ep physics at HERA

Masahiro Kuze
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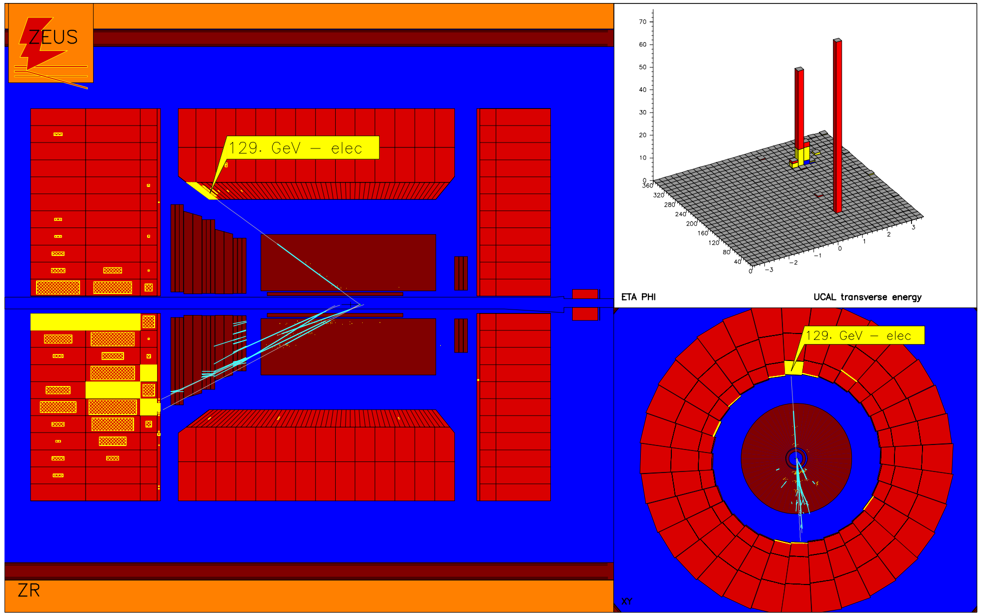
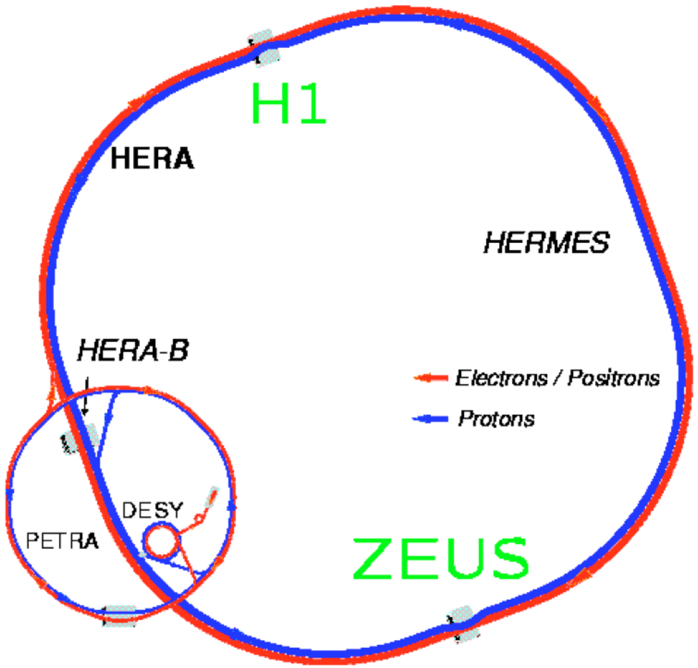
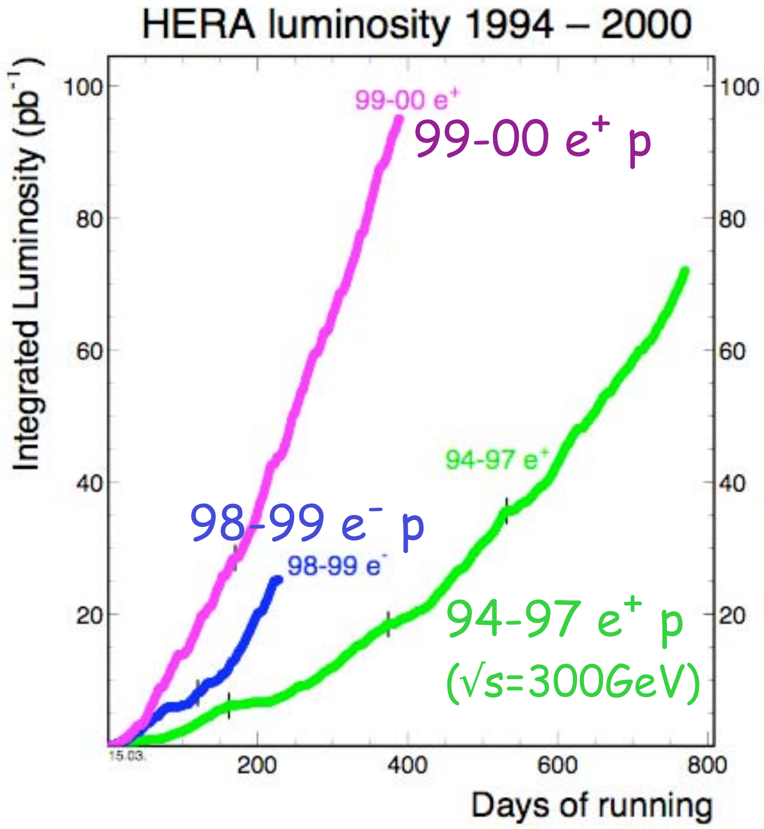
On behalf of H1 and ZEUS collaborations

- HERA and experiments
- Proton structure
- Search for new physics
- Status and results from HERA-II



HERA *ep* Collider at DESY/Hamburg

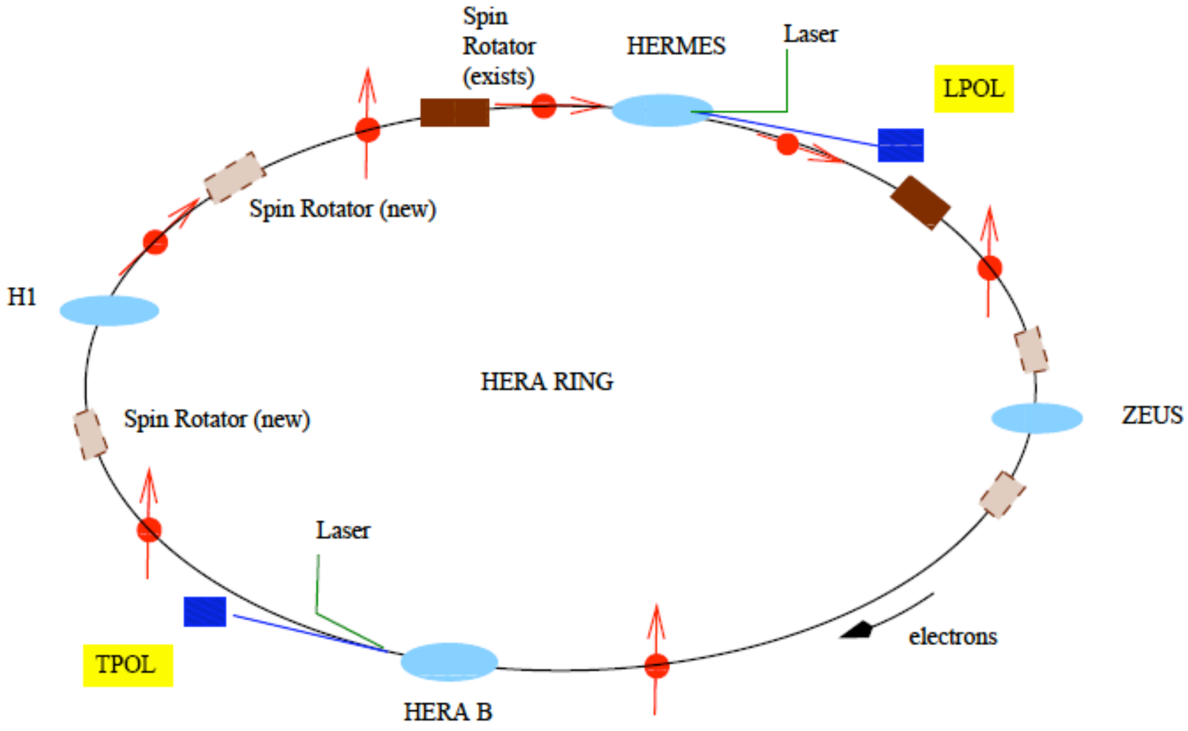




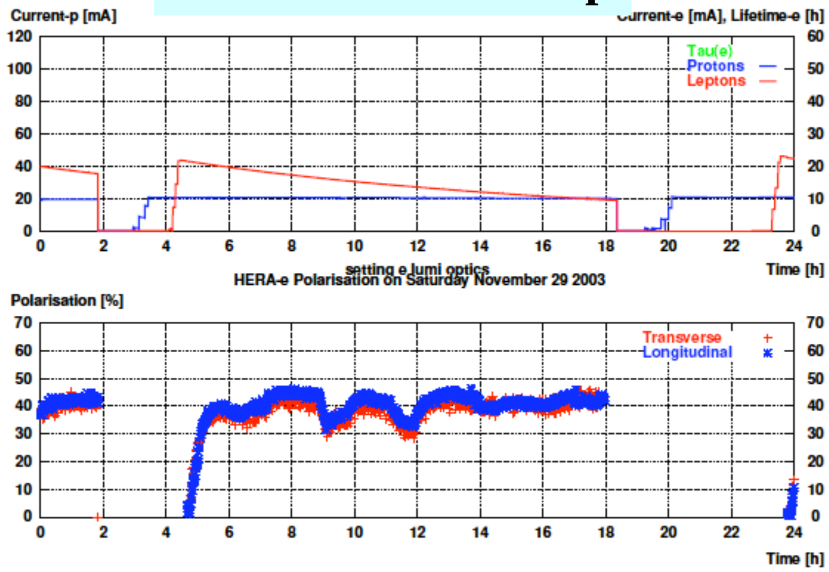
- E_p=920GeV ⊗ E_e=27.5GeV (e^+ or e^-) ⇒ $\sqrt{s} = 318\,GeV$
- 2 colliding experiments and 2 fixed-target experiments
- HERA-I on-tape luminosity: ~110 pb^{-1} e^+p, ~15 pb^{-1} e^-p ('98-'99) /exp't.

HERA-II (2003-2007)

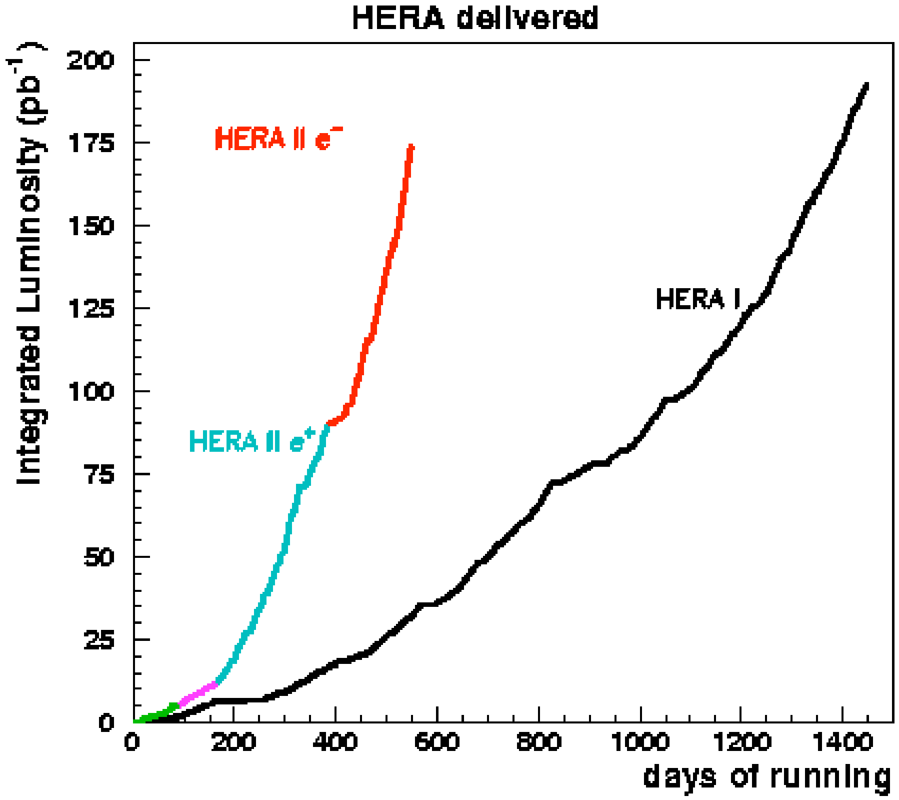
- High luminosity + Longitudinal lepton polarization
  - Also detector upgrades (e.g. new or extended micro-vertex for *b*,*c* tagging)

