Physics at HERA

Summer Student Lectures
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Overview Part 2

- Exotics
  - Model Dependent Searches
  - Model Independent Searches
- Jet Physics
  - Cross Sections
  - Strong Coupling
- Heavy Quarks
  - Charm
  - Beauty
- Diffraction

personal selection!
many more analyses
are done!

Exotics or
Beyond the Standard Modell

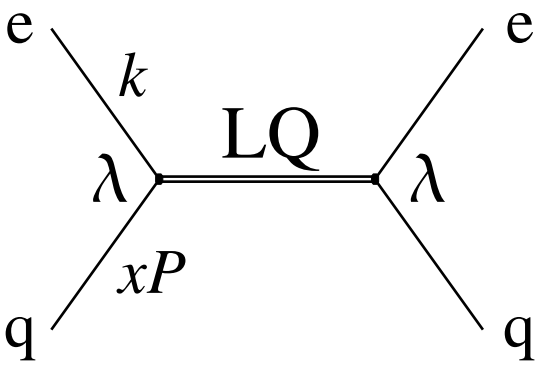
New Particles

many theories predict more particles than the SM:

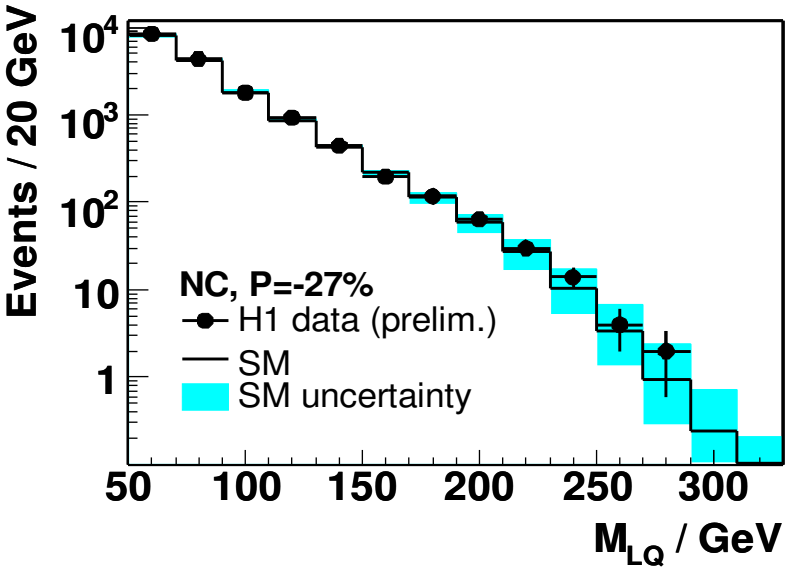
- SUSY:
  - every Standard Model particle has a supersymmetric partner
  - fermion partners are bosons, boson partners fermions
- leptoquarks
  - particle with lepton and quark properties
  - can be produced resonantly in *ep* collisions
- ... exited fermions, contact interactions, large extradimensions ...

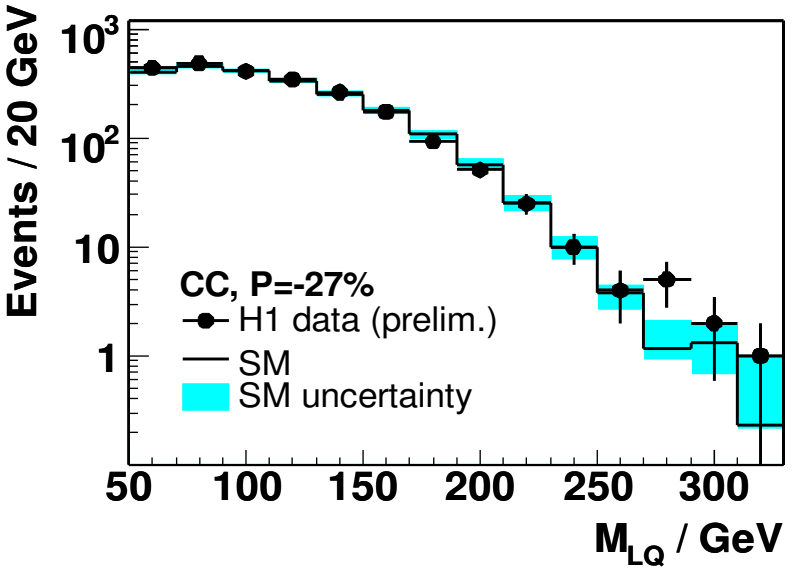
but experimentally search also model-independent!

Leptoquarks

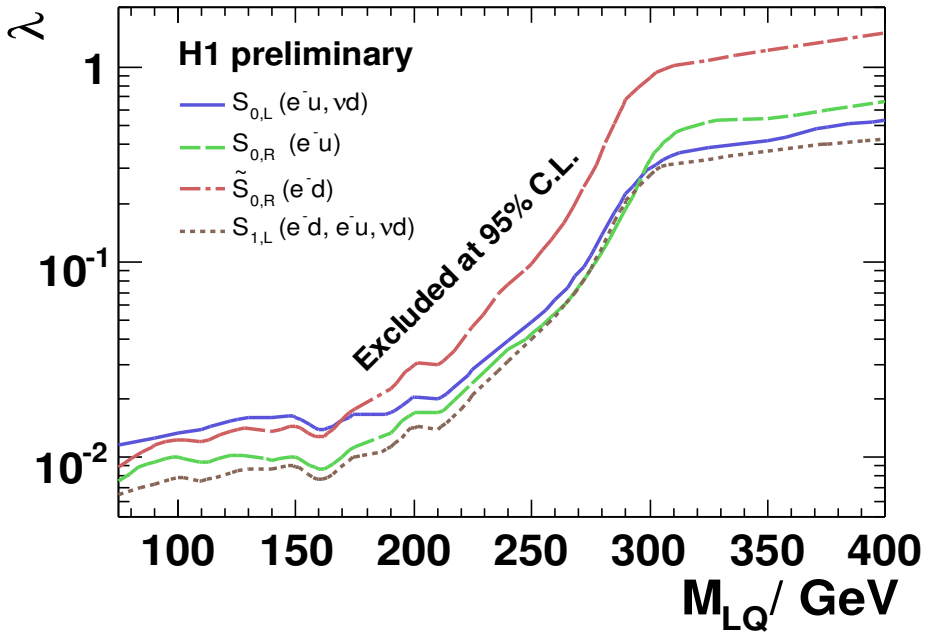


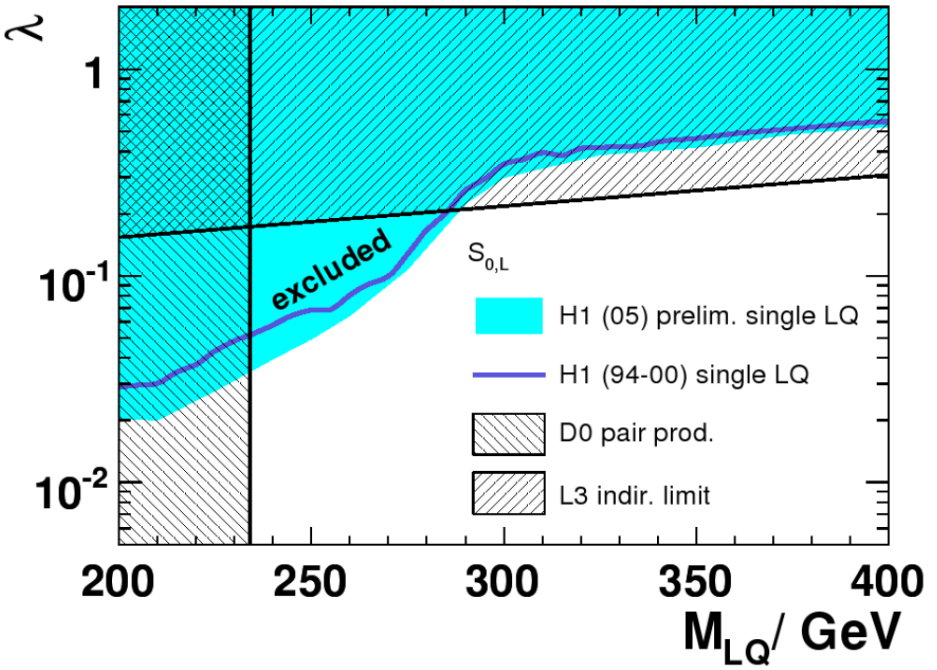
- looks the same as NC process
- $M_{LQ}^2 = (xP + k)^2 = xs$
- compare measured cross section with SM expectation
- derive limits on coupling λ





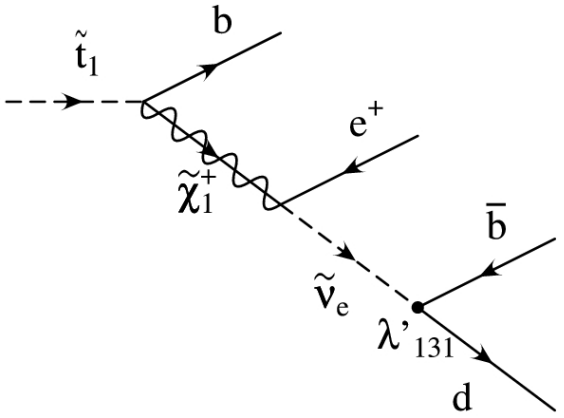
Limits on Leptoquarks

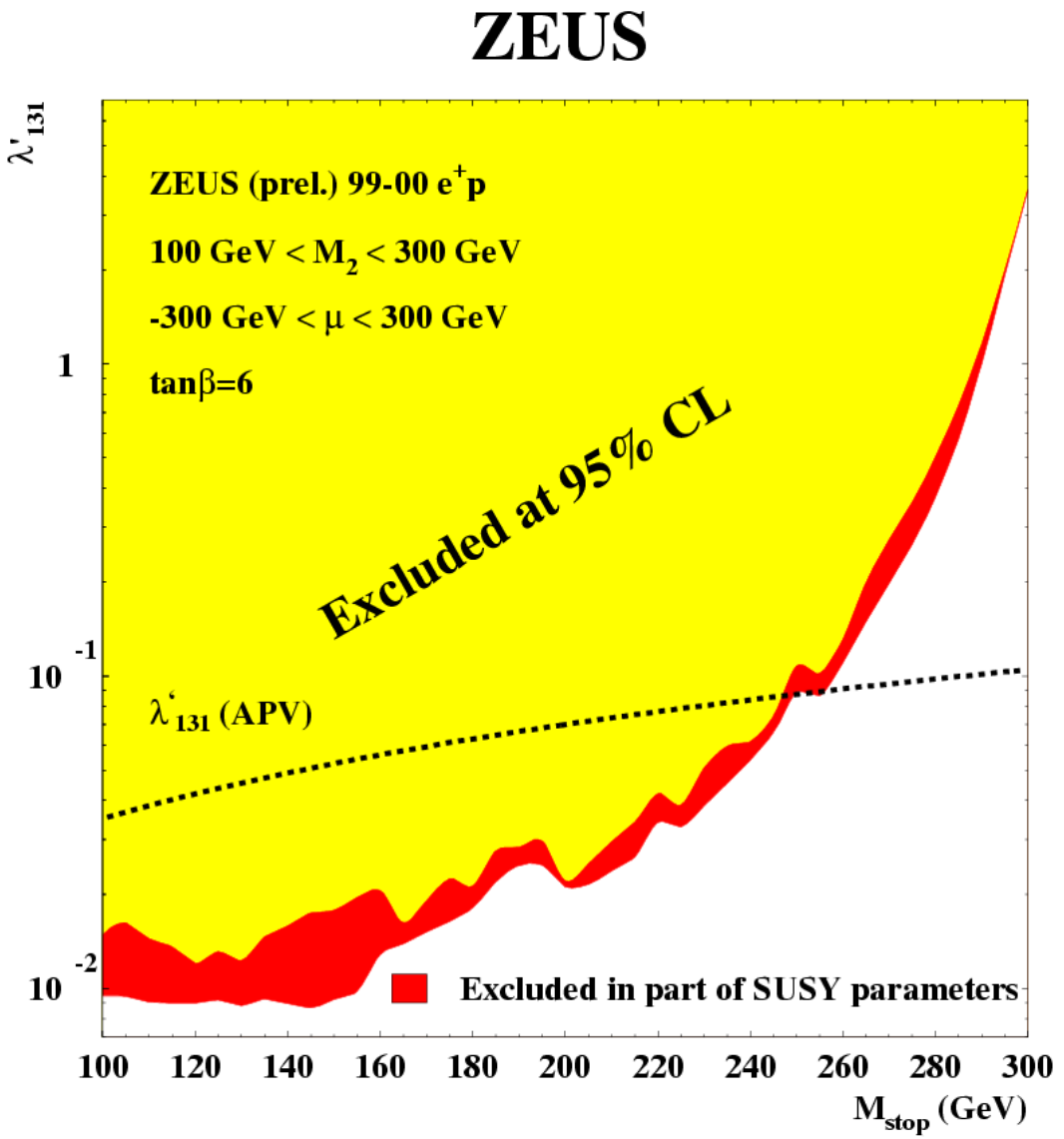




SUSY

- R parity violation: single SUSY particle can be produced
- limits depend on many parameters (masses, couplings)
- example: stop





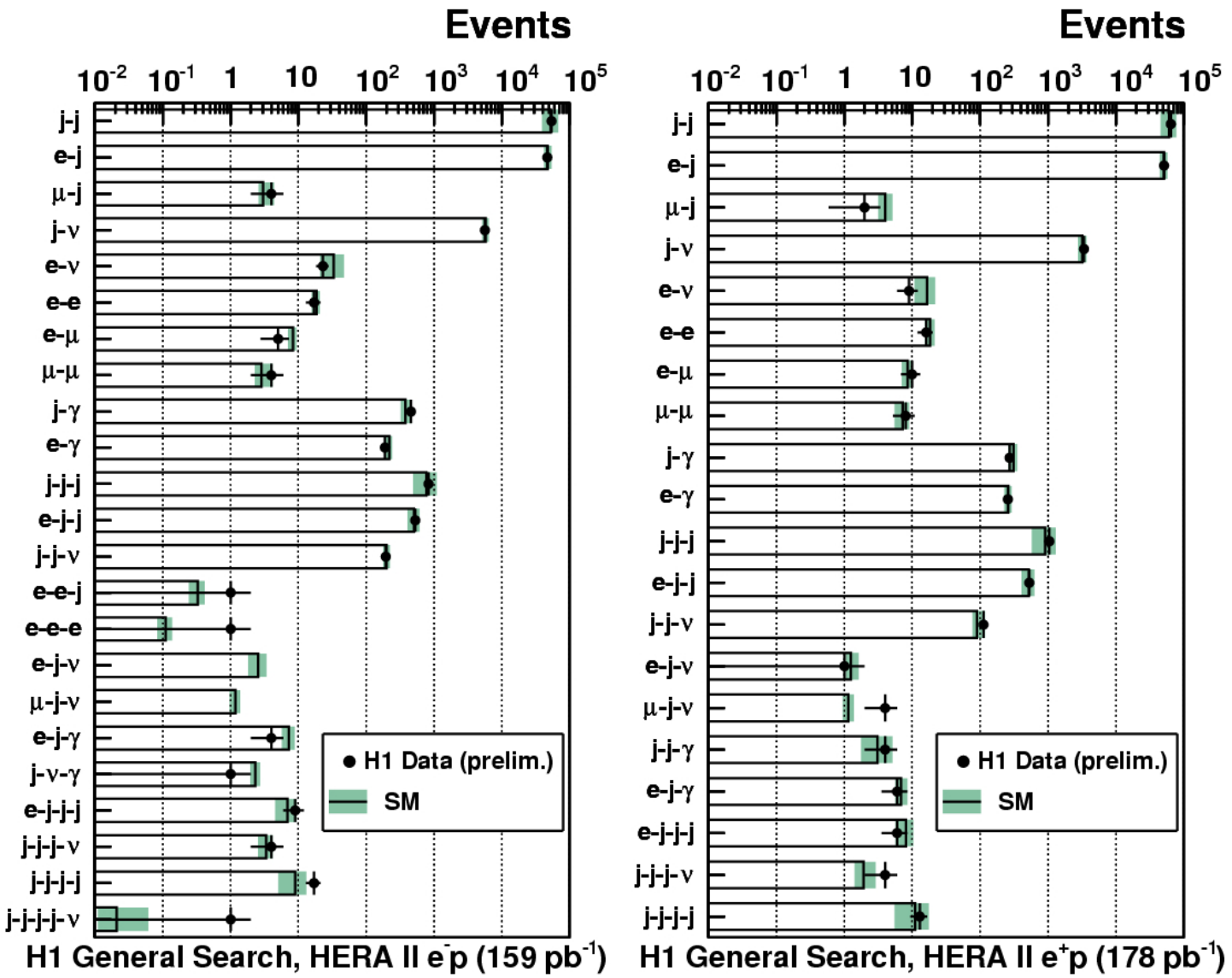
General Searches

- idea: new particles have typically large mass

➔ final state should contain particles with large transverse momentum from the decay

