Recent measurements of the hadronic final state at HERA

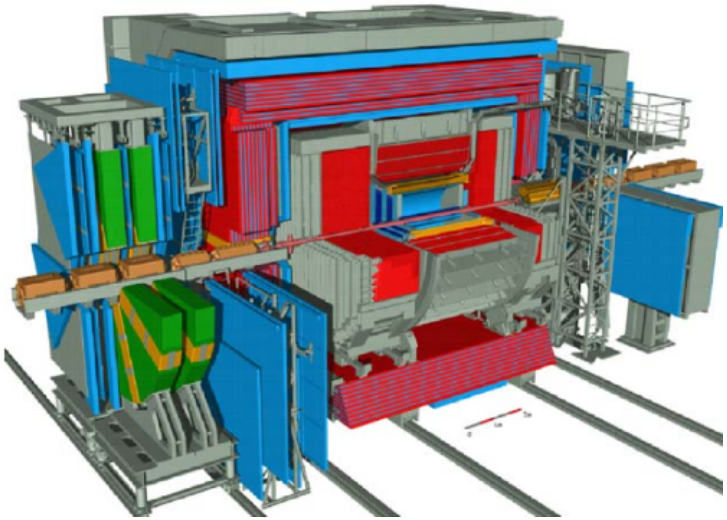
Michel Sauter
Ruprecht-Karls-Universität Heidelberg

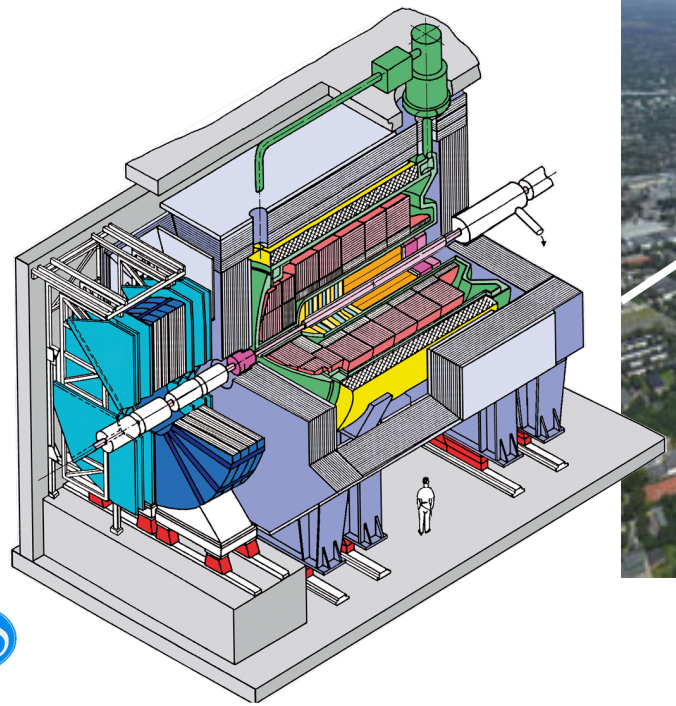
LowX Meeting 2014
June 2014, Japan

- Measurement of Feynman-x Spectra of Photons and Neutrons in the Very Forward Direction in DIS at HERA , DESY-14-035 arXiv:1404.0201,
- Search for QCD Instanton-Induced Processes in DIS at HERA, H1prelim-14-031

The HERA ep collider (1992 – 2007) at DESY in Hamburg

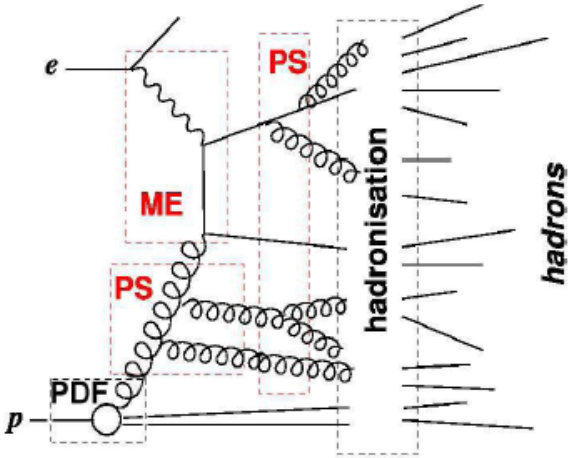
- ep collider:
- $e^{\pm}$ energy: 27.6 GeV
- p energy: 920 GeV, 460 GeV
- Center of mass energy: 318 GeV, 225 GeV
- 2 collider experiments: H1 and ZEUS



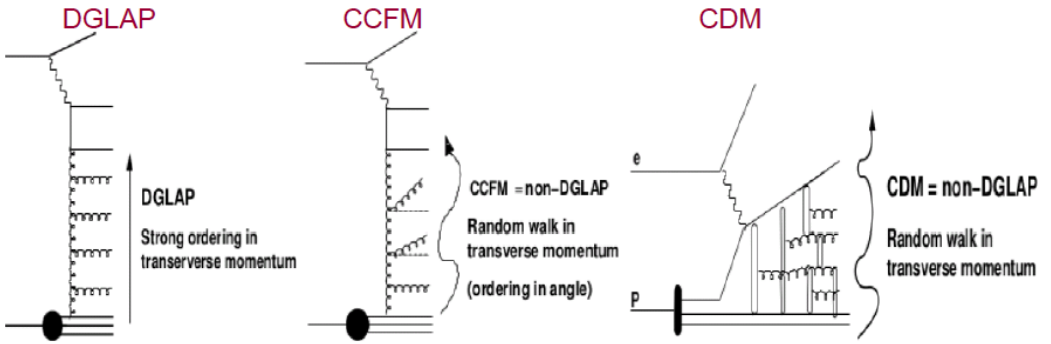


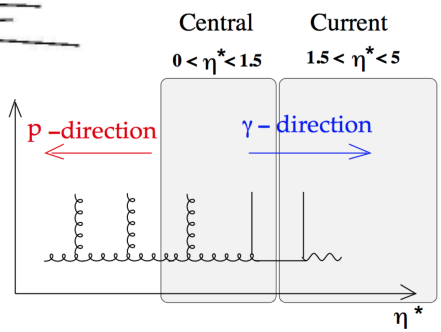
Hadronic final state at HERA: a few examples

