Linear Colliders

J. Alcaraz
CERN/CIEMAT

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- Introduction: why do we need a LC ?
- Collider options, features, problems
- Detector requirements
- Physics

SOME ARGUMENTS

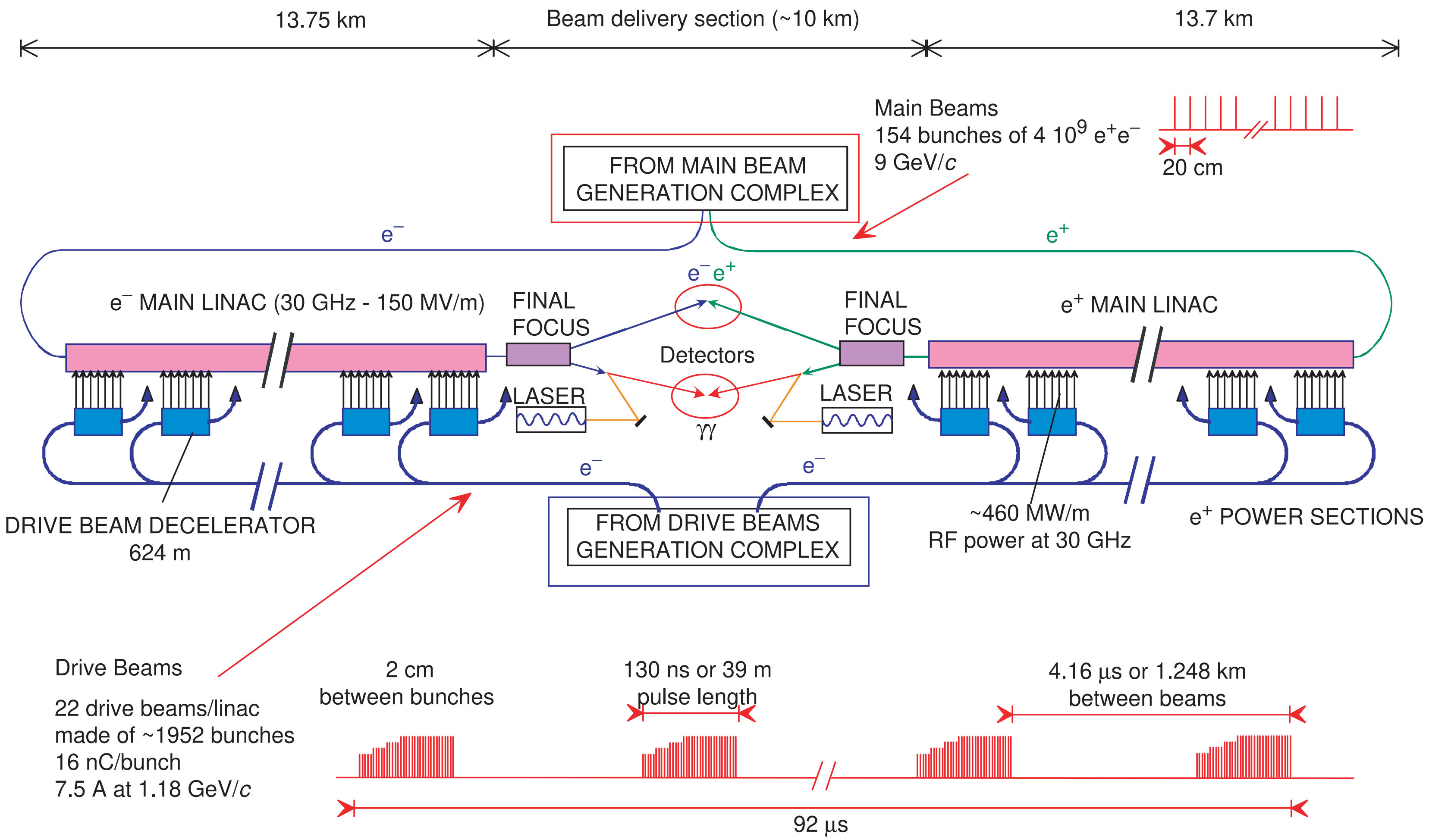
- No chance to build new e^+e^- circular machines with higher $\sqrt{s}$: ultimate acceptable limit would be $\sqrt{s} \sim 2m_t$
- Historically, e^+e^- and hadron machines have been useful and complementary in HEP
  LHC at $\sqrt{s} = 14$ TeV $\Leftrightarrow$ LC at $\sqrt{s} \simeq 2$ TeV

CERN OPTIONS AFTER LHC

1. CLIC (Compact e^+e^- Linear Collider at $\sqrt{s} \gtrsim 3$ TeV): long R&D required
2. $\mu^+\mu^-$ Collider: too long R&D required; first step: neutrino factory
3. VLHC (Very Large Hadron Collider): too costly for the time being

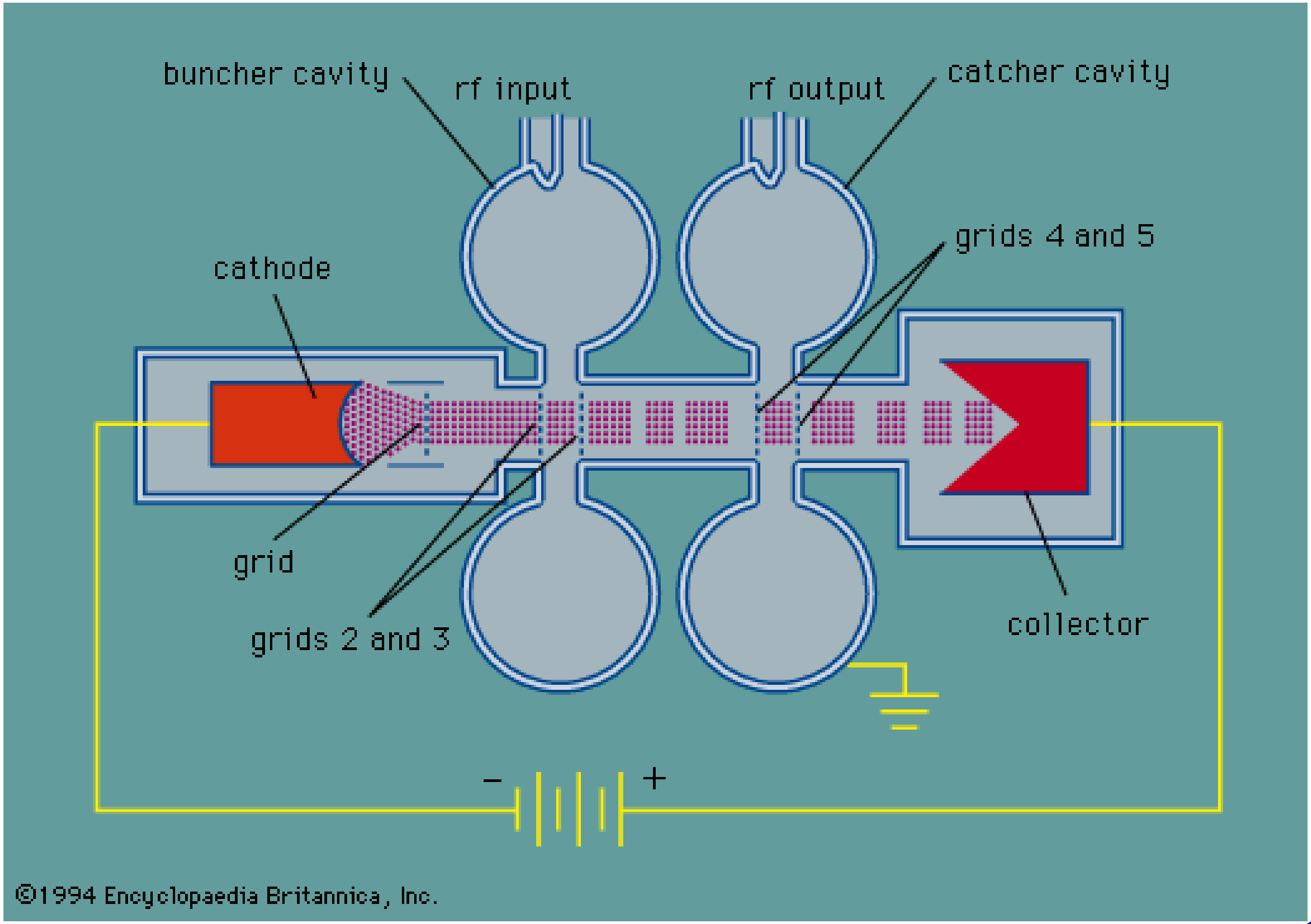
The physics case is justified (see rest of the talk)
even at $500 \text{ GeV} \lesssim \sqrt{s} \lesssim 1 \text{ TeV}$

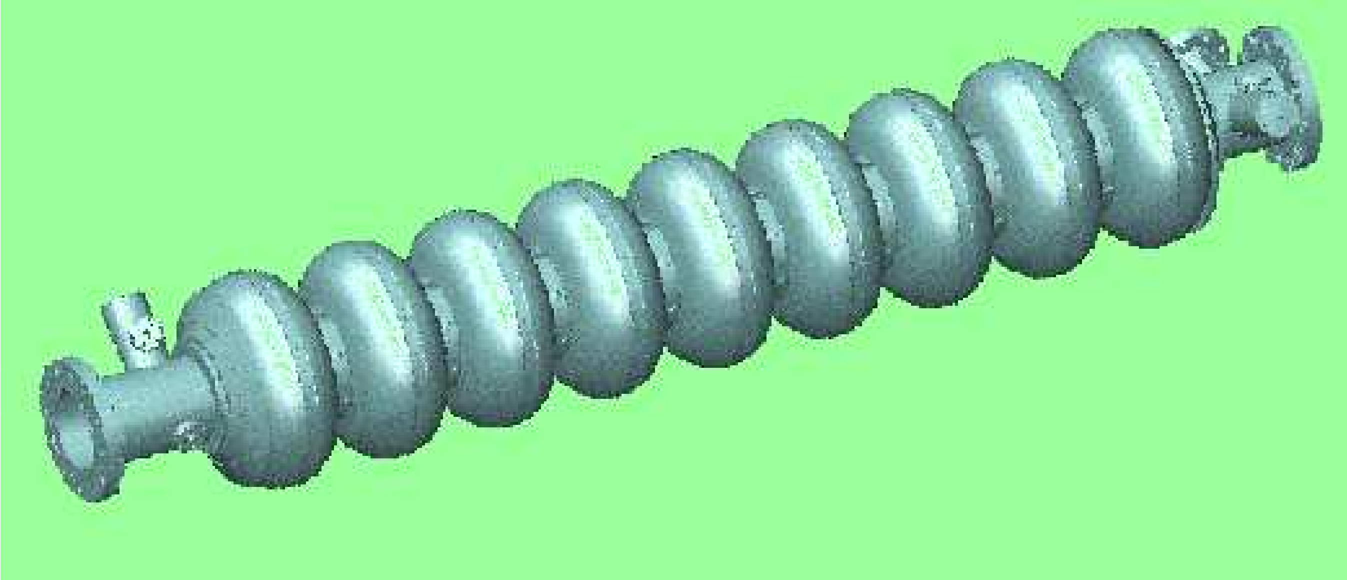
CLIC: $\sqrt{s} \gtrsim 3$ TeV in $d \sim 30$ km $\Rightarrow$ 100 MV/m

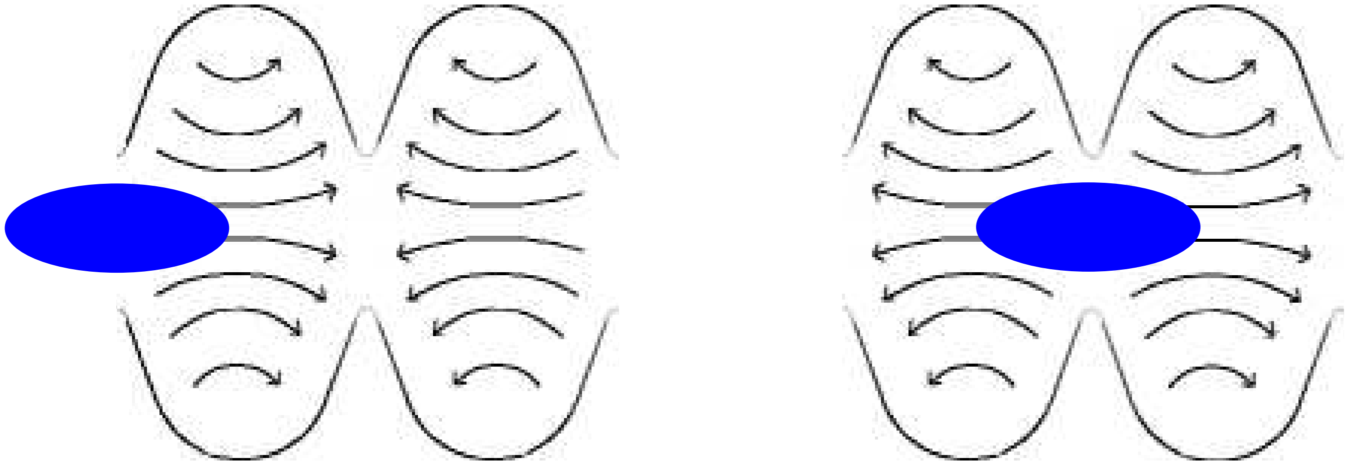


Two-beam Acceleration Technique

Acceleration Techniques: Microwave Frequency from Klystrons





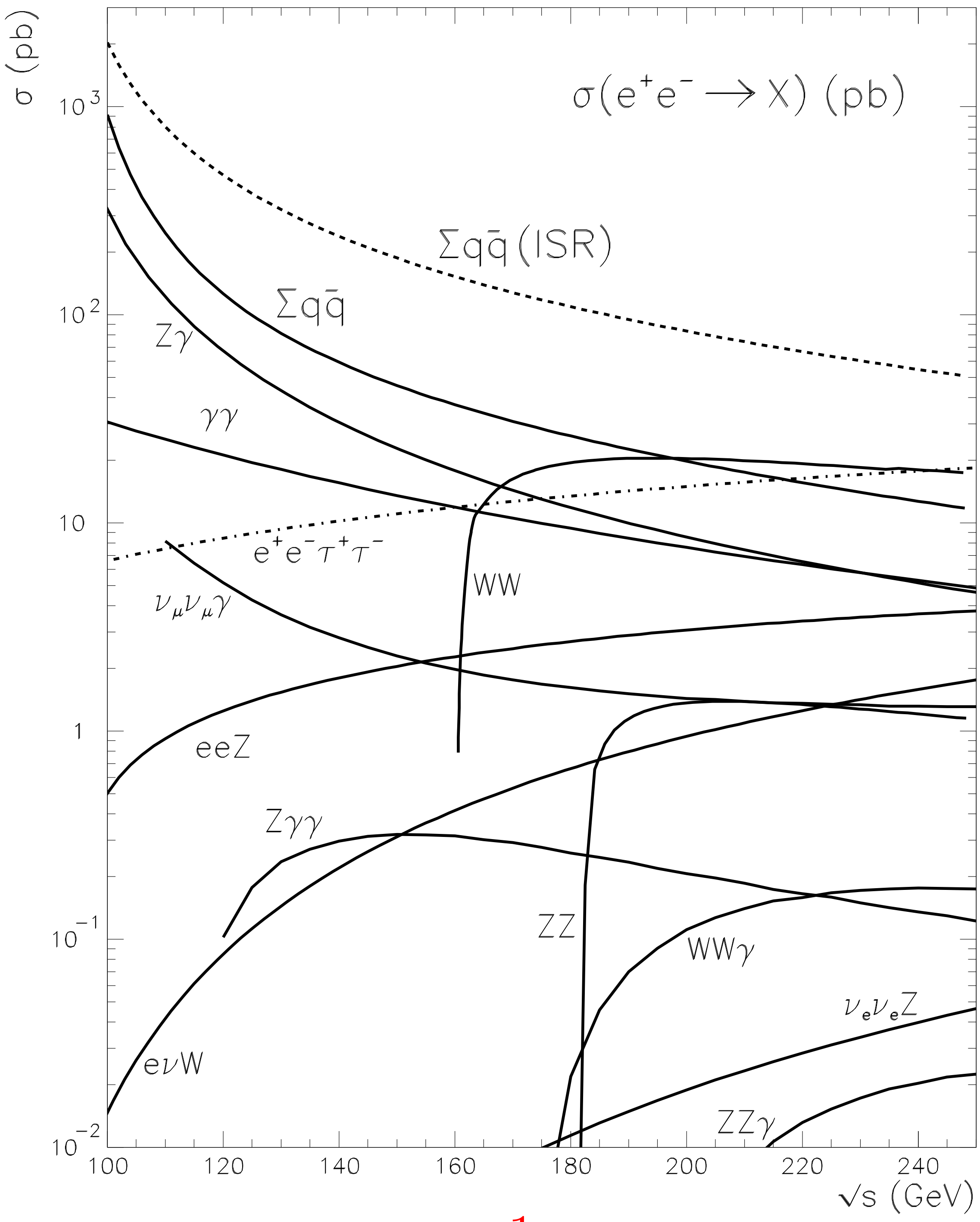


Increase Gradient $\rightarrow$ High Frequency and/or Minimal Losses

Radiofrequency Bands in Acceleration

Band	Frequency (GHz)	Accelerator
L band	1-2	TESLA (1.3 GHz)
S band	2-4	SLC (2.9 GHz)
C band	4-8	JLC C-band (5.7 GHz)
X band	8-12	NLC/JLC (11.4 GHz)
K band	12-40	CLIC (30 GHz)

- **TESLA: Low Frequency with high Energy Transfer**
  - Superconducting Cavities, 25 MV/m ($\sqrt{s} = 500$ GeV) to 35 MV/m ($\sqrt{s} = 800$ GeV)
- **NLC/JLC: High Frequency**
  - New environment and new problems
- **CLIC: Extremely High Frequencies**
  - Two beam acceleration requires years of R& D



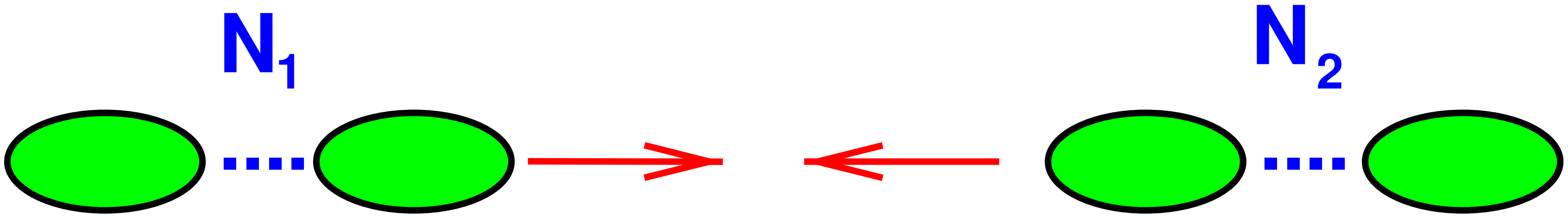
Cross sections $\propto \frac{1}{s}$ in many cases

Increase Luminosity at large $\sqrt{s}$!!

$$N_{events} = \mathcal{L}\sigma$$

Implications of High Luminosity

$$\mathcal{L} = \frac{N_1 N_2 \ \nu}{4\pi \ \sigma_x \sigma_y}$$

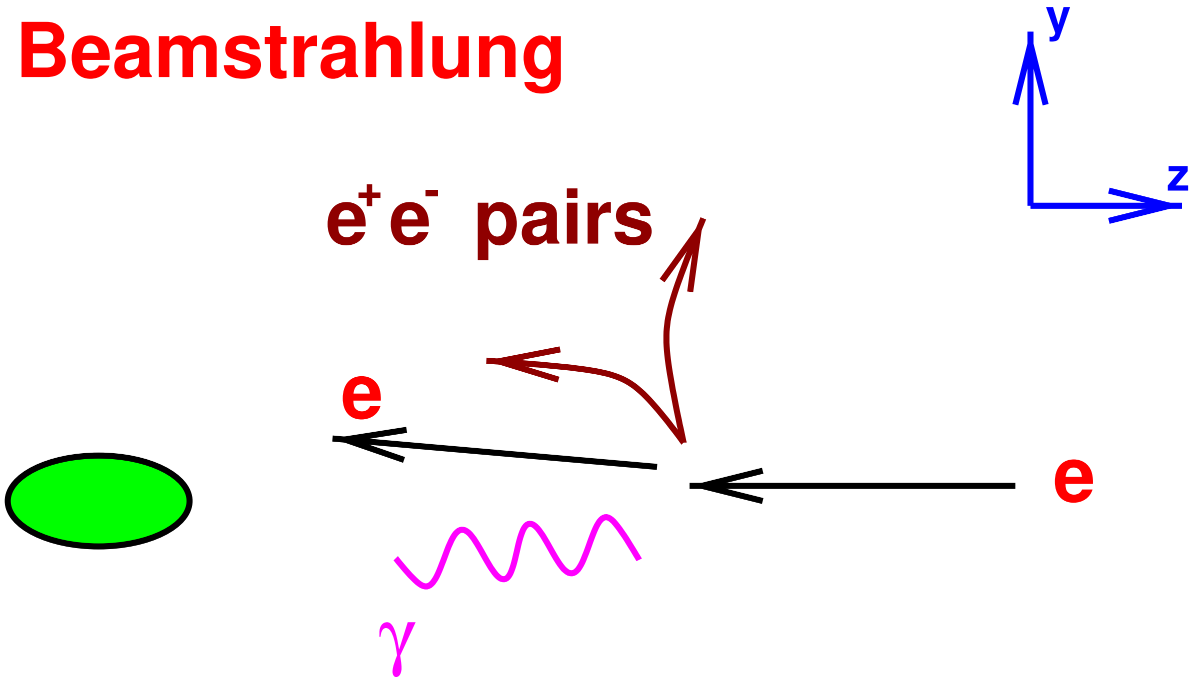


High $\mathcal{L}$ ($\gtrsim 10^{34}$ cm^{-2} s^{-1}) implies:

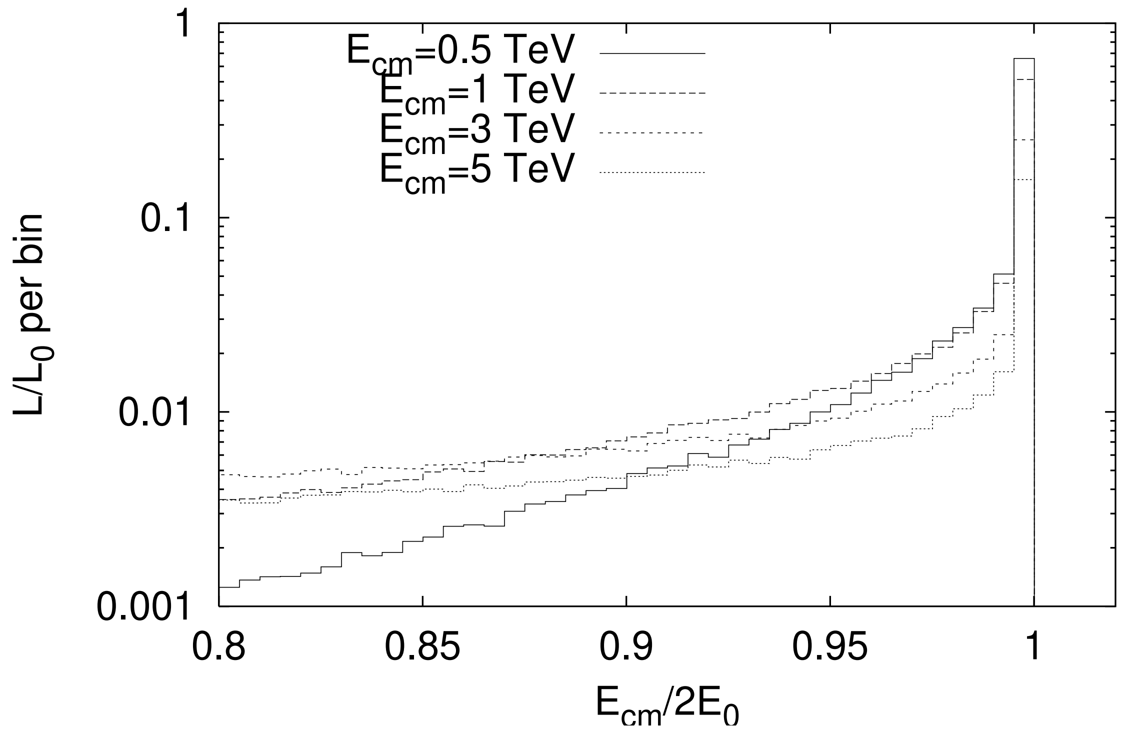
Many Bunches
High Repetition Rate
Small beam spot sizes
($\sigma_x \approx 300 - 500$ nm, $\sigma_y \approx 5$ nm)

New Problems!!