  - jets
  - electrons
  - muons
  - photons
  - neutrinos (missing transverse momentum)

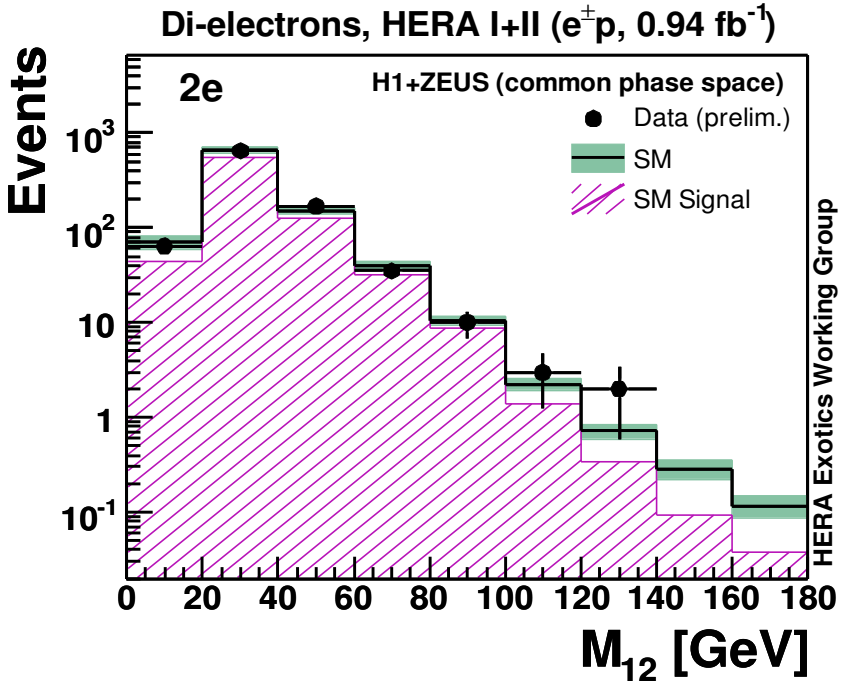
General Searches

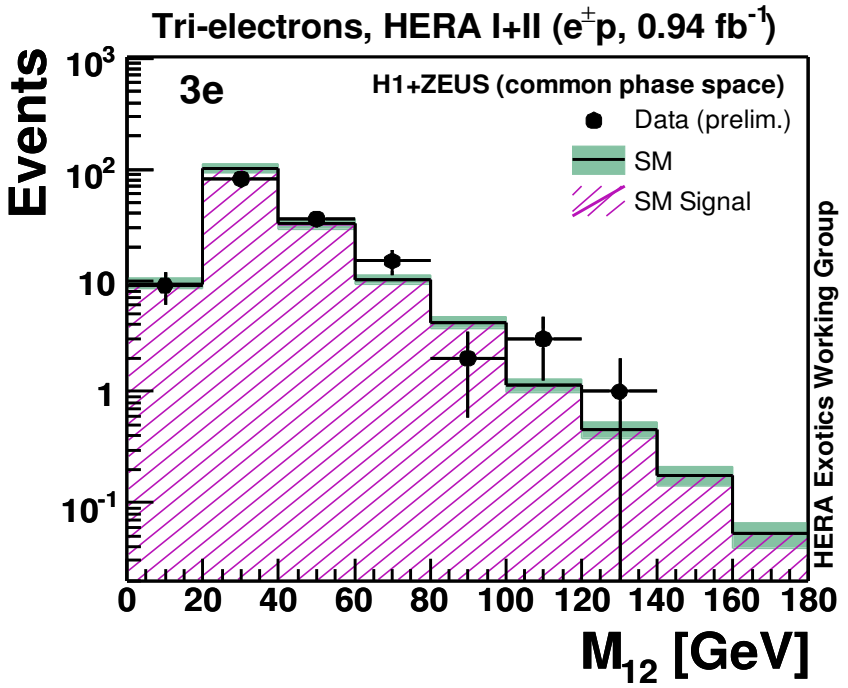


every channel in reasonable agreement with the standard model

Multi-Leptons

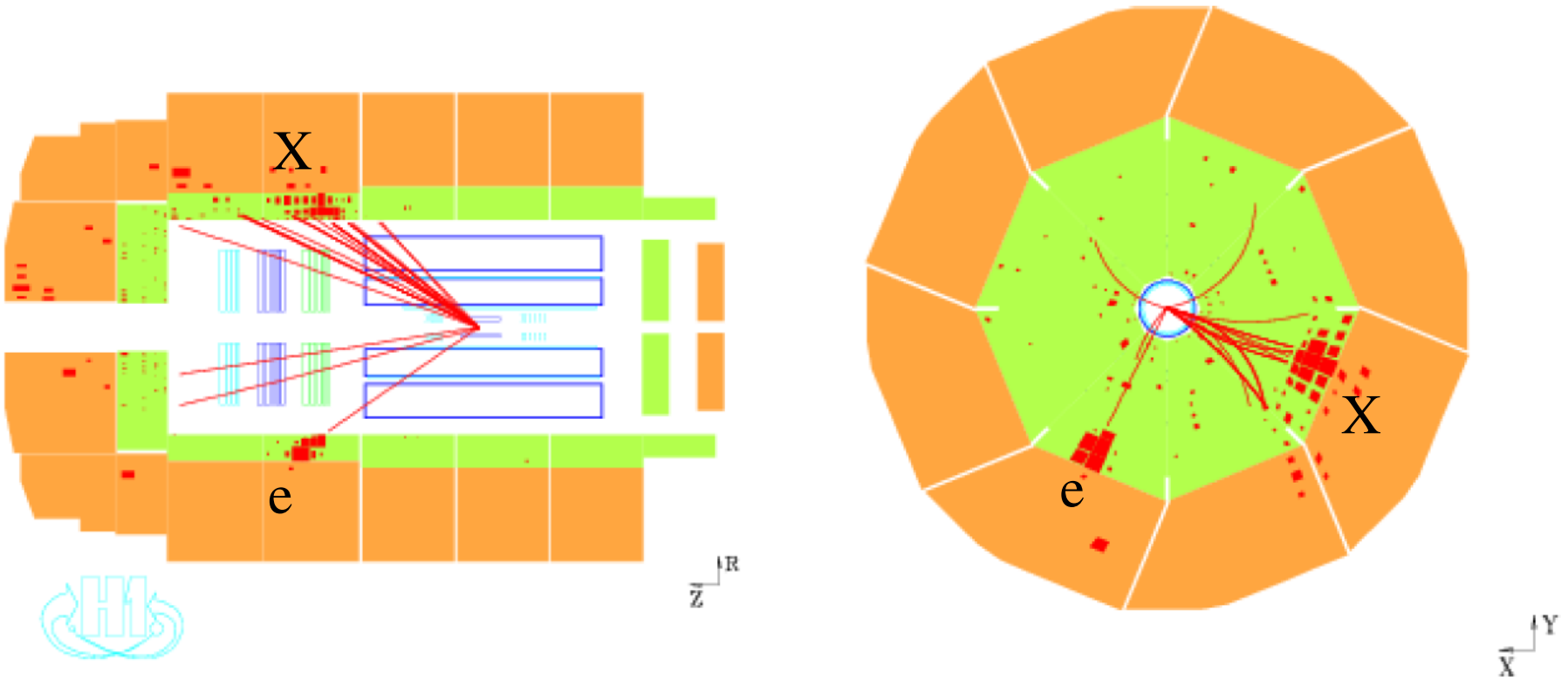
in HERA1 a small excess of di- and tri-electron events at high transverse momenta observed by H1





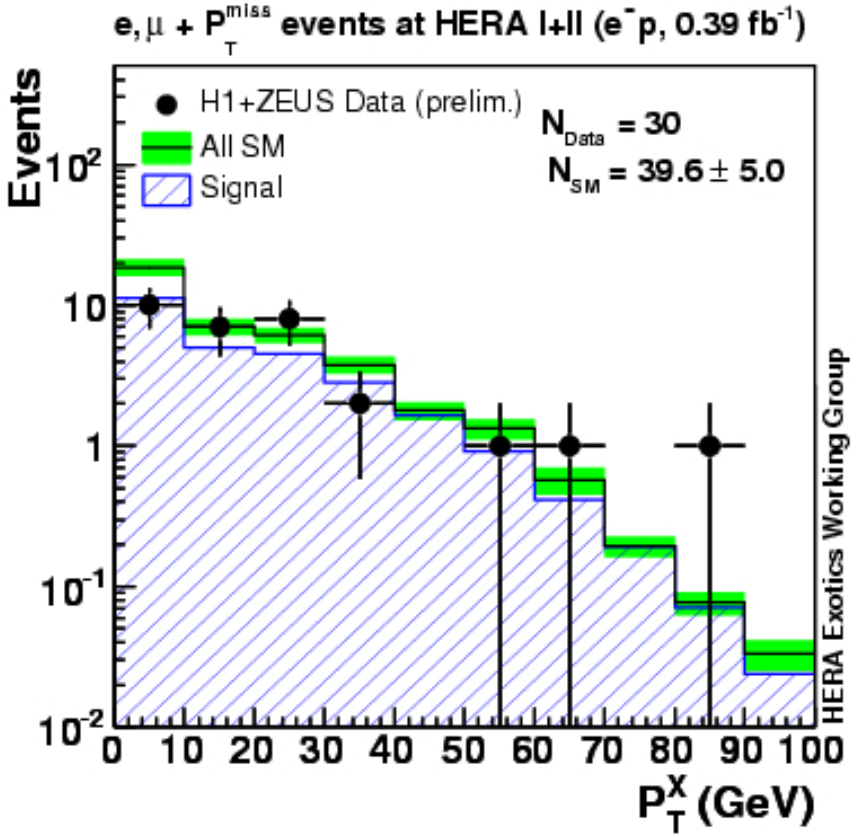
HERA2 data show no significant excess

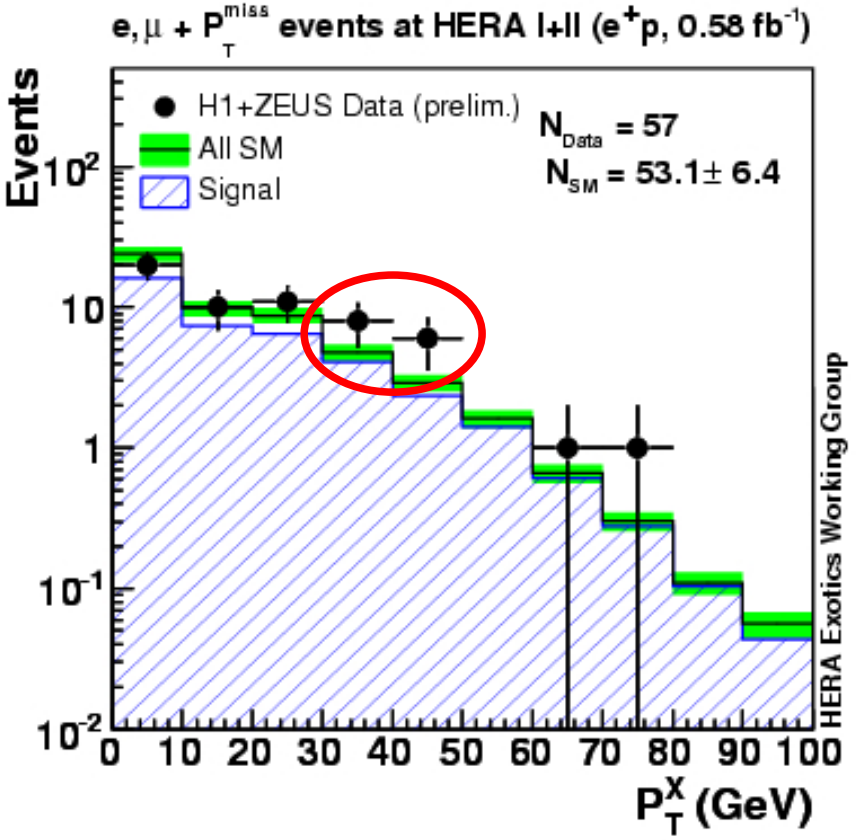
Isolated Leptons and Missing P_T



- spectacular events
- excess in HERA1 data at large transverse momenta of the hadronic system (P_T^X) seen by H1

Isolated Leptons and Missing P_T





- no excess in e^- data
- what about e^+?

Isolated Leptons and Missing P_T

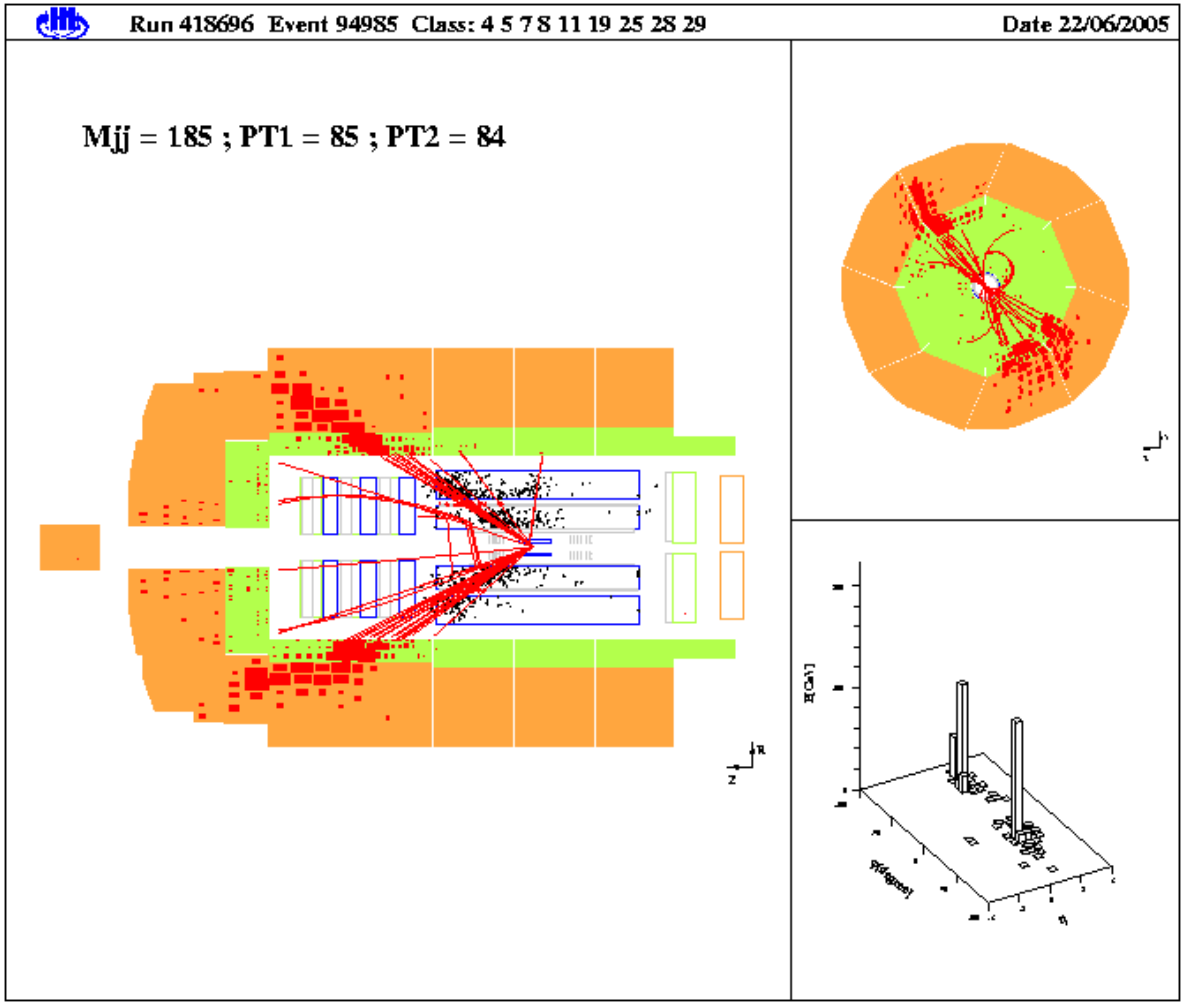
H1+ZEUS Preliminary l+P_T^{miss} events at HERA I+II		Electron obs./exp. (Signal contribution)	Muon obs./exp. (Signal contribution)	Combined obs./exp. (Signal contribution)
1994-2007 e^+p	Full Sample	39 / 41.3 ± 5.0 (70%)	18 / 11.8 ± 1.6 (85%)	57 / 53.1 ± 6.4 (73%)
0.58 fb^{-1}	$P_T^X > 25$ GeV	12 / 7.4 ± 1.0 (78%)	11 / 7.2 ± 1.0 (85%)	23 / 14.6 ± 1.9 (81%)
1998-2006 e^-p	Full Sample	25 / 31.6 ± 4.1 (63%)	5 / 8.0 ± 1.1 (86%)	30 / 39.6 ± 5.0 (68%)
0.39 fb^{-1}	$P_T^X > 25$ GeV	4 / 6.0 ± 0.8 (67%)	2 / 4.8 ± 0.7 (87%)	6 / 10.6 ± 1.4 (76%)
1994-2007 $e^\pm p$	Full Sample	64 / 72.9 ± 8.9 (67%)	23 / 19.9 ± 2.6 (85%)	87 / 92.7 ± 11.2 (71%)
0.97 fb^{-1}	$P_T^X > 25$ GeV	16 / 13.3 ± 1.7 (73%)	13 / 12.0 ± 1.6 (86%)	29 / 25.3 ± 3.2 (79%)

- H1+ZEUS combined: 1.8 σ excess
- H1 alone: 2.9 σ excess

?

