Hadronic Final States at HERA

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On behalf of the H1 and ZEUS collaborations

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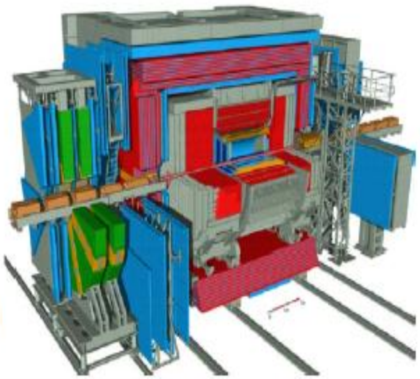
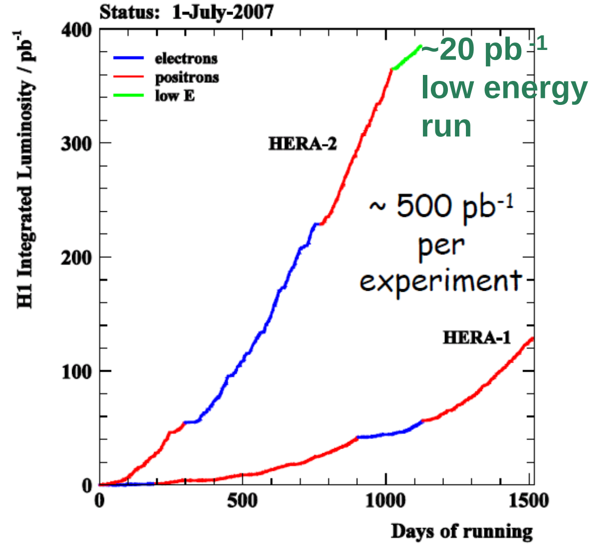
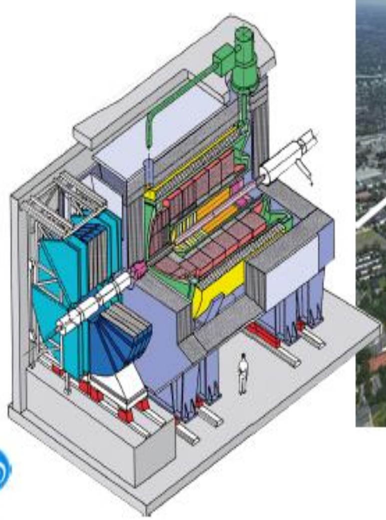
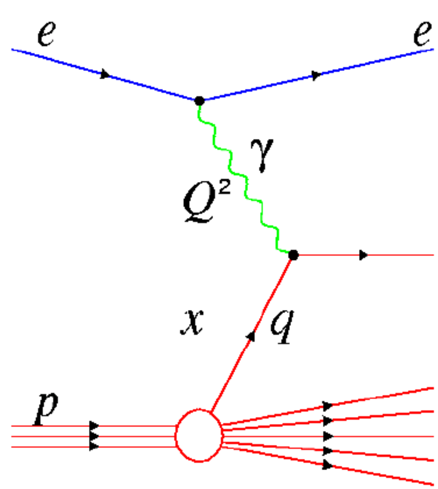
HERA experiments

- ep collider:
- $e^{\pm}$ energy: 27.6 GeV
- p energy: 920 GeV
- Center of mass energy: 319 GeV
- 2 collider experiments: H1 and ZEUS
- Integrated luminosity: ~0.5 fb^{-1} (per experiment)









Q^2 – photon virtuality ($Q^2 > 1$ GeV^2 for DIS)
x – Bjorken scaling variable
y – inelasticity in proton rest frame

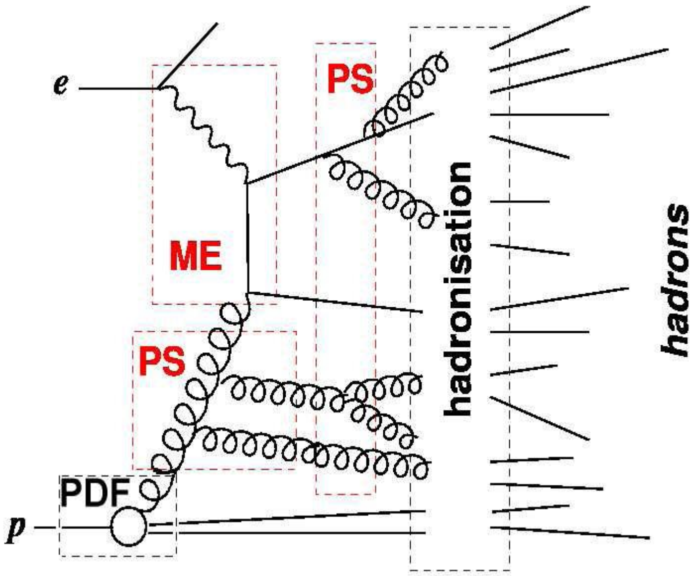
Hadronic Final States at HERA

Outline

1. Charged particle spectra (H1):
   - With proton energy E_p =920 GeV and $\sqrt{s}$ = 319 GeV
     EPJ C73 (2013) 2406
   - With proton energy E_p=460 GeV and $\sqrt{s}$ = 225 GeV
     H1prelim-13-032
2. Momentum Distributions for K^0_S and $\Lambda/\bar{\Lambda}$ (ZEUS):
   - JHEP 03 (2012) 020
3. Very Forward Neutron and Photon Production (H1):
   - H1prelim-13-012

Hadron Production at HERA

The underlying dynamics of hadron production in high energy particle interaction is still not fully understood



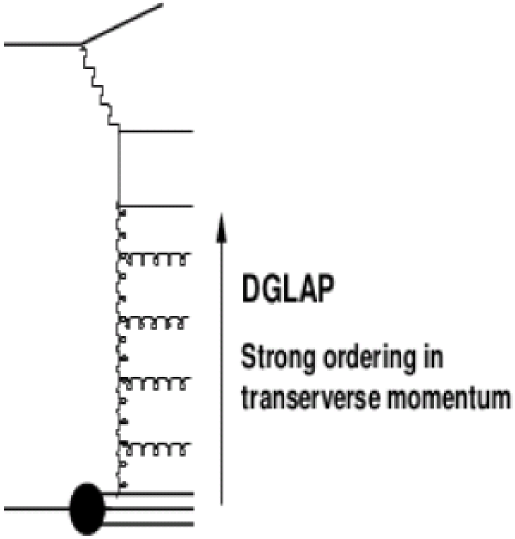
Hadron Factorisation =>
PDF ⊗ ME ⊗ Fragmentation Function (FF)

Two classes of analysis presented

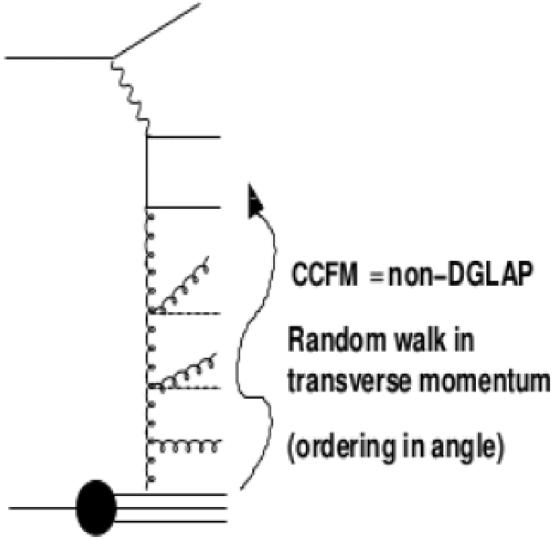
- Hadrons detected in the central detectors
  Hadronisation of protons produced by the hard subprocesses (ME)
- Hadrons close to the proton beam direction
  Proton fragmentation

Parton Evolution Models

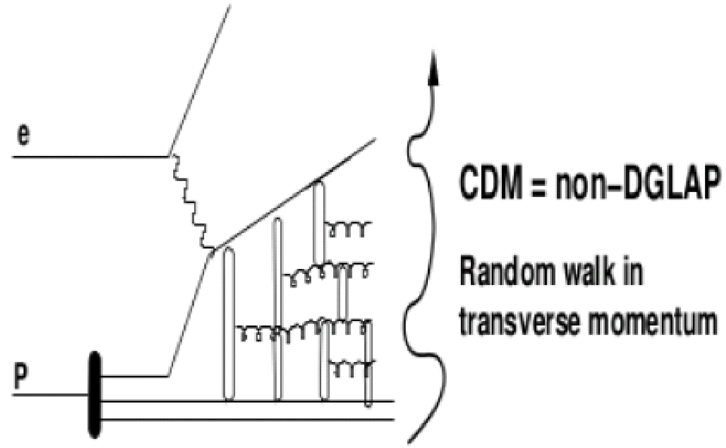
RAPGAP/HERWIG++ DGLAP



CASCADE CCFM



DJANGOH CDM



DGLAP: strong k_T ordering $k^2_{T0} \ll \ldots \ll k^2_{Ti} \ll \ldots \ll Q^2$

- RAPGAP (LO ME + DGLAP parton showers)
- HERWIG++ (POWHEG + DGLAP parton showers)
- Valid for large Q^2 and not too small x

