Physics Studies for a Staged Construction of CLIC

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with thanks to all those who contributed to the CLIC studies

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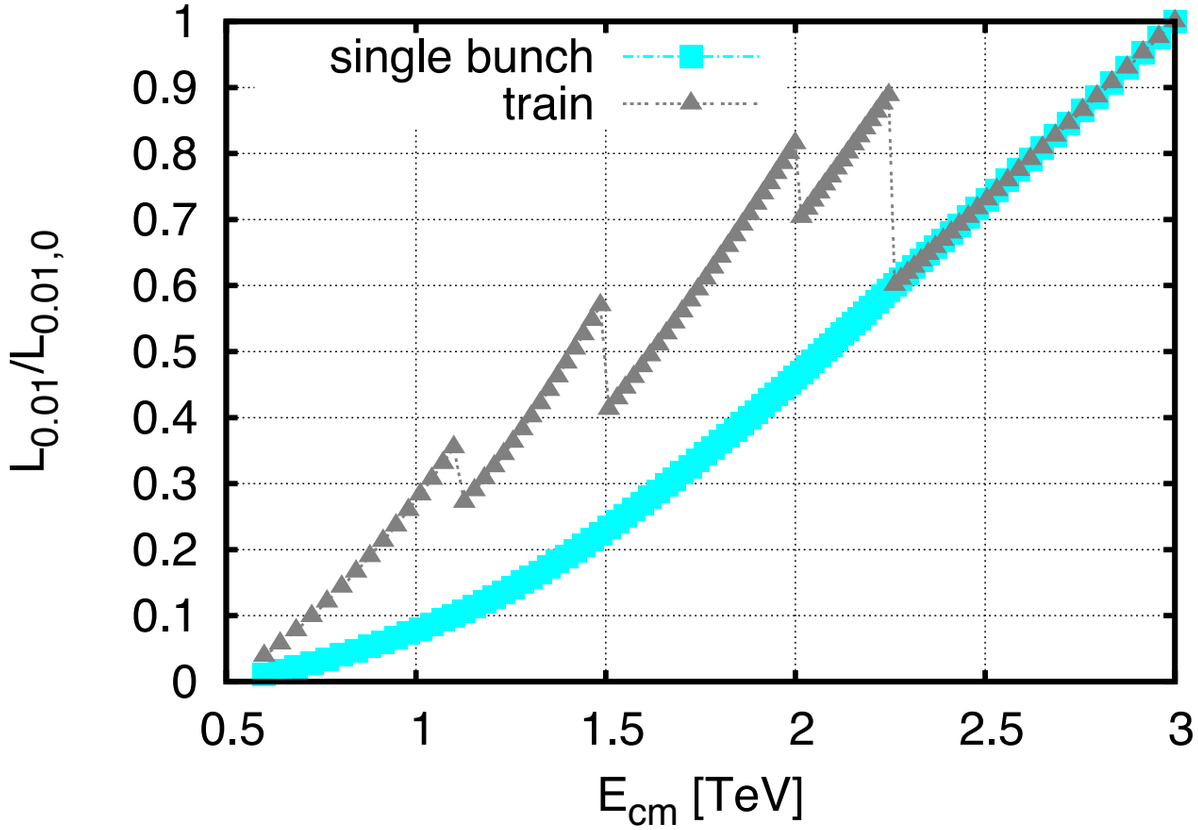
Excellence Cluster Universe

Outline

- CLIC - Staged Implementation
- Benchmark processes - Physics in Stages
- “Guaranteed Physics”: Higgs & Top
- Beyond the Standard Model: SUSY
- Summary / Outlook

Motivation

- Interesting physics (may) exists at various energies:
  - Few 100 GeV: (almost) guaranteed - SM - Higgs, Top
  - Still unknown: BSM physics, potentially various thresholds in the few 100 GeV to few TeV - region
    - Need high luminosity for low and high energies!
- Significant luminosity penalty when operating far below design energy (is mitigated by changing bunch train length, but more than a factor 3 in energy is impractical)



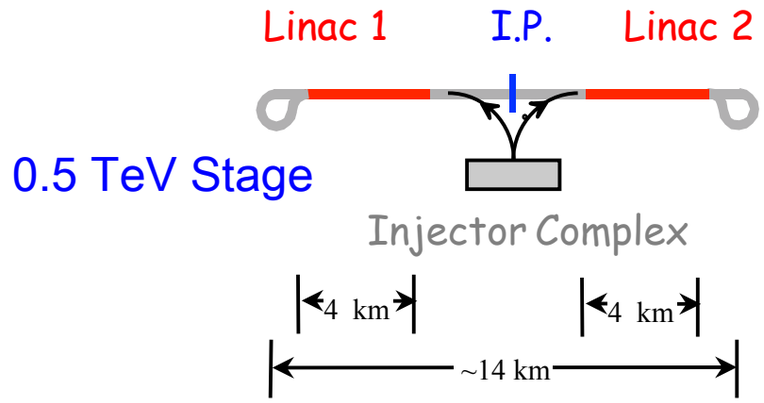
- Start with physics during construction phase for higher energies

Staged Construction of CLIC

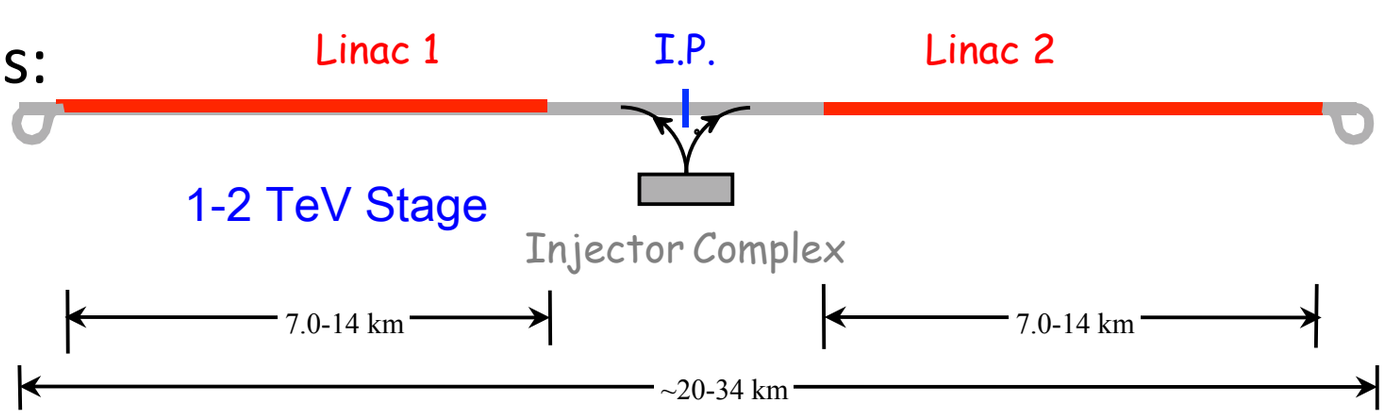
- Realistic scenario:

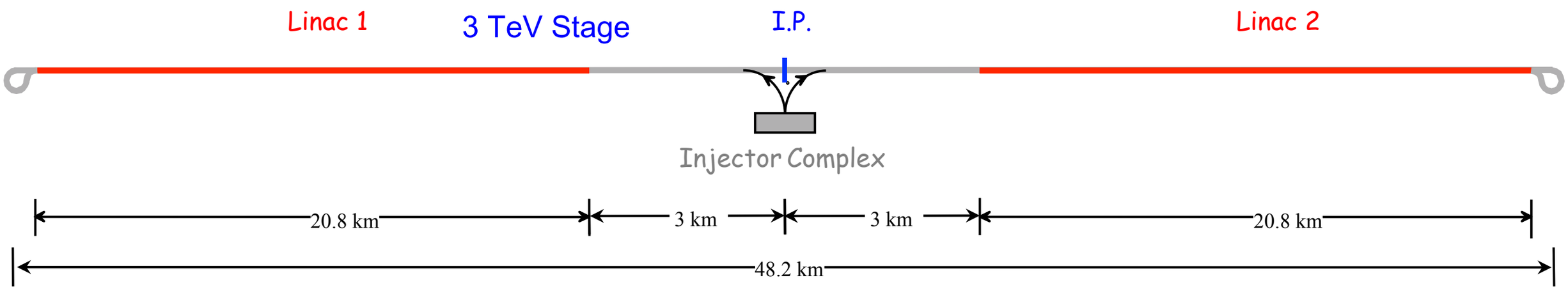
  3 energy stages, exact energies to be determined by future results

  - A 1.4 TeV CLIC requires only one drive beam complex: A natural intermediate stage



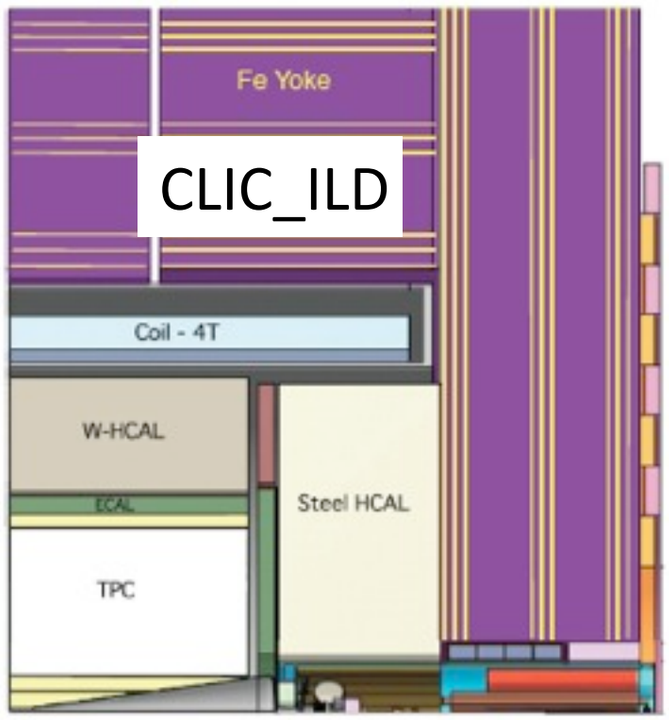
- Assumptions for benchmark studies:
  - 500 GeV: 500 fb^{-1}
  - 1.4 TeV: 1.5 ab^{-1}
  - 3 TeV: 2 ab^{-1}

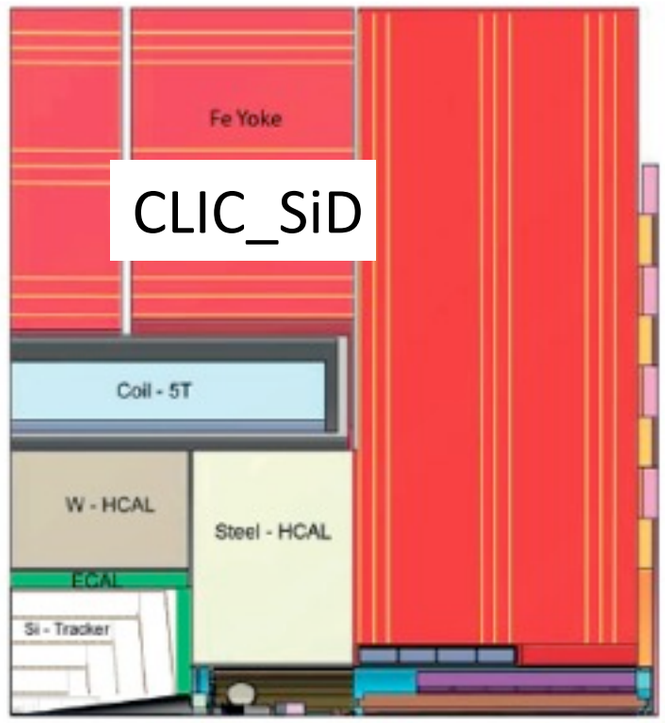




Detectors and Experimental Environment at CLIC

- Detectors based on ILC concepts - With energy and environment-specific modifications:
  - deeper HCAL
  - precision timing
  - modified vertex detector
  - redesigned forward region





- Main event reconstruction challenge:

  Pile-up of $\gamma\gamma \rightarrow$ hadrons mini-jet events
  - Included in simulation studies by overlaying $\gamma\gamma \rightarrow$ hadrons events on physics events
  - Rejected by timing and/or p_t cuts

Varies significantly with energy

Hadron events above 2 GeV:

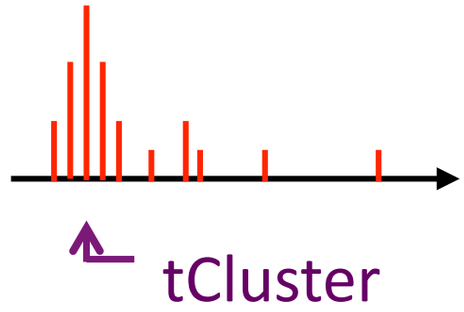
350 GeV:	0.05 / BX
500 GeV:	0.3 / BX
1.4 TeV:	1.3 / BX
3 TeV:	3.2 / BX

Event Reconstruction & Timing Cuts

- Triggerless readout of bunchtrain

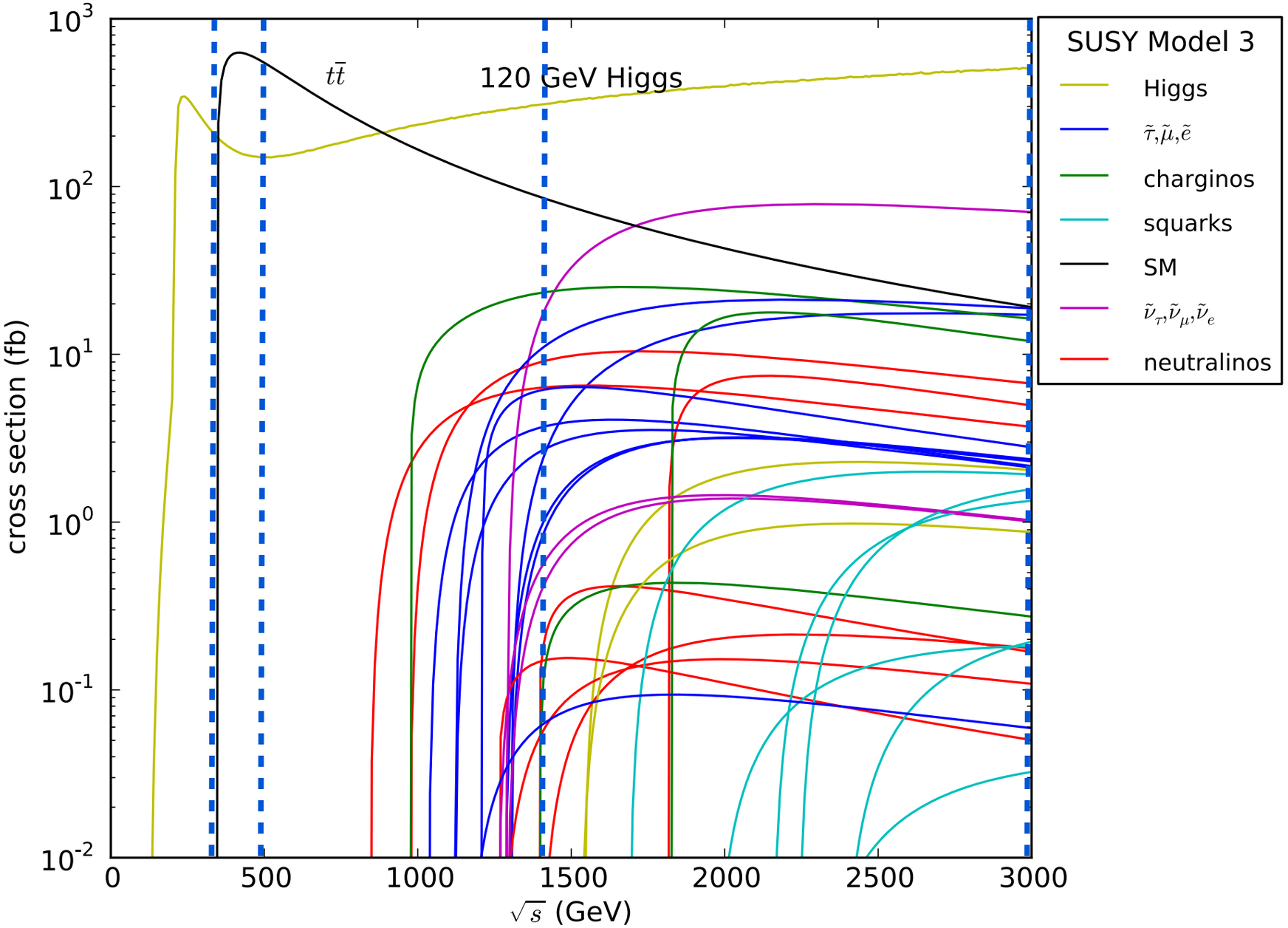
- Time of physics event determined offline