Jet Physics & the Strong Coupling α_S

What are Jets?



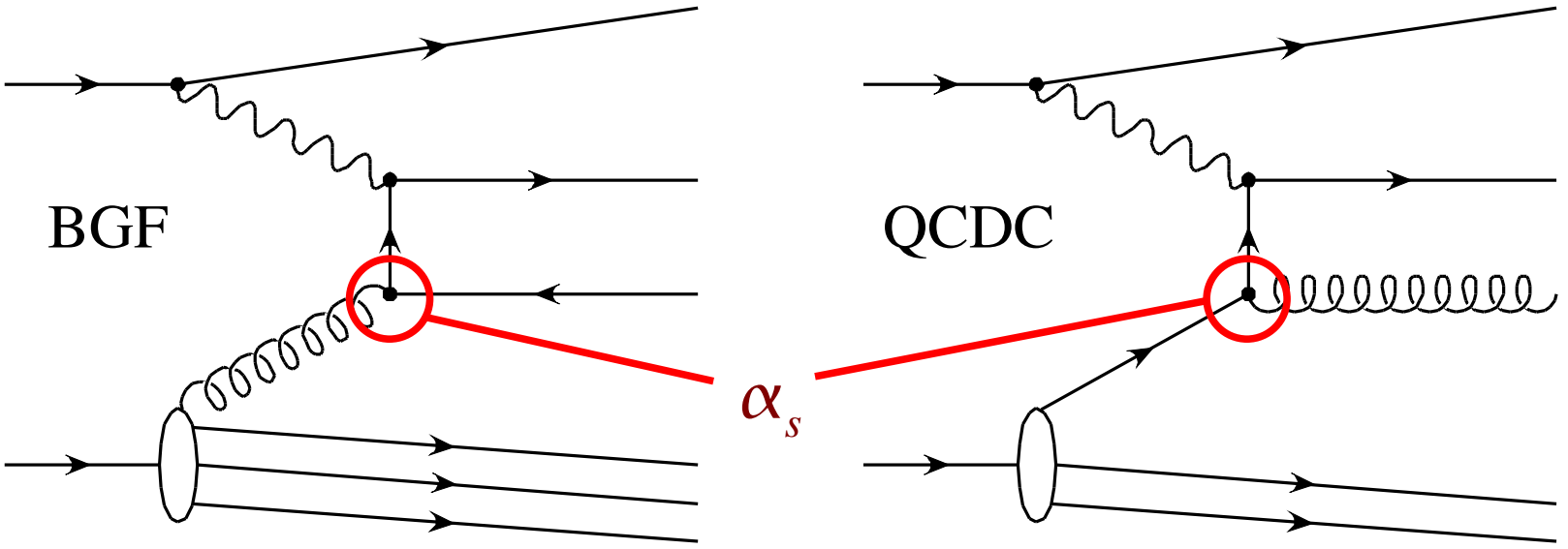
- jets are narrow bundles of hadrons originating from quarks or gluons
- can be used to study QCD and the strong coupling

How Are Jets Produced?

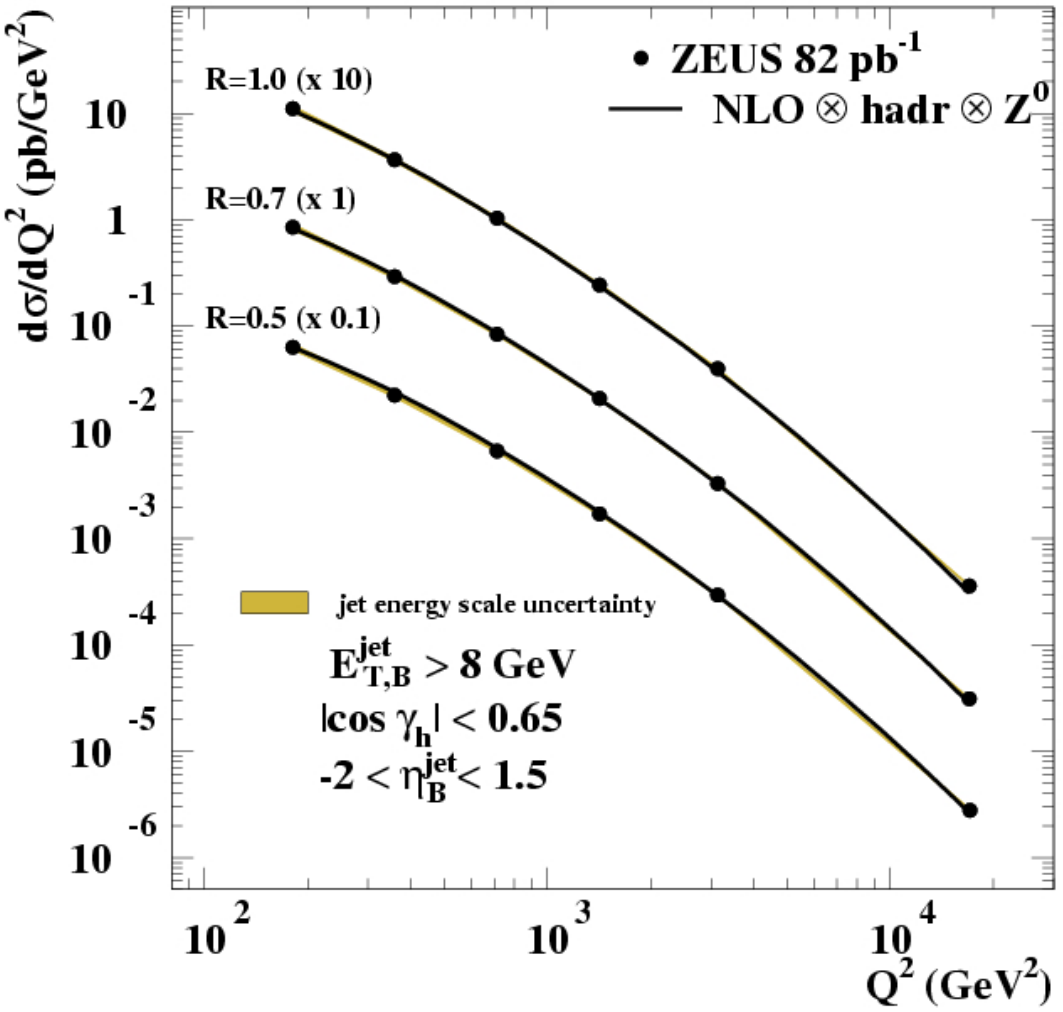
- do analysis in a frame where photon and proton collide head-on (e.g. Breit frame)

➔ LO DIS cannot produce transverse momentum

➔ jets with transverse momentum can originate from boson-gluon fusion (BGF) or QCD-Compton (QCDC) processes

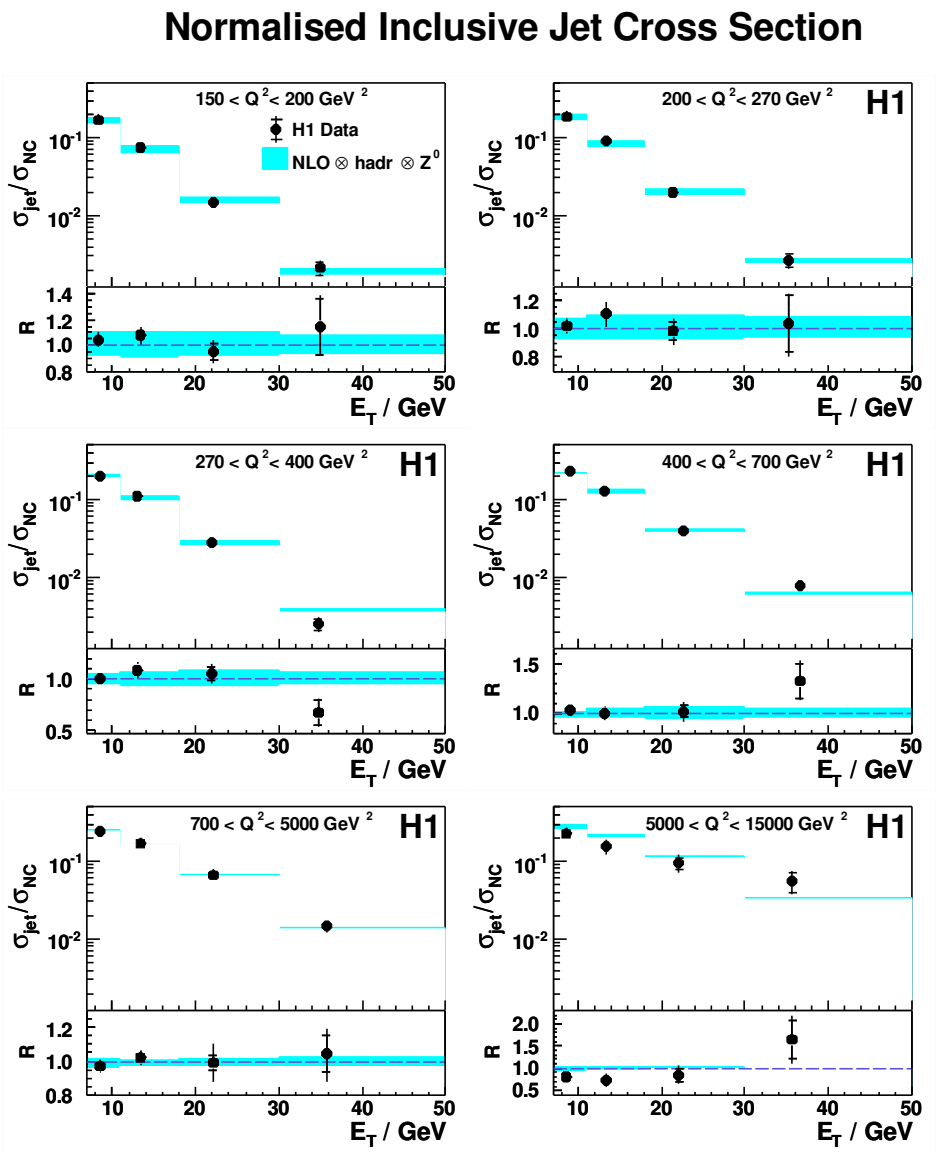


Jet Cross Sections



- theory curve:
  - NLO QCD calculation
  - PDFs
  - α_s
  - hadronisation
- very good agreement of theory and data
- uncertainty on PDF and theory input leads to uncertainty on α_s