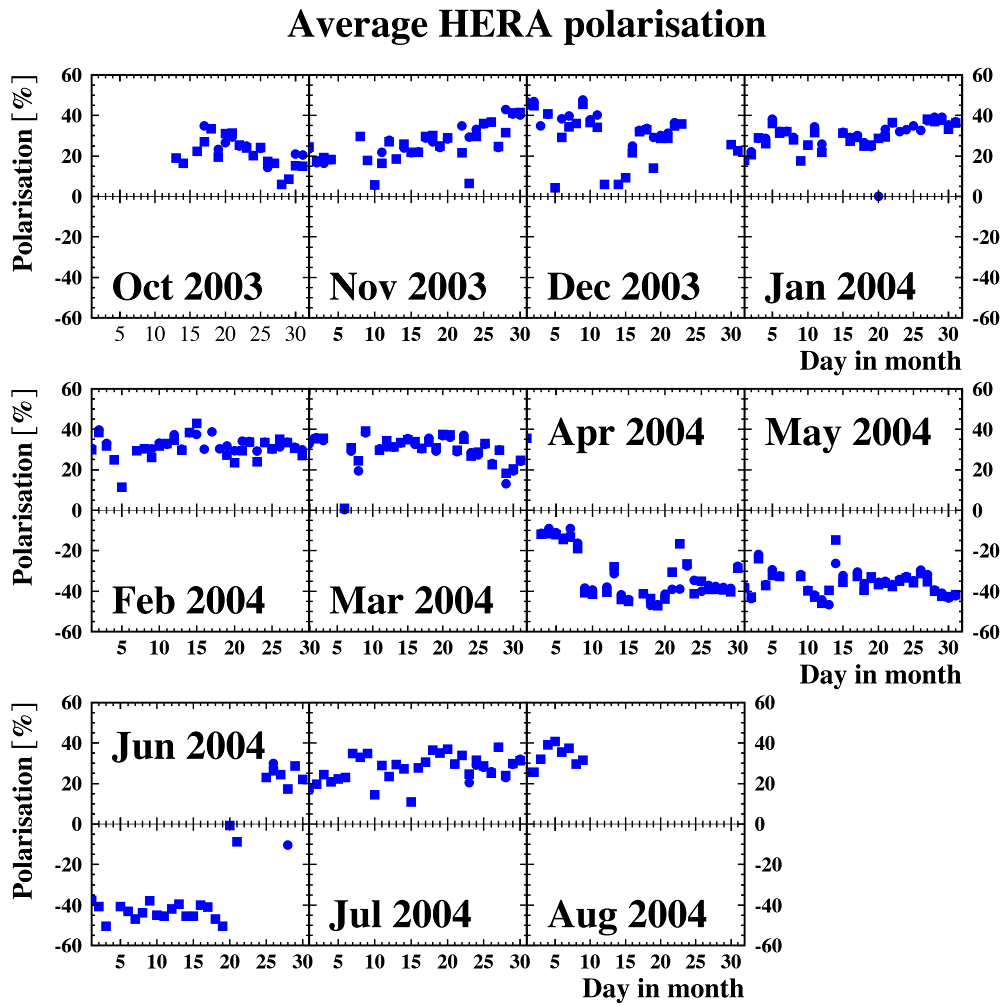


Polarization build-up



High-lumi data-taking well on its way

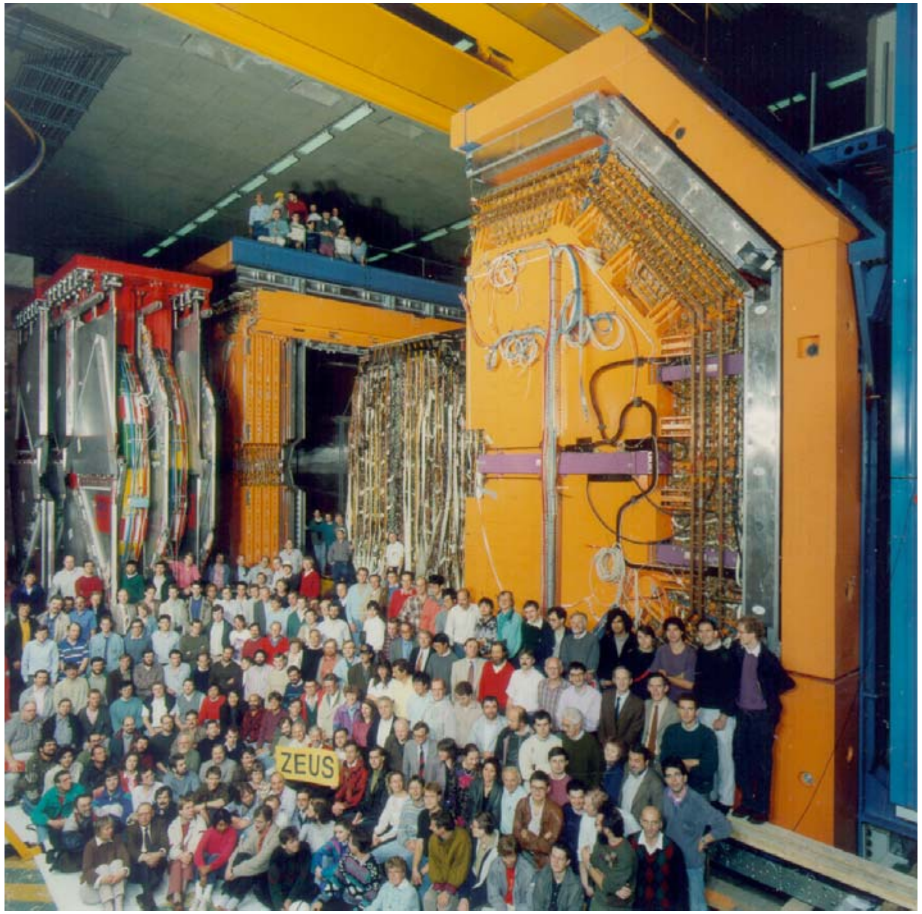




Excellent accelerator performance.
Exp. conditions under control.
$\rightarrow$700 pb^{-1} $e^{\pm}_{L,R}$ till 2007.

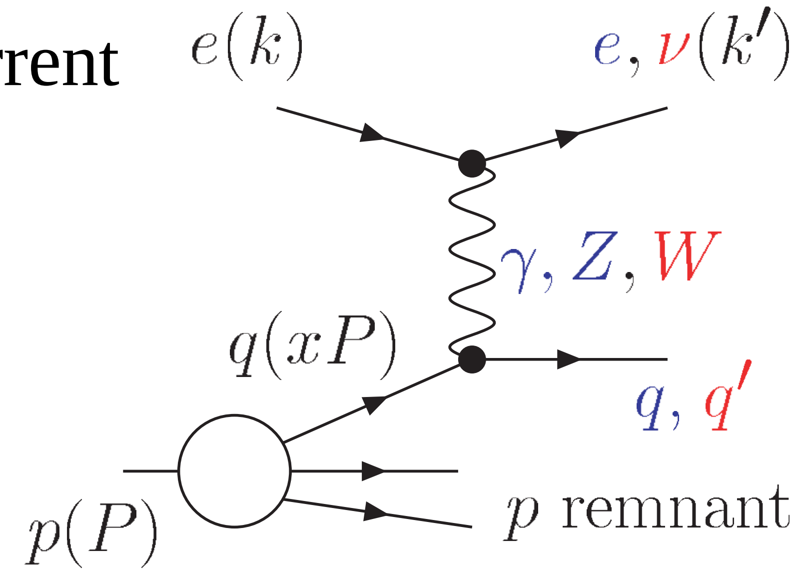
The Detectors

- ZEUS Detector
  - Uranium-Scintillator calorimeter
    - $\sigma(E)/E = 18\%/\sqrt{E}$ for electrons
    - $\sigma(E)/E = 35\%/\sqrt{E}$ for hadrons
  - Central tracking detector
    - $\sigma(p_T)/p_T =$ $0.0058\,p_T \oplus 0.0065 \oplus 0.0014/p_T$
- H1 Detector
  - Liquid-Ar calorimeter
    - $\sigma(E)/E = 12\%/\sqrt{E}$ for electrons
    - $\sigma(E)/E = 50\%/\sqrt{E}$ for hadrons
  - Central tracking detector



HERA: *the* QCD machine

- Probe the proton = our most familiar micro-cosmos with a point-like lepton probe. 'giant electron-microscope'
- Bjorken *x*: Fractional momentum of a parton in the nucleon.
- 1/*Q* (momentum transfer) gives the spacial resolution.
- Neutral or Charged current in t-channel propagator



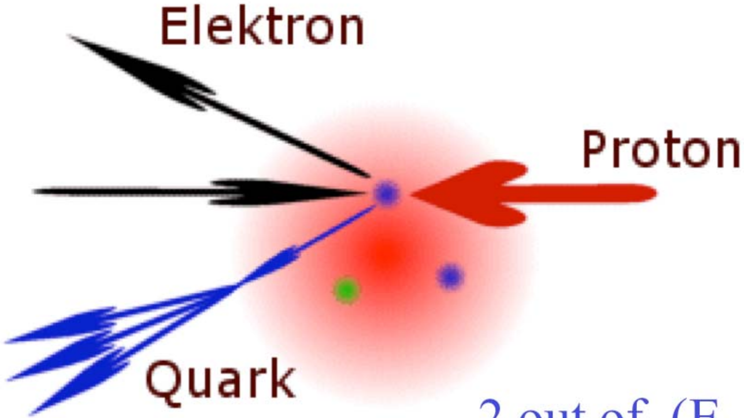
$Q^2 = sxy$

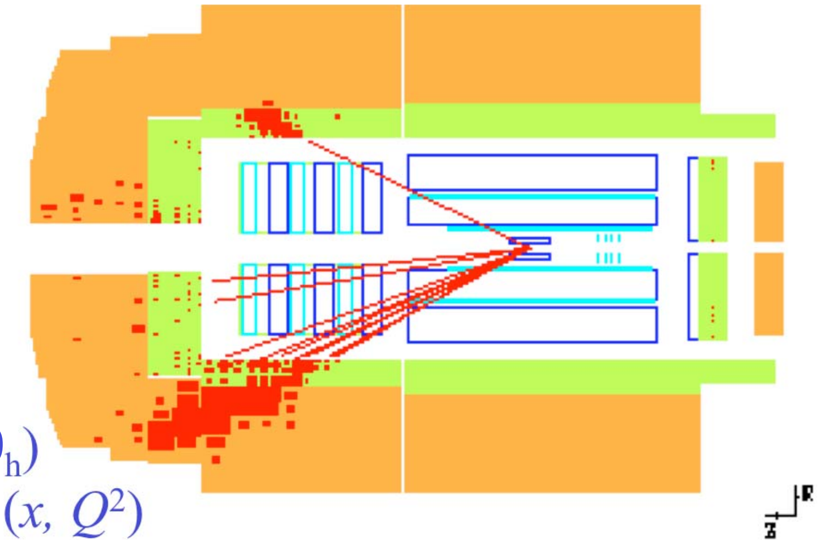
$$Q^2 = -(k - k')^2$$

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

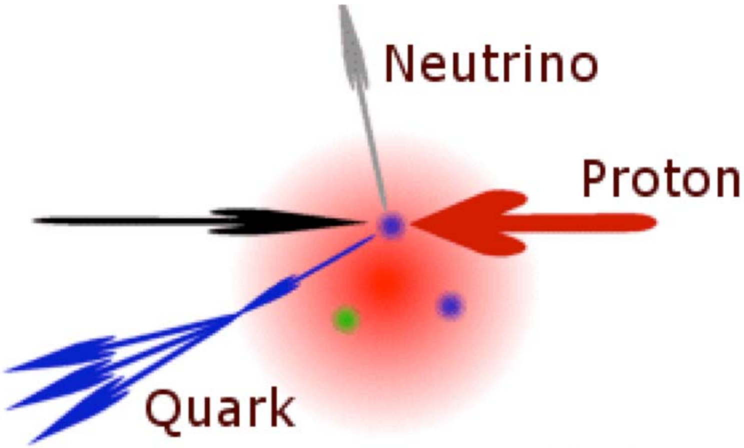
$$y = \frac{P \cdot (k - k')}{P \cdot k}$$

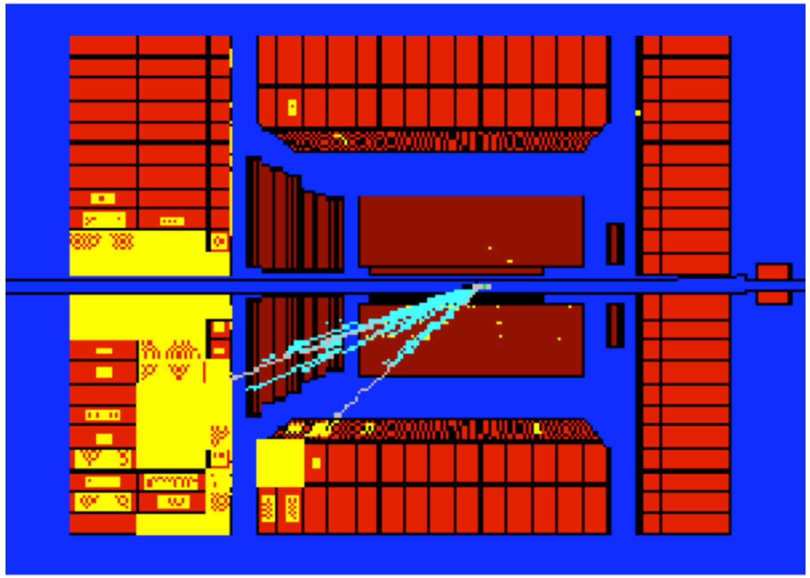
Example of high-Q^2 NC/CC events





2 out of $(E_e, \theta_e, E_h, \theta_h)$
$\rightarrow$ Reconstruction of (x, Q^2)

