Physics with muon collider

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Muon based Colliders

- A $\mu^+\mu^-$ collider offers an ideal technology to extend lepton high energy frontier in the multi-TeV range:
  - No synchrotron radiation (limit of e^+e^- circular colliders)
  - No beamstrahlung (limit of e^+e^- linear colliders)
  - but muon lifetime is 2.2 μs (at rest)
- Best performances in terms of luminosity and power consumption

- Great potentiality if the technology proves its feasibility:
  - cooled muon source
  - fast acceleration
  - μ Collider
  - radiation Safety (muon decay in accelerator and detector)

The strength of a μ–beam facility lies in its richness:

- Muon rare processes
- Neutrino physics
- Higgs factory
- Multi-TeV frontier

Take 1

Get 4 !

Focus here

μ–colliders can essentially do the HE program of e^+e^- colliders with added bonus (and some limitations)

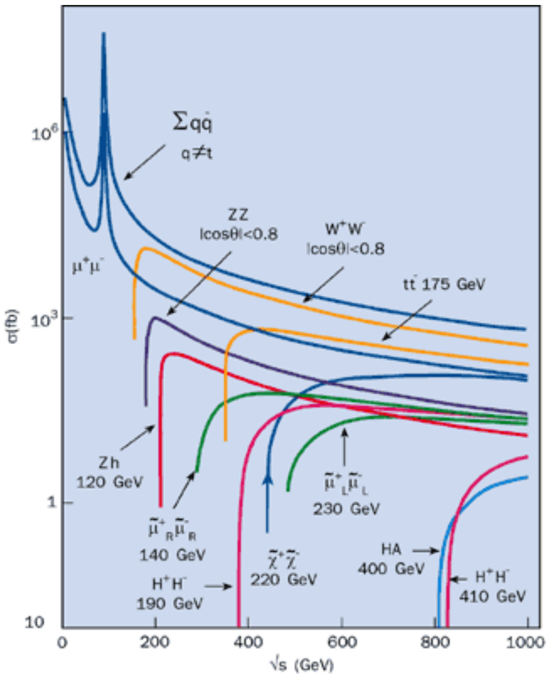
Giudice

TeV/Multi-TeV Lepton Collider Basics

- At $\sqrt{s}=M_H$ resonant Higgs production
- For $\sqrt{s}$<500GeV
  – SM threshold region: top pairs; W^+W^-; ZZ; Zh; ...
- For $\sqrt{s}$>500GeV
  – For SM pair production

R = σ/σQED($\mu^+\mu^-$ -> e^+e^-) ~ flat

  – High luminosity required



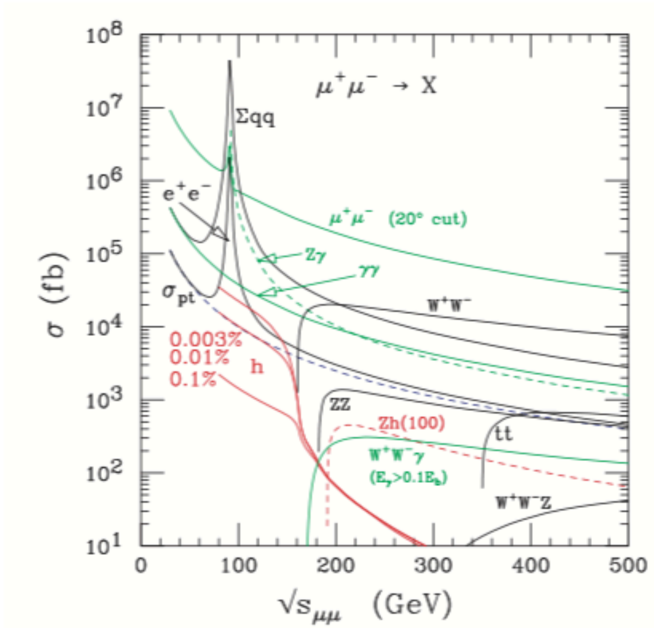
MultiTeV Lepton Collider Basics

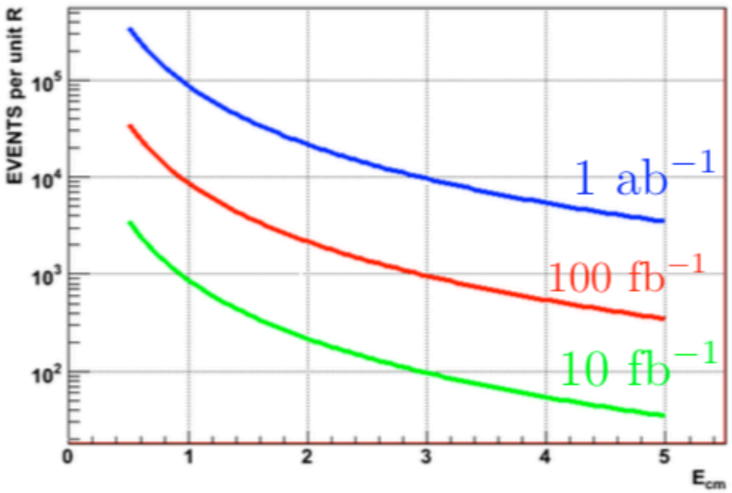
- For $\sqrt{s}$ < 500 GeV
  - SM threshold region: top pairs; W^+W^-; Z^0Z^0; Z^0h; ...
- For $\sqrt{s}$ > 500 GeV
  - For SM pair production ($|\theta|$ > 10°)

    $R = \sigma / \sigma_{QED}(\mu^+\mu^- \to e^+e^-) \sim$ flat

    $$\sigma_{\mathrm{QED}}(\mu^+\mu^- \to e^+e^-) = \frac{4\pi\alpha^2}{3s} = \frac{86.8\ \mathrm{fb}}{s(\mathrm{TeV}^2)}$$
  - High luminosity required

Standard Model Cross Sections





$$\sqrt{s} = 3.0\ \mathrm{TeV} \quad \mathcal{L} = 10^{34}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1} \to 100\ \mathrm{fb}^{-1}\mathrm{year}^{-1}$$

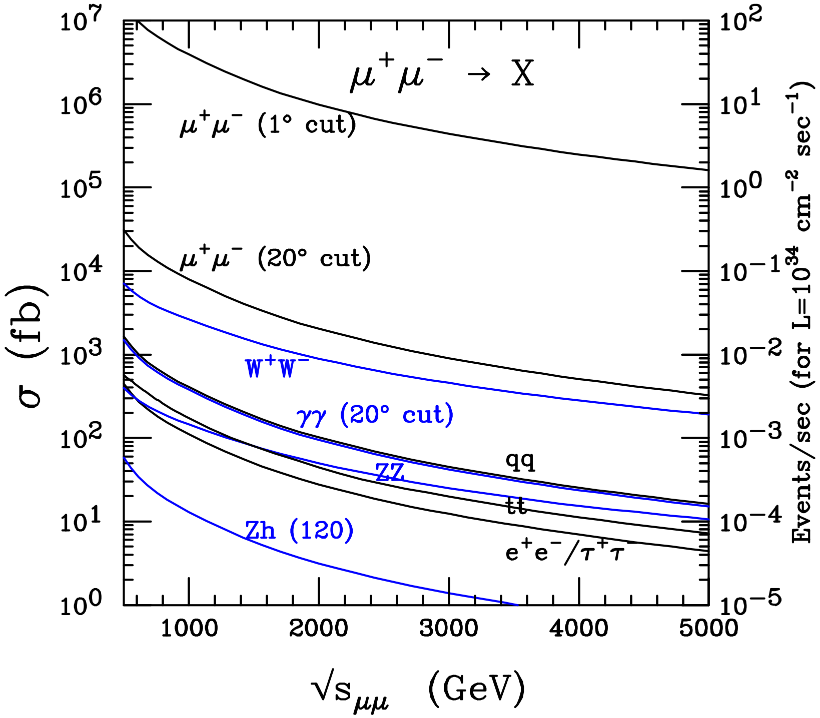
⇒ 965 events/unit of R

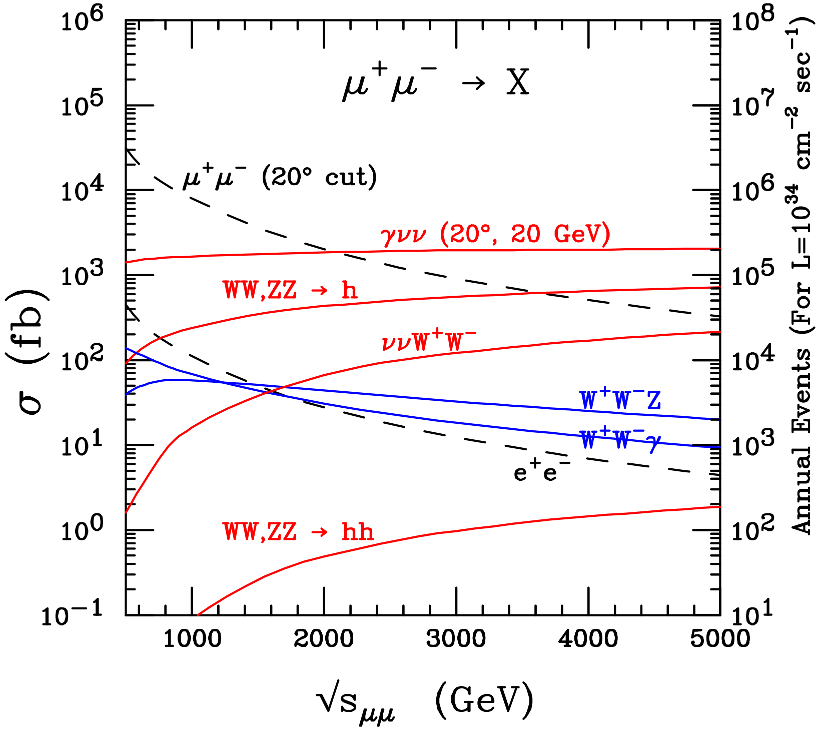
Processes with R ≥ 0.1 can be studied

Total - 540 K SM events per year

== 10^{36} $cm^{-2}\ s^{-1}$@ √s 30 TeV

SM at a muon collider:



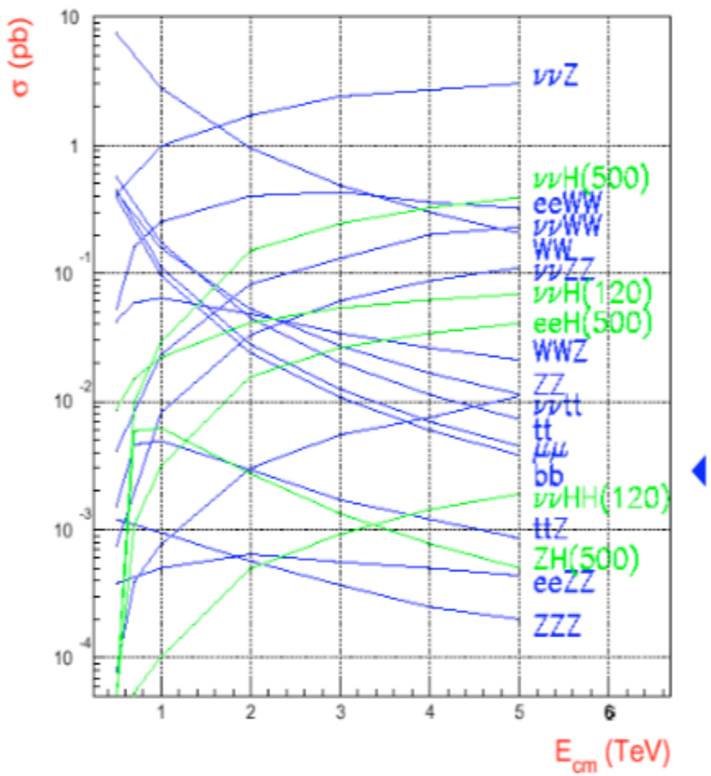


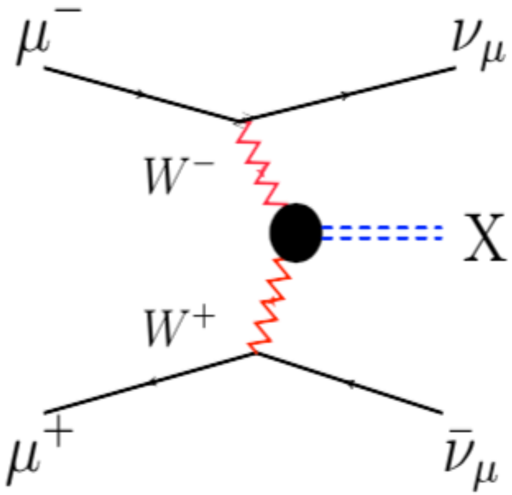
Vector boson fusion

- For $\sqrt{s} > 1$ TeV - Fusion Processes
  - Large cross sections
  - Increase with s.
  - Important at multi-Tev energies
  - $M_X^2 < s$

- Backgrounds for SUSY processes
- t-channel processes sensitive to angular cuts

CLIC (or MC e<->μ)



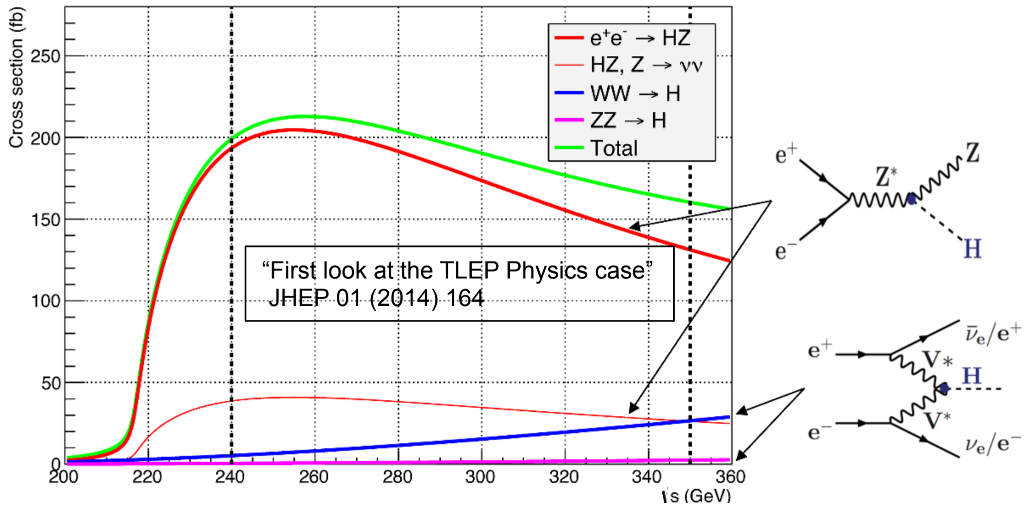


$$\sigma(s) = C \ln\left(\frac{s}{M_X^2}\right) + \ldots$$

Higgs Physics

Higgs boson production

- Muons are leptons, like electrons
  - Muon colliders can a priori do everything that e^+e^- colliders can do, e.g.:

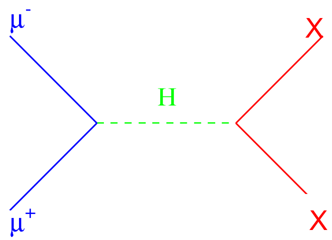


    - FCC-ee luminosity: 0.5 – 1.1 × 10^{35} $cm^{-2}s^{-1}$ / IP and up to 4 IPs
    - Muon collider luminosity: few× 10^{33} $cm^{-2}s^{-1}$ / IP
  - Precision on branching ratios, couplings, width, mass, etc. , with 2 IPs
    - A factor 10 better at FCC-ee (and twice better at ILC) than at a muon collider

SM Higgs resonance

- Resonant production

$$\sigma(\mu^+\mu^- \to H^0) = \frac{4\pi\Gamma_H^2 Br(H^0 \to \mu^+\mu^-)}{(\hat{s} - M_H^2)^2 + \Gamma_H^2 M_H^2}$$



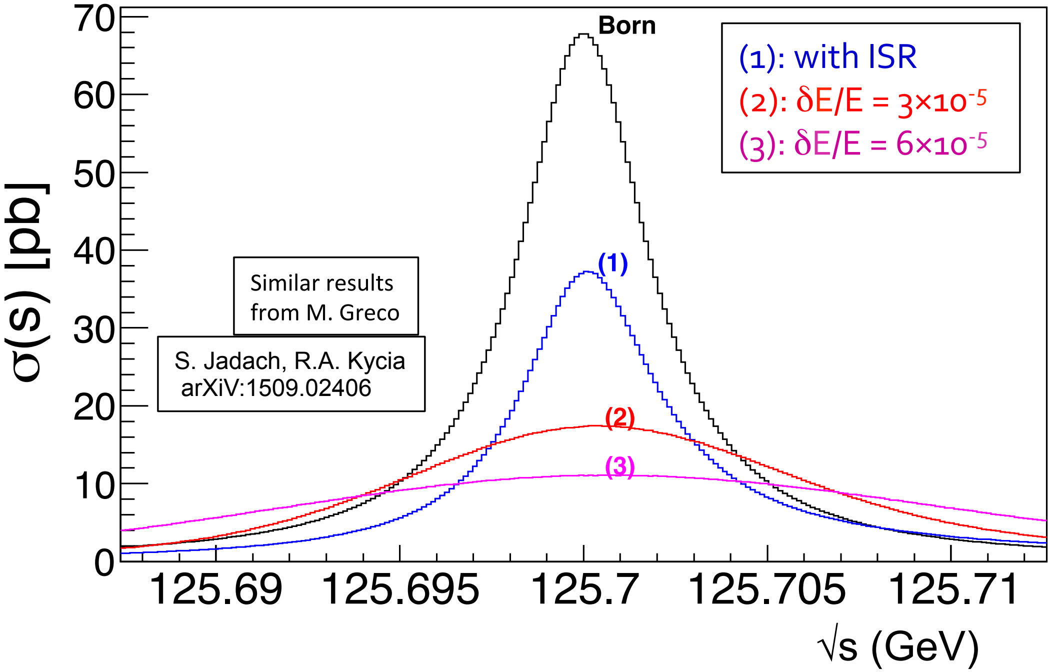
Major background:
$\mu^+\mu^- \to Z/\gamma^* \to XX$

– Convoluted with
  - Beam energy spectrum
  - Initial state radiation (ignored in most studies)

– The measurement of the lineshape gives access to
  - The Higgs mass, m_H
  - The Higgs width, Γ_H
  - The branching ratio into $\mu^+\mu^-$, BR($H \to \mu\mu$)
    – Hence, the coupling of the Higgs to the muon, $g_{H\mu\mu}$
  - Some branching fractions and couplings, with exclusive decays

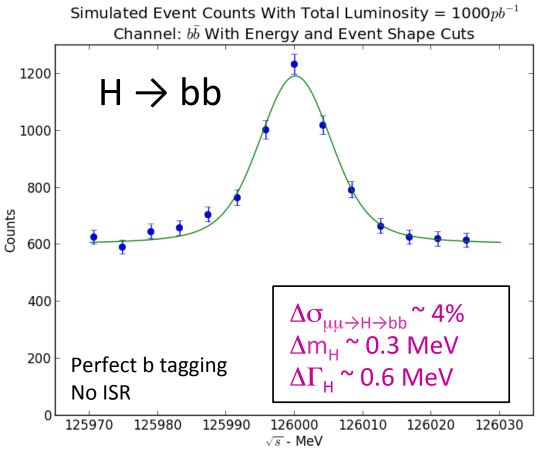
SM Higgs resonance

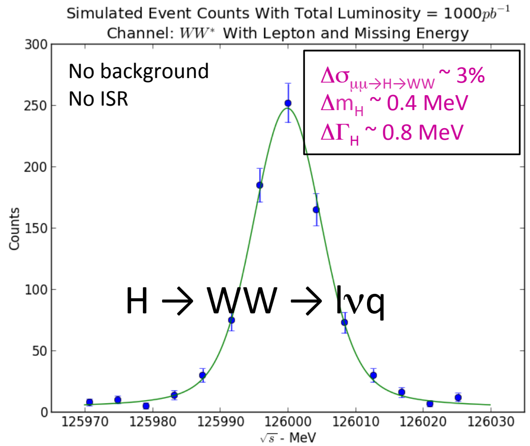
- Muons are heavy, unlike electrons: $m_\mu/m_e \sim 200$
  - Large direct coupling to the Higgs boson: $\sigma(\mu^+\mu^- \rightarrow H) \sim 40{,}000 \times \sigma(e^+e^- \rightarrow H)$
  - Much less synchrotron radiation, hence potentially superb energy definition
    - $\delta E/E$ can be reduced to 3-4 × 10^{-5} with more longitudinal cooling
      - Albeit with equivalent reduction of luminosity: 2 – 8 × 10^{31} $cm^{-2}s^{-1}$

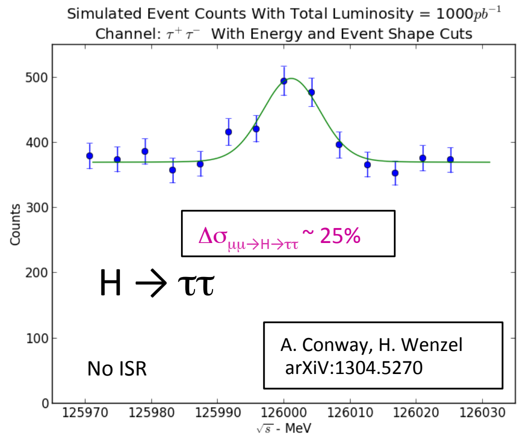


- $\sigma(\mu^+\mu^- \rightarrow H) \sim 15$ pb
  (ISR often forgotten…)
- 200 – 800 pb^{-1} / yr
- 3000 – 12000 Higgs / yr

Scan of the SM Higgs resonance







- Notes
  - Some optimism in these numbers (perfect b tag, only Z bkgd, no beam bkgd…)
  - Errors to be increased to account for ISR
  - A better scan strategy should be designed (less in the sides, more in the peak)
  - The numbers are for 5 years at low luminosity, and 1.2 year after lumi upgrade
    - Combined numbers (next slide) given for 5 (low lumi) + 5 (upgrade) years.