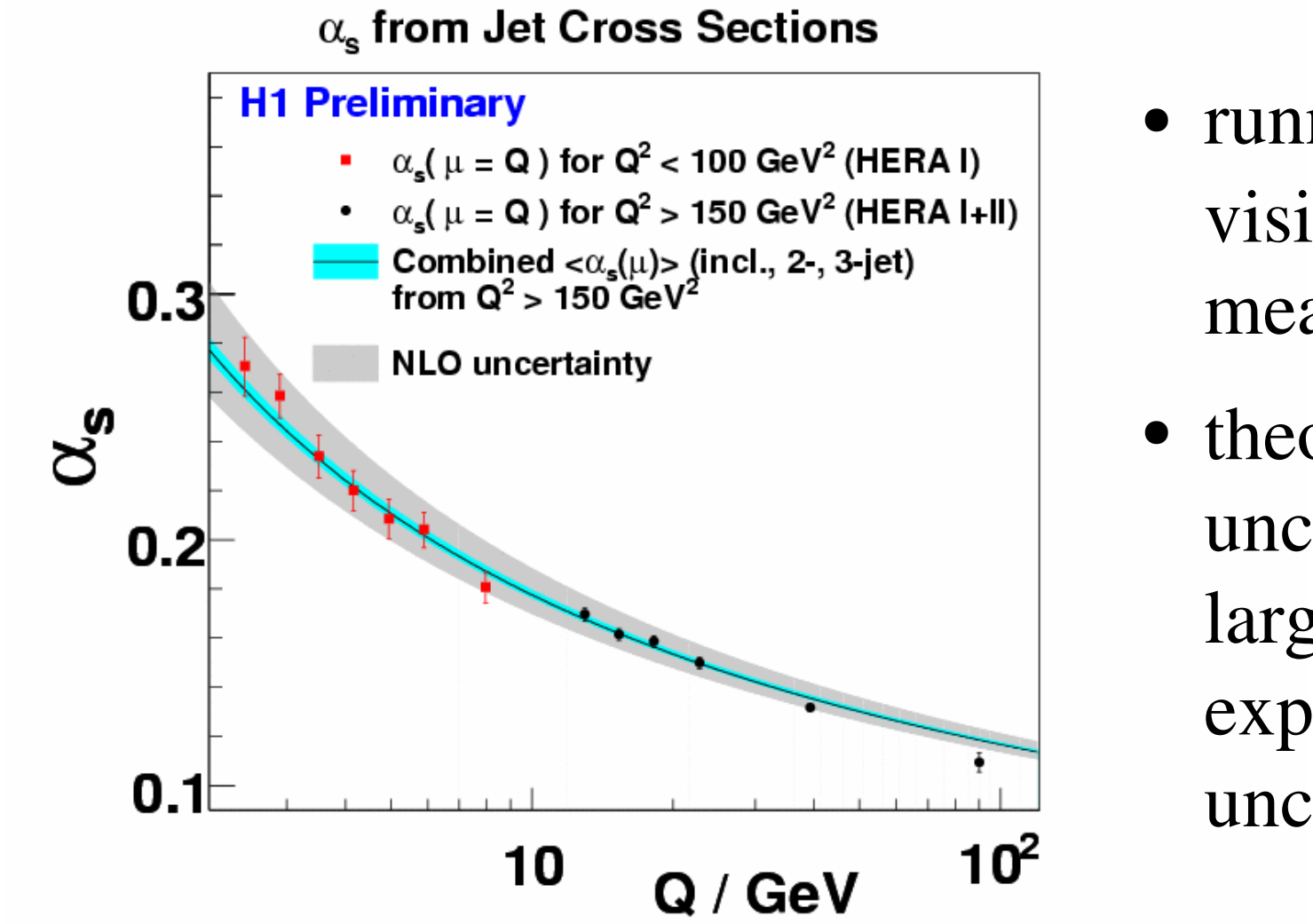
Jet Cross Sections



ratio of jet cross section to inclusive cross section has reduced uncertainties

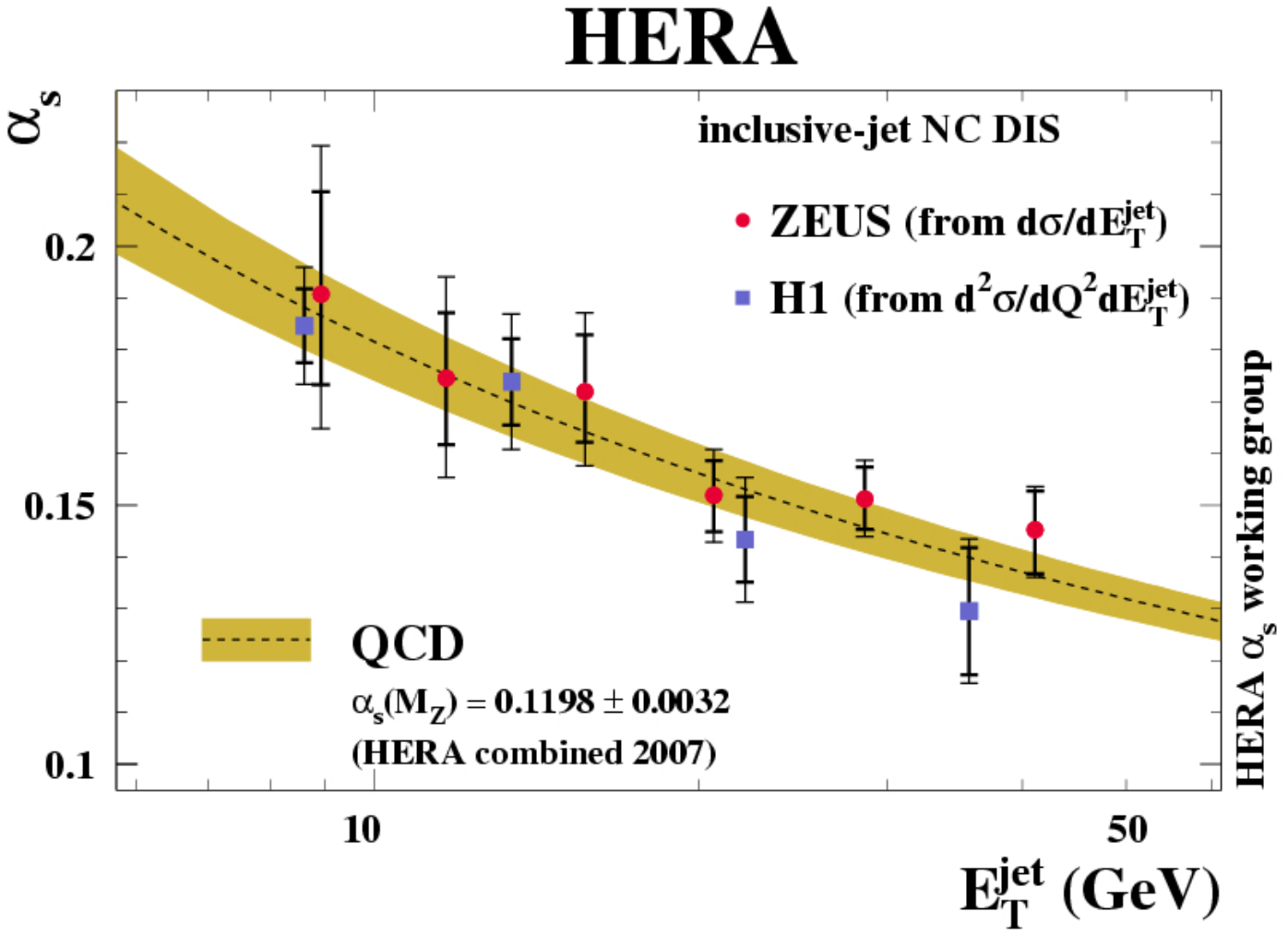
- systematic
- PDFs

α_S from Jets



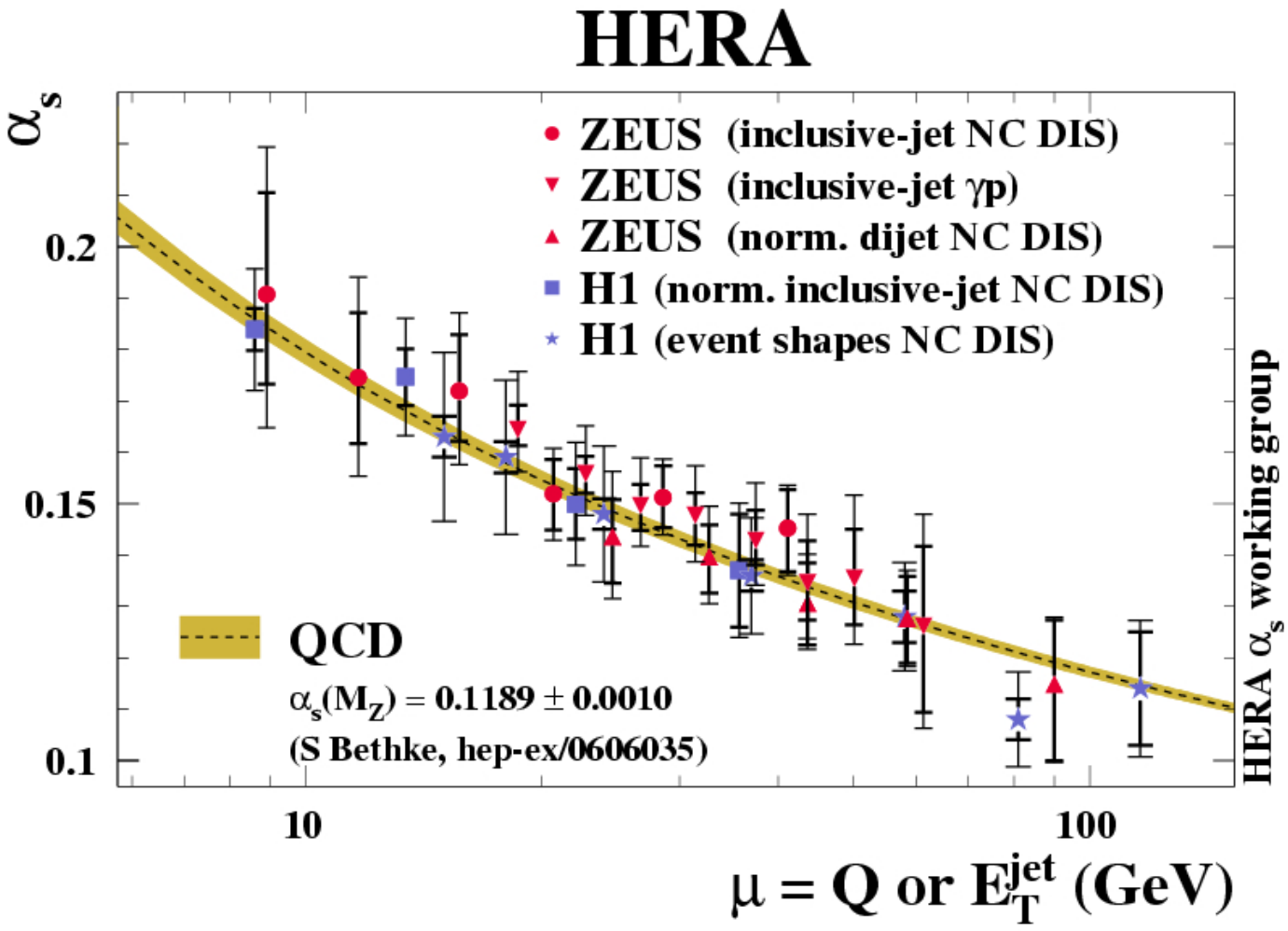
- running of α_S visible in one measurement
- theory uncertainties larger than experimental uncertainties

Running of α_S



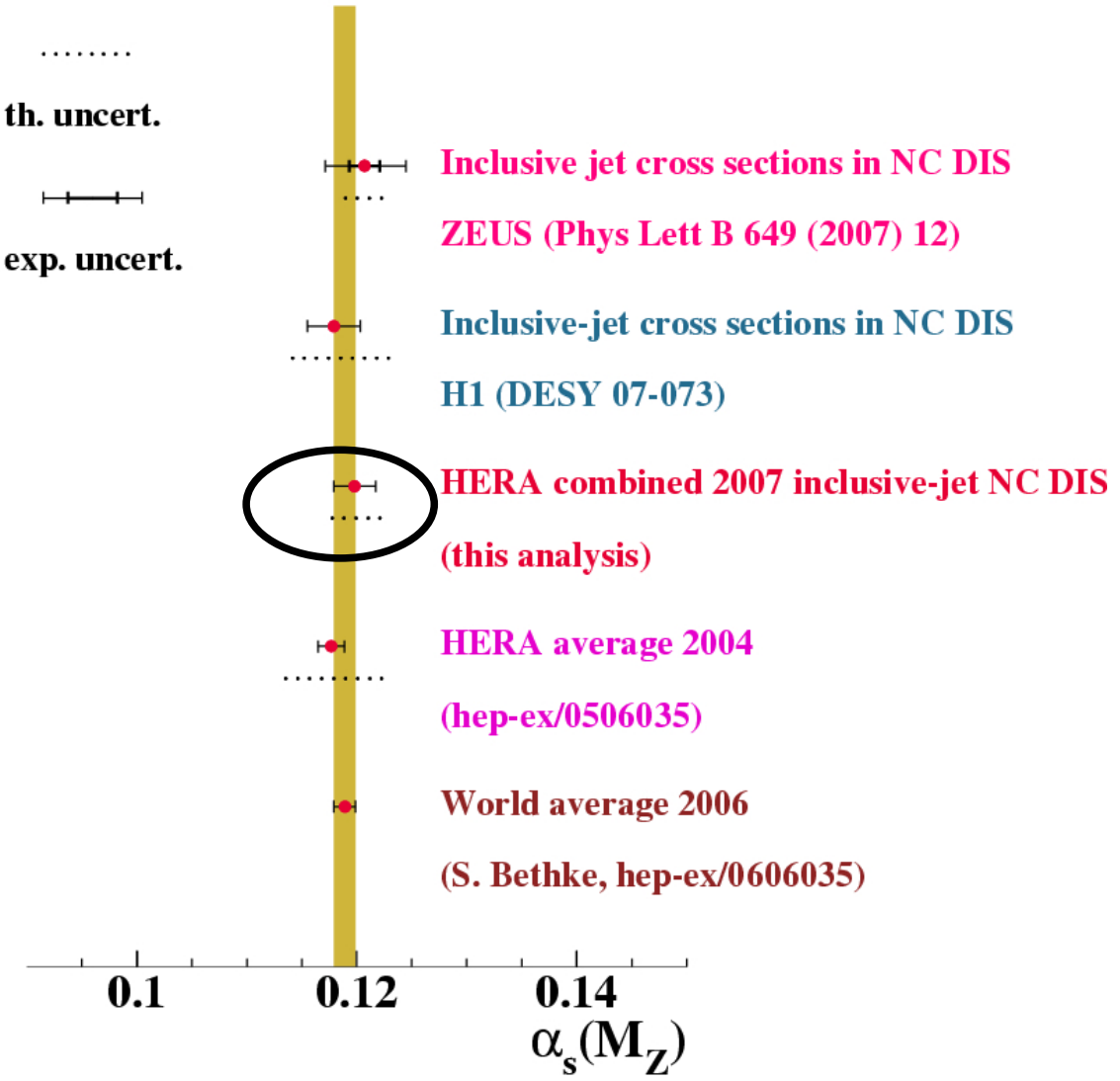
combine α_S measurements with smallest errors in fit

