HERA and the LHC

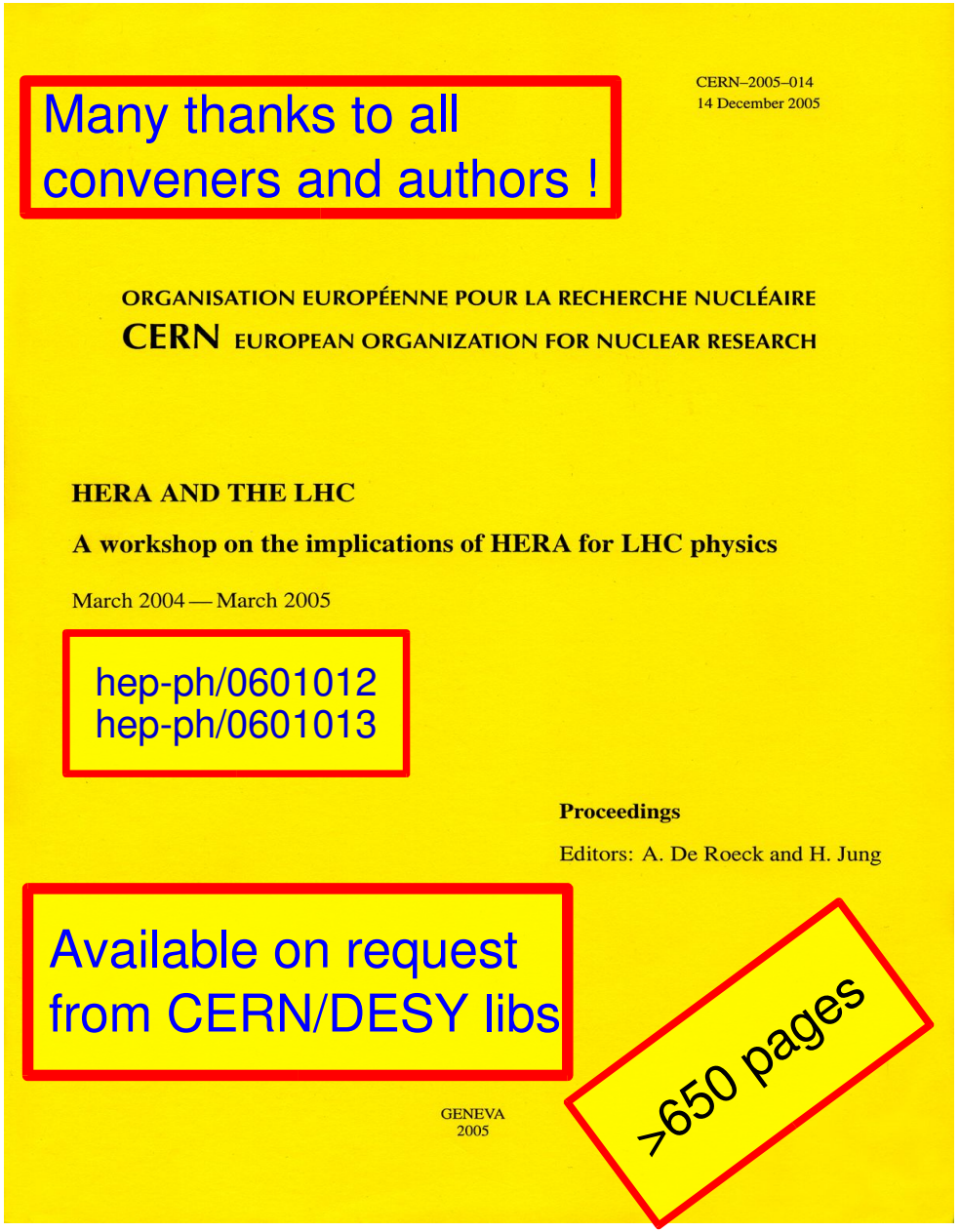
H. Jung (DESY)

"…The mechanic, who wishes to do his work well, must first sharpen his tools …"

—Chapter15, "**The Analects**" attributed to Confucius, translated by James Legge. (from X. Zu talk at DIS05)

Lesson 1

HERA and the LHC



"…The mechanic, who wishes to do his work well, must first sharpen his tools …"

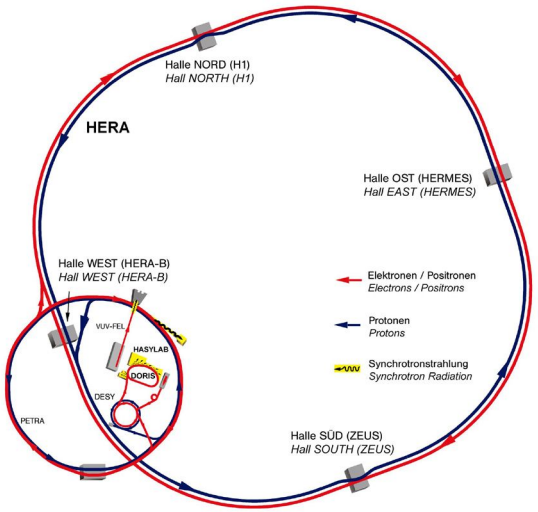
—Chapter15, "**The Analects**" attributed to Confucius, translated by James Legge. (from X. Zu talk at DIS05)

- *Aims of the workshop*
- *Outcome, results and future (personal selection)*
  - *HERA is important for the physics reach of LHC*
  - *further HERA measurements desirable*
  - *HERA experience valuable for LHC*

Why HERA and LHC ?

