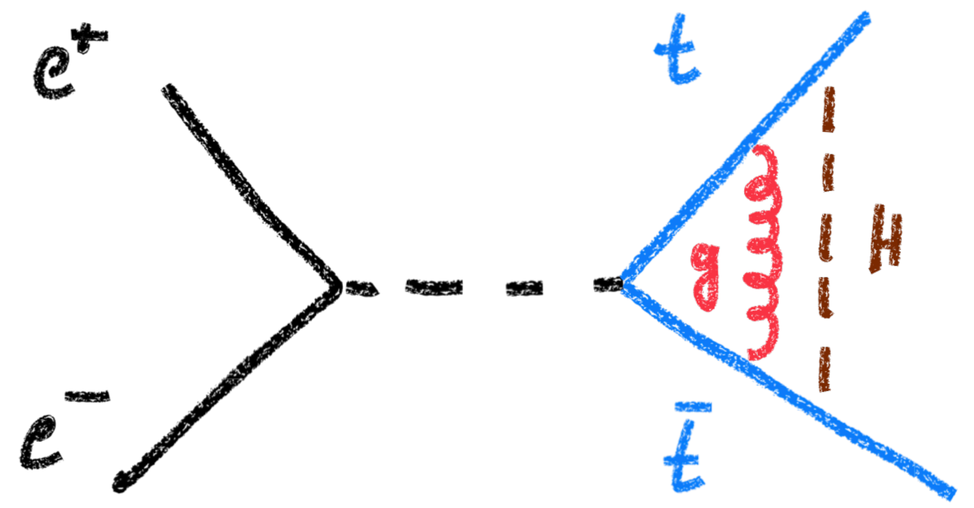
- Exploit precise theoretical calculations of cross section in the threshold region, in well-defined mass schemes (m_t^{PS}, m_t^{1S}…) -> Can be converted directly into MSbar mass.

The threshold is sensitive to top quark properties

The Top Pair Threshold

Sensitivity to Top Quark Parameters



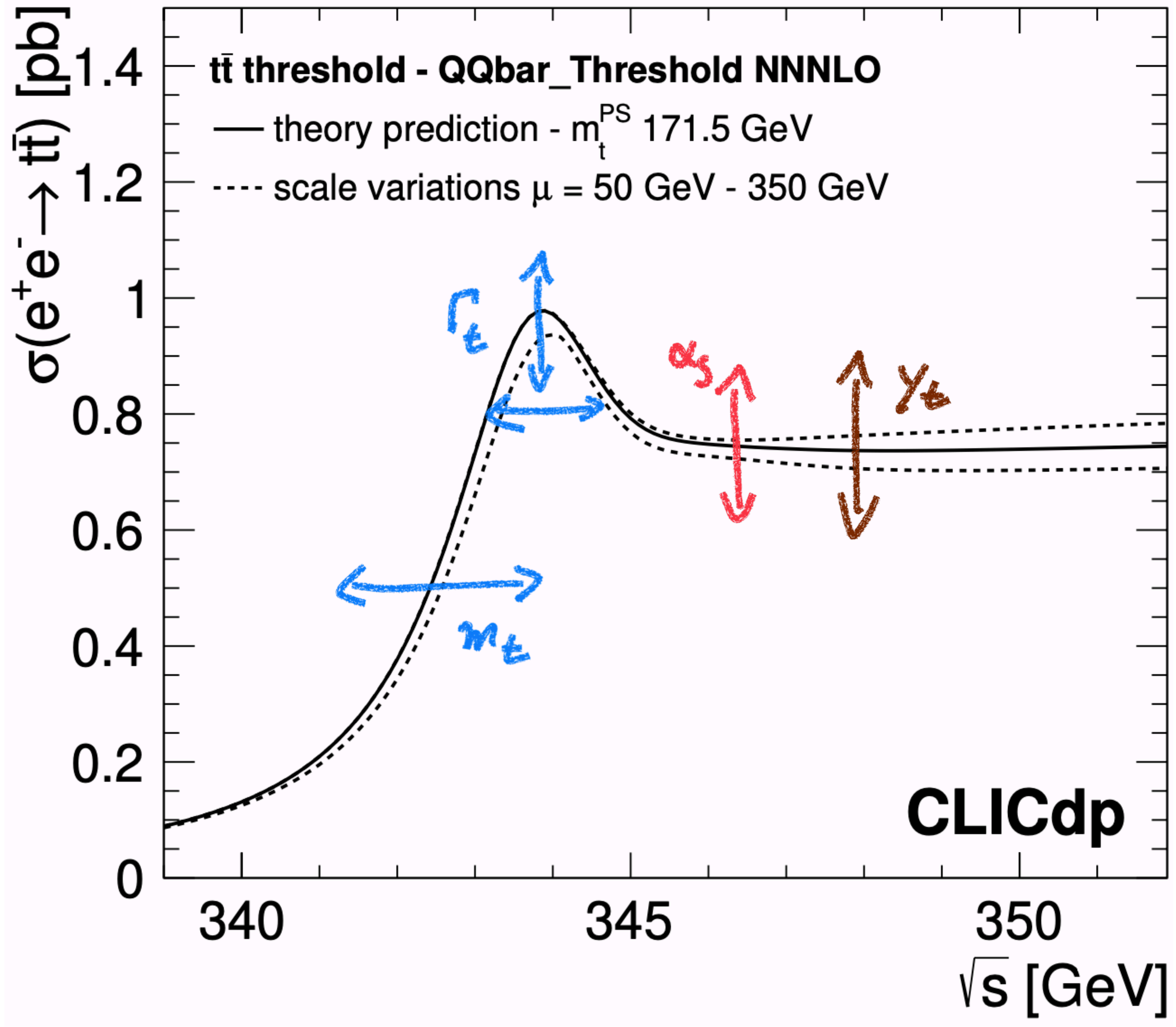


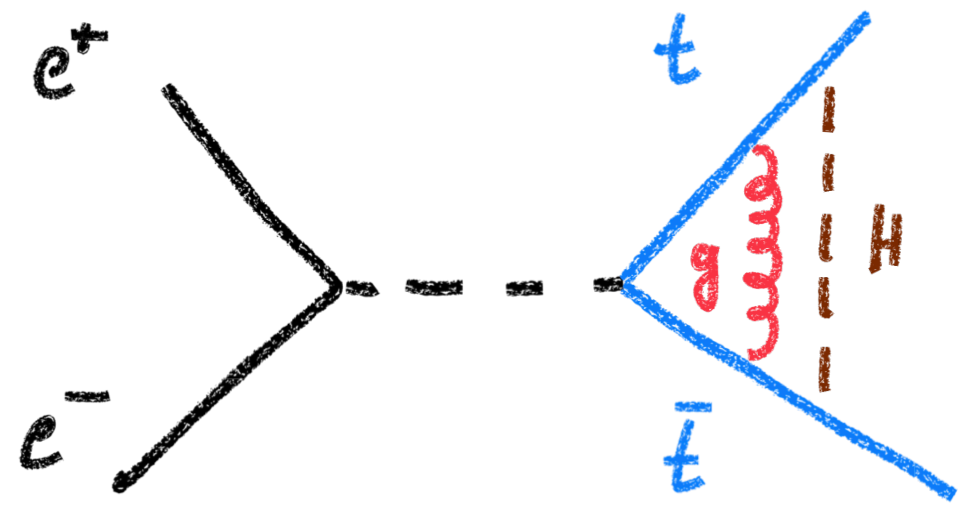
- Exploit precise theoretical calculations of cross section in the threshold region, in well-defined mass schemes (m_t^{PS}, m_t^{1S}…) -> Can be converted directly into MSbar mass.

The threshold is sensitive to top quark properties

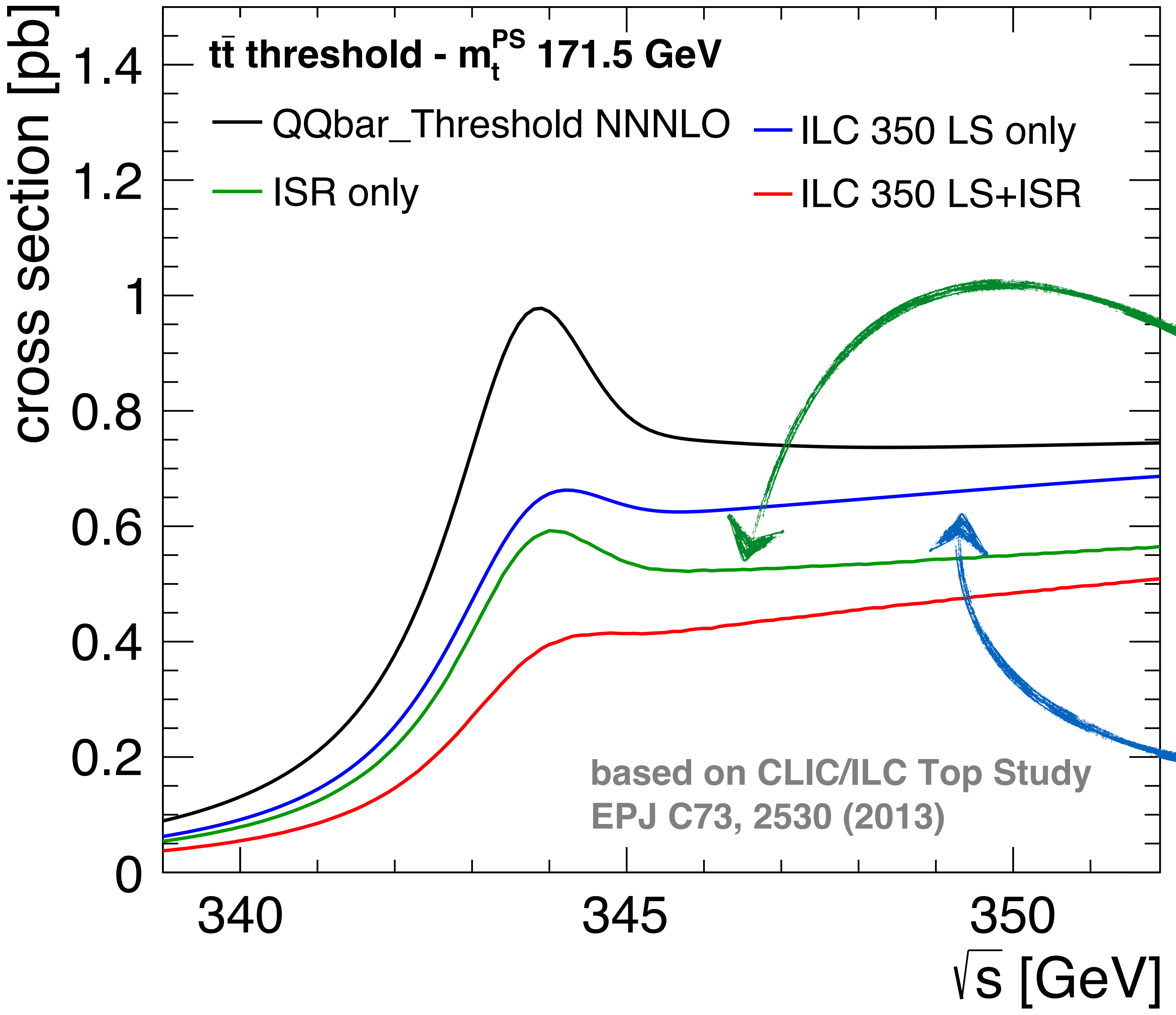
The Top Pair Threshold

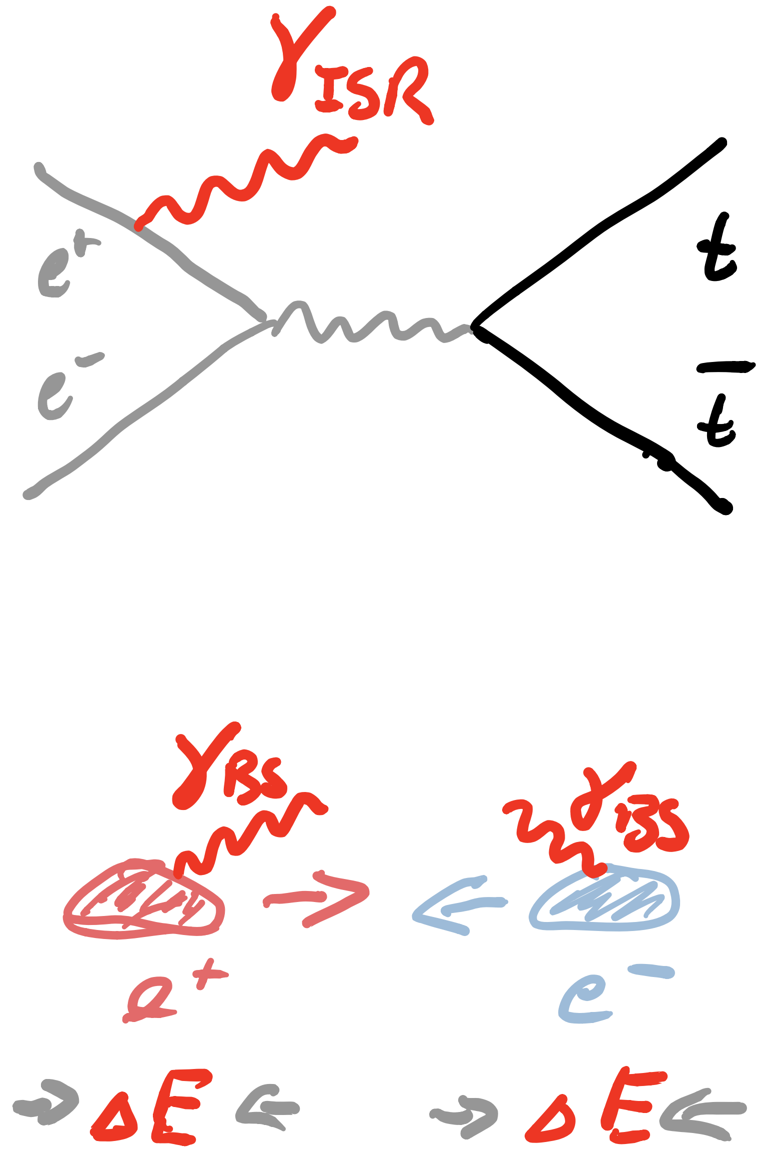
Sensitivity to Top Quark Parameters





- Exploit 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.



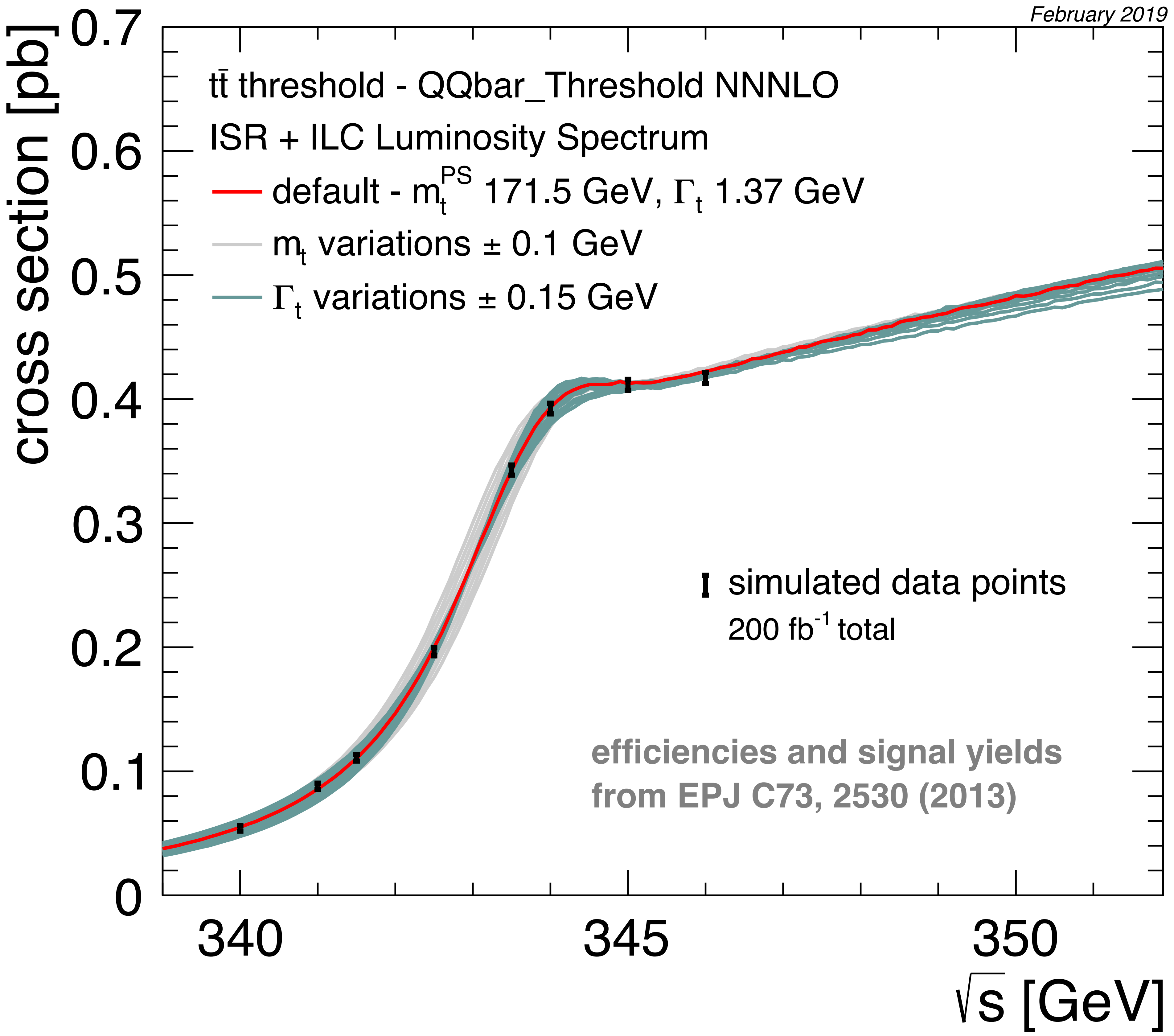


The threshold is sensitive to top quark properties

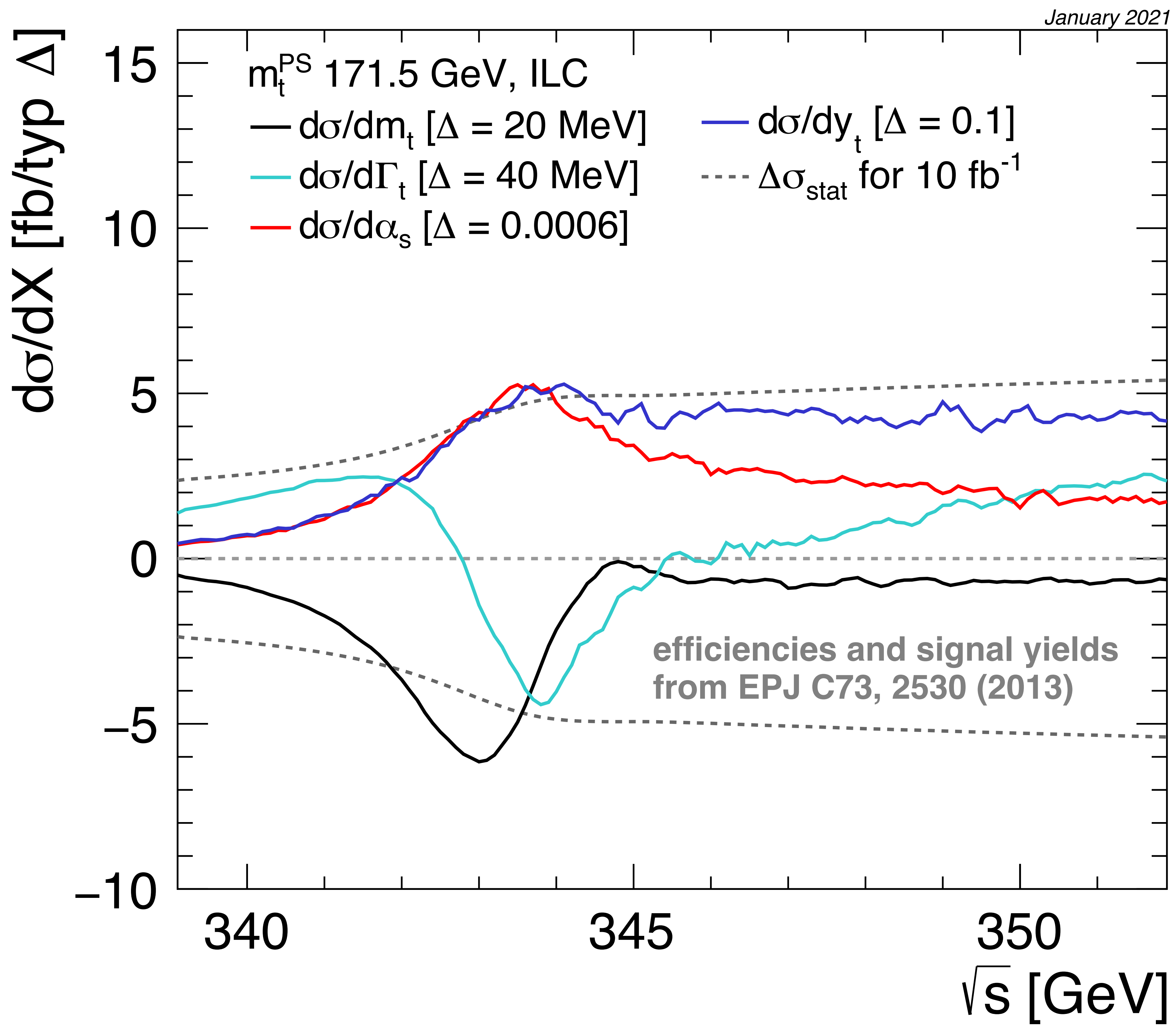
… and influenced by em physics and collider parameters

The Mass at Threshold - ILC

Ultimate Precision



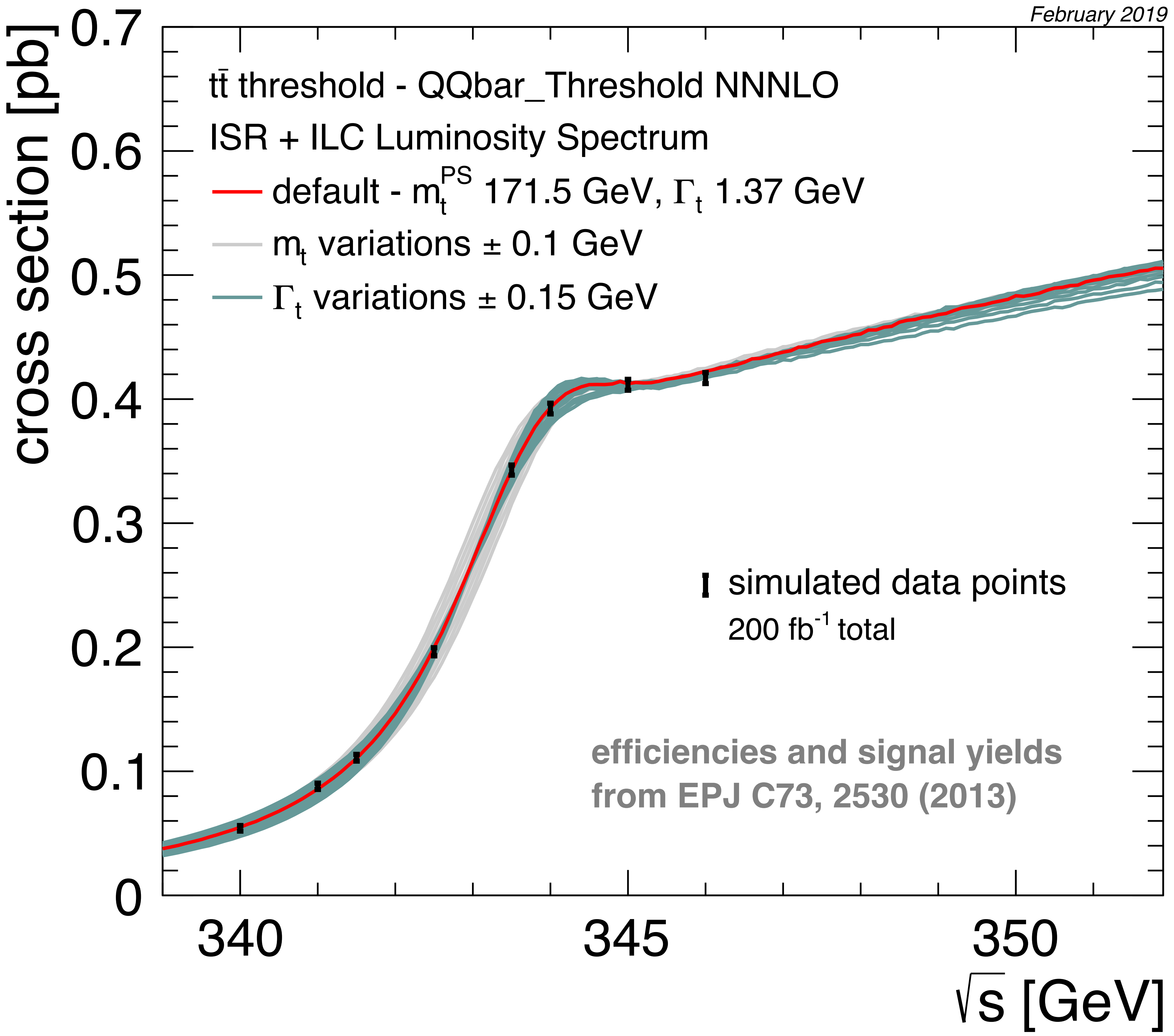
- Extracting mass from measurement of the cross section at different points along the threshold
  - Sensitivity to different parameters depends on position along the threshold



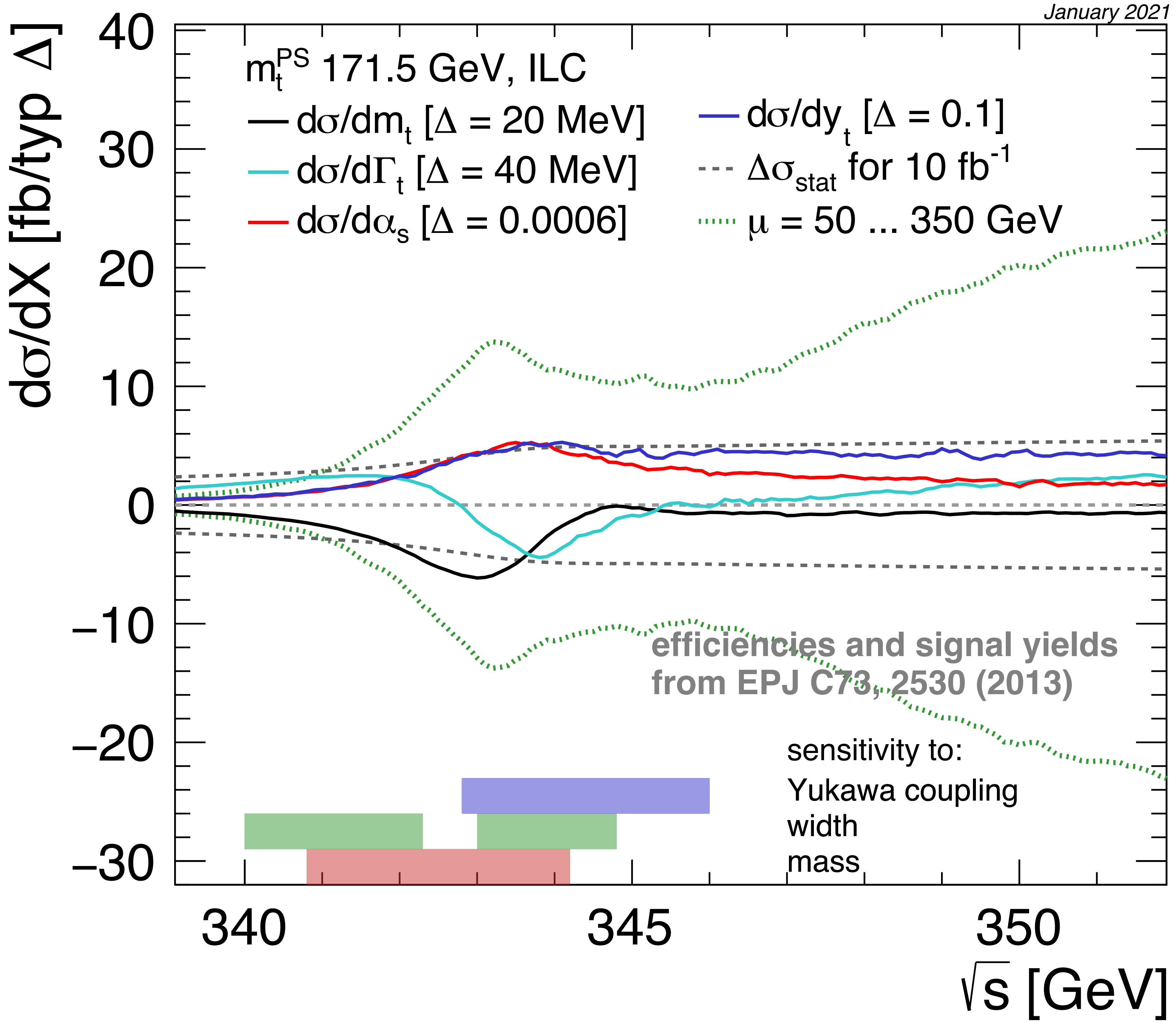
arXiv:1902.07246; EPJ C73, 2530 (2013)