Beyond DGLAP (random walk in k_T)

- CASCADE (off shell ME + CCFM parton showers)
  - Valid for both: large and small x
- DJANGOH (LO ME + CDM parton showers)
  - Valid at low x and not large Q^2

Fragmentation parameters tuned to e^+e^- data (ALEPH tune)

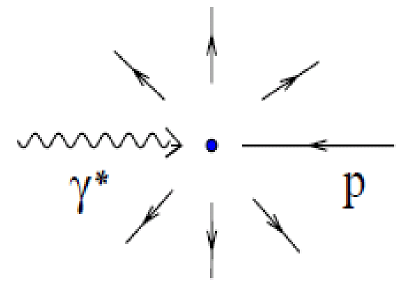
HFS and parton cascade dynamics

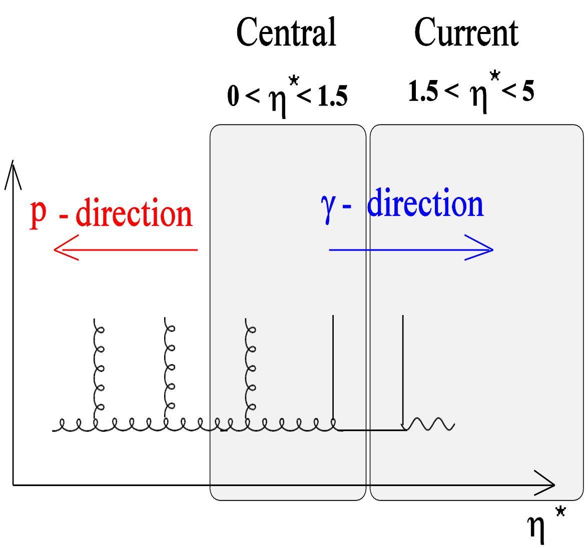
EPJ C73 (2013) 2406

As $F_2(x,Q^2)$ has little sensitivity to cascade dynamics (DGLAP and beyond-DGLAP) investigations of cascade dynamics in semi-inclusive reactions ep -> e'hX has been conducted at H1 detector at DESY:.

HERA beam energies: **E_e = 27.6 GeV,** **E_p =920 GeV,**
Kinematic region: **low photon virtuality ($5 < Q^2 < 100$ GeV^2).**
small Bjorken x ($10^{-4} < x < 10^{-2}$)

Charged particles spectra are measured as function of pseudorapidity (η*) and transverse momentum (p^*_T) in hadronic centre-of-mass system (Θ* with respect to virtual photon)





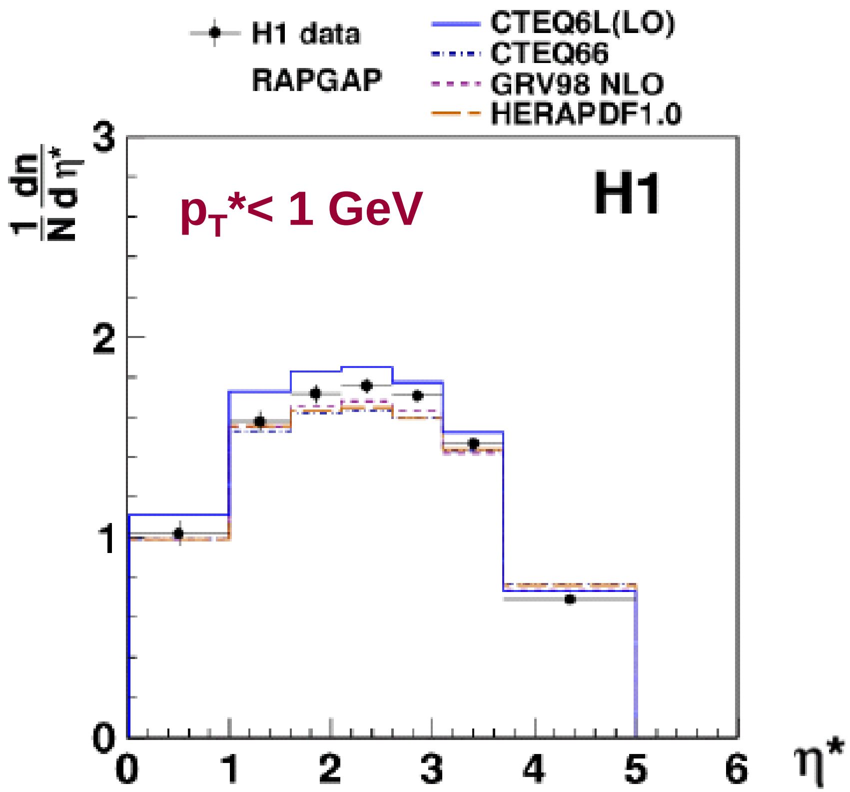
To distinguish hadronisation effects from effects due to parton evolution signature the measurements are divided into two regions:

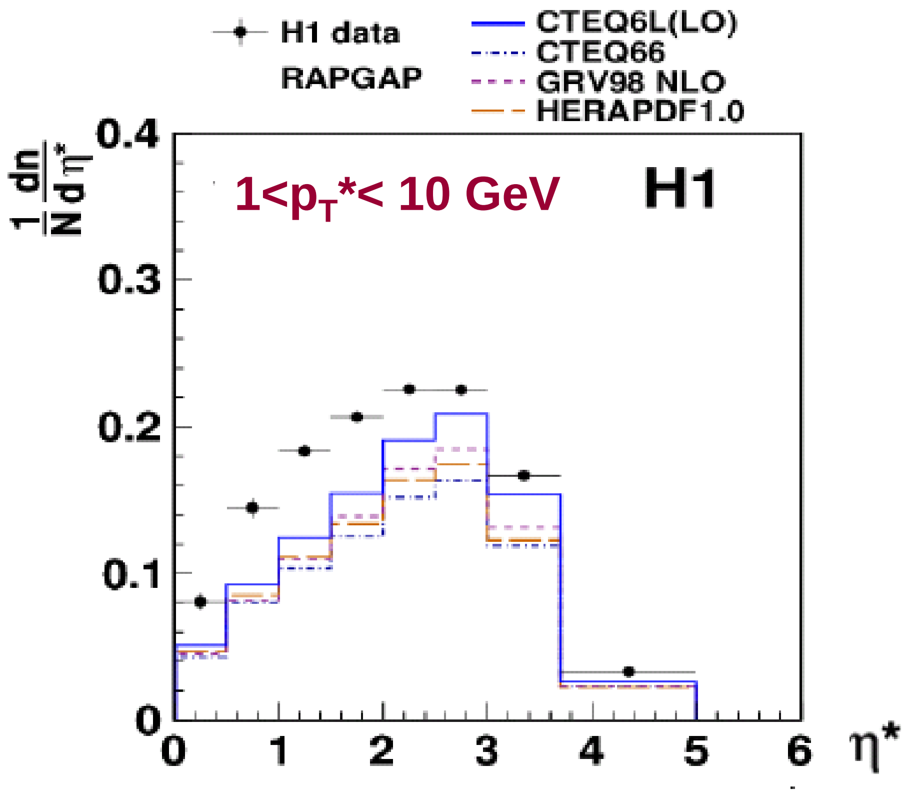
- at low p^*_T ($0<p^*_T<1$ GeV) predominantly sensitive to hadronisation
- at high p^*_T ($1<p^*_T<10$ GeV) predominantly sensitive to parton dynamics.

