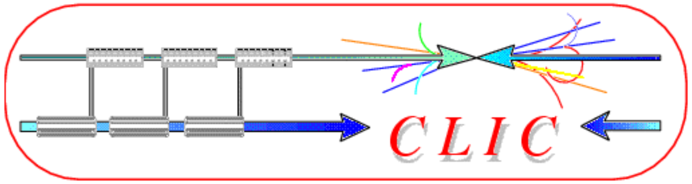
CLIC Physics Studies
Present and Future

A.De Roeck
CERN

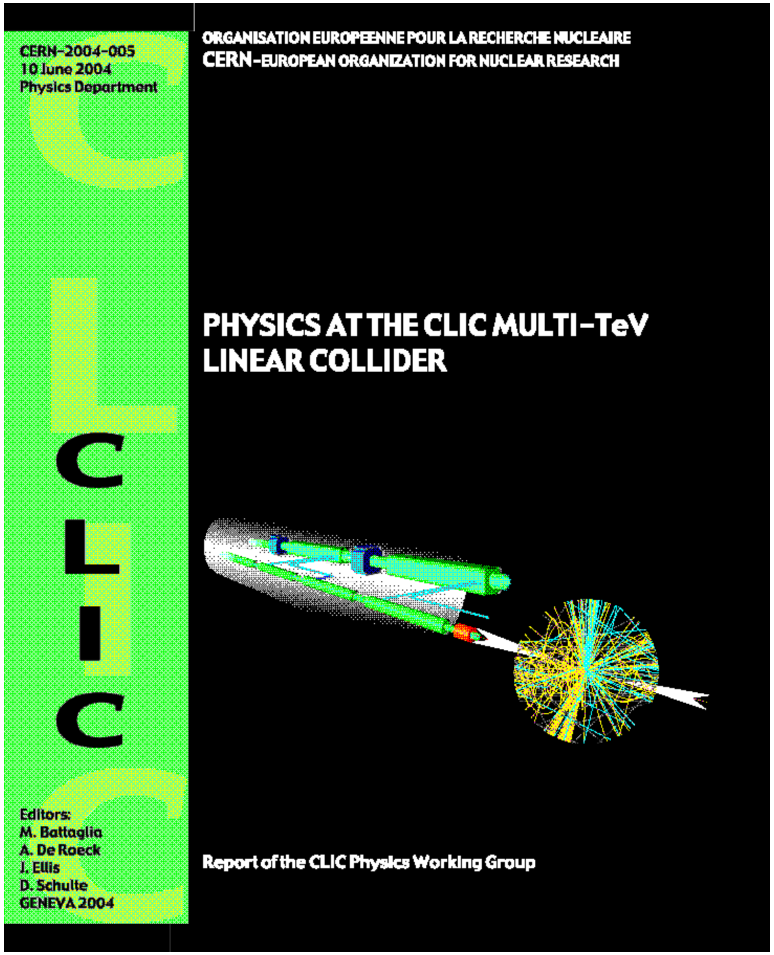


CLIC Physics Report Published

Results of the CLIC physics study phase-I

What is the CLIC Physics potential

83 authors



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ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
CERN-EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CLIC

PHYSICS AT THE CLIC MULTI-TeV LINEAR COLLIDER

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D. Schulte
GENEVA 2004

Report of the CLIC Physics Working Group

Turkish contributions
- 4th family
- Lepto-quarks
- Excited leptons

(generator studies)

What should be done for CLIC physics study Phase-II?

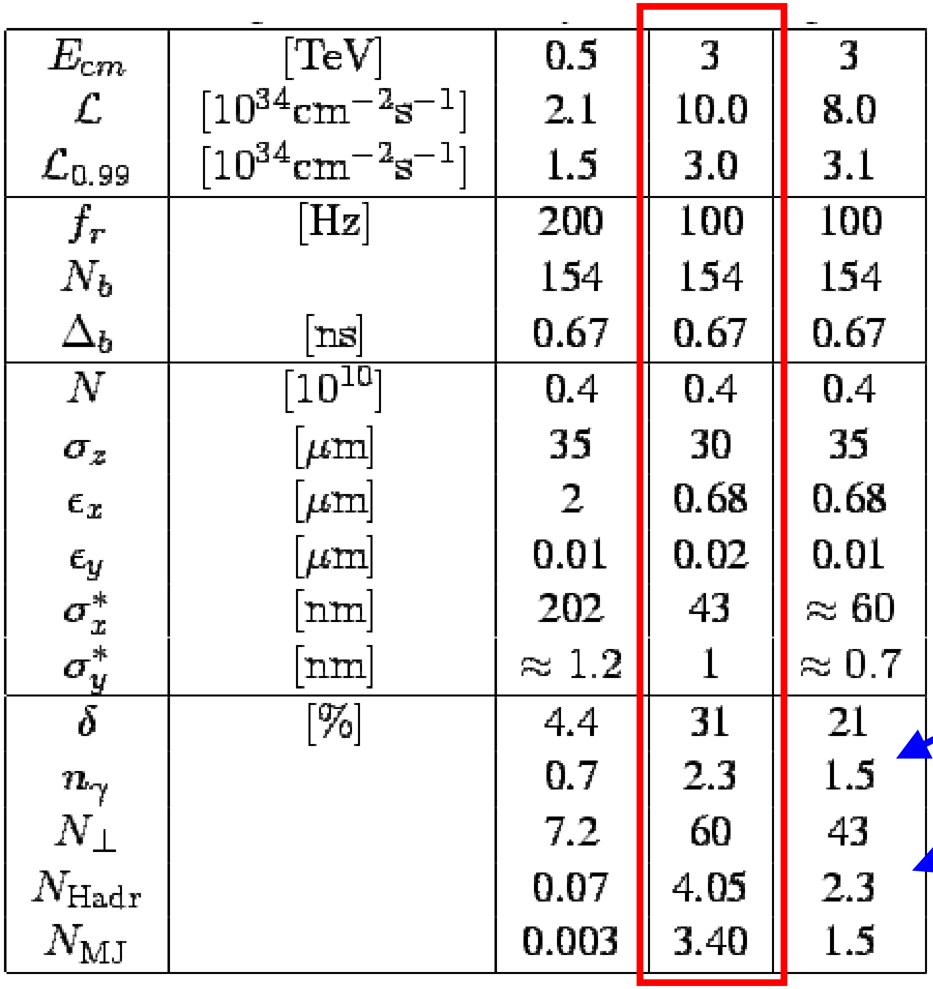
CLIC physics studies phase-II

Start fall 2004 (discussion with PH management)

- New & more detailed studies on physics processes
  - Some processes have been just touched upon, others are new
  - Some new backgrounds identified (muons)
- Detector optimization
  - Study so far uses a somewhat adapted TESLA detector
- Initiate/link with detector R&D
  - If we want to be ready to know how to built a detector for CLIC (tracker, calorimeter, timestamping)
- Study other options for CLIC ? I.e. lower energy 'start up' options
  - ep option (γp,γA options)
  - Cliche ($\gamma\gamma$ factory)
  - Z factory?
  - Higgs factory
  - Compare with TeV class collider (0.5-1 TeV)
  - Full energy $\gamma\gamma$ and $e\gamma$ option for CLIC

CLIC Parameters

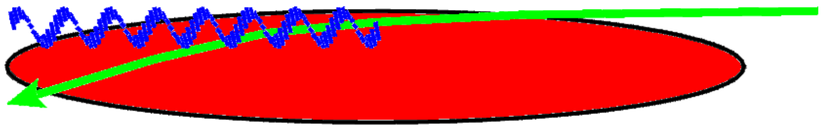
CLIC 3 TeV e+e- collider with a luminosity ~ $10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (1 ab^{-1}/year)



E_{cm}	[TeV]	0.5	3	3
$\mathcal{L}$	$[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	2.1	10.0	8.0
$\mathcal{L}_{0.99}$	$[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	1.5	3.0	3.1
f_r	[Hz]	200	100	100
N_b		154	154	154
Δ_b	[ns]	0.67	0.67	0.67
N	$[10^{10}]$	0.4	0.4	0.4
σ_z	[μm]	35	30	35
ϵ_x	[μm]	2	0.68	0.68
ϵ_y	[μm]	0.01	0.02	0.01
σ_x^*	[nm]	202	43	≈ 60
σ_y^*	[nm]	≈ 1.2	1	≈ 0.7
δ	[%]	4.4	31	21
n_γ		0.7	2.3	1.5
$N_\perp$		7.2	60	43
N_{Hadr}		0.07	4.05	2.3
N_{MJ}		0.003	3.40	1.5

old **new**

To reach this high luminosity: CLIC has to operate in a regime of high beamstrahlung



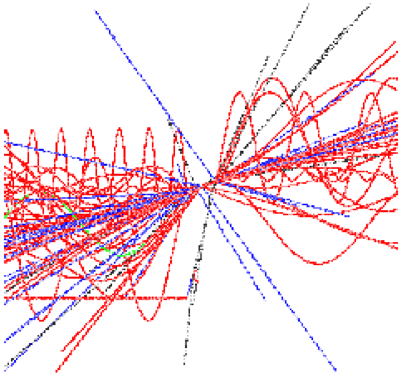
Expect large backgrounds

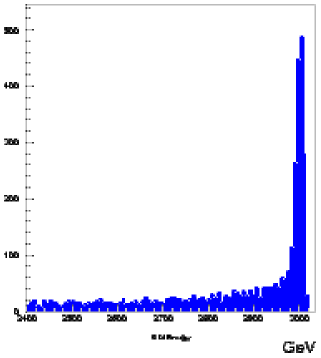
# of photons/beam particle

- e+e- pair production
- γ γ events
- Muon backgrounds
- Neutrons
- Synchrotron radiation

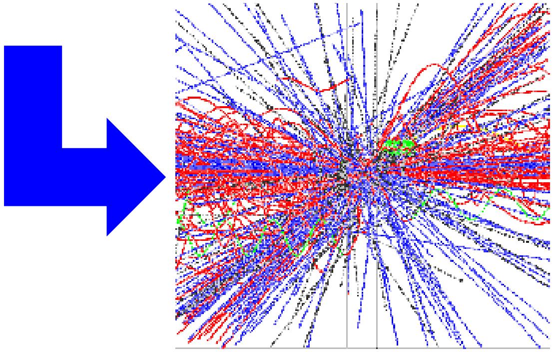
Expect distorted lumi spectrum

CLIC Tools for Background/Detector

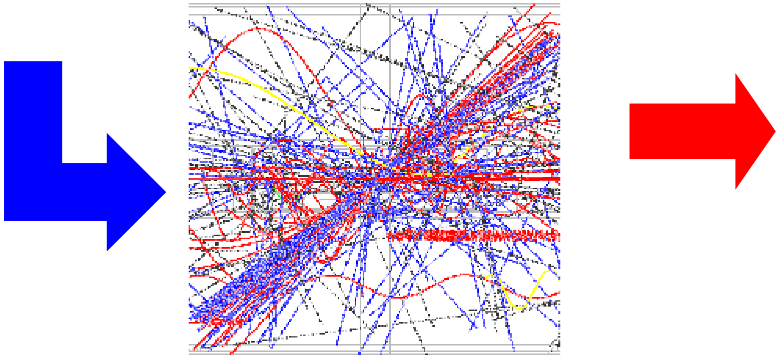




Physics generators (COMPHEP PYTHIA6,…)
+ CLIC lumi spectrum (CALYPSO)