Transverse momentum of charged particles

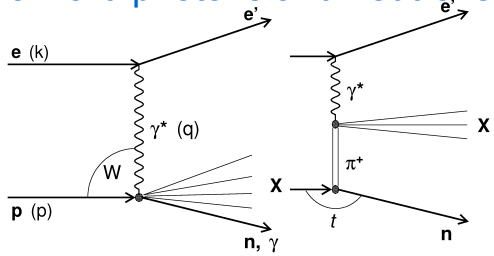


Parton Evolution Models

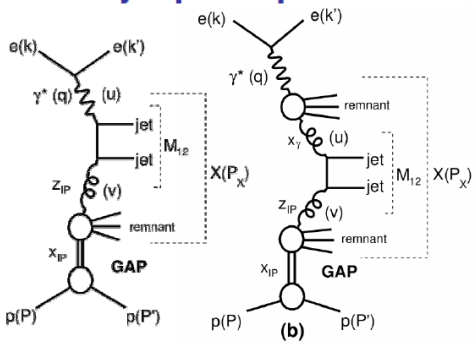




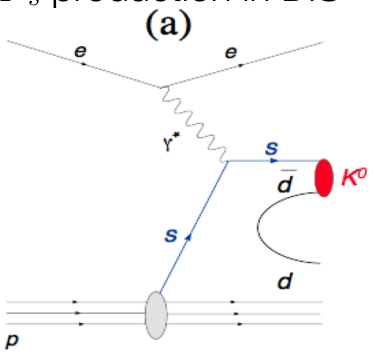
Forward photons and neutrons

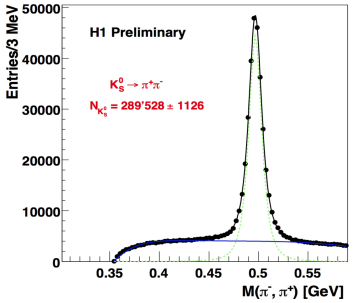


Diffractive dijet photoproduction

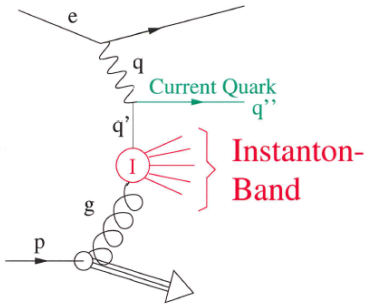


K^0_s production in DIS

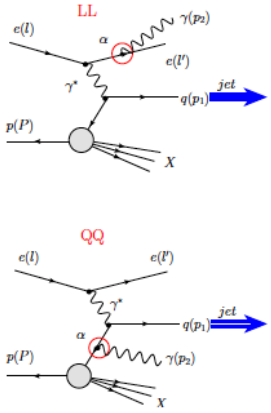




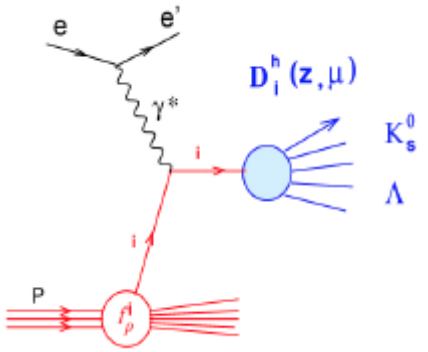
Instantons, "fireball"-like final state



Prompt photons + jets in DIS

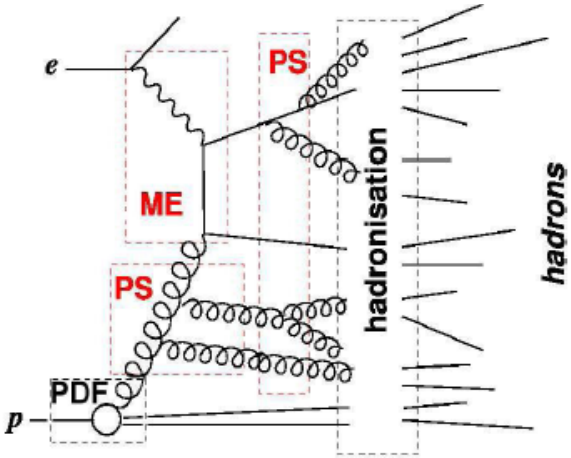


Fragmentation function (FF) for K^0_s and Λ

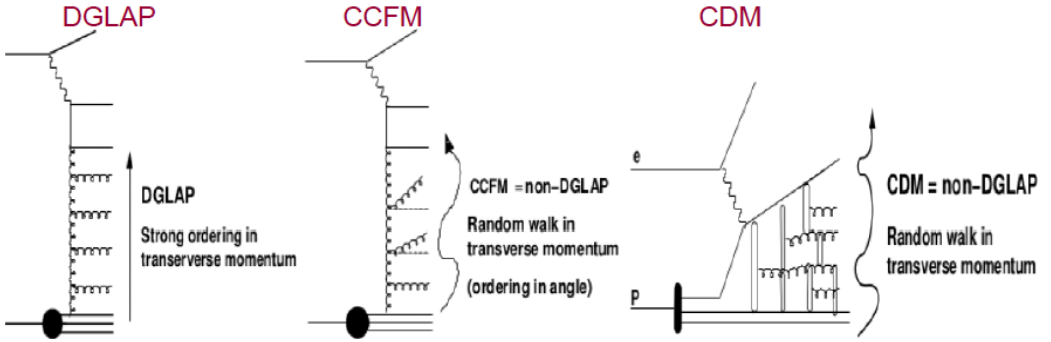


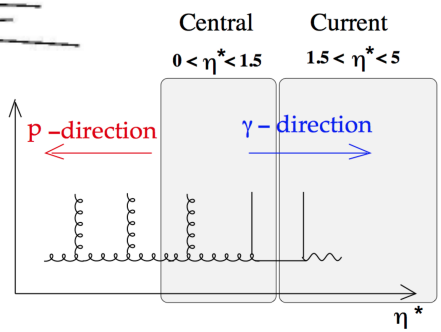
Hadronic final state at HERA: discussed today

Transverse momentum of charged particles

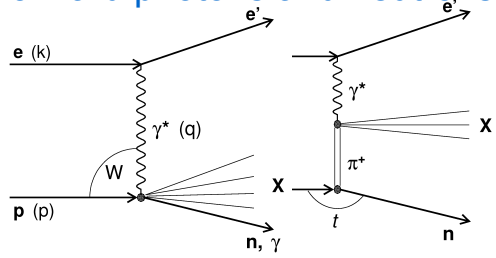


Parton Evolution Models

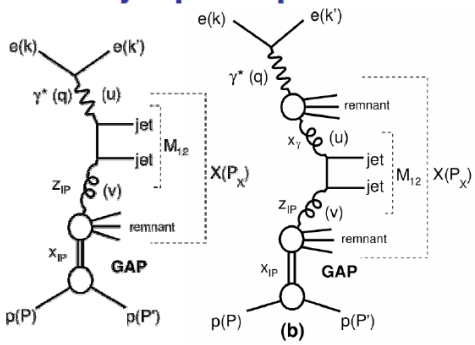




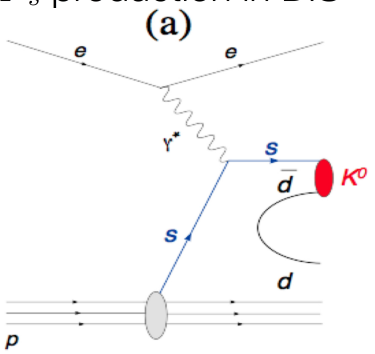
Forward photons and neutrons

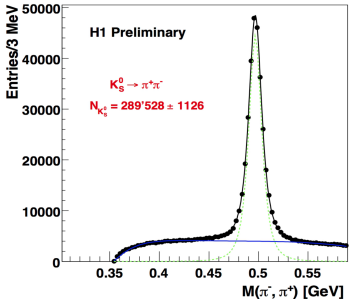


Diffractive dijet photoproduction

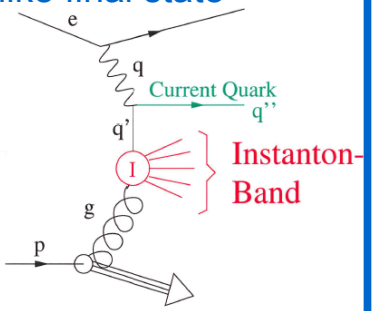


K^0_s production in DIS

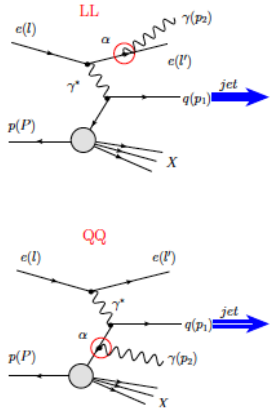




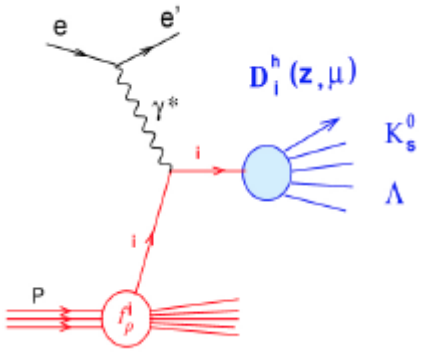
Instantons, "fireball"-like final state



Prompt photons + jets in DIS



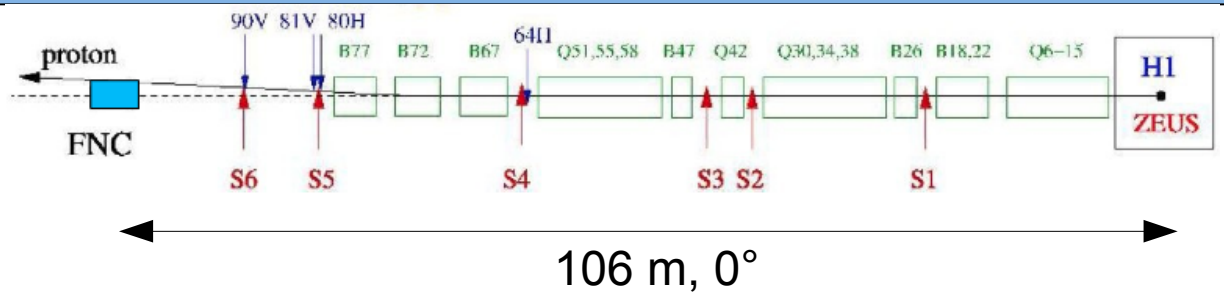
Fragmentation function (FF) for K^0_s and Λ

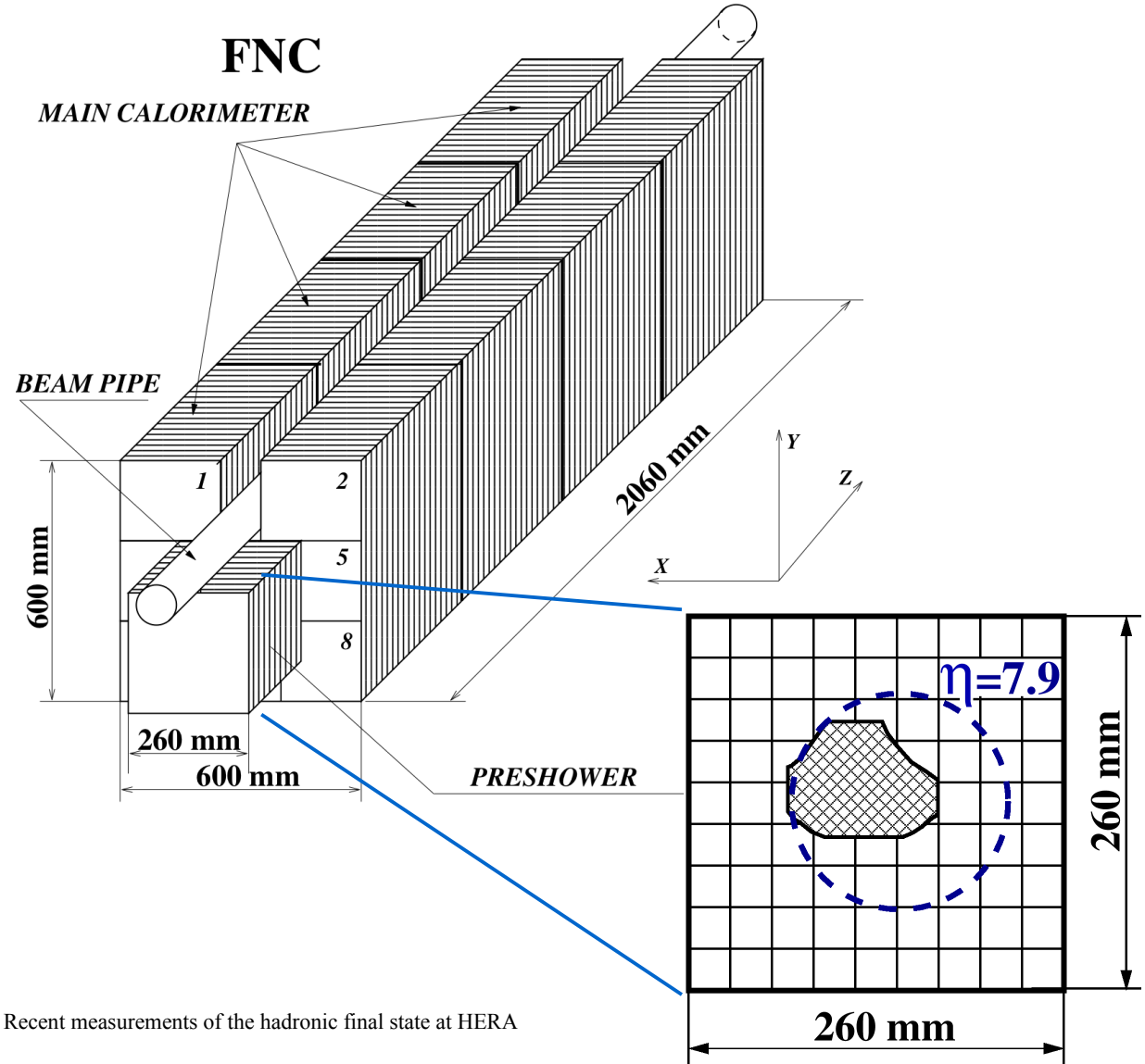


- Measurement of Feynman-x Spectra of Photons and Neutrons in the Very Forward Direction in DIS at HERA
  - DESY-14-035, arXiv:1404.0201 (accepted by EPJC)

The Forward Neutron Calorimeter of H1 (FNC)

- Situated in very forward direction at ~106m, 0° → $\eta > 7.9$.
- Lead sandwich calorimeter with two section: preshower-calorimeter and main calorimeter.
- Allows efficient discrimination of photons from neutrons. (Photons are absorbed completely in preshower-calorimeter.)