Possible results with 1 fb^{-1}

- Simulated results with backgrounds and cuts
  - 1 fb^{-1} = 1 yr (10^7 sec) @ $1x10^{32}$

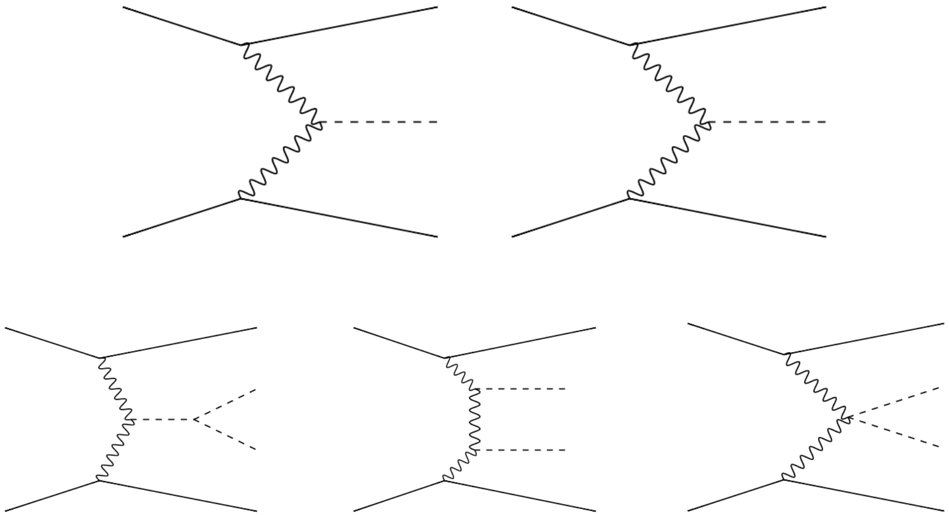
Channel		$\Gamma_{H\to X}(MeV)$	$\Delta M_H(MeV)$	$Br(H^0 \to X)$
Total	Raw	4.56 ± 1.52	0.13 ± 0.16	0.96 ± 0.04
	Cut	5.57 ± 1.33	-0.02 ± 0.14	0.65 ± 0.01
$b\bar{b}$	Raw	3.49 ± 1.83	-0.06 ± 0.19	0.67 ± 0.05
	Cut	4.78 ± 0.48	0.01 ± 0.05	0.271 ± 0.001
$WW*$	Raw	4.06 ± 0.24	0.00 ± 0.07	0.217 ± 0.001
	Cut	3.96 ± 0.17	-0.16 ± 0.04	0.1271 ± 0.0002
$\tau^+\tau^-$	Raw	4.82 ± 4.46	-0.54 ± 0.47	0.0623 ± 0.0005
	Cut	0.84 ± 2.97	1.07 ± 0.30	0.24 ± 0.23
$\gamma\gamma$	Raw	2.85 ± 5.73	-0.6 ± 0.9	0.0035 ± 0.0001
	Cut	—	—	—

YKK FNAL study
arxiv1308.2143

  - Combined:
    - $\sigma(M_H)$ ~ 0.03 MeV (<~ 100 MeV @ILC-500)
    - $\sigma(\Gamma_H)$ ~ 0.16 MeV (0.08 MeV @ILC-500)

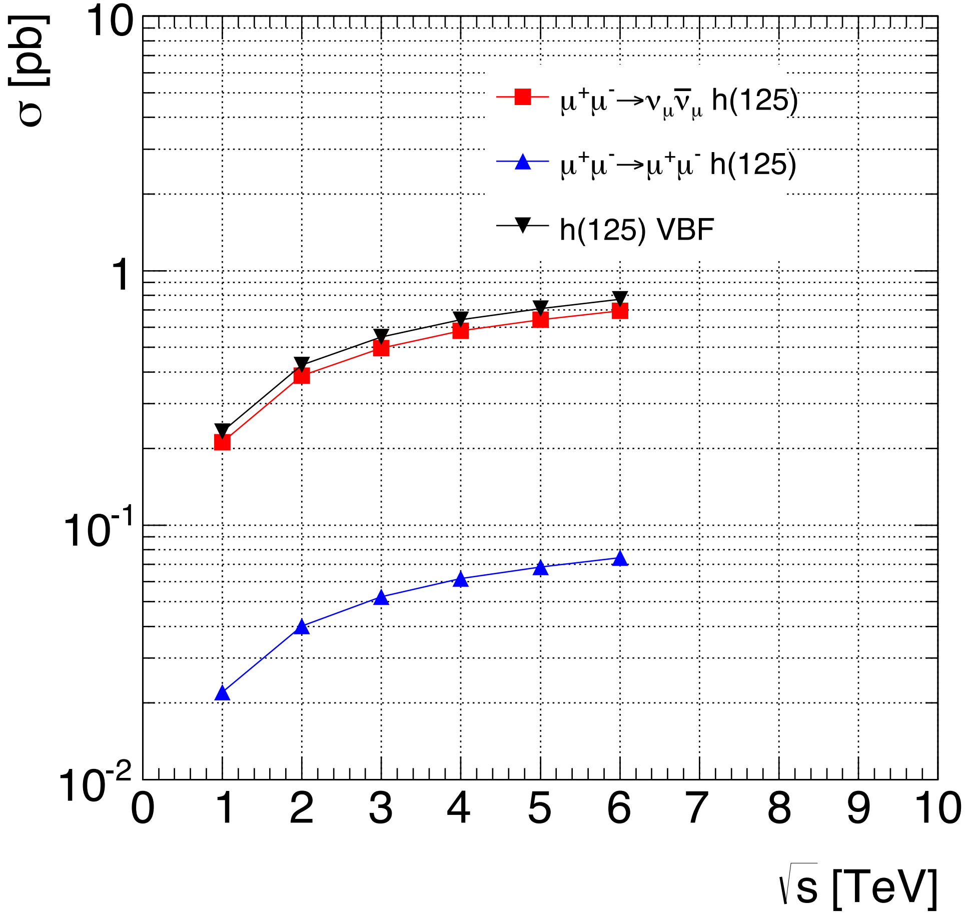
Higgs production for multiTev muon collider

– VBF dominant production mode



- WHIZARD event generator for cross section computation
  – http://whizard.hepforge.org/