The Mass at Threshold - ILC

Ultimate Precision



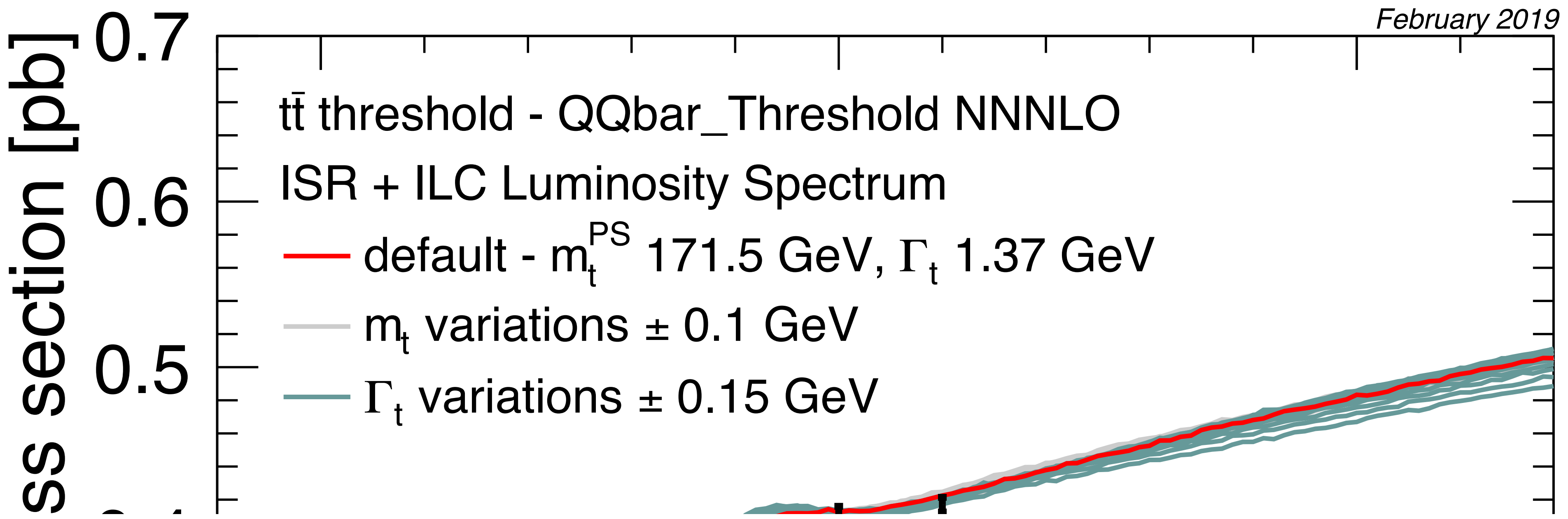
- Extracting mass from measurement of the cross section at different points along the threshold
  - Sensitivity to different parameters depends on position along the threshold



arXiv:1902.07246; EPJ C73, 2530 (2013)

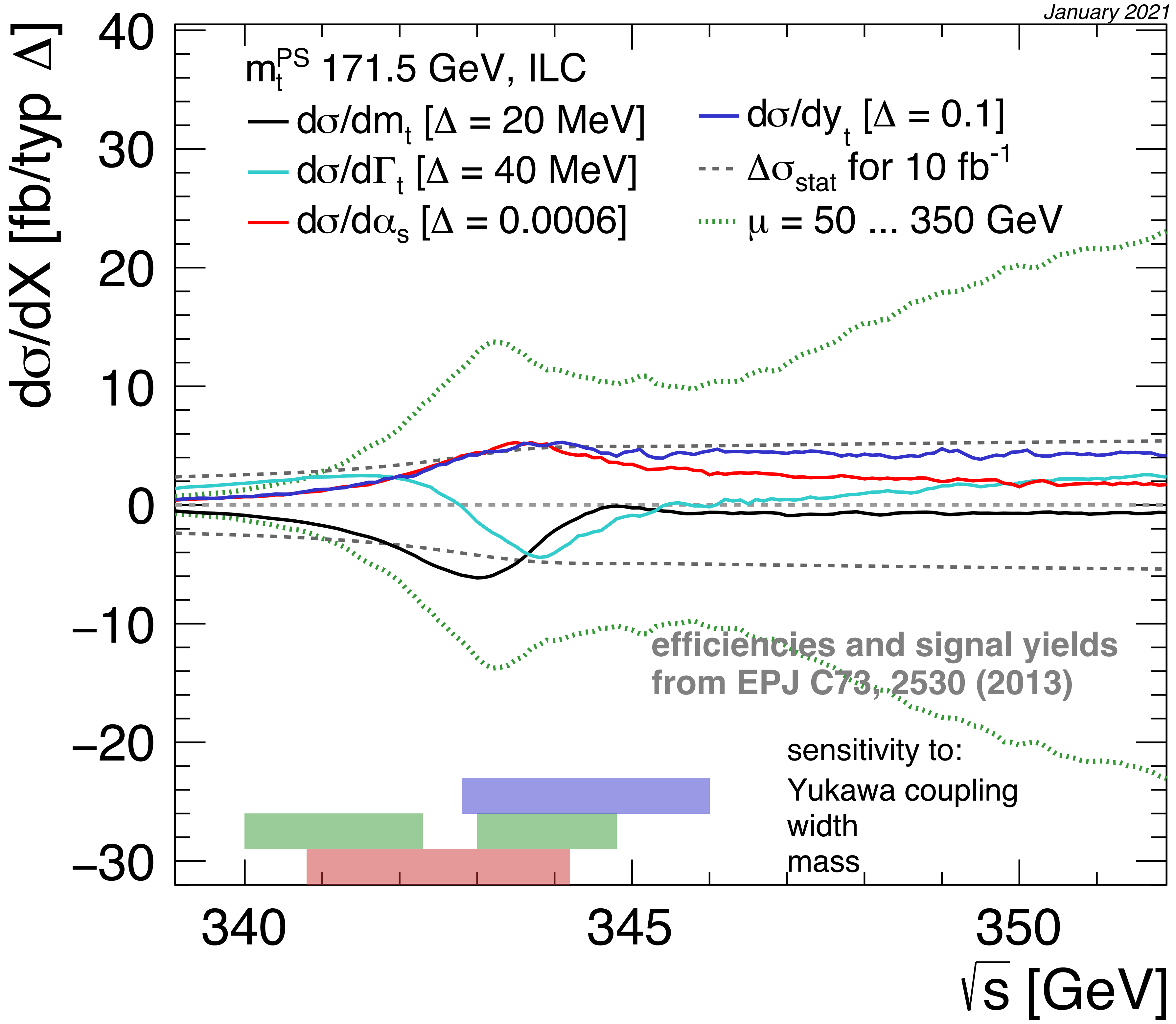
The Mass at Threshold - ILC

Ultimate Precision



error source	Δm_t^{PS} [MeV]
stat. error (200 fb^{-1})	13
theory (NNNLO scale variations, PS scheme)	40
parametric (α_s, current WA) (30 MeV/0.001)	35
non-resonant contributions (such as single top)	< 40
residual background / selection efficiency	10 – 20
luminosity spectrum uncertainty	< 10
beam energy uncertainty	< 17
combined theory & parametric	30 – 50
combined experimental & backgrounds	25 - 50
total (stat. + syst.)	40 – 75

- Extracting mass from measurement of the cross section at different points along the threshold
    - Sensitivity to different parameters depends on position along the threshold

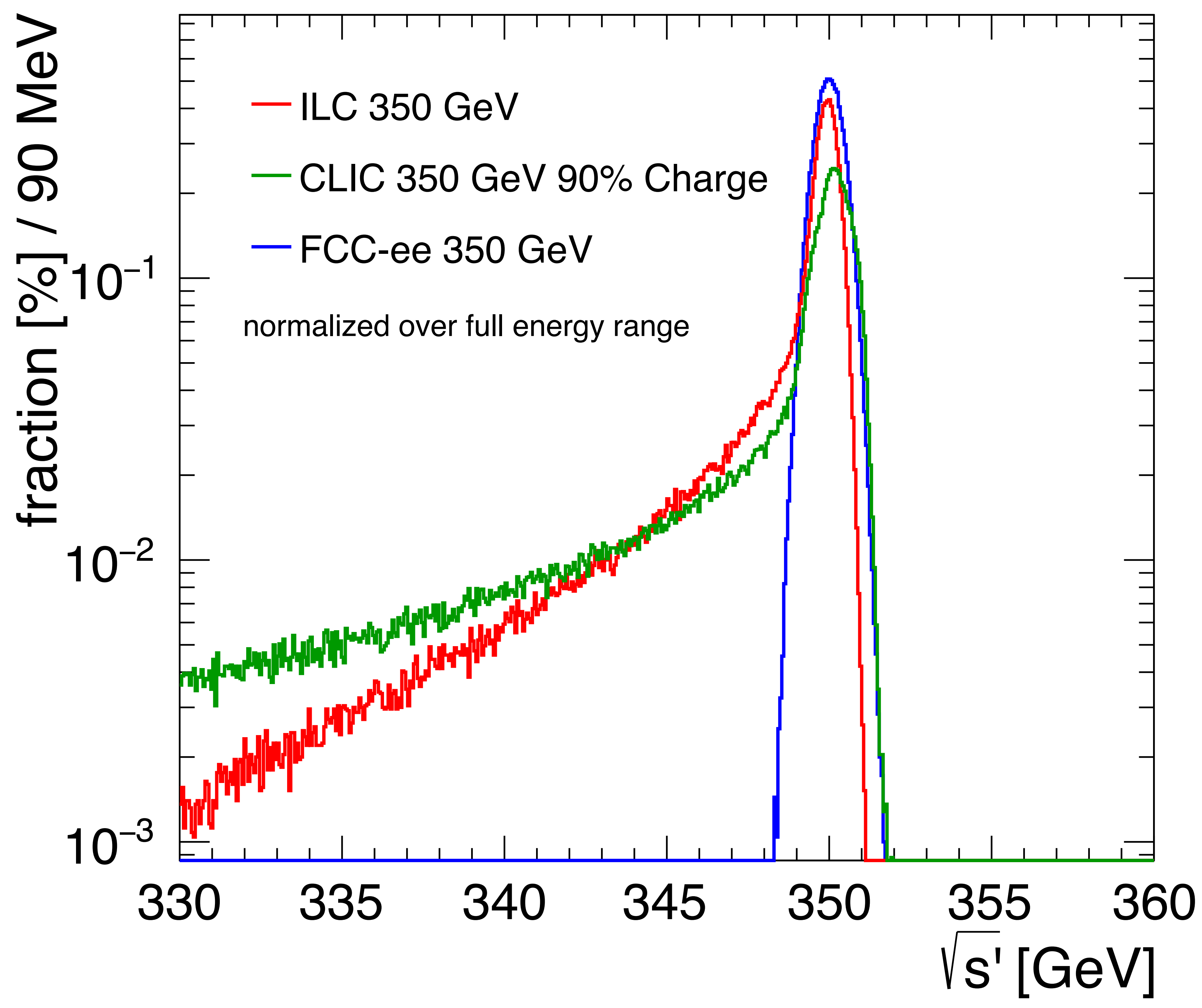


arXiv:1902.07246; EPJ C73, 2530 (2013)

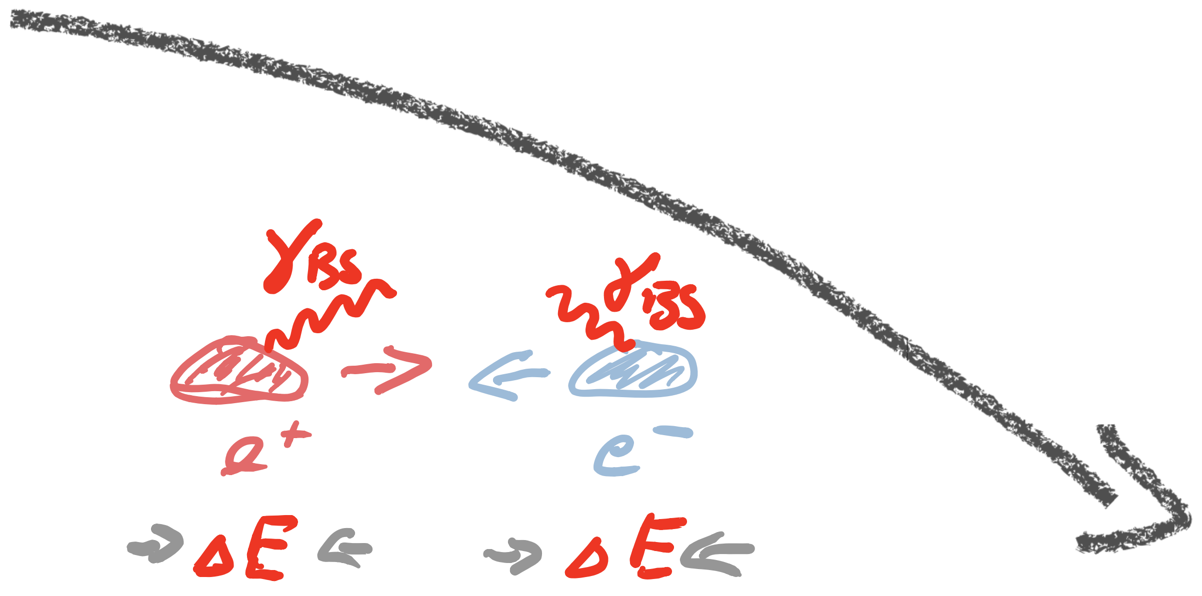
Collider Dependence

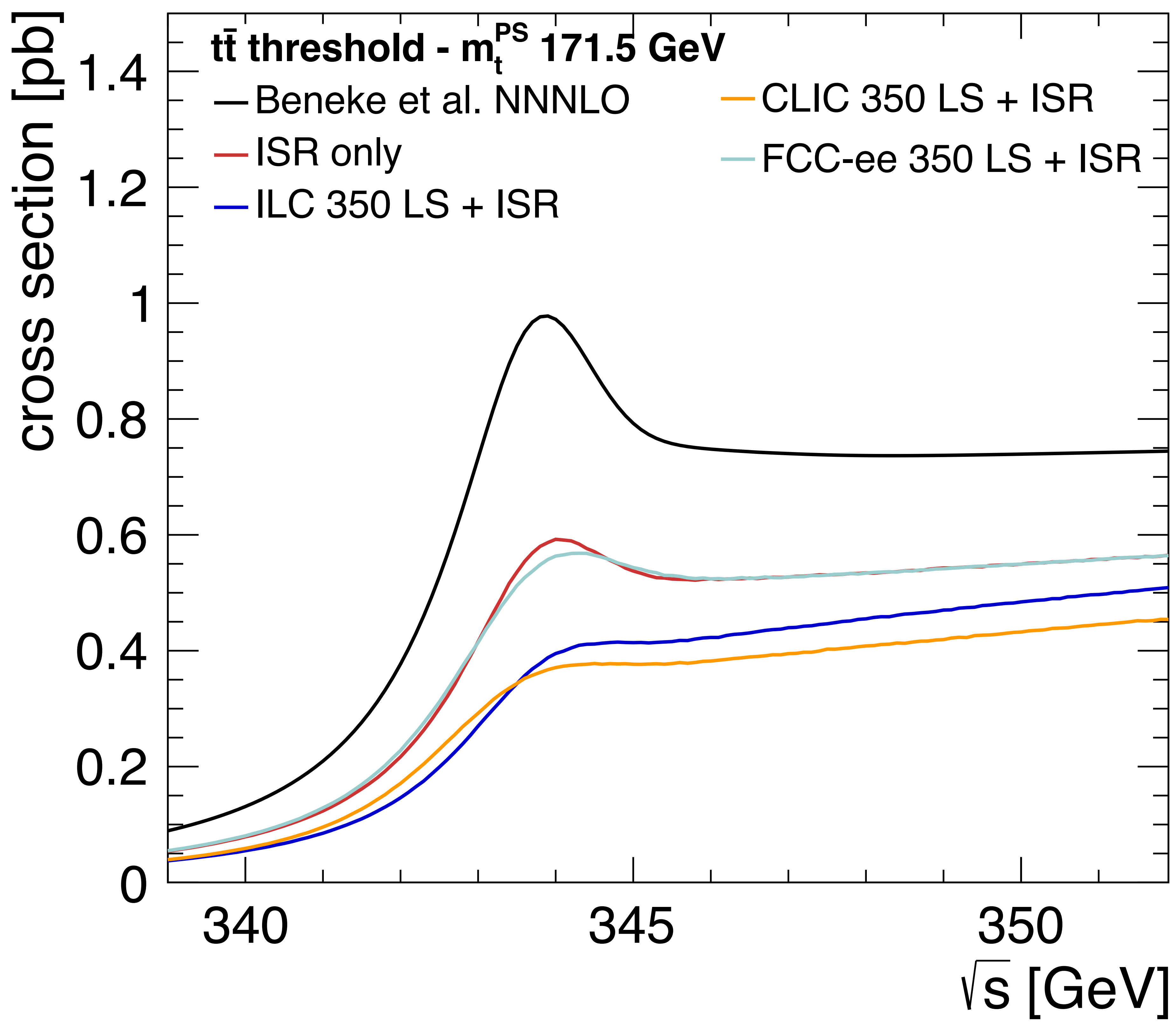
The Threshold at Linear and Circular Colliders

MAX-PLANCK-INSTITUT FÜR PHYSIK



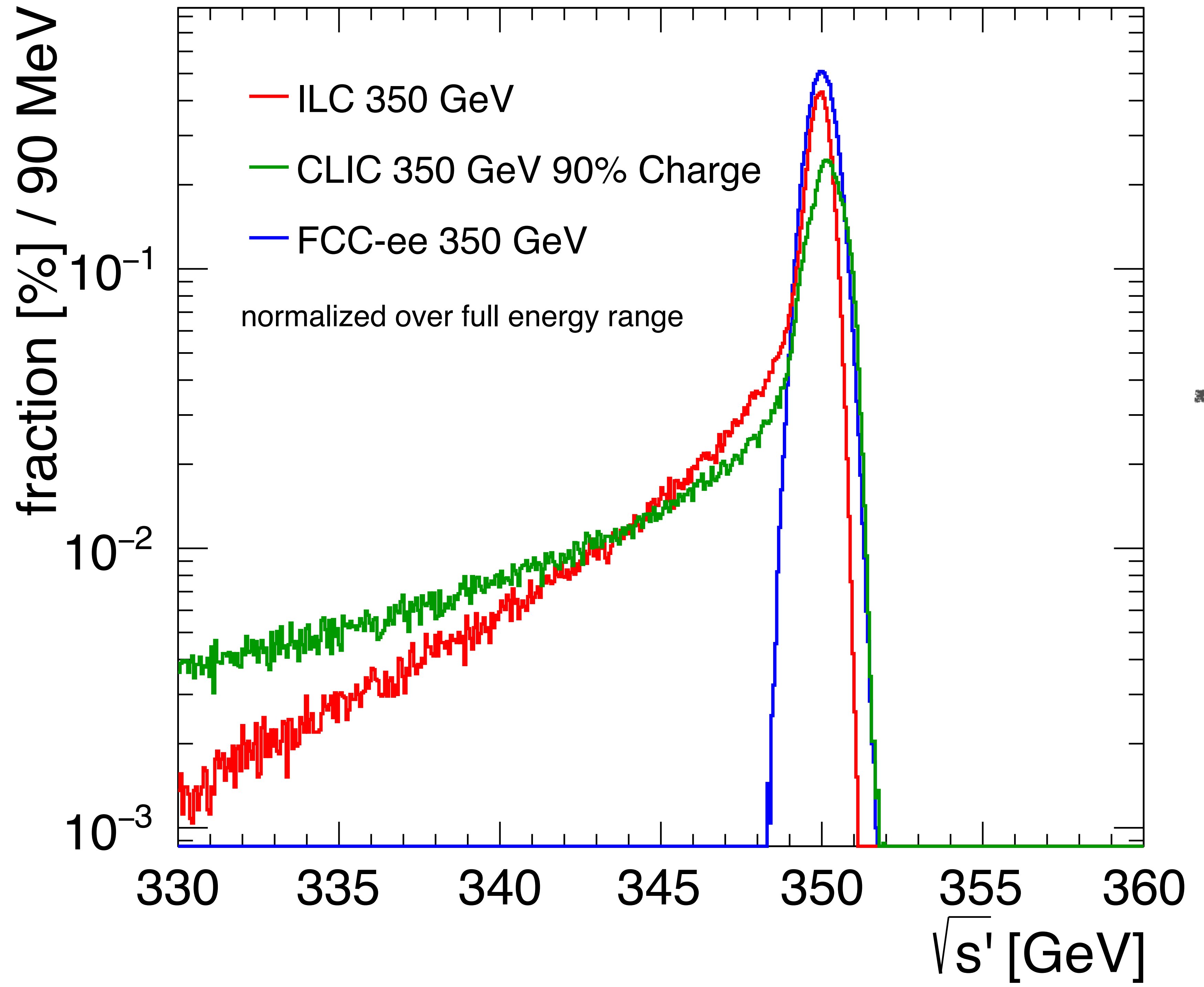
- The key difference between different colliders: The luminosity spectrum



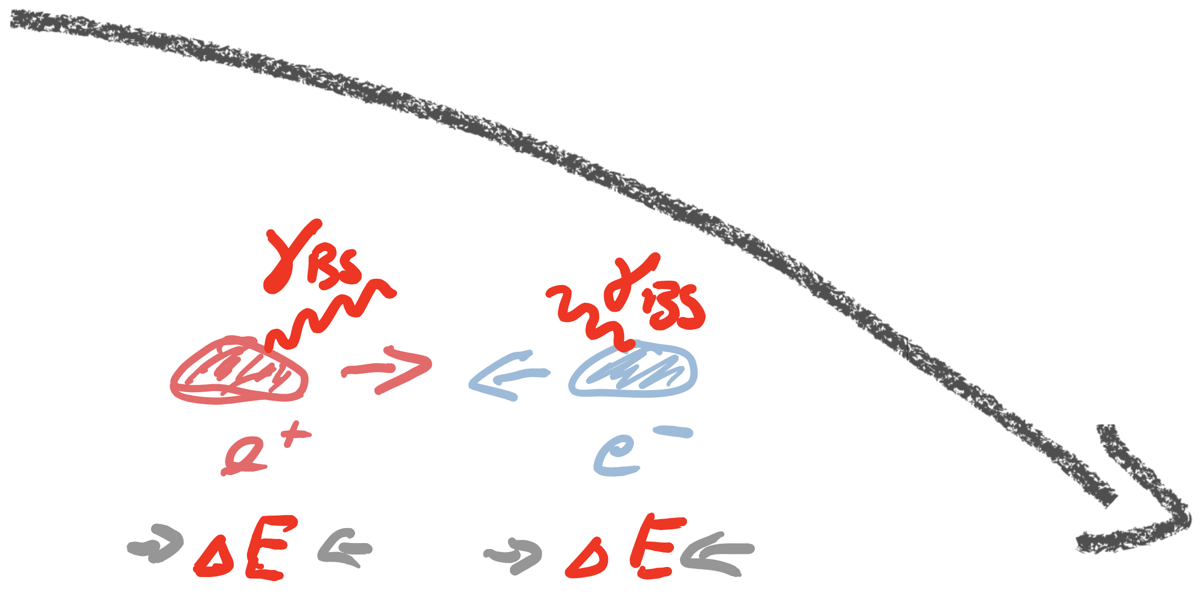


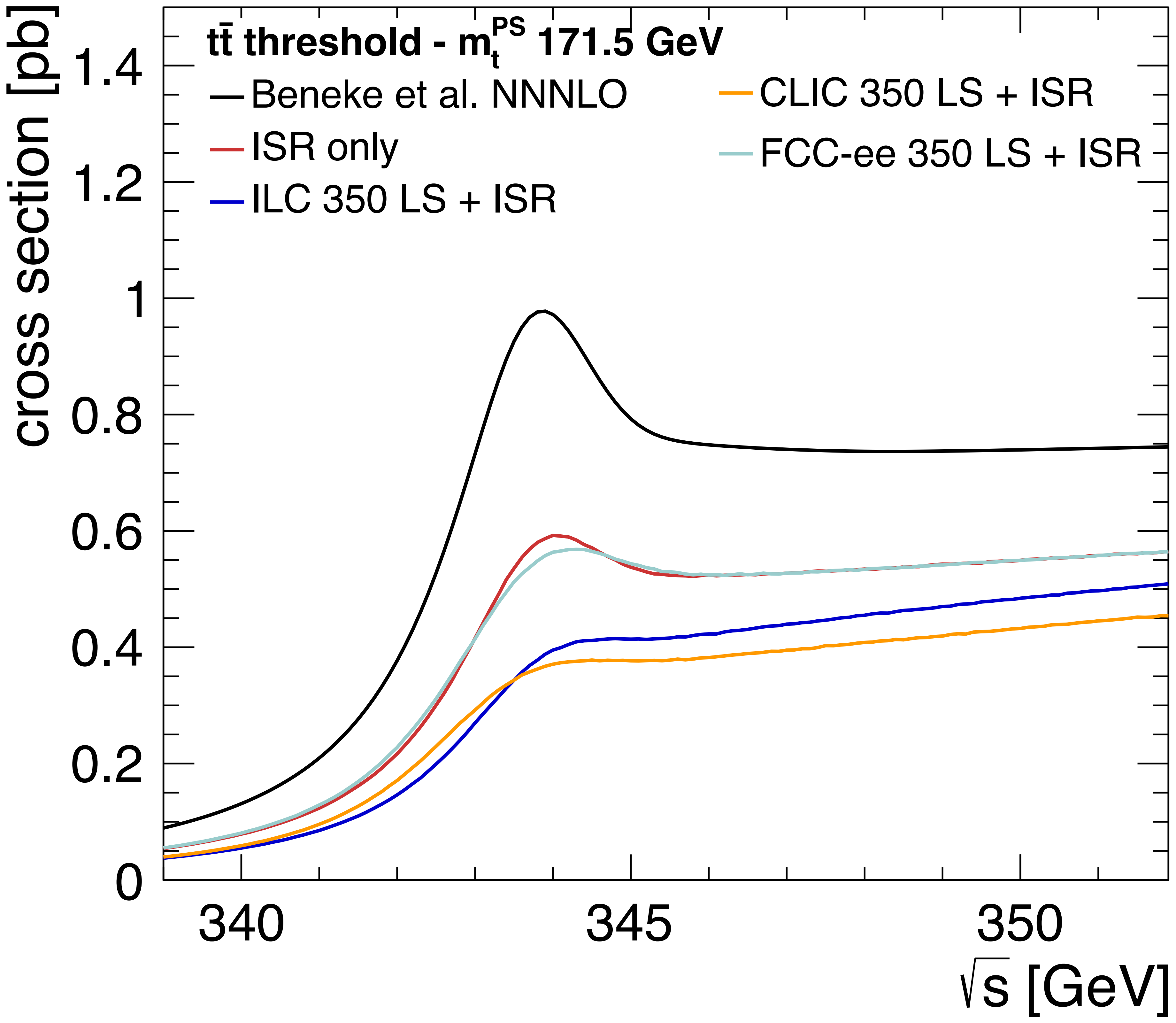
Collider Dependence

The Threshold at Linear and Circular Colliders



- The key difference between different colliders: The luminosity spectrum





- Assuming an integrated luminosity of 200 fb^{-1} (default for ILC, FCCee, x2 of CLIC standard scenario - 10 points spaced by 1 GeV)
- Standard fit of mass only:

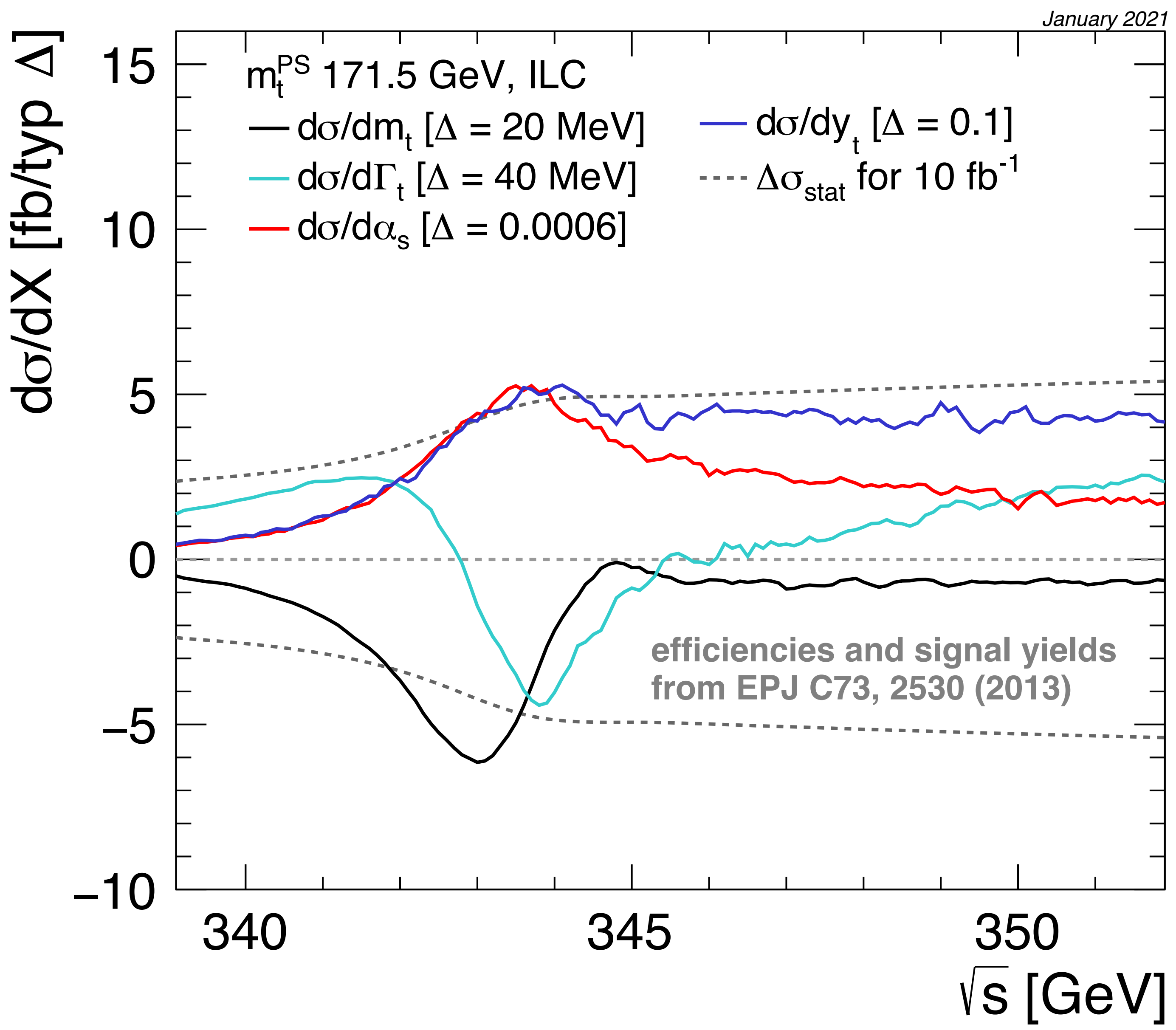
ILC 12.2 MeV [stat]
CLIC 13.3 MeV [stat]
FCCee 10.0 MeV [stat]

NB: Current theory uncertainties ~ 40 MeV

The Threshold beyond Mass

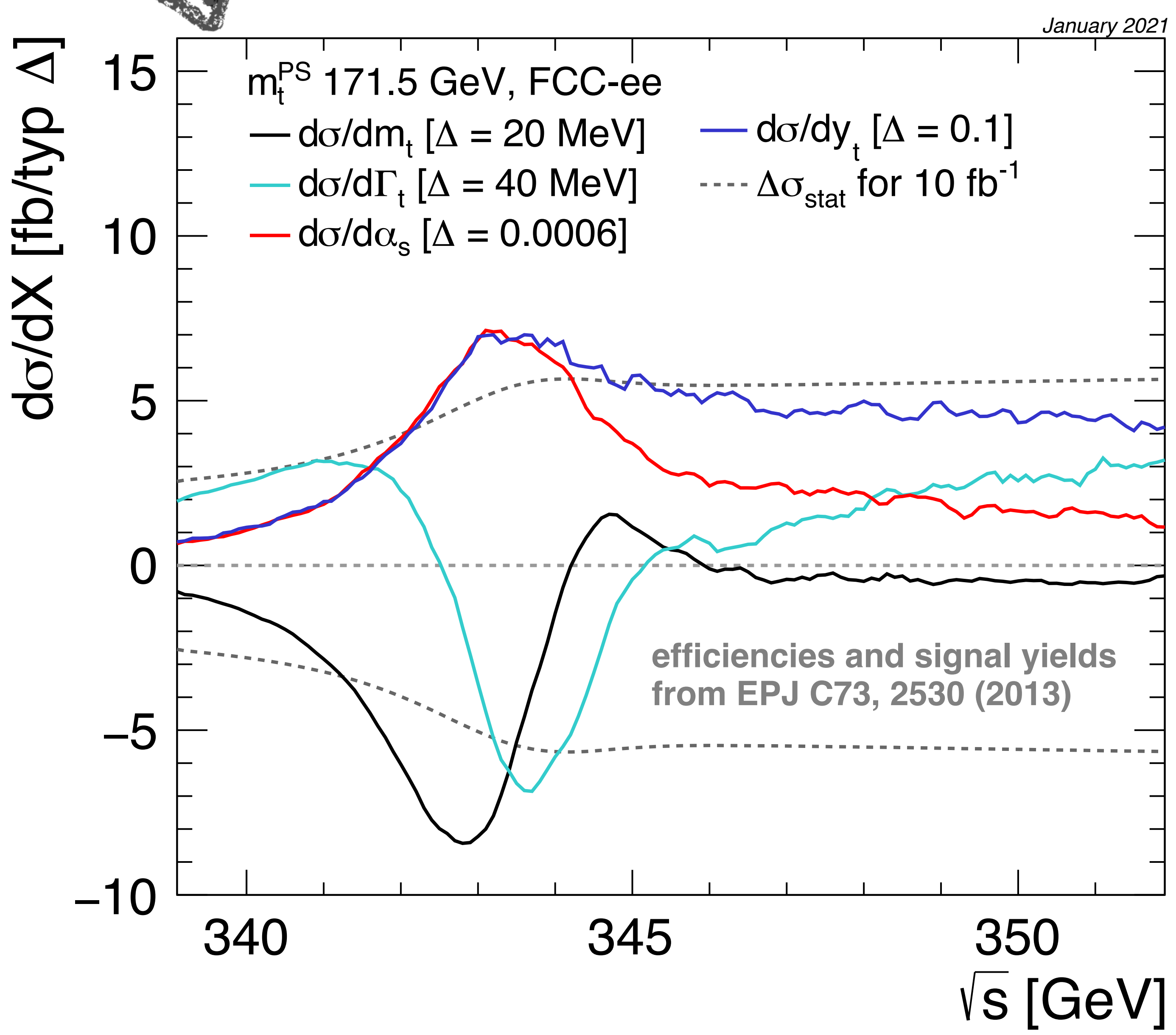
Multi-parameter Studies

- Here: Simultaneous extraction of mass and width



ILC

Lumi-Spectrum

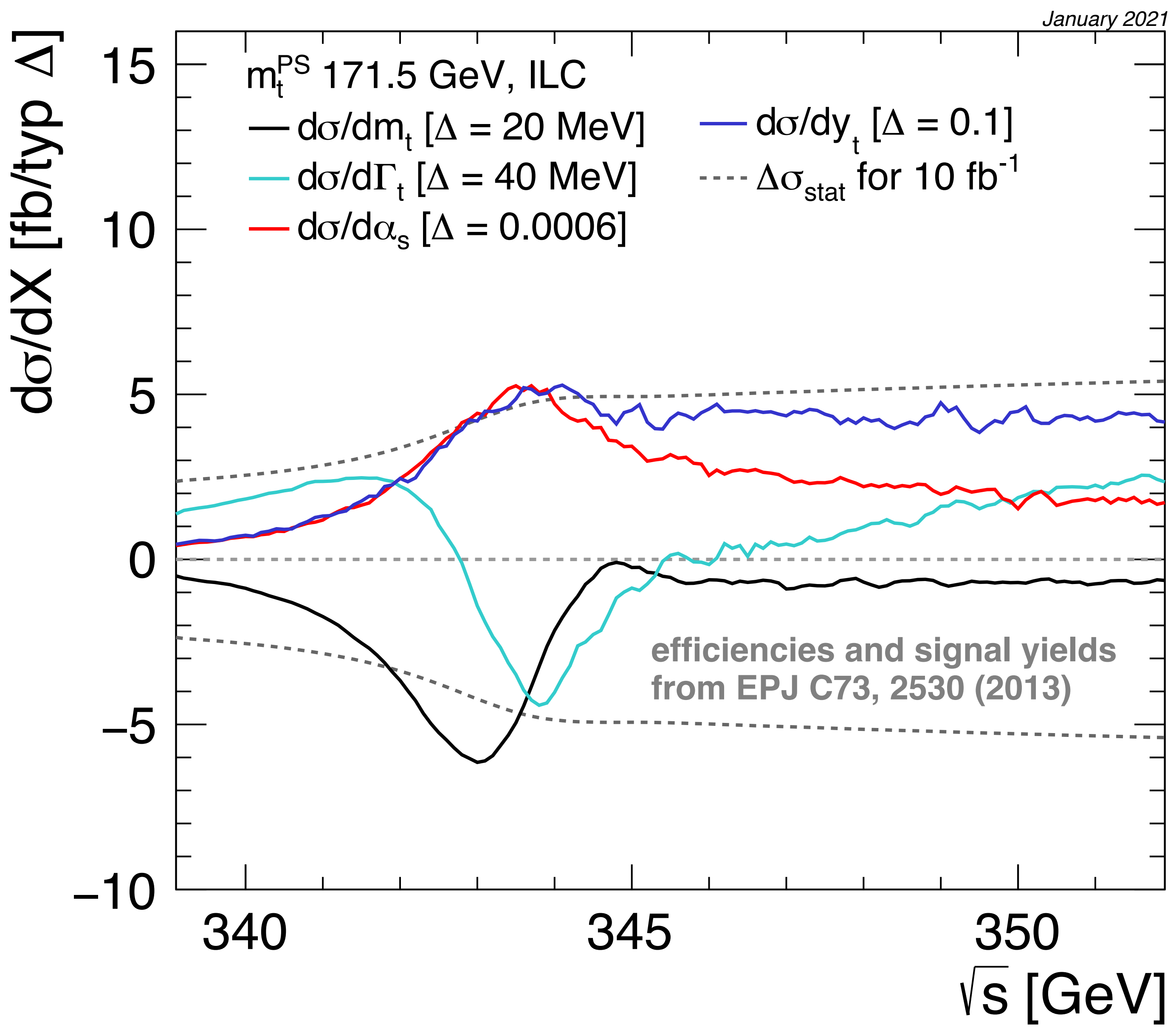


FCC-ee

The Threshold beyond Mass

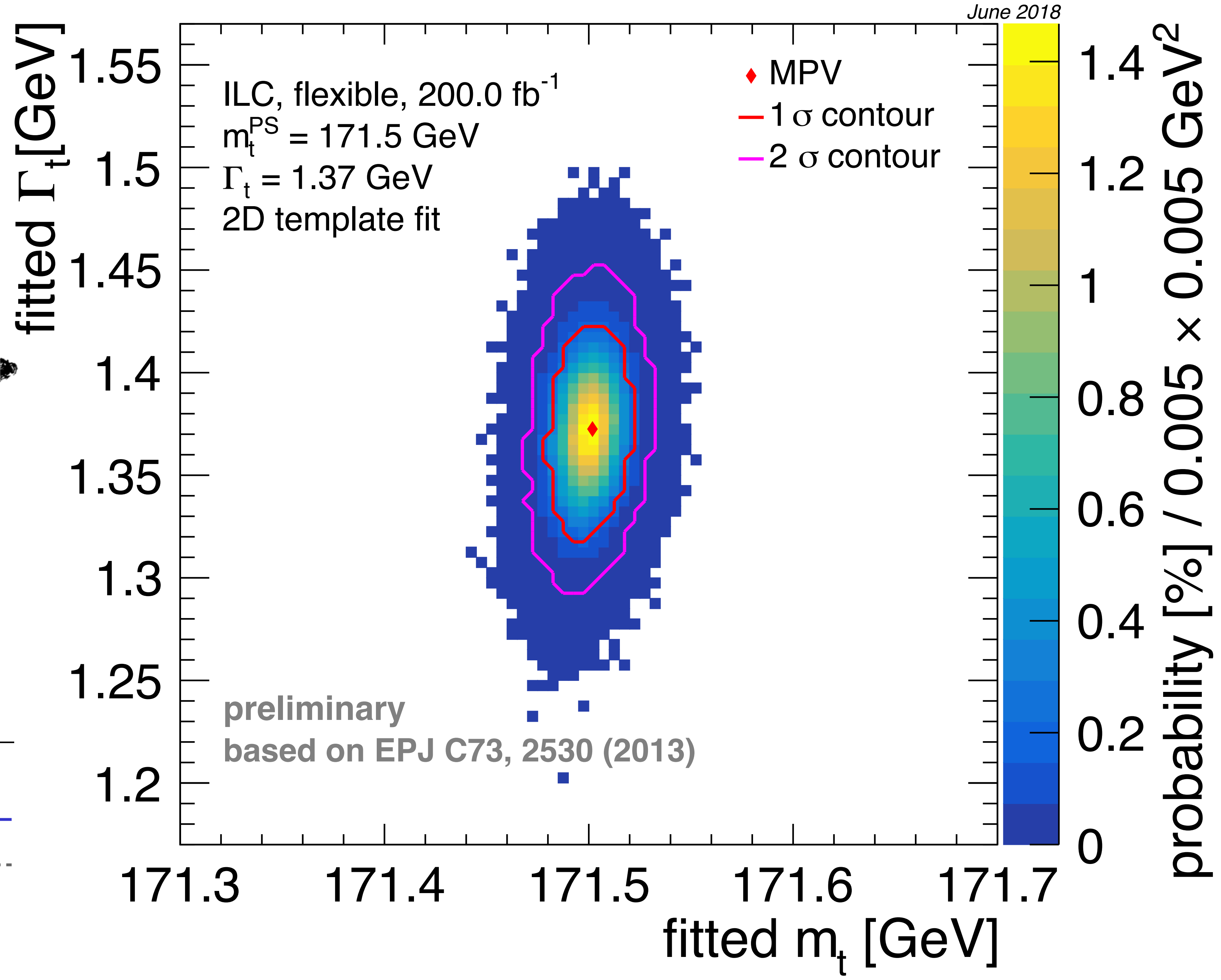
Multi-parameter Studies

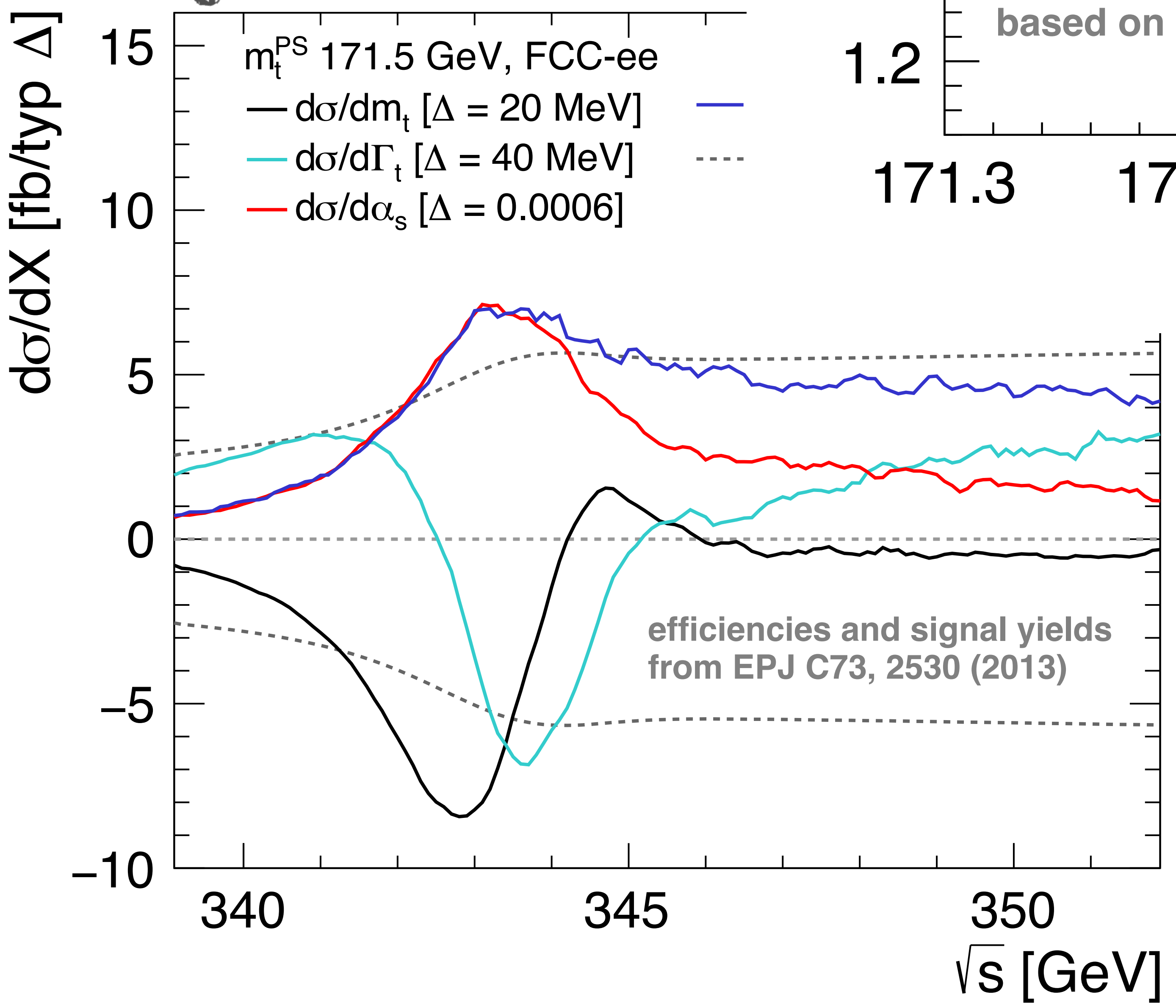
- Here: Simultaneous extraction of mass and width



ILC

Lumi-Spectrum





FCC-ee

The Threshold beyond Mass

Multi-parameter Studies

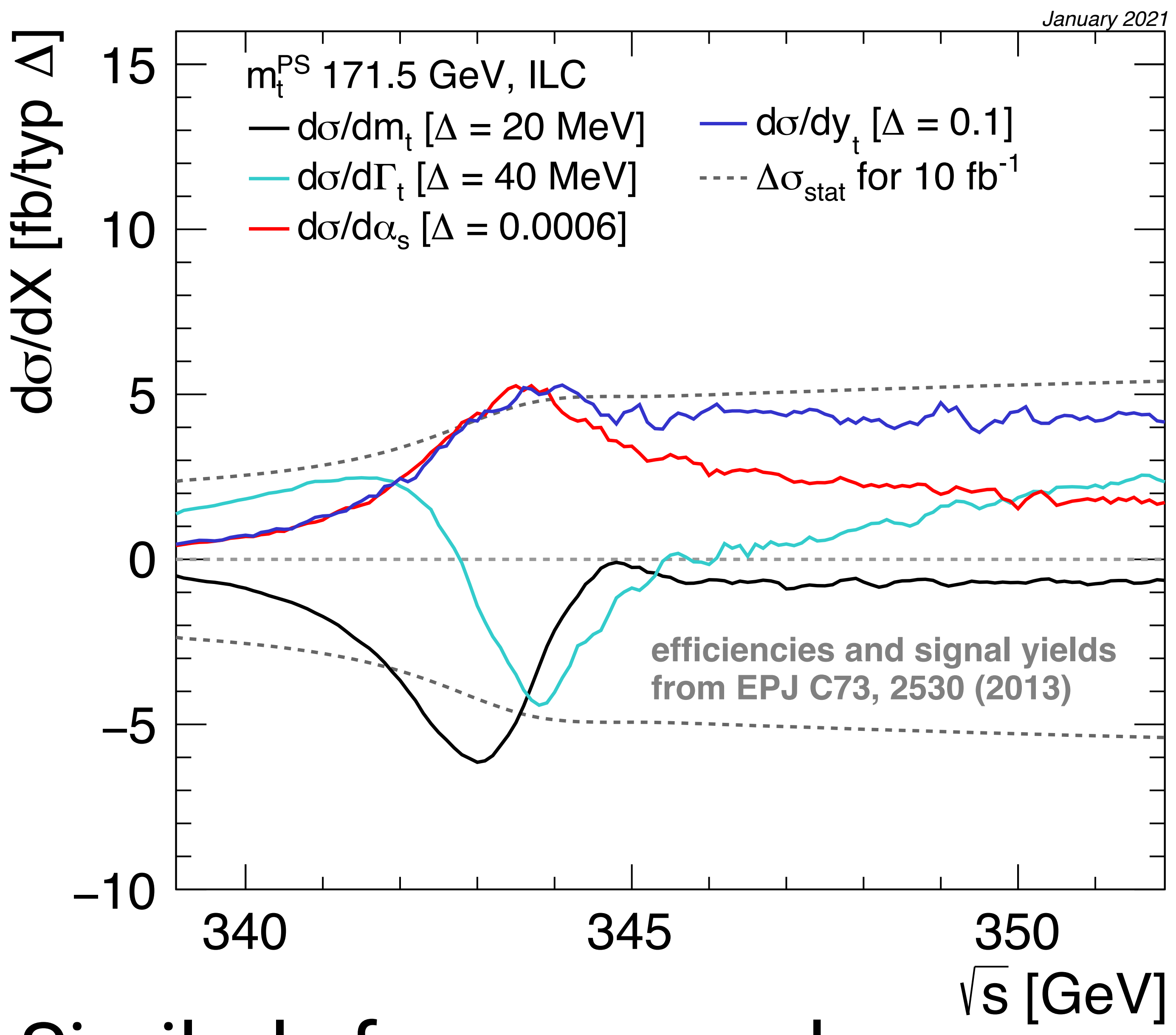
MAX-PLANCK-INSTITUT FÜR PHYSIK

- Here: Simultaneous extraction of mass and width

The Threshold beyond Mass

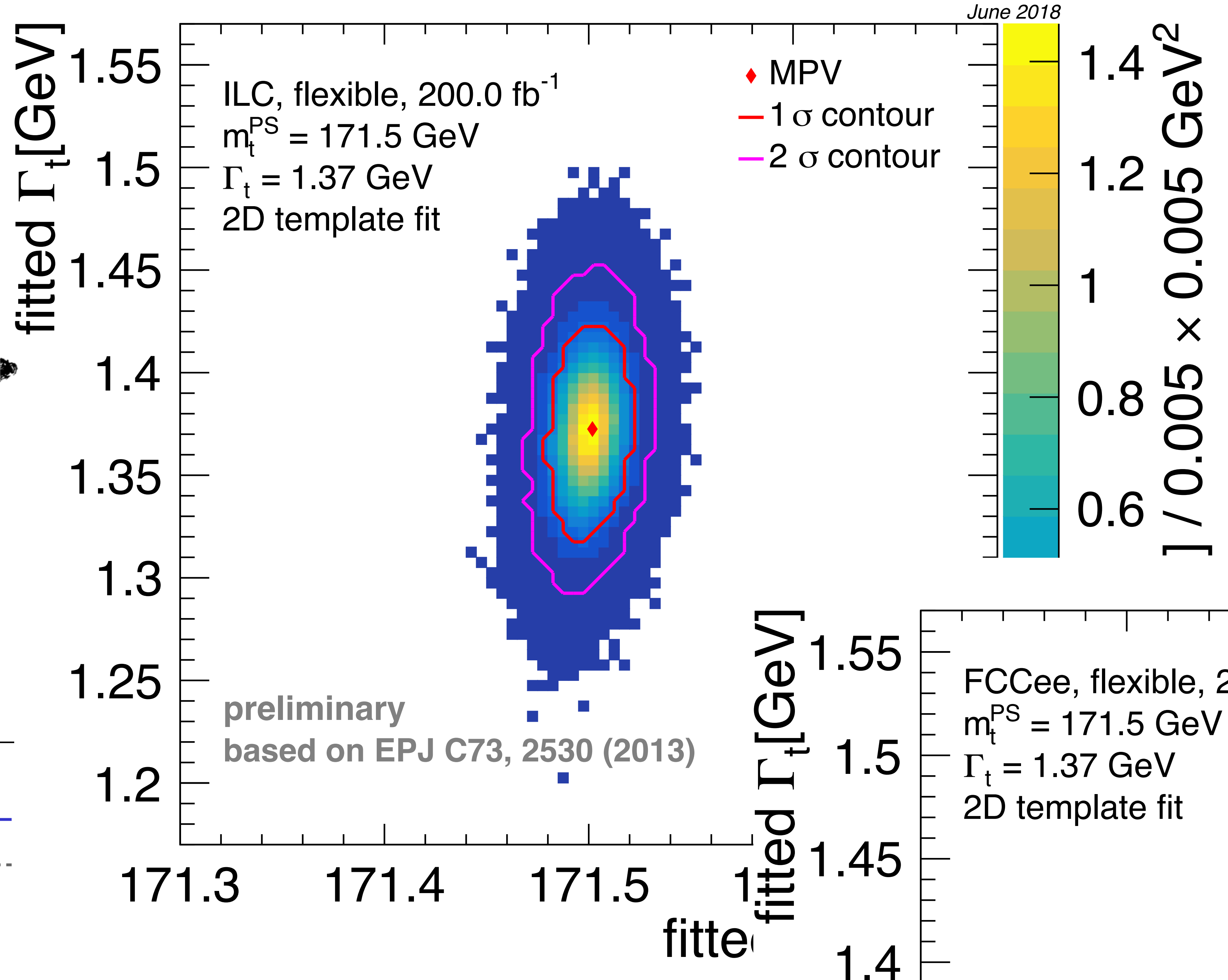
Multi-parameter Studies

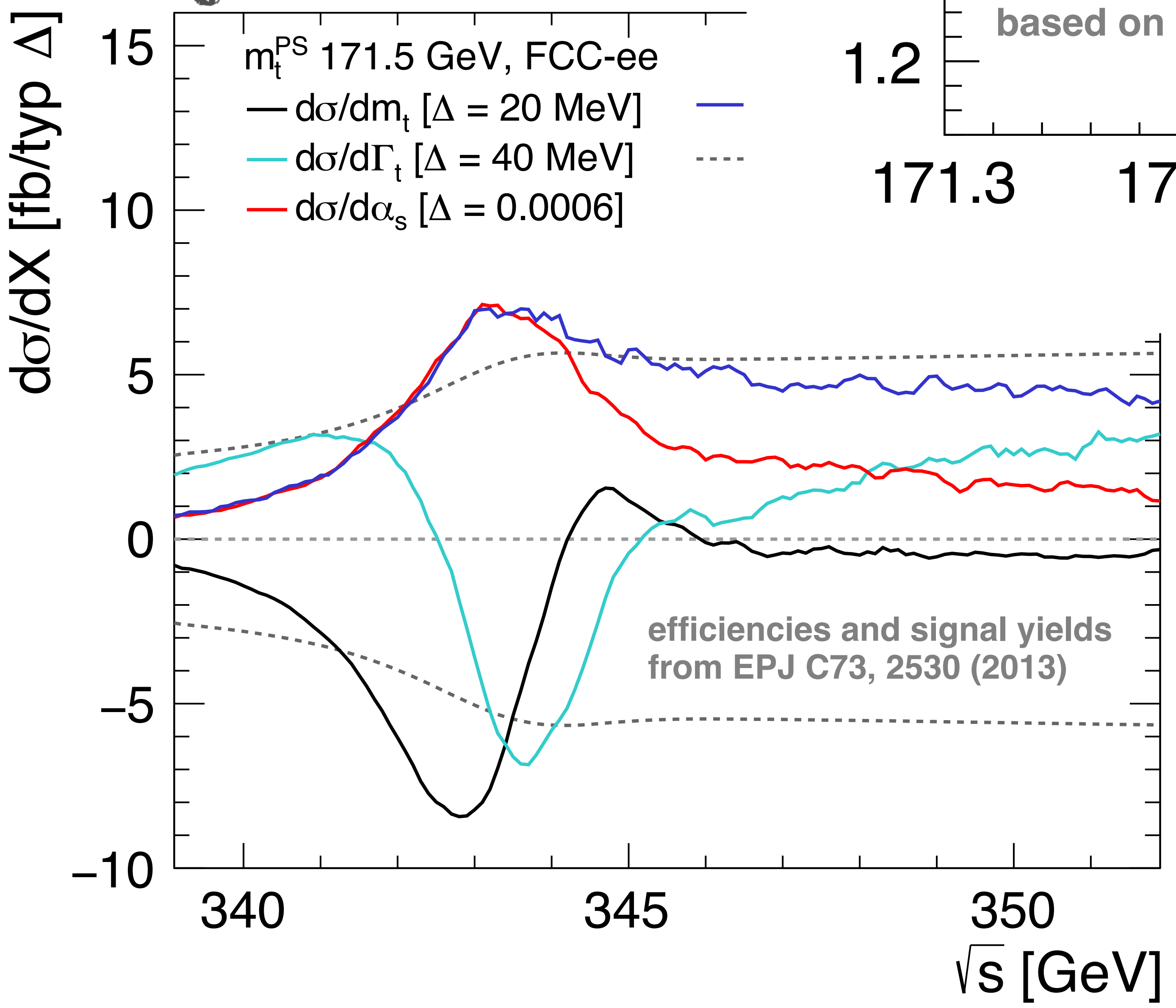
- Here: Simultaneous extraction of mass and width