- Use timing information from all detector subsystems to determine time of individual clusters and particles
  Calorimeters of particular importance!
  - Cluster-based timing cuts & p_T cuts to reject background



- Event reconstruction with PFA using timing information
- Use well-adapted jet finding algorithms to further mitigate effects of background
  - based on LHC experience (FastJet)

Benchmark Studies: Physics in Stages



- 500 GeV machine
  - Top threshold scan
  - Top mass in continuum
  - Higgs mass, BR
- 1.4 TeV machine
  - Higgs selfcoupling
  - Various SUSY studies in specific model (Model III)
- 3 TeV maching
  - Higgs selfcoupling
  - Various SUSY studies in Physics & Detectors CDR SUSY model

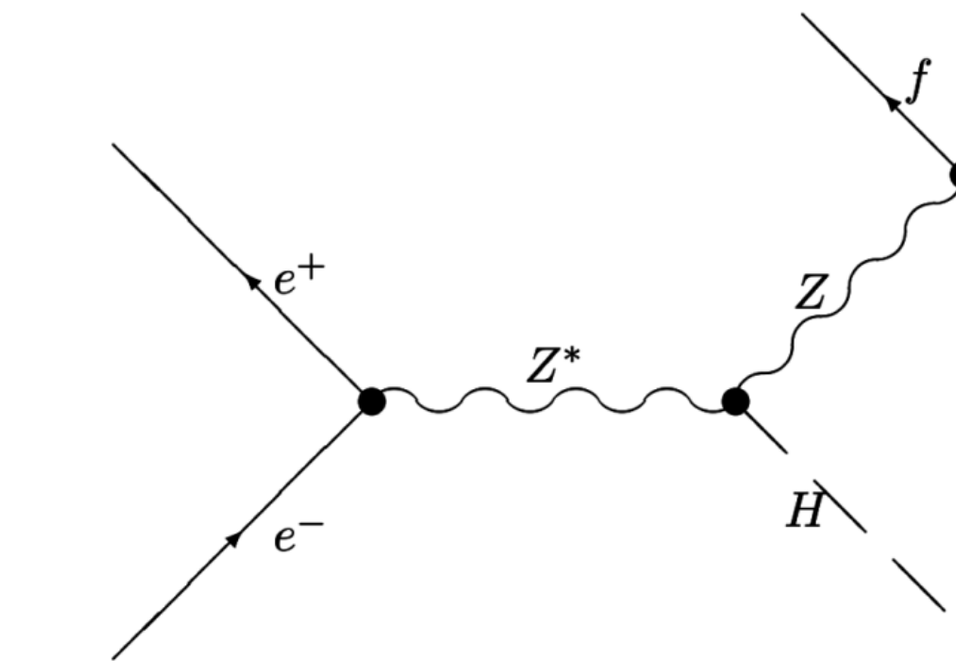
Standard Model

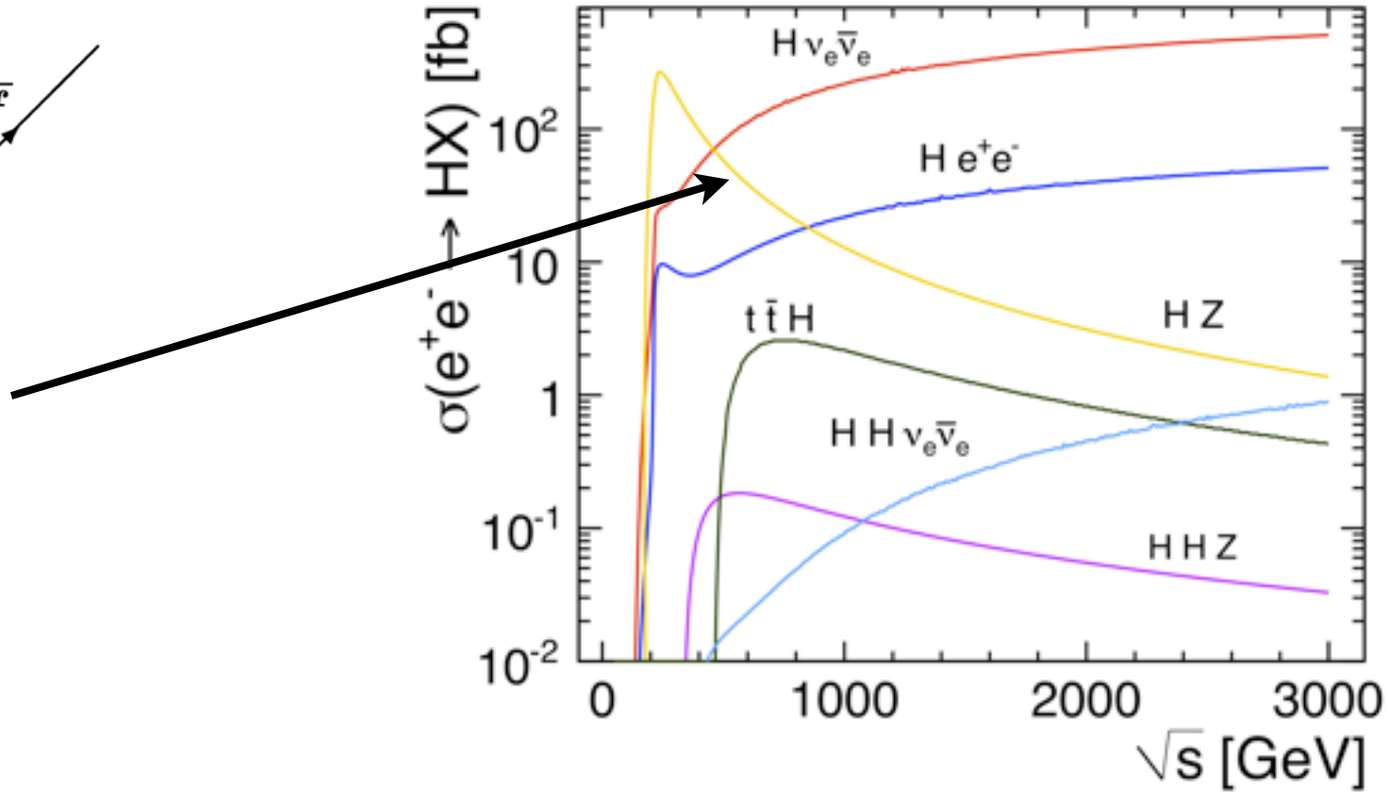
Higgs - Model-Independent Mass & Branching Ratios

- Measurement of Higgs mass and cross section in Z recoil:

  No built-in assumption on Higgs decay modes

  - Allows to detect invisible decay modes by precise cross section measurements and comparison to visible decays





Difficult significantly above threshold:

- Low cross section
- Reduced resolution for leptons from Z decay
- Higher SM background

Perform study at 500 GeV and 350 GeV:

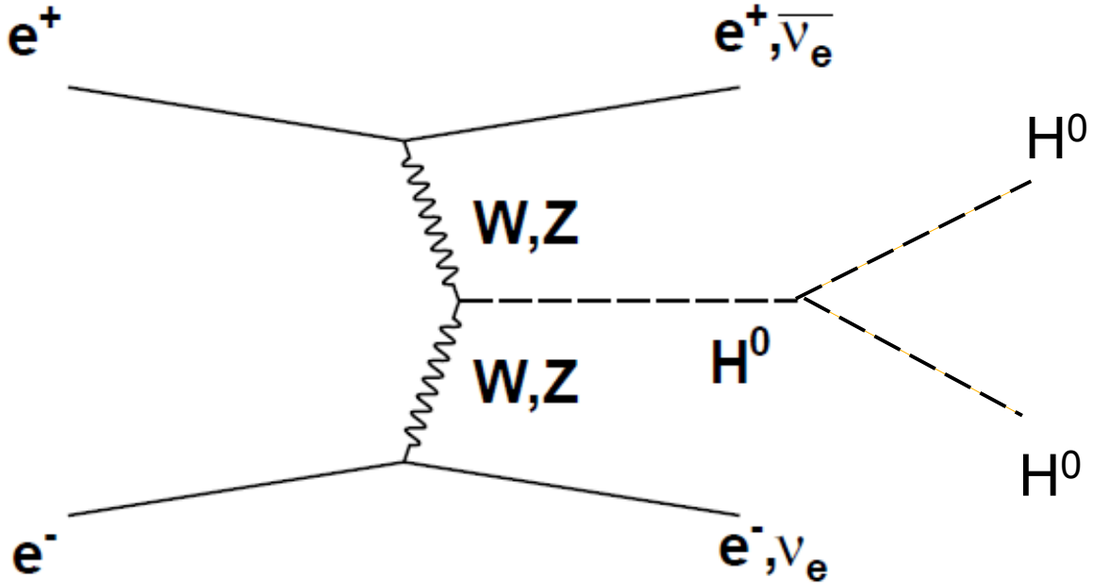
Work in progress!

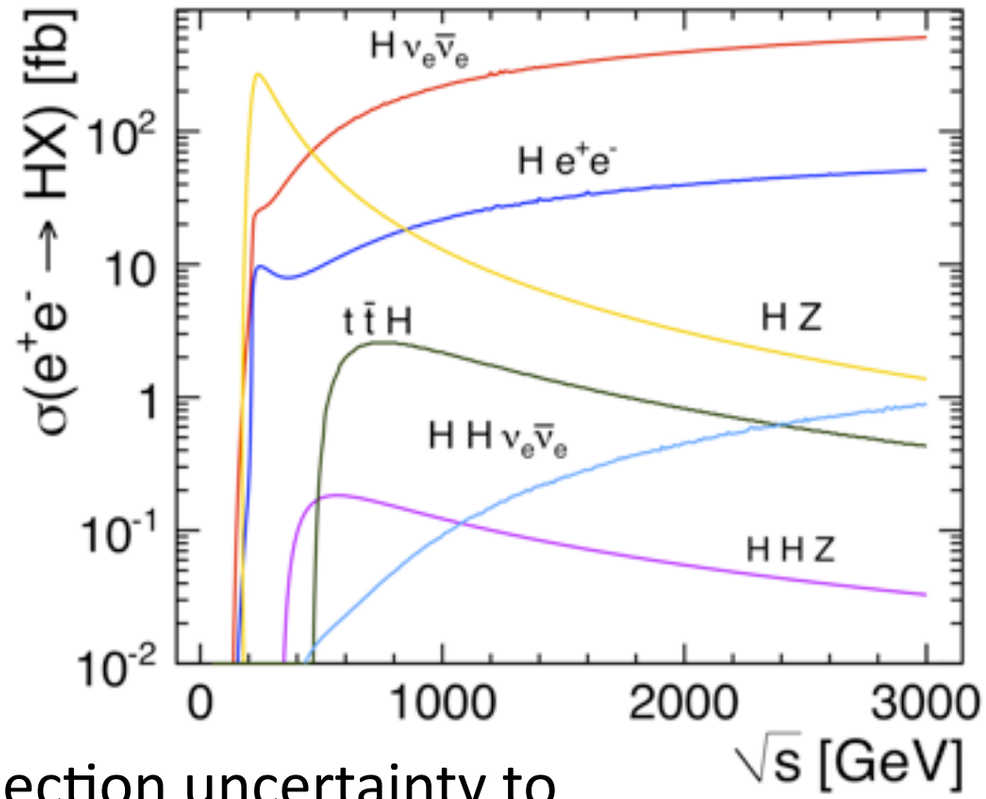
Higgs - Selfcoupling

- Measurement of the trilinear coupling λ

m_h = 120 GeV

- At energies above 1 TeV, WW fusion to HHνν final state dominates





- The measurement:
  Cross section of HHνν

Relation of cross section uncertainty to trilinear coupling currently under investigation

$$\frac{\Delta\lambda_{hhh}}{\lambda_{hhh}} = x \cdot \frac{\Delta\sigma}{\sigma}$$

at 3 TeV: x ~ 1.6
at 1.4 TeV: x ~ 1
including ISR and BS

preliminary!

Higgs Selfcoupling at 1.4 TeV and 3 TeV

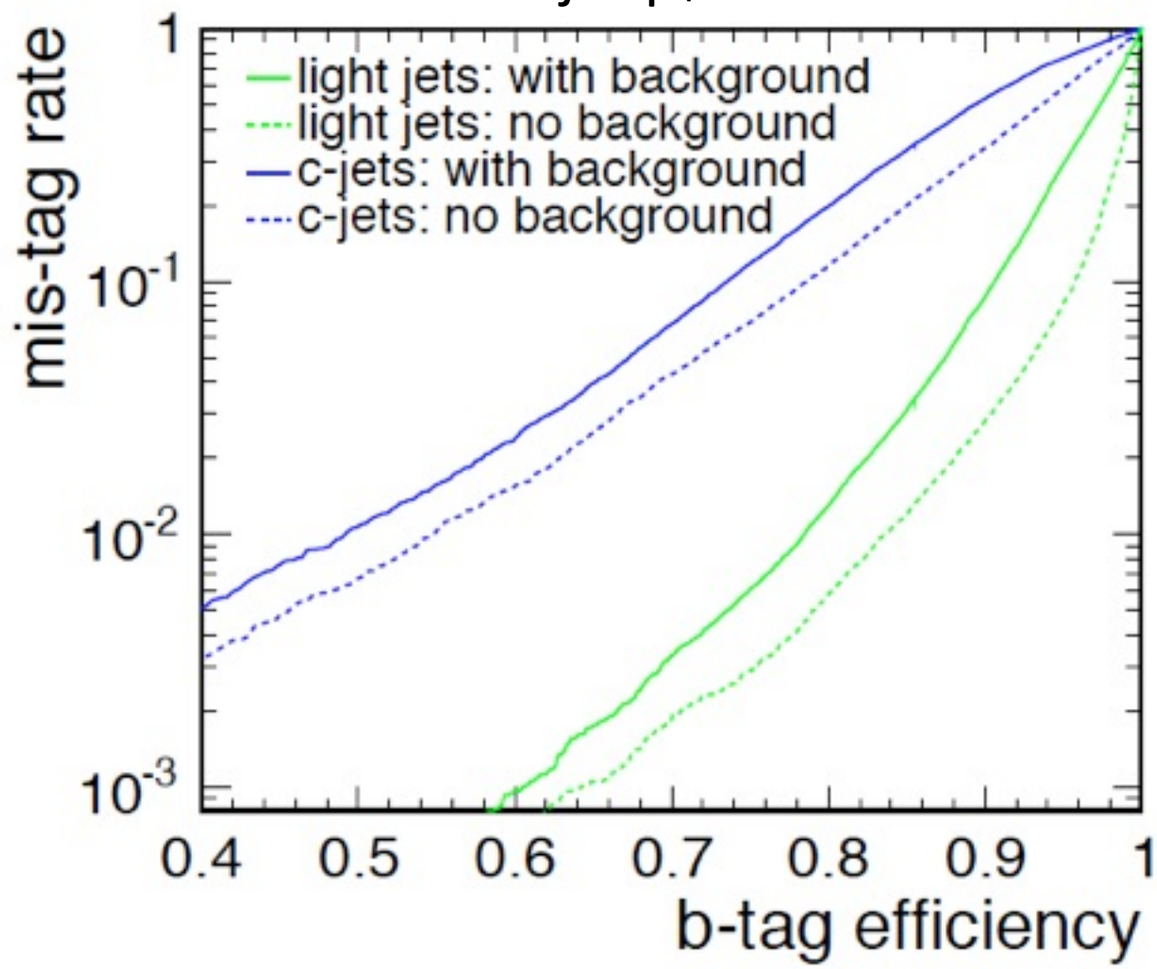
- Main challenges:
  - Small signal cross-section: ~ 0.9 fb
  - Large backgrounds
  - Quality of flavor tagging in presence of $\gamma\gamma \rightarrow$ hadrons pile-up

Higgs reconstruction in decay to b quarks-
Makes use of excellent flavor tagging

Work in progress:

Using Neural Network for background rejection
Extract cross section to determine λ

mean jet p_T ~ 70 GeV

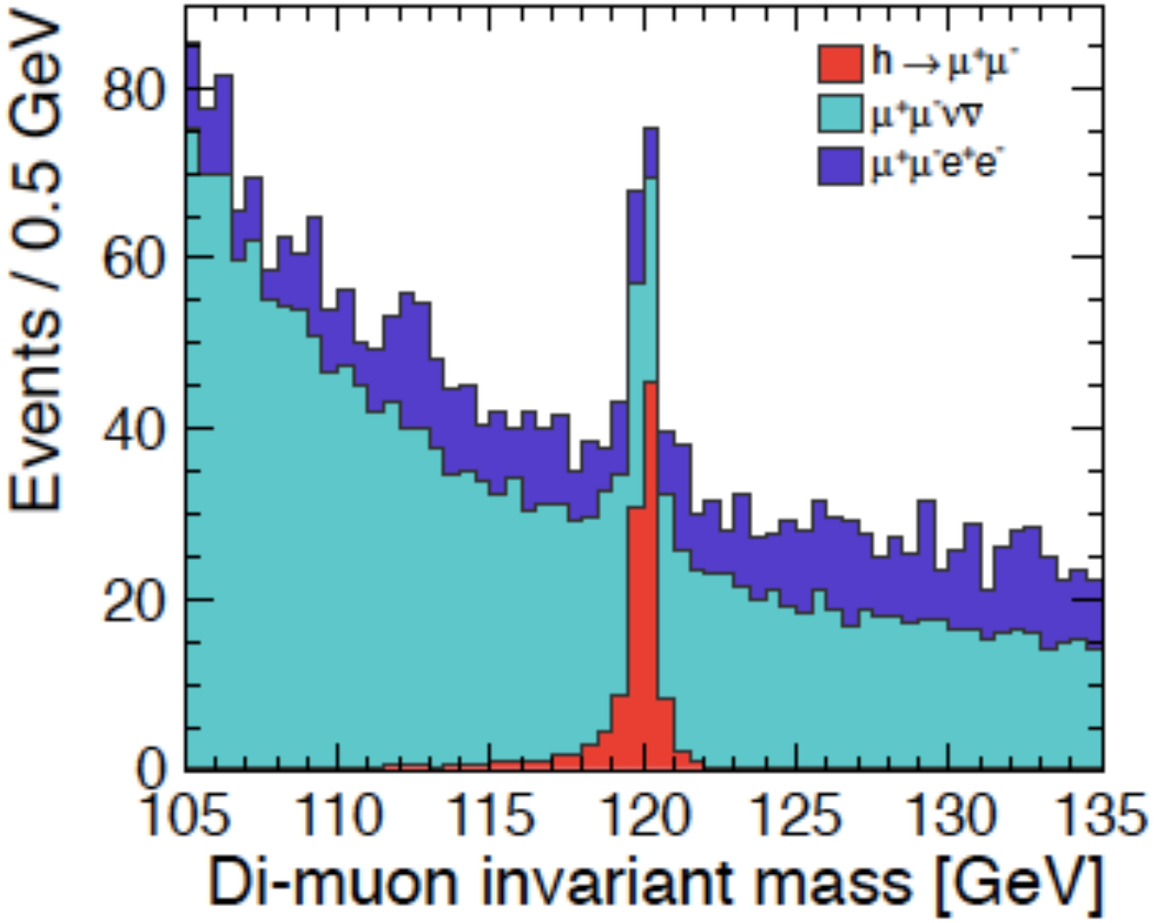


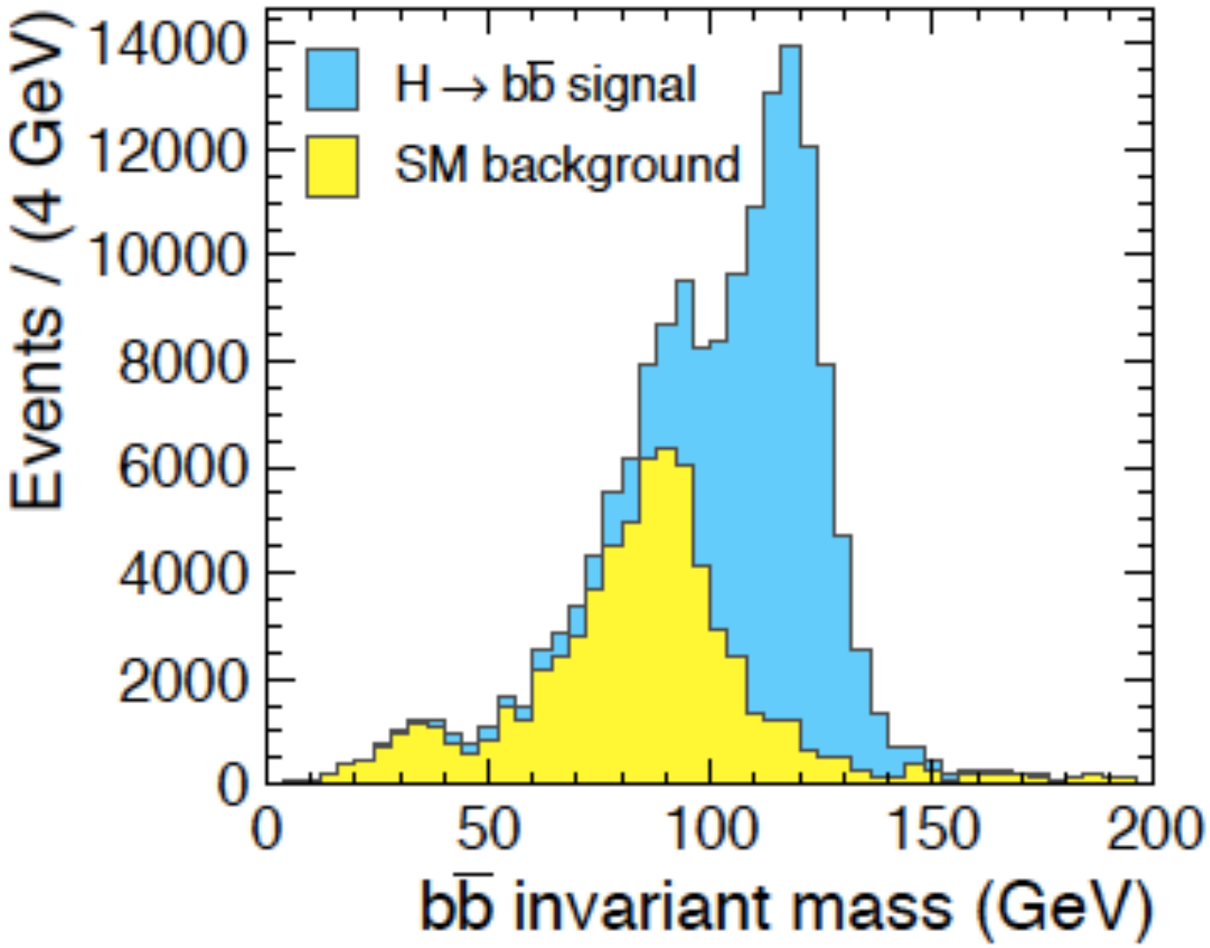
Efficient, high purity flavor tagging also possible in presence of background

Higgs Branching Fractions at 3 TeV

- Exploit high production cross section and high luminosity
  - Measure also rare decays

15% stat. precision on σ(H→μμ) requires forward electron tagging to suppress background





0.22% stat. precision on σ(H→bb)

3.2% stat. precision on σ(H→cc)

LCD-Note-2011-035, LCD-Note-2011-036

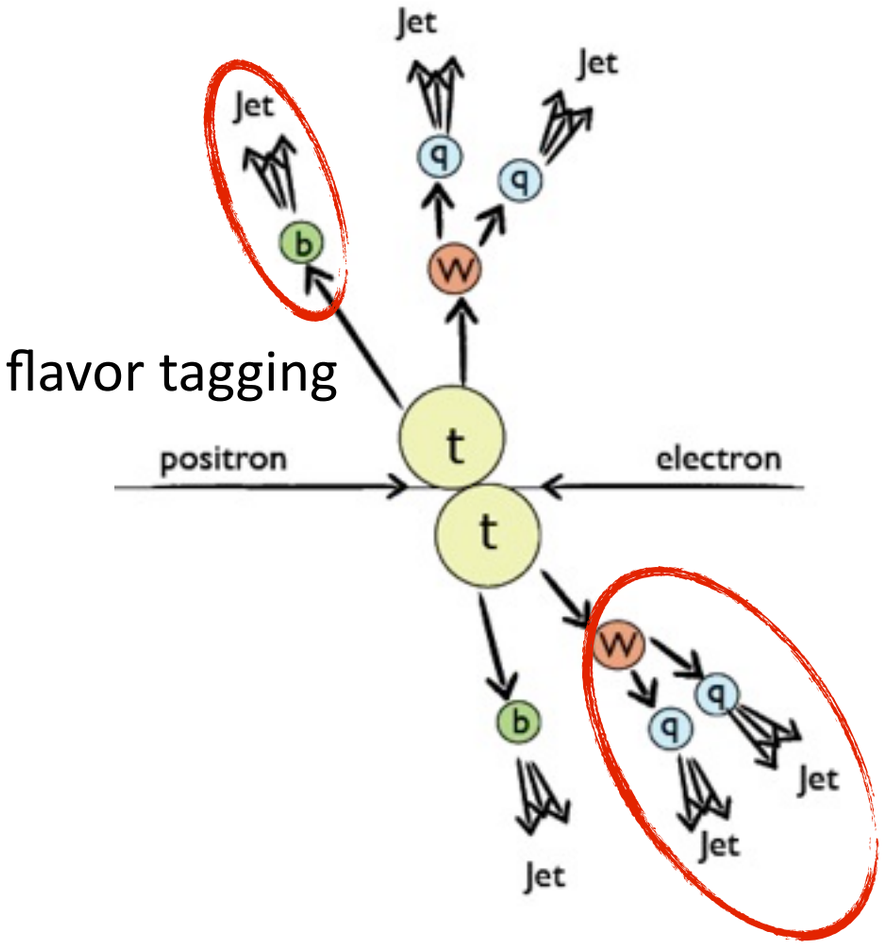
Top Mass Measurements at CLIC

- Two approaches at Linear Colliders:
- Threshold scan:
  - Theoretically well understood
  - Measurement of top pair production cross section at several points around threshold
  - Requires dedicated operation of machine for extended period

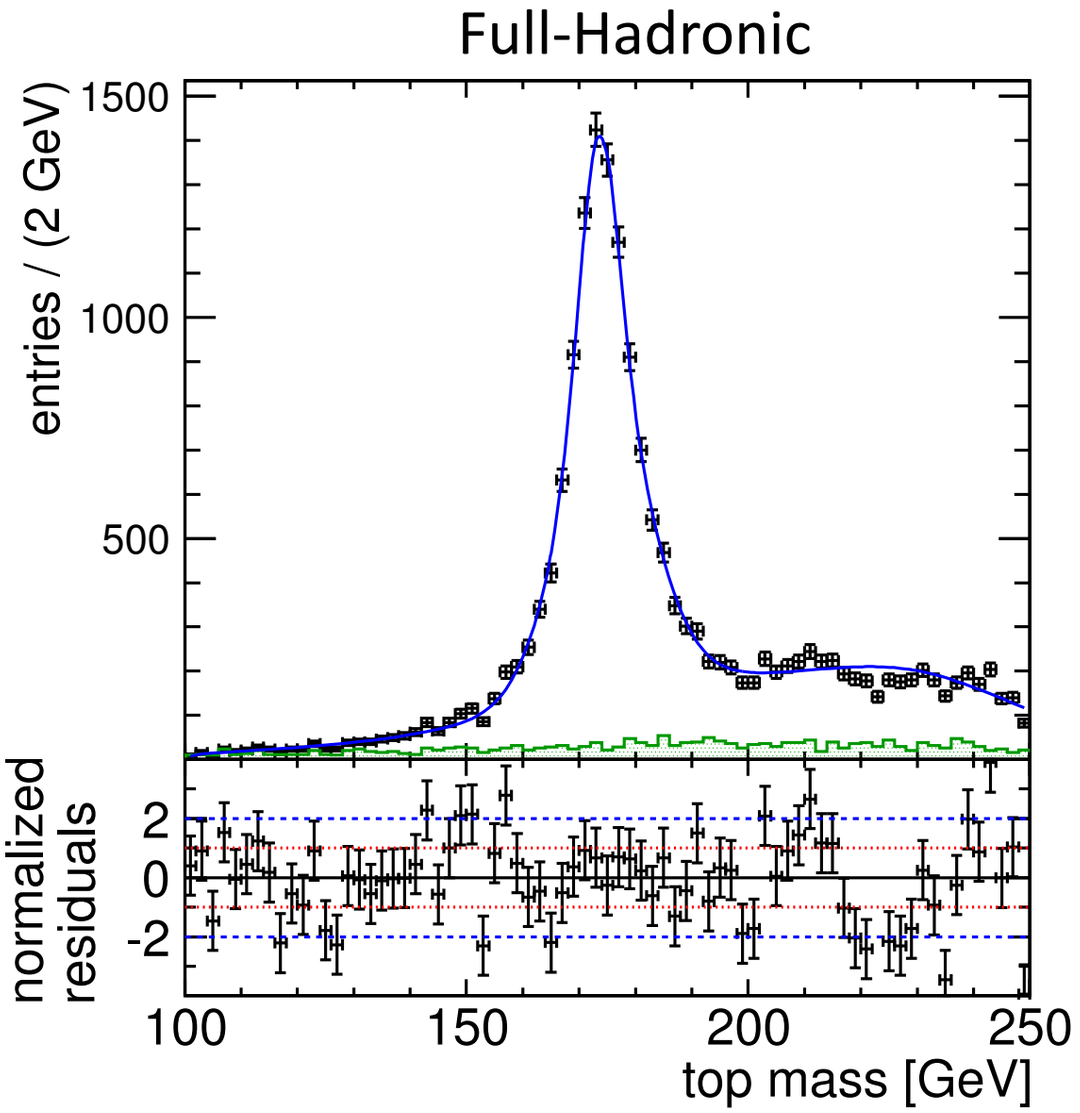
- Mass measurement from invariant mass of decay products:
  - Theoretically problematic (experiments measure “event generator top mass”, treatment of QCD corrections ill-defined) - progress is being made
  - Requires excellent jet and lepton reconstruction, helped by kinematic constraints
  - Can be performed at arbitrary energy above threshold - does not compete with other measurements, high integrated luminosity unproblematic

Top Mass from Invariant Mass of Decay Products

- Measurement of top pairs at 500 GeV
  - Kinematic fit to optimize mass resolution - also serves as background rejection



jet energy,
invariant mass



- Top mass stat. error with 100 fb^{-1}:
  80 (90) MeV all-hadronic (semi-leptonic)

LCD-Note-2011-026

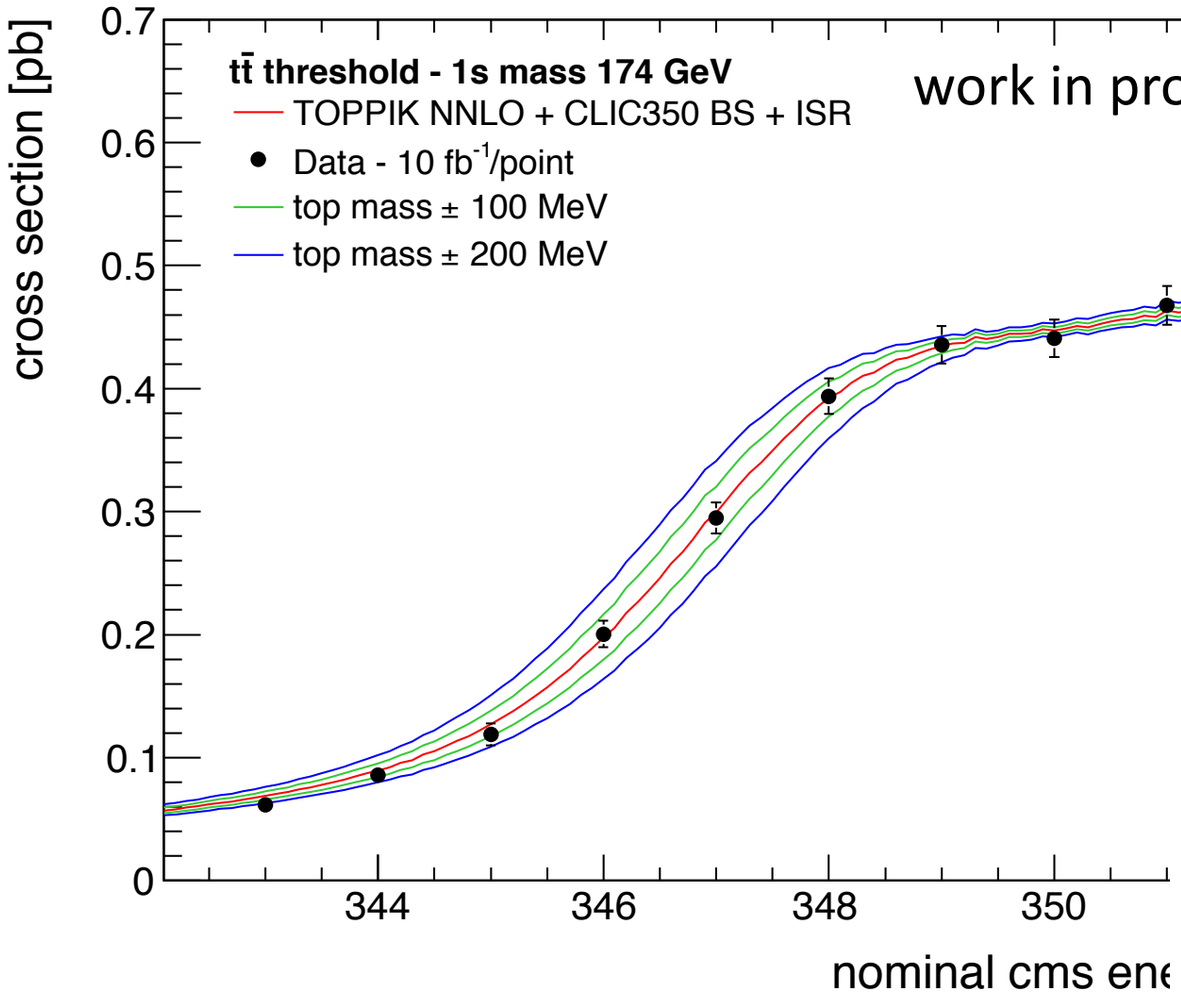
Top Threshold Scan

- Running the 500 GeV machine at around 350 GeV allows to scan the ttbar threshold

