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Measurement of the Higgs boson decay to muons at a CLIC collider operating at 1.4 TeV and 3 TeV

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[on behalf of the CLIC Detector and Physics Study]

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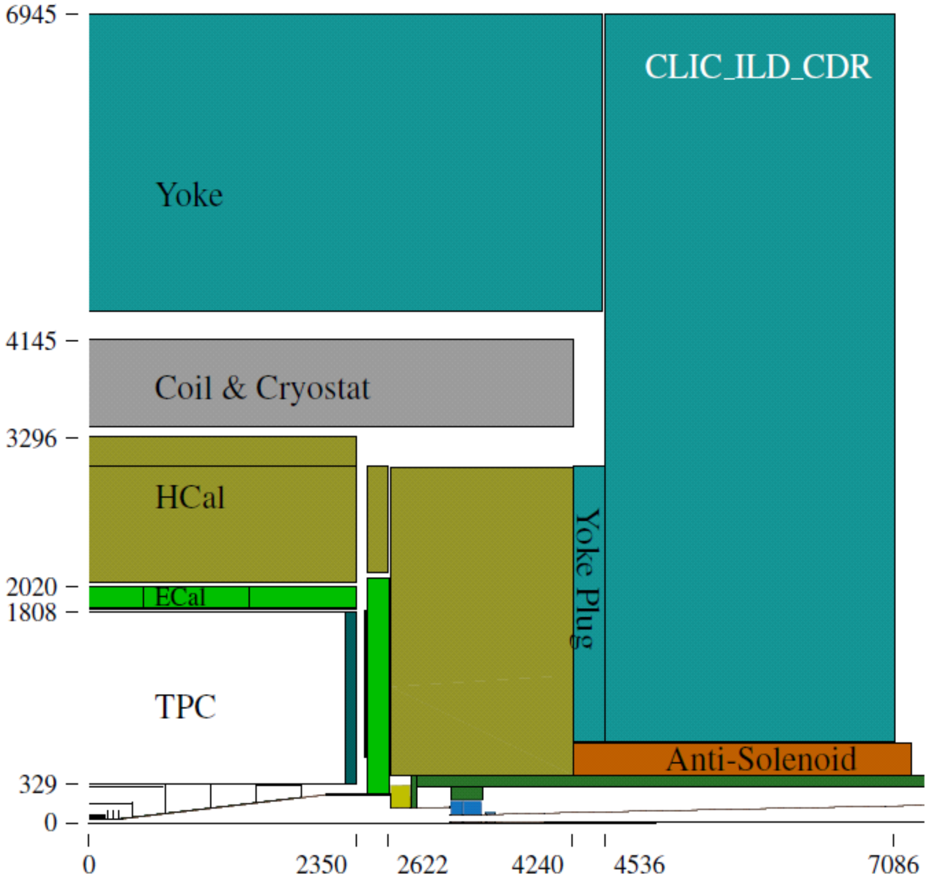
Overview

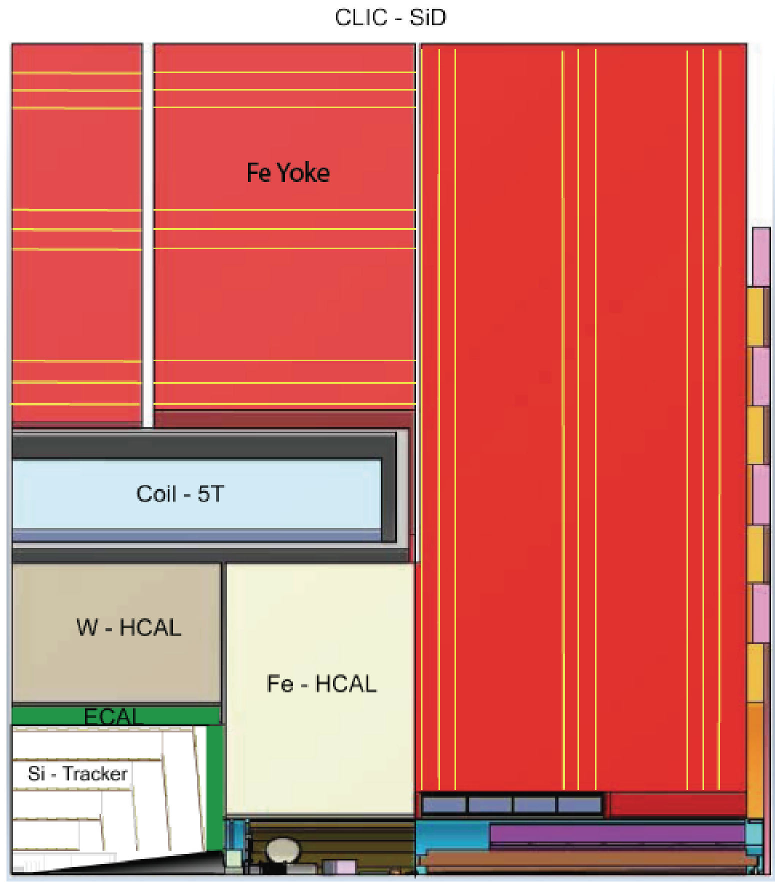
- Motivation for the measurement
- Detector for CLIC
- Higgs production and decays at CLIC
- Event simulation
- Method of the measurement
- Multivariate approach in background suppression
- Di-muon invariant mass fit and BR extraction
- Impact of momentum resolution and forward electron tagging
- Conclusion

