Physics with THERA (TESLA on HERA)

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- Introduction
  - Studying the THERA option
  - Kinematics outreach
- Machine and detector visions
  - THERA layout and parameters
  - Detector requirements
- Some selected physics topics
  - QCD at low x and Q^2
  - Heavy quarks
  - High-Q^2 cross sections, α_s
  - New phenomena
- Conclusions and plans

The following report is based on work of the THERA study group and on discussions with the DESY accelerator experts.

The THERA study group

Meetings:

Previous: 08–09.02 and 14–15.04.2000
Future: 18–20.10.2000 (tentative date)
Please join if you are interested!

	Working Groups	Convenors
•	**Low x**	P Newman (U Birmingham) E Levin (Tel Aviv) A Levy (Tel Aviv)
•	**Heavy Flavours**	K Daum (Wuppertal) L Gladilin (U Hamburg,Moscow)
•	**Photon structure**	J Butterworth (UC London) S Söldner-Rembold (CERN/U Freiburg) M Krawczyk (Warsawa)
•	**High Q^2**	E Perez (Saclay) K Long (IC London) M Kuze (KEK Tanashi)
•	**QCD and MC simulation**	L Lönnblad (U Lund) H Spiesberger (U Mainz) H Jung(U Lund)
•	**Detector and Infrastructure**	L Bauerdick (DESY HH) J Crittenden (U Bonn) U Katz (U Bonn) M Klein (DESY Z) D Pitzl (DESY HH)
•	**Machine**	S Schlenstedt(DESY Z) U Schneekloth(DESY)
•	**Polarization**	E Rondio (Warsawa) A Deshpande (Yale U)
•	**Nuclei**	M Strikman (Penn State)
•	**Gamma**	S Sultansoy (Ankara)

More information in
`http://www.ifh.de/thera`

Questions and objectives

Questions:

Feasibility:
can the THERA project be realized without negative interference with TESLA?

Physics potential:
what can be learned from THERA?

Objectives:

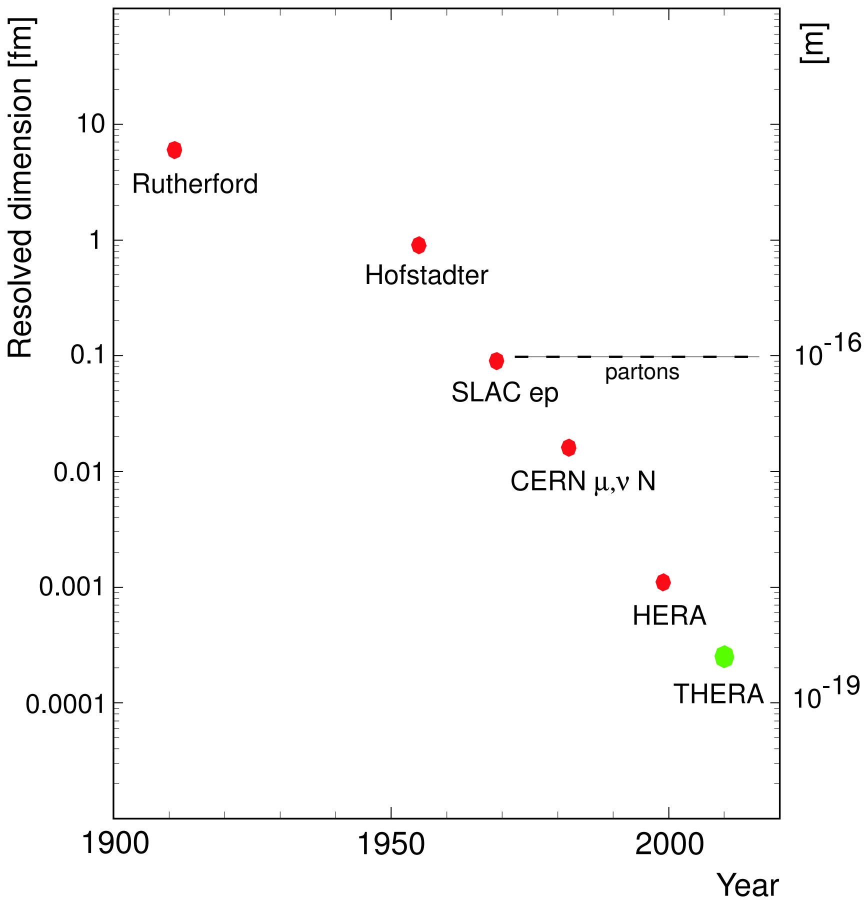
Answer the above questions.

Document the results.

Section in TESLA TDR:

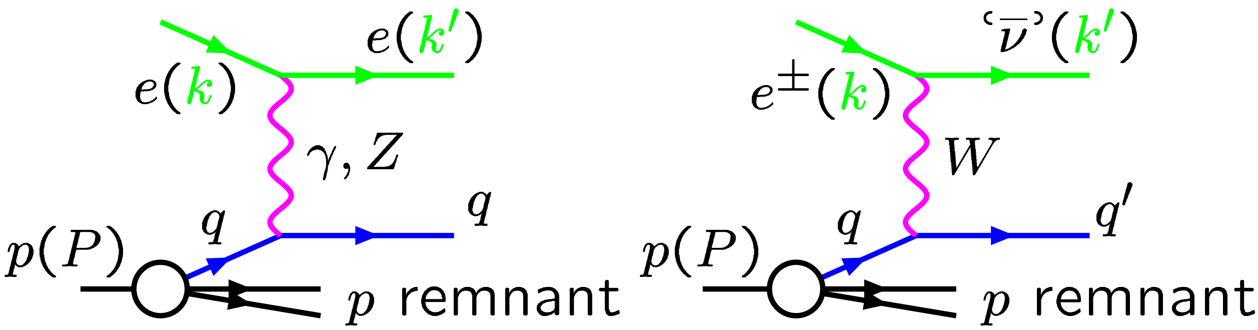
physics potential of a TESLA–HERA ep option

(draft 10/2000, final by spring 2001)



THERA is the canonical successor of a series of very successful DIS experiments

Kinematics of ep scattering



Neutral Current (NC) | Charged Current (CC)

ep center-of-mass energy squared:

$$s = (k + P)^2 = 4E_e E_p$$

four-momentum transfer:

$$Q^2 = -(k - k')^2 = 2E_e E'(1 + \cos\theta_e)$$

$\theta_e = e$ scattering angle w.r.t. proton direction

momentum fraction of struck quark:

$$x = \frac{Q^2}{2\,(k - k') \cdot P}$$

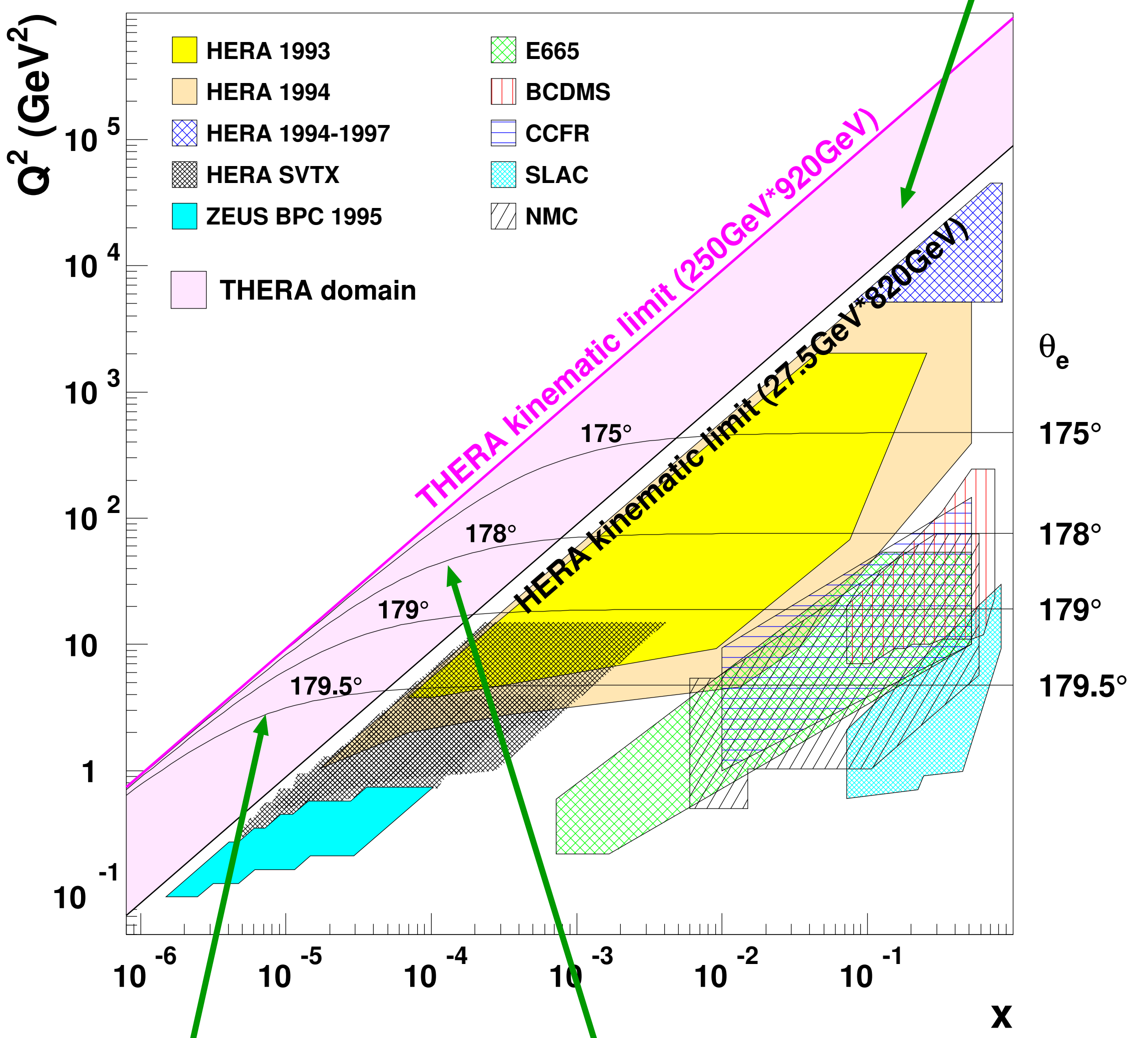
inelasticity:

$$y = \frac{(k - k') \cdot P}{k \cdot P} = \frac{Q^2}{xs}$$

The THERA outreach

Extend HERA range by
$\sim$ 1 order of magnitude
to higher x and Q^2

+ "electroweak region"
+ new phenomena?
− small cross sections



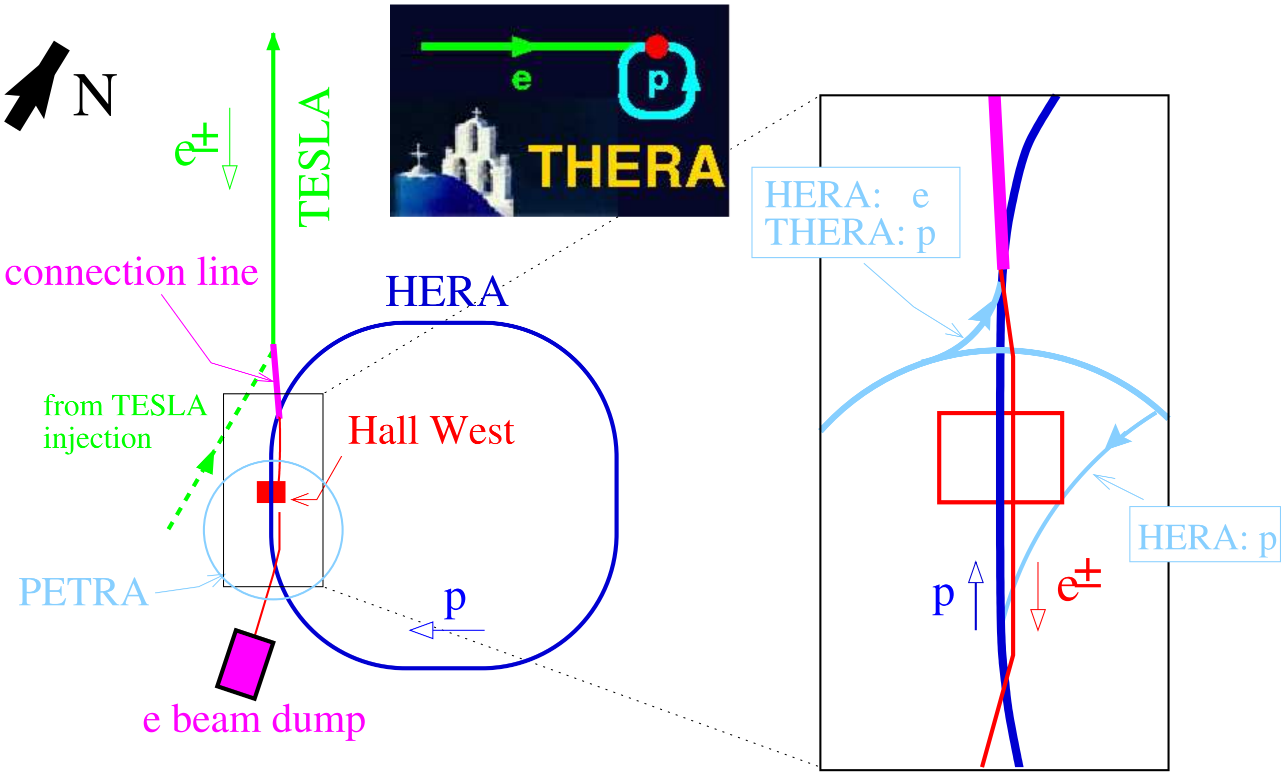
Reach $x =$ a few $\times 10^{-6}$
at $Q^2 \gtrsim 1$ GeV^2

+ high parton densities
+ new QCD effects
+ large cross section
− difficult to measure

Cover one decade of Q^2
in perturbative regime
for $x \sim 10^{-4}$

+ onset of pQCD
+ gluon density, α_s, ...
+ forward jets, ...

The THERA complex



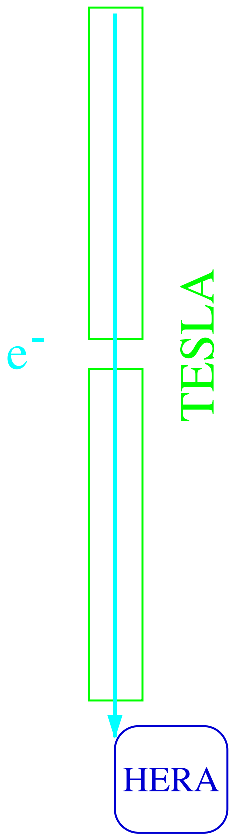
HERA p-ring and tunnel modifications

- Reverse proton direction
  - New magnets for p injection to HERA (7 T or new tunnel)
  - Move p dump or beam kickers
- ep beam separation, new p focusing
- Option: Additional RF to reduce p emittance
- Transfer e beam into and out of HERA tunnel

New components

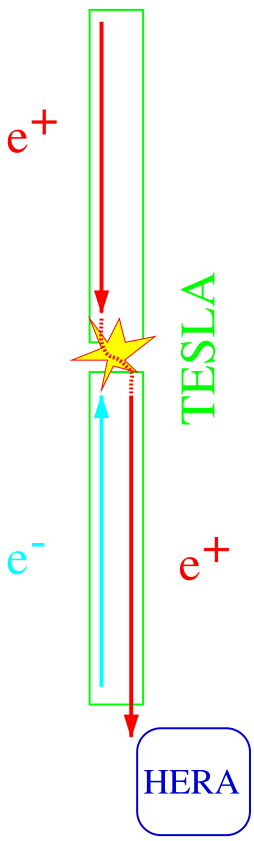
- Transfer line from TESLA to HERA
  - civil engineering, not on DESY area
  - no active beam line elements
  - "thin" tube might be sufficient
- e beam dump
  - $1 \times 1 \times 8\,\mathrm{m}^3$ H_2O in 4 m concrete walls
  - tunnel HERA→dump
  - not clear whether sufficient space on DESY area

THERA running modes



Dedicated mode

+ Use full length of TESLA, get maximal energy and beam power
+ No modification of TESLA necessary
− TESLA (e^+e^-) and THERA (ep) operation mutually exclusive
− Only e^- available, e^+ production needs high-energy e^- beam at "far end" of TESLA (reduces luminosity by factor 2)
− Full TESLA energy probably not usable (beam separation)



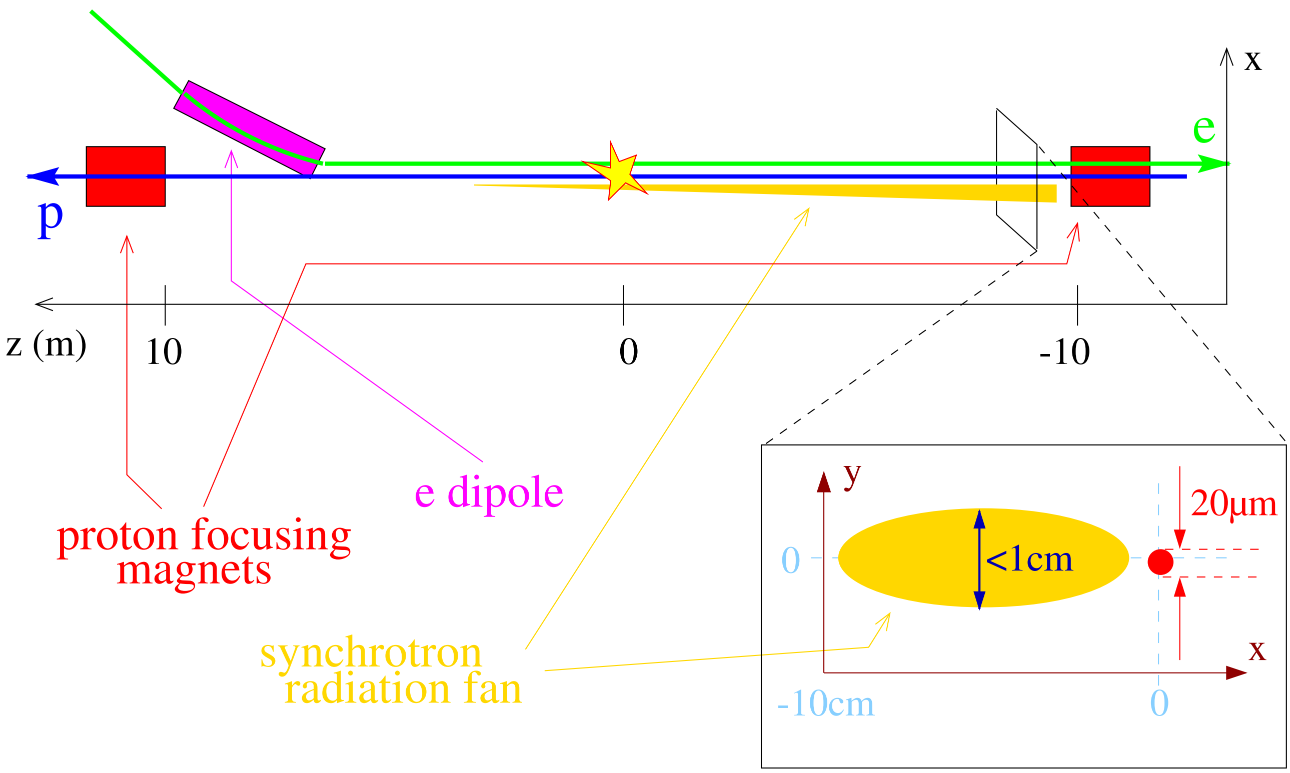
Symbiotic mode

+ Simultaneous operation of, TESLA and THERA, no efficiency or luminosity loss for TESLA
+ Relaxes time constraints for THERA
− Requires extra beam line in one TESLA arm (moderate effort)
− Only e^+ available
− Maximal e energy and beam power 50% lower than for dedicated mode
− Transport of e^+ beam through e^+e^- interaction region difficult, induces radiation and energy spread

THERA parameters

bunch structure	TESLA: trains of 2800 bunches, Δt=337 ns, 950 μs/train, repetition rate 5 Hz; HERA: time structure enforced by DESY3: Δt=96 ns $\times$ $(11/n)$ (Δt=352 ns for n=3); HERA and TESLA can be matched
e beam energy	Symbiotic: limited to $\sim$ 400 GeV Dedicated: TESLA allows $\sim$ 800 GeV But: $E_e \lesssim$ 500 GeV required for beam separation
luminosity	Standard: $10^{30}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ ($10\,\mathrm{pb}^{-1}$/y) Possible: enhancement by factor $2-4$ by reducing p emittance; substantial effort (RF, ...) Further increase: R&D beyond current concepts (proton cooling) Warning: $\mathcal{L} \times E_e \sim$ const.
polarization	Electrons: no obvious problems to transfer polarization from TESLA to THERA Protons: studied as future HERA option; active R&D program at DESY; slightly easier for THERA since no vertical bends?