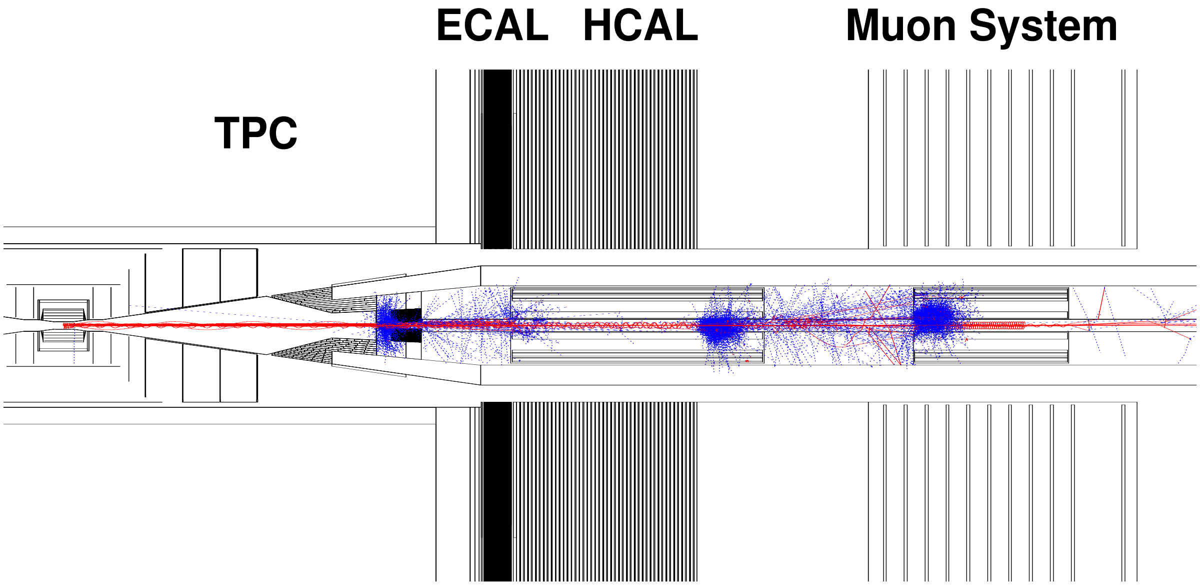
Beamstrahlung



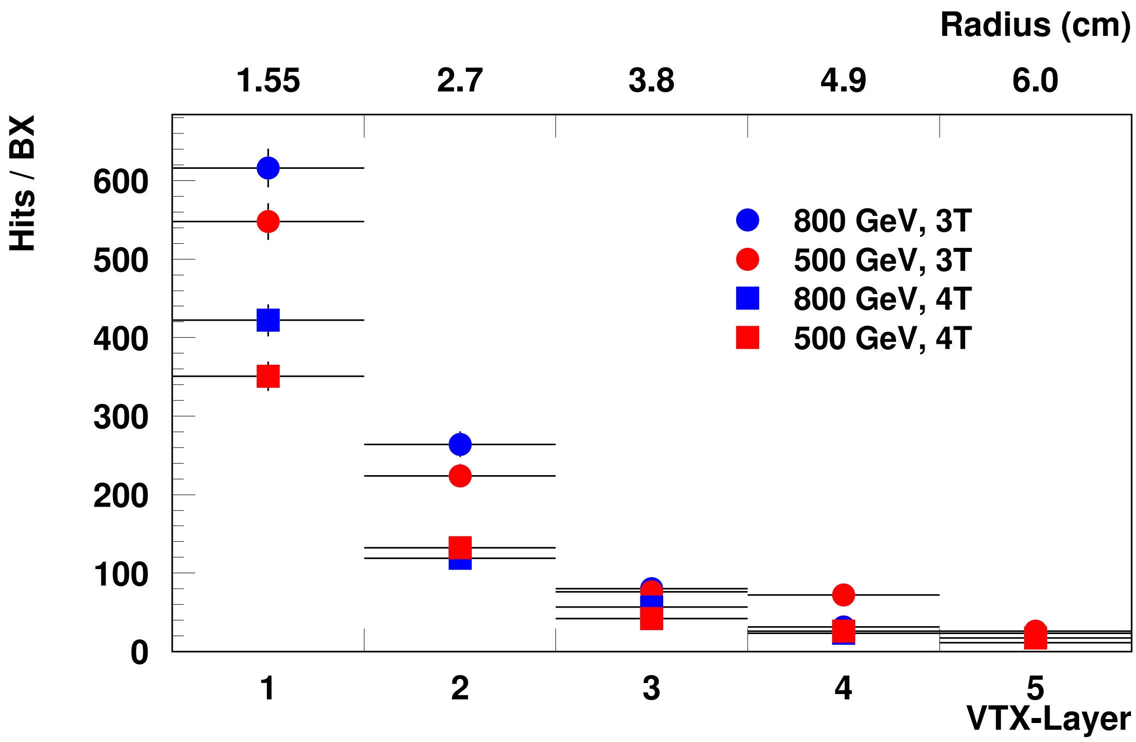
$$\text{Fractional Losses} \propto \frac{\sqrt{s}}{(\sigma_x + \sigma_y)^2}$$

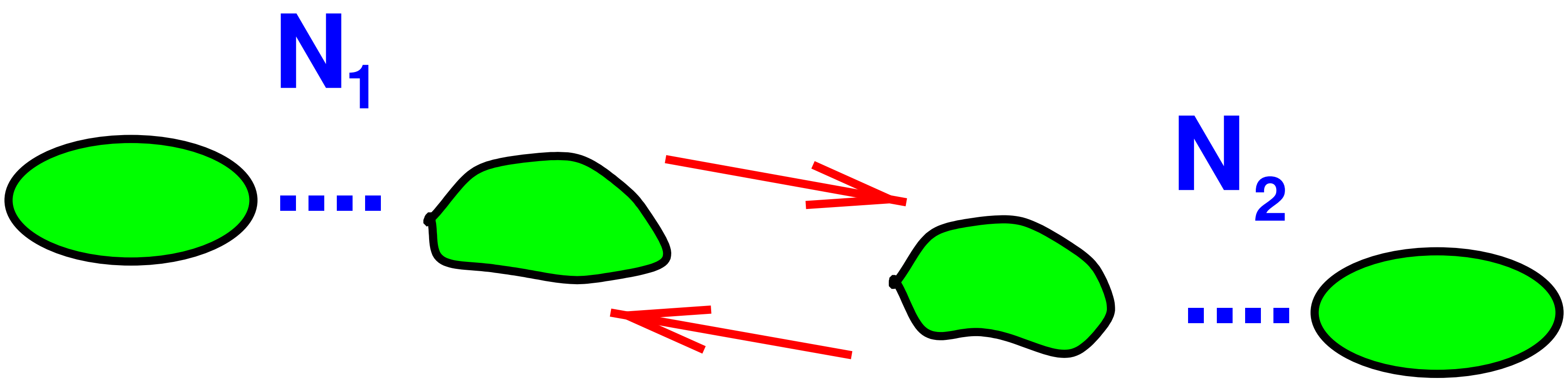


Mask at $\theta \lesssim 80 mrad$



At the Vertex Detector





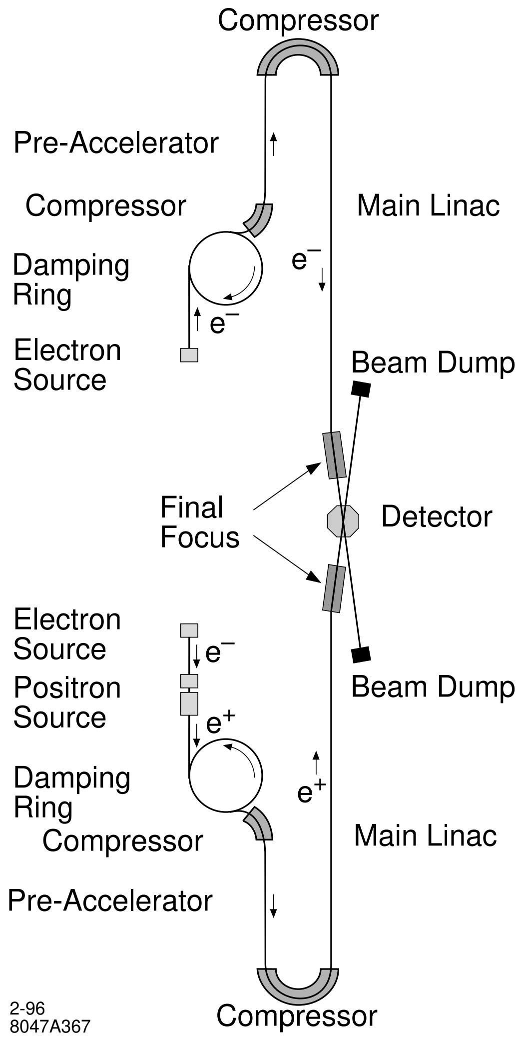
Disruption

Pinch effect

We need:

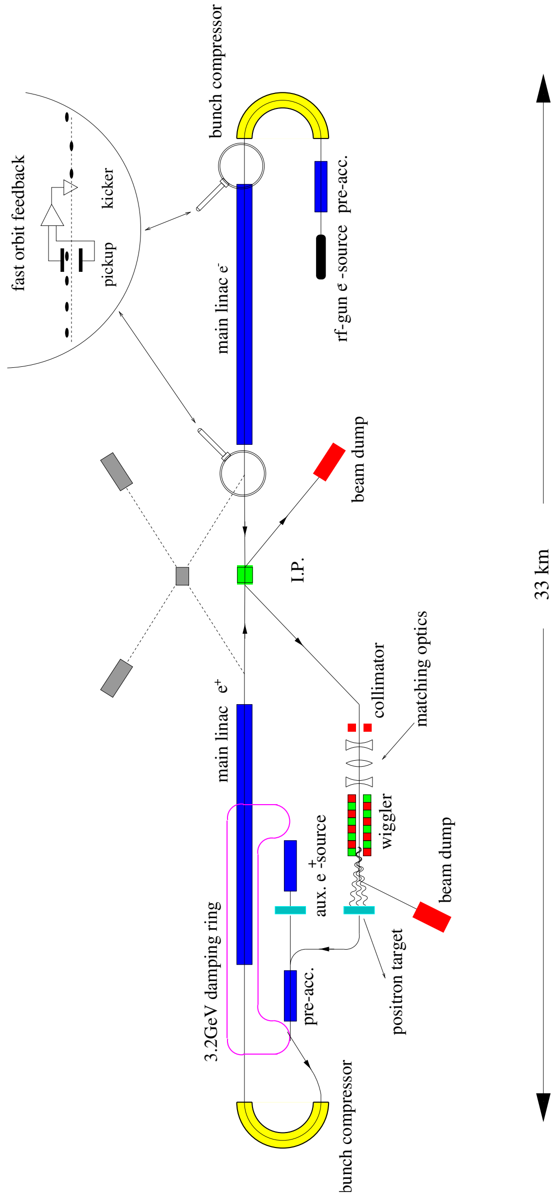
- Beam Correction/Feedback Systems
- Experimental cross check/determination of luminosity and beamstrahlung spectra

The American Project: NLC



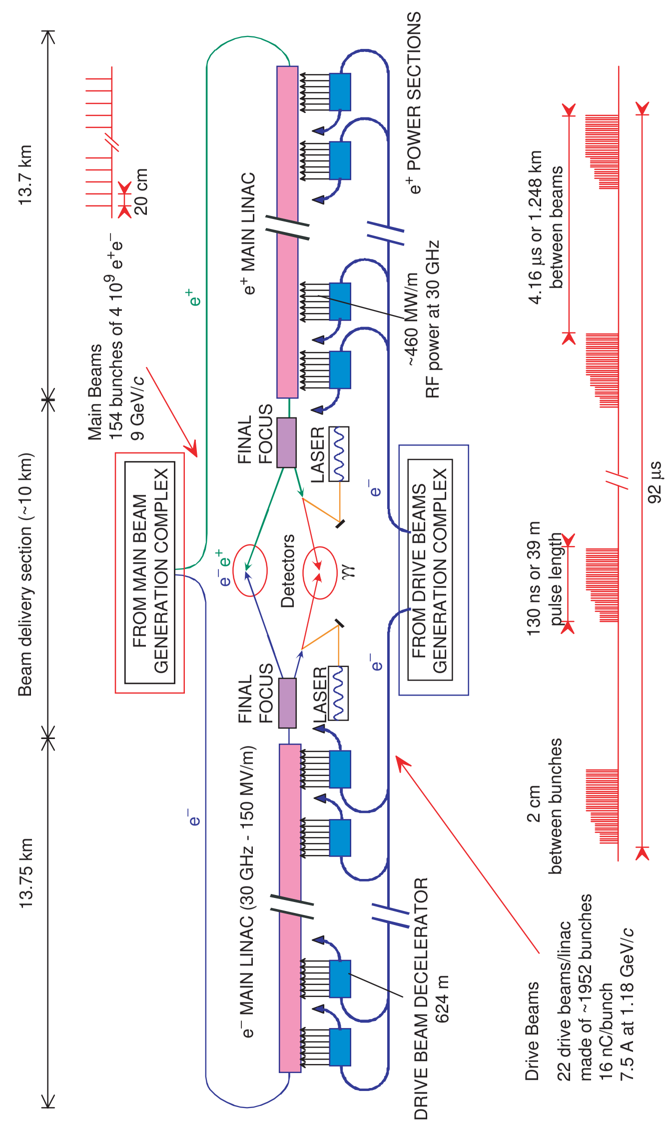
- X-band RF System: 11.4 GHz
  $\rightarrow$ emittance issues
- Effective gradients:
  30 MV/m at $\sqrt{s} = 500$ GeV,
  55 MV/m at $\sqrt{s} = 1$ TeV
- Luminosity: $0.5 - 1.0\ 10^{34}$ cm^{-2} s^{-1}
- Bunch Separation: 1.4 ns,
  90 bunches/pulse
  $\rightarrow$ crossing angle at the IP

The European Project: TESLA



- L-band SC RF System: 1.3 GHz
  $\longrightarrow$ emittance OK
- Effective gradients:
  25 MV/m at $\sqrt{s} = 500$ GeV,
  35 MV/m at $\sqrt{s} = 800$ GeV
- Luminosity: $4 - 5\ 10^{34}$ cm^{-2} s^{-1}
- Bunch Separation: 200-300 ns,
  > 2500 bunches/pulse
  $\longrightarrow$ head-on collisions, feedback system

CLIC



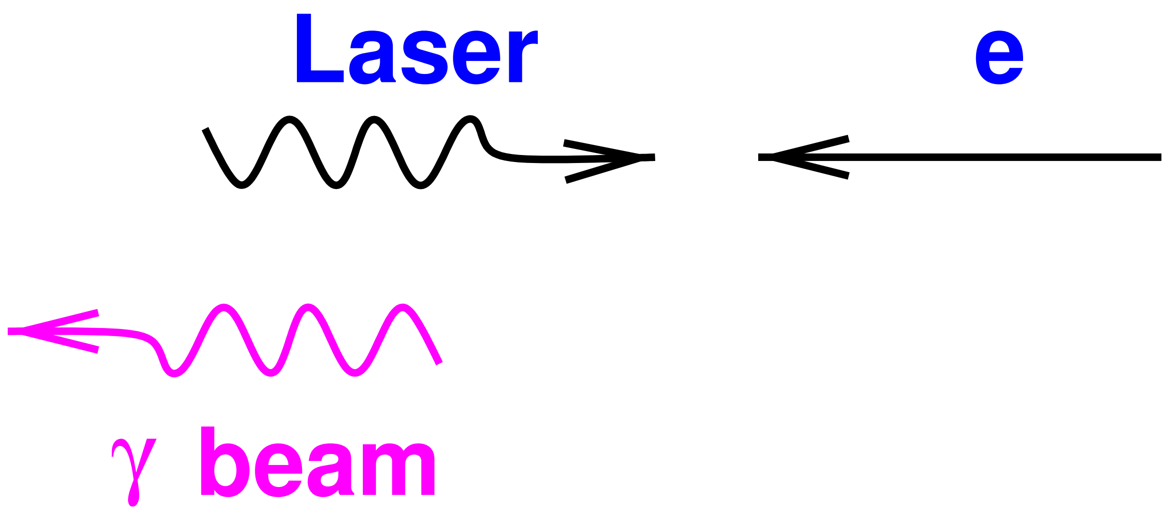
- K-band two-beam based RF System: 30 GHz
- Effective gradients: 150 MV/m at $\sqrt{s} = 3$ TeV
- Luminosity: 10^{35} cm^{-2} s^{-1}
- Bunch Separation: 0.67 ns, 150 bunches/pulse

- Evolving facility as a function of $\sqrt{s}$ and physics priorities

- Polarizations: $\mathcal{P}_{\mathrm{e}^-} \sim 80\%$, $\mathcal{P}_{\mathrm{e}^+} \sim 60\%$

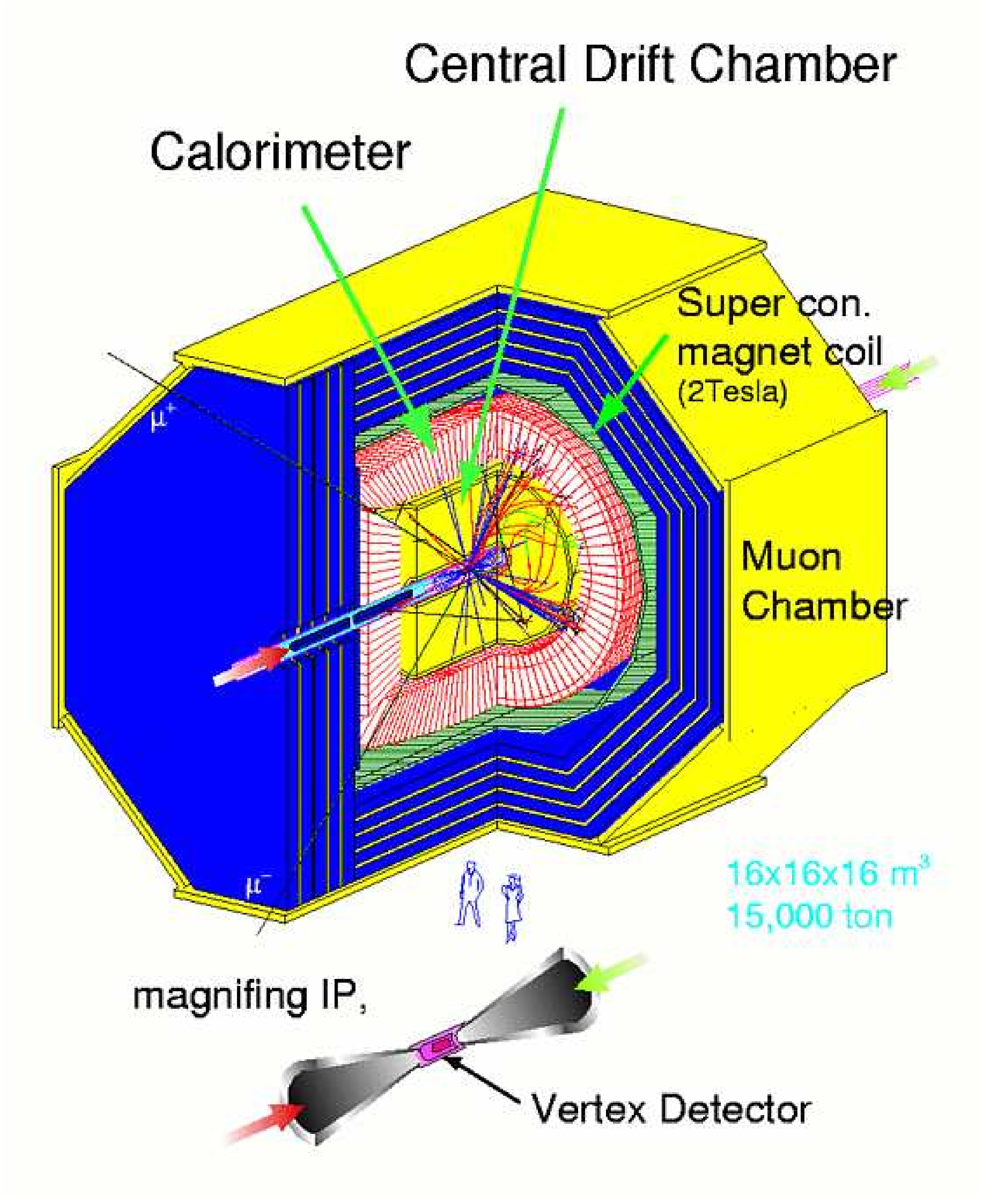
- $\mathrm{e}^-\mathrm{e}^-$, $\mathrm{e}\gamma$, $\gamma\gamma$ options

Compton Back-scattering



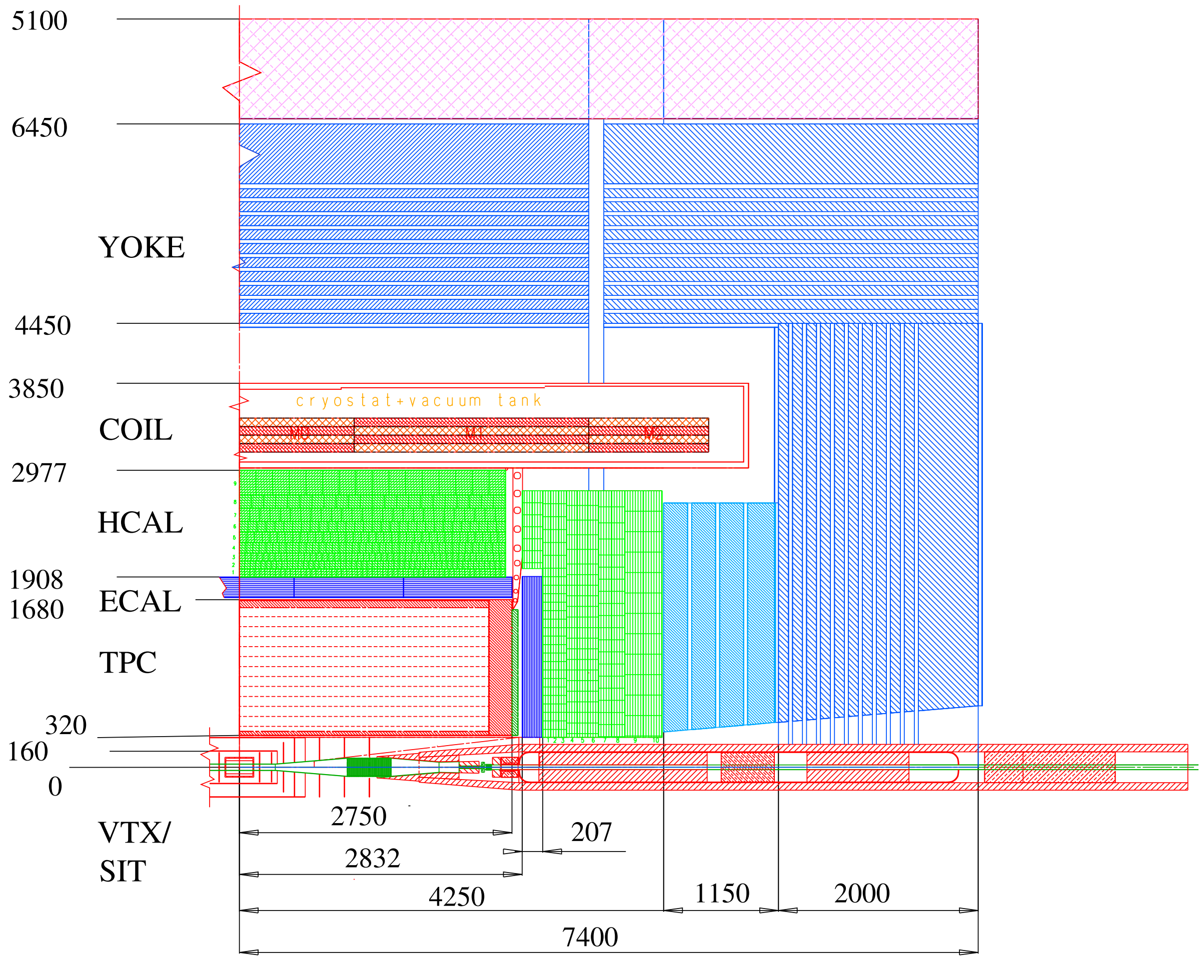
- Self Amplified Spontaneous Emission Free Electron Laser (SASE FEL)

Typical Detector (JLC)



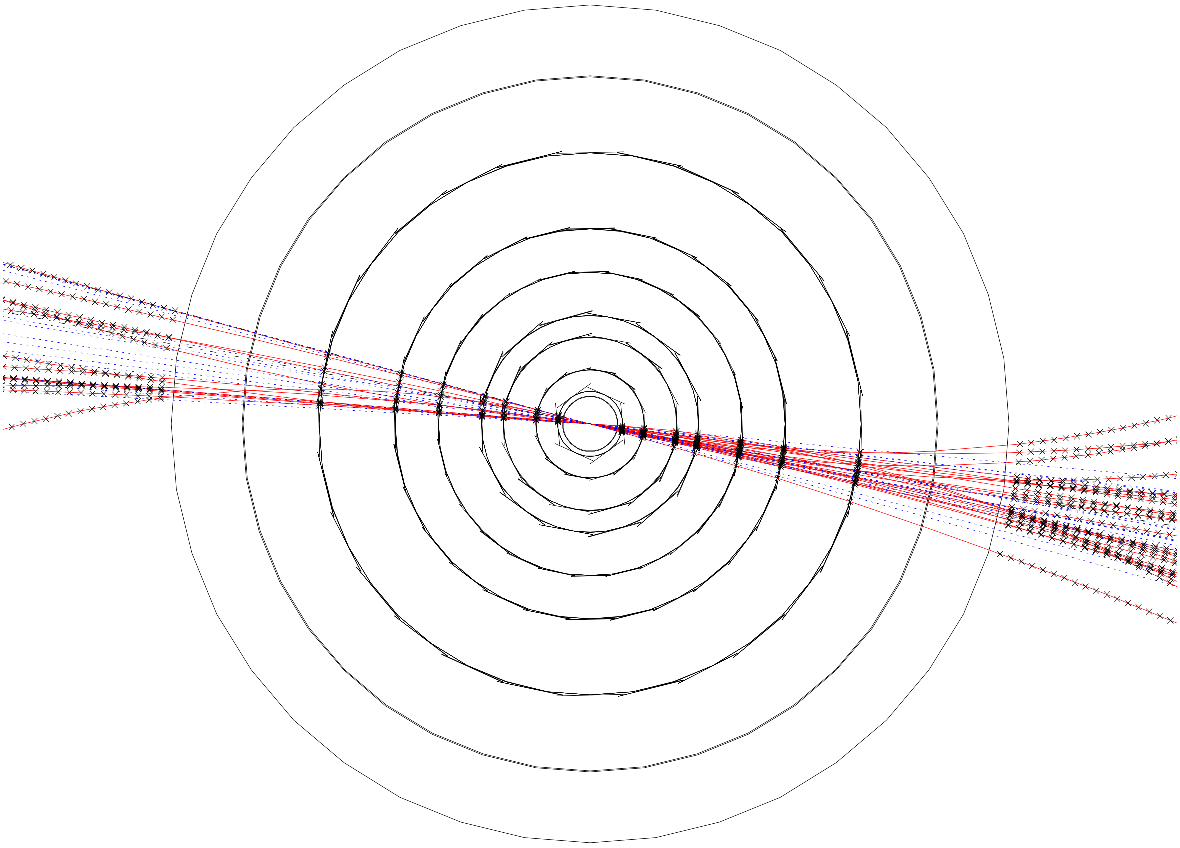
Similar to LEP detectors, but . . .