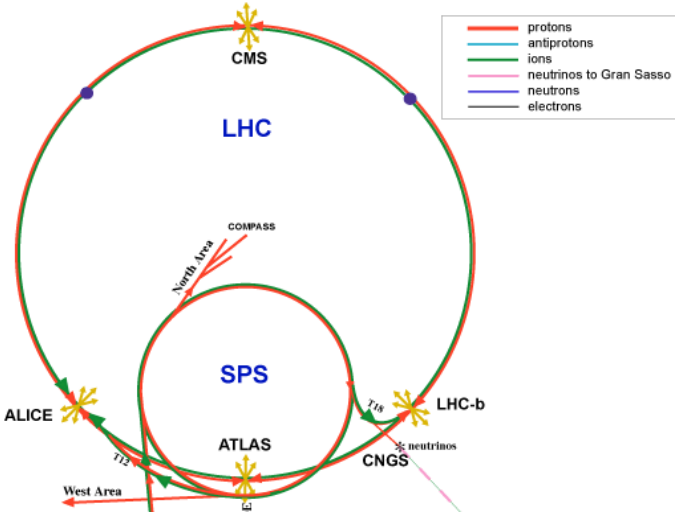
electron proton collider HERA
$\sqrt{s}$ = 320 GeV

proton proton collider LHC
$\sqrt{s}$ = 14 TeV



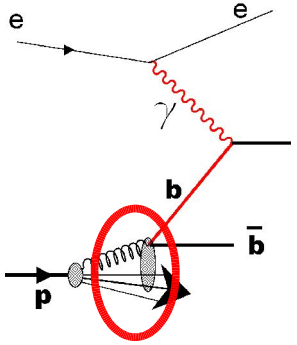
typical range

$$\sqrt{\frac{Q^2}{s}} \sim 0.01$$



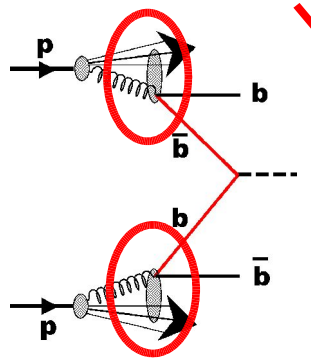
HERA: QCD
structure of the proton

LHC: Higgs, SUSY etc,
but mostly QCD...



$$\sqrt{\frac{Q^2}{s}} \sim 0.01$$

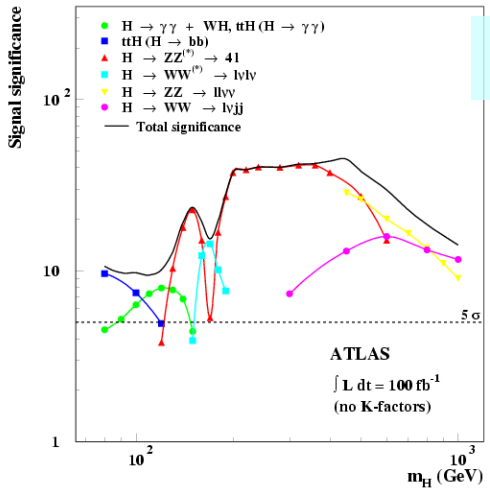
for $Q^2 \sim 10\ \mathrm{GeV}^2$



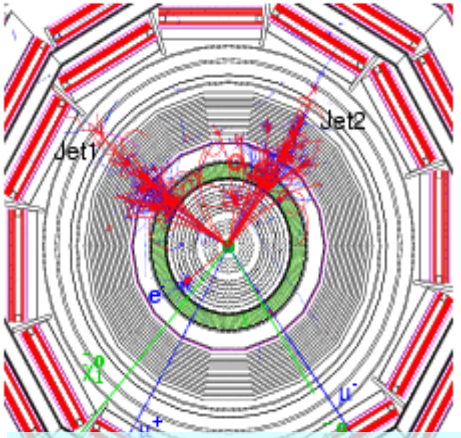
$$\sqrt{\frac{M^2}{s}} \sim 0.01$$

for $M \sim 140\ \mathrm{GeV}$

Physics at the LHC: examples

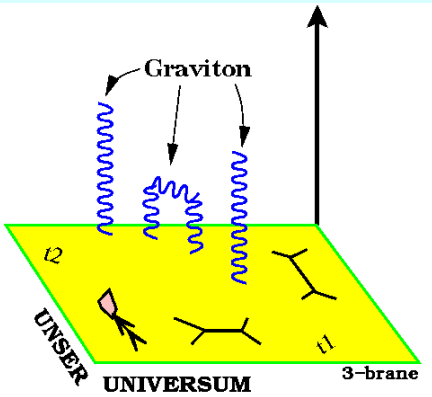


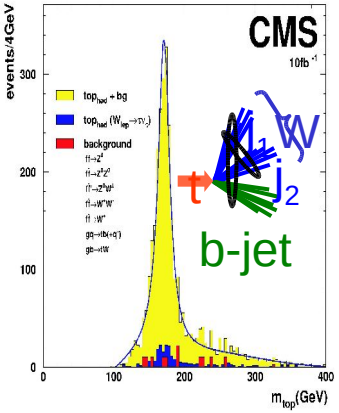
Higgs!



Supersymmetry?

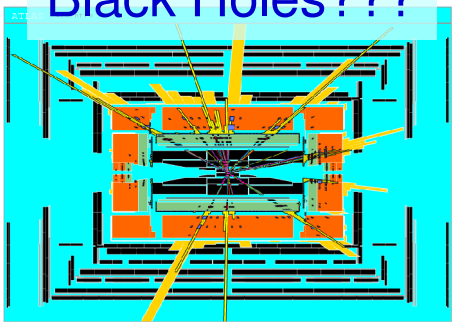
Extra Dimensions?