Running of α_s



comparison with other HERA measurements

$\alpha_s(M_Z)$



HERA measurements often dominated by systematic and theoretical uncertainties

→ use only selected datasets to extract α_s with minimal uncertainty

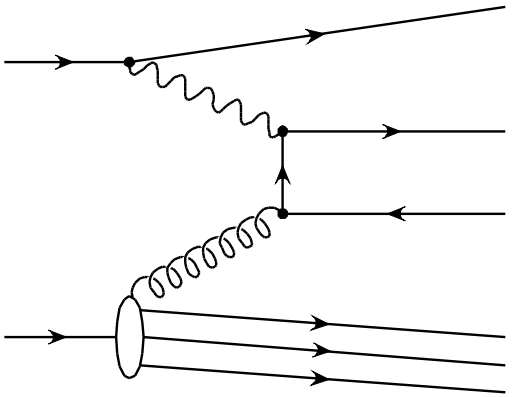
→ HERA value very competitive

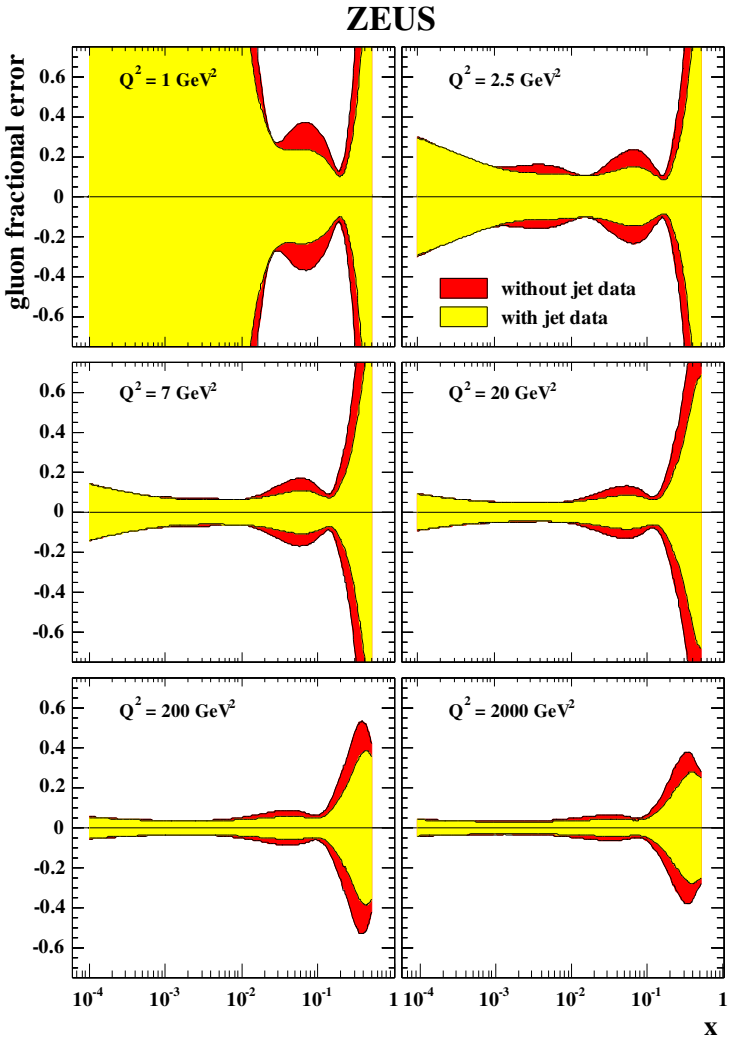
Improved Parton Densities

- F_2 is only indirectly sensitive to the gluon

➔ global fits (MRST, CTEQ) use Tevatron jet data

➔ alternative: use HERA (di-)jet data

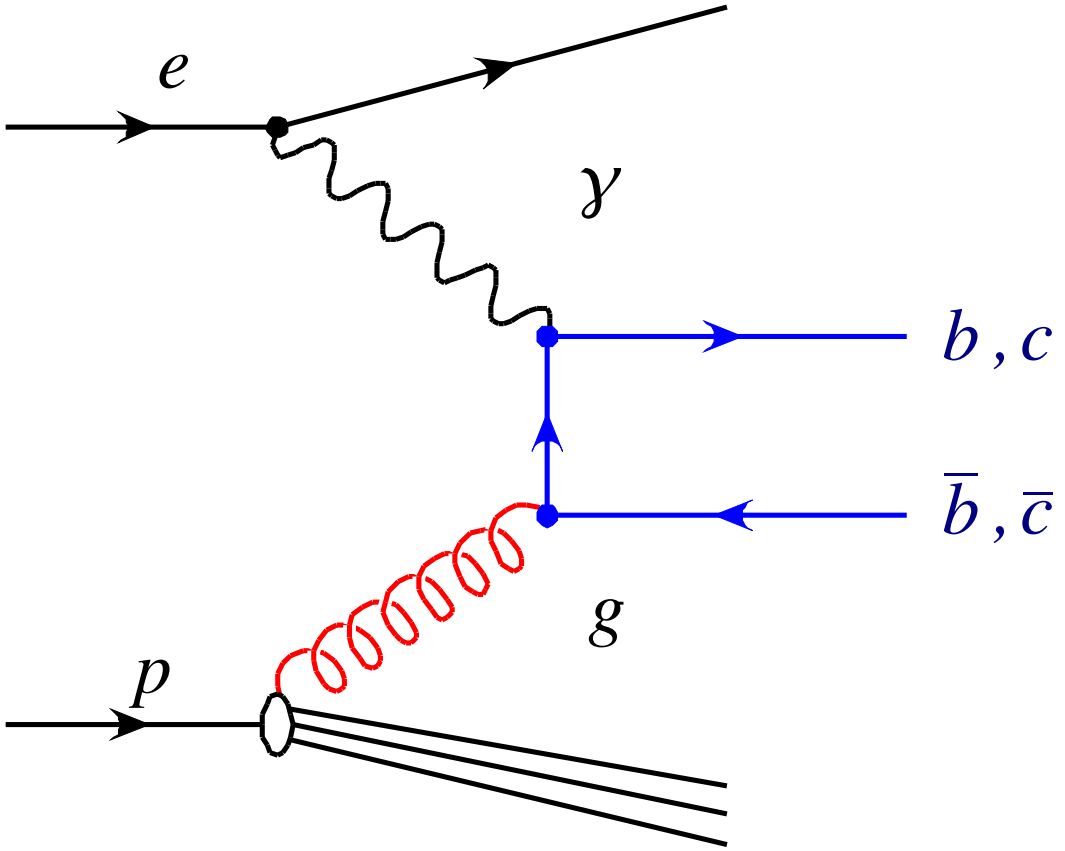




improvement at medium to large x

Heavy Quarks

Production of Heavy Quarks



predominantly via boson gluon fusion

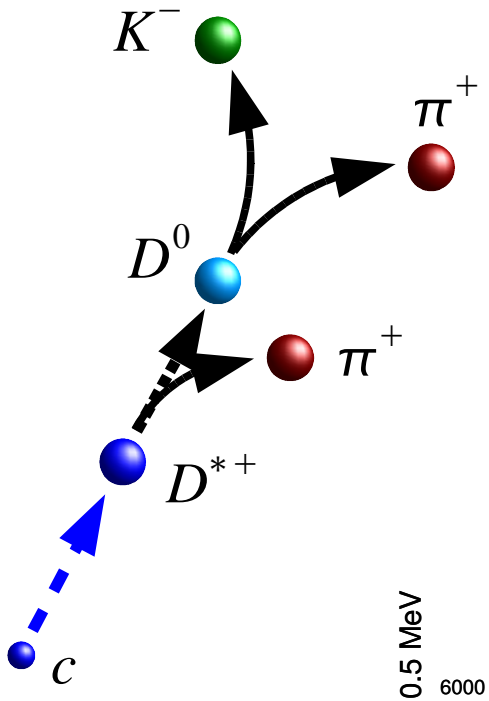
large quark mass allows pQCD calculations

directly sensitive to gluon density in the proton

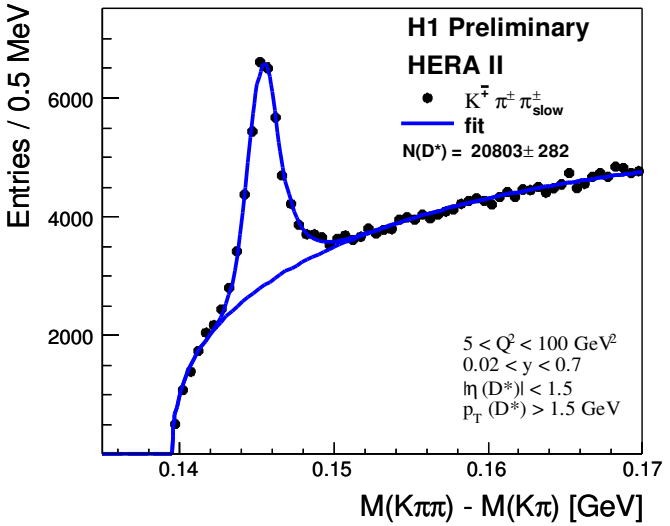
heavy quark contribution to structure function

$$\frac{d^2\sigma^{b\bar{b}}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+ \left[F_2^{b\bar{b}}(x,Q^2) - \frac{y^2}{Y_+} F_L^{b\bar{b}}(x,Q^2) \right]$$

Reconstruction of *charm* Quarks

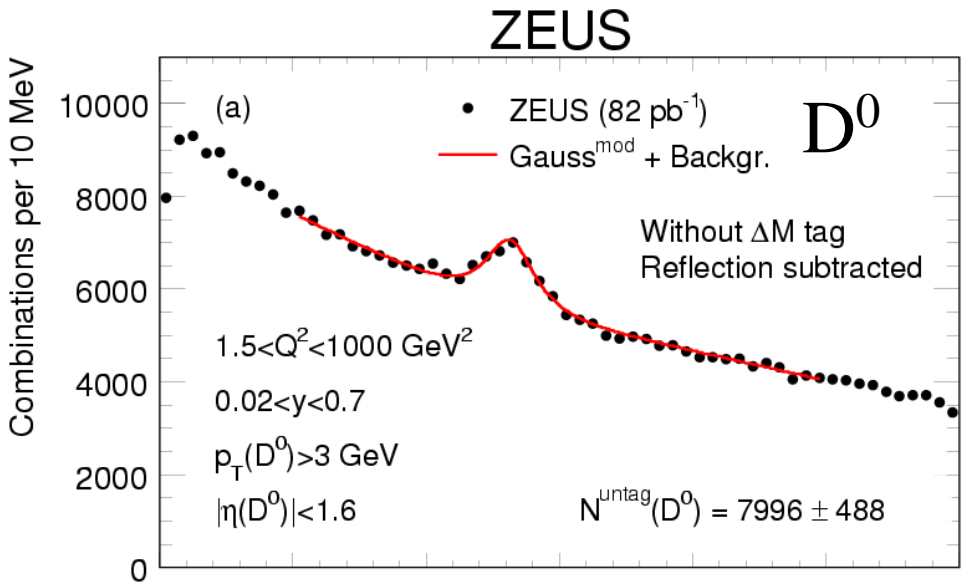


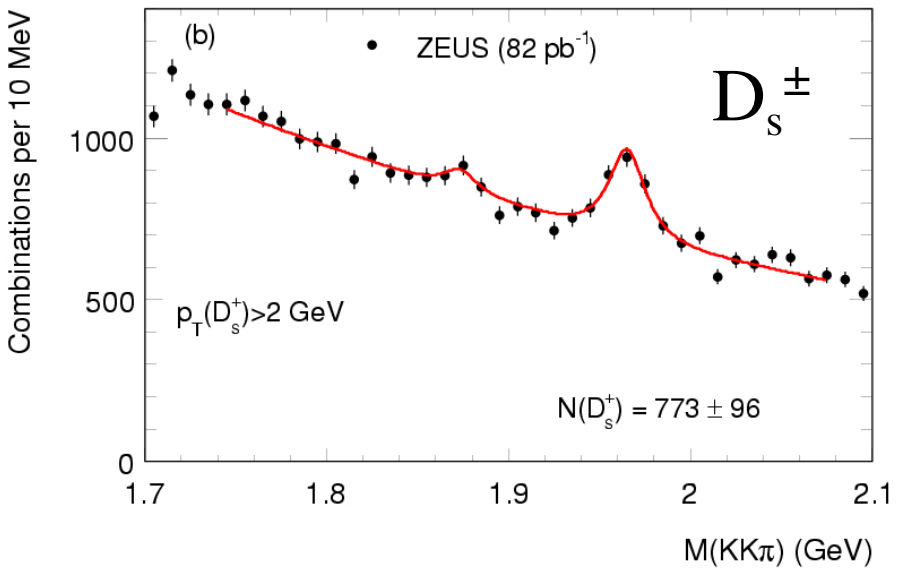
- fragmentation $c \to D^*$ meson (25,5%)
- „golden decay“ (2,6%)
  $D^{*+} \to D^0 \pi_s^+ \to K^- \pi^+ \pi_s^+$
  - only charged decay particles
  - small mass difference $\Delta M = m(D^*) - m(D^0)$

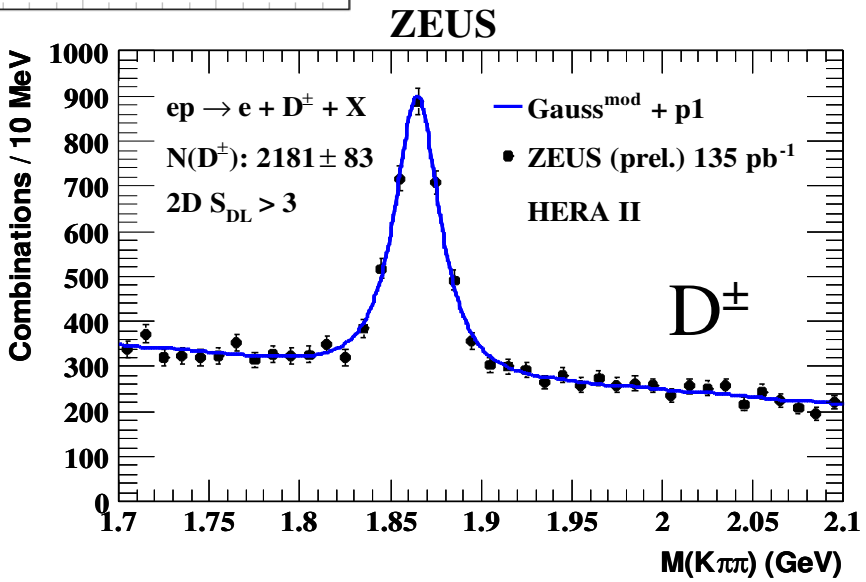


- small momentum of the „slow“ π_s
- good experimental resolution (~1 MeV)

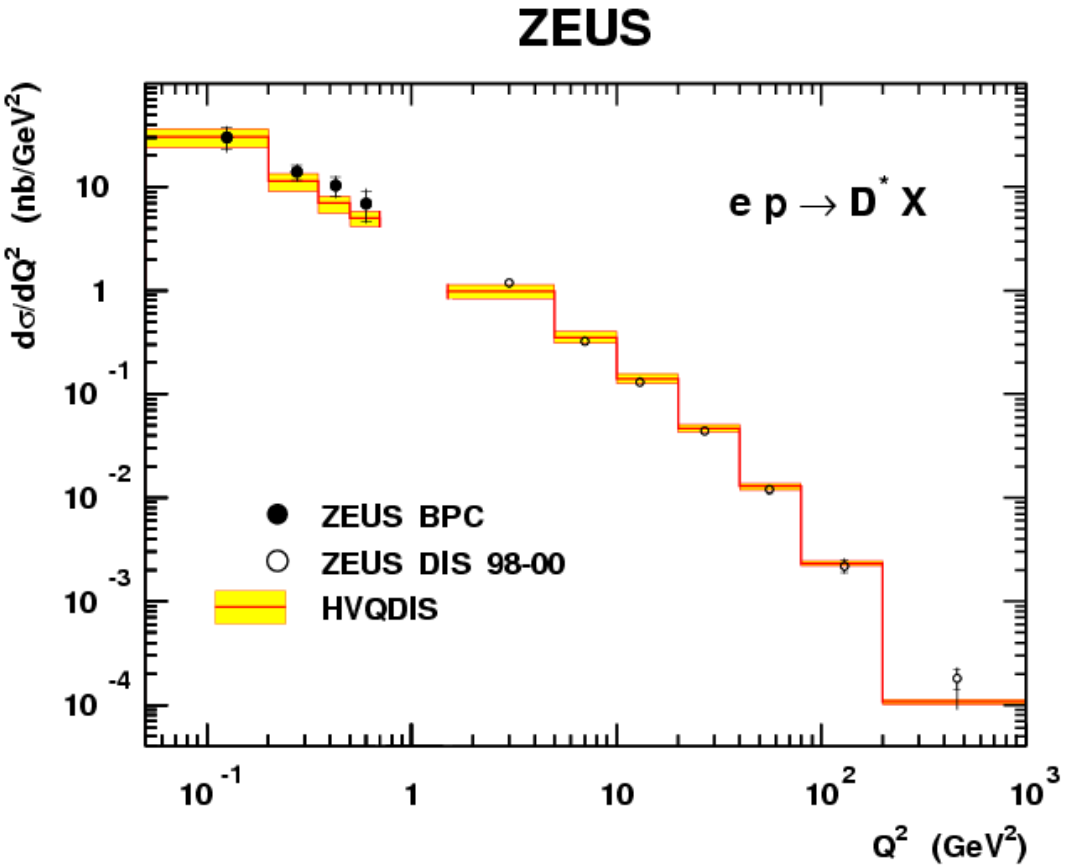
More *charm* Signals







D* Cross Section

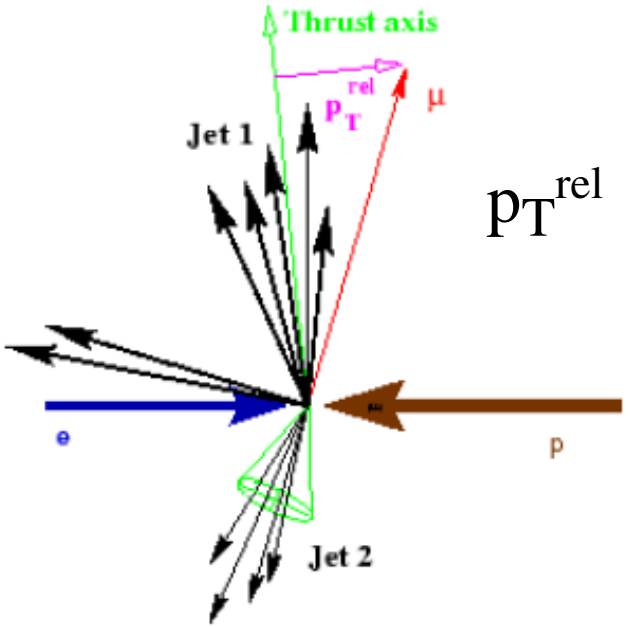


good description by NLO pQCD calculation (HVQDIS) in full measured Q^2 range (> 4 orders of magnitude)

PDF: ZEUS PDF extracted from inclusive DIS

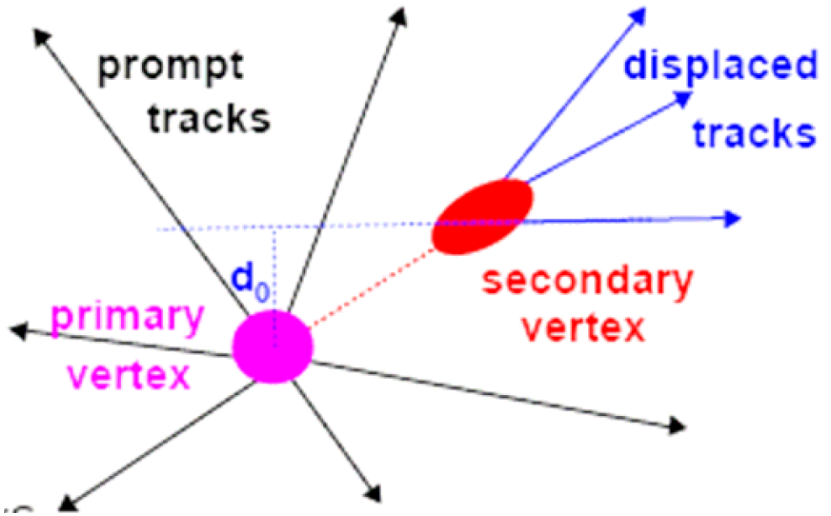
Tagging of *beauty* Quarks

- large transverse momenta due to large mass
- semileptonic decay
- long lifetime (*beauty* ~500 μm, *charm* ~100-300 μm)