THERA interaction region

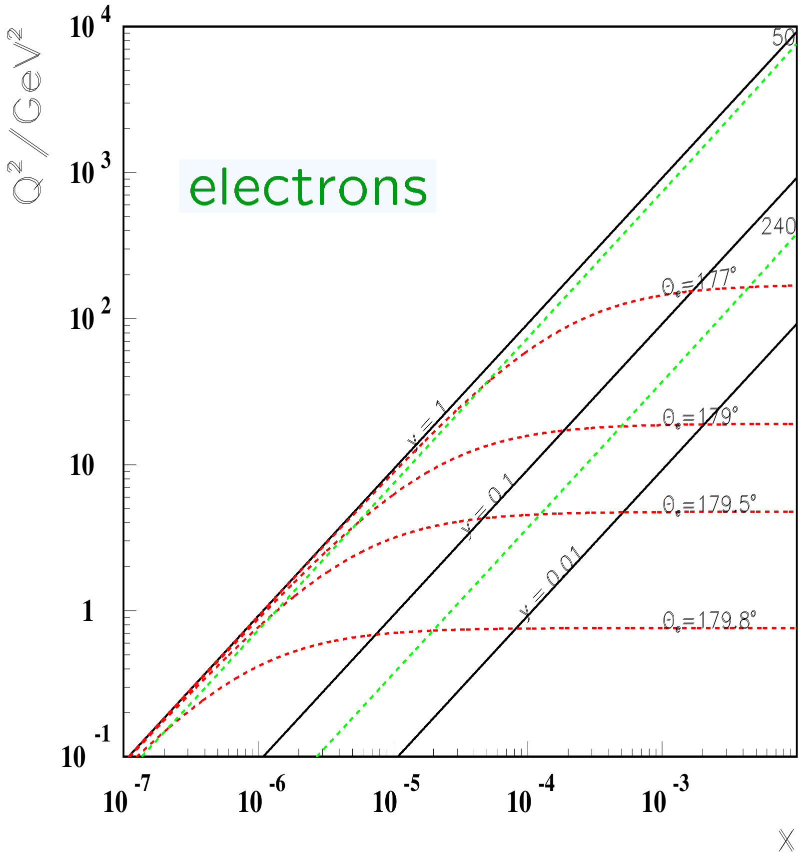


beam elements:	protons: $\sim 10\,\text{m}$ from IP preferred: symmetric setup, superconducting lenses
interaction zone:	longitudinal: proton-dominated, like in HERA ($\sim 10\,\text{cm}$) transverse: circular, diameter $\sim 20\,\mu\text{m}$
sync. radiation:	a fan of ca. $10\,\text{cm} \times 1\,\text{cm}$ at $10\,\text{m}$ distance from I.P.
crossing angle:	head-on collisions preferred

- √ measurements at $\theta \sim 0.5^\circ$ possible with (almost) 2π coverage
- √ e, γ and p taggers possible
- √ vertex constraint useful for heavy-flavor measurements

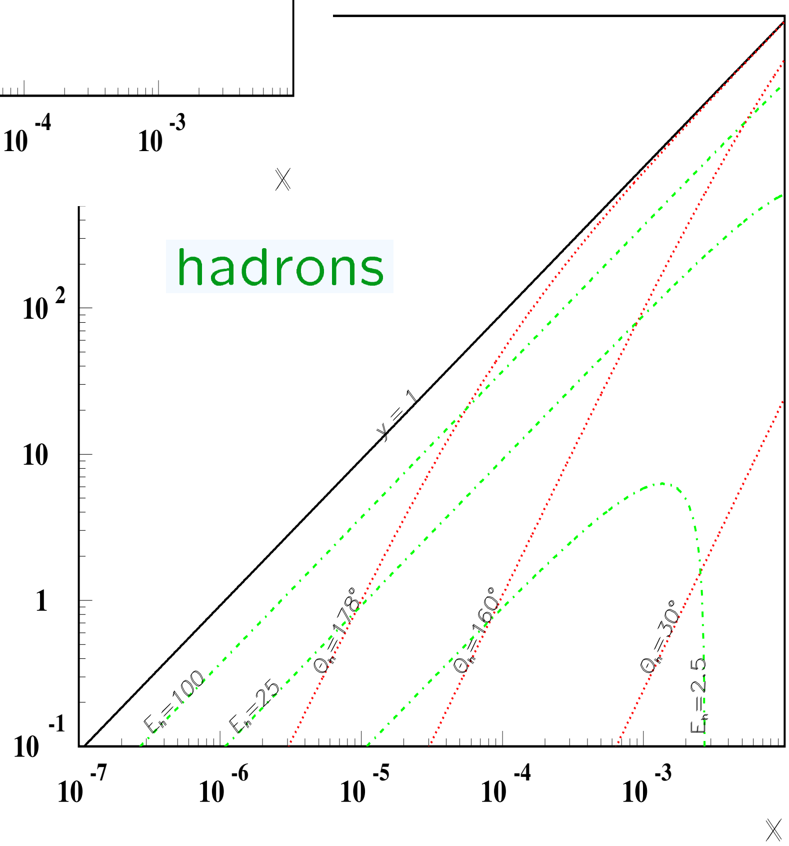
Kinematics at low x and Q^2

THERA: 250 GeV (e) $\times$ 920 GeV (p)



electrons:
in narrow
backward cone
($Q^2 \lesssim 100$ GeV^2)

high energy:
$E' \sim (1 - y) E_e$

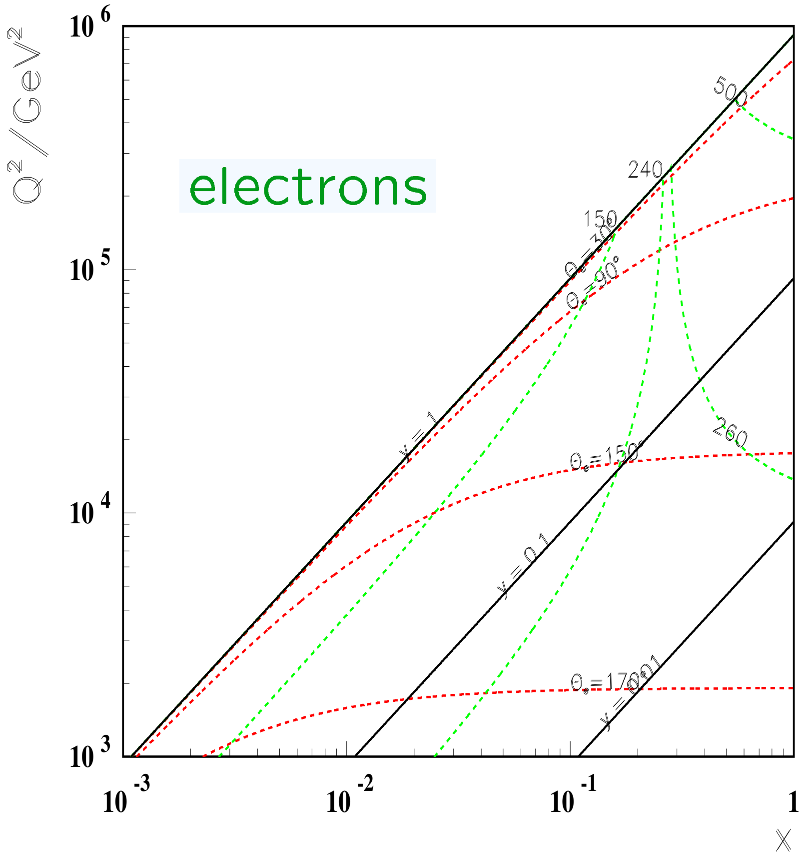


hadrons:
also very backward

typical energy:
$E_h \sim y E_e$

Kinematics at high Q^2

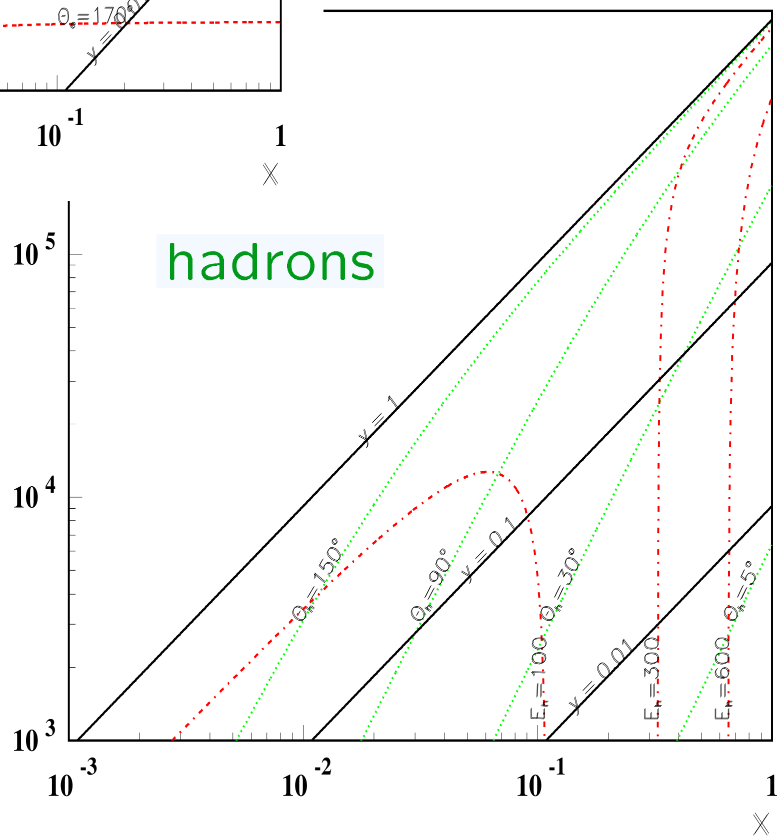
THERA: 250 GeV (e) $\times$ 920 GeV (p)