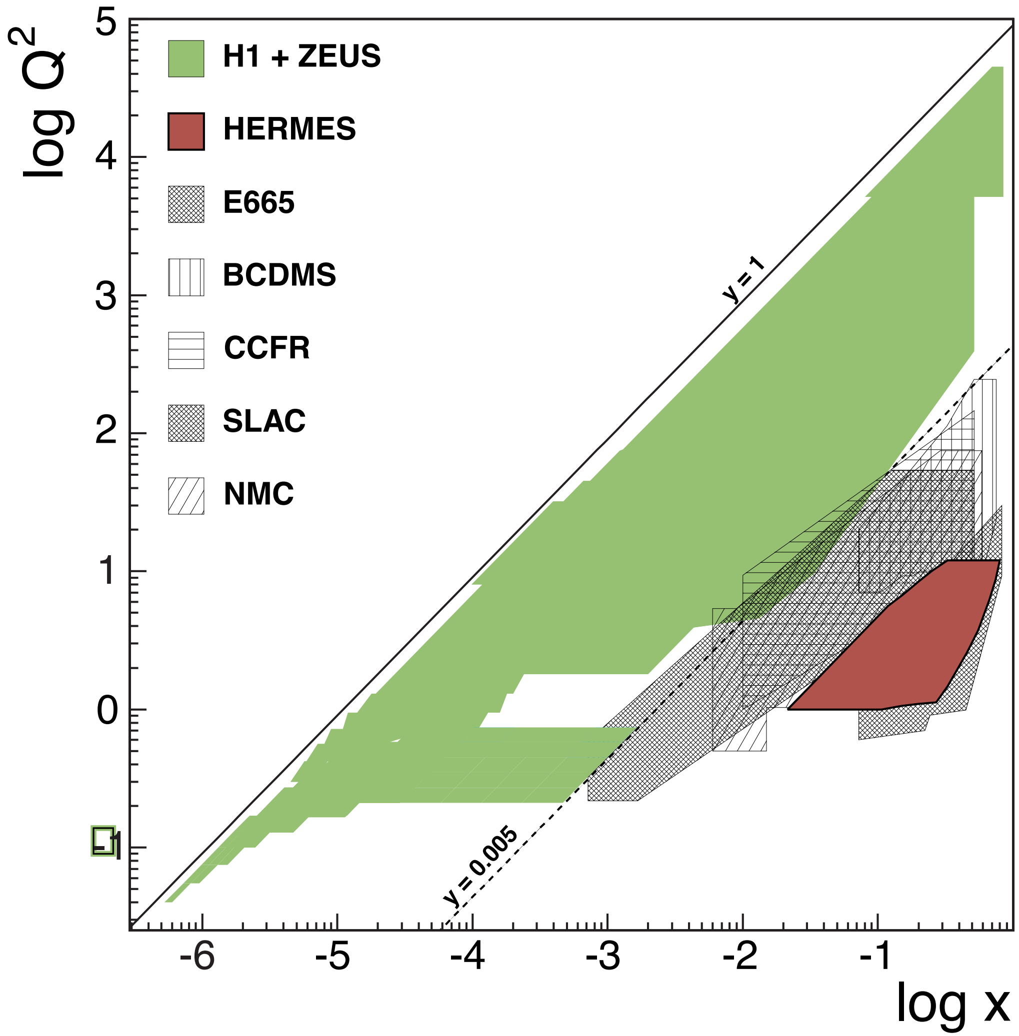




$(E_h, \theta_h) \rightarrow (x, Q^2)$

Kinematic region probed

- > 100x larger kinematic reach compared to fixed-target DIS experiments at CERN, DESY, FNAL, SLAC… (if proton is at rest, HERA CM energy means E_e=54TeV)
- At high Q^2, probe the validity of QCD at smallest distance → Quark structure? New particles? (Q^2=40,000 GeV^2 →1/Q=0.001 fm)
- At low Q^2, probe the low-x region → very soft constituents of proton; Saturation? Breakdown of standard DGLAP formalism (BFKL) ?



Cross section & Structure functions

- NC differential cross section

$$\frac{d^2\sigma_{e^\pm p}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}[Y^+F_2(x, Q^2) \mp Y^-xF_3(x, Q^2) - y^2F_L(x, Q^2)]$$

$$F_2 = \sum xq_f^+(x, Q^2)[e_f^2 - 2e_f v_f v_e P_Z + (v_f^2+a_f^2)(v_e^2+a_e^2)P_Z^2]$$

$$xF_3 = \sum xq_f^-(x, Q^2)[- 2e_f a_f a_e P_Z + 4v_f a_f v_e a_e P_Z^2]$$

(f=u,d,c,s,b)

$$xq_f^\pm = xq_f(x,Q^2) \pm x\bar{q}_f(x,Q^2)$$ (Parton Distribution Functions)

$$P_Z = \sin^{-2}2\theta_W \cdot Q^2/(Q^2+M_Z^2)$$ (Z-exchange & γ–Z interference)

$Y^\pm = 1 \pm (1-y)^2$, e_f: quark charge, v_i/a_i: EW couplings

$F_L = F_2 - 2xF_1$ (→0 in LO QCD, longitudinal Str. Function)

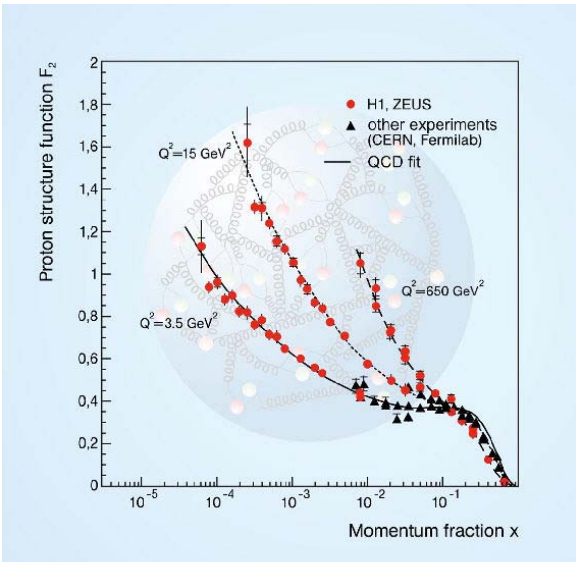
Proton structure function F_2

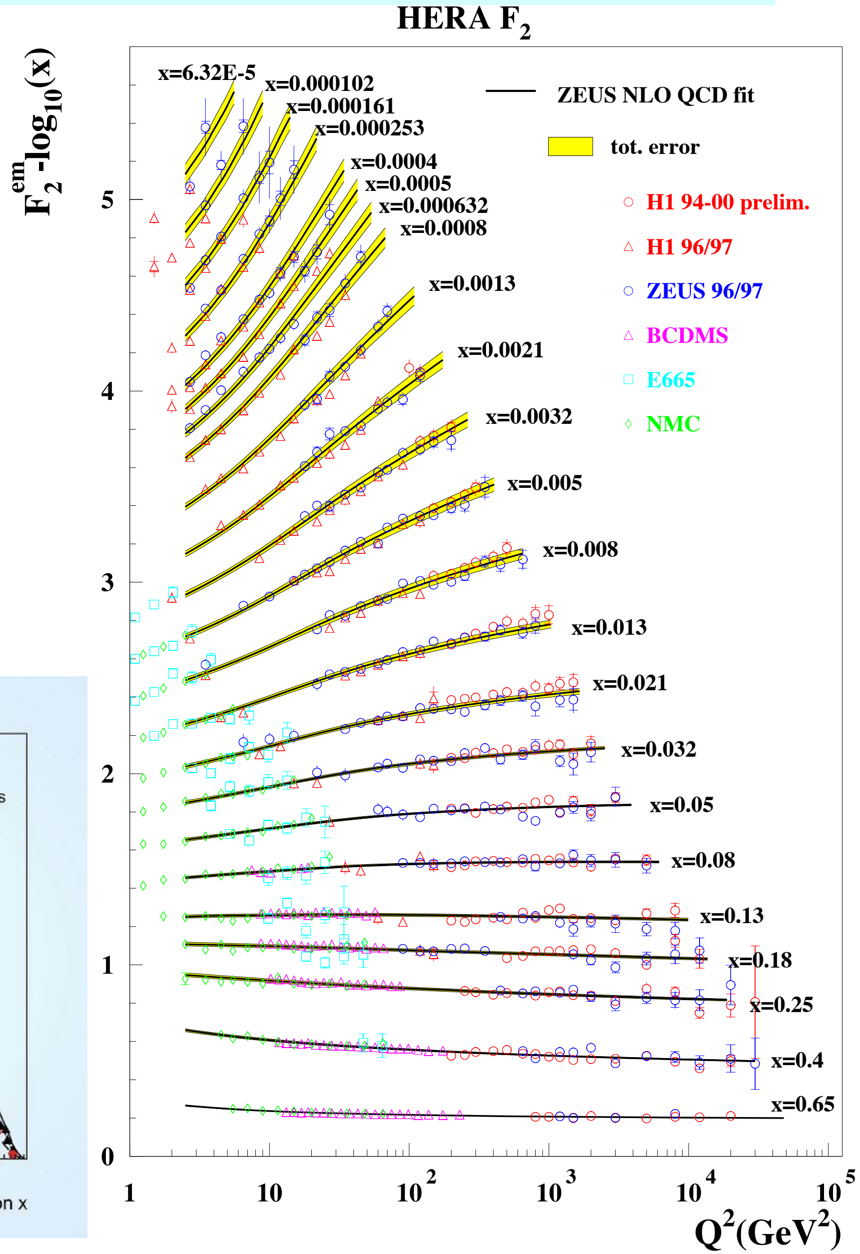
- At low *x*, strong scaling violation is seen.

  Large gluon density + $g \to q\bar{q}$ splitting
  $\to F_2$ increases

- Lines = result of NLO QCD fit
  - All data points well described over 5 orders of magnitude.

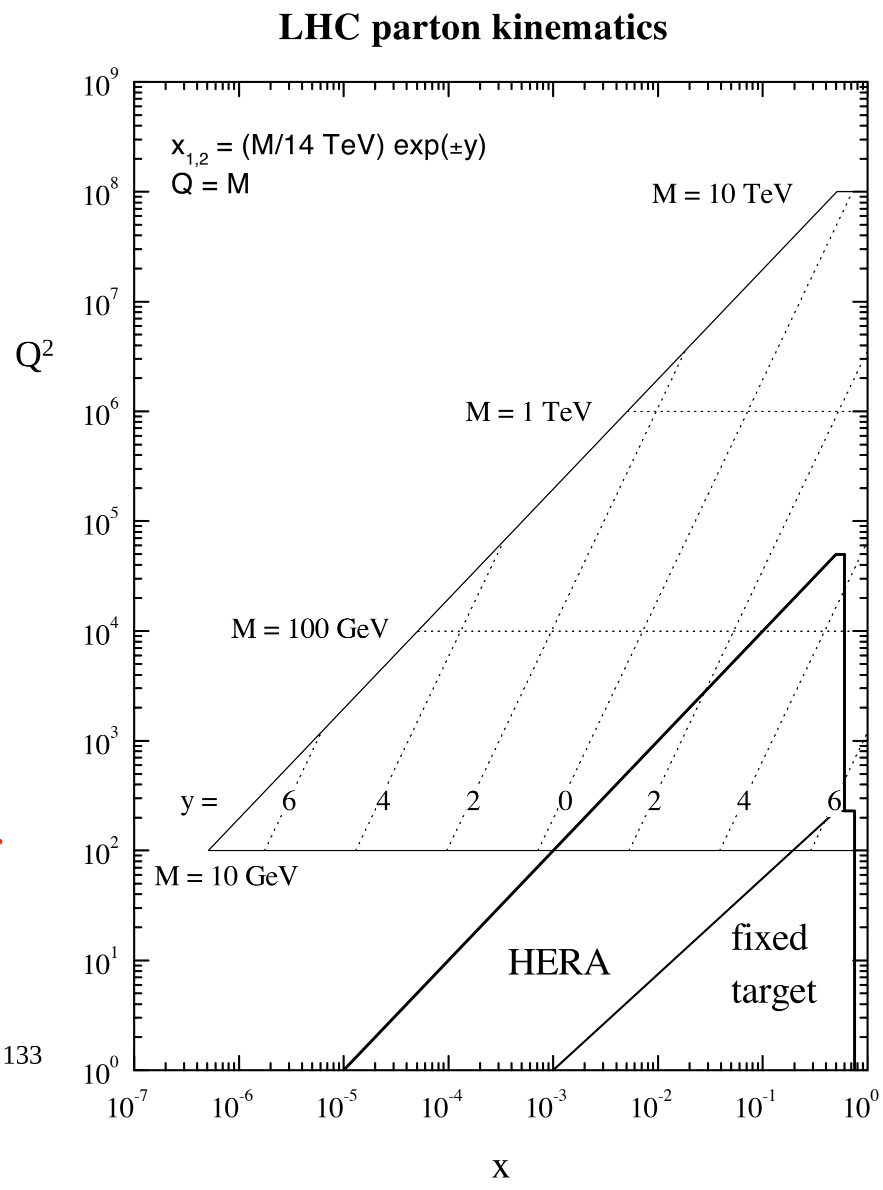
- Triumph of perturbative QCD (Gross, Politzer, Wilczek)