The p^*_T dependence is studied in the pseudorapidity intervals:

0< η*<1.5 (central region)
1.5< η*<5 (current region)

Pseudorapidity distribution (DGLAP model)

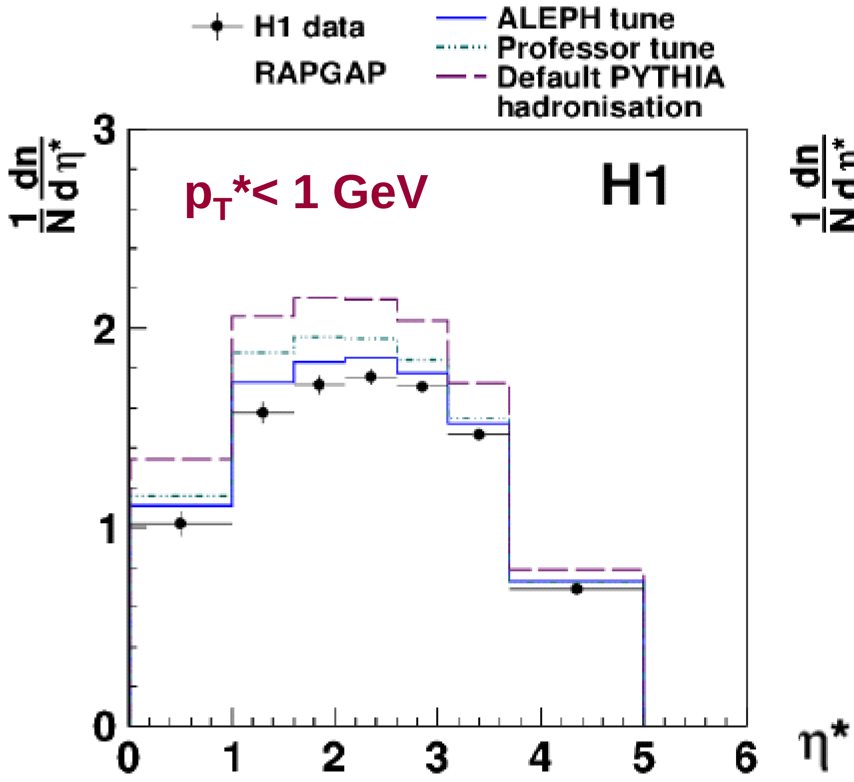


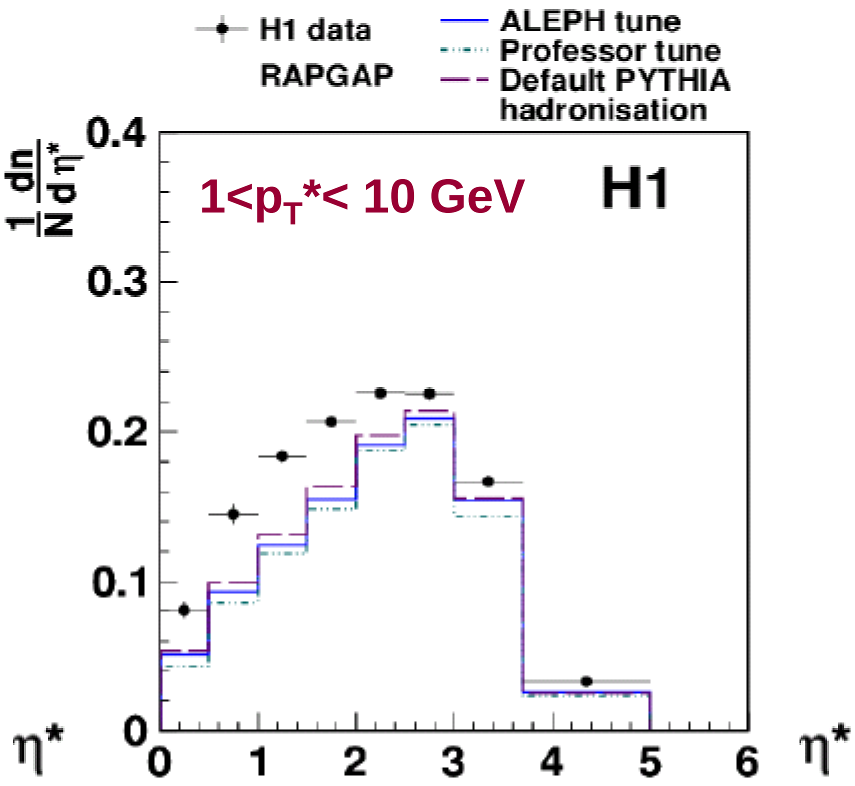


- All predictions are close to data
- LO + parton shower predictions using different p-PDFs at NLO are close to each other

- None of the predictions describe the data
- Differences between predictions for various PDFs are smaller than differences to the data

Effect of Hadronisation in the DGLAP Model

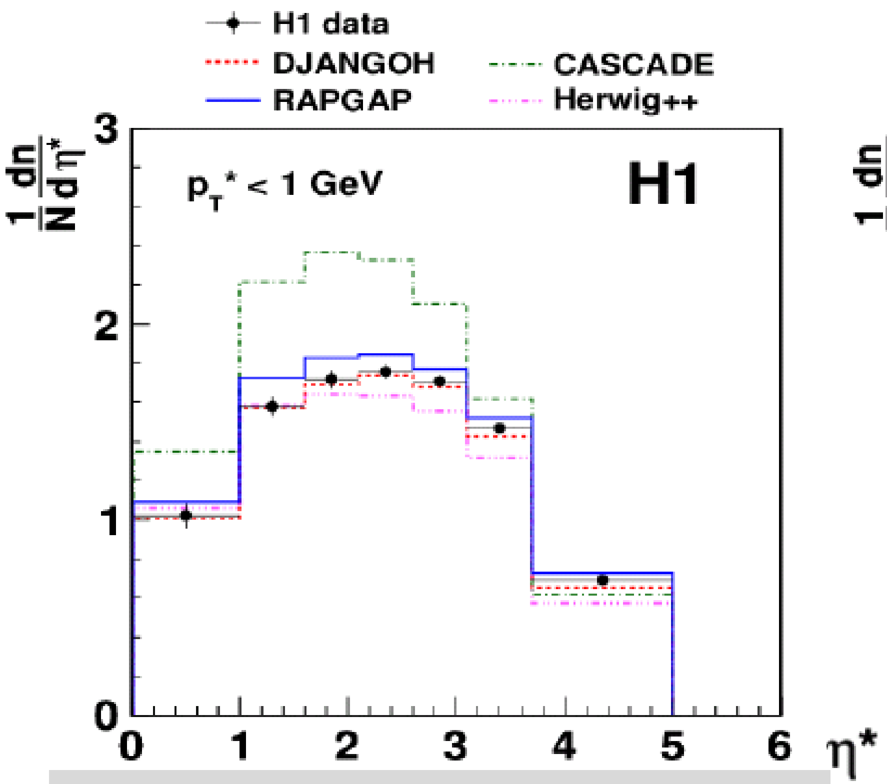


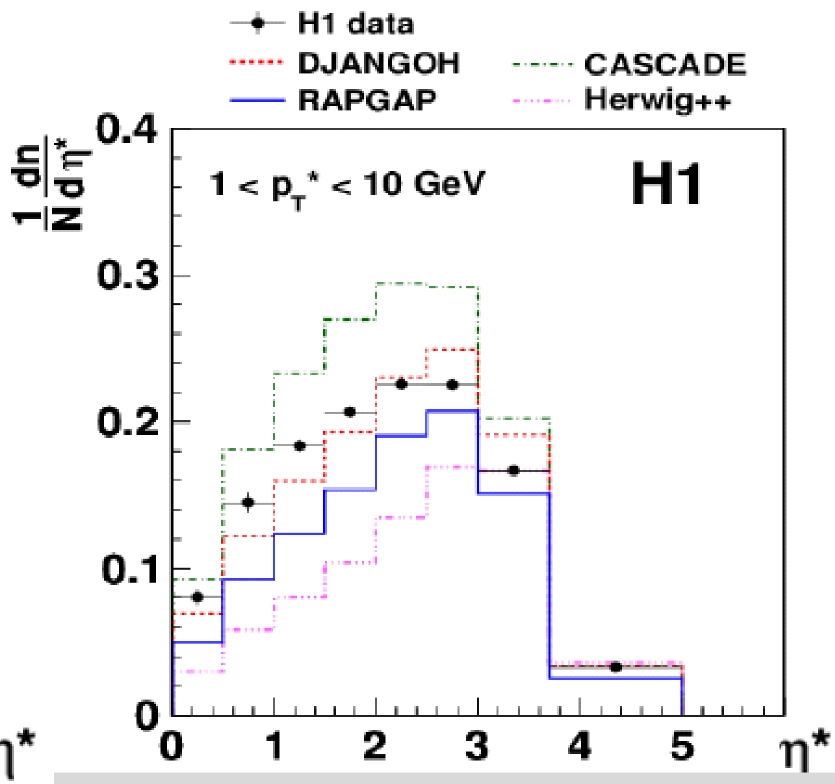


- Sensitive to tuning of hadronisation parameters
- ALEPH tuning (e^+e^-) describes the data best

- Small sensitivity to hadronisation as expected
- Parton dynamics of the RAPGAP model fails to describe the data