electrons:
central/forward

energy:
up to E_p
(like at HERA)

kinematic peak:
$x_\circ = E_e/E_p$



hadrons:
central/forward

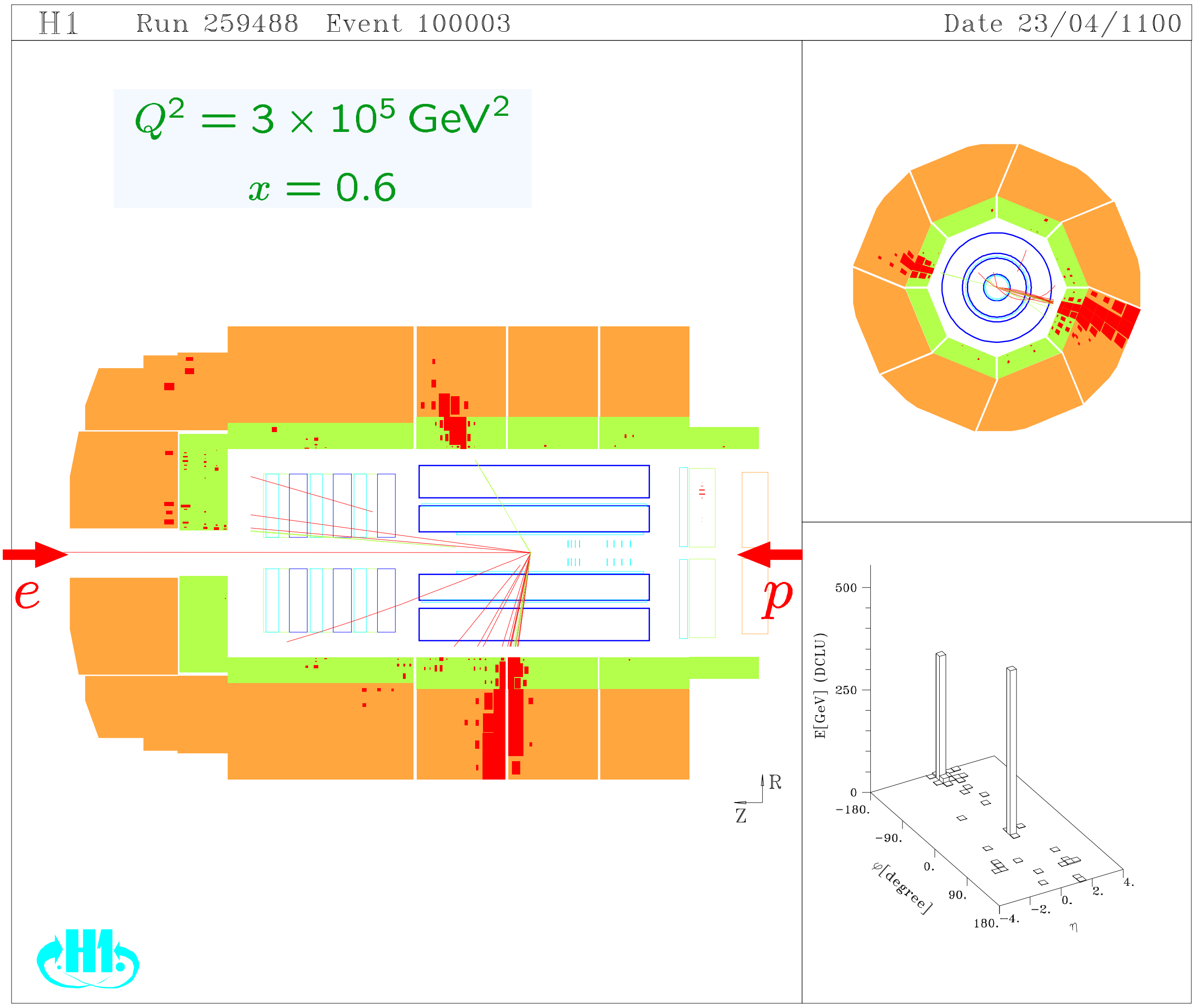
E_h up to E_p

$Q^2 = (2xE_p \tan\frac{\theta_h}{2})^2$
$\Rightarrow$ cover small θ_h
to reach low y

($\Rightarrow$ Q^2 lever arm)

A high-Q^2 event at THERA

THERA NC DIS event
simulated in H1 detector
(250 GeV (e) $\times$ 920 GeV (p))



Such events are contained in central detector
Can ZEUS/H1 detectors cover central region?

Detector requirements

high x and Q^2:

Requires central detector

- ZEUS or H1 detector usable?
- Problems: age, calorimeter linearity, tracking resolution ($\int B\,dl$)

"Simple" solution possible?

low x and Q^2:

Electron and hadronic system are very backward:

- acceptance at least to 179.5°
- 2π azimuthal coverage for background rejection & trigger
- e/h separation (also in jets)
- good e energy resolution crucial for kinematic reconstruction
- good angular resolution (tracking)
- jet measurements at $E_h \approx E_e$

Highly demanding requirements for backward detector

forward:

Jets, heavy quarks:

- require maximal rapidity coverage

Forward detector design?

taggers:

We want more than DIS:

- photoproduction: backward e tagger
- luminosity, ISR: backward γ tagger
- diffraction: forward p tagger

No prohibiting constraints

QCD at low x and Q^2

goals:

- Assess proton structure at low x
- Understand QCD vacuum in perturbative non-DGLAP domain (large $\ln(1/x)$ and $Q^2 \gtrsim \mathcal{O}(1\,\text{GeV}^2)$)
- What happens as cross sections approach unitarity limit?
  When does saturation set in?
- ...

• : mentioned in the following

answers expected from THERA:

- scaling violations, F_L and $g(x)$
- vector meson cross sections
- diffraction at large mass M_X
  $\Rightarrow$ jet production, parton dynamics
- forward jet production at $x \lesssim 10^{-4}$
  $\Rightarrow$ BFKL, ...

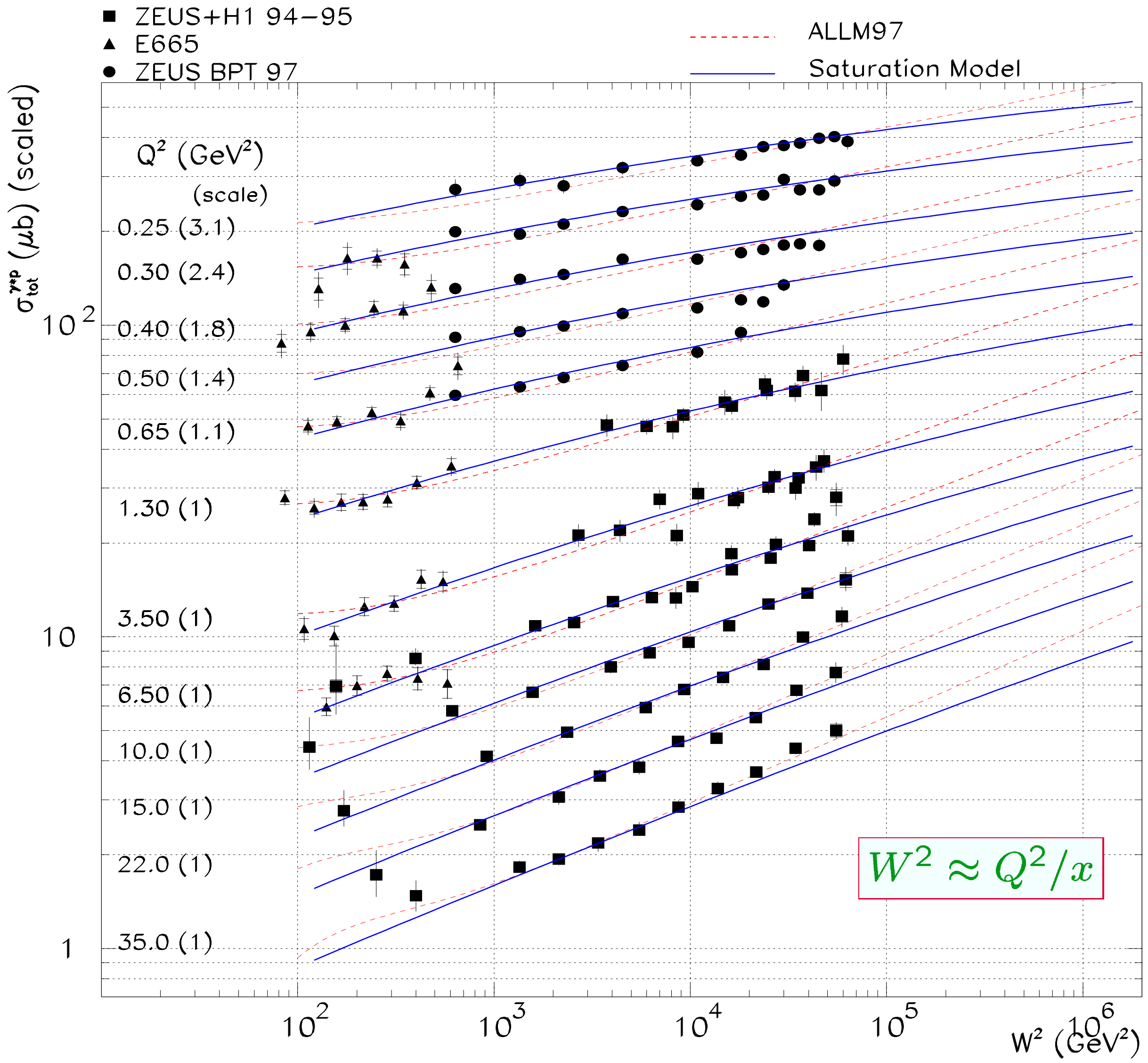
additional options:

- Polarized protons in HERA
  $\Rightarrow$ spin structure functions
- Light/heavy nuclei in HERA
  $\Rightarrow$ $\sigma(A)/\sigma(d)$
- γp collisions by
  using back-scattered laser light
  $\Rightarrow$ photon structure, ...