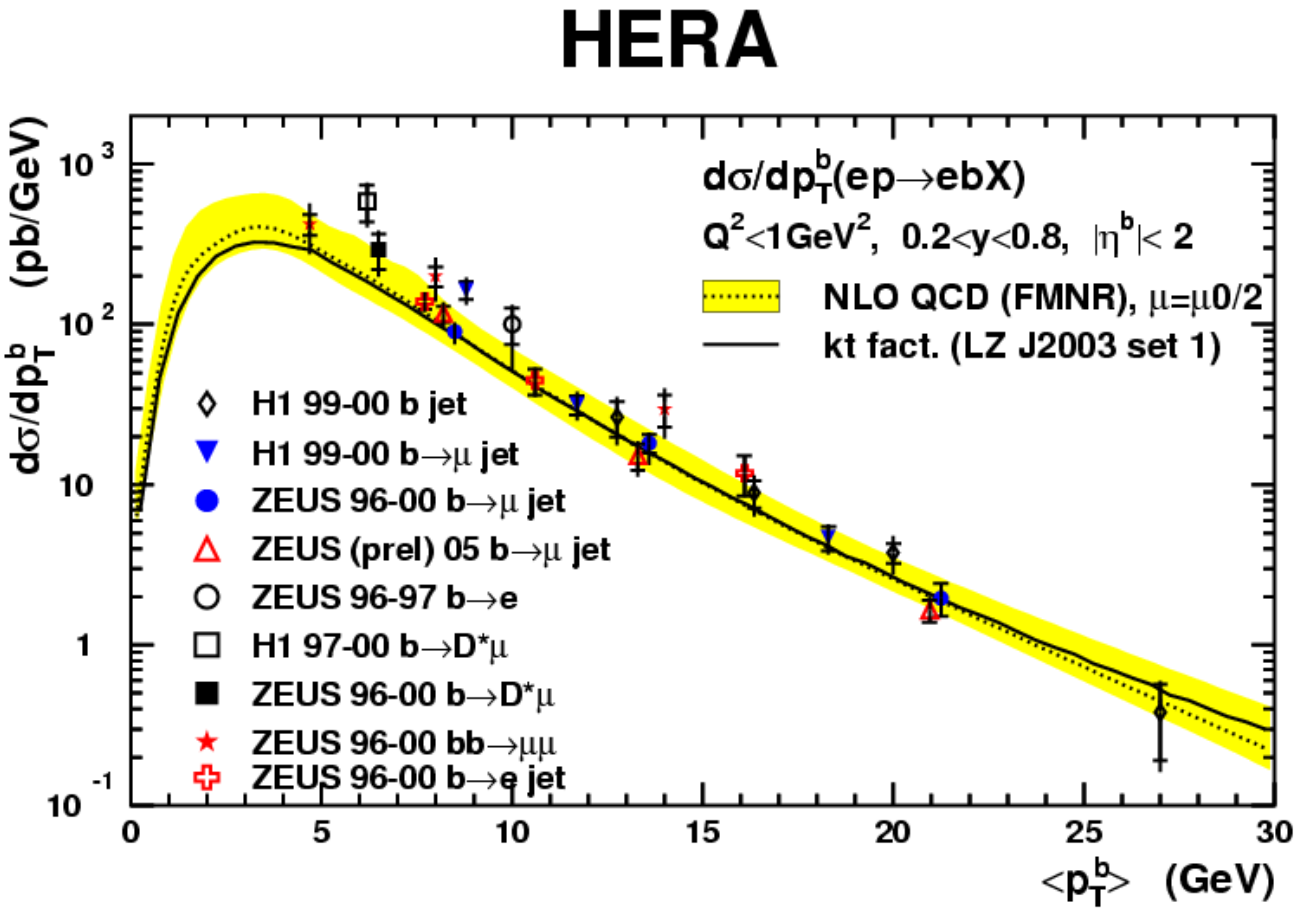


p_T^{rel}

lifetime tagging



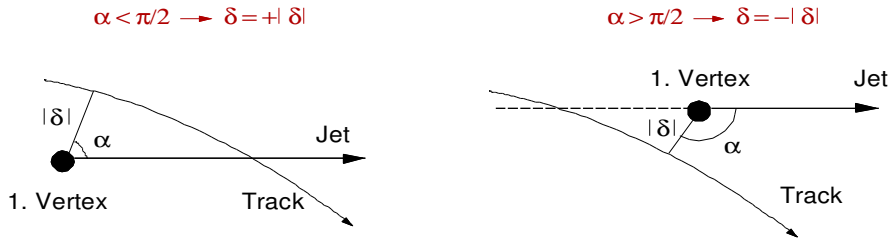
beauty Cross Section Results



some data higher than NLO QCD theory,
but good agreement for the most precise data

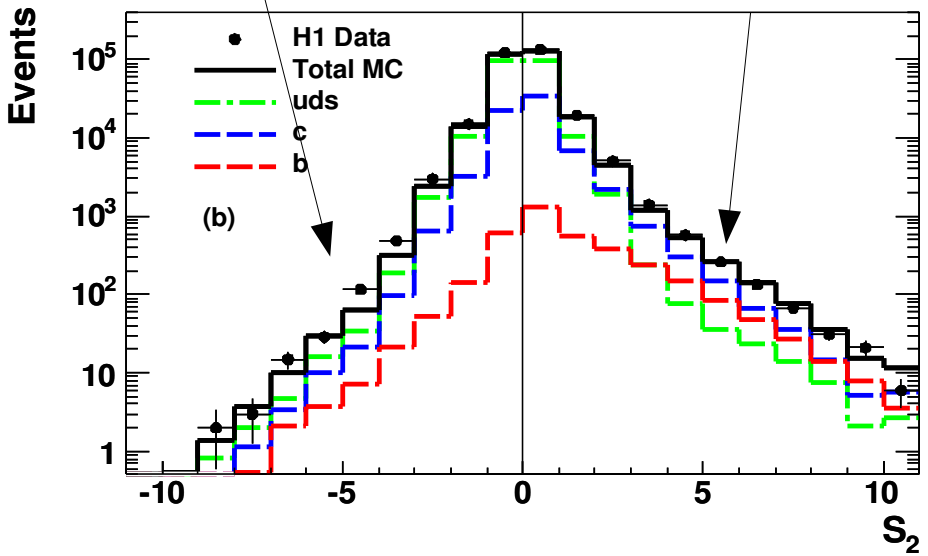
Inclusive Lifetime Tagging

signed impact parameter δ



resolution

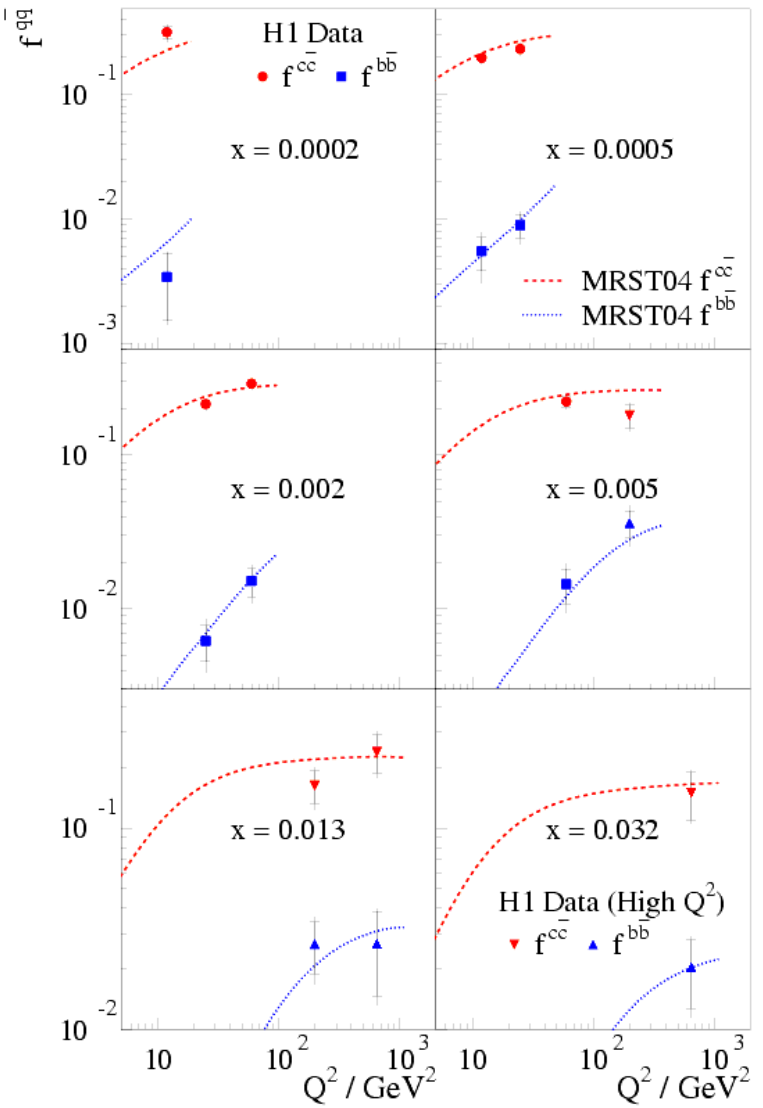
resolution & lifetime



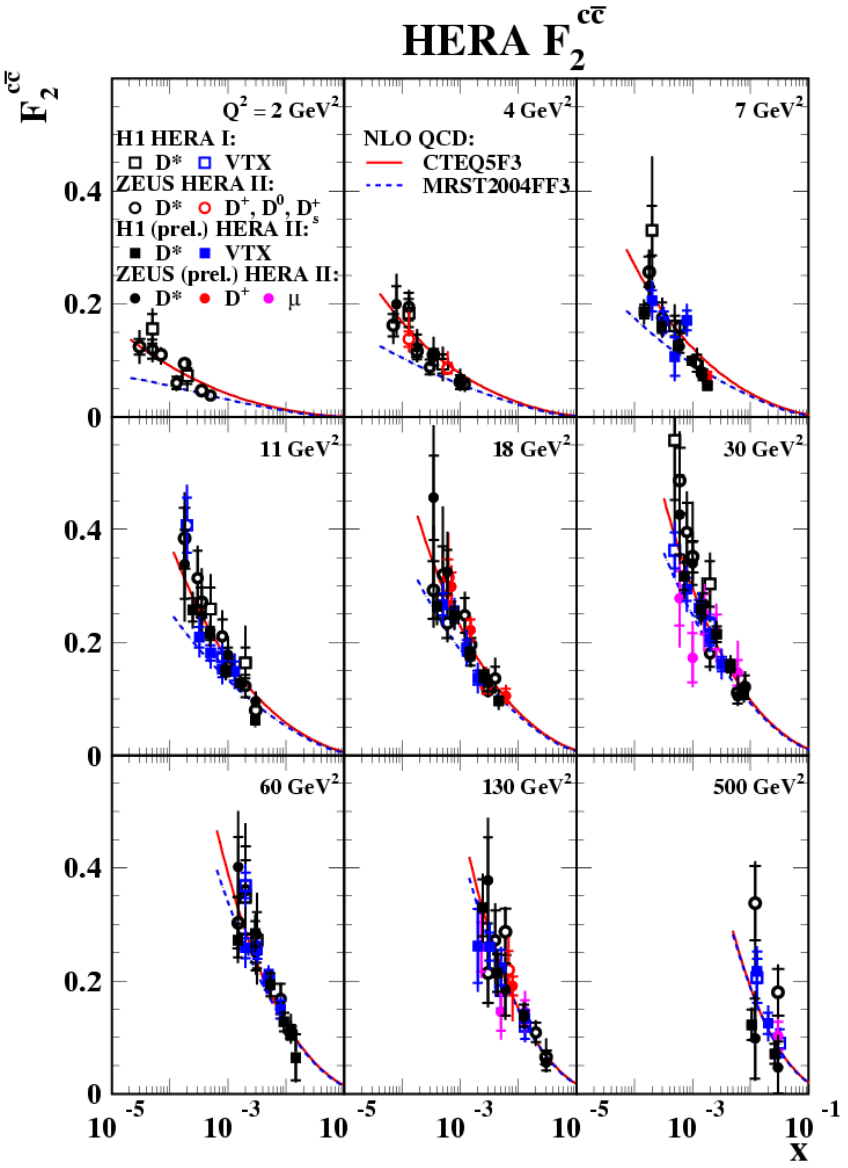
- both experiments have silicon vertex detectors
- inclusive method: use all tracks
- study significance of the (signed) impact parameter: $S = \delta / \sigma(\delta)$
- allows separation of beauty, charm and light quarks

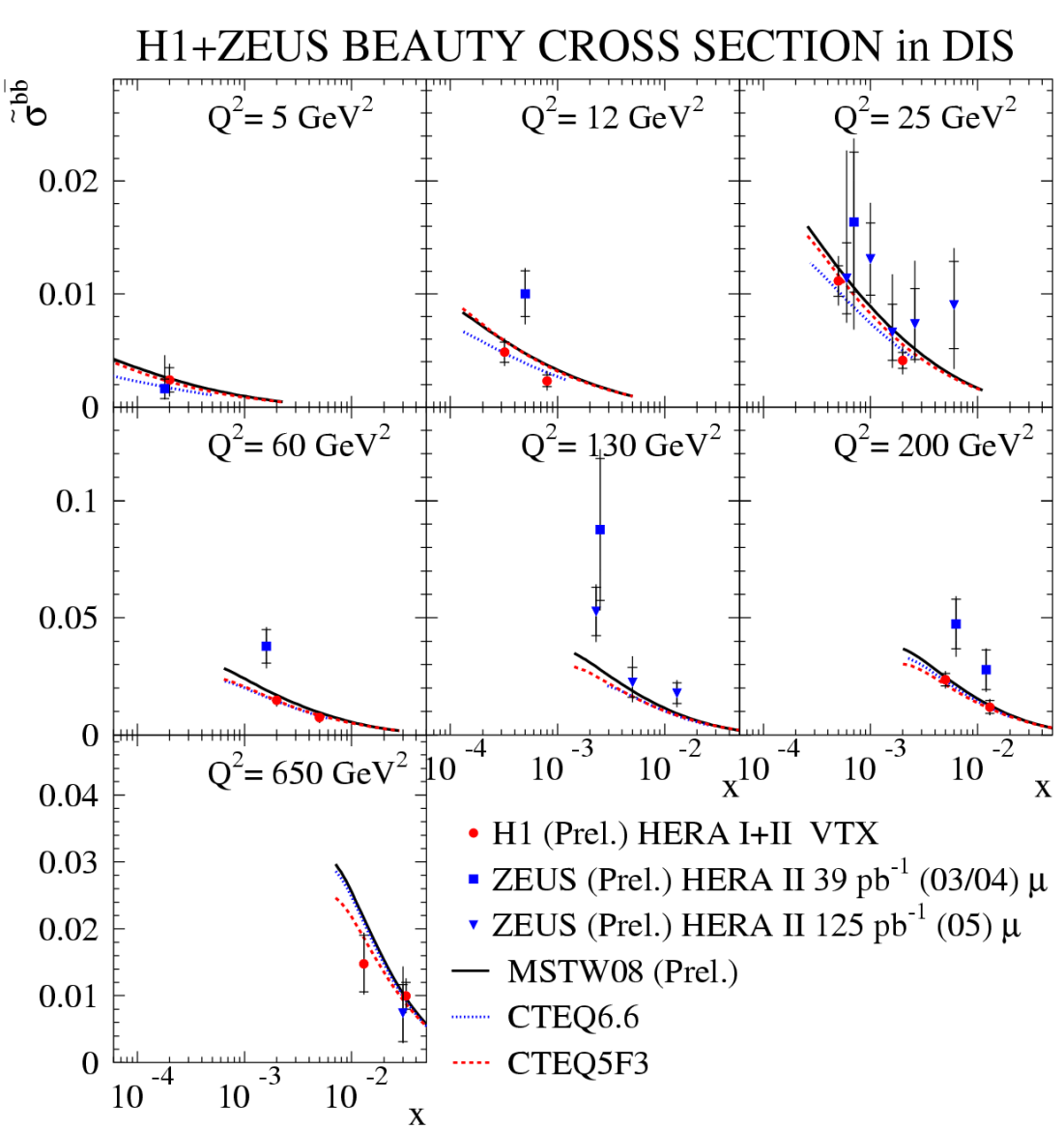
Contribution to the Cross Section

- large charm fraction (up to ~30%)
- small beauty fraction (‰ to few %)
- charm and beauty thresholds
- reasonable description by theory