Parameters:

- Main calorimeter:
  - $8.9\,\lambda$
  - $\sigma(E)/E \approx 63\%/\sqrt{E[GeV]} \oplus 3\%$
  - $\sigma(x,y)/E \approx 10\,cm/\sqrt{E[GeV]} \oplus 0.6\,cm$
- Preshower calorimeter:
  - $1.6\,\lambda$
  - $\sigma(E)/E \approx 20\%/\sqrt{E[GeV]} \oplus 2\%$
  - $\sigma(x,y)/E \approx 2\,mm$
- Acceptance ~ 30%

Neutron and Photon Production in Forward Direction

Photons in forward direction:

- Almost exclusively originate from decays of neutral mesons produced in fragmentation of the proton.

Neutrons in forward direction:

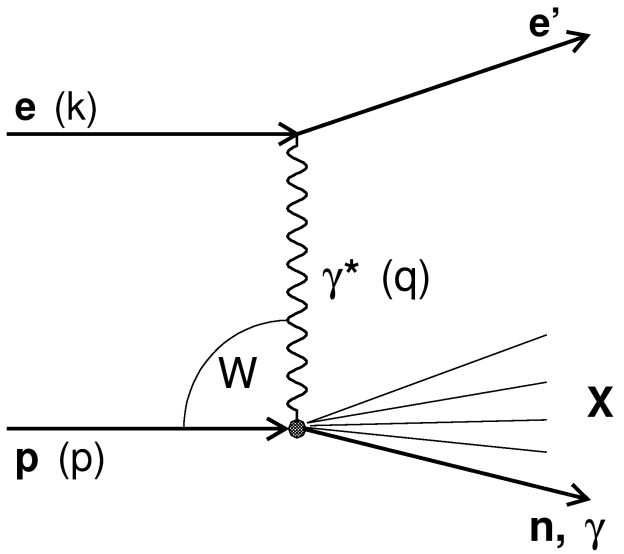
- From decays of neutral mesons produced in fragmentation of the proton.
- Production via pion exchange (Color singlet process).

DIS kinematics:

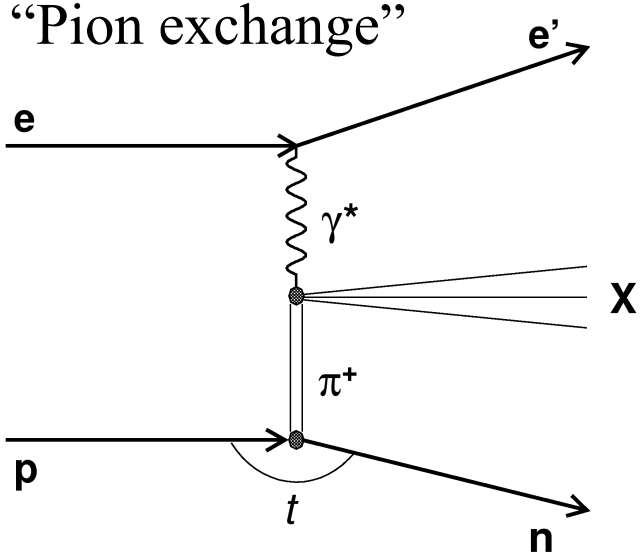
- Photon virtuality: Q^2
- Squared cm energy of ep system: s
- CM energy of γp system: W
- Feynman-x: $x_F = 2\, p^*_{\parallel} / W$

  (Approx. the longitudinal momentum fraction of the neutron)

"Proton fragmentation"

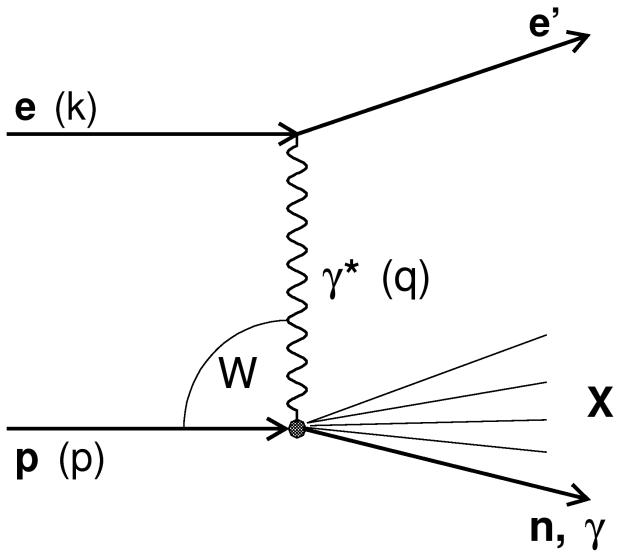


"Pion exchange"



ep scattering MC models

"Proton fragmentation"



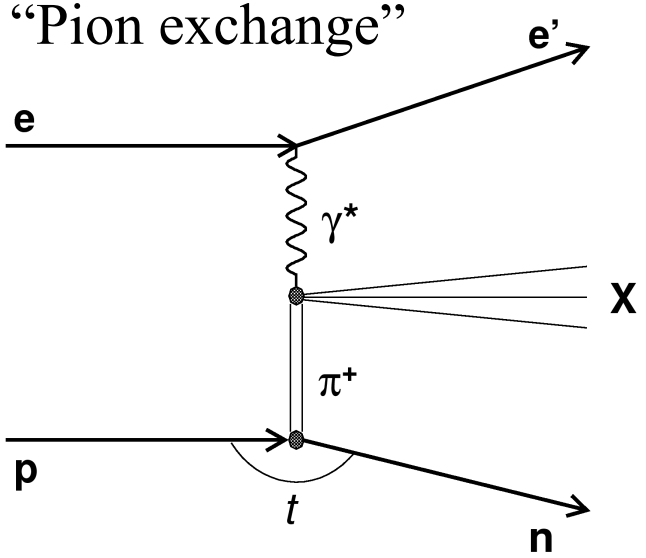
LEPTO

- DJANGOH and Leading Log PS for higher order QCD effects.

Color Dipole Model (CDM)

- DJANGOH and ARIADNE for color dipole model

"Pion exchange"



RAPGAGP-π

- RAPGAP with virtual photon scattering exclusively off exchanged pion.

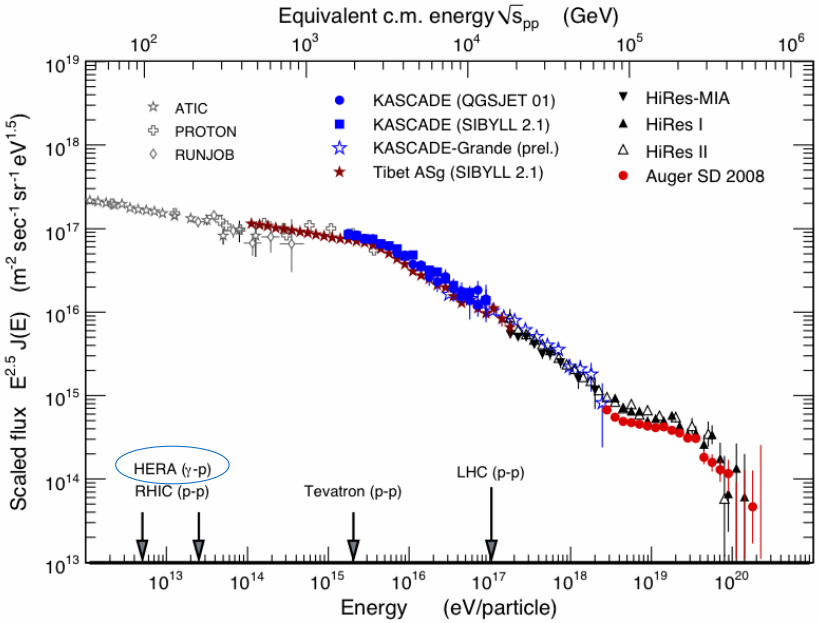
➢ All models with Lund string fragmentation.

Motivation

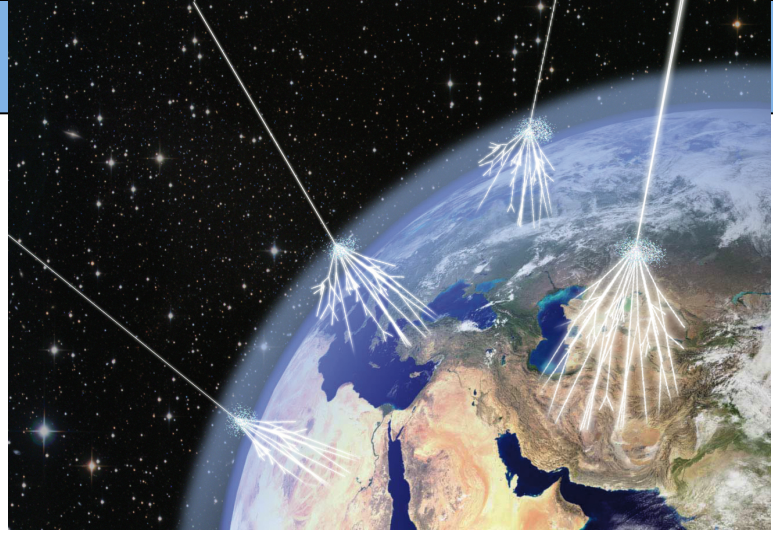
1. Confront data with ep MCs in extreme corner of phase space
   - Previous forward neutron analysis only can be well described by combination of proton-fragmentation and pion exchange:
     - 0.7 LEPTO + 0.6 RAPGAP-π
     - 1.4 CDM + 0.6 RAPGAP-π
   - Previous forward photon analysis: single differential spectra are not well described by models.
   - This analysis: compare forward meson ($\pi \rightarrow \gamma\gamma$) and forward baryon production double-differentially in the same variables.

2. Test Feynman-scaling of photons and neutrons in forward direction:
   - Expect shape of Feynman-x to be independent of centre-of-mass energy W.

