Deep Inelastic Scatterng at HERA

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Physics 290E Seminar
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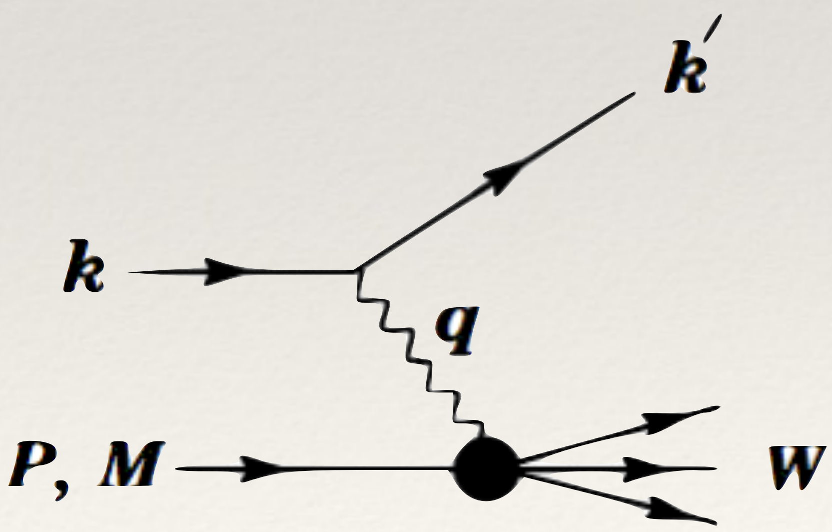
Outline

- DIS theory review
- HERA = ZEUS + H1 detectors
- Results

Deep Inelastic Scattering ⚡ Review

- High-energy lepton-nucleon collision
  - High = relative to QCD scale ~ 200 MeV
- Interpret as lepton interacting directly with quark or gluon
- Long list of "invariants" formed from two basic quantities: incoming and outgoing lepton momentum k and k'



Classic DIS "Feynman" diagram [1]

Invariants…here they are

$\nu = \dfrac{q \cdot P}{M} = E - E'$ is the lepton's energy loss in the nucleon rest frame (in earlier literature sometimes $\nu = q \cdot P$). Here, E and E' are the initial and final lepton energies in the nucleon rest frame.

$Q^2 = -q^2 = 2(EE' - \overrightarrow{k} \cdot \overrightarrow{k}') - m_\ell^2 - m_{\ell'}^2$ where $m_\ell (m_{\ell'})$ is the initial (final) lepton mass. If $EE' \sin^2(\theta/2) \gg m_\ell^2, m_{\ell'}^2$, then

$\approx 4EE' \sin^2(\theta/2)$, where θ is the lepton's scattering angle with respect to the lepton beam direction.

$x = \dfrac{Q^2}{2M\nu}$ where, in the parton model, x is the fraction of the nucleon's momentum carried by the struck quark.

$y = \dfrac{q \cdot P}{k \cdot P} = \dfrac{\nu}{E}$ is the fraction of the lepton's energy lost in the nucleon rest frame.

$W^2 = (P + q)^2 = M^2 + 2M\nu - Q^2$ is the mass squared of the system X recoiling against the scattered lepton.

$s = (k + P)^2 = \dfrac{Q^2}{xy} + M^2 + m_\ell^2$ is the center-of-mass energy squared of the lepton-nucleon system.

Too many, if you ask me [1]

Invariants…here they are

- $x = -q^2/(2q \cdot P)$
- In what universe is that the "fraction of nucleon momentum carried by the quark?"

$\nu = \dfrac{q \cdot P}{M} = E$ … earlier … and final

$Q^2 = -q^2 = 2$ … pton mass.

$\approx 4EE' \sin$ … he lepton beam direction.

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- A: The infinite-momentum frame, where the struck quark's final momentum is $0 = (xP + q)^2 = 0 + 2xq \cdot P + q^2$
- This "intuition" brought to you by Bjorken and Feynman

system.

Too many, if you ask me [1]

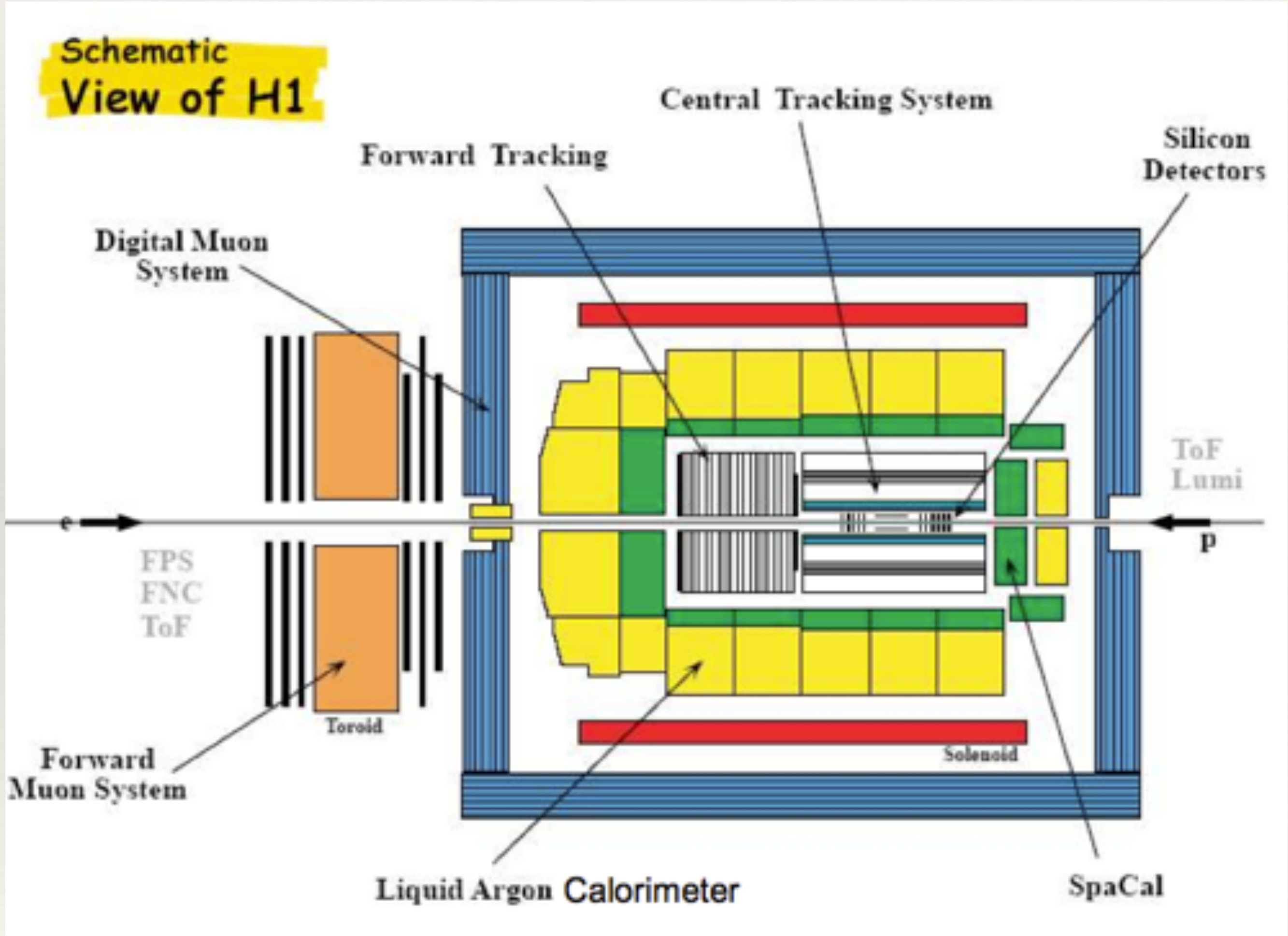
Why DIS?