Parton Evolution Models



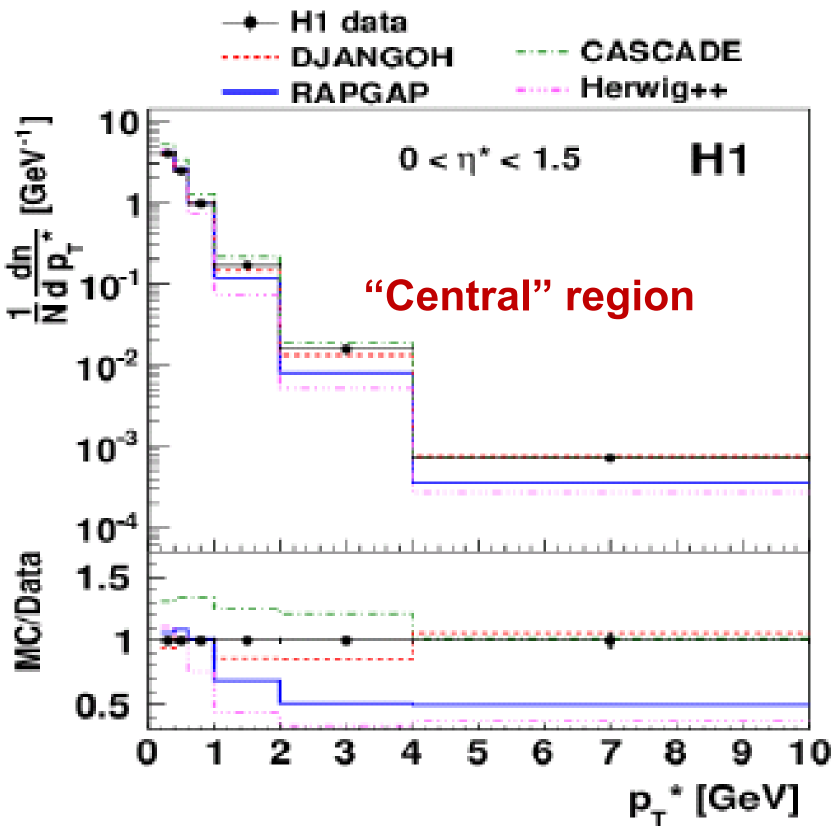


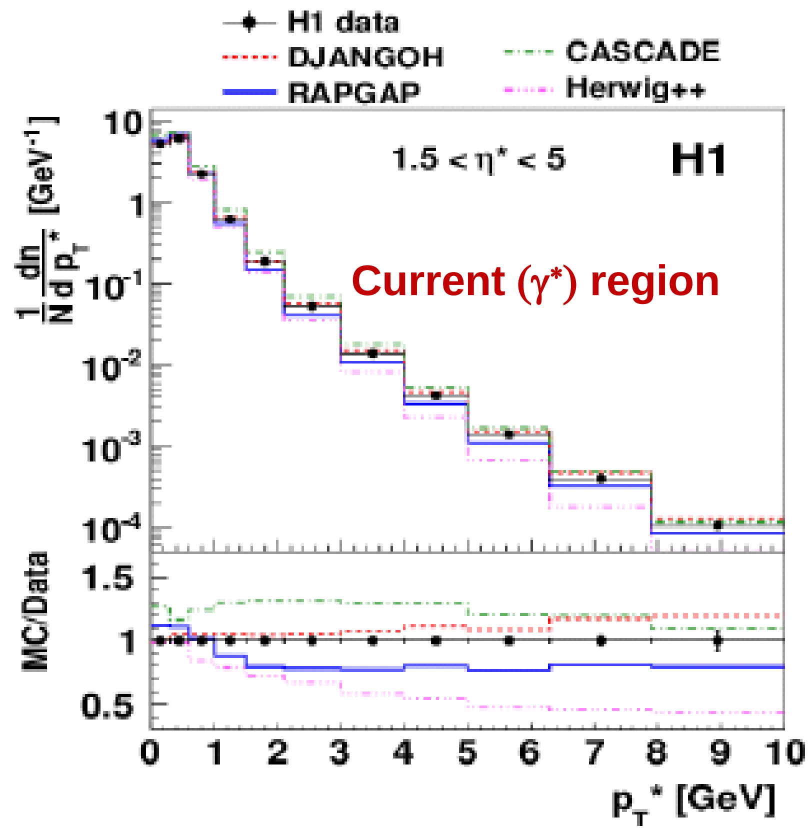
All models, except CASCADE, describe the data within PDF uncertainties

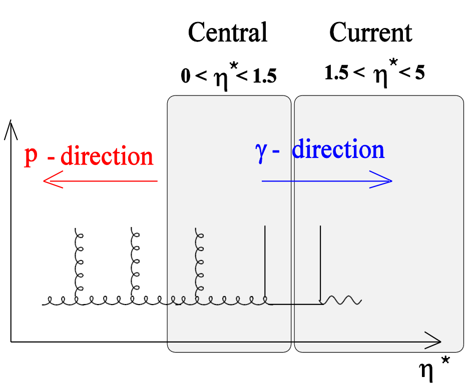
- Large differences between the various models
- RAPGAP and HERWIG++ (DGLAP models) undershoot the data for $\eta^* < 3$

DJANGOH (CDM) describes the data better than other models in both p^*_T regions

Transverse momentum distribution



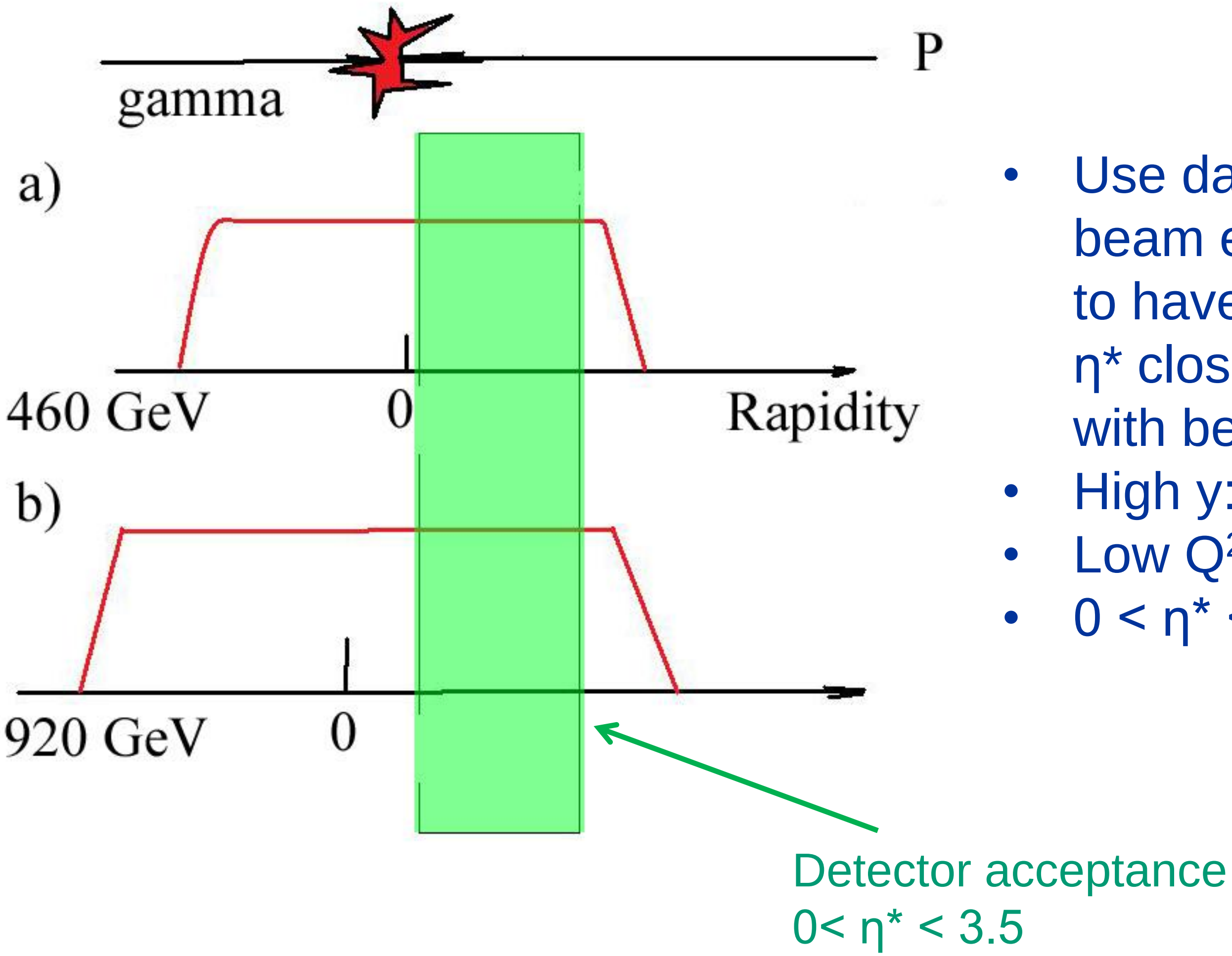




- Predictions based on different parton shower dynamics differ significantly at high p^*_T.
- RAPGAP and HERWIG++ (DGLAP) strongly undershoots the data in the central but also in the current region
- DJANGOH (CDM) provides the best description of experimental data in both p^*_T and η^* regions but still is not good