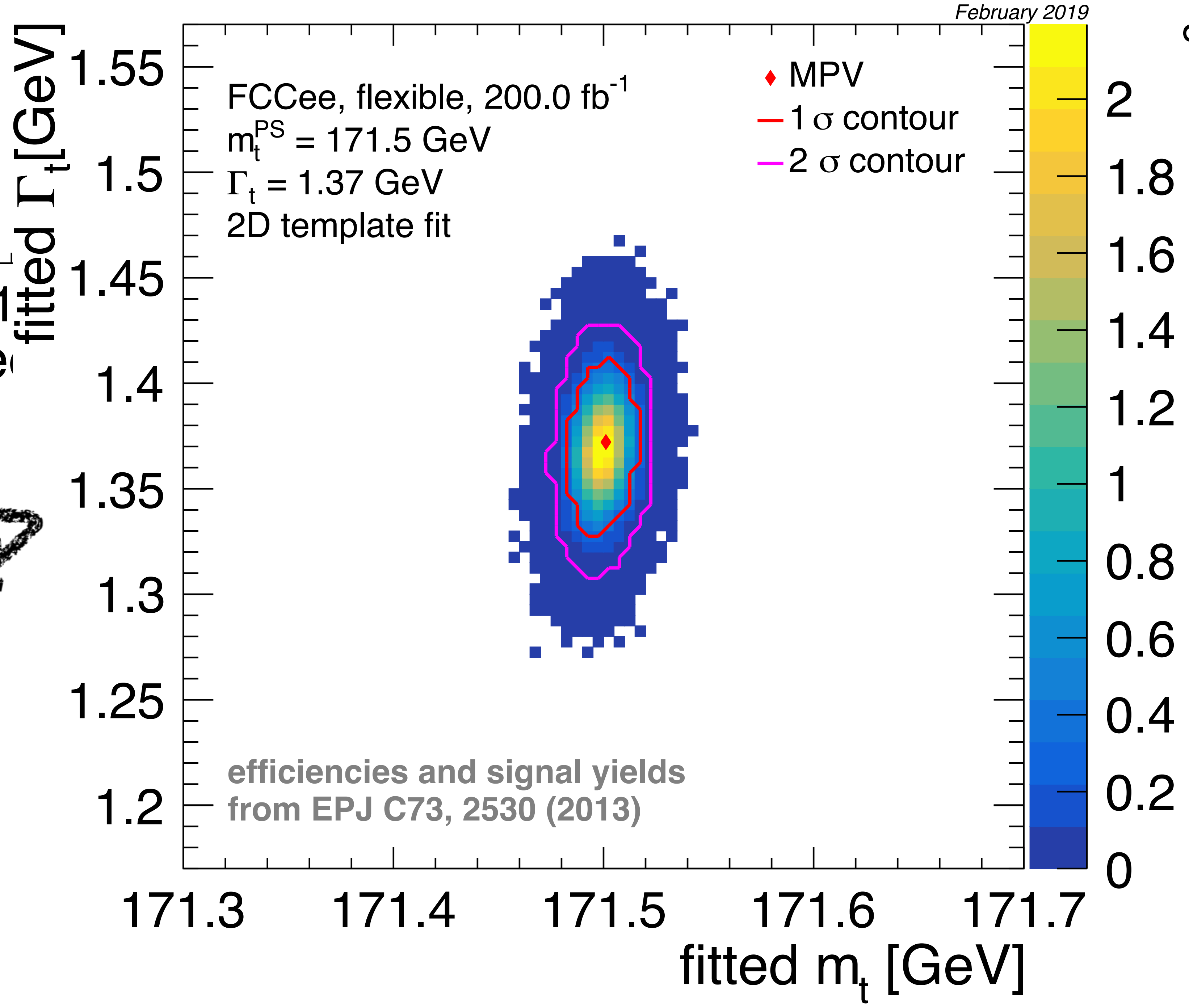
ILC

Lumi-Spectrum





FCC-ee



Similarly for mass and y_t

Combined fit increases statistical uncertainties wrt marginalized values, typical precision:

mass: 20 - 30 MeV

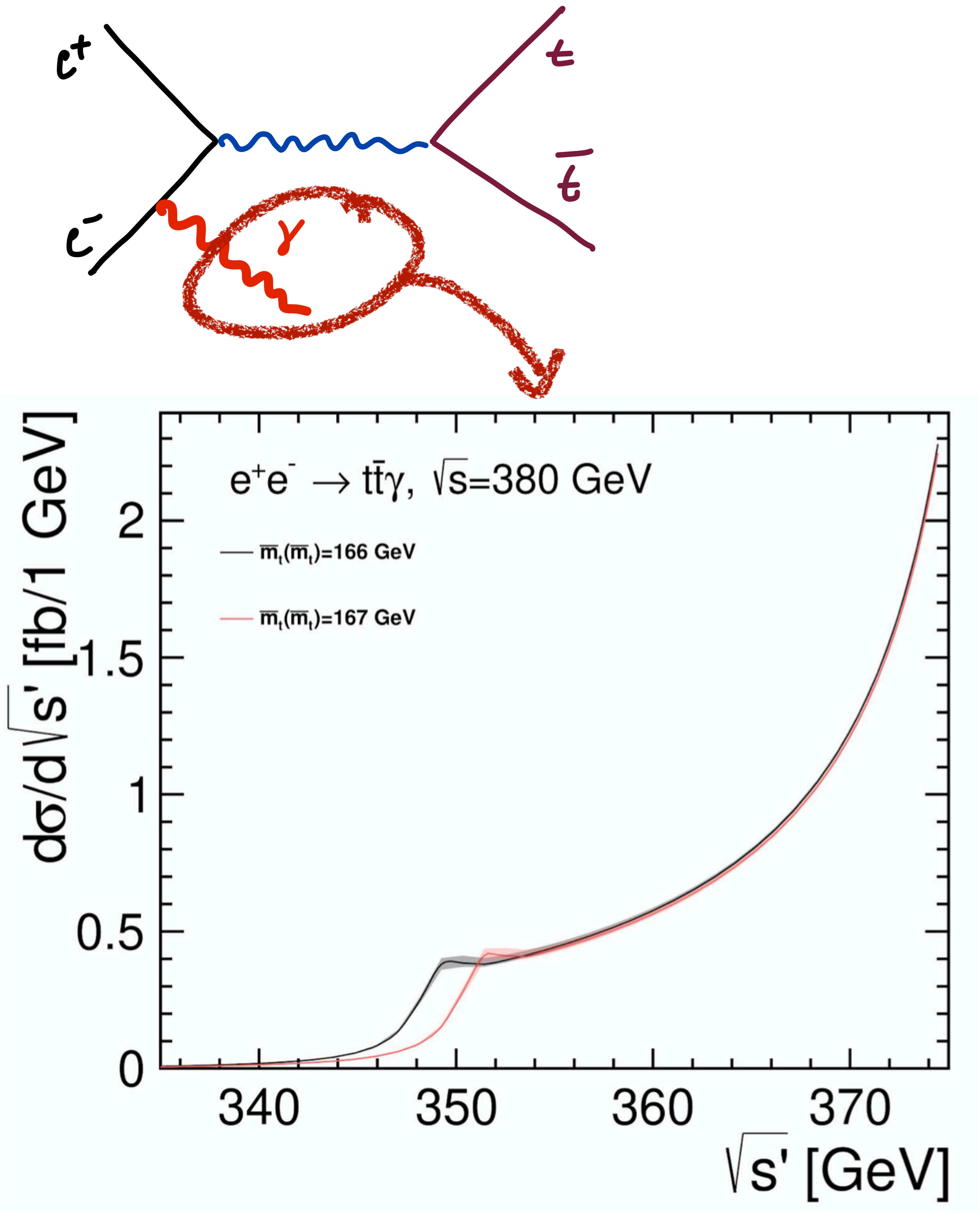
width: 45 - 60 MeV; y_t: 10% - 15%

Mass in radiative Events

Theoretically safe in the Continuum

MAX-PLANCK-INSTITUT FÜR PHYSIK

- Combining the advantage of well-defined mass schemes and the convenience of above-threshold running

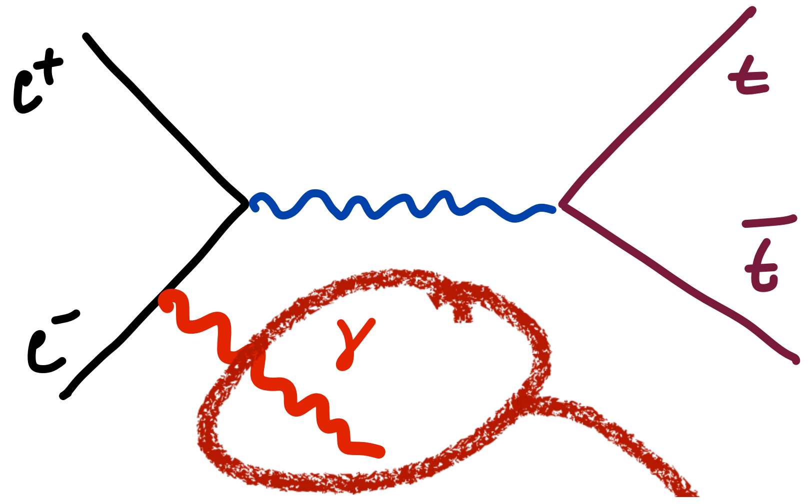


PLB 804, 135353 (2020)

Mass in radiative Events

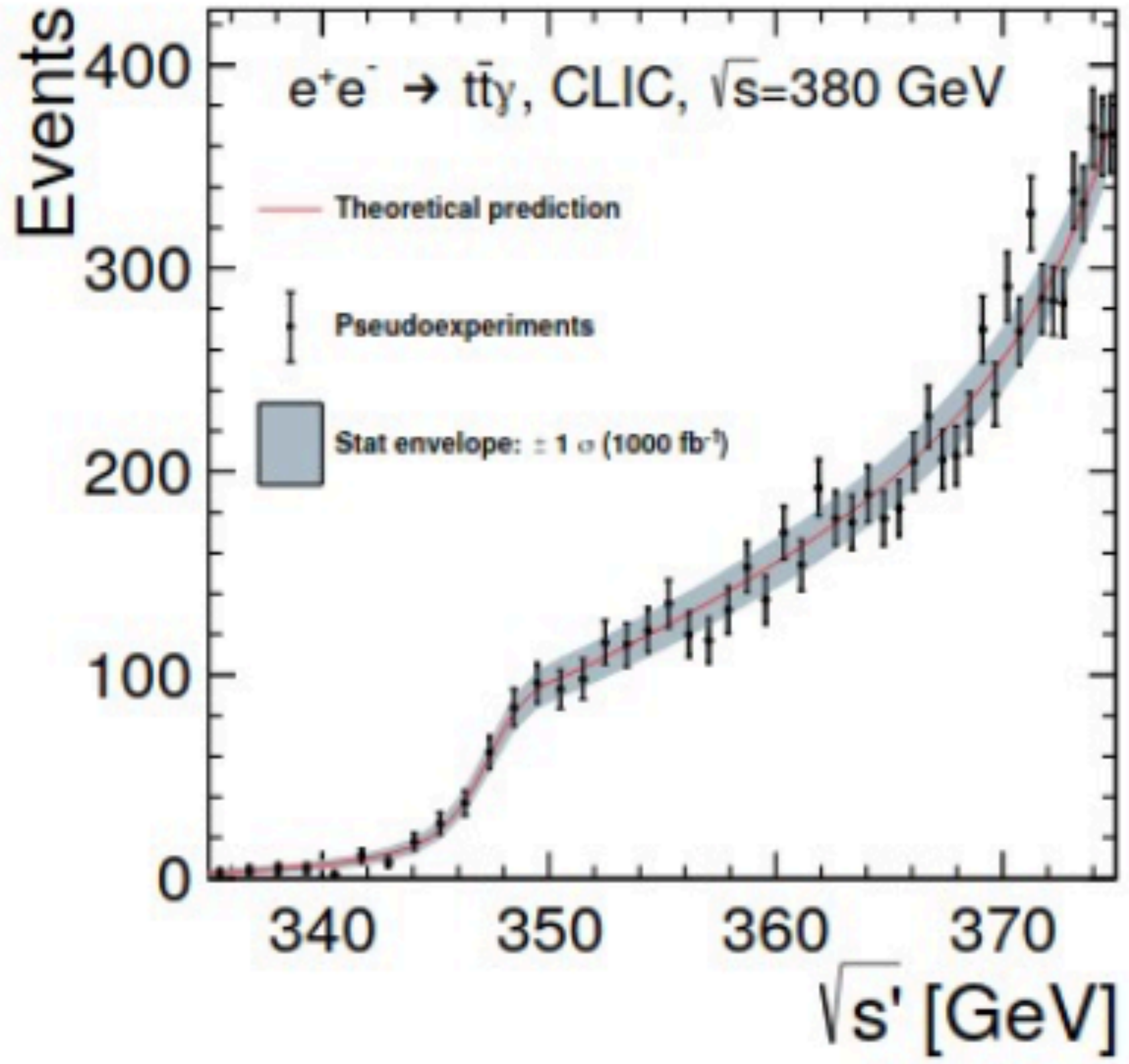
Theoretically safe in the Continuum

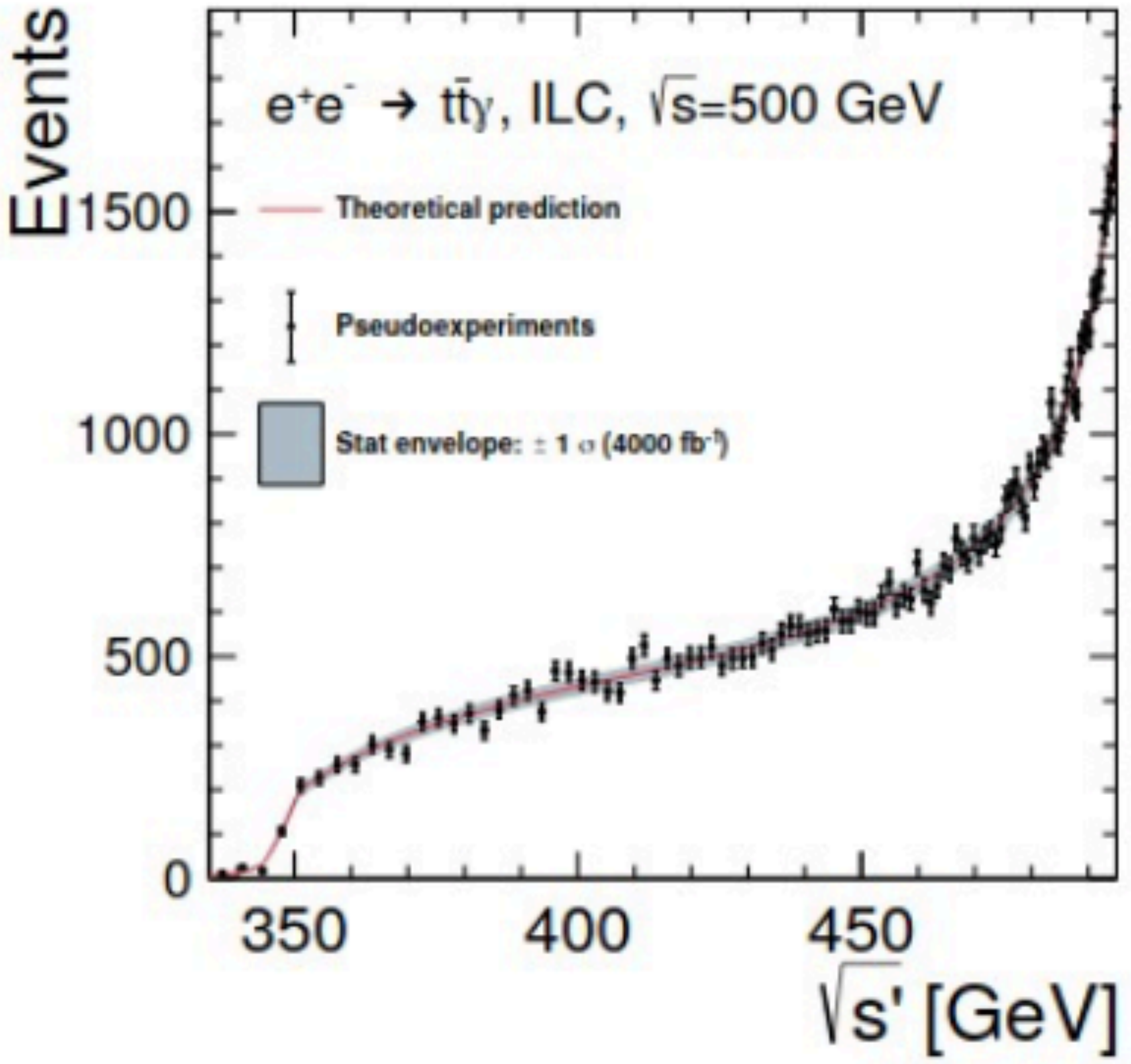
- Combining the advantage of well-defined mass schemes and the convenience of above-threshold running



matched NNLO + NNLL calculation, luminosity spectrum folded in explicitly; Extraction of short distance MSR mass

	CLIC, $\sqrt{s} = 380$ GeV		ILC, $\sqrt{s} = 500$ GeV	
cms energy	CLIC, $\sqrt{s} = 380$ GeV		ILC, $\sqrt{s} = 500$ GeV	
luminosity [fb^{-1}]	500	1000	500	4000
statistical	140 MeV	90 MeV	350 MeV	110 MeV
theory	46 MeV		55 MeV	
lum. spectrum	20 MeV		20 MeV	
photon response	16 MeV		85 MeV	
total	150 MeV	110 MeV	360 MeV	150 MeV





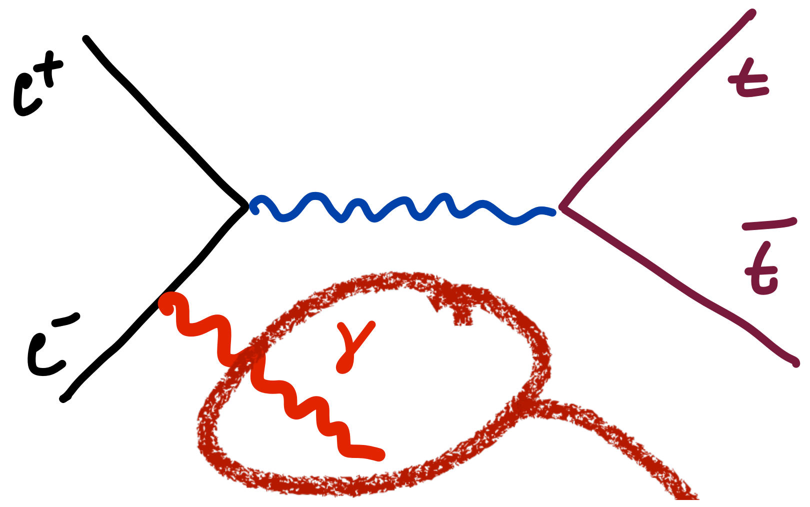
PLB 804, 135353 (2020)

Mass in radiative Events

Theoretically safe in the Continuum

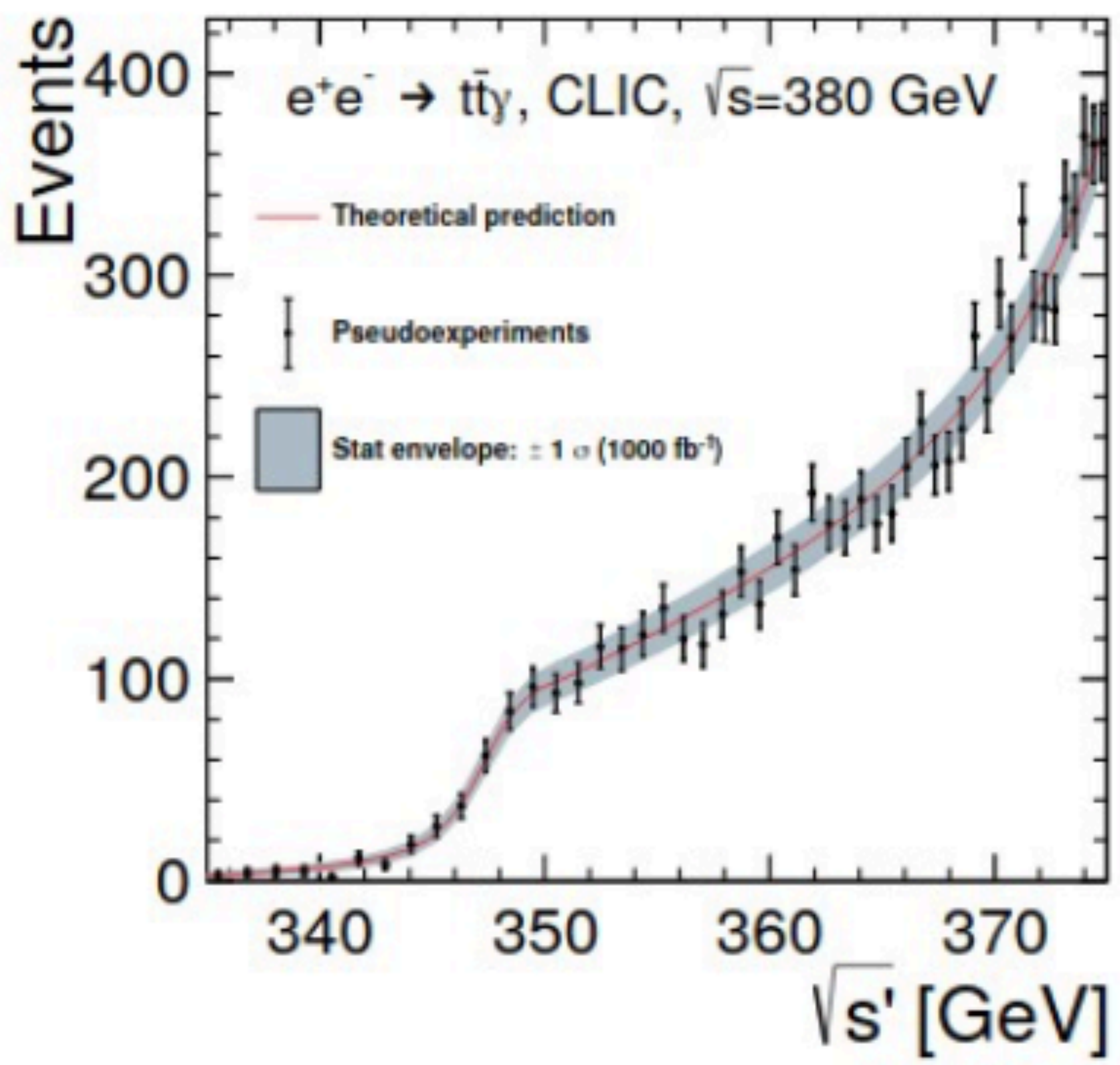
MAX-PLANCK-INSTITUT FÜR PHYSIK

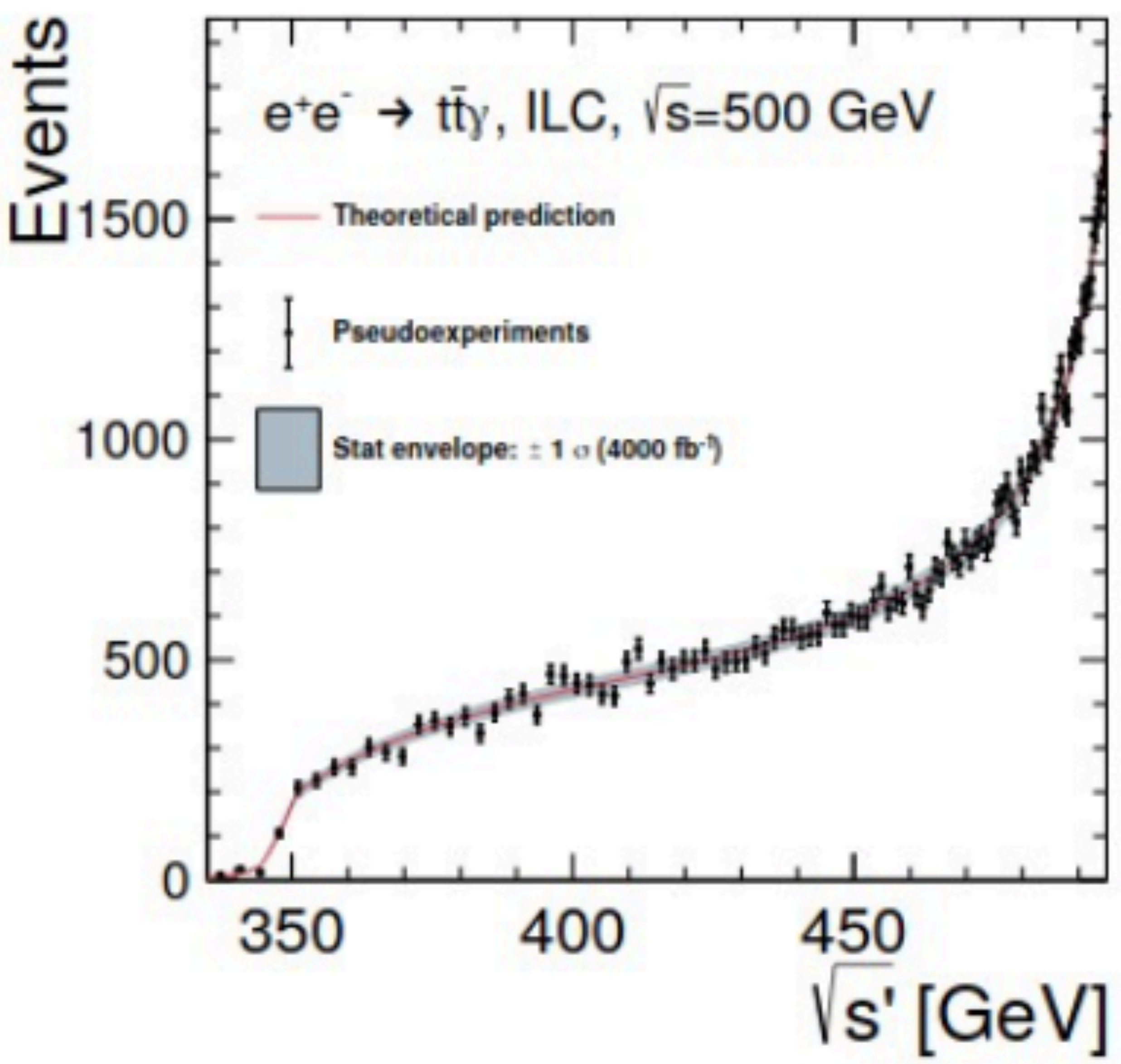
- Combining the advantage of well-defined mass schemes and the convenience of above-threshold running



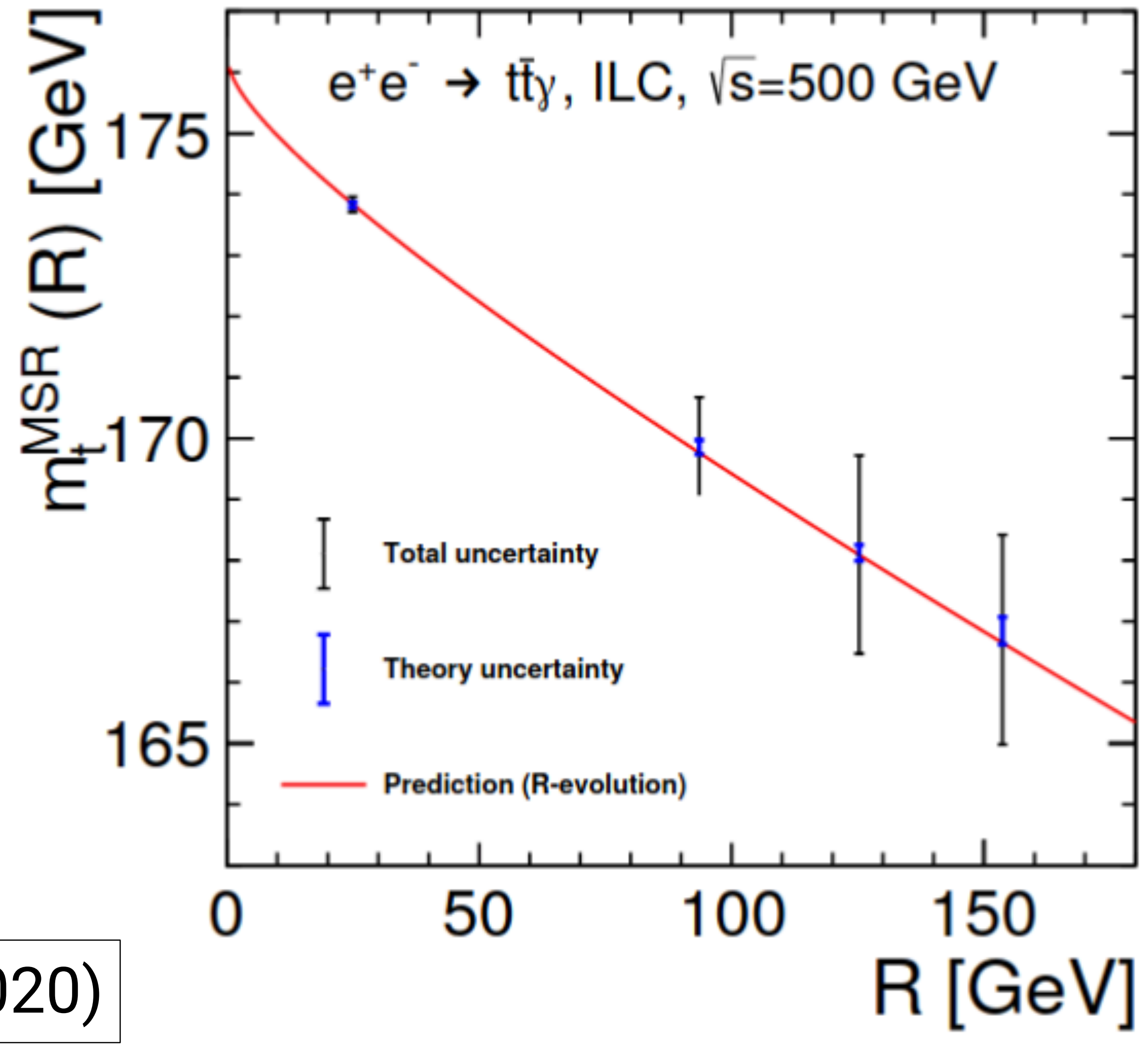
matched NNLO + NNLL calculation, luminosity spectrum folded in explicitly; Extraction of short distance MSR mass

cms energy	CLIC, $\sqrt{s} = 380\,\text{GeV}$		ILC, $\sqrt{s} = 500\,\text{GeV}$	
luminosity $[\text{fb}^{-1}]$	500	1000	500	4000
statistical	140 MeV	90 MeV	350 MeV	110 MeV
theory	46 MeV		55 MeV	
lum. spectrum	20 MeV		20 MeV	
photon response	16 MeV		85 MeV	
total	150 MeV	110 MeV	360 MeV	150 MeV





can provide 5σ evidence for scale evolution ("running") of the top quark MSR mass from ILC500 data alone