- Allows us to probe fundamental QCD physics
- Measure Parton Distribution Functions (PDFs) which conveniently (and predictably) depend on x and Q^2
- Measure strong coupling constant α_s
- Measure cross section ratios
  - predictable from QCD given PDF and α_s

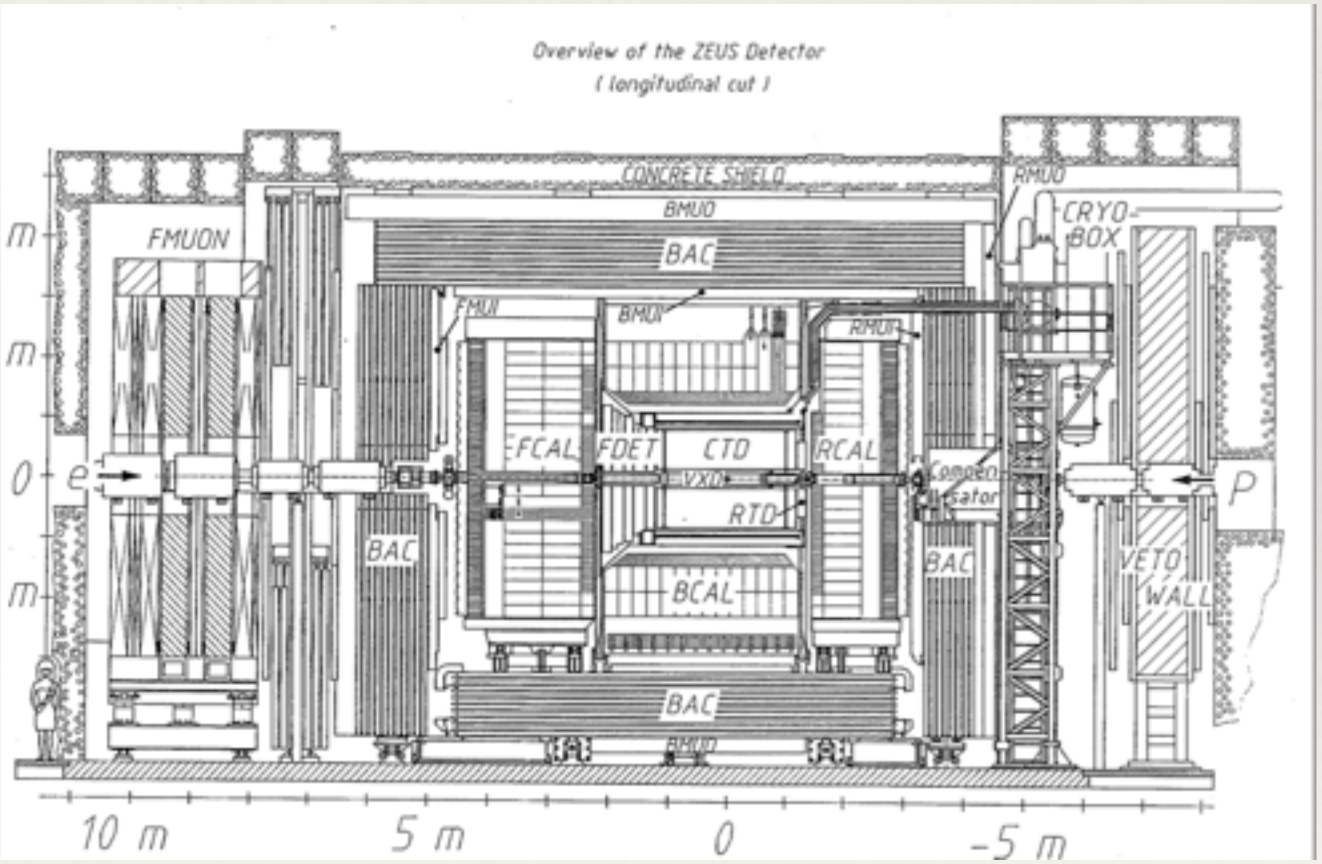
Quantity to measure

- No surprise here: cross sections at colliders
- Work backwards to get to structure functions, PDFs, and α_s