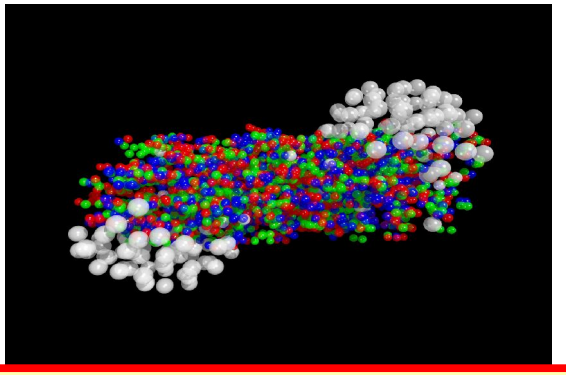


Precision measurements e.g top!

Black Holes???



QGP?

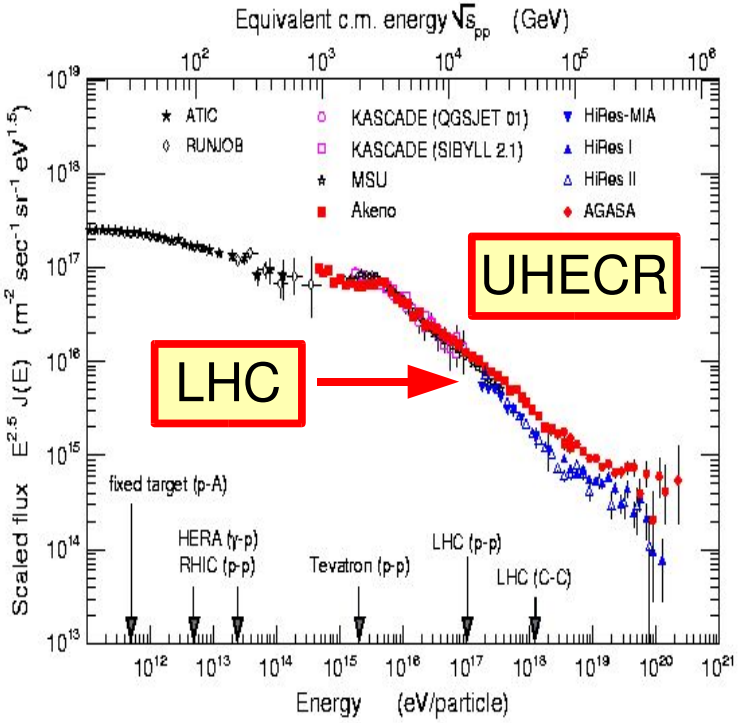


QCD is a MUST for all new physics !!!

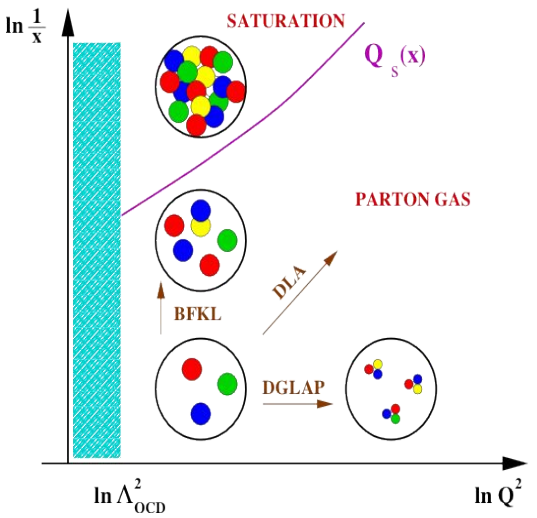
best understanding of PDFs, jets, heavy quarks, diffraction and phenomenology is needed !!!

Physics at the LHC: other examples

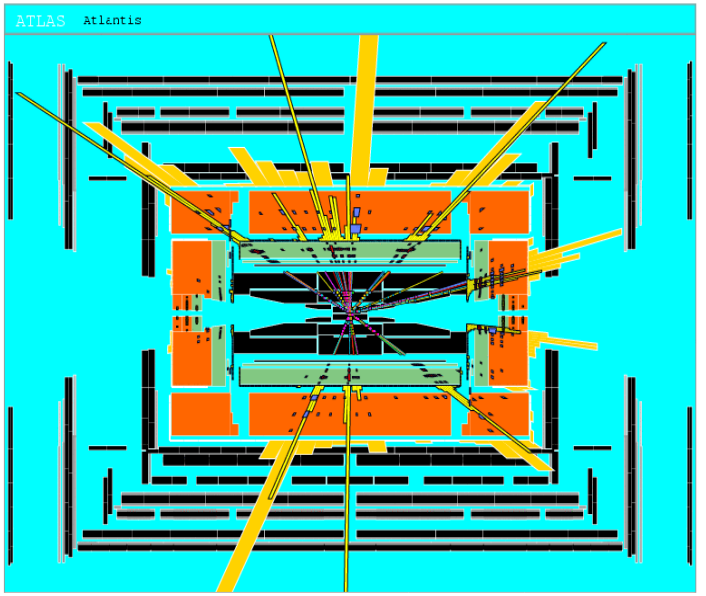
High energy hadron showers



Color glass Condensate



Multi Jet event:
Is it Multiple Interaction
or Black hole production



QCD @ LHC in its own!!!
High scale QCD, jets, UHECR, smallest x,
parton saturation - new phase in QCD - non-linear phenomena