Motivation

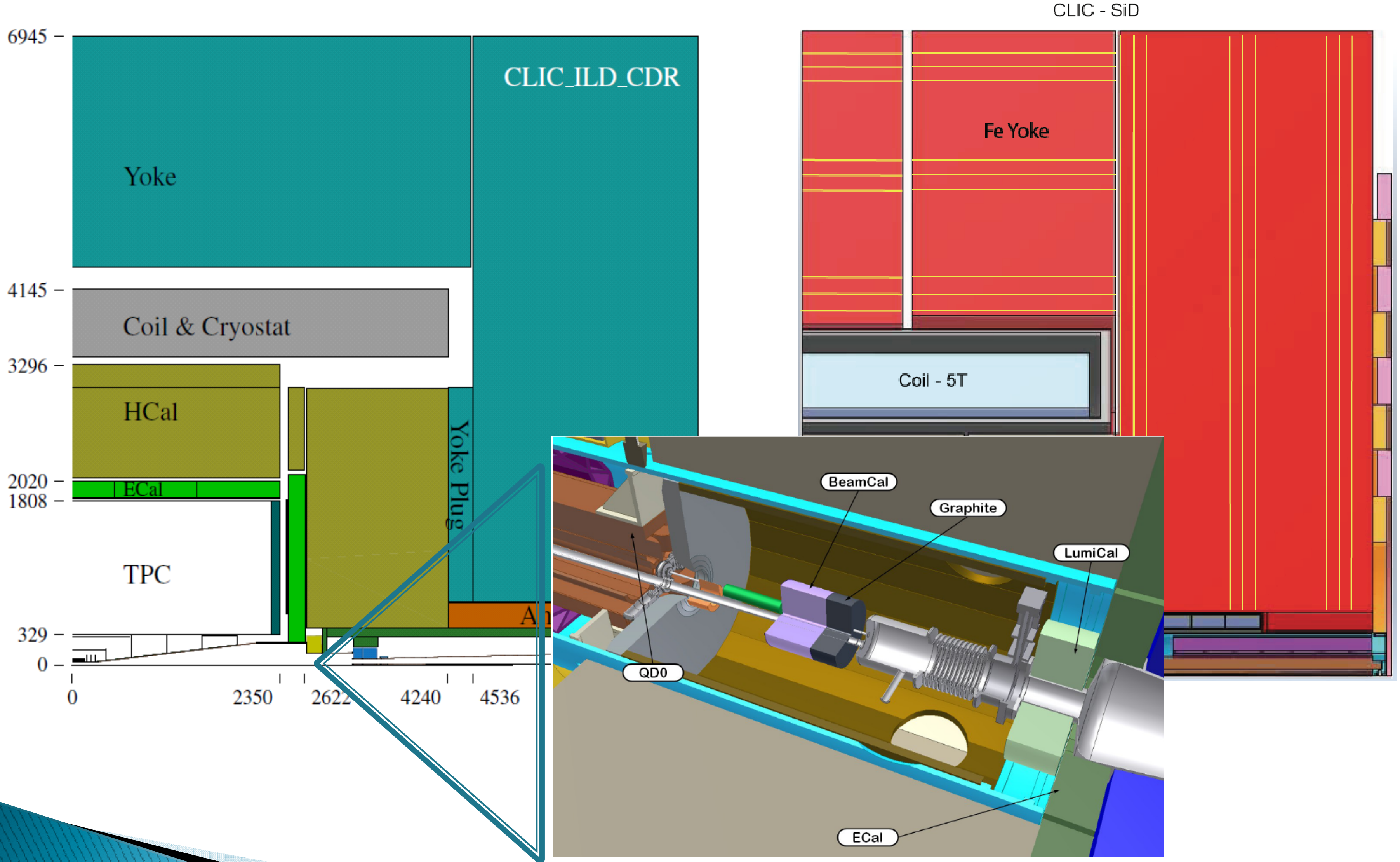
- In SM Higgs BRs depend only on Higgs mass $\Rightarrow$ potential probe for New Physics (i.e. coupling to second-generation fermions)
- Challenging measurement due to low signal yield (estimated $BR(h \to \mu^- \mu^+) \sim 2.8 \cdot 10^{-4}$)
- Requires excellent momentum resolution $\left(\frac{\Delta p_T}{p_T^2} \leq 2 \cdot 10^{-5}\, GeV^{-1} \right)$ in the barrel, also in the forward region $\left(\frac{\Delta p_T}{p_T^2} \sim 10^{-4}\, GeV^{-1} \right)$
- $\nu_e \overline{\nu_e} h \to \mu^- \mu^+$ CLIC Higgs physics CDR benchmark – addressed at both 3 TeV [LCD-Note-2011-035] and 1.4 TeV