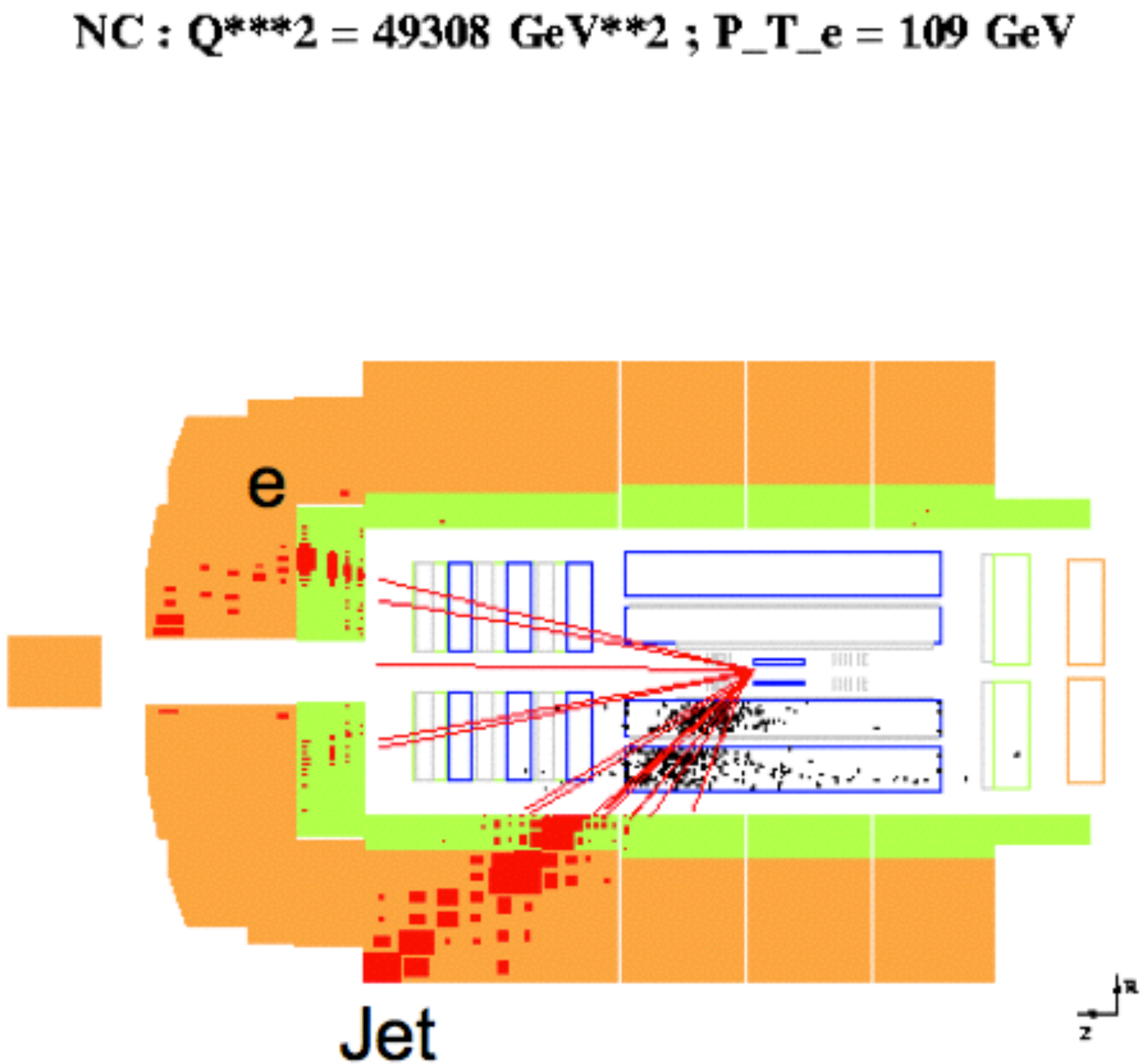
The Detectors at HERA

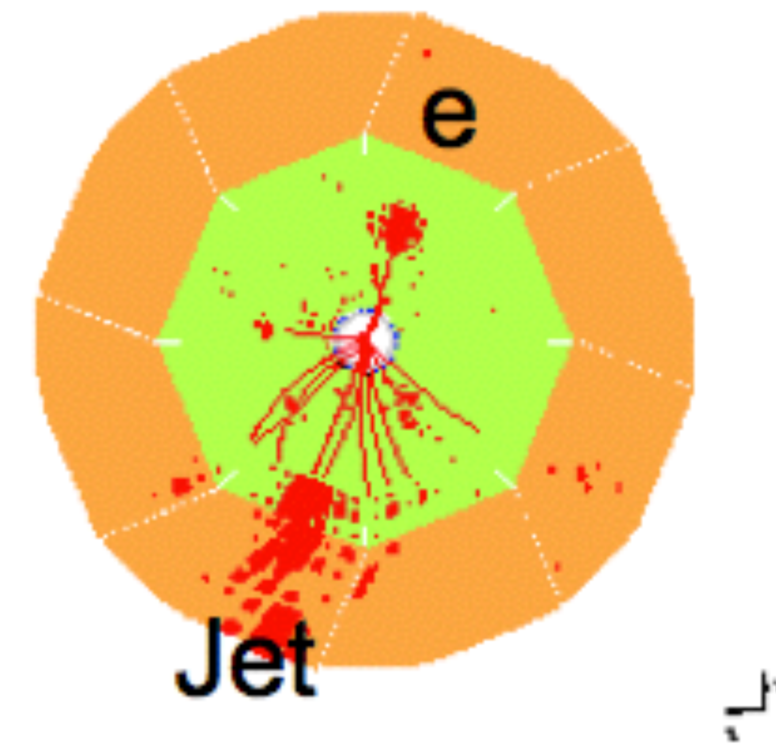


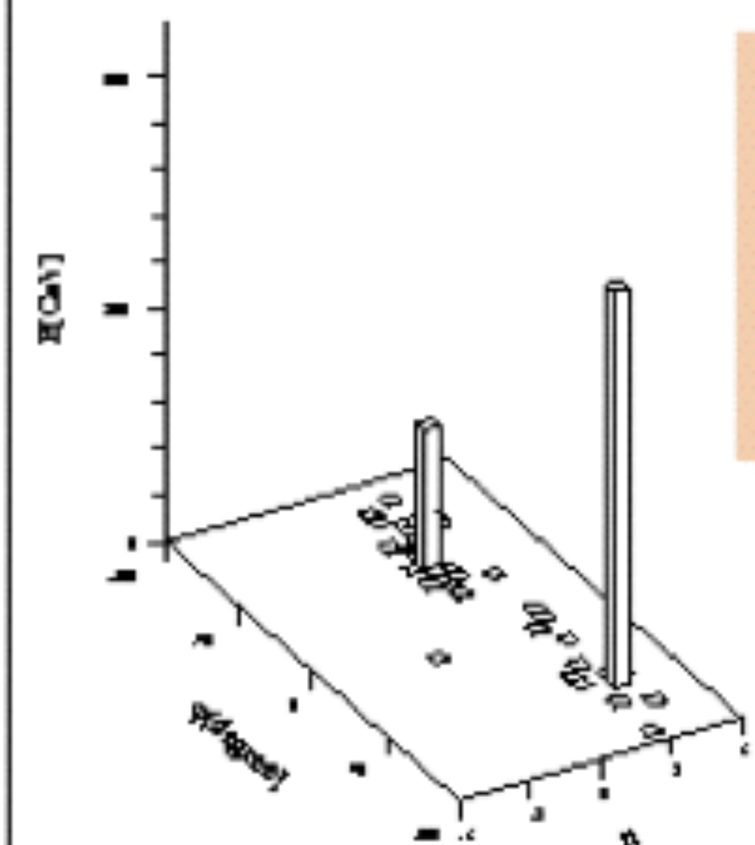
H1 instrumentation [2]



ZEUS instrumentation [3]