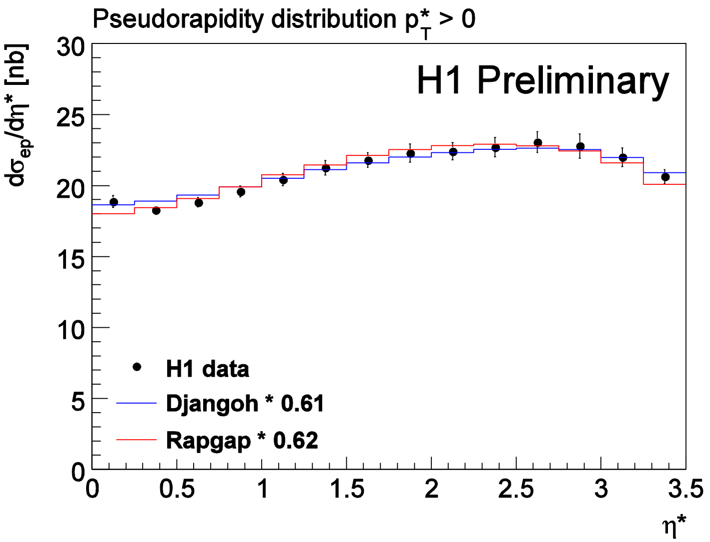
Charged Particles Spectra at Low $\sqrt{s}$

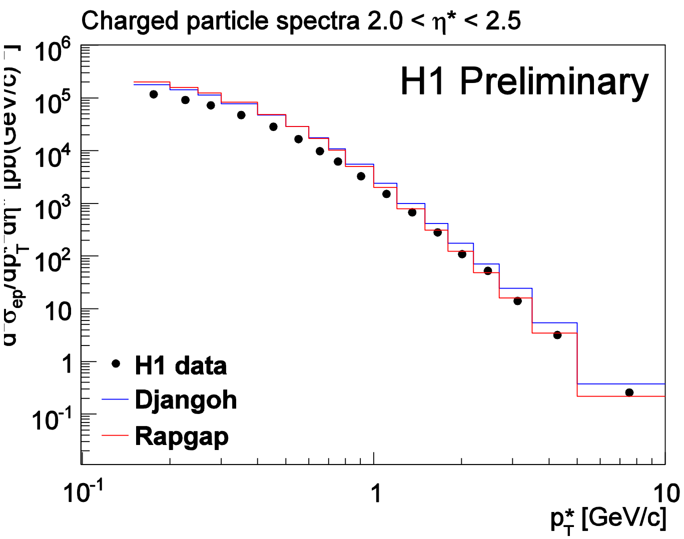
H1prelim-13-032

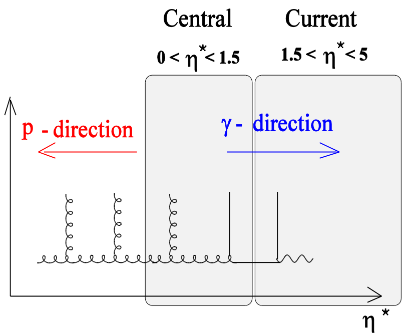


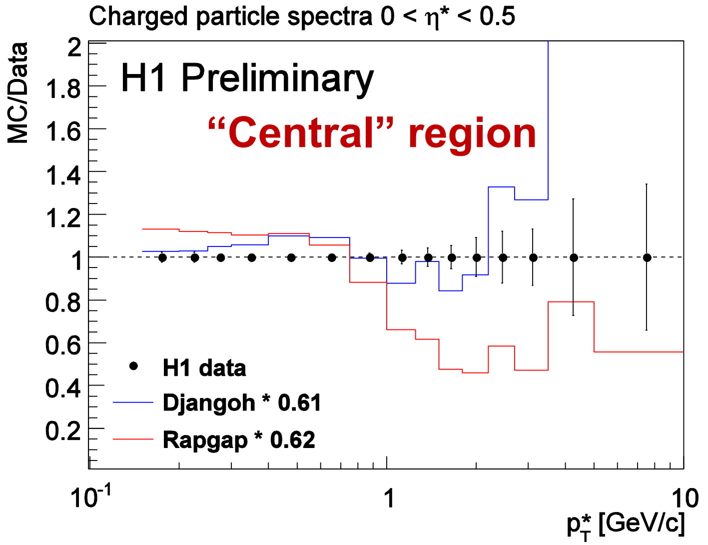
- Use data with reduced proton beam energy E_p = 460 GeV to have higher acceptance in η* closer to the central region with better resolution
- High y: $0.35 < y < 0.8$
- Low Q^2: $5 < Q^2 < 10$ GeV^2
- $0 < \eta^* < 3.5$

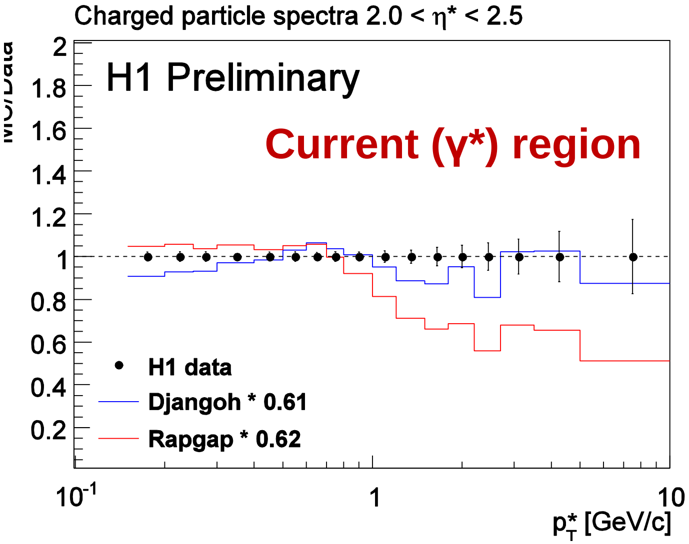
Data and MC Comparison







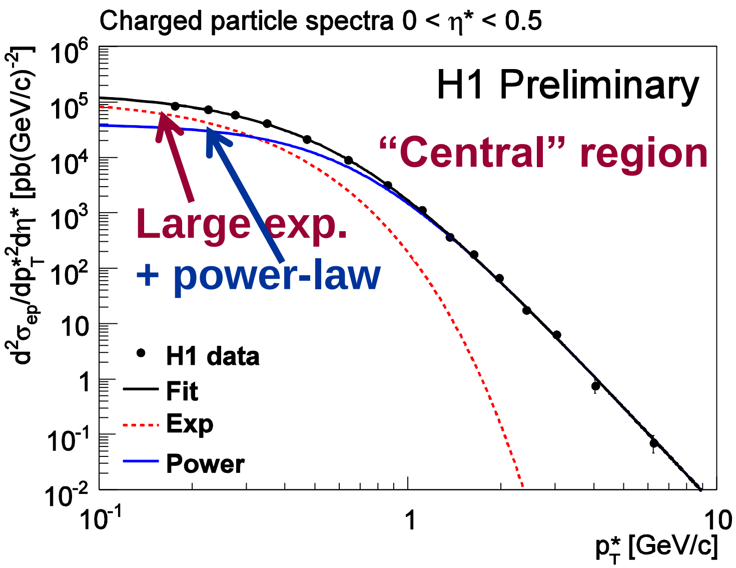




DJANGOH and RAPGAP describe the shape of η^* distribution well, but none describes the shape of p^*_T spectra

Charged Particles Density at Low $\sqrt{s}$

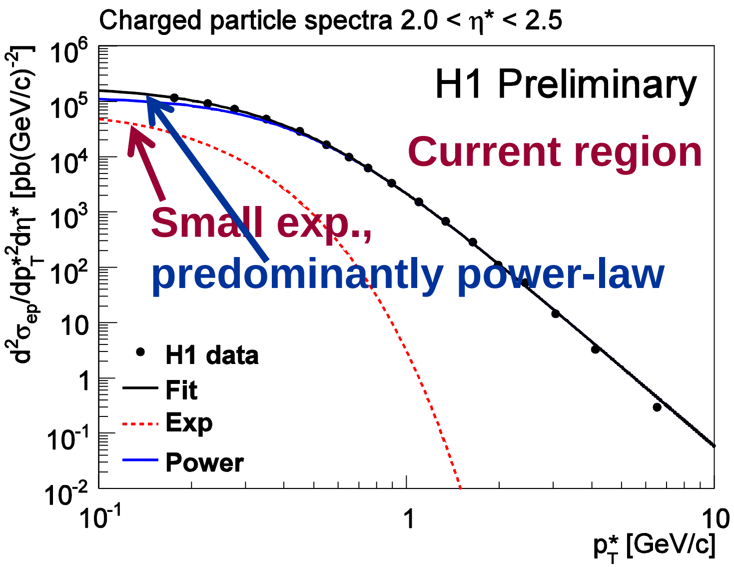
Phenomenological model (A.Bylinkin, A.Rostovtsev) successfully describes p_T spectra as a sum of exponential (Boltzmann-like) and a power-low functions.