+ γ γ→ hadrons background
e.g. overlay 20 bunch crossings
(+ e+e- pair background files…)

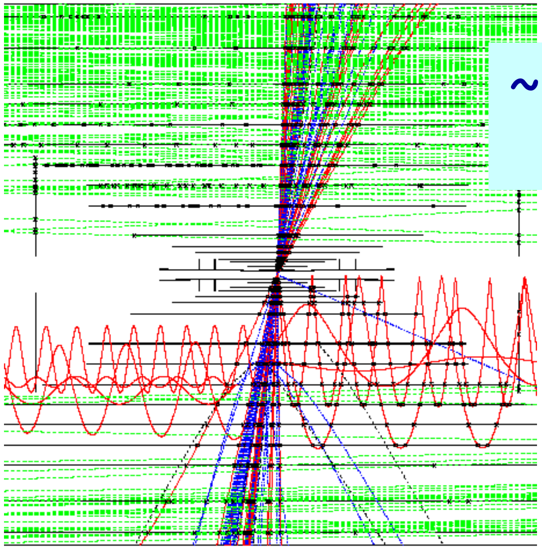


Detector simulation
- SIMDET (fast simulation)
- GEANT3 based program

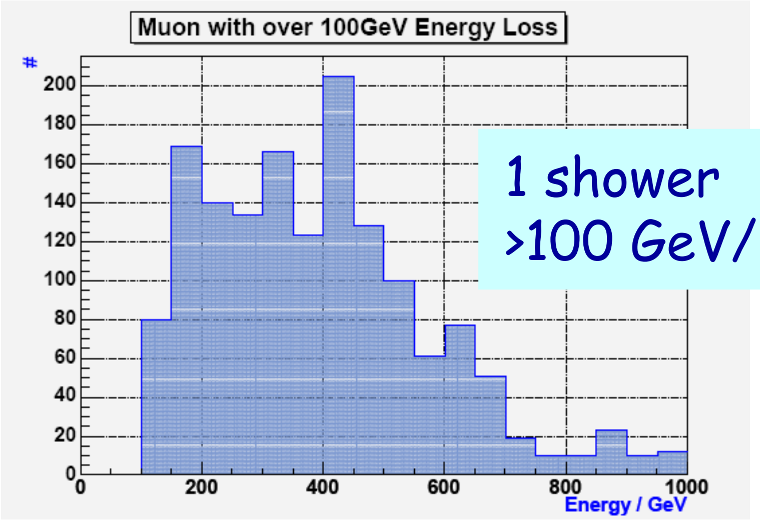
⇒Study benchmark processes

Muon Background

$e^+e^- \to t\bar{t}$ AT $\sqrt{s} = 3$ TeV
+ MUON BACKGROUND (10 BX)



~20 muons per bx



1 shower >100 GeV/5 bx

Muon pairs produced in em interactions upstream of the IP e.g beam halo scraping collimators

GEANT3 simulation, taking into account the full CLIC beam delivery system

# of muons expected in the detector ~ few thousand/bunch train (150 bunches/100ns)

⇒ OK for (silicon like) tracker
⇒ Calorimeter? Full study needed

⇒ EFFECT ON PHYSICS??

Detector Parameters

Detector	CLIC
Vertexing	$15\mu m \oplus \frac{35\mu m GeV/c}{p \sin^{3/2}\theta}$ $15\mu m \oplus \frac{35\mu m GeV/c}{p \sin^{5/2}\theta}$
Solenoidal Field	$B = 4\ T$
Tracking	$\frac{\delta p_t}{{p_t}^2} = 5. \times 10^{-5}$
E.m. Calorimeter	$\frac{\delta E}{E(GeV)} = 0.10\frac{1}{\sqrt{E}} \oplus 0.01$
Had. Calorimeter	$\frac{\delta E}{E\ (GeV)} = 0.40\frac{1}{\sqrt{E}} \oplus 0.04$
μ Detector	Instrumented Fe yoke $\frac{\delta p}{p} \simeq 30\%$ at 100 GeV/c
Energy Flow	$\frac{\delta E}{E\ (GeV)} \simeq 0.3\frac{1}{\sqrt{E}}$
Acceptance	$\lvert\cos\theta\rvert < 0.98$
mask	120 mrad
beampipe	3 cm
small angle tagger	$\theta_{min} = 40$ mrad

Starting point: the TESLA TDR detector
Adapted to CLIC environment

First ideas:

3–15 cm	VDET
15–80 cm	Silicon/forward disks
80–240 cm	TPC
240–280 cm	ECAL (30 X_0)
280–400 cm	HCAL (6λ)
400–450 cm	Coil (4T)
450–800 cm	Fe/muon

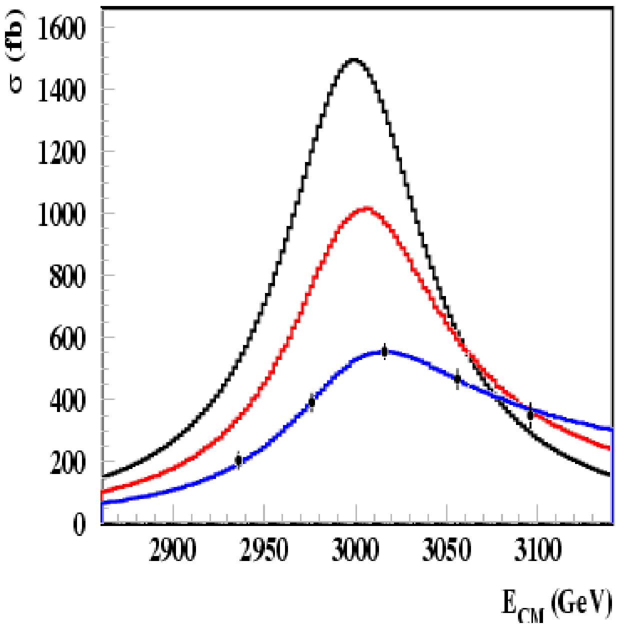
..or all silicon (15-120 cm)
more compact...

Next step: further studies needed to optimize the detector

A few results and suggestions for studies for CLIC Physics Phase-II

Resonance Production

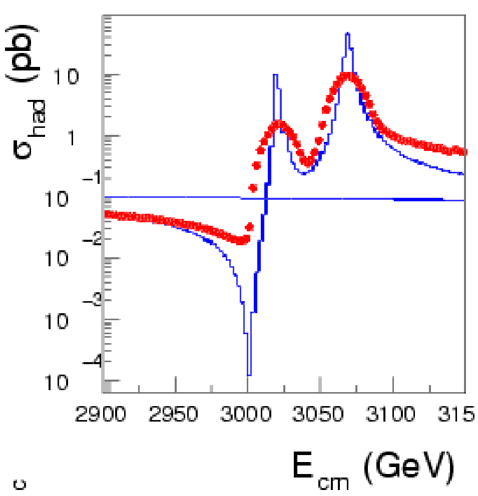
Resonance scans, e.g. a Z′

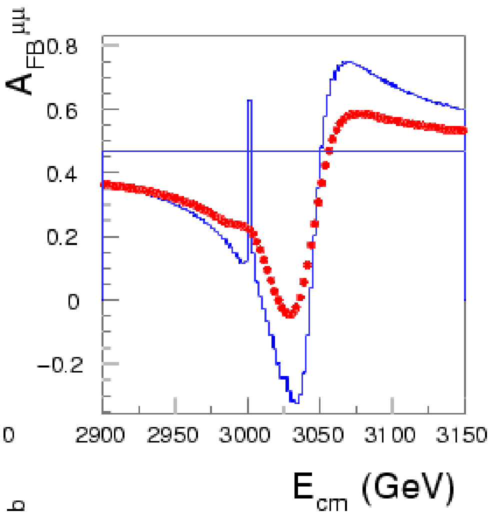


FIT ACCURACY

Observable	Breit Wigner	CLIC.01	CLIC.02
$M_{Z'}$ (GeV)	3000 ± .12	± .15	± .21
$\Gamma(Z')/\Gamma_{SM}$	1. ± .001	± .003	± .004
σ^{eff}_{peak} (fb)	1493 ± 2.0	564 ± 1.7	669 ± 2.9

1 ab^{-1} ⇒ $\delta M/M \sim 10^{-4}$ & $\delta\Gamma/\Gamma = 3.10^{-3}$



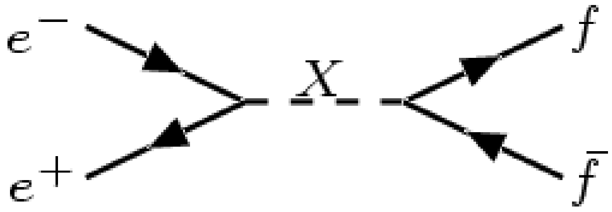


Degenerate resonances
e.g. D-BESS model

Can measure ΔM down to 13 GeV

Smeared lumi spectrum allows
still for precision measurements

Precision Measurements

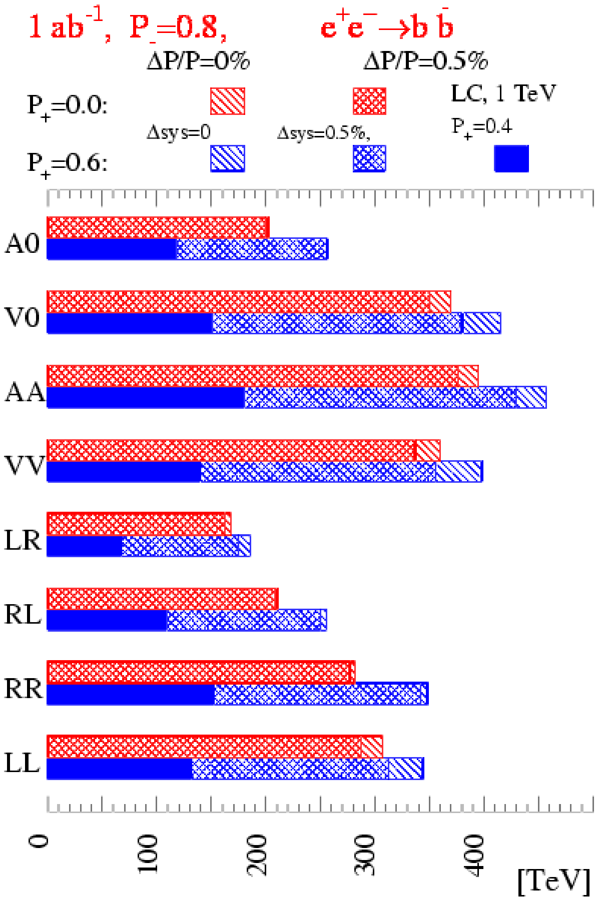


Measure $\sigma_{b\bar b}$, $A_{FB}^{\mu^+\mu^-}$ and $A_{FB}^{b\bar b}$

Examples: $\frac{\delta\sigma_{b\bar b}}{\sigma_{b\bar b}} = 0.012/\ 1\ \mathrm{ab}^{-1}$

$$\frac{\delta A_{FB}^{\mu^+\mu^-}}{A_{FB}^{\mu^+\mu^-}} = 0.018/\ 1\ \mathrm{ab}^{-1}$$