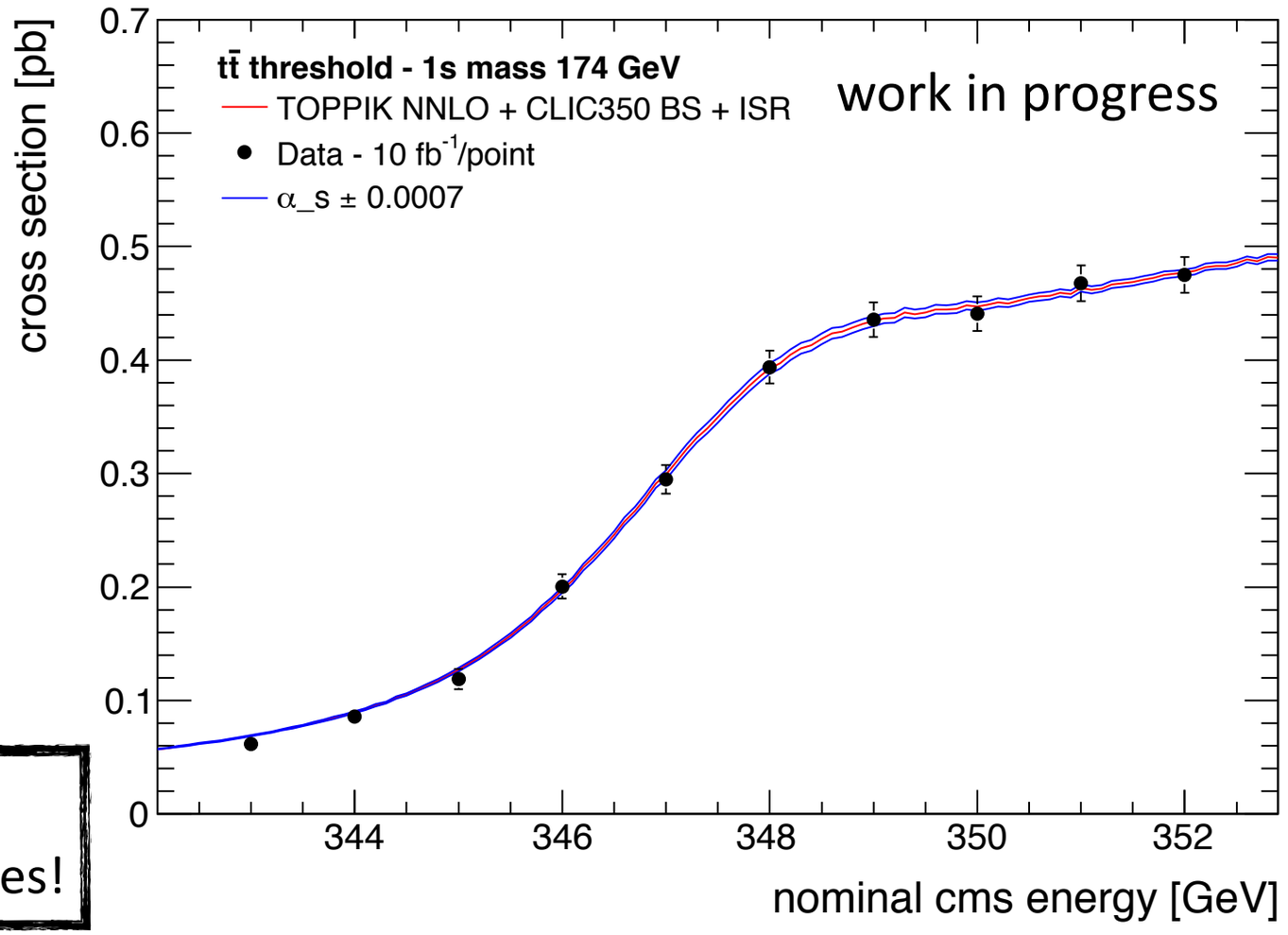
- Strategy of the study:
  - NNLO calculations of the ttbar threshold with TOPPIK (A.Hoang, T. Teubner): provides the production cross section
  - Full simulations of top pairs slightly above threshold in PYTHIA to obtain efficiencies, background rejection - Includes overlay of $\gamma\gamma \rightarrow$ hadrons
  - Top mass extracted from a fit of the background-subtracted cross section, fit based on NNLO calculations

- Current status:
  - NNLO calculations (including ISR and CLIC beamspectrum at 350 GeV) available
  - Full simulation of signal and background with overlay ongoing: Currently using selection efficiency at 500 GeV, with background levels scaled to 350 GeV (increase with 1/s) to get first impression of sensitivities

Top Threshold - Mass Sensitivity at CLIC



- High sensitivity to top mass in the turn-on region: Possibility for optimized choice of energy points



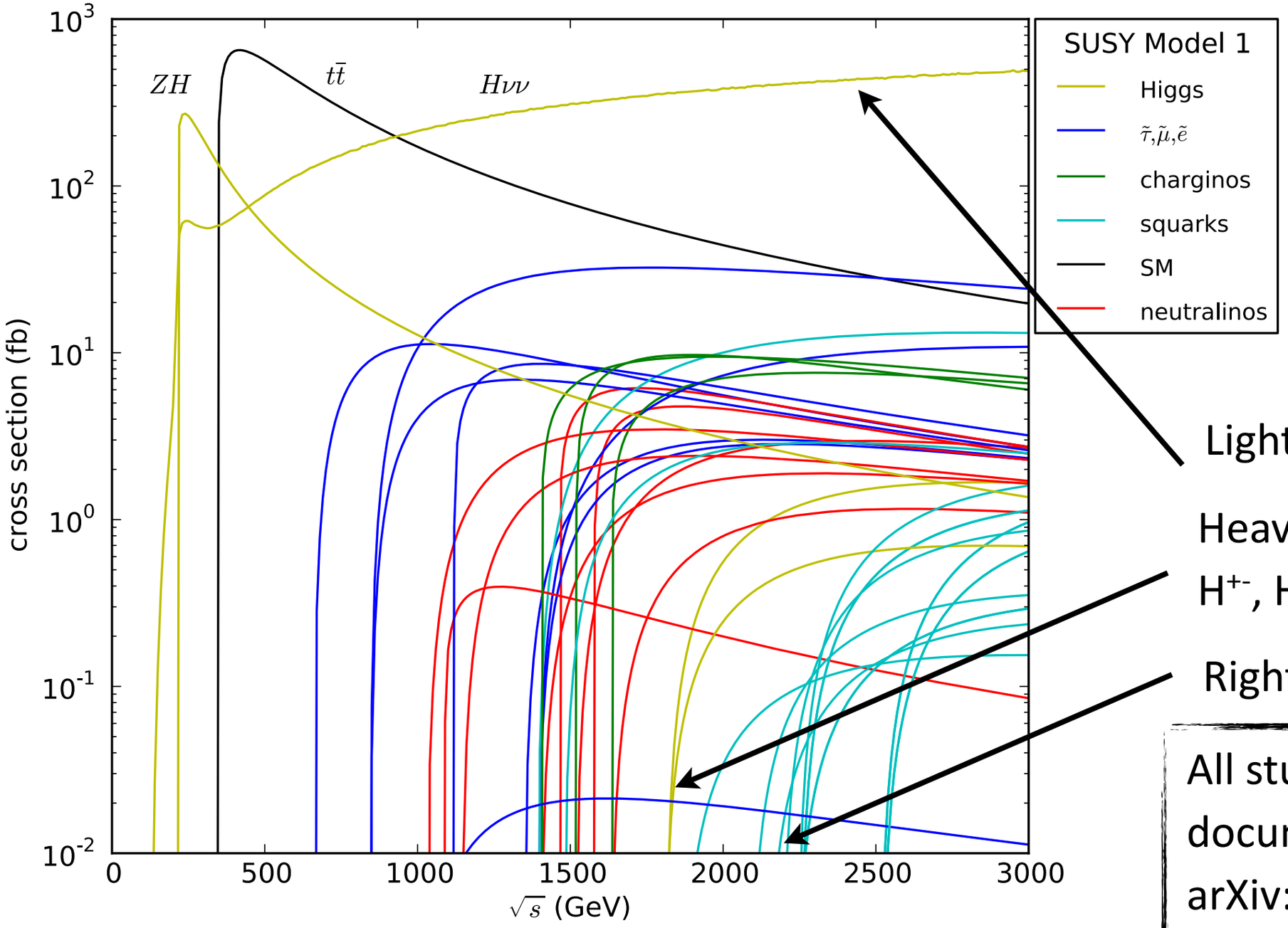
- Sensitivity also to α_s, but error on current world average already hard to beat

preliminary:
500 GeV selection efficiencies!

Beyond the Standard Model

3 TeV SUSY Studies - Model I

- Two SUSY scenarios with non-unified gaugino masses - Chosen to illustrate detector performance, emphasis on high-mass states for the 3 TeV case



Model 1:
Squarks within CLIC 3 TeV reach, heavy neutral and charged Higgs

Light Higgs in W Fusion

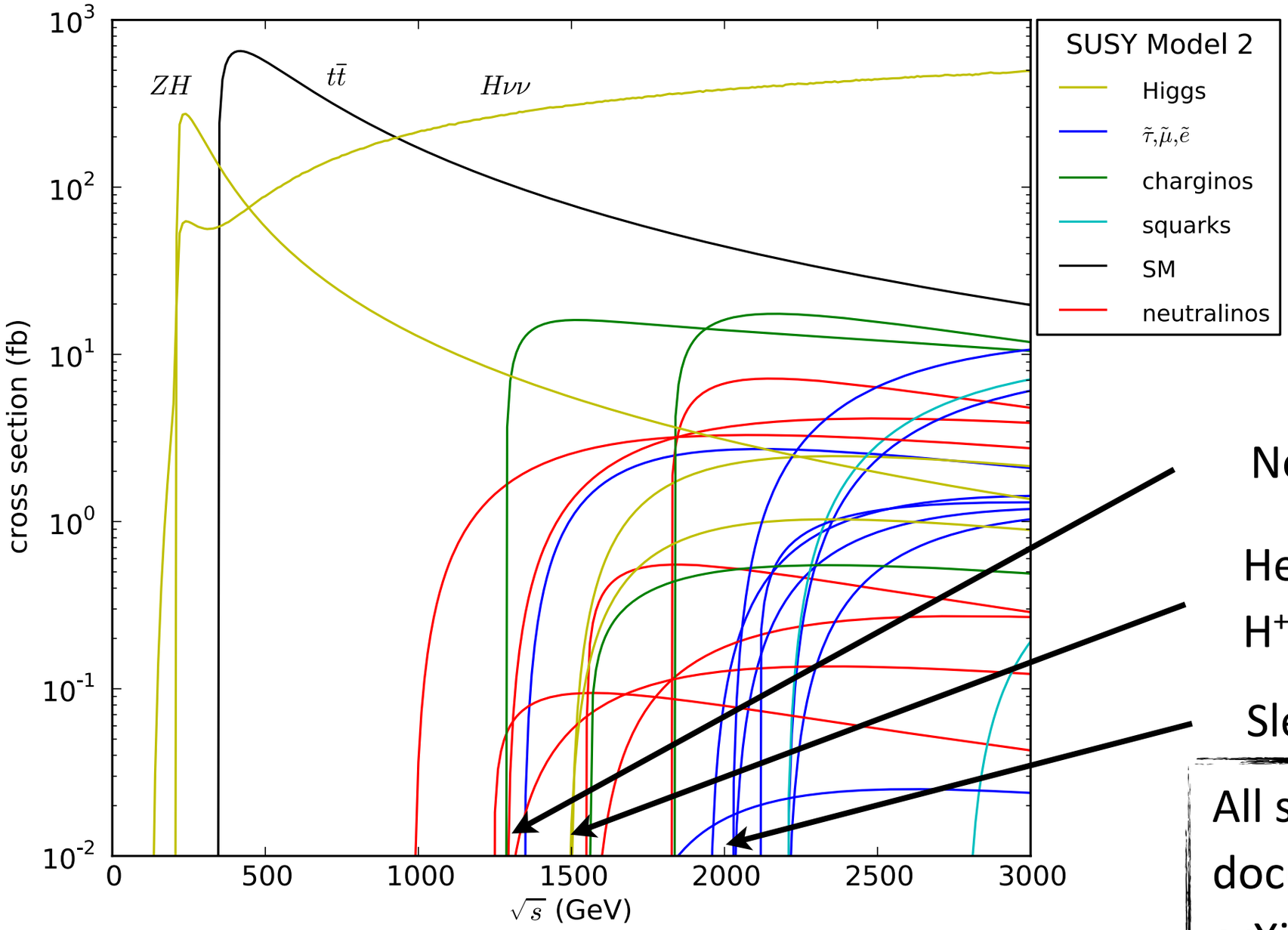
Heavy Higgs:
H^{+-}, H^0A^0

Right Squarks

All studies extensively documented in CLIC CDR vol2: arXiv:1202.5940

3 TeV SUSY Studies - Model II

- Two SUSY scenarios with non-unified gaugino masses - Chosen to illustrate detector performance, emphasis on high-mass states for the 3 TeV case



Model 2:
High mass sleptons,
Light charginos and neutralinos dominated by single decay mode

