The International Linear Collider – a precision probe for physics in the post-LHC era

Madhu Dixit
TRIUMF/Carleton University

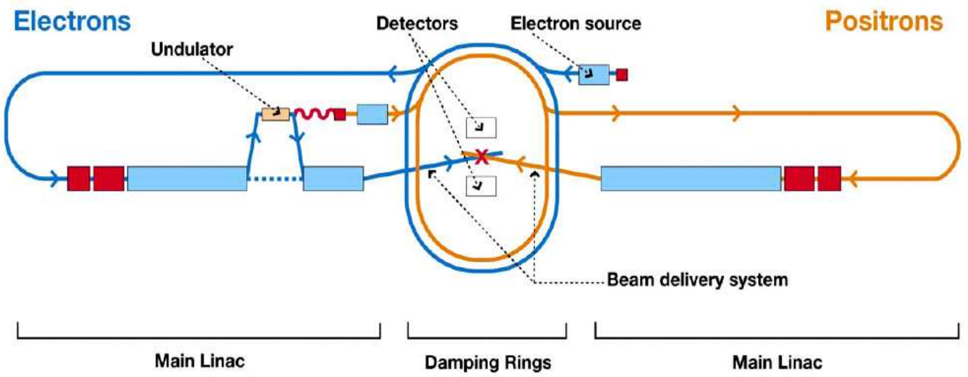
Session WE-P2, CAP Congress
Quebec City, 11 June 2008

The ILC - the next high energy physics accelerator after the LHC

- LHC starts this summer - p+p at 14 TeV
- New Physics discoveries appear imminent
- ILC will be the next world facility for particle physics after the LHC.
- The ILC physics case & its experiments
- Canadian R&D toward building the detector for the ILC
- Outlook

The International Linear Collider ILC

ILC



$e^+ e^-$ Linear Collider E_{cm} adjustable from 200 – 500 GeV

Two experiments, complementary & contrasting technologies

Single interaction region, 14 mrad crossing angle

Luminosity → $\int Ldt = 500\ \mathrm{fb}^{-1}$ in 4 years

Ability to scan between 200 and 500 GeV

Energy stability and precision below 0.1%

Electron polarization at least 80%

The machine upgradeable to 1 TeV

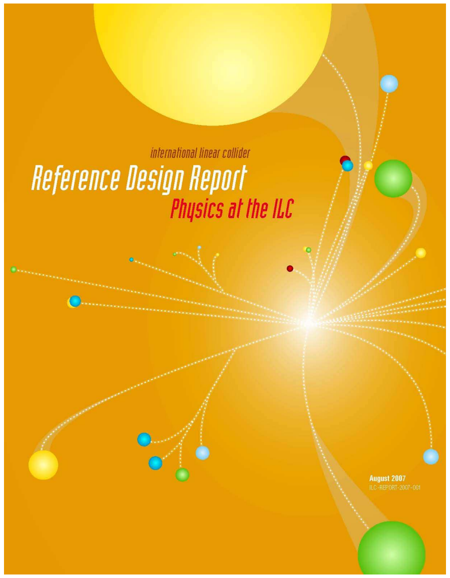
INTERNATIONAL LINEAR COLLIDER REFERENCE DESIGN REPORT
AUGUST, 2007

ILC Global Design Effort & World Wide Study

V1: EXECUTIVE SUMMARY

international linear collider
Reference Design Report
Executive Summary
August 2007

V2: PHYSICS

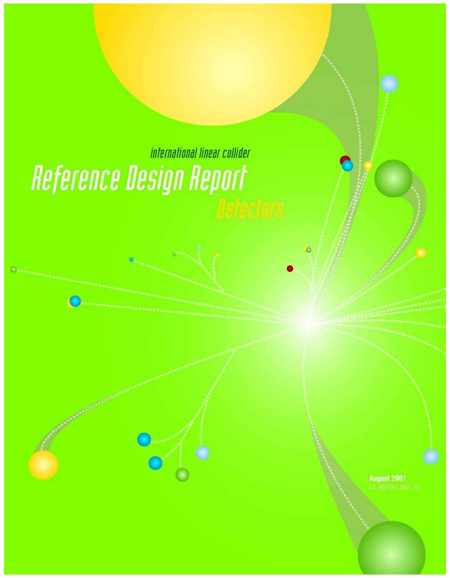


international linear collider
Reference Design Report
Physics at the ILC
August 2007

V3: ACCELERATOR

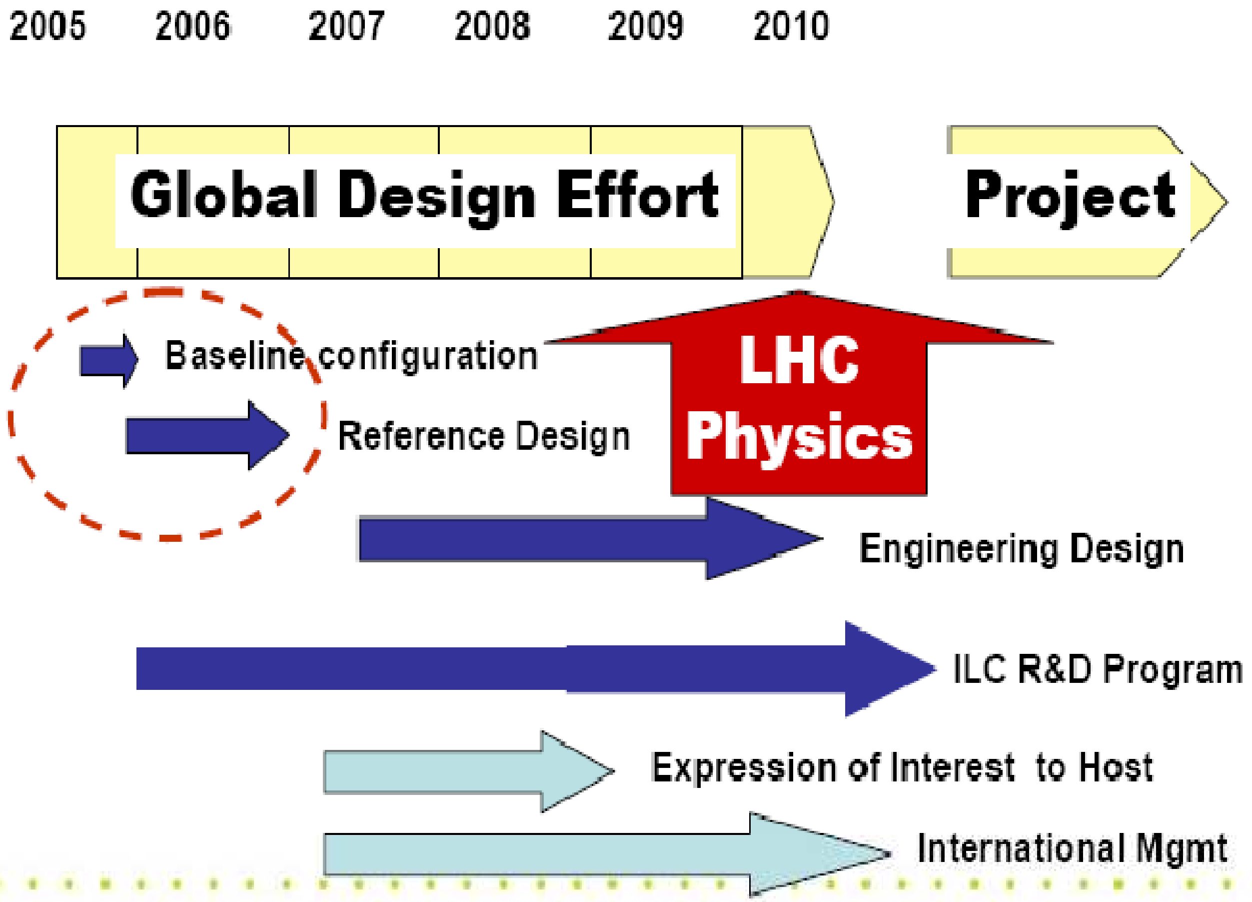
international linear collider
Reference Design Report
Accelerator
August 2007

V4: DETECTORS



international linear collider
Reference Design Report
Detectors
August 2007

The GDE Plan and Schedule



2005 2006 2007 2008 2009 2010

Global Design Effort

Project

Baseline configuration

Reference Design

LHC Physics

Engineering Design

ILC R&D Program

Expression of Interest to Host

International Mgmt

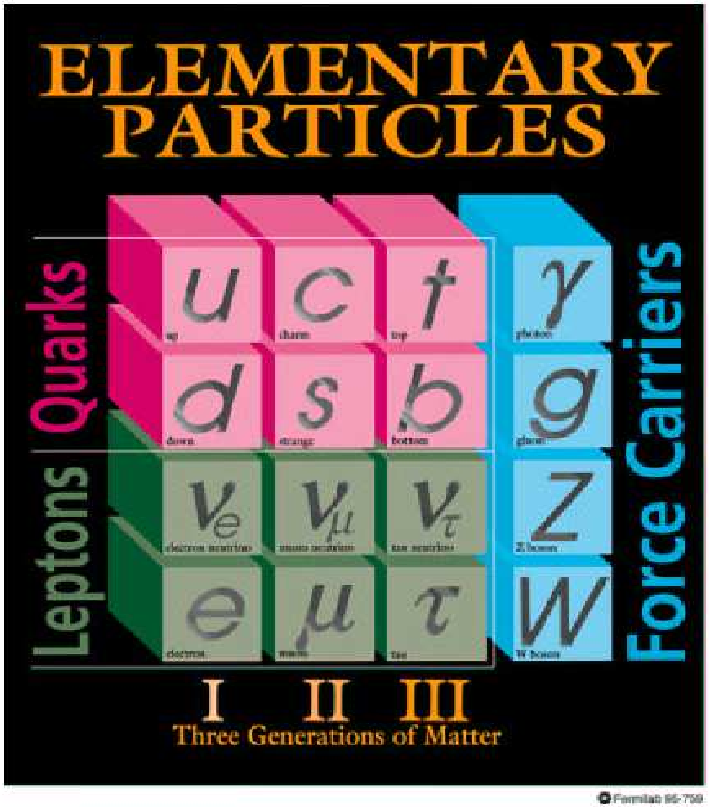
Including Detectors

December, 2007

- UK: STFC cuts ILC funding
- US: The Congress cuts ILC budget by 75% three months into the new fiscal year. Money already spent.
- Aftermath:
  - Revised schedule
  - Maintain momentum
  - Focus on critical R&D items
  - Prepare for LHC results
  - Scientific case for ILC still valid

The Standard Model (SM)