Workshop Aims

- To identify and prioritize those measurements to be made at HERA which have an impact on the physics reach of the LHC.
- To encourage and stimulate transfer of knowledge between the HERA and LHC communities and establish an ongoing interaction.
- To encourage and stimulate theory and phenomenological efforts.
- To examine and improve theoretical and experimental tools.
- To increase the quantitative understanding of the implication of HERA measurements on LHC physics.

http://www.desy.de/~heralhc

Chairs: A. De Roeck (CERN) , H. Jung (DESY)

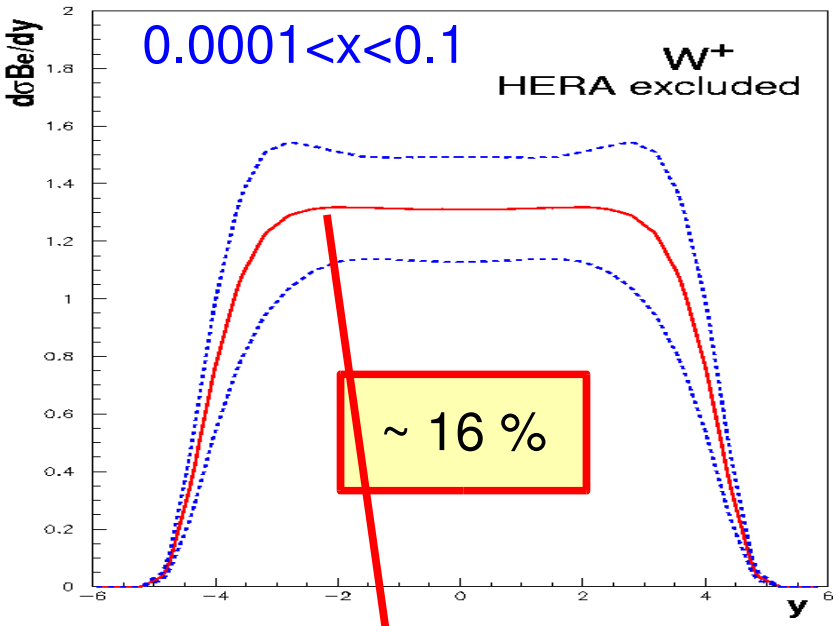
Startup: 26-27 March 2004 CERN (~ 250 participants)

Final meeting: 21-24 March 2005 DESY (~ 150 participants)

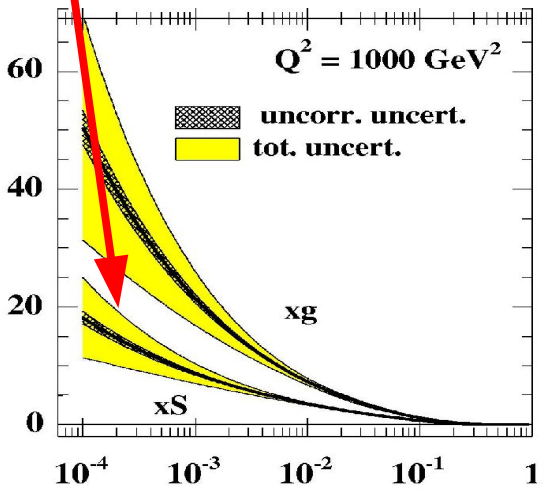
How well did we do ?????

Does LHC really need HERA ?

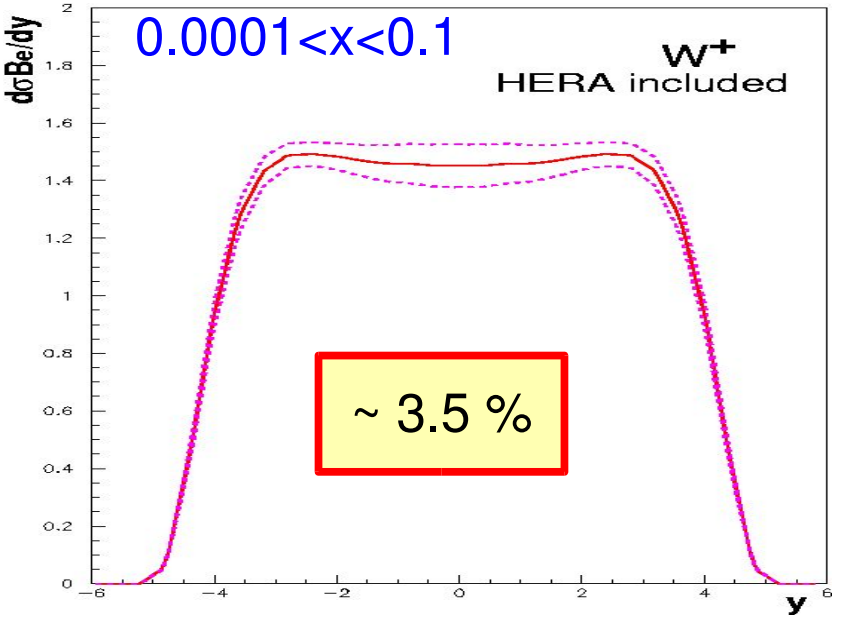
- W prod. at LHC without HERA:



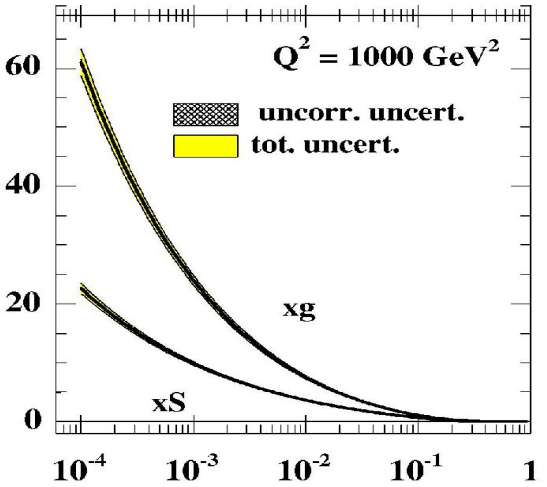
- PDFs without HERA:



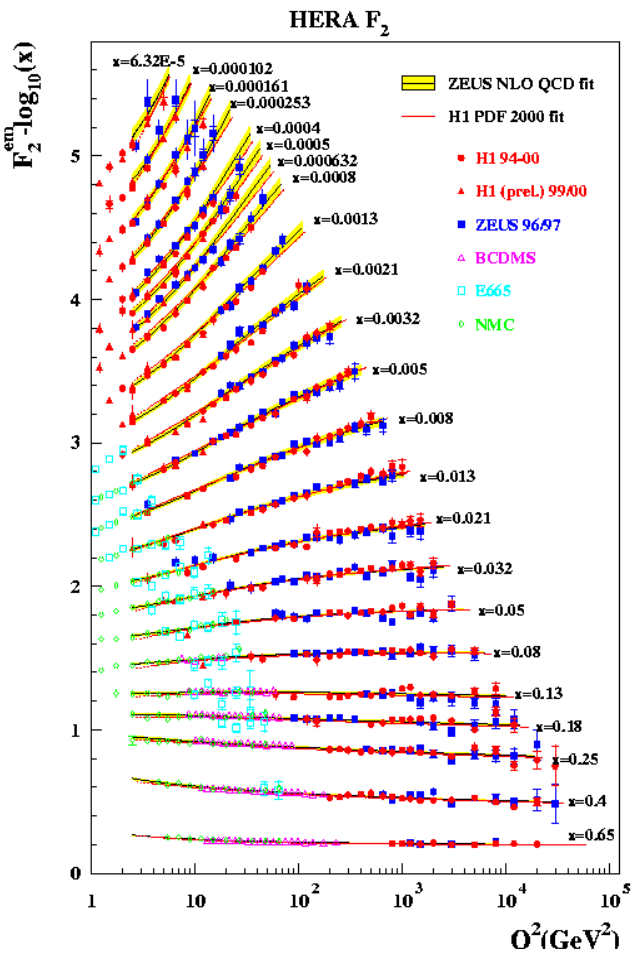
- W prod. at LHC including HERA

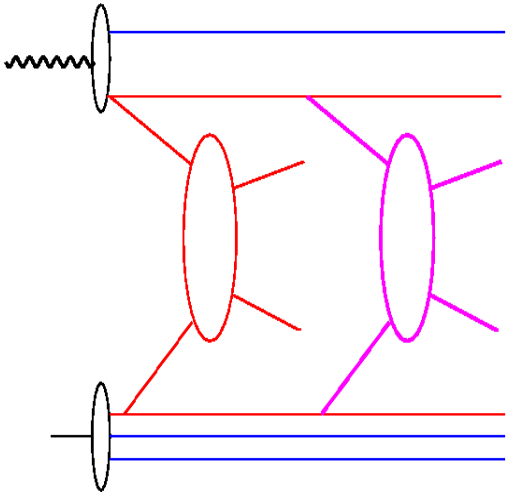


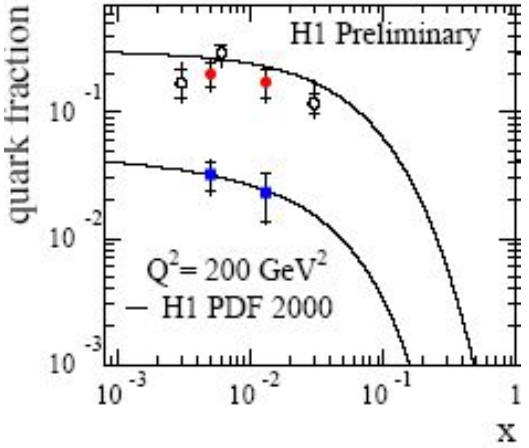
- PDFs including HERA:



Topics of the workshop





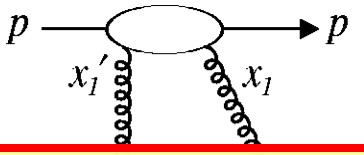


Multijets & final states Underlying events, un-integrated pdfs

L. Lonnblad, V. Khoze, N. Tuning, C Buttar, J. Butterworth, S. Banerjee, D. Traynor

Heavy quarks: B quark pdfs of the proton, fragmentation fct, u-pdfs

M. Cacciari, U. Uwer, M. Smizanska, M.Corradi, A. Dainese, C. Weiser, A. Meyer



Structure functions and parton distributions

S. Forte, S. Moch M. Dittmar, A. Glazov M. Botje, J. Butterworth

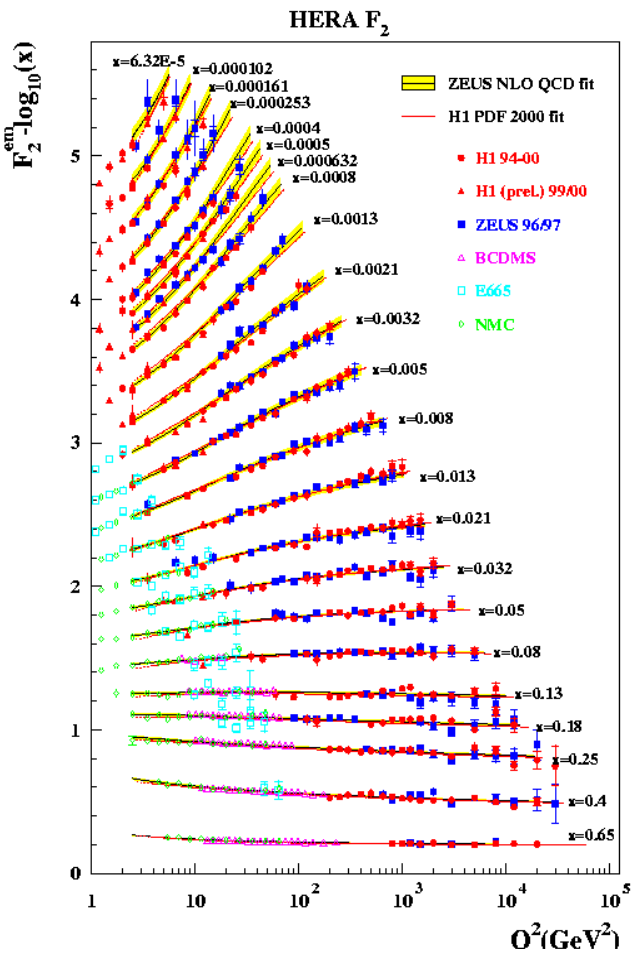
Diffraction

J. Forshaw , M. Diehl, K. Piotrzkowski, R. Orava, H. Kowalski, P. vanMechelen, M. Rijssenbeek, B. Cox

MC - Tools

M. Seymour, A. Nikitenko, E. Richter-Was, P. Robbe, V. Lendermann

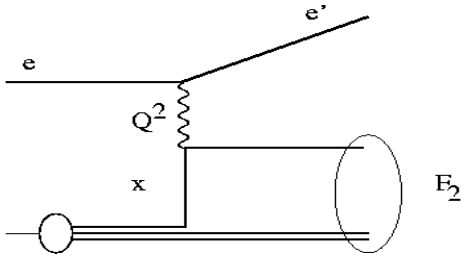
Topics of the workshop

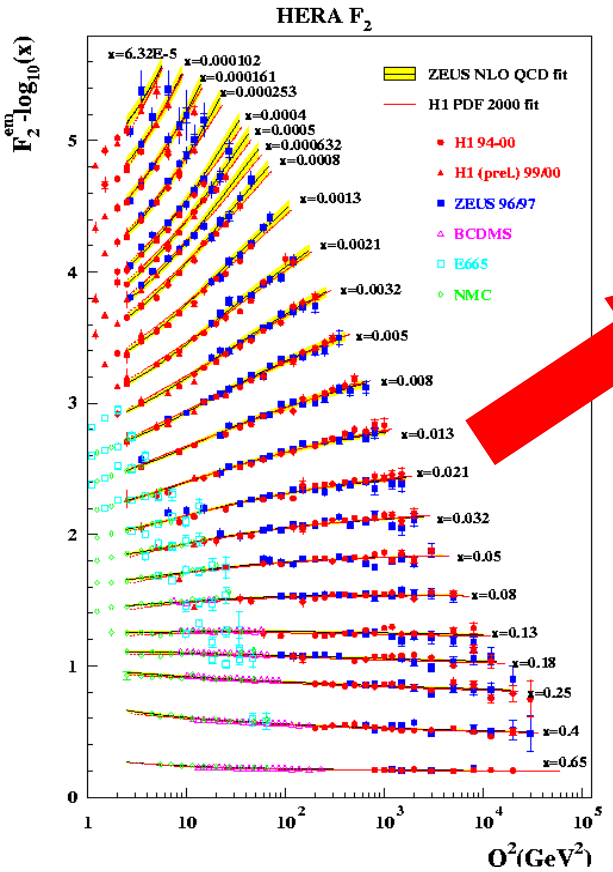


Structure functions and parton distributions
LHC: cross sections/precision

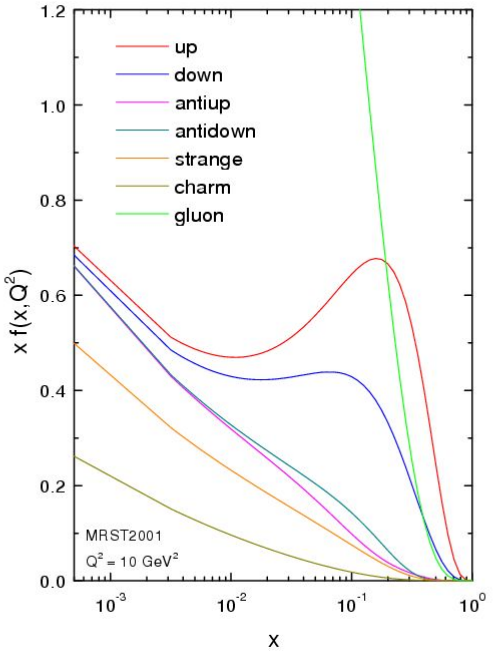
- experimental uncertainties in PDFs:
  - impact of HERA measurements
    - high statistics with HERA II
    - combining experiments: NEW
    - combing F_2 and final states NEW
    - dedicated measurements
      - F_L
      - deuterons
  - howto determine pdfs at LHC
- theoretical
  - 3-loop splitting functions: NEW
  - 3-loop coefficient functions: NEW
  - benchmarking of PDFs
  - small x, large x resummations
- Potential experimental & theoretical accuraries
  - estimates of systematics
  - Improved cross section calculations:
    - NNLO for W/Z

