XVII International Workshop in Deep Inelastic Scattering and Related Topics

DIS2009, 26-30 April, Madrid, Spain

Summary of the Hadronic Final State and QCD working group

Gavin Hesketh, Albert Knutsson, Leszek Motyka

Part 1 – Measurements in *ep collision*

Hadronic Final State and QCD working group

52 talks in total: 18 theory talks and 34 experimental talks (5 of the talks joint with the EW/BSM working group)

Summary talk splitted in to 3 parts:

***ep* experiments – Albert Knutsson**

***pp* experiments – Gavin Hesketh**

Theory – Leszek Motyka

ep talks

CLAS – H1 – HERMES – ZEUS 17 talks

- **Jet physics**
  - Jets and alpha_s (H1/Arnd Specka)
  - Jets and alpha_s (ZEUS/Claire Gwenlan)
  - Jet substructure in NC DIS (ZEUS/Elias Ron)
  - Angular Correlations in three-jet events in ep collisions (ZEUS/Stephen Magill)

- **Particle production/Strangeness production/Hadronization**
  - K* production at low Q2 (H1/Deniz Sunar)
  - K*/Rho/Phi in Photoproduction (H1/Anna Kropivnitskaya)
  - K0sK0s Resonnces (ZEUS/David Saxon)
  - Strangeness production at low Q2 (H1/Grazyna Nowak)
  - Meson photoproduction (CLAS/Steffen Strauch)
  - Hadronization from DIS (CLAS/Ken Hicks)
  - Study of the Few Nucleon System (CLAS/Yordanka Ilieva)
  - Nuclear pt-broadening of semi-inclusive produced mesons (HERMES/Yves van Haarlem)

- **Charged particles**
  - Charge particle asymmetries at high Q2 (H1/Dan Traynor)
  - Scales momentum distributions of charged particles in dijet photoproduction (ZEUS/John Morris)
  - Underlying event in photoproduction (H1/Lluis Marti)

- **Prompt photons**
  - Prompt photons in DIS (ZEUS/Matthew Forrest)
  - Prompt photons in photoproduction (H1/Krzysztof Nowak)

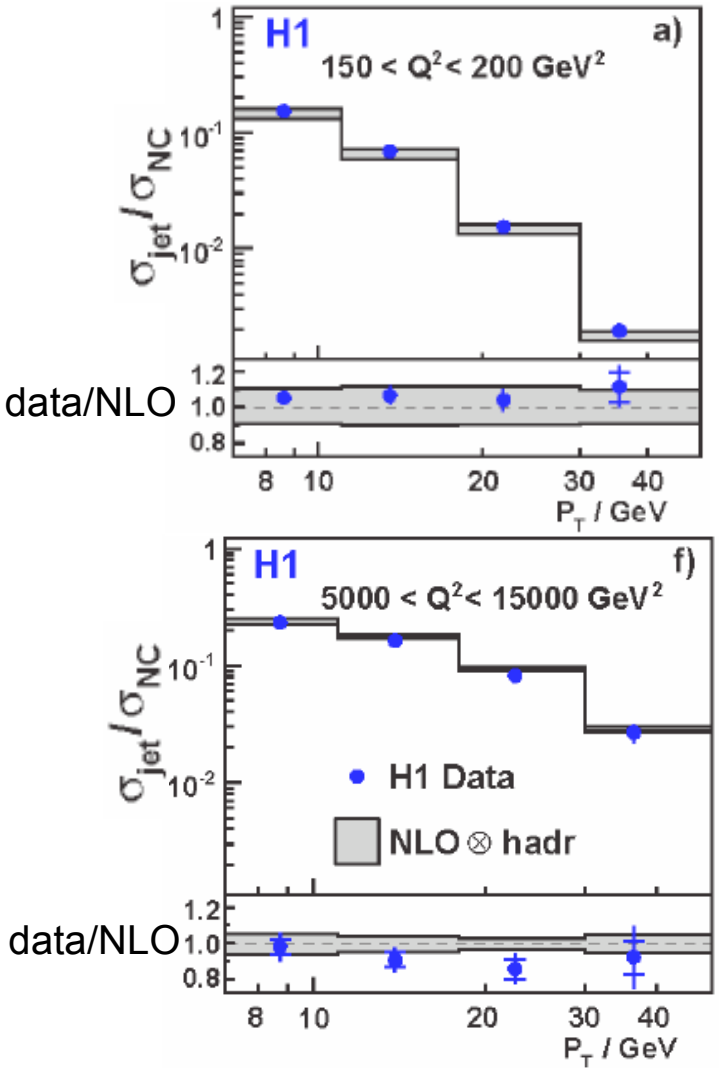
Jets and alpha_s (H1)

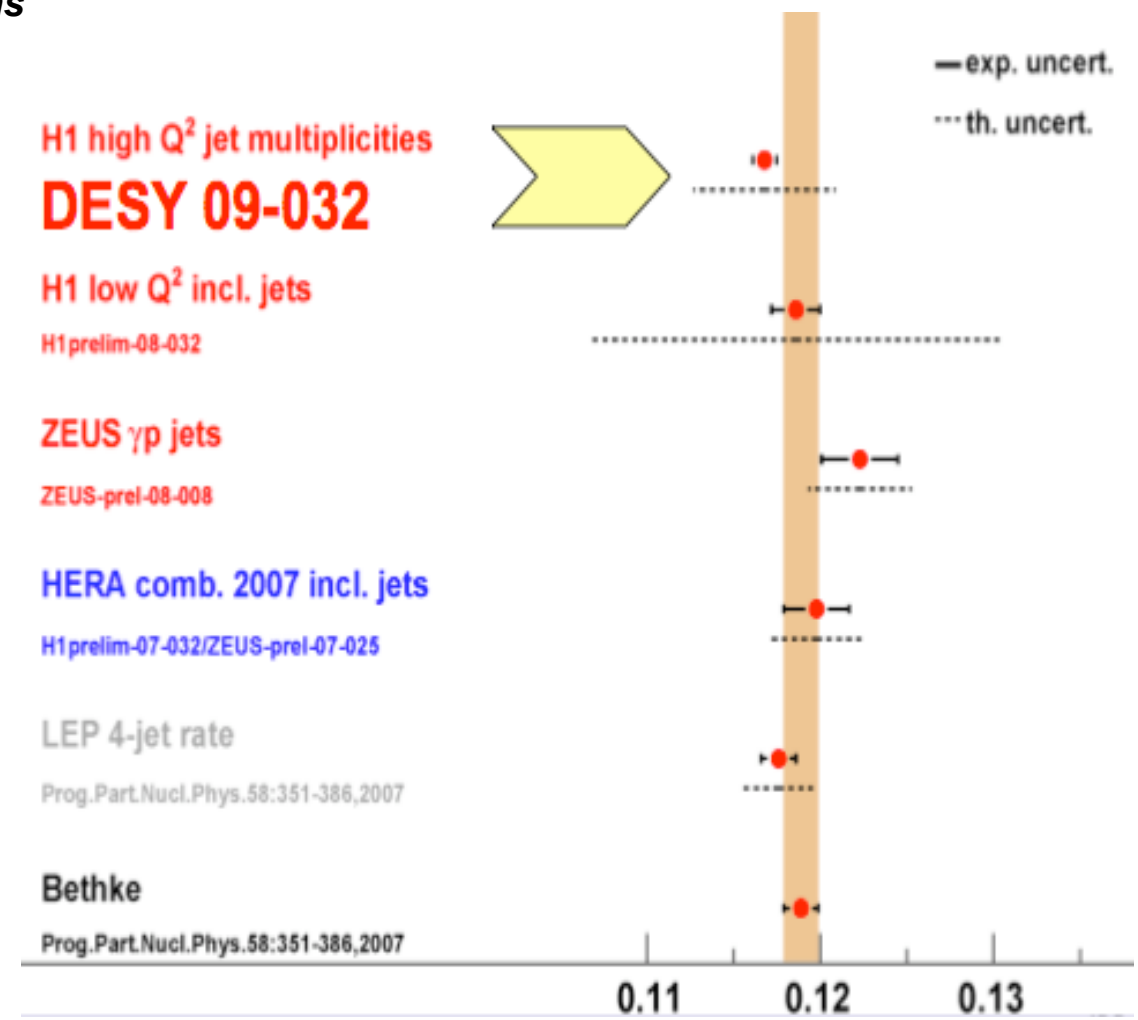
Arnd Specka

Combined alpha_s fit from normalized inclusive, 2- and 3-jet cross-sections at high Q2

395 pb^{-1}

Example: Normalized inclusive jet cross-sections





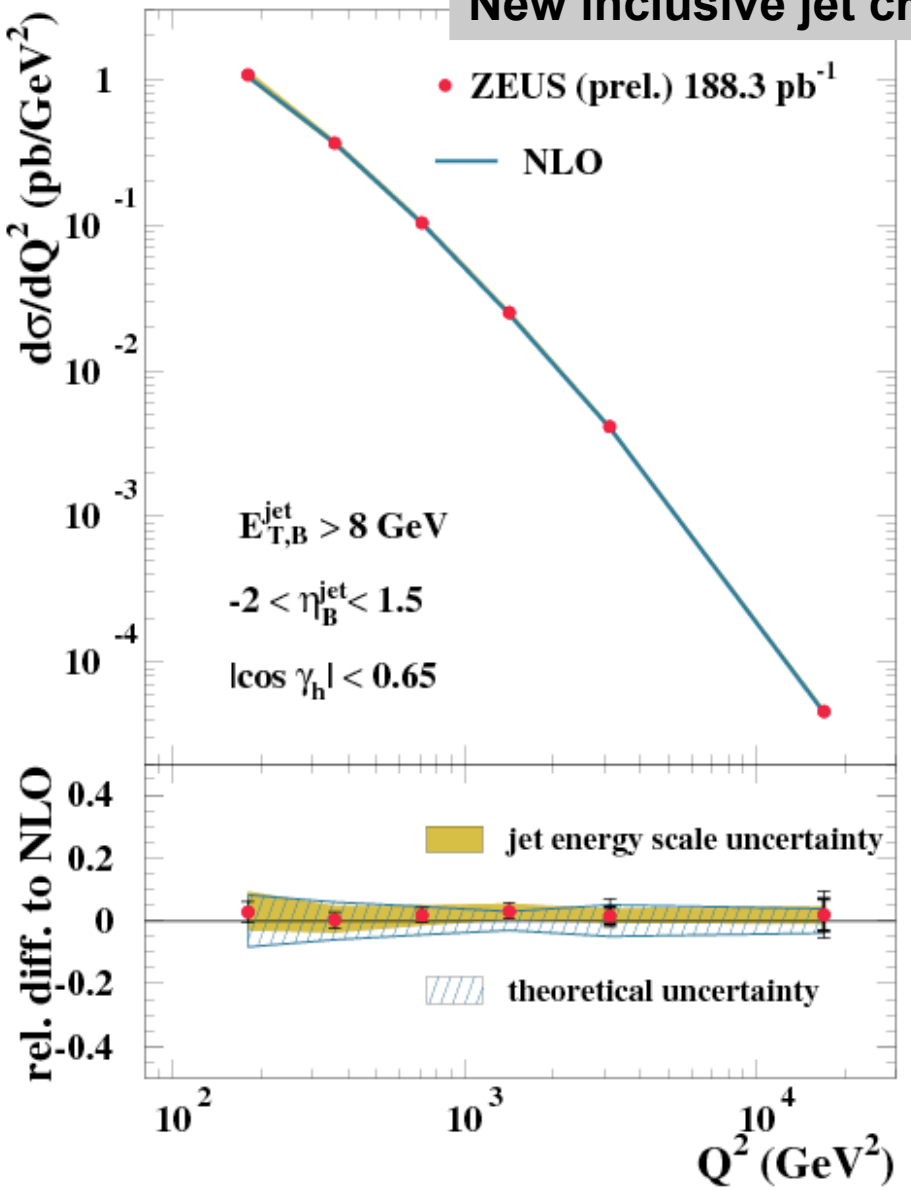
$$\alpha_s(m_Z) = 0.1168 \pm 0.0007\,(\text{exp})\,^{+0.0046}_{-0.0030}(\text{th}) \pm 0.0016\,(\text{PDF})$$

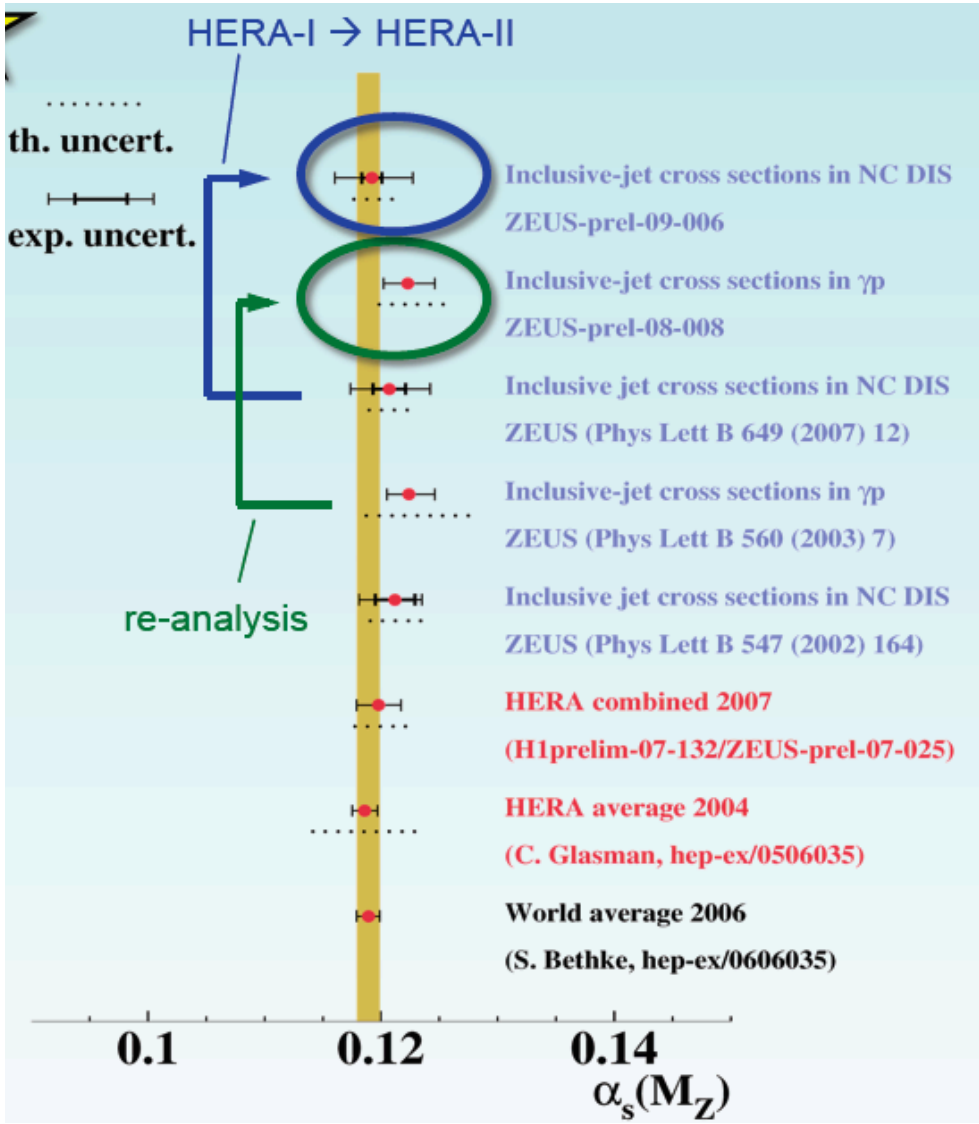
Experimental error < 1%.
Large theoretical uncertainty.

Jets and alpha_s (ZEUS)

Claire Gwenlan

New inclusive jet cross-sections and alpha_s fit





➔ extracted from the measured **$d\sigma/dQ^2$** for $Q^2 > 500$ GeV^2 ↓ (yields smallest α_s uncert.)

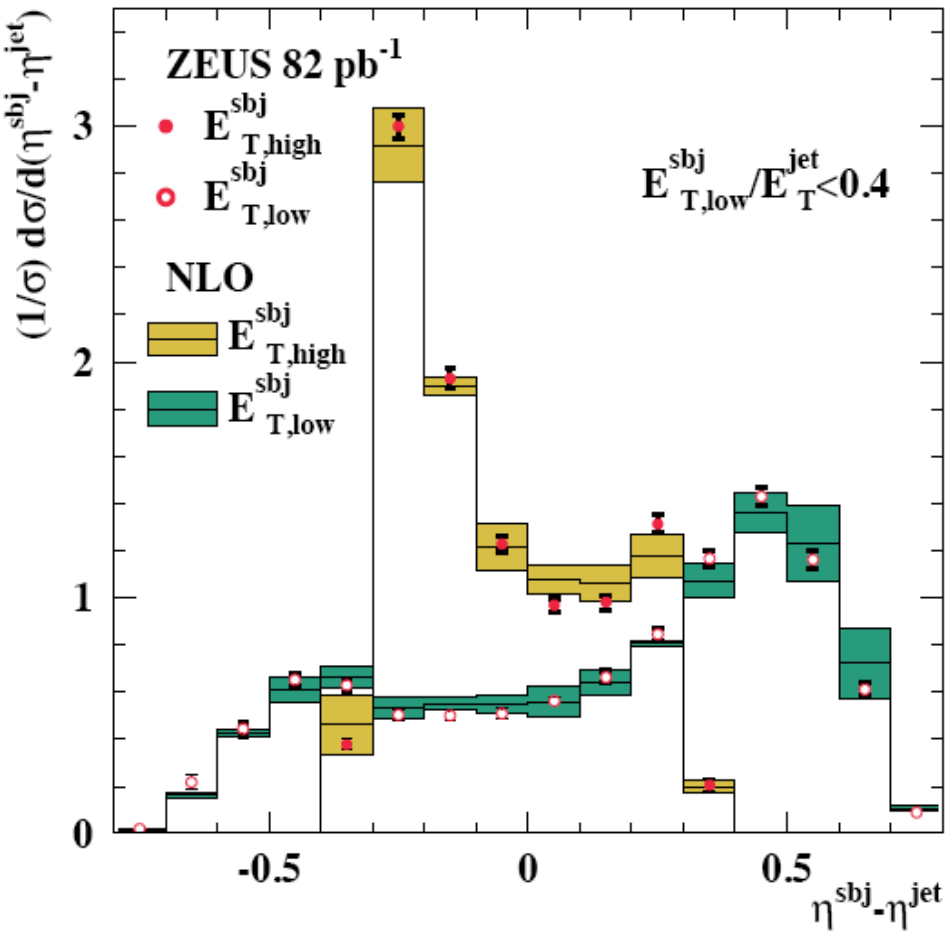
$$\alpha_s(M_Z) = 0.1192 \pm 0.0009\,(\text{stat.})^{+0.0035}_{-0.0032}(\text{exp.})^{+0.0020}_{-0.0021}(\text{th.})\ \ (3.5\%\ \text{total})$$

Jet substructure in NC DIS (ZEUS)

Elias Ron

Internal structure of jets gives insight into the **Parton to Hadron transition** and **Color Coherence effects**

Subjets are obtained within a jet by **reapplying the kt cluster algorithm on all particles within the jet**, with a smaller distance parameter.



Color coherence effects:

Soft subjet in the forward (proton beam) direction

Hard subjet in the backward part of the jet

Data well described by NLO calculations

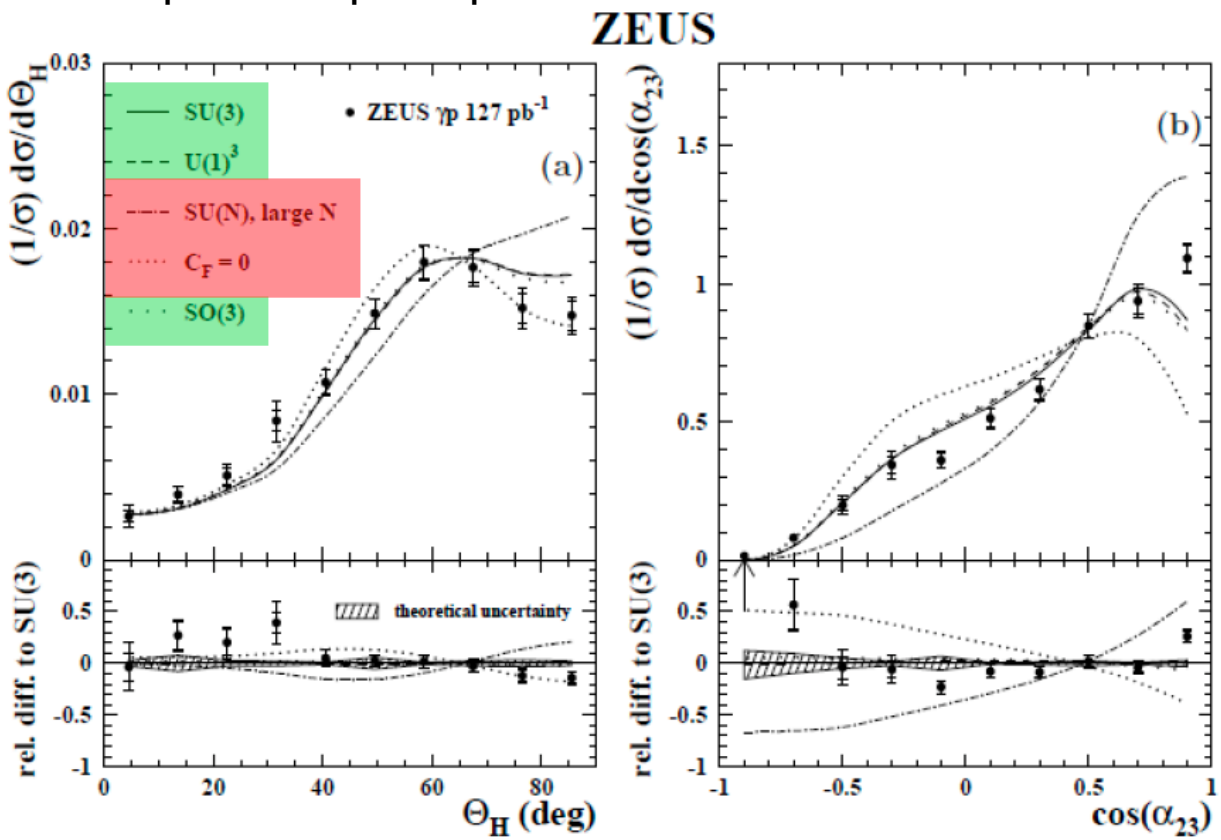
Angular correlations in three-jet events in ep collisions (ZEUS)

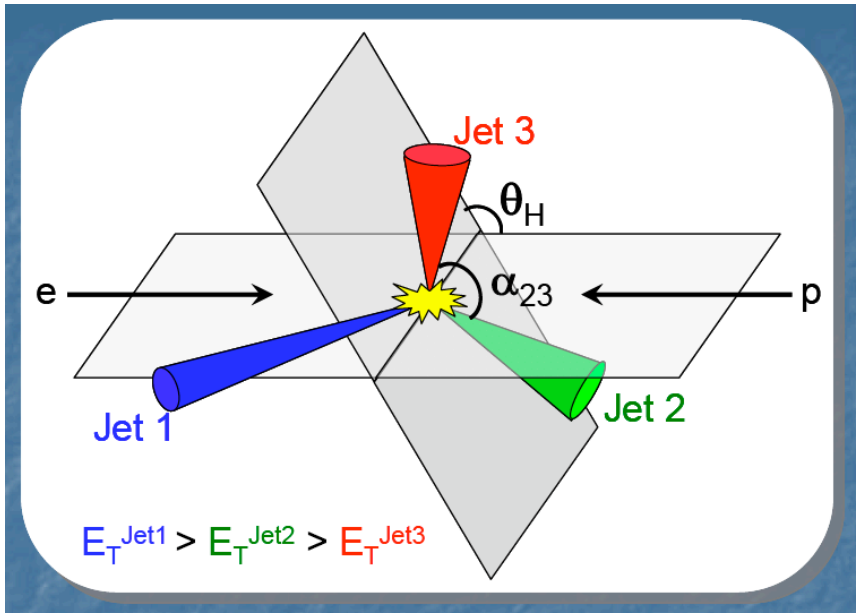
Stephen Magill

Another fundamental in QCD: Color factors

Define different angular variables expected to be sensitive to jet structure and color configuration

Example from photoproduction:

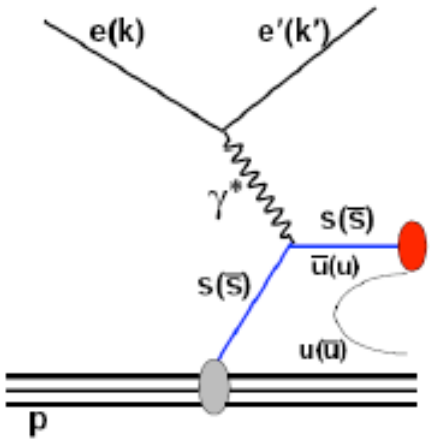




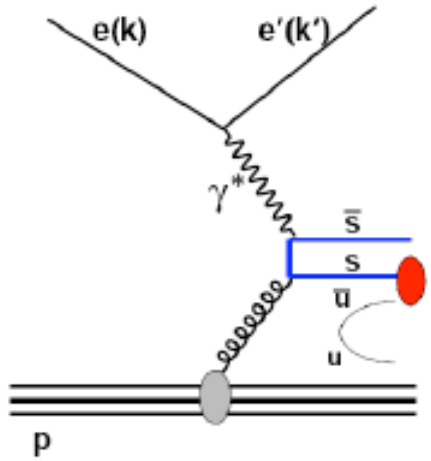
Gauge group SU(3) describes all angular variables in photoproduction and DIS.

Strangeness production

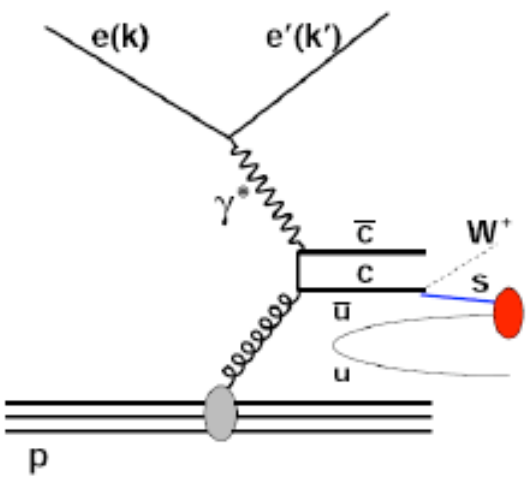
- Hard scattering of s sea quark



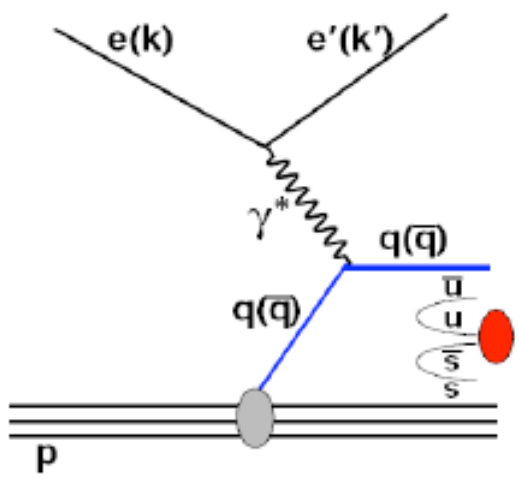
- Boson-gluon fusion



- Heavy quark decay (non-perturbative)



- String fragmentation (non-perturbative)



Different production mechanisms, but the non-pertubative contributions dominates.