Building Blocks of Matter



© Fermilab 95-759

Symmetry

$SU(3)_C \times SU(2)_L \times U(1)_Y$

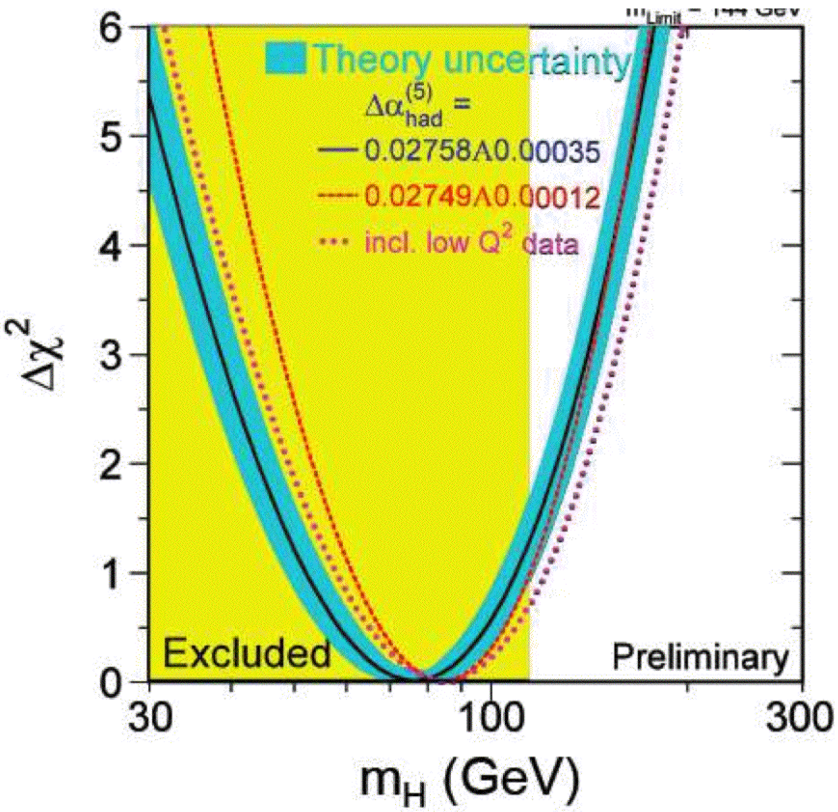
QCD

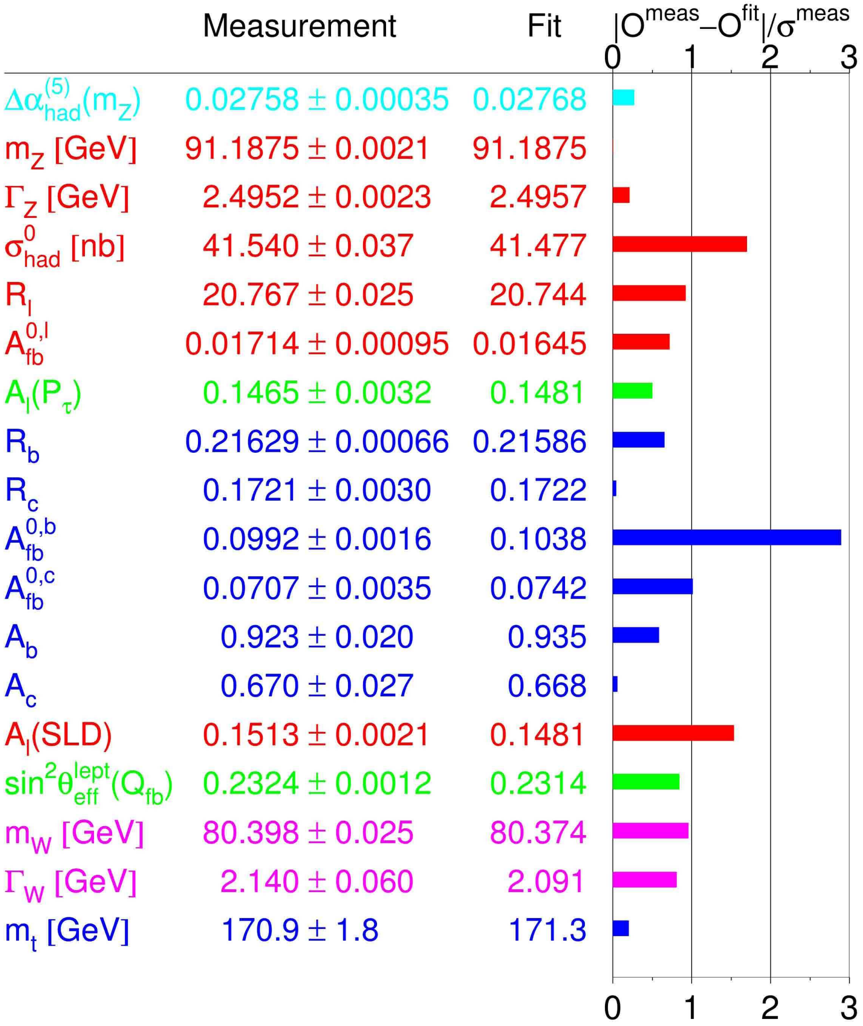
Electroweak theory

- EW symmetry spontaneously broken through Higgs mechanism
- SM highly successful, internally consistent in agreement with experiments within ~ 0.1%.

The neutral scalar Higgs particle responsible for EW symmetry breaking remains undiscovered

Higgs constrains from precision SM fits

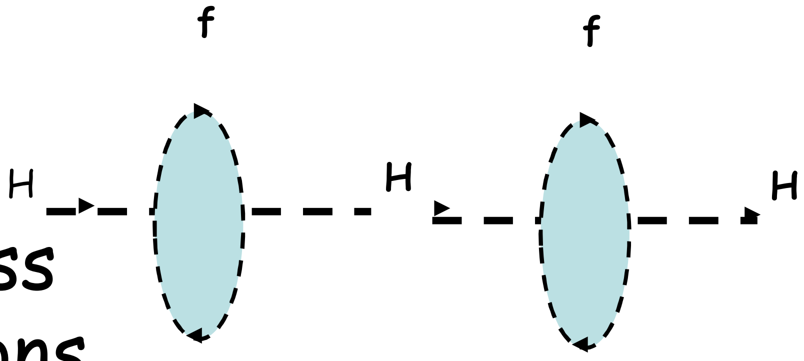




	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ^0_{had} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3

$114.4 < M_{Hi} < 144$ GeV
from LEP exclusion & SM fits
M_t & M_W from CDF & D0

Telltale signs for New Physics



❑The predicted Higgs mass unexpectedly low ~ 100 GeV

$M_H \sim 10^{19}$ GeV near Planck mass from large radiative corrections

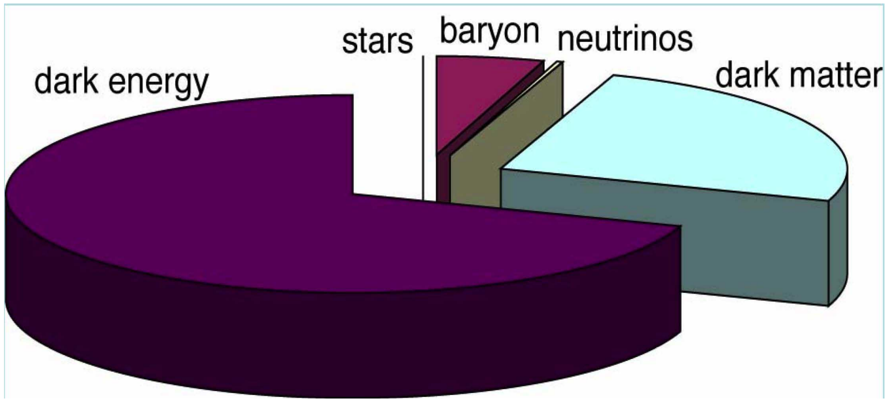
❑Low Higgs mass requires term by term cancellation of divergences

- Fine-tuning to cancel divergences is unnatural
- With Supersymmetry at ~ 1 TeV, sparticle loops naturally cancel particle loop divergences

- If no Higgs below ~ TeV, New Strong Interactions among W Z bosons needed to restore unitarity.

Cosmic connections

- ❑Existence of Dark Matter (DM) is well established.



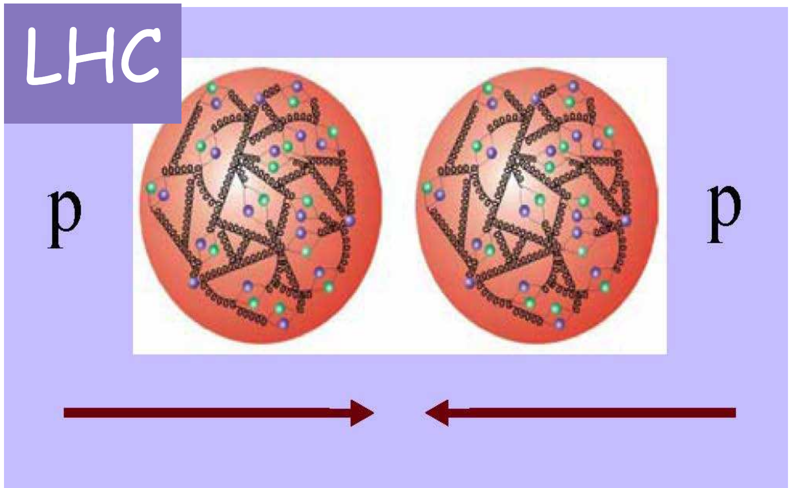
~ 1 TeV Weakly Interacting Massive particles (WIMP) could account for the observed DM density.
Can WIMP be the lowest mass SuperSymmetric particle?

- ❑How to Unify gravity with other forces?

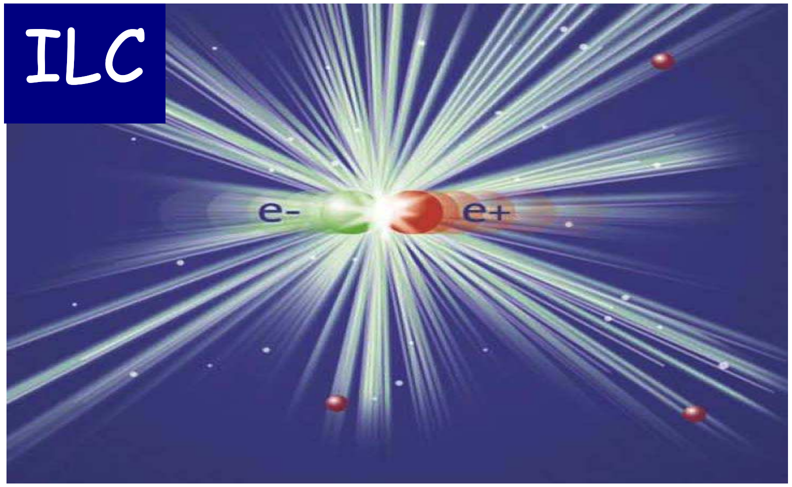
Motivates String theory & Extra Dimensions
Part of the solution for other problems

TeV physics with the LHC & with the ILC

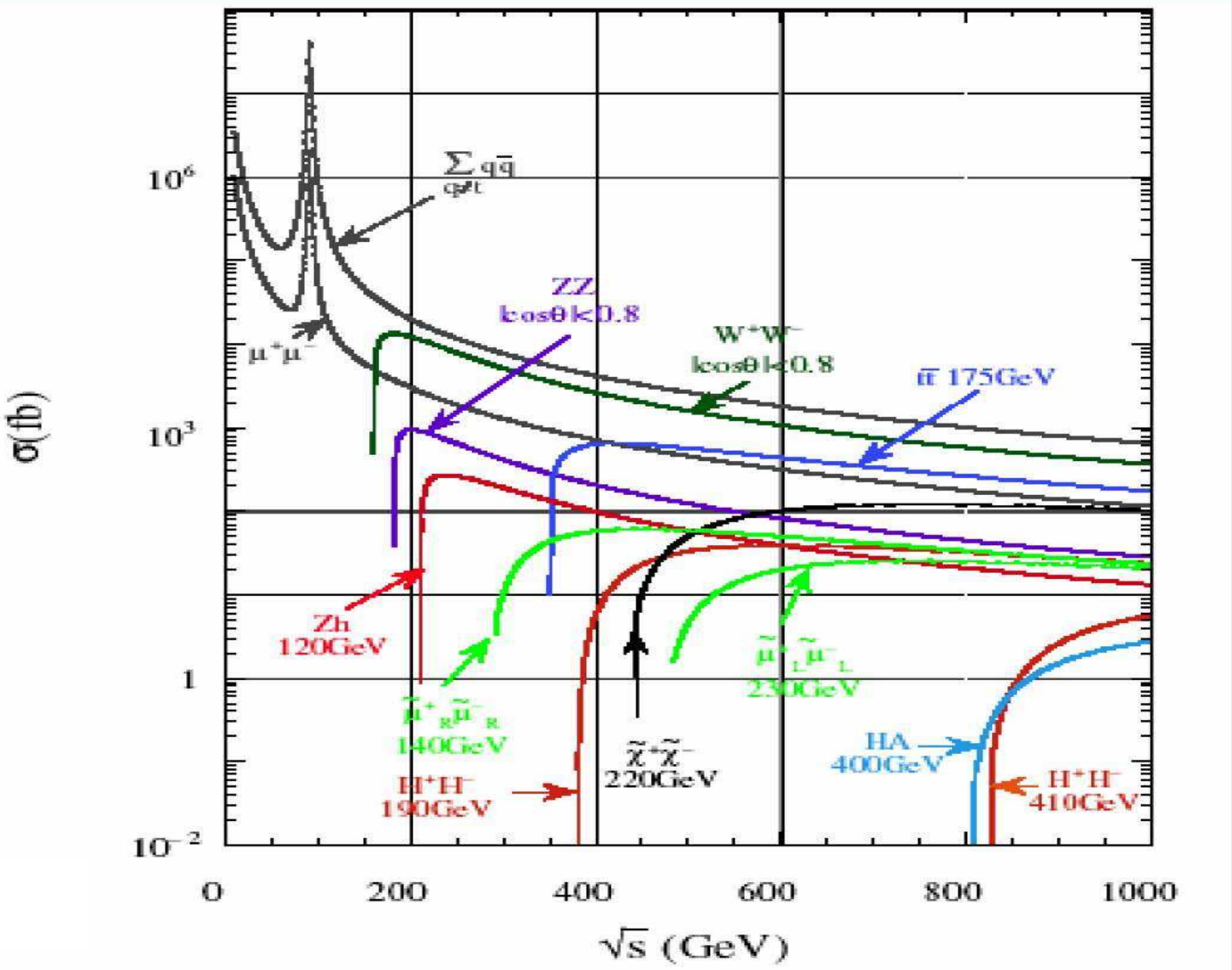
- CM parton-parton collisions
- Unknown E_{CM} & quantum numbers.
- Can discover TeV physics directly



- Clean point like collisions
- E_{CM} & quantum numbers tunable
- Use polarization to suppresse backgrounds
- A powerful tool to probe New Physics