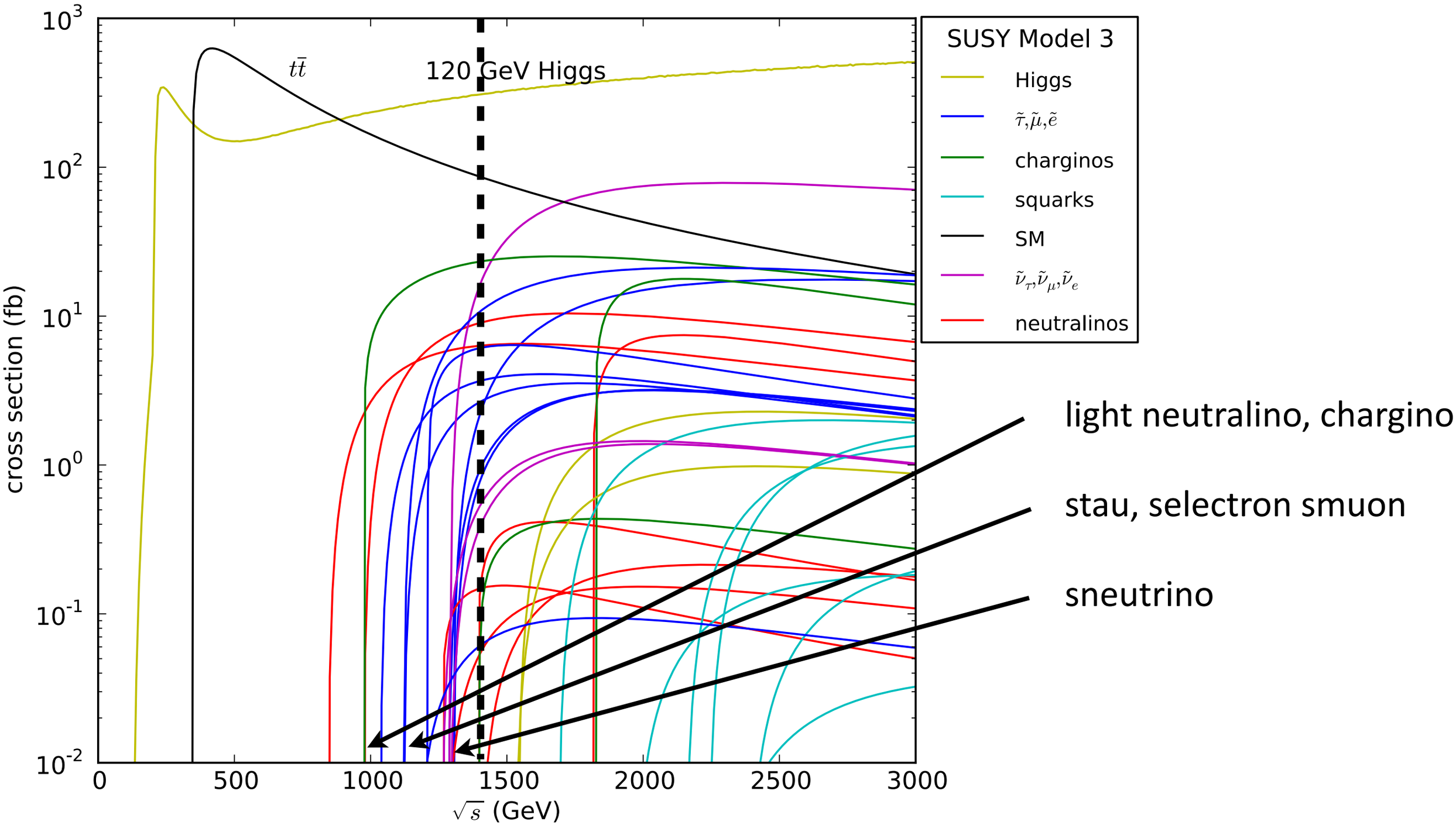
Neutralinos, Charginos

Heavy Higgs:
H^{+-}, H^0A^0

Sleptons

All studies extensively documented in CLIC CDR vol2: arXiv:1202.5940

1.4 TeV SUSY Studies - Model III

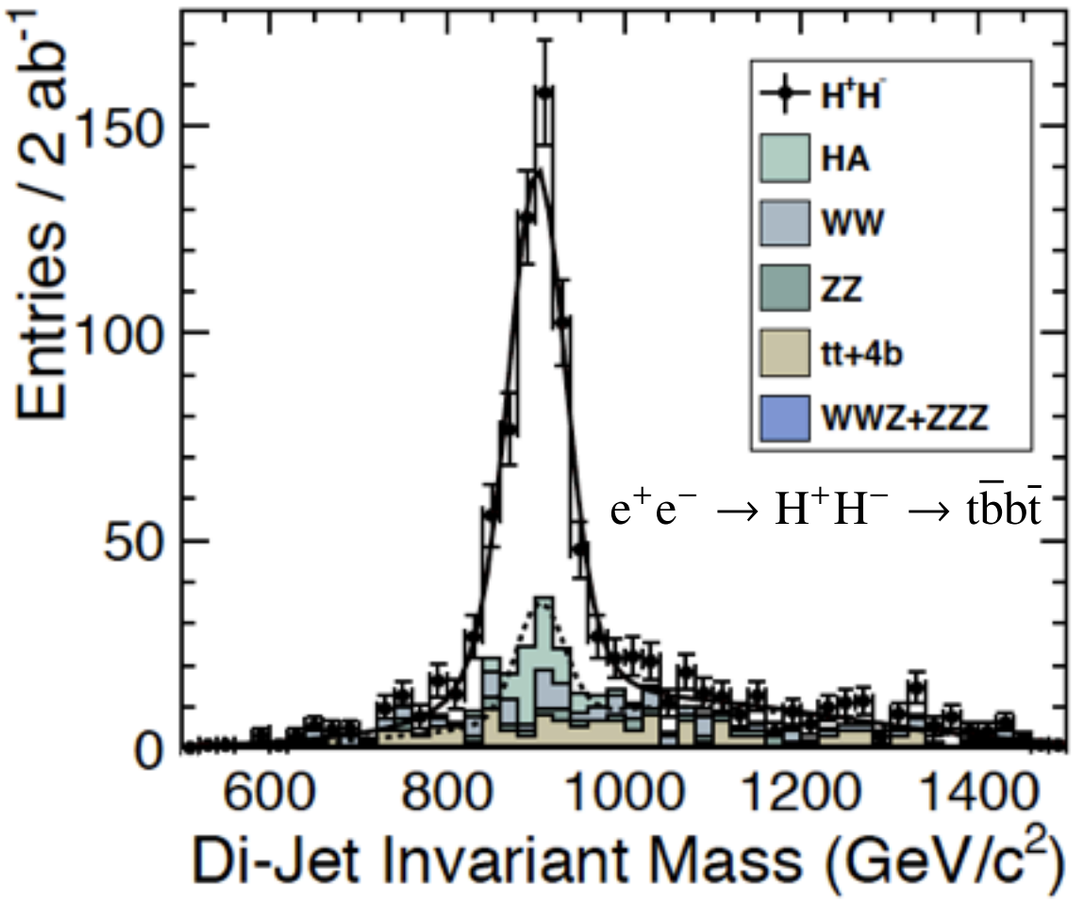


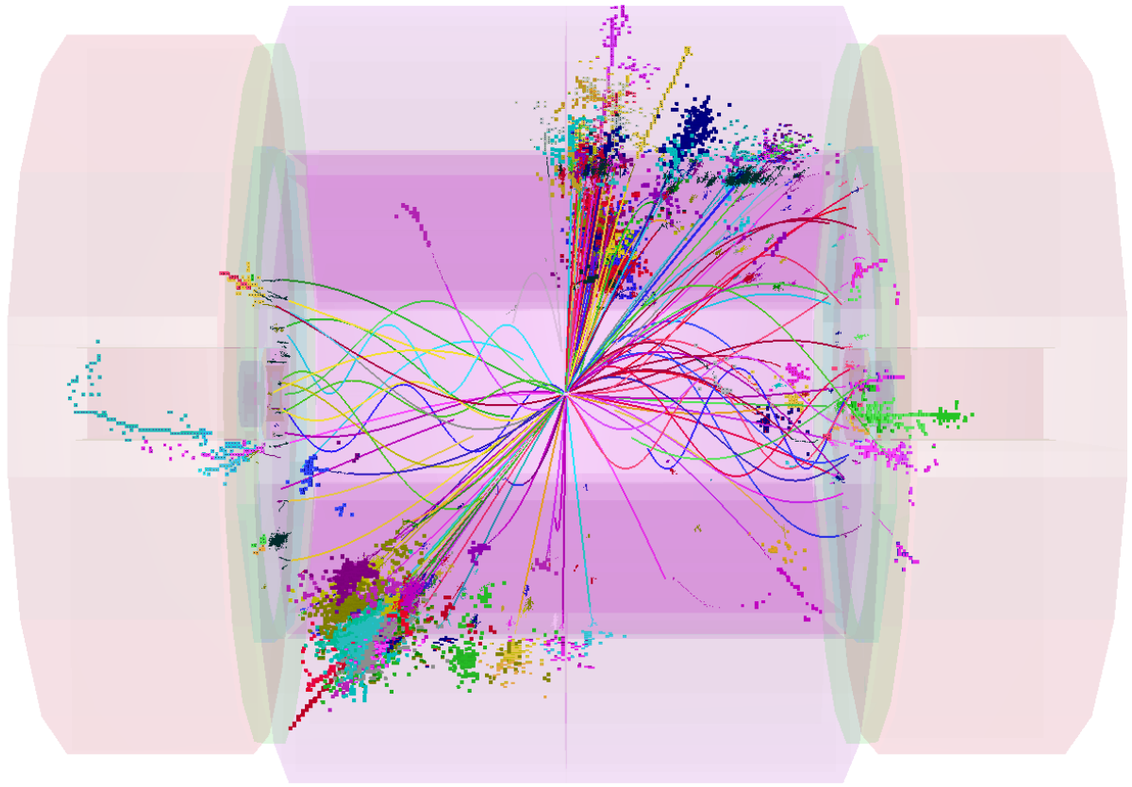
The SUSY Higgs Sector at 3 TeV

- Heavy charged and neutral Higgses:

$$e^+e^- \to H^0A^0 \to b\bar{b}b\bar{b}$$
$$e^+e^- \to H^+H^- \to t\bar{b}b\bar{t}$$

Model I: 905 GeV mass





8-Jet final states, flavor tagging crucial!

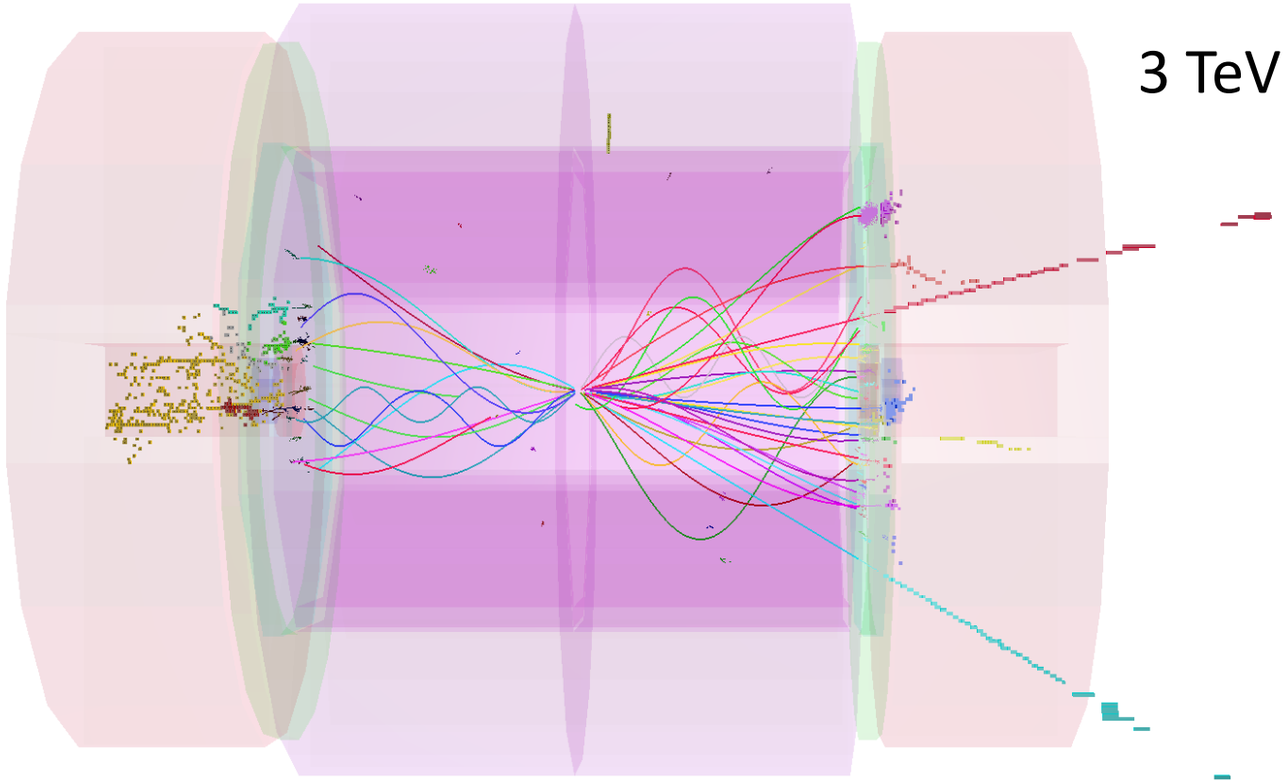
- 0.3% mass resolution, 20% - 30% resolution on the width

LCD-Note-2010-006

Sleptons: Clean events

- High-energy leptons easy to identify, in particular after rejection of minijet-background

- Strategy:
  - Pre-selection cuts requiring high energy leptons inside detector acceptance with large di-lepton mass
  - Boosted Decision Tree using lepton energies, momenta, masses,acoplanarity

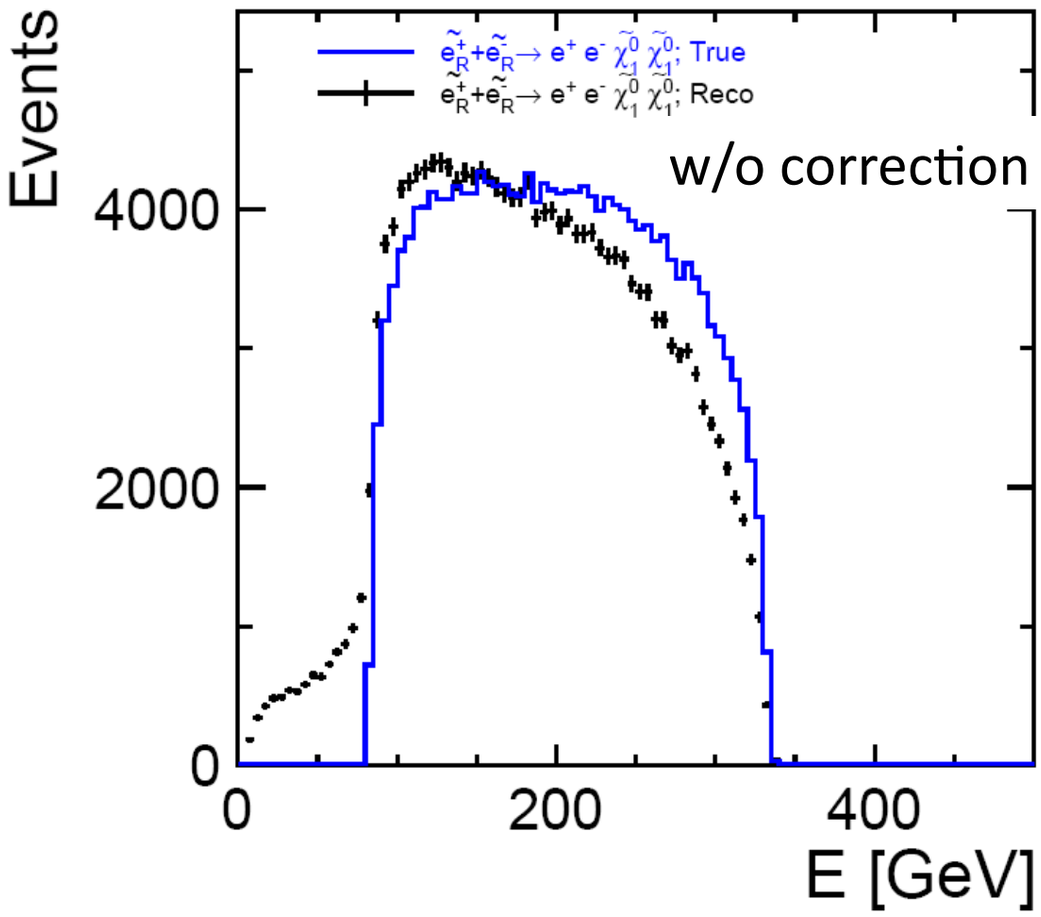


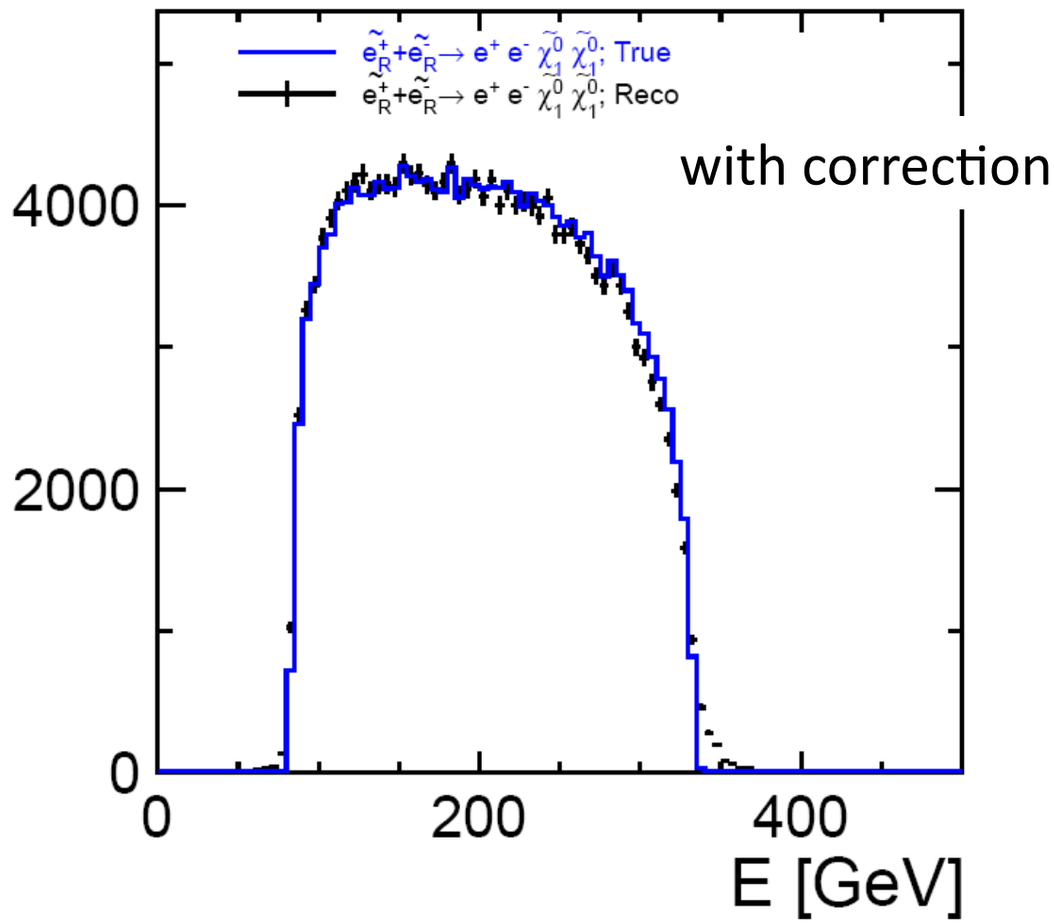
$$e^+e^- \to \tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$