Relevance for LHC

- Low-x PDF only measured at HERA:
  x > as low as 10^{-4} important for
  100GeV<M<1TeV in 'central' region at LHC.
- High-x PDF:
  Q^2 evolution to <~10^4 GeV^2 checked at HERA.
  QCD still works: prediction power.
- Crucial inputs for signal cross section and QCD-background estimation.
  - Higgs, SUSY, top-pair, W/Z (luminosity)…



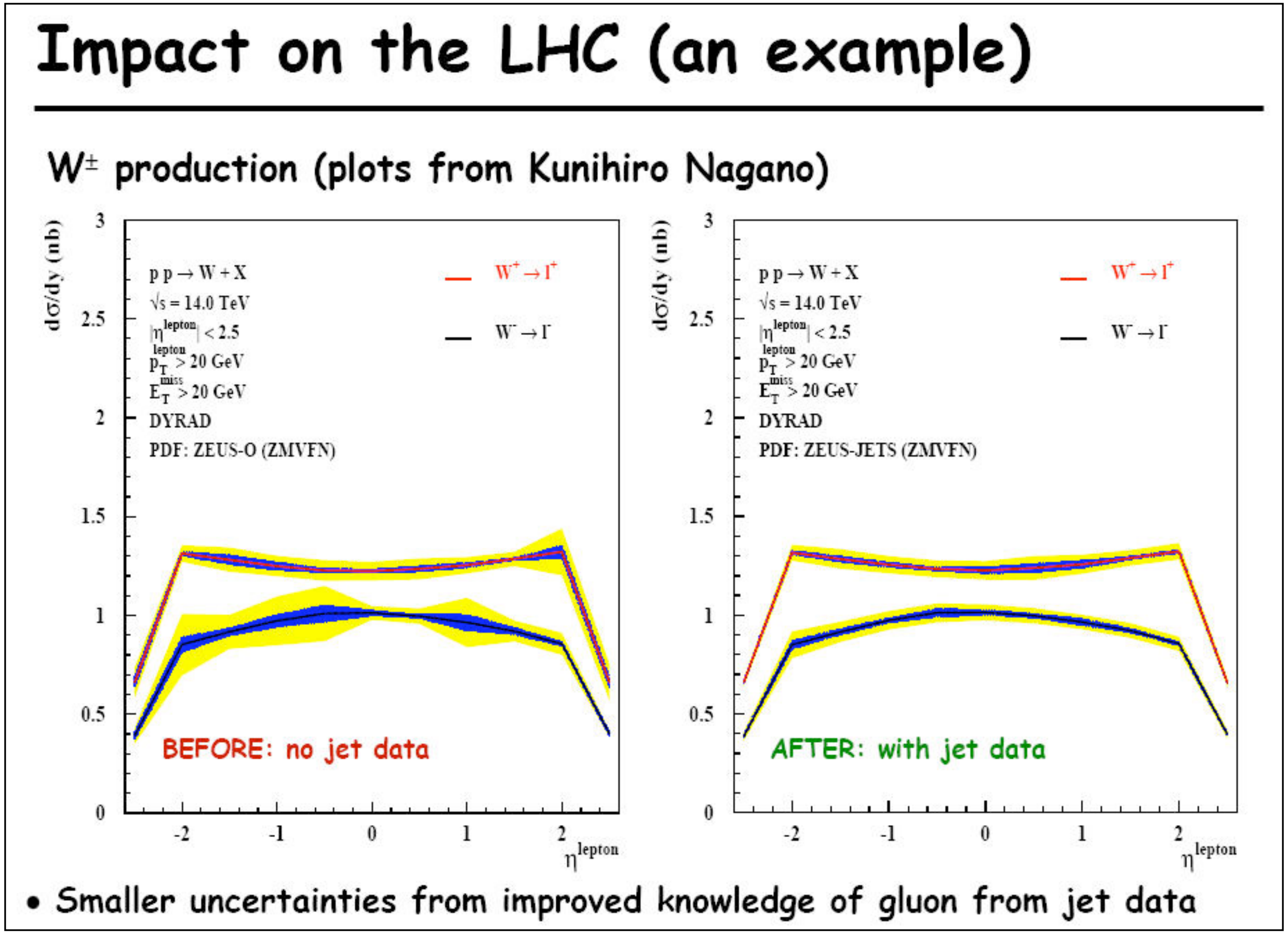
Martin et al., EPJC 14 (2000) 133

Relevance for LHC (cont'd)

- HERA-LHC WS: impact of new ZEUS PDF using jet data

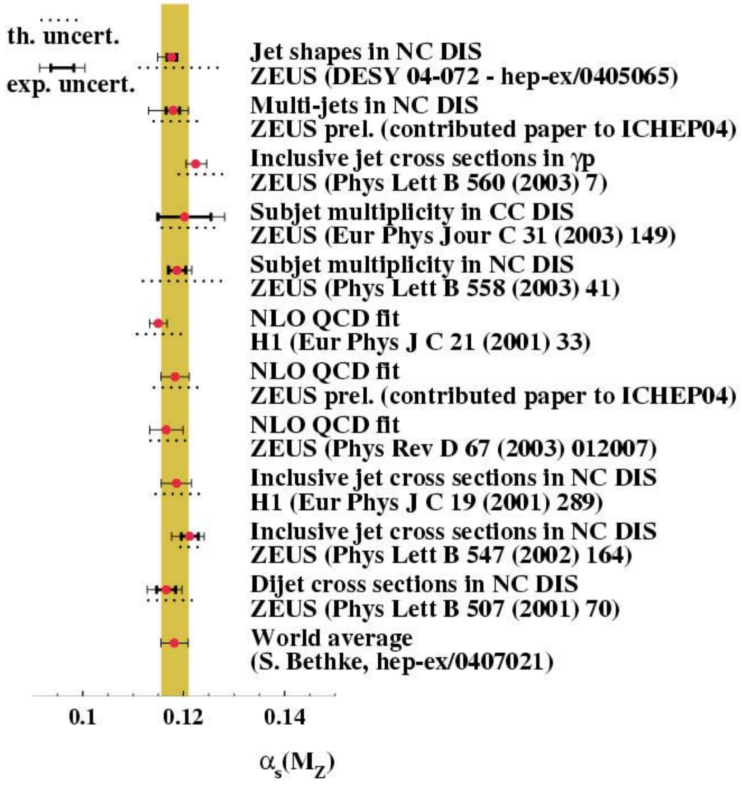
jet data: sensitive to middle-high-x gluons ($\gamma^* g \rightarrow jj$)

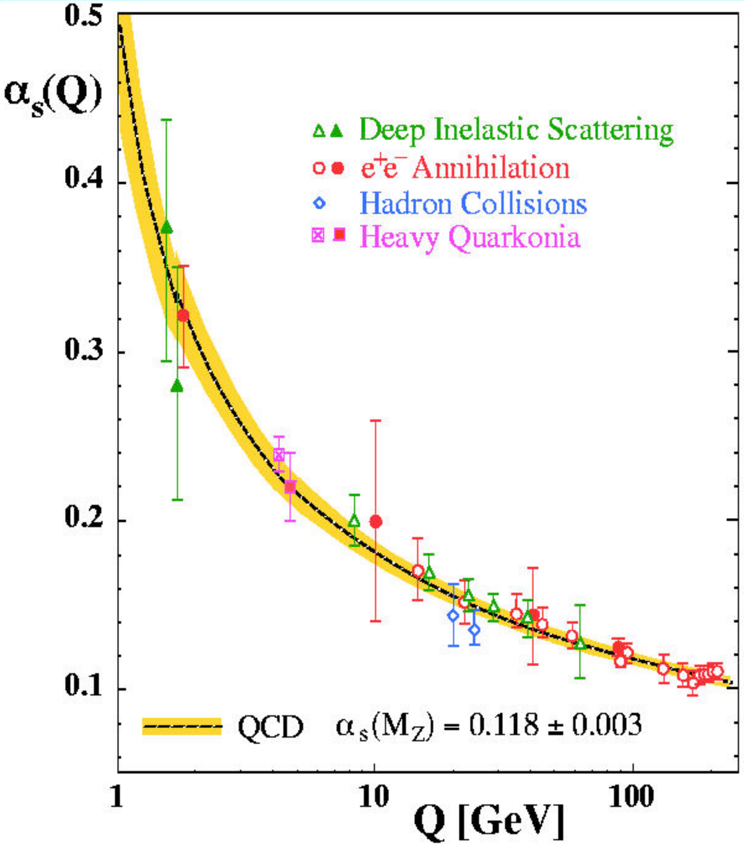
cf. F_2 data primarily sensitive to quarks



C.Gwenlan HERA-LHC WS

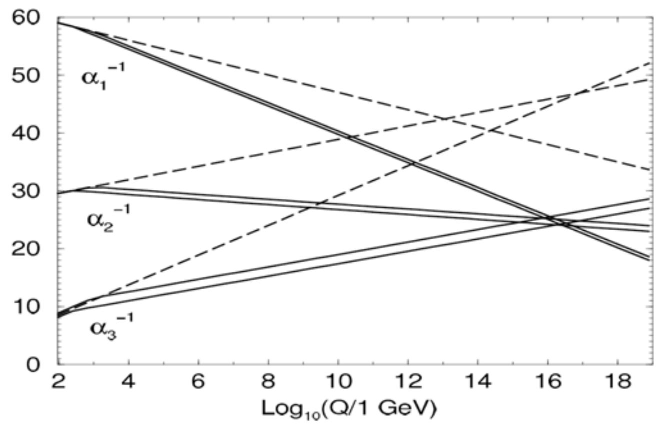
Pinning down α_s





Bethke and Zerwas, Physik J. Dec/2004

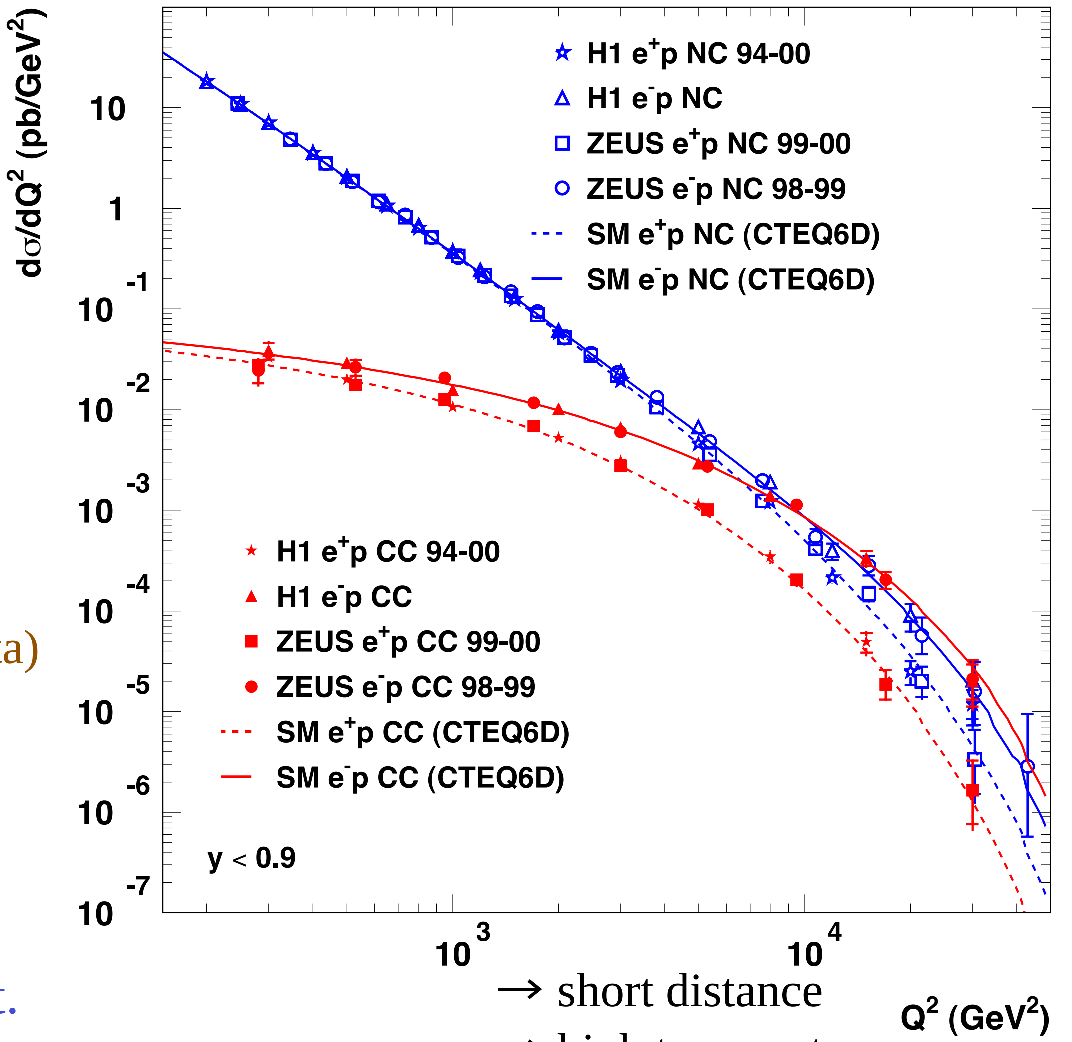
- One of the most fundamental parameters
- Measured with various methods
- Giving very competitive precision.