Saturation

Virtual photon-proton interactions at low x

- are characterized by two transverse scales:
  $1/Q$ =transverse size of virtual $q\bar{q}$ pair
  $R_0 \sim (x/x_0)^{\lambda/2}$ = color dipole size
  (typical distance between quarks)
- Saturation expected for $R_0 \gg 1/Q$
  at HERA: at $Q^2 \sim 1\,\mathrm{GeV}^2$, non-perturbative
  at THERA: at $Q^2 \sim 2-3\,\mathrm{GeV}^2$, perturbative
- THERA reaches lower x at higher Q^2
  $\Rightarrow$ new insights expected.



The gluon density at low x

At low x: $(\partial F_2/\partial \ln Q^2) \sim \alpha_s x g(x)$

need sufficient Q^2 range to disentangle:

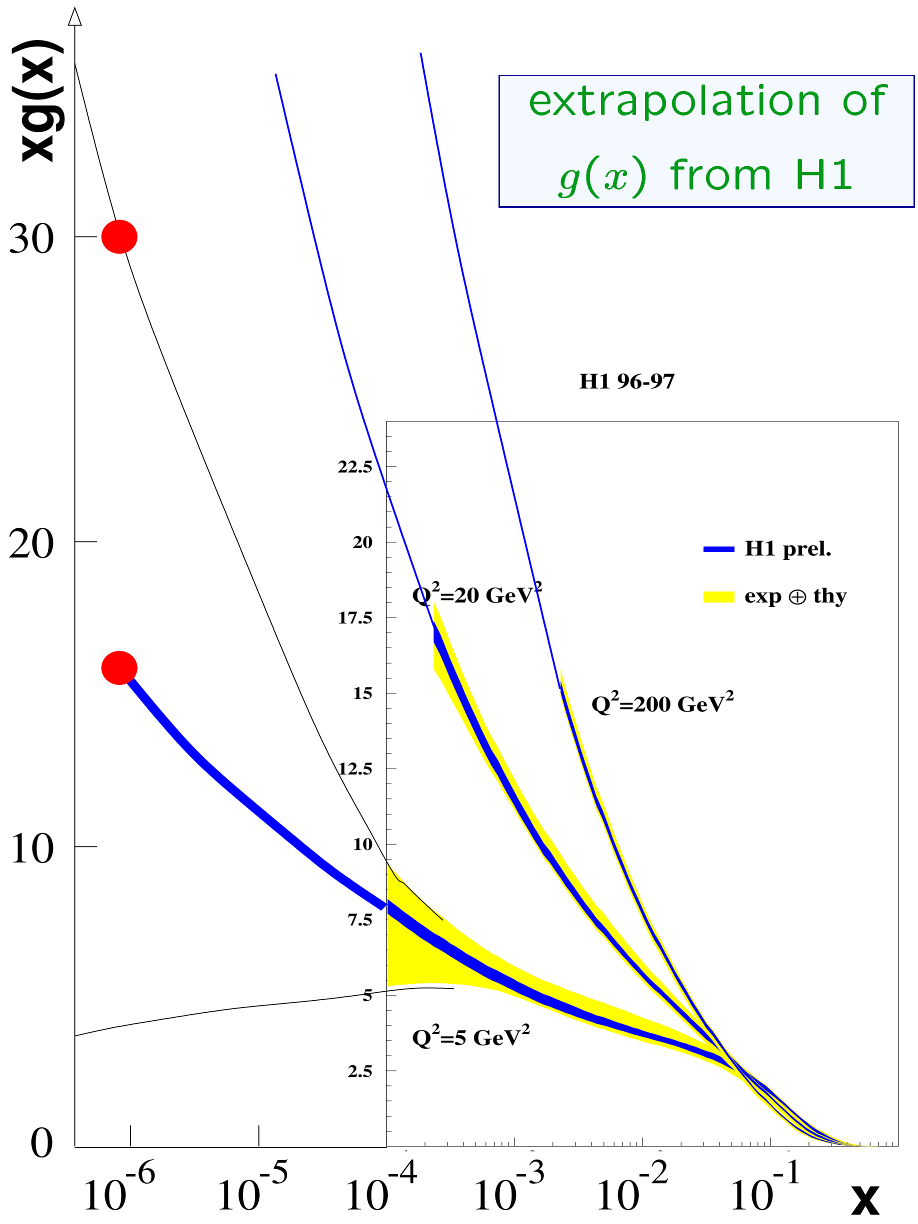
- pQCD evolution
- higher-twist effects
- saturation
- non-pQCD effects
- ...

need THERA to reach sufficiently large Q^2 at $x \sim 10^{-4}$

unitarity limit

$R_0 = 1/Q$ $\Rightarrow$ saturation

extrapolation of $g(x)$ from H1

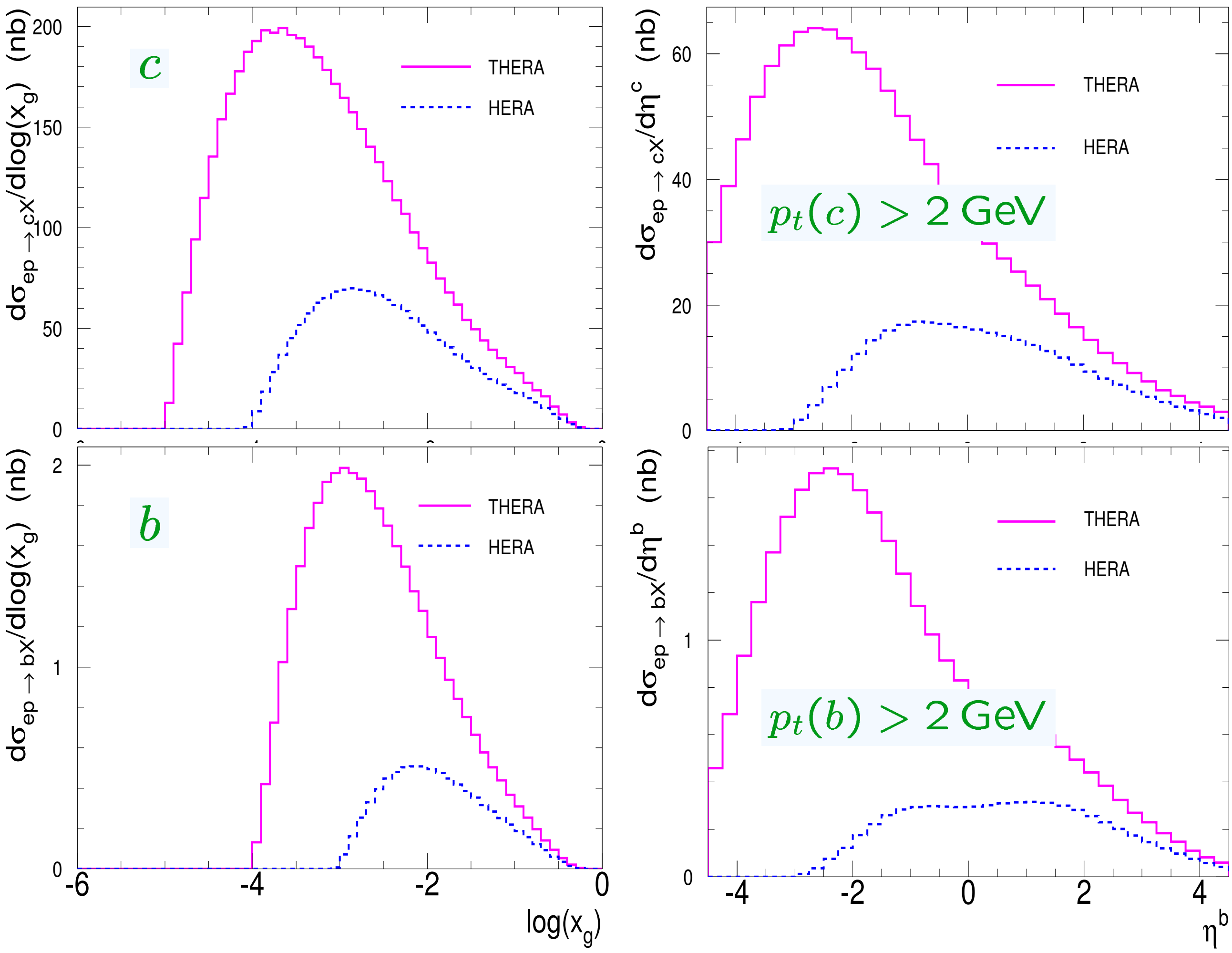


Heavy flavor physics

Heavy quark production and what we learn from it

	process	information
DIS	$\gamma^* c/b \to c/b$	heavy flavor QCD, PDFs
	$\gamma^* g \to c\bar{c}, b\bar{b}$	QCD, $g(x)$ in proton
	$W^- \bar{s} \to \bar{c}$, $W^- g \to s\bar{c}$	$s(x)$ and $g(x)$ in proton
PHP	$\gamma g \to c\bar{c}, b\bar{b}$	gluon distribution in proton
	$\gamma g \to c/\bar{c}$ + Rest, $\gamma g \to b/\bar{b}$ + Rest	heavy quark content of γ (resolved processes)