- Direct information about fragmentation parameters.

- Gain knowledge of hadronisation.

- Measure final state Particle – Anti Particle asymmetries:

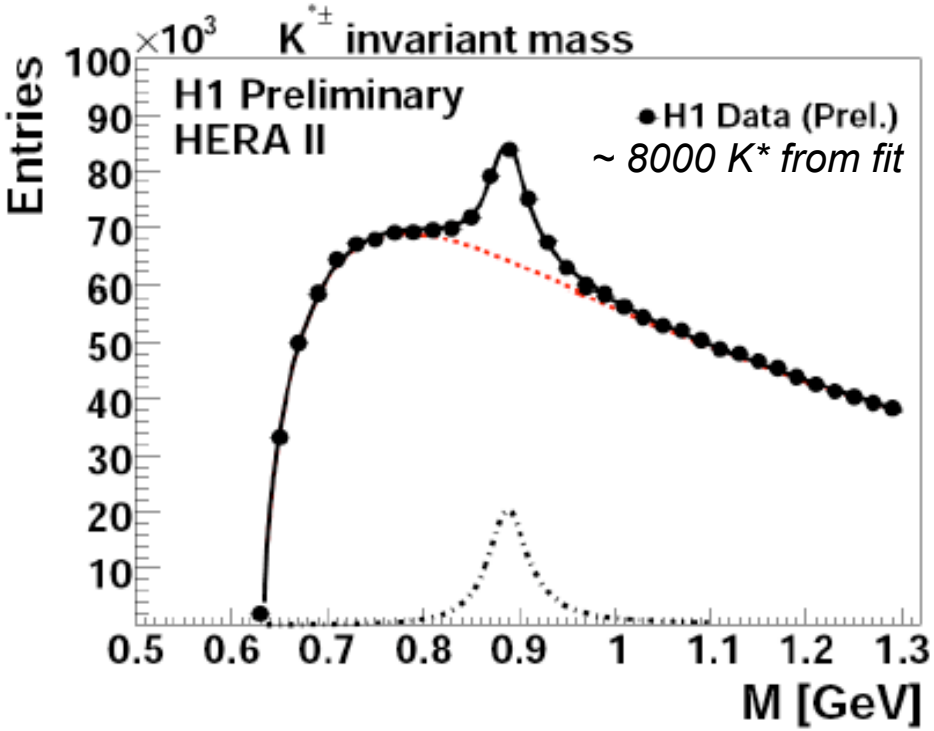
  Asymmetries in quark-sea?

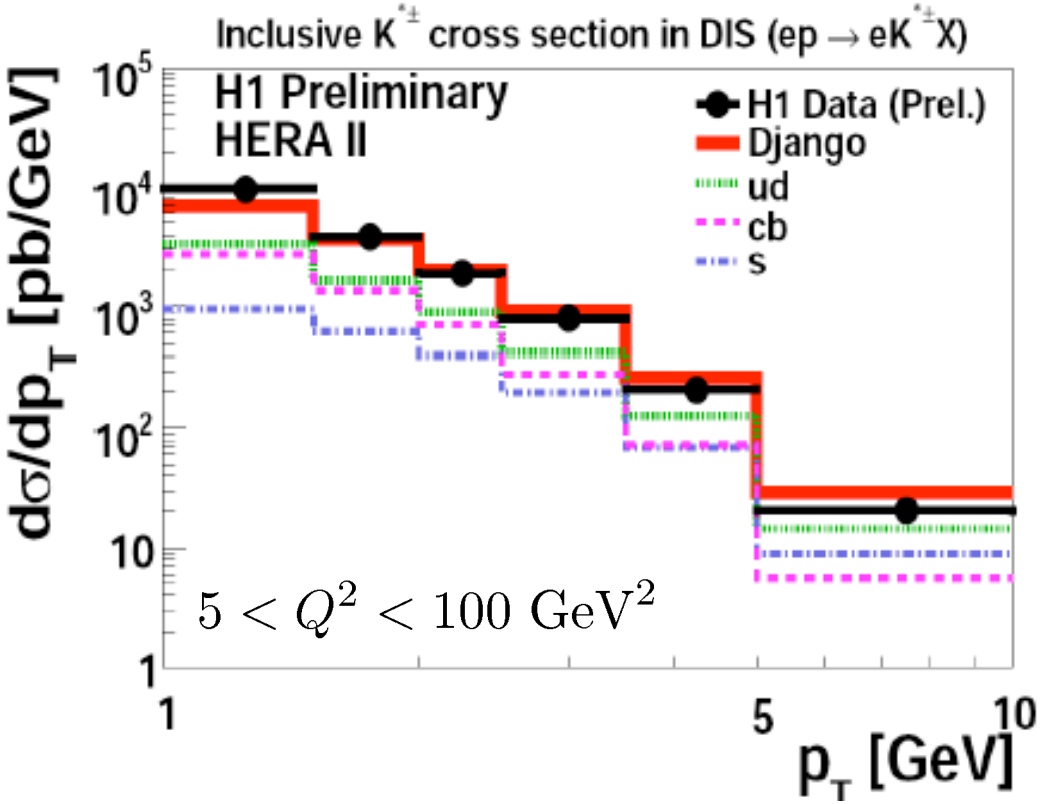
  Quantum number transfer from proton beam?

In HFS and QCD working group: Lambdas, K*, K0s

K* production at low Q2 (H1)

Deniz Sunar





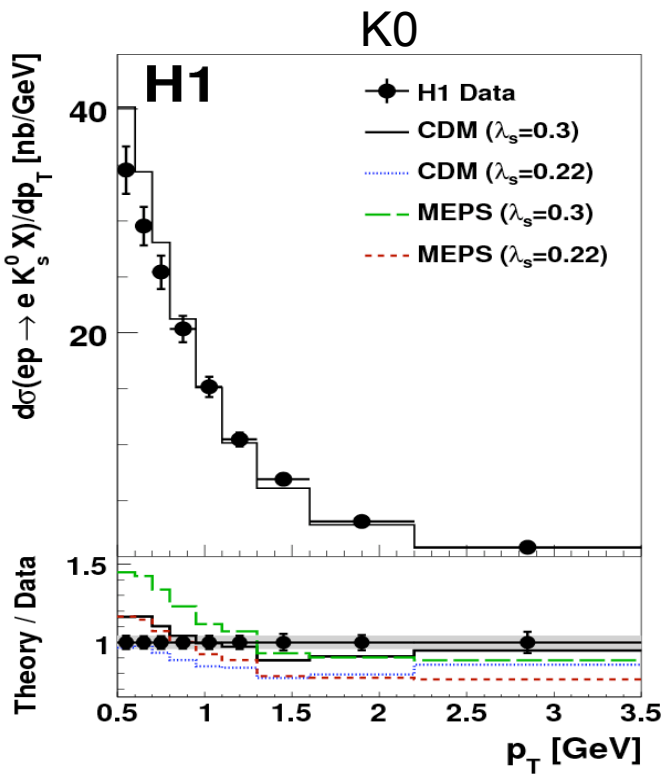
MC cross-section decomposed in initial quark contributions:

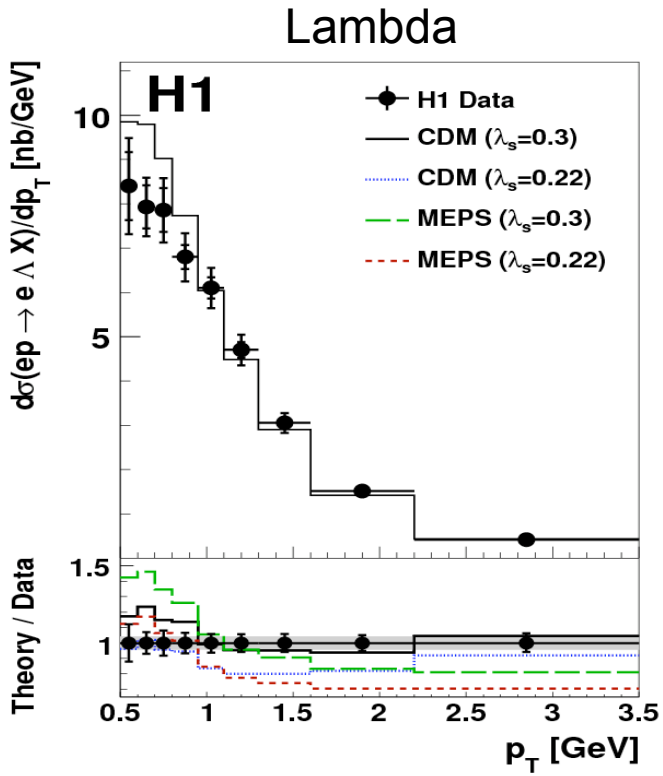
→ Strange quark production from fragmentation (*ud*) dominates.

Strangeness production in DIS (H1)

Grazyna Nowak

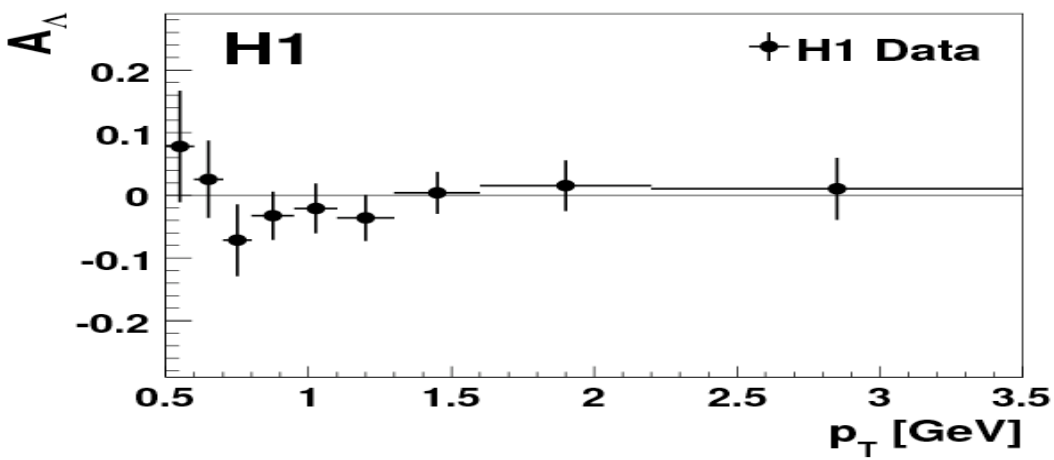
$2 < Q^2 < 100\ \mathrm{GeV}^2$





Sensitivity to fragmentation parameters.

No value of the strangeness suppression factor does a perfect job.



$$A_\Lambda = \frac{\sigma_{vis}(ep \to e\Lambda X) - \sigma_{vis}(ep \to e\bar{\Lambda} X)}{\sigma_{vis}(ep \to e\Lambda X) + \sigma_{vis}(ep \to e\bar{\Lambda} X)}$$

No evidence of baryon number transfer from proton beam to the final state.

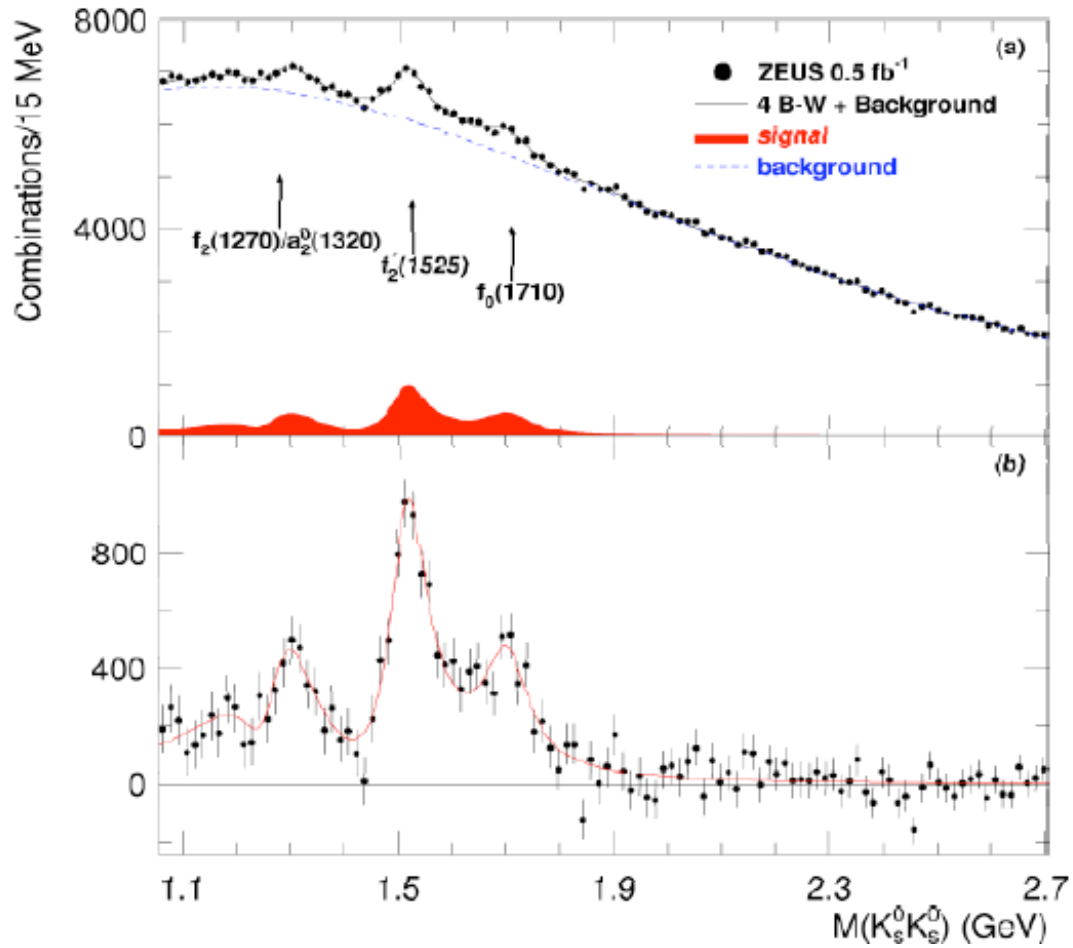
K0sK0s resonances (ZEUS)

David Saxon

Full HERA data set (0.5 fb^{-1}, 77% from HERA II)

90% photoproduction ($Q^2 < 1\ GeV^2$), rest DIS

672418 $K^0_s K^0_s$ pairs

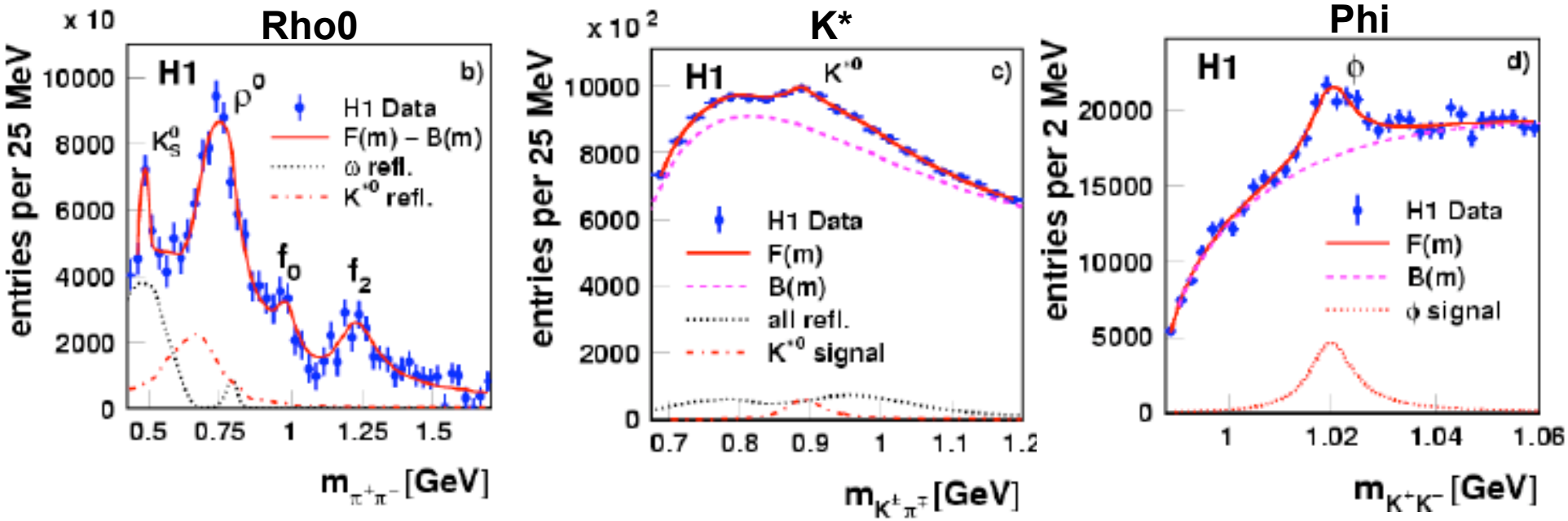


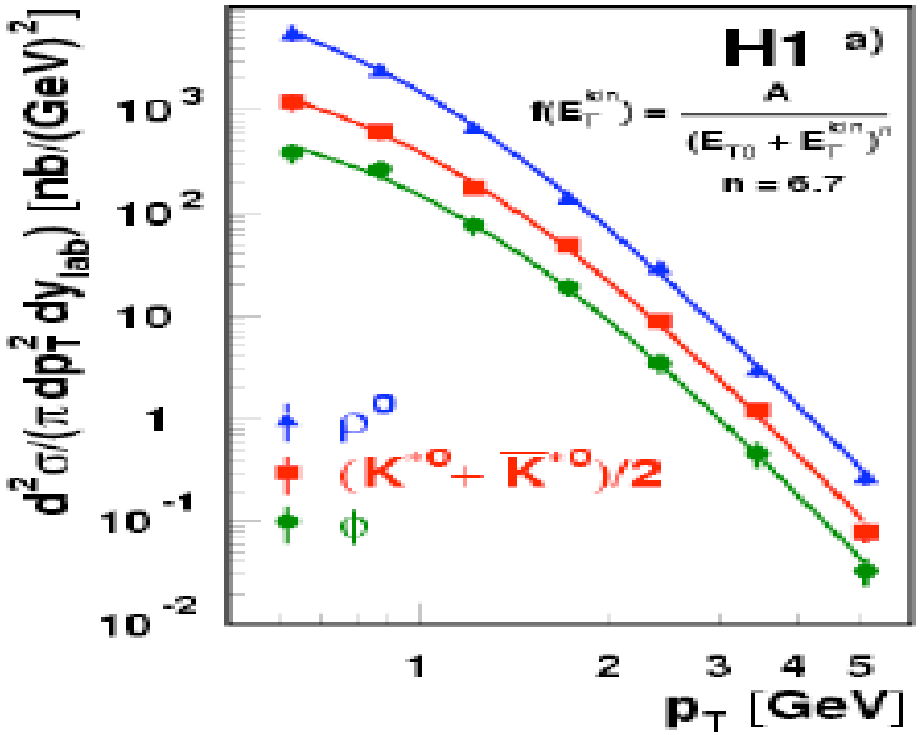
Several resonances seen. Glueball candidate:

$f_0(1710)$ clearly observed. Not a glueball if the same state as $f_J(1710)$ seen in $\gamma\gamma$

Rho0, K*, Phi production in photoproduction (H1)

Anna Kropivnitskaya





Pt spectra described by the same power law.

$$\frac{A}{(E_{T_0} + E_T^{kin})^n}$$

Transverse momentum broadening in Nuclear Semi-Inclusive DIS (HERMES and CLAS)

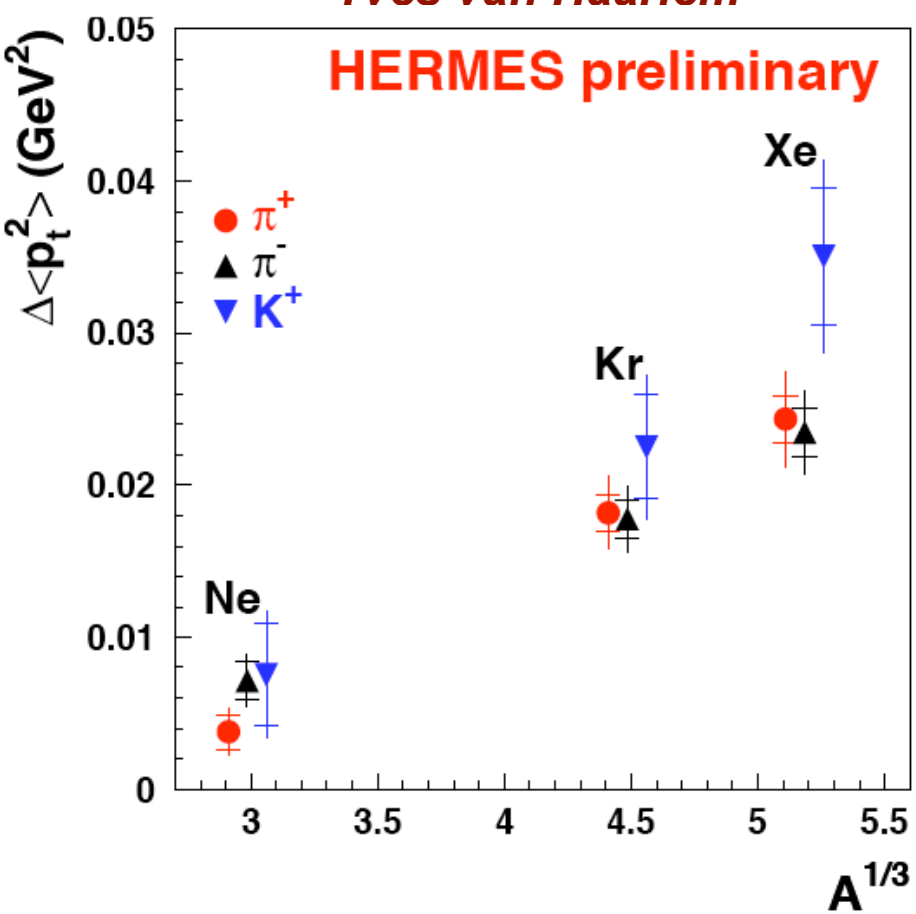
Broadening of the transverse momentum of the hadron when propagation through (cold) matter:

$$\Delta\langle p_t^2\rangle^h = \langle p_t^2\rangle_A^h - \langle p_t^2\rangle_D^h$$

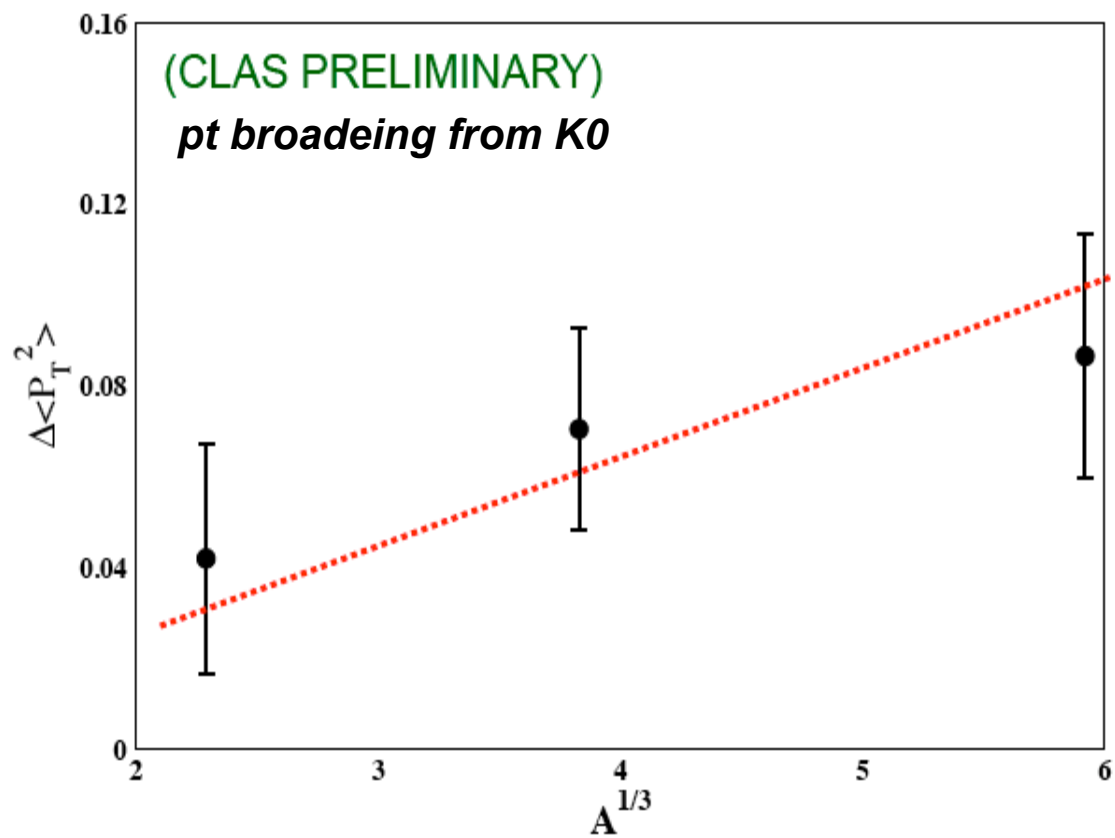
pt=transverse momentum of produced hadron using target:

Mass number *A* or **Deuterium (*D*)**

Yves van Haarlem



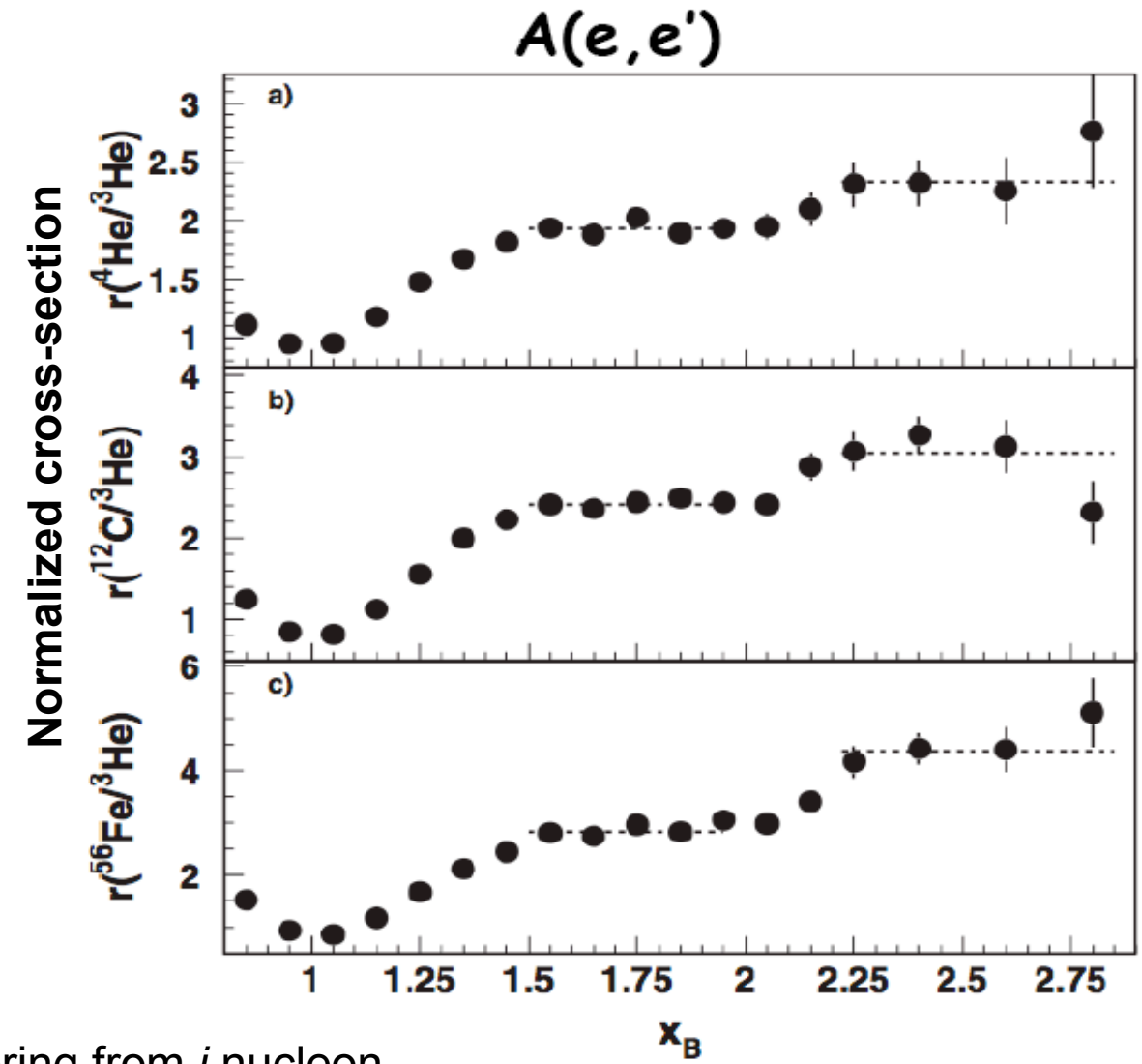
Ken Hicks



Study of Few Nucleon Systems (CLAS)

Yordanka Ilieva

Evidence for Short Range Correlations (SRC):



Scattering from *j* nucleon expected to dominate between

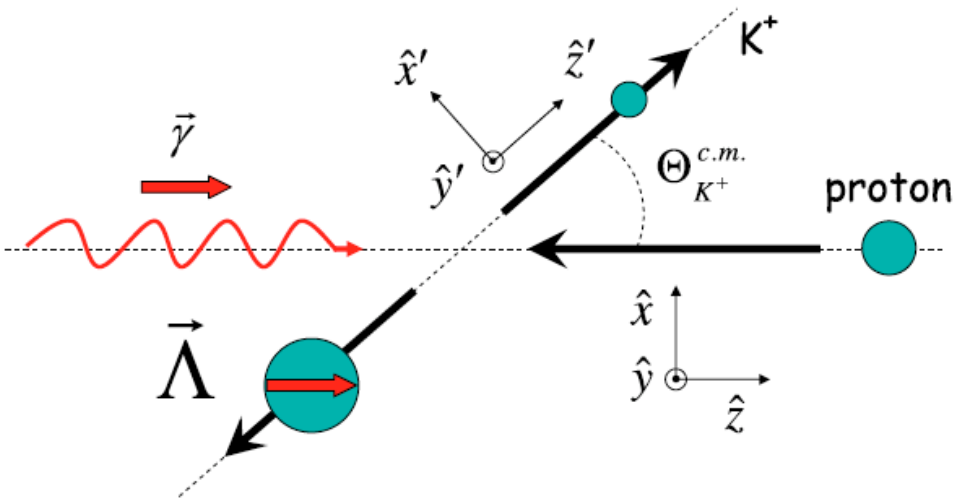
$$j < x_{\mathrm{Bjorken}} < j + 1$$

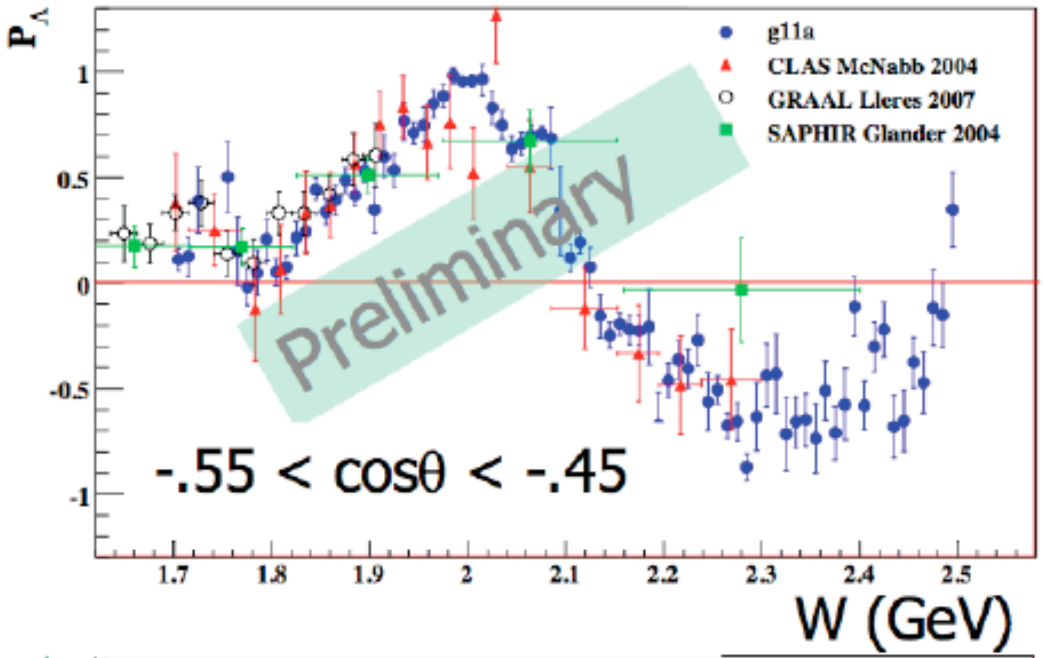
→ **First plateau 2 nucleon correlation.**
Second plateau 3 nucleon correlation.

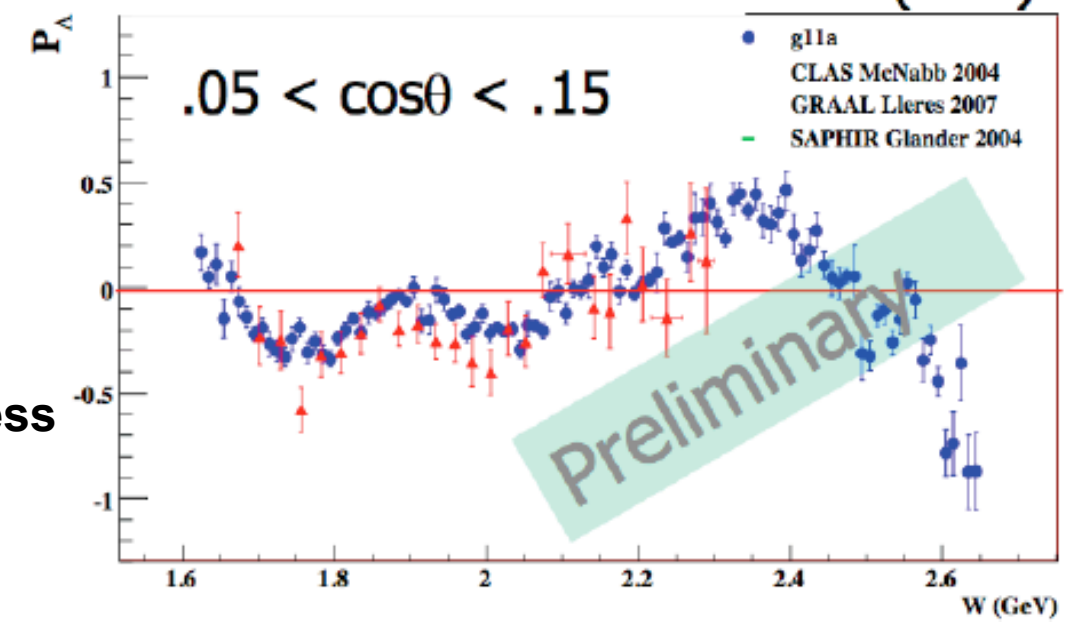
Hyperon Recoil Polarization (CLAS)

Steffen Strauch

Induced polarization (P_Λ) from photon beam to hyperon:



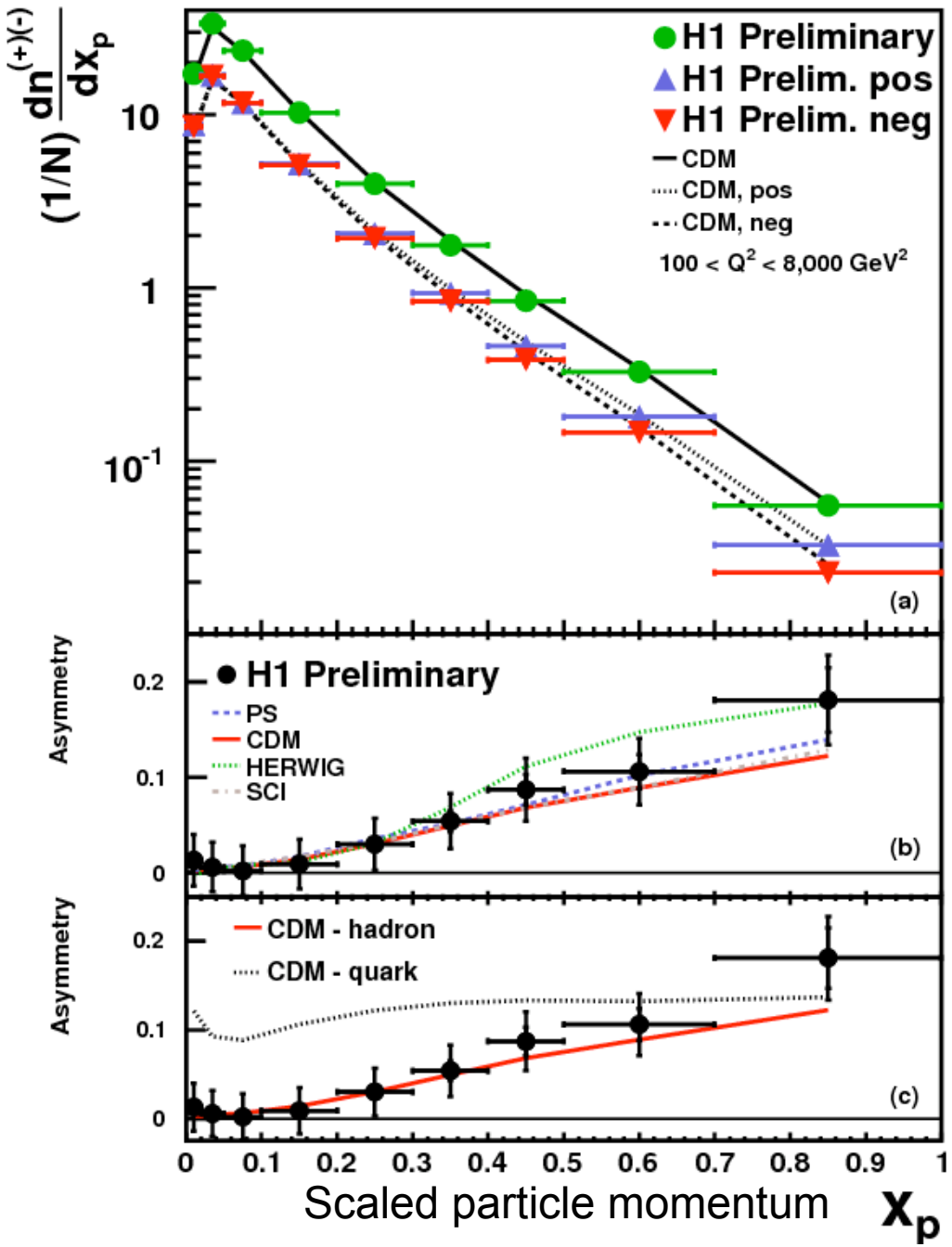




- **New CLAS data (blue)** best coverage
- Partial wave analysis at CLAS in progress

Charge particle asymmetries in high Q2 DIS (H1)

Dan Traynor



Scaled particle momentum: $x_p = \frac{(2P_h)}{Q}$

Low x_p: Similar distributions for + and -

High x_p: Charge asymmetry

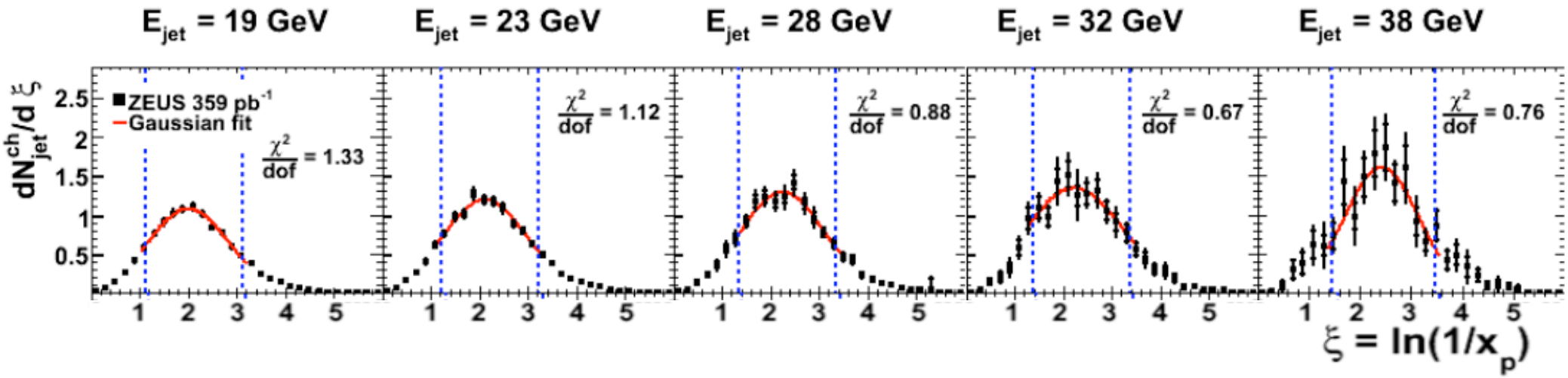
Various Monte Carlo models describe the charge asymmetry

$$\text{Asymmetry} = \frac{pos - neg}{pos + neg}$$

Scaled momentum distributions of charged particles in dijet photoproduction (ZEUS)

John Morris

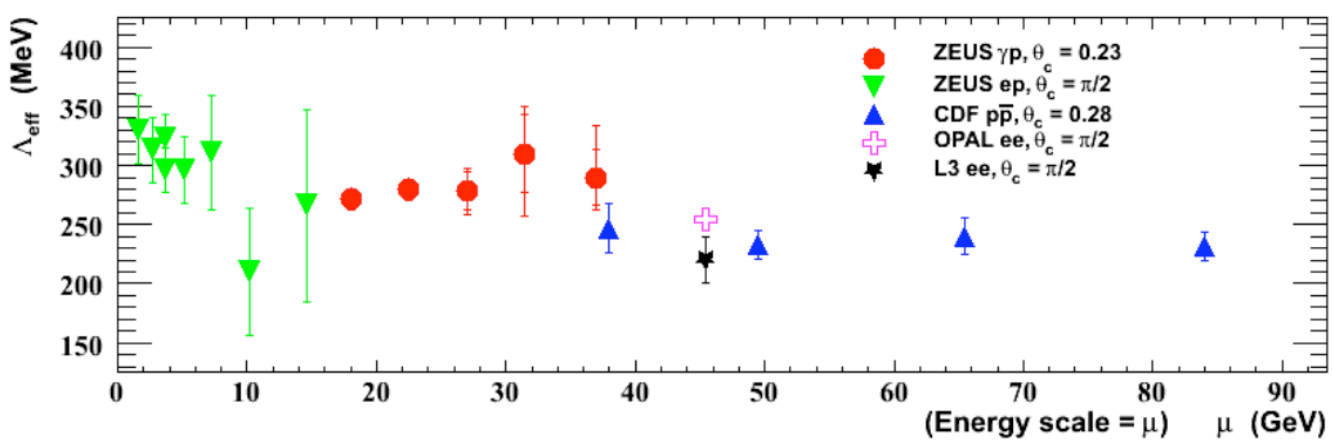
Scaled momentum $\xi = \ln(1/x)$ of charges particles inside cones around jet axes (where the fragmentation should be well defined).



By making fits to the peaks one can extract the model parameter:

$$\Lambda_{\text{eff}} = 275 \pm 4\,(\text{stat.})^{+4}_{-8}\,(\text{syst.})\ \text{MeV}$$

Absolute cutoff in Modified Leading Log Approximation (MLLA) - Expected to be universal

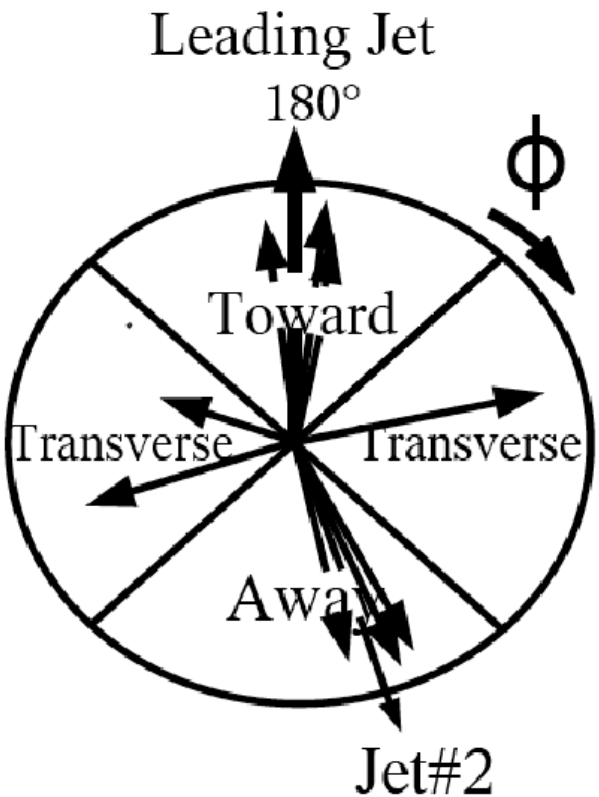


Underlying event in photoproduction (H1)

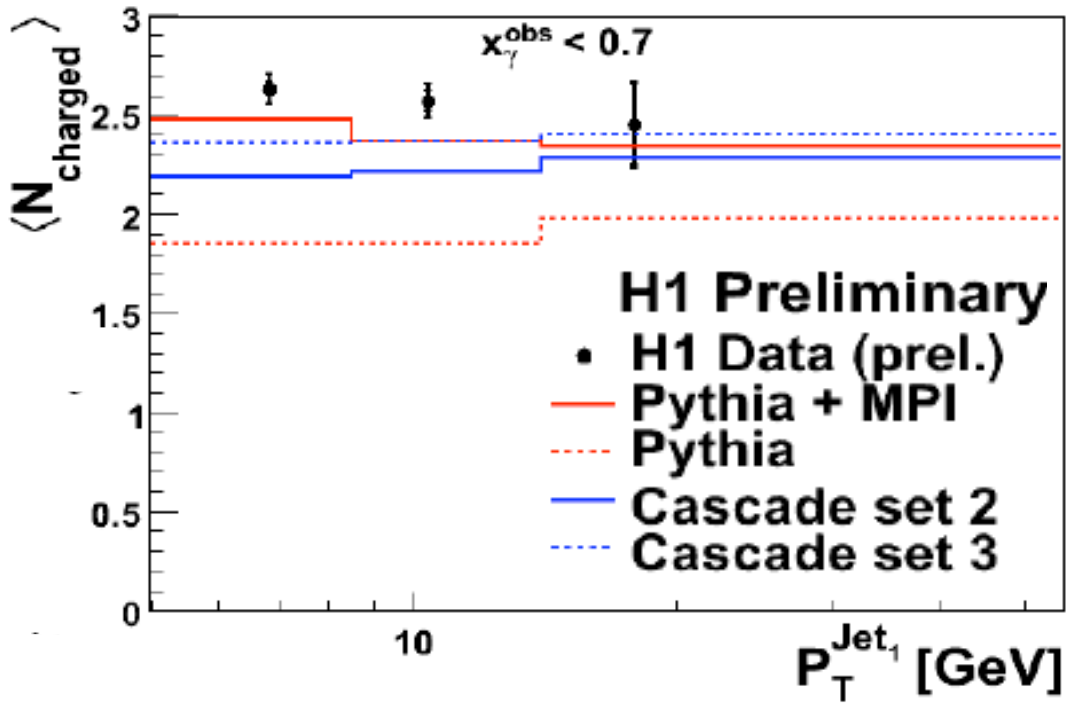
Lluis Marti

UE analysis a la TEVATRON – at HERA.

Investigate the average charge particle multiplicities transverse to the leading jet.

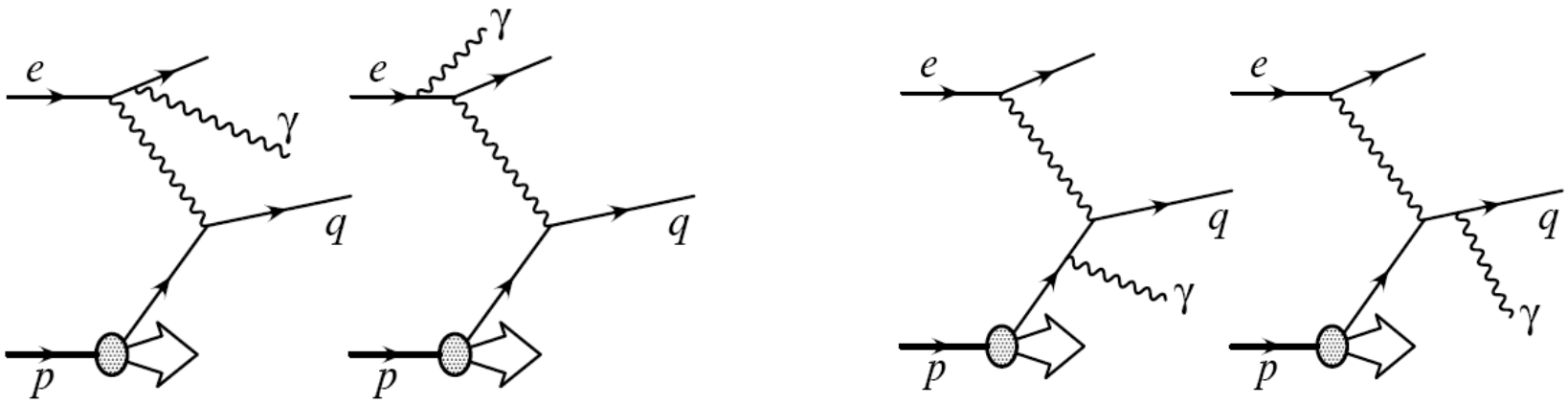


Transverse region with highest scalar transverse momentum sum



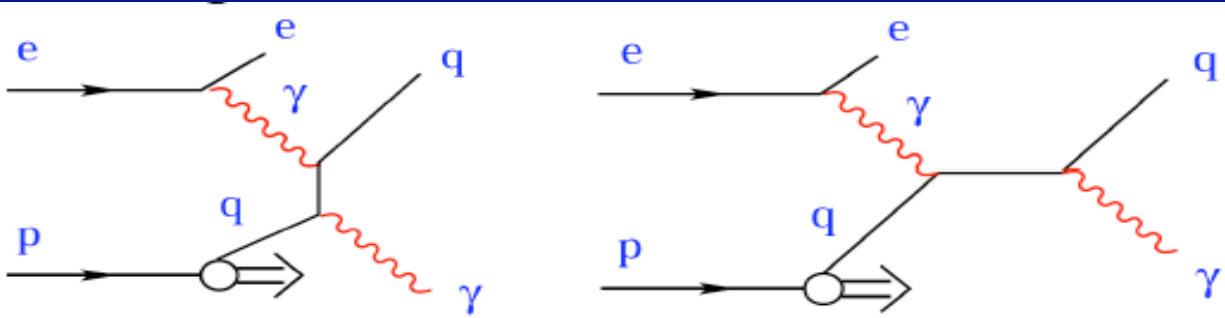
PYTHIA: needs Multi Parton Interactions in order to describe the data.
CASCADE, kt factorization (CCFM) based parton showers – no MPI:
in competition with MPI if correct unintegrated PDF is chosen

Prompt photons in DIS and photoproduction

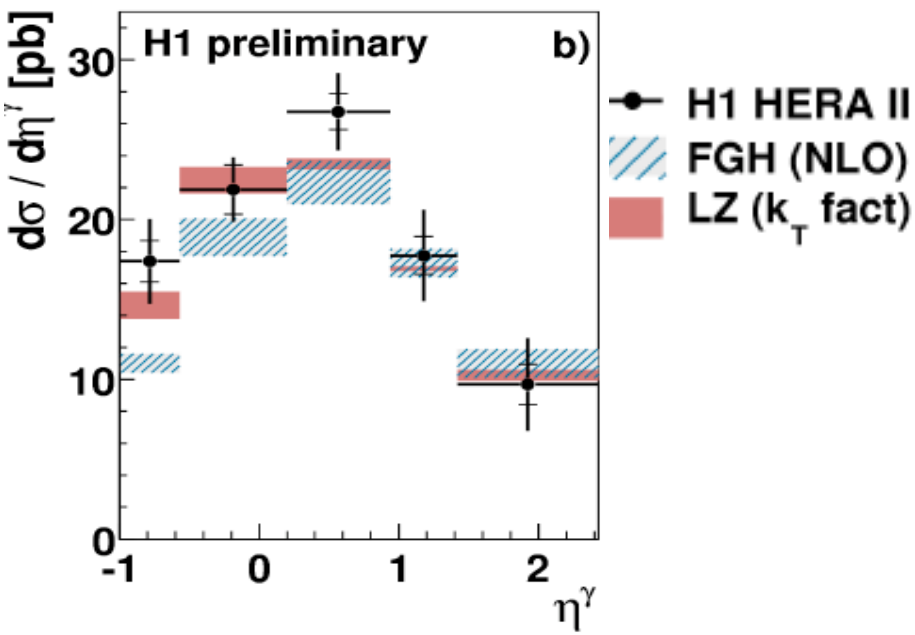


- **Low hadronization corrections**
- **Sensitivity to quark and gluon PDFs of photon and proton**
- **Large number of available calculations (see example on next slide, more info and different approaches with the separate talk)**
- **Measured in photoproduction and DIS**