Detector for CLIC

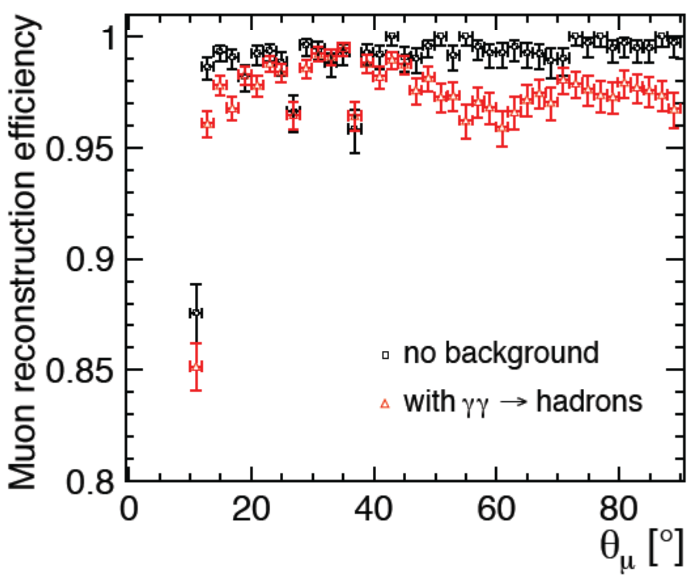


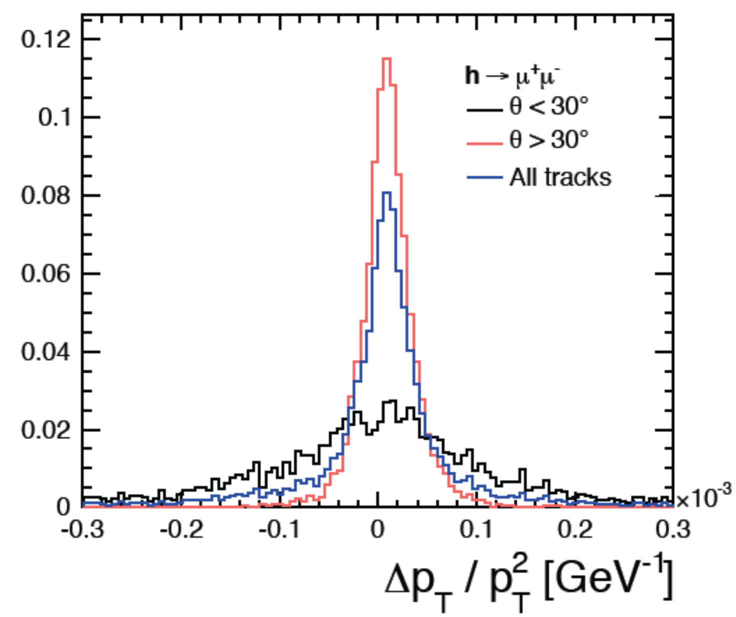


Detector for CLIC

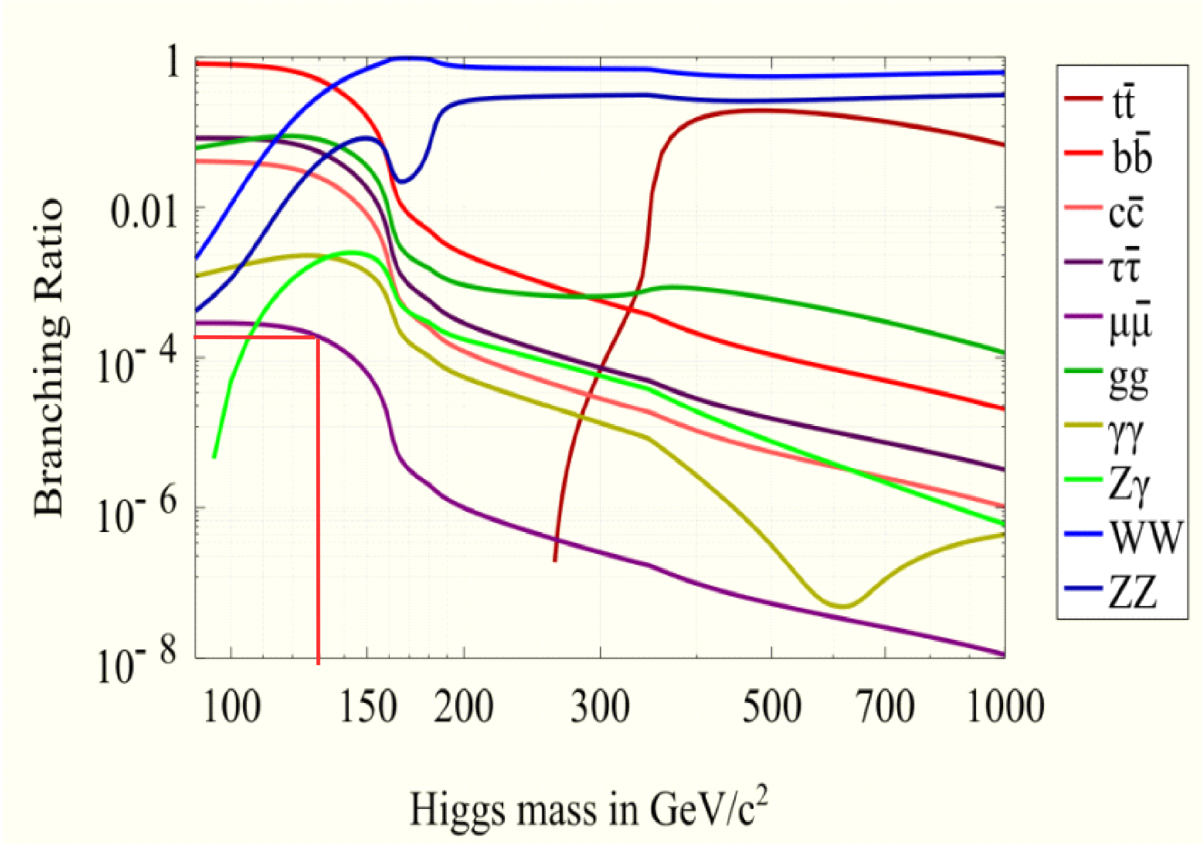


- Challenging p_T muon reconstruction down to the lowest angles ⇒ translates into m(μμ) mass width
- Iron yoke instrumented with 9 active layers for μ identification
- Momentum resolution has $\frac{1}{p_T}$ dependence due to multiple scattering
- $\frac{\Delta p_T}{p_T^2} : 1.1 \cdot 10^{-4} - 3.5 \cdot 10^{-5} GeV^{-1}$ depending on the θ region

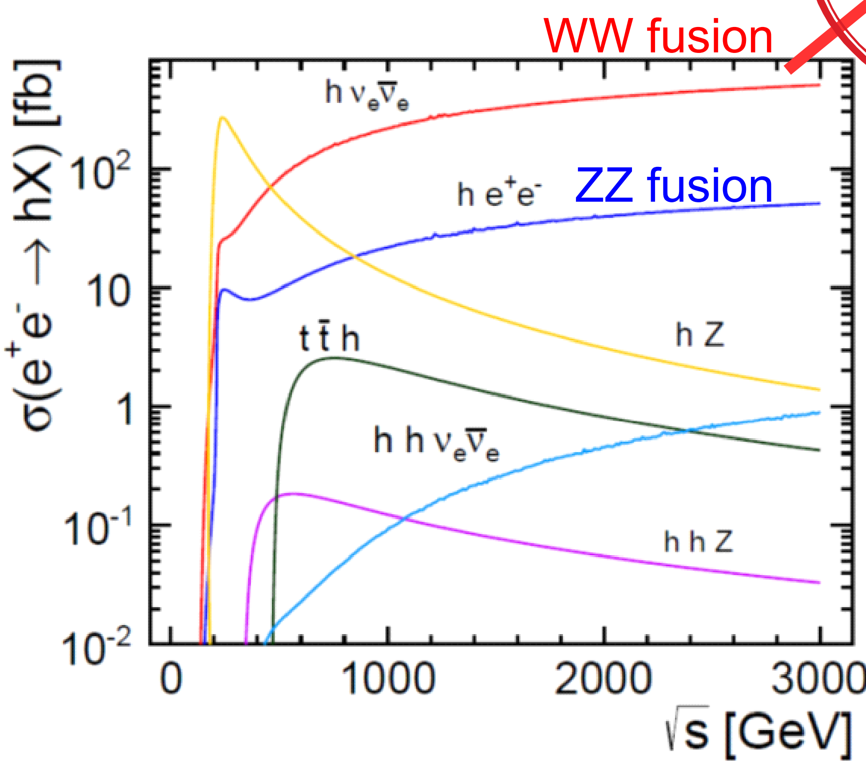


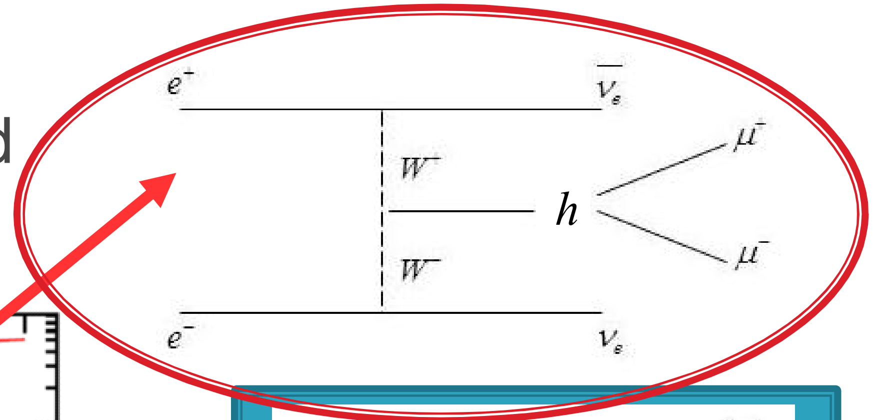


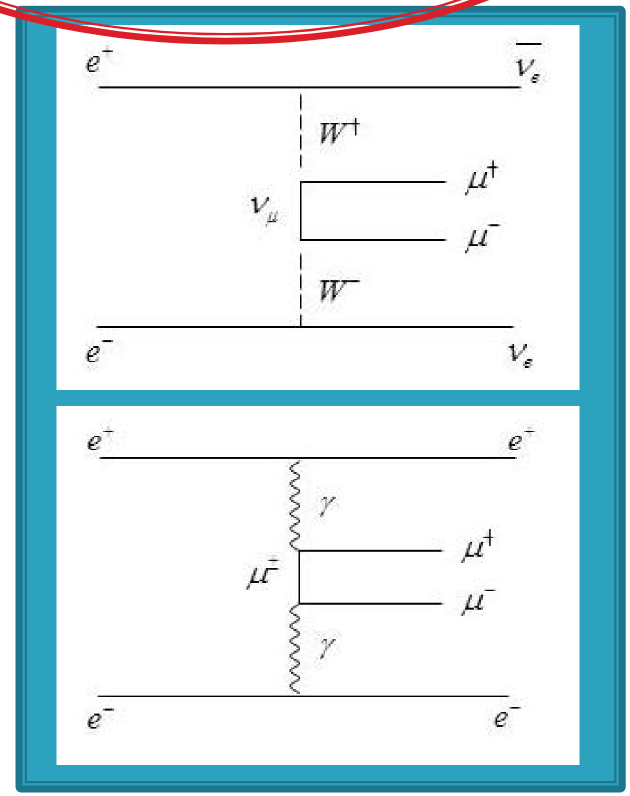
Higgs decays



Signal and background







$$e\gamma_{BS} \rightarrow e\mu^{-}\mu^{+}$$
$$\gamma_{BS}\gamma_{BS} \rightarrow hadrons$$