- Cross sections 3-20 times larger than at HERA
- backward coverage essential

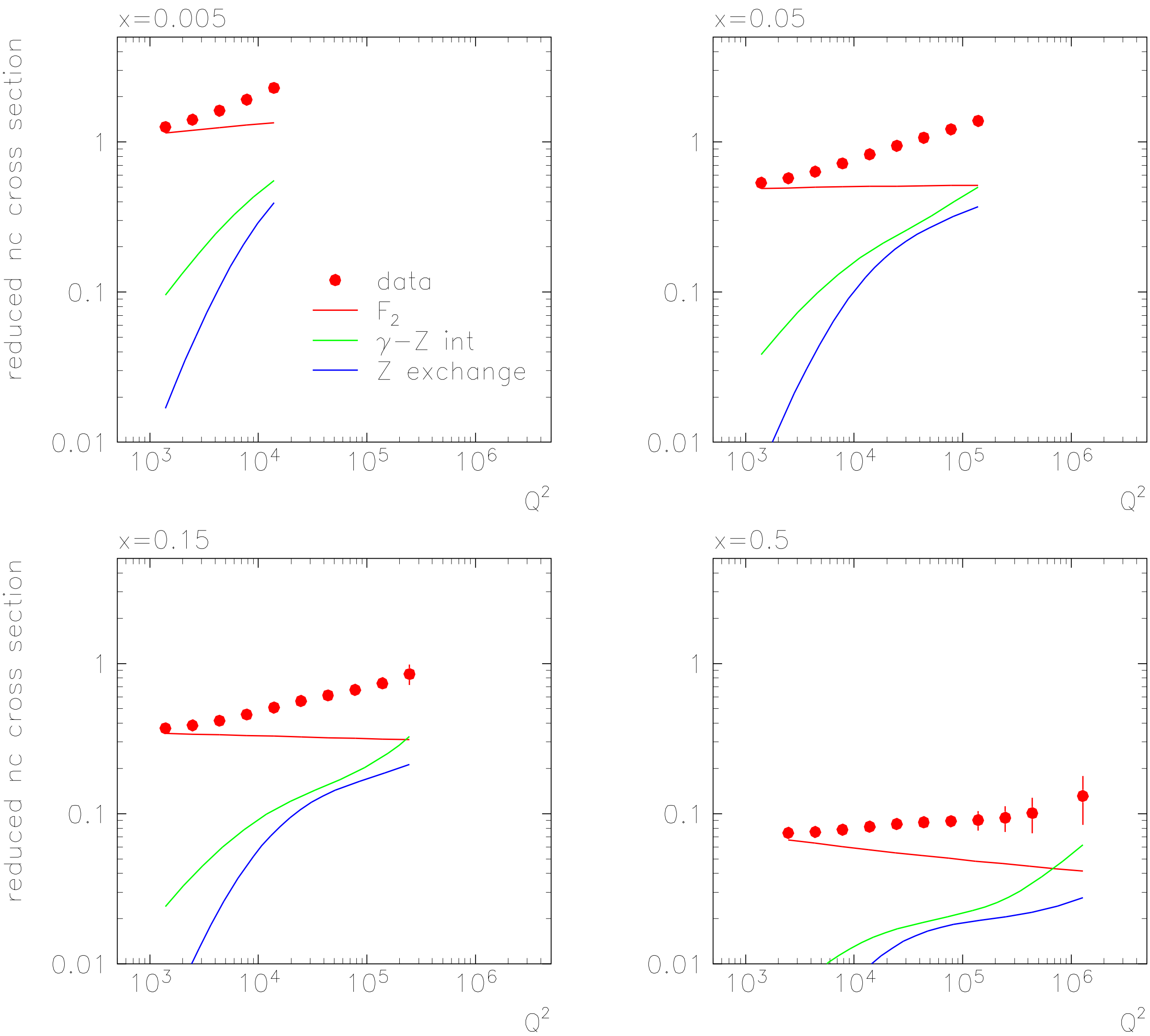


DIS at high Q^2

Reduced NC cross section:

$$\tilde{\sigma}^{NC} = \frac{xQ^4}{2\pi\alpha^2(1+(1-y)^2)} \cdot \frac{d^2\sigma^{NC}}{dx\,dQ^2}$$

- THERA high-Q^2 domain: large Z contributions
- Reasonable measurement accuracy up to $Q^2 \sim 10^6\,\mathrm{GeV}^2$, also at high x (200 pb^{-1} assumed)
- Large Q^2 range of combined data allows precision measurement of α_s and PDFs



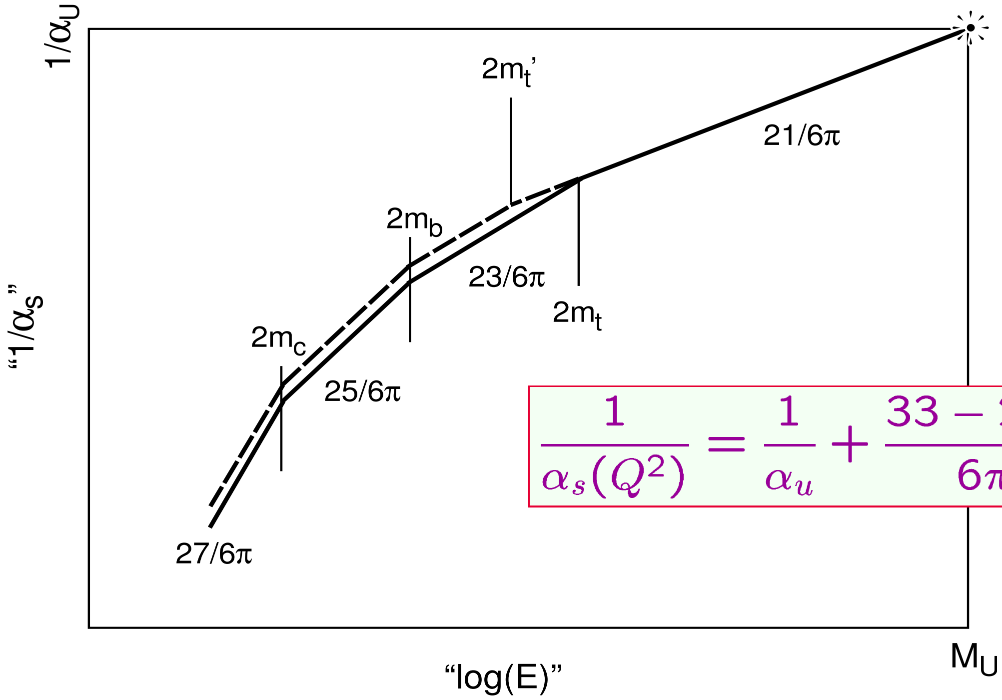
Precision measurement of α_s

α_s determination at THERA:

- Expected theoretical uncertainty:
  $\Delta_{\text{the}}\alpha_s = 0.001$ (3-loop calculation)
- Experimental determination from scaling violations using THERA, HERA and fixed-target data in high-Q^2 region of pQCD:
  $\Delta_{\text{exp}}\alpha_s = 0.0005$ (preliminary result)
- free of final–state effects!

Highly relevant for

- precision measurements of α, G_F, $\sin^2\theta_w$, $g-2$,
- LHC analyses,
- ...



$$\frac{1}{\alpha_s(Q^2)} = \frac{1}{\alpha_u} + \frac{33-2N_f}{6\pi} \cdot \ln\frac{Q}{M_u}$$

Note: New colored particles would increase N_f above a threshold $Q^2 \sim M_x^2$

Exploiting the e polarization

The e polarization can help:

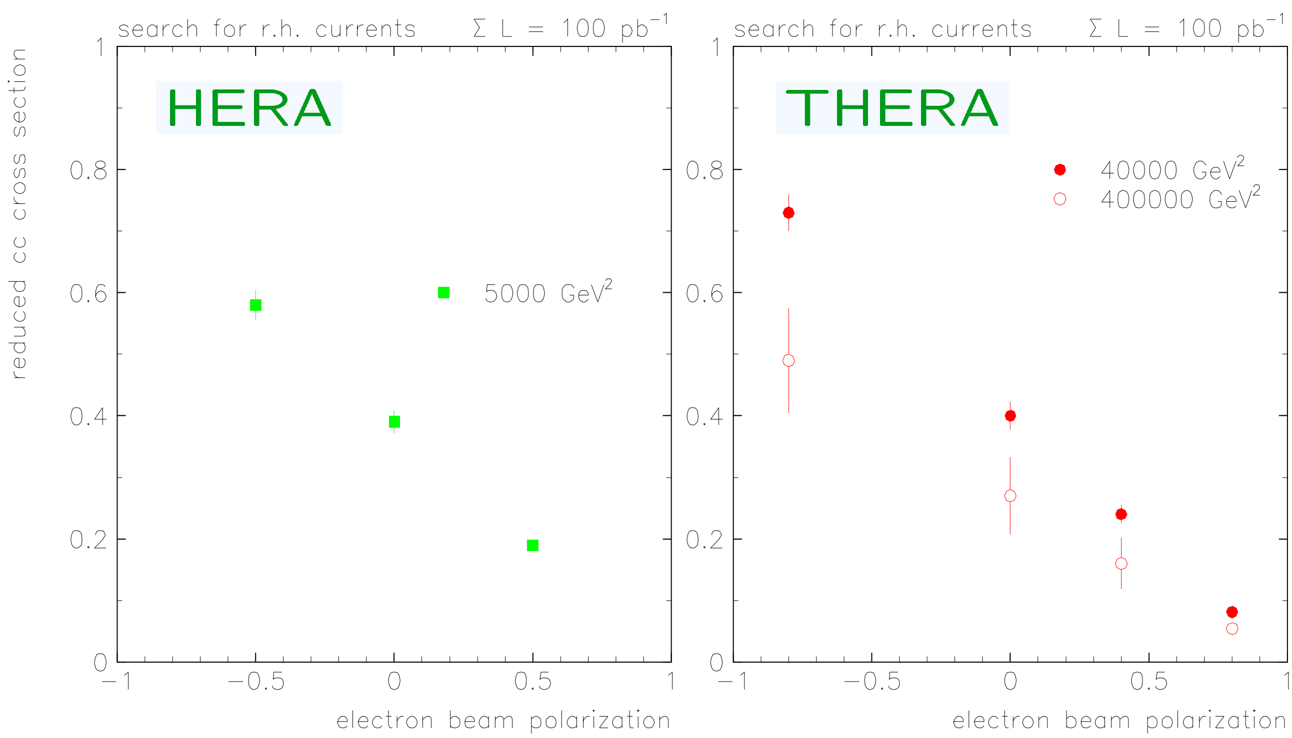
- in electroweak analyses of DIS cross sections
- in searches for new phenomena
- for spin-dependent PDF and QCD studies
  if polarized protons and/or nuclei are available