3. Provide input to cosmic air shower models
   - Ratio between neutral and non-neutral particles
   - Scaling or non-scaling of neutral particles
   - Tune leading particle energy distributions.



Cosmic Air Shower Models

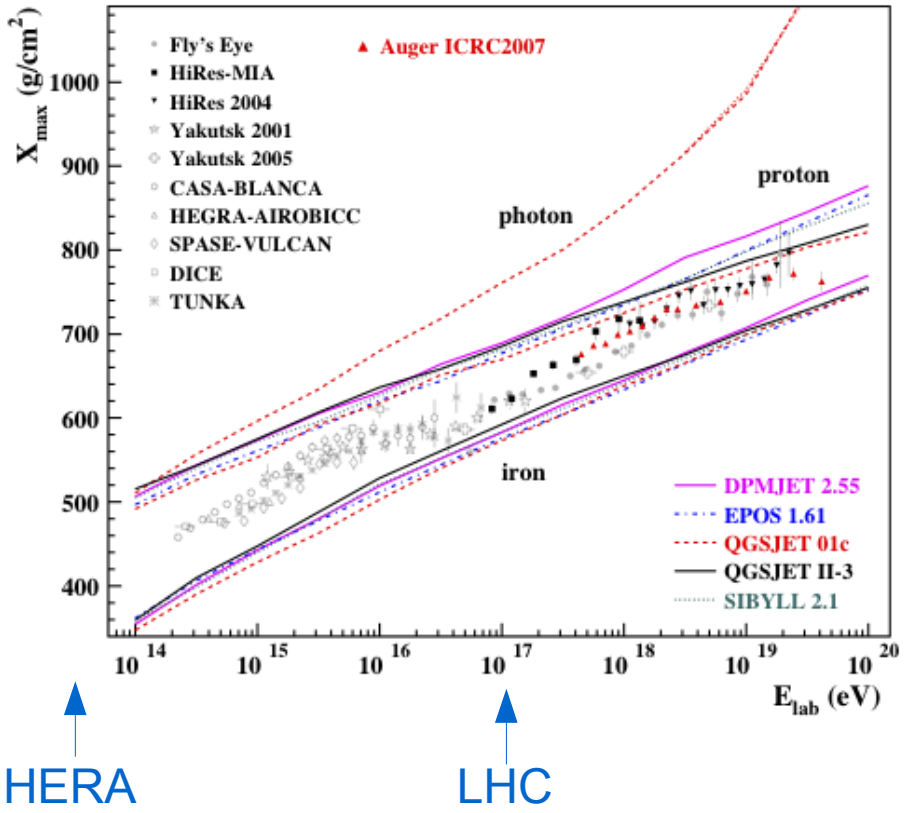


Cosmic Air Shower Models, confronted with the data:

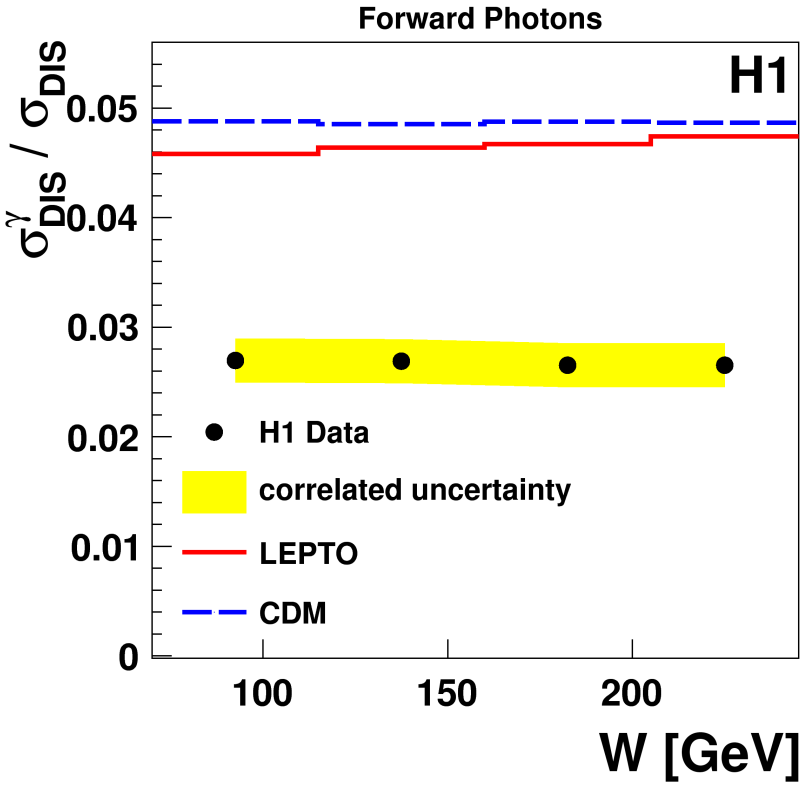
- SIBYLL 2.1, QGSJET 01, QGSJET II-04, EPOS LHC
- Adapted to ep-scattering via interface to PHOJET.
- Models are based on Regge-Theory, Regge-Gribov approximation, pQCD (but details may differ).

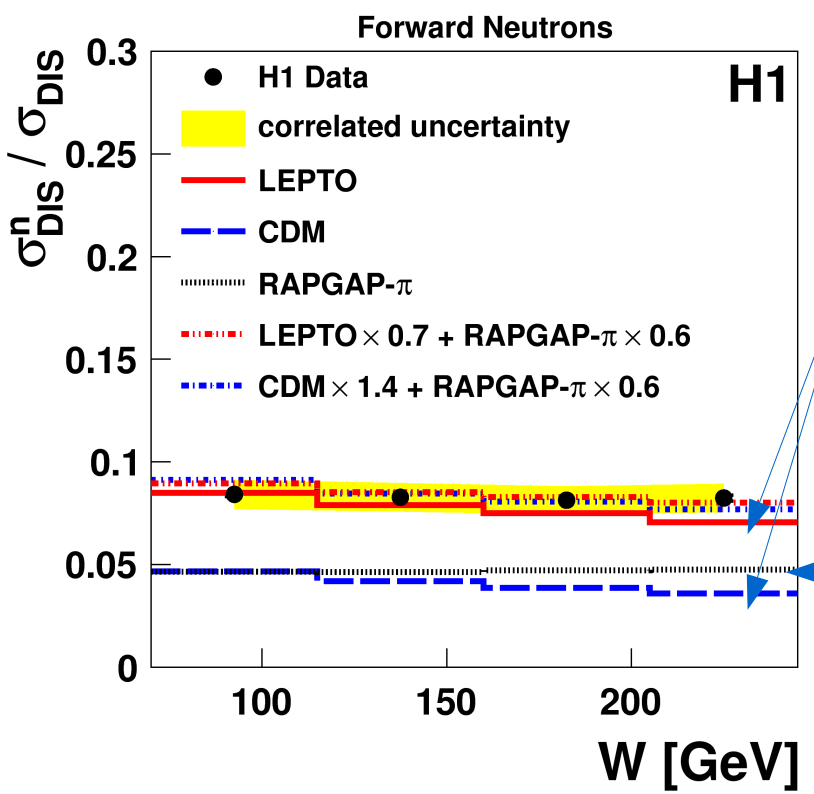
Mean depth of shower maximum compared to model predictions

- Data from colliers can provide input to air showering models.