Observable	Relative Stat. Accuracy $\delta\mathcal{O}/\mathcal{O}$ for 1 ab^{-1}
$\sigma_{\mu^+\mu^-}$	± 0.010
$\sigma_{b\bar b}$	± 0.012
$\sigma_{t\bar t}$	± 0.014
$A_{FB}^{\mu\mu}$	± 0.018
A_{FB}^{bb}	± 0.055
A_{FB}^{tt}	± 0.040



E.g.: Contact interactions:
Sensitivity to scales up to
100-400 TeV

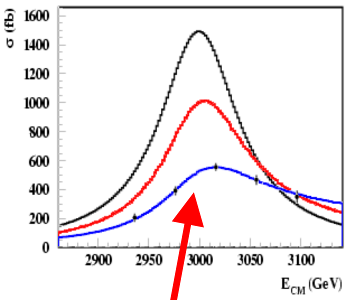
Examples/overview of Physics Reach

Measurements at CLIC (5 TeV / 1 ab^{-1})

Higgs (Light)	λ_{HHH} to $\sim 5-10\%$ (5 ab^{-1})
Higgs (Light)	$g_{H\mu\mu}$ to $\sim 3.5-10\%$ (5 ab^{-1})
Higgs (Heavy)	2.0 TeV (e^+e^-) 3.5 TeV ($\gamma\gamma$)
squarks	2.5 TeV
sleptons	2.5 TeV
Z' (direct)	5 TeV
Z' (indirect)	30 TeV
l^*, q^*	5 TeV
TGC (95%)	0.00008
Λ compos.	400 TeV
$W_L W_L$	$>$ 5 TeV
ED (ADD)	30 TeV (e^+e^-) 55 TeV ($\gamma\gamma$)
ED (RS)	18 TeV (c=0.2)
ED (TeV^{-1})	80 TeV
Resonances	$\delta M/M, \delta\Gamma/\Gamma \sim 10^{-3}$
Black Holes	5 TeV

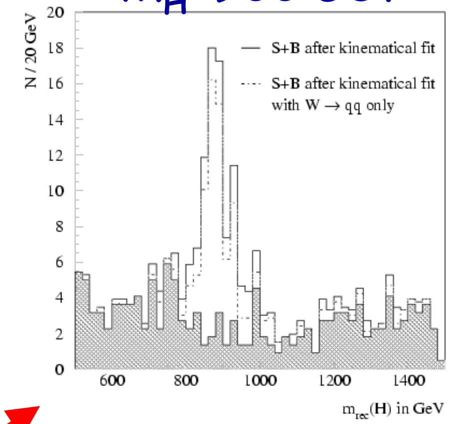
CLIC physics study
CERN Yellow Report

Assume $M_{Z'}$ = 3.0 TeV and
$\Gamma(Z')/M_{Z'} \simeq \Gamma(Z^0)/M_{Z^0}$



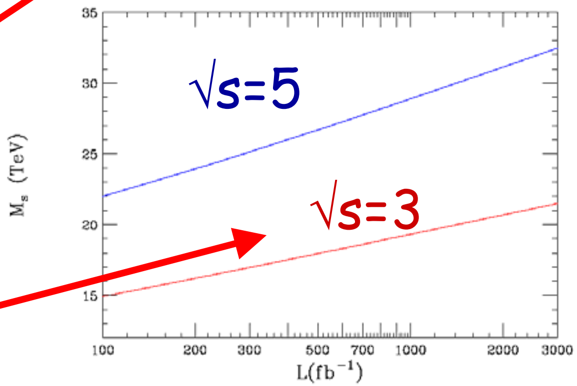
$\Rightarrow$ FIT ACCURACY (1AB^{-1})
$\delta M'_Z/M'_Z \sim 10^{-4}$ $\delta\Gamma'_Z/\Gamma'_Z \sim 3\cdot 10^{-3}$

M$_H$=900 GeV



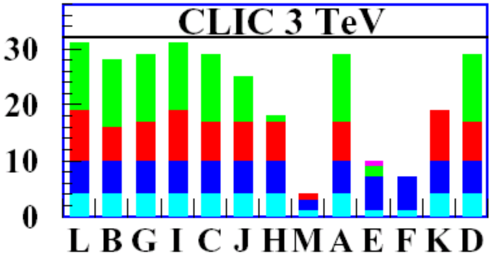
New Z' resonance

Heavy Higgs



ADD Extra Dimensions

Supersymmetric particles:
# of higgses, sleptons
gauginos, squarks
detected for benchmark
scenarios (hep-ph/0306219)



Summary: CLIC vs Hadron Colliders

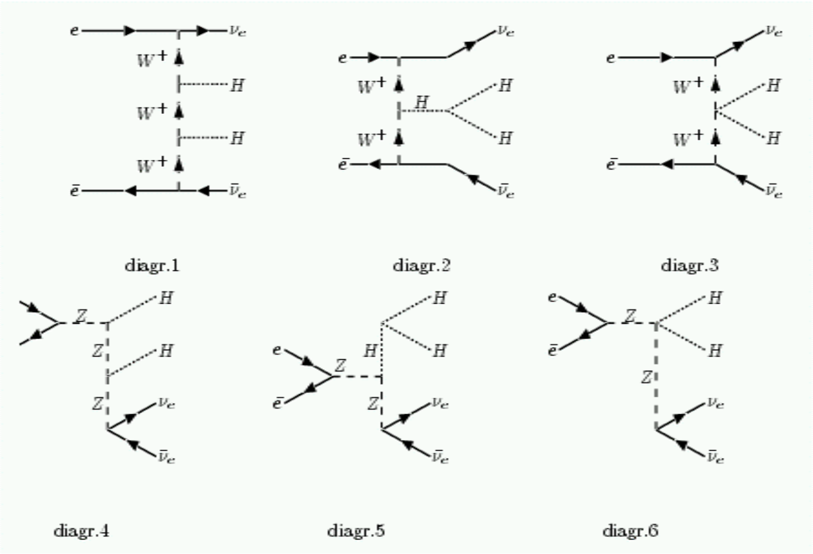
ADR, F. Gianotti, J. Ellis hep-ph/0112004 + updates
U. Bauer et al. hep-ph/0201227

Process	LHC 14 TeV 100 fb^{-1}	SLHC 14 TeV 1000 fb^{-1}	VLHC* 200 TeV 100 fb^{-1}	CLIC 3-5 TeV 1000 fb^{-1}
squarks (TeV)	2.5	3	20.	1.5-2.5
sleptons (TeV)	0.34			1.5-2.5
Z' (TeV)	5.4	6.5	30-40	20-30
q^* (TeV)	6.5	7.5	70-75	3-5
l^* (TeV)	3.4			3-5
ED (ADD/2D/TeV)	9	12	65	30-55
$W_L W_L$	3.4 σ	$>$ 4.0 σ	30 σ	70-90 σ
TGC (95%)	0.0014	0.0006	0.0003	0.00013- 0.00008
Λ Compos (TeV)	30	40	100	300-400

CLIC Comparable to VLHC

* Very Large Hadron Collider: 233 km Circumference

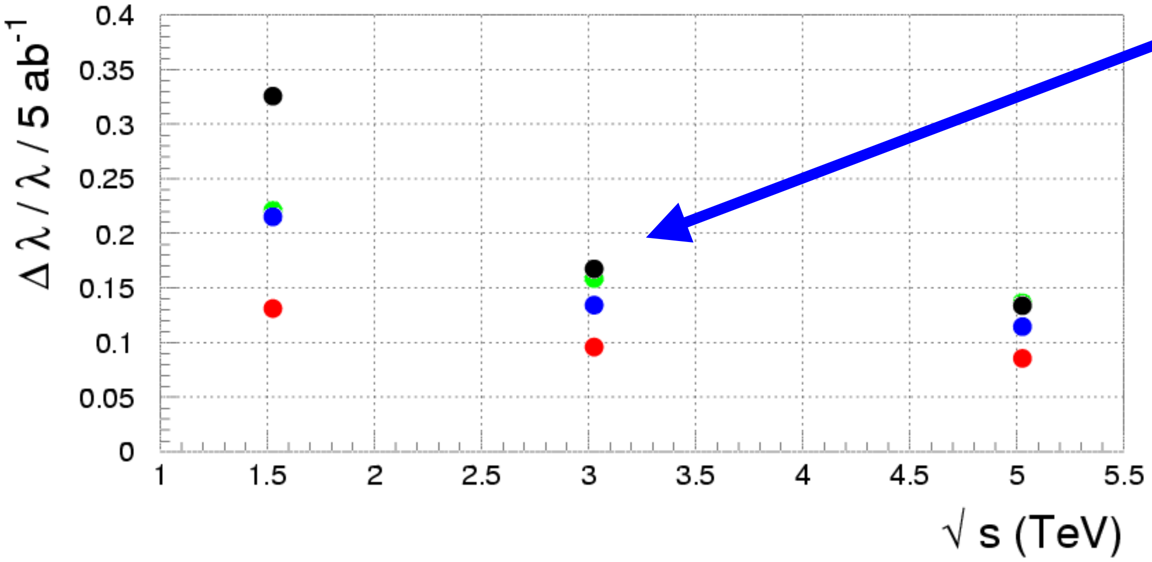
Higgs Potential: e+e- →HHνν



Precision on λ_{HHH} for 5 ab^{-1} for Higgs masses in the range

- 🔴 m_H = 120 GeV
- 🔵 m_H = 140 GeV
- 🟢 m_H = 180 GeV
- ⚫ m_H = 240 GeV

3 TeV



Can improves by using spin Information and polarization (factor 1.5)?
Important to study in detail!