Evidence of Electro-Weak Unification

- At low Q^2:
  NC ~ $1/Q^4$ (EM current)
  CC ~ G_F^2 (Weak current)
- At high Q^2 ($> M_Z^2, M_W^2$):
  Both NC and CC mediated by unified EW current. $\sigma_{NC} \sim \sigma_{CC}$
- Dumping of σ_{CC} at high Q^2 comes from W propagator.
  M_w = 82.9 ±1.8 GeV (from H1 HERA-I data)
- Space-like: q^2(boson) << 0
  Completely different phase-space from time-like bosons
  at LEP and Tevatron ($q^2 > 0$).
  Complementary evidence/measurement.

Back in the history of Universe

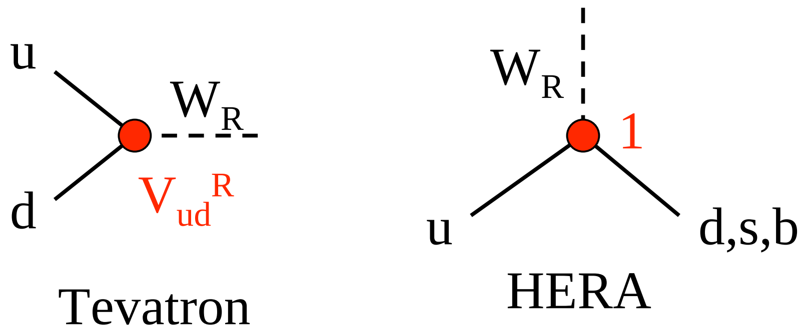


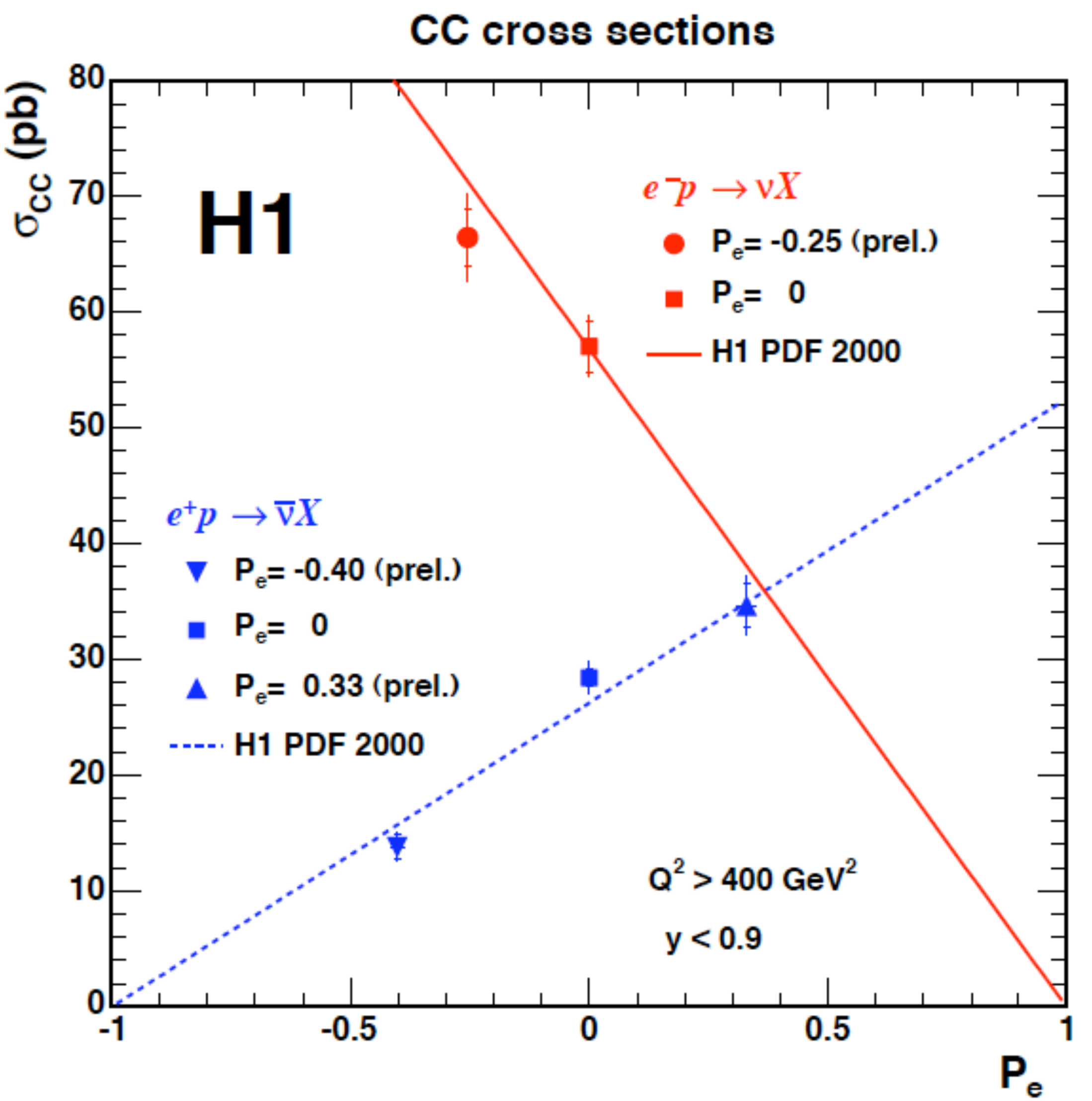
→ short distance
→ high temperature
→ early universe

Polarized CC cross sections from HERA-II

- CC - pure left-handed.
  $\sigma = (1 \pm P)\,\sigma_{P=0}$
- Deviation from 0 at P=±1
  → can search for right-handed weak current. Sensitivity with 1fb^{-1}: $M(W_R)$~400GeV.

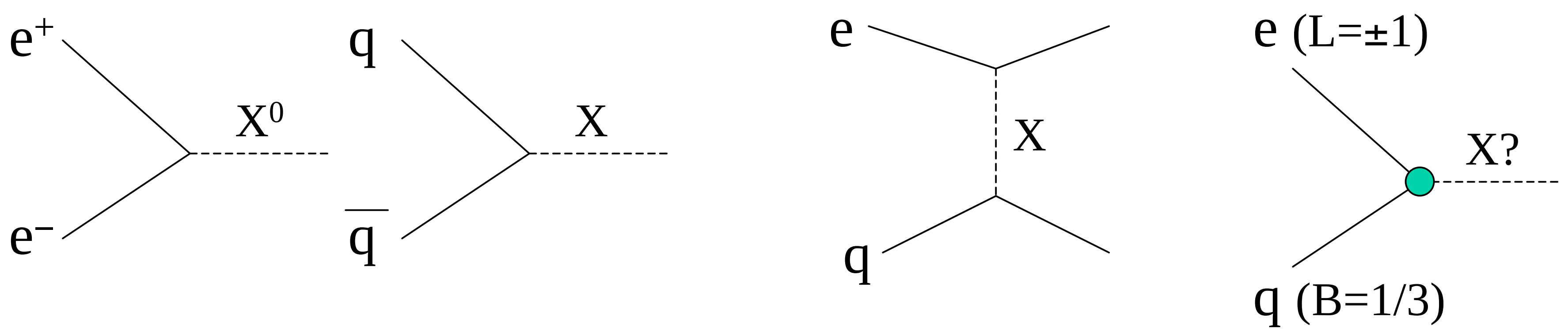
- Do not depend on right-handed CKM matrix element V_{ud}^R.





HERA is *not* only a QCD machine.

- LEP/Tevatron: e^+e^- / $q\bar{q}$ annihilation = ‘matterless’ initial state
  → s-channel (time-like) production of gauge bosons or new ‘non-matter’ particles (e.g. Higgs), or pair-production of matter particles (e.g. top pair) possible.
- HERA = eq collision = non-zero initial L/B numbers
  → t-channel (space-like) exchange of gauge bosons or new particles, or s-channel production of new particles possessing both L and B numbers, or exotic states of matter particles (e.g. excited fermions) are probed.

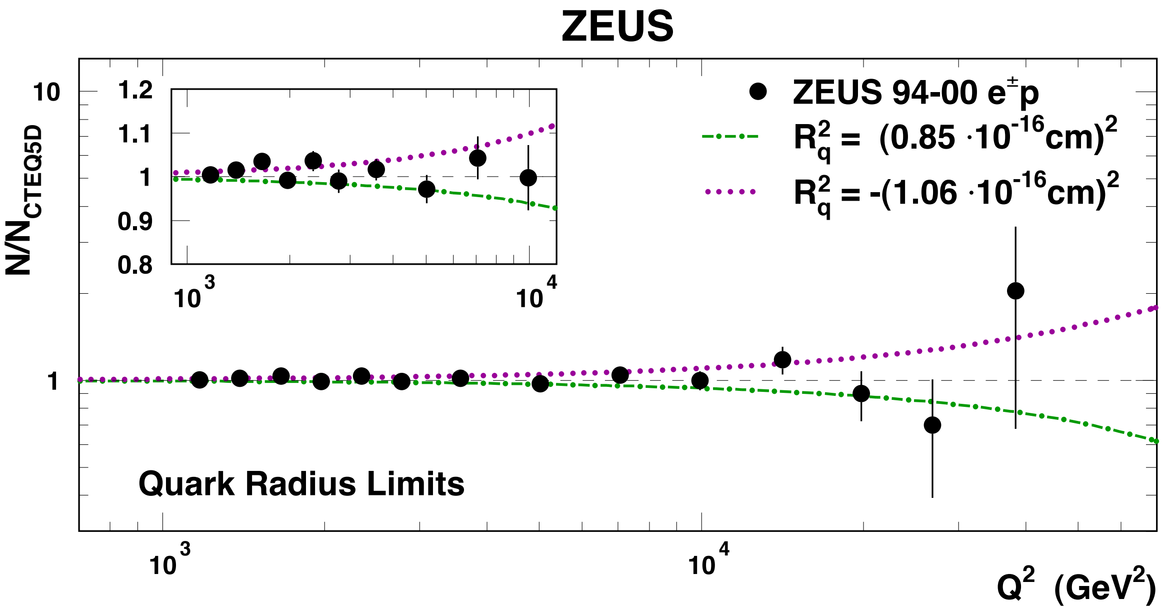


First natural question: is quark elementary?

- Repeat 'form-factor measurement' as Hofstadter did, but at $Q^2 \sim 40{,}000\ \mathrm{GeV}^2$ instead of $1\ \mathrm{GeV}^2$.
  - Resolution = $1/Q \sim 10^{-16}$cm = 0.001 proton radius
- If quark has a finite radius, cross section will decrease as the probe 'penetrates' into it (sees less EW charge).

$$\sigma = \sigma_{SM}(1 - \langle R_q{}^2 \rangle Q^2/6)^2$$

- Limits on quark size
  (assuming electron is pointlike)
  ZEUS: $R_q < 0.85 \times 10^{-16}$ cm
  H1: $R_q < 1.0 \times 10^{-16}$ cm
  (95% CL)



Contact Interactions

- Physics at very high mass-scale could still be 'felt' at lower energies via virtual effects.

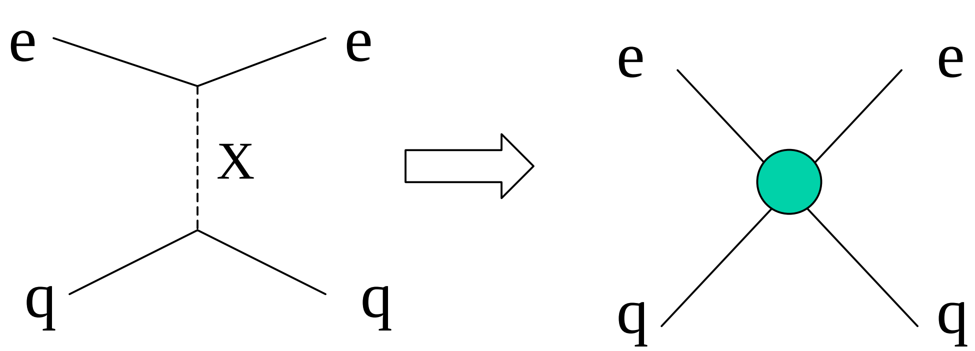
  e.g. new gauge bosons, composite fermions, …

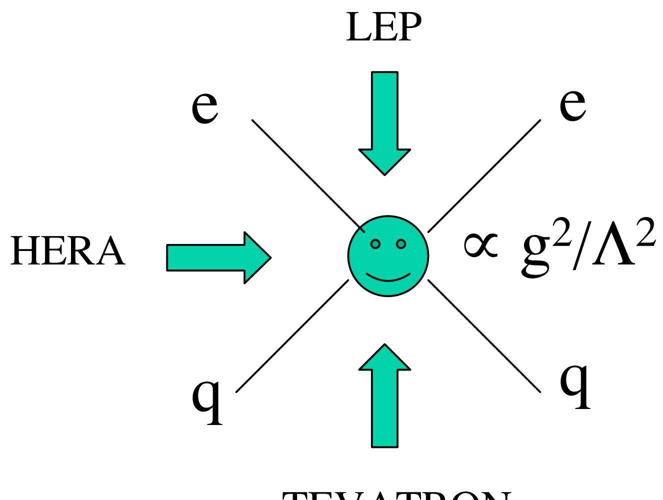
- Generically described as CI Lagrangian

  eeqq vector CI: $$L_{CI} = \sum_{i,j=L,R}^{q=u,d} \eta_{ij}^{q} (\bar{e}_i \gamma^{\mu} e_i)(\bar{q}_j \gamma_{\mu} q_j)$$ i/j: lepton/quark chirality