High selection efficiencies, 97% for di-muon and 94% for di-electron final states

Sleptons at 1.4 and 3 TeV

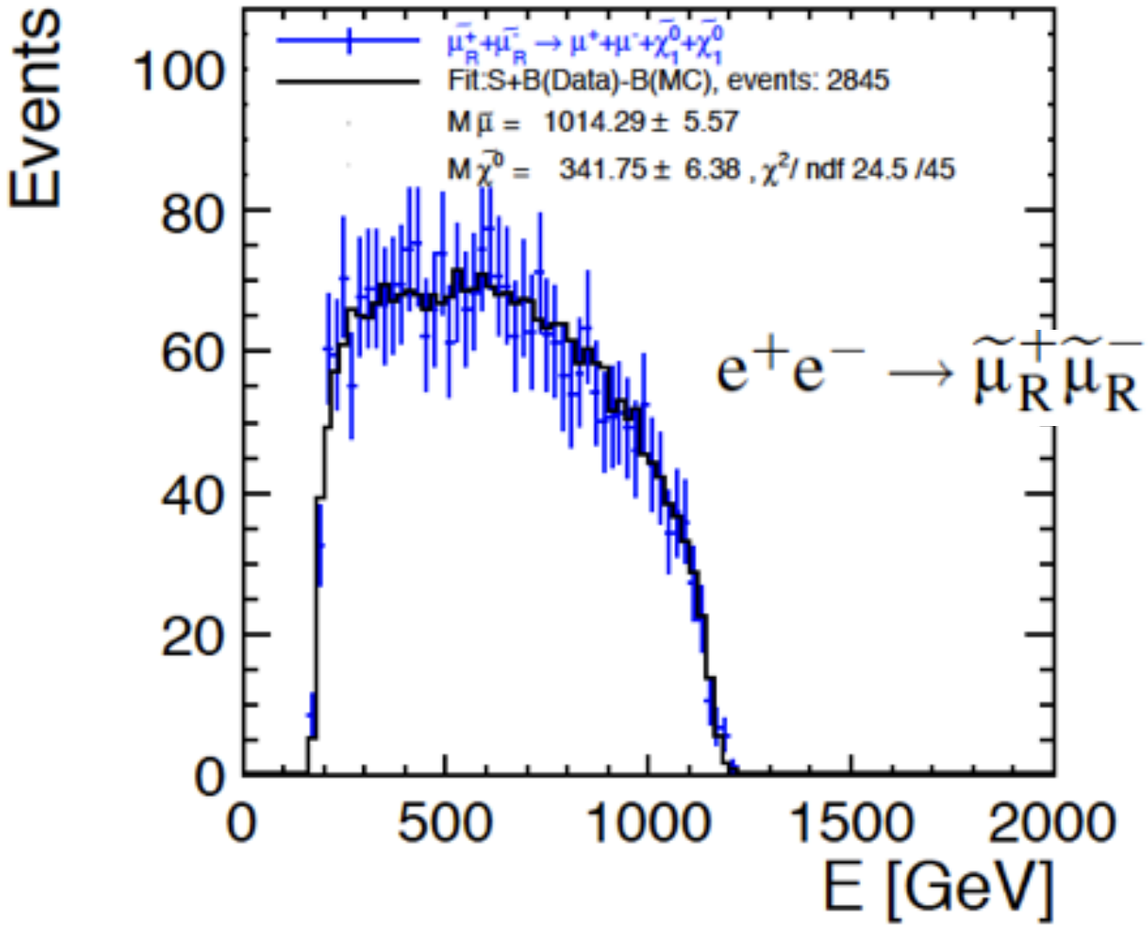
- Model III selectron & smuon masses: right: 559 GeV, left: 650 GeV
- Reconstruction of two high-energy leptons
  - Quite insensitive to γγ → hadrons background, clean samples with isolation & p_t cuts
  - Key reconstruction feature: Photon radiation correction (in particular for electrons)

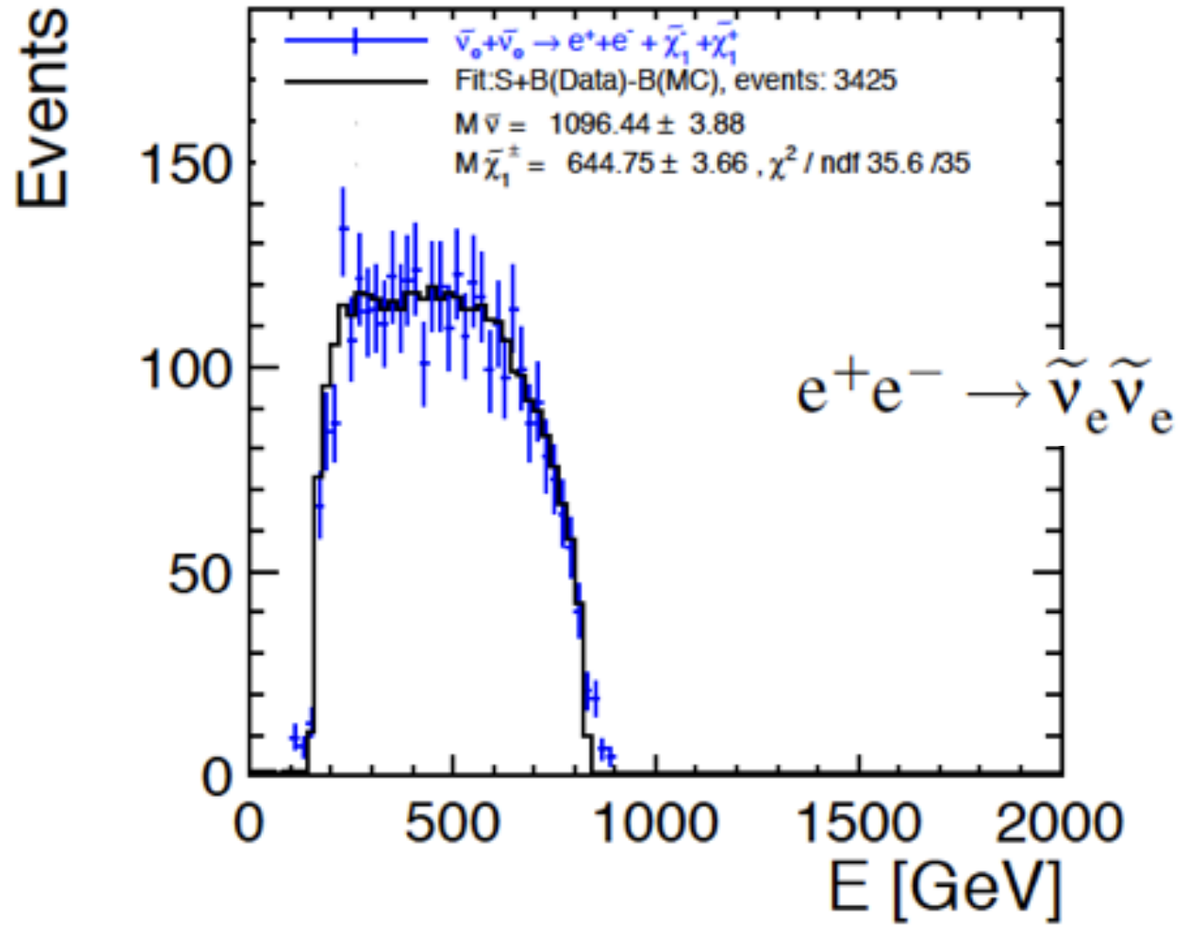




Sleptons: Mass Resolution at 3 TeV

- At 3 TeV: TeV-scale sleptons





- Background rejection with multivariate techniques
- Mass fit using beam energy spectrum, simultaneous fit of slepton and gaugino mass, ~ 0.5% precision

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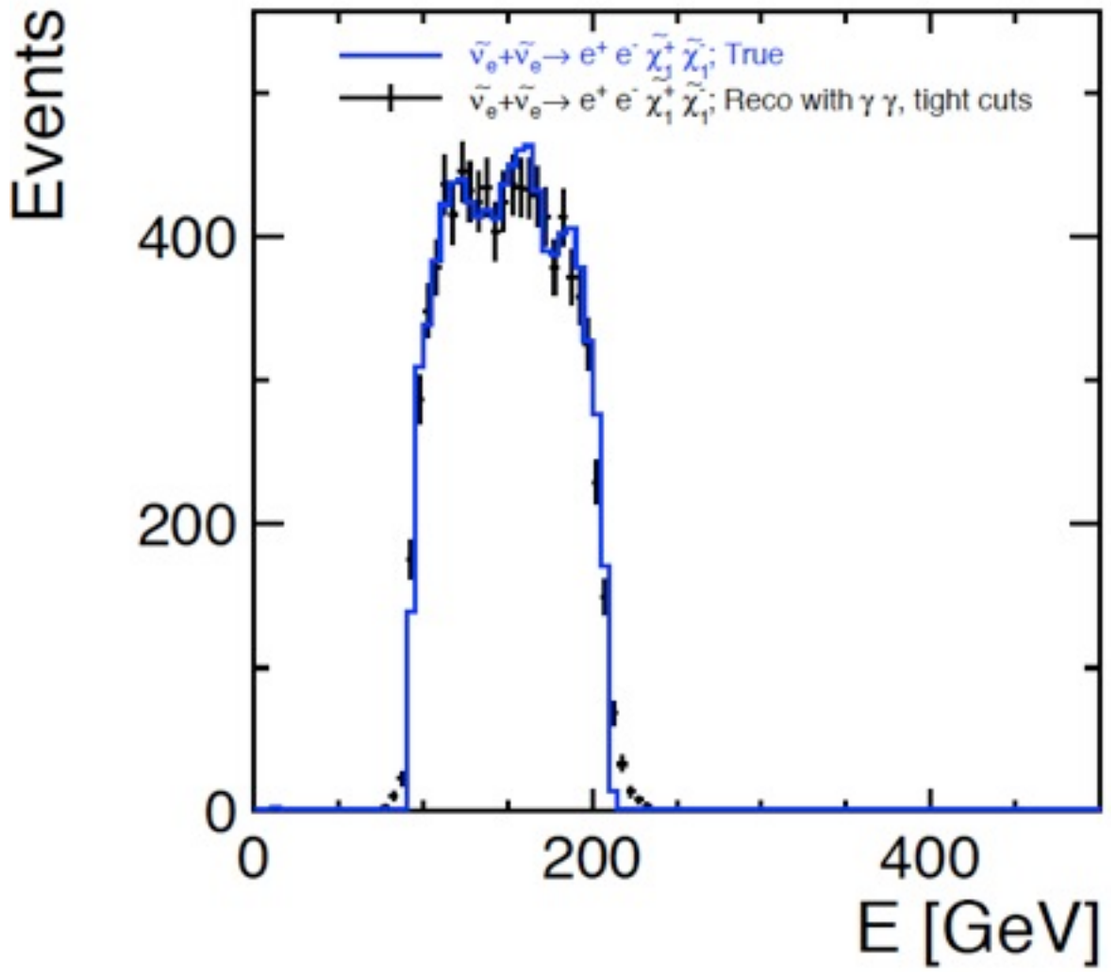
Further Slepton Studies

- Study of staus at 1.4 TeV (stau masses 517 GeV and 642 GeV) in progress
  - Main challenge: Tau reconstruction and tau energy measurement
- Sneutrino studies also at 1.4 TeV (mass 644 GeV)
  - Challenges mainly due to low cross section - close to production threshold!

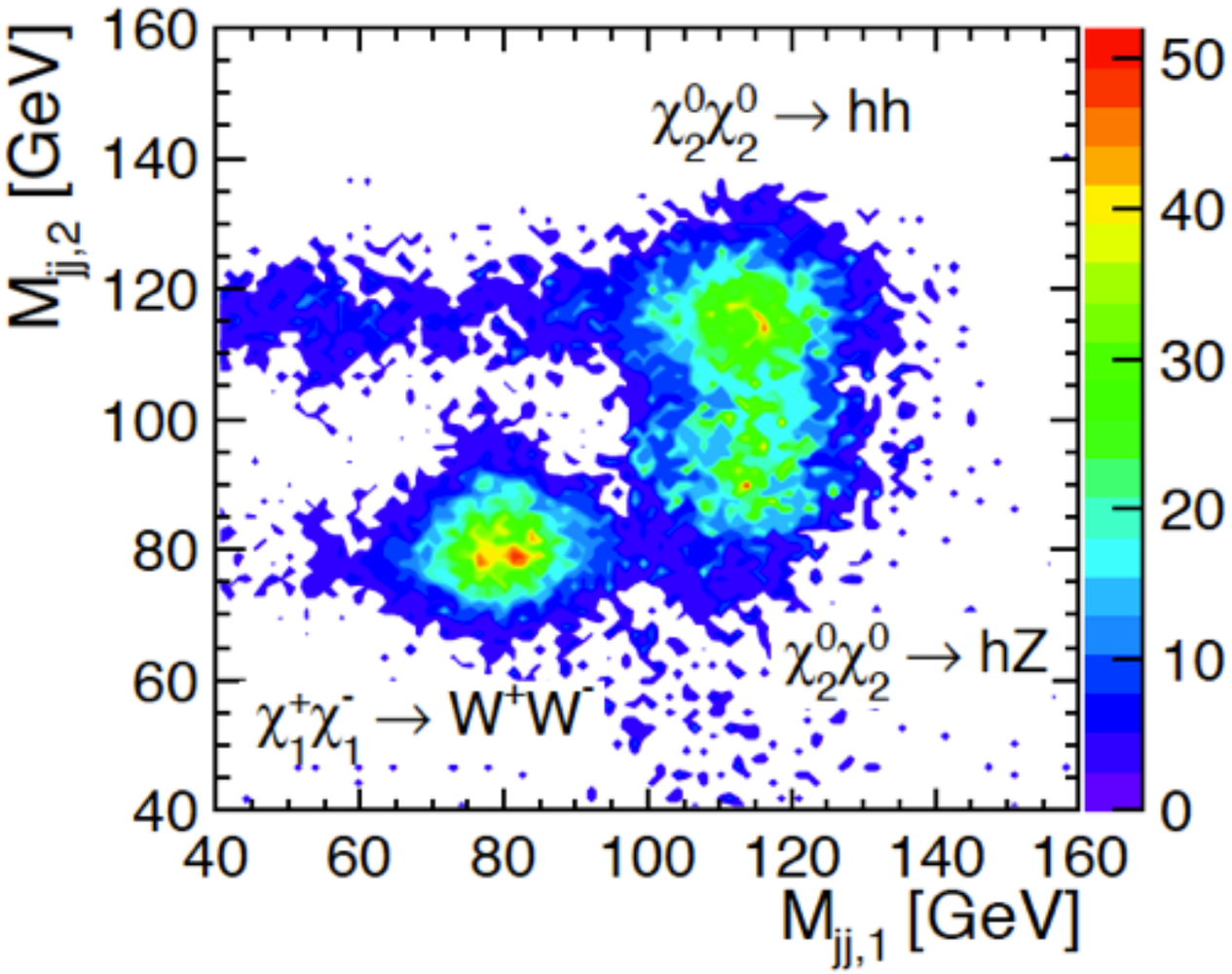


Work in progress:
Despite small cross-section, expect
~12 GeV resolution on sneutrino
and chargino mass