Cross sections for physics at ILC



ILC sensitivity to New Physics

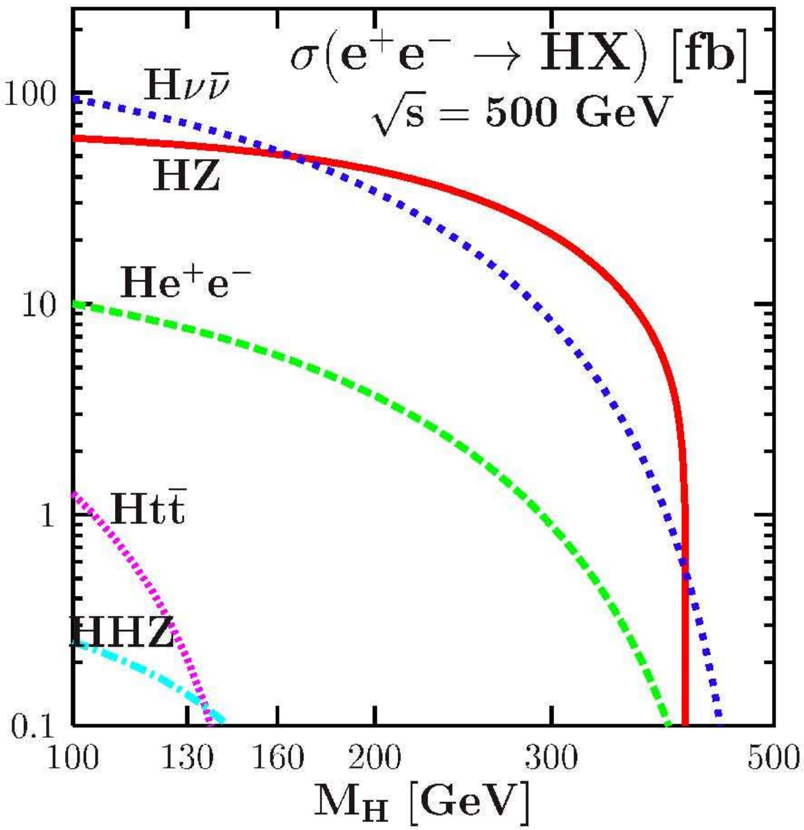
The LHC has higher mass reach, but precision makes ILC the ultimate probe of new physics

- ILC physics menu:
  - The nature of electromagnetic symmetry breaking & detailed study of the Higgs
  - Supersymmetry, its mass spectrum & parameters
  - New gauge interactions
  - Extra dimensions
  - Precision measurements
    - $\Delta M_{Top} \approx$ 100 MeV, $\Delta\Gamma_{Top} \approx$ 2%
    - ΔM_Z & $\Delta M_W \approx$ 5 MeV (from 30 MeV)
    - $\Delta(\sin^2\vartheta) \approx 10^{-5}$ (from $2 \cdot 10^{-4}$)
- LHC & ILC Complementary
- Essential to understanding the New Physics

Higgs physics at the ILC

- Detailed precision measurements
- Establish spin, parity (SM Higgs 0^+)
- Measure decay modes to discriminate between SM and SuperSymmetric Higgs
- Higgs couplings to gauge bosons & to itself to confirm its role in EW symmetry breaking

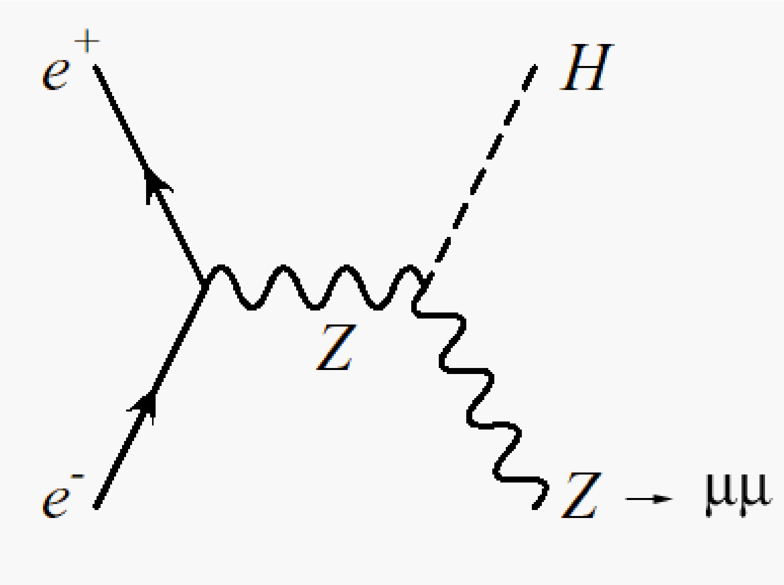
Higgs production at the ILC



ILC RDR, arXiv:0709.1893

ttH kinematically limited at 500 GeV ILC

Higgsstraulung - the Golden channel for Higgs studies



$e^+ e^- \to ZH$

$Z \to \mu^+ \mu^-$; $e^+ e^-$

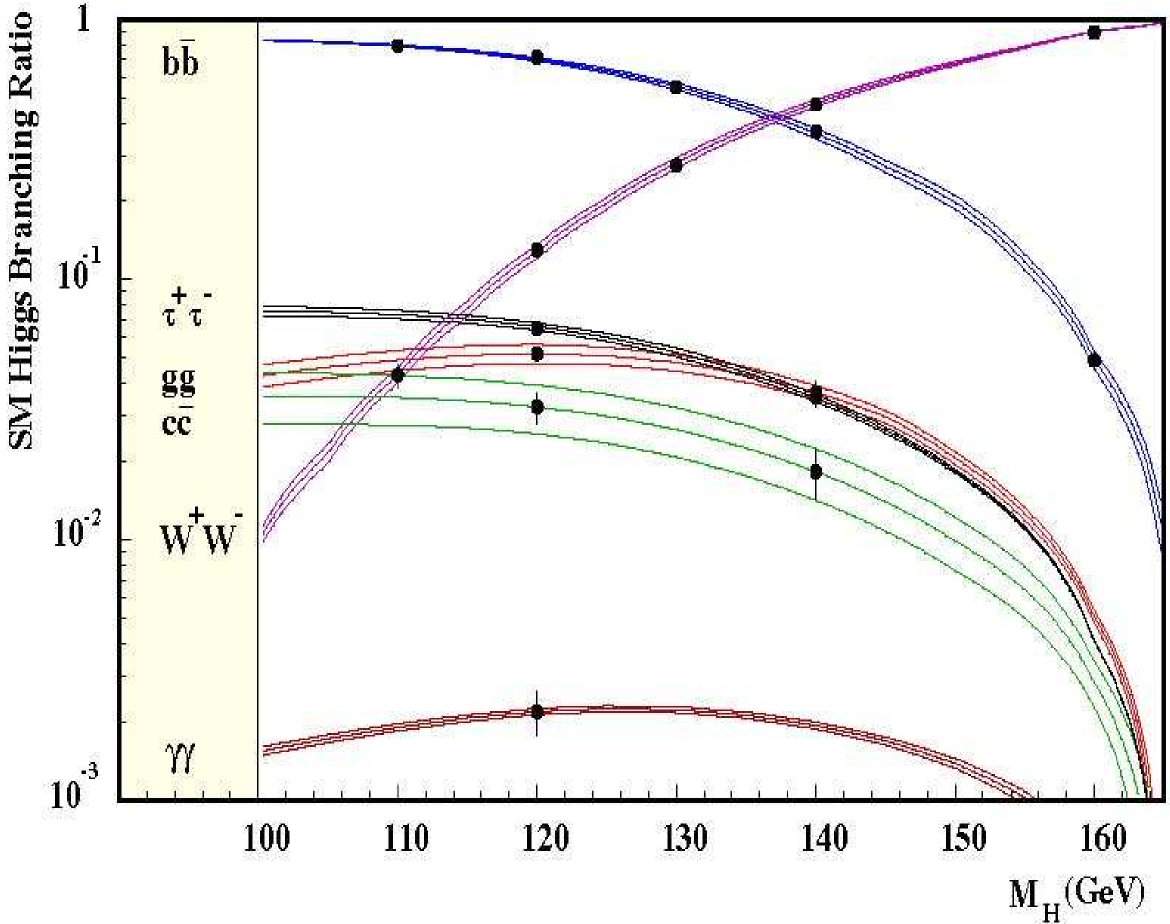
Evidence of new physics if the Higgs production rate is not as expected

- I. Higgs mass & production rates measured independent of decay modes - includes even invisible Higgs decays
- II. Enables detailed studies with tagged Higgs
- III. Fully establish Higgs mechanism!
- IV. Higgs factory

Some examples….

Measurements of Higgs production couplings, decay branching ratios (from ILC RDR)

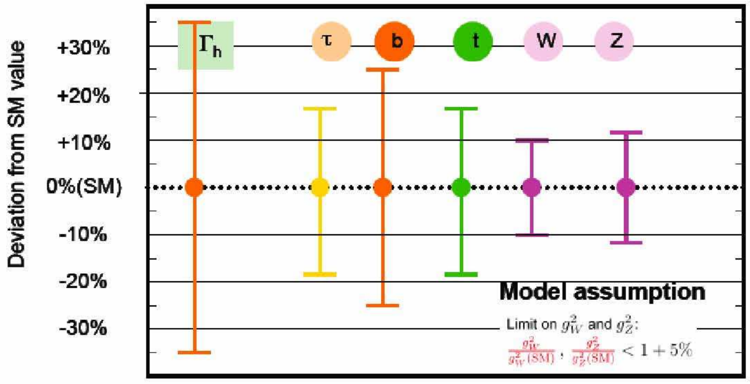
Decay	Rel. precision (%)
b b	1.0–2.4
c c	8.1–12.3
τ τ	4.6–7.1
g g	4.8–10
W W	3.6–5.3
γ γ	23 - 35



Makes possible model independent extraction of Higgs couplings, constraints non SM Higgs - only possible at ILC