VBF Higgs production



@sqrt(s) = 3 TeV

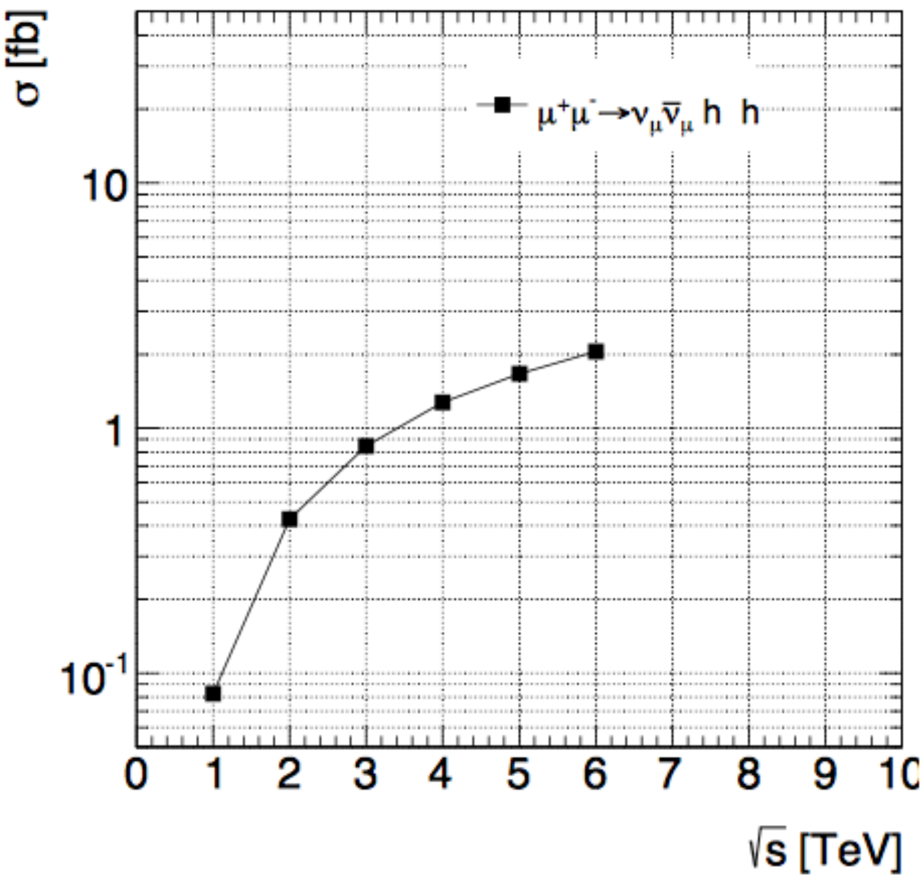
μμ->vvH : 495 fb

μμ->μμh : 52 fb

R Di Nardo, M Rotondo, G Simi

Analysis study
to be performed

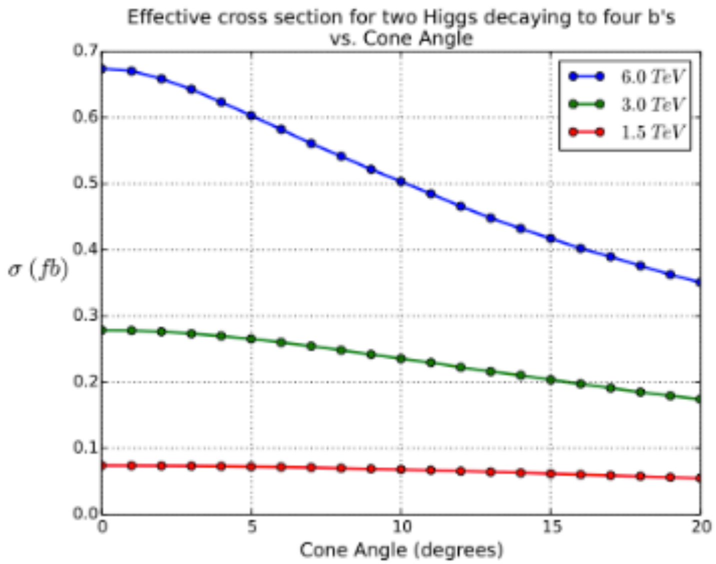
VBF HH production



@sqrt(s) = 3 TeV
μμ->vvHH : 0.9 fb

@sqrt(s) = 6 TeV
μμ->vvHH : 2.1 fb

Machine bkg limitations:
xs with 4b in det. acceptance



Not yet detailed studies

A.Conway, H.Wenzel, R.Lipton and E.Eichten,
arXiv:1405.5910

SM Higgs

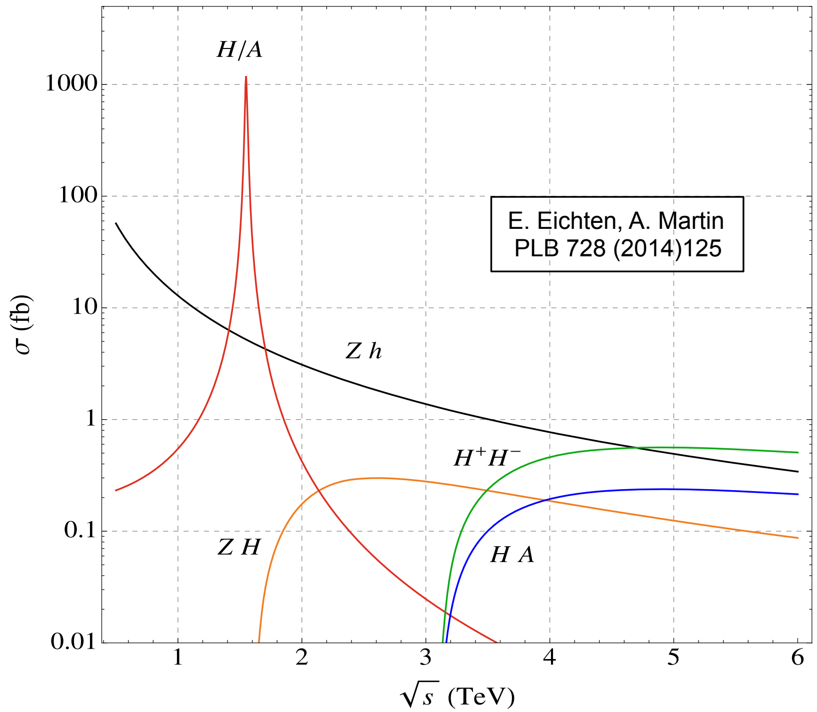
Error on	μμ resonance	ILC	FCC-ee
m_H (MeV)	0.06	30	8
Γ_H (MeV)	0.17	0.16	0.04
g_{Hbb}	2.3%	1.5%	0.4%
g_{HWW}	2.2%	0.8%	0.2%
$g_{H\tau\tau}$	5%	1.9%	0.5%
$g_{H\gamma\gamma}$	10%	7.8%	1.5%
$g_{H\mu\mu}$	2.1%	20%	6.2%
g_{HZZ}	–	0.6%	0.15%
g_{Hcc}	–	2.7%	0.7%
g_{Hgg}	–	2.3%	0.8%
BR_{invis}	–	<0.5%	<0.1%

P. Janot

- Resonant Higgs production:
  - Unique measurements of *mh* and *Γh*
  (mh ~ 0.1 MeV, *Γh* ~ 0.2 MeV)
  - Best test of 2nd generation Higgs couplings (h → $\mu+\mu-$)
- HZ production:
  - Similar to e^+e^- measurements but lower statistics factor 10 (ILC/CEPC) 100 FCC-ee
- VBF at mutiTeV
  - High xs(O(1Pb)@6TeV) & high lumi better statistics than FCC-ee ?
  - Competitive (probably best) measurement of HH production

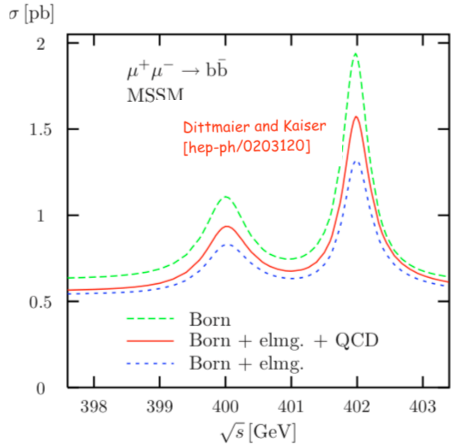
BSM Higgs Physics

BSM Higgs boson production



- Resonant H/A production
  $\mu^+\mu^- \to H,A$

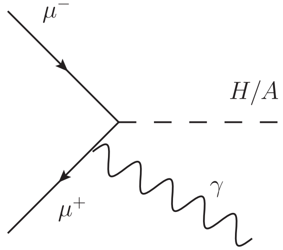
2 states separation √s<900 GeV

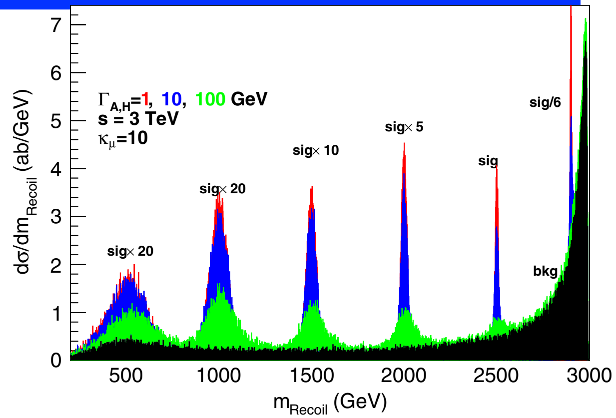


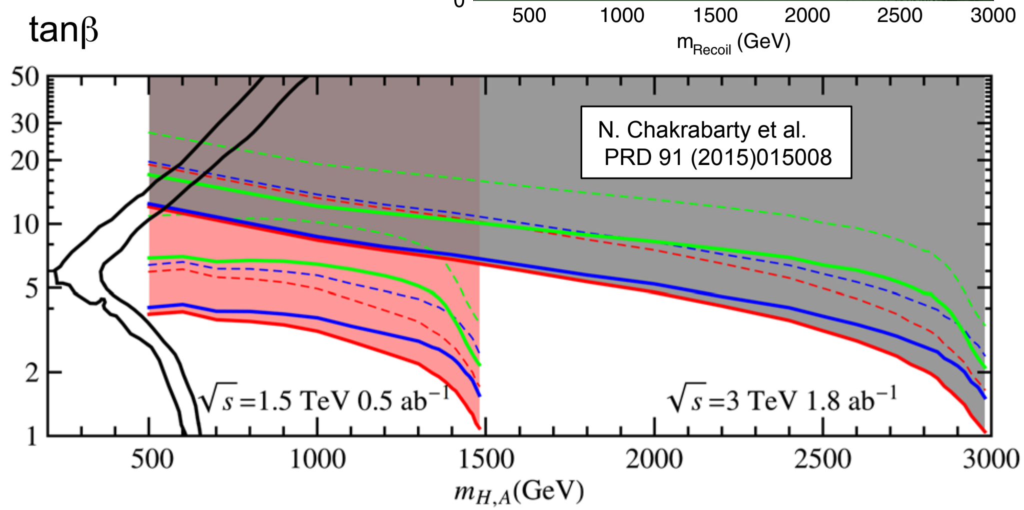
- Pair production like e^+e^-

Radiative return H/A production

- Automatic mass scan with radiative returns in μμ collisions
  - Select event with an energetic photon
    - Check the recoil mass $m_{Recoil} = [s - 2E_\gamma\sqrt{s}]^{1/2}$







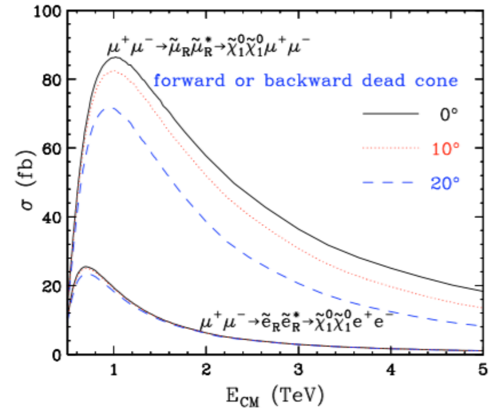
  - Can "see" H and A
    - If tanβ > 5

BSM Physics

SUSY

- $\mu^+\mu^- \rightarrow \tilde{e}_1^+\tilde{e}_1^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-$
  - Angular cut at 20° from beam direction:
    - 50% reduction for smuon pairs
    - 20% reduction for selectron pairs
  - Mass measurements using edge method better for MC than CLIC:

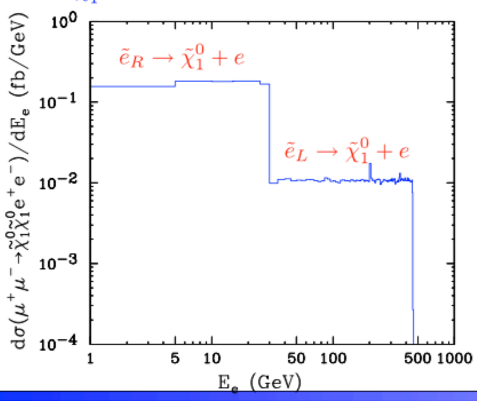
$$E_{\max/\min} = \frac{1}{2} M_{\tilde{e}} \left[1 - \frac{M^2_{\tilde{\chi}_1^0}}{M^2_{\tilde{e}}} \right] \gamma(1 \pm \beta)$$