Prompt photons in *ep*

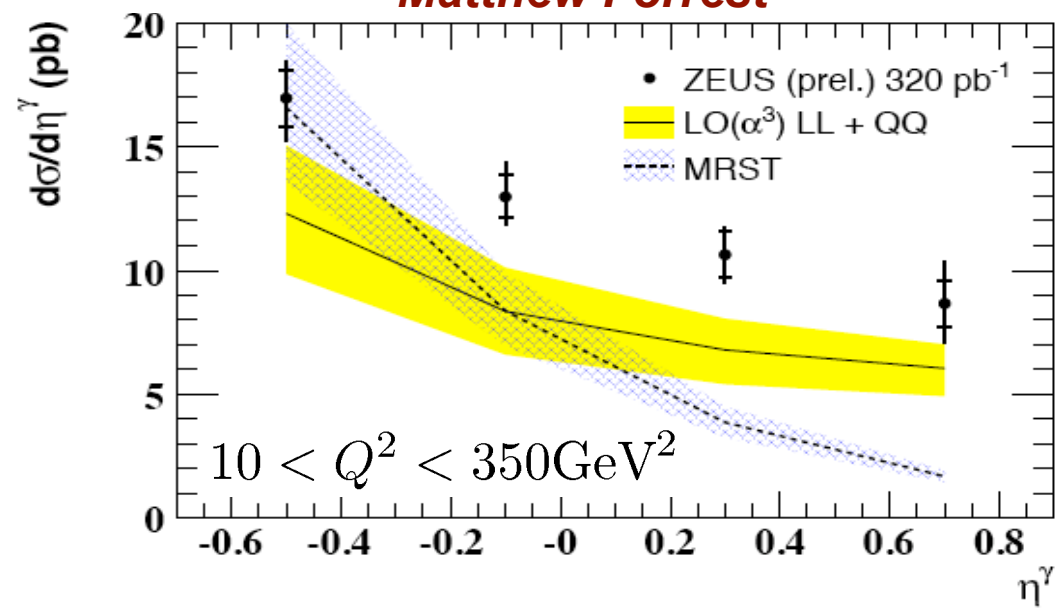


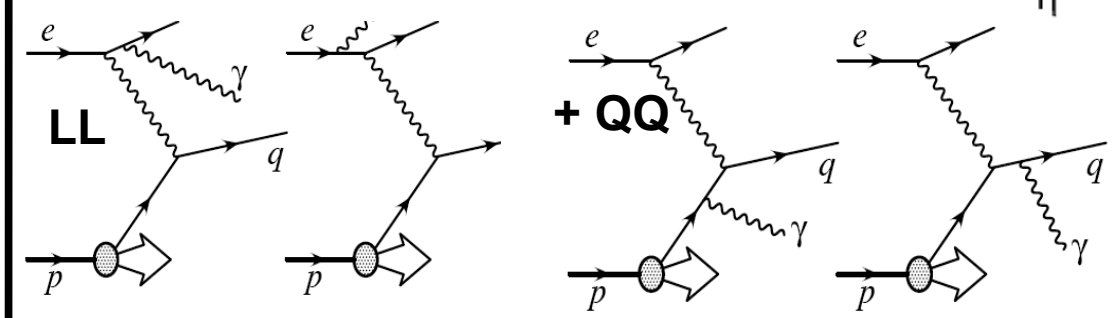
Photoproduction (H1)
Krzysztof Nowak



kt factorization approach describes eta distribution

DIS (ZEUS)
Matthew Forrest





LO: too low cross-section

Some highlights of the ep physics

- **Very high precision on the jet measurements, but we lack theoretical accuracy. We need NNLO. See talks on jets and alpha_s.**

- **Measurements for increasing our understanding of fragmentation. See e.g. talks on strangeness production**

- **Prompt photon measurements - test of e.g. fixed order calculations and the kt-factorization approach.**

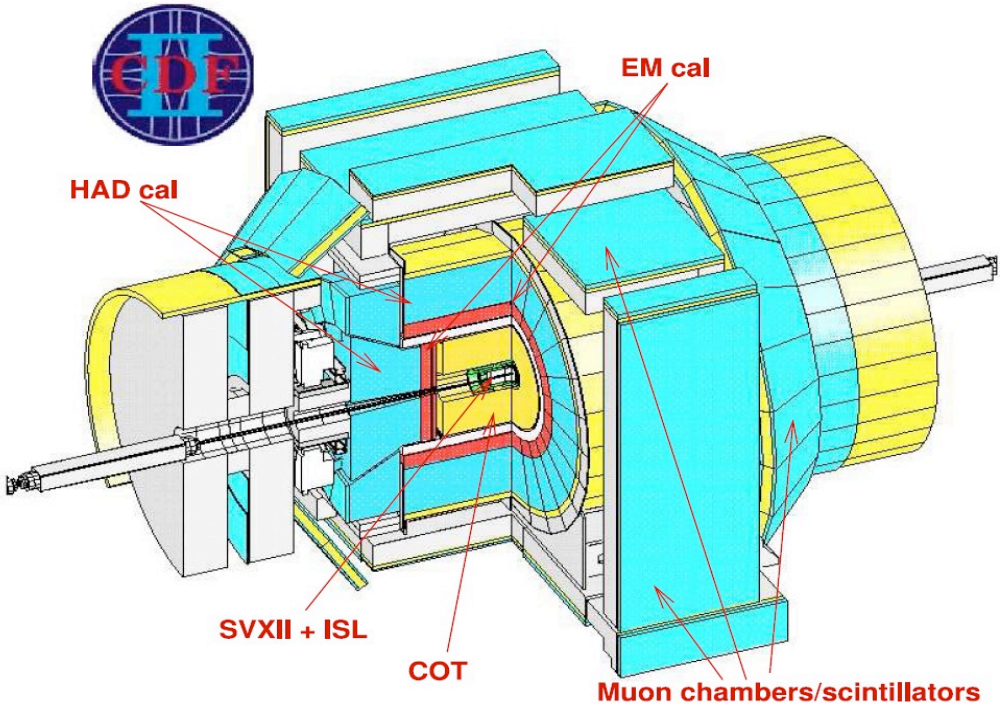
- **Wide range of measurements with charged particles**
  (Charge asym., Scaled mom. dist., Extraction of MLLA model parameter, Underlying Event)

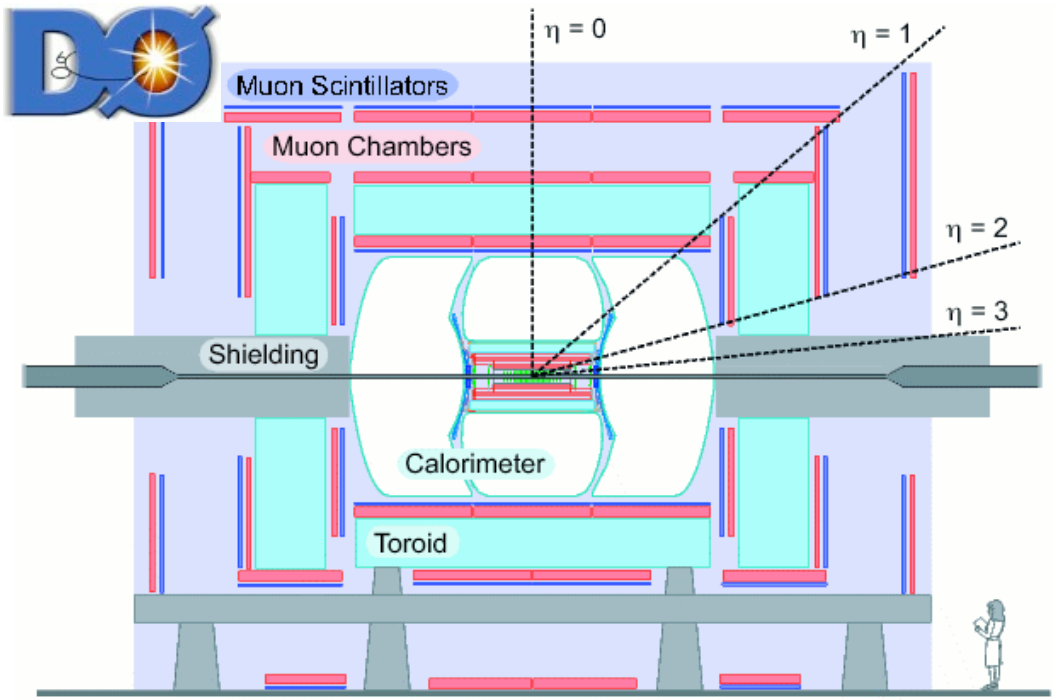
Thanks to the organizers !!!!!
Thanks to the speakers !!!!!
Thanks to my co-conveners !!!!!

QCD + HFS:
Tevatron (8 talks)
and LHC (9 talks)

Gavin Hesketh, Albert Knutsson, Leszek Motyka
Northeastern University

Tevatron





Tevatron performing very well

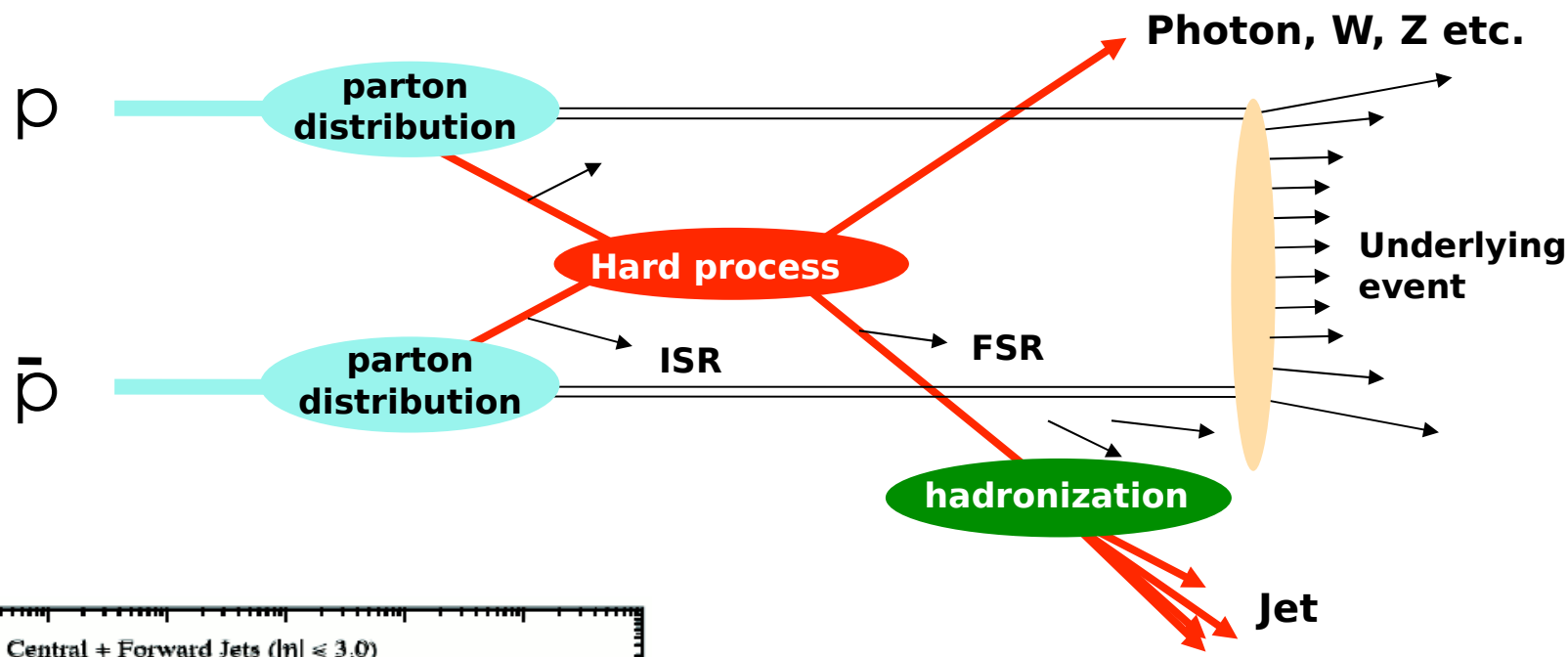
- 6.5 fb-1 delivered (per experiment)
  - 2 fb^{-1} recorded in 2008 alone
- projection: > 9 fb^{-1} by end of 2010
- running in 2011 under discussion

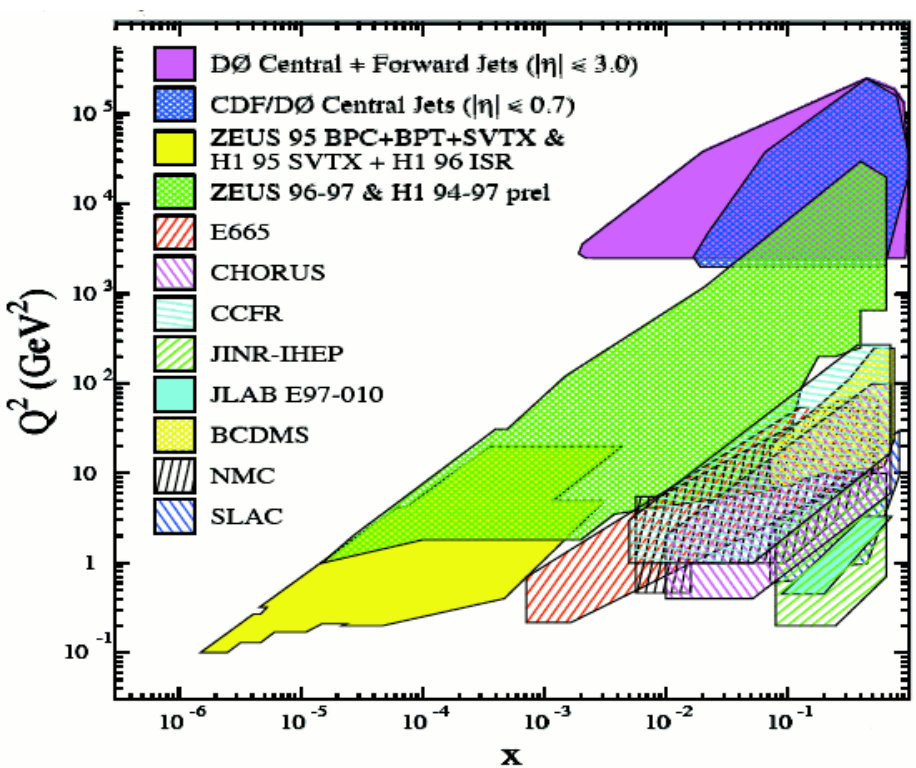
Both experiments keeping up!

- data taking efficiency > 85 %
- many new results since DIS 2008

Results shown use 0.7 – 2.7 fb^{-1}

QCD at the Tevatron





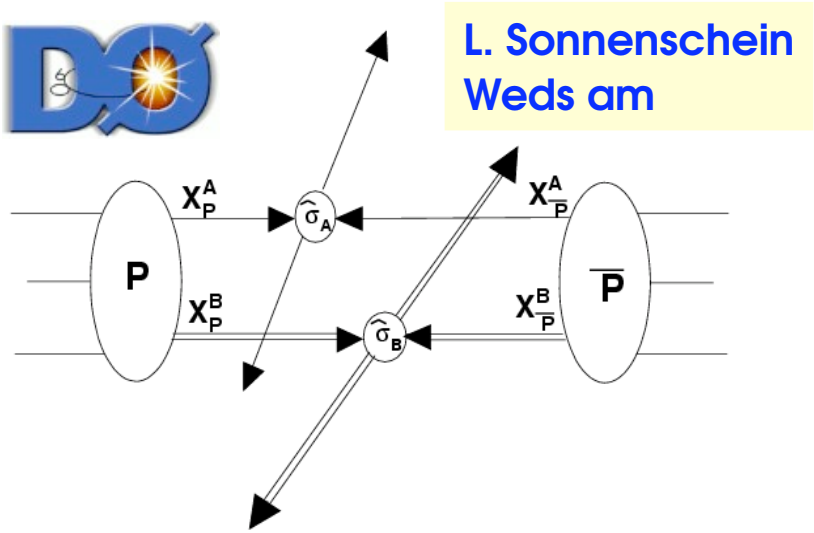
Many results:

- underlying event & jet shapes
- inclusive jets
- photon + jets
- heavy boson + jets

Impossible to do justice to every talk!

Underlying Event

Double parton interactions:
- information about proton structure
- important background



Tag primary interaction A= γ+jet
Identify second interaction B=di-jets

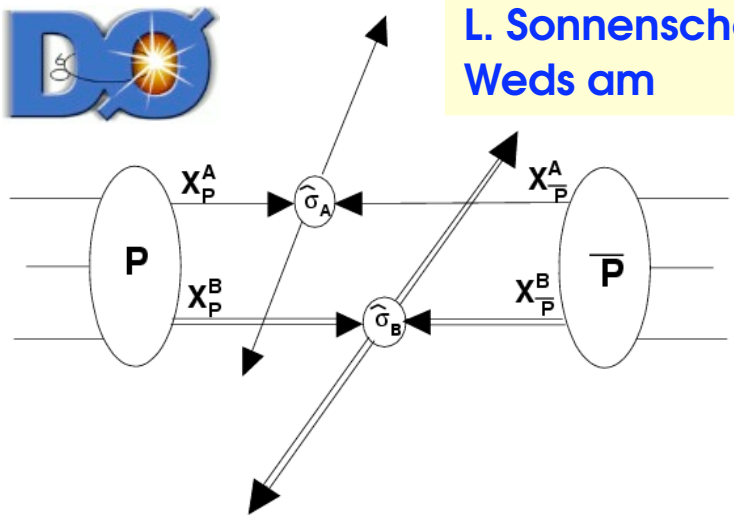
Extract effective cross section:

$$\sigma_{DP} = m \cdot \sigma_A \cdot \frac{\sigma_B}{2\sigma_{eff}}$$

Measured: $\langle\sigma_{eff}\rangle$ = 15.1 $\pm$ 1.9 pb
Consistent with previous CDF result

Underlying Event

Double parton interactions:
- information about proton structure
- important background



L. Sonnenschein
Weds am

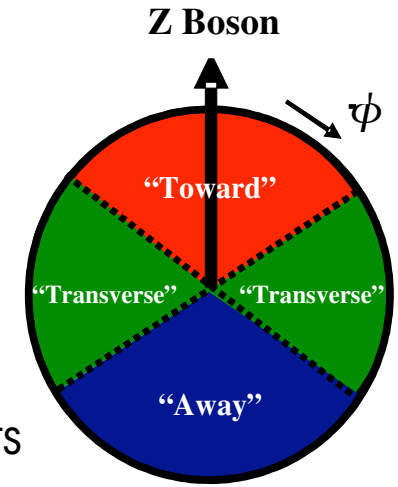
Tag primary interaction A= γ+jet
Identify second interaction B=di-jets

Extract effective cross section:

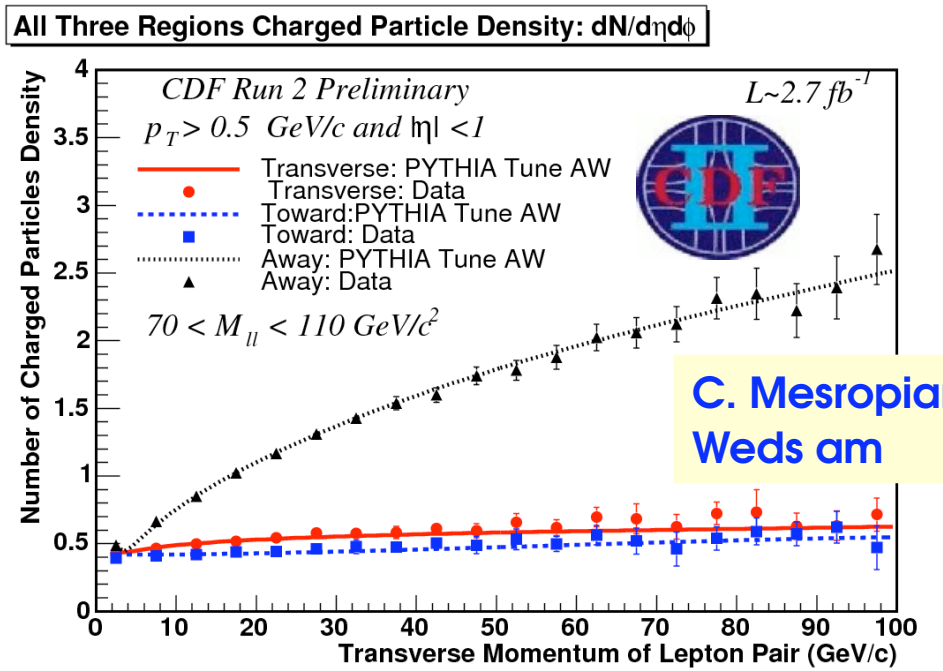
$$\sigma_{DP} = m \cdot \sigma_A \cdot \frac{\sigma_B}{2\sigma_{eff}}$$

Measured: $\langle\sigma_{eff}\rangle$ = 15.1 ± 1.9 pb
Consistent with previous CDF result

Several studies at CDF
Update classic method:
- now use Z events



Compare to PYTHIA
- tuned on jet data
- good agreement in Z events



C. Mesropian,
Weds am

Also CDF studies of jet shapes (M Martinez):
- PYTHIA tunes describe data well
- b jet situation less clear, need more study

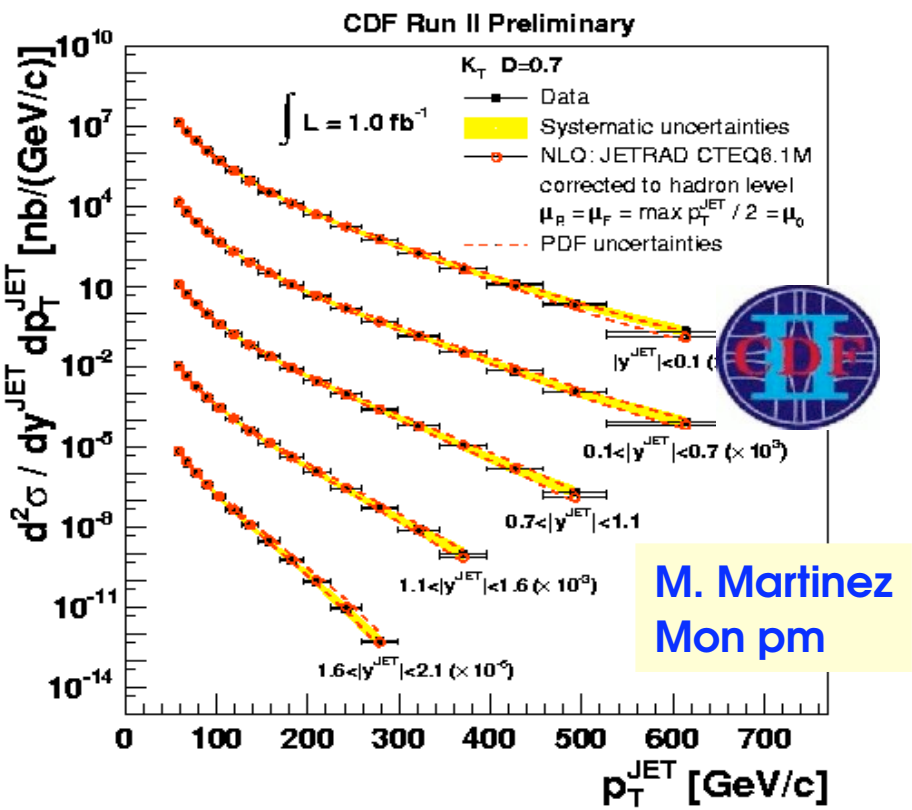
Inclusive Jets

Unprecedented JES precision at hadron collider:

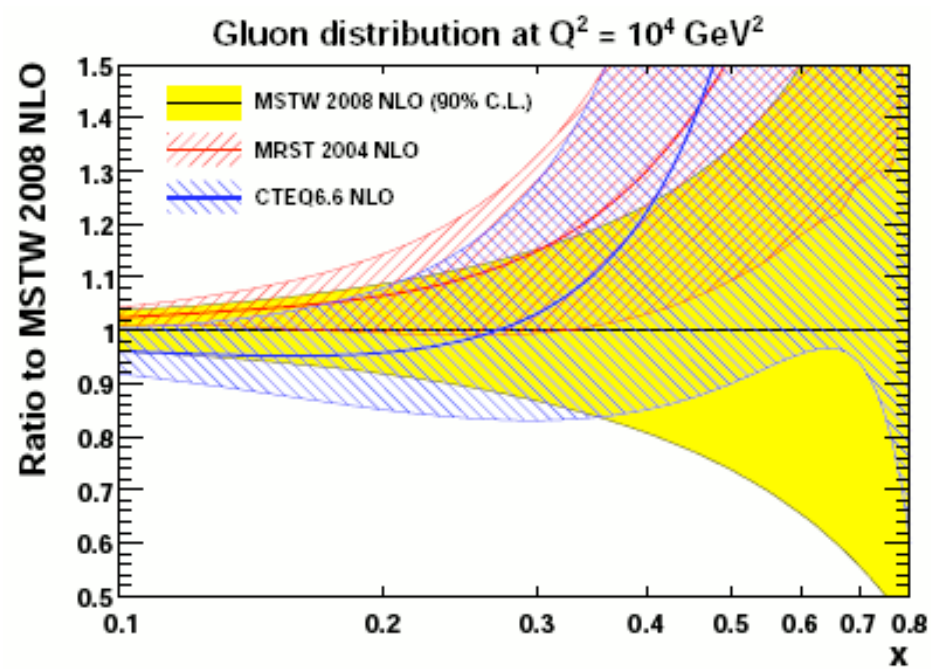
1-2 % (D0), 2-3% (CDF); took several year to achieve.

Measurements of inclusive jet cross sections:

- constrain high-x gluon -> favour less than previous fits
- used in new MSTW 2008 PDF set
- Run I jet data no longer included.



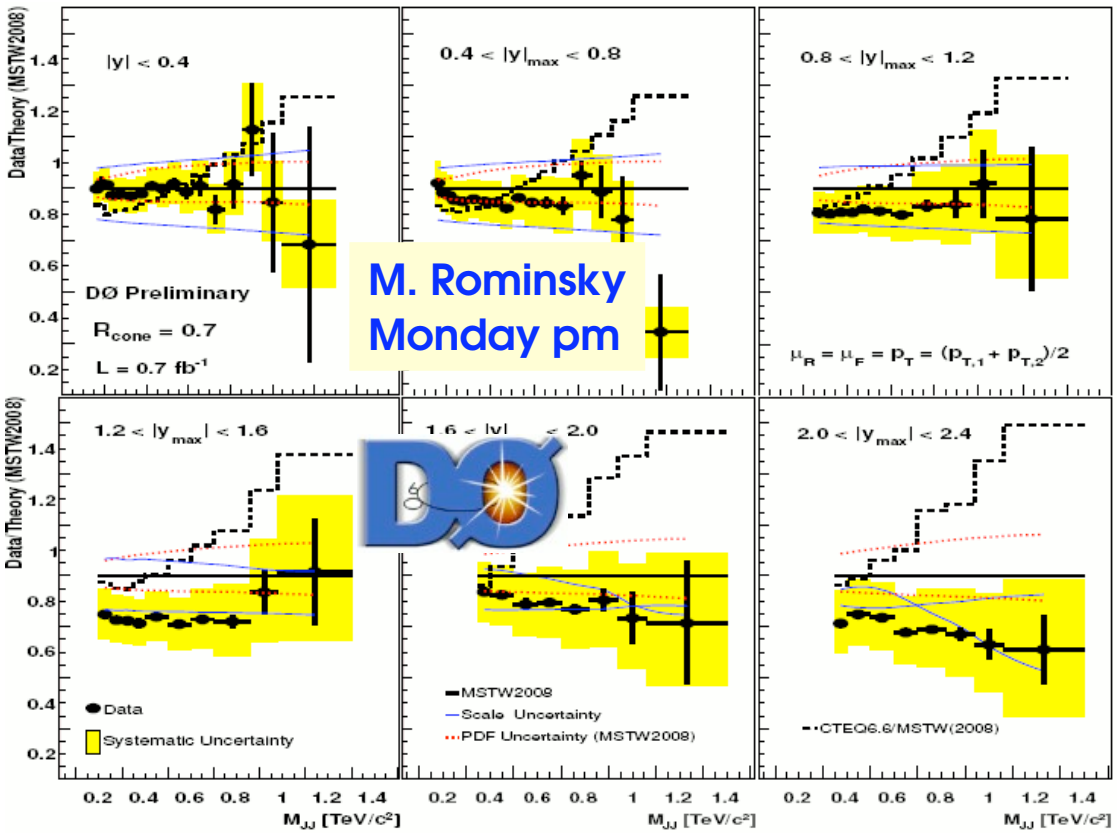
M. Martinez
Mon pm



Di-jet Mass, Angles

Following inclusive jet results in 2008, further tests of NLO/PDFs:

- di-jet mass in 6 $|y_{jet}|$ regions
- NLO agrees within systematics
- favour even less gluon at high-x?