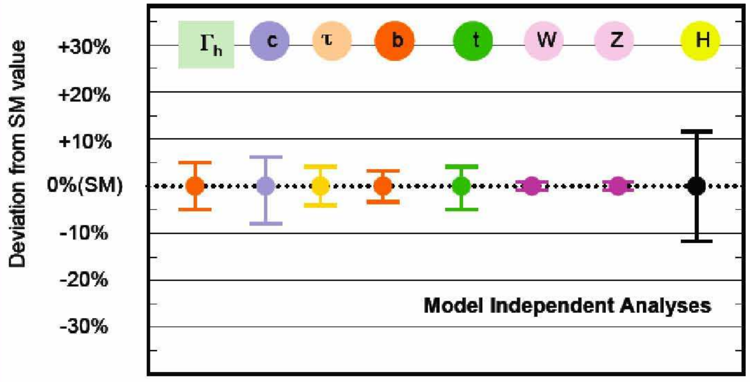
Coupling Precision

LHC 300 fb^{-1} x 2



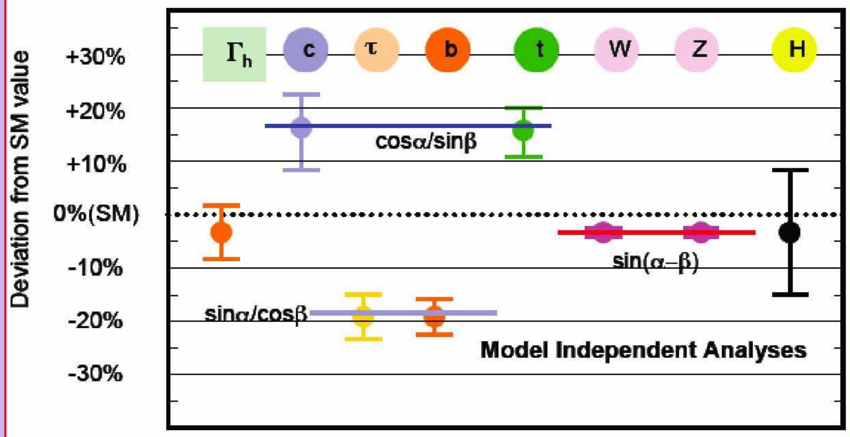
Coupling Precision

ILC



SUSY or 2HDM

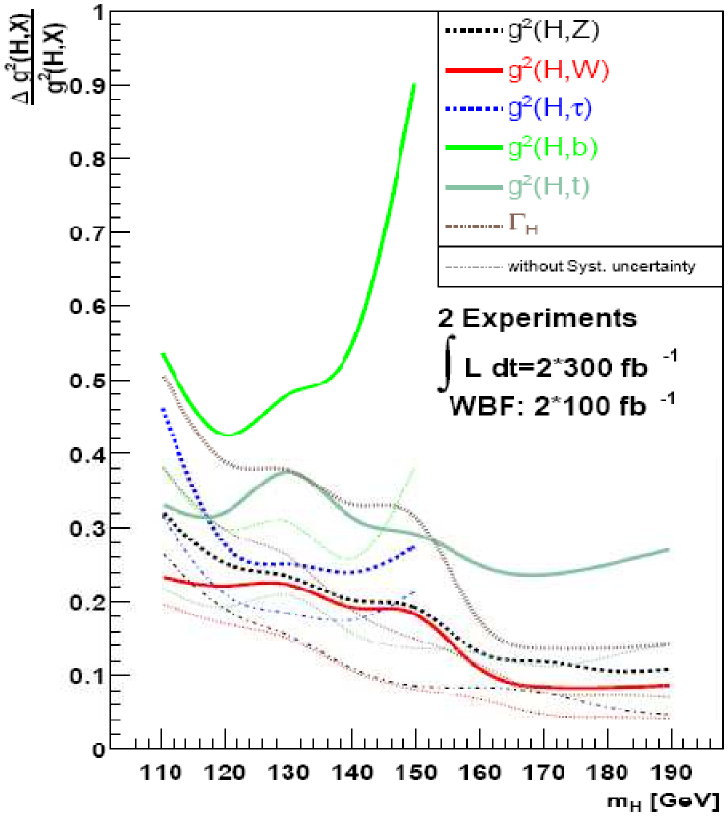
ILC



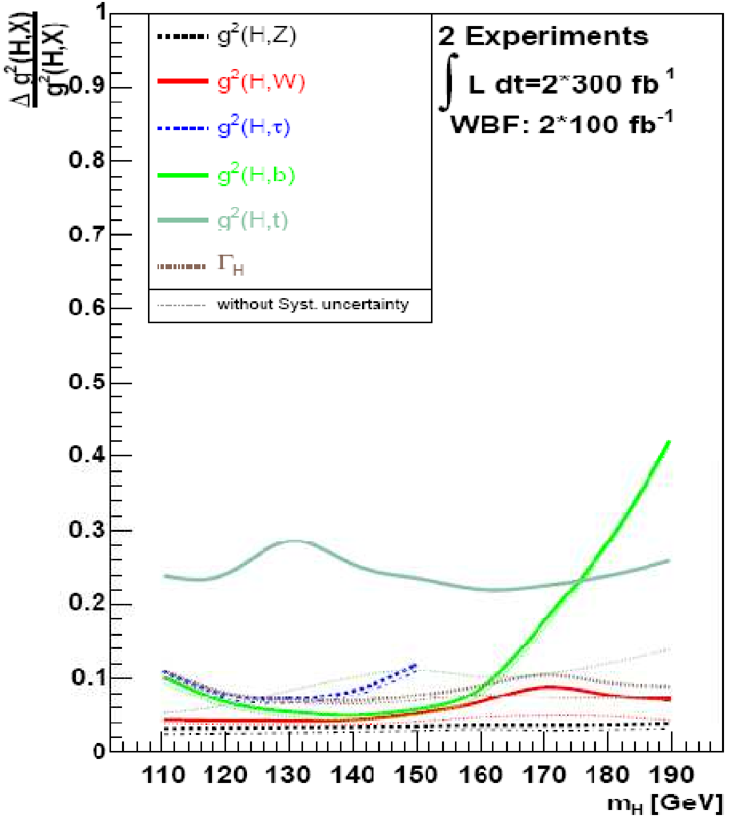
Yamashita

LHC-ILC interplay on Higgs couplings

LHC + mild model assumptions



LHC+ILC model independent



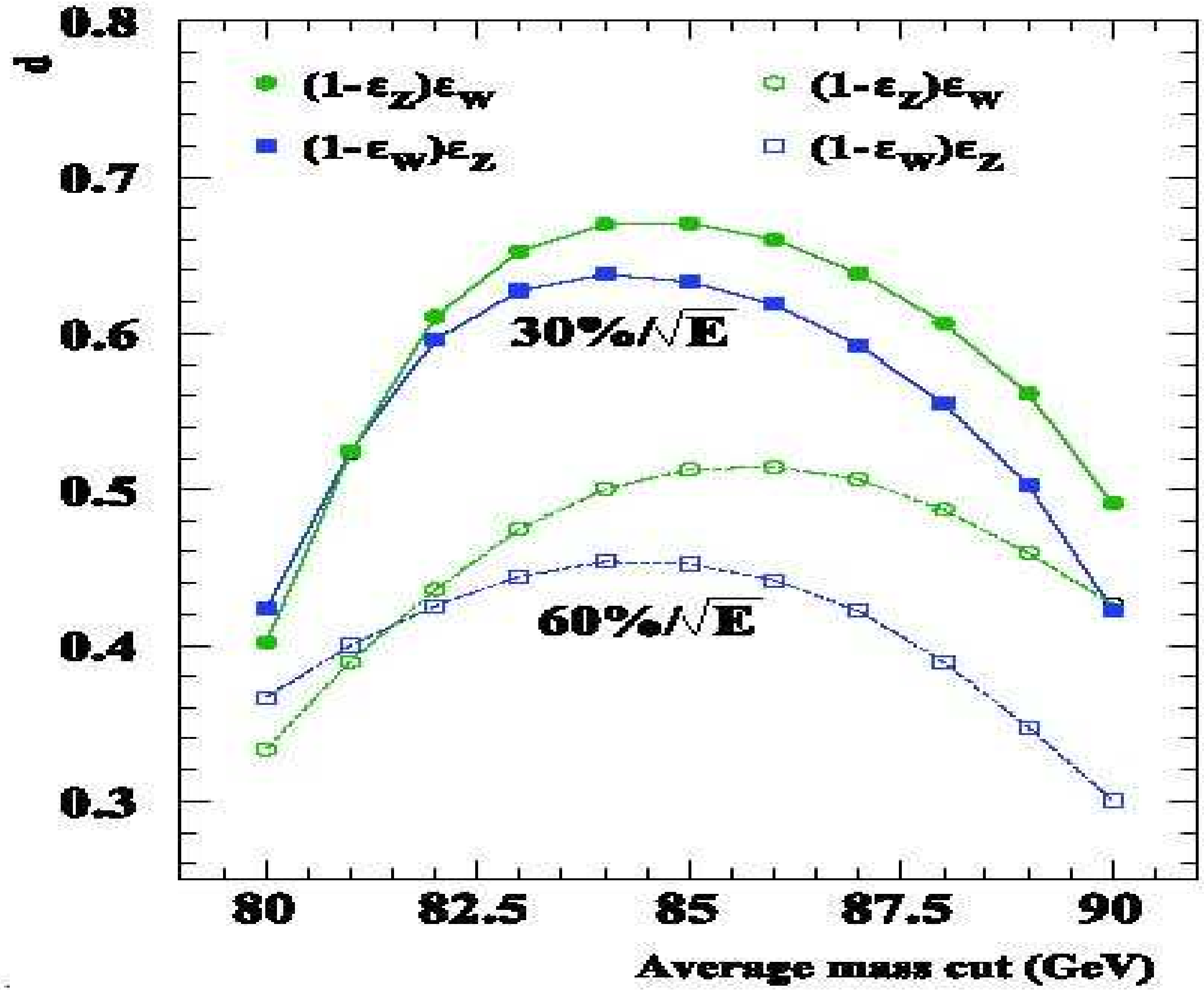
`KD,Dührssen,Heinemyer,Logan,Rainwater,Weiglein,Zeppenfeld - preliminary`

Precision mostly dominated by ILC. ttH coupling better than LHC alone due to ILC input to LHC fit.

Detector requirements for ILC physics

- Excellent vertex resolution
  - Impact parameter $5\,\mu m \oplus \frac{10\,\mu m\ GeV/c}{p \sin^{3/2}(\theta)}$ (~1/ 3 of SLD)
  - Improve tracking momentum resolution,
  - Identify heavy flavors decays for Higgs studies
  - Efficient Z, W & t reconstruction

- Calorimeter: Highest, granularity & resolution
  - Particle flow to measure separately charged particle, photons and neutral energy to improve resolution
  - Resolution ~ 30% / √(E) (2 time better than LEP)
  - High purity W & Z reconstruction
  - Higgs reconstruction in multijet events

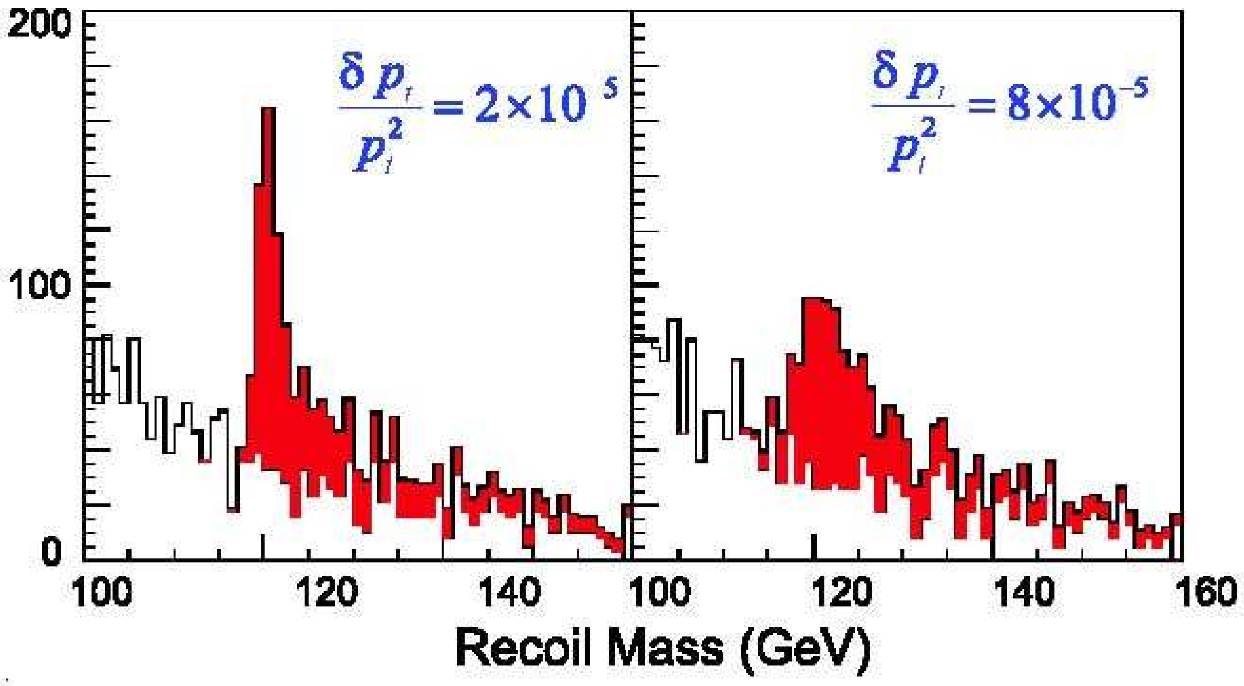


Purity "d" for $e^+ e^- \rightarrow \nu$ νbar WW/e^+e^-ZZ events versus invariant mass cut for two values of calorimeter resolution [from ILC RDR]

Measure Higgs with precision limited only by the knowledge of beam energy

Unprecedented demands on the tracker momentum resolution

$\Delta(1/p_T) \sim 2$ to 3×10^{-5} $(\mathrm{GeV}/c)^{-1}$ more than 10 times better than at LEP!



$\mu^+ \mu^-$ recoil mass at $\sqrt{s}$ = 500 GeV. M_H = 120 GeV, for two values of the tracker resolution.

A TPC tracker for the ILC

TPC an ideal central tracker for ILC

- Low mass, minimal photon conversion
- High efficiency, high granularity continuous tracking,
- Excellent pattern recognition,
- Particle ID
  - $\Delta(1/p_T) \sim 1 \times 10^{-4}$ (GeV-1) (TPC alone)
  - $\sim 3.10^{-5}$ (GeV-1) (vertex + Si inner tracker + TPC)

TPC parameters:

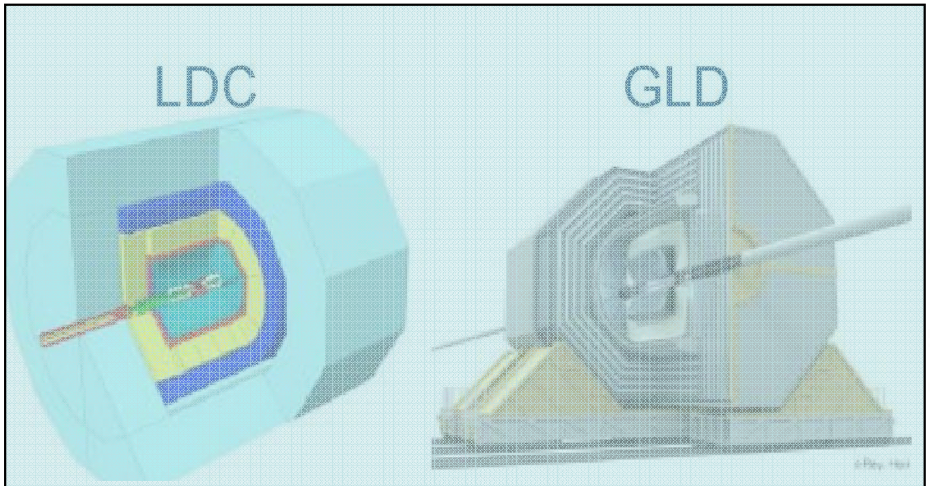
- 200 track points
- **$\sigma(r, \varphi) \leq 100\ \mu m$ includes stiff 90° tracks ~ 2 m drift**
- $\sigma(z) \sim 1$ mm
- $\sigma_{2\ track}(r, \varphi) \sim 2$ mm
- $\sigma_{2\ track}(z) \sim 5$ mm
- $dE/dx \sim 5\%$

ILC detector development in Canada

TPC	Carleton, Montreal & Victoria	NSERC supported since 2001
Calorimetry	McGil & Regina	Proposed new initiative

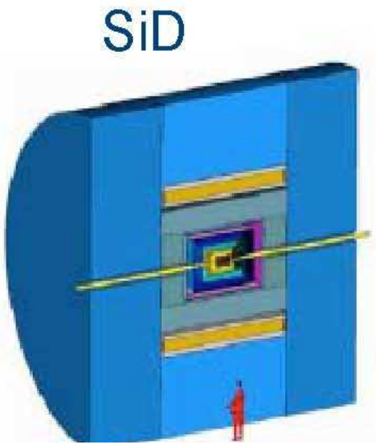
Significant progress in ILC TPC R&D with Canada among the leading world groups