From HERA F_2 to Higgs at LHC



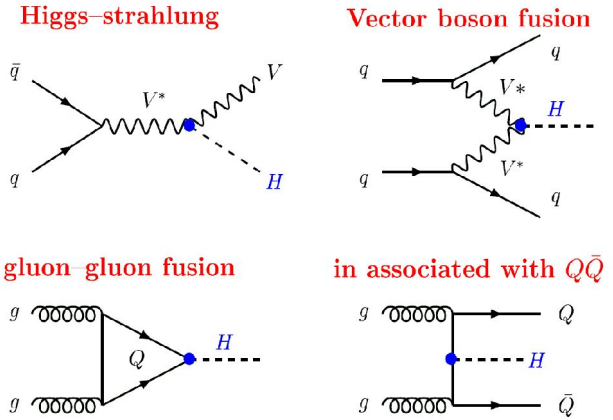


total x-section, F_2

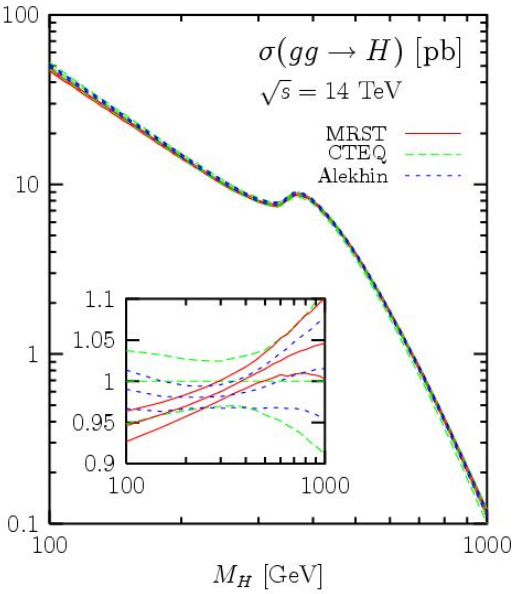


extract parton densities

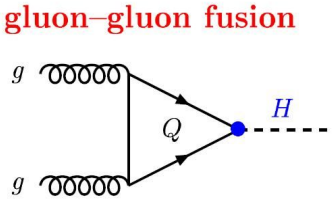
from J. Stirling



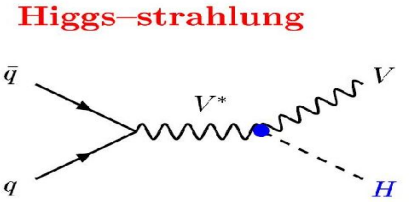
calculate Higgs prod

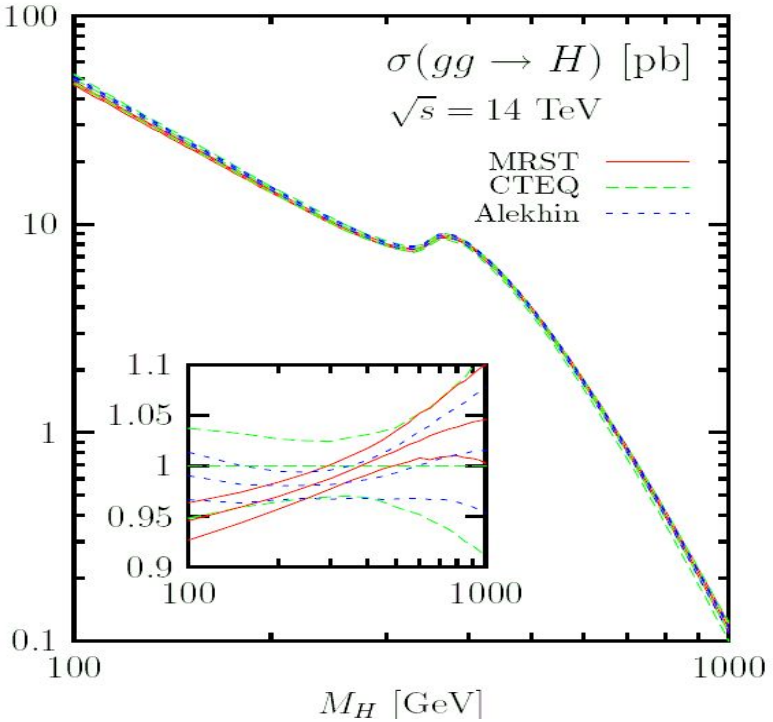


PDF uncertainty for Higgs prod.