M. Rominsky
Monday pm

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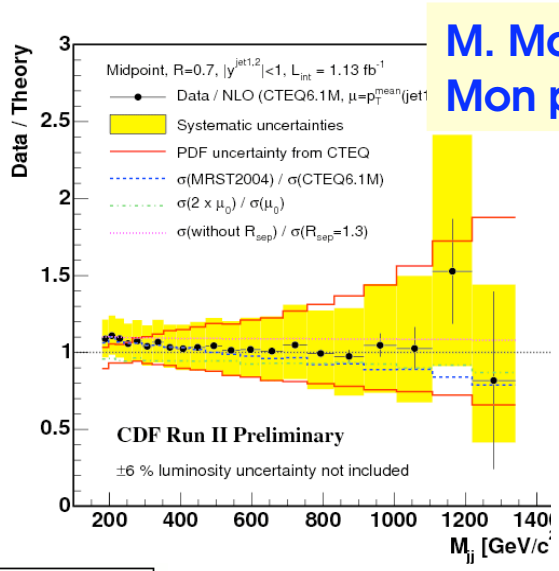
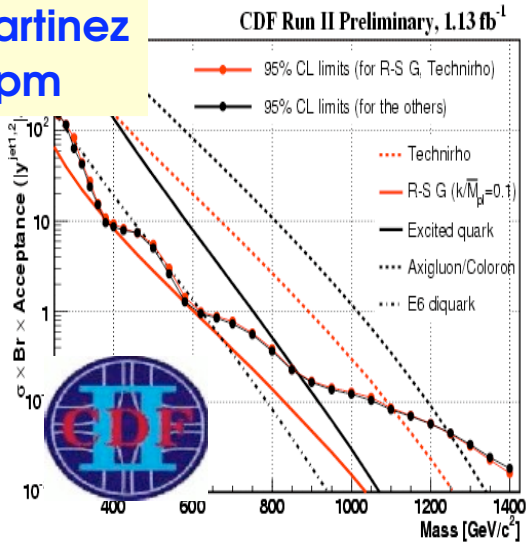
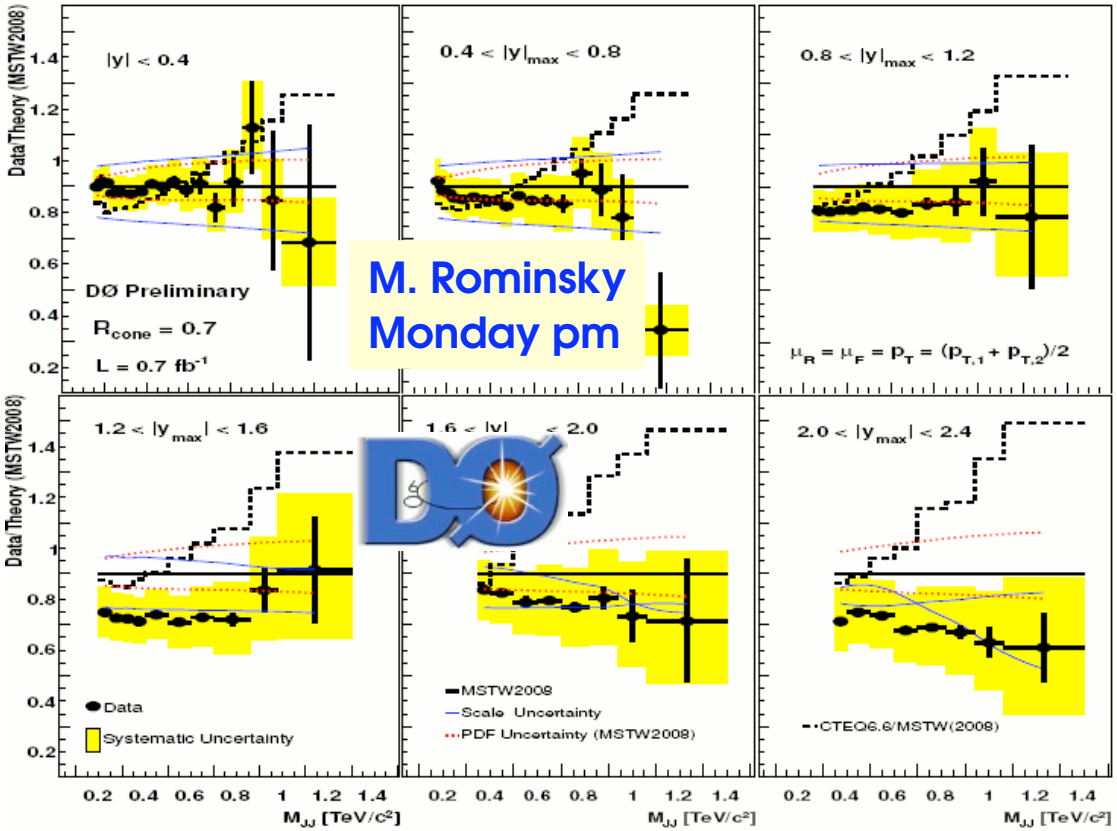
Also carry out new physics searches







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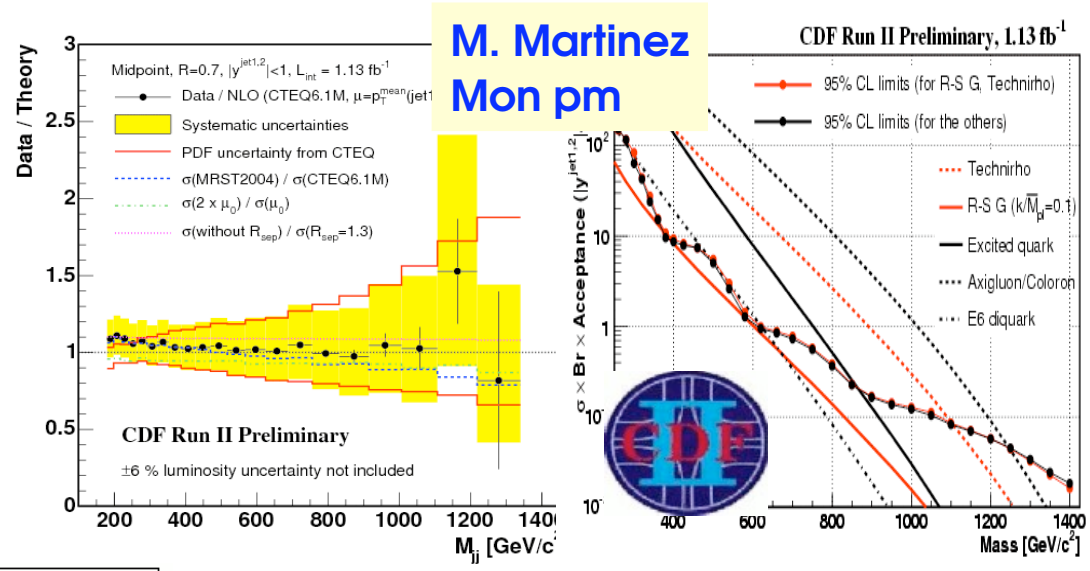
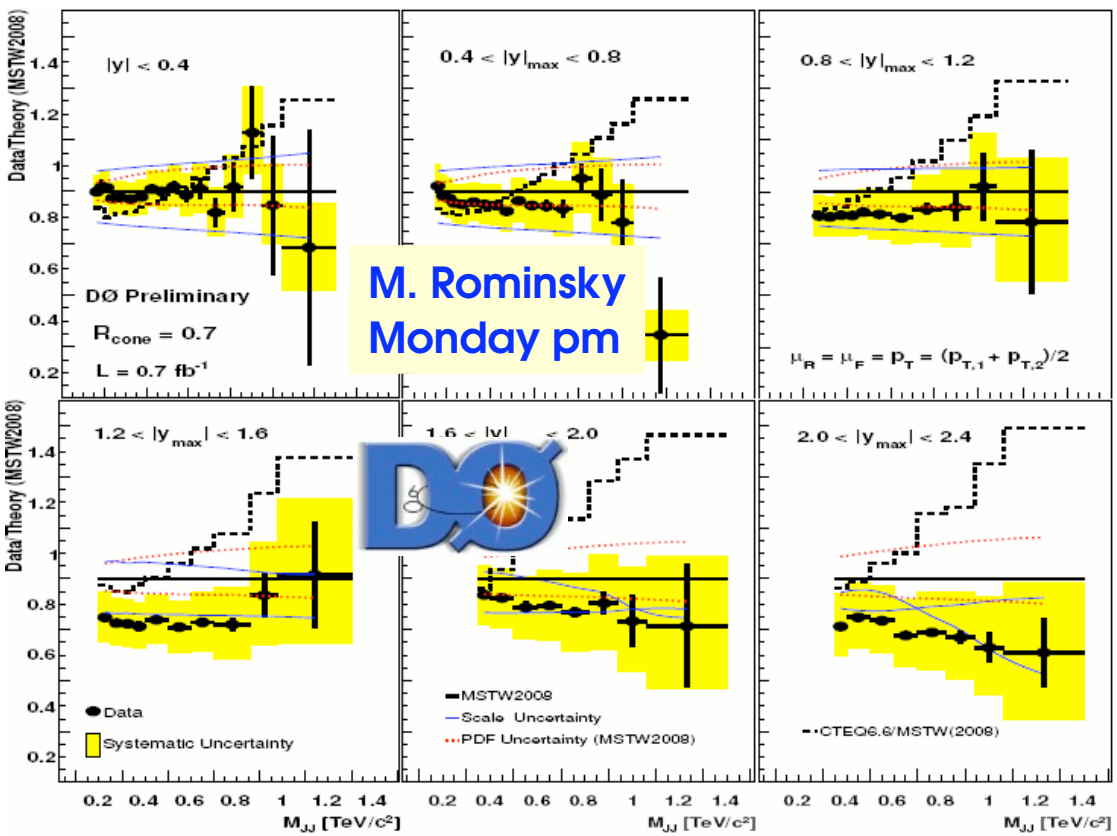
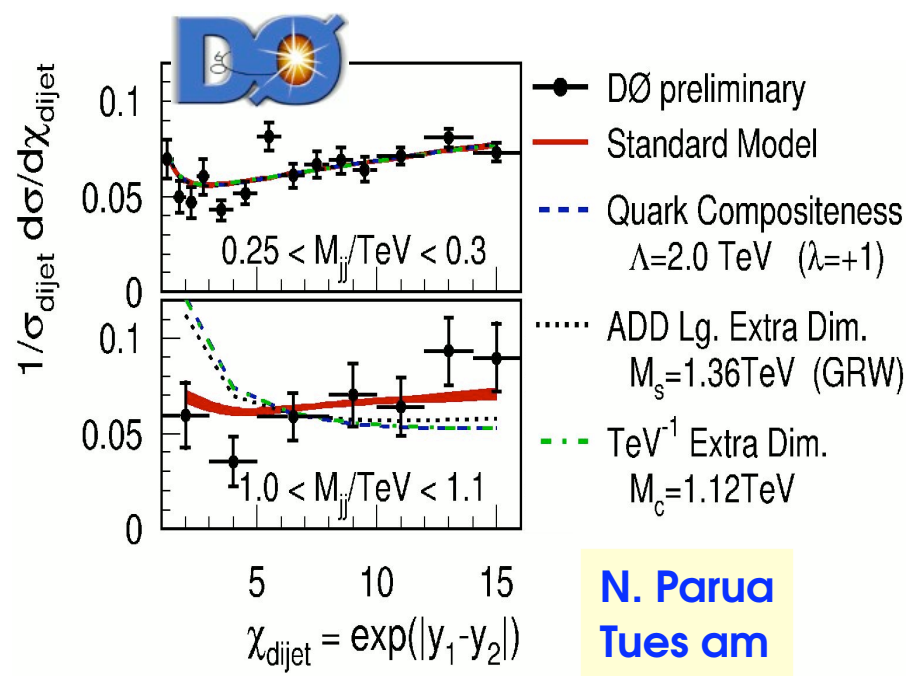
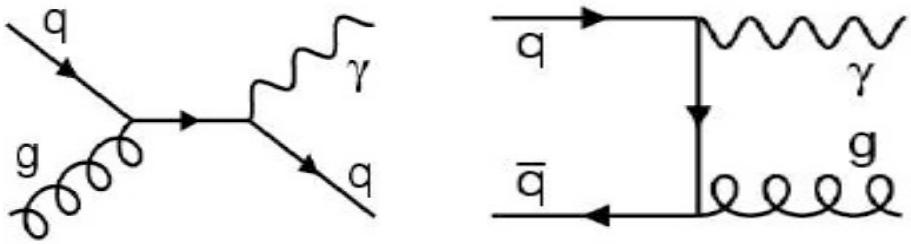






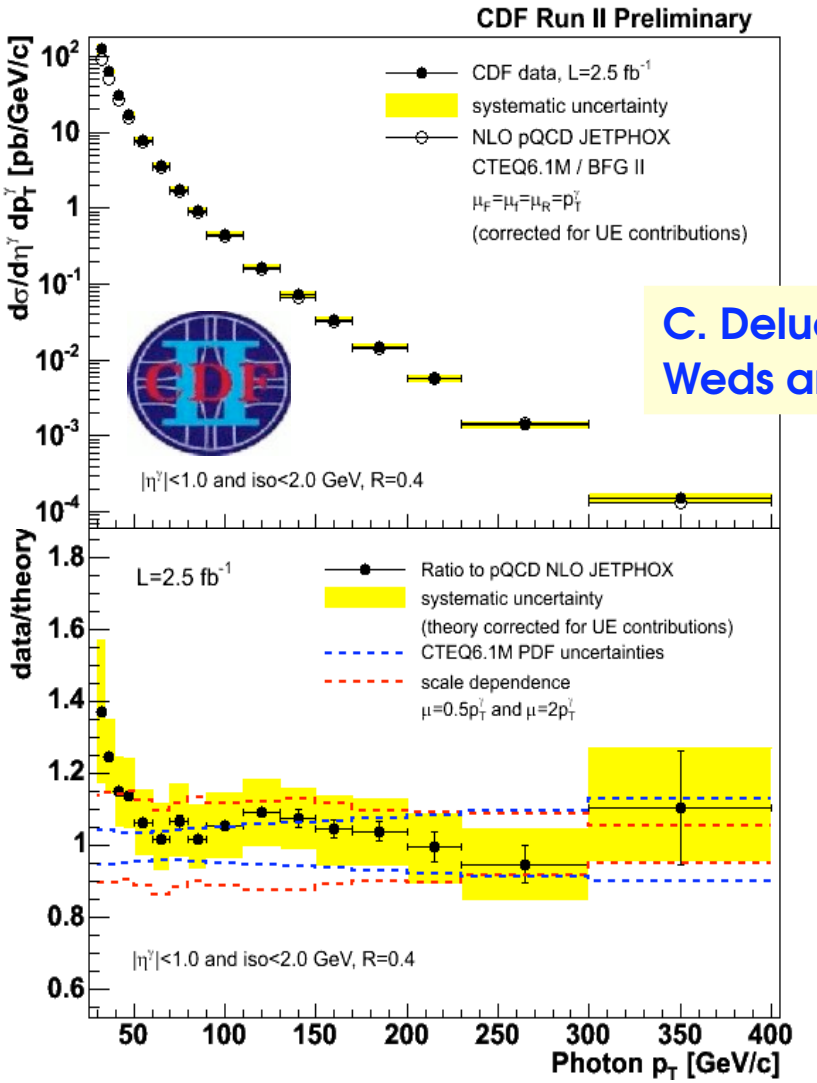
Photons (+jets)

Photons as direct probe of hard interactions



New CDF inclusive photon result:

- confirms low pT shape seen at D0, UA2



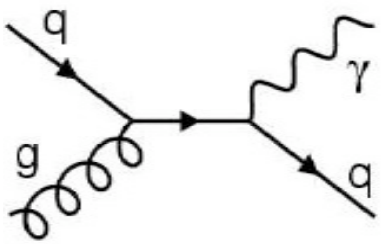
C. Deluca, Weds am

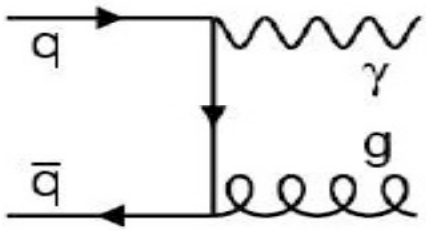
Something missing from theory?

- higher orders, fragmentation, ..?

Photons (+jets)

Photons as direct probe of hard interactions



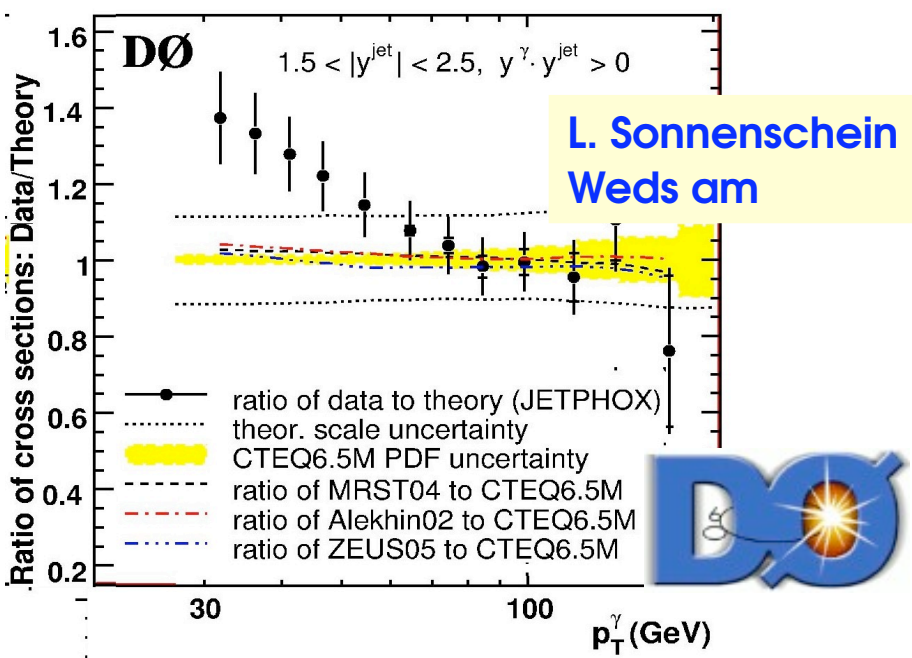


New CDF inclusive photon result:

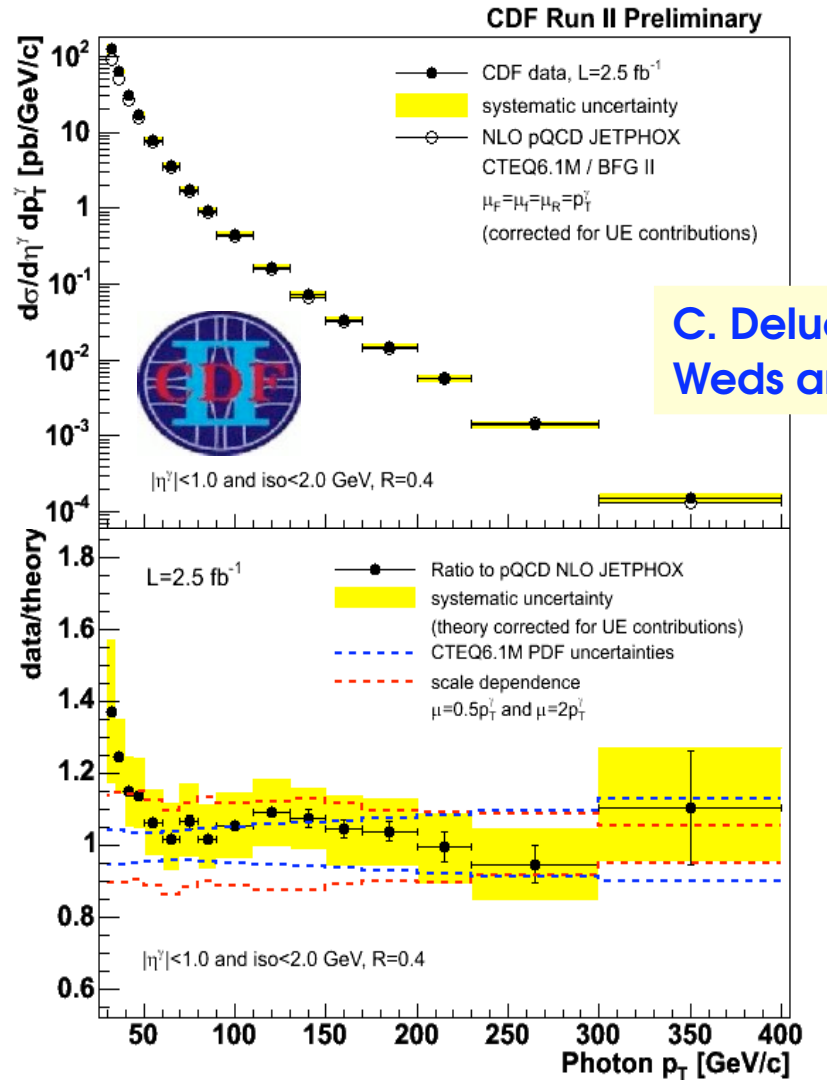
- confirms low pT shape seen at D0, UA2

D0 add jet information:

- look in bins of jet and photon y
- disagreement still there



L. Sonnenschein
Weds am



C. Deluca,
Weds am

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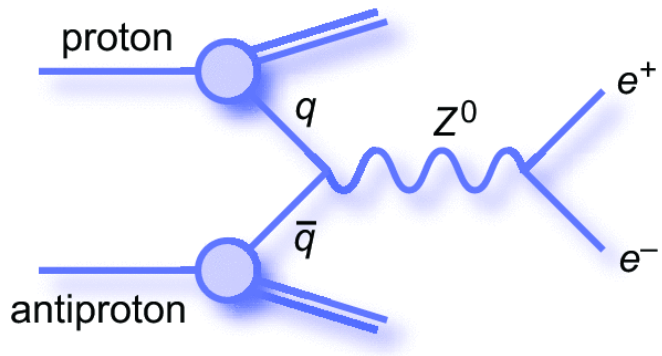
Z + jets

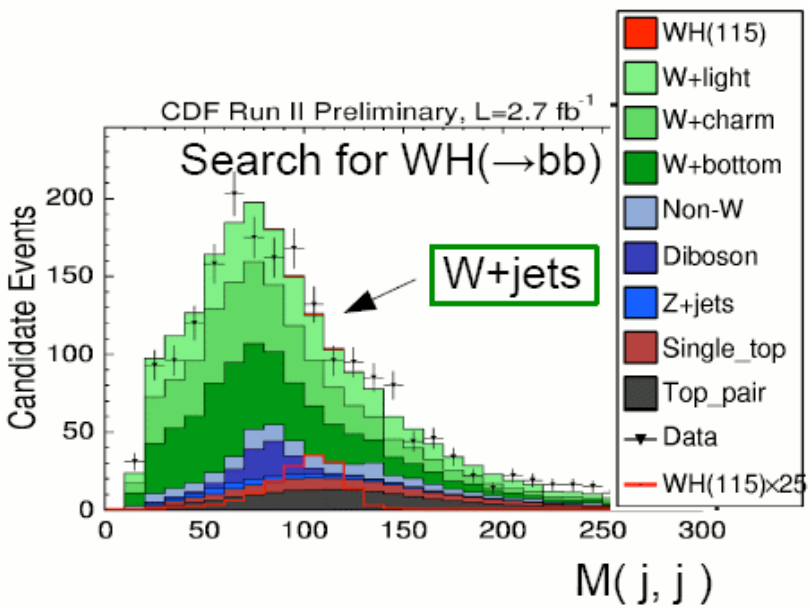


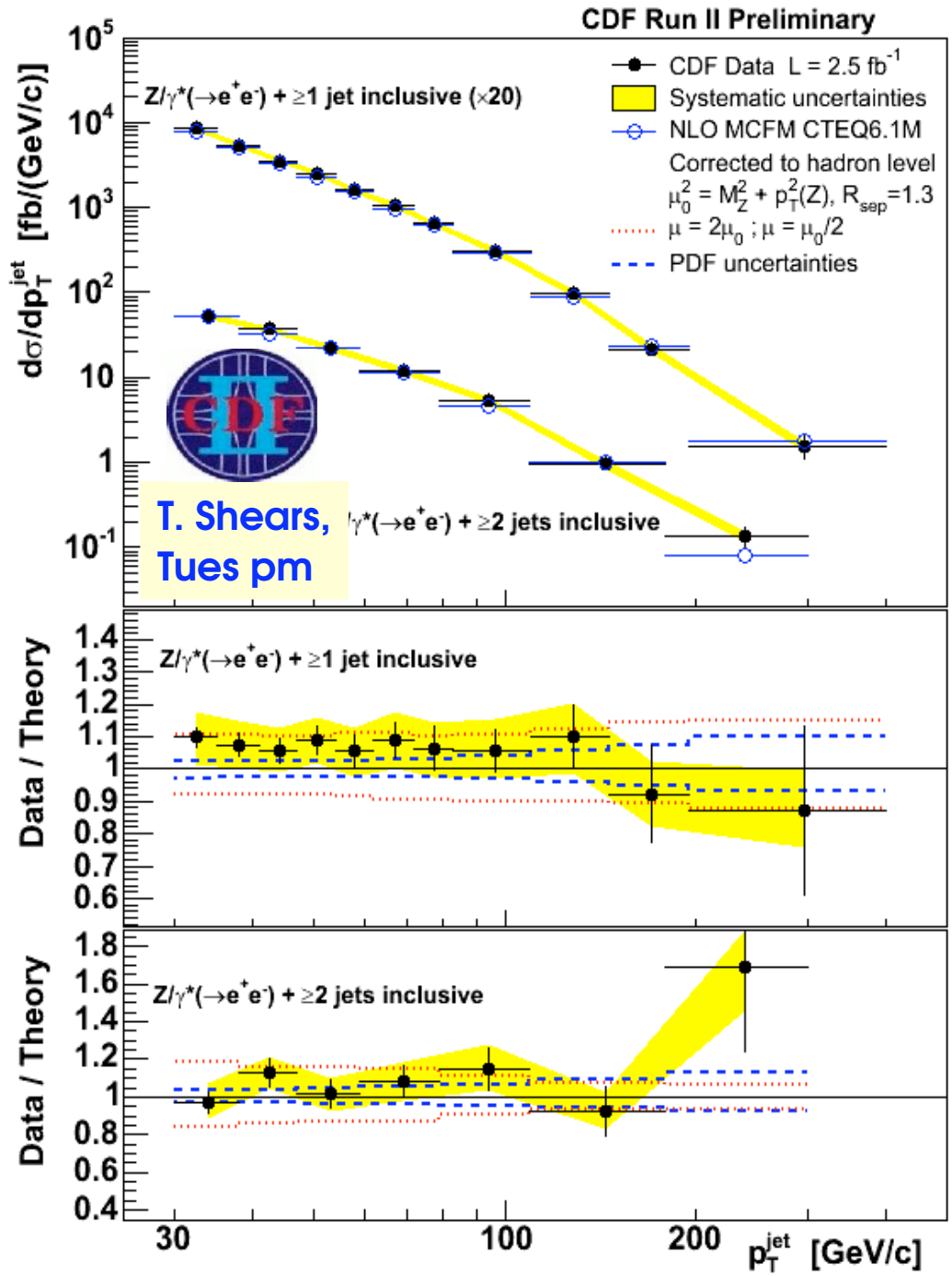
Study heavy boson production:

- probe pQCD (NLO to W/Z+2 jets)
- validate current simulations:
  - PYTHIA, HERWIG, ALPGEN, SHERPA
  - essential tools for Tevatron and LHC!