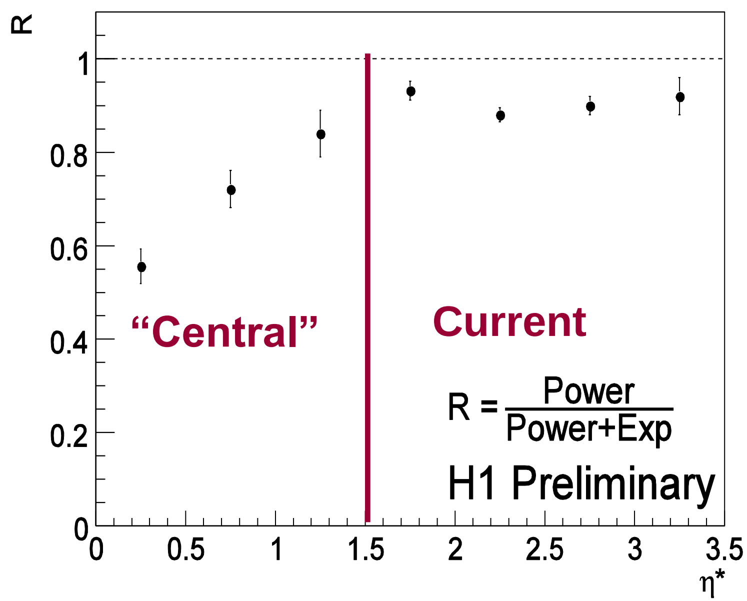


Observe transition between two contributions: from power-law distribution in the current region (large η*) to significant exponential contribution when approaching the proton fragmentation region

The power law contribution is always dominating:

- >90% at large η*
- ~ 55% at η* = 0





Scaled Momentum Distributions for K_S^0 and $\Lambda/\bar{\Lambda}$ in DIS

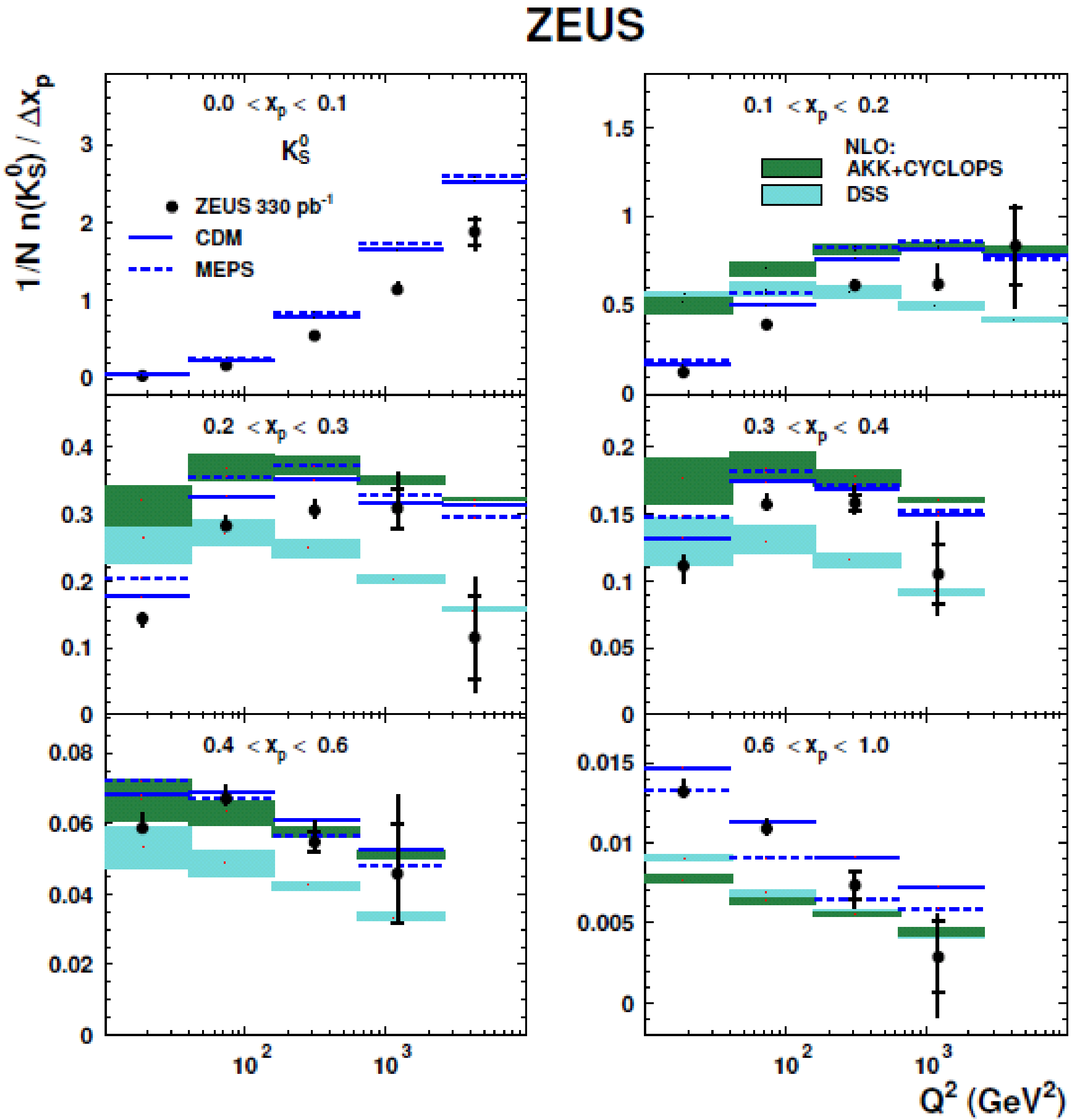
JHEP 03 (2012) 020

Fragmentation Functions (FFs) are usually extracted from e^+e^- annihilations into charge hadrons. These data are very precise and predicted cross sections do not depend on PDFs. However,

- they don't provide information about quark and anti-quark contributions to the FFs,
- gluon fragmentation remain largely unconstrained
- these data have poor statistics at large z (momentum fraction of $\mathbf{K_S^0}$)

Aiming to further constrain the FFs, scaled momentum ($x_P = 2P^{Breit}/\sqrt{Q^2}$) distributions in Q^2 bins were measured in the current region in Breit frame. The distributions are presented as functions of Q^2 and x_P in the kinematic region of $10 < Q^2 < 40000$ GeV^2 and $0.001 < x < 0.75$.

Scaled Momentum Distributions: K_S^0



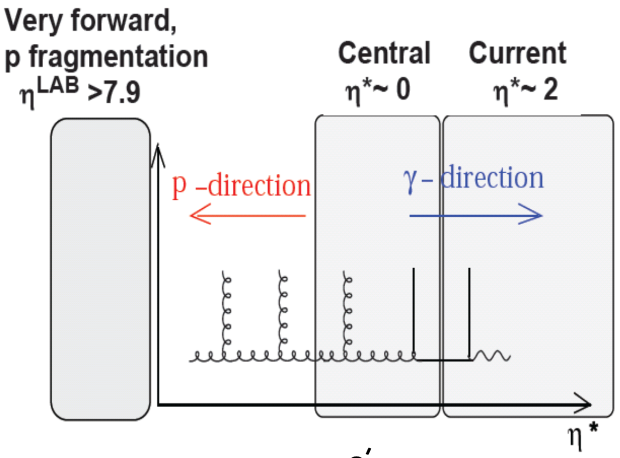
- Clear scaling violation: with increasing Q the PS for soft gluon radiation increases, leading to a rise of the number of soft particles with small x_P and decrease at large x_P
- CDM (Ariadne) and MEPS (Lepto) describe the shapes of the distributions well, while overestimating the overall production of **K_S^0** by 10 to 20%
- NLO QCD models don't describe the data.