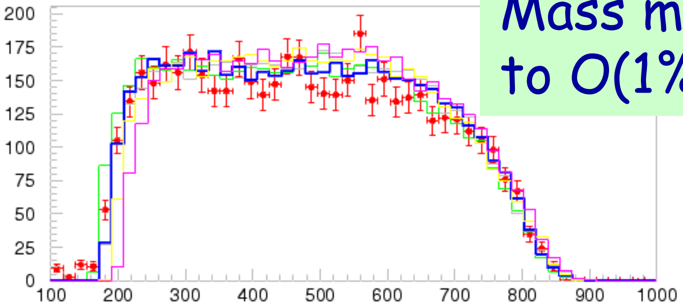
SUSY Mass Measurements

E.G. $m_{1/2} = 1500$ GeV, $m_0 = 420$ GeV, $\tan\beta = 20$, $A = 0$ GeV, $sign(\mu) > 0$ (mSUGRA) (point H)

$\Rightarrow M_{\tilde{\mu}} = 1150$ GeV

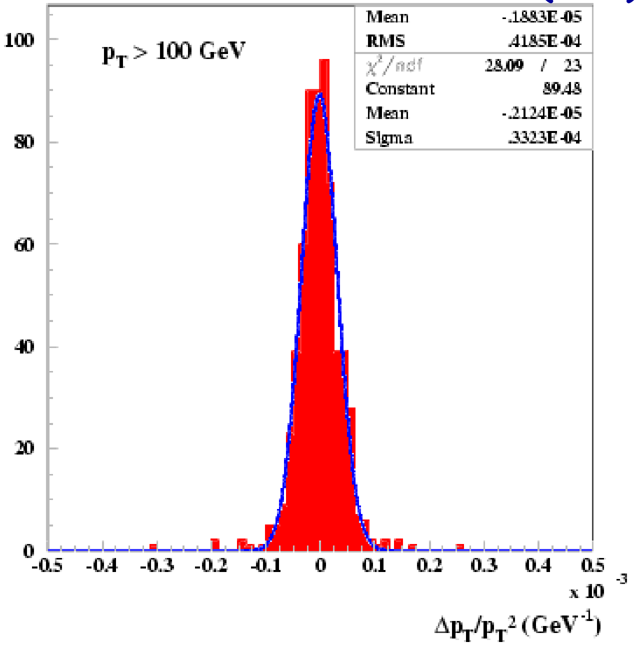
Measure inclusive muon spectrum in $\tilde{\mu} \rightarrow \mu\chi^0$

$$\Rightarrow E_{max/min} = \frac{E_{beam}}{2}(1 - \frac{M^2_{\chi^0}}{M^2_{tilde\mu}}) \times (1 \pm \sqrt{1 - \frac{M^2_{\tilde{\mu}}}{E^2_{beam}}})$$



Mass measurements to O(1%)

Momentum resolution (G3)

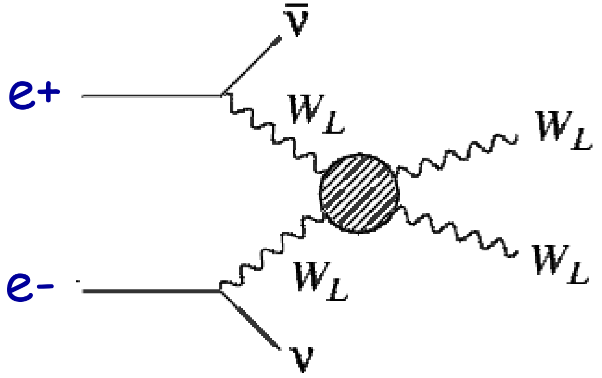


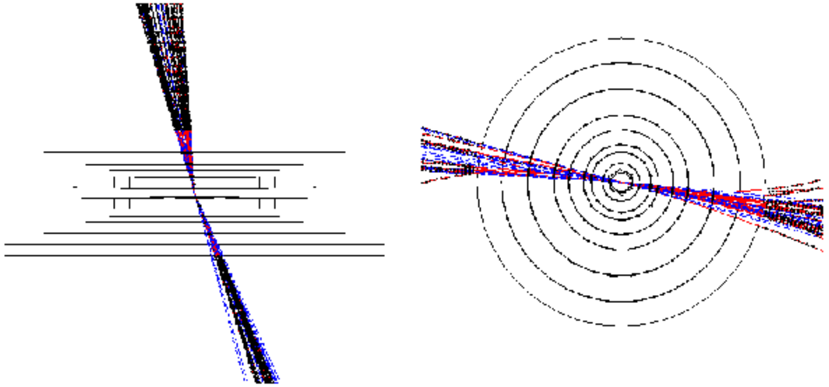
Momentum resolution $\delta p_t/p_t^2 \sim 10^{-4}$ GeV^{-1} adequate for this measurement

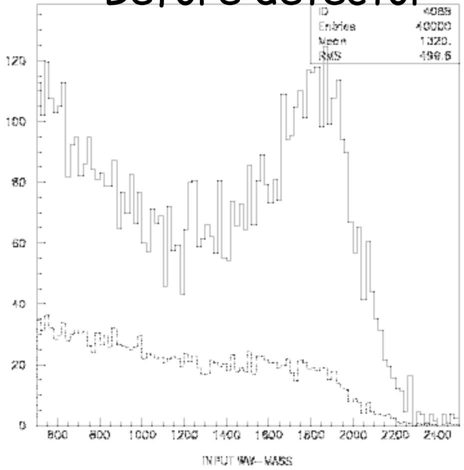
So far only the smuon and χ_2 mass
Precision studied
What about squarks, other gauginos, other sleptons, etc…?

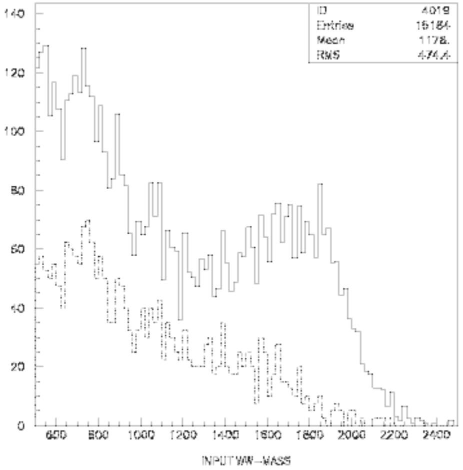
WW Scattering

In case that there is no Higgs:
WW scattering will show effects of strong dynamics in the TeV region
$\Rightarrow$ Study $WW \rightarrow WW$ scattering






Before detector


After detector

These measurements are difficult at the LHC.
So far only 1 example studied

$\Rightarrow$Needs further studies eg. LET models, others…
Has impact on detectors!

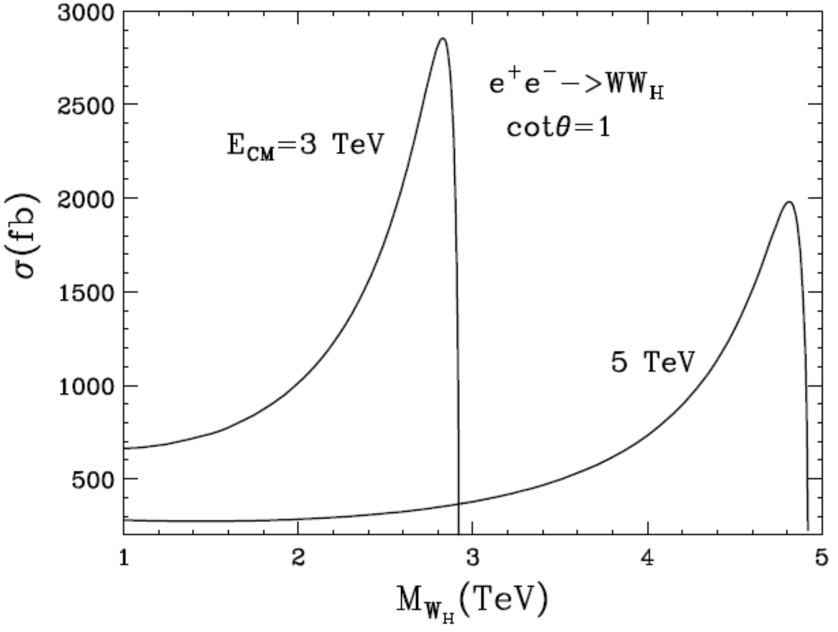
Little Higgs Models

- Stabelizing the Higgs with new weakly coupled fermions and Gauge bosons

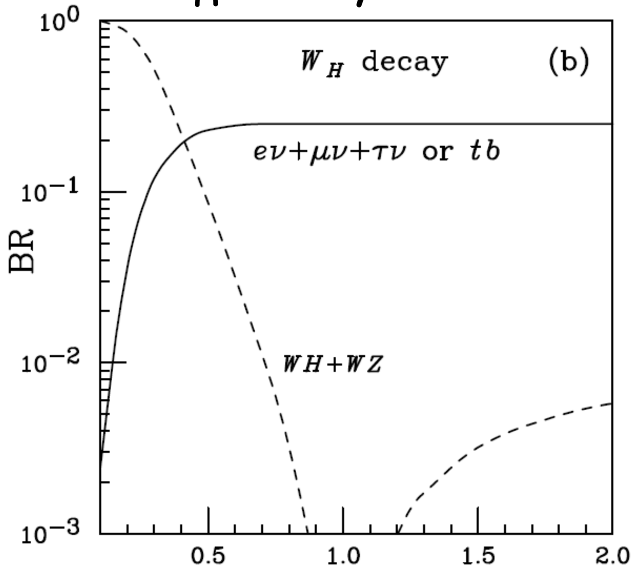
⇒ Expect 'new top' T quark and new W_H,Z_H around 1 TeV.

⇒ Expect the new gauge bosons to be copiously be produced at a LC, e.g. via the associated production e+e-→ WW_H

Cross section



W_H decay modes



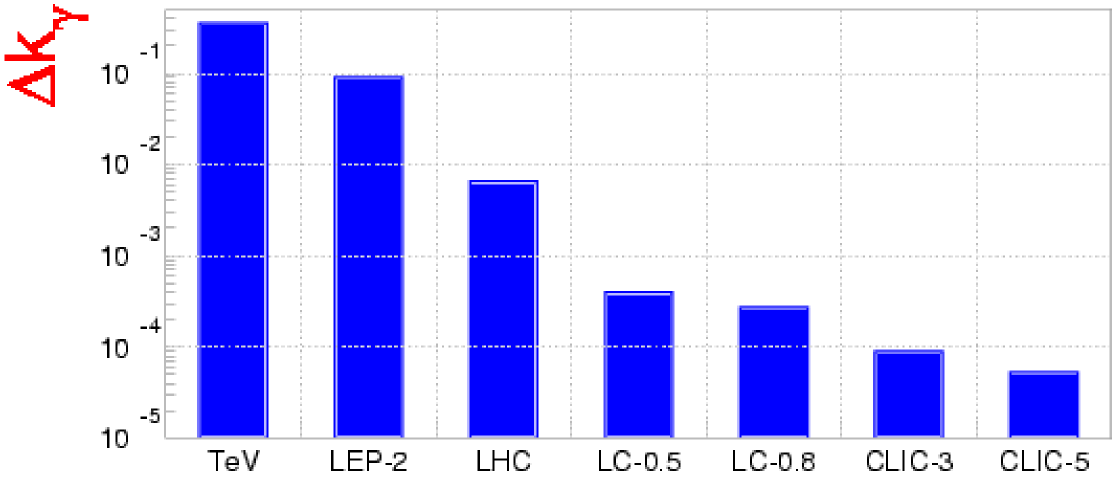
cotθ =Gauge coupling mixing parameter

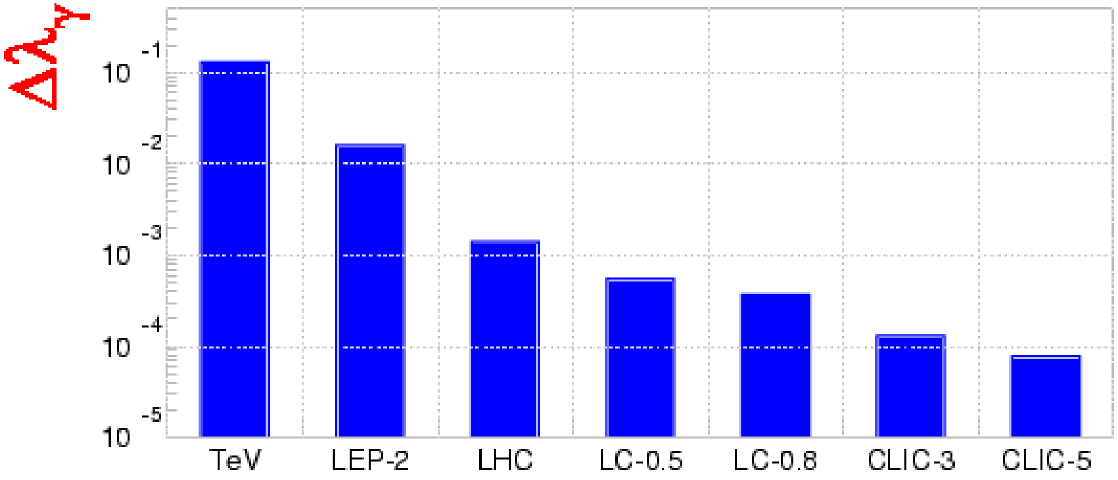
Allow for detailed studies of W_H (and other new particles) properties