Also important as background:

- main background to top, higgs, ...





T. Shears, Tues pm

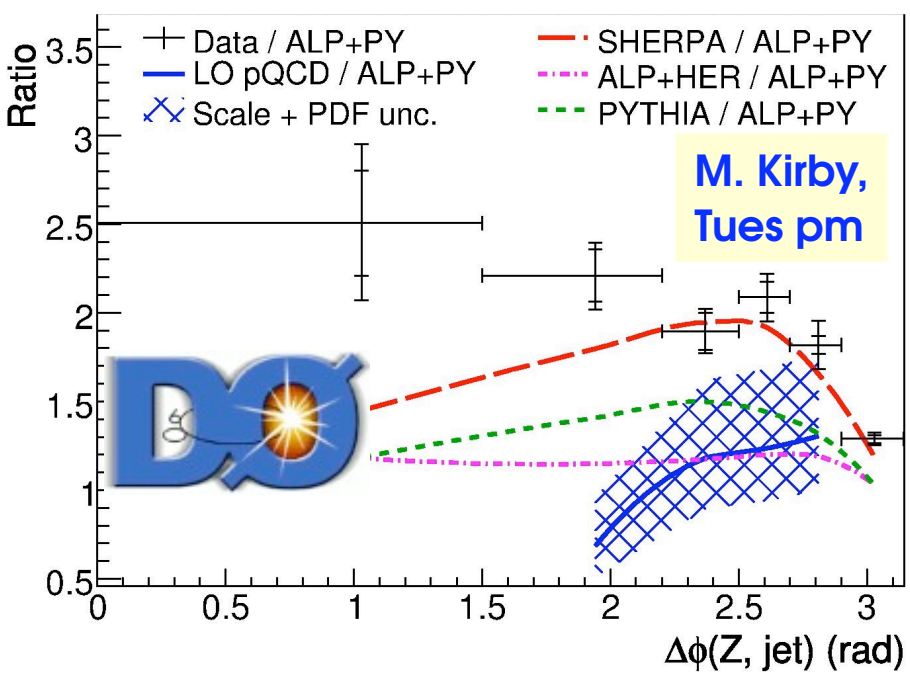
Z + jets

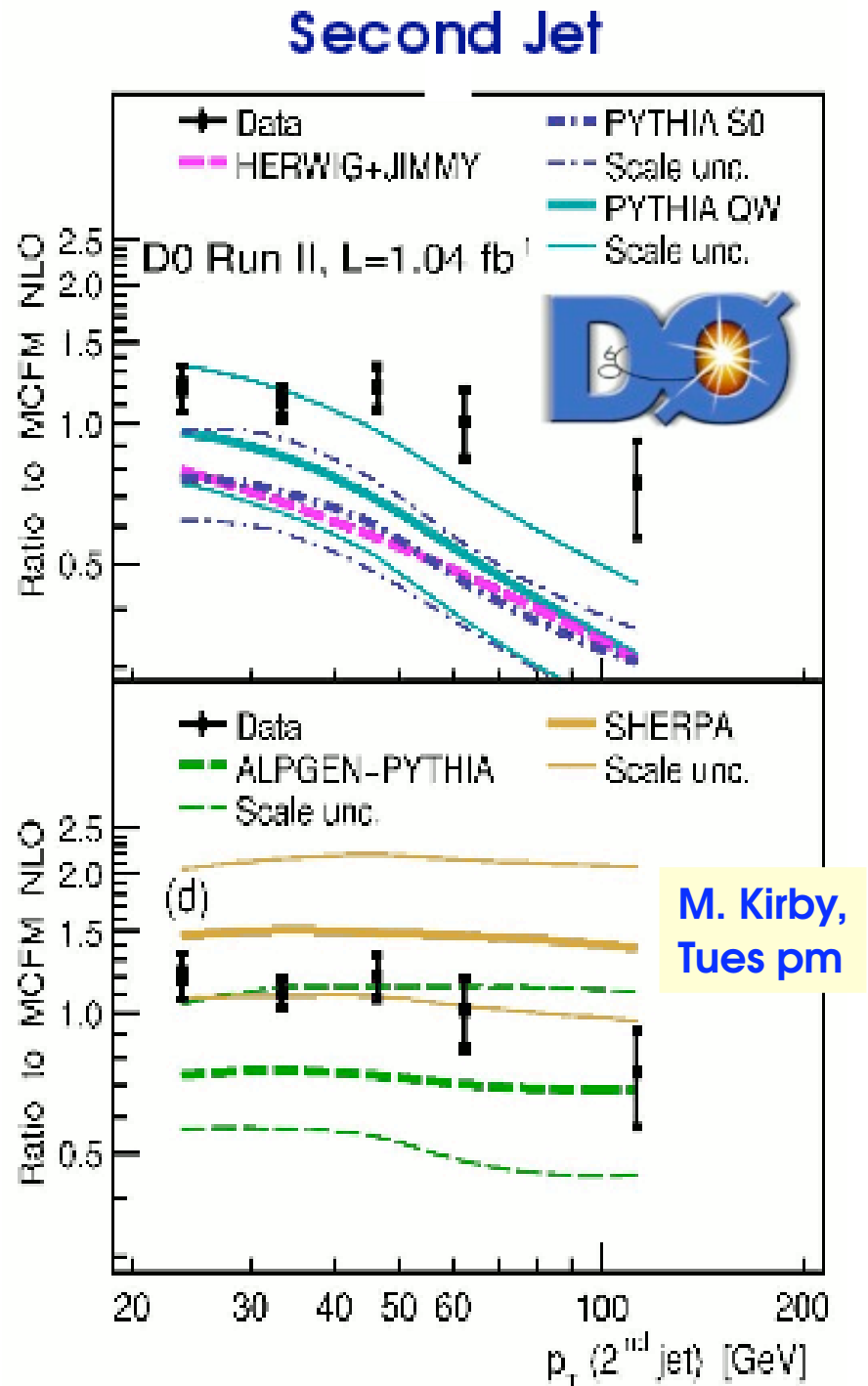
D0 measures many differential cross sections:

- 1st, 2nd, 3rd jet pT
- Z p_T & y (>= 1 jet in event), leading jet y
- Δy, $\Delta\phi$ (Z, leading jet)

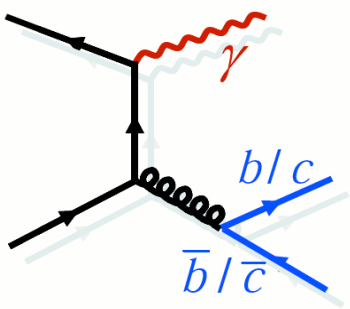
Comparisons to NLO and generators:

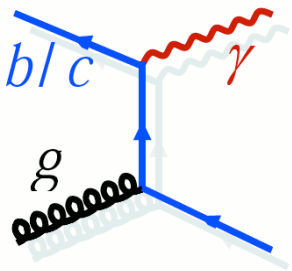
- NLO generally agrees with data
- PYTHIA / HERWIG deficits in 2nd, 3rd jet
- ALPGEN generally describes pT shapes
- SHERPA generally describes angle shapes
- Tuning needed!





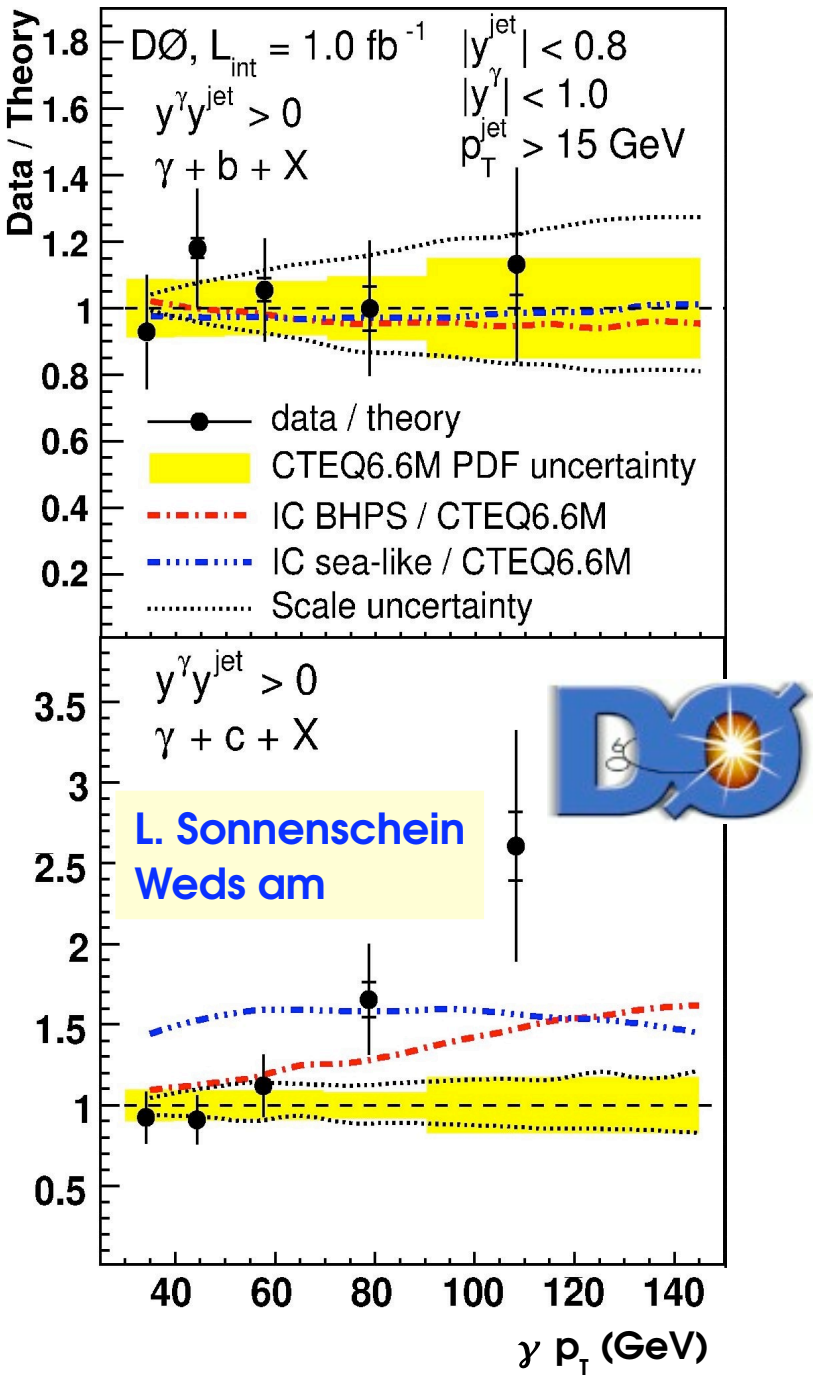
Bosons + HF





Measurement of photon + HF (D0):

- disagreement in charm jets



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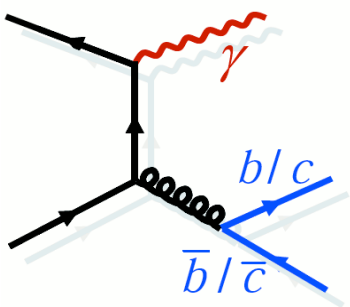
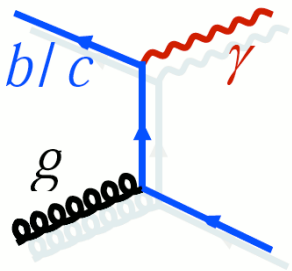




Measurement of photon + HF (D0):

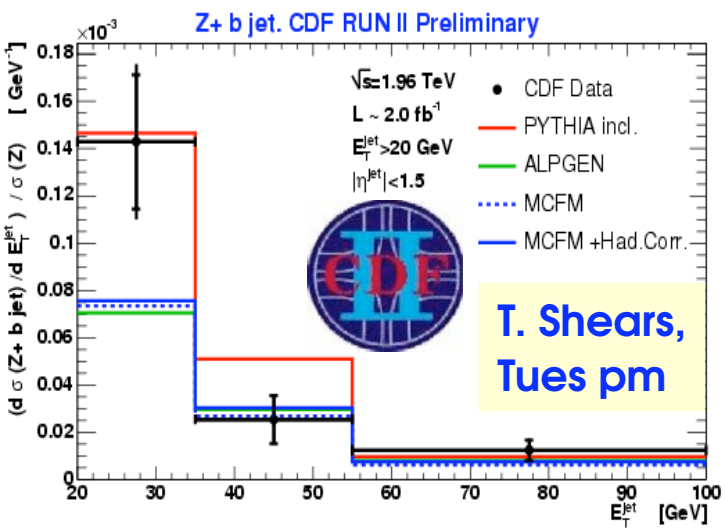
- disagreement in charm jets

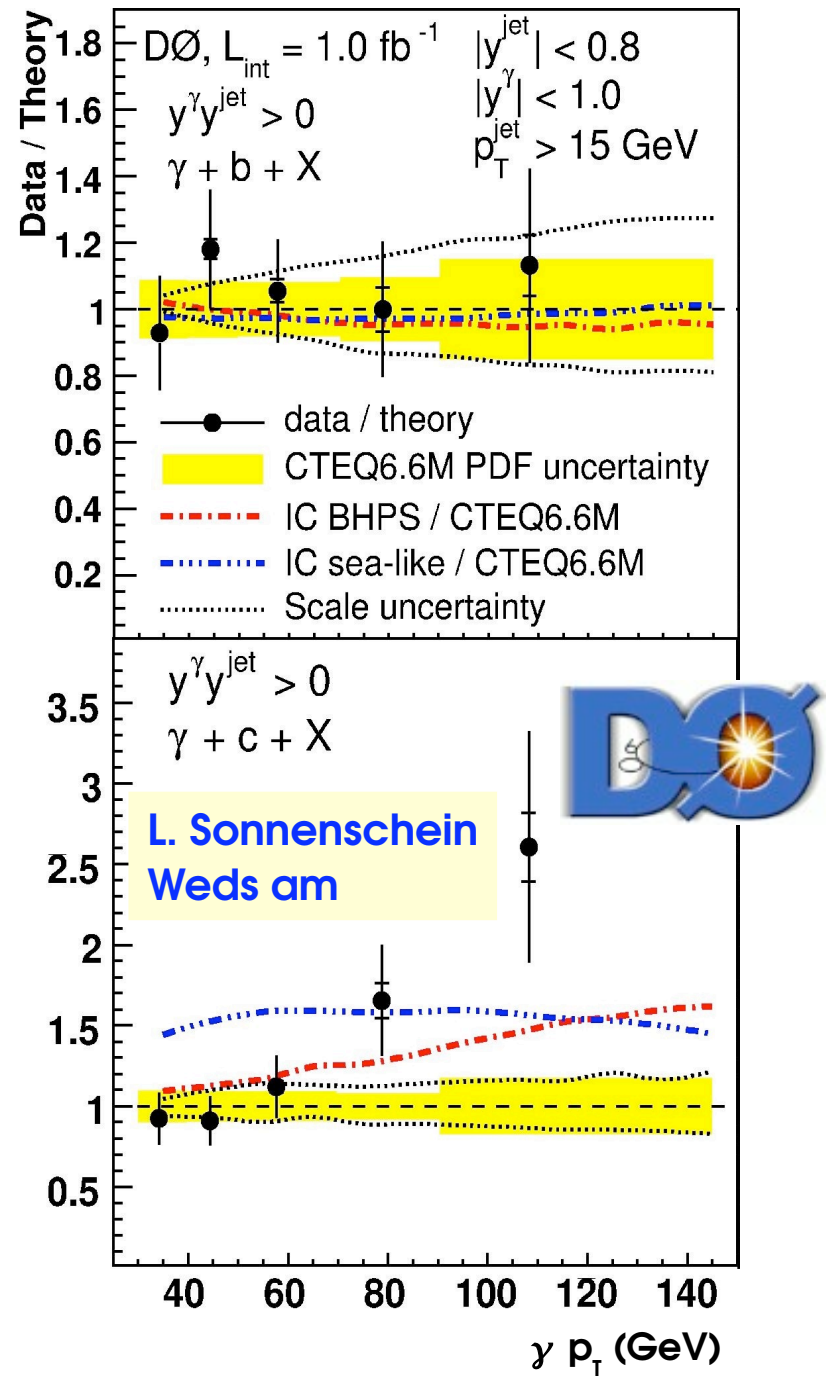
Measurement of Z+b (CDF):

- first differential measurements
- agreement with NLO
- ALPGEN/PYTHIA factors of 2 apart

Measurement of W+b cross section (CDF):

- ALPGEN low by x3; no NLO prediction yet





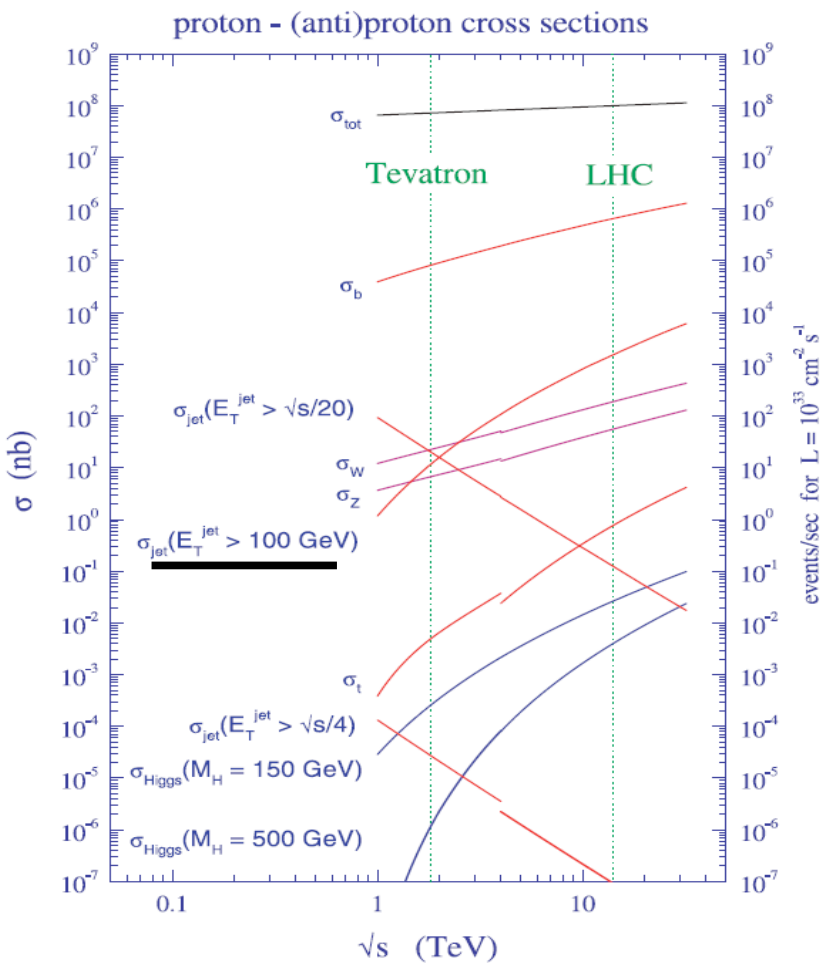
On to the LHC

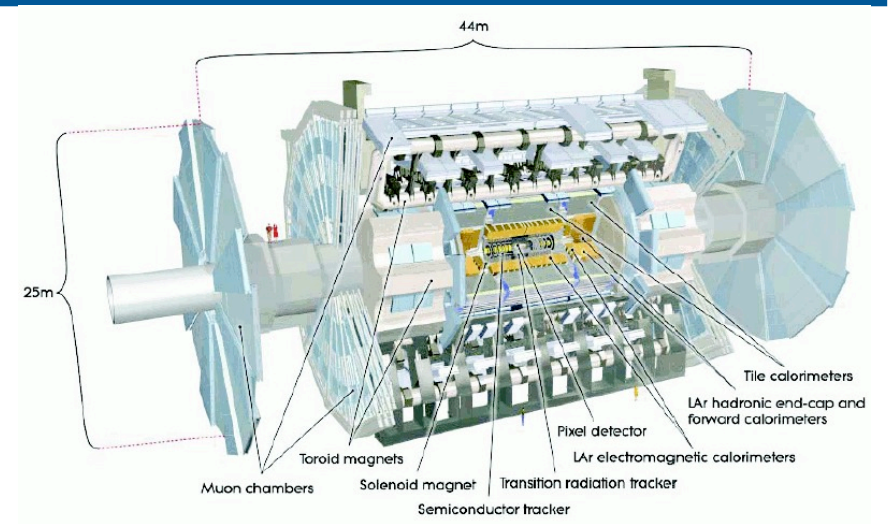
Reports from ATLAS, CMS and LHCb:

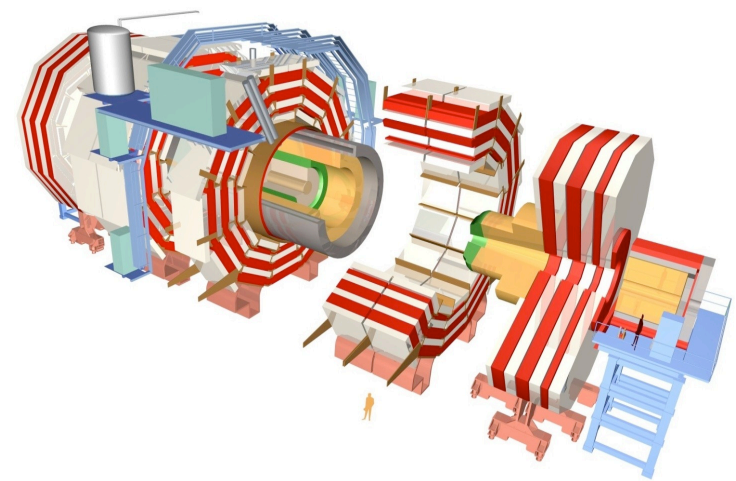
- commissioning and plans for first data
  - what to expect with first 10-100 pb^{-1}

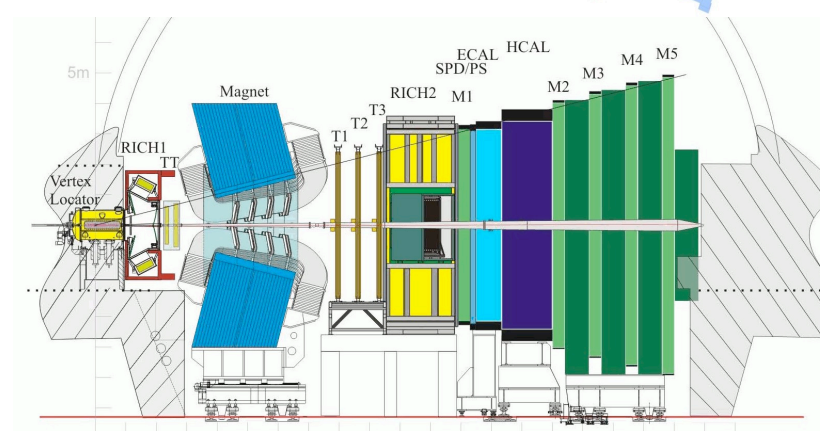
Testing QCD in new energy regime:

- establish basic signals, look for surprises!





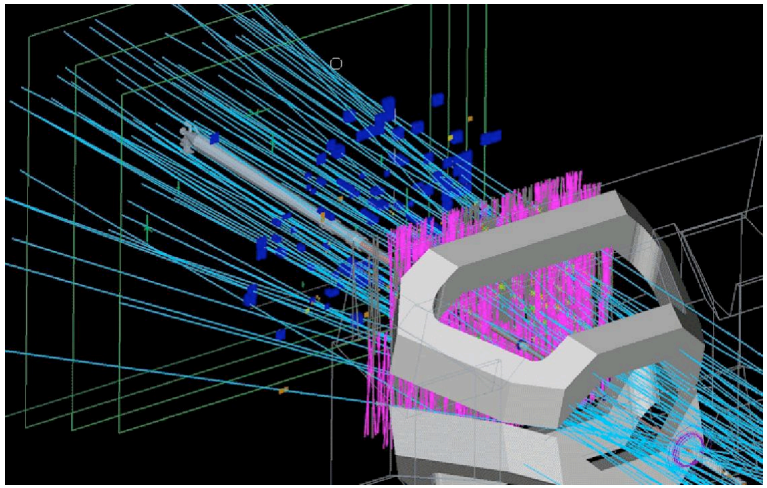


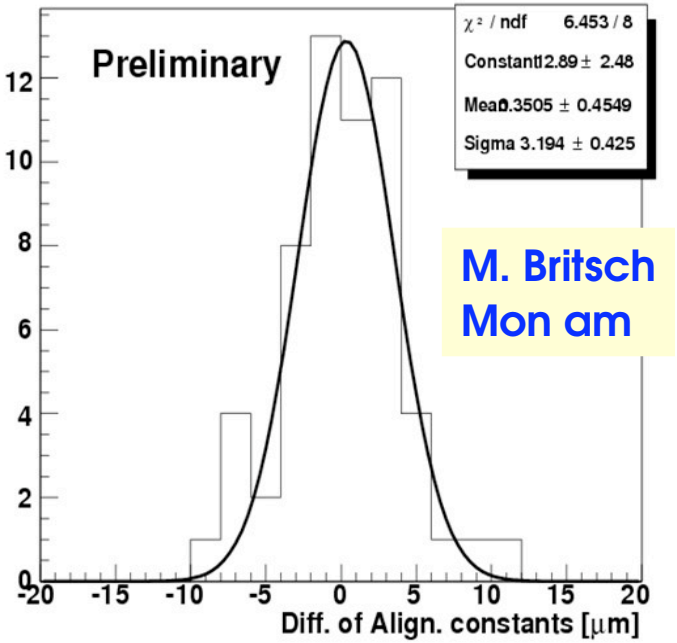


LHCb Commissioning

LHCb: precision measurements of CP violation, rare decays and heavy flavour physics
- forward spectrometer: $1.9 < \eta < 4.9$
- precise vertex resolution, particle ID, dedicated triggers.