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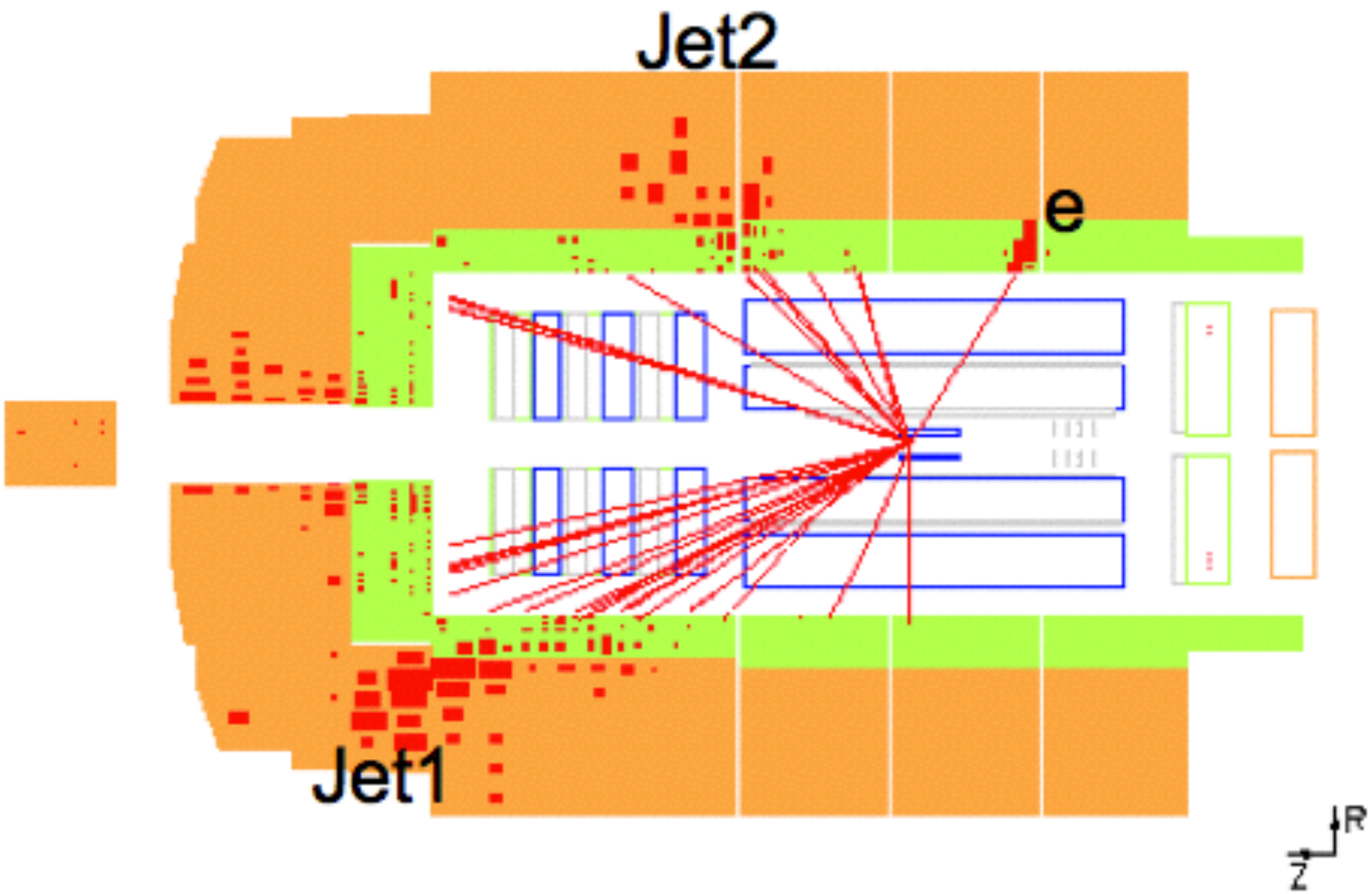
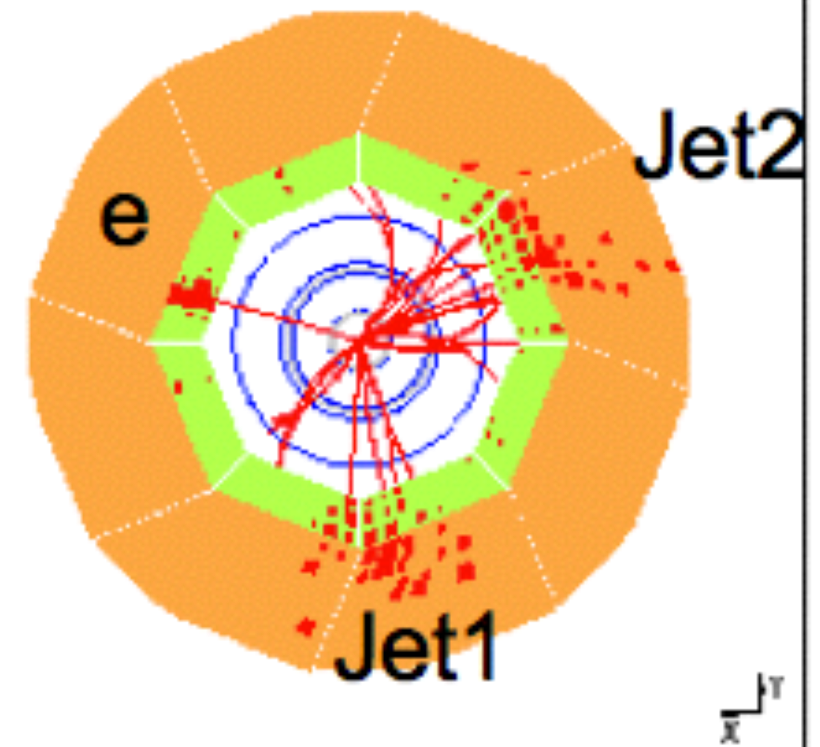
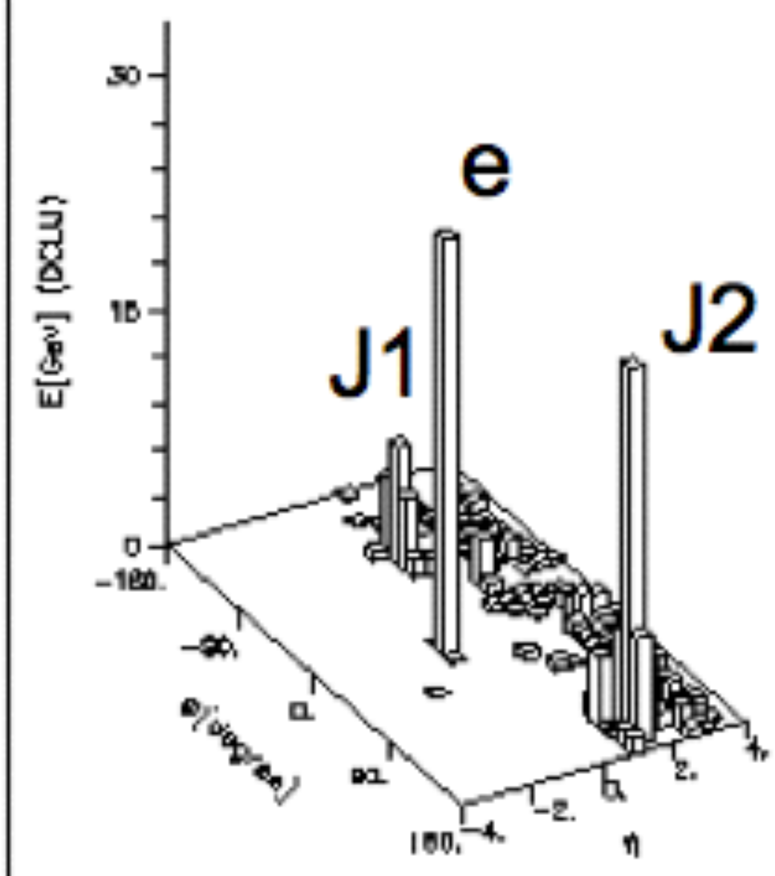
H1 event display [2]