profiting from very low background levels in
2 leptons + 4 jets channel

Charginos, Neutralinos at 1.4 and 3 TeV

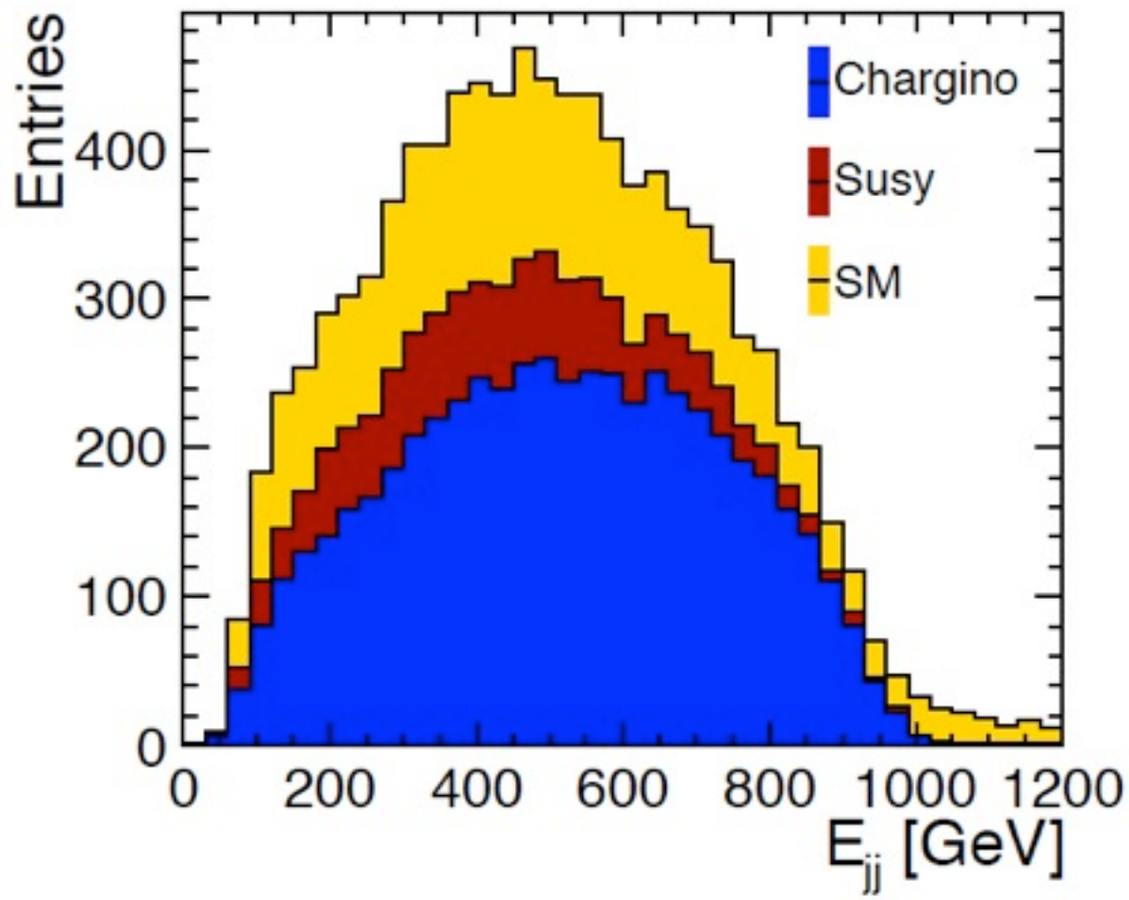
- A perfect example for the power of PFA:
  - Multi-jet final states and missing energy



- Mass determined through template fit
  Statistical precision ~ 1%

3 TeV, Neutralino & Chargino-Masses of 643 GeV

$$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^- \to W^+W^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$
$$e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_2^0 \to h(Z)h(Z)\tilde{\chi}_1^0\tilde{\chi}_1^0$$



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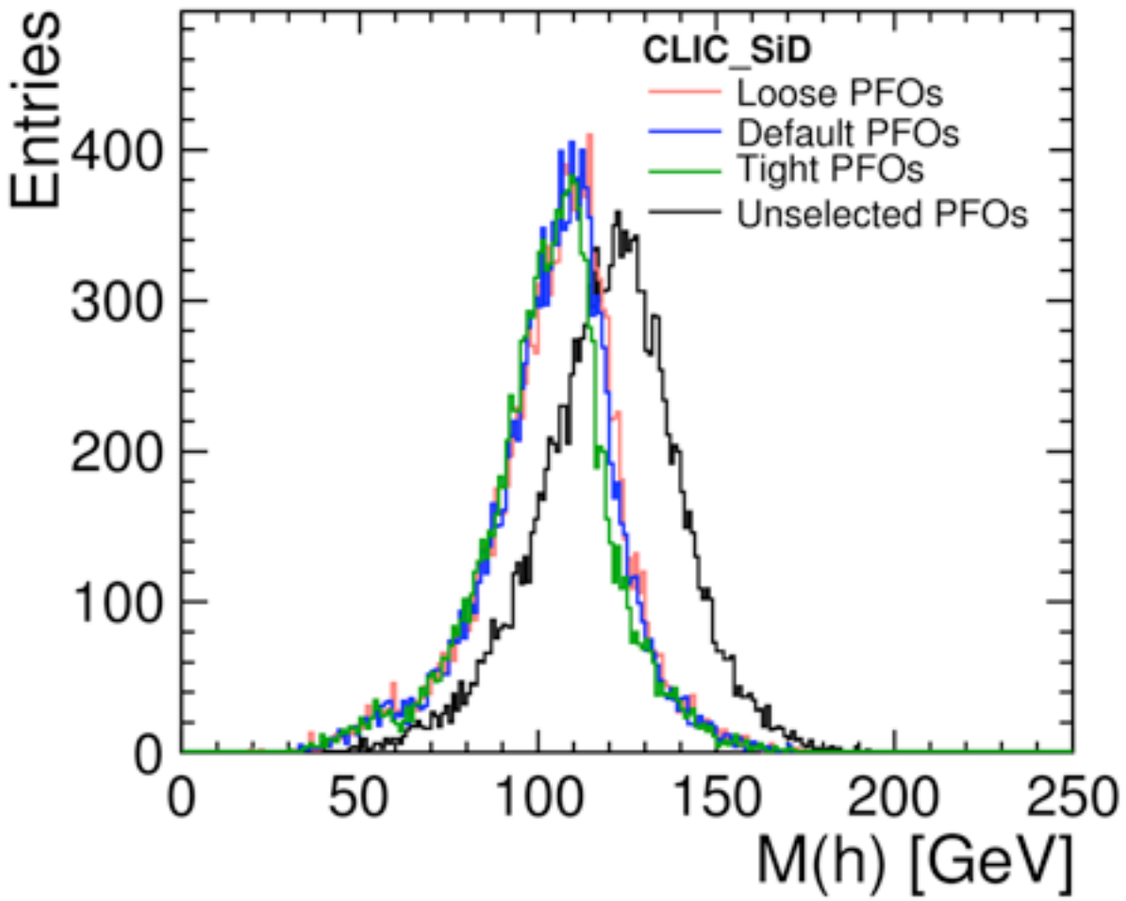
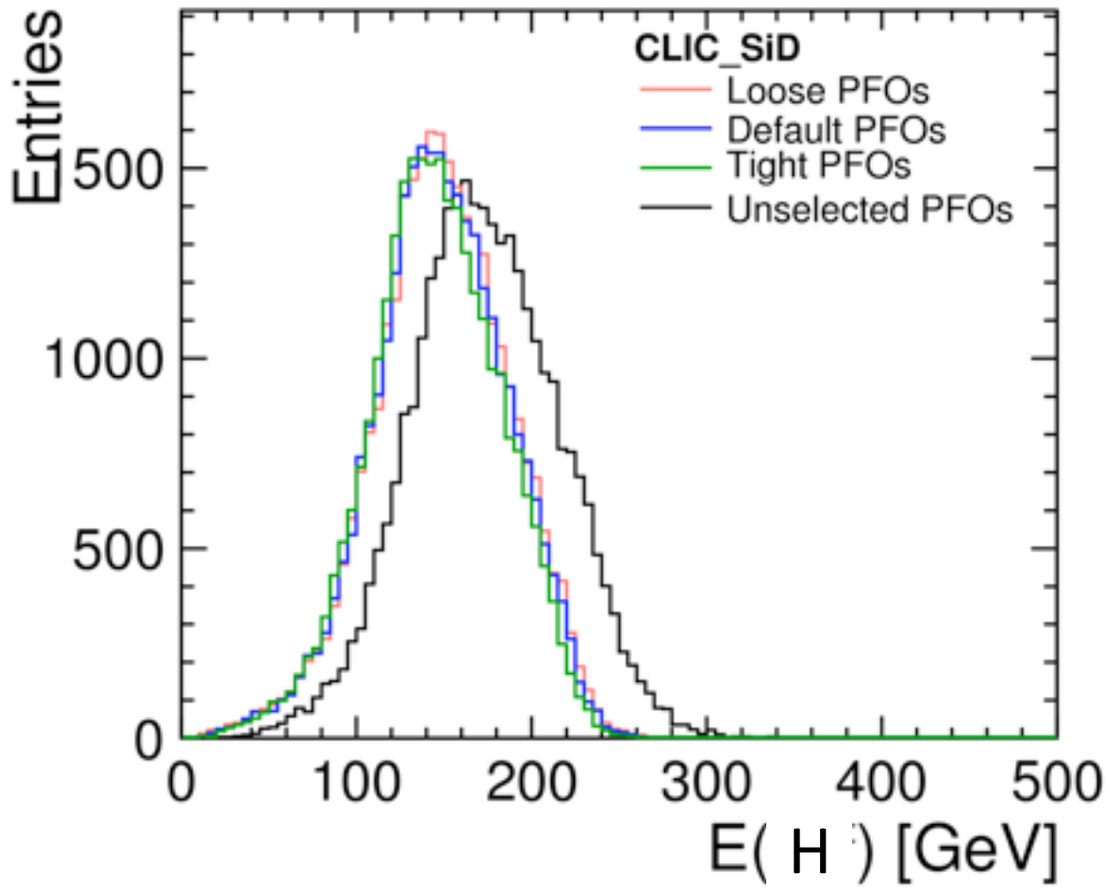
Charginos, Neutralinos at 1.4 and 3 TeV

- Charginos & Neutralinos in Model III at 1.4 TeV - Work in progress:
  - Neutralino2 decays to 95% into HX_1, H almost at rest

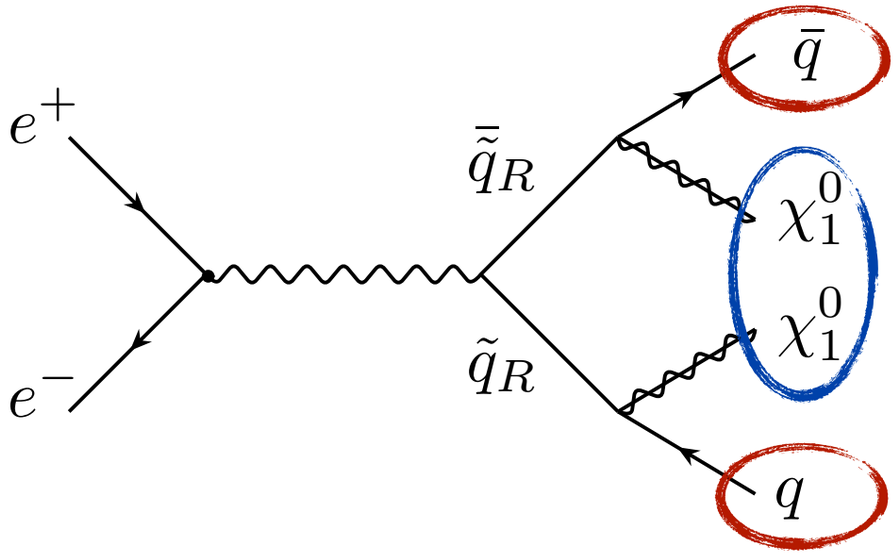


Higgs reconstruction in the presence of $\gamma\gamma \rightarrow$ hadrons background:
Timing cuts crucial!



Extracting Neutralino mass from energy distribution of di-jet system

Masses of light-flavored Squarks at 3 TeV



two highly energetic jets

missing energy

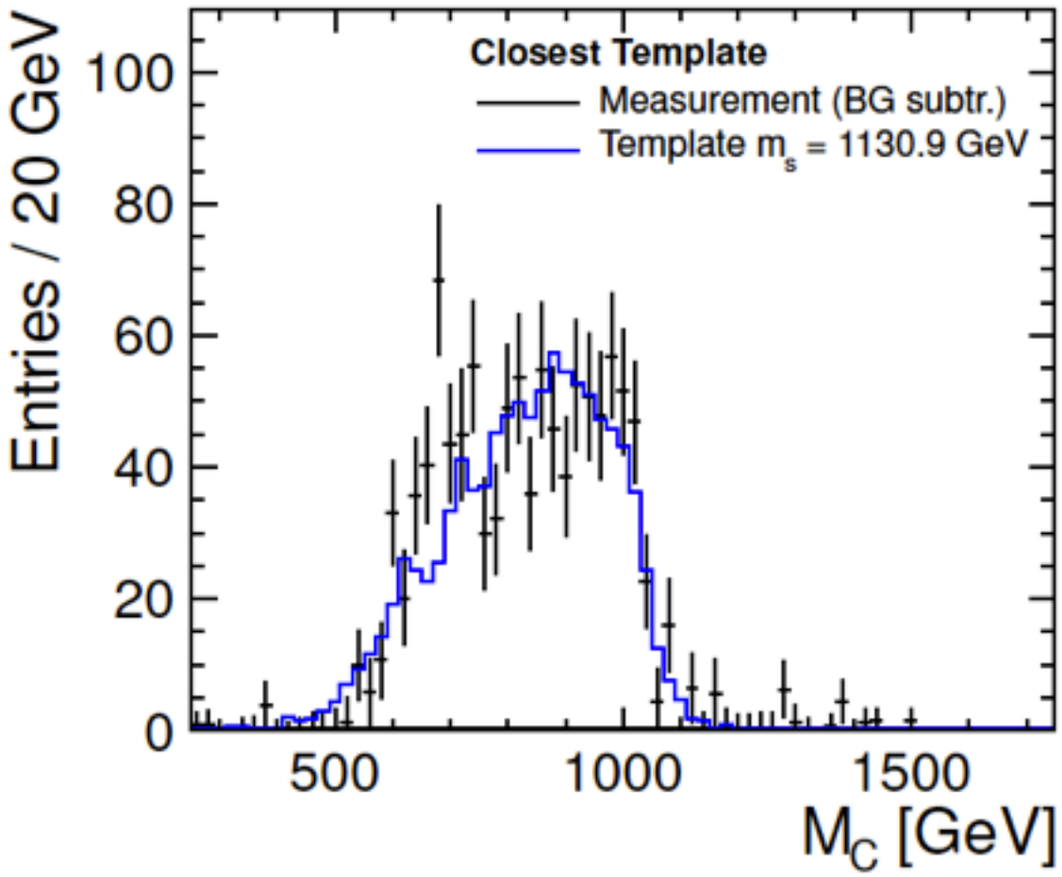
Right-Squark masses of 1.12 TeV
(up & down -type nearly mass degenerate)

- Mass measurement:

$$M_C = \sqrt{2(E_1 E_2 + \vec{p}_1 \cdot \vec{p}_2)}$$

Independent of s: Reduced sensitivity to luminosity spectrum, mass extraction assuming knowledge of Neutralino mass

- Mass from template fit:
  0.5% statistical precision



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Conclusion

- In realistic scenarios, CLIC will be constructed in several stages:

  Interesting physics at each stage!