3 ILC Detector Concepts - 2 with TPCs

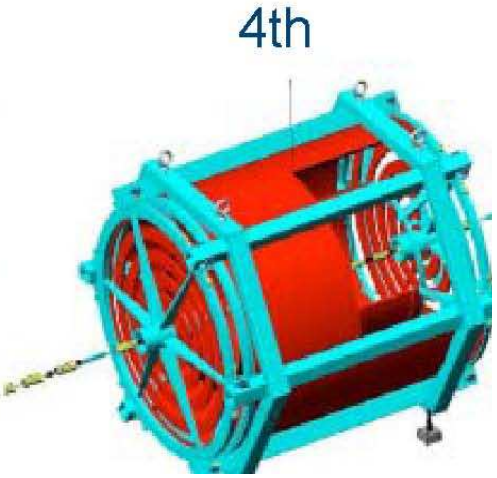


TPC (B=4T)

TPC (B=3T)



Silicon (B=5T)



TPC (B=3.5 T)

International Large Detector (ILD)

- LOI (Letters of Intent) by 31 March 2009
- LsOI evaluated by IDAG for a Technical Design Proposal
- The collaborations to produce Engineering Design Reports (EDRs) by 2012

Limits on achievableTPC resolution

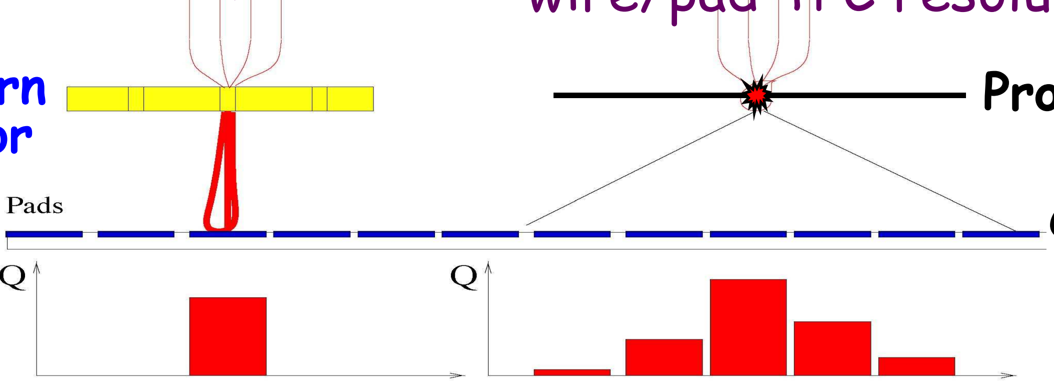
- The physics limit of TPC resolution comes from transverse diffusion:

$$\sigma_x^2 \approx \frac{D_{Tr}^2 \cdot z}{N_{eff}}$$ N_{eff} = effective electron statistics.

- For best resolution, choose a gas with smallest diffusion in a high B field

Pad width limits the MPGD TPC resolution

ExB systematics limits wire/pad TPC resolution



Micro Pattern Gas Detector

Anode pads width w

Proportional wire

Cathode pads width w

Direct signal on MPGD anode pads

Induced cathode signal determined by geometry

For small diffusion, less precise centroid for wide pads

$$\sigma_x^2 \approx \sigma_0^2 + \frac{1}{N_{eff}}\left[D_{Tr}^2 z + w^2/12\right]$$

Accurate centroid determination possible with wide pads

$$\sigma_x^2 \approx \sigma_0^2 + \frac{D_{Tr}^2 \cdot z}{N_{eff}}$$

Micro-Pattern Gas Detector development for the ILC TPC

ILC tracker goal: $\sigma_{r\varphi} \leq 100\ \mu m$ including stiff 90° 2 m drift tracks

Anode wire/cathode pad TPC resolution limited by ExB effects
Negligible ExB effects for Micro Pattern Gas Detectors (MPGD)

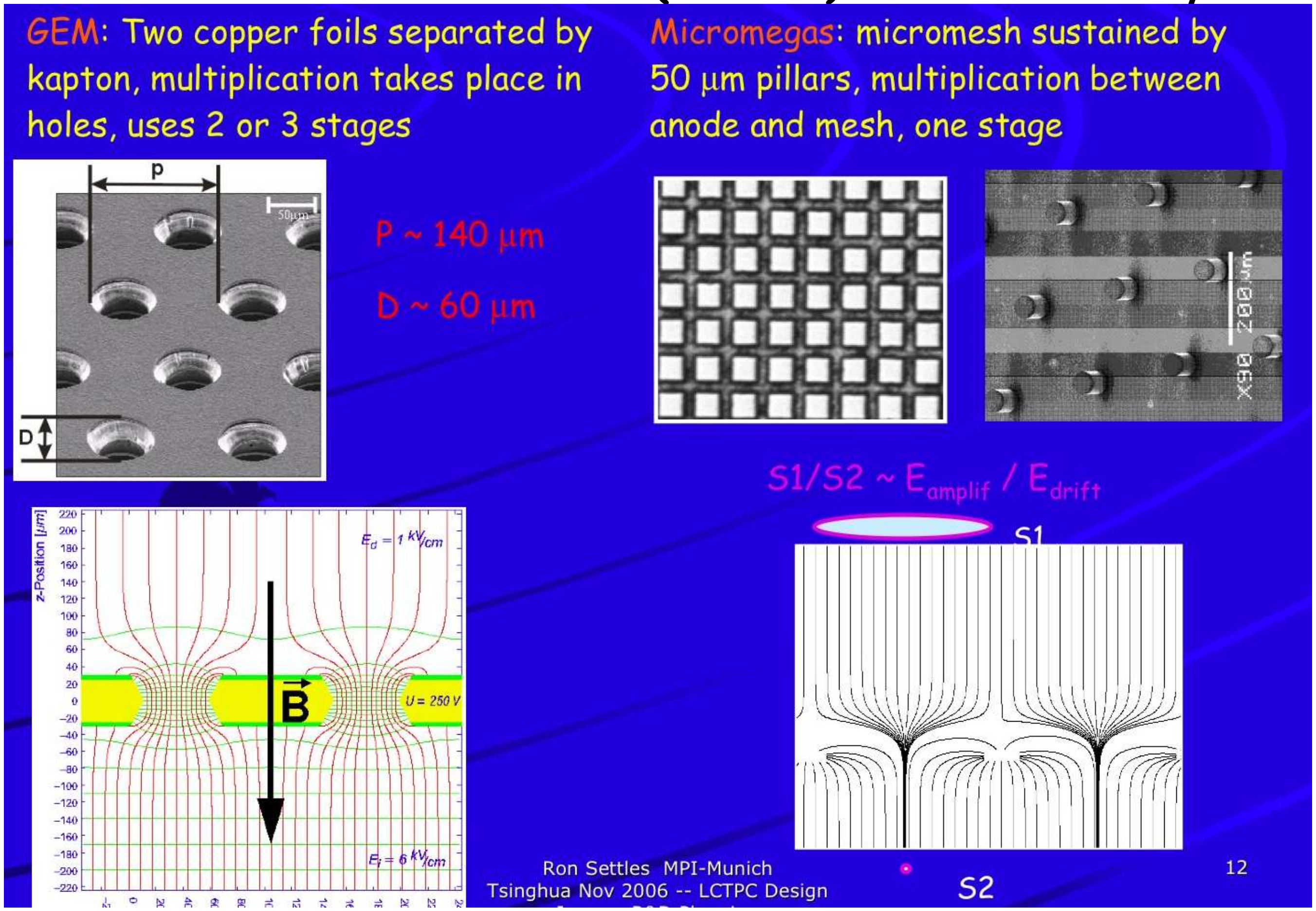
TESLA TPC TDR : 2 mm x 6 mm pads (1,500,000 channels) with GEMs or Micromegas
LC TPC R&D: 2 mm pads too wide with conventional readout
For the GEM ~ 1 mm wide pads (~3,000,000 channels)
Even narrower pads would be needed for the Micromegas

The new MPGD readout concept of charge dispersion to achieve good resolution with ~ 2 mm x 6 mm pads.

ILC challenge: σ_{Tr} ~ 100 μm (all tracks 2 m drift)

Classical anode wire/cathode pad TPC limited by ExB effects

Micro Pattern Gas Detectors (MPGD) not limited by ExB effect



GEM: Two copper foils separated by kapton, multiplication takes place in holes, uses 2 or 3 stages

Micromegas: micromesh sustained by 50 μm pillars, multiplication between anode and mesh, one stage

P ~ 140 μm

D ~ 60 μm

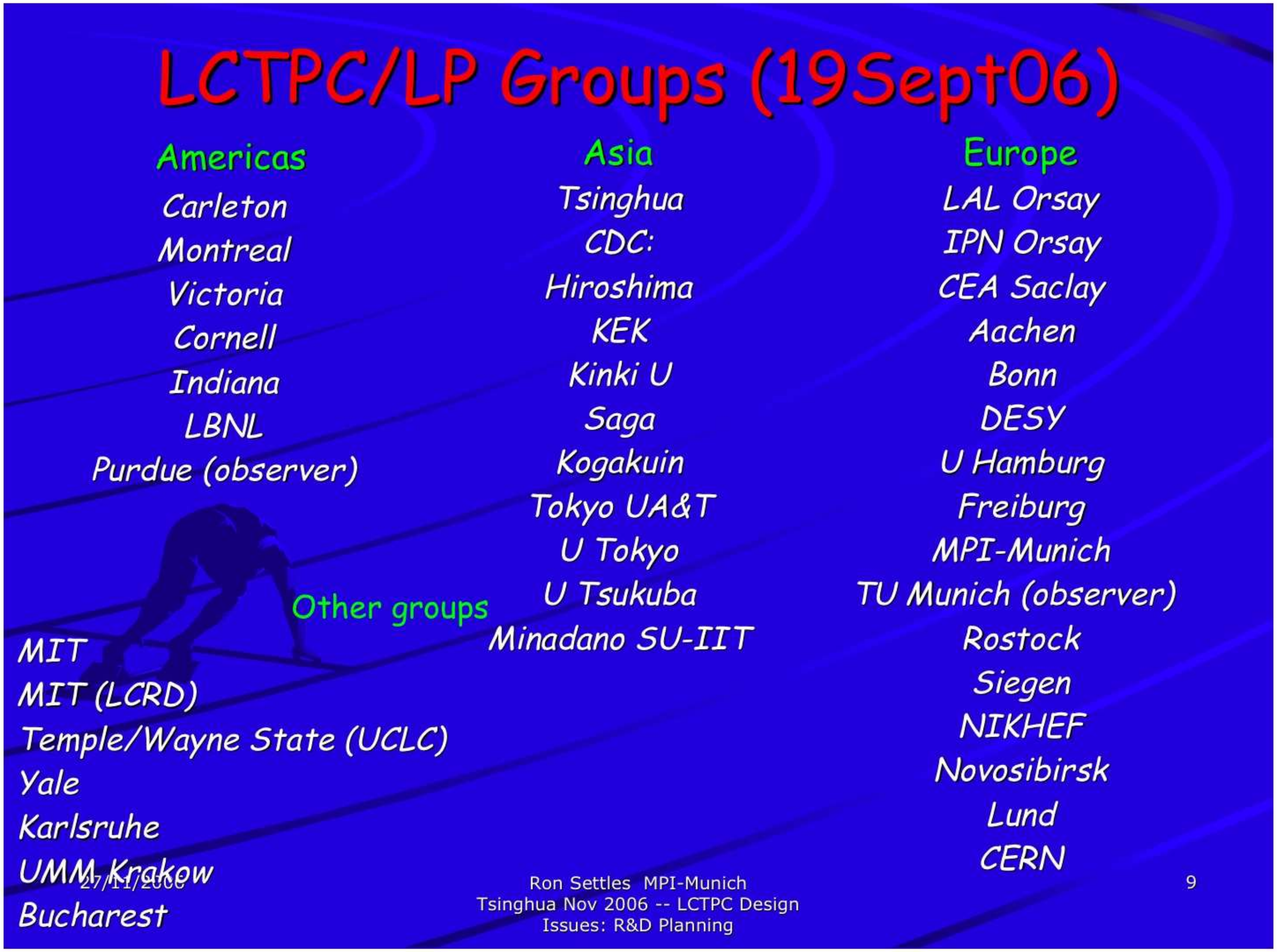
$S1/S2 \sim E_{amplif} / E_{drift}$

Ron Settles MPI-Munich

Tsinghua Nov 2006 -- LCTPC Design

Worldwide R&D to develop MPGD readout for the ILC TPC

TPC R&D for the ILC - a world wide effort



LCTPC/LP Groups (19Sept06)

Americas
- Carleton
- Montreal
- Victoria
- Cornell
- Indiana
- LBNL
- Purdue (observer)

Asia
- Tsinghua
- CDC:
- Hiroshima
- KEK
- Kinki U
- Saga
- Kogakuin
- Tokyo UA&T
- U Tokyo
- U Tsukuba
- Minadano SU-IIT

Europe
- LAL Orsay
- IPN Orsay
- CEA Saclay
- Aachen
- Bonn
- DESY
- U Hamburg
- Freiburg
- MPI-Munich
- TU Munich (observer)
- Rostock
- Siegen
- NIKHEF
- Novosibirsk
- Lund
- CERN