Effect of beamstrahlung

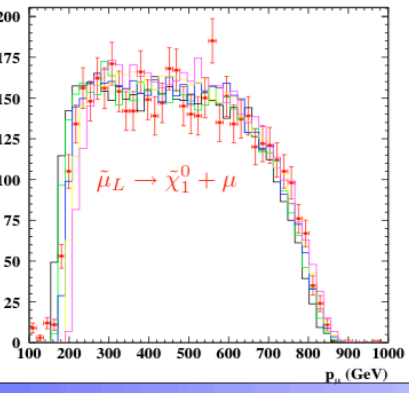
Kong, Winter (MC)

$m_{\tilde{\chi}_1^0} = 212;\ m_{\tilde{e}_R} = 222;\ m_{\tilde{e}_L} = 374$ GeV

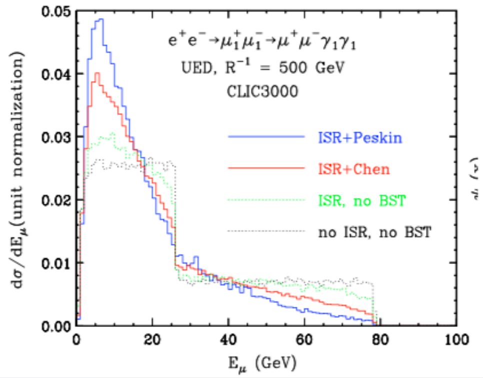


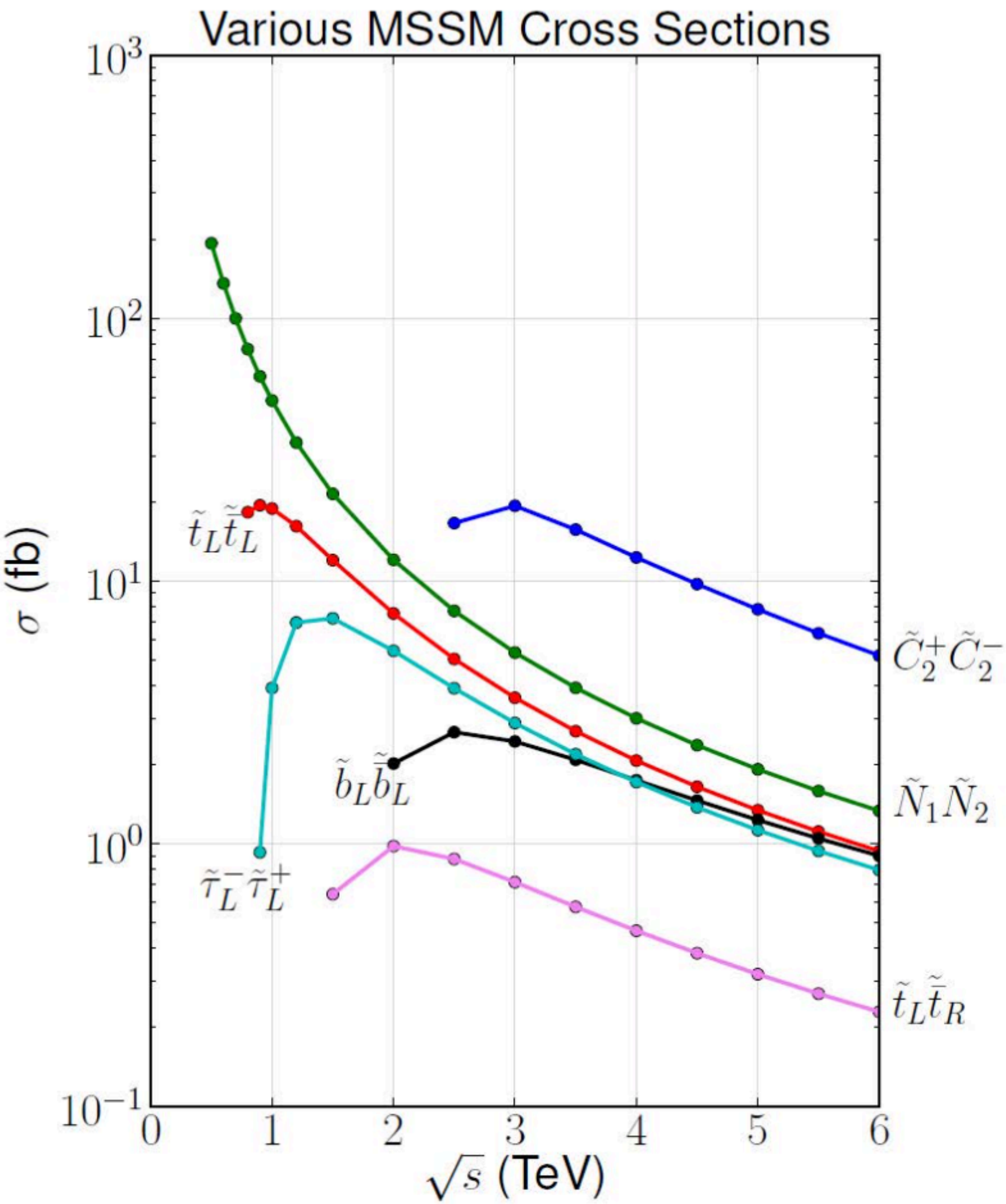
CLIC report (2004)

$m_{\tilde{\chi}_1^0} = 660$ GeV; $m_{\tilde{\mu}_L} = 1150$ GeV



Datta, Kong and Matchev [arXiv:hep-ph/0508161]





Various MSSM Cross Sections
10^3
10^2
10^1
10^0
10^{-1}
σ (fb)
0
1
2
3
4
5
6
$\sqrt{s}$ (TeV)
$\tilde{t}_L\bar{\tilde{t}}_L$
$\tilde{C}_2^+\tilde{C}_2^-$
$\tilde{b}_L\bar{\tilde{b}}_L$
$\tilde{N}_1\tilde{N}_2$
$\tilde{\tau}_L^-\tilde{\tau}_L^+$
$\tilde{t}_L\bar{\tilde{t}}_R$

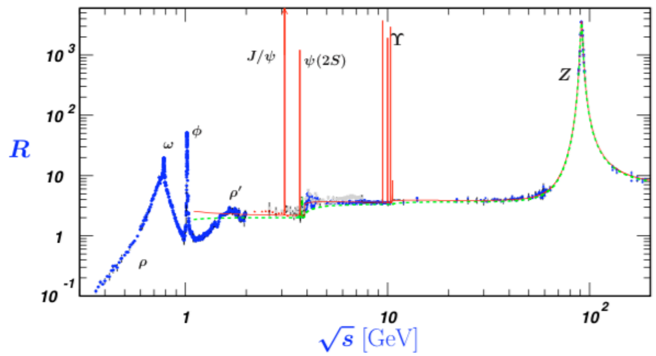
Resonances

- Universal behavior for s-channel resonance

$$\sigma(E) = \frac{2J+1}{(2S_1+1)(2S_2+1)} \frac{4\pi}{k^2} \left[\frac{\Gamma^2/4}{(E-E_0)^2+\Gamma^2/4} \right] B_{in} B_{out}$$

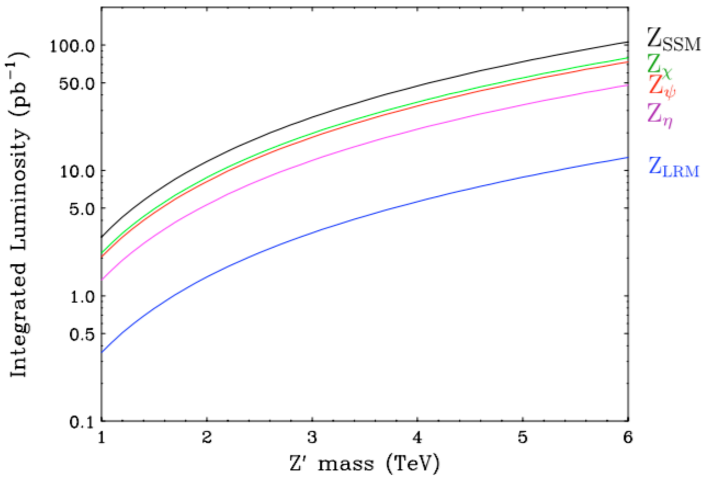
Convolute with beam resolution ΔE.
If $\Delta E \ll \Gamma$

$$R_{\text{peak}} = (2J+1) 3 \frac{B(\mu^+\mu^-) B(visible)}{\alpha^2_{\text{EM}}}$$



- Can use to set minimum required luminosity for a muon colider:
  - Likely new physics candidates:
    - scalars: h, H^0, A^0,...
    - gauge bosons: Z'
    - new dynamics: bound states
    - ED: KK modes
  - Example - new gauge boson: Z'
    - SSM, E6, LRM
    - 5σ discovery limits: 4-5 TeV at LHC (@ 300 fb^{-1})

Minimum luminosity at Z' peak:
$\mathcal{L} = 0.5\text{-}5.0 \times 10^{30}$ cm^{-2} sec^{-1}
for M(Z') -> 1.5-5.0 TeV



The integrated luminosity required to produce 1000 $\mu^+\mu^-$ -> Z' events on the peak

Strong dynamics

- Solves the Naturalness Problem: Electroweak Symmetry Breaking is generated dynamically at a nearby scale. May or may not be a light Higgs boson.

Theoretical issues

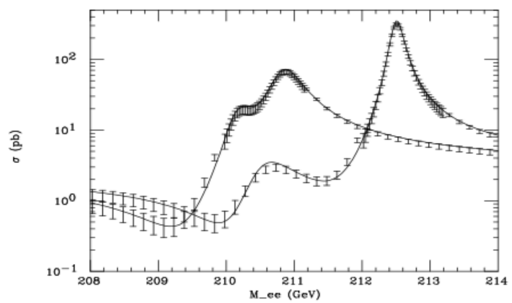
- What is the spectrum of low-lying states?
- What is the ultraviolet completion? Gauge group? Fermion representations?
- What is the energy scale of the new dynamics?
- Any new insight into quark and/or lepton flavor mixing and CP violation?
- ...

Technicolor, ETC, Walking TC, Topcolor , ...