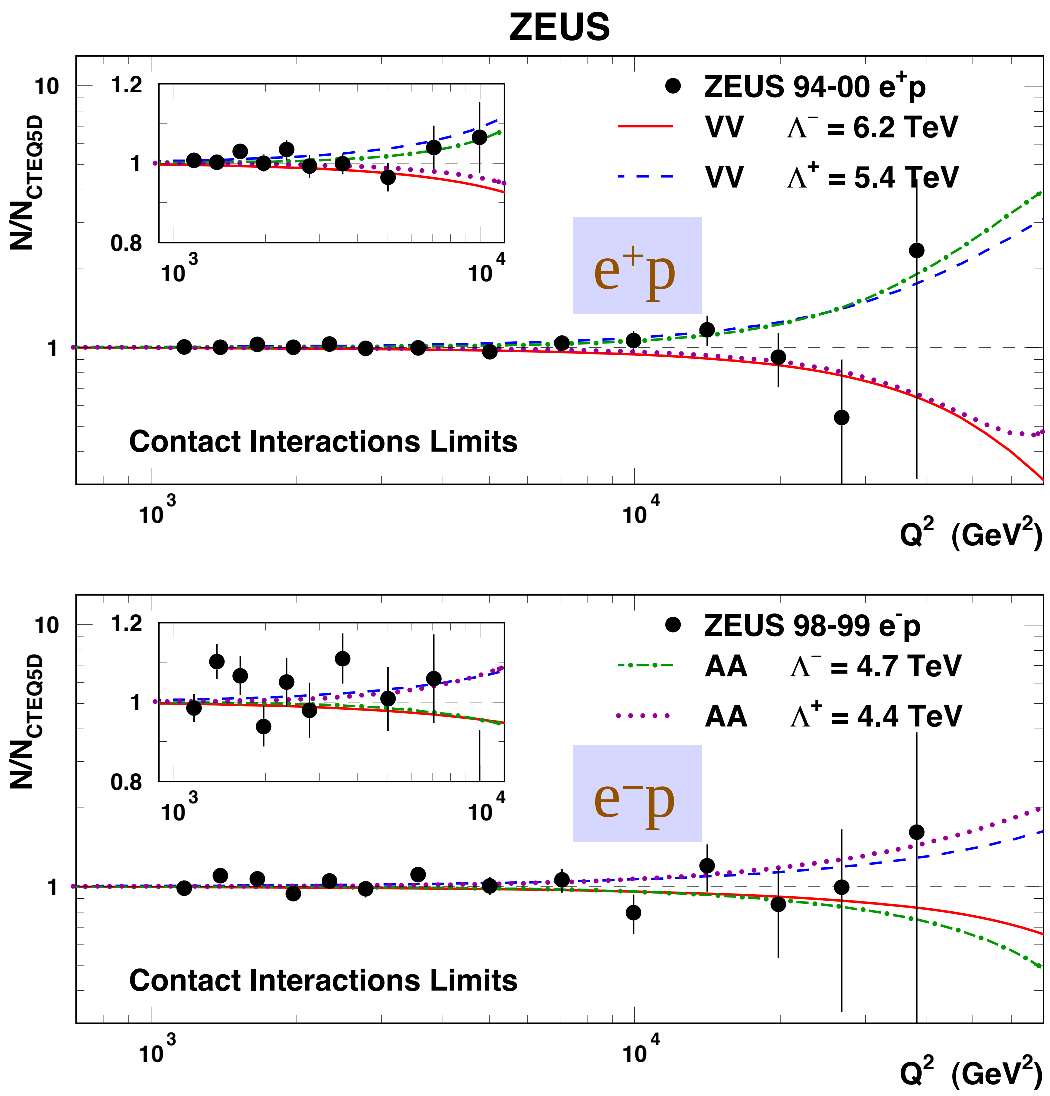
  $\eta = g^2/\Lambda^2$ (g: unknown coupling, convention takes $g^2=4\pi$; Λ: new physics scale)

  Analogy: early days of weak int. ('large' M_W) = 4-fermion CI. $G_{Fermi} \sim e^2/\sin^2\theta_W M_W^2$





Contact Interactions (2)



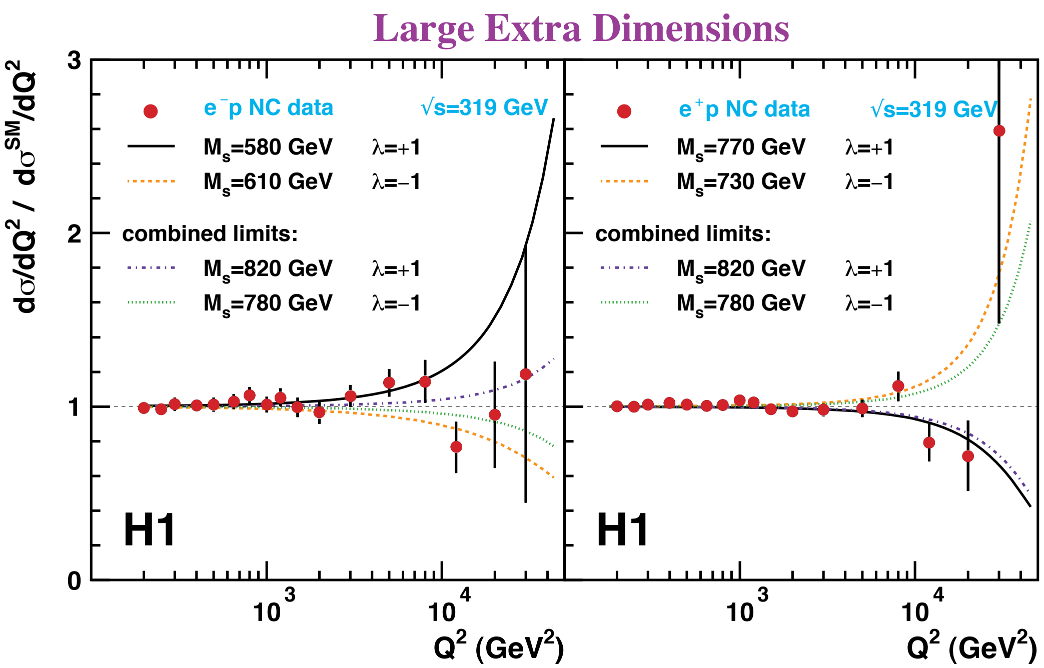
- Fit CI models to Q^2 dist. of data (example: AA=LL–LR–RL+RR)
- Different sign of $\eta \rightarrow$ different interference of CI–SM
- Limits on Λ on various models: 1.7 - 6.2 TeV (ZEUS) 1.6 - 5.5 TeV (H1)

Comparable to Tevatron/LEP limits on eeqq CI

Large Extra Dimensions

- <u>Arkani-Hamed, Dimopoulos and Dvali:</u>
  Assume n extra dimensions compactified to scale R, where only gravity propagates.
  Real GUT scale could be as low as TeV ($R^n M_s^{n+2} \sim M^2_{Planck}$)

- <u>Collider consequence:</u> exchange of Kaluza-Klein excitations of gravitons would modify SM-particle scattering at high energy.



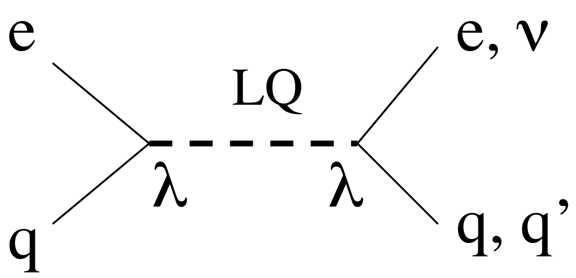
- <u>HERA:</u> eeqq CI formalism with λ/M_s^4 as a parameter

- $\lambda=+1$: M_s > 0.82 TeV (H1)
  0.78 TeV (ZEUS)
  $\lambda=-1$: M_s > 0.78 TeV (H1)
  0.79 TeV (ZEUS)

- LEP, Tevatron limits ~ 1 TeV

Leptoquarks

- Lepton & Quark = elementary fermions: could have fundamental new interaction.
  New state with L and B numbers: Leptoquark
- Predicted in many GUT models.
  - Could be scalar or vector.
  - Could be matter-matter (F=L+3B=±2, l^-q) or antimatter-matter (F=0, l^+q) state.
- HERA: s-channel *eq* fusion produces LQ.
  - Resonance in eq (νq) invariant mass in NC(CC) events.
  - e^+p data sensitive to F=0 LQ, e^-p sensitive to F=2 LQ.
  - Production cross section $\propto \lambda^2$
- No excess observed over SM predictions.



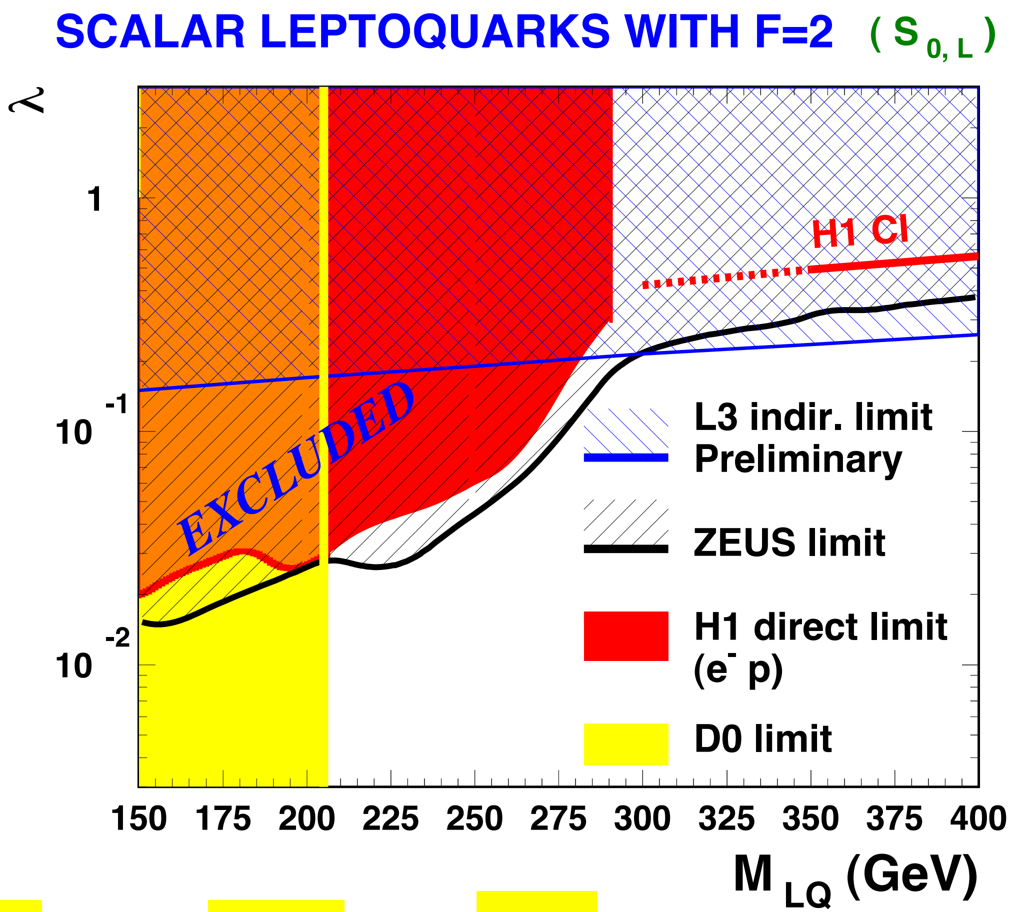
λ: Yukawa coupling

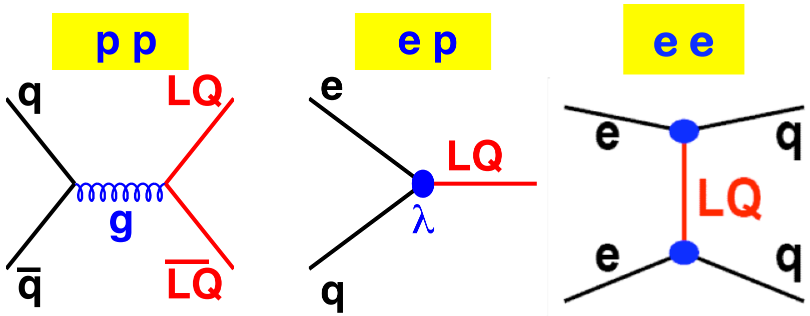
LQ limits compared to other colliders

- Example: S_L^0 LQ
  (Buchmüller-Rückl-Wyler classification)
  This LQ decays 50% to eq, 50% to νq
  → NC and CC results combined.