Other groups
- MIT
- MIT (LCRD)
- Temple/Wayne State (UCLC)
- Yale
- Karlsruhe
- UMM Krakow
- Bucharest

Finding the avalanche position on a proportional wire

Charge division on a proportional wire

Telegraph equation (1-D):

$$\frac{L}{R}\frac{\partial^2 Q}{\partial t^2}+\frac{\partial Q}{\partial t}=\frac{1}{RC}\frac{\partial^2 Q}{\partial x^2}$$

Deposit point charge at t=0

Solution for charge density (L ~ 0)

$$Q(x,t)=\sqrt{\frac{RC}{4\pi t}}\,e^{\frac{-x^2 RC}{4t}}$$

Generalize charge division to charge dispersion in 2D

Finding the avalanche location on a MPGD resistive anode surface

Telegraph equation 2-D generalization

$$\frac{\partial Q}{\partial t}=\frac{1}{RC}\left[\frac{\partial^2 Q}{\partial r^2}+\frac{1}{r}\frac{\partial Q}{\partial r}\right]$$

Solution for charge density in 2-D

$$Q(r,t)=\frac{RC}{2t}\,e^{\frac{-r^2 RC}{4t}}$$

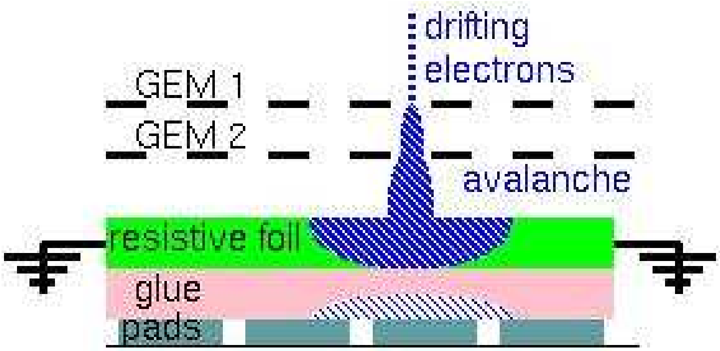
Charge dispersion in a MPGD with a resistive anode

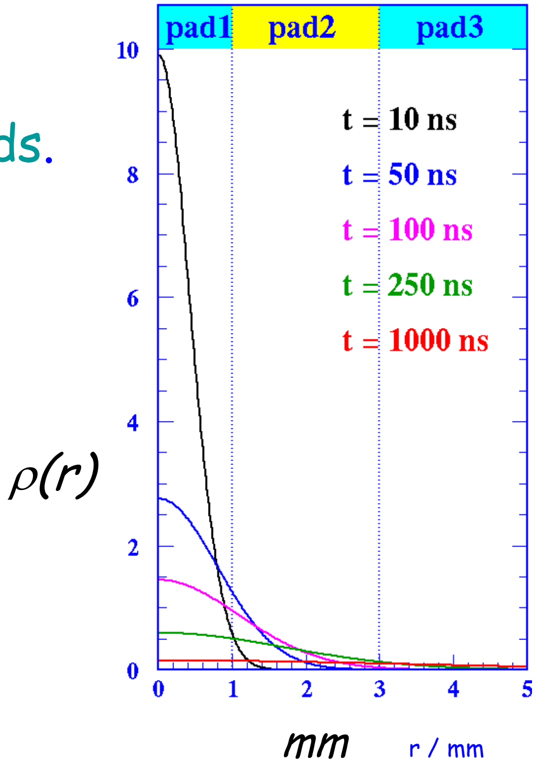
- Modified GEM anode with a high resistivity film bonded to a readout plane with an insulating spacer.
- 2-dimensional continuous RC network defined by material properties & geometry.
- Point charge at r = 0 & t = 0 disperses with time.
- Time dependent anode charge density sampled by readout pads.

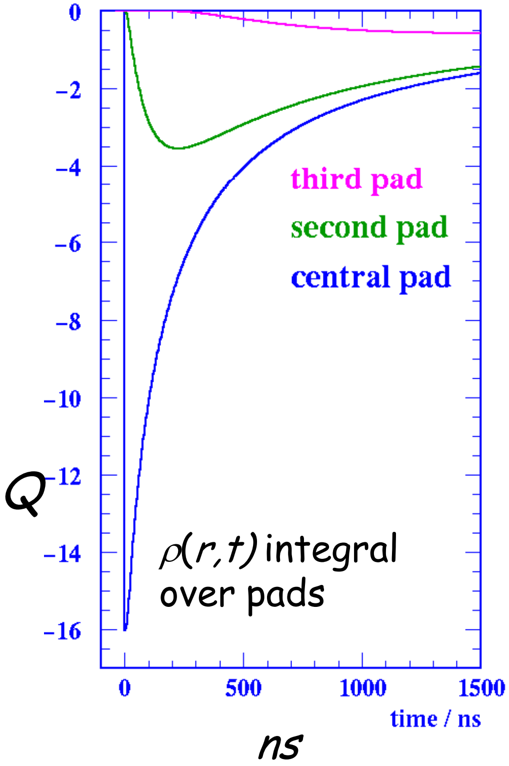
Equation for surface charge density function on the 2-dim. continuous RC network:

$$\frac{\partial\rho}{\partial t}=\frac{1}{RC}\left[\frac{\partial^2\rho}{\partial r^2}+\frac{1}{r}\frac{\partial\rho}{\partial r}\right]$$

$$\Rightarrow \rho(r,t)=\frac{RC}{2t}e^{\frac{-r^2RC}{4t}}$$







M.S.Dixit et.al., Nucl. Instrum. Methods A518 (2004) 721.

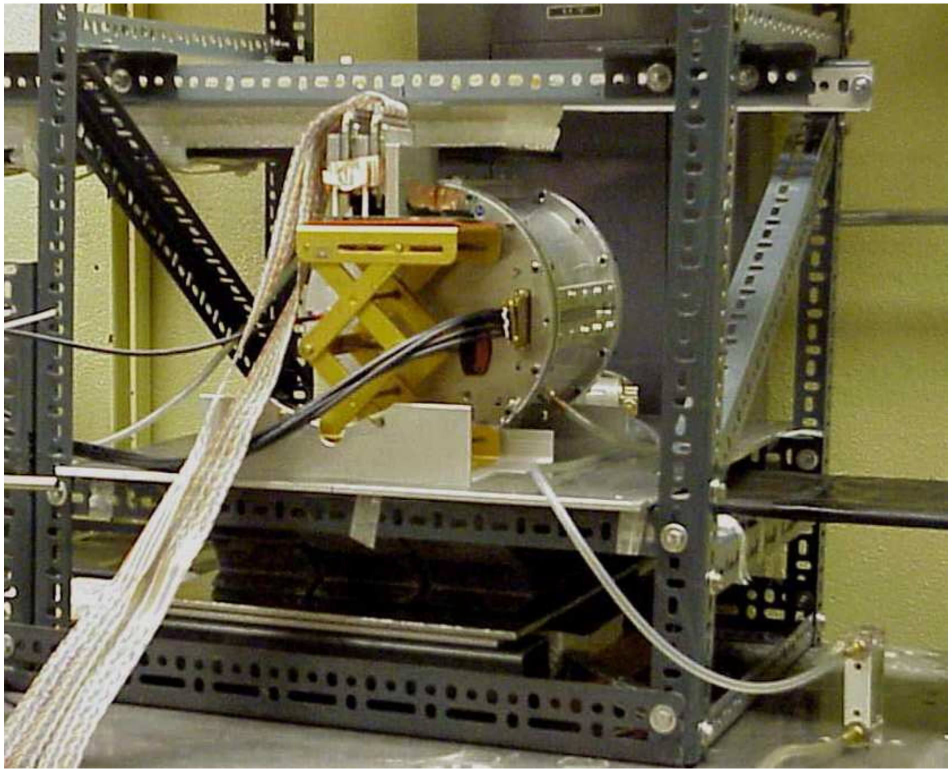
Simulating the charge dispersion phenomenon

M.S.Dixit and A. Rankin, Nucl. Instrum. Methods A566 (2006) 281.

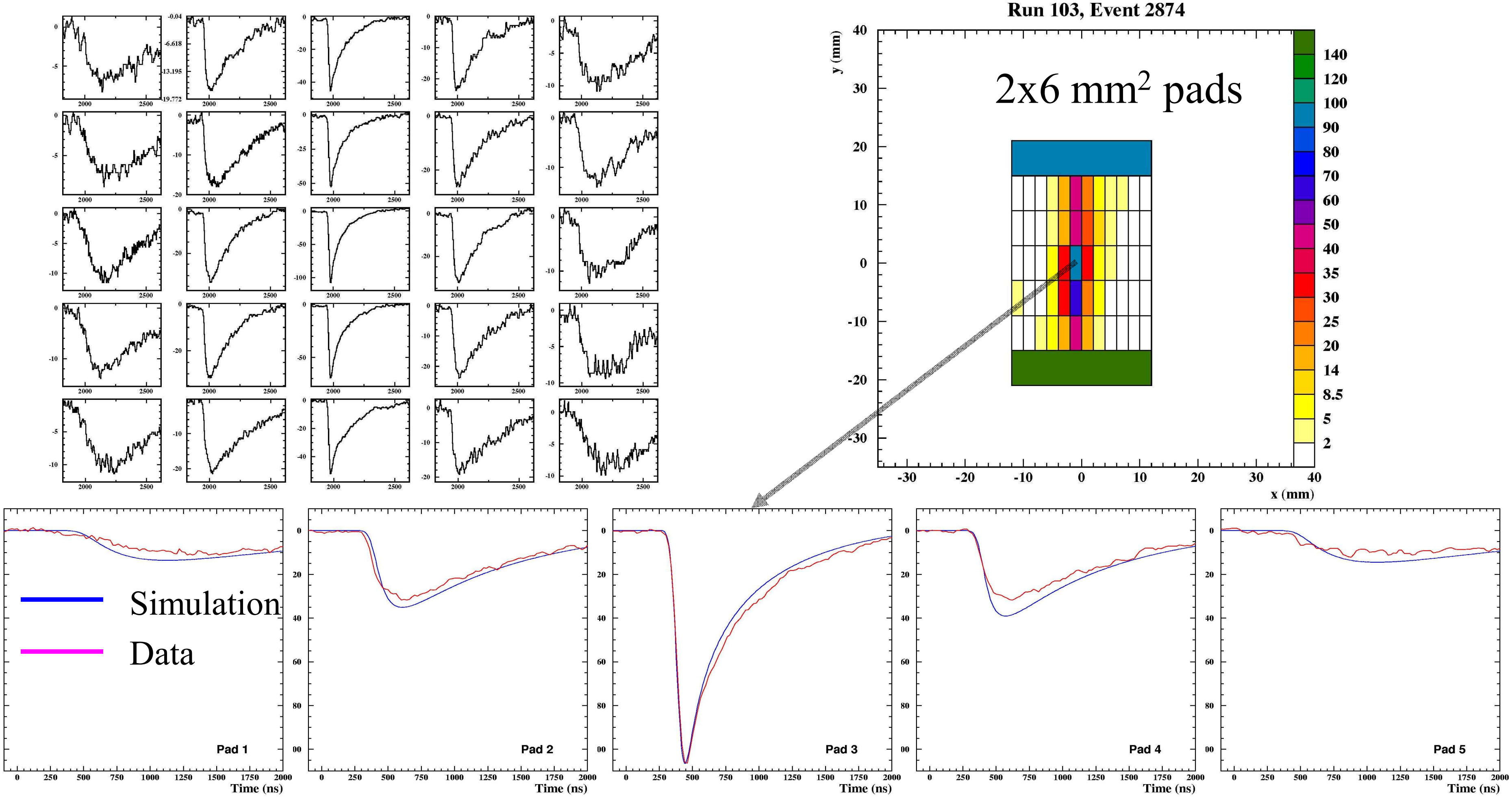
- The charge dispersion equation describe the time evolution of a point like charge deposited on the MPGD resistive anode at $t = 0$.
- For improved understanding & to compare to experiment, one must include the effects of:
  - Longitudinal & transverse diffusion in the gas.
  - Intrinsic rise time T_{rise} of the detector charge pulse.
  - The effect of preamplifier rise and fall times t_r & t_f.
  - And for particle tracks, the effects of primary ionization clustering.