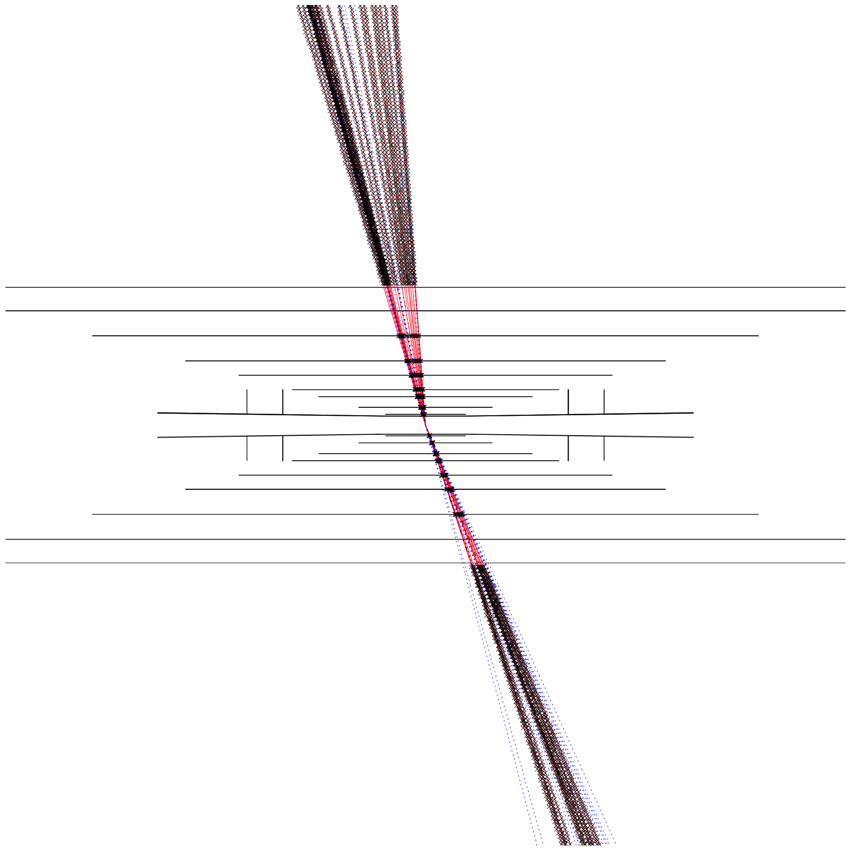
Typical Detector (TESLA)



- Full Coverage and Hermeticity
- High precision tracking
- High granularity
- Energy Flow Reconstruction
- Almost Ideal Particle Identification

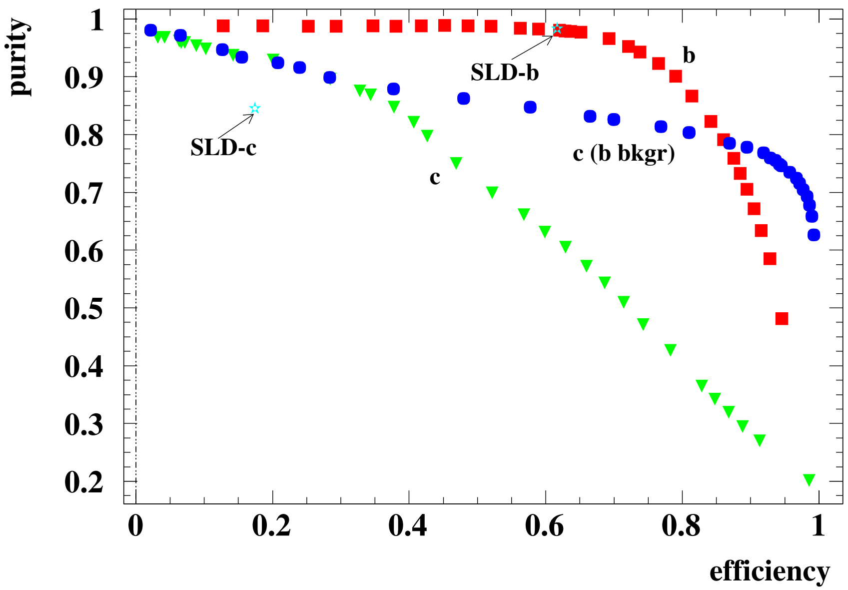
Granularity? $e^+e^- \rightarrow WW$ *event at CLIC . . .*

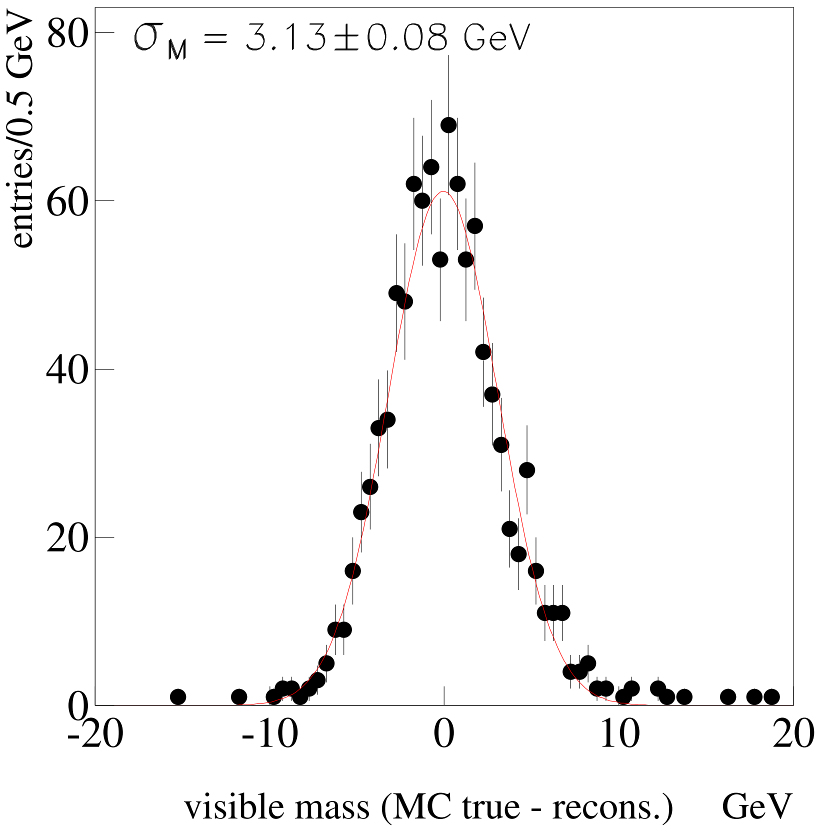




Energy Flow

Particle Id





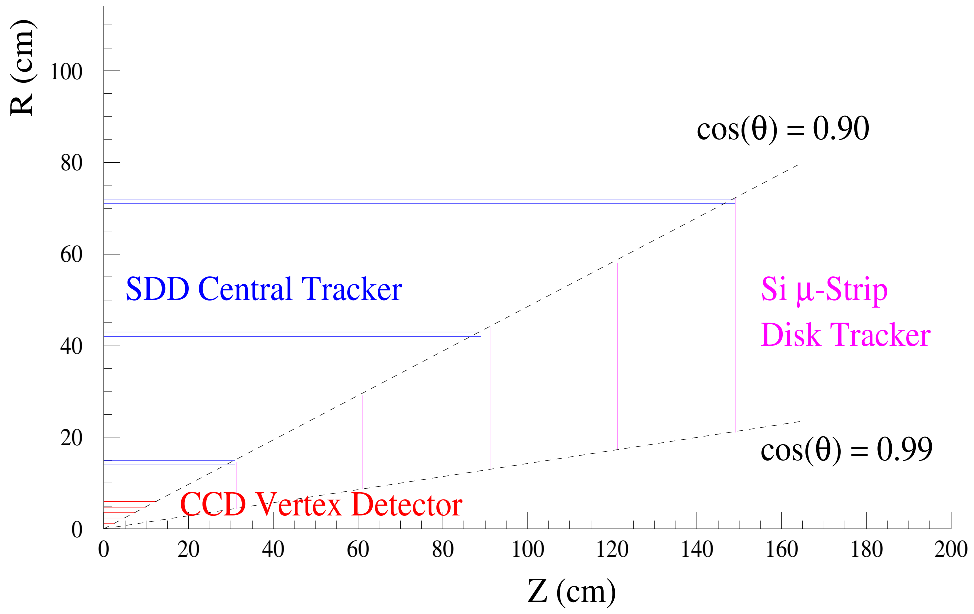
Almost Pure Identification of heavy quarks with high efficiency: $\epsilon_b \approx 60\%$, $\epsilon_c \approx 40\%$

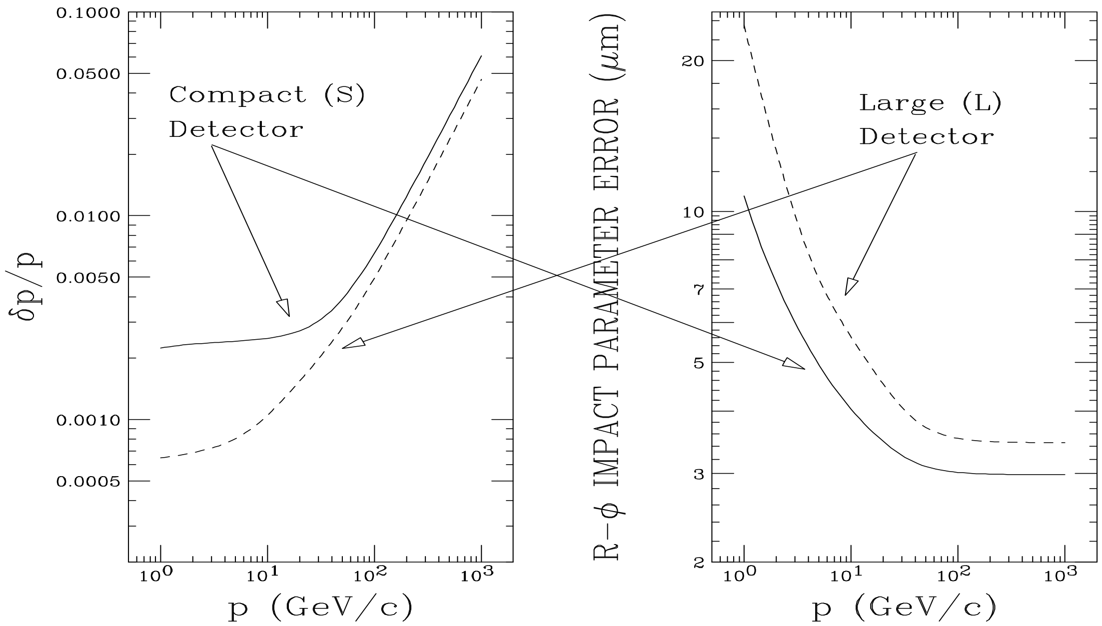
Twice better than LEP detectors in Z decays

TESLA Goals

Subdetector	Goal
COIL	4 T, uniformity $\leq 10^{-3}$
Vertex Detector (VTX)	$\delta(IP_{r\phi,z}) \leq 5\,\mu\mathrm{m} \oplus \frac{10\,\mu\mathrm{m}\;\;\mathrm{GeV}/c}{p\sin^{3/2}\theta}$
Central Tracker (TPC)	$\delta(1/p_t)_{\mathrm{TPC}} < 2\ 10^{-4}(\mathrm{GeV/c})^{-1}$ $\sigma(dE/dx) \leq$ 5%
Electromag. Calo. (ECAL)	$\frac{\delta E}{E} \leq 0.10\frac{1}{\sqrt{E}} \oplus 0.01$ (E in GeV) fine granularity in 3D
Hadron Calo. (HCAL)	$\frac{\delta E}{E} \leq 0.50\frac{1}{\sqrt{E}} \oplus 0.04$ (E in GeV) fine granularity in 3D
Fe Yoke (MUON)	Tail catcher and high efficiency muon tracker
Tracking Overall	$\delta(\frac{1}{p_t}) \leq 5\ 10^{-5}(\mathrm{GeV/c})^{-1}$ systematics $\leq 10\,\mu\mathrm{m}$
Energy Flow	$\frac{\delta E}{E} \simeq 0.3\frac{1}{\sqrt{E}}$ (E in GeV)

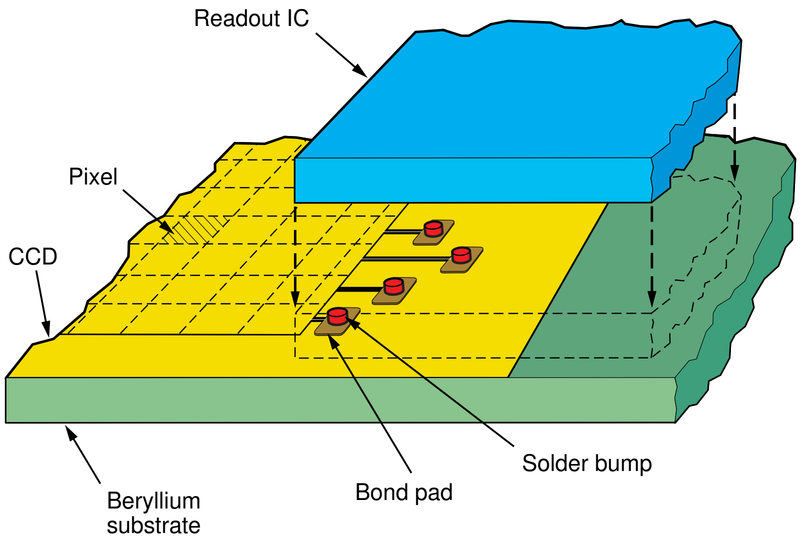
Small detector (American S Design) ?





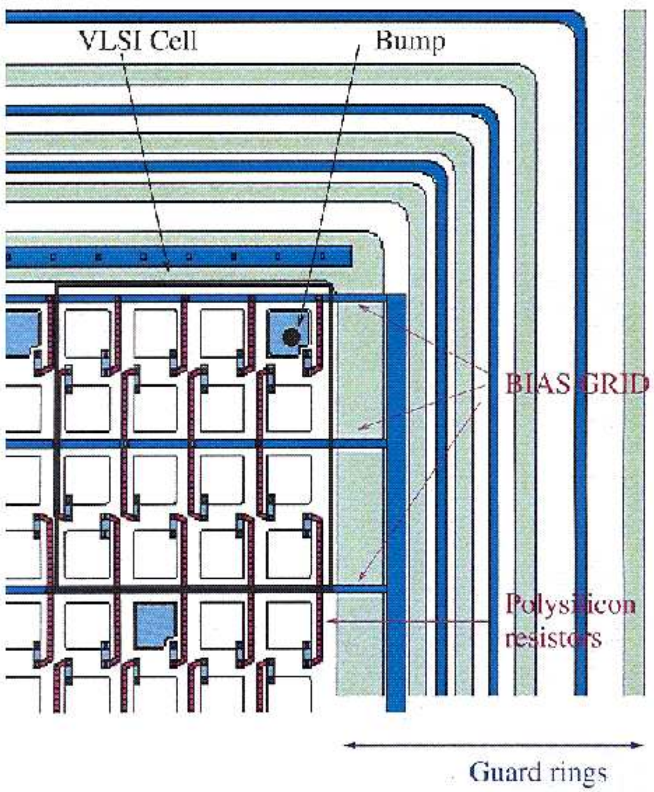
- Large $\vec{B} \Rightarrow$ VTX closer to the beam pipe
- Still precise enough
- Smaller $\Rightarrow$ Cheaper
- Granularity, dE/dX ??

CCDs



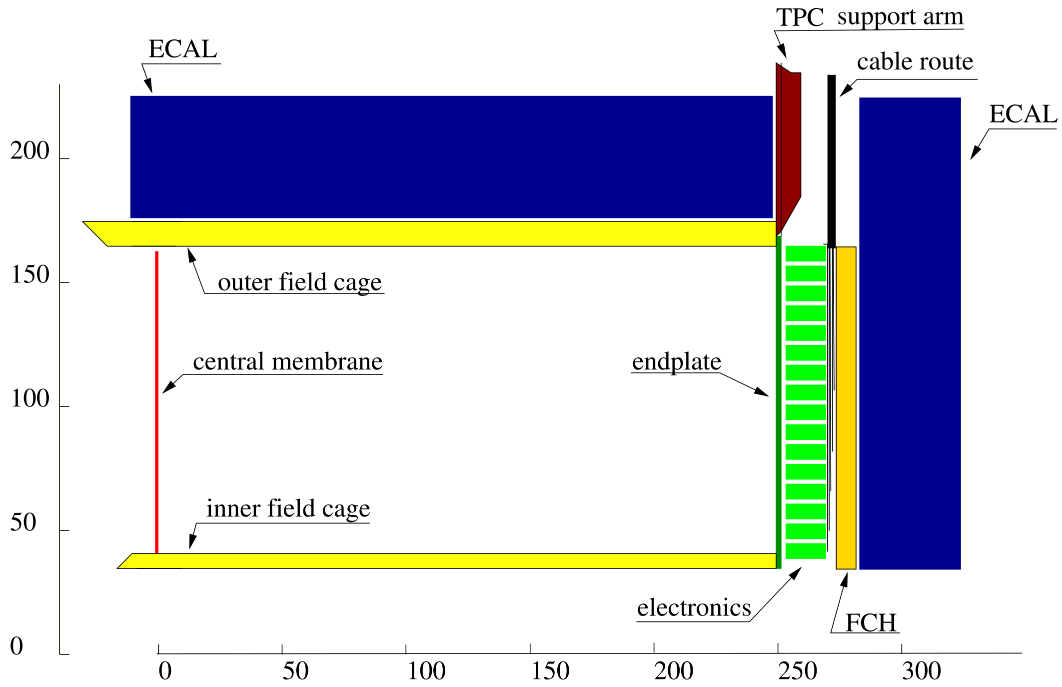
- Advantages: well known detectors (SLD)
- Main problems: readout speed, radiation hardness

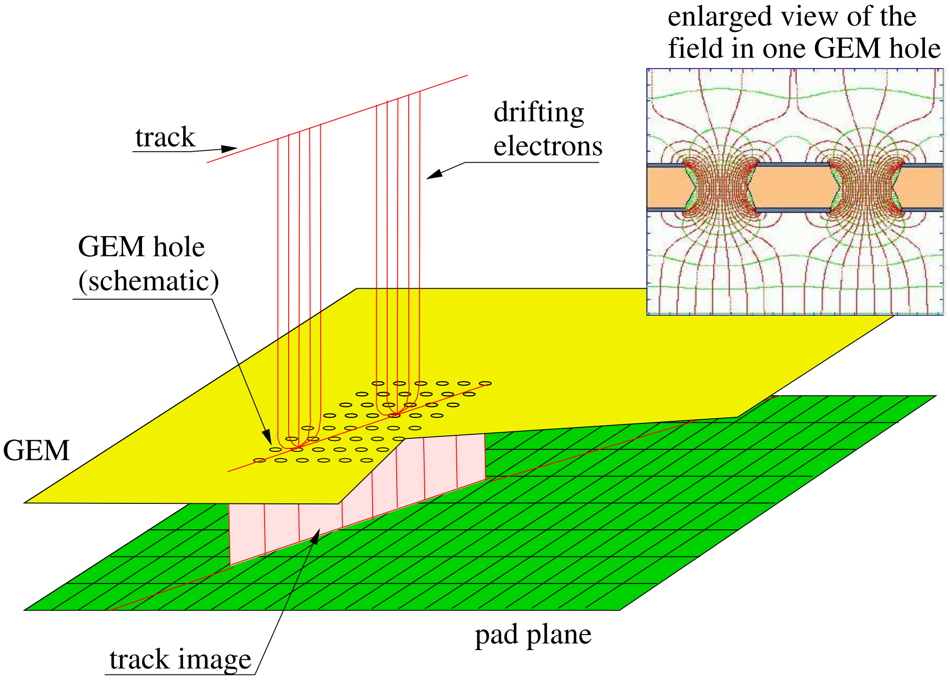
Active Pixel Sensors



- Advantages: Individual readout, radiation hardness
- Main problems: pixel dimensions, scaling