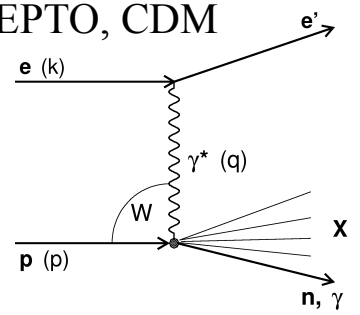


Normalized Cross Sections as a function of W

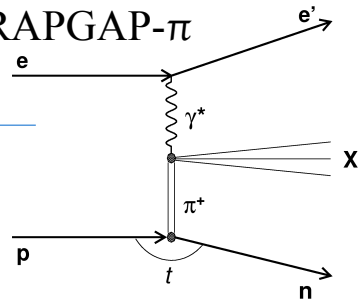




"Proton fragmentation"
LEPTO, CDM



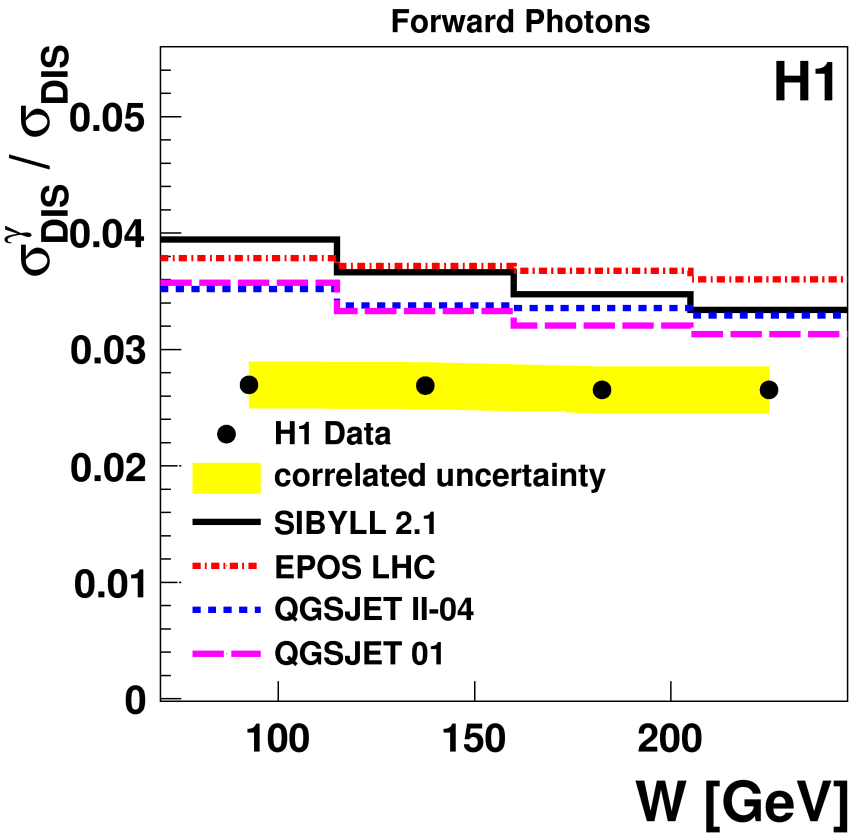
"Pion exchange"
RAPGAP-π

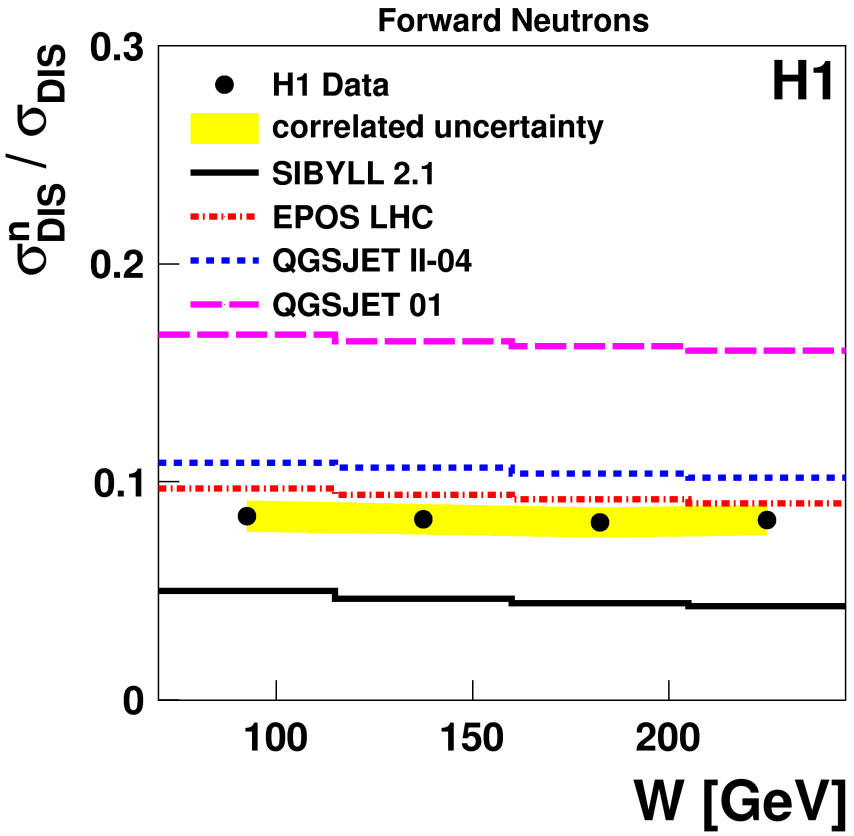


- Cross section independent of presence of forward neutron or photon. (limited fragmentation hypothesis fulfilled.)

- LEPTO and CDM predict a too high forward photon rate (~70%)
- LEPTO prediction for forward neutrons is consistent with data, CDM too low.
- Shown in previous measurement: neutron energy distribution can only be described by combination of standard fragmentation and pion exchange. Model combination describes forward neutron data well. (Weighing factors determined by fit to energy distribution.)

Normalized Cross Sections as a function of W





- All cosmic air-shower models predict a too high photon rate (~30-40%) and a slightly falling W spectrum (not seen in data).
- The cosmic air-shower models show some spread for the forward neutron cross sections. No significant W-dependence seen, as in data.

Normalized Cross Sections as a function of x_F in 3 W bins

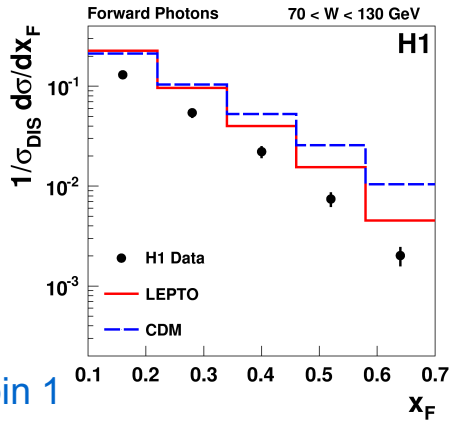
Forward photons

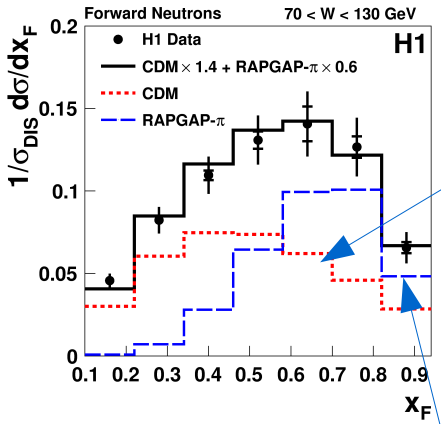
- LEPTO and CDM overestimate rate.
- Shape of measurement described by LEPTO, CDM too hard.

Forward neutrons

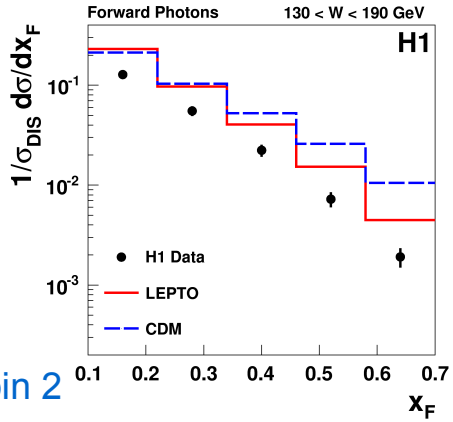
- Combination of CMD and RAPGAP-π show a good description of the data.
- Combination of LEPTO and RAPGAP-π works equally well (not shown).

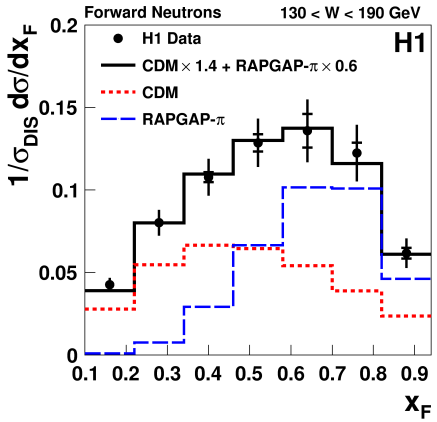
W-bin 1



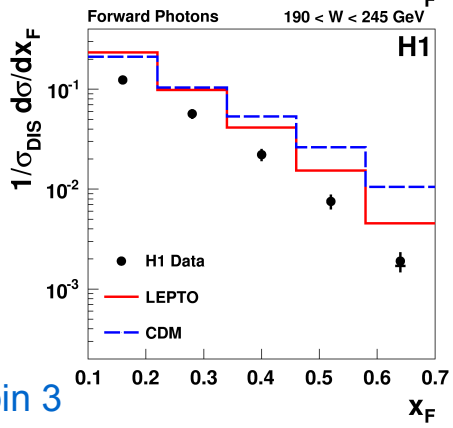


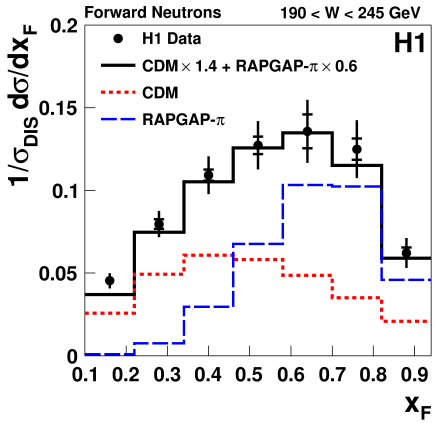
W-bin 2



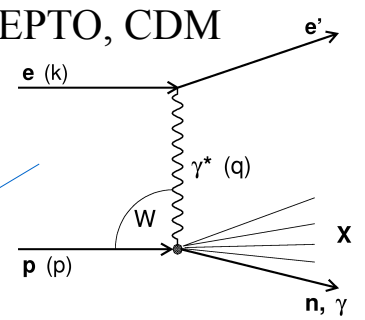


W-bin 3

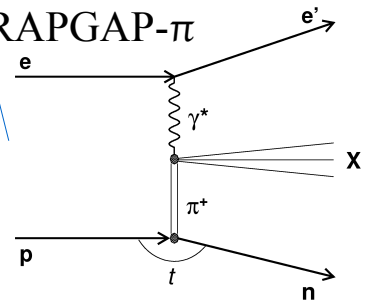




"Proton fragmentation"
LEPTO, CDM



"Pion exchange"
RAPGAP-π



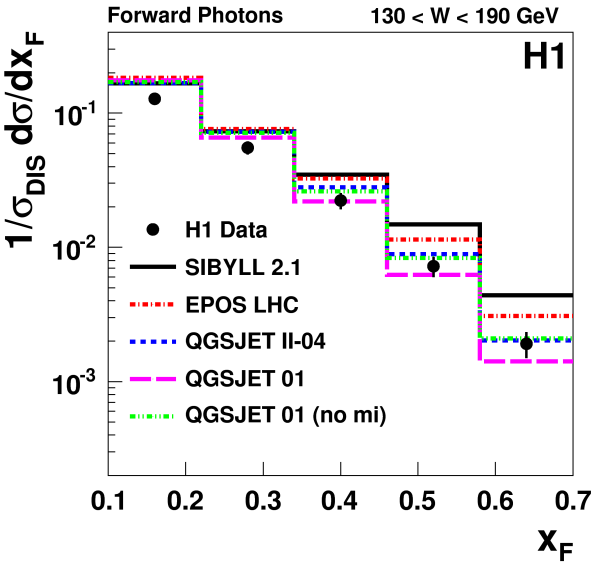
Normalized Cross Sections as a function of x_F for W bin 2

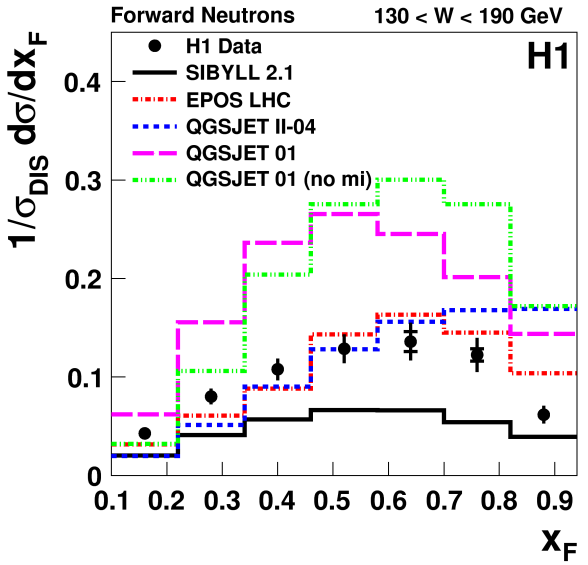
Forward photons:

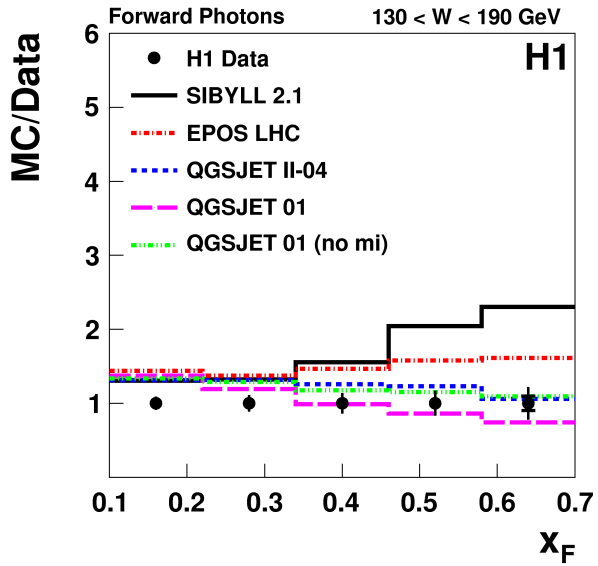
- All cosmic air-shower models predict a too high rate at low x_F.
- Shape of cross section in general better for air-shower models than for standard ep-MCs, in particular for EPOS LHC.

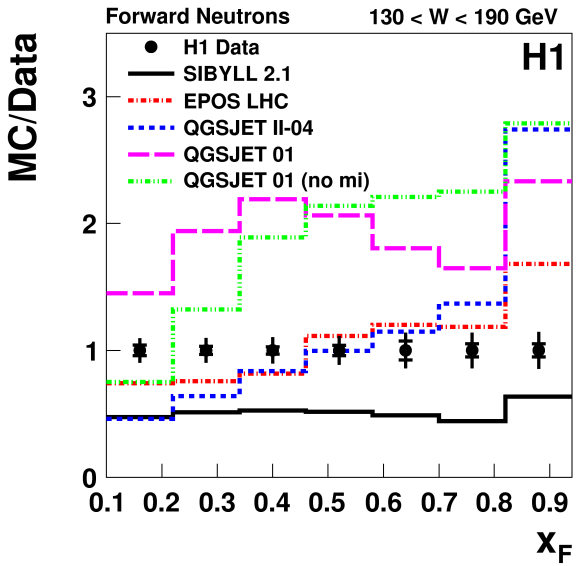
Forward neutrons:

- The air cosmic air-shower models predict very different neutron x_F-spectra.
- EPOS LHC provides a reasonable description except at highest xF values.
- SIBYLL 2.1: describes shape, fails in normalization.
- QGSJETT II-04: to hard xF dependence.
- QGSJET 01, too high rate.





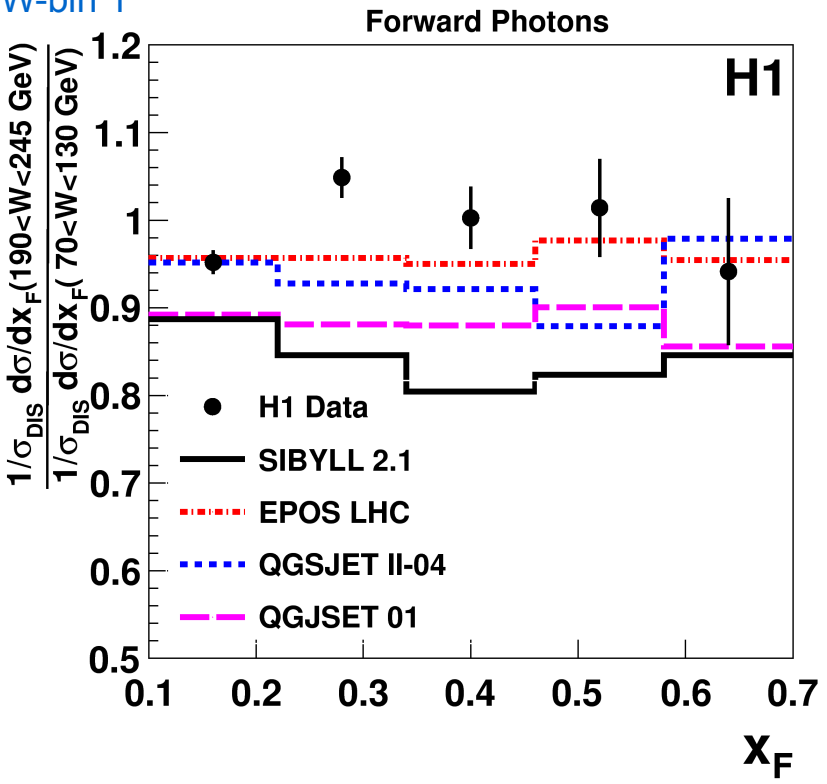


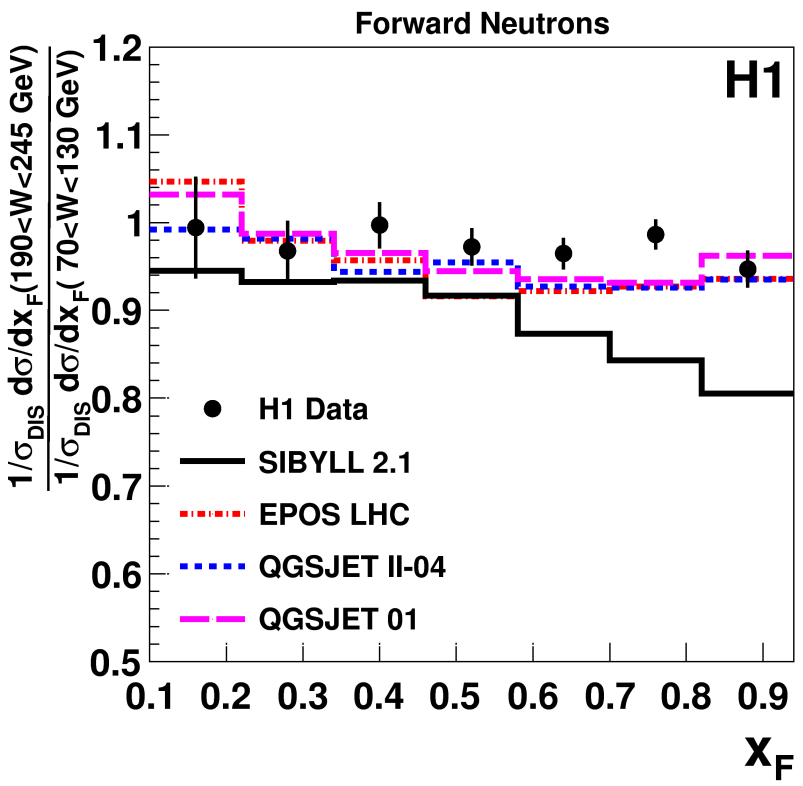


Feynman scaling

- Expect Feynman-x distributions to stay unchanged as a function of W.
  - Compare Feynman-x distributions in 3 W-bins, by ratios W-bin 2/W-bin 1, W-bin 3 / W-bin 1.

W-bin 3 / W-bin 1





- Data show no x_F dependence, → compatible with Feynman scaling.
- The cosmic ray models show deviations from Feynman scaling for forward photons.
- For forward neutrons the cosmic ray models are consistent with Feynman scaling, except SIBYLL 2.1
- ep-MCs are compatible with Feynman scaling (not shown).

- Search for QCD Instanton-Induced Processes in DIS at HERA
  - H1prelim-14-031
  - Based on full HERAII data sample

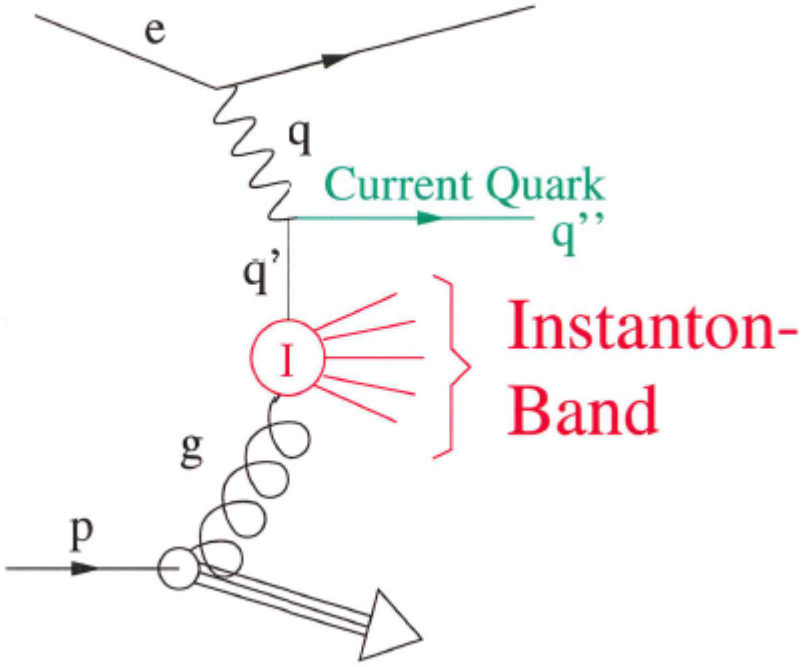
QCD-Instatons in DIS

QCD-Instantons

- … are non-perturbative fluctuations of the gluon field.
- … represent tunneling transitions between topologically non-equivalent vacua.
- … are a novel non-perturbative QCD effect at high energies, not forbidden in SM.

QCD-Instantons in DIS

- Dominant process in DIS isQuark gluon fusion
- Theory and phenomenology worked out by A. Ringwald & F. Schrempp in I-perturbation theory.