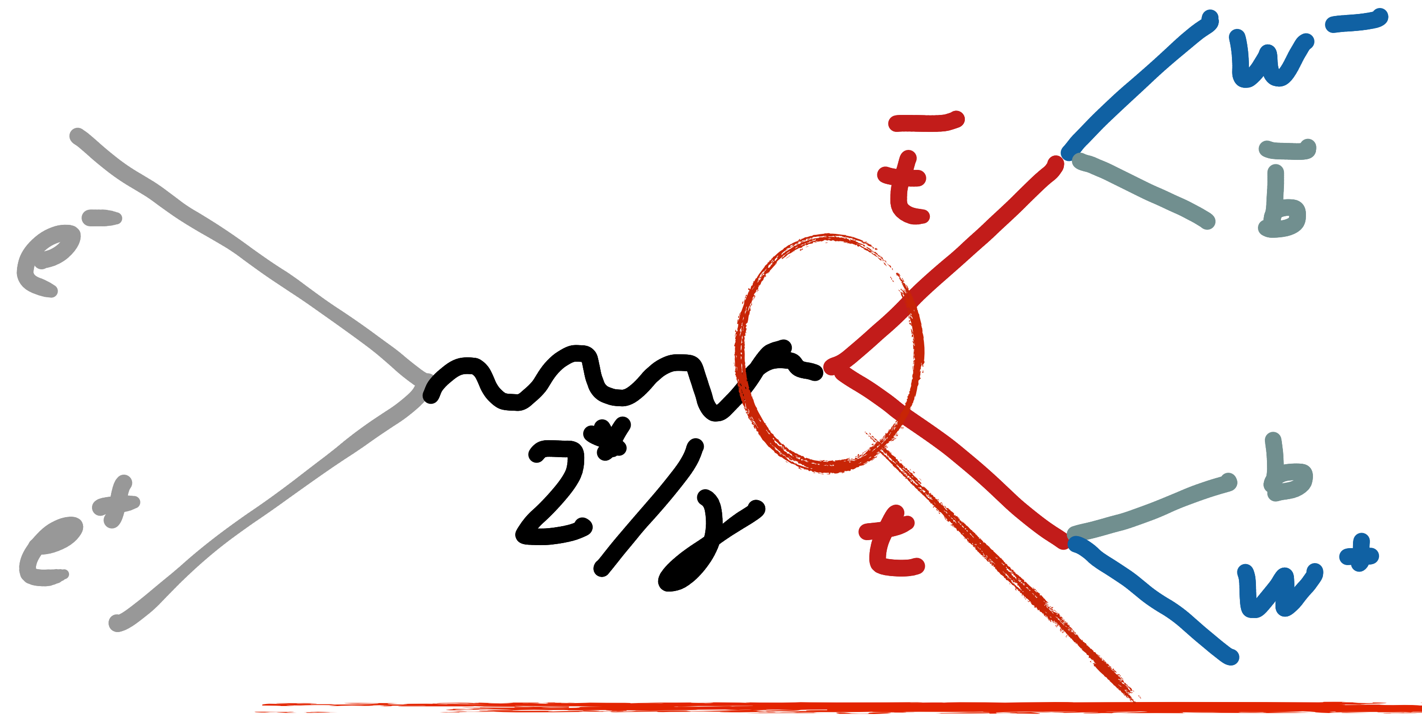


PLB 804, 135353 (2020)

Top Quarks as a Probe for New Physics

Electroweak Couplings

Exploiting Energy and Polarisation



In total: 5 non-trivial CP-conserving form factors:

$$F^{\gamma}_{1V} \quad F^{\gamma}_{1A} \quad F^{\gamma}_{2V}$$
$$F^{Z}_{1V} \quad F^{Z}_{1A} \quad F^{Z}_{2V}$$

= 0 due to gauge invariance

$$\Gamma^{ttX}_{\mu}(k^2, q, \overline{q}) = ie\left\{\gamma_\mu\left(\widetilde{F}^X_{1V}(k^2) + \gamma_5\widetilde{F}^X_{1A}(k^2)\right) + \frac{(q-\overline{q})_\mu}{2m_t}\left(\widetilde{F}^X_{2V}(k^2) + \gamma_5\widetilde{F}^X_{2A}(k^2)\right)\right\}$$

X: Z, γ   *A*: axial coupling   *V*: vector coupling

- Accessible through measurements of:
  - Total cross-section
  - Forward-backward Asymmetry AFB
  - Helicity Angle λ distribution (related to fraction of left- and right-handed tops)
- For each: Two polarizations e^-_L - e^+_R, e^-_R - e^+_L

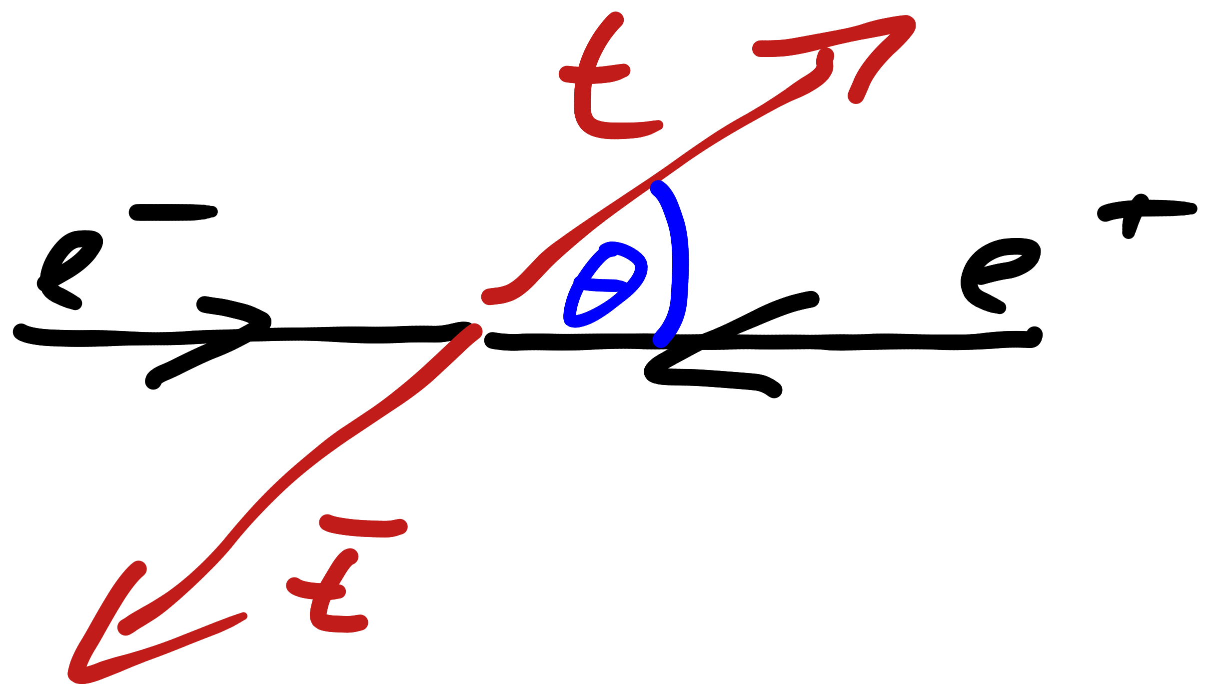
➪ Polarized beams at linear colliders crucial

Electroweak Couplings

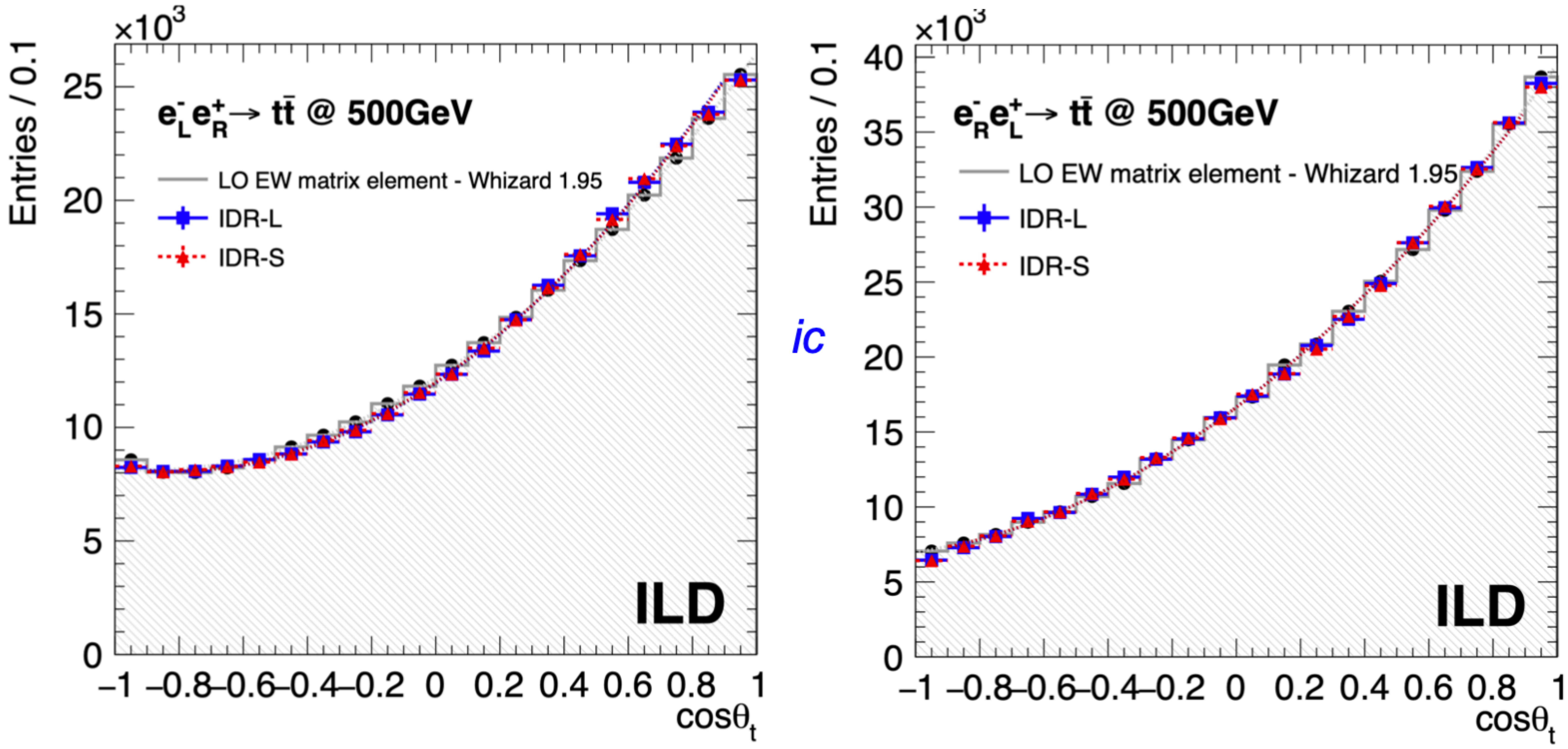
Example Measurement

- One example:
  forward-backward asymmetry

$$A^t_{FB} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$



0.5% precision on A_{FB} for
4 ab^{-1} at 500 GeV



semi-leptonic events

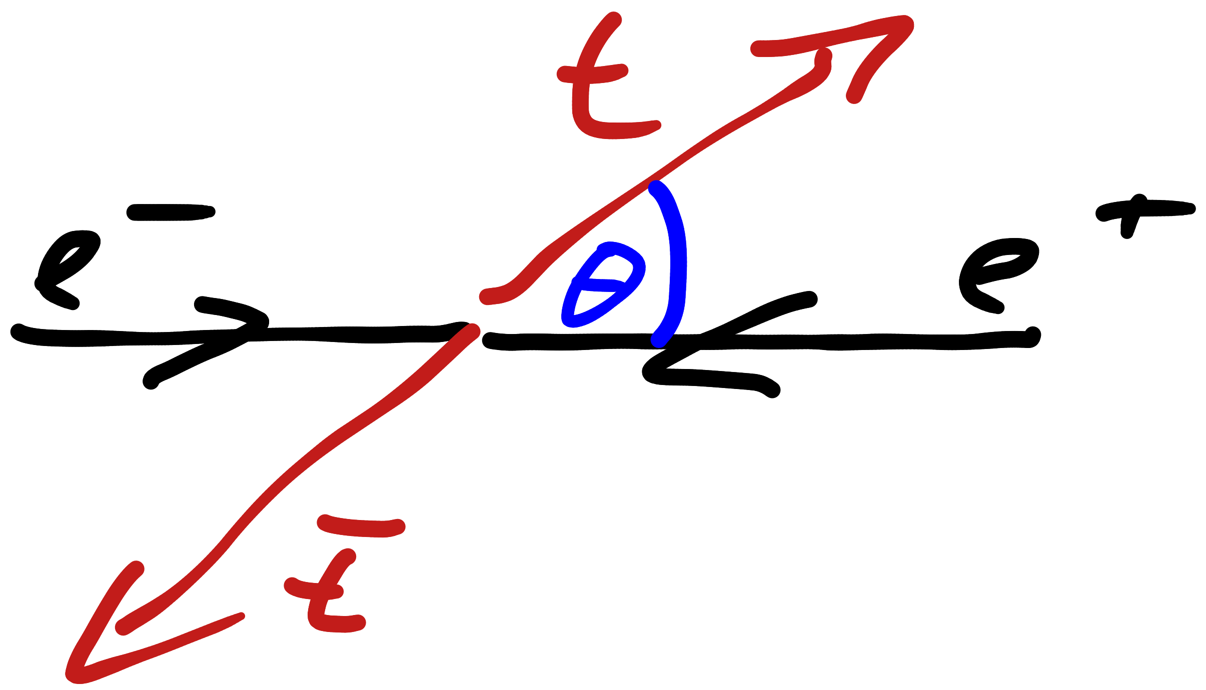
arXiv:2003.01116; JHEP 11, 003 (2019)

Electroweak Couplings

Example Measurement

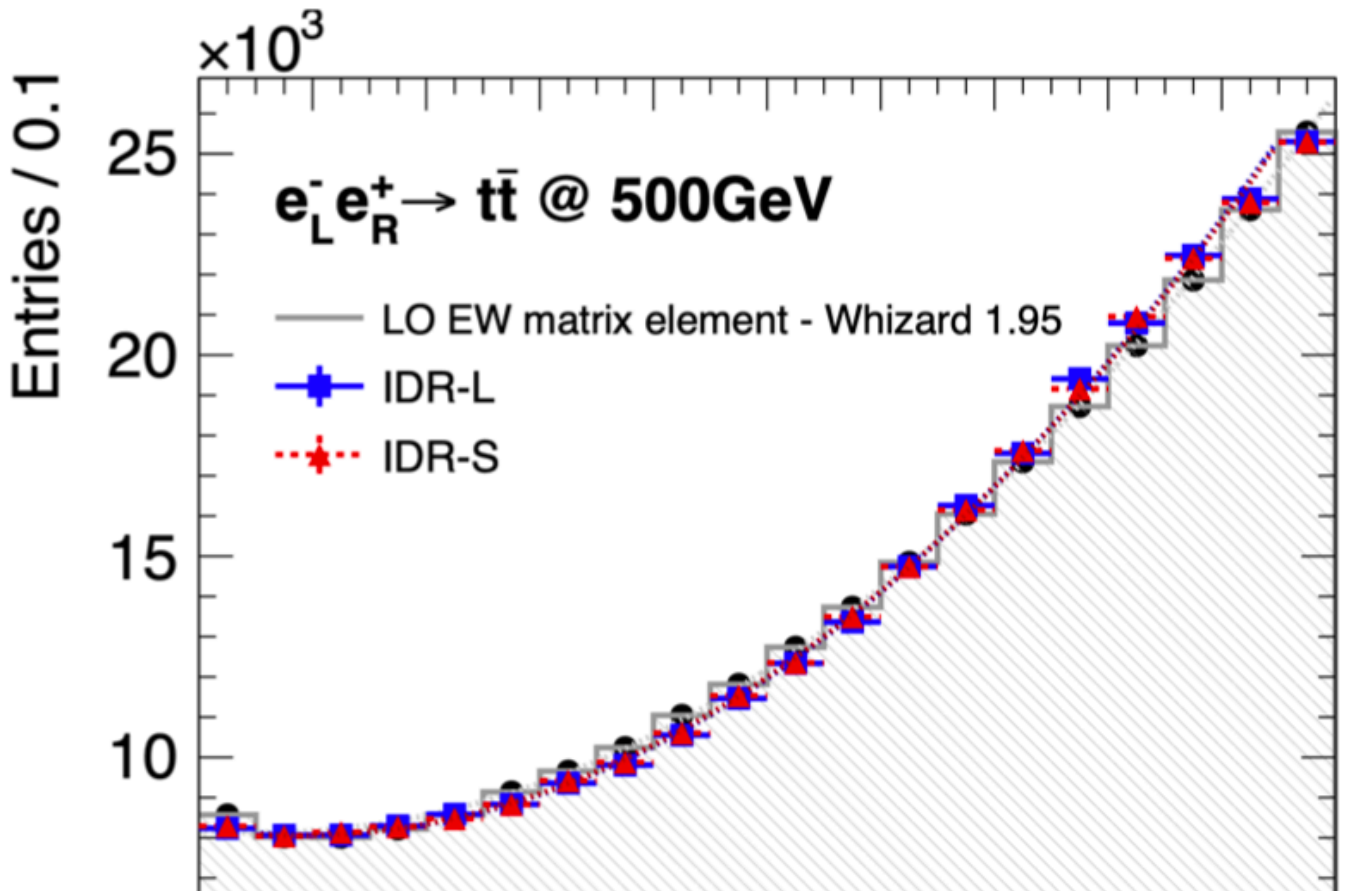
- One example:
  forward-backward asymmetry

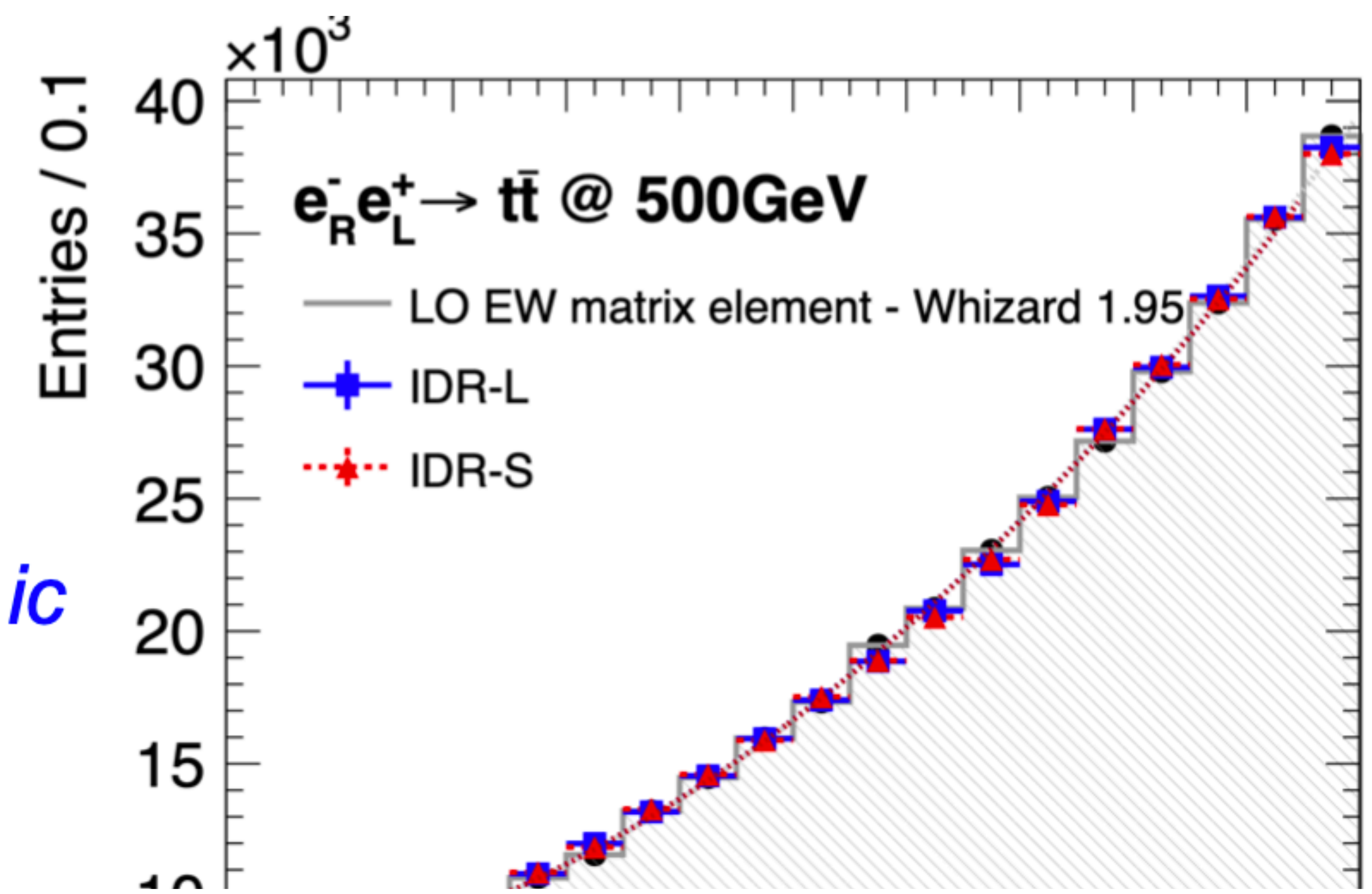
$$A_{FB}^{t} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$

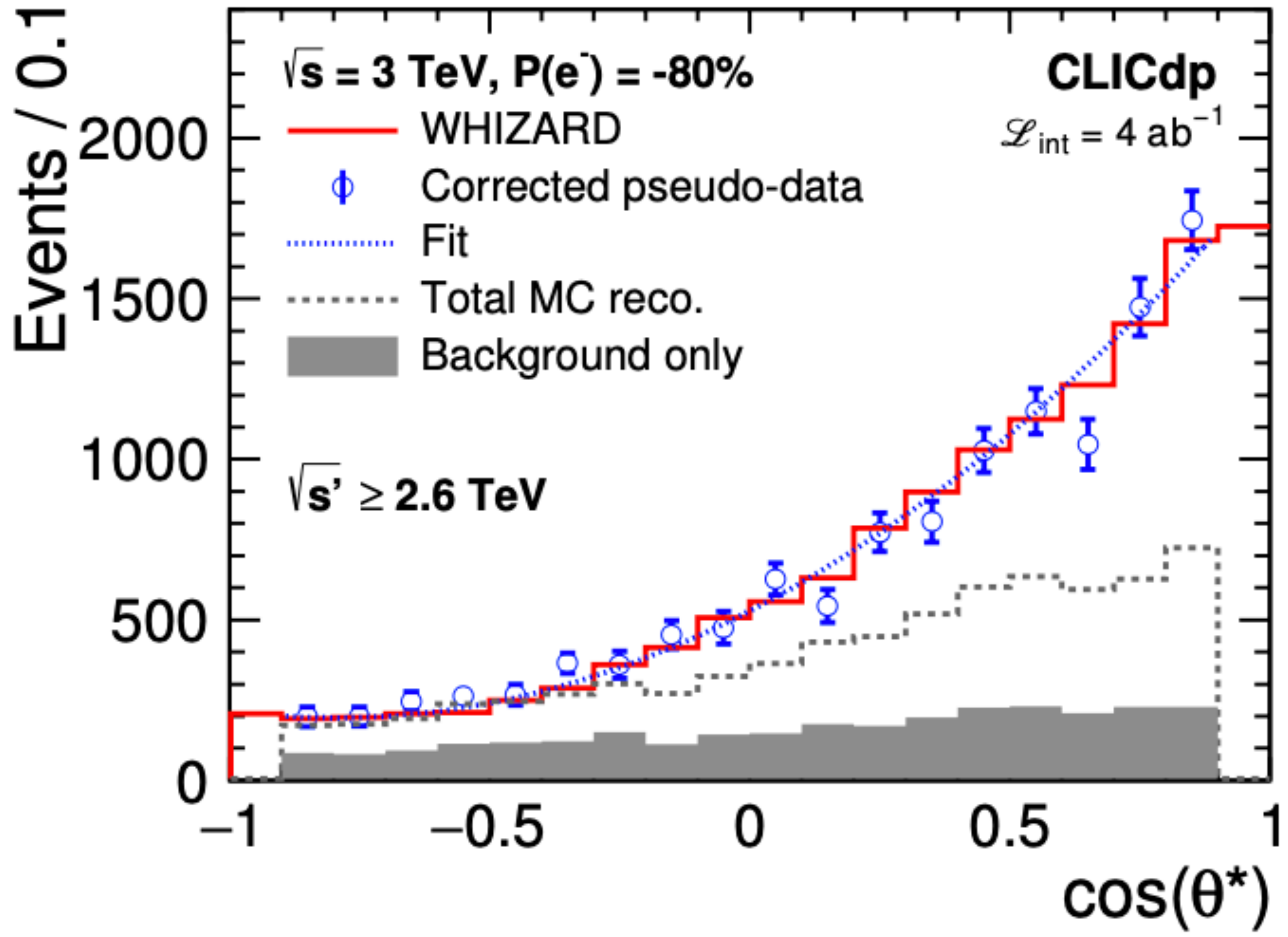


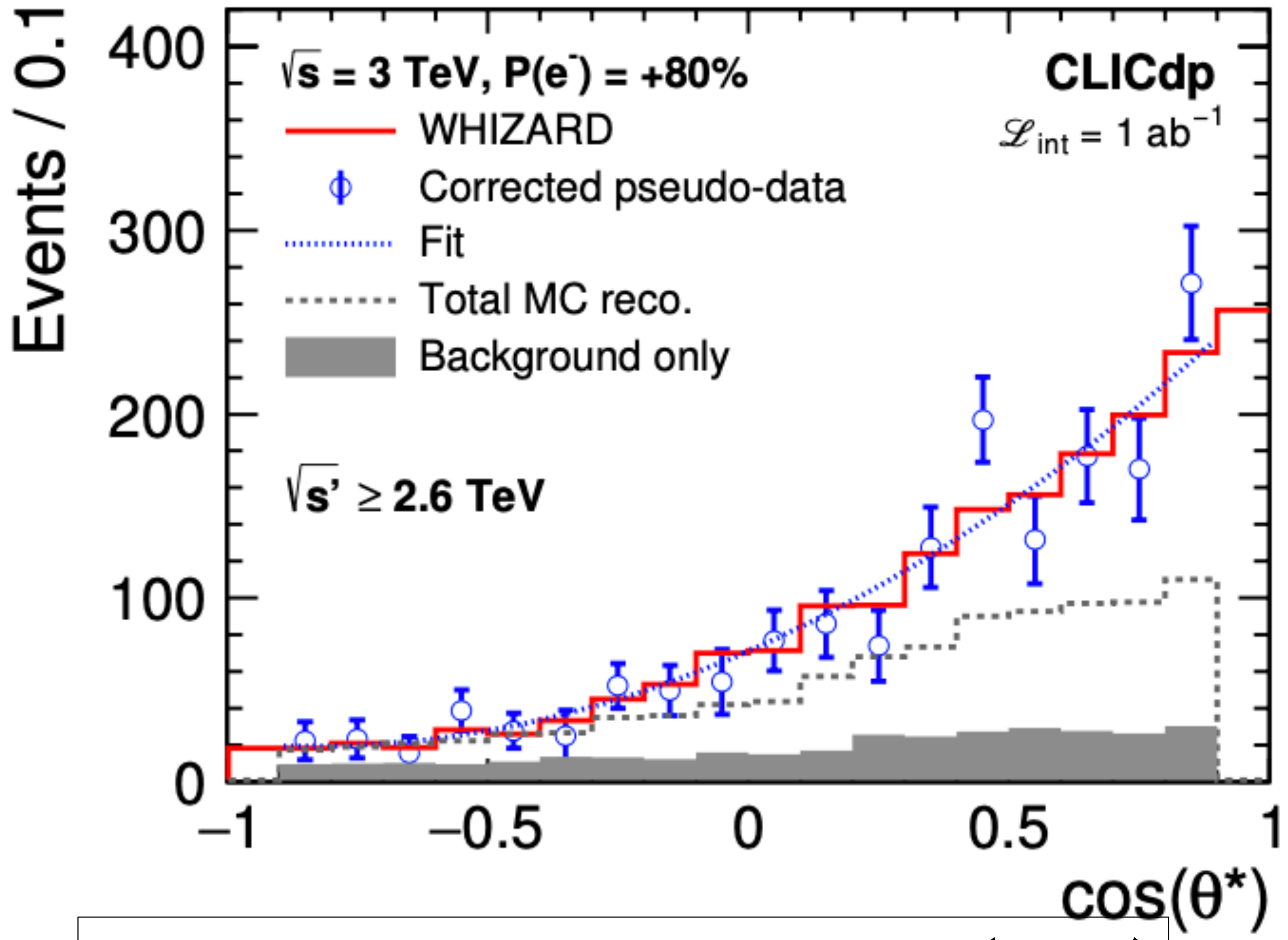
0.5% precision on A_{FB} for
4 ab^{-1} at 500 GeV