Scaled momentum distribution for Λ has similar behavior

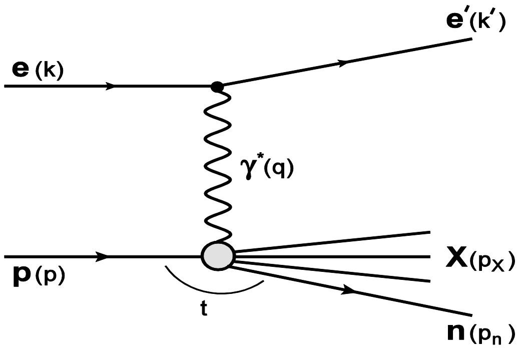
Very Forward Neutron and Photon Production in DIS

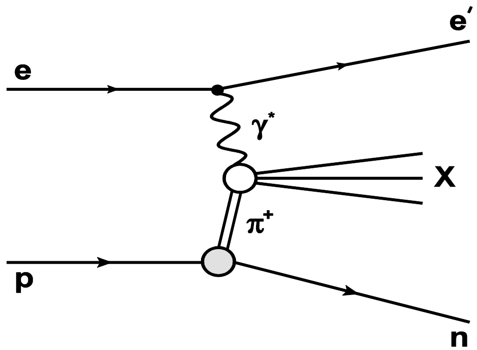
H1prelim-13-012

Measurements of Forward Particles are important for understanding of proton fragmentation mechanism and are interesting for tuning hadron interaction in Cosmic Ray models.



Forward photons and neutrons ($\eta^{LAB} > 7.9$) measured in the FNC Calorimeter (106m from IP)





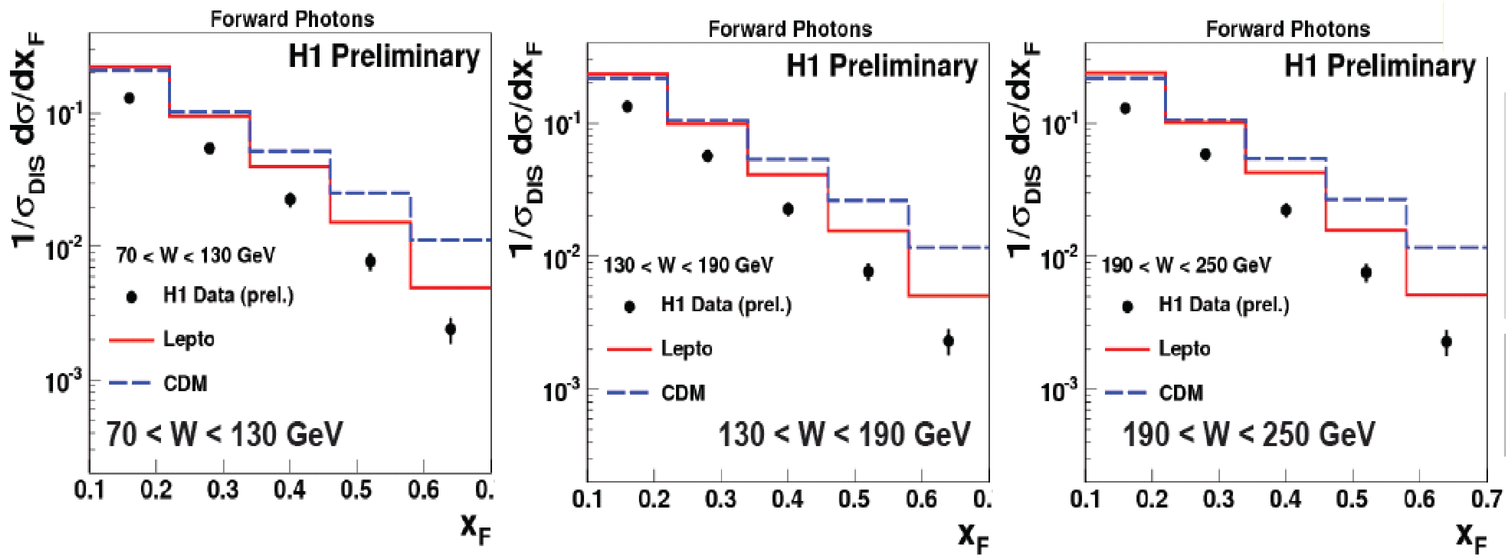
Forward Photons are produced mainly in π^0 decay from hadronisation of the proton remnant

Forward Neutrons are produced by proton fragmentation and by the π exchange mechanism, p -> n + π^+

Study Feynman x_F distributions at different γ^*p CM energies (W):

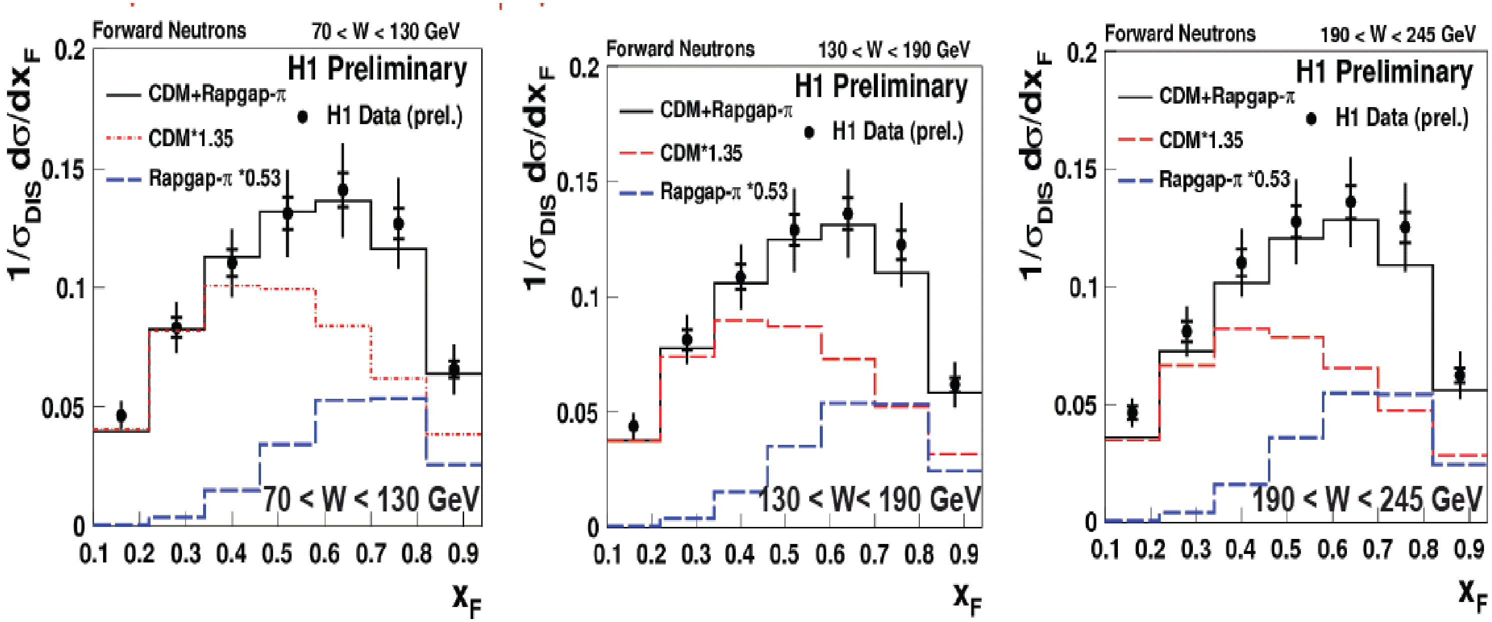
$x_F = p^*_{||} / p^*_{||max} = 2p^*_{||} / W$

Very Forward Photons and Neutrons: Normalised to DIS Cross Section Distribution in W bins



Data significantly lower than predicted by MC (CDM/Data ~1.7)