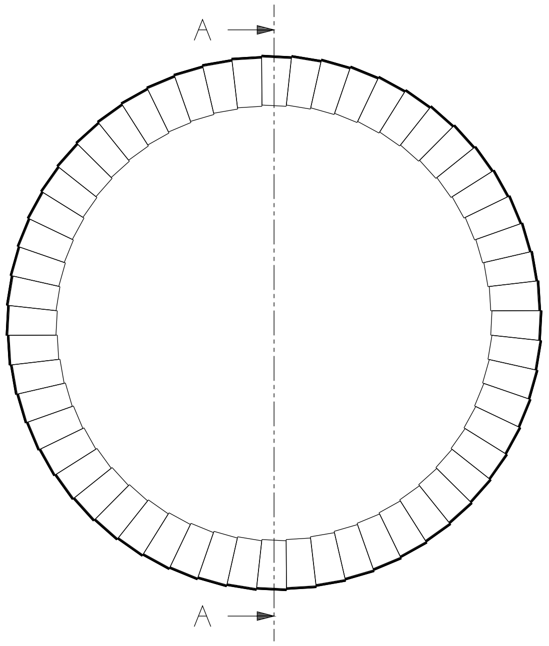
Central Tracking: TPC

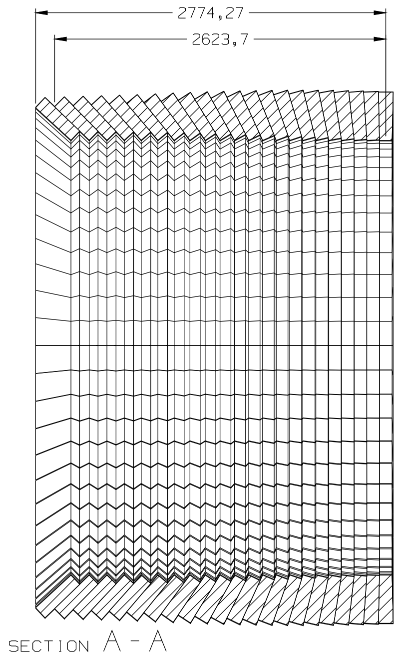




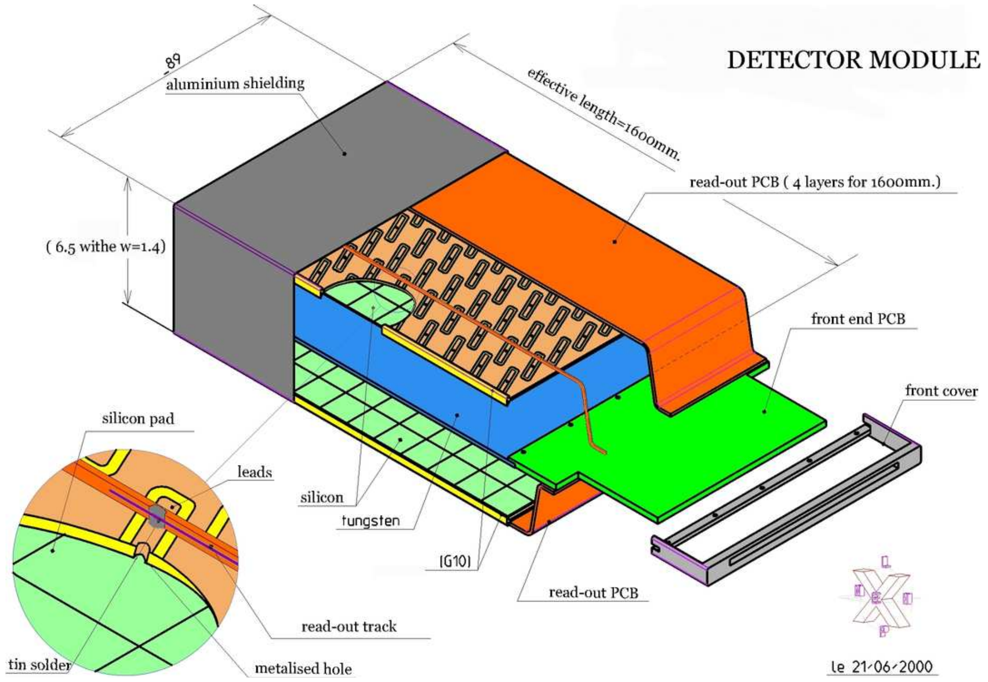
Issues: Gating, backgrounds

Shashlik Option

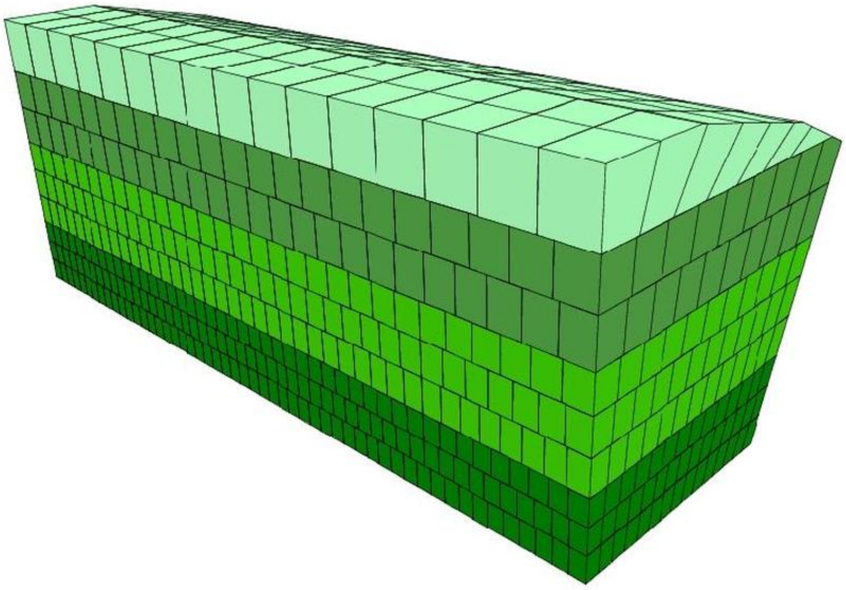




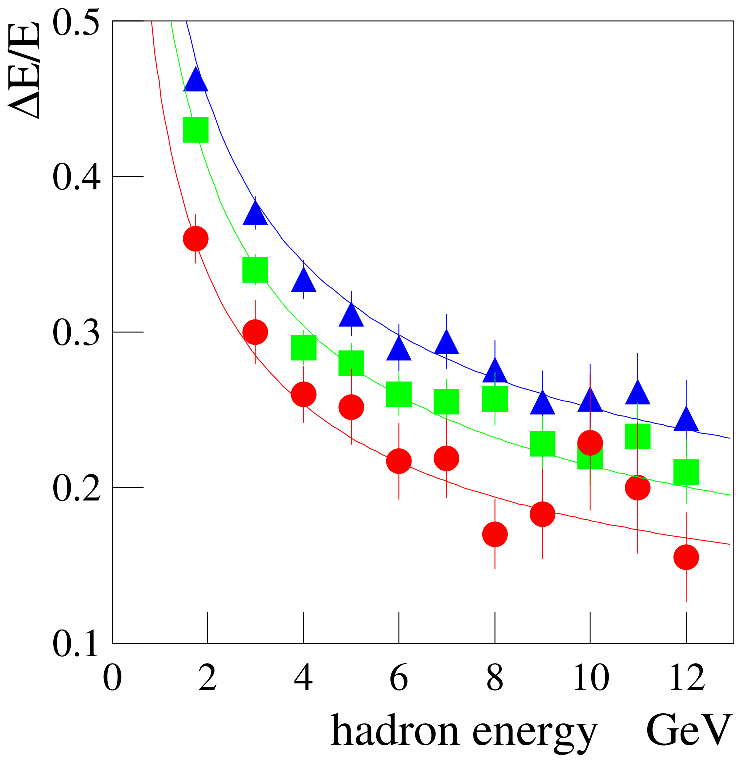
Si-W Option



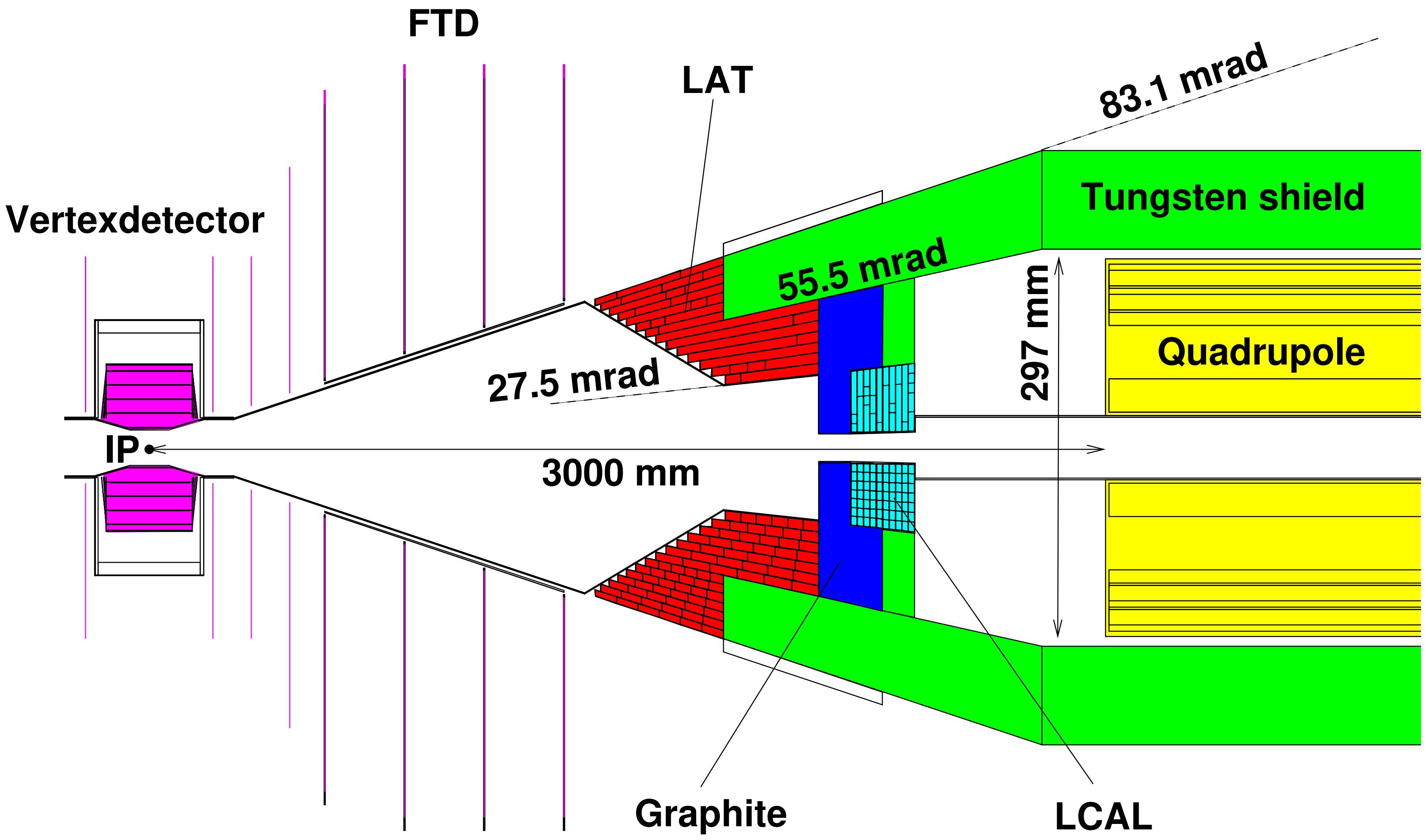
Tile Calorimeter Option



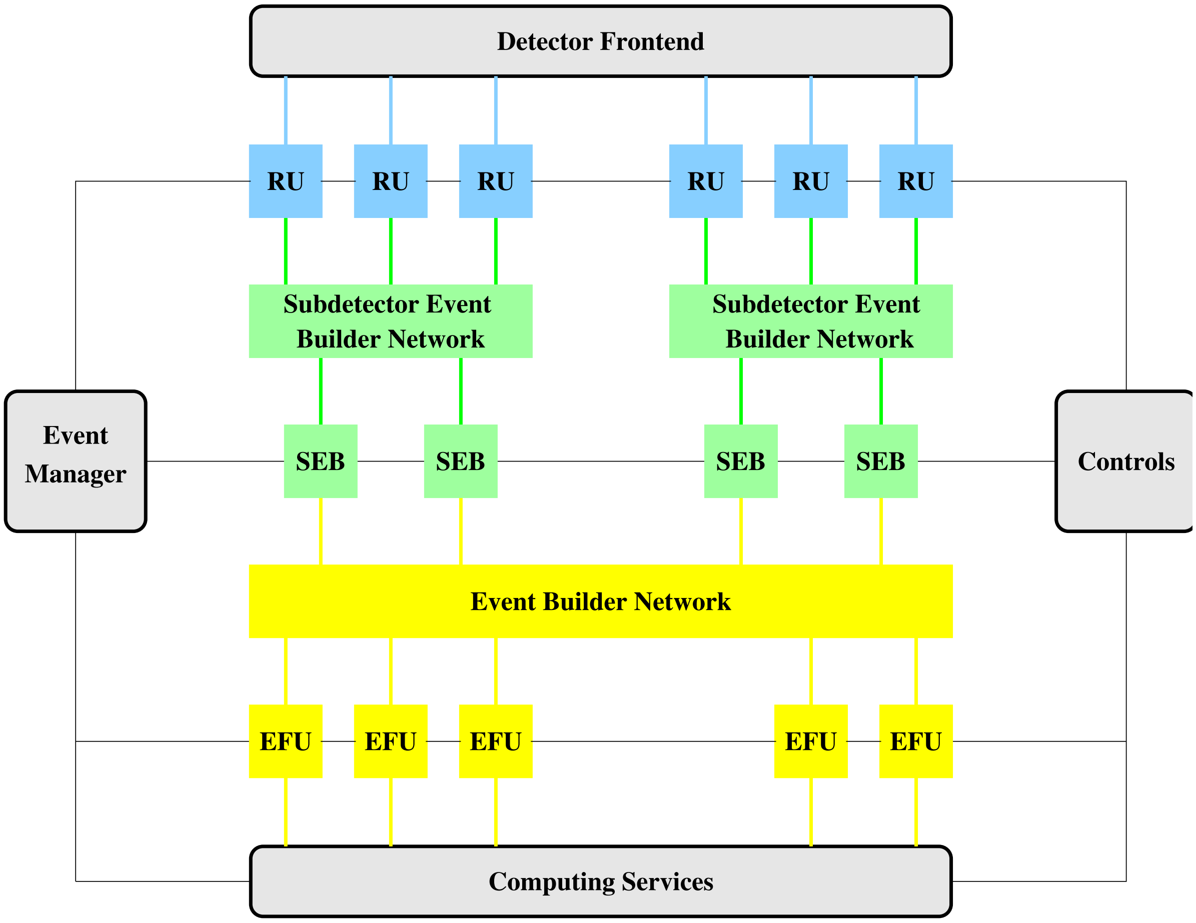
"Counting cells" Option

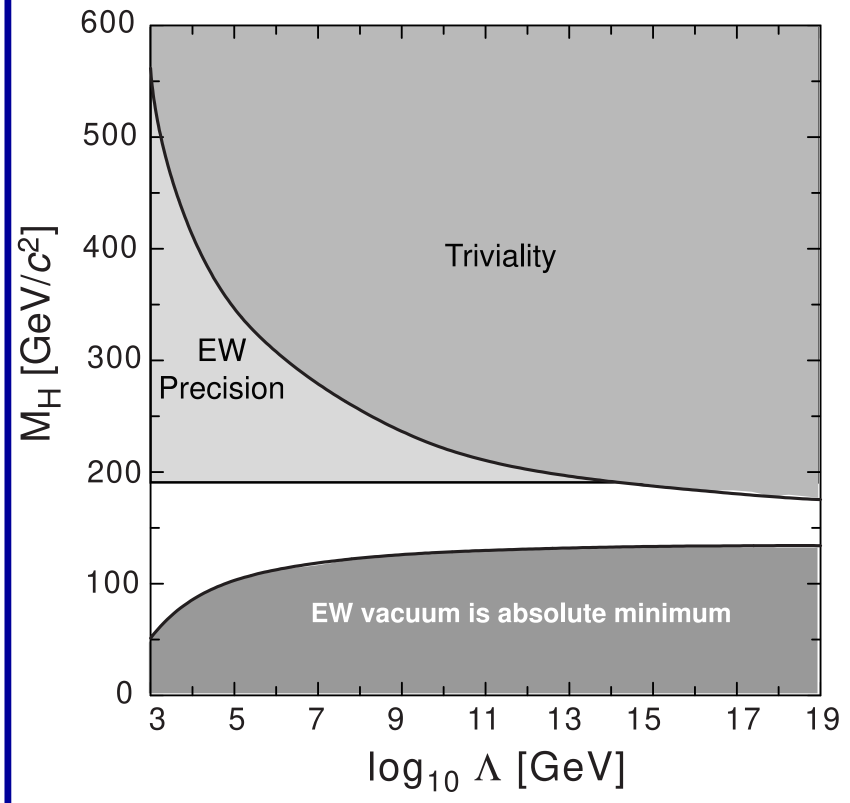


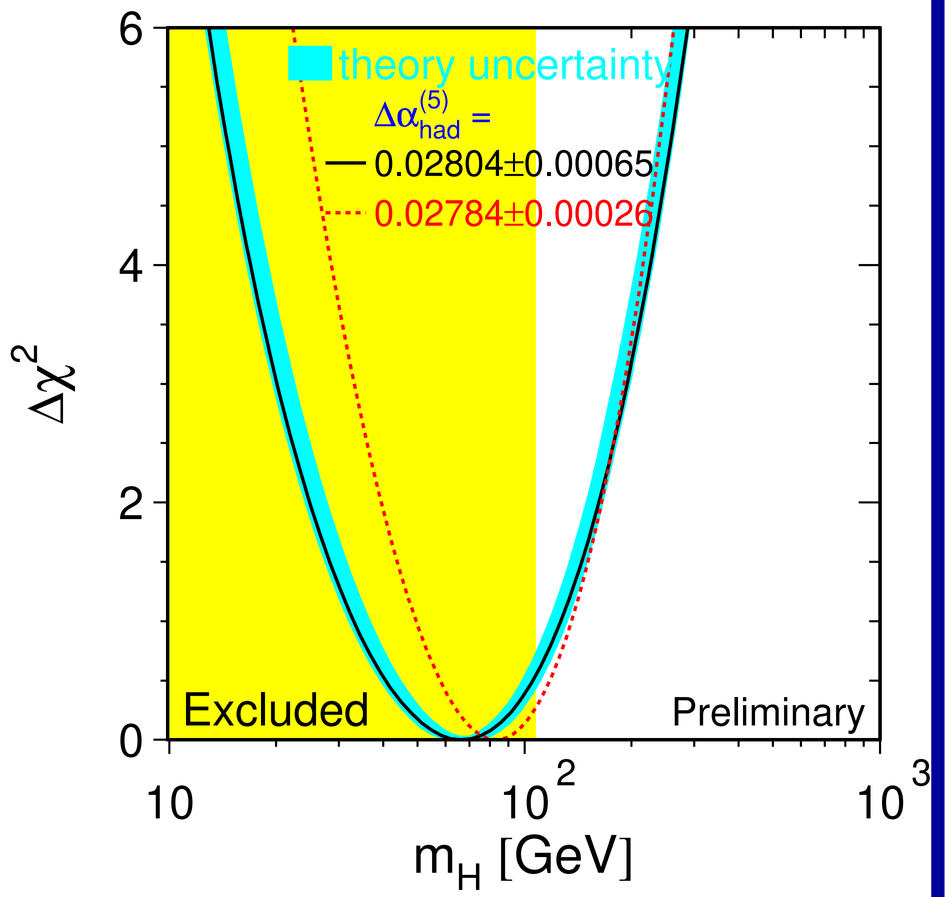
Luminosity Detector and Mask



- No hardware trigger
- 200 ms to build one event
- Selection by Software

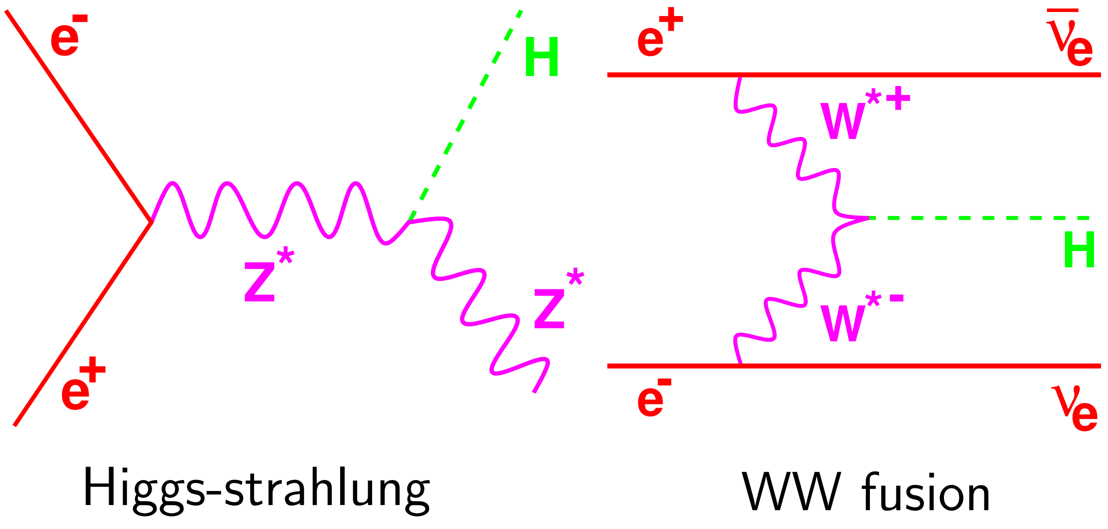


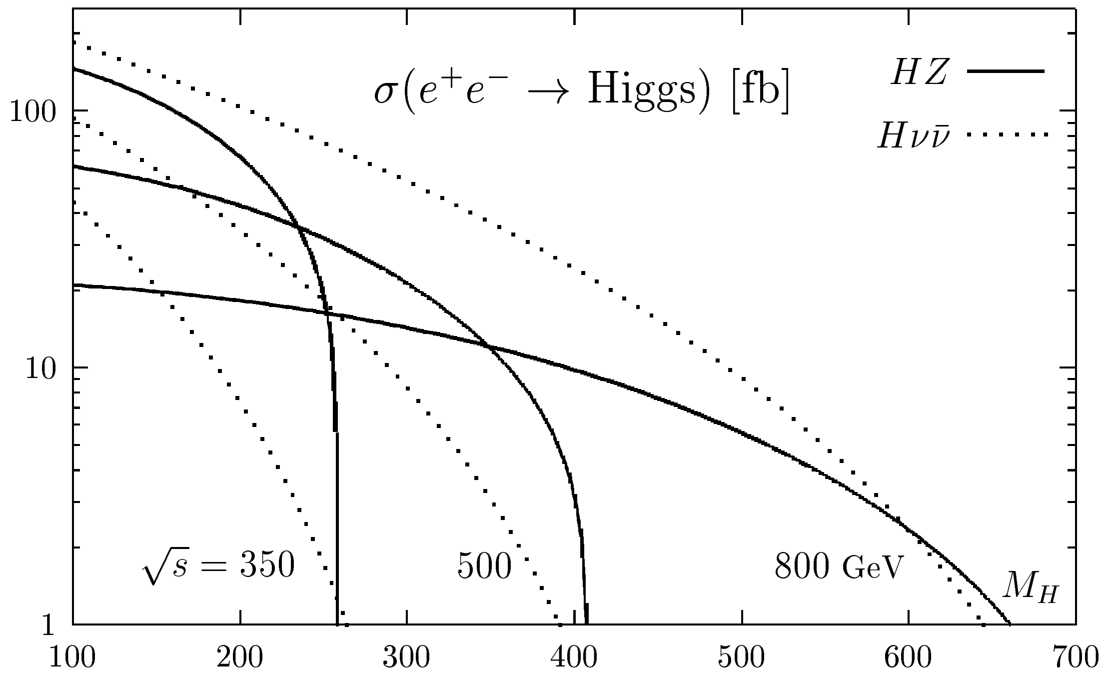




Only a narrow band is allowed if there is no new physics up to 10^{19} GeV

$m_{\rm H} \lesssim 200$ GeV at 95% CL

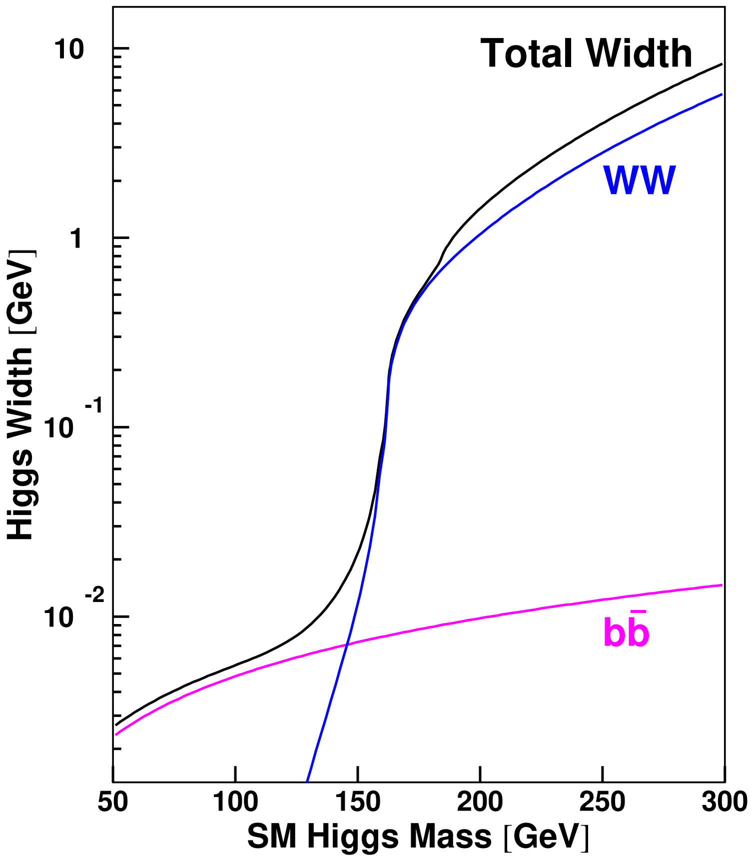


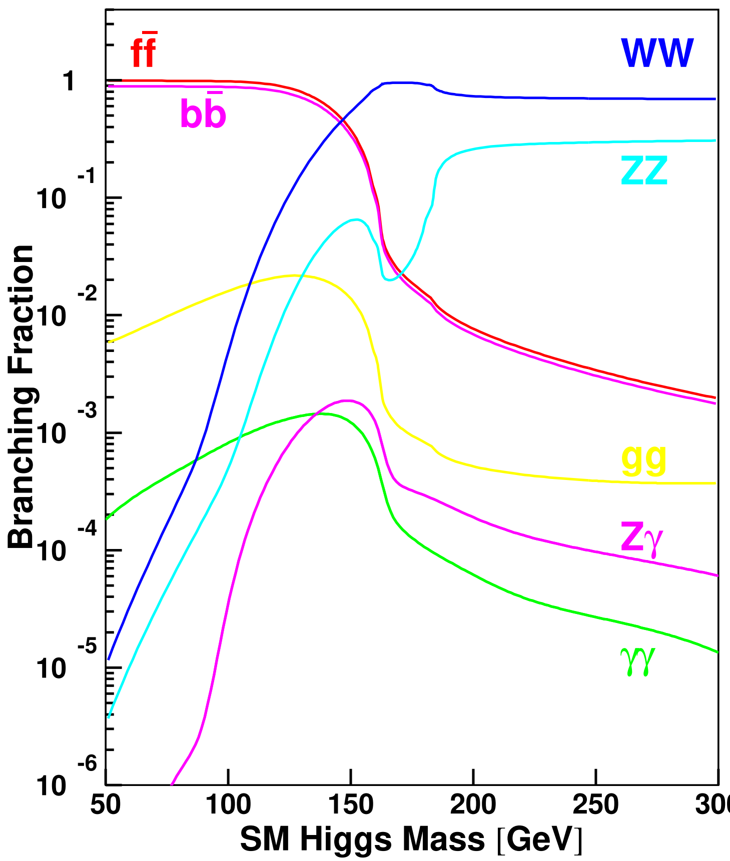


Higgs-strahlung dominant at low $\sqrt{s}$

WW fusion dominant at large $\sqrt{s}$

SM Higgs Branching Fractions

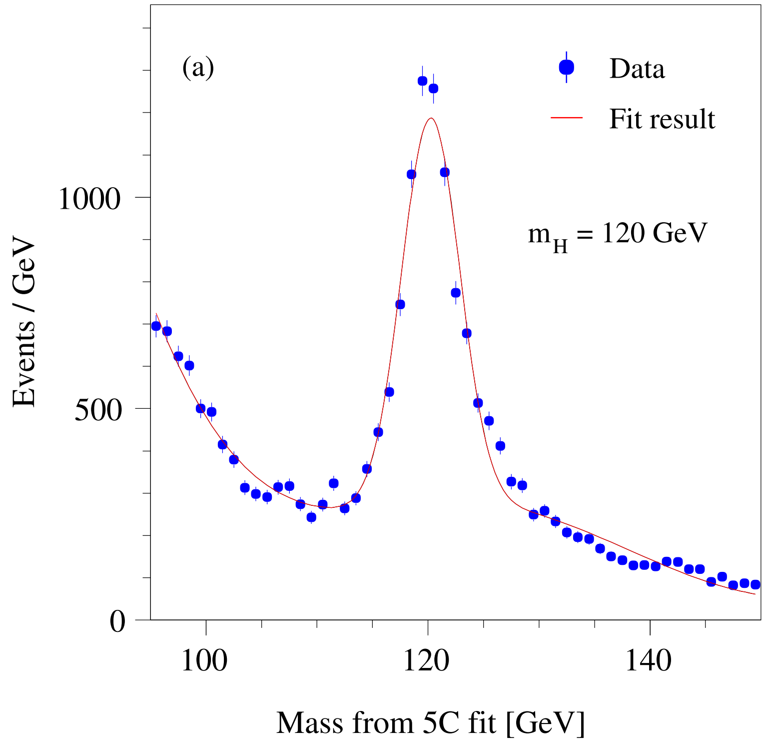




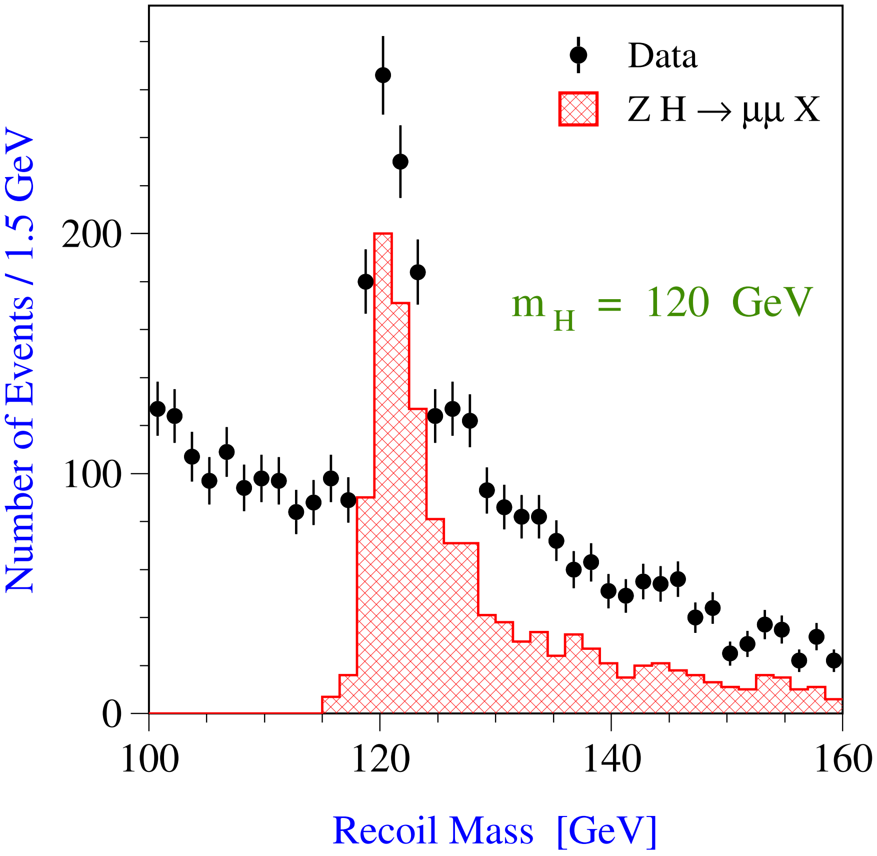
Two different behaviours: $m_{\rm H} < 2m_{\rm W}$ and $m_{\rm H} > 2m_{\rm W}$)

$\rm H \to \gamma\gamma$, $\rm H \to gg$, $\rm H \to Z\gamma$: interesting if New Physics

Exclusive: $b\bar{b}q\bar{q}$



Inclusive: Recoil Mass



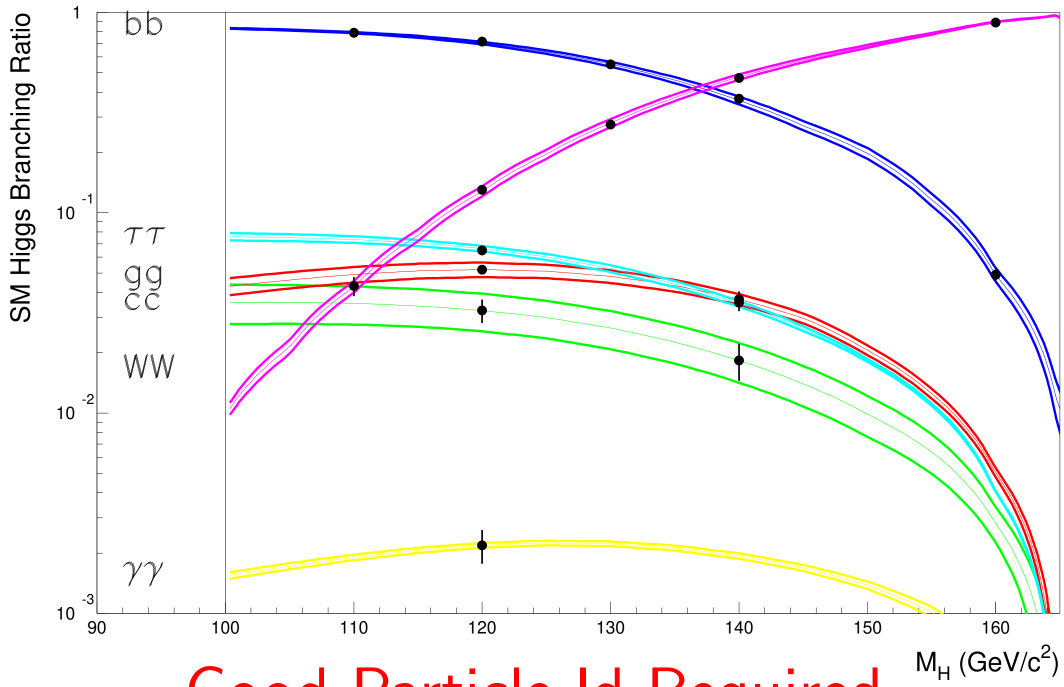
$\Delta m_{\mathrm{H}} \approx 50$ MeV

Dominated by detector resolution

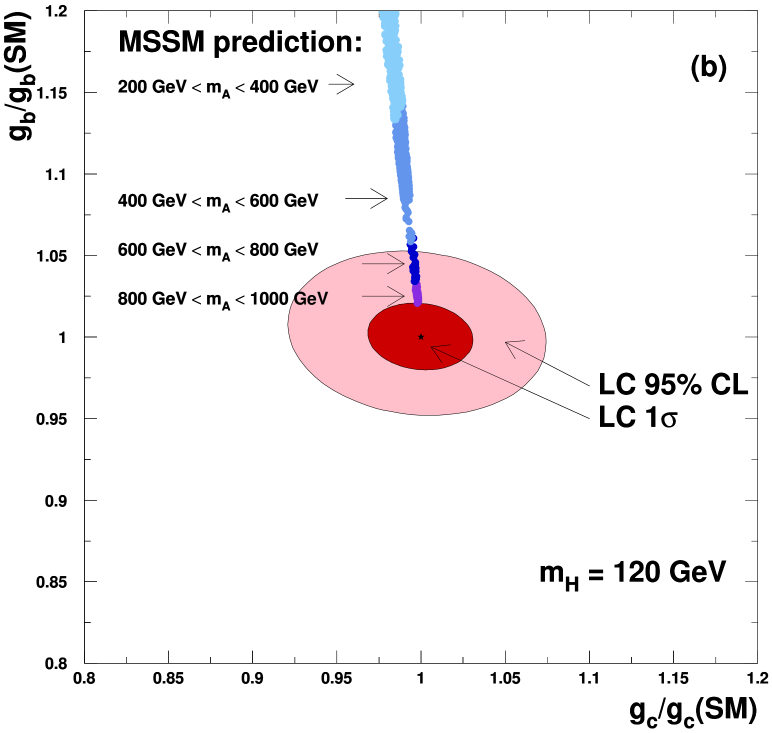
$\epsilon \neq \epsilon(X)$!!