  - Exact energies driven by physics thresholds and machine considerations

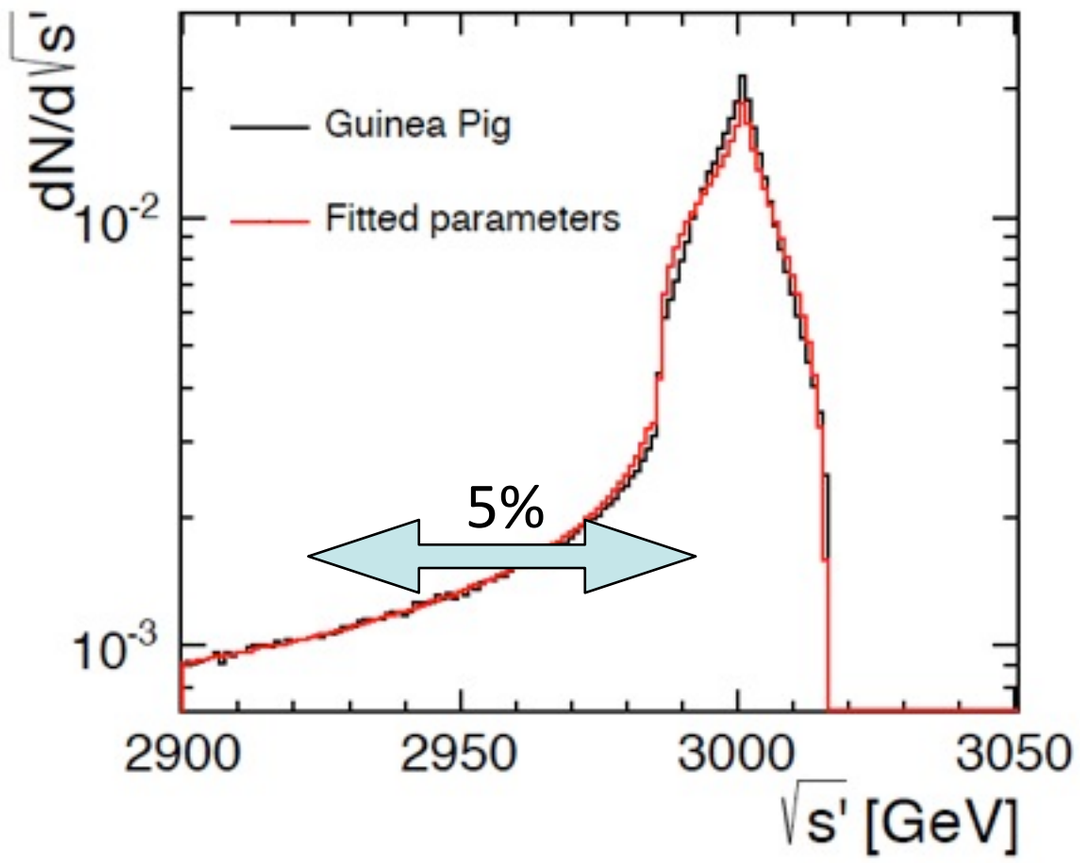
- For the CDR, we are studying a rich program:
  - Precision Standard Model physics
    - Full exploration of the Higgs
    - Top measurements
  - Supersymmetry in a variety of models: Gauginos, Sleptons, Squarks

- Full simulations including luminosity spectrum and backgrounds show that precision measurements can be done!

Backup

Systematics from Luminosity Spectrum

- The luminosity spectrum enters in most analyses: Affects edge shapes, cross section normalizations,...
- Ongoing studies to assess precision of spectrum measurement with wide-angle Bhabha scattering



- Ad-hoc study: move 5% from peak to tail and vice versa - final accuracy expected to be significantly better
- Impact:
  - Sleptons: smaller than stat. uncertainty, except X_1^0 mass: up to 1%
  - Charginos / Neutralinos: 0.5 x stat. uncertainty on mass
  - Squarks: Far below stat. uncertainty on mass due to choice of M_C (indirect sensitvity to Neutralino mass)

SUSY Model III - The Details

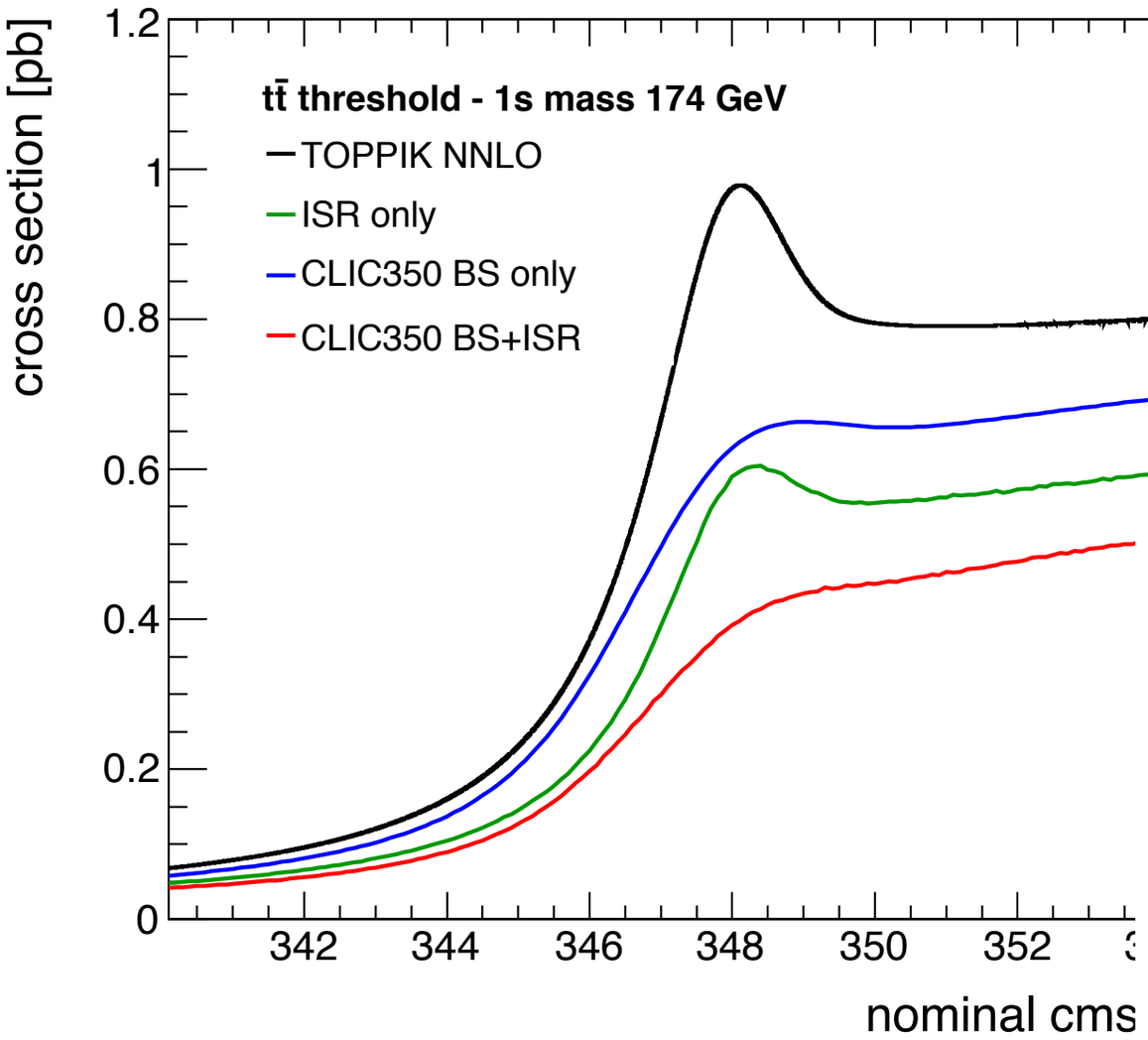
$$
\begin{aligned}
\text{Neutralinos } (\tilde{N}_{1,2,3,4}): &\quad 357,\ 487,\ 904,\ 911 \\
\text{Charginos } (\tilde{C}_{1,2}): &\quad 487,\ 911 \\
\text{Sleptons } (\tilde{e}_R, \tilde{e}_L, \tilde{\nu}_e): &\quad 559,\ 650,\ 644 \\
(\tilde{\tau}_1, \tilde{\tau}_2, \tilde{\nu}_\tau): &\quad 517,\ 642,\ 630 \\
\text{Squarks } (\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2): &\quad 844,\ 1120,\ 1078,\ 1191 \\
(\tilde{d}_R, \tilde{u}_R, \tilde{d}_L, \tilde{u}_L): &\quad 2167,\ 2181,\ 2197,\ 2196 \\
\text{Higgs bosons } (h^0, A^0, H^0, H^\pm): &\quad 117.8,\ 765,\ 765,\ 769
\end{aligned}
$$

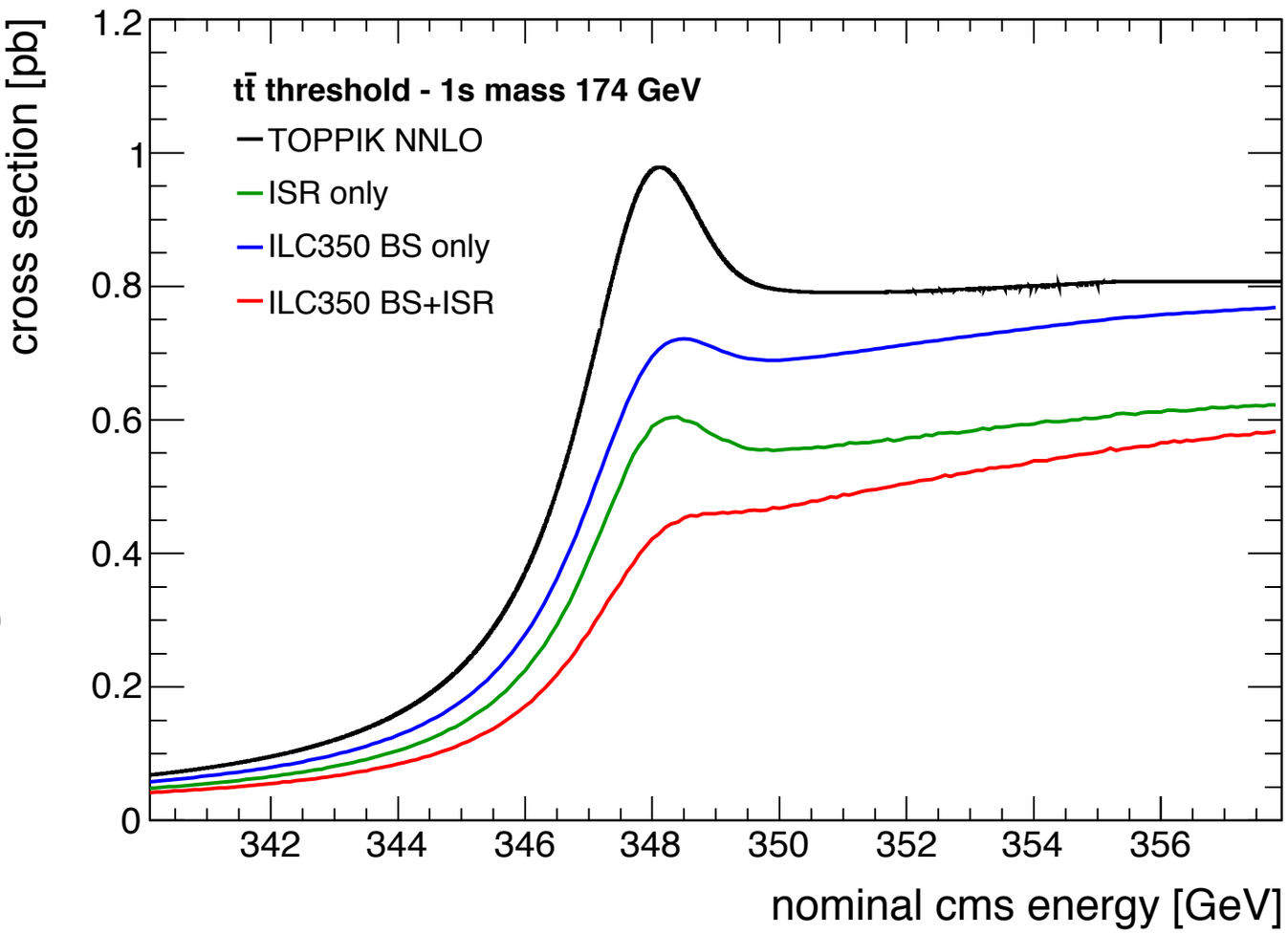
At 1.4 TeV:
Pair production of sleptons and gauginos

$$
\begin{aligned}
\Omega_{\mathrm{DM}} h^2 &= 0.110 \\
\sigma_{\mathrm{SI}}(\text{nucleon}, \tilde{N}_1) &= 7.4 \times 10^{-10}\,\mathrm{pb} \\
\Delta(g-2)_\mu &= 6.35 \times 10^{-10} \\
\mathrm{BR}(B_s \to \mu^+\mu^-) &= 4.0 \times 10^{-9} \\
\mathrm{BR}(b \to s\gamma) &= 3.26 \times 10^{-4}
\end{aligned}
$$

Squarks, heavy Higgs above threshold

Top Threshold: CLIC vs ILC



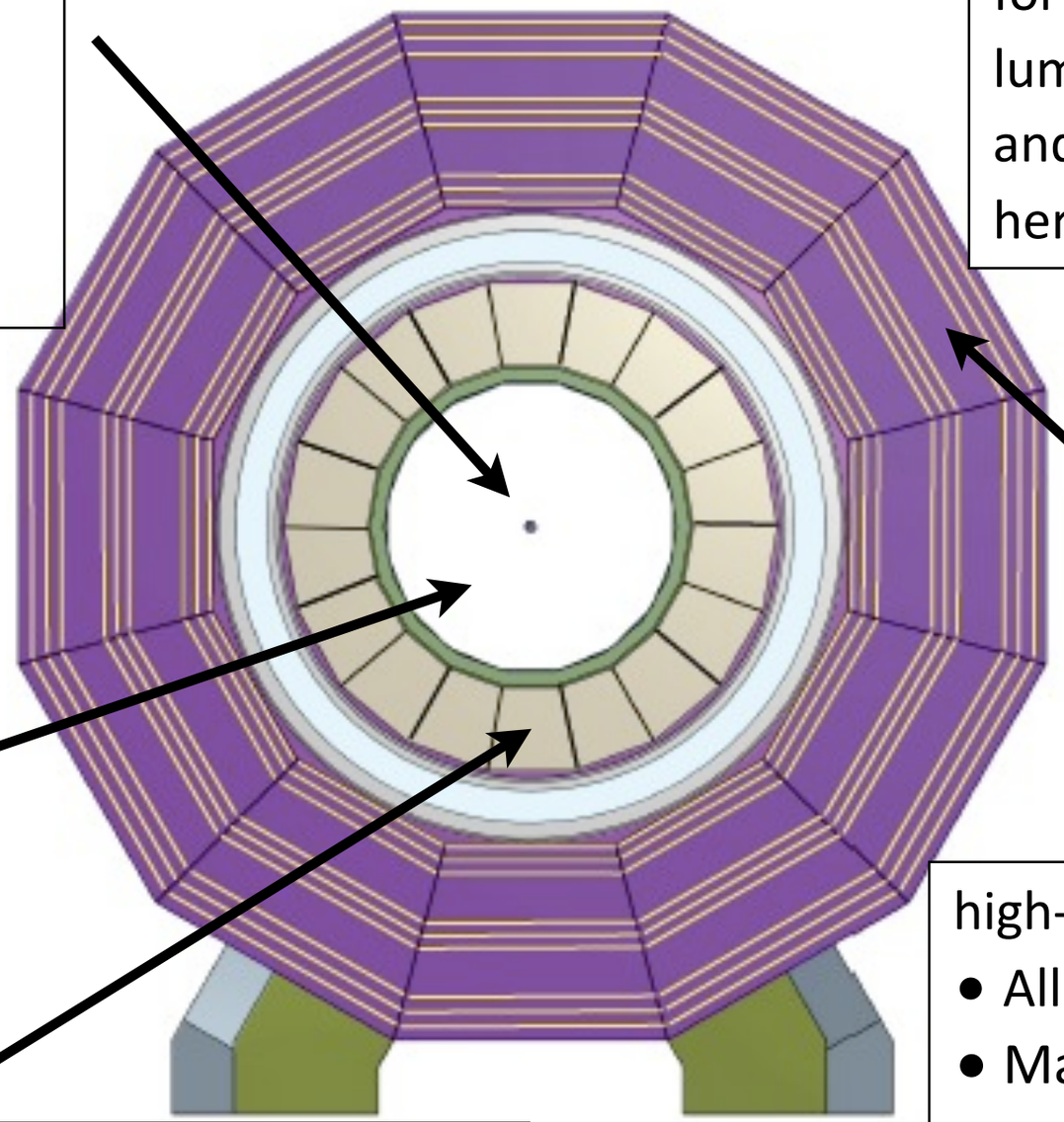


Broader beam energy spectrum leads to softening of edge: Some reduction of sensitivity, but not a show stopper!

CLIC_ILD Detector - Main Features

low-mass, high precision vertex detector:
Si pixel detector
Si strip inner tracker
ILD (500GeV): 15mm
CLIC_ILD (500GeV): 25mm
CLIC_ILD (3TeV): 31mm

Detectors concept follows the ILC designs: CLIC_ILD



forward calorimeters for luminosity measurements and overall detector hermeticity

magnet yoke with muon detector / tail catcher

precision tracking:
- SiD: Si strip main tracker
- ILD: TPC main tracker

high-field solenoid
- All detectors inside solenoid
- Magnetic field:
  CLIC_ILD at 4 T

highly granular calorimeters for particle flow
- Hcal: 7.5 λ, steel in endcap, tungsten in barrel