⇒ NEEDS a dedicated study (also for Z_H, T)

Triple Gauge Couplings

High precision analysis of the self coupling of the EW gauge bosons





Expectation of the precision for $\Delta\lambda_\gamma$ and $\Delta\kappa_\gamma \sim 10^{-4}$

Measurements for one year of high luminosity for the future colliders

A detailed simulation is still needed for this process

Other Topics in Summary

- Excited lepton production
- Production of 4th family quarks and leptons
- Leptoquarks
- Effects of non-commutative interactions on physical observables
- Transplanckian effects when the centre of mass system energy is above the fundamental gravity mass scale
- Lepton size measurements

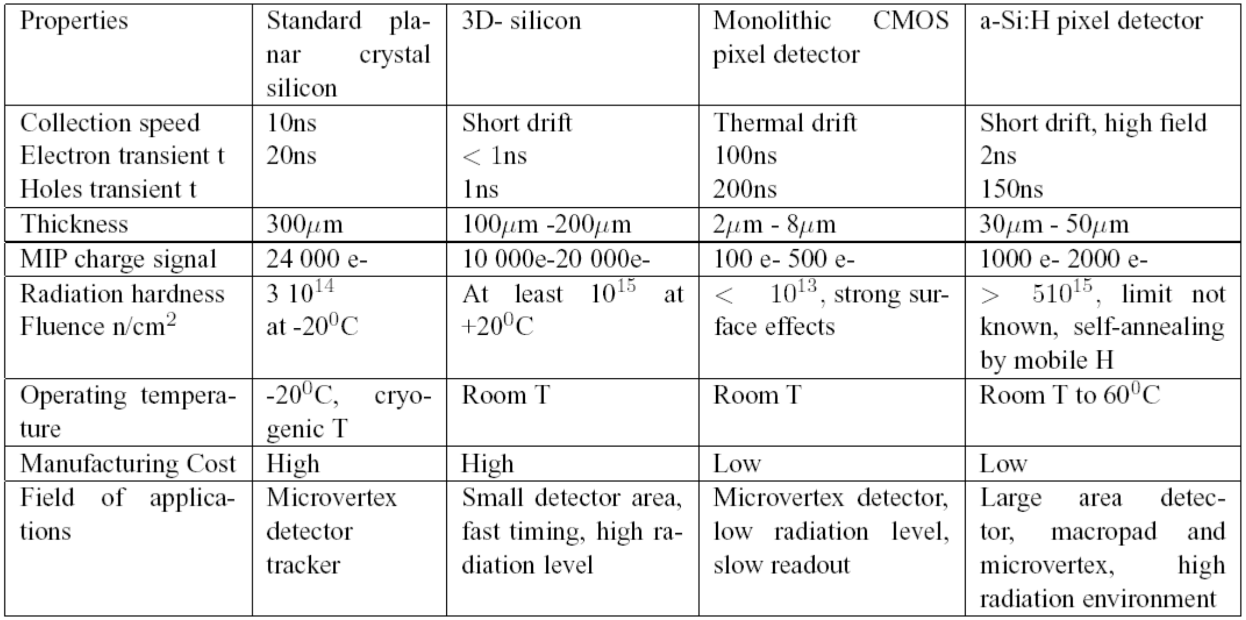
All these processes need a detailed study…

- Split Supersymmetry (long living gluinos)
- Higgless Extra Dimensions Models (effects in TeV range like WW scattering)
- …

New developments in Theory with new signatures in TeV range…

Detector R&D

Tracking Technologies



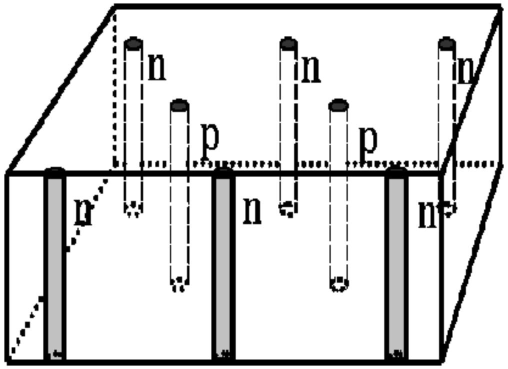
Properties	Standard planar crystal silicon	3D- silicon	Monolithic CMOS pixel detector	a-Si:H pixel detector
Collection speed Electron transient t Holes transient t	10ns 20ns	Short drift $<$ 1ns 1ns	Thermal drift 100ns 200ns	Short drift, high field 2ns 150ns
Thickness	300μm	100μm -200μm	2μm - 8μm	30μm - 50μm
MIP charge signal	24 000 e-	10 000e-20 000e-	100 e- 500 e-	1000 e- 2000 e-
Radiation hardness Fluence n/cm^2	3 10^{14} at -20^0C	At least 10^{15} at +20^0C	$<$ 10^{13}, strong surface effects	$>$ 510^{15}, limit not known, self-annealing by mobile H
Operating temperature	-20^0C, cryogenic T	Room T	Room T	Room T to 60^0C
Manufacturing Cost	High	High	Low	Low
Field of applications	Microvertex detector tracker	Small detector area, fast timing, high radiation level	Microvertex detector, low radiation level, slow readout	Large area detector, macropad and microvertex, high radiation environment

- Time stamping will be important O(ns)
- Macro-pixels?
- Radiation however not a big issue
  ~ 5 10^{10} neutrons/cm^{-2}/year

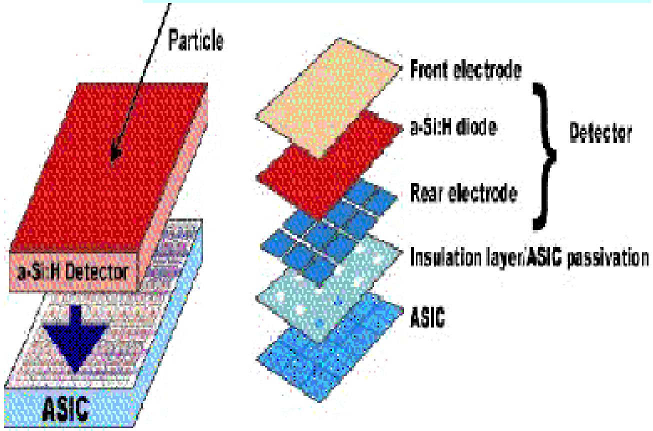
⇒R&D required

⇒In context of SLHC R&D or
Join/follow the NLC R&D program

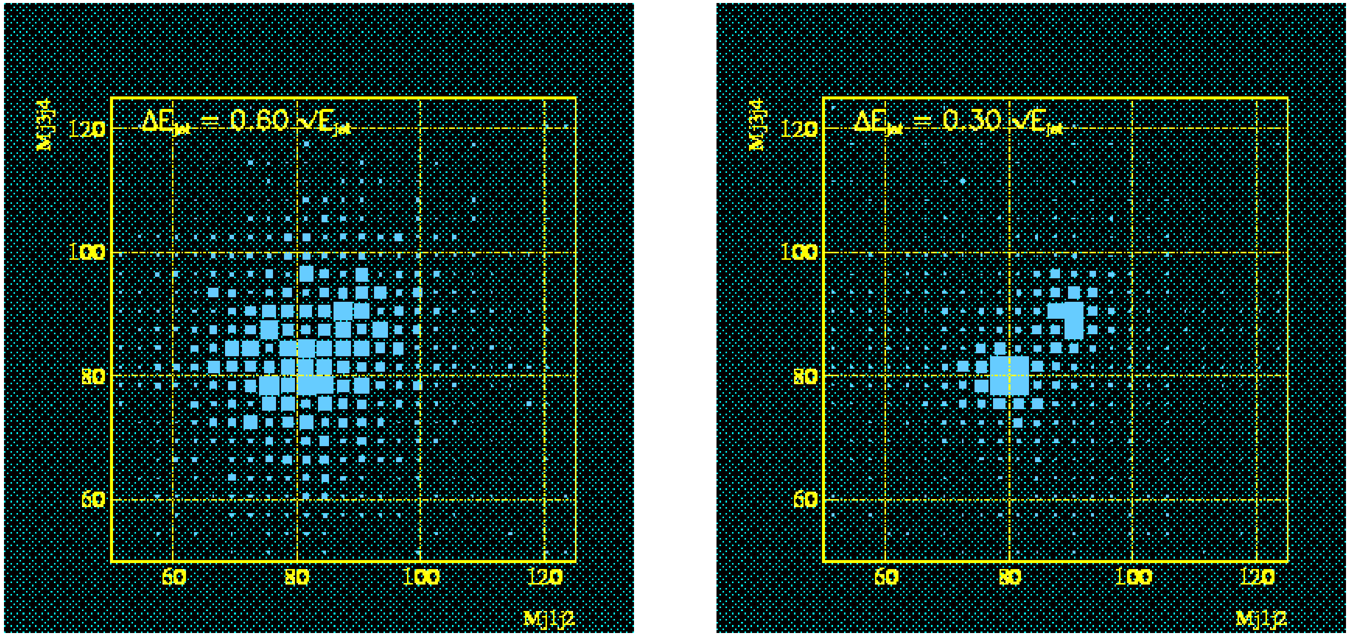
3D Silicon



Amorphous Silicon



Calorimetry



$$e^+e^- \to \nu\bar{\nu}W^+W^-, \nu\bar{\nu}ZZ\,, \qquad W, Z \to \text{2jets}$$

Importance of good energy resolution (e.g via energy flow)
Interesting developments in TeV-class LC working groups
e.g. compact 3D EM calorimeters, or “digital” hadronic calorimeters
⇒Detailed simulation studies of key processes required
⇒R&D accordingly afterwards/Join LC efforts?