Event simulation

- Event sample: 1.5 ab^{-1} (2 ab^{-1}) corresponding to 4 years operation with 50% data taking efficiency at 1.4 TeV (3 TeV)
- Large main background samples in order to extract PDFs
- Event generation: WHIZARD 1.95 (+ISR), x-angle 20 mrad (Lorentz boost of the final state particles), Higgs decay: PYTHIA 6.4 (+FSR), Lumi spectrum: GuineaPig 1.4.4
- Preselection:
  - Two reconstructed muons
  - p_T>5 GeV preselection
  - (105-135) GeV di-muon mass window

Method of the $BR(h \to \mu^+\mu^-)$ measurement

- Expected shape of data (signal + background) has to be fitted (unbinned likelihood fit) by the invariant mass shapes estimated in simulation to derive the number of signal events:

$$\sigma_{ww\_fusion} \cdot BR(h \to \mu^+\mu^-) = N/(L \cdot \varepsilon_S)$$

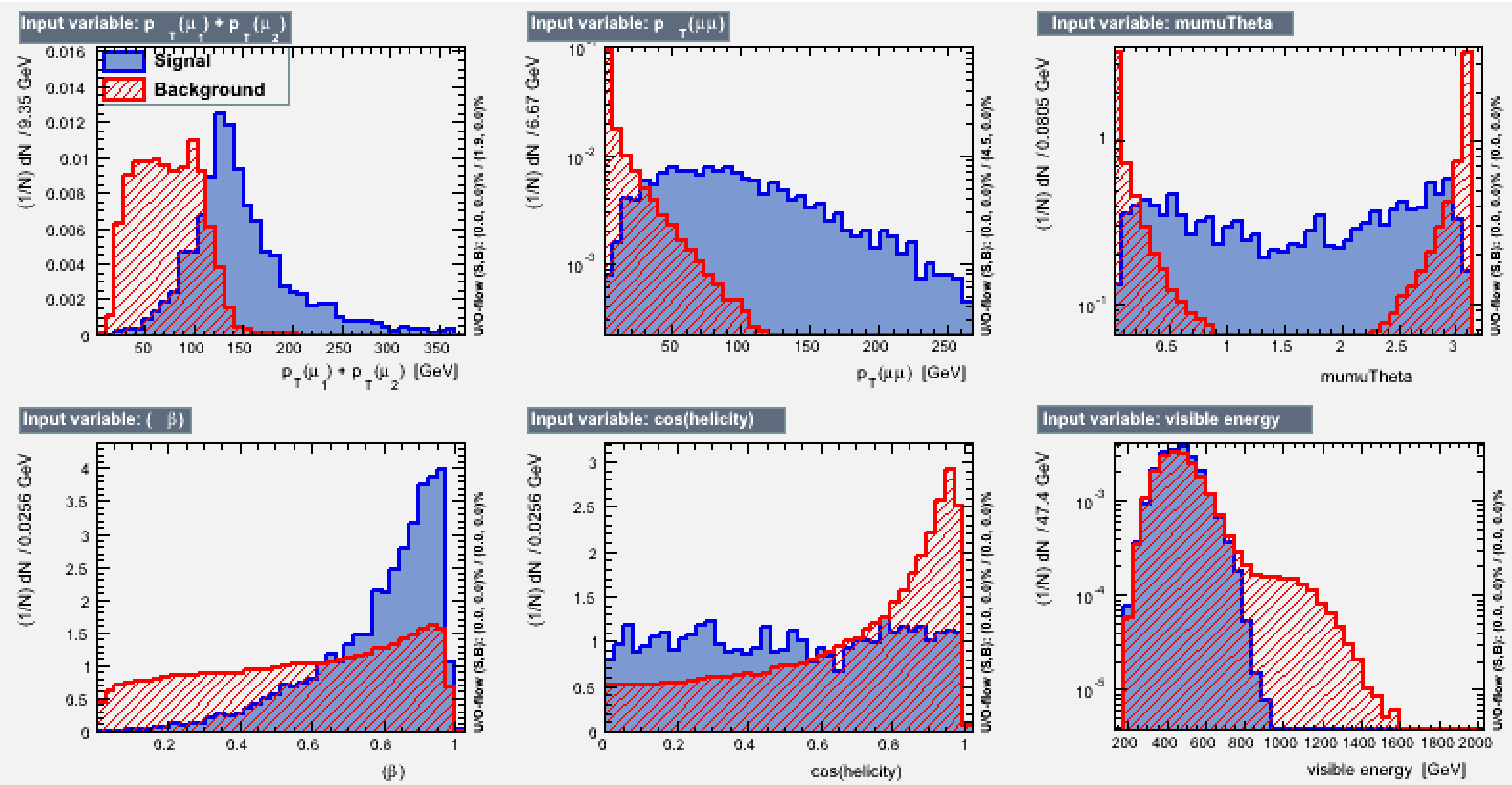
- Sufficient number of Toy MC experiments (i.e. 1000) gives estimates of N_S

- Toy MC: samples drown from the fully simulated signal events + bck PDFs to generate random event samples $(N_i = \sigma_i \cdot \varepsilon_i \cdot L)$

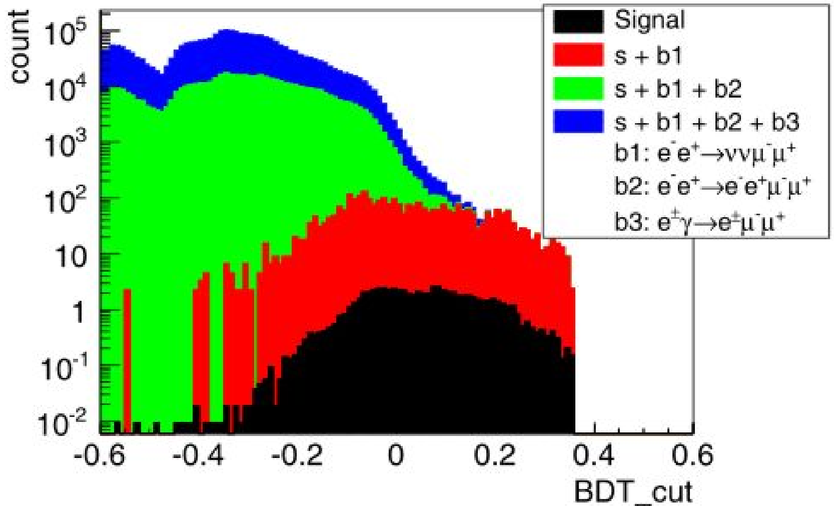
- One needs as large as possible statistics to describe the signal and background (extract PDFs)