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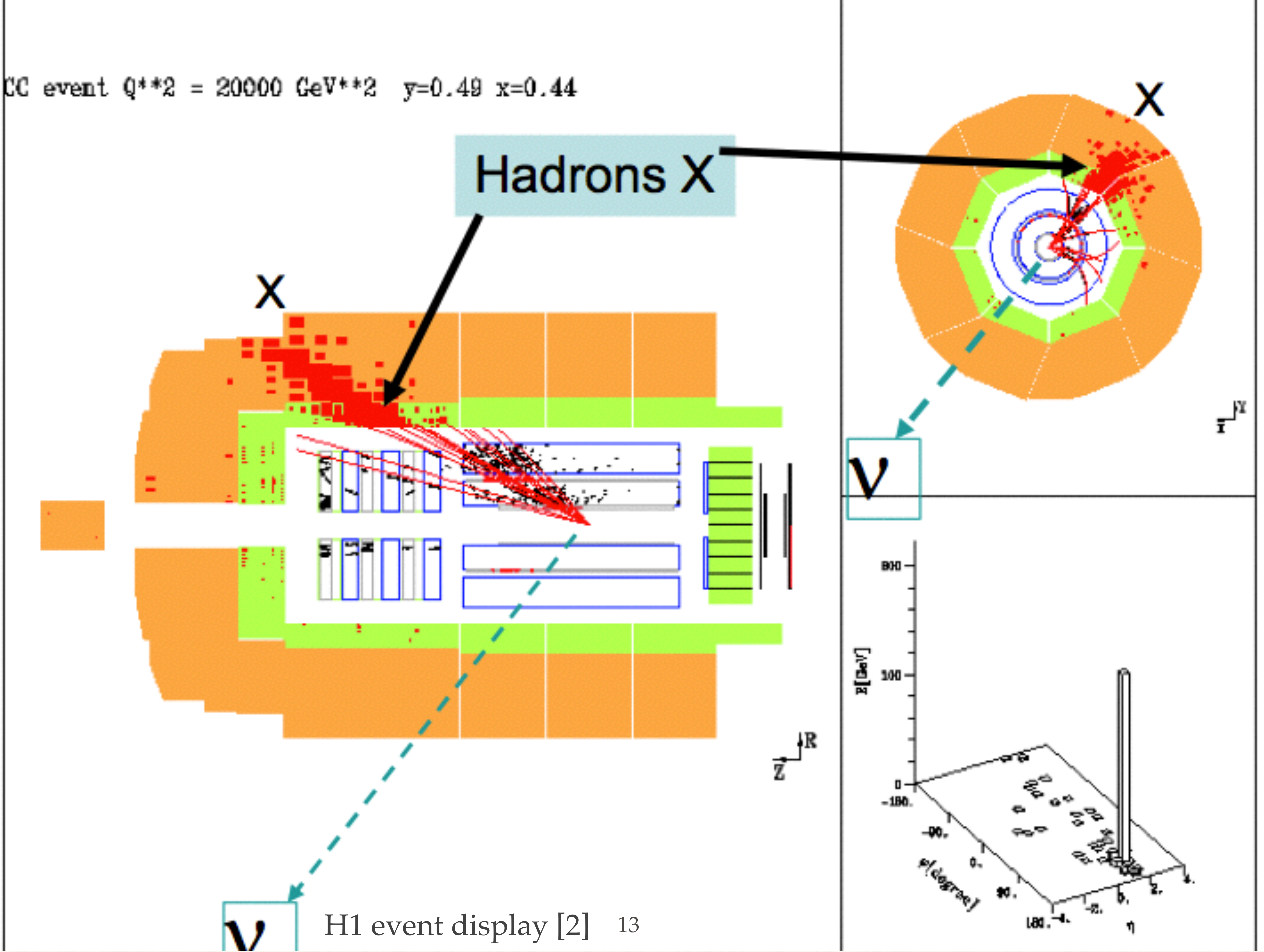
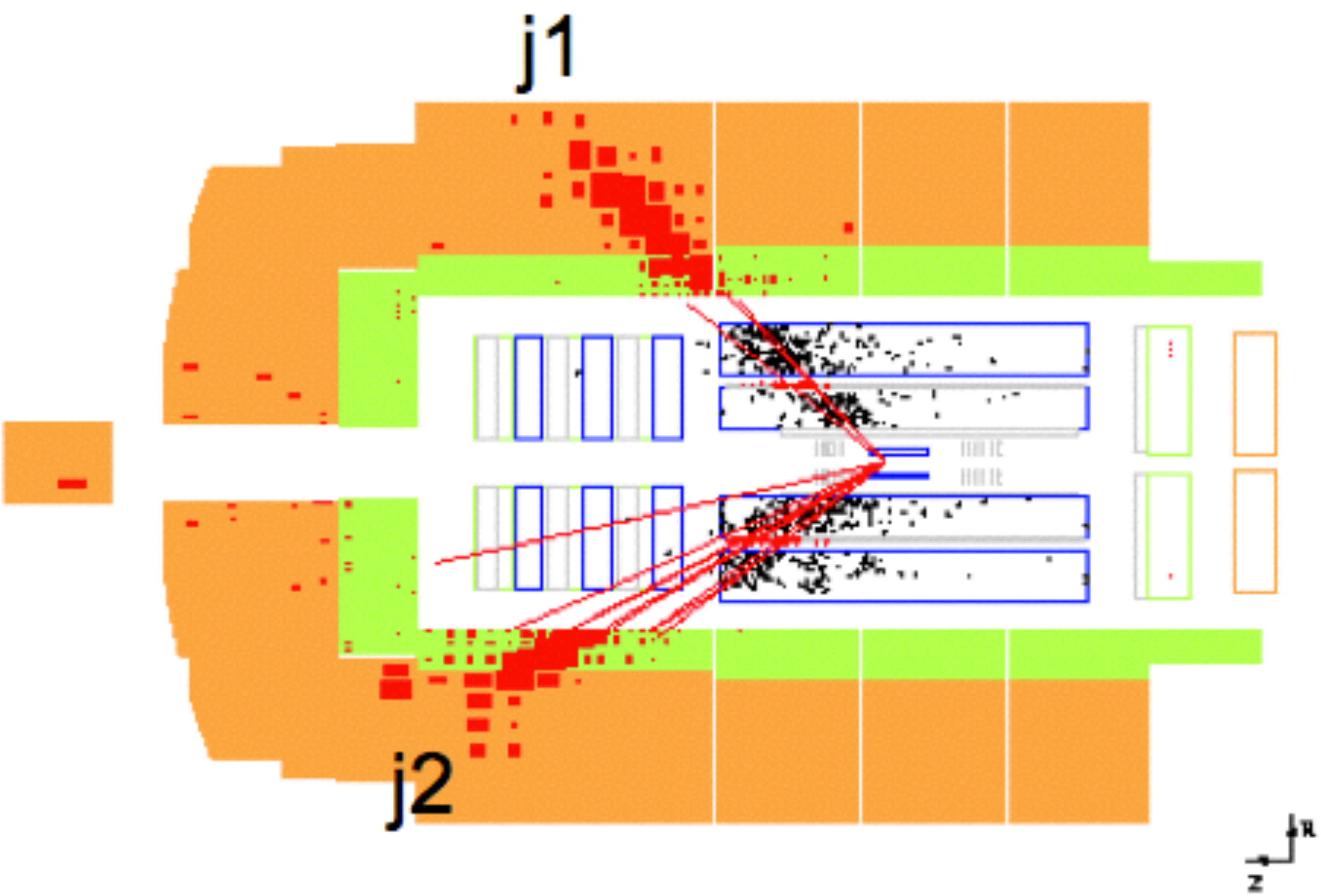
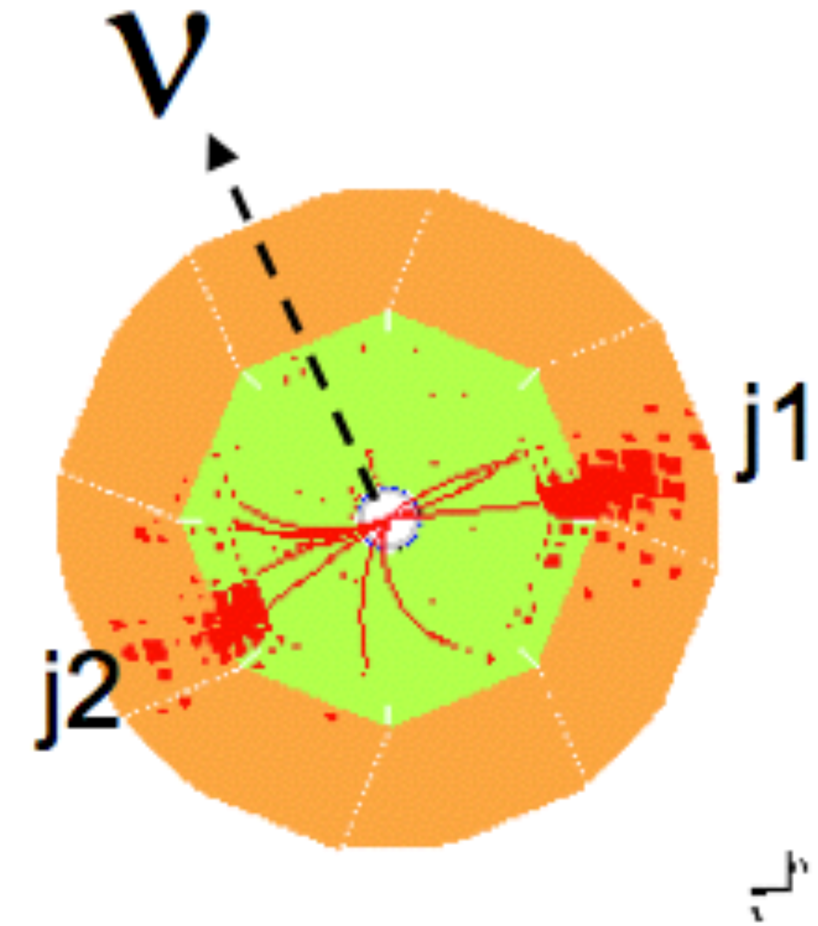
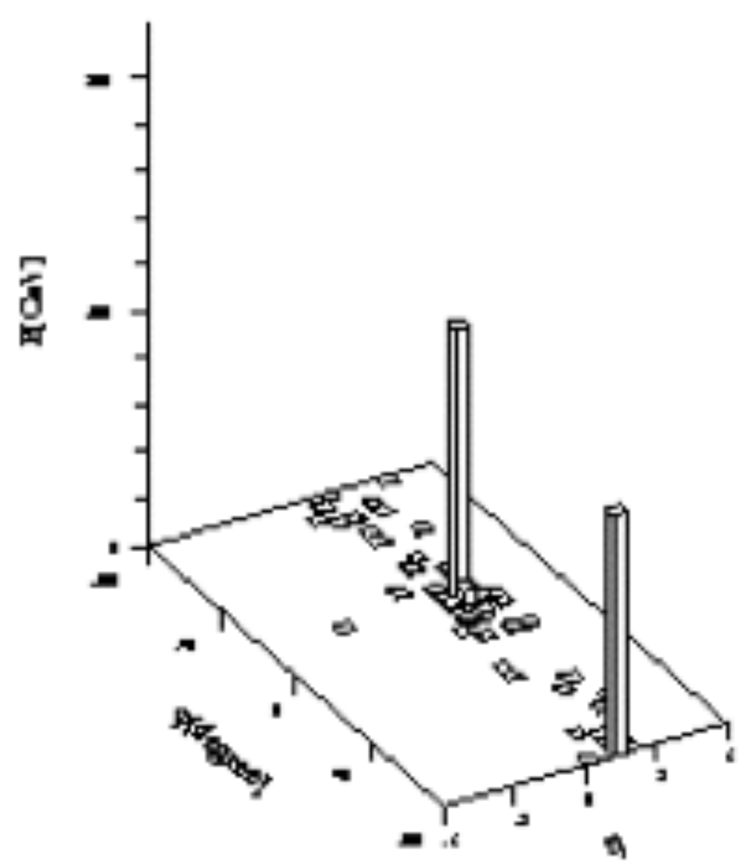