Detector alignment & commissioning:
- using cosmics, beam-gas, beam on collimator





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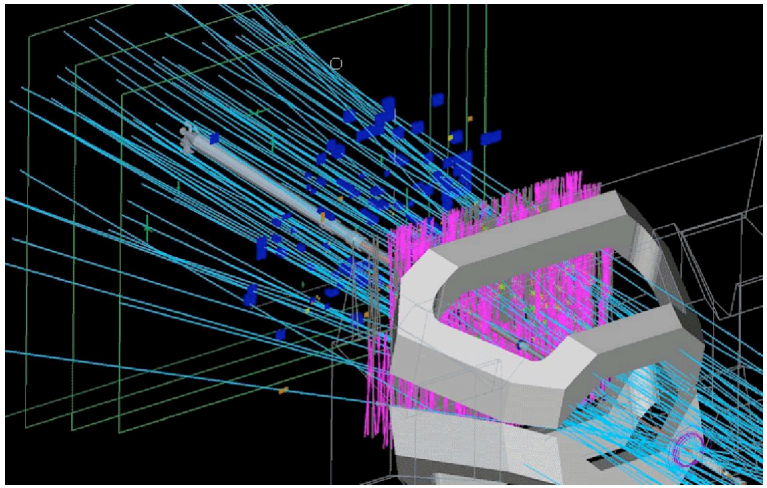
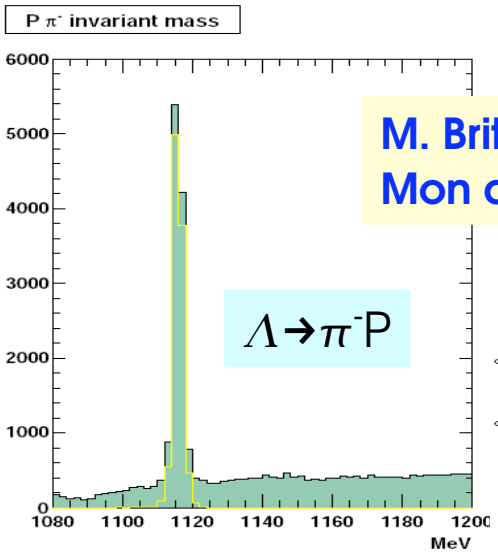
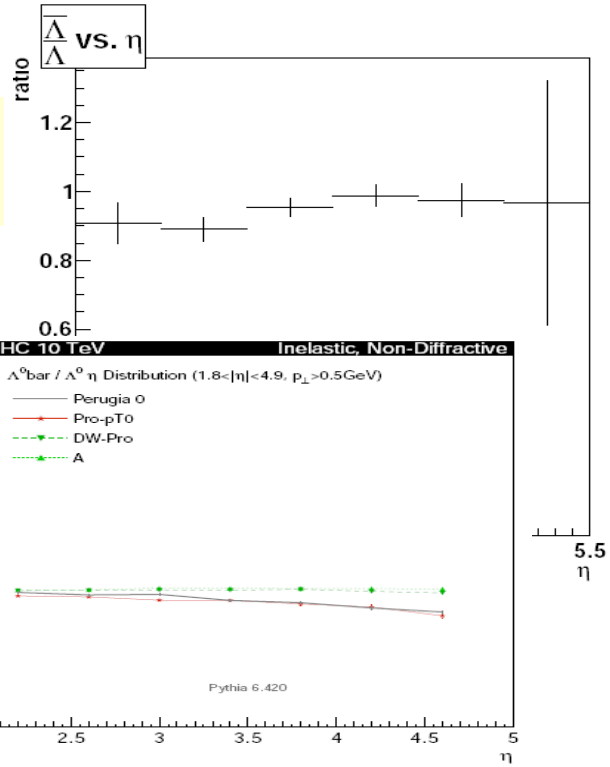
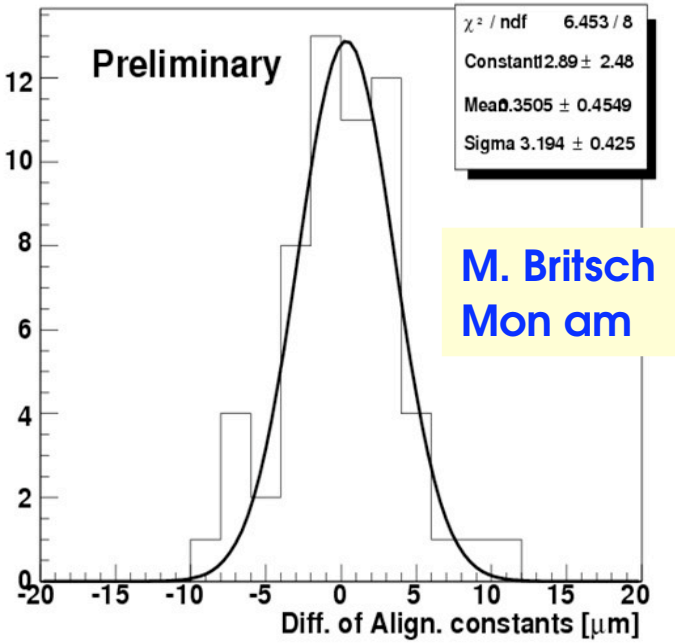
MC study of early measurements:
- based on 10^8 events (one day of min-bias!)
- charge track ratios to 1%
- establish K, Λ, and D signals and asymmetries







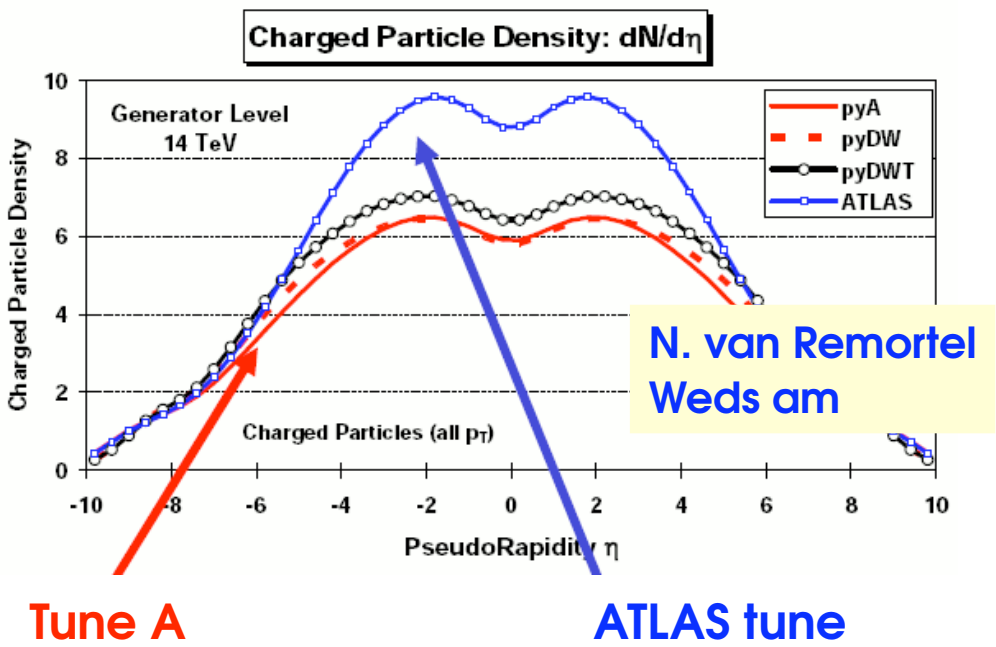


Underlying Event

Essential early ATLAS and CMS measurements:

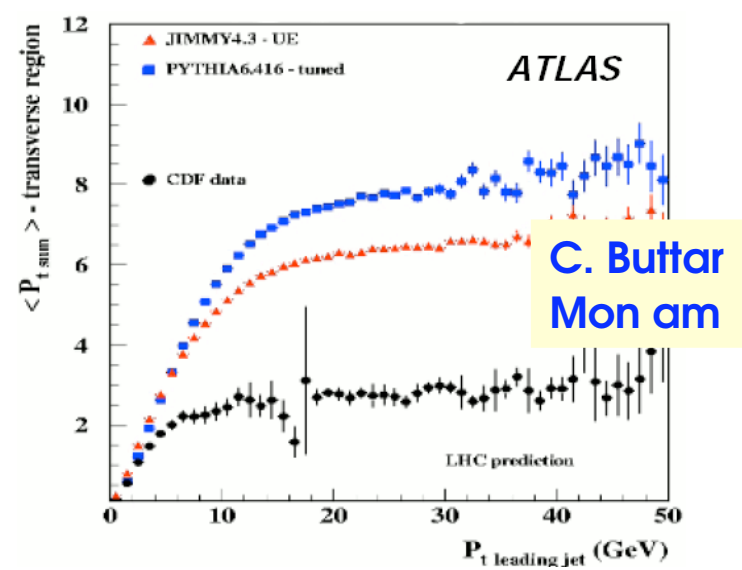
- at high instantaneous luminosity, average of 19 interactions overlaid!
- do underlying event models scale to LHC energy?
    - affects jet corrections, lepton isolation, etc

PYTHIA tunes disagree at LHC



Recent PYTHIA tune match CDF data at 630 and 1800 GeV

PYTHIA and JIMMY disagree at LHC



See also L. Mucibello, Weds am

High Energy Jets

Determining the JES at LHC:

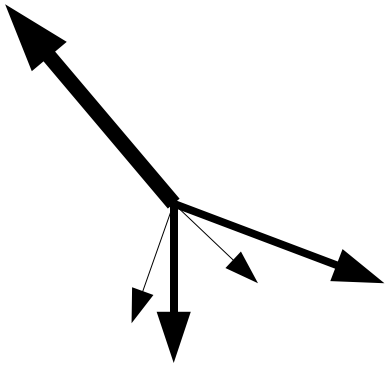
- similar methods to Tevatron:
- pT balance in photon + jet events
  - 1-2 % stat. unc. with 100 pb^{-1}
  - 1-2 % systematics
- use Z+jet events at low p_T
  - 1 % stat. unc. with 300 pb^{-1}
  - 5-10 % systematics from F/ISR & UE

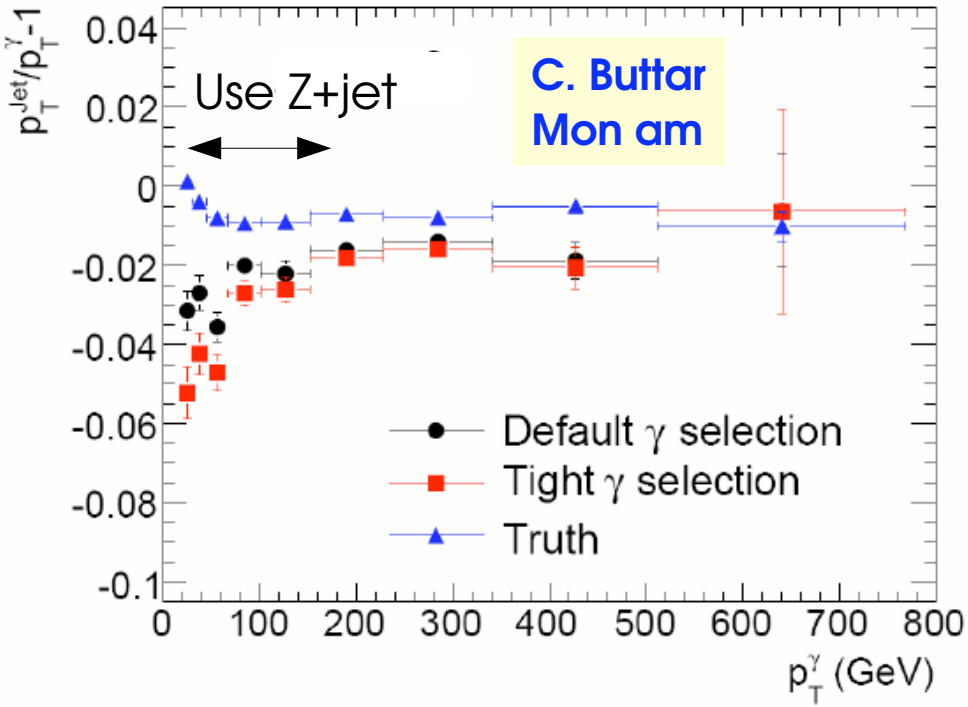
To reach high x, need JES at high p_T:

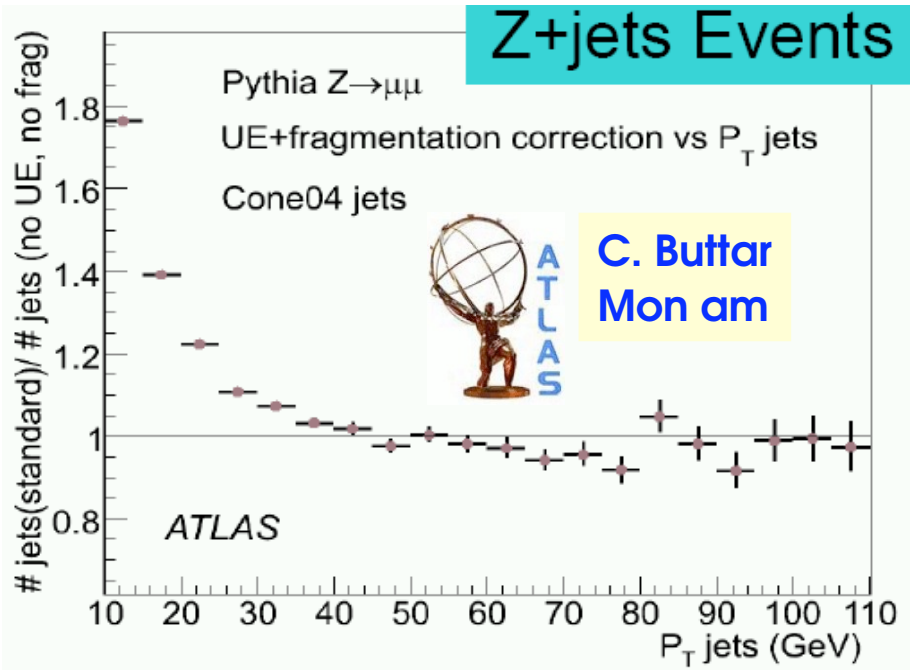
- p_T balance in multi-jets:
  - ~8 % systematic from softer jet JES

High-x gluon measurements "challenging"

- systematics dominated by physics effects
- may be better understood with data?







Jet Kinematics

Exploit increased energy reach

- even without precise JES

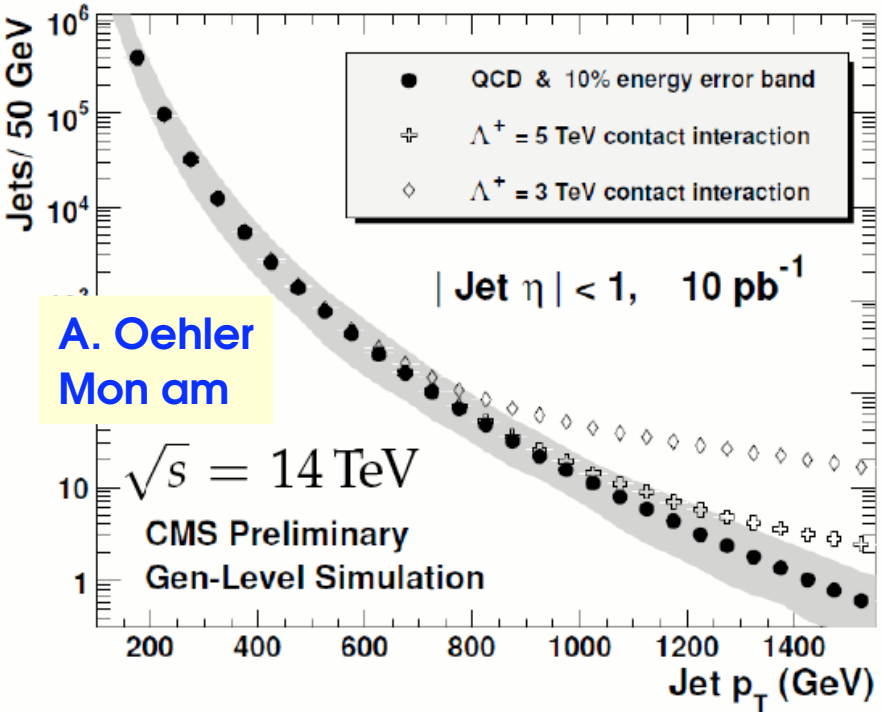
Studies of:

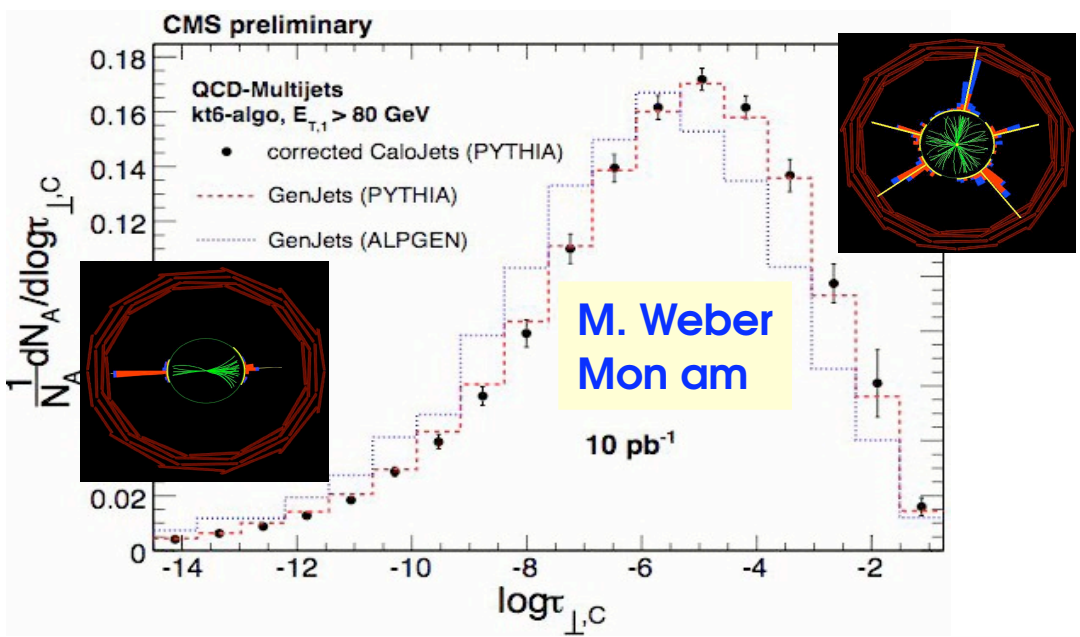
- jet angles: thrust, $\Delta\phi$
  - tune simulations to match data
- jet p_T, di-jet θ^*, di-jet mass
  - and ratio in forward and central jets

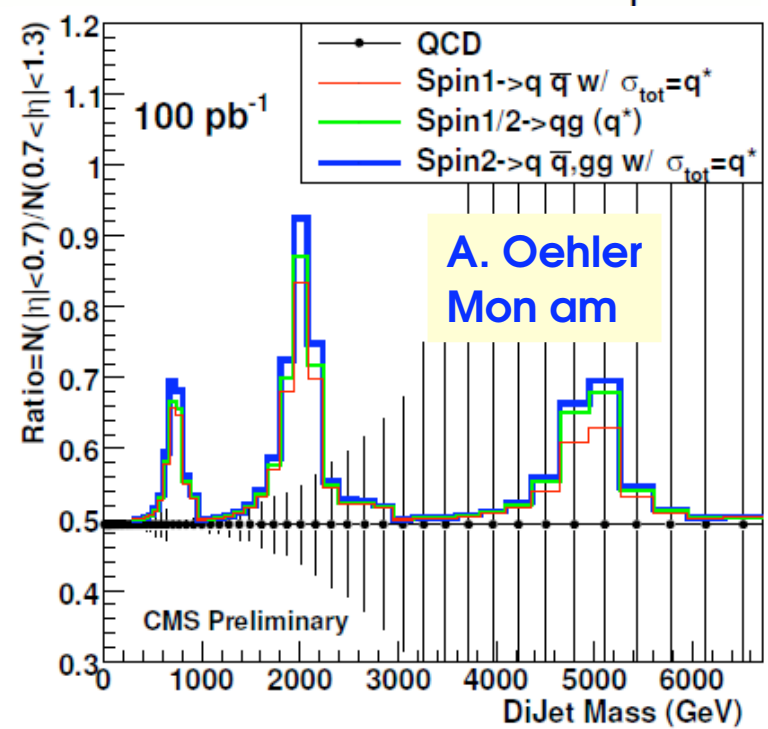
10pb^{-1} at 14 TeV: pass Tevatron limits!

See also studies of forward jets at CMS:

- low-x gluon, Mueller- Navelet dijet models
- **S Cerci, Monday pm**







W/Z + Jets

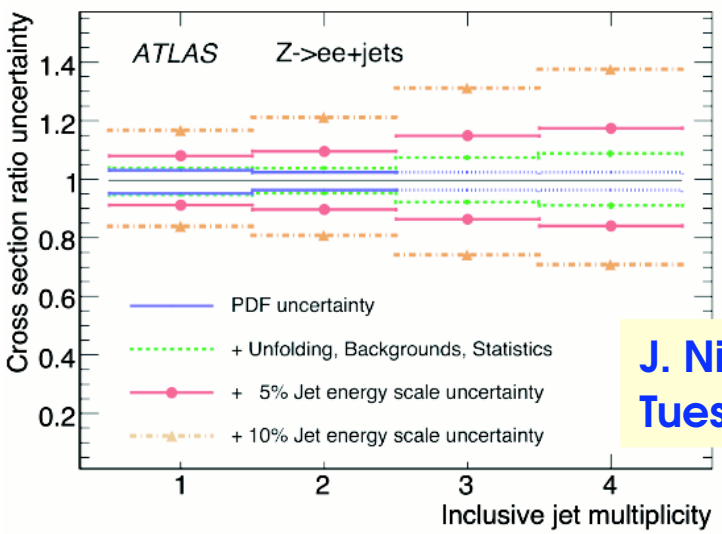
With 100pb^{-1} at 10 TeV: 250 k W, 25k Z (in leptonic channels)

Establish W/Z (+jets) signals early on at ATLAS, CMS:

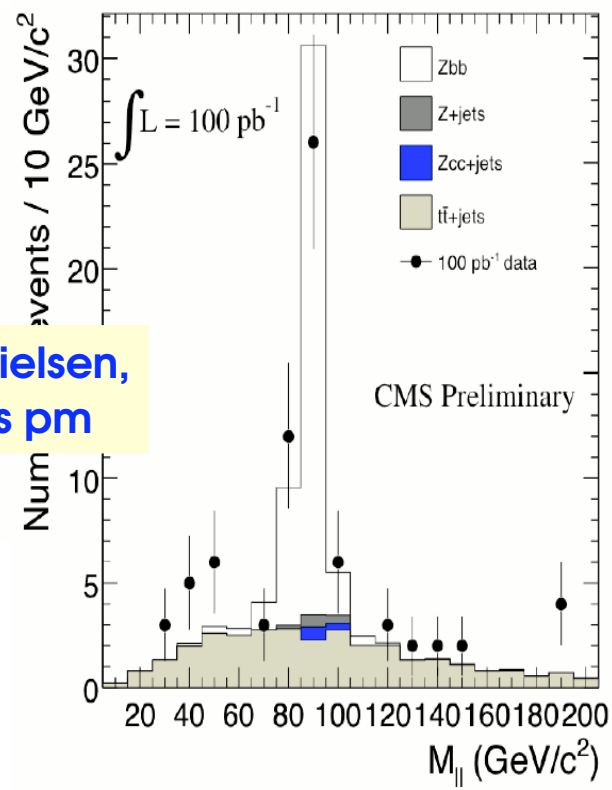
- calibration of lepton efficiencies
- test pQCD predictions, event generator modelling
- searches for new physics in W+jets (top, SUSY-like), W/Z+b-jets (Higgs)

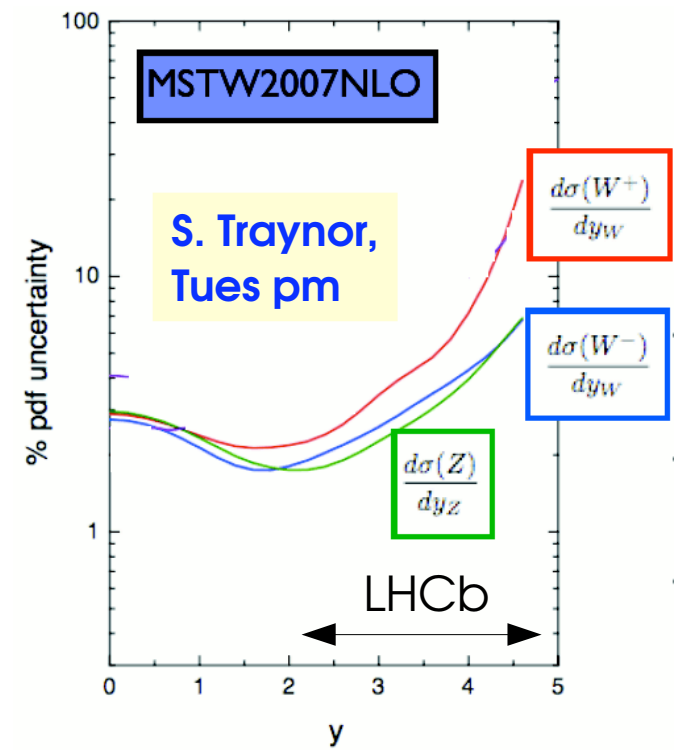
At LHCb, use forward W/Z production to constrain PDFs

- measure cross section ratios to ~1 % level for 1.9 < | y | < 5



J. Nielsen, Tues pm





Conclusions

Many interesting talks,

thanks to all speakers and participants,

and fellow conveners!