Charge dispersion prototype tests

- 15 cm drift length
- GEMs/Micromegas
- Detailed simulation
- Cosmic tests B = 0
- Beam tests
- High field cosmic tests



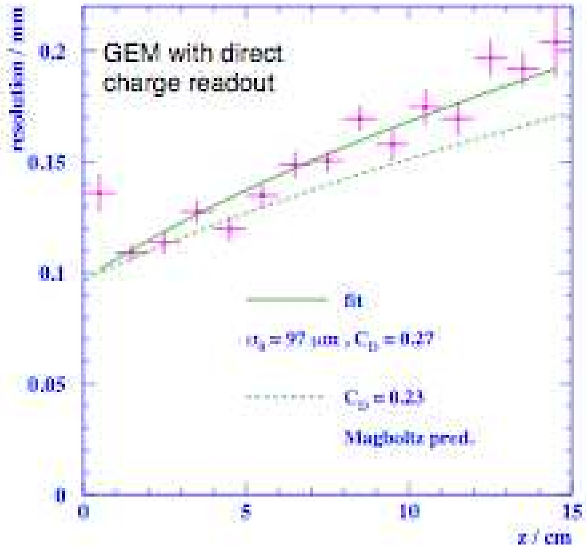
GEM TPC charge dispersion simulation (B=0)
Cosmic ray track, Z = 67 mm Ar+10%CO_2



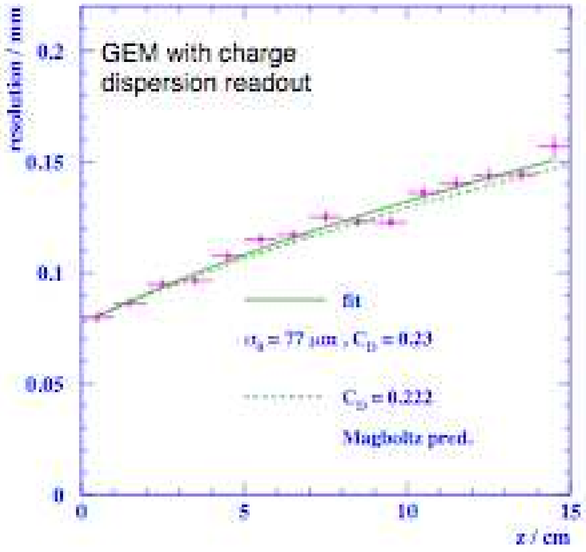
Centre pulse used for normalization - no other free parameters.

Transverse resolution (B=0) - Cosmic Rays
Ar+10%CO_2

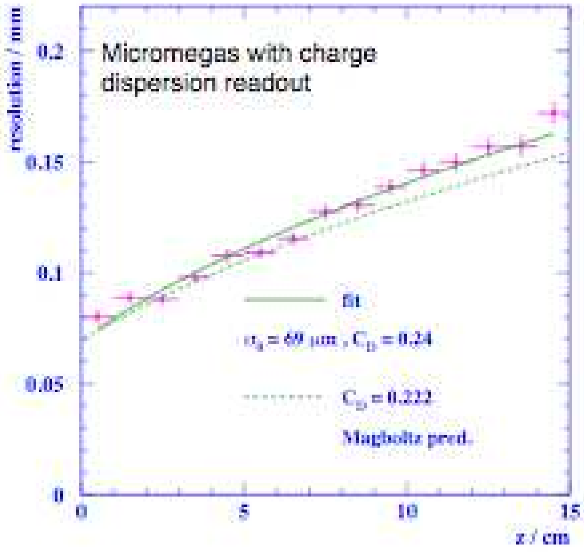
R.K.Carnegie et.al.,
NIM A538 (2005) 372



K. Boudjemline et al.,
NIM. A574, 22 (2007).



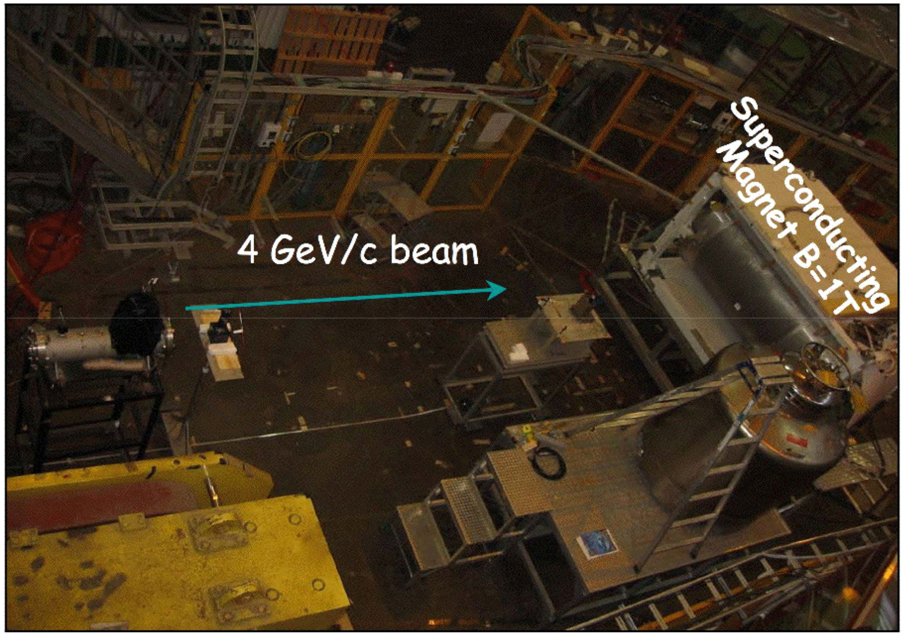
A. Bellerive et al,
LCWS 2005, Stanford



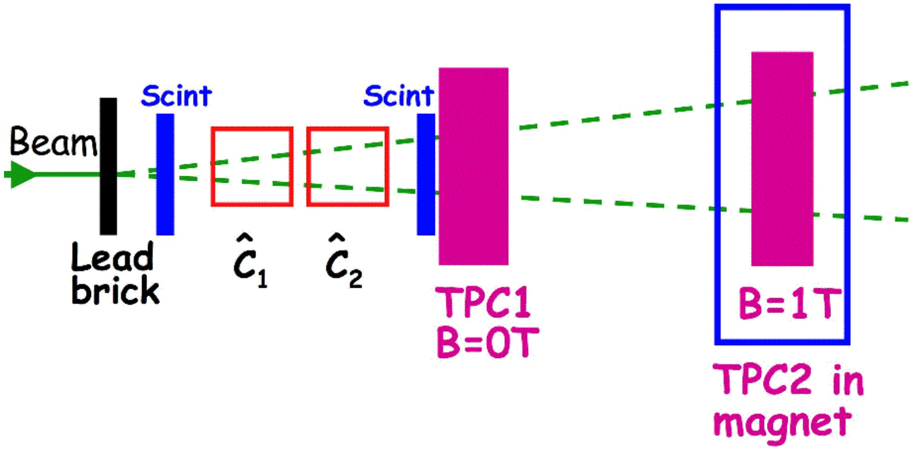
.... $\sqrt{\sigma_0{}^2 + \frac{C_D{}^2}{N_e} z}$

Compared to conventional readout, charge dispersion gives better resolution for the GEM and the Micromegas.

KEK beam test at 1 Tesla Canadian/French & Japan/German TPCs



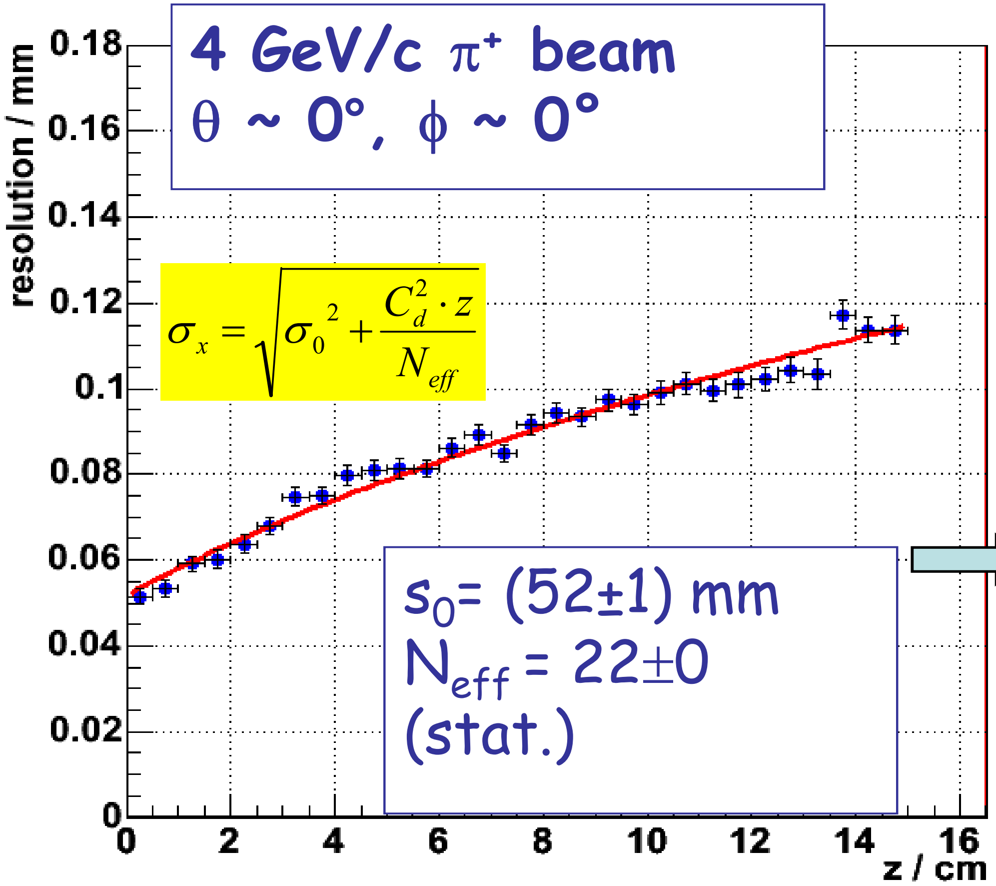
- 4 GeV/c hadrons (mostly πs)
- 0.5 & 1 GeV/c electrons
- Super conducting 1.2 T magnet without return yoke
- Inner diameter : 850 mm
- Effective length: 1 m



Canadian TPC in the beam outside the magnet

Transverse spatial resolution Ar+5%iC4H10
E=70V/cm D_{Tr} = 125 μm/√cm (Magboltz) @ B= 1T

Micromegas TPC 2 x 6 mm² pads - Charge dispersion readout



4 GeV/c π^+ beam
θ ~ 0°, ϕ ~ 0°

$$\sigma_x = \sqrt{\sigma_0{}^2 + \frac{C_d^2 \cdot z}{N_{eff}}}$$

s_0= (52±1) mm
N_{eff} = 22±0
(stat.)

- Strong suppression of transverse diffusion at 4 T.

Examples:

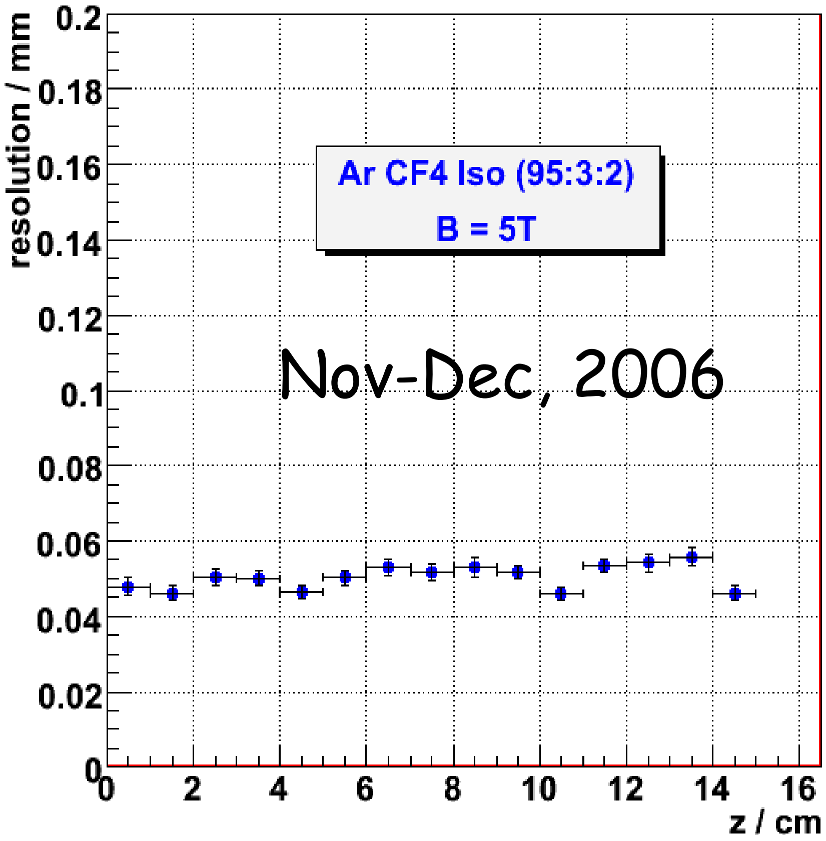
D_{Tr}~ 25 μm/√cm (Ar/CH4 91/9)
Aleph TPC gas
~ 20 μm/√cm (Ar/CF4 97/3)

Extrapolate to B = 4T
Use D_{Tr} = 25 μm/√cm
Resolution (2x6 mm² pads)
σ_{Tr} ≈ 100 μm (2.5 m drift)