H1 event display [2]

CC ? : M_jj = 148 GeV ; P_T_miss = 35 GeV



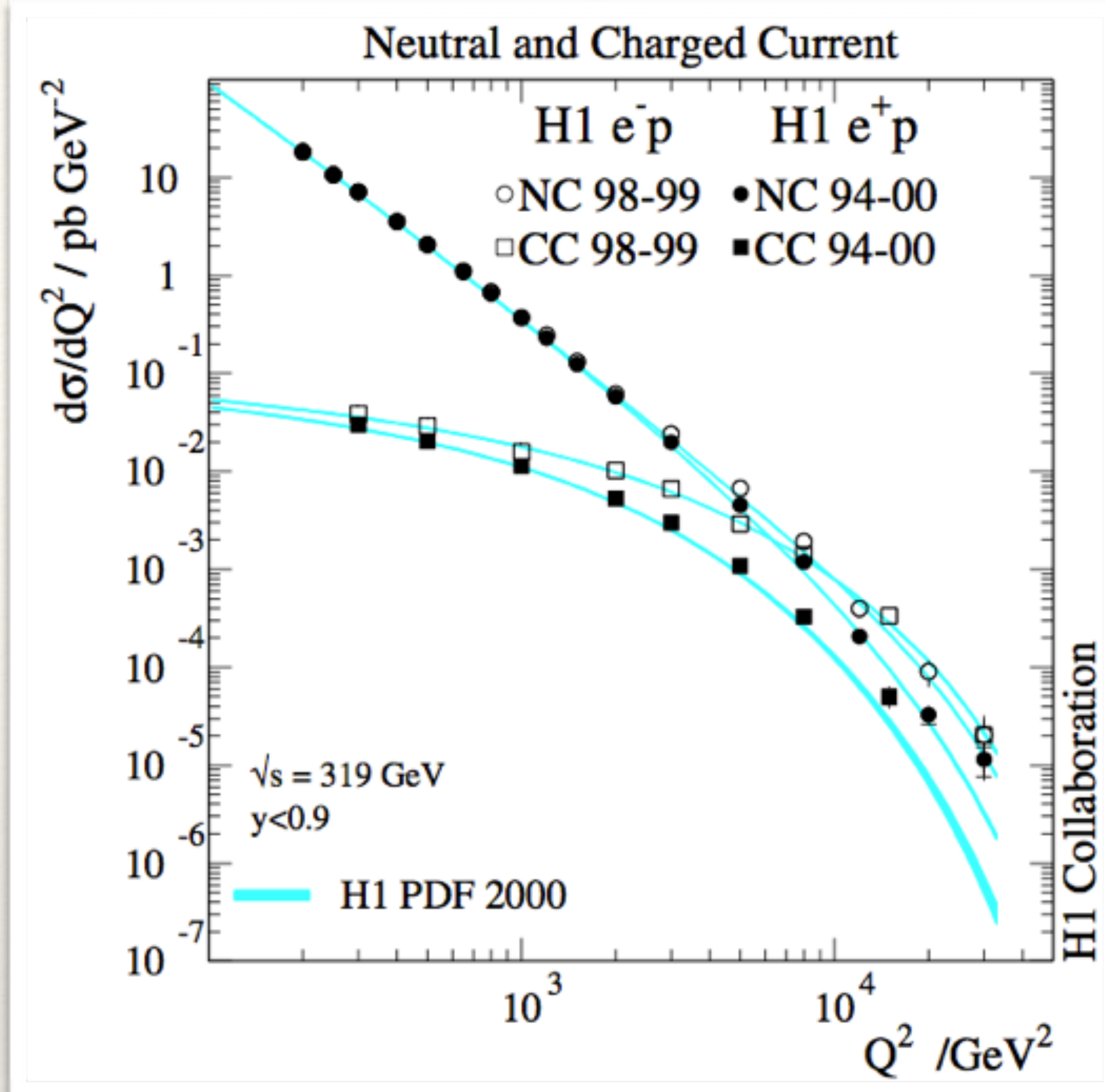




H1 event display [2]

Background and other Considerations

- Photoproduction background
  - (CC) electron escapes down beam pipe & fluctuation in calorimeter generates "missing" E_T
  - (NC) electron escapes down beam pip & hadron mimics electron signal
  - Minimize by requiring energy conservation (NC) and analyzing the energy flow relative to $P_{hadronic}$ (CC)
- Initial state bremsstrahlung (radiative corrections)
  - (NC) Photons escape down beam pipe. Minimize by enforcing energy conservation



H1 data & fit [4]

Measured data

The measured cross sections for CC and NC. The bands show the results of the fit, which are accurate over 6 orders of magnitude in σ.

Performing the χ^2 fit

- Fit to gluons, up-type, anti-up-type, down-type, and anti-down-type. Try to separate out *s*, *c*, *b* later
- Start with trial PDFs then "predict" cross section
- Use smart parametrization that relies on physics
  - *U*, *D* must account for valence quarks while $\bar{U}$, $\bar{D}$ are sea quarks only → more parameters for *U*, *D*
  - B_q's must all be equal

$$xg(x) = A_g x^{B_g} (1-x)^{C_g} \cdot [1 + D_g x]$$
$$xU(x) = A_U x^{B_U} (1-x)^{C_U} \cdot [1 + D_U x + F_U x^3]$$
$$xD(x) = A_D x^{B_D} (1-x)^{C_D} \cdot [1 + D_D x]$$
$$x\overline{U}(x) = A_{\overline{U}} x^{B_{\overline{U}}} (1-x)^{C_{\overline{U}}}$$
$$x\overline{D}(x) = A_{\overline{D}} x^{B_{\overline{D}}} (1-x)^{C_{\overline{D}}} ,$$

Fitter parametrization [4]

Performing the χ^2 fit (2)

- Get from PDF to cross section
- Tons of formulas. Here are parts of the CC & NC computations

$$[xF_3^{\gamma Z}, xF_3^Z] = 2x\sum_q [e_q a_q, v_q a_q]\{q - \bar{q}\}$$

FYI not a commutator

$$x\tilde{F}_3 \equiv -\, a_e \frac{\kappa Q^2}{(Q^2 + M_Z^2)} xF_3^{\gamma Z} + (2v_e a_e)\left(\frac{\kappa Q^2}{Q^2 + M_Z^2}\right)^2 xF_3^Z$$