Study of options with CLIC

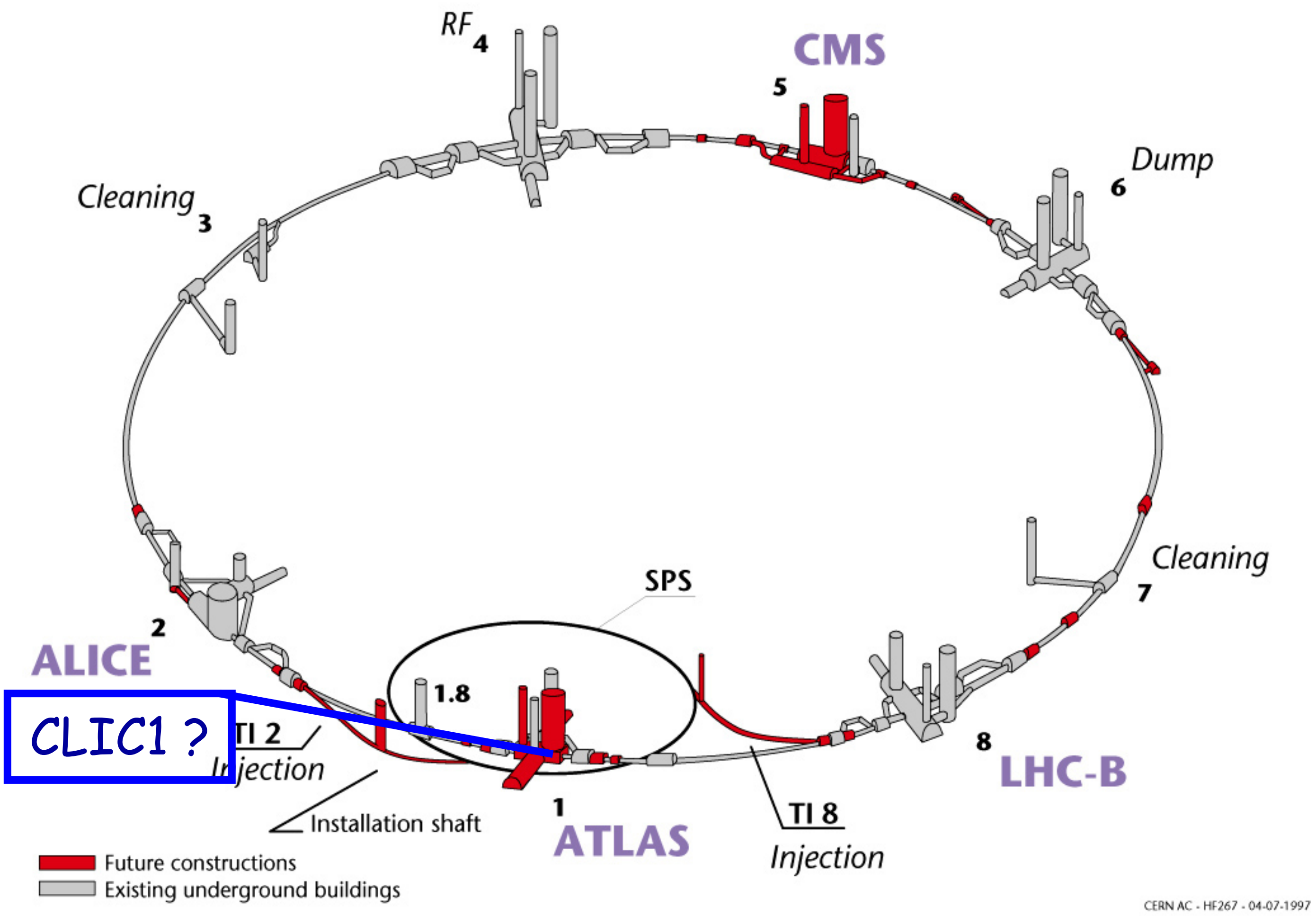
Here only some comments on ep option

ep collisions

- Physics: ADR, "future ep possibilities at DESY and CERN"
  Proc DIS98 (Brussels)
  → TESLA ⊗ HERA and LEP ⊗ LHC (LEP Beam Energy 67 GeV)
  Also: ADR hep-ph/9801378 but for TESLA ⊗ HERA only
- Machine: (CLIC ⊗ LHC)
  August 2002 brainstorm meeting of Turkish Group (Sultansoy, Cakir, Cetin) with CLIC group representatives.
  70 GeV ⊗ 7 TeV and 500 GeV ⊗ 7 TeV
  Discussion on possible luminosity
  L= 10^{28} cm^{-2} s^{-1} to 10^{30}-10^{31} cm^{-2} s^{-1} (see CLIC Note 589)
  Q: can an ep collider live with LHC superbunches?
- Program discussed
  Low luminosity/low energy: QCD explorer 10^{28} –10^{29} $cm^{-2}s^{-1}$ ok
  'High' luminosity/low energy: similar as THERA (= TESLA ⊗ HERA)
  Only one CLIC module required (5 bunches i.s.o. 154 only to start)
  High energy/luminosity: High energy frontier → probing new physics

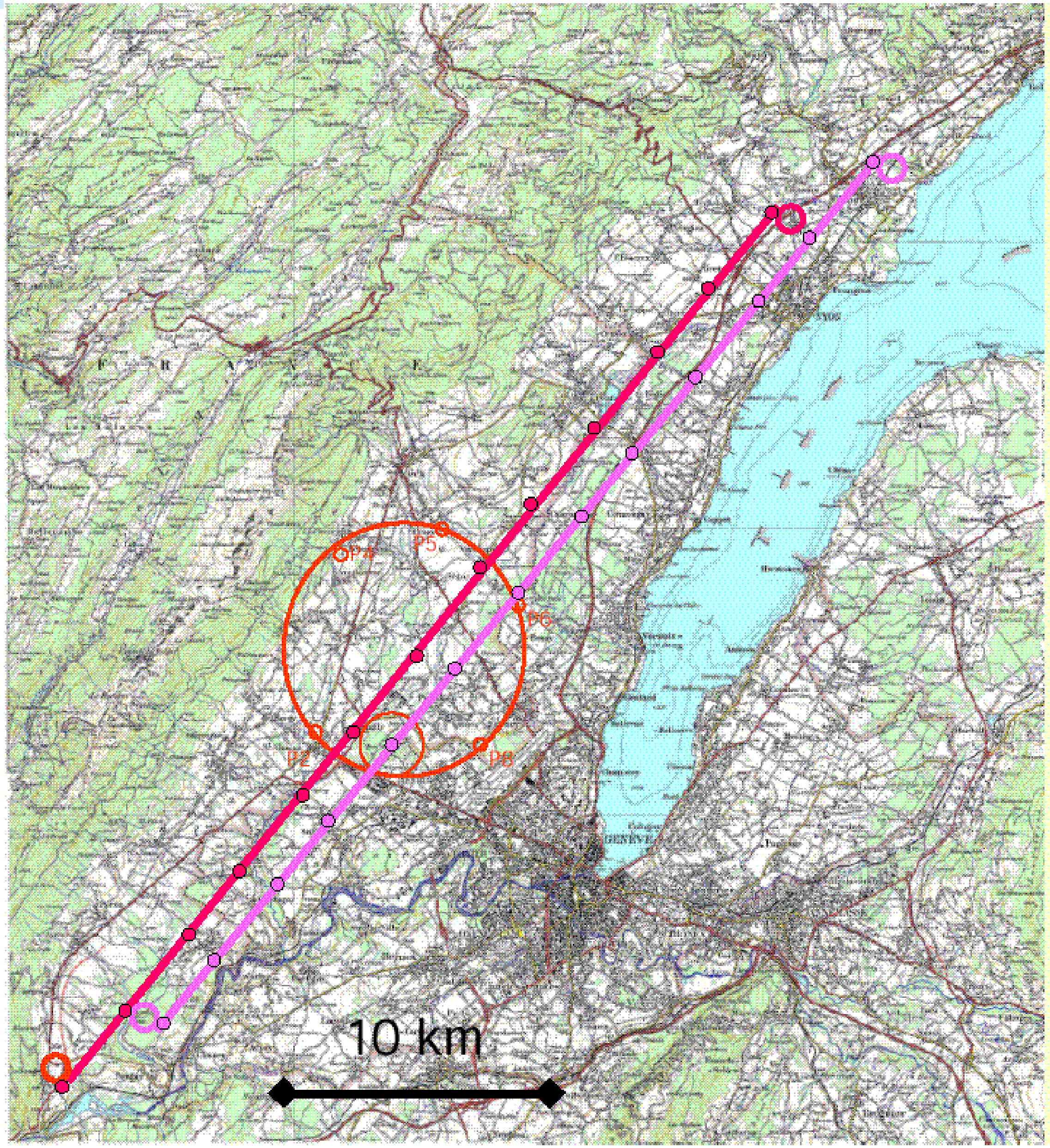
Where can be the ep IP?

Layout of the LEP tunnel including future LHC infrastructures.



CLIC1 ?

Building CLIC at CERN?



Following up a question

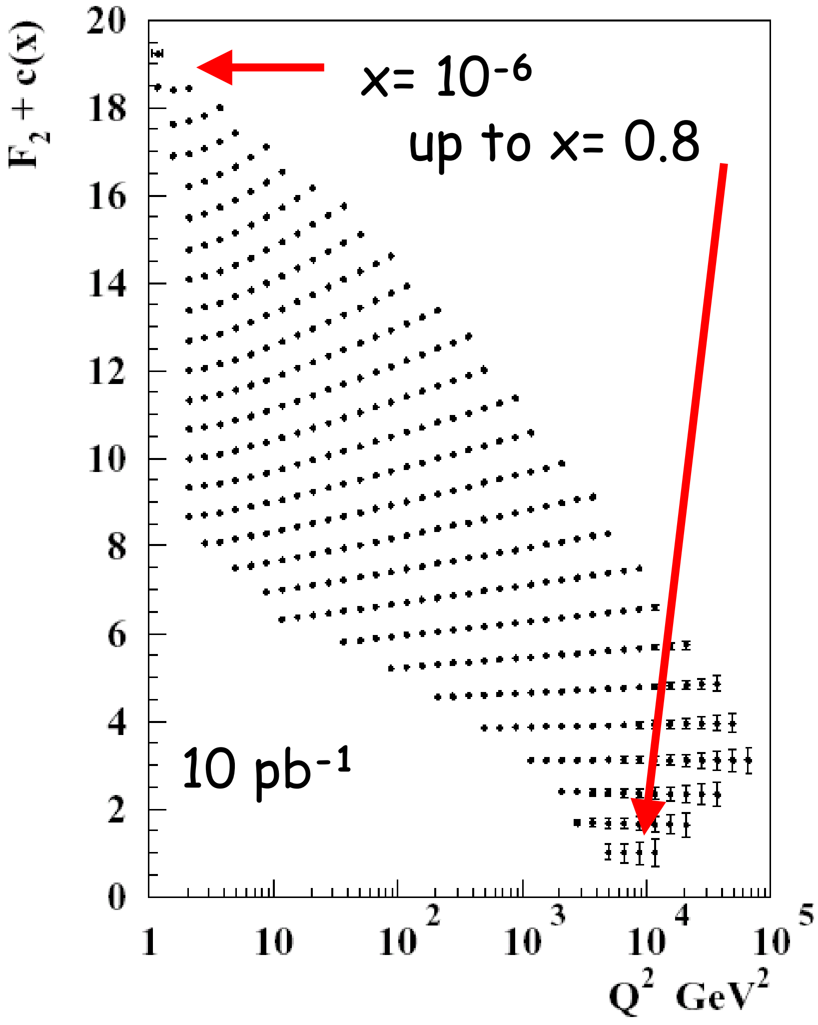
It is possible!