No missing channels

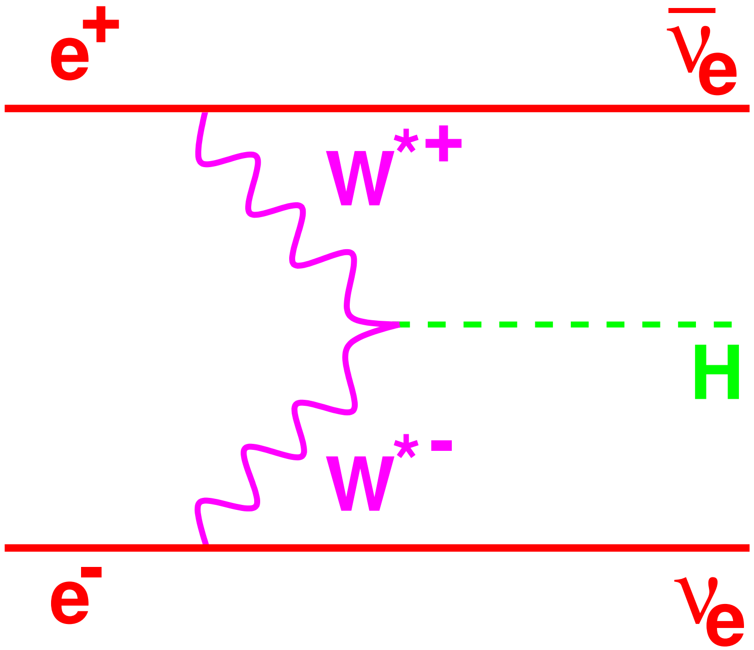
Total σ Measurement



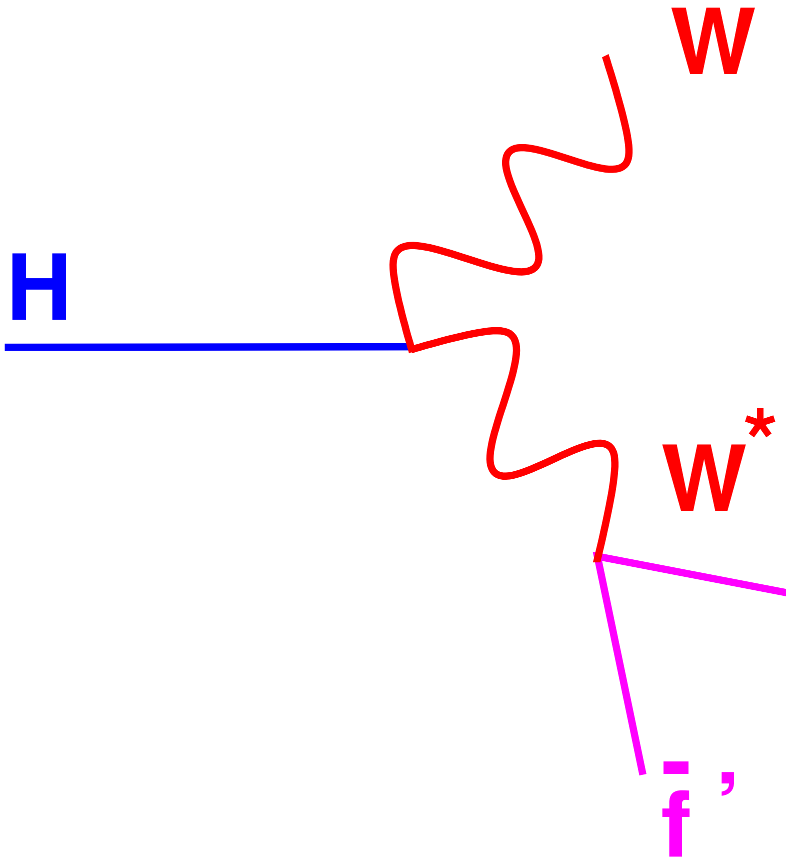
Good Particle Id Required
Experimental Precision ≈ few %



Sensitive to Physics beyond SM



Cross section gives Γ_{WW}

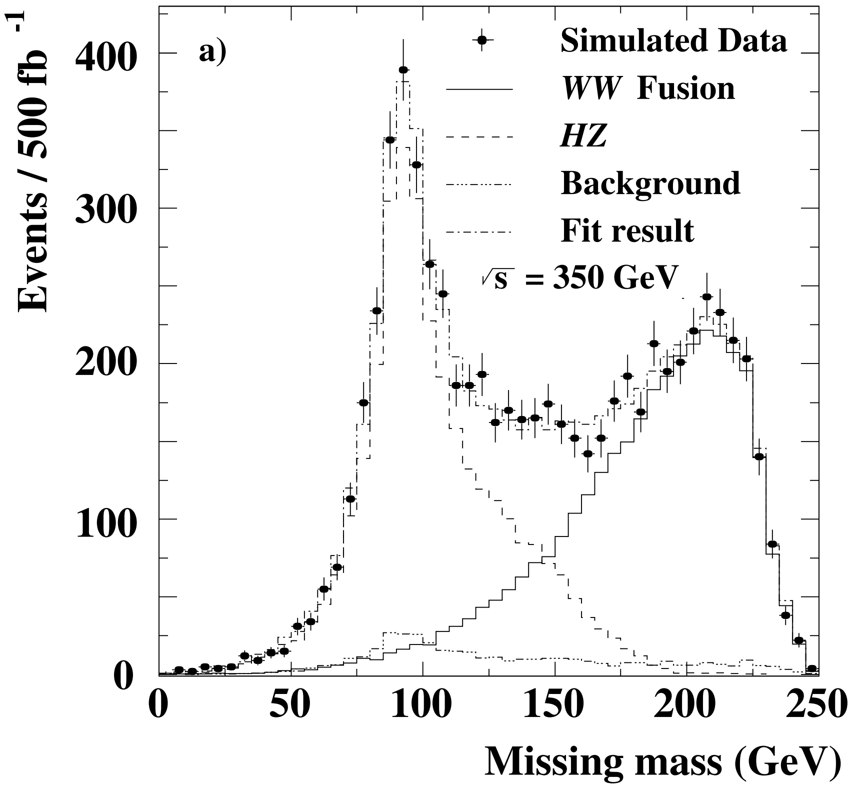


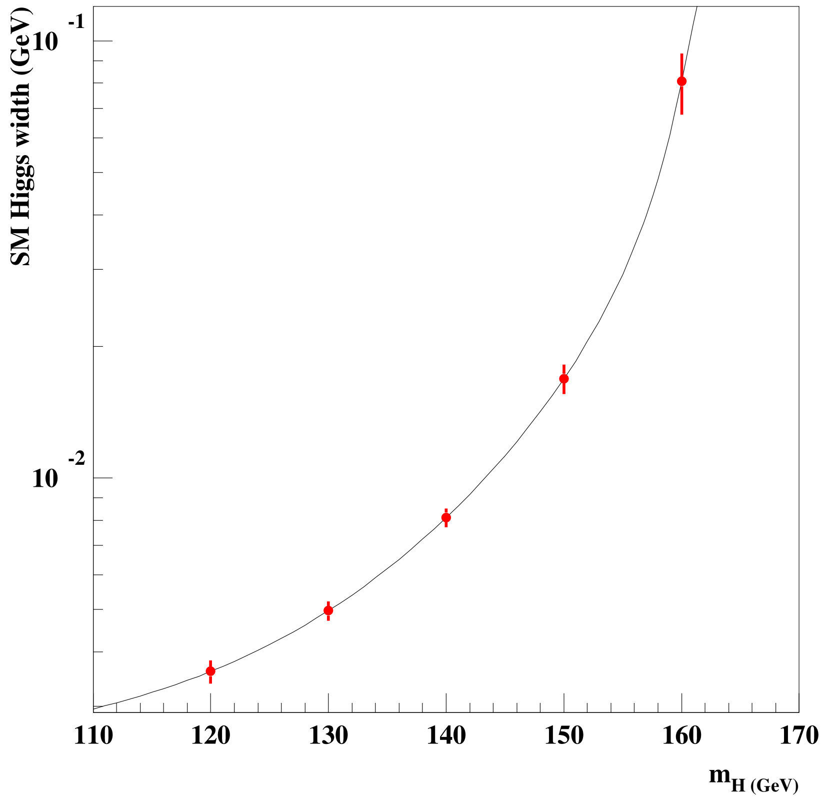
It gives $\mathrm{Br}(\mathrm{H} \to \mathrm{WW})$

$$\Gamma_{\mathrm{H}} = \frac{\Gamma_{\mathrm{WW}}}{\mathrm{Br}(\mathrm{H} \to \mathrm{WW})},$$

NO THEORETICAL ASSUMPTIONS

Total Width Measurement. Best Method



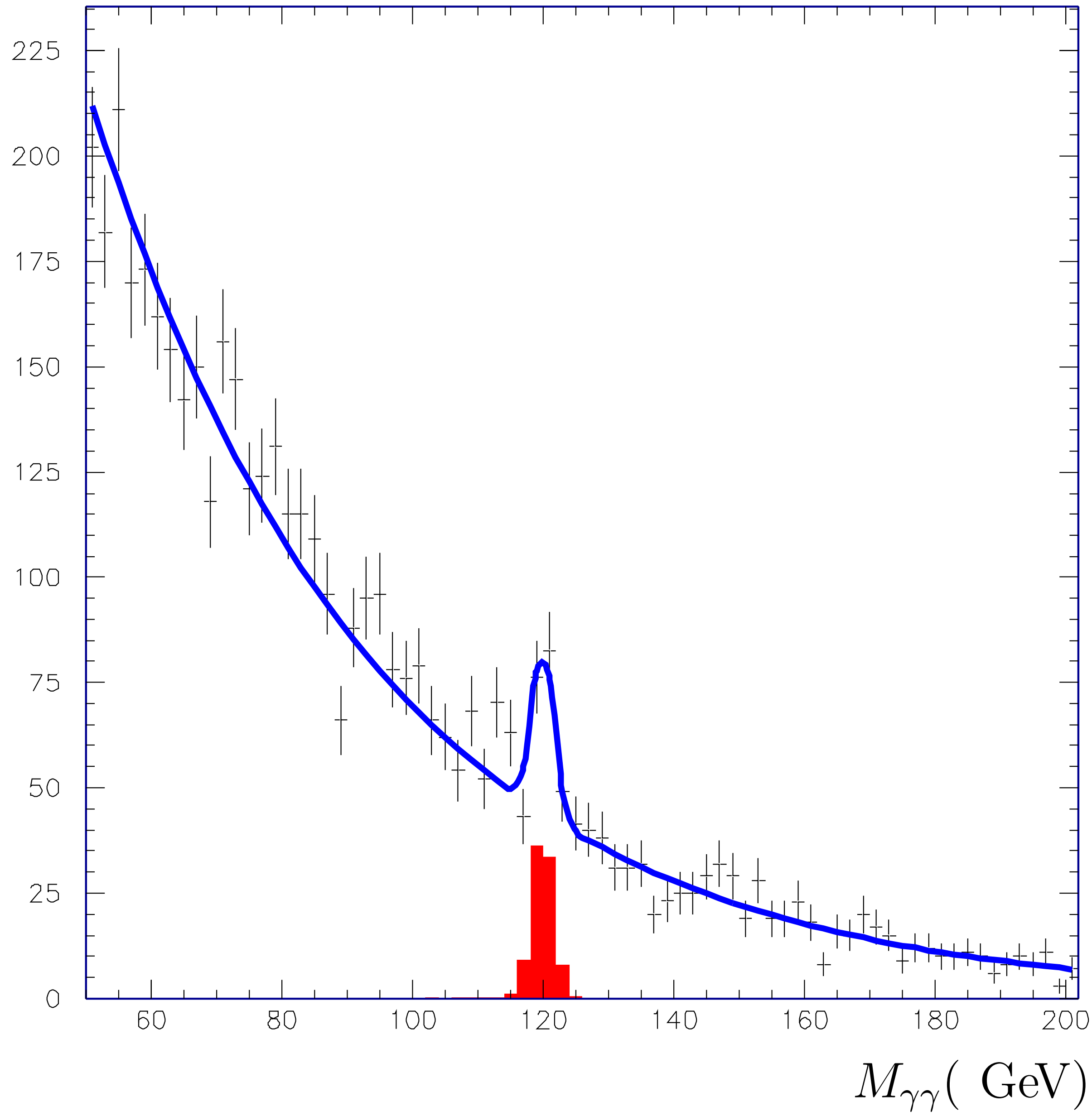


$\sigma(e^+e^- \to WW\nu\bar{\nu})$

Γ_H accuracy

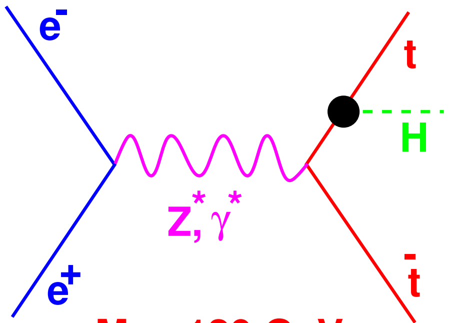
$(\sqrt{s} = 500\ \mathrm{GeV}, 500\ \mathrm{fb}^{-1})$

Total Width Measurement for $m_{\rm H} = 120$ GeV

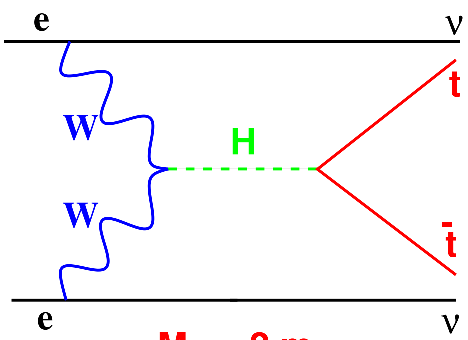


Inputs	$\Delta\Gamma_{\rm H}/\Gamma_{\rm H}$
$e^+e^- \to WW\nu\bar{\nu}$ and $H \to WW^*$	**5.7%**
$e^+e^- \to HZ$ and $H \to WW^*$	**5.6%**
$\gamma\gamma \to H$ and $H \to \gamma\gamma$	**19%**

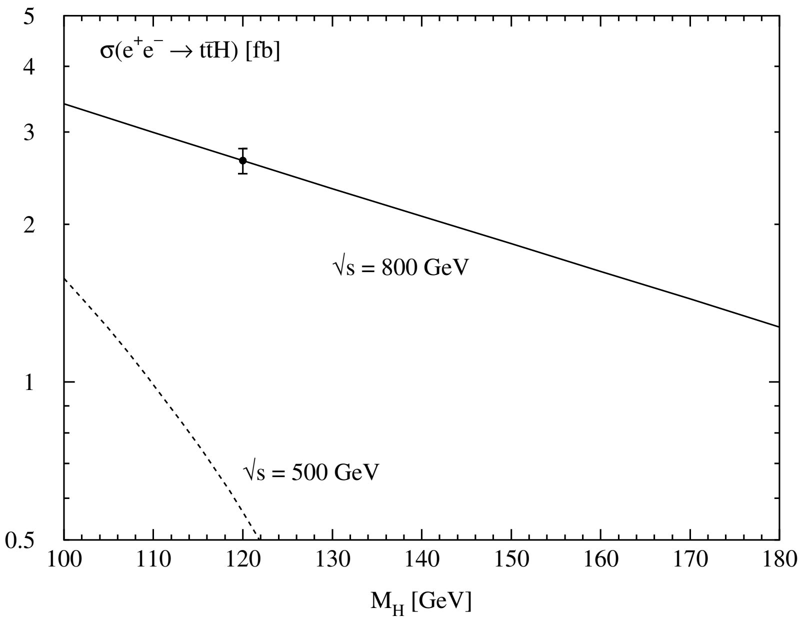
$Ht\bar{t}$ *Coupling*

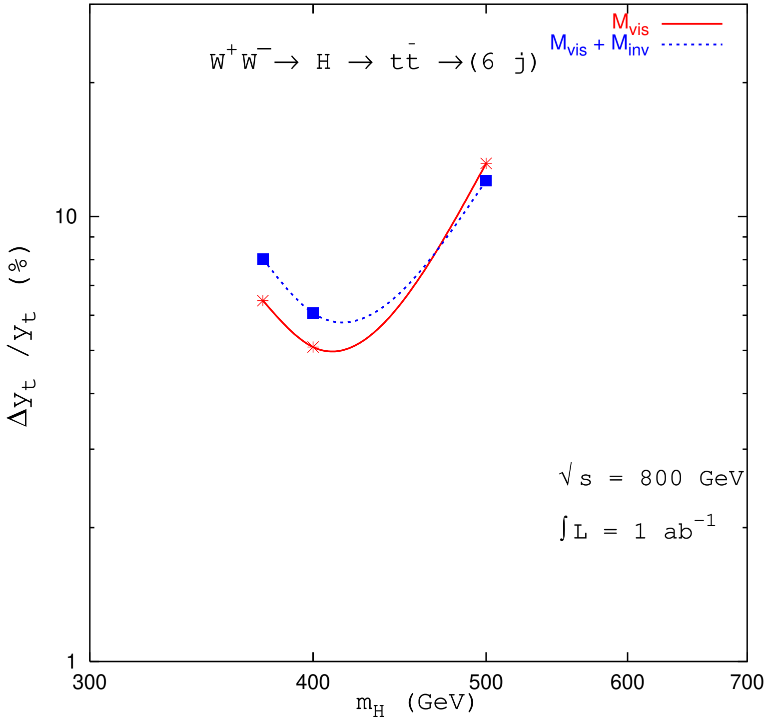


$M_H = 120$ GeV



$M_H > 2\ m_t$

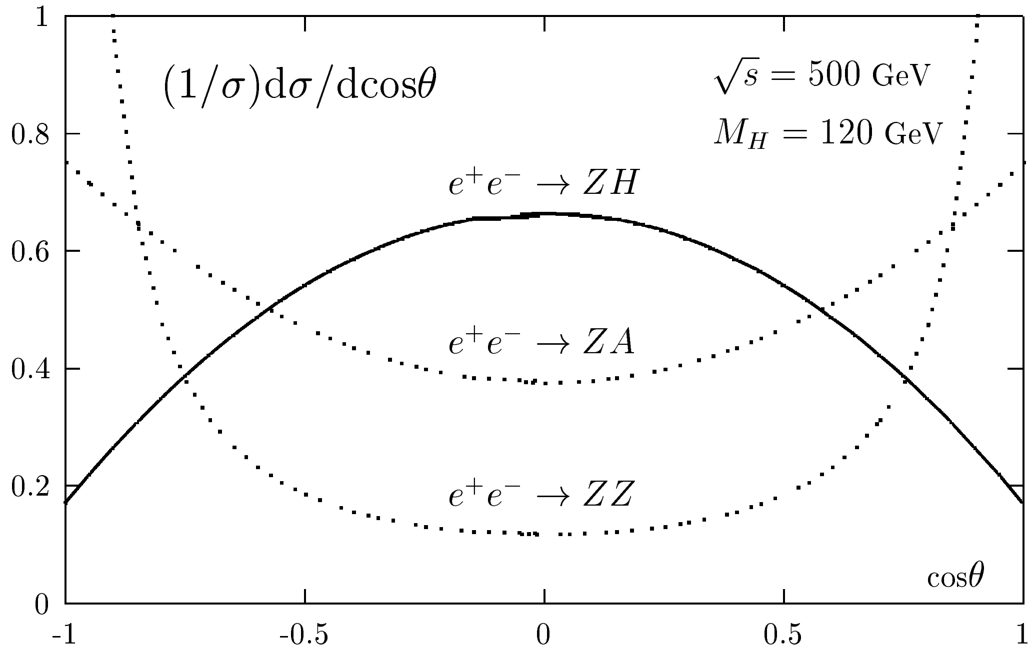




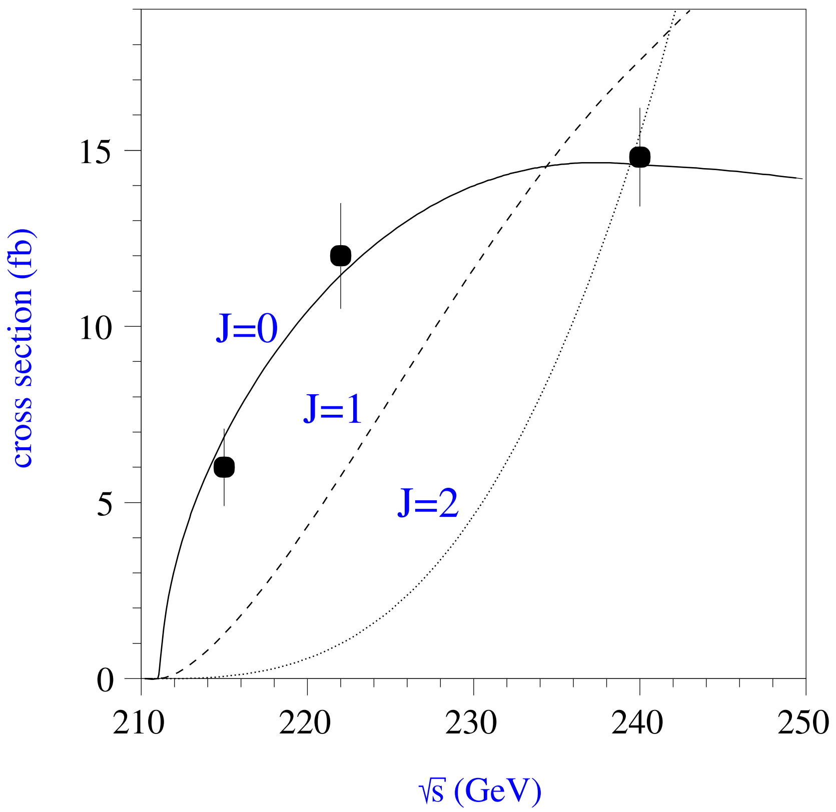
$< 10\%$ precision !!

Not possible at the LHC !!

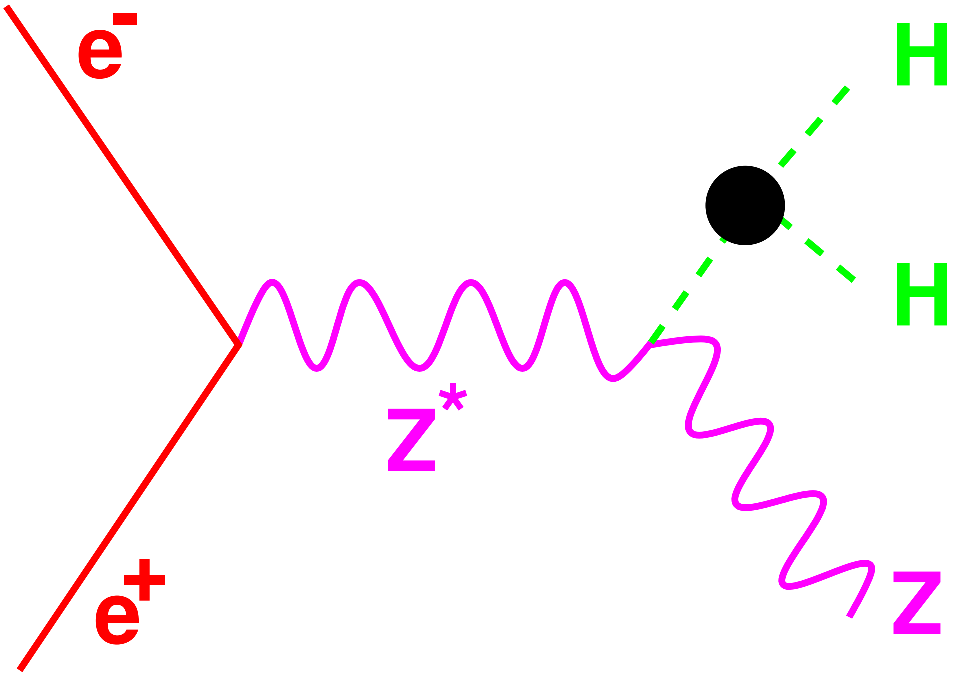
Is the Higgs a pure 0^{++} state?