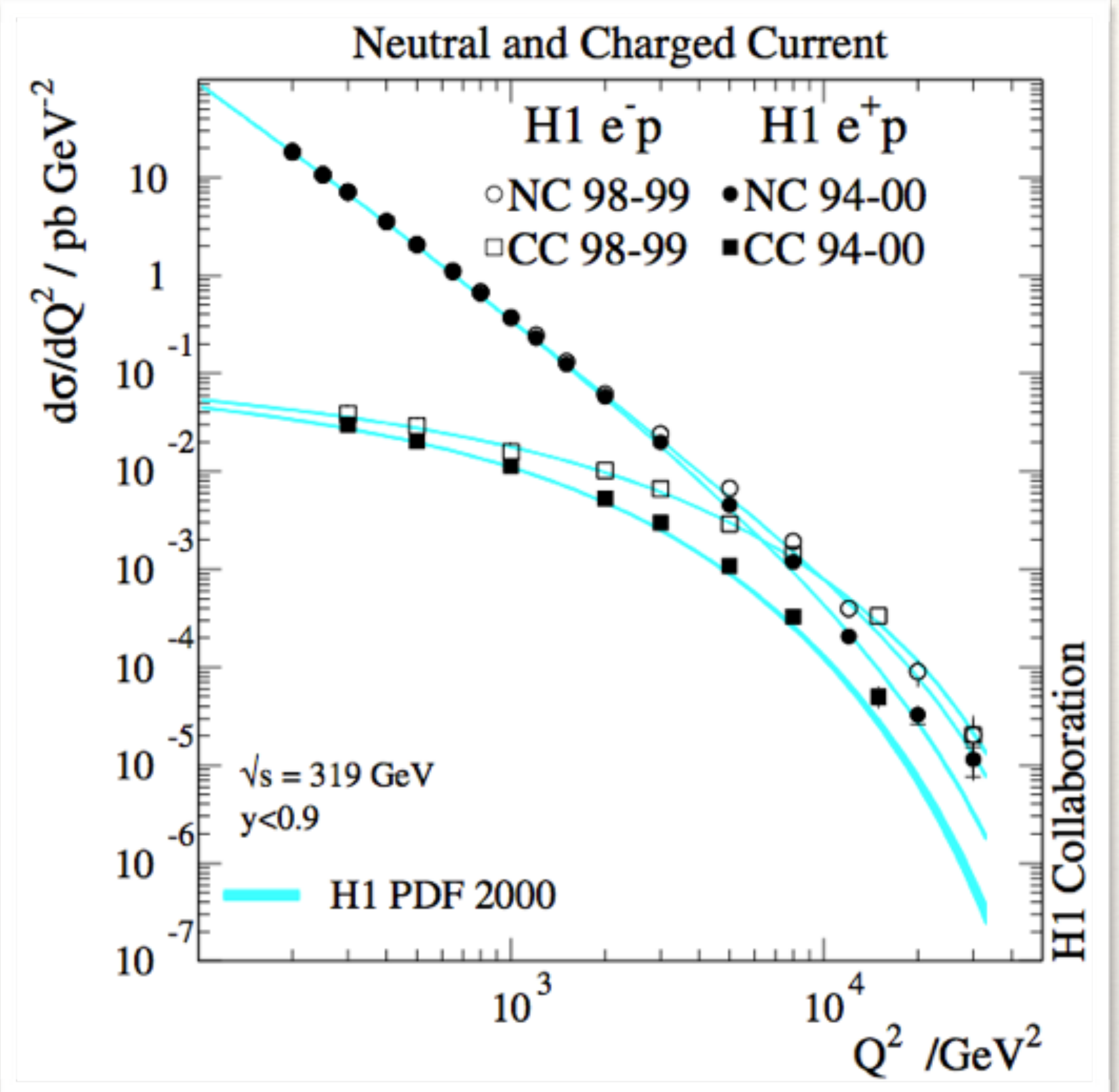
$$\frac{\mathrm{d}^2\sigma_{NC}^{\pm}}{\mathrm{d}x\,\mathrm{d}Q^2} = \frac{2\pi\alpha^2}{xQ^4}\,\phi_{NC}^{\pm}\,(1 + \Delta_{NC}^{\pm,weak}),$$

with $\phi_{NC}^{\pm} = Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_L$,

$$W_2^+ = x(\overline{U} + D), \quad xW_3^+ = x(D - \overline{U})$$
$$W_2^- = x(U + \overline{D}), \quad xW_3^- = x(U - \overline{D})$$

$$\phi_{CC}^{\pm} = \frac{1}{2}(Y_+ W_2^{\pm} \mp Y_- xW_3^{\pm} - y^2 W_L^{\pm}),$$

$$\frac{\mathrm{d}^2\sigma_{CC}^{\pm}}{\mathrm{d}x\,\mathrm{d}Q^2} = \frac{G_F^2}{2\pi x}\left[\frac{M_W^2}{Q^2 + M_W^2}\right]^2 \times \phi_{CC}^{\pm}\,(1 + \Delta_{CC}^{\pm,weak})$$



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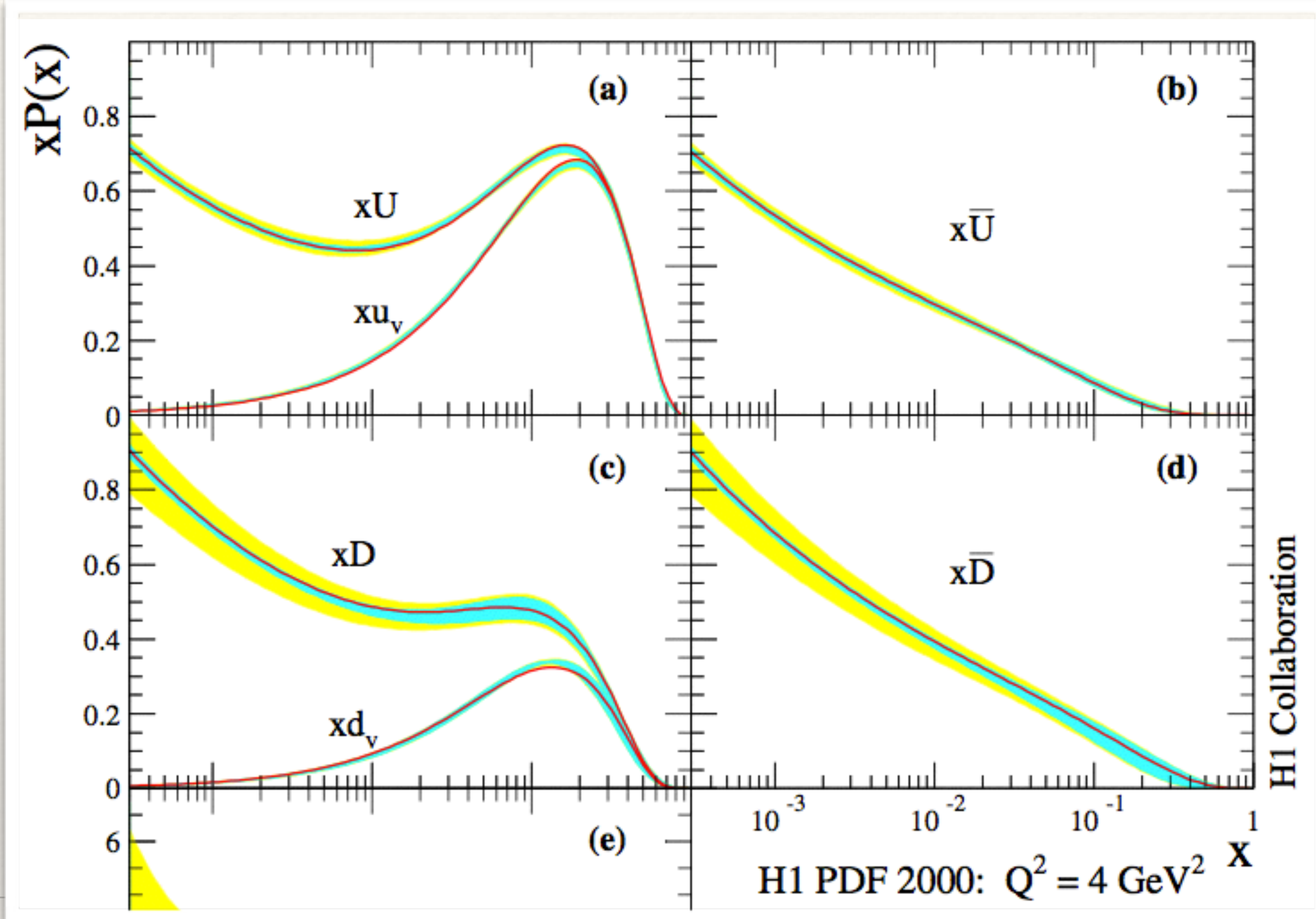
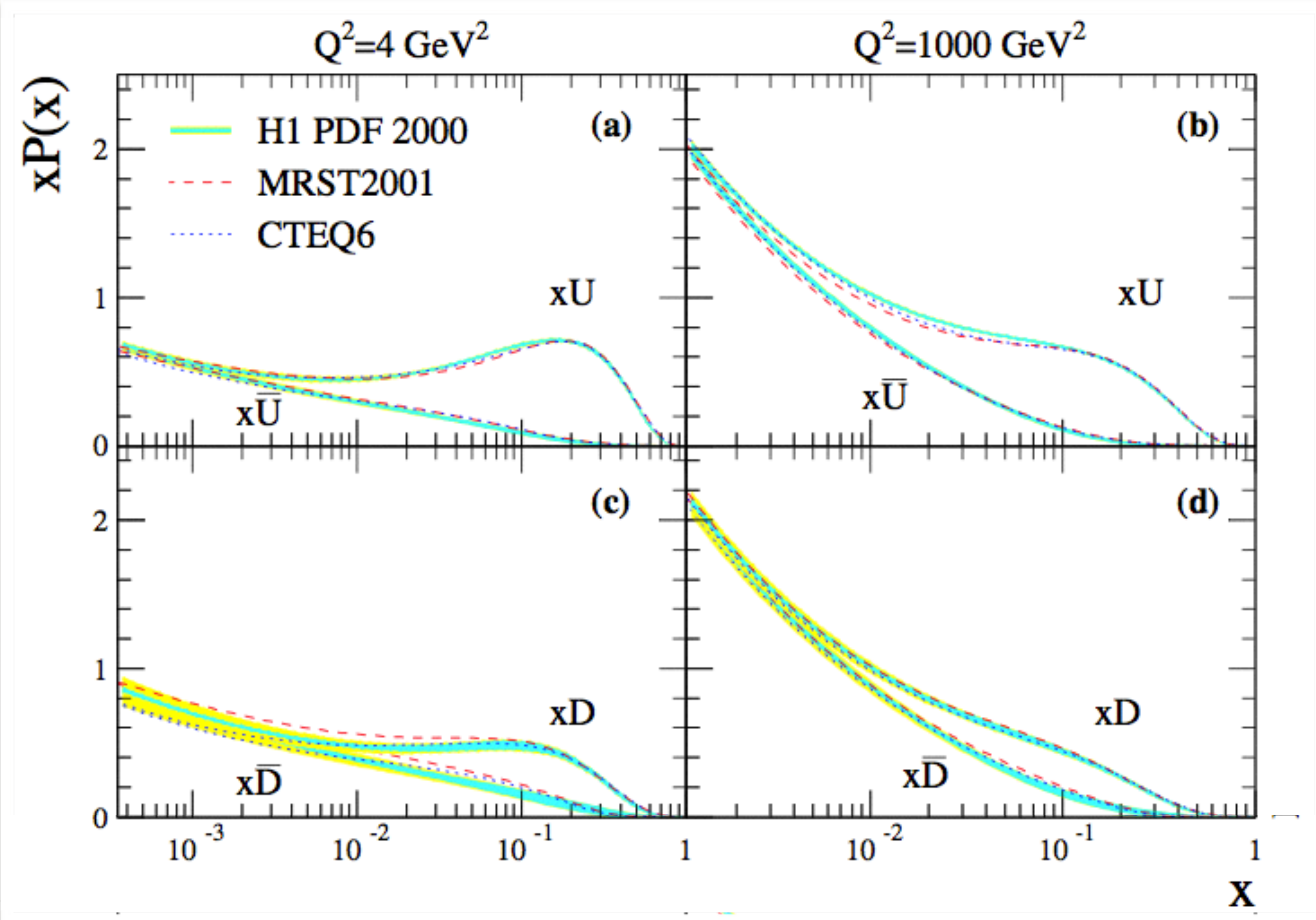