Example:

search for right-handed charged currents

$$\tilde{\sigma}^{CC} = \frac{2\pi x}{G_F^2} \frac{Q^2 + M_W^2}{M_W^2} \cdot \frac{d^2\sigma^{NC}}{dx\, dQ^2} \propto P$$

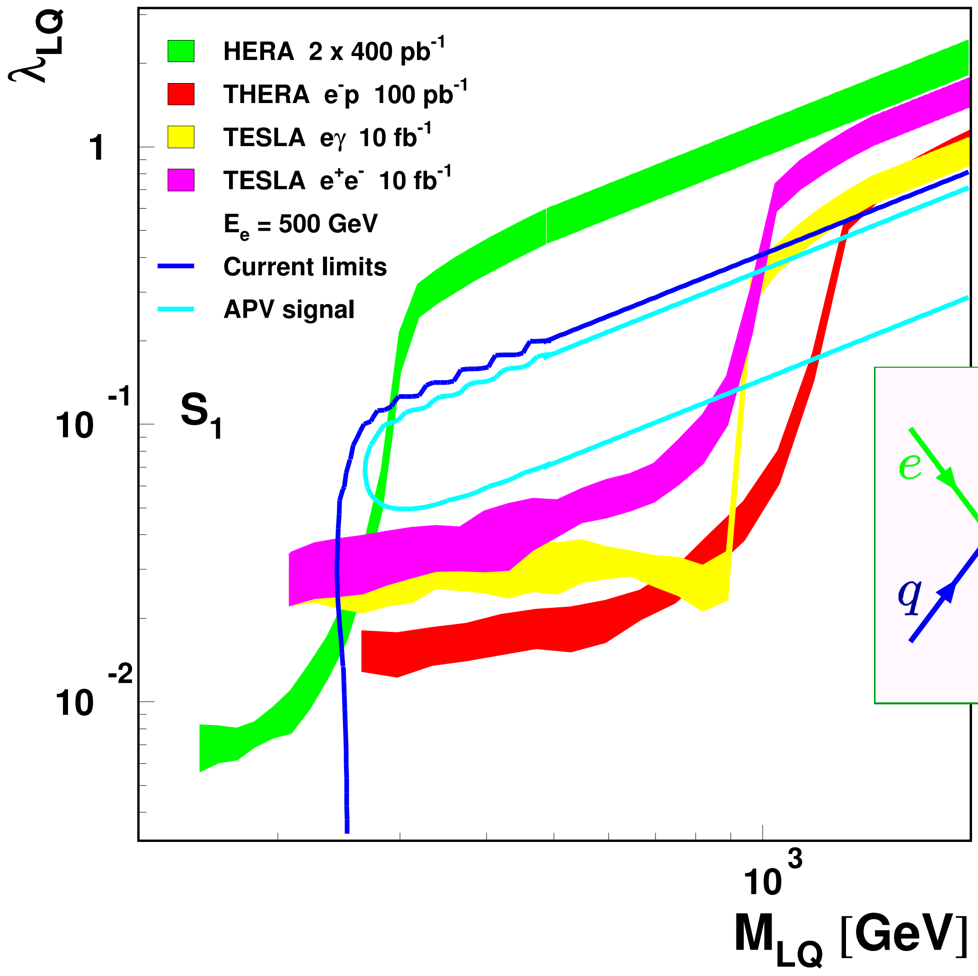
- TESLA offers large $|P|$
  $\Rightarrow$ large lever arm for testing $\tilde{\sigma}^{CC} \propto P$
- Increase of Q^2 by an order of magnitude
  w.r.t to HERA $\Rightarrow$ increased sensitivity range

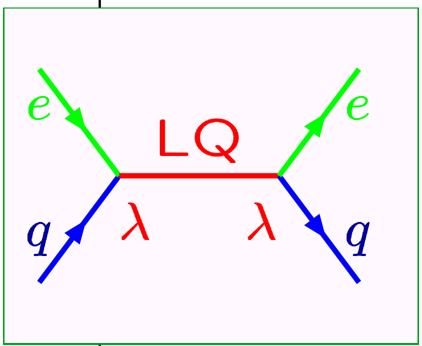


Leptoquarks and squarks

Leptoquarks and R_P-violating squarks:

- couple to eq with Yukawa coupling λ
- can be resonantly produced in ep scattering
  $\sigma_{\mathrm{LQ}} \propto \lambda^2 \cdot q(x = M^2_{\mathrm{LQ}}/s)$
- THERA increases current sensitivity ...





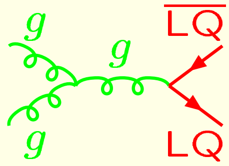
Note: Experimental hints for LQs exist
(>3σ, mostly from APV data
A.F. Żarnecki, hep-ph/0003271)

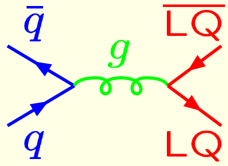
- If real: THERA="LQ factory" for $M_{\mathrm{LQ}} \lesssim 0.8$ TeV
- e charge and pol. allow to determine LQ properties
  (P. Taxil, E. Tugcu, J.M. Virey, hep-ph/9912272)

Competing with LHC

LQ production at LHC & Tevatron:

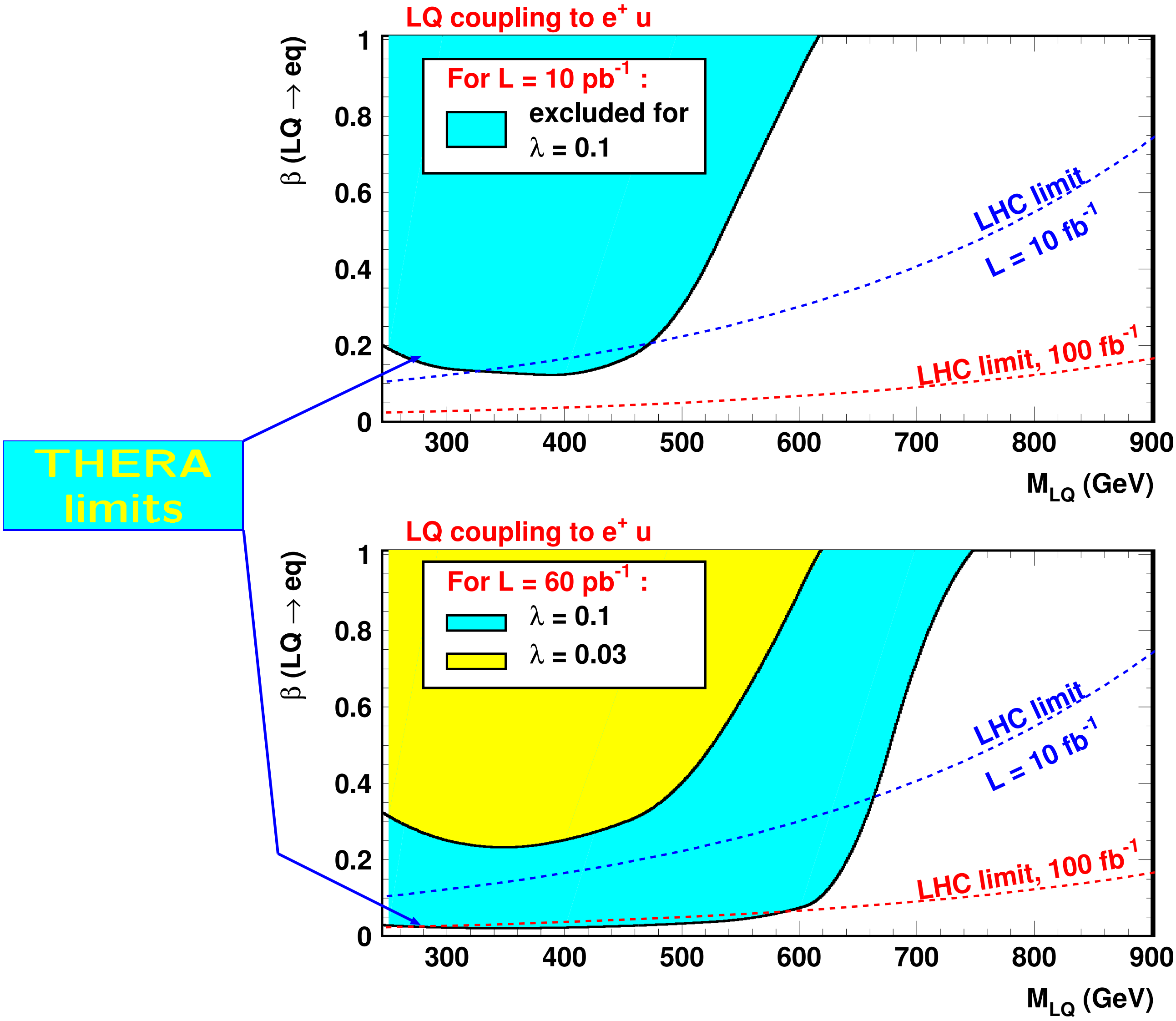
$$\sigma(p\bar{p} \to \mathrm{LQ}\,\overline{\mathrm{LQ}}\,X) \propto \left| \quad + \quad + \dots \right|^2$$





$$\sigma(p\bar{p} \to \mathrm{LQ}\,\overline{\mathrm{LQ}}\,X \to eeqq\,X) \propto \mathrm{BR}(\mathrm{LQ} \to eq)^2$$