Extrapolation confirmed 5 T cosmic tests at DESY

COSMo (Carleton, Orsay, Saclay, Montreal) Micromegas TPC

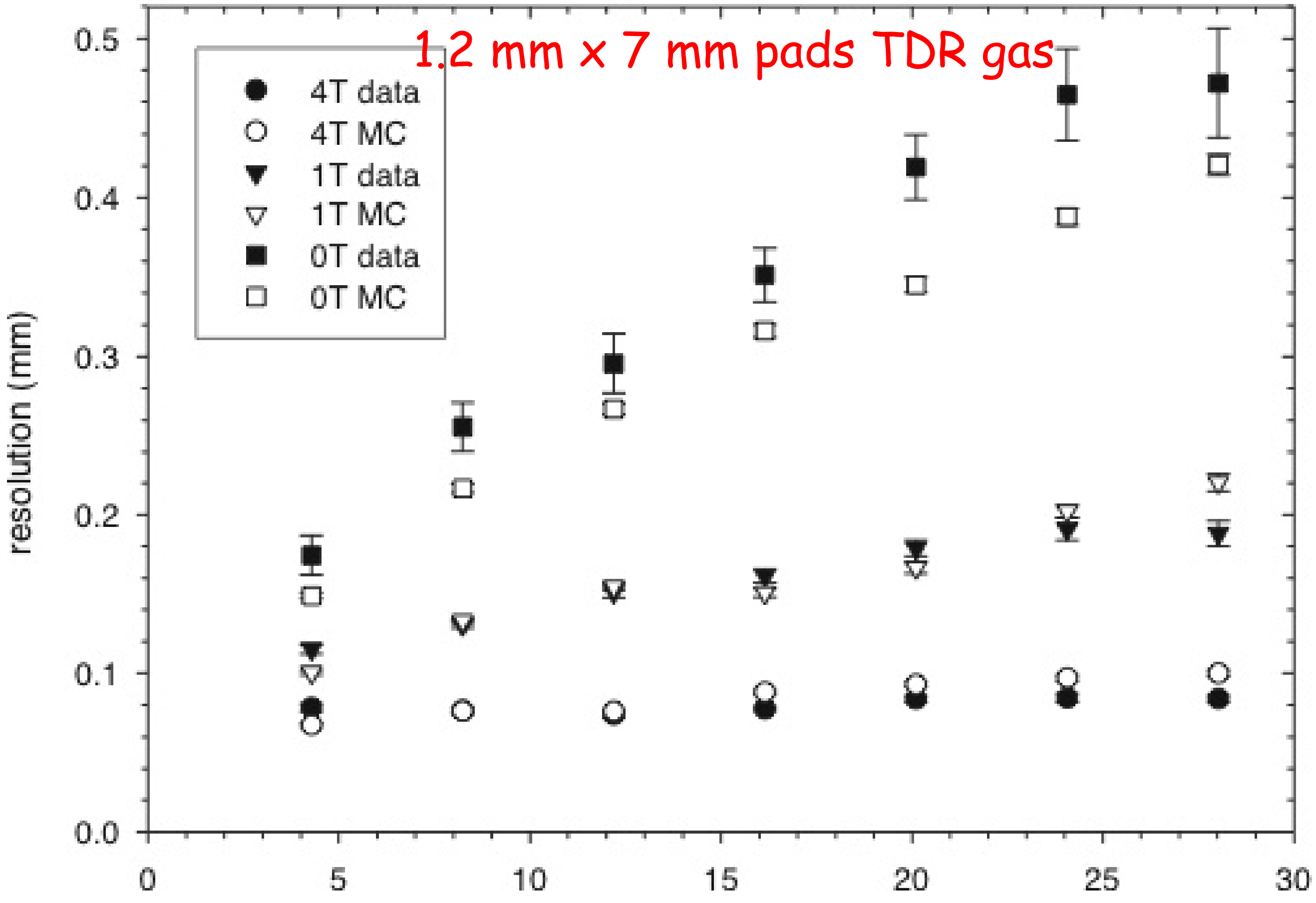
D_{Tr}= 19 μm/√cm, 2 x 6 mm^2 pads



M. Dixit et. al, NIM A 581, 254 (2007)

~ 50 μm av. resolution over 15 cm (diffusion negligible) 100 μm over 2 meters looks within reach!

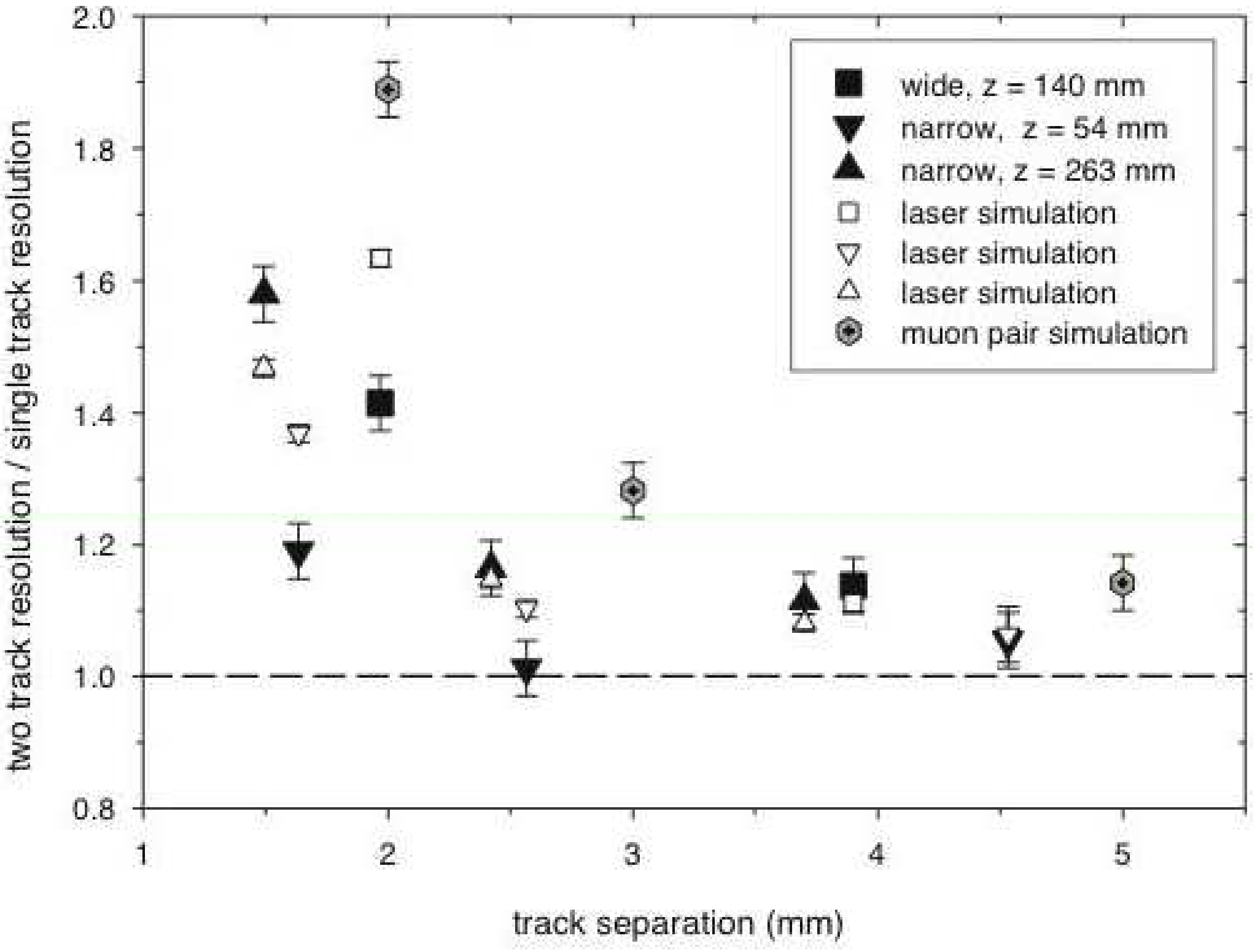
GEM-TPC cosmic tests at DESY done by Victoria Group
Transverse resolution vs. B field



Resolution gets better with B

Transverse 2-track resolution measured with a laser (Victoria group)

a



Good resolution achieved for tracks separated by > 1.5 x pad width

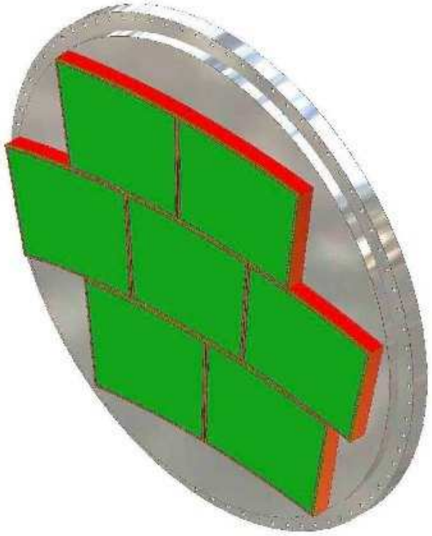
Preparing the TPC for ILC

- A formal Linear Collider TPC (LC-TPC) collaboration recently formed
- Goal - construct a 1 meter prototype & comprehensive beam tests in a 4 T magnet in a beam with ILC like time structure with **realistic electronics** by 2010(12)
- Two possible readout options being developed
  - 1) GEM with 1 mm pads
  - 2) Micromegas with ~ 2 mm pads with charge dispersion readout

1 m Large Prototype TPC for tests at DESY (2007-2010)

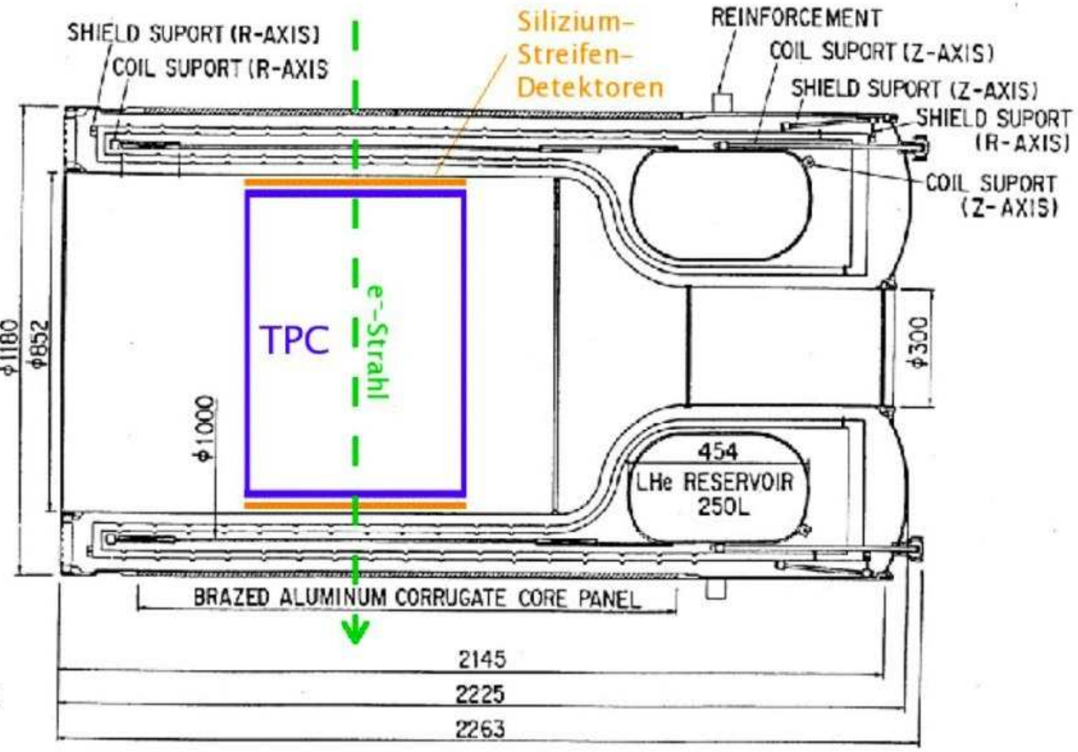
7 panels GEMs with 1 mm pads & Micromegas with 2 mm wide pads

Up to 10,000 instrumented channels



TPC endplate: 7 modules with Micromegas with charge dispersion readout.

To be built by Canada and France



Large prototype in the 1 T magnet PCMAG. The 6 GeV electron beam will enter through the magnet coil transverse to the drift direction. The magnet has no iron.

GDE Timeline

- TDP I : 2010
  - Technical risk reduction
  - Cost risk reduction
  - Global design
- TDP II : 2012
  - RD unit test (KEK)
  - Complete necessary technical designs (exceptions)
  - Project plan by consensus
- Detailed engineering will follow before construction

Detector Timeline

- Detector Design Phase I : 2010
  - Focus on critical R&Ds
  - LOI validation by IDAG
    (March 31 09 LOI deadline)
  - Update physics performance
  - MDI
- Detector Design Phase II : 2012
  - React to LHC results
  - Confirm physics performance
  - Complete necessary R&Ds
  - Complete technical designs
  - Cost (reliable)

Summary

- The physics case for the ILC is compelling
- Expect to gain momentum after LHC results
- At 5 T, an unprecedented flat ~ 50 μm resolution has been demonstrated with 2 x 6 mm^2 readout pads for drift distances up to 15 cm. The ILC-TPC resolution goal ~100 μm for all tracks up to 2 m drift appears feasible (Carleton & UVIC).
- The innovative Canadian MPGD readout concept of charge dispersion a serious candidate for the ILC TPC readout.
- New calorimetry initiative in Canada (Regina & McGill)
- Canadian responsibilities for large 1 m prototype tests to 2010
  - Construct seven large Micromegas panels with charge dispersion shared with France (Carleton & Montreal)
  - Calibration (Victoria)
  - Electronics development (Carleton & Montreal)