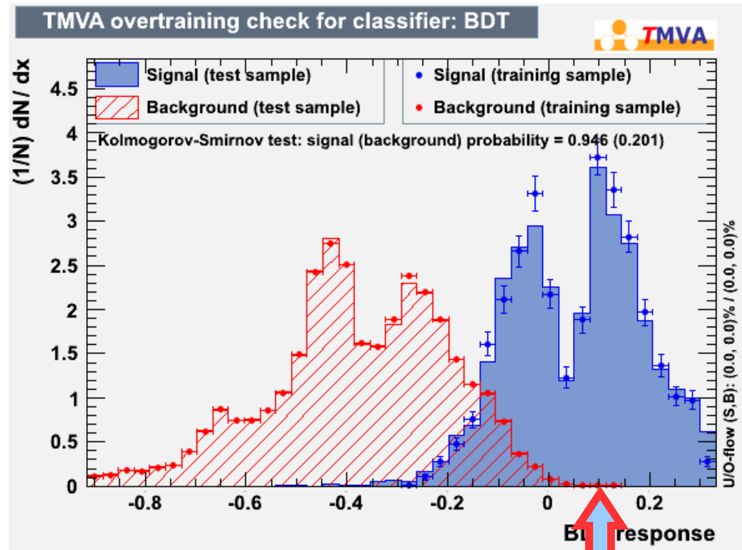
Multivariate approach in background suppression

$e^+e^- \to e^+e^-\mu^+\mu^-$ at 1.4 TeV

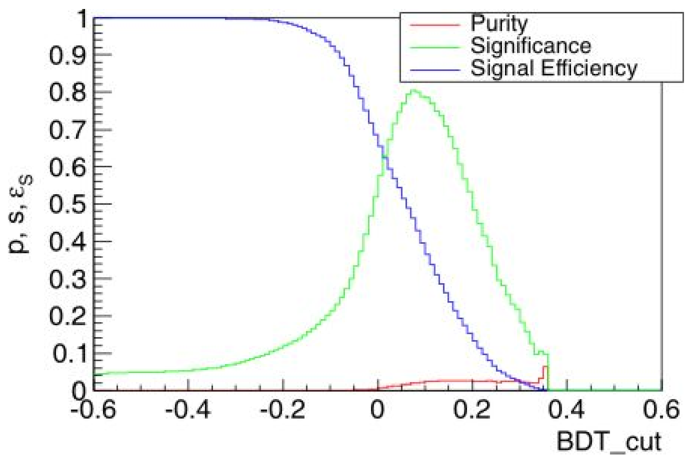


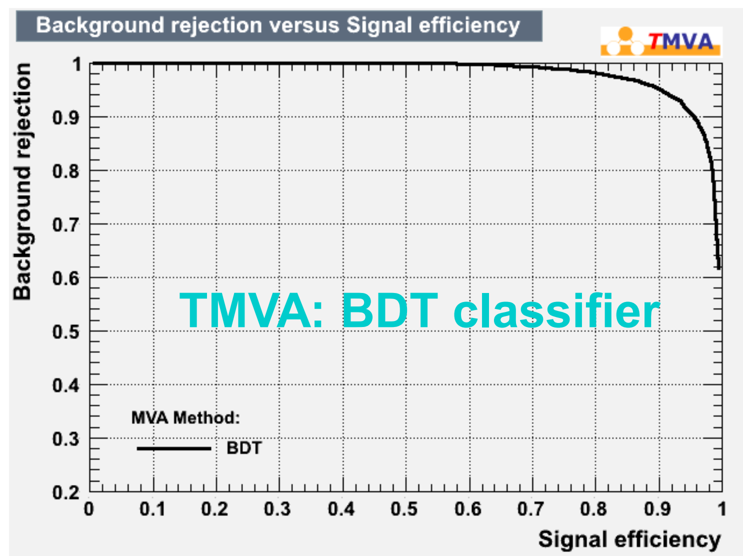
MVA performance (1.4 TeV)