Contribution to the Structure Function

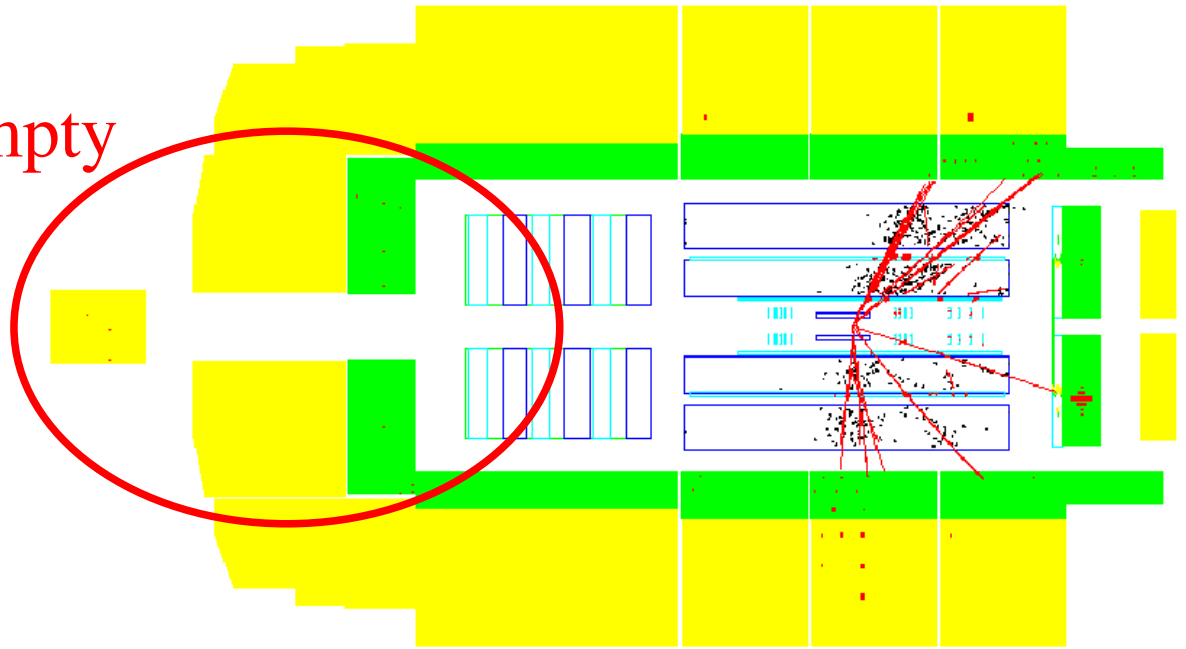




Diffraction

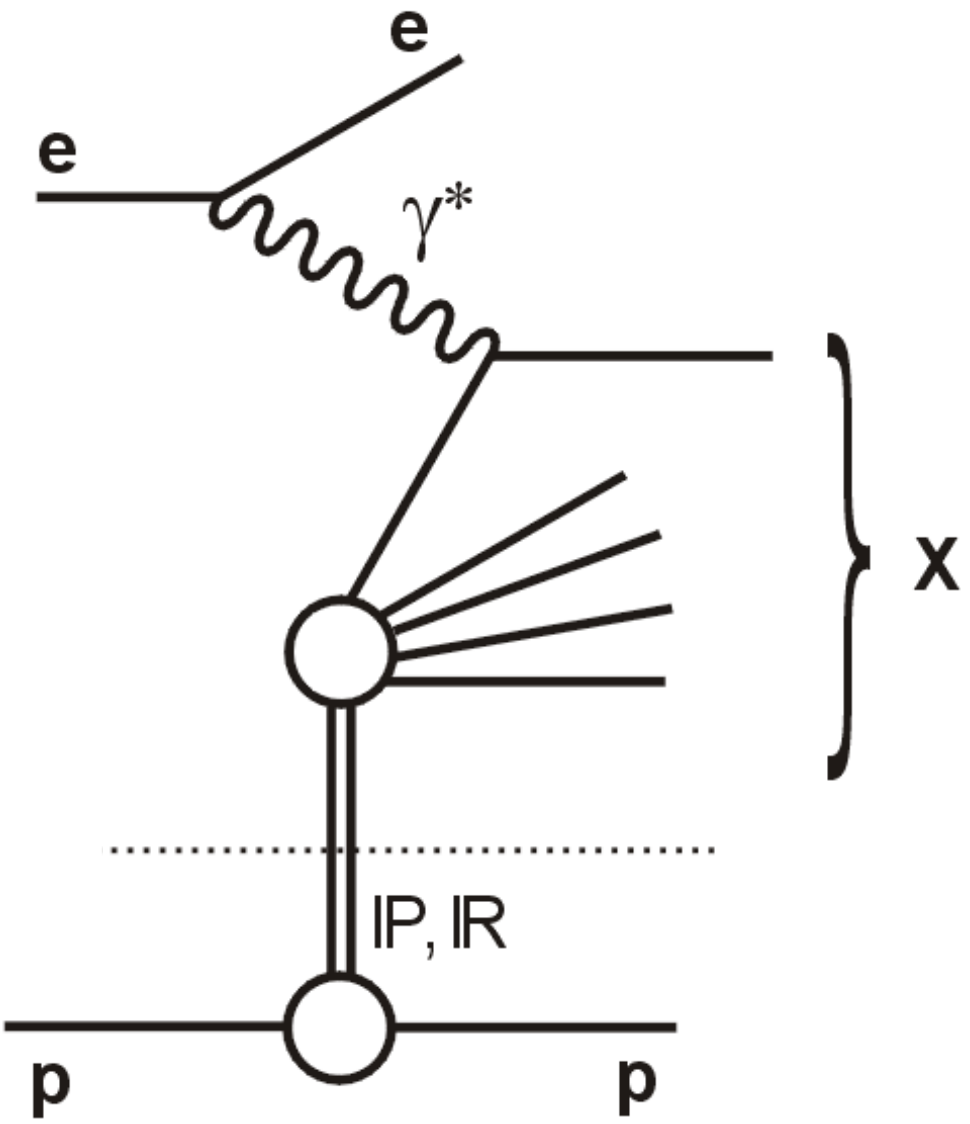
What is Diffraction?

- in general: in DIS events the proton breaks up
- in diffraction: the proton stays intact
  (but nevertheless $W>M_P$)



surprise: ~10% of all events at HERA are diffractive!

Diffraction

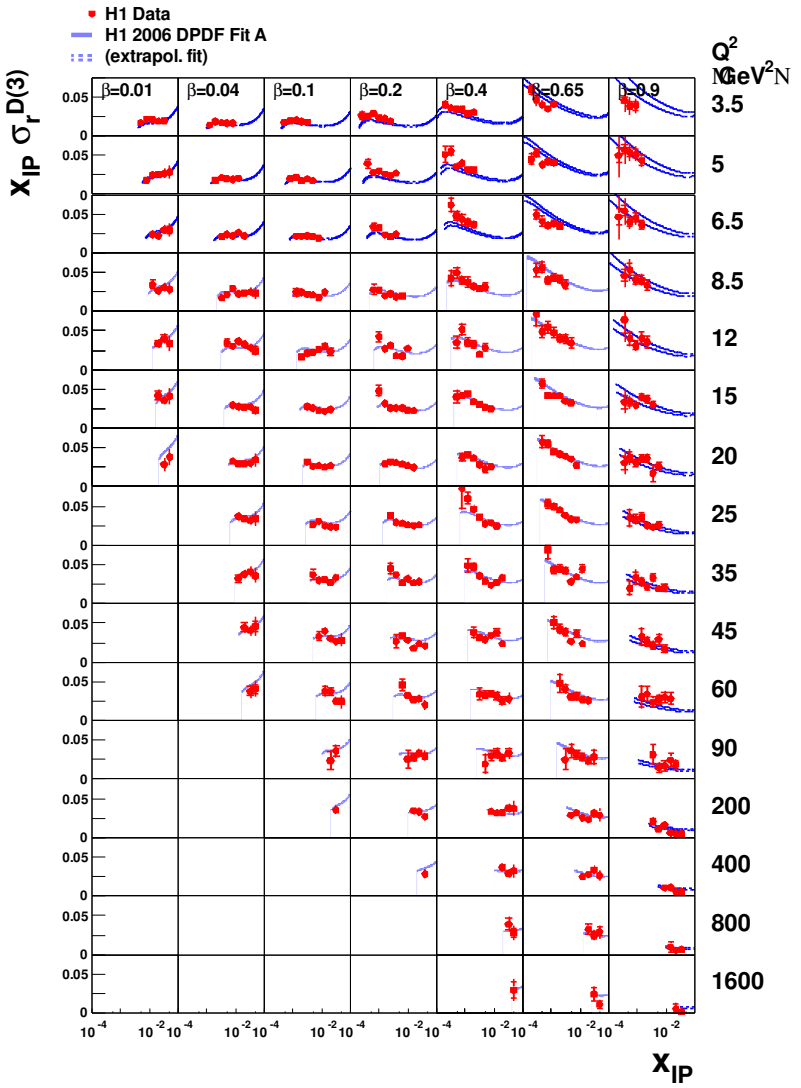


- idea: interaction between photon and proton by a „Pomeron“
  - colourless
  - already used to describe low energy hadron-hadron scattering
  - no particle!

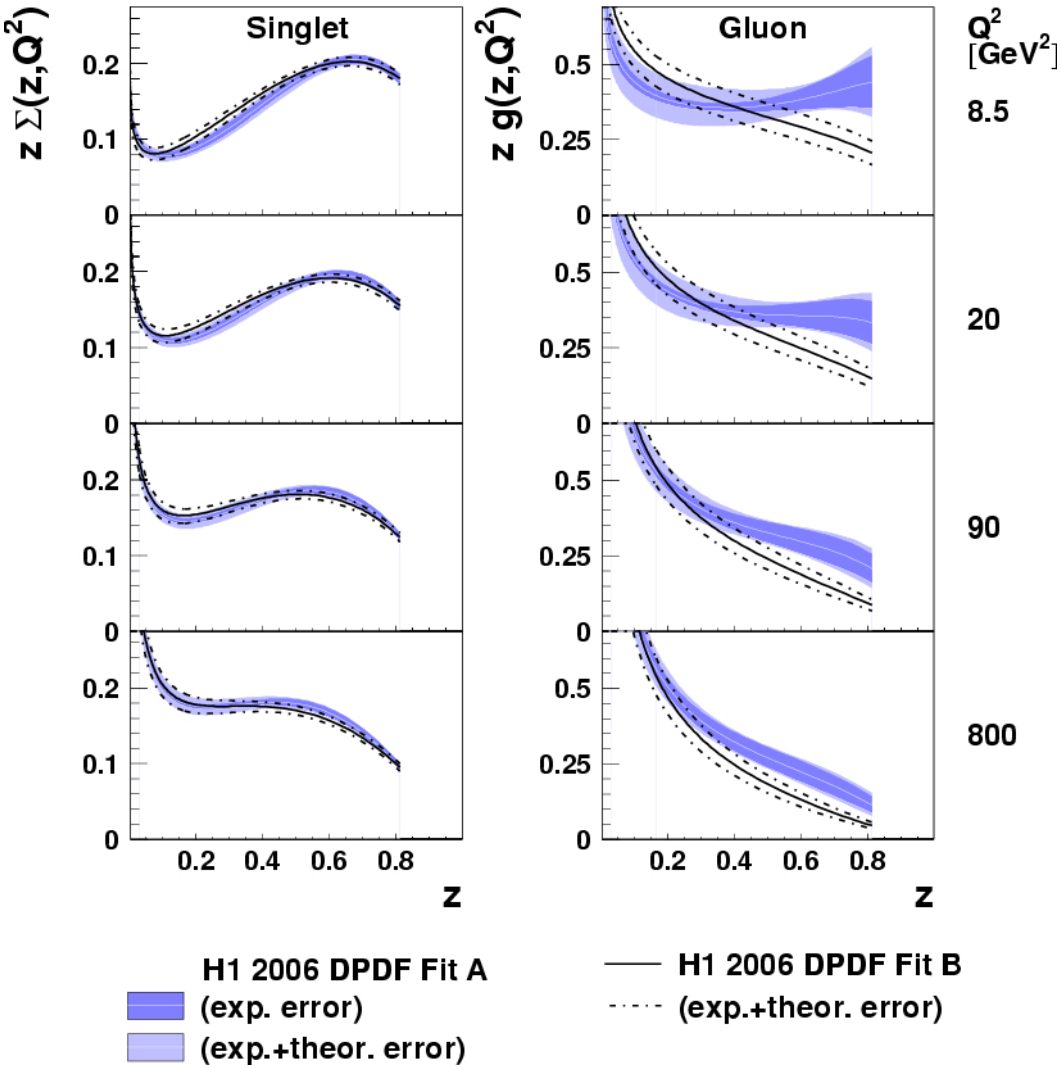
Physics in Diffraction

- many things similar to inclusive DIS
  - diffractive parton densities
  - jets in diffraction
  - heavy flavour in diffraction
- test of factorization
  - are the parton densities the same for all diffractive processes?
  - or: does the Pomeron know what happens at the photon vertex?

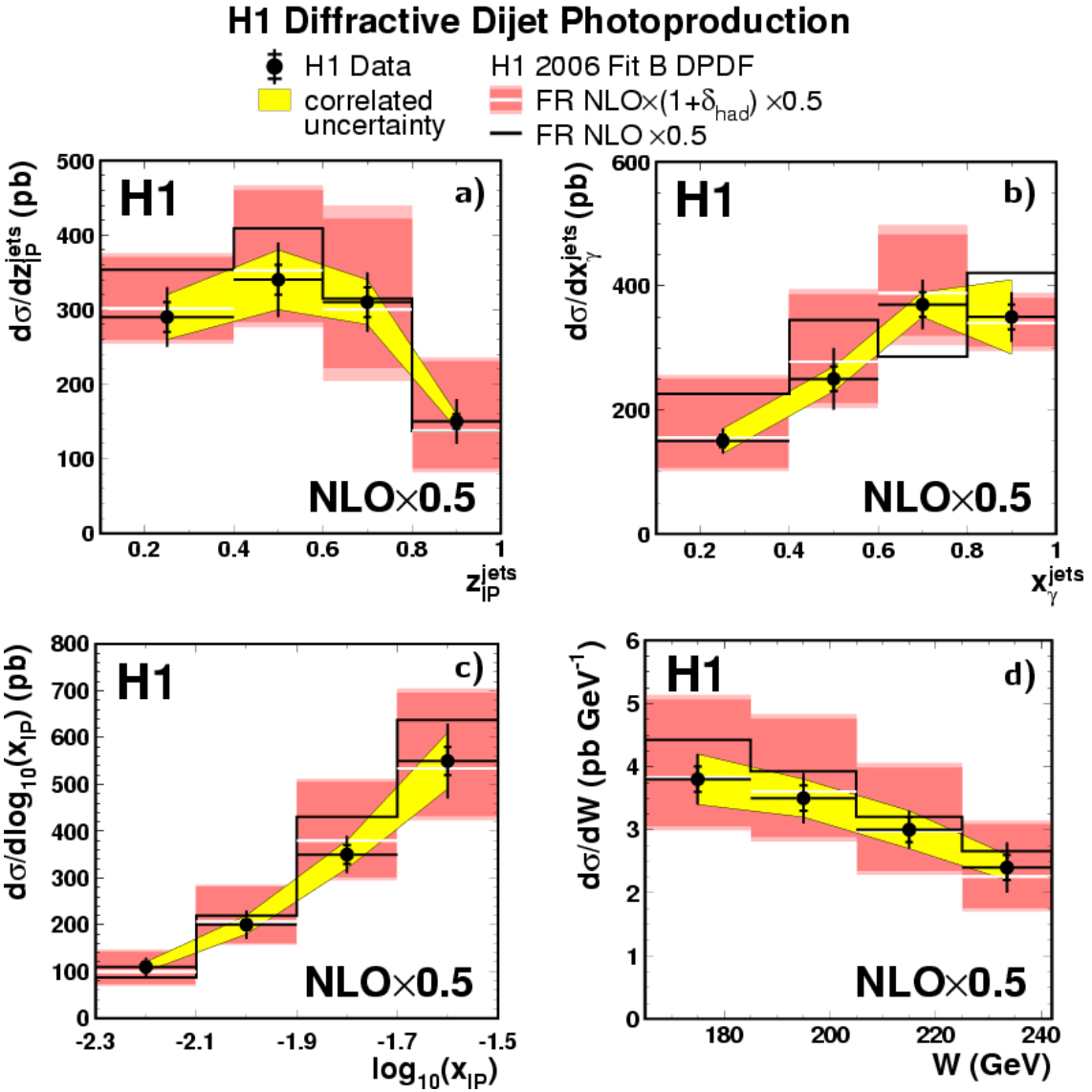
Diffractive Parton Densities



Singlet = Quark



Diffractive Dijet Cross Sections



- shape of the QCD theory prediction agrees with the data
- normalization is wrong by a factor 2