Results

Final fitted models of PDFs at 4 GeV². Note $q_v = Q - \overline{Q}$ are the valence quark PDFs.



Results

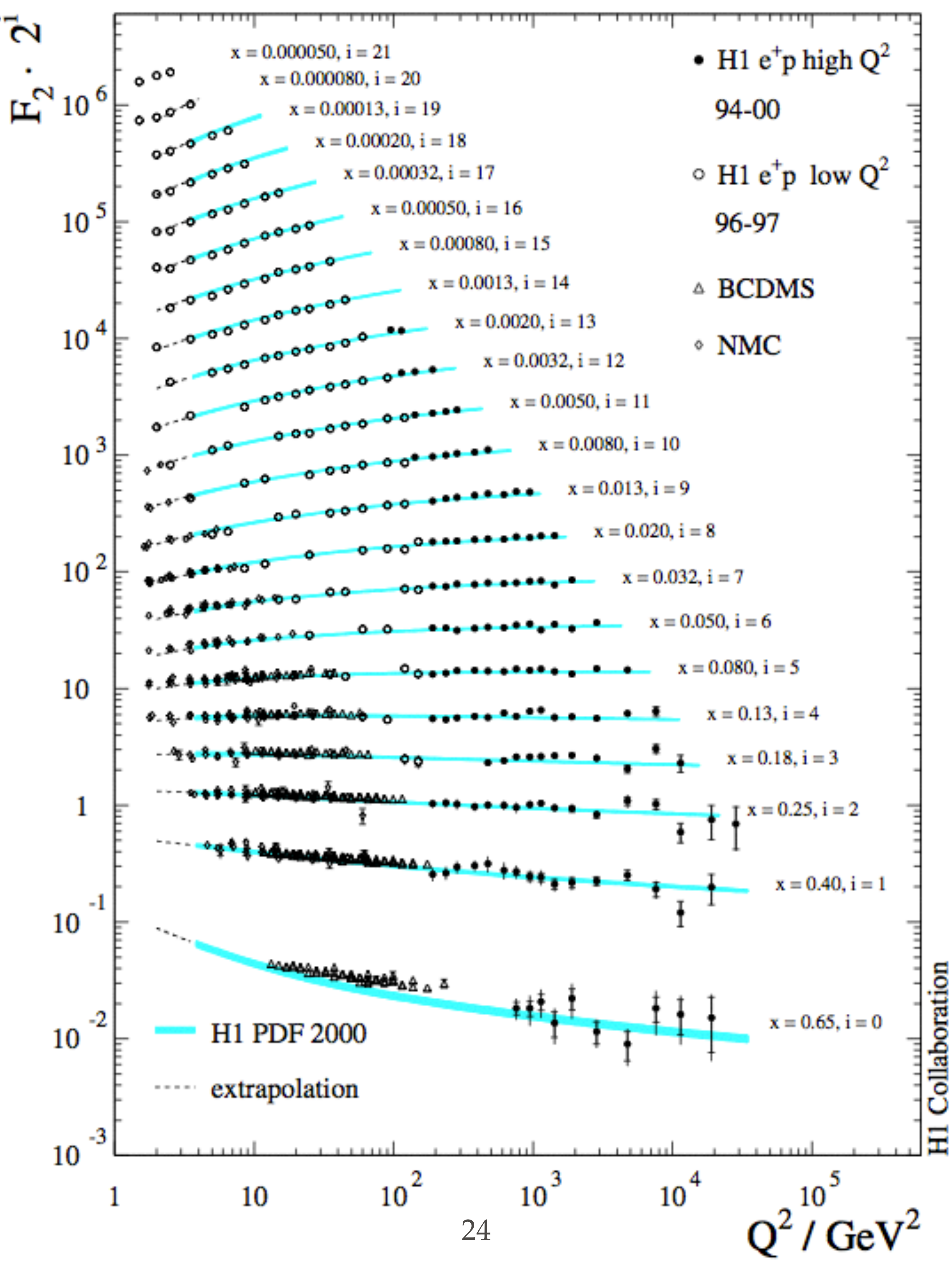
PDFs varied by energy using the DGLAP evolution equations.

Conclusions

- DIS is a fantastic probe of QCD dynamics
- There is a lot of complex structure hidden in what look like simple cross section plots
- Sure enough, the proton is made of *uud*
- One final plot…

References

- [1] PDG Structure Functions Review. K.A. Olive et al. (Particle Data Group), Chin. Phys. C, 38, 090001 (2014) and 2015 update.
- [2] H1 Events Tutorial http://www-h1.desy.de/pictures/H1-short.event.tutorial2.pdf.
- [3] ZEUS 1993 Status Report http://www-zeus.desy.de/bluebook/.
- [4] The H1 Collaboration, Eur. Phys. J. C **30**, 1 (2003).
- (to learn about DGLAP) http://www.scholarpedia.org/article/QCD_evolution_equations_for_parton_densities



H1 Measurement and QCD Analysis [4]

Thank You