250 GeV e^+ x 820 GeV p

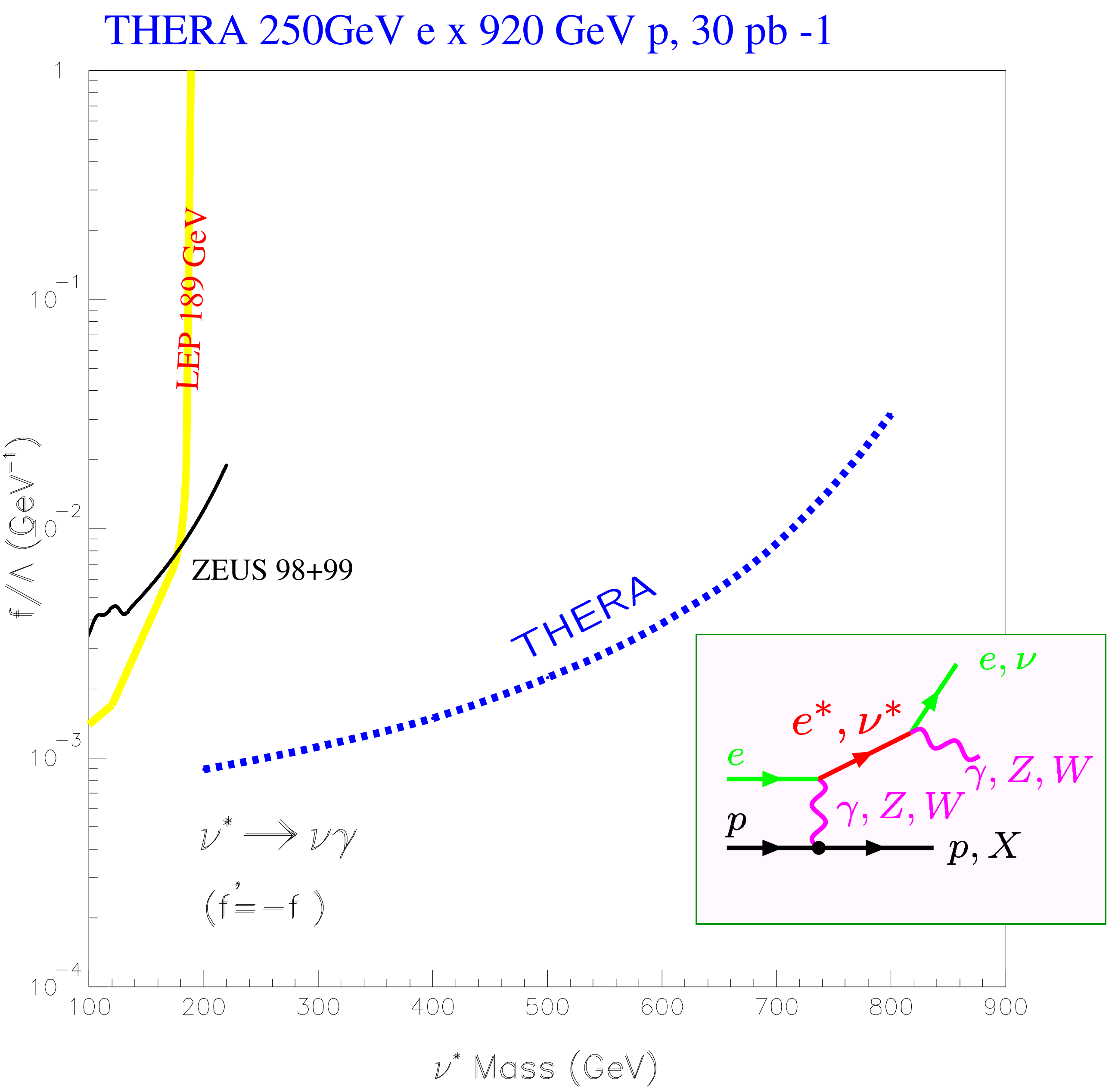


The discovery potential of LHC is larger, but complementary data from THERA if LQ is in reach!

Excited fermions

If fermions are composite ...

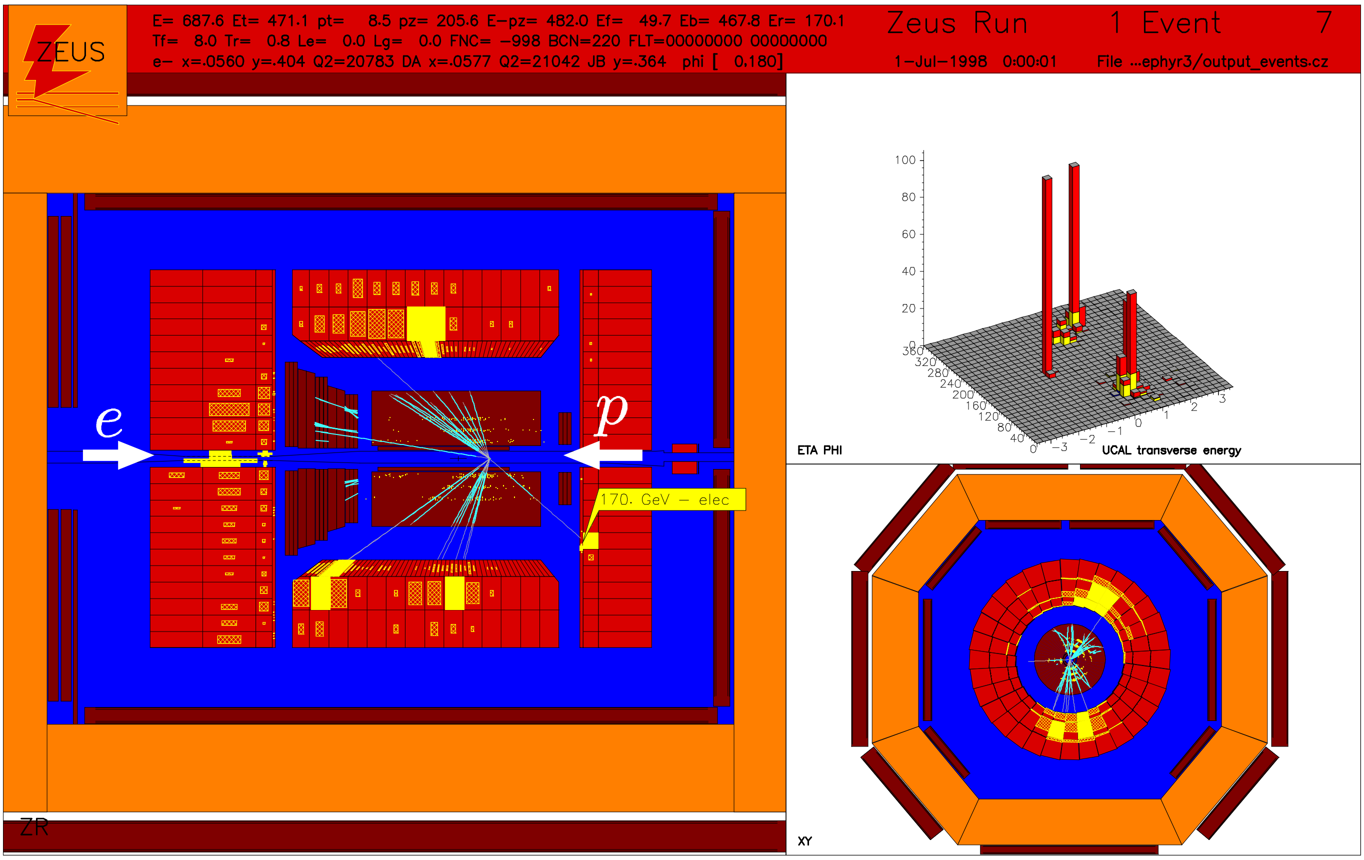
- e^*, ν^* and q^* can be directly produced at THERA
- competition:
  $e^+e^- \to f\overline{f^*}$ at TESLA,
  $q\bar{q} \to f^*\overline{f^*}$ (Drell-Yan) at LHC
- But: cross section at LHC is suppressed
  by factor $\mathcal{O}(\alpha/\alpha_s)$ w.r.t. LQ channel



A ν^* event at THERA

ν^* production at THERA
simulated in ZEUS detector
(250 GeV (e) $\times$ 920 GeV (p))

$$ep \to \nu^* + j + X \to e + 3j + X$$
$$(\nu^* \to eW \to eq\bar{q})$$
$$M_{\nu^*} = 400 \text{ GeV}$$



Event is almost completely
contained ($E - p_z = 482$ GeV)

Conclusions and Plans

The TESLA×HERA (THERA) ep mode is being studied. The goal is to assess and document the physics potential and technical feasibility and to contribute a chapter to the TESLA TDR.

No obvious show-stoppers so far.
It seems possible that
THERA could run in parallel with TESLA.

THERA seems to offer many attractive possibilities, in particular for investigating the dynamics of strong interactions.

The success of THERA depends critically on the detector design.

Let's establish a list of fundamental questions to a future ep machine at $\sqrt{s} = 1$ TeV!

You are invited to join the effort!

Thanks to all who have contributed or will contribute.