$BDT_{cut} > 0.072$

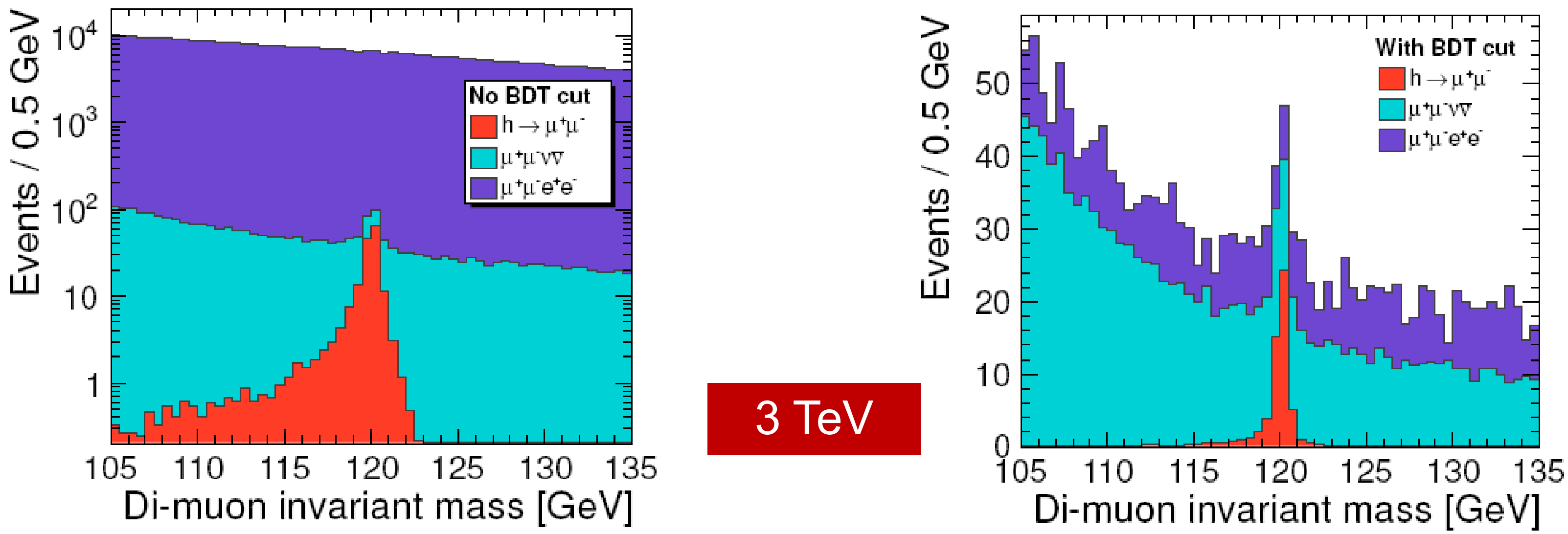


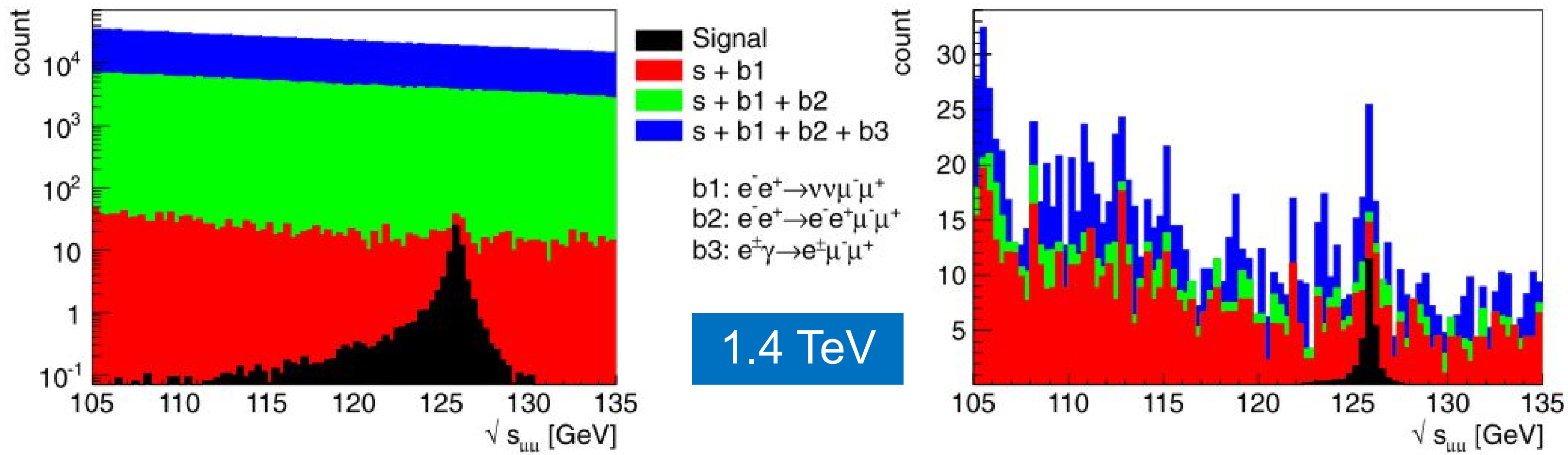


TMVA: BDT classifier

Minimal relative statistical error $(\sigma_{BR}/BR) \Leftrightarrow$ maximization of significance or $Pur{\cdot}Eff$

Reduction of the dominant $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ background by factor 1000

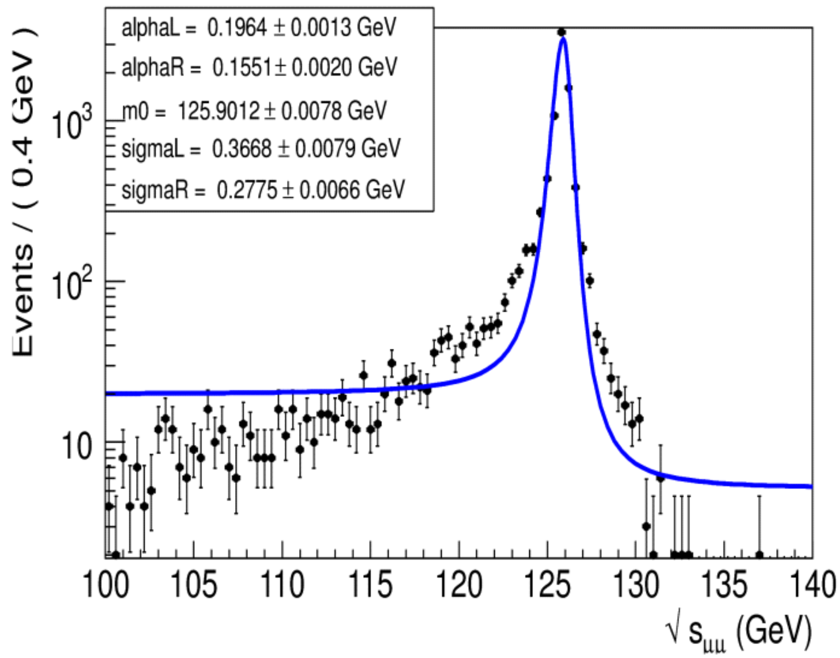




Di-muon invariant mass fit and BR extraction

Signal PDFs

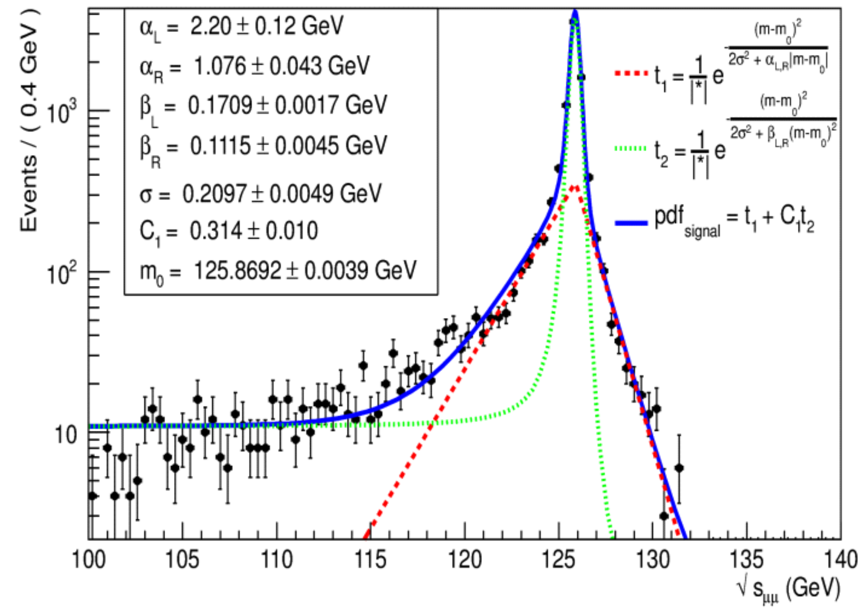
3 TeV



Double-sided Gaussian

5 parameters

1.4 TeV



Composite Gaussian: exp. tail + flat tail

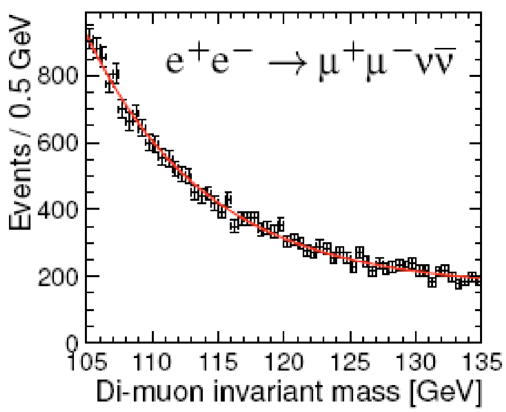
7 parameters

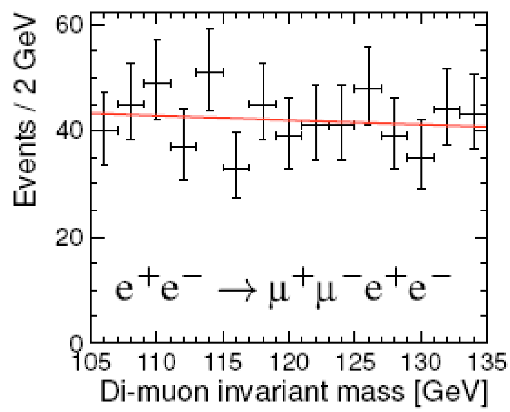
Di-muon invariant mass fit and BR extraction