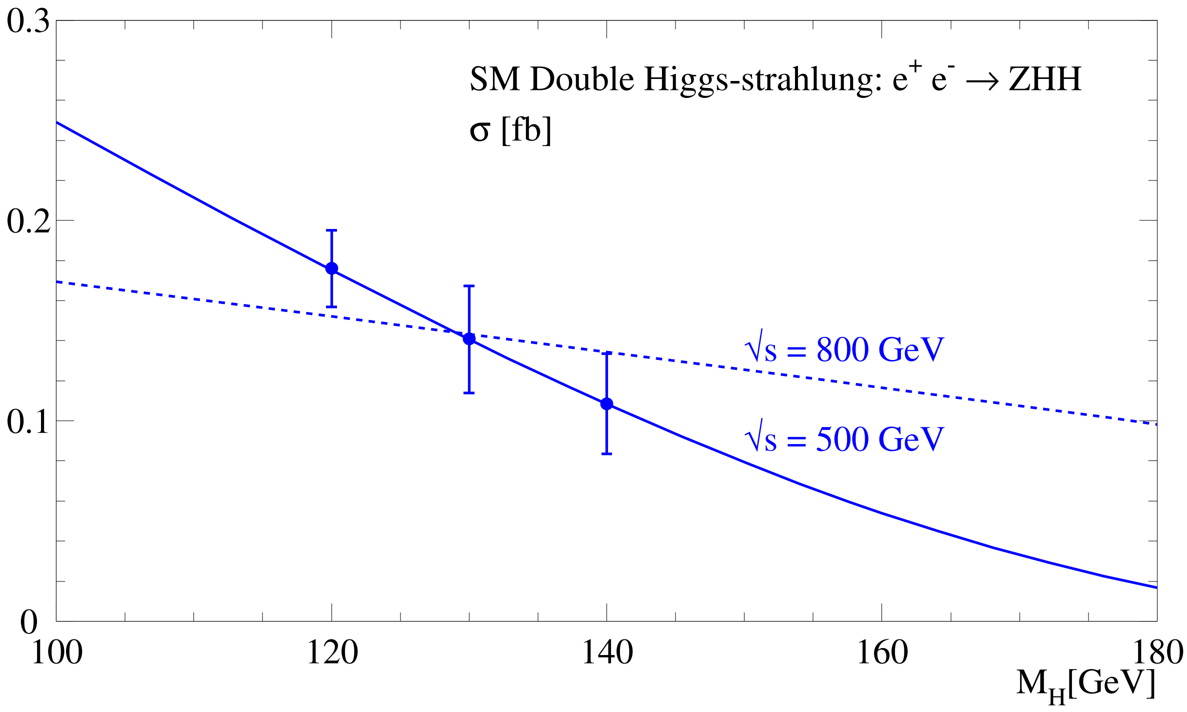
a) $\mathrm{e^+e^-} \to \mathrm{HZ}$ angular distribution



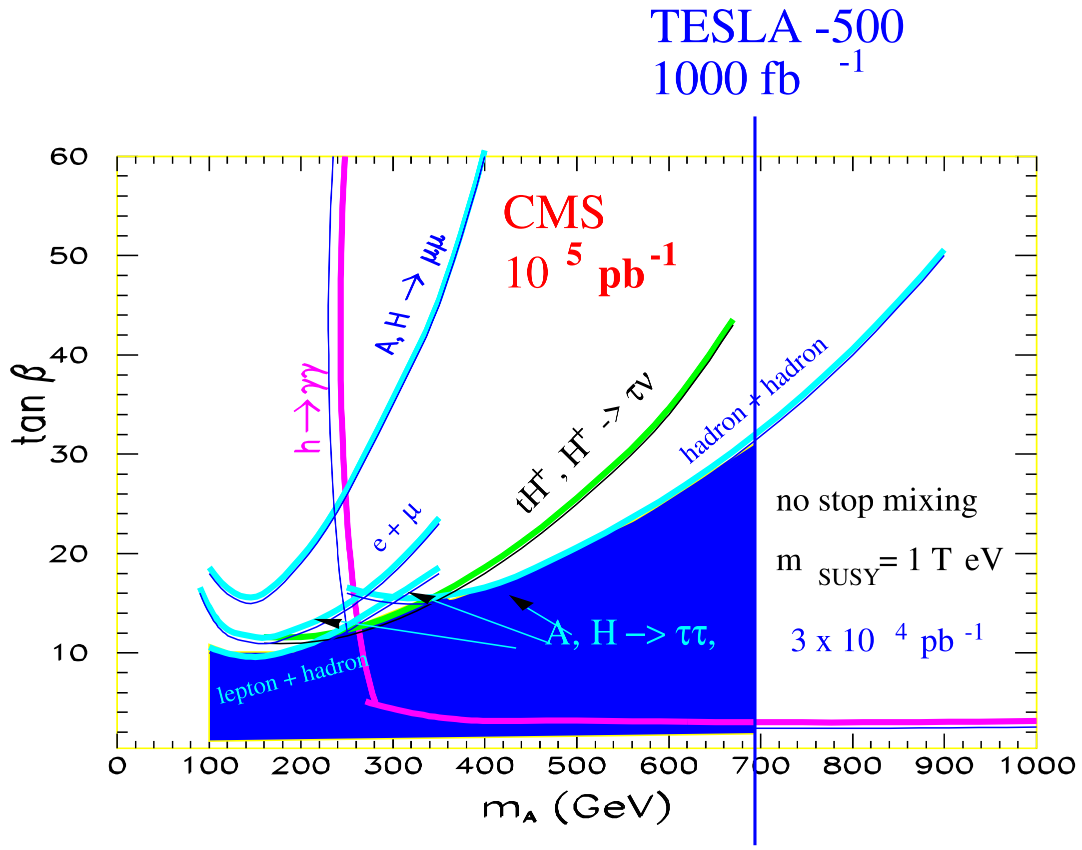
b) $\sigma(\mathrm{e^+e^-} \to \mathrm{HZ})$ at threshold

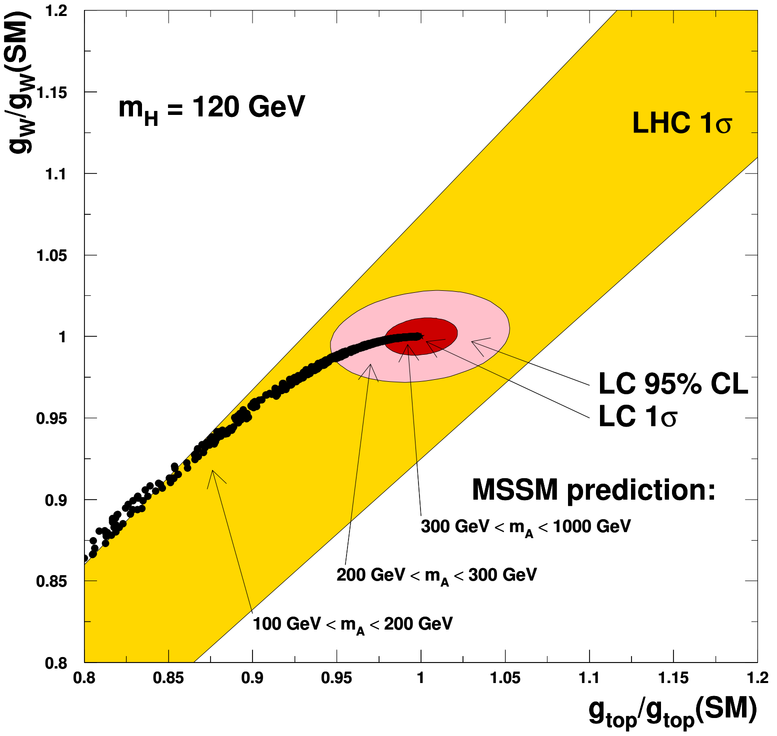


$$V=\lambda v H^2+\lambda v H^3+\frac{1}{4}\lambda H^4$$



Difficult Measurement, but very important


TESLA -500
1000 fb -1
CMS
10 5 pb -1
tan β
m_A (GeV)
h→γγ
A, H → μμ
e + μ
tH+, H+ -> τν
hadron + hadron
lepton + hadron
A, H -> ττ,
no stop mixing
m SUSY= 1 T eV
3 x 10 4 pb -1


m_H = 120 GeV
LHC 1σ
LC 95% CL
LC 1σ
MSSM prediction:
300 GeV < m_A < 1000 GeV
200 GeV < m_A < 300 GeV
100 GeV < m_A < 200 GeV
g_W/g_W(SM)
g_top/g_top(SM)

Measurement	Typical Precision at LC
Mass	**50 MeV**
Total Width	**6%**
Partial Widths	few %
Spin and Parity	YES
Higgs Self-couplings	**15%** ?

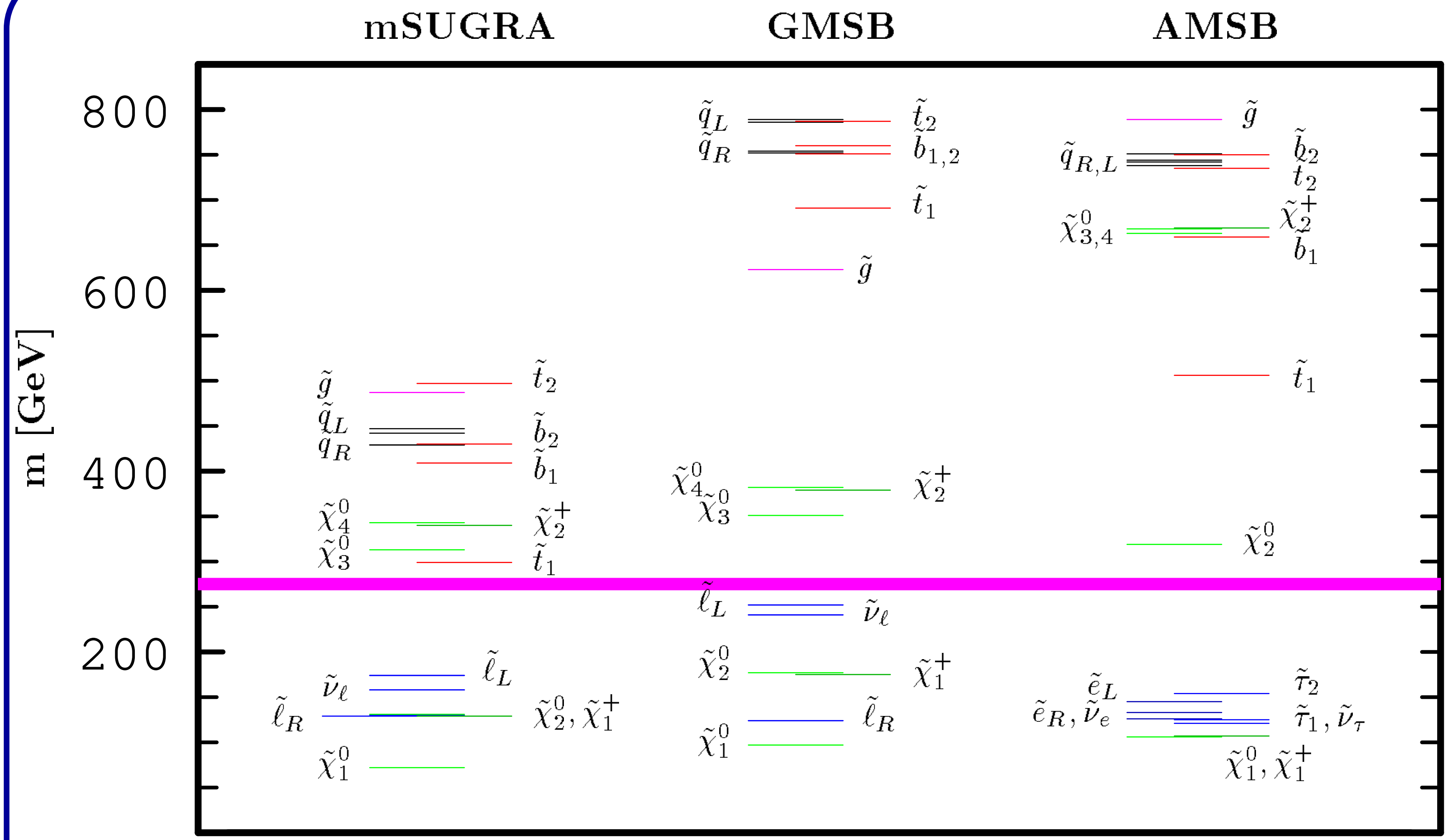
Measurement	What for ?	At LHC
Mass	Test validity of SM	OK
Total Width	Missing decays, new physics?	Maybe
Partial Widths	Mass, which new physics?	Some
Spin and Parity	CP-odd mixture?	?
Higgs Self-couplings	Test of the Higgs mechanism	NO

	Spin 0	Spin $\frac{1}{2}$ Weak Eig.	Spin $\frac{1}{2}$ Mass Eig.	Spin 1
Matter	$\tilde{\nu}$ $\tilde{\ell}$ $\tilde{q}$	ν_{MNS} ℓ_{MNS} q_{CKM}	ν ℓ q	
Interactions	$H^\pm$ h, H, A	$\tilde{g}$ $\tilde{H}^\pm, \tilde{W}^\pm$ $\tilde{h}_u^0, \tilde{h}_d^0, \tilde{W}^0, \tilde{B}^0$	$\tilde{\chi}_i^\pm$ $\tilde{\chi}_i^0$	g $W^\pm$ Z, γ

- It implies the existence at least two Higgs doublets
- Duplication of the number of particles: fermions $\leftrightarrow$ bosons

- Good theoretical arguments for SUSY at the TeV scale
- Price to pay: many unknown parameters and new problems

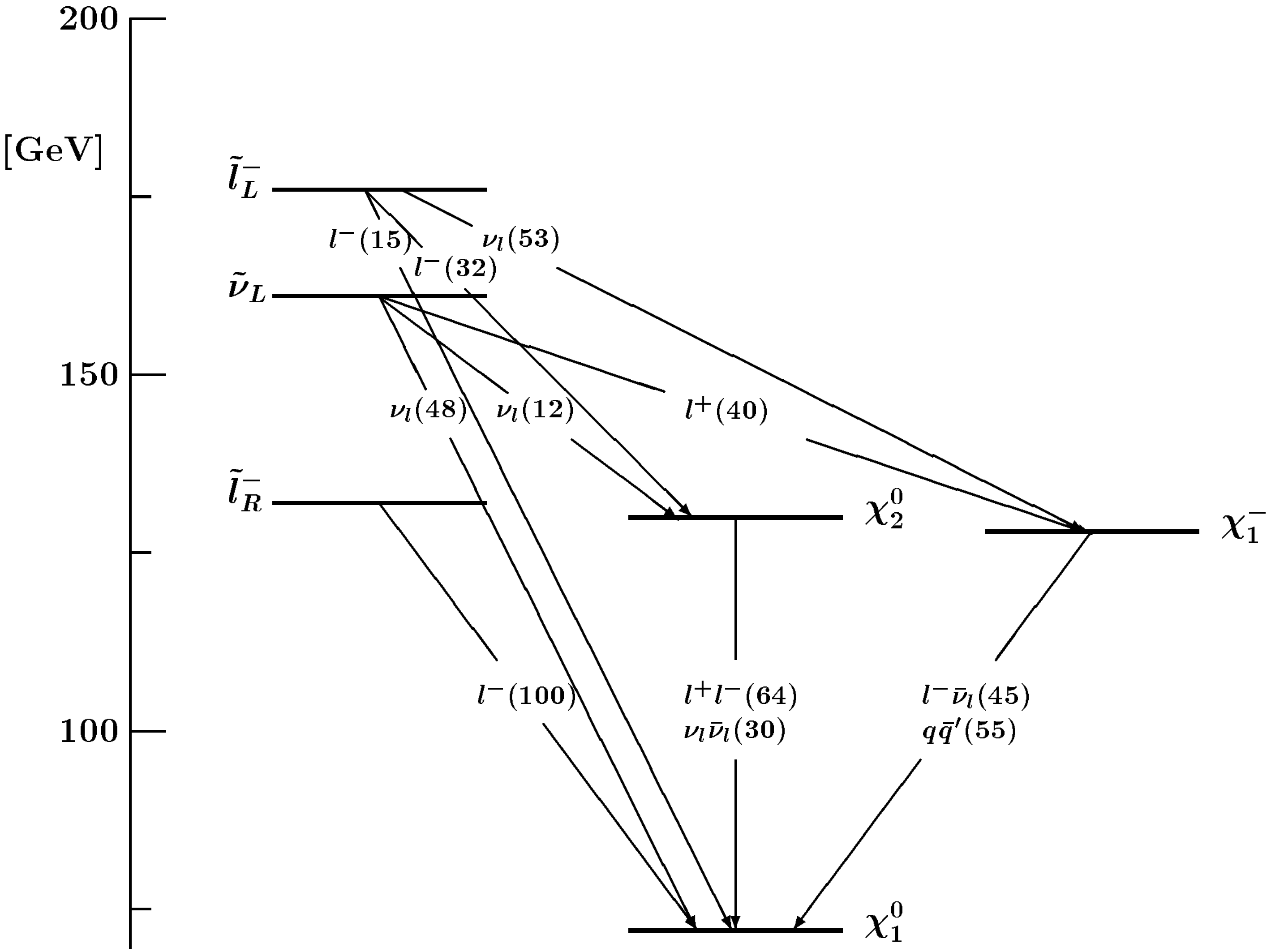
MSSM at the LC



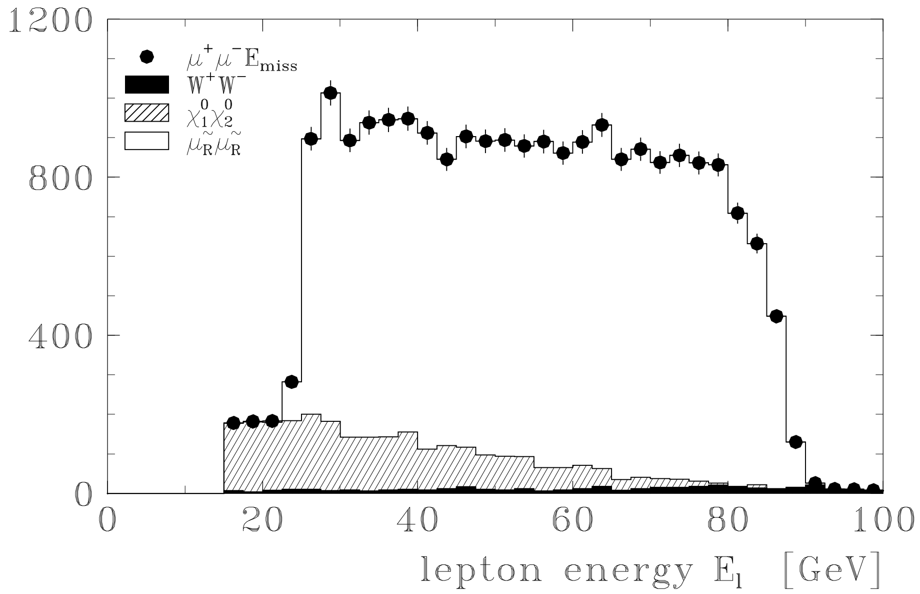
$\sqrt{s} \approx 500$ GeV: Search for sleptons, neutralinos and charginos

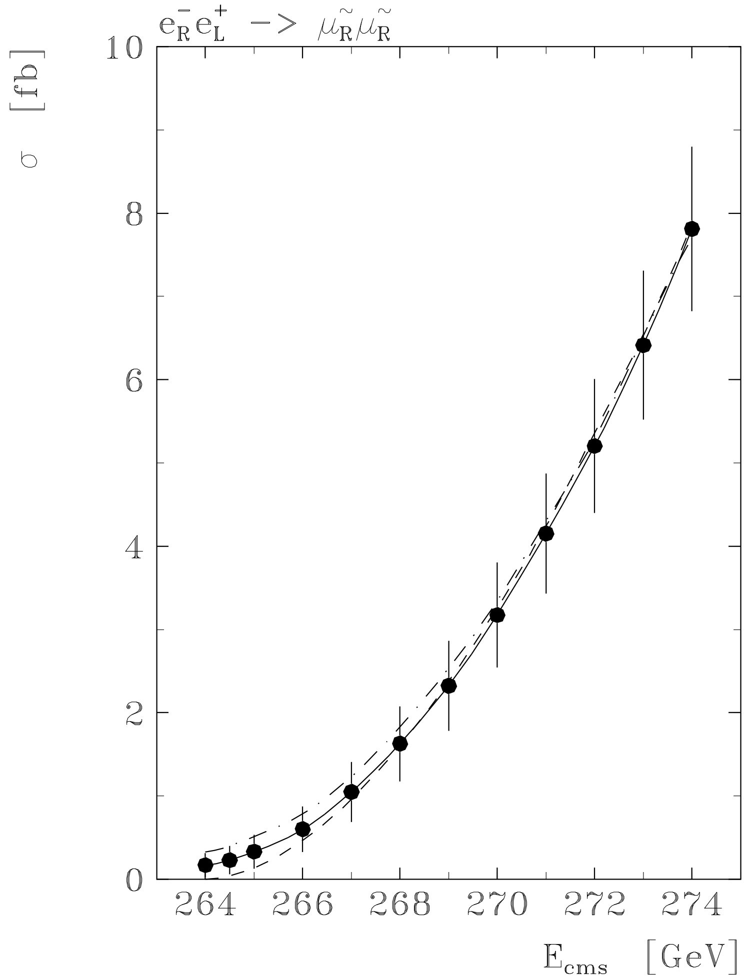
High Precision Spectroscopy $\rightarrow$ Establish the SUSY scenario

MSSM Spectroscopy at the LC



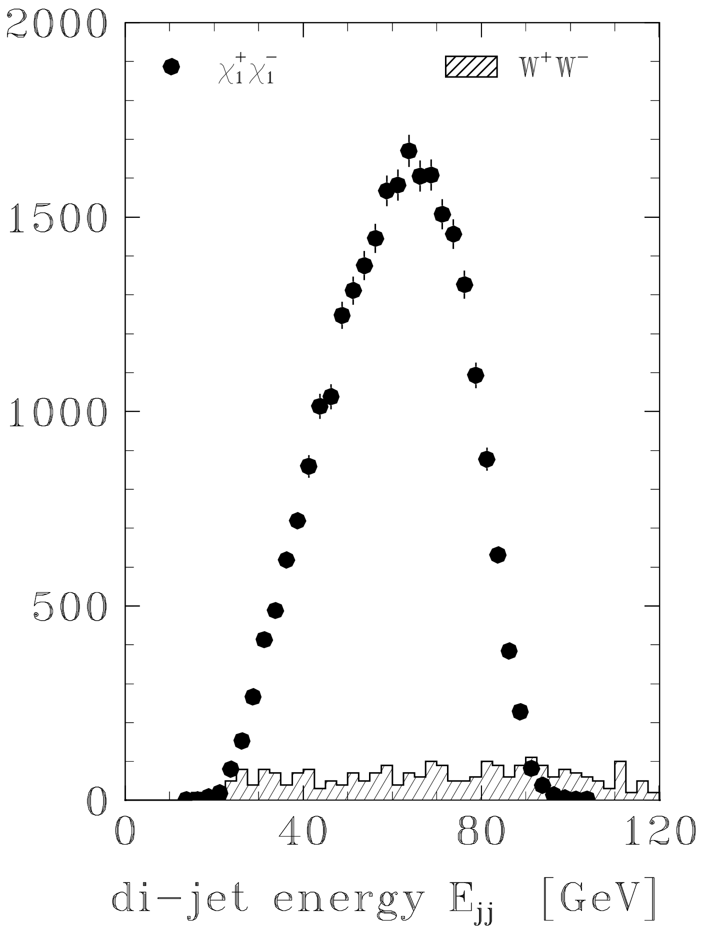
$$e^-_R e^+_L \to \tilde{\mu}_R \tilde{\mu}_R \to \mu^+\mu^- \tilde{\chi}^0_1 \tilde{\chi}^0_1$$





- End-points $\to m_{\tilde{\mu}_R}, m_{\tilde{\chi}^0_1}$
- Threshold scan $\to m_{\tilde{\mu}_R}$
- Mass precision $\approx 0.1\%$
- Beam polarization is useful ($P_{e^-} \approx 80\%, P_{e^+} \approx 60\%$?)

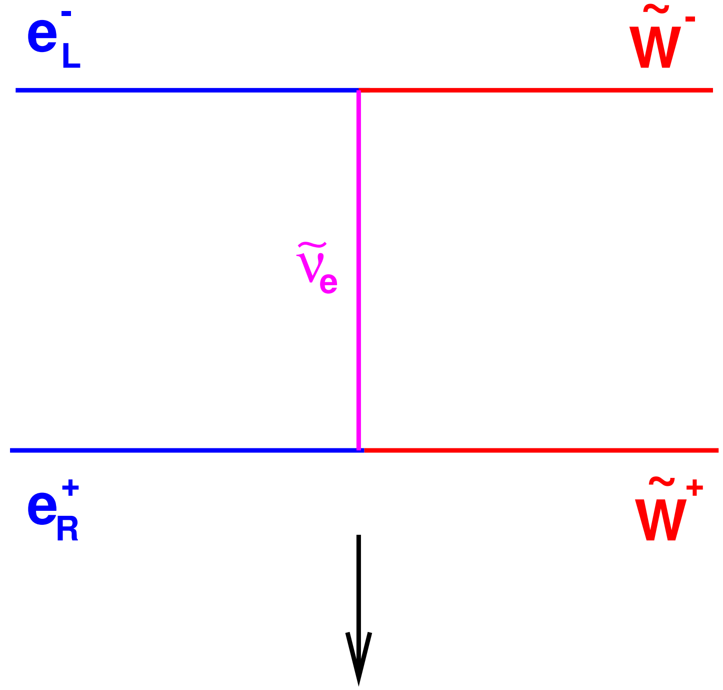
$$e^-_L e^+_R \to \tilde{\chi}^-_1 \tilde{\chi}^+_1 \to \ell^\pm \nu \tilde{\chi}^0_1 q\bar{q}' \tilde{\chi}^0_1$$



$$\delta m_{\tilde{\chi}^-_1} \approx 200 \text{ MeV}$$

$$e^- e^+ \to \tilde{\chi}^-_i \tilde{\chi}^+_j$$

Acces to $\tilde{W}^-$-$\tilde{H}^-$ mixing by varying the beam polarization

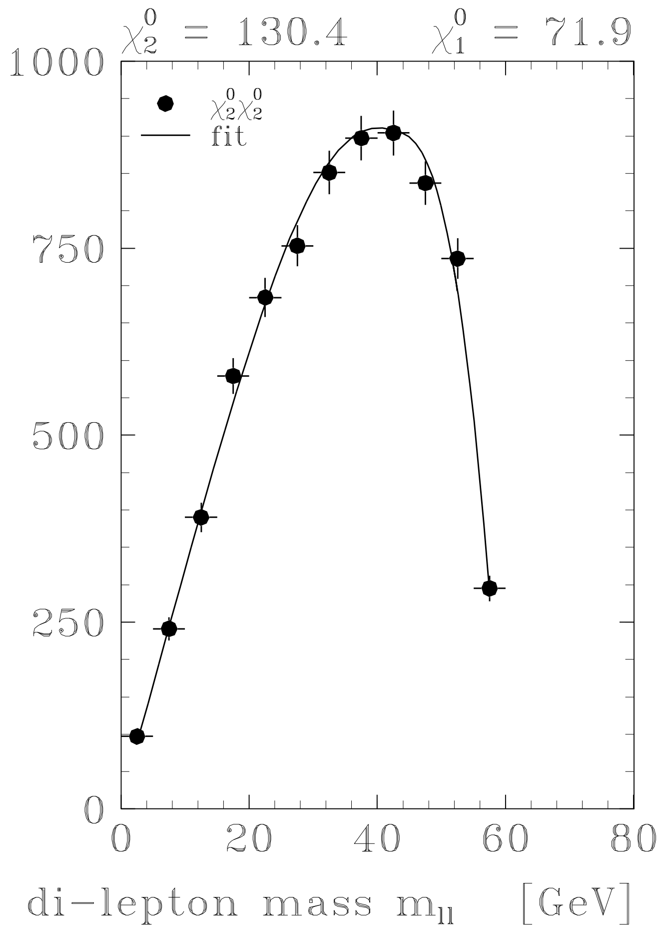


Measurement of tanβ , μ , M_2

$$\delta\mu \approx \delta M_2 \lesssim 1\%$$

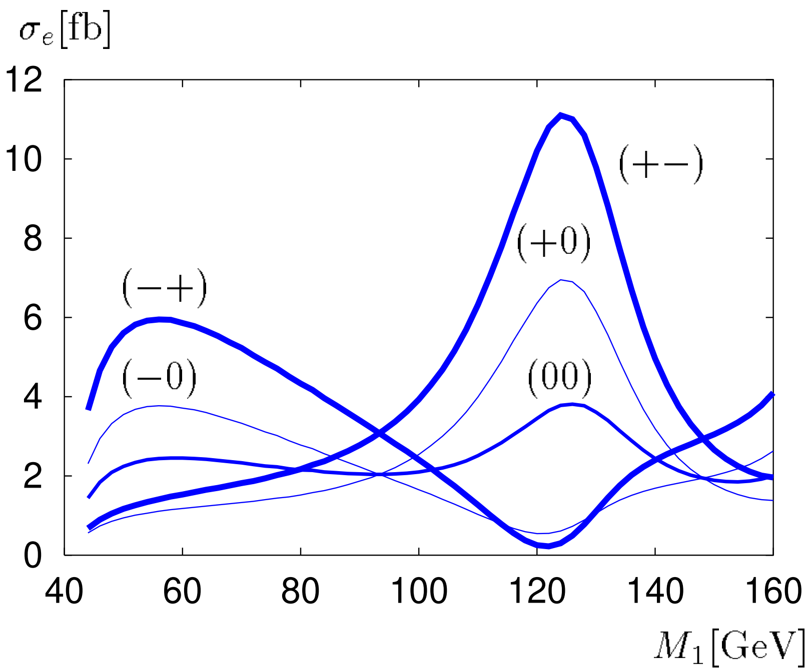
Neutralinos at the LC

$e_L^- e_R^+ \to \tilde{\chi}_2^0 \tilde{\chi}_2^0 \to \ell^+ \ell^- \tilde{\chi}_1^0 \ell^+ \ell^- \tilde{\chi}_1^0$



$\delta m_{\tilde{\chi}^0_{1,2}} \approx 150 - 300$ MeV

$e^- e^+ \to \tilde{\chi}_2^0 \tilde{\chi}_2^0 \to e^+ e^- \tilde{\chi}_1^0 e^+ e^- \tilde{\chi}_1^0$



$\tilde{h}_u^0, \tilde{h}_d^0, \tilde{W}^0, \tilde{B}^0$ mixing in the Neutralino Sector

Sensitive to M_1

More . . .