Geological analyses show that there is a contineous stretch of 40 km parallel to the Jura and the lake, with good geological conditions.

However: Not easy to be tangential to LHC

Structure Functions

$$\frac{d^2\sigma^{e^\pm p}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left(\underbrace{Y_+\tilde{F}_2(x,Q^2)\mp Y_- x\tilde{F}_3(x,Q^2) - y^2 F_L(x,Q^2)}\right)$$

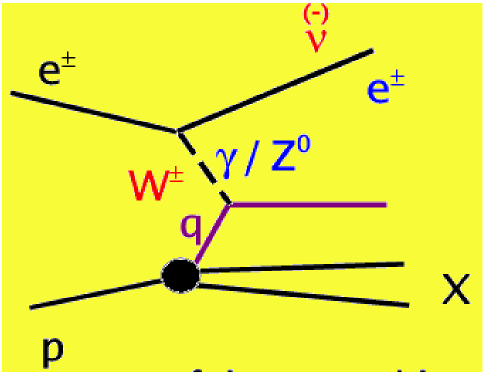


x= 10^{-6}

up to x= 0.8

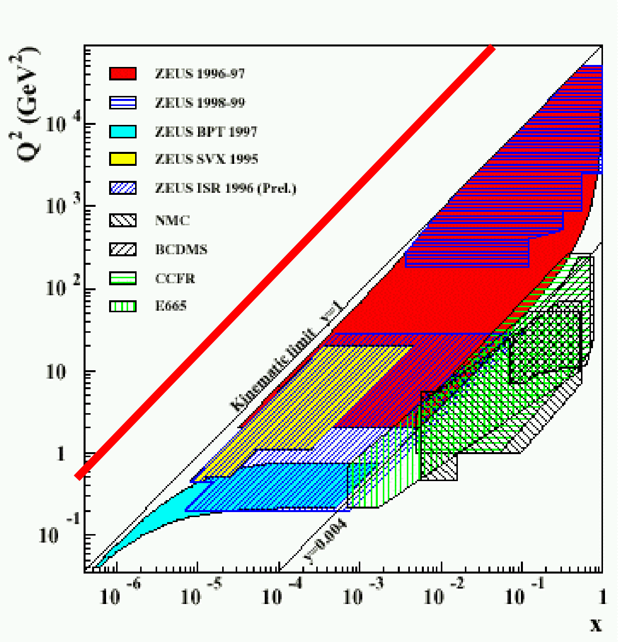
10 pb^{-1}

Bjorken-x:
Momentum fraction
of the quark
in the proton



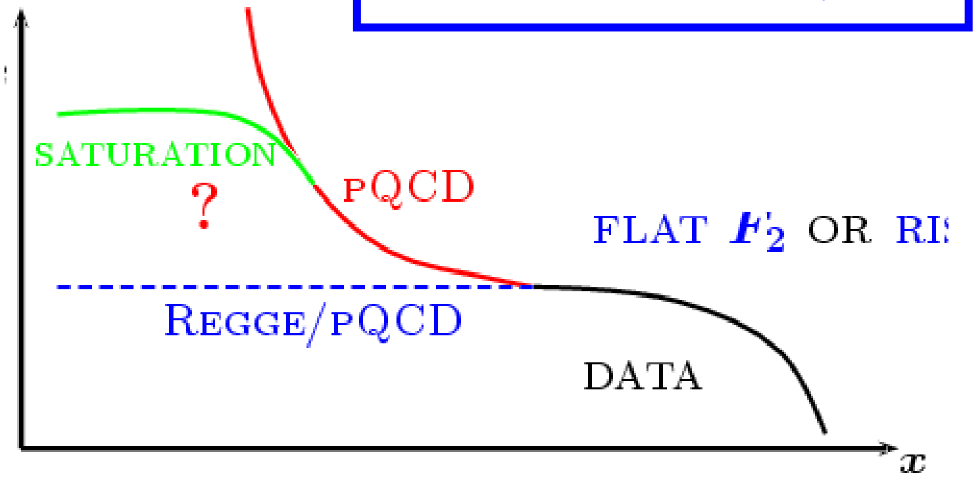
F2 → quark distributions

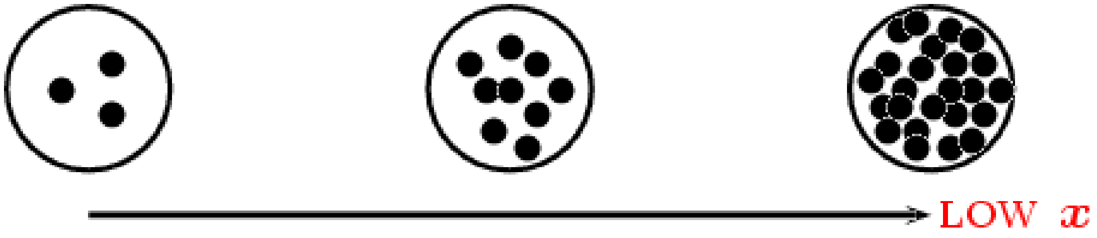
Extend HERA kinematic range by factor 10!

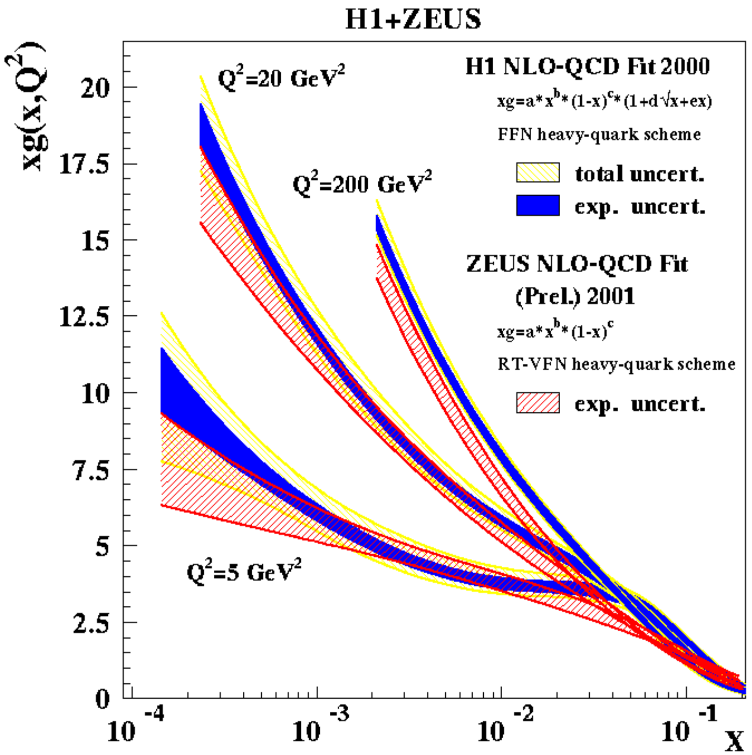


Parton Densities and Saturation

Parton distribution

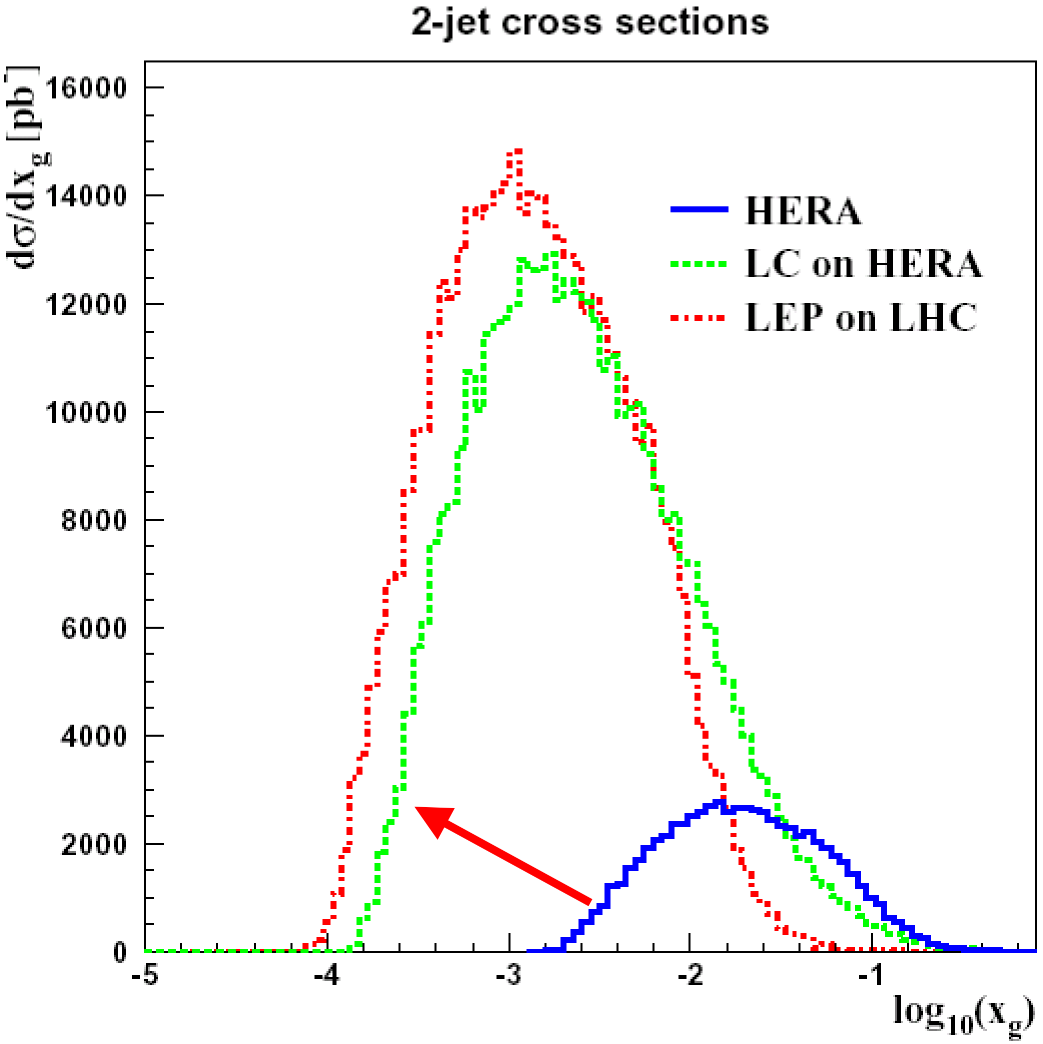


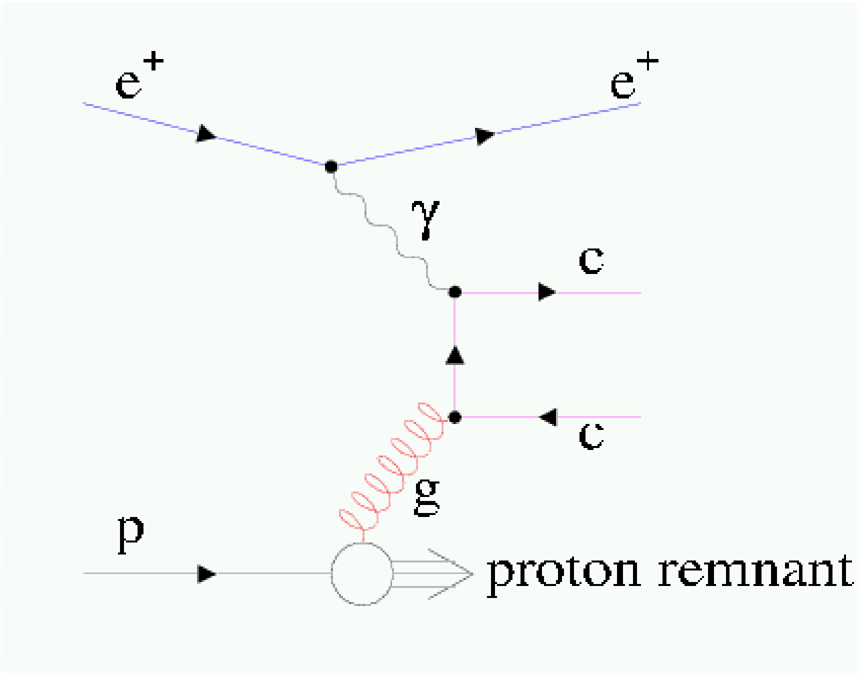




Parton saturation at low x?
Formation of hot-spots in the proton?