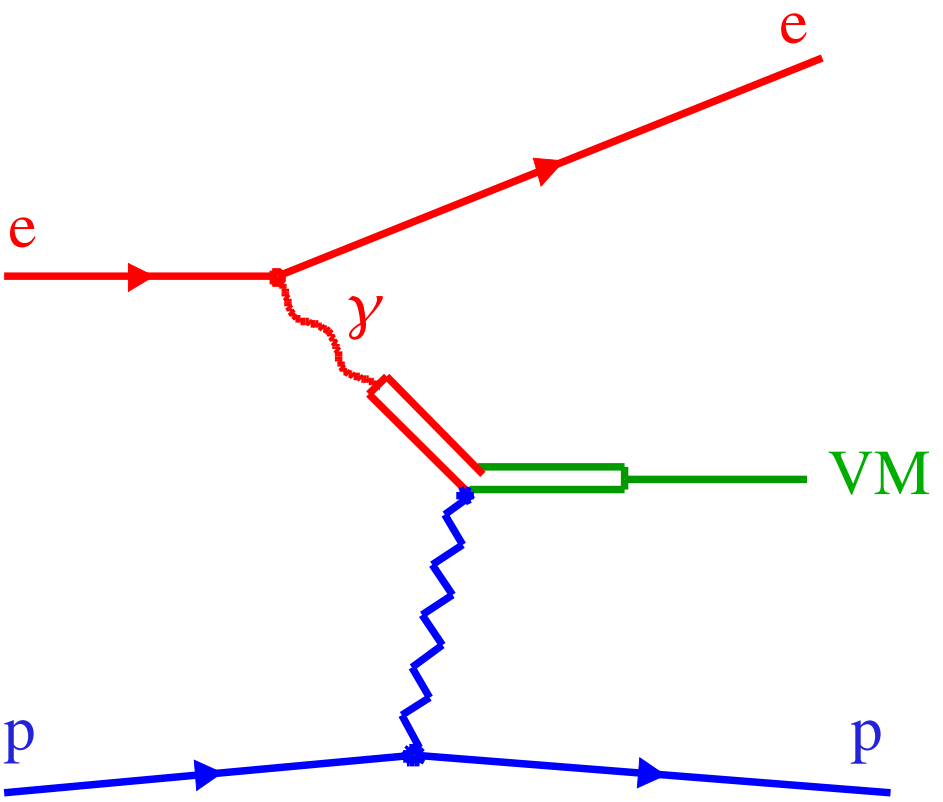
➔ factorization is broken!

Vector Mesons in Diffraction

- vector mesons (VM= ρ, ω, φ, J/ψ, ...) have the same quantum numbers as the photon

➔ photon can fluctuate into a VM, afterwards the VM can scatter off the proton

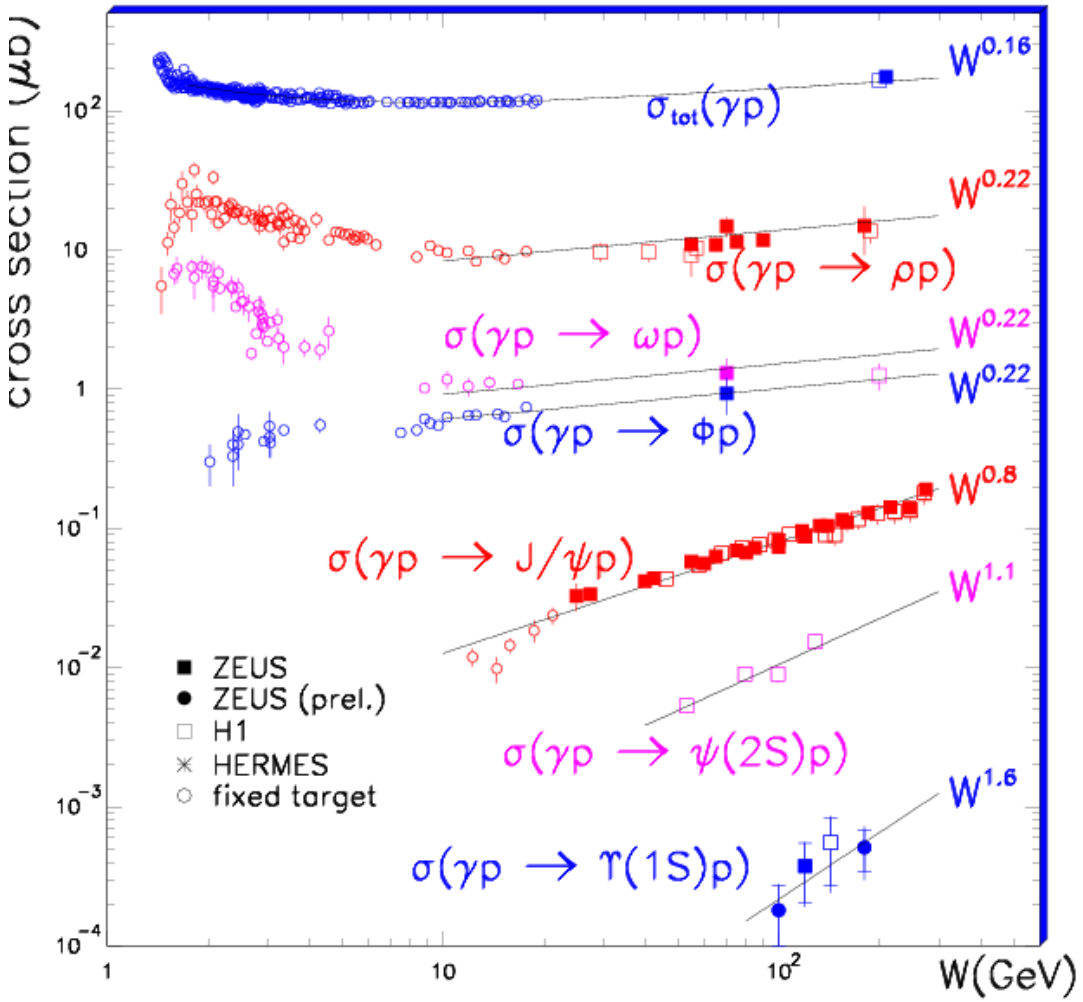
➔ „hadron-hadron“ scattering



Vector Mesons in Diffraction

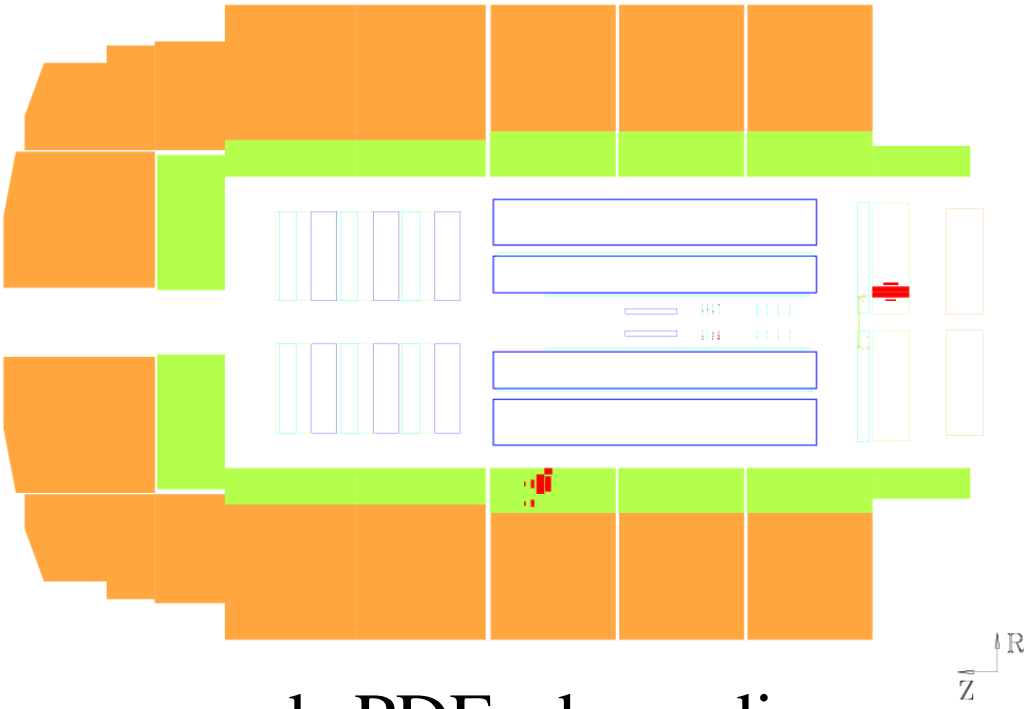
- light VMs (ρ, ω, φ) show the same dependence on the γp center-of-mass energy W
- heavier VMs (J/ψ, Υ) show increasing W dependence with mass

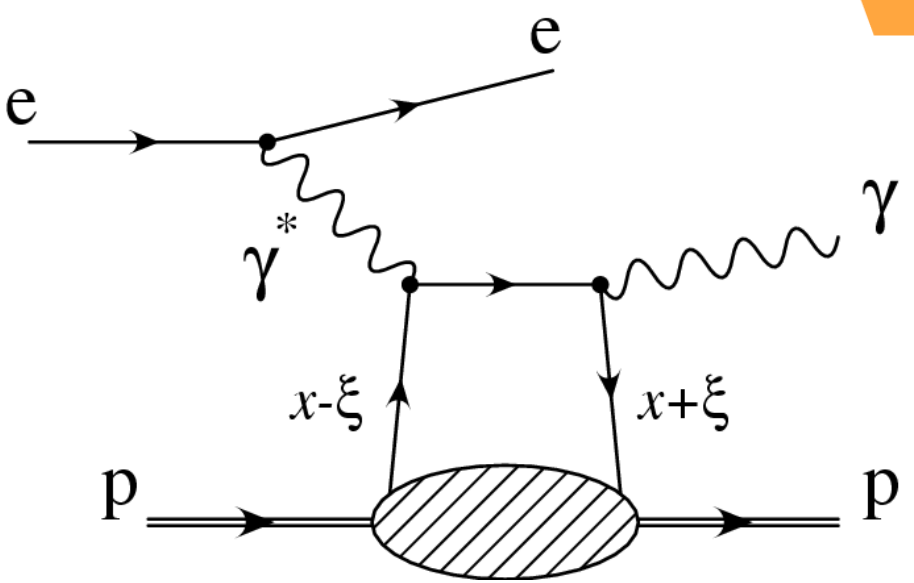
➔ simple „Pomeron“ picture doesn't work!



Deeply Virtual Compton Scattering

production of a real photon by scattering of a virtual photon on a proton





needs PDFs depending on x and „skewedness“ ξ

→ Generalized PDFs, extending standard PDFs to elastic form factors

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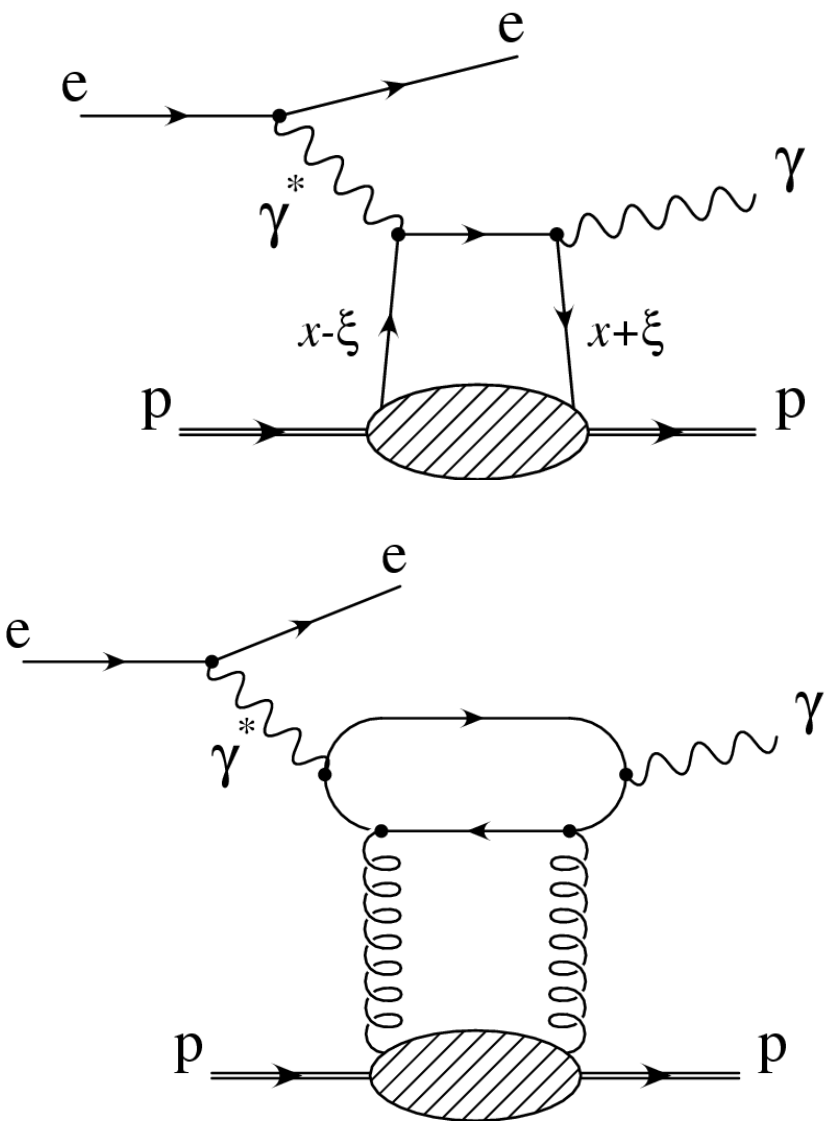

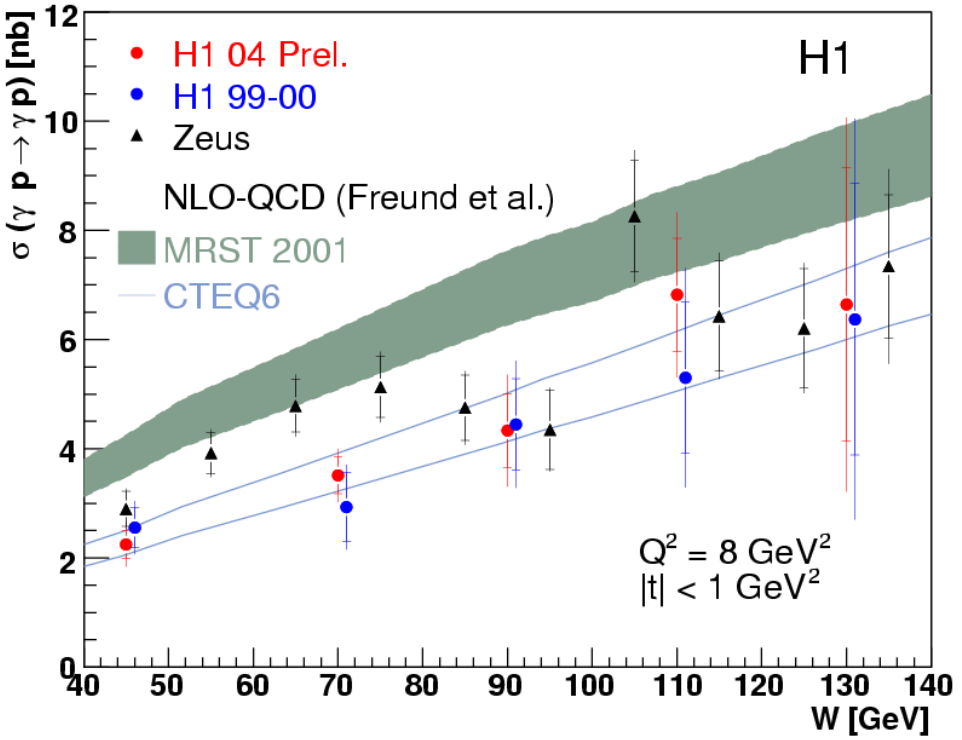

similar W dependence as heavy vector mesons

→ 2-gluon-exchange

Summary

- HERA offered unique possibilities to study the structure of the proton
- perturbative QCD is a big success to desribe HERA data
- no significant deviation from the Standard Model found
- always prepare for the unexpected!