- Also studied at higher energy, with boosted reconstruction at CLIC









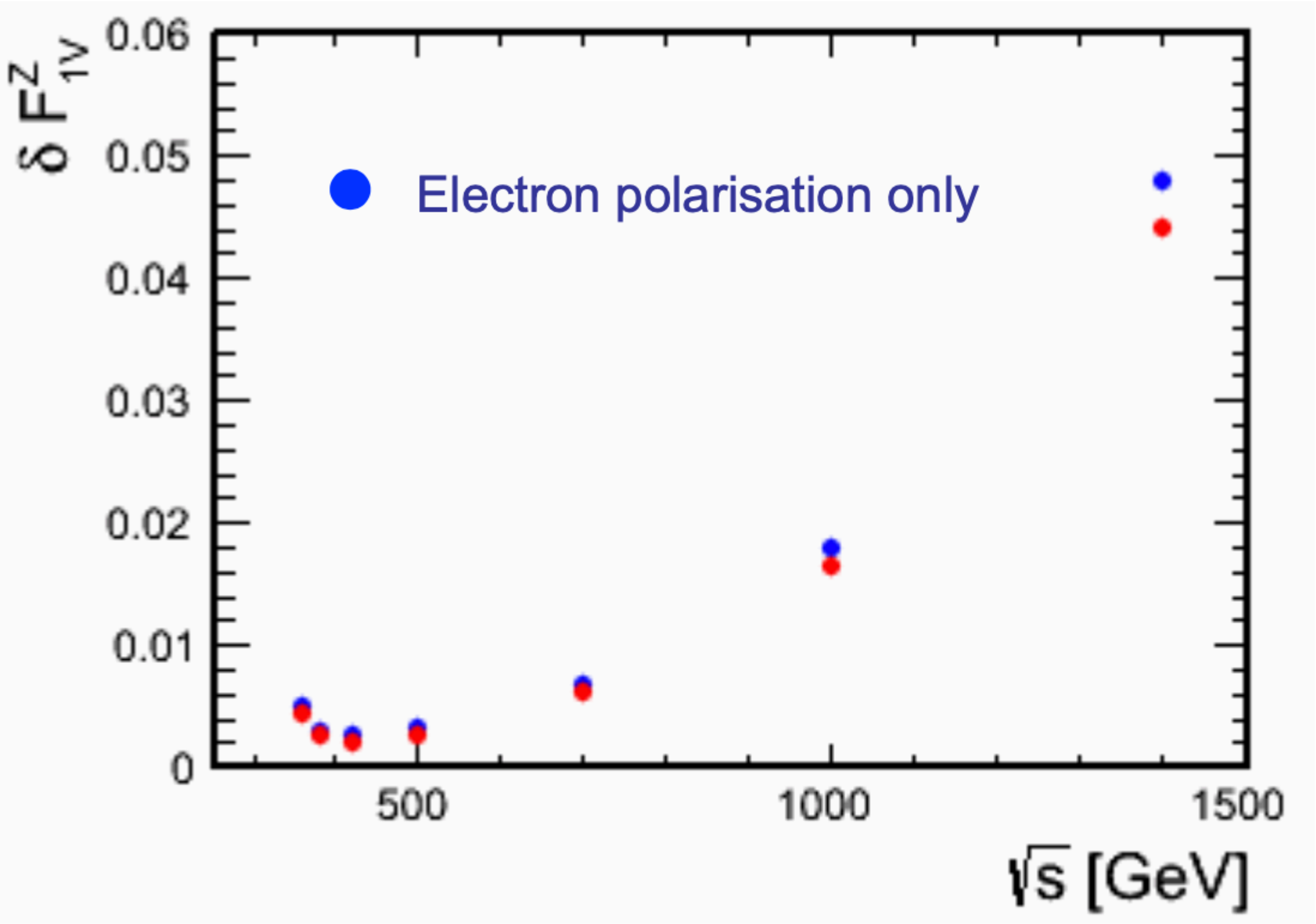
arXiv:2003.01116; JHEP 11, 003 (2019)

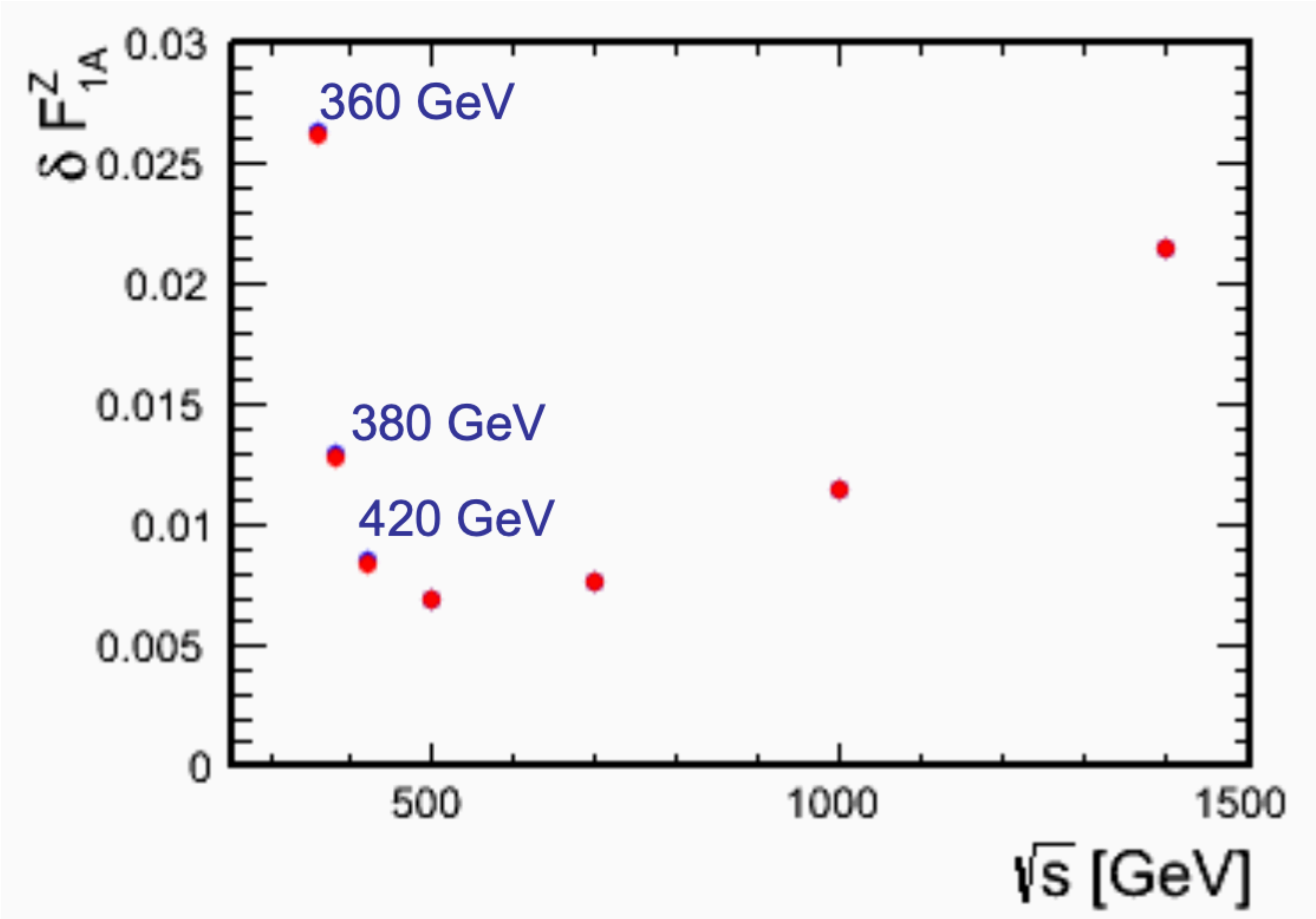
Electroweak Couplings: The Role of Energy

The Choice of Collider Energy Stages

- Studied in the context of CLIC: Choice of the first energy stage a balance between Higgs and Top physics

500 fb^{-1} with 50:50 -80%/+30% +80%/-30% polarisation





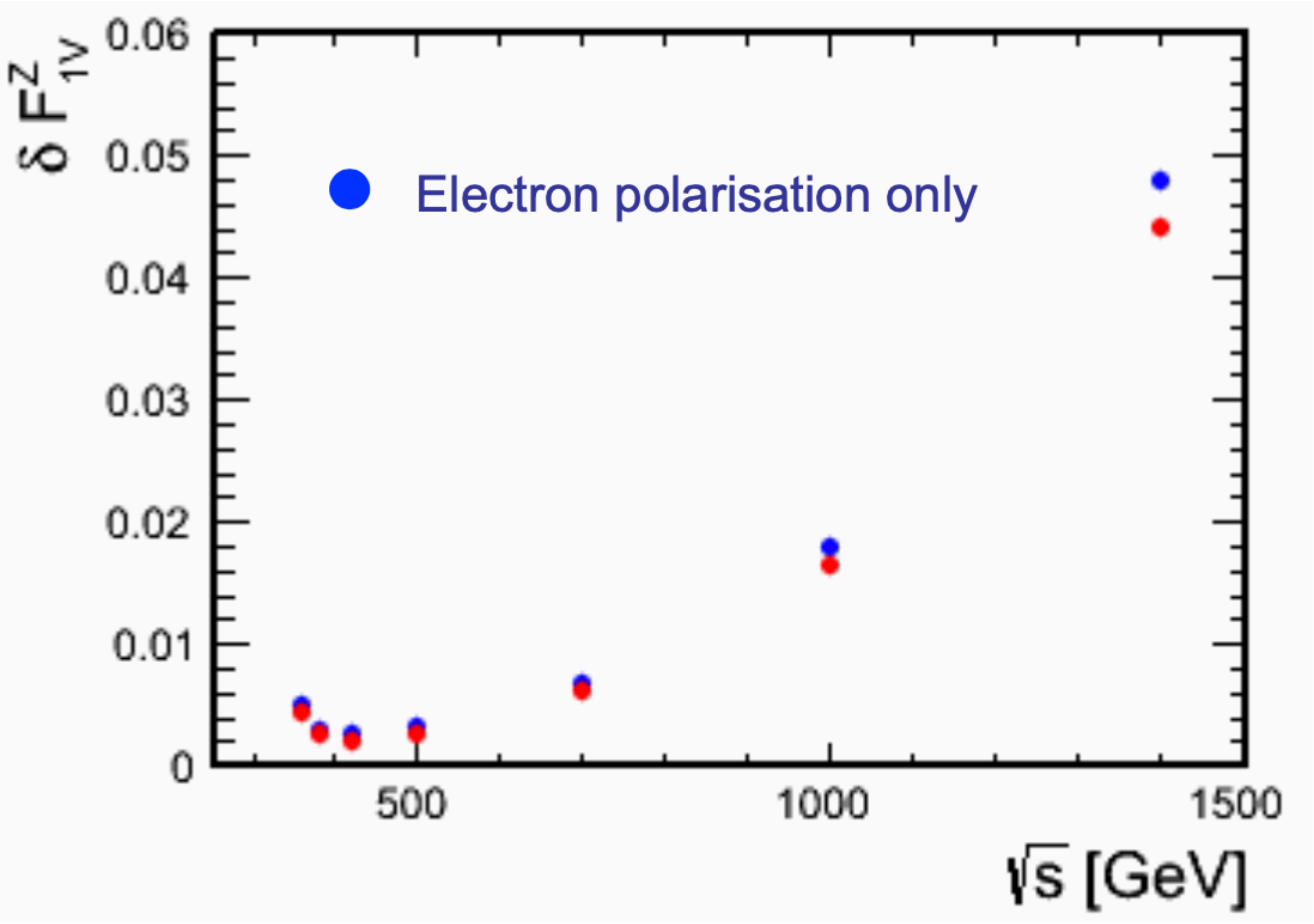
Moving away from threshold is beneficial because of boost

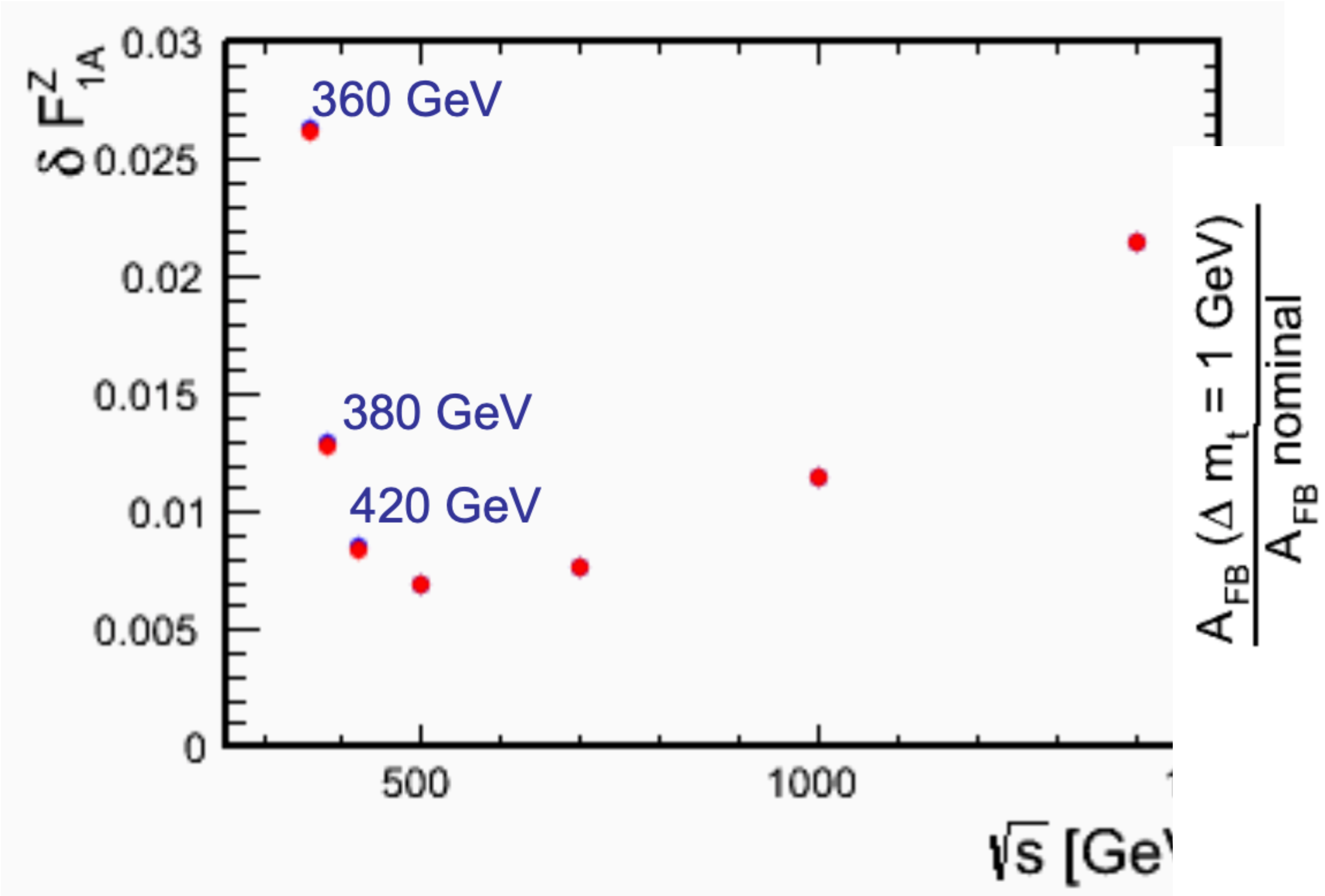
Electroweak Couplings: The Role of Energy

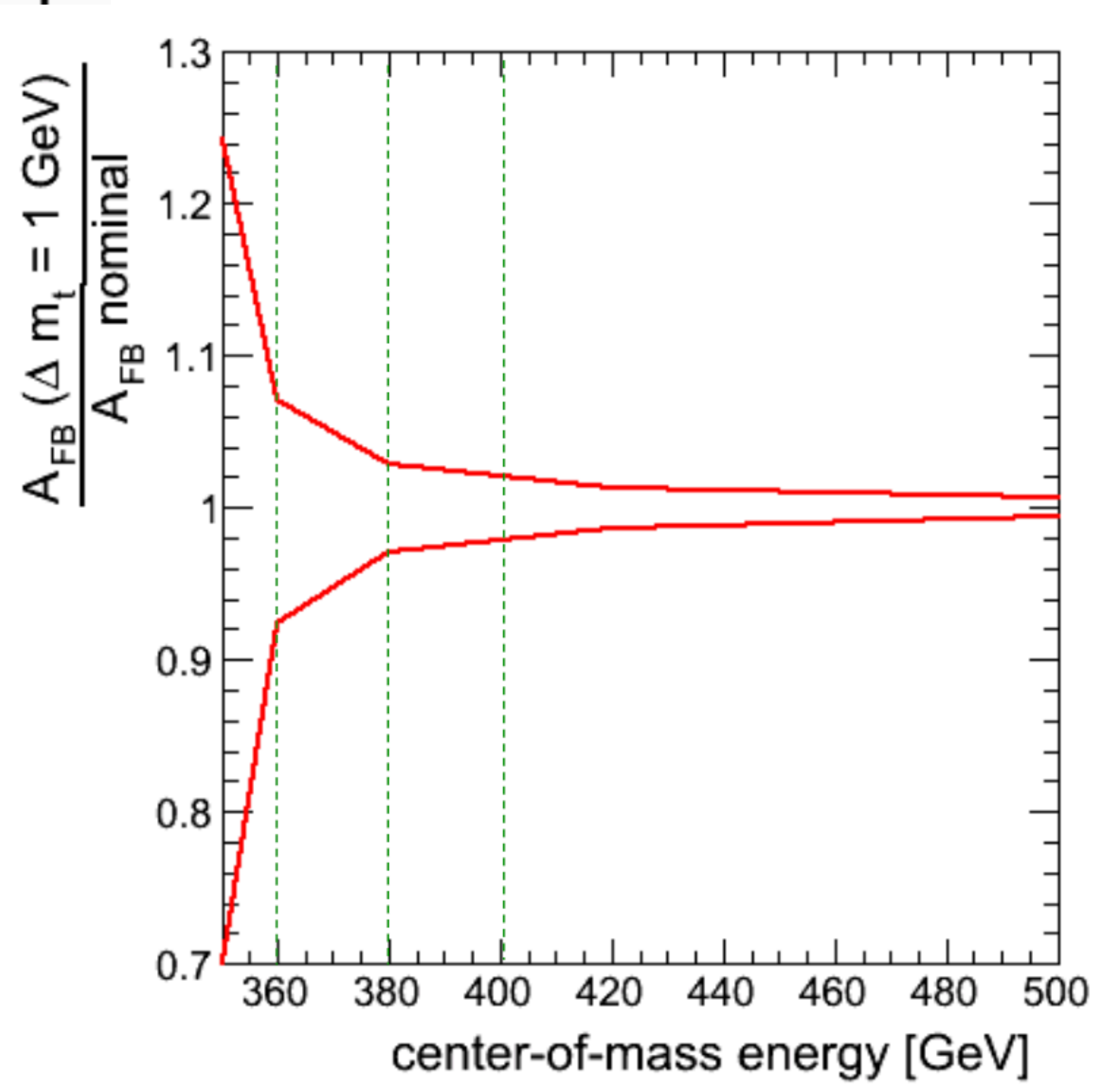
The Choice of Collider Energy Stages

- Studied in the context of CLIC: Choice of the first energy stage a balance between Higgs and Top physics

500 fb^{-1} with 50:50 -80%/+30% +80%/-30% polarisation







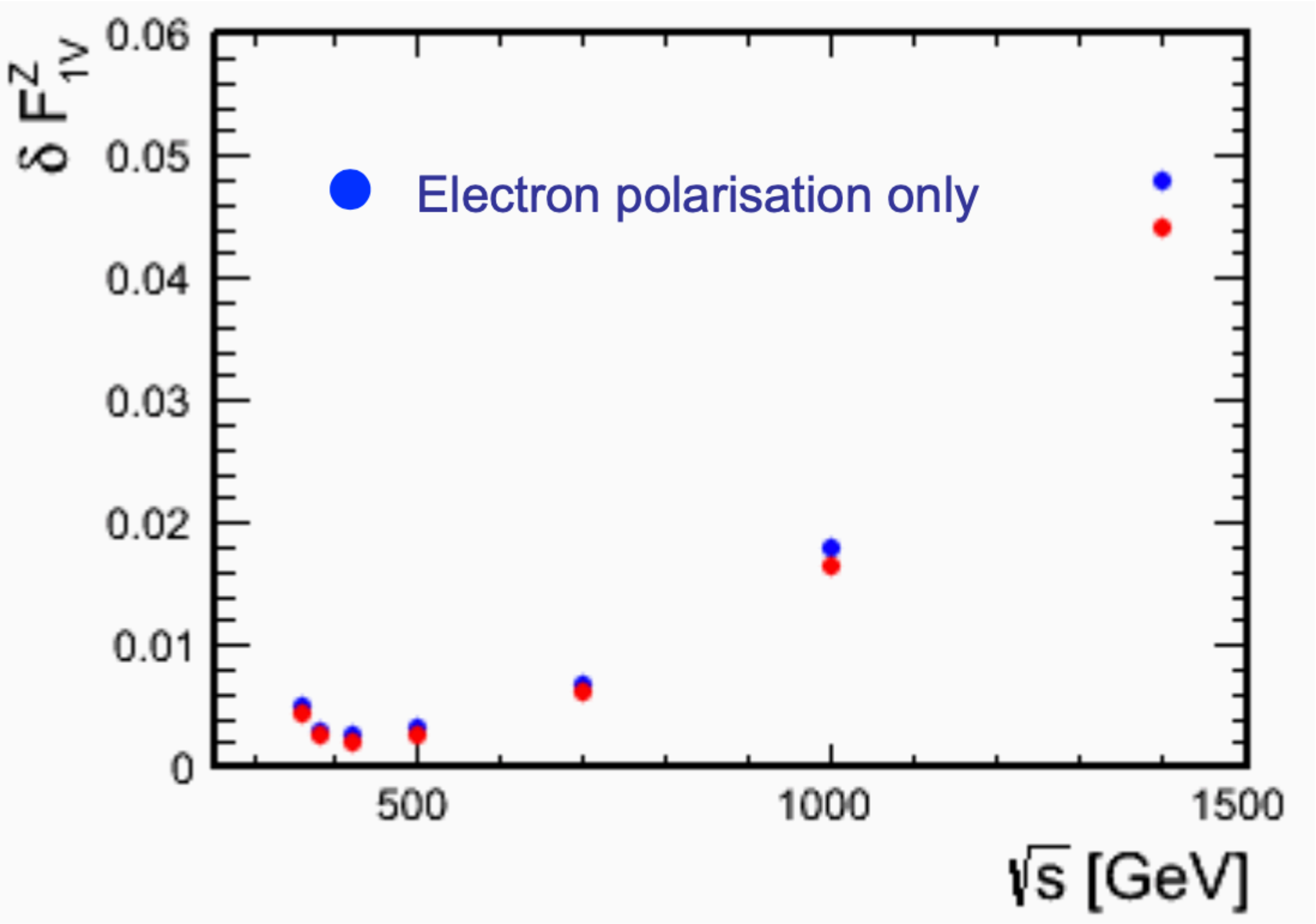
Moving away from threshold is beneficial because of boost
… and parametric uncertainties.

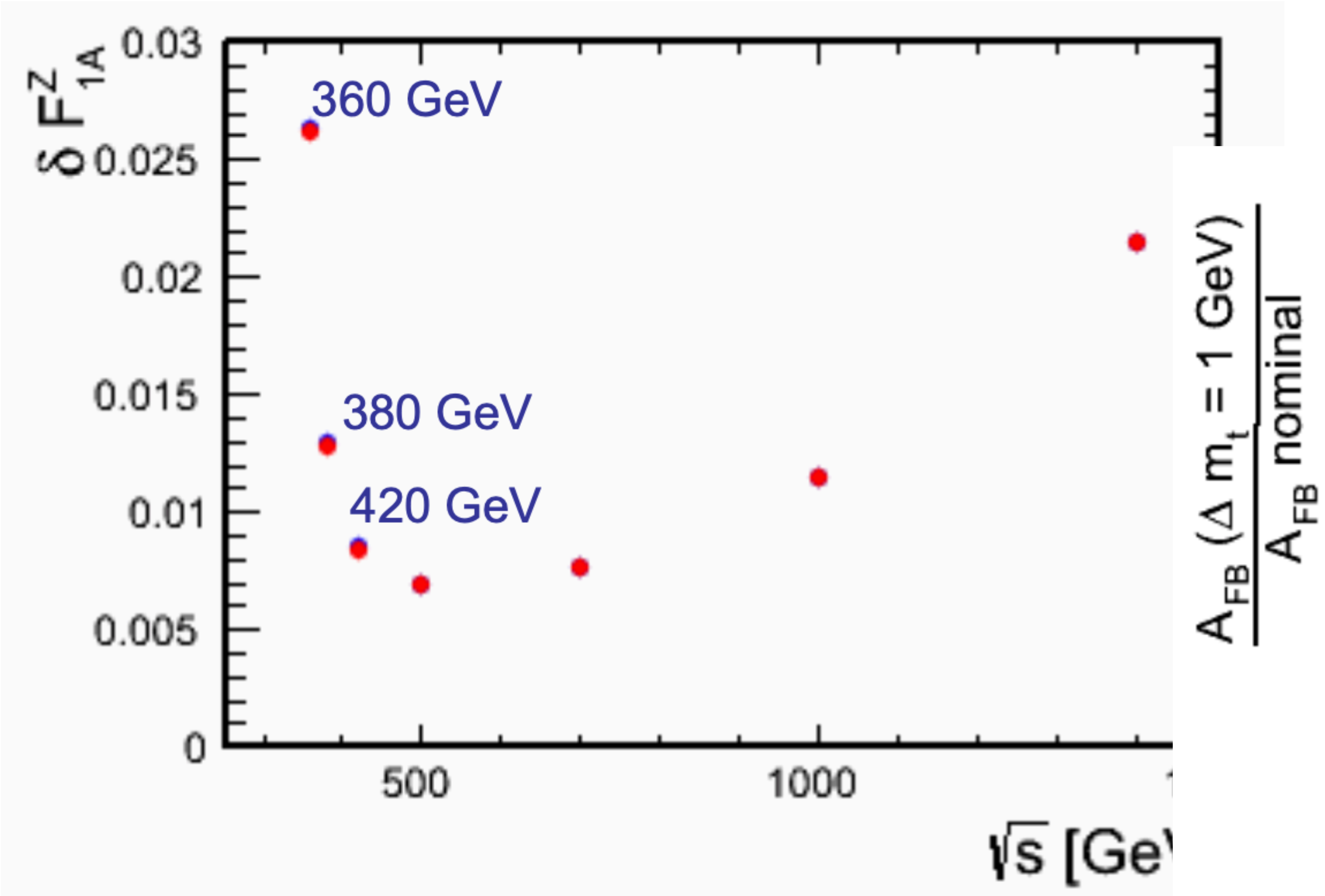
Electroweak Couplings: The Role of Energy