Gluon distribution from jets/charm

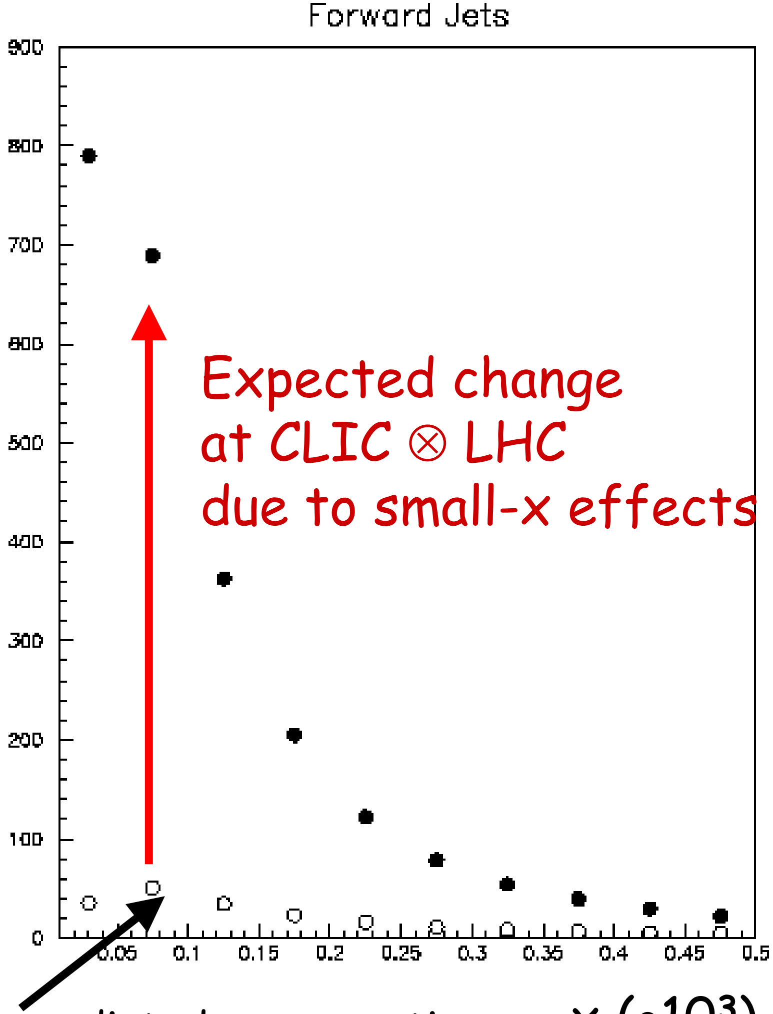




Extract gluon distribution directly from di-jets or charm events down to 10^{-4}

BFKL Jets

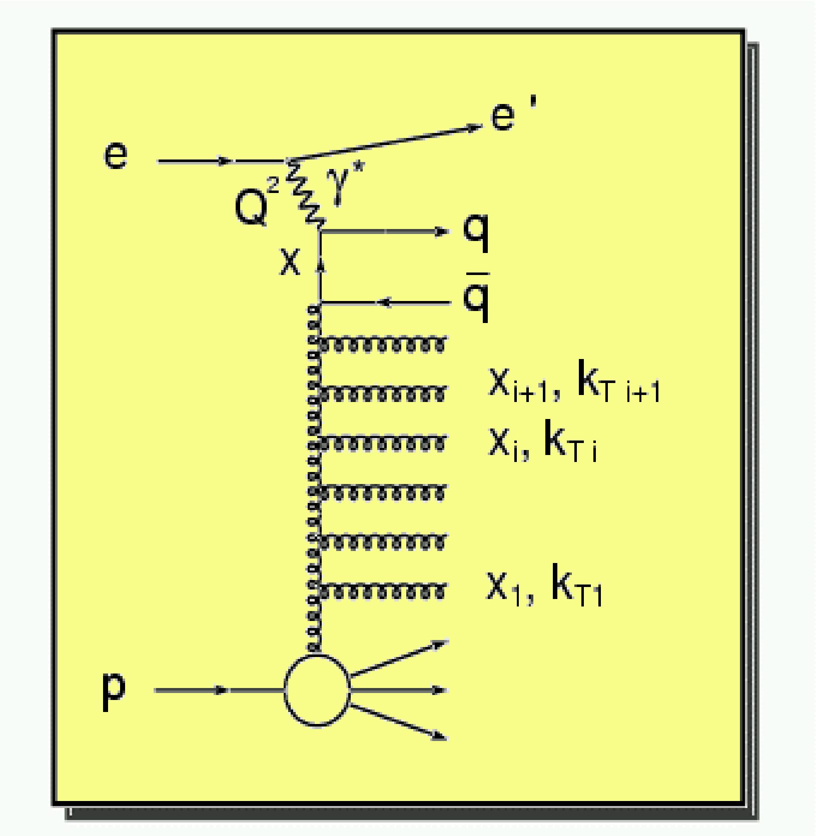
Forward jet cross section



Expected change
at CLIC ⊗ LHC
due to small-x effects

DGLAP predicted cross section

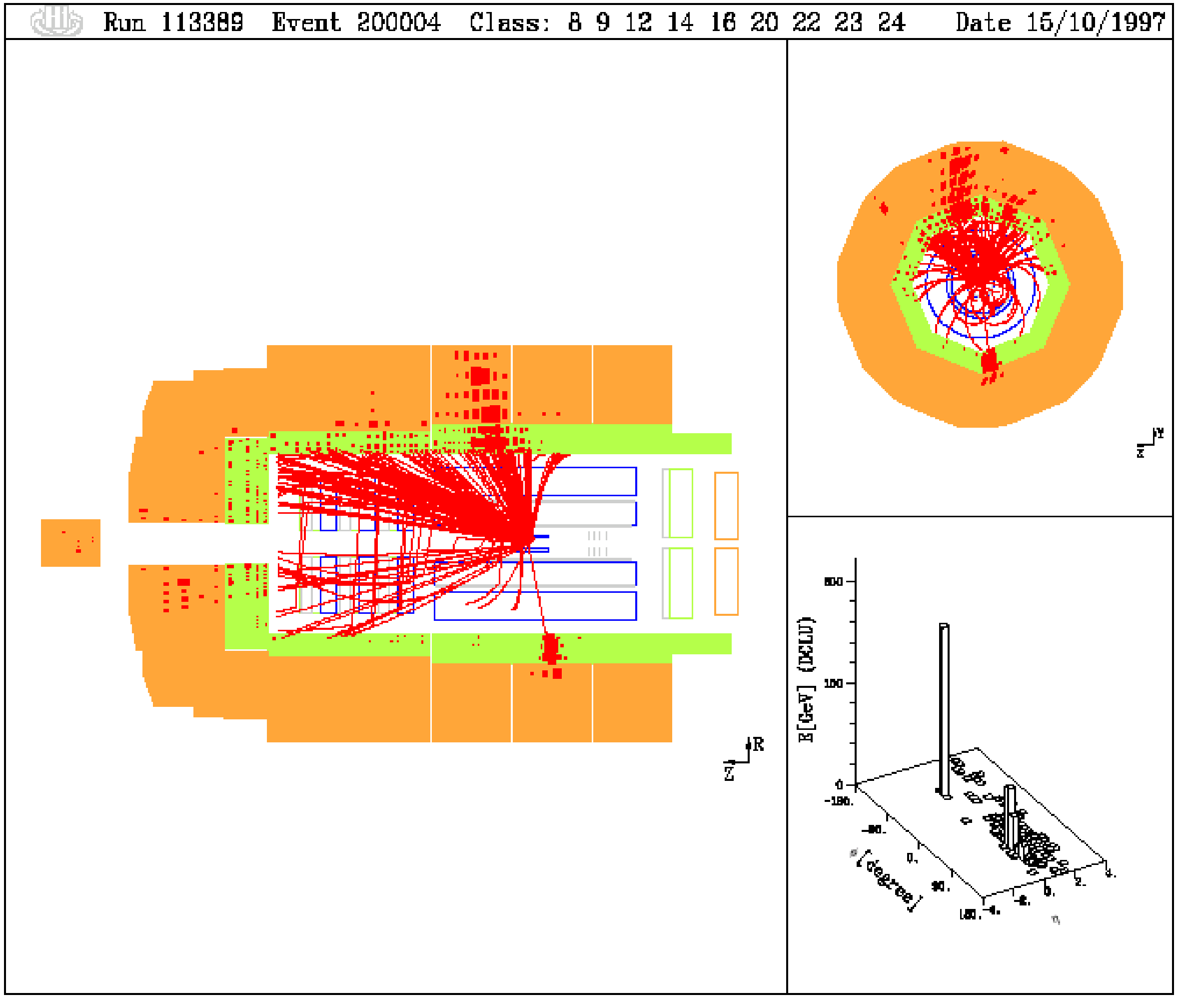
x (•10³)



Small-x dynamics (BFKL) effect?
Still mystery at HERA!

High Q^2 event

Region where one as largest chance for new physics



$Q^2 = 20000$ GeV^2

Cross section for Events with

$Q^2 > 2.10^4$ GeV^2
12 pb

$Q^2 > 10^5$ GeV^2
0.5 pb

Needs at least
$L = 10^{30}$cm^{-2} s^{-1}

Conclusions

- Phase-I study of physics for CLIC finalized and documented in CERN-2004-005
- Physics studies for the CLIC report have included the effects of the detector, and backgrounds such as e+e- pairs and $\gamma\gamma$ events. The muon background is only partially studied.
- Several channels have not yet been studied in full detail (incl backgrounds etc.). Several new ideas/signatures for physics in the TeV range are emerging and need to be studied
- Detector R&D will be needed (tracking with good time stamping, better calorimetry, forward detectors for lumi, etc.).
  A detailed, more complete, study is one of the most important issues to address for a continuing CLIC physics study group.
- Options for CLIC: in order to take ep or other options seriously, some kind of report summarizing the physics potential (& perhaps machine challenges/benefits in terms of CLIC 'roadmap') is needed.