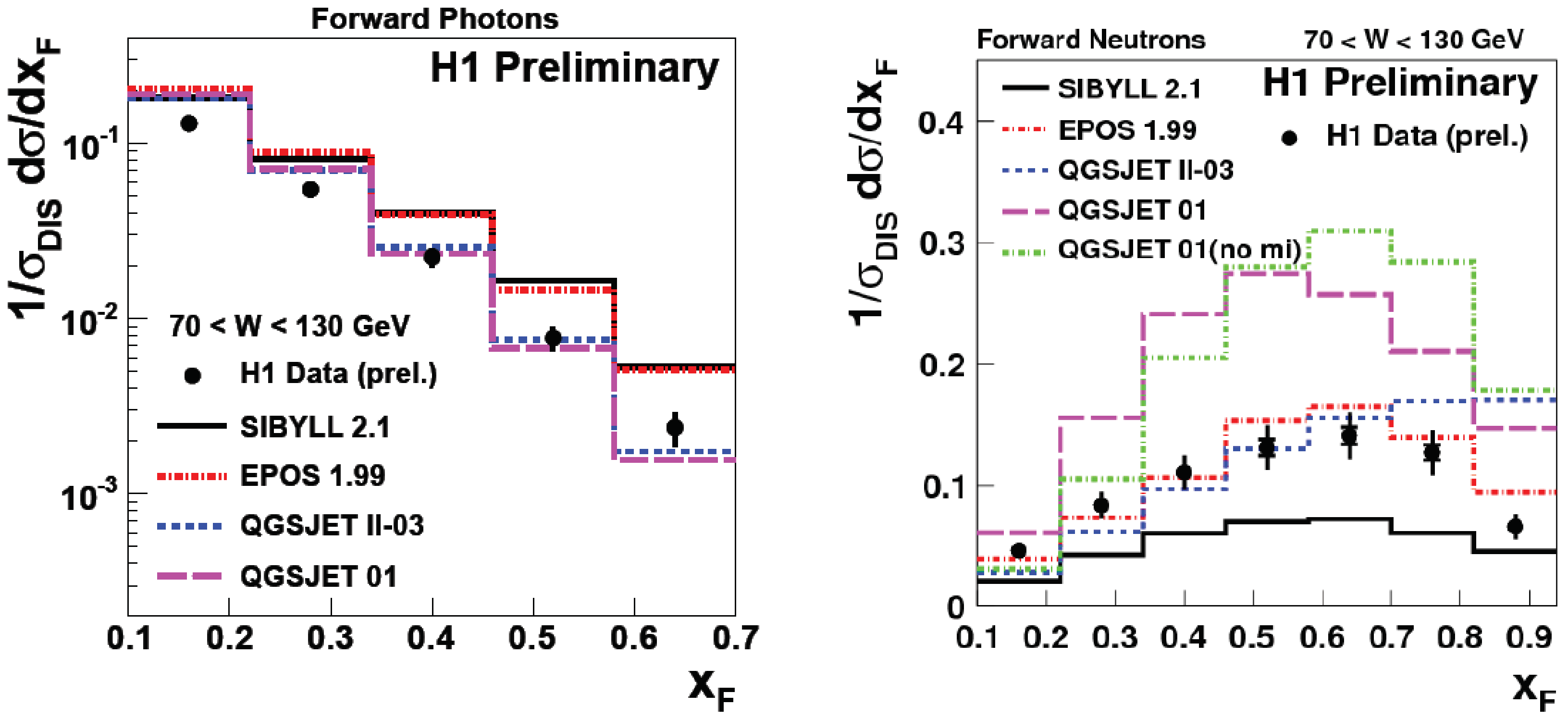
CDM predict much harder x_F spectra



Fragmentation contribution larger than predicted by MC.

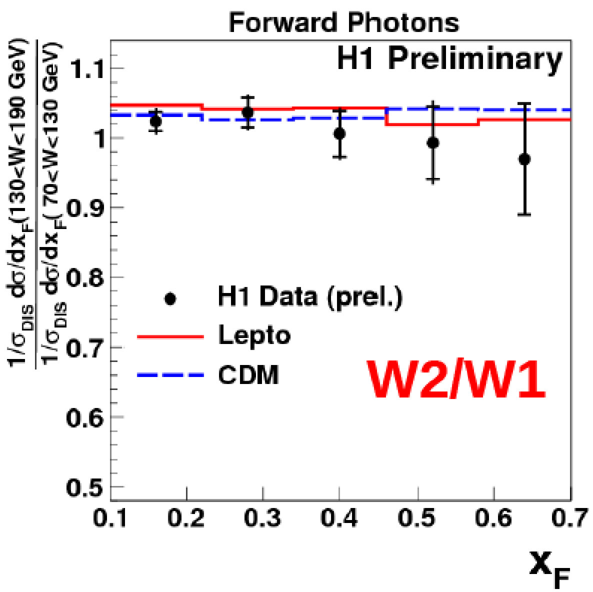
Neutron rate described by combination 1.35*CDM + 0.53*(π-exchange RAPGAP)

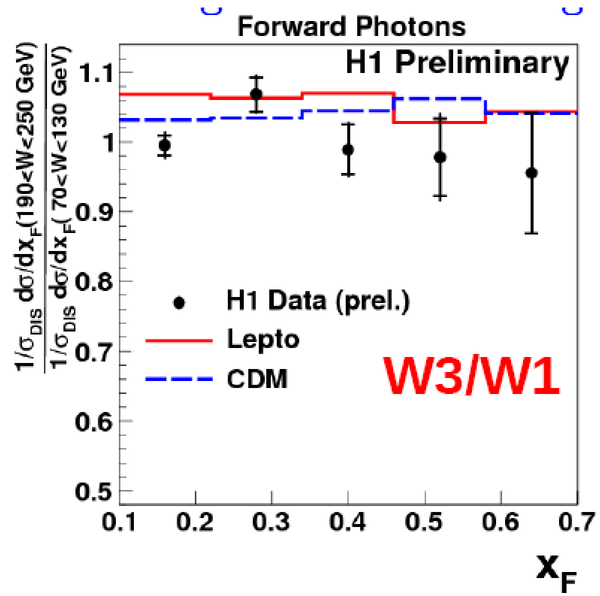
Very Forward Photons and Neutrons: Comparison with the Cosmic Ray Hadronic Interaction Models



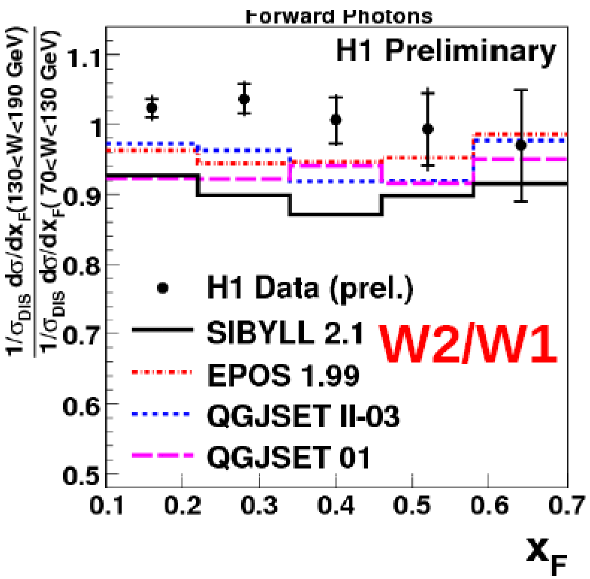
- Large difference between the Cosmic Ray model predictions
- None of the models describes simultaneously the photon and neutron measurements

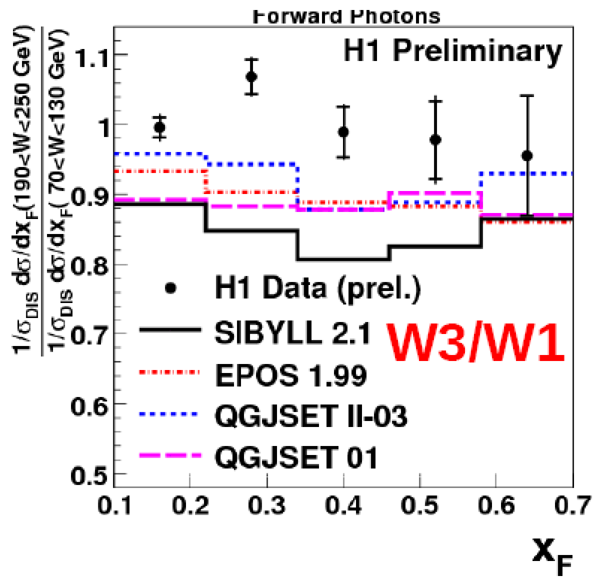
Very Forward Photons and Neutrons: Feynman Scaling Testing





70 < W1 < 130 GeV
130 < W2 < 190 GeV
190 < W3 < 250 GeV





Data consistent with being constant within error => support Feynman Scaling

CR Models show W dependence

Summary

Charged Particle

- Transverse momentum and pseudorapidity spectra were measured with H1 detector at HERA at $\sqrt{s}$ = 319 GeV and $\sqrt{s}$ = *225 GeV*
- Different tunes of hadronisation parameters were studied in the low p_T* region
- Models with different implementations of parton dynamics (CDM, DGLAP, CCFM) were studied in the high p_T* region
- DGLAP like models are significantly below the data for $\eta^* < 3$
- DJANGOH (CDM) gives the best description of charged particle spectra

- Phenomenological model for hadron production with an exponential and a power-low contributions has been tested on ep data
- A significant exponential contribution is needed in the central region, but not in the current region => within the model this is a sign for a change in the production dynamics with η^*

Strange hadron

- Scaled momentum distributions show scaling violation
- NLO QCD calculations fail to describe the data
- Measurements will further constrain the FFs of quarks, anti-quarks and gluons

Forward photon and neutron production

- Provide important input for proton fragmentation
- Data constrain proton fragmentation models and Cosmic Ray models
- Photon rate in all MC models significantly overshoot the data
- None of models describes photon and neutron data simultaneously well