For example with a new strong interaction at TeV scale expect:

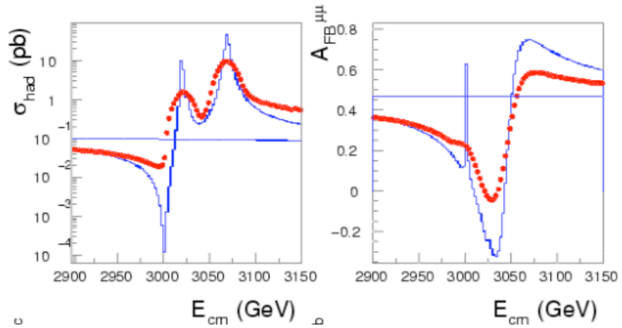
- Technipions – s channel production (Higgs like)
- Technirhos – Nearby resonances (ρ_T,ω_T)- need fine energy resolution of muon collider.

Eichten, Lane, Womersley PRL 80, 5489 (1998)
$M(\rho_T)$ = 210 GeV $M(\omega_T)$ = 211, 209 GeV
MC 40 steps (total 1 fb^{-1})



good benchmark processes

CLIC – D-BESS model (resolution 13 GeV)



Extradimensions

- Solves the Naturalness Problem: The effective GUT scale is moved closer.

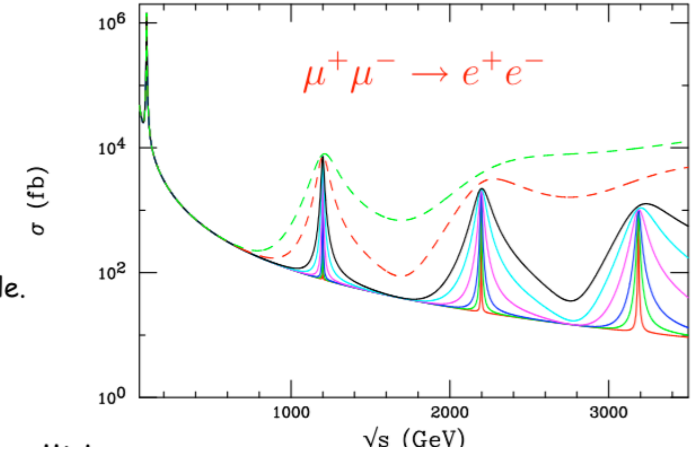
Theoretical issues

- How many dimensions?
- Which interactions (other than gravity) extend into the extra dimensions?
- At what scale does gravity become a strong interaction?
- What happens above that scale?
- ...

Randall-Sundrum model:
warped extra dimensions

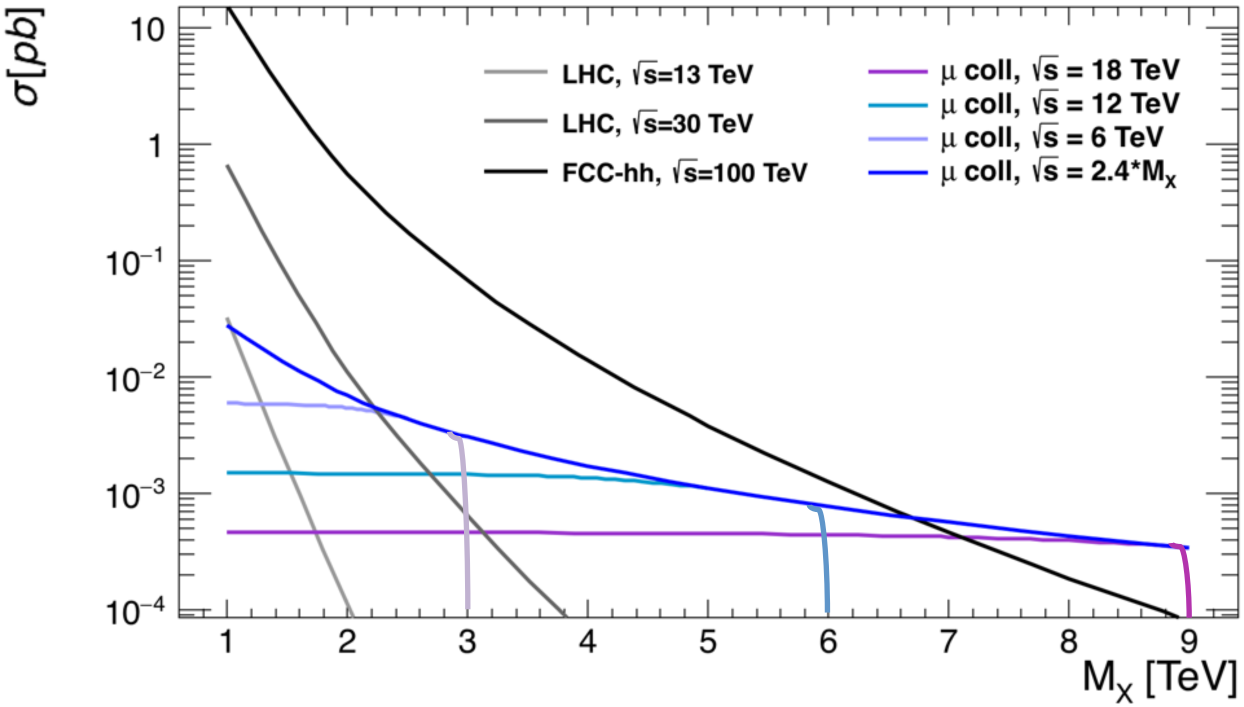
- two parameters:
  - mass scale ∝ first KK mode;
  - width ∝ 5D curvature / effective 4D Planck scale.

possible KK modes



Muon collider vs hadron collider

- Study the same benchmark used for White Paper:
  - New heavy particles, both colored and EW charged (~vector like quarks)➔ xsec can be predicted
  - FCC reach stops at M_X = 7 TeV
- Hadron machine pays the price of the exponentially falling PDF ➔ multi-TeV muon machine can be competitive!



[Wulzer]

Experimental environment

1. the luminosity and frequency of crossings are such that
pile-up will not be a problem. Situation better than LHC/CLIC/FCC-hh

2. the main background arises from $\mu \rightarrow e\nu\nu$ decays with off momentum/axis electron radiate
or hit material around the detector (low beta point is most achromatic)
10^{12} muons → 10^{9} $e^{\pm}$ produced per turn ➔ produce lots of photons and neutrons.

Shielding against these backgrounds is necessary. 10-15° cones of tungsten have been proposed
seems OK. Never worse than the background at HL-LHC! But much lower physics rates
Much work to do. Situation worse than e+e- colliders.
much reduced with the e+e- muon source option

3. luminosity measurement with $\mu\mu \rightarrow \mu\mu$ (muon equivalent to Bhabha scattering)
has to be done through this shielding (probably OK, needs to be demonstrated)

4. HF design similar to that of ILC/CLIC detectors (beam constraint is more constraining)

5. High energy collider more similar to LHC

U.S. Muon Accelerator Program

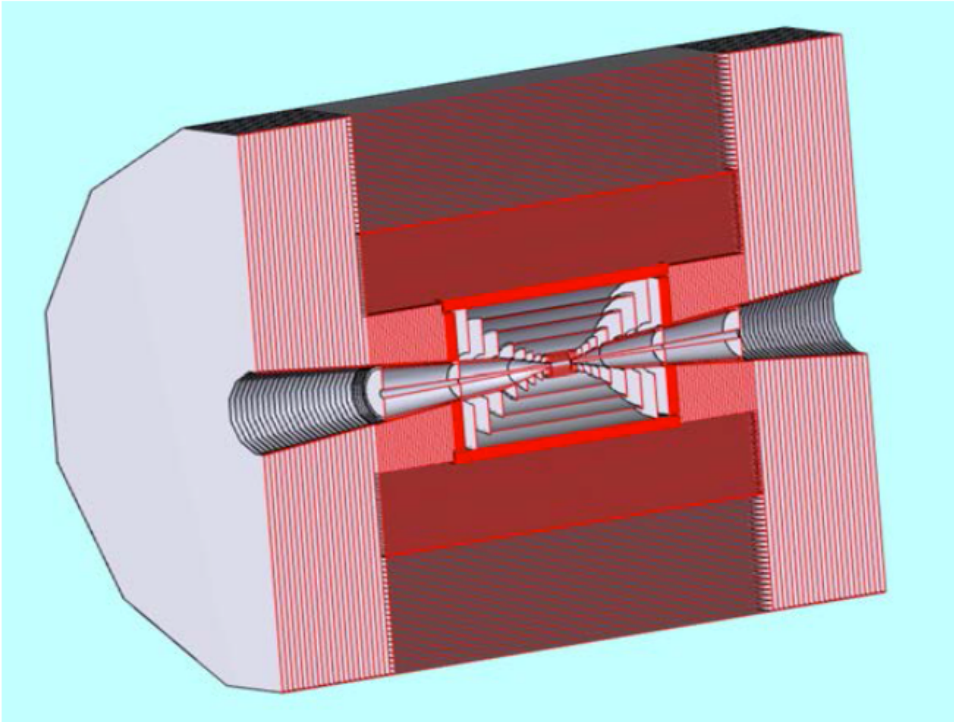
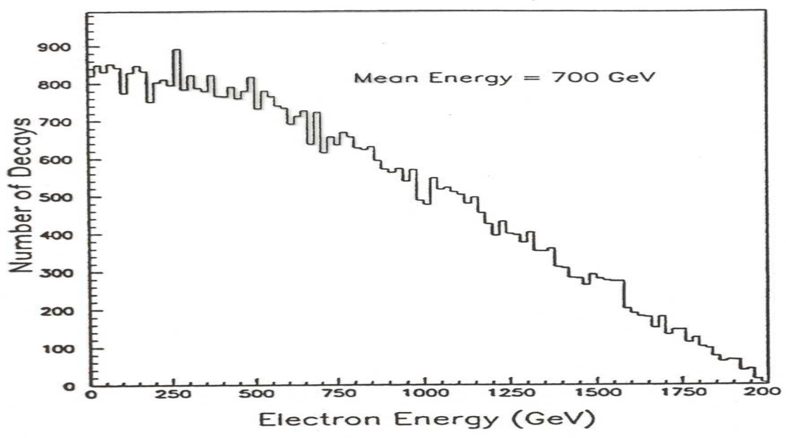


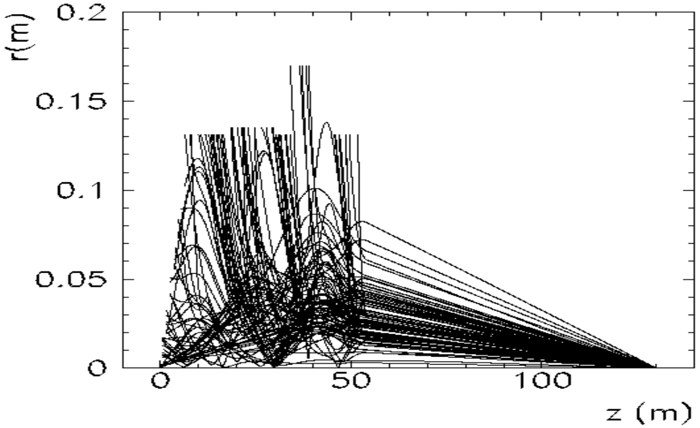
Figure 23: Cross sectional view of a possible Higgs Factory Muon Collider detector showing the tungsten cones shielding the detector from beam related backgrounds.