- Light $\tilde{t}$ searches (may escape detection at hadron colliders)
- $\tilde{\tau}$ decay analyses $\rightarrow$ large $\tan\beta$
- Other MSSM Scenarios: GMSB, AMSB
- R-parity Violation
- e^-e^-, $e^-\gamma$ and $\gamma\gamma$ options
- Non-minimal SUSY

LC versus LHC

- LC: clean environment to identify all SUSY processes separately
- LC: model independent analyses (masses and properties)
- LC: more precise measurements ($\lesssim 1\%$ in many cases)
- LC will complement the LHC information, pointing to a specific scenario beyond the SM
- LHC has a large discovery potential

Real: $e^+e^- \rightarrow \gamma G$

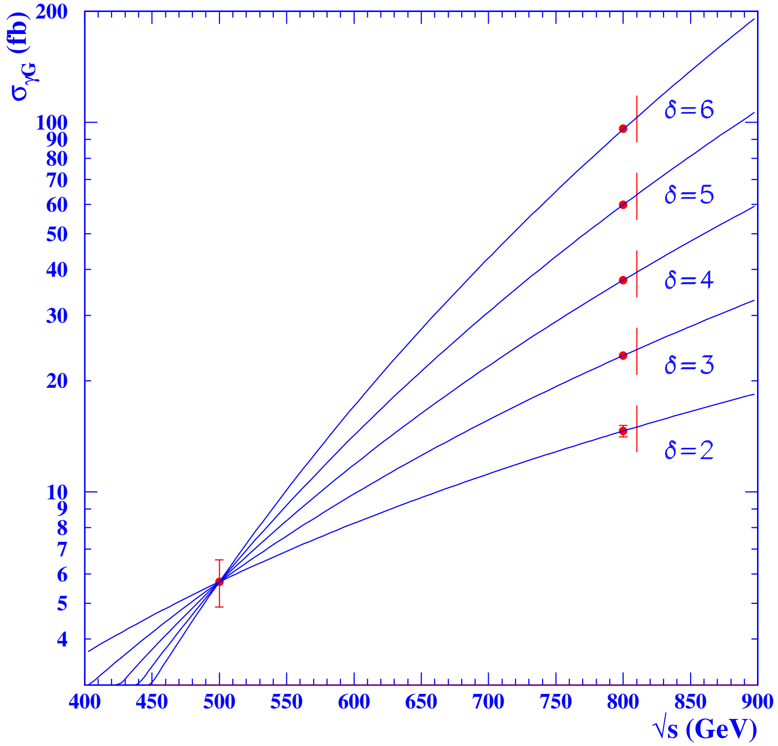
Virtual: $e^+e^- \rightarrow G^* \rightarrow b\bar{b}$

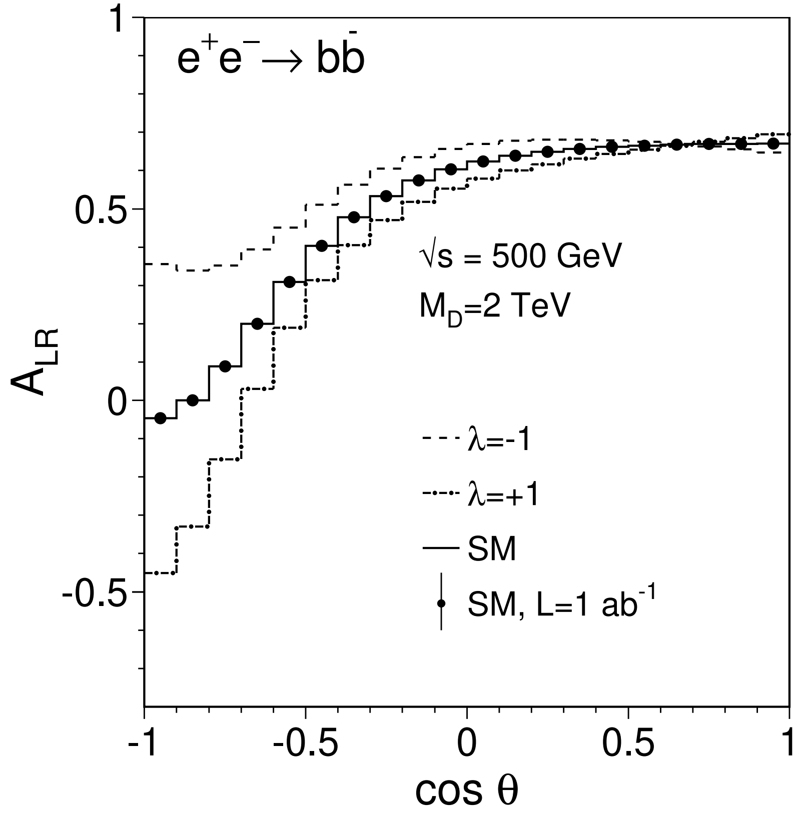
Single Photon Signature

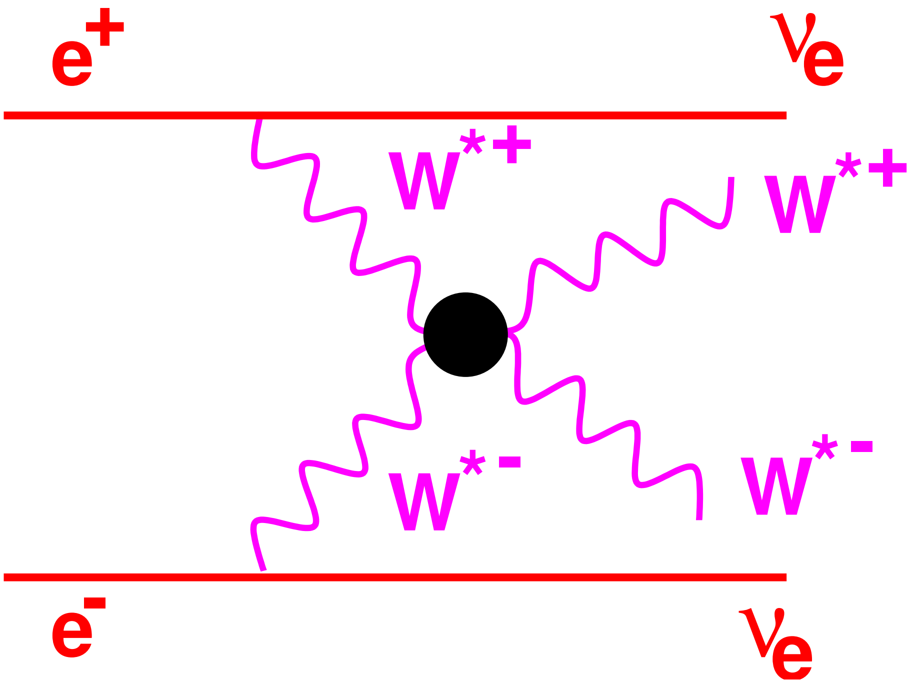
Effects $\propto \frac{\lambda}{M_D^4}$

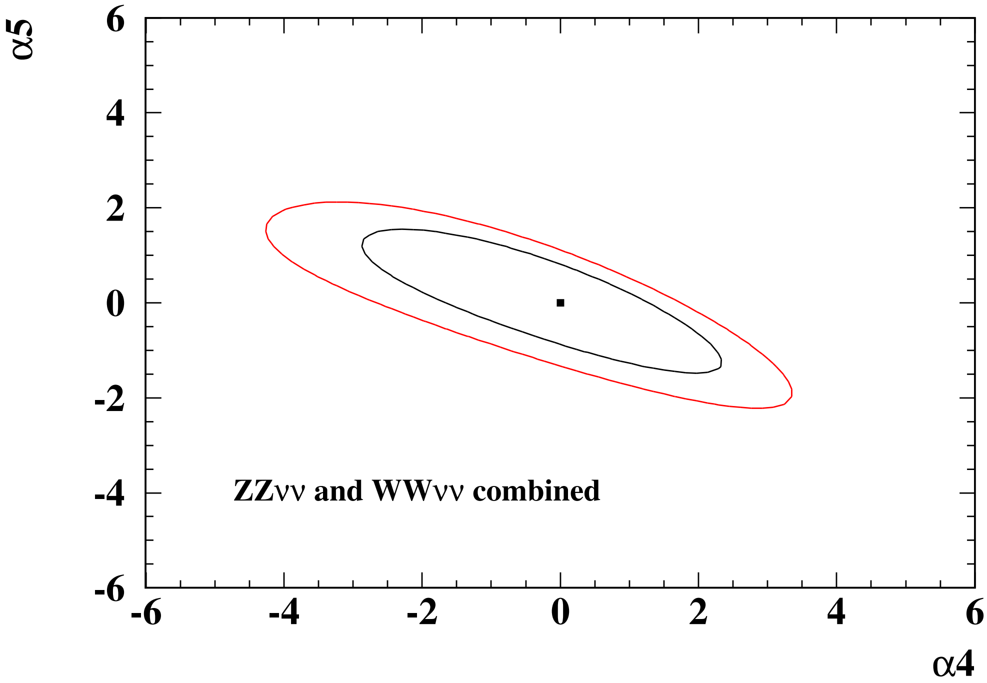
How many dimensions?

Sensitivity to $M_D \lesssim 5$ TeV

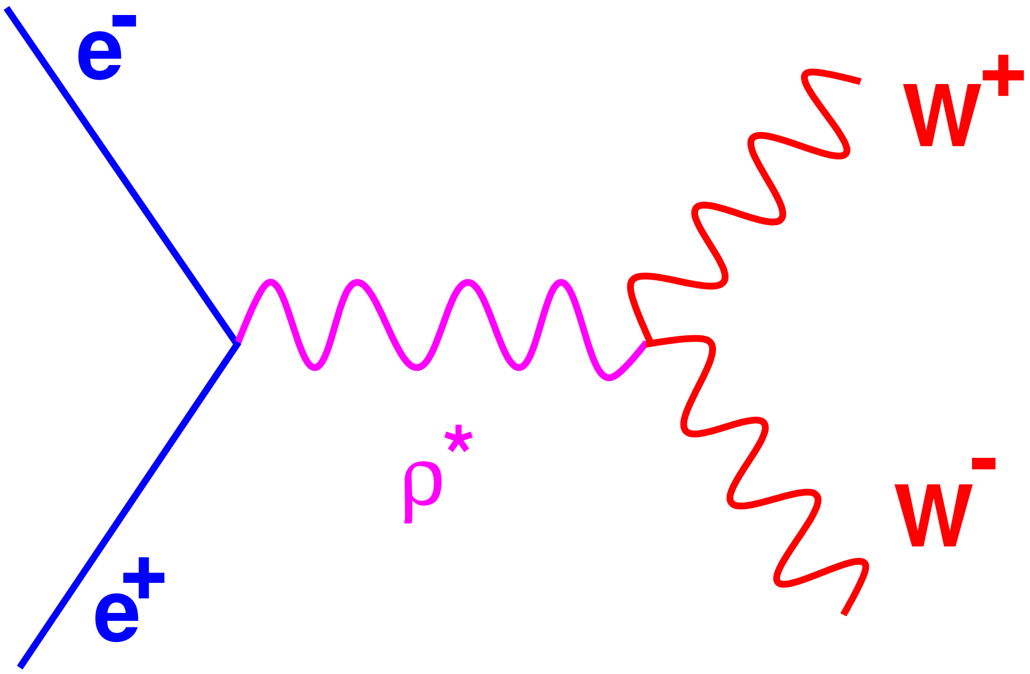




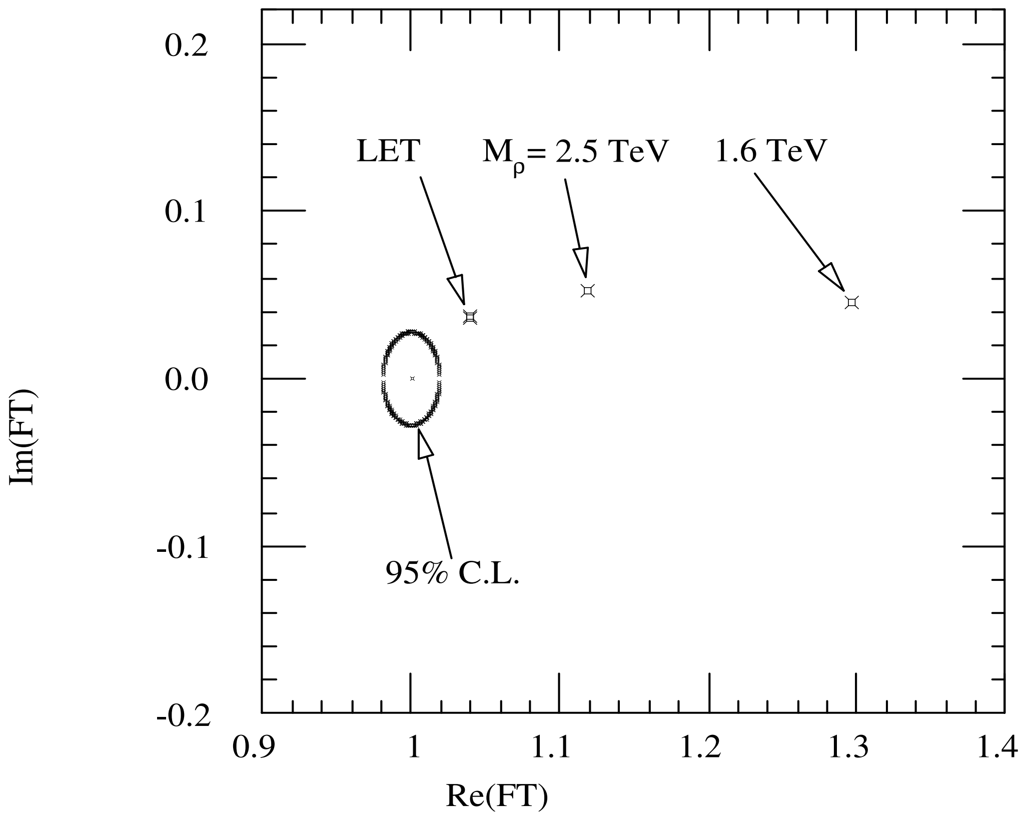




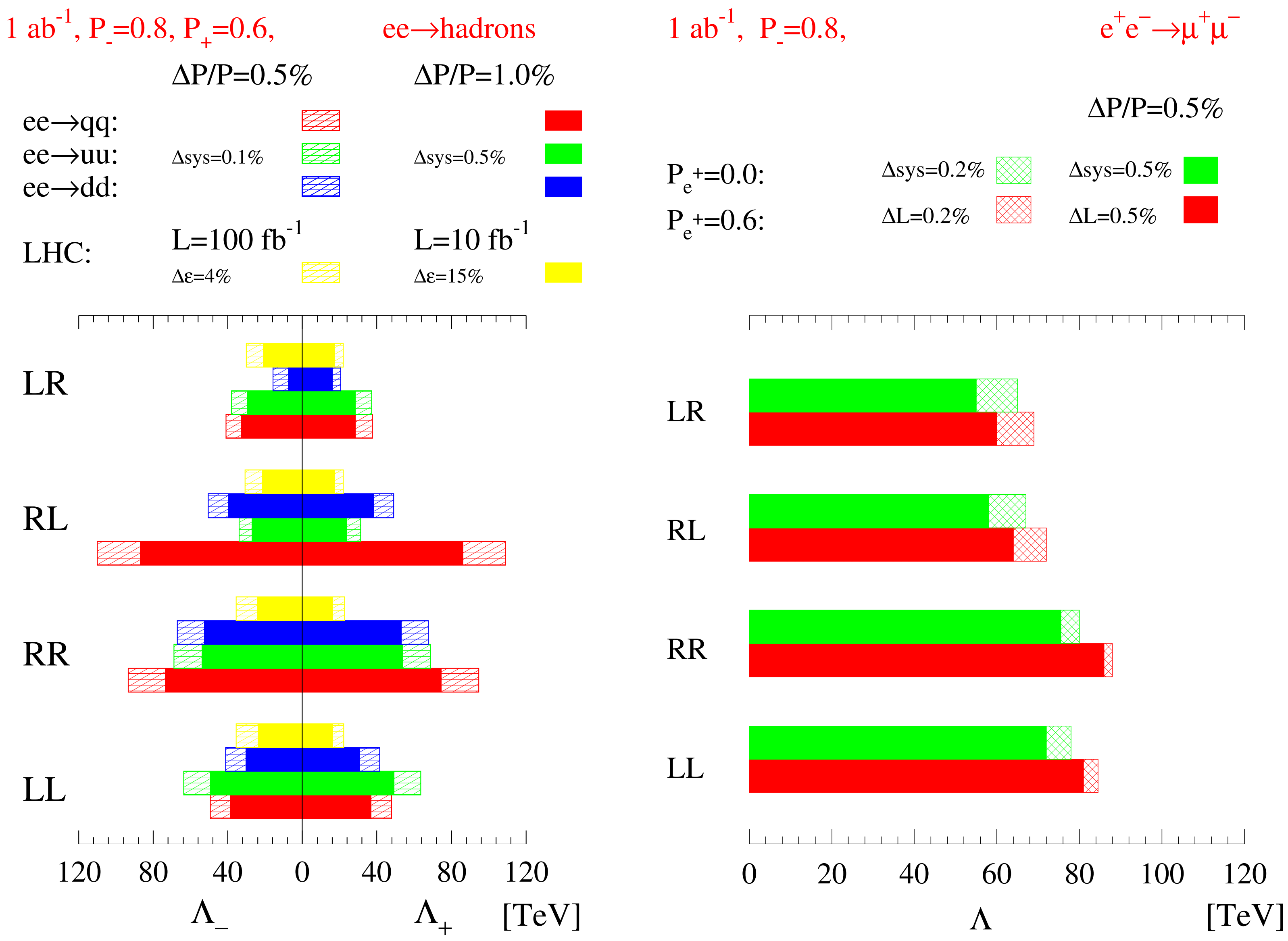
$$\Lambda_4 \lesssim 2 \text{ TeV} \; ; \; \Lambda_5 \lesssim 3 \text{ TeV}$$



ECM=800 GEV L=500 fb^{-1}



Compositeness? Contact $e^+e^-f\bar{f}$ *Interactions*



Physics Interest

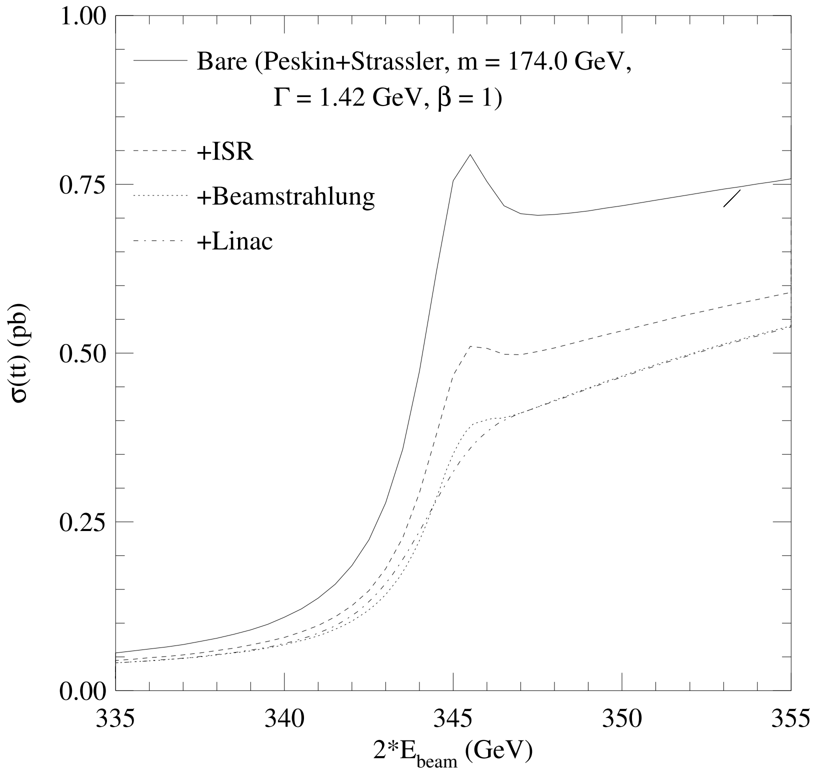
- Large mass, $\sim$ electroweak scale
- Relation with EWSB?
- Relation with Flavour Structure of the SM?