Hadronic Final States & QCD Theory Summary

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Overview of theory part

- **Fixed Order Calculations (2 talks)**
- **Soft Gluon Resummation (5)**
- **Monte Carlo (2.5)**
- **kT – factorisation and kinematics (5.5)**
- Fragmentation – (2)
- Jet algorithms, jet variables (1)
- Multiple Scattering (0)

[Peter Uwer]

Fixed Order: Top-antitop + jet at NLO

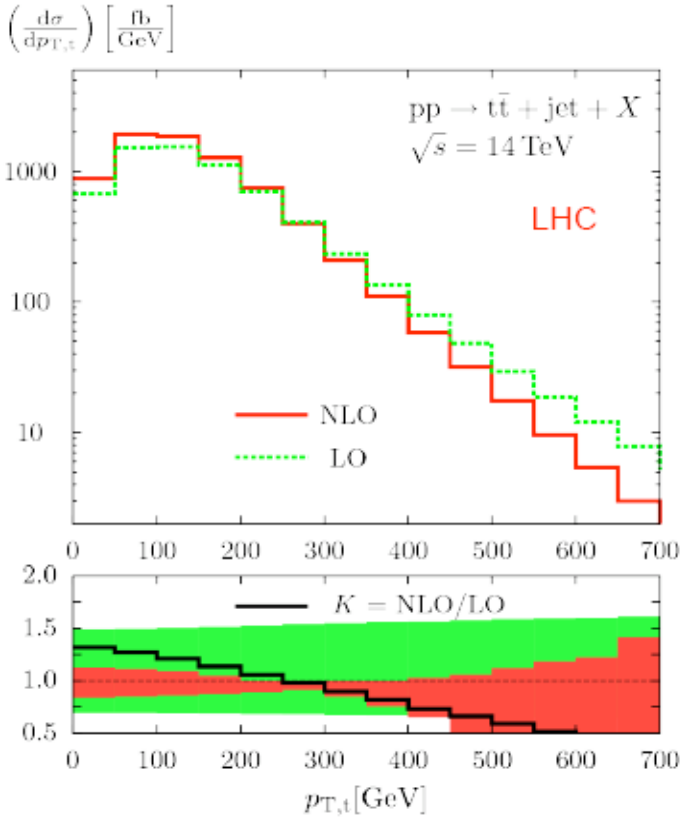
tt + jet process may probe the anomalous top – gluon coupling

Important for discovery of Higgs boson by VBF

One loop calculation completed

pT-dependent K-factor

Top pT distribution



[M. Grazzini]

Drell-Yan at NNLO

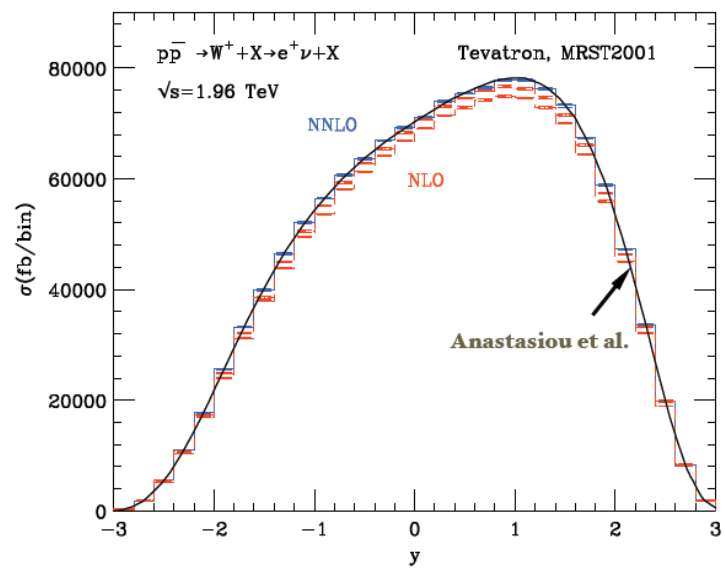
Calculation includes γ – Z interference, finite width effects, leptonic decay of the vector boson and corresponding spin correlations

It cross checks earlier results for DY@NNLO

Results are implemented in parton level event generator

Arbitrary cuts possible on the final state leptons and the associated jet activity, possible to compute all kinematical distributions and acceptancies

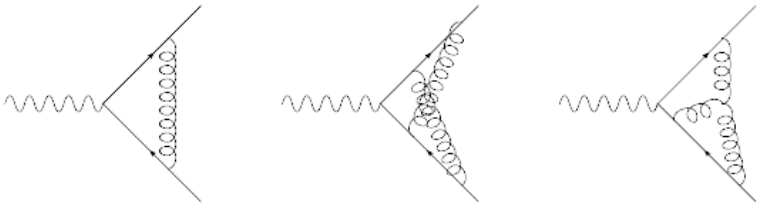
NNLO effect are small – but theoretical precision impressive!



[C. White]

Soft gluon resummation

Emission of soft gluons from fast lines: soft-collinear and soft logarithms



Perturbative resummation based on factorisation theorems and RG equation

New: proof of exponentiation of logs at the next-to-eikonal approximation

$$\frac{d\sigma}{d\xi} = \sum_{n,m} \alpha^n \left[c^0_{nm} \frac{\log^m(\xi)}{\xi} + c^1_{nm} \log^m(\xi) + \ldots \right]$$

Method: path integral formulation of the soft radiation theory

$$S(x,p) = \int \mathcal{D}x\mathcal{D}p \exp\left[-ip(T)x(T) + i\int_0^T dt(p\dot{x} - H(p,x)) \right]$$

[M. Grazzini]

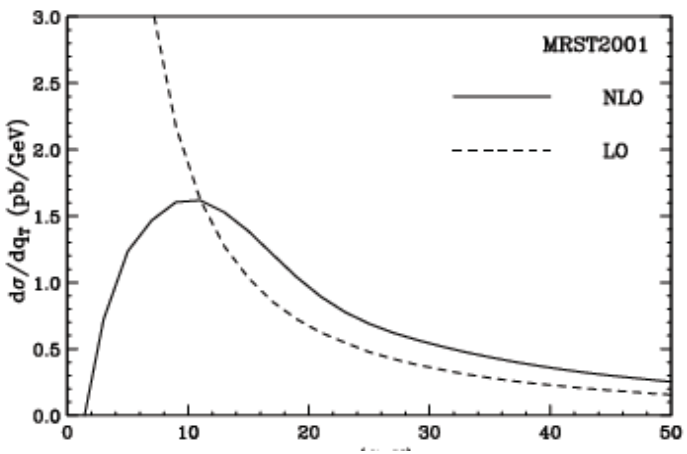
pT - resummation

Large logarithms of qT appear at fixed order,

$$\alpha_S^n \ln^{2n} M^2/q_T^2$$

coming from soft-collinear and soft gluon emissions: Resummation

Large corrections and stabilisation of the cross section at low qT

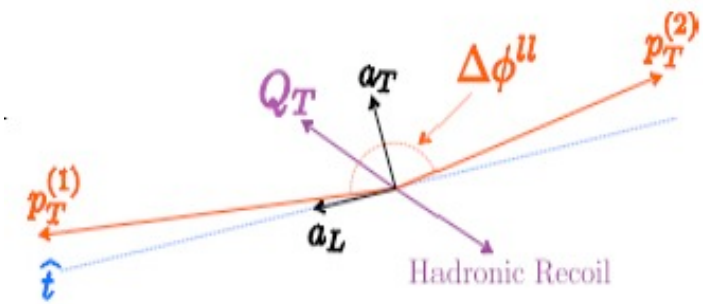


[R. Delgado]

Resummation for new observable

$$a_T = |\vec{Q}_T \times \hat{t}|$$

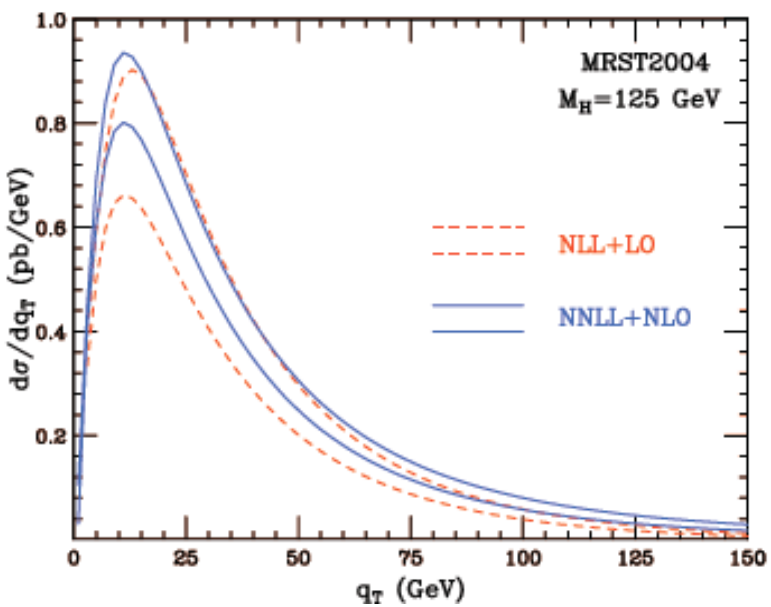
Component of boson qT
Perpendicular to thrust
(relatively easy experimentally)



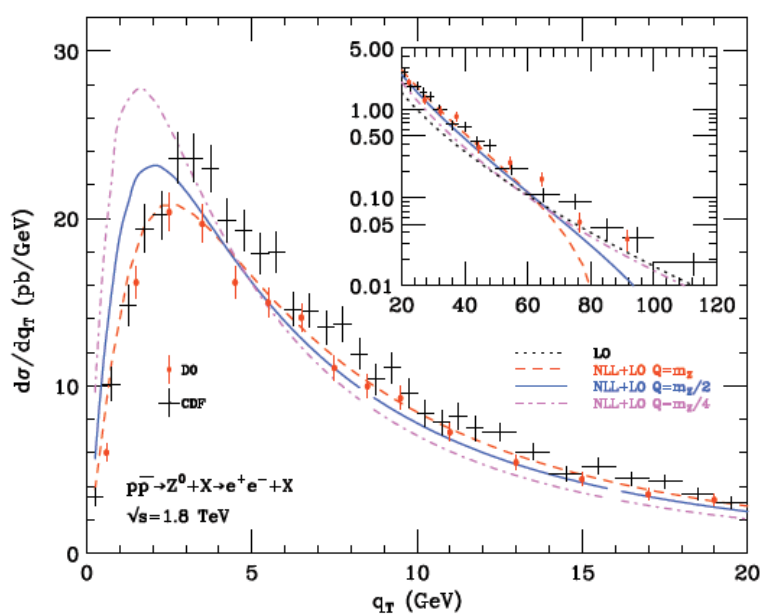
Phenomenological results

[M. Grazzini]

Higgs boson: NNLL + NLO



Z: NLL + LO (2008)

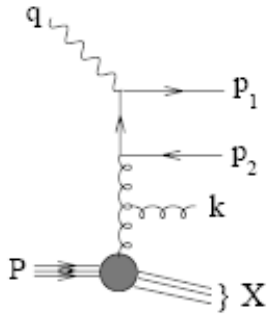


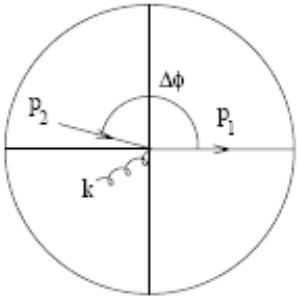
Evaluated before: WW, ZZ: NLL+LO, NLO; slepton pair-production

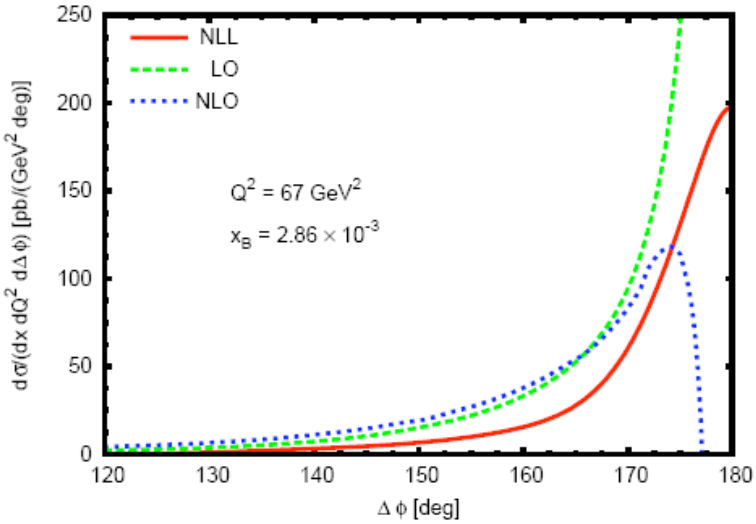
Soft gluon resummation for jets

Azimuthal dijet decorrelation due to soft gluons

[A. Banfi]

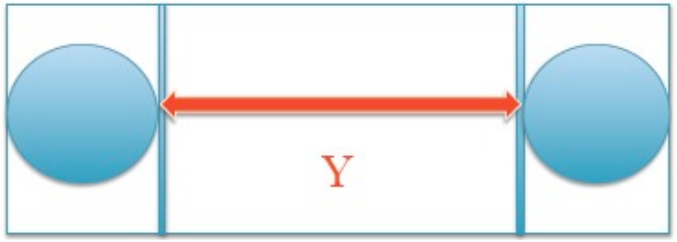






Gaps between jets

[S. Marzani]



Non-global logarithms found before

Effects of the NG logs studied

Phenomenological studies start

Monte Carlo (collinear)

CKKW-L matching of Parton Shower and NLO Matrix Element

- kT separation of ME / shower [L. Lönnblad]
- Multiplicity-dependent Sudakov form-factors
- Matrix elements evaluated at the NLO
- Smooth and consistent matching of ME and PS
- So far done for e+e-, implementation for pp in progress

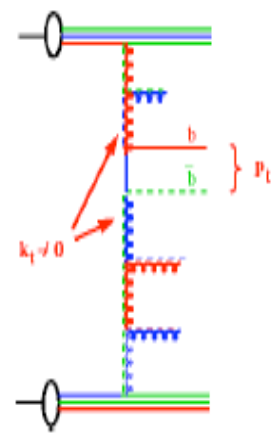
New numerical package was created for fast NLO calculation of jet and charm cross-sections [H. Kawamura]

Towards more accurate kinematics: kT – factorisation and Cascade

[H. Jung]

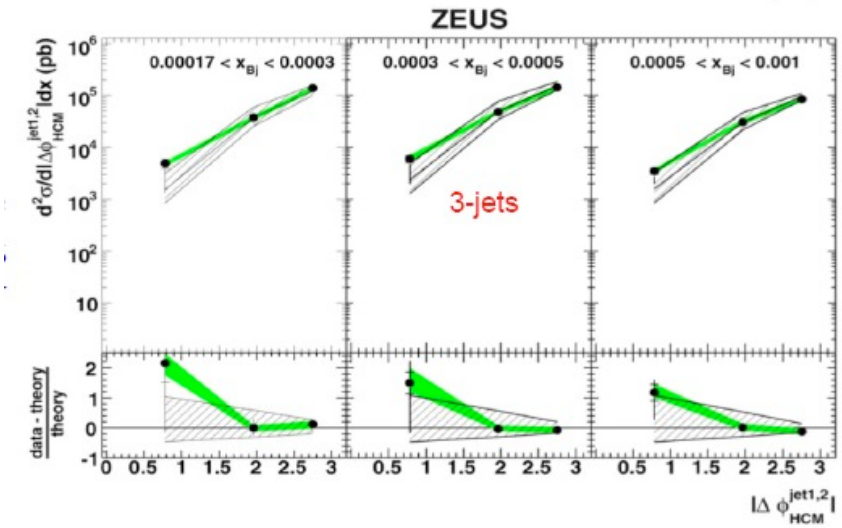
Cascade: Monte Carlo code based on the idea of kT –factorisation for HERA,Tevatron, LHC

Unintegrated parrton distribution functions - parton showers with angular ordering (CCFM) (not kT-ordering) and off-shell matrix elements



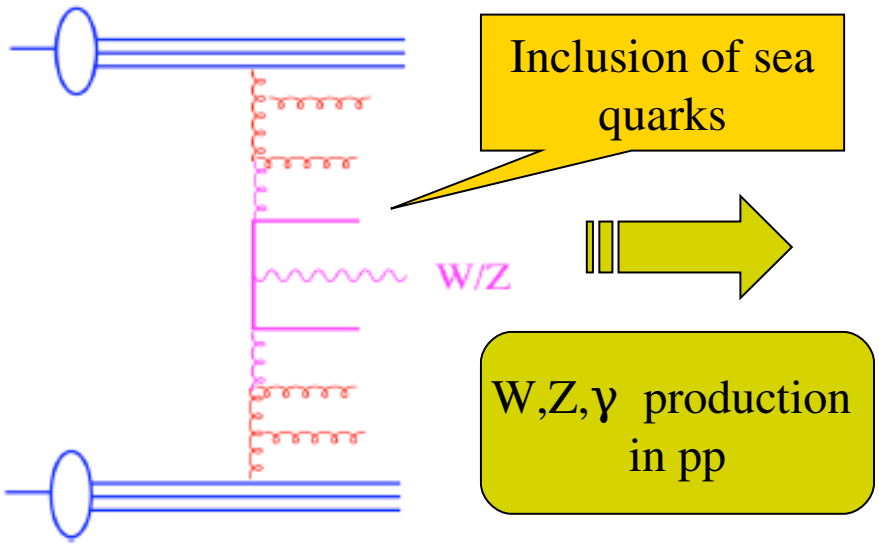
Particularly useful at small x

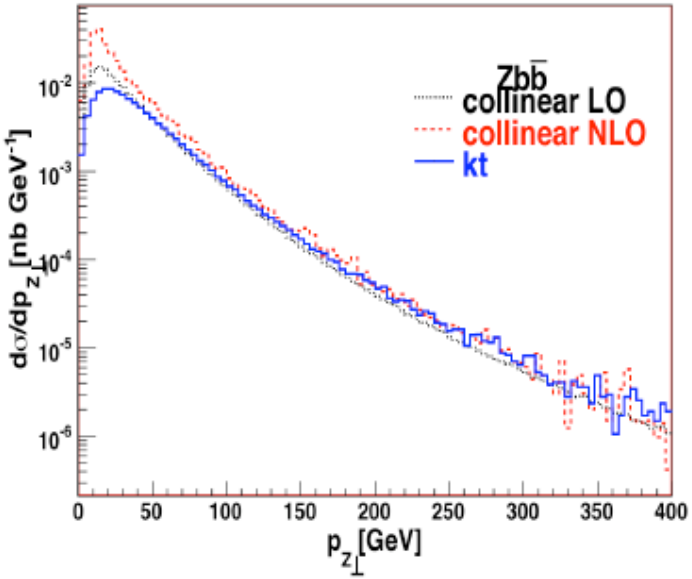
Example: 3-jets at HERA: LO Cascade does better than NLO collinear description



[H. Jung, M. Deak]

Recent and new in Cascade





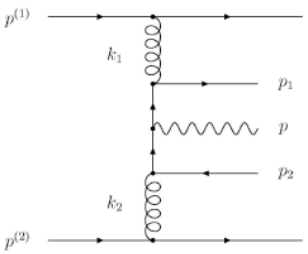
CCFM valence quark evolution added

Quark-gluon cotribution to forward jet production qg* to qg

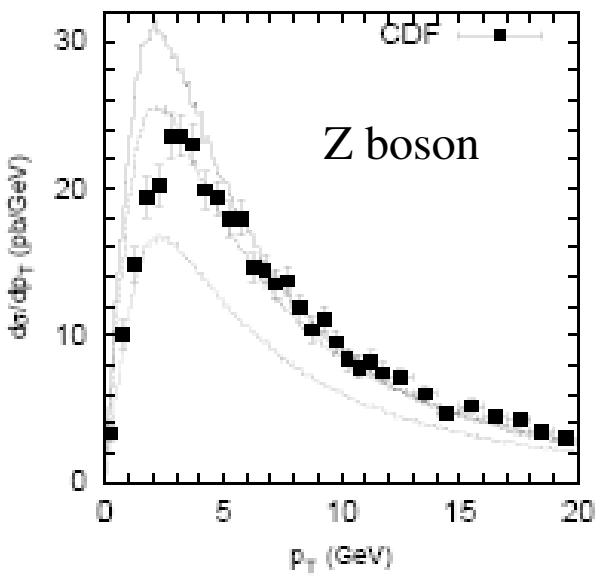
Also: implementation of unitarity corections at small kT (gluon saturation)

Photons and EW bosons from kT factorisation

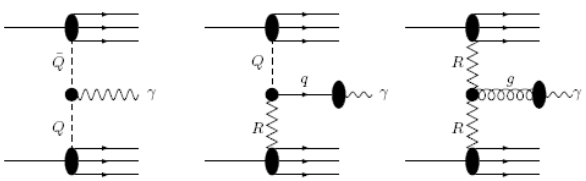
W and Z bosons at Tevatron



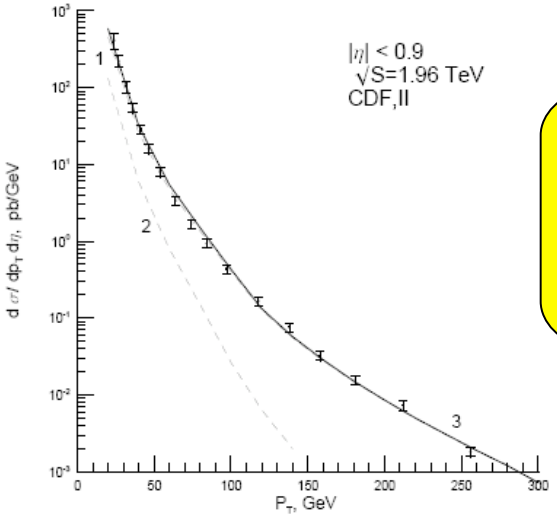
[N. Zotov]



Prompt γ and γγ
using effective Lipatov vertices



V. Saleev]

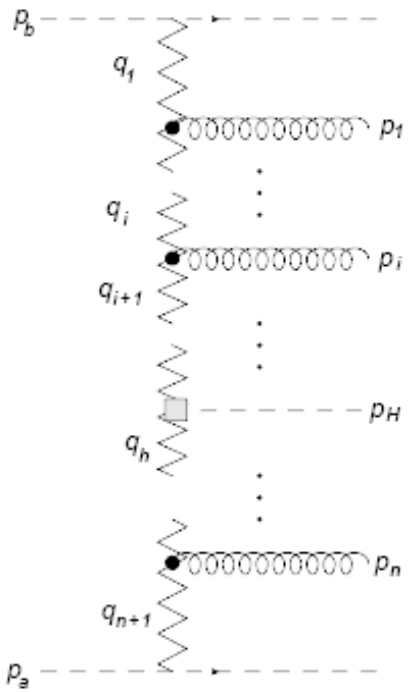


Good overall description of data from HERA and Tevatron

[C. White]

Higgs boson + jets

Fadin-Kuraev-Lipatov factorisation in multi-Regge kinematics



Generation of Higgs boson + multiple jets

MC approach based on BFKL-like ladders

Modified: inclusion of longitudinal degrees of freedom into propagators and vertices - better agreement with exact QCD amplitudes

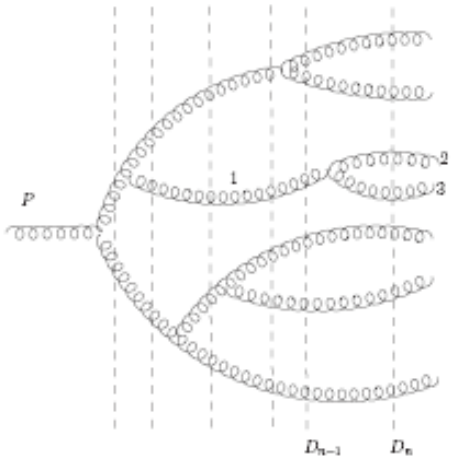
Accurate phase space representation

Code available!

[A. Staśto]

QCD evolution on the light-front

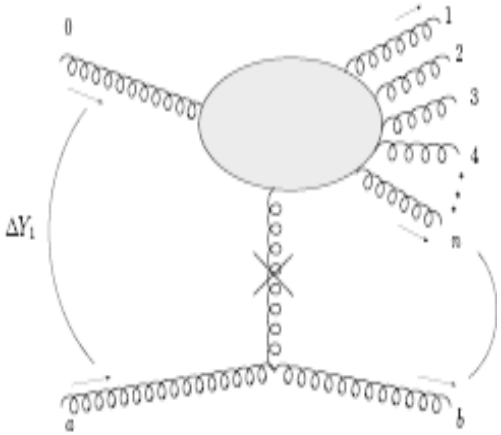
Idea: compute gluon cascades in QCD on the light front **keeping exact kinematics**



Results:

Modified colour dipole evolution kernel,
that approximately resums important
(most singular) higher order corrections to BFKL

For MHV configurations:
Exact tree level n-gluon wave function
Exact gluon fragmentation into n gluons
MHV amplitudes reproduced

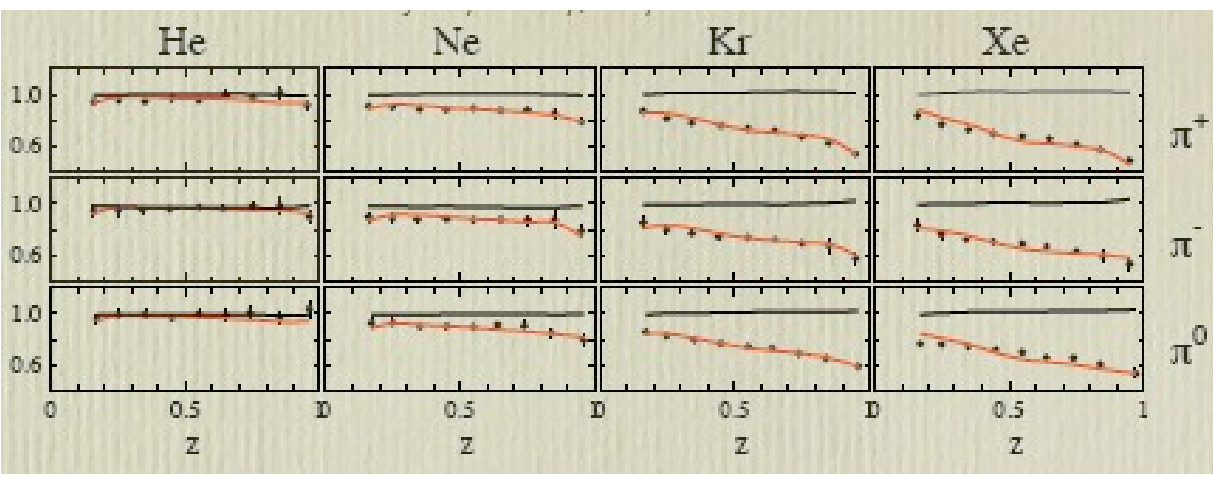


Fragmentation

[R. Sassot]

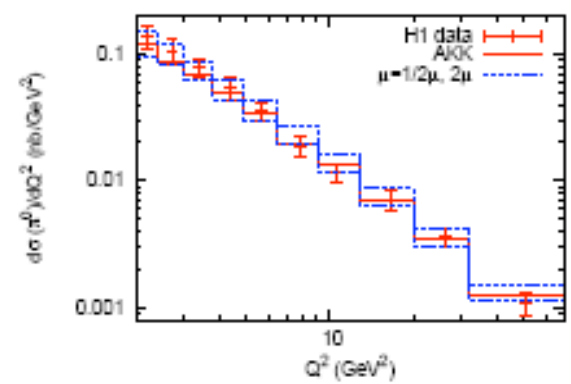
Fragmentation functions in nuclear medium

Standard NLO evolution of FF
Nuclear medium effects – fitted initial conditions
Good description of HERMES and RHIC data for pions
Main effect found: parton energy loss



[C. Sandoval]

NLO calculation of single hadron production in NC DIS using AKK fragmentation function



[Y. Delenda]

Jet pT and hadronisation

- Corrections to jet observables occur due to drag force coming from non-perturbative emissions
- The NP effects can be described with a universal model (data!)
- Hadronisation effects given by the model depend on the jet algorithm, but dependence on jet radius R is universal

$$\langle \delta p_t \rangle \approx -\frac{1}{R} \mathcal{M}\, 0.5\,\mathrm{GeV},$$

M = 1 – 1.5 depending on jet algorithm

Conclusions: hot topics in HFS `09

- Higher order calculations and implementations
- Soft gluon resummation and EW/jet observables
- Quest for better kinematical description of multi-parton production

Many thanks to all the Speakers

and

to the Organizers!