- Tevatron: LQ pair-production with strong coupling
  - Limits independent on λ
  - Lower sensitivity to LQ → νq

- LEP2: virtual effects in $e^+e^- \rightarrow$ hadrons

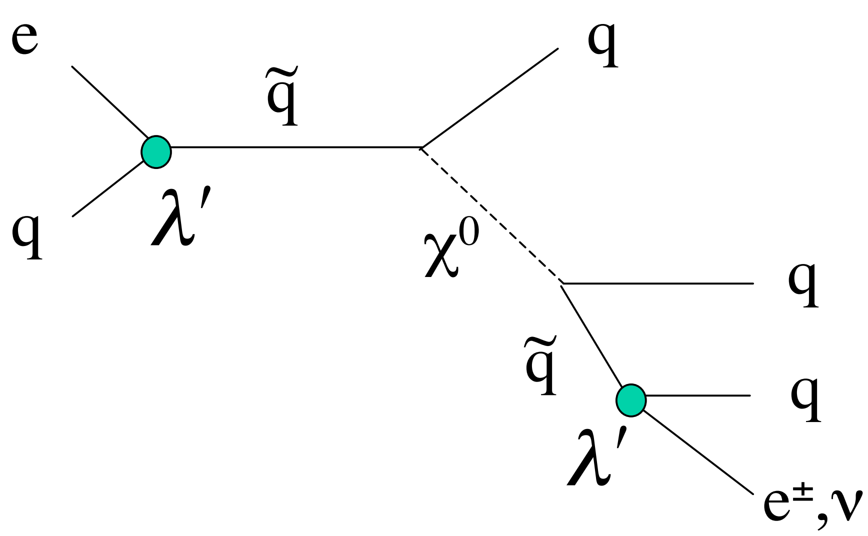




(E.Perez LP03)

Supersymmetry

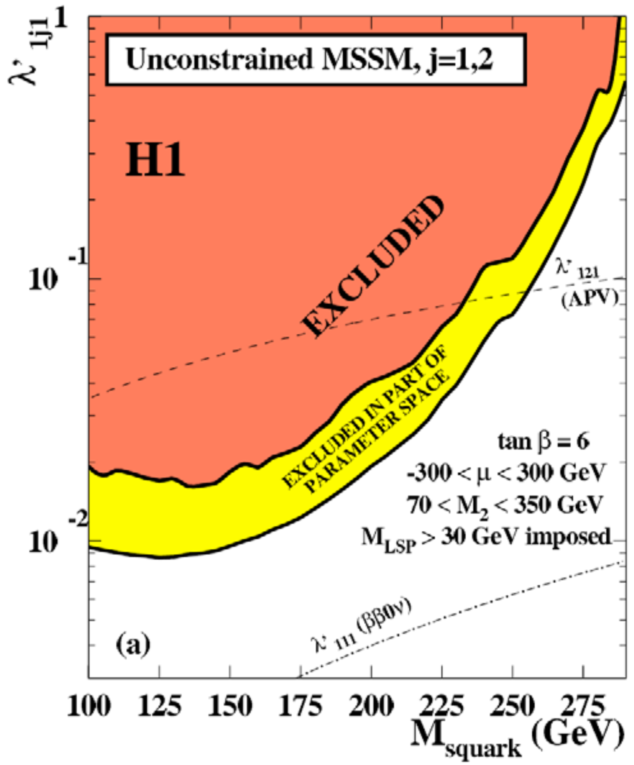
- SUSY: all fermions (bosons) have super-partener bosons (fermions)
- Most general SUSY Lagrangian contains a term violating L-number:
  $\lambda'_{ijk} L_i Q_j \bar{D}_k$ λ'_{ijk}: R-parity-violating Yukawa coupling
- Resonant single production of squark possible at HERA
  e.g. λ'_{131} : $e^+ d \rightarrow \tilde{t}_L$
- Production analogous to LQ, but decay can be more complicated
  (gauge decay to q+χ, followed by cascade χ decay)
  e.g. multi-jets + lepton final state



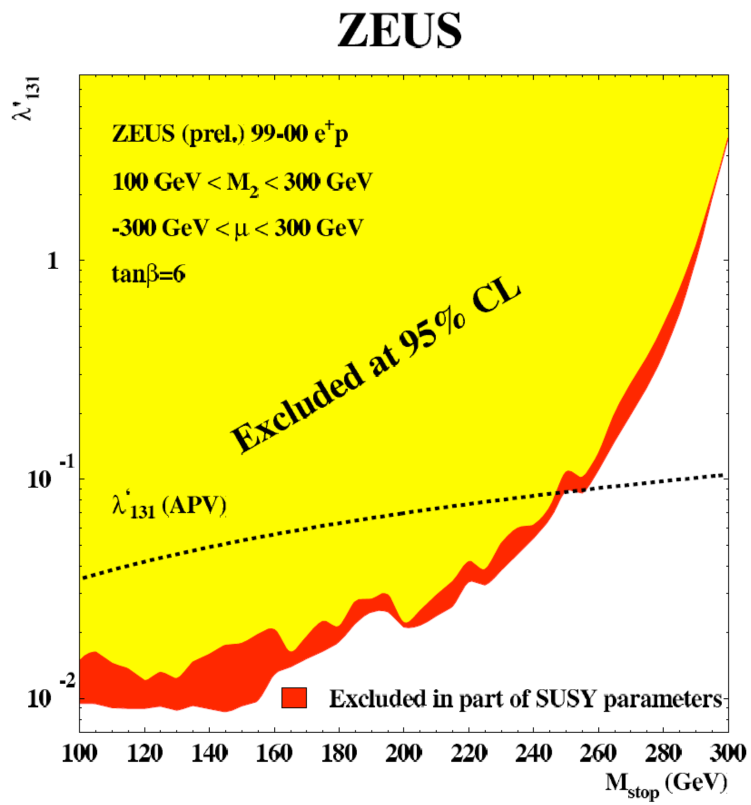
Limits on RPV coupling vs. M_{squark}

- Cover most of the final-state branching ratios; no excess found.
- MSSM parameter scan: limits on λ' as a function of squark mass.
- Explore new regions (down to λ'~0.01) for λ'_{121} and λ'_{131}, for squark masses below 300GeV.

$\tilde{u}_L, \tilde{c}_L$



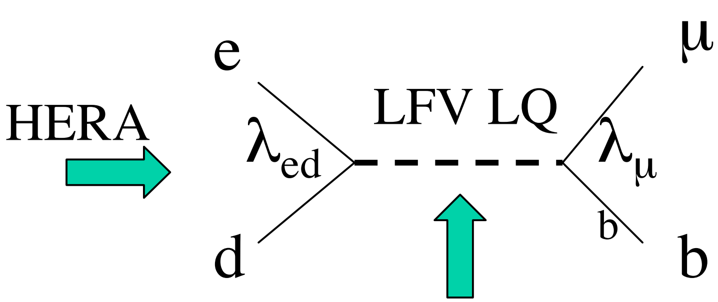
$\tilde{t}_L$

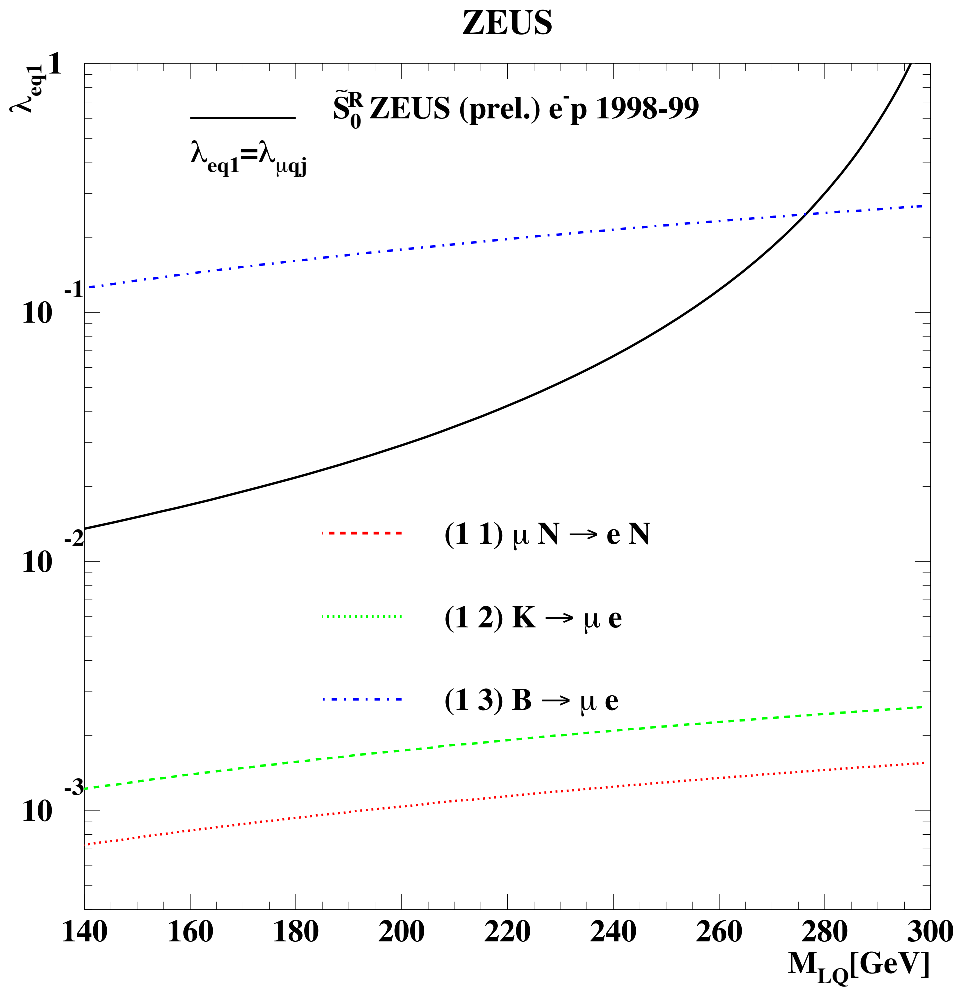


Forbidden Lepton/Quark Transitions

(1) LFV

- ep→μX, ep→τX
  Strictly forbidden in SM
  (ν-osc. gives negligible rates)
- No event found: limits expressed in context of LFV LQs
  (coupling to 2 lepton generations)
- Strong limits exist for light quarks, but HERA is competitive for heavy-quark couplings.





LFV (cont'd)

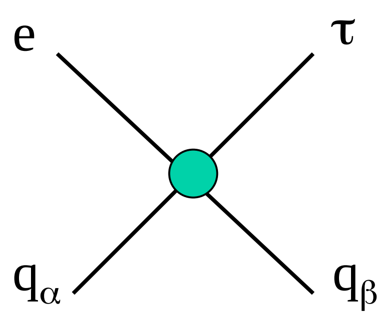
- For very heavy LQs: CI limits $\lambda_{eq_\alpha}\lambda_{lq_\beta}/M_{LQ}^2$ (TeV^{-2}) for quark generations (α,β)

  black - best low-energy limits

  red - ZEUS limits

- Example: e→τ transition

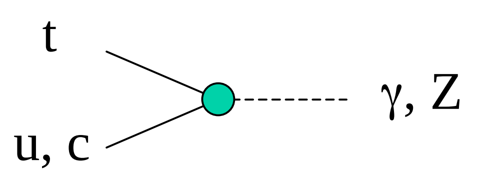
  Again, stringent limits for (α,β)=(1,1), but HERA has high potential for higher generations



$e \to \tau$	ZEUS 94-97			$\|F\| = 2$			
$\alpha\beta$	S_0^L $e^+\bar{u}_\alpha$	S_0^R $e^+\bar{u}_\alpha$	$\tilde{S}_0^R$ $e^+\bar{d}_\alpha$	S_1^L $e^+(\bar{u}+\sqrt{2}\bar{d})_\alpha$	$V_{1/2}^L$ $e^+\bar{d}_\alpha$	$V_{1/2}^R$ $e^+(\bar{u}+\bar{d})_\alpha$	$\tilde{V}_{1/2}^L$ $e^+\bar{u}_\alpha$
1 1	G_F 0.3 5.4	$\tau\to\pi e$ 0.4 5.4	$\tau\to\pi e$ 0.4 7.1	G_F 0.3 2.8	$\tau\to\pi e$ 0.2 2.6	$\tau\to\pi e$ 0.1 1.3	$\tau\to\pi e$ 0.2 1.7
1 2	$K\to\pi\nu\bar{\nu}$ 10^{-3} 14	14	$\tau\to Ke$ 5 9.3	$K\to\pi\nu\bar{\nu}$ 10^{-3} 4.6	$K\to\pi\nu\bar{\nu}$ 5×10^{-4} 5.5	$\tau\to Ke$ 3 4.5	8.2
1 3	V_{ub} 0.4 •	•	$B\to\tau\bar{e}X$ 8 12	V_{ub} 0.4 5.5	$B\to\tau\bar{e}X$ 4 8.4	$B\to\tau\bar{e}X$ 4 8.4	•
2 1	$K\to\pi\nu\bar{\nu}$ 10^{-3} 5.9	5.9	$\tau\to Ke$ 5 7.8	$K\to\pi\nu\bar{\nu}$ 10^{-3} 3.2	$K\to\pi\nu\bar{\nu}$ 5×10^{-4} 2.5	$\tau\to Ke$ 3 1.3	1.6
2 2	$\tau\to ee\bar{e}$ 20 19	$\tau\to ee\bar{e}$ 20 19	$\tau\to ee\bar{e}$ 66 13	$\tau\to ee\bar{e}$ 55 6.2	$\tau\to ee\bar{e}$ 33 6.5	$\tau\to ee\bar{e}$ 15 5.2	$\tau\to ee\bar{e}$ 10 9.7
2 3	$B\to l\nu X$ 4 •	•	$B\to\tau\bar{e}X$ 8 17	$B\to l\nu X$ 4 8.1	$B\to\tau\bar{e}X$ 4 11	$B\to\tau\bar{e}X$ 4 11	•
3 1	$B\to l\nu X$ 4 •	•	$B\to\tau\bar{e}X$ 8 9.3	$B\to l\nu X$ 4 4.7	$B\to\tau\bar{e}X$ 4 2.6	$B\to\tau\bar{e}X$ 4 2.6	•
3 2	$B\to l\nu X$ 4 •	•	$B\to\tau\bar{e}X$ 8 21	$B\to l\nu X$ 4 10.2	$B\to\tau\bar{e}X$ 4 7.6	$B\to\tau\bar{e}X$ 4 7.6	•
3 3	•	•	$\tau\to ee\bar{e}$ 66 30	$\tau\to ee\bar{e}$ 55 16	$\tau\to ee\bar{e}$ 33 15	$\tau\to ee\bar{e}$ 15 15	•

(2) FCNC in top sector

- Flavour-Changing Neutral Currents
  Absent in SM at tree level (GIM)
  Small rate when top in the loop.
  e.g. $K_L \to \mu\mu$, $b \to s\gamma$
- Top FCNC: negligible SM rate, not very tightly constrained.
  → sensitive to physics beyond SM.