Background Sources

- Muon Decay Background
  - Electron Showers from high energy electrons.
  - Bremsstrahlung Radiation for decay electrons in magnetic fields.
  - Photonuclear Interactions
    - Source of hadrons background.
  - Bethe-Heitler muon production.
- Beam Halo
  - Beam Scraping at 180° from IP to reduce halo. Could it cause some?
  - Collider sources such as magnet misalignments.
- Beam-Beam Interactions.
  - Believed to be small.

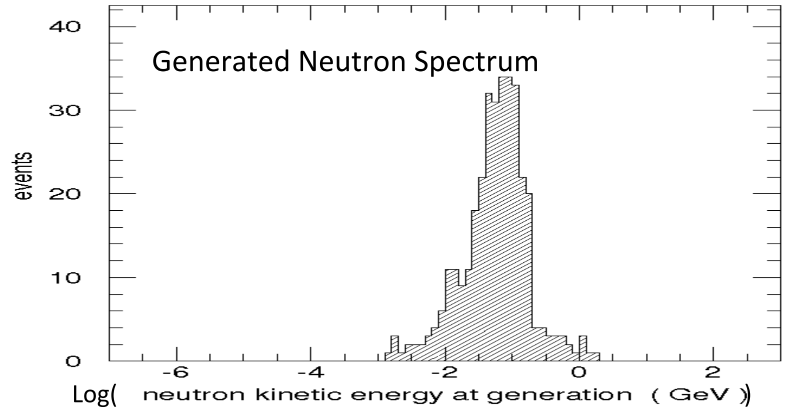
Muon Decay Background

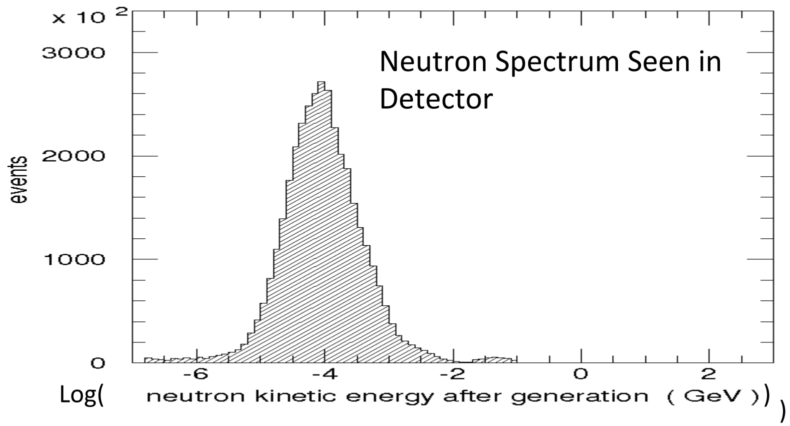


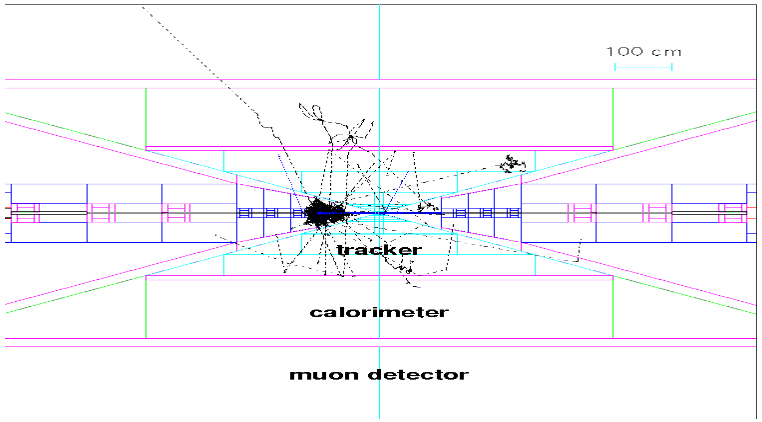


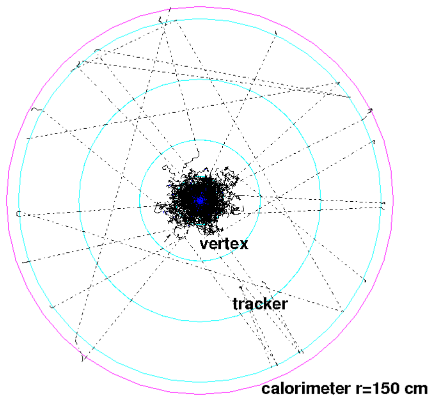
- Upper figure shows electron energy spectrum from decay of 2 TeV muons.
  - 2×10^{12} Muons/bunch in each beam
  - 2.6×10^{5} decays/meter
  - Mean Decay Electron energy = 700 GeV
- Lower figure shows trajectories of decay electrons.
  - Electron decay angles are of the order of ~10 microradians.
  - In the final focus section, the decay electrons tend to stay in the beam pipe until they see the final focus quad fields.