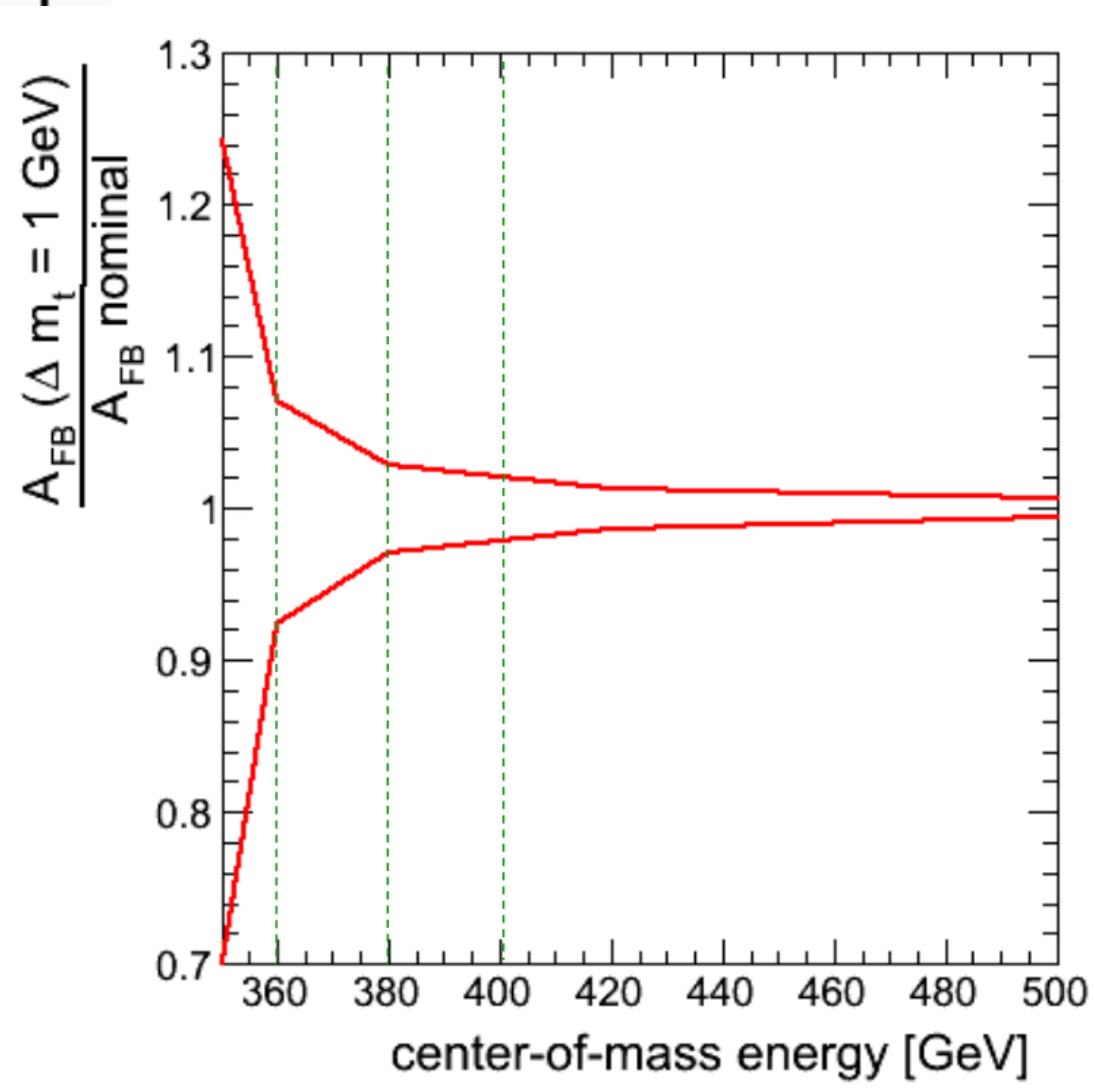
The Choice of Collider Energy Stages

- Studied in the context of CLIC: Choice of the first energy stage a balance between Higgs and Top physics

500 fb^{-1} with 50:50 -80%/+30% +80%/-30% polarisation





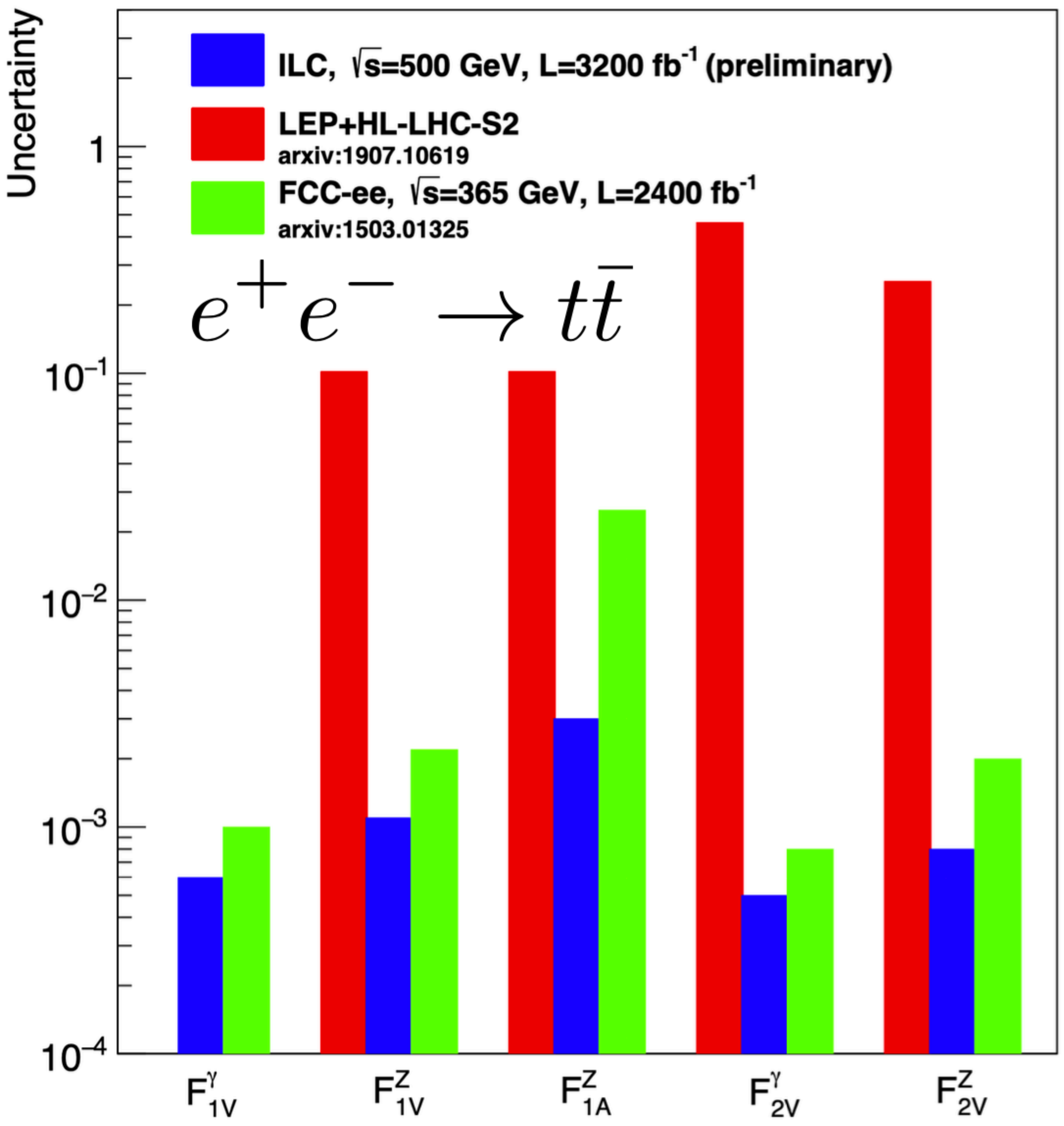


Moving away from threshold is beneficial because of boost
… and parametric uncertainties.

Going too far hurts because of cross section

Electroweak Couplings

Projected Results for ILC and FCC-ee



- Electron-positron colliders can significantly improve over HL-LHC
- Different techniques used for ILC, FCC-ee studies:
  - ILC using polarized beams to separate helicity in intial state
  - FCC-ee study making use of self-analyzing properties of top and W decay

  ➩ Complementary approaches!

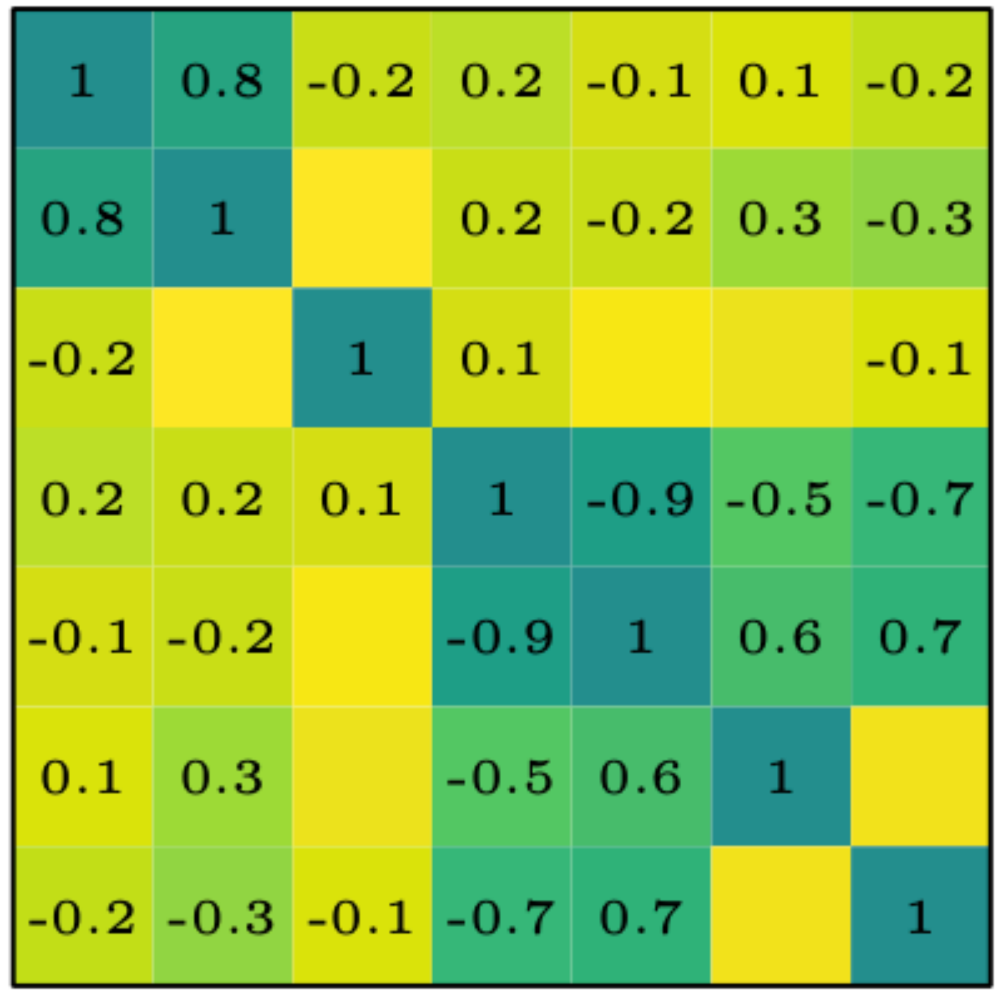
Details / relative performance depends on luminosity projections

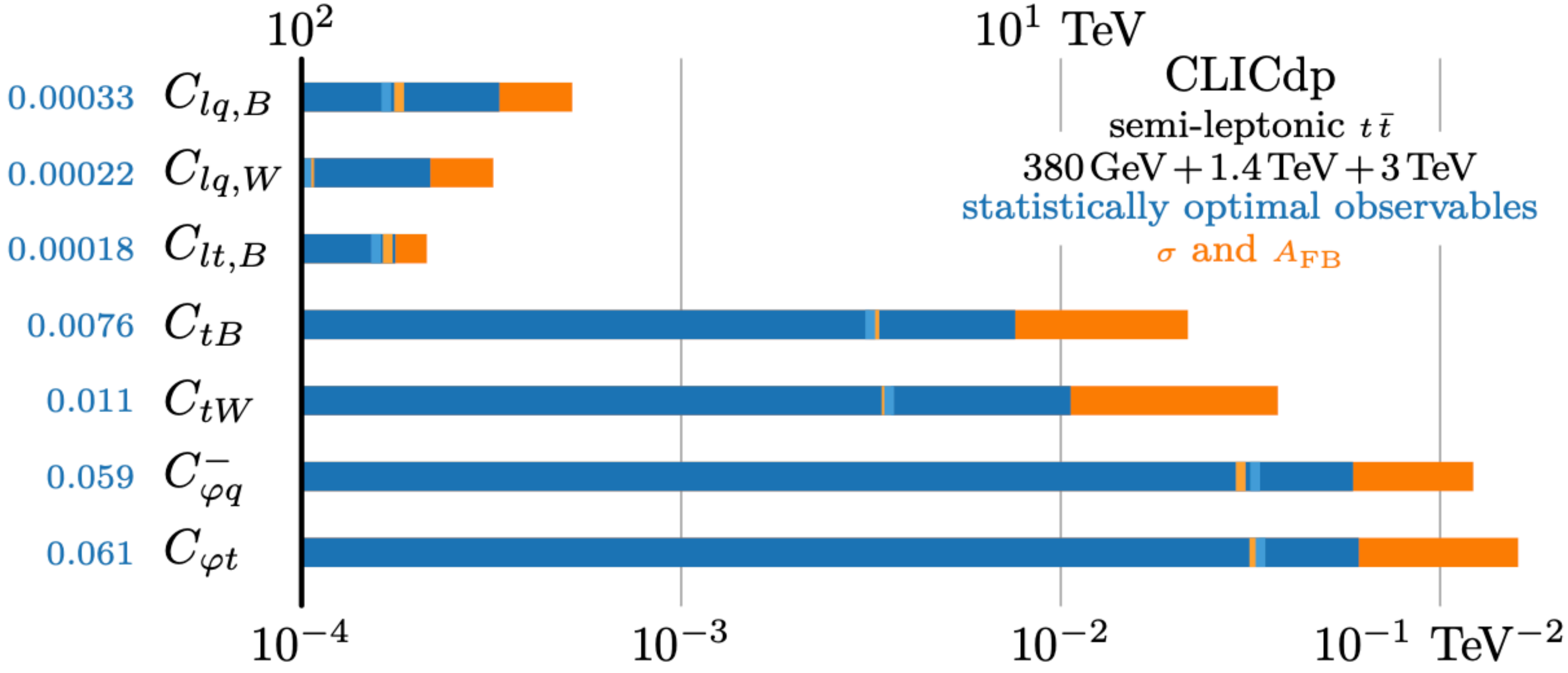
arXiv:2003.01116

Global Analysis of Top Pair Data

EFTs to constrain New Physics

- EFT interpretation of top pair events enables reaching far into the multi-TeV space



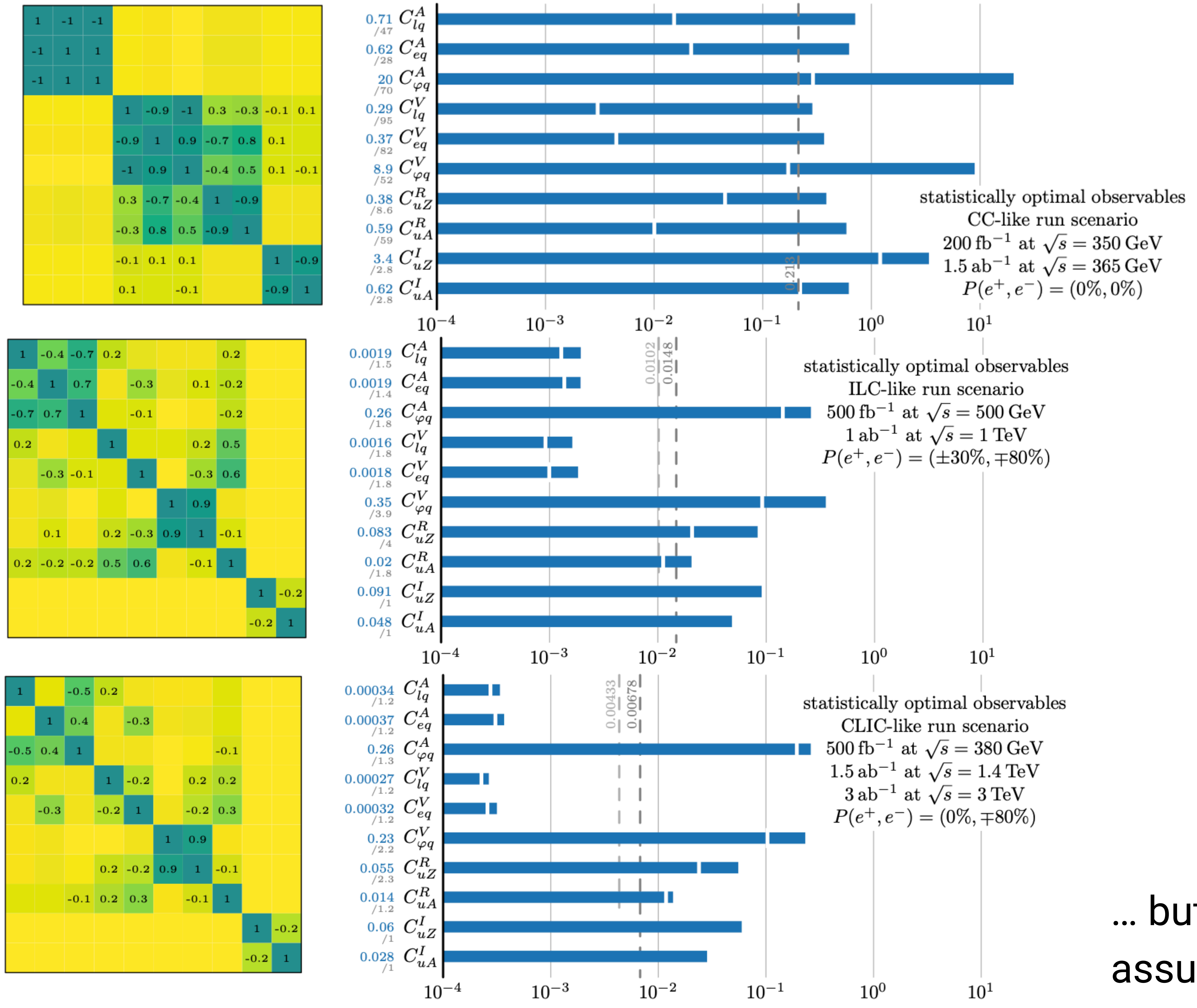


Illustrated for CLIC: Extending beyond cross section and A_{FB} with “statistically optimal observables” which fully use differential information further increases the potential

JHEP 11, 003 (2019)

Global Analysis of Top Pair Data

EFTs for Linear and Circular Colliders



FCC-ee-like

ILC-like

Higher energy and polarization significantly extend the reach

CLIC-like

… but not with the currently assumed luminosity projections

JHEP 10, 168 (2018)

Searching for BSM Decays

A question of top pair statistics

- The clean environment at e^+e^- colliders is a perfect environment to search for FCNC decays:
  - t -> cγ
  - t -> cH
  - t -> cE_{miss} (heavy neutral particle)

extensive study for CLIC

1 ab^{-1} @ 380 GeV

Builds on excellent charm tagging

Searching for BSM Decays

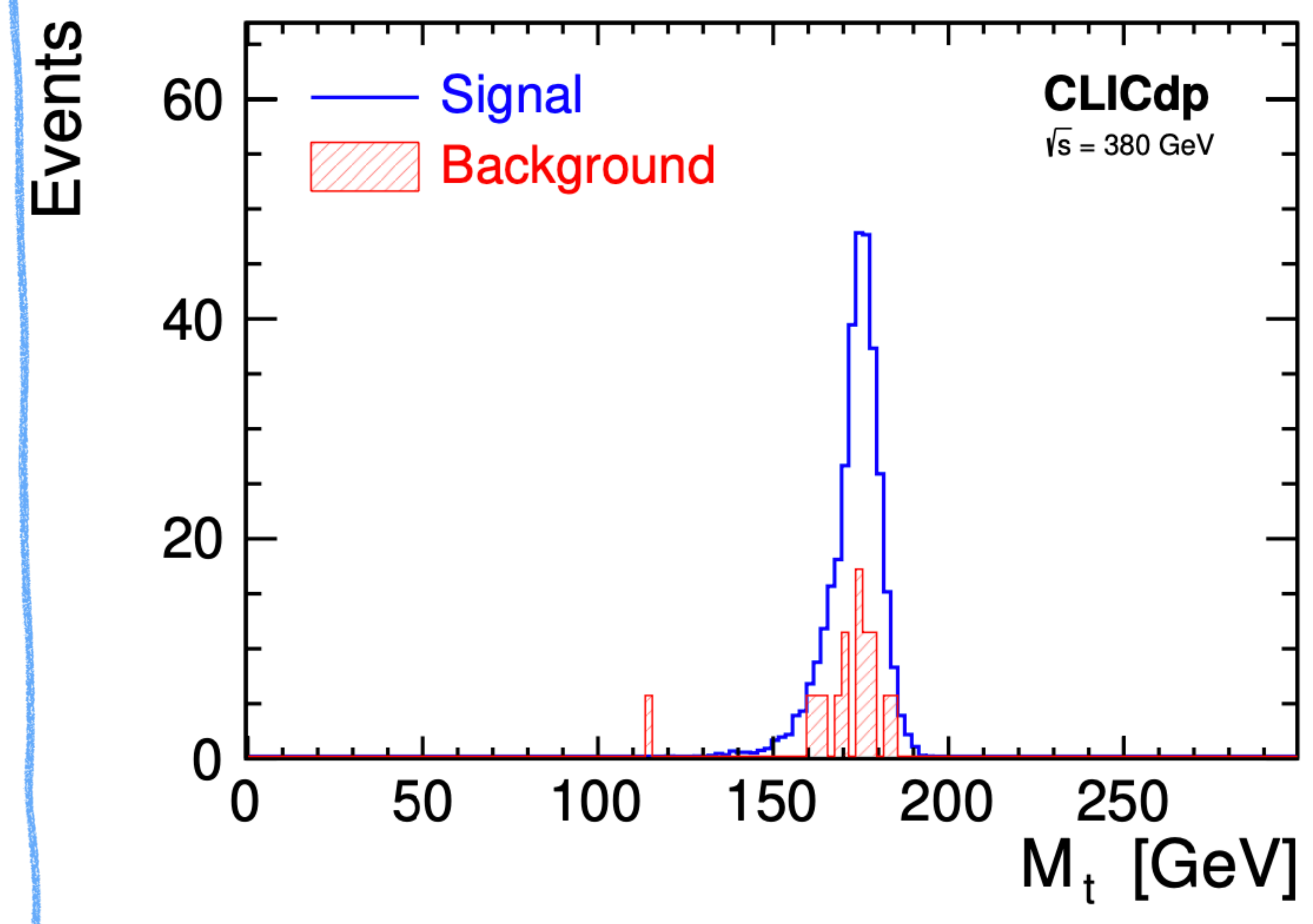
A question of top pair statistics

- The clean environment at e^+e^- colliders is a perfect environment to search for FCNC decays:
  - t -> cγ
  - t -> cH
  - t -> cE_{miss} (heavy neutral particle)

extensive study for CLIC

1 ab^{-1} @ 380 GeV

Builds on excellent charm tagging



$$BR(t \to c\gamma) < 2.6 \times 10^{-5}$$

Searching for BSM Decays

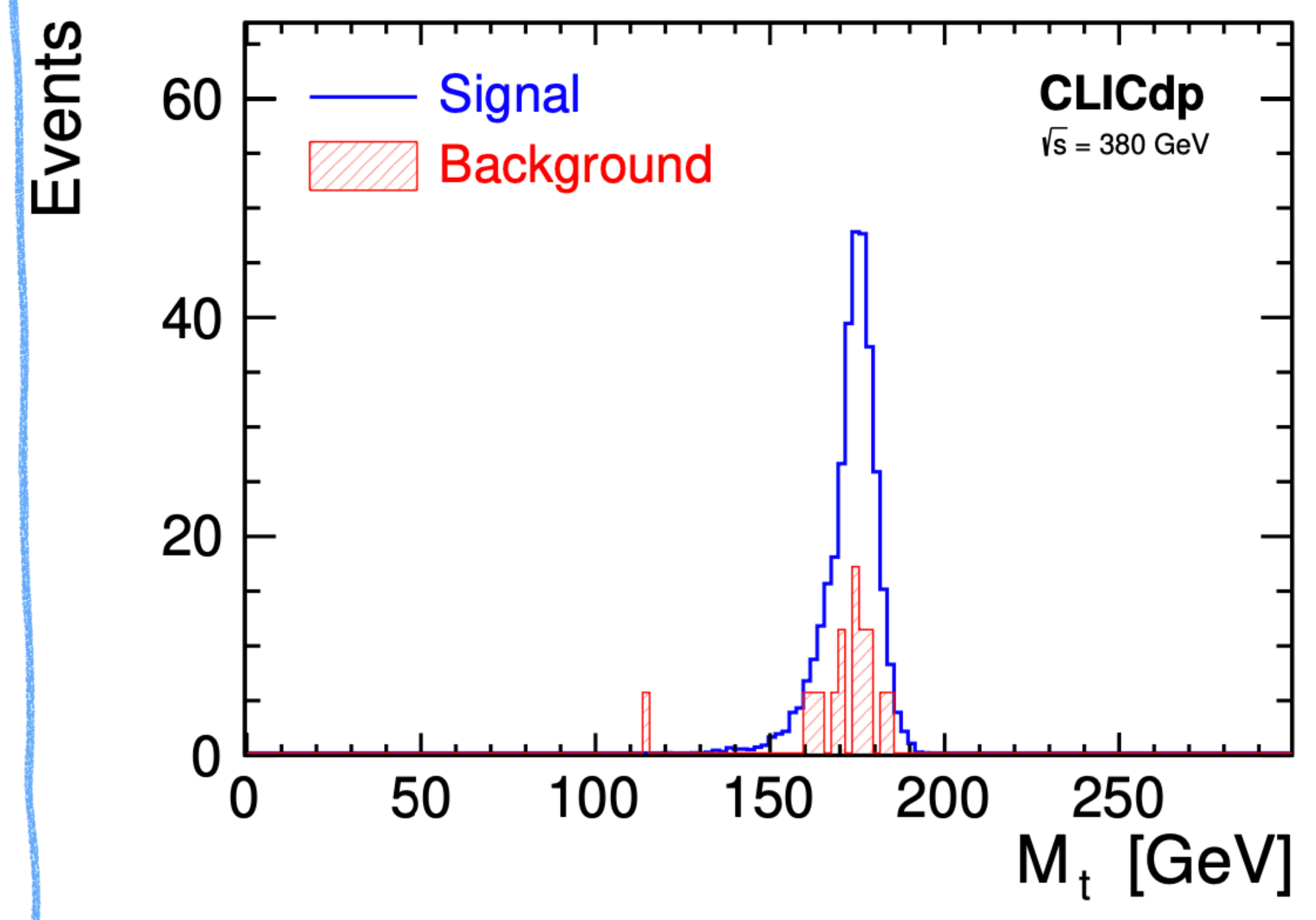
A question of top pair statistics

- The clean environment at e^+e^- colliders is a perfect environment to search for FCNC decays:
  - t -> cγ
  - t -> cH
  - t -> cE_{miss} (heavy neutral particle)

extensive study for CLIC

1 ab^{-1} @ 380 GeV

Builds on excellent charm tagging



$$\mathrm{BR}(t \to c\gamma) < 2.6 \times 10^{-5}$$

$$\mathrm{BR}(t \to cH) \times \mathrm{BR}(H \to b\bar{b}) < 8.8 \times 10^{-5}$$