- HERA: ep → tX (→bW^+X), sensitive to t-u-γ coupling (u-quark in proton)
  Probes unexplored region from
  LEP ($e^+e^- \to$ tq), Tevatron (t→ γq, Zq)
  (they also explore t-c-γ/Z coupling)

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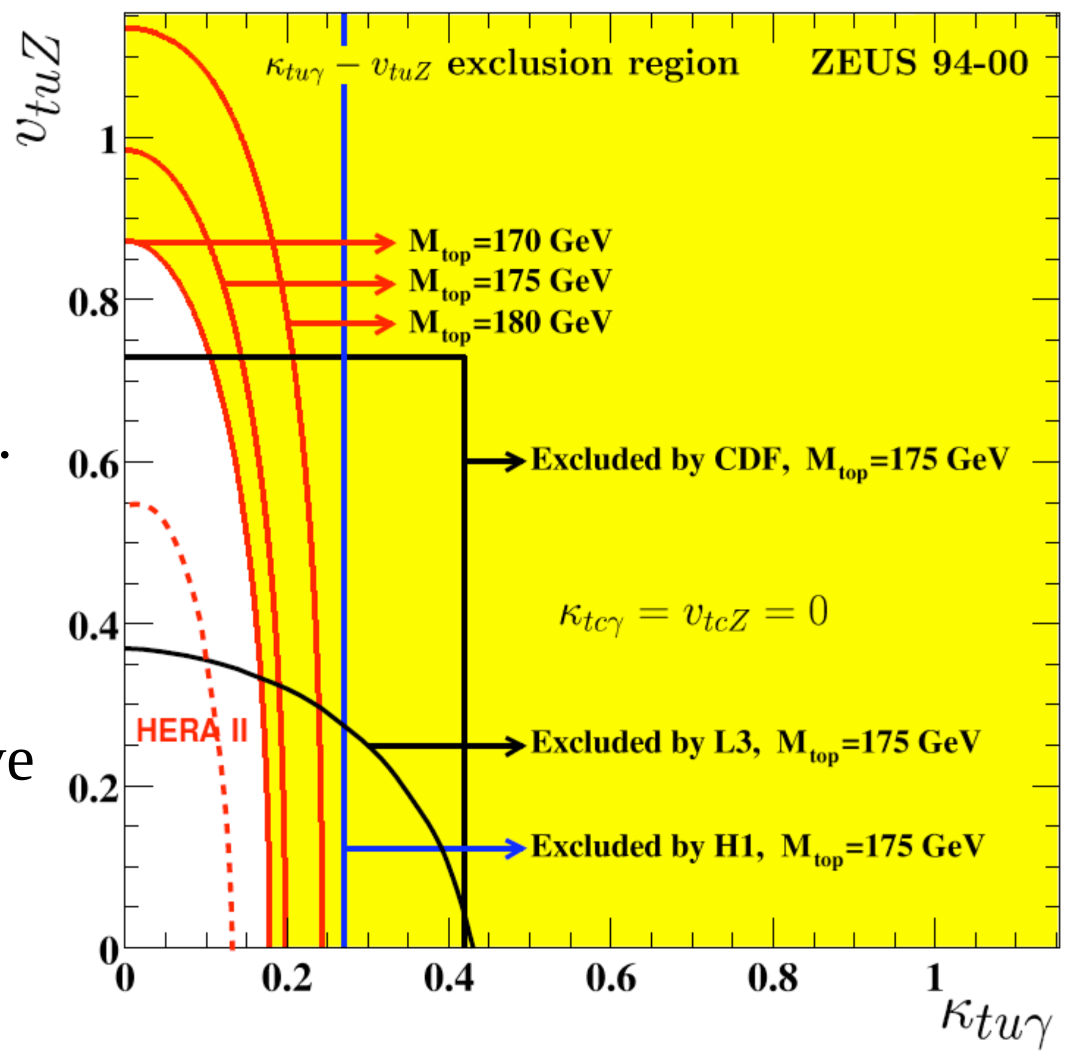
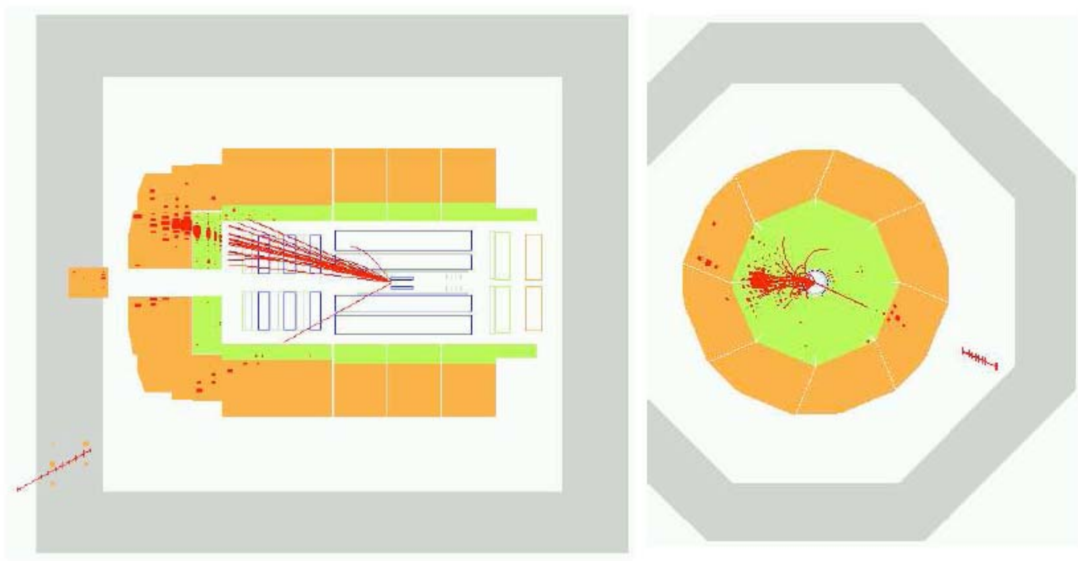
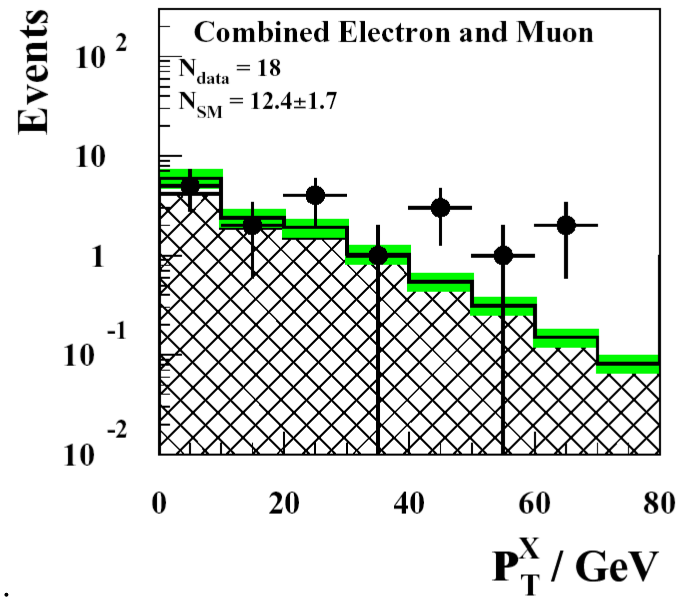


Puzzling 'Isolated Lepton' events

- FCNC top decay $t \to bW \to bl\nu$: "lepton+missing Pt+large Pt(had)"
  Dominant SM background: on-shell W production (σ ~1 pb)
  H1 has had an excess in this channel: Pt(l)>10, Pt(miss)>12,Pt(had)>25GeV
  e: N_{obs}=4, N_{SM}=1.49±0.25 μ: N_{obs}=6, N_{SM}=1.44±0.26 Phys. Lett. B561 (2003) 241
- ZEUS data consistent with SM: Pt(l)>5, Pt(miss)>20(e)10(μ),Pt(had)>25GeV
  e: N_{obs}=2, N_{SM}=2.90±0.45 μ: N_{obs}=5, N_{SM}=2.75±0.21 Phys. Lett. B559 (2003) 153
- ZEUS looked at τ final state (hadronic decay) and see outstanding events
  - τ: N_{obs}=2, N_{SM}=0.20±0.05 Pt(jet,track)>5, Pt(miss)>20,Pt(had)>25GeV PLB583(2004)41

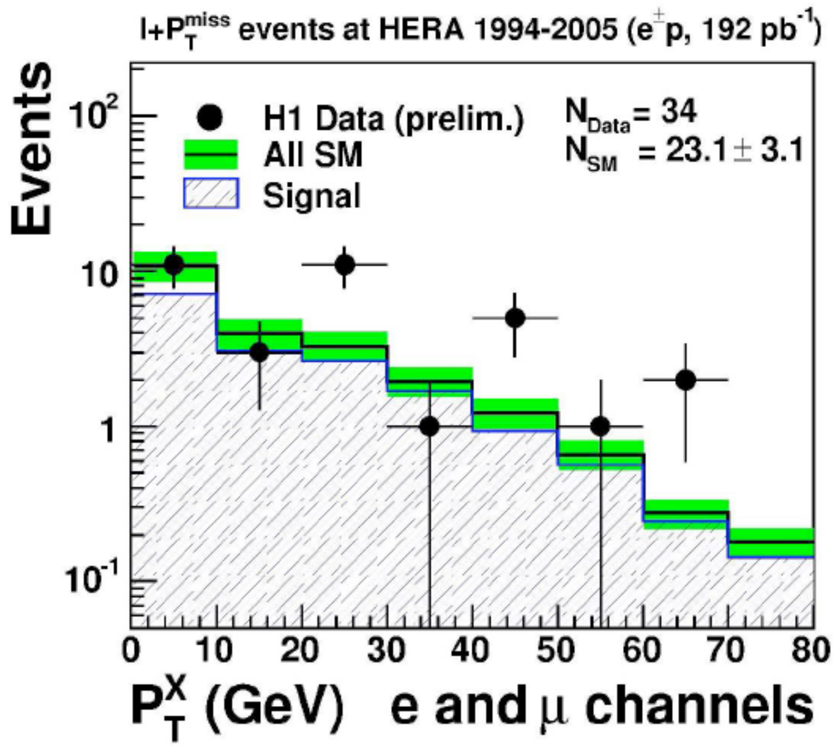




High-Pt leptons – latest numbers

- H1 update with HERA-II data (74 pb^{-1} $e^{\pm}p$)
  - 6 new electron events at Pt(had)>25GeV
  - No new muon event
  - Overall excess in e+μ channels
- τ search at H1
  - No excess seen (HERA-I data)

- More data needed to resolve the puzzle.



$e^{\pm}p$ data (1994-2005) 192 pb^{-1}

	Electron obs./exp. (W)	Muon obs./exp. (W)	Tau[①] obs./exp. (W)
All P_T^X	25/18.3 ± 2.5 (70%)	9/4.8 ± 0.8 (85%)	5/5.8 ± 1.4 (15%)
P_T^X > 25 GeV	11/3.0 ± 0.6 (81%)	6/3.0 ± 0.6 (86%)	0/0.5 ± 0.1 (49%)

① $e^{\pm}p$ (1996-2000) 108 pb^{-1}

Summary

- High-Q^2 *ep* collision at HERA: precise determination of PDF, pinning down gluon density and α_s.
  - Solid confidence on perturbative QCD (after 30 years).
  - Indispensable inputs to LHC physics.
- Short-distance *eq* collision: unique opportunity to search for particles and forces beyond SM.
  - Many results competitive/complementary with other colliders.
- HERA-II running with lepton polarization well on its way. Plan to deliver 700 pb^{-1} of $e^{\pm}_{L,R}$ till 2007.
  - Especially a big leap in $e^{-}p$ data (only ~15 pb^{-1} in HERA-I).
- Please stay tuned!