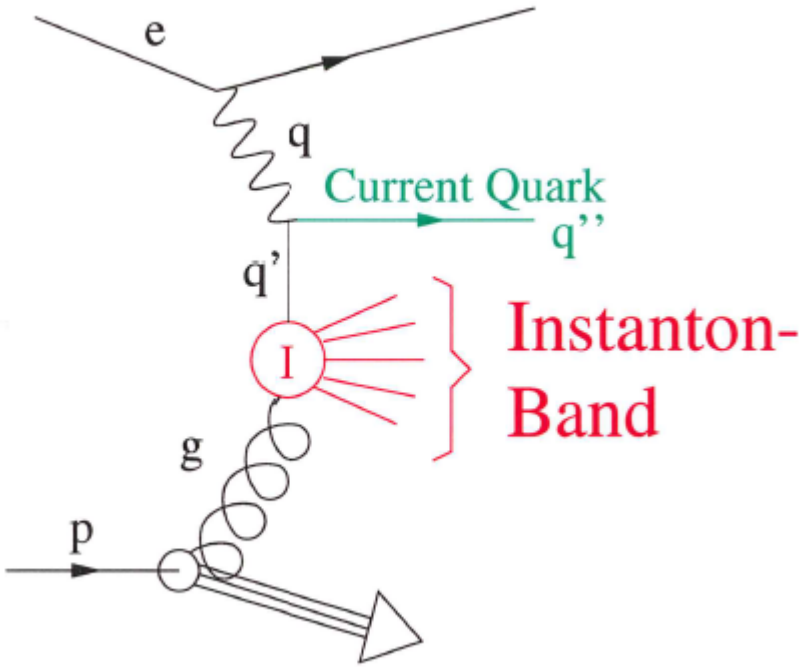


Predicted DIS cross section:

- Large enough to make an experimental observation possible
- Much much smaller than inclusive DIS cross section → experimentally challenging!

S. Moch, A. Ringwald, F. Schrempp, Nucl Phys. B 507 (1997) 134 [hep-ph/9609445],
A. Ringwald, F. Schrempp, Phys. Lett. B 438 (1998) 217 [hep-ph/9806528],
A. Ringwald, F. Schrempp, Phys. Lett. B 459 (1999) 249 [hep-ph/9903039].

Hadronic final state signature of instantons



Instantons events

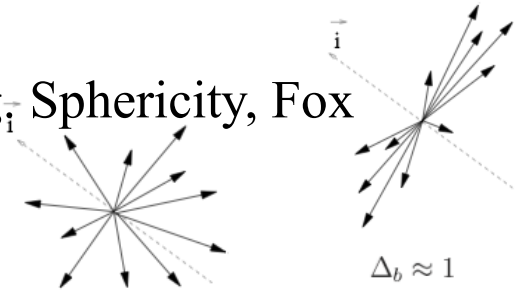
- … have a "fireball"-like final state with a very high number of hadrons. → leads to a densely populated band, flat in φ.
- … a high total transverse energy.
- … and additional hard jet (not from instanton).

Analysis selection:

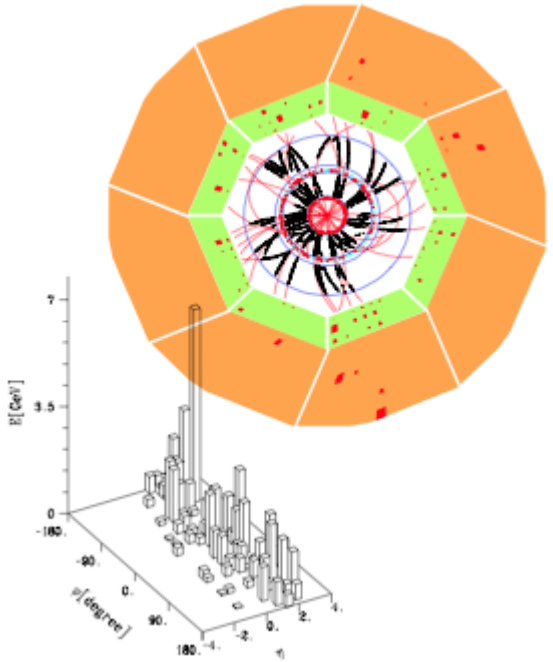
- DIS selection
- Find hardest jet
- Boost to objects from instaton band $\langle\eta\rangle = \pm 1$ to instanton rest frame

Discrimination observables in instanton rest-frame:

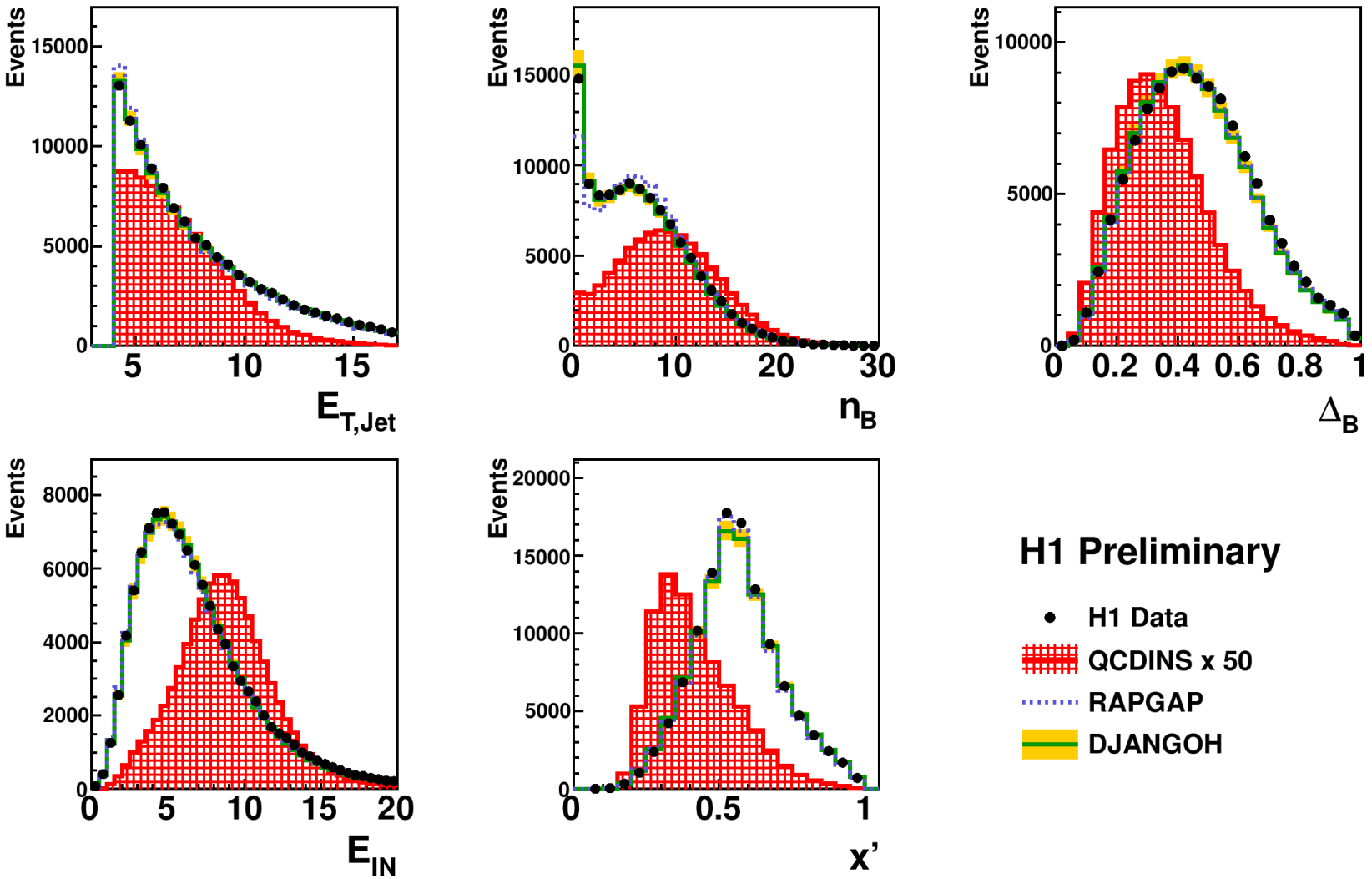
- Number of charged particles in band, n_B
- Transverse energy of band E_{TB}
- Set of topological quantities: e.g. Sphericity, Fox Wolfram moments, isotropy



- Variables combined in one discriminator (Multi Variate Analysis)