Background PDFs

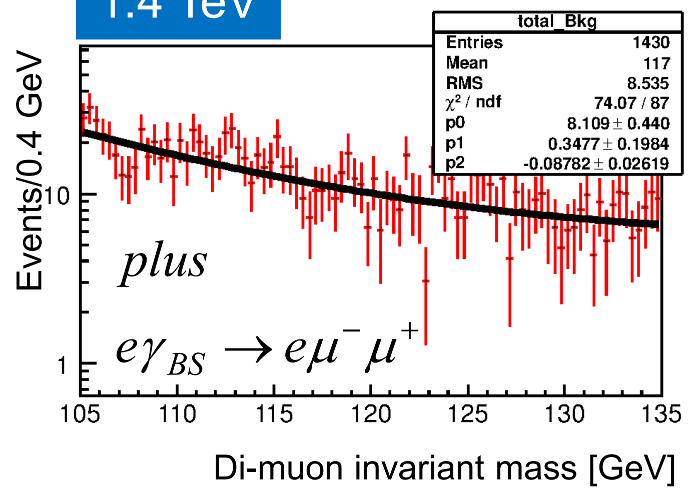
3 TeV

$$f(x) = r\, n_0\, e^{\lambda x} + (1-r)\, n_0$$





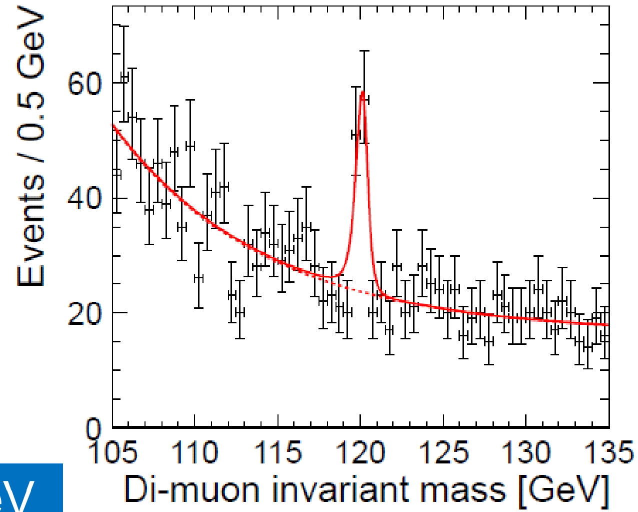
1.4 TeV

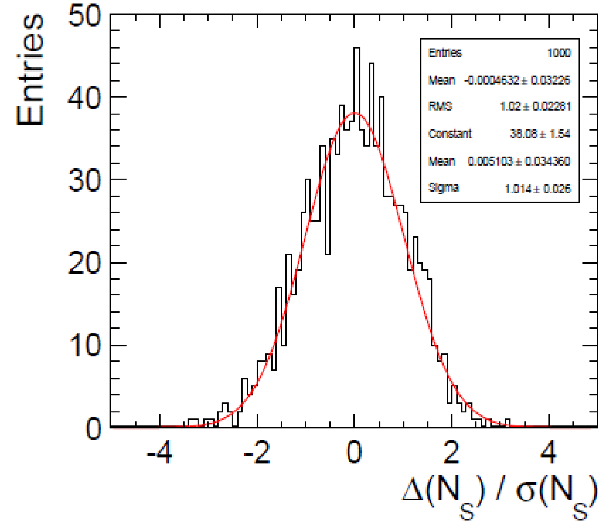


- Expected shape of data (signal + background) is for each Toy MC fitted with $f = k \cdot f_S + (1-k) \cdot f_{BDK} \Rightarrow N_S = k \cdot \int f\, dm$, integration range *105-135 GeV*
- Make N_s and pull distributions to estimate N_S uncertainties and proves the shape descriptions with PDFs

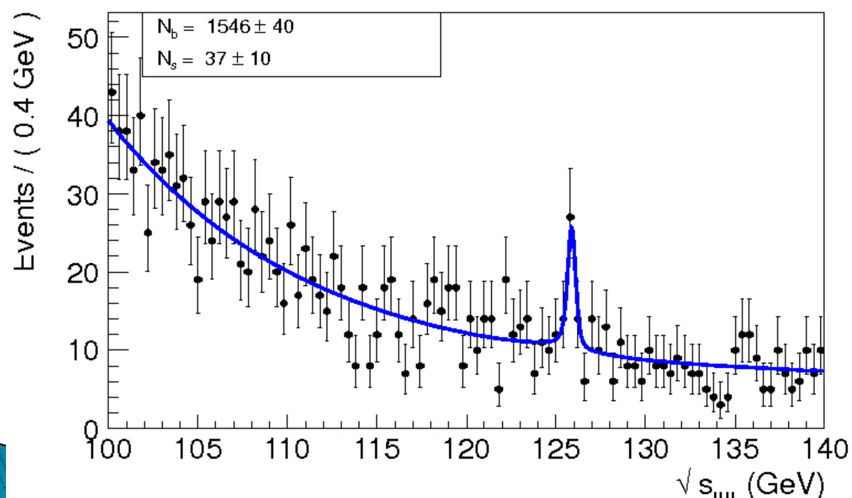
Toy MC experiments

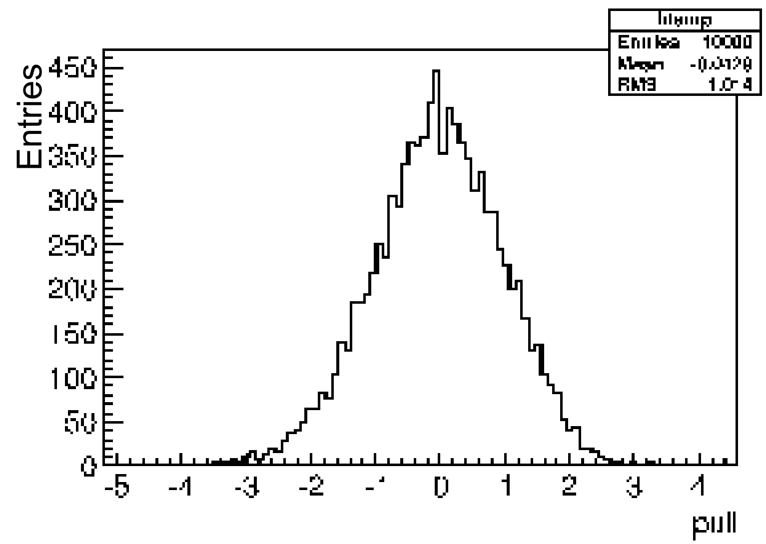
3 TeV





1.4 TeV





Results

3 TeV	$h \to \mu\mu$
Signal events	53±14
Signal efficiency	21.7%
$\sigma_{h\nu\nu} x BR_{h \to \mu\mu}$	0.121fb
Stat. uncertainty	26.3%

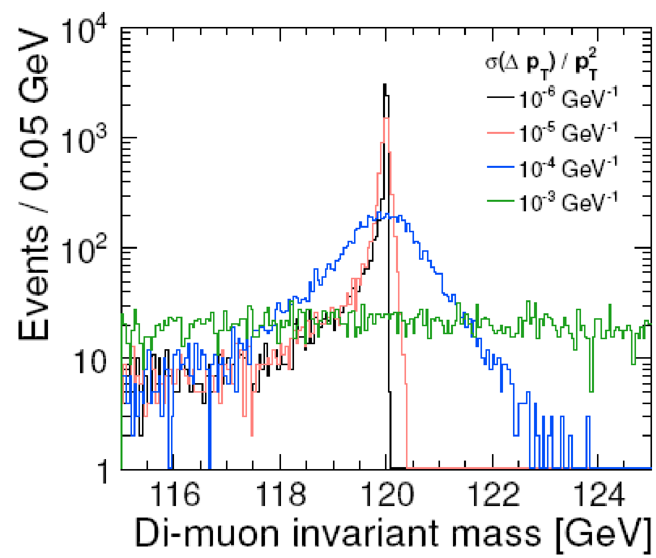
1.4 TeV	$h \to \mu\mu$
Signal events	34±10
Signal efficiency	43.0%
$\sigma_{h\nu\nu} x BR_{h \to \mu\mu}$	0.052fb
Stat. uncertainty	30.0%