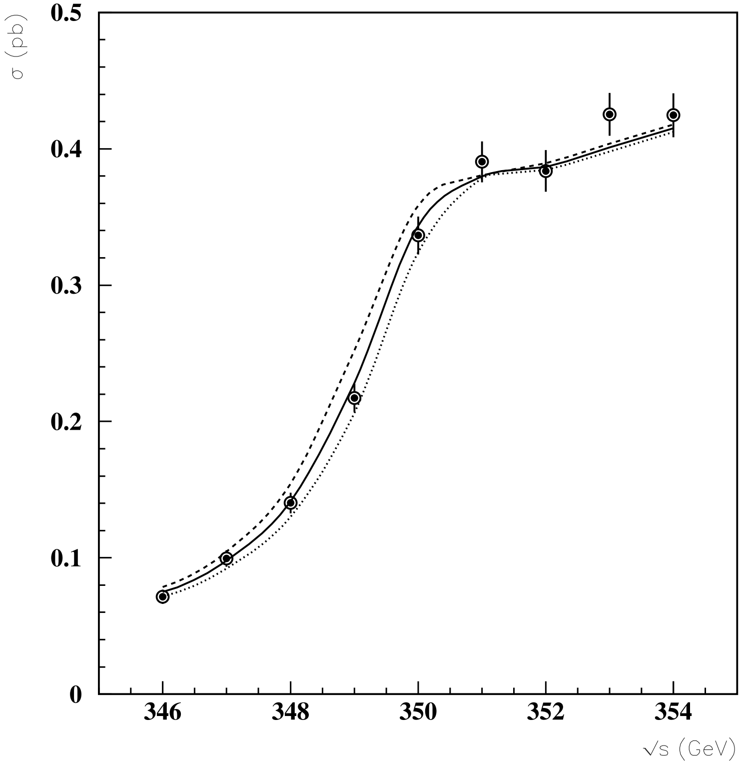
Physics Program

- Top quark Mass and Width at $\mathrm{t\bar{t}}$ Threshold
- Form-factors in Production and Decay
- Search for Rare Top Decays

Experimental Effects

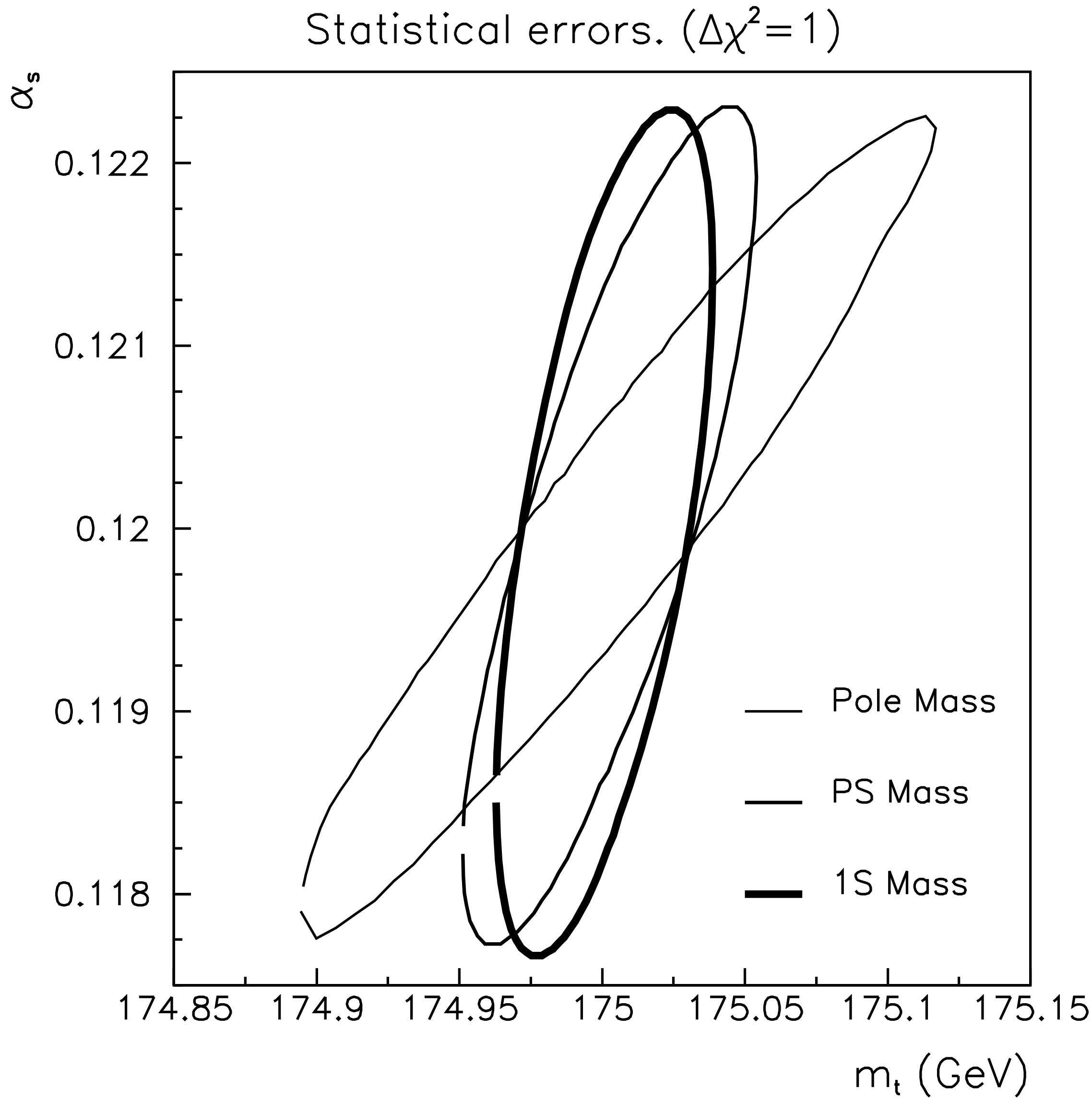
TESLA





- $\Gamma_{\rm t} \gg \Lambda_{QCD} \Rightarrow \tau_{decay} \ll \tau_{resonance}$
- Threshold curve sensitive to $m_{\rm t}$ and α_s
- $< p_{\rm t} > \sim \alpha_s \frac{m_{\rm t}}{2}$

Simultaneous Measurement of m_t and α_s

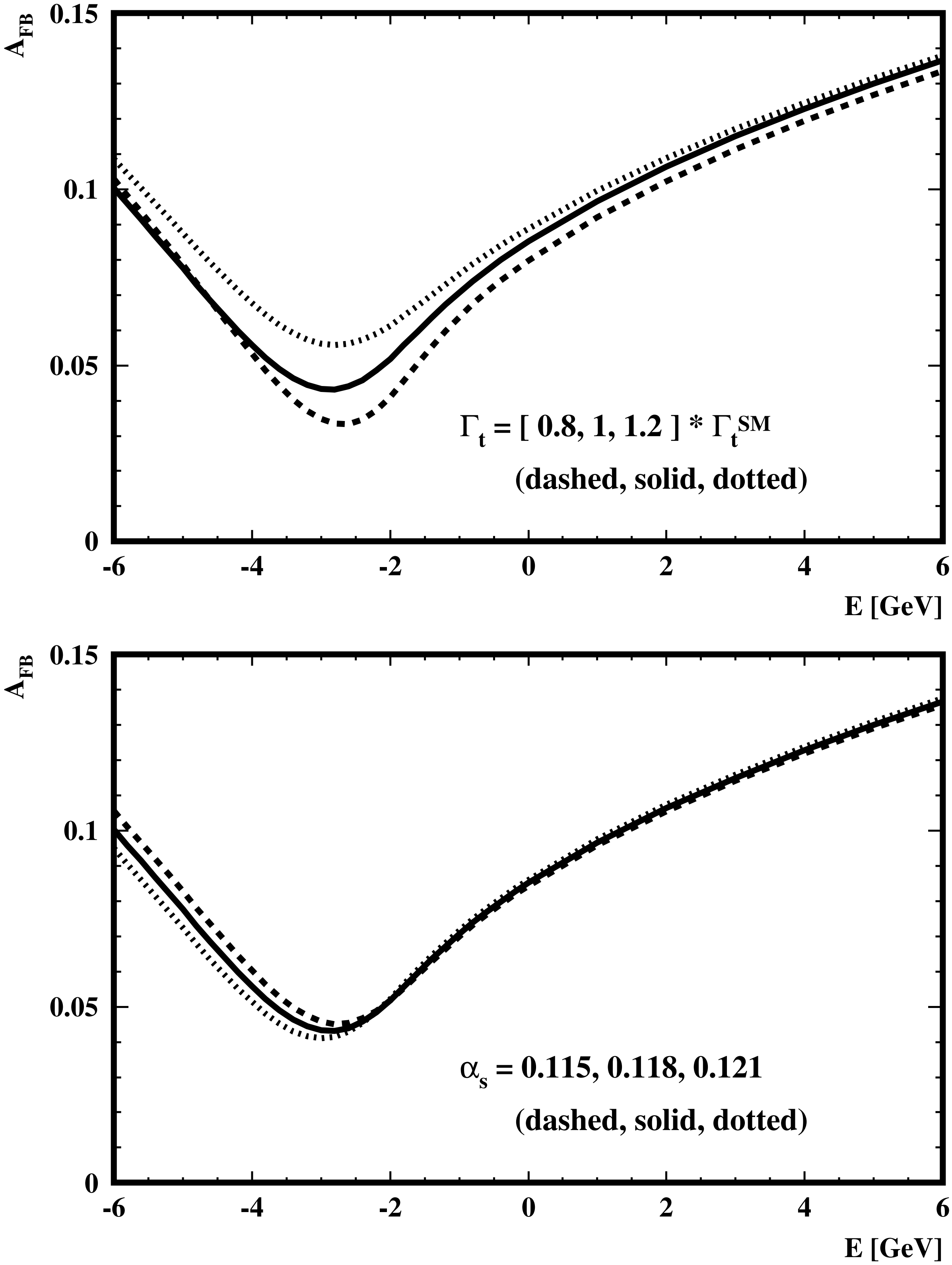


Correlation depends on the mass scheme for the definition of m_t

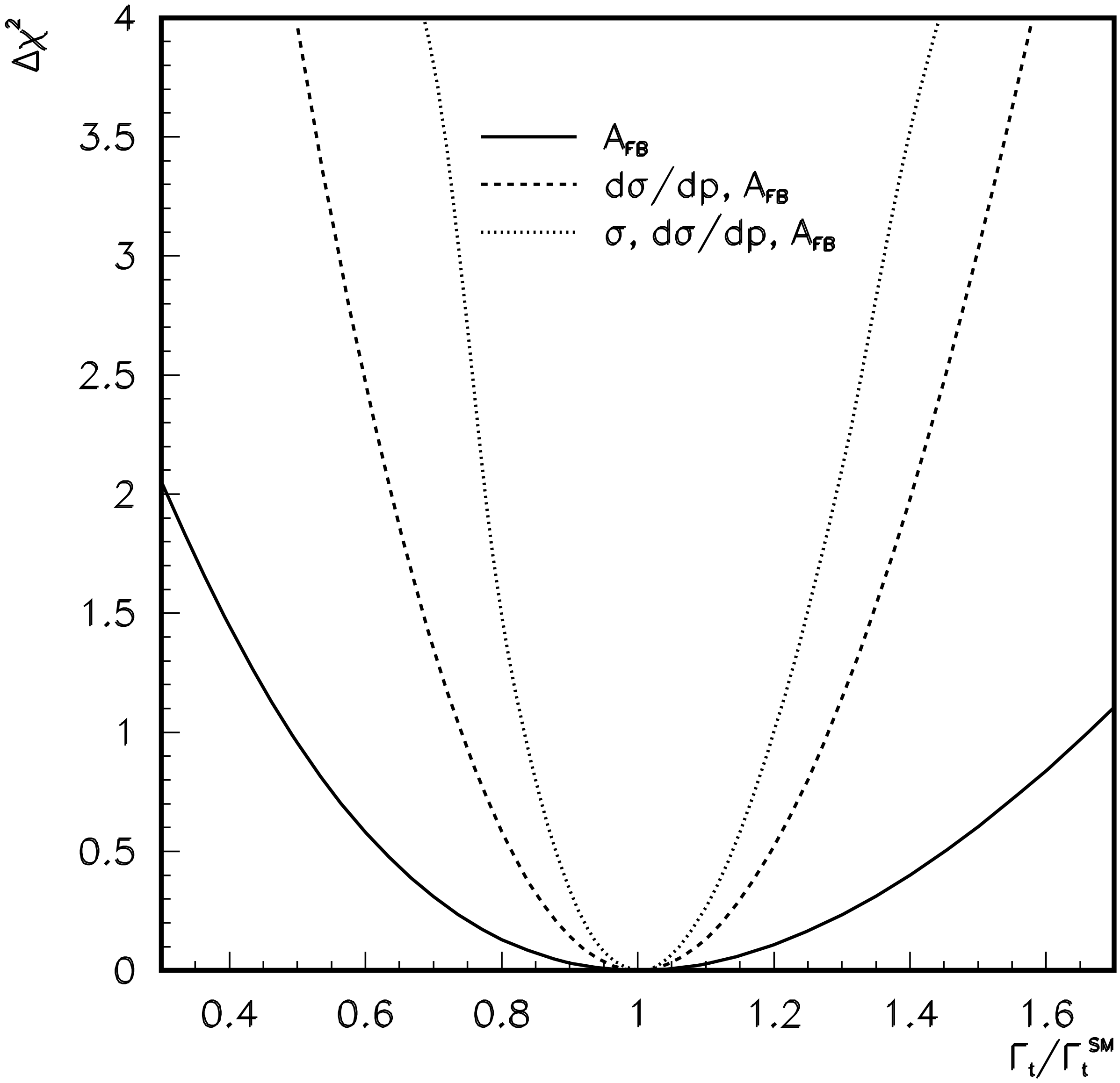
$$(\delta m_\mathrm{t})_{stat} \approx 50 \text{ MeV}, \ (\delta \alpha_s)_{stat} \approx 0.0024$$

But potentially large theory uncertainties for α_s

Measurement of Γ_t

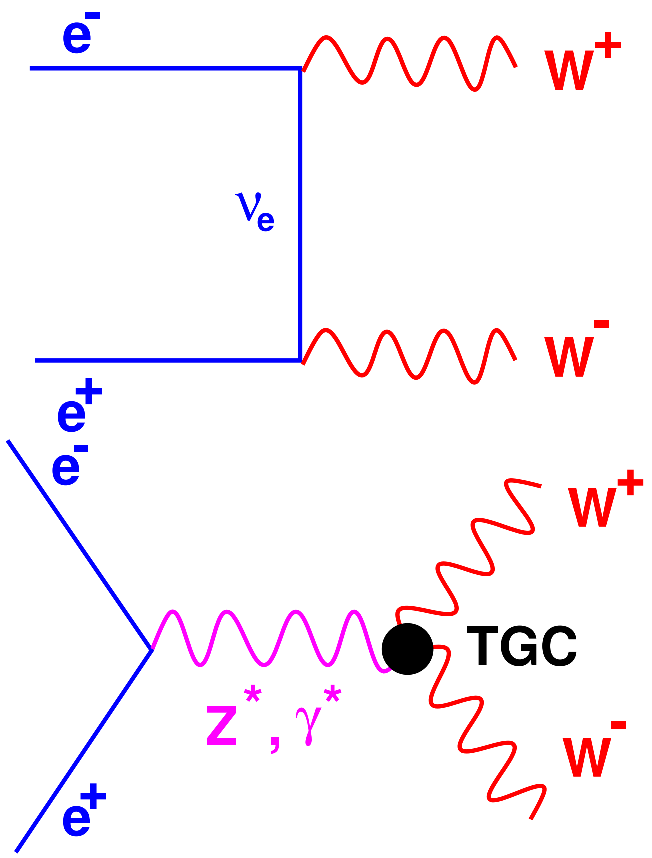


Measurement of Γ_t

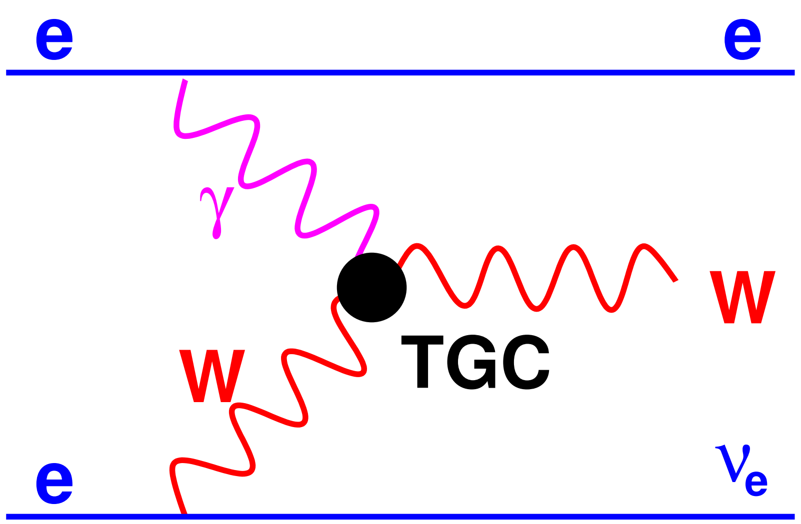


$$\frac{\delta\Gamma_t}{\Gamma_t} \sim 15\%$$

Electroweak Physics. W Production



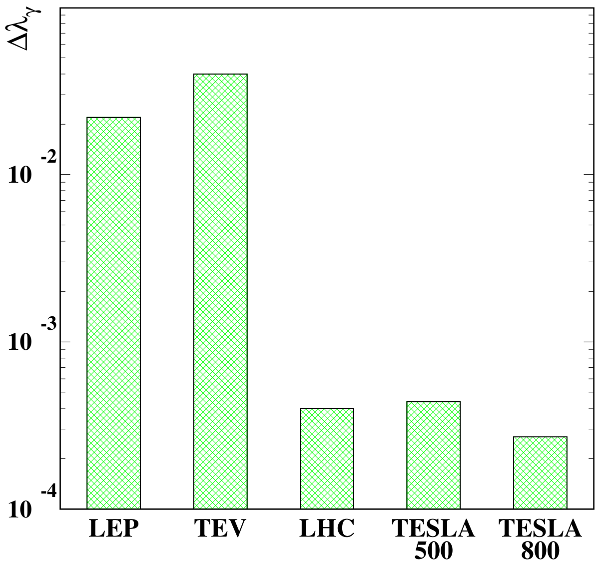
Only V-A Coupling at High Energies

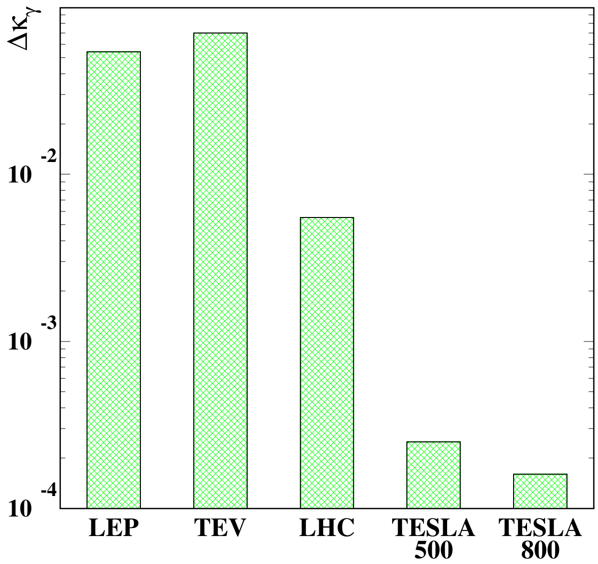


Dominant Process at large $\sqrt{s}$

Anomalous Triple Gauge Couplings at large $\sqrt{s}$

- Sensitivity $\propto \left(\frac{s}{\Lambda}\right)^n$
- Reconstructed level $\simeq$ Generator Level
- Beam Polarization is useful



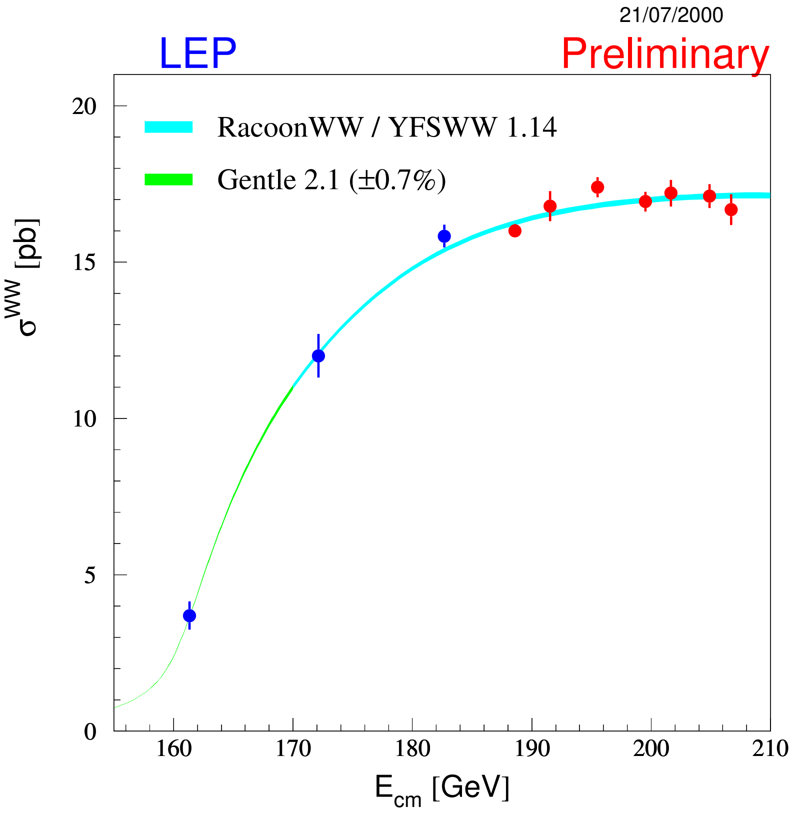


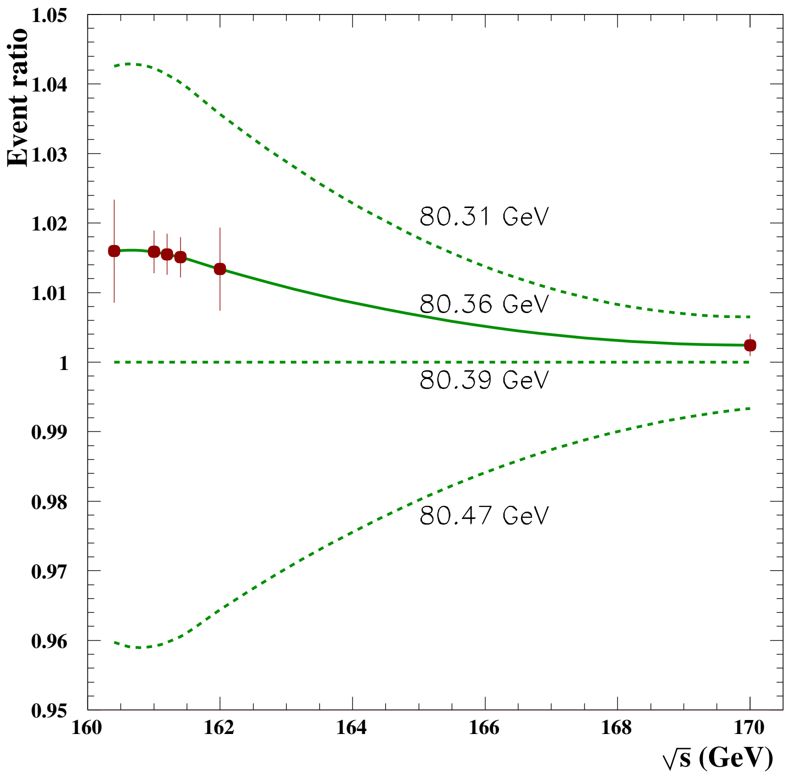
SM contributions to $\Delta\lambda_\gamma, \Delta\kappa_\gamma \sim 10^{-3}$

Back to LEP? GigaZ: 10^9 Z

	LEP/SLC/Tev [?]	TESLA
$\sin^2\theta^{\ell}_{\rm eff}$	0.23146 ± 0.00017	± 0.000013
lineshape observables:		
$m_{\rm Z}$	91.1875 ± 0.0021 GeV	± 0.0021 GeV
$\alpha_s(m_{\rm Z}^2)$	0.1183 ± 0.0027	± 0.0009
$\Delta\rho_\ell$	$(0.55 \pm 0.10) \cdot 10^{-2}$	$\pm 0.05 \cdot 10^{-2}$
N_ν	2.984 ± 0.008	± 0.004
heavy flavours:		
$\mathcal{A}_{\rm b}$	0.898 ± 0.015	± 0.001
$R^0_{\rm b}$	0.21653 ± 0.00069	± 0.00014

One order of magnitude improvement on $\sin^2\theta^{\ell}_{\rm eff}, \mathcal{A}_{\rm b}$



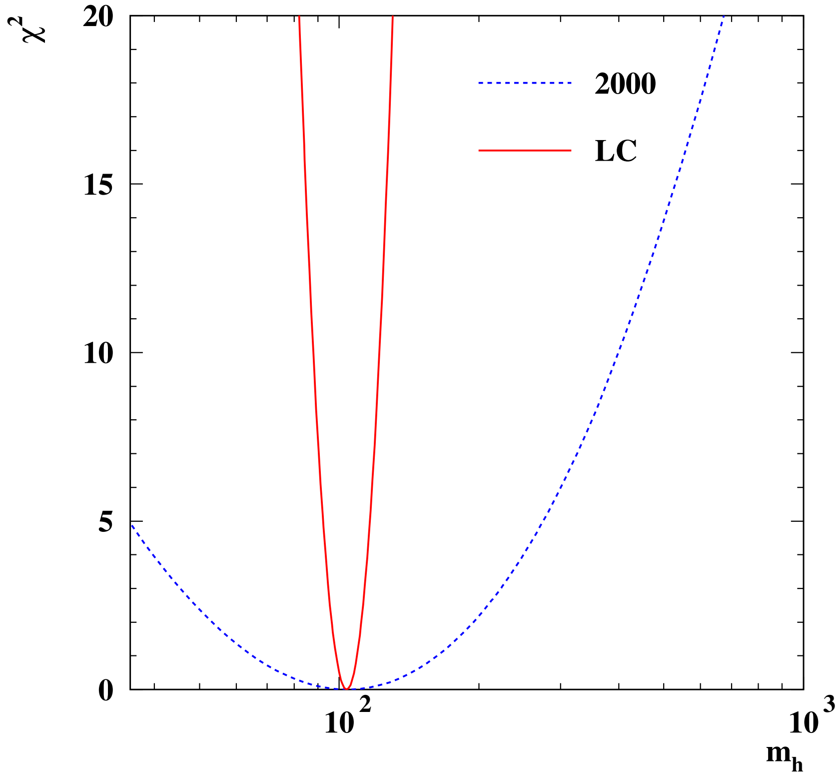


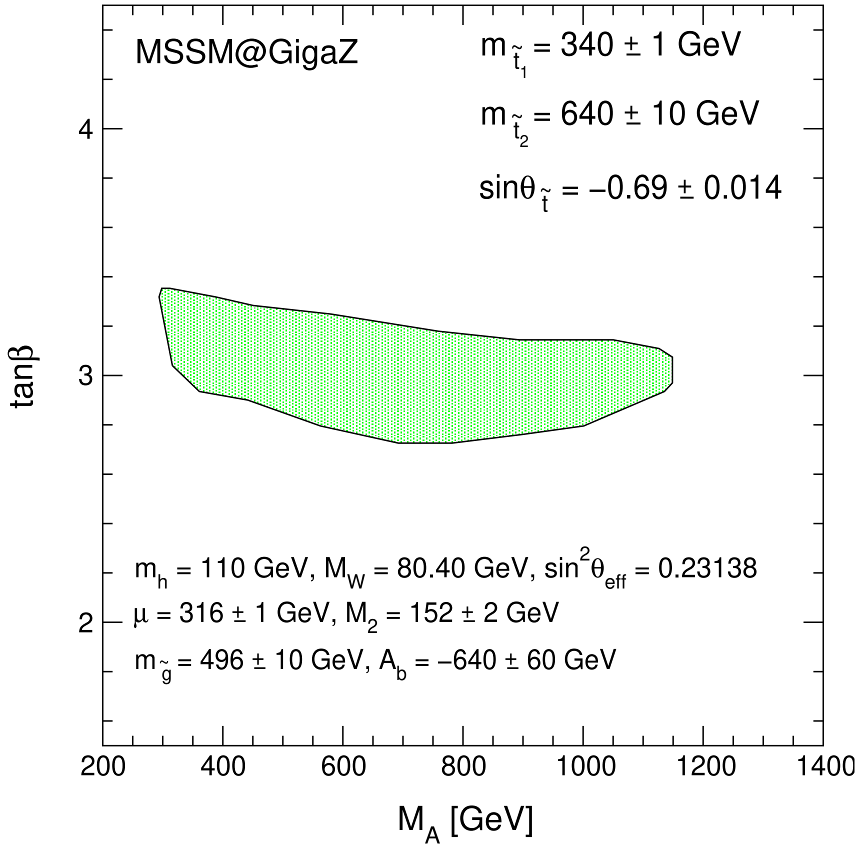
Lack of statistics at LEP
for a threshold scan

at $\sqrt{s} = 161$ GeV

Feasible at TESLA
with 100 fb^{-1}

$\Delta m_W(exp) \approx 6$ MeV


χ^2
20
15
10
5
0
10^2
10^3
m_h
2000
LC


MSSM@GigaZ
$m_{\tilde{t}_1}$ = 340 ± 1 GeV
$m_{\tilde{t}_2}$ = 640 ± 10 GeV
$\sin\theta_{\tilde{t}}$ = −0.69 ± 0.014
m_h = 110 GeV, M_W = 80.40 GeV, $\sin^2\theta_{eff}$ = 0.23138
μ = 316 ± 1 GeV, M_2 = 152 ± 2 GeV
$m_{\tilde{g}}$ = 496 ± 10 GeV, A_b = −640 ± 60 GeV
tanβ
4
3
2
200
400
600
800
1000
1200
1400
M_A [GeV]

Paul Grannis conclusions at LCWS2000

Conclusion

- The physics case for the LC with a 1st stage at ~ 500 GeV is very strong. We need a linear collider to study EWSB in any scenario. We know enough to make the choice now.
- With present lack of understanding of how EWSB is manifested, flexibility of Linear Collider design (energy, $\mathcal{L}$, beam particles) is essential. The LC will be an evolving facility.
- The cost will be high. Unless we internationalize so as to satisfy the needs of all regions and allow productive collaboration, we jeopardize the prospect of the LC, or any other new frontier facility anywhere.