Neutron Background

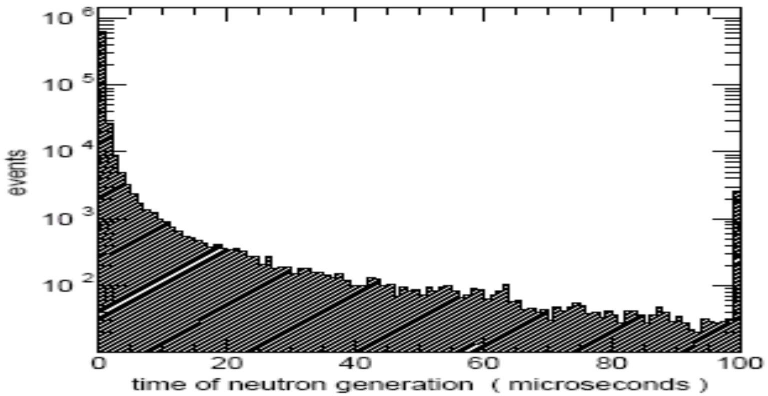


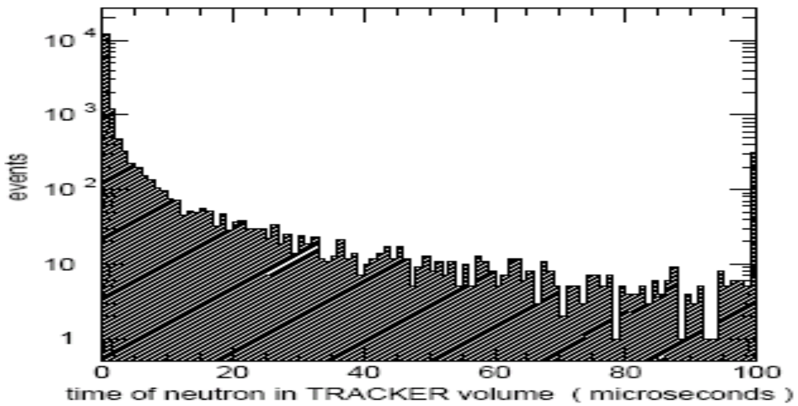






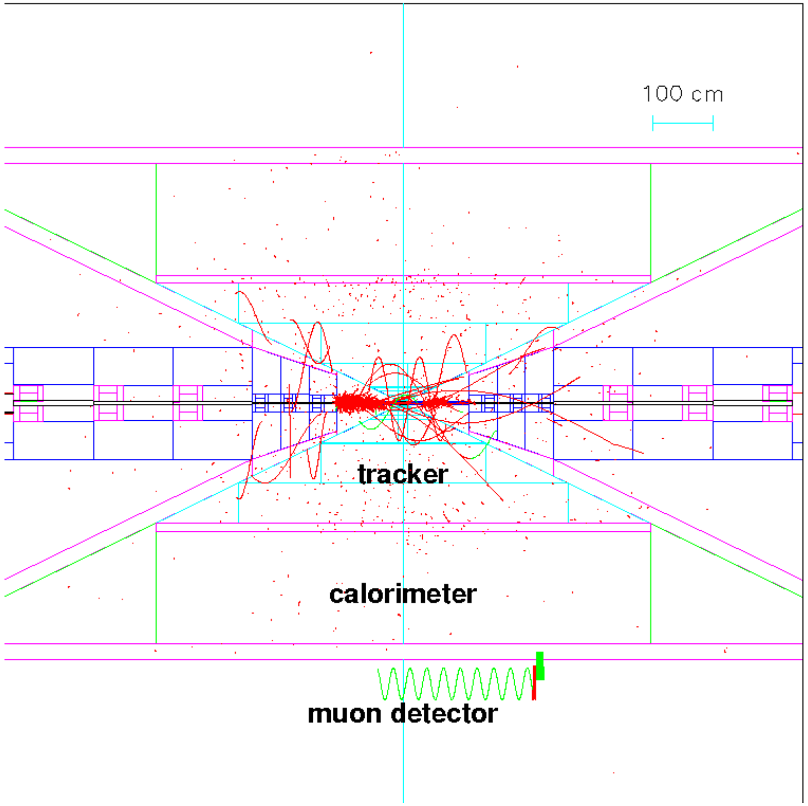
Time Distribution of Neutron Background

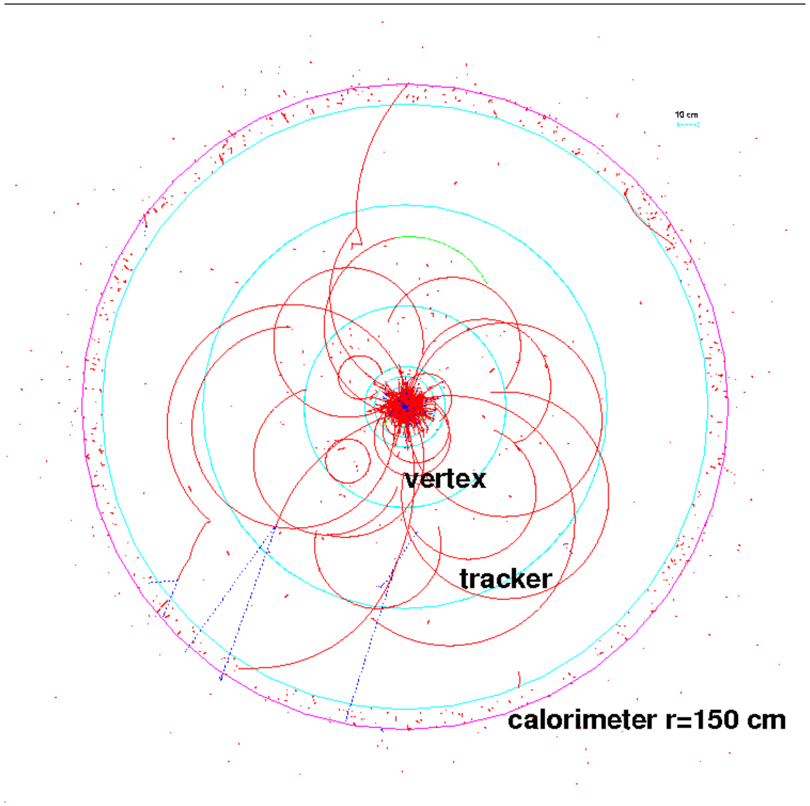




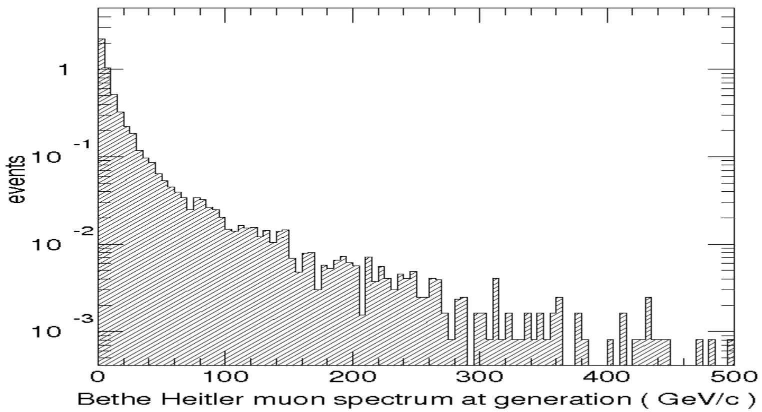
- The top distribution shows the time distribution of the neutron background generated.
- The lower distribution shows the time distribution of the neutron background that is seen in the tracker.
- The neutron flux has fallen by two orders of magnitude before the next bunch crossing (10 μs later).

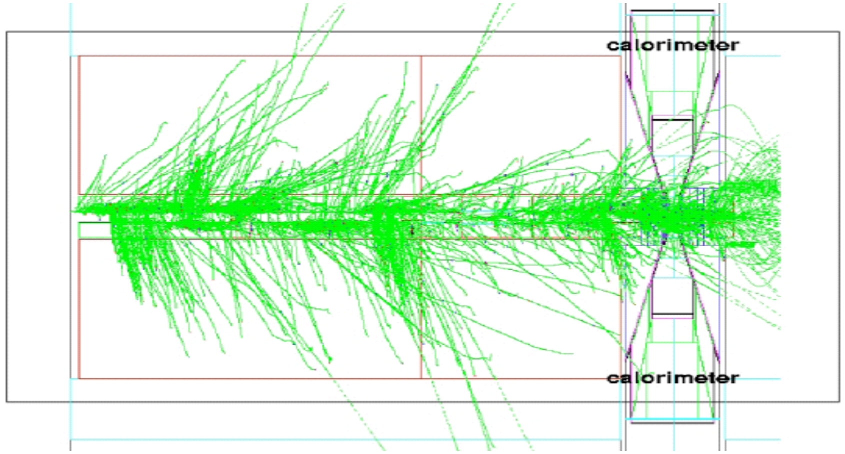
Pion Background in the Detector





Bethe-Heitler Muon Trajectories for the 2×2 TeV Collider



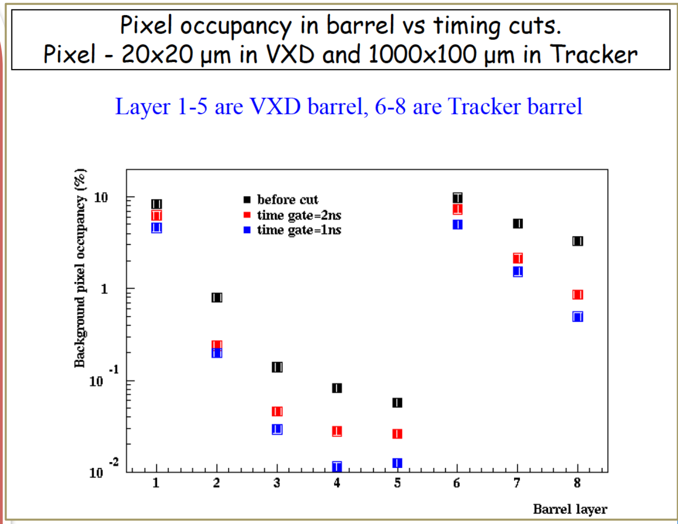


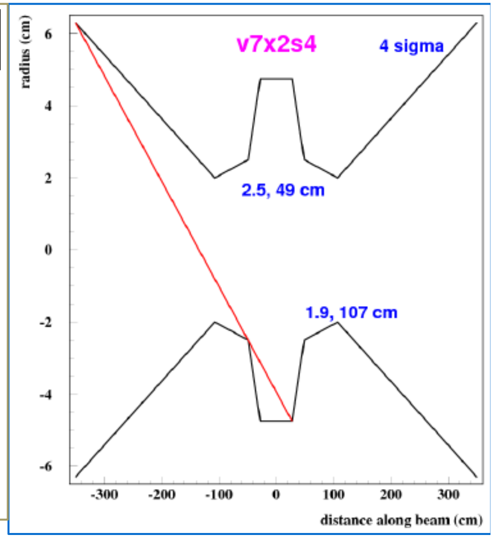
Muon pair production at beam pipe
for example
μN->$\mu\mu^{+}\mu^{-}$N
eN->e$\mu^{+}\mu^{-}$N
(electrons are more likely to hit beam pipe).

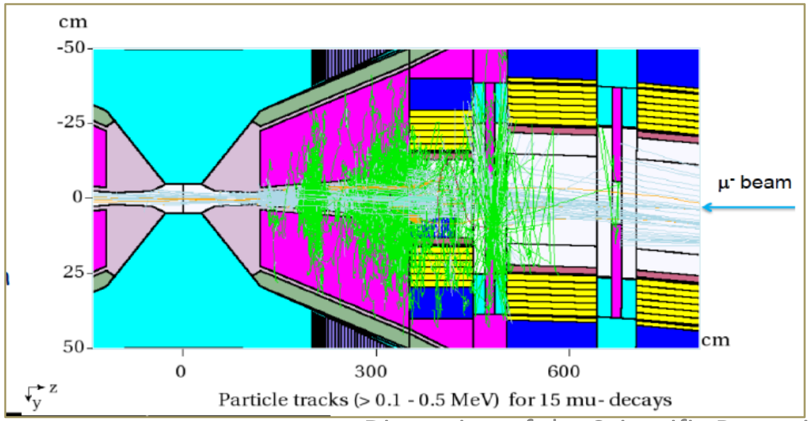
M. Palmer

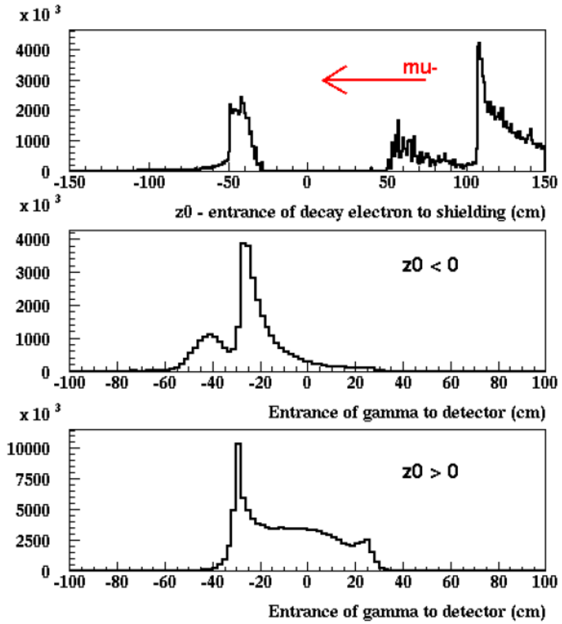
Machine Detector Interface

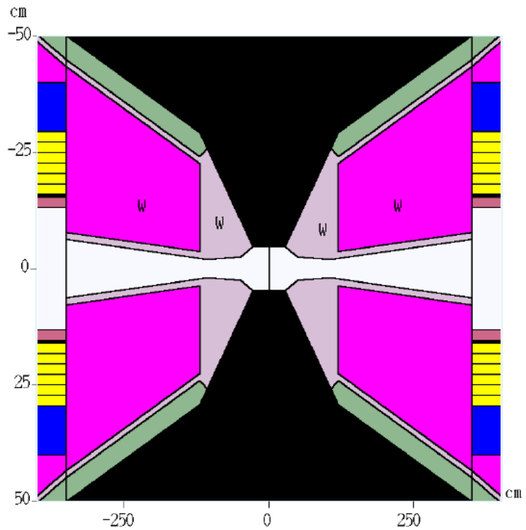
- ✓ Backgrounds appear manageable with suitable detector pixelation and timing rejection
- ✓ Recent study of hit rates comparing MARS, EGS and FLUKA appear consistent to within factors of <2
  - ⇨ Significant improvement in our confidence of detector performance











Conclusion

- Higgs Factory (~125 GeV)
  - Very precise determinations of *mh* and Γh
  - Test of Higgs μμ coupling
- Higgs physics at higher energies
  - ZH ~factor 10 in accuracy worse wrt FCCee (2 wrt ILC/CEPC)
  - Very promising H and HH σ values at MultiTeV
    (need to be studied)
- BSM physics
  - Explore very high energy frontier with pair production (provided sufficient luminosity) up to ?
  - Best for new resonances (negligible beamstrahlung, reduced ISR) additional Higgs bosons in particular
  - BSM in VBF not studied yet