Searching for BSM Decays

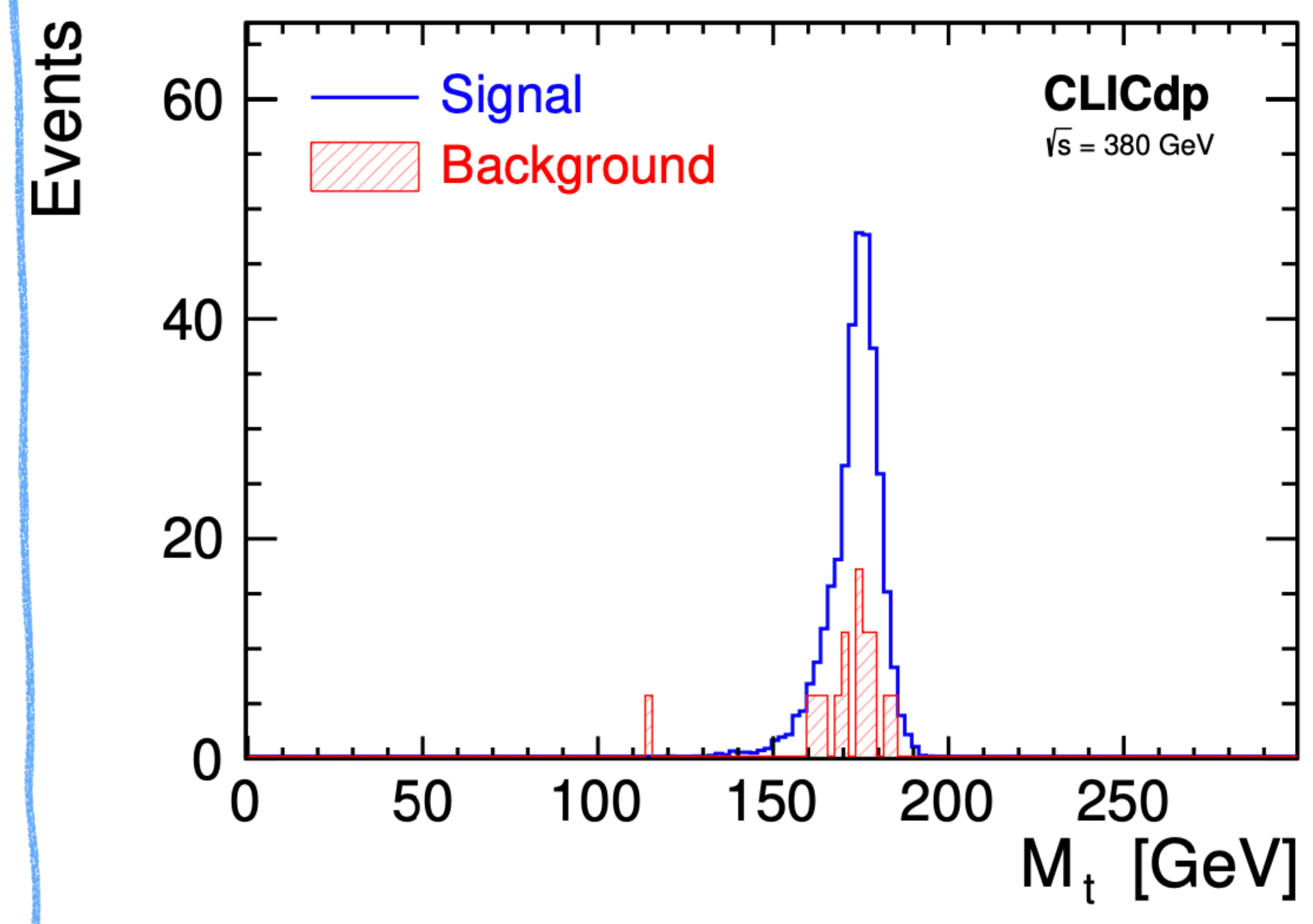
A question of top pair statistics

- The clean environment at e^+e^- colliders is a perfect environment to search for FCNC decays:
  - t -> cγ
  - t -> cH
  - t -> cE_{miss} (heavy neutral particle)

extensive study for CLIC

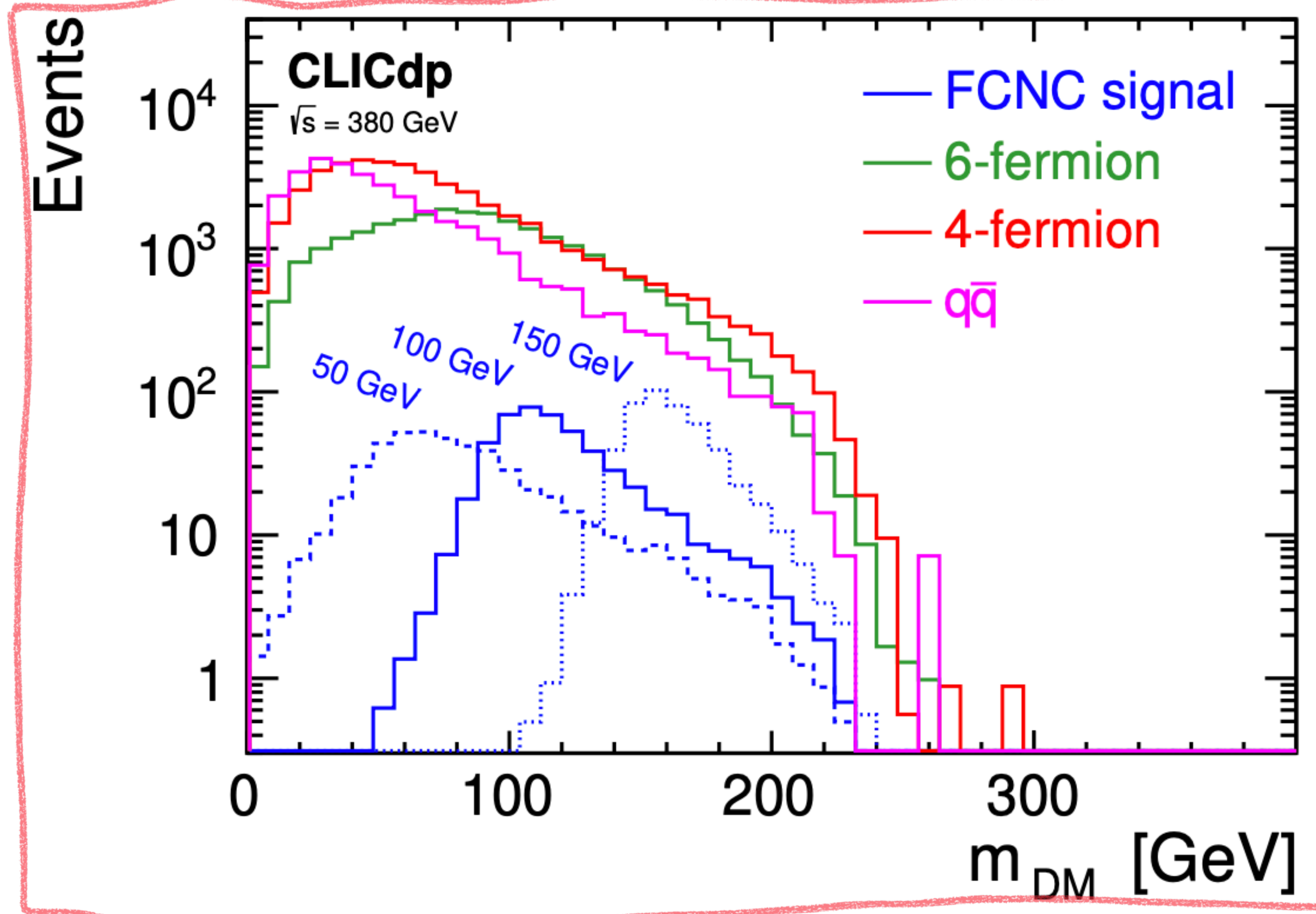
1 ab^{-1} @ 380 GeV

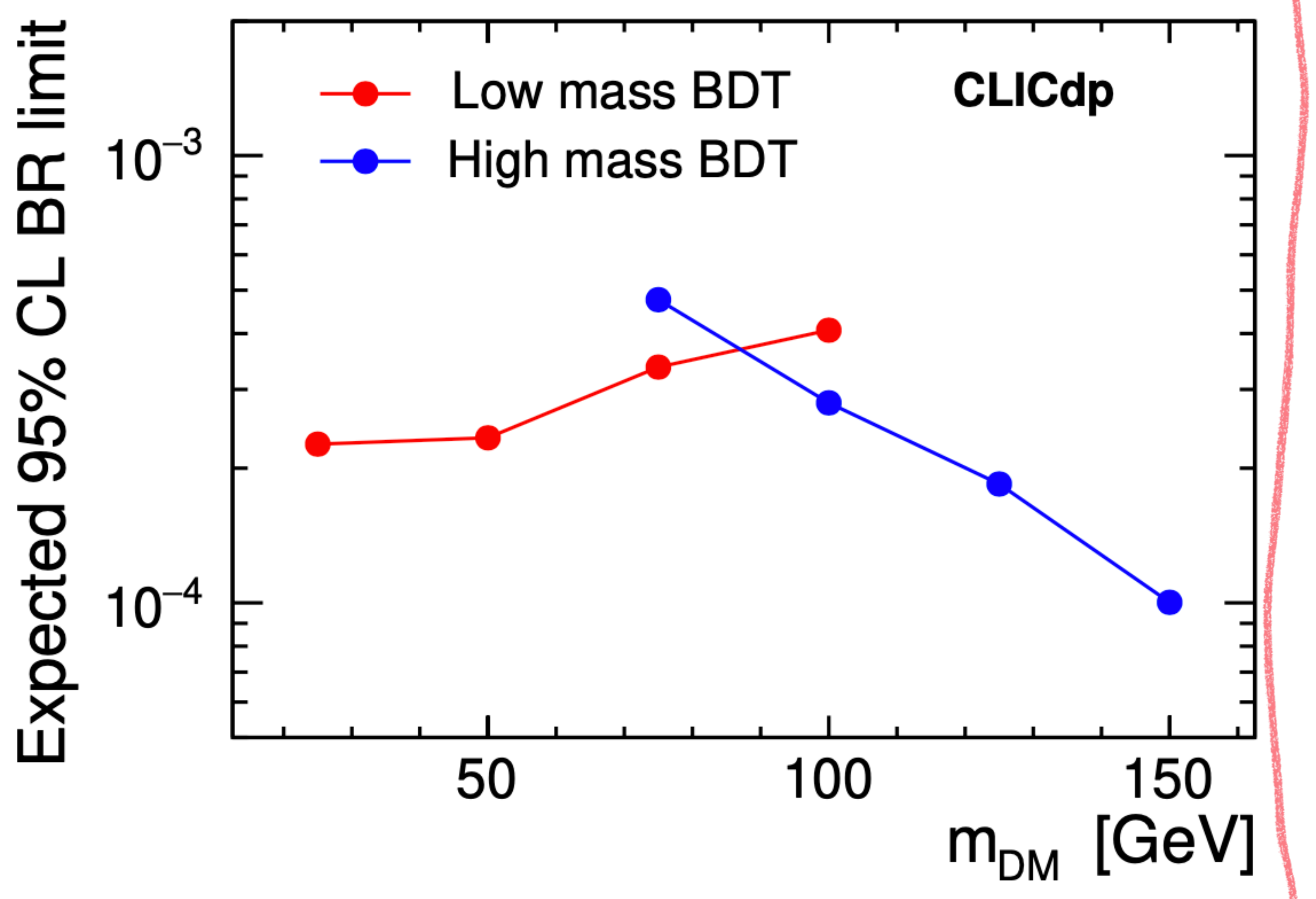
Builds on excellent charm tagging



$$\mathrm{BR}(t \to c\gamma) < 2.6 \times 10^{-5}$$

$$\mathrm{BR}(t \to cH) \times \mathrm{BR}(H \to b\bar{b}) < 8.8 \times 10^{-5}$$

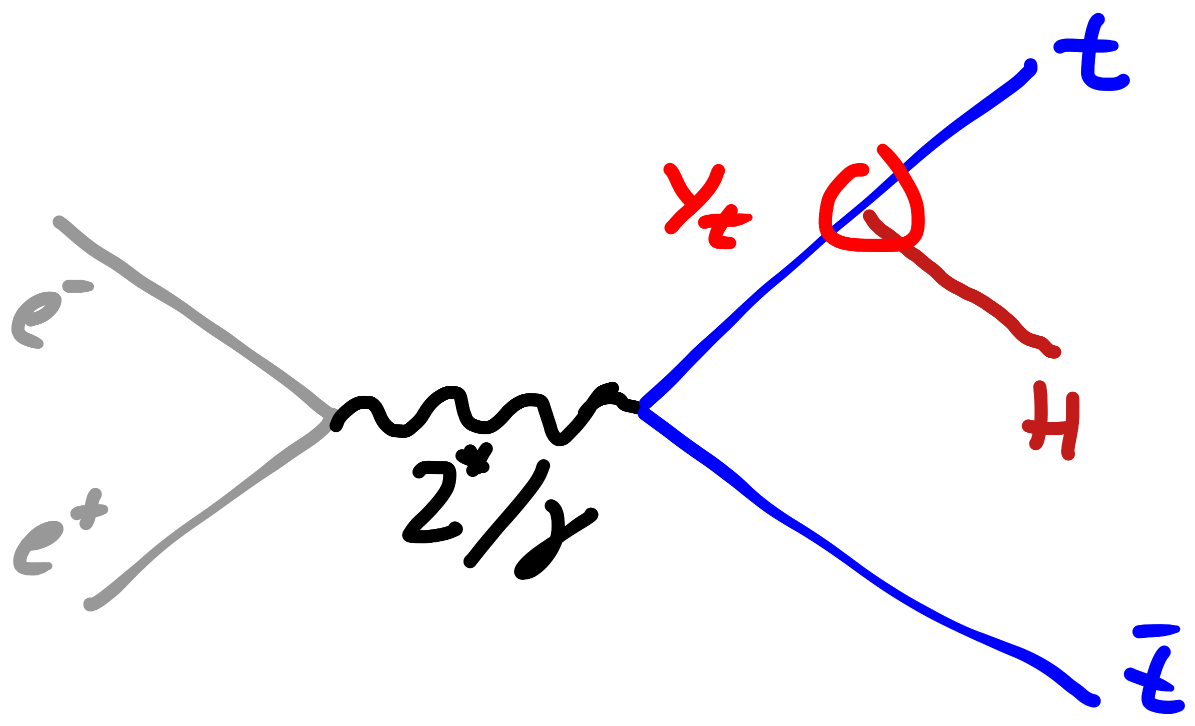


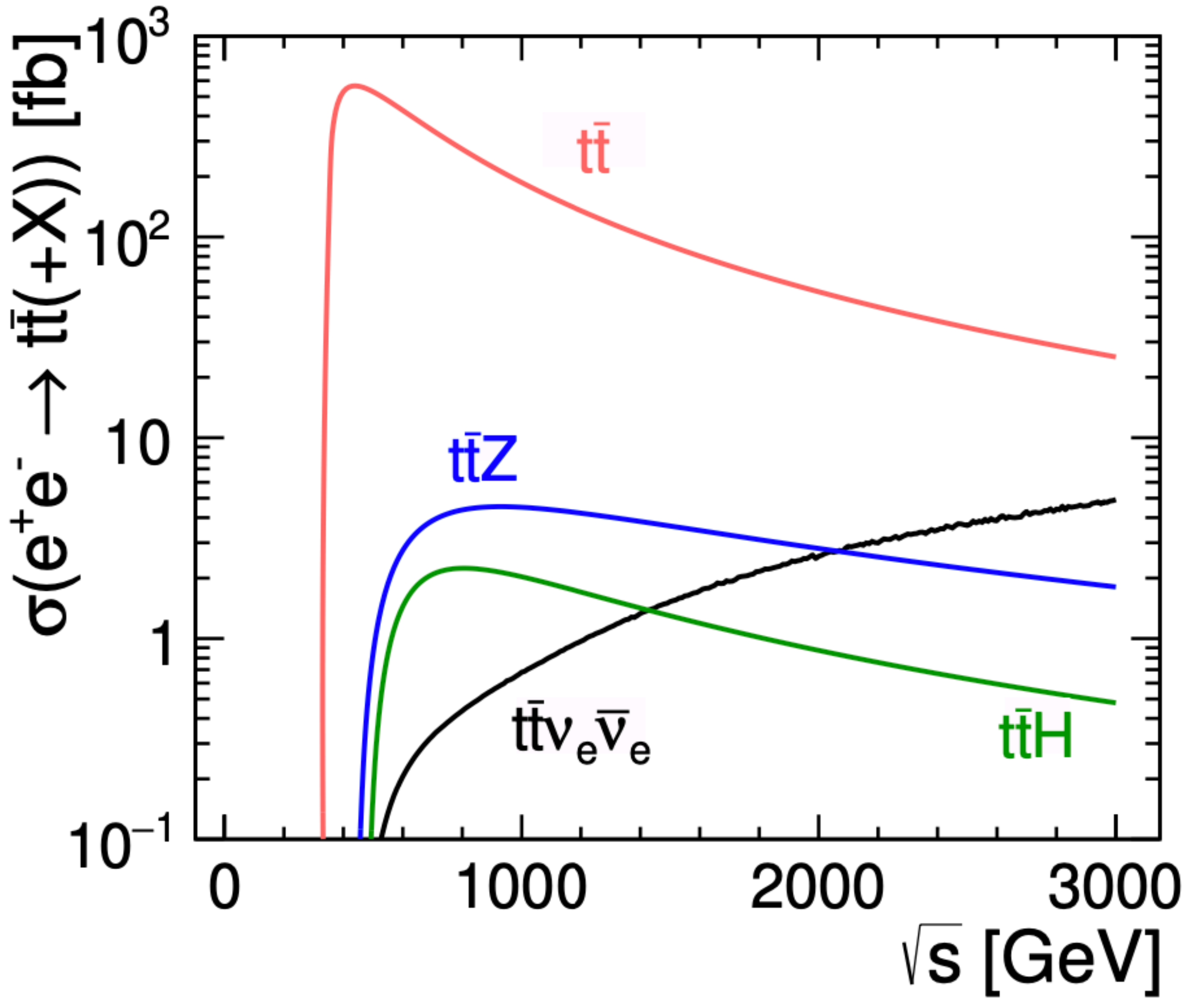


The Top Yukawa Coupling

Direct Measurements

- Energies of 500 GeV and up enable direct measurement of top Yukawa via ttH:



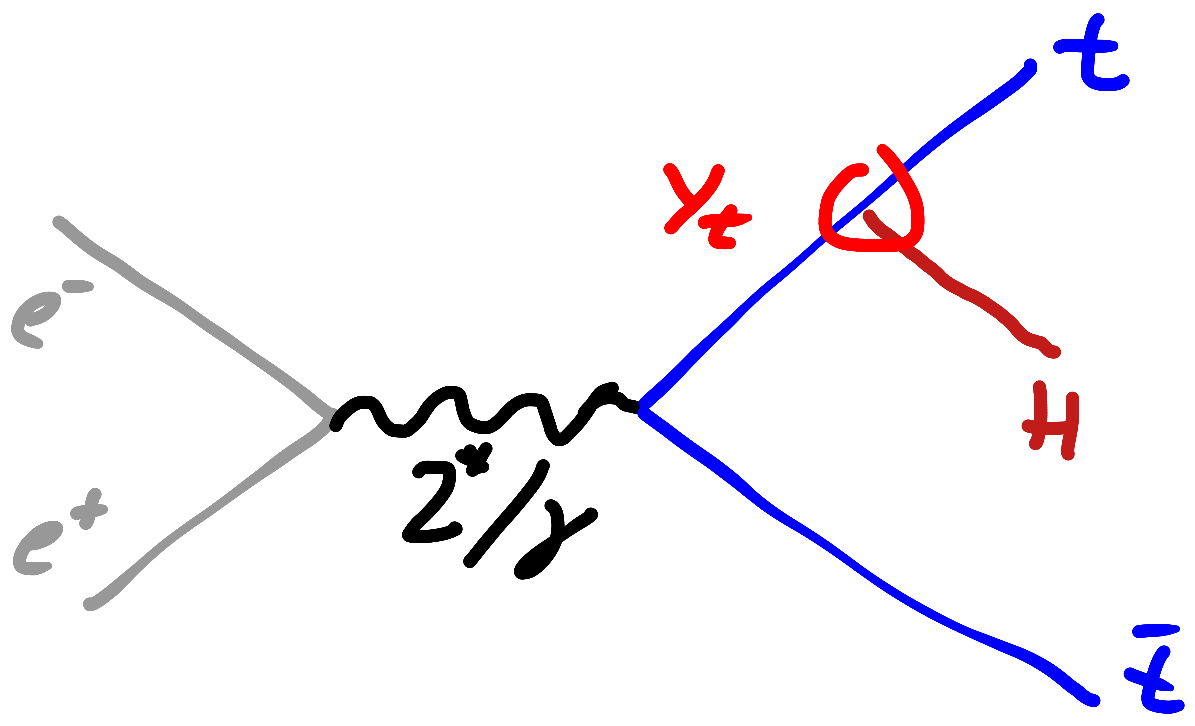


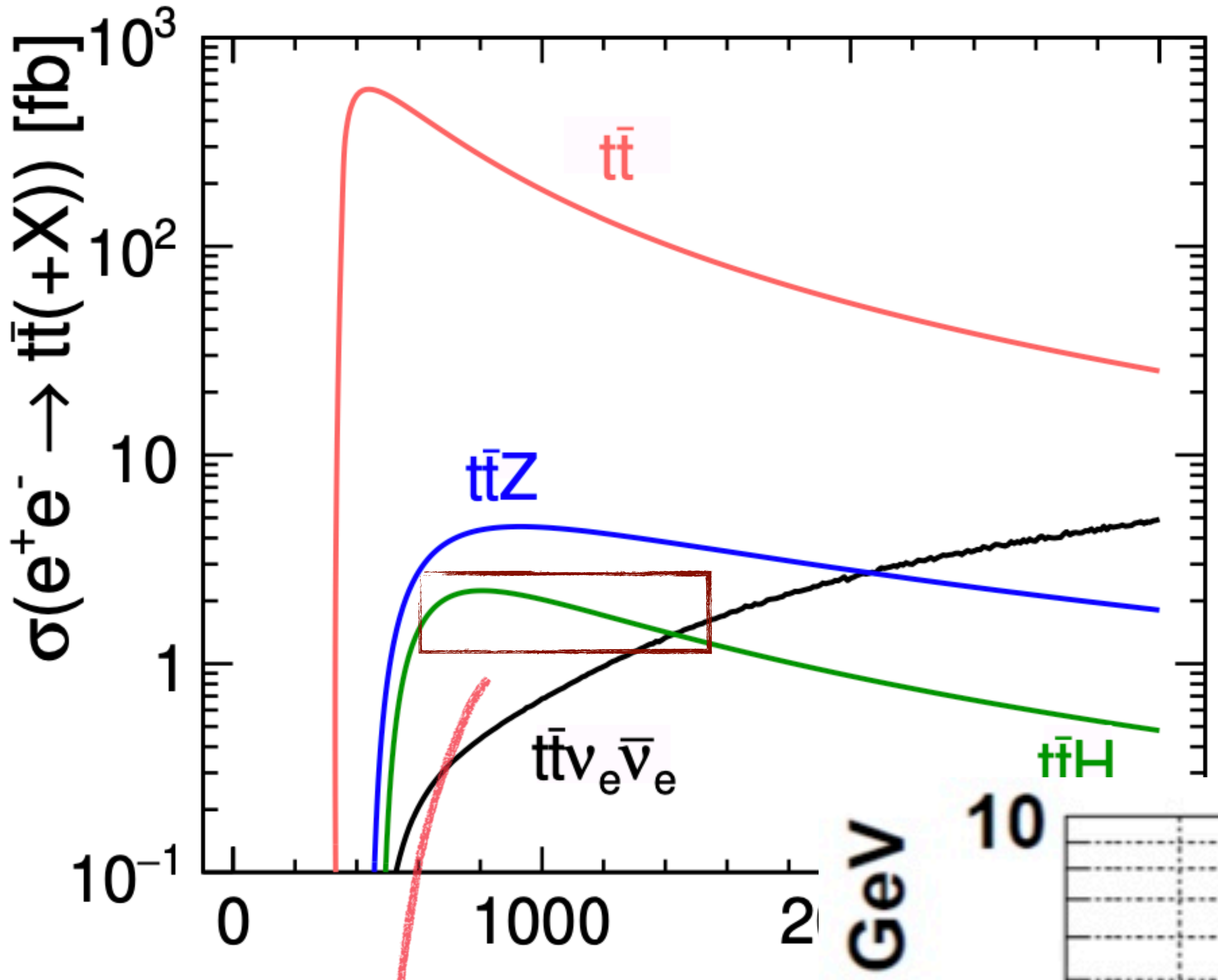
arXiv:1903.01629; JHEP 11, 003 (2019)

The Top Yukawa Coupling

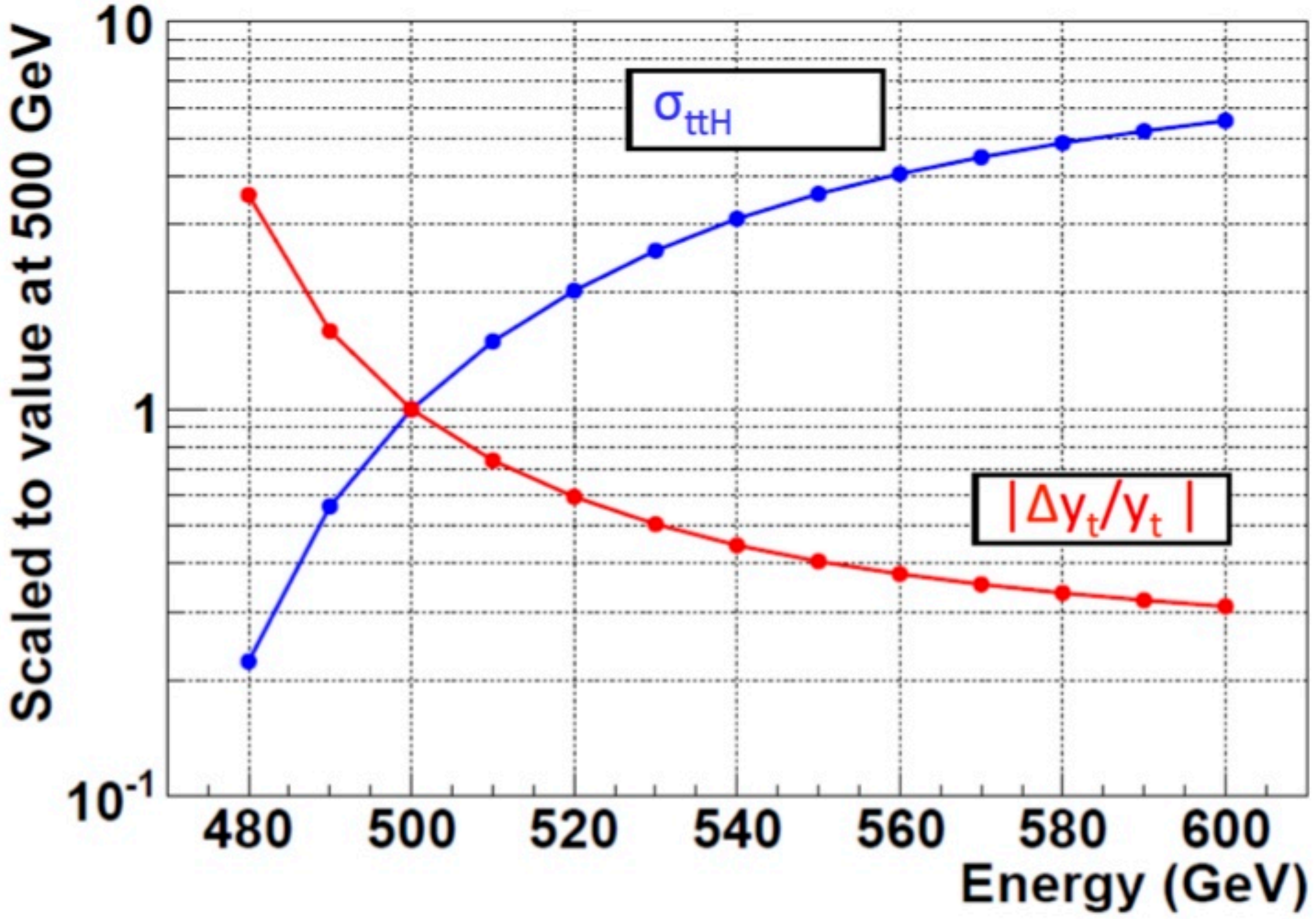
Direct Measurements

- Energies of 500 GeV and up enable direct measurement of top Yukawa via ttH:





Energy matters: “sweet spot” in the range of 550 GeV - 1.5 TeV



For ILC: Interesting at 550 GeV:
2.8% with 4 ab^{-1}

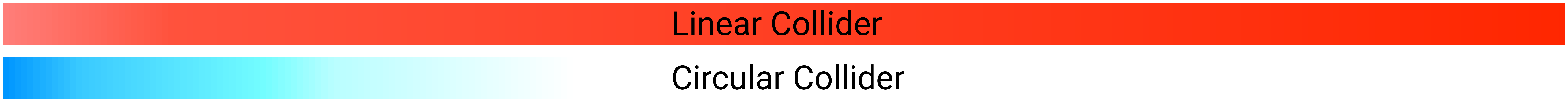
1 TeV, 2.5 ab^{-1}: 2%

CLIC at 1.5 TeV, 2.5 ab^{-1}: ~ 2.7% on y_t

arXiv:1903.01629; JHEP 11, 003 (2019)

Conclusions

- Top quark physics is an essential pillar of a future e^+e^- program at the energy frontier
- It includes:
  - A scan of the top quark pair threshold
  - Measurements of top quarks in the continuum to study top quark properties, couplings and search for exotic decays as a comprehensive SM and BSM program
- Energies from 350 GeV, “moderately” above threshold (≤ 500 GeV), and highest energies (≥ 500 GeV - 3 TeV)



  - polarisation significantly contributes to the physics reach at higher energy

The linear colliders ILC and CLIC have a rich demonstrated potential that extends far beyond HL-LHC.
At and slightly above the threshold, FCC-ee provides comparable, partially complementary possibilites.

Conclusions

MAX-PLANCK-INSTITUT
FÜR PHYSIK

- Top quark physics is an essential pillar of a future e^+e^- program at the energy frontier
- It includes:
  - A scan of the top quark pair threshold
  - Measurements of top quarks in the continuum to study top quark properties, couplings and search for exotic decays as a comprehensive SM and BSM program
- Energies from 350 GeV, “moderately” above threshold (≤ 500 GeV), and highest energies (≥ 500 GeV - 3 TeV)

Linear Collider

Circular Collider

  - polarisation significantly contributes to the physics reach at higher energy

The linear colliders ILC and CLIC have a rich demonstrated potential that extends far beyond HL-LHC.
At and slightly above the threshold, FCC-ee provides comparable, partially complementary possibilites.

➾ In a “dream world” with both a linear and a circular e^+e^- collider, top quark physics is the domain of linear machines, with a natural first-stage energy of 350/380 GeV, and higher-energy stages at 550 GeV or beyond.