Impact of momentum resolution and forward electron tagging

	LumiCalCut$_{95}$	LumiCalCut$_{99}$	BeamCalCut$_{30}$	BeamCalCut$_{70}$
Signal events	120 ± 17	127 ± 18	130 ± 18	132 ± 18
Signal efficiency	49.3%	53.2%	55.1%	55.9%
$\sigma_{h\nu_e\bar{\nu}_e} \times BR_{h\to\mu^+\mu^-}$	0.121 fb	0.119 fb	0.118 fb	0.118 fb
Stat. uncertainty **23.3%→**	15.0%	14.3%	14.1%	13.8%

- *$BR(h\to\mu^+\mu^-)$* tests excellent momentum resolution
- Forward region calorimetry plays important role to veto electron spectators from 4-f processes

$\sigma(\Delta p_T)/p_T^2$	$\sigma(\Delta M(\mu\mu))$	Stat. uncertainty
10^{-3} GeV^{-1}	6.5 GeV	-
10^{-4} GeV^{-1}	0.70 GeV	34.3%
10^{-5} GeV^{-1}	0.068 GeV	18.2%
10^{-6} GeV^{-1}	0.022 GeV	16.0%



Conclusions

- There is strong motivation in physics BSM in BR measurement of the rare $h \rightarrow \mu^+\mu^-$ decay at CLIC.

- The measurement itself tests excellent muon identification and momentum resolution of the detector.

- It has been shown that $BR(h \rightarrow \mu^+\mu^-)$ can be measured with a statistical accuracy $\leq$ 30%, at both 1.4 and 3 TeV CLIC assuming 4 years of operation.

- Systematic uncertainties are estimated to be negligible compared to the statistical uncertainty.

Additional material

Event samples and x-sections

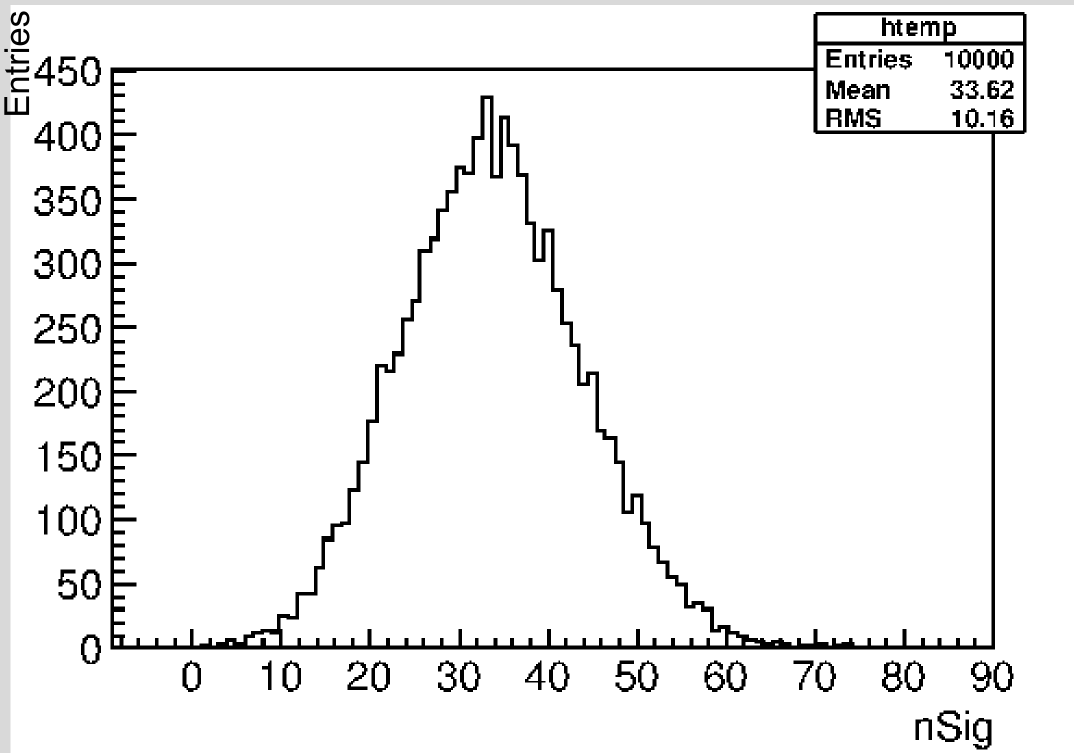
Process **3 TeV**	σ [fb]	N_{events}	Short label
$e^+e^- \to h\nu_e\bar{\nu}_e;\ h \to \mu^+\mu^-$ (signal)	0.120	21000	$h \to \mu^+\mu^-$
$e^+e^- \to \mu^+\mu^-\nu\bar{\nu}$	132	5000000	$\mu^+\mu^-\nu\bar{\nu}$
$e^+e^- \to \mu^+\mu^-e^+e^-$	346[A]	1350000	$\mu^+\mu^-e^+e^-$
$e^+e^- \to \mu^+\mu^-$	12[B]	10000	$\mu^+\mu^-$
$e^+e^- \to \tau^+\tau^-$	250	100000	$\tau^+\tau^-$
$e^+e^- \to \tau^+\tau^-\nu\bar{\nu}$	125	100000	$\tau^+\tau^-\nu\bar{\nu}$
$\gamma\gamma \to \mu^+\mu^-$ (generator level only)	20000[B]	1000000	$\gamma\gamma \to \mu^+\mu^-$

[A] Including a cut of $100\,\mathrm{GeV} < M(\mu\mu) < 140\,\mathrm{GeV}$ and requiring a minimum polar angle for both muons of 8°.
[B] Including a cut of $100\,\mathrm{GeV} < M(\mu\mu) < 140\,\mathrm{GeV}$.

Process **1.4 TeV**	σ[fb]	N_{events}	Short label
$e^+e^- \to h\nu_e\bar{\nu}_e; h \to \mu^+\mu^-$ (signal)	0.0522	24000	$h \to \mu^+\mu^-$
$e^+e^- \to \mu^+\mu^-\nu\bar{\nu}$	129	236000	$\mu^+\mu^-\nu\bar{\nu}$
$e^+e^- \to \mu^+\mu^-e^+e^-$	431[A]	1000000	$\mu^+\mu^-e^+e^-$
$e^\pm\gamma \to e^\pm\mu^+\mu^-$	1280(x2) [A]	2000000	$e^\pm\mu^+\mu^-$

[A] Including a cut of $100GeV < M(\mu^+\mu^-) < 140GeV$ and requiring a minimum polar angle for both muons of 8°.

Toy MC signal (1.4 TeV)



σ_{BR} relative statistical error vs. BDT_{cut}