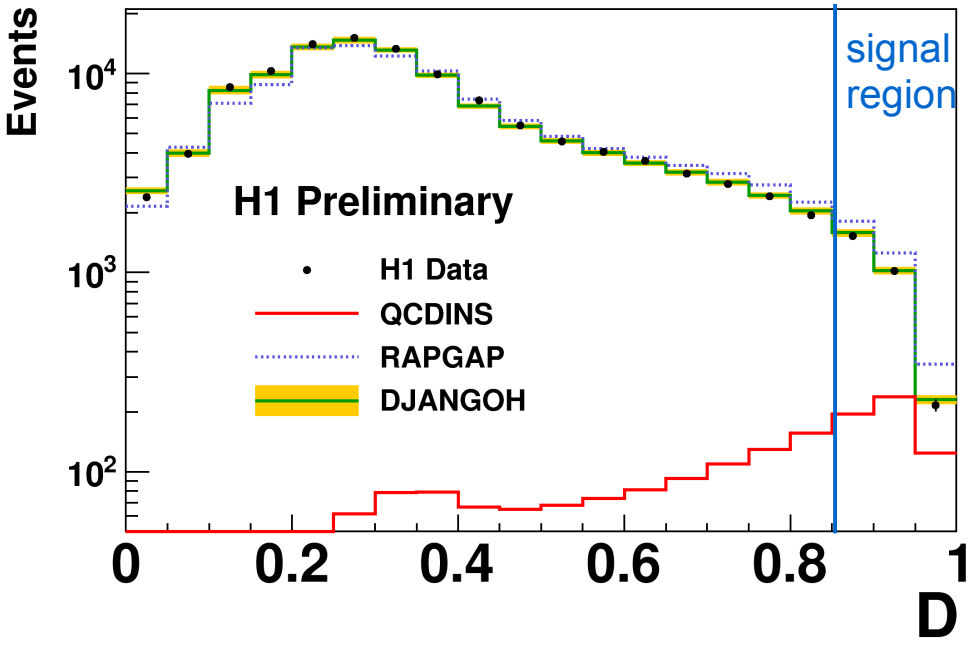
Input variables to MVA



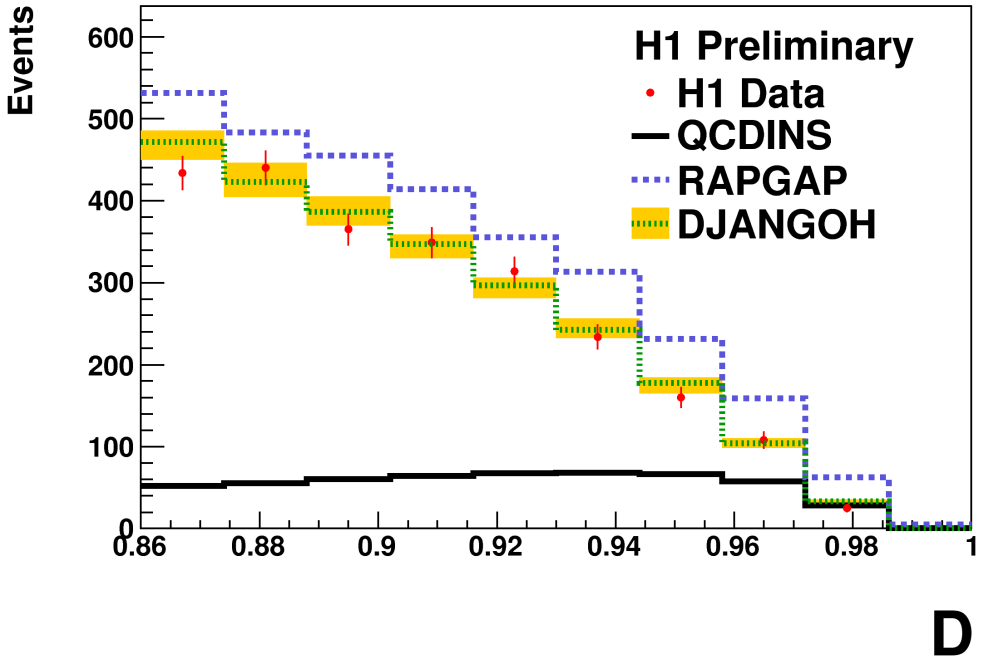
- Clear difference in all distributions between signal and background.
- Good description of all input distributions.

Combined discriminator (MVA)

- Full phase space of analysis



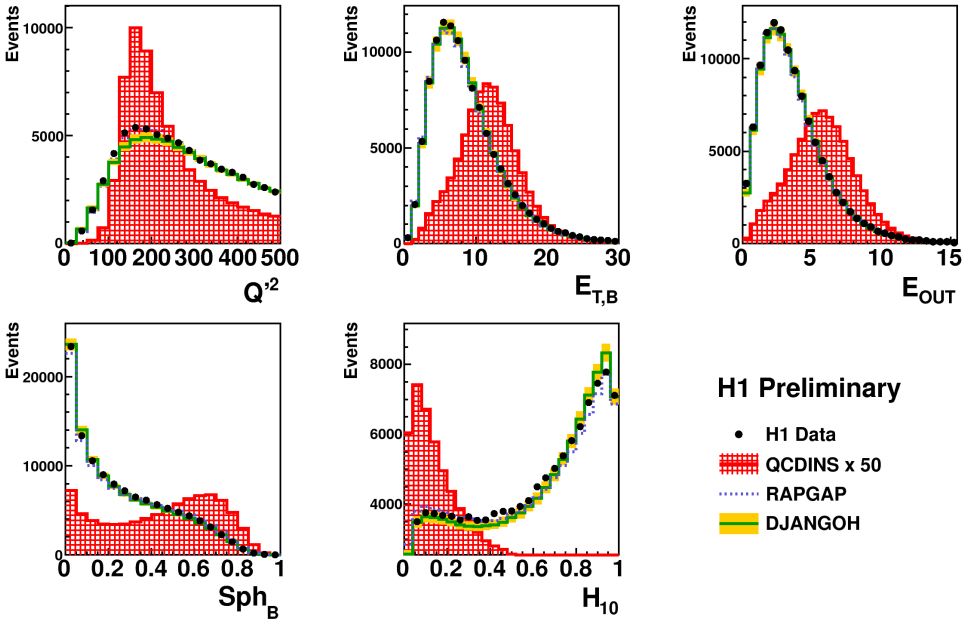
- Signal region



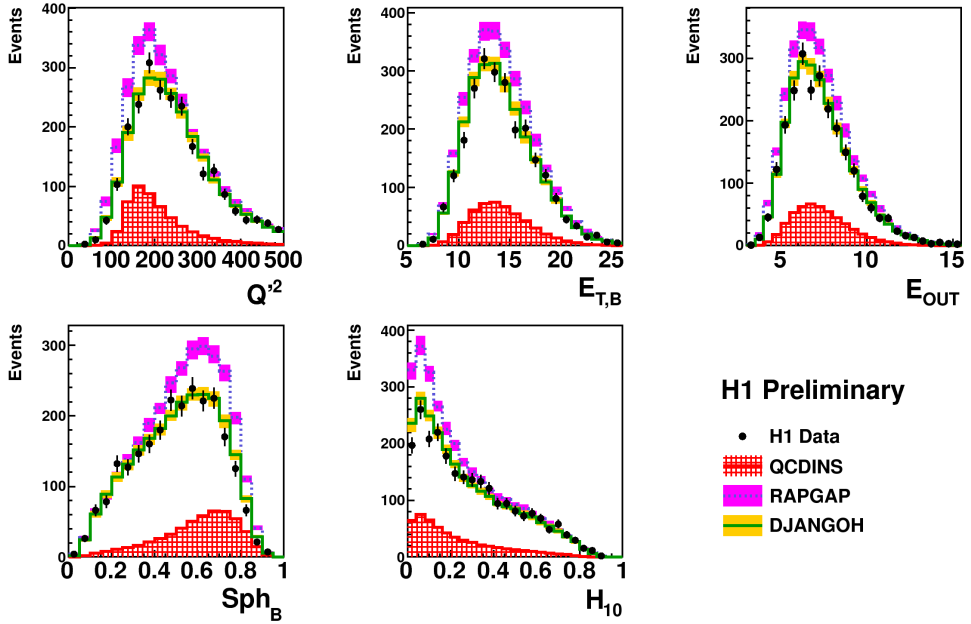
- Data are consistent with the background, in full range of the discriminator D.
- No evidence for a QCD instanton in the form predicted by the Ringwald-Schremp model.

Control distributions for discriminating variables not used in MVA

- Full phase space of analysis

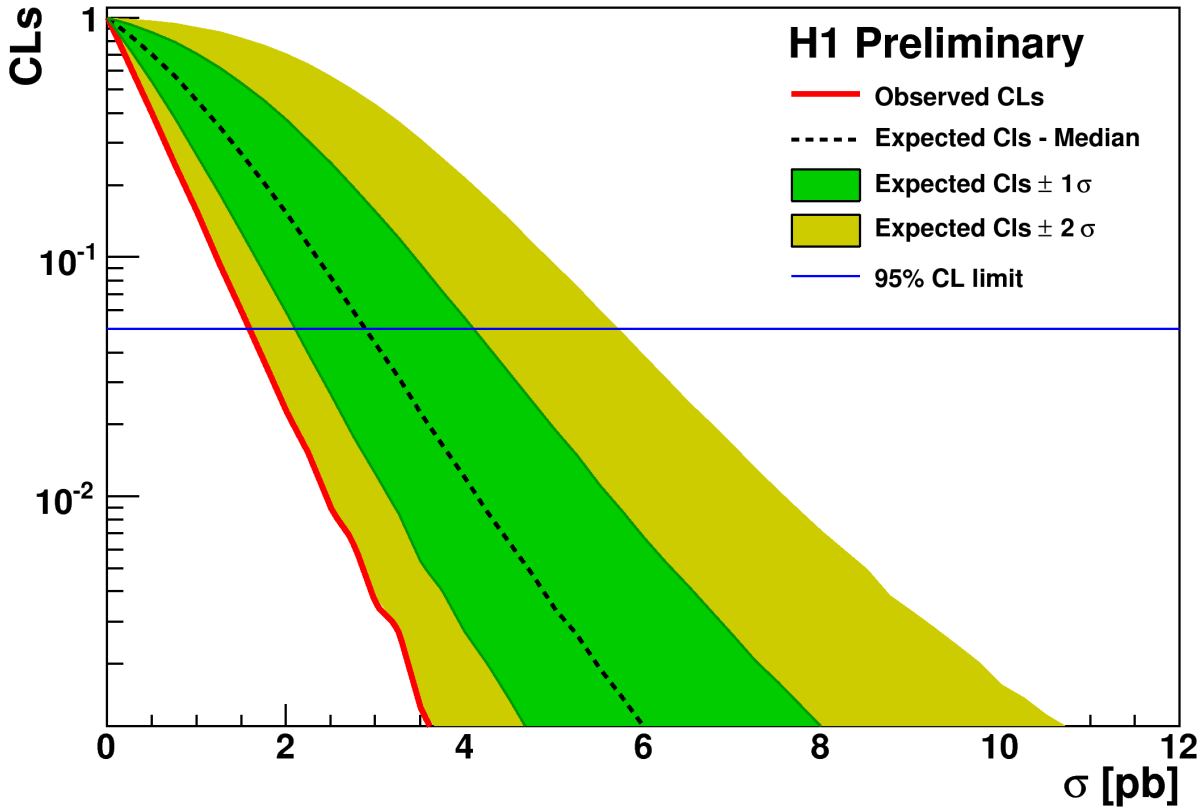


- Signal region



- Good description of discrimination distributions, not used in the MVA.
- Also in these variables no excess in signal region seen.

Upper limit



- Predicted cross section for the phase space of the analysis:
  10 ± 2 pb

- Determined upper limit on the instanton at 95% confidence level:
  1.6 pb

Summary and Conclusions

- Forward neutrons and photons:
  - DIS ep models: photon rate overestimated, neutron spectrum well described by combination of proton fragmentation and pion-exchange.
  - Cosmic Air shower modes: none describes neutron and photon spectra simultaneously well.

- Search for Instantons:
  - Data are consistent with the background, no evidence for an Instanton (in the Ringwald-Schremp model) seen.
  - Upper limit on instanton cross-section: 1.6 pb at 95% confidence level.