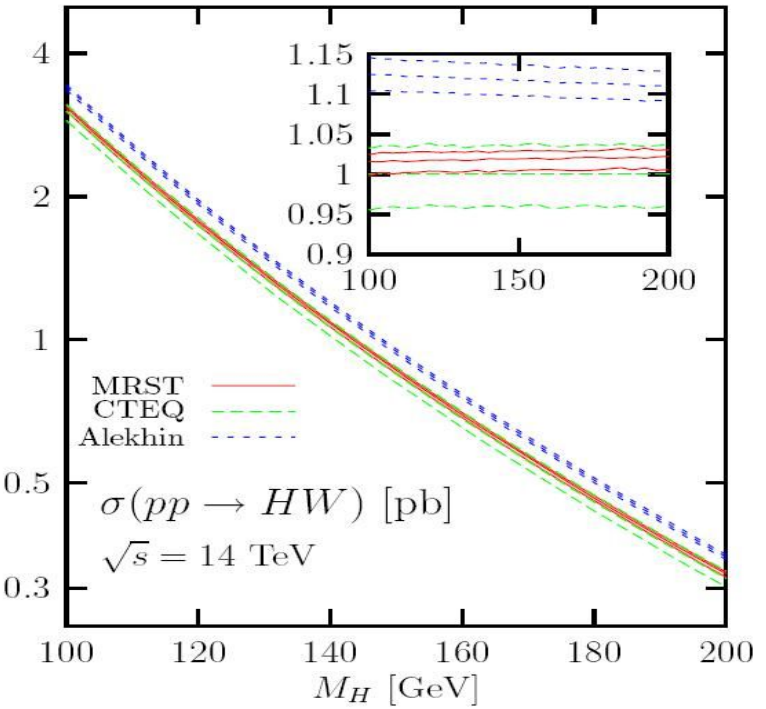


from Djouadi & Ferrag





Gluon induced... ~ 10 %

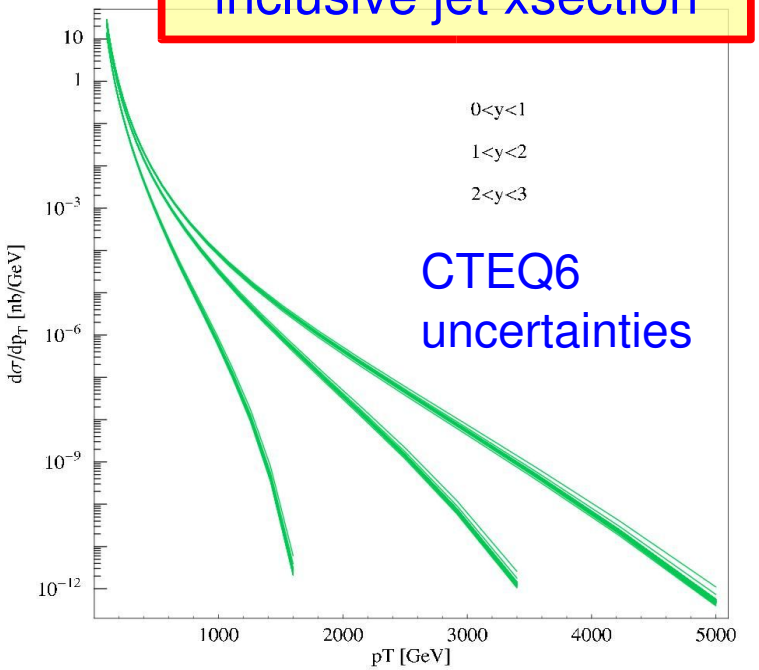


Quark induced ~ 10 % difference

PDFs do not agree within respective errors (J. Stirling) !!!!

Why precise PDFs for LHC

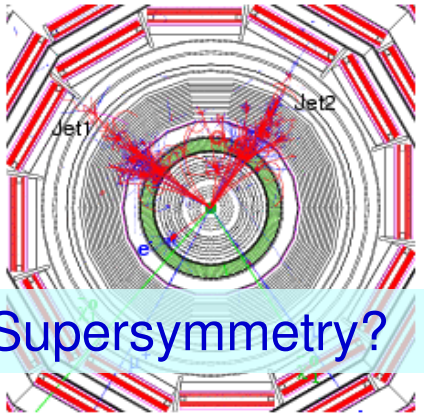
inclusive jet xsection



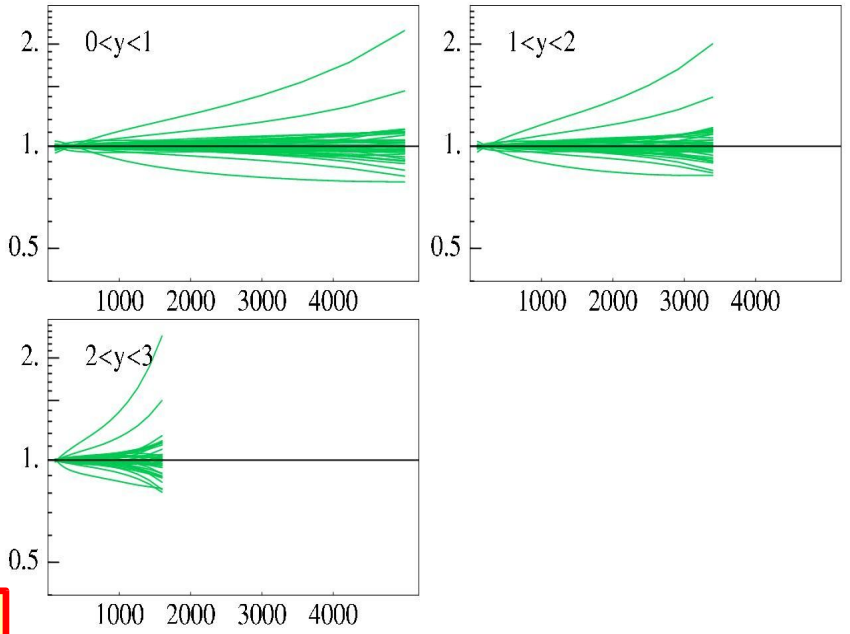
D.Stump et al hep-ph/0303013

Signature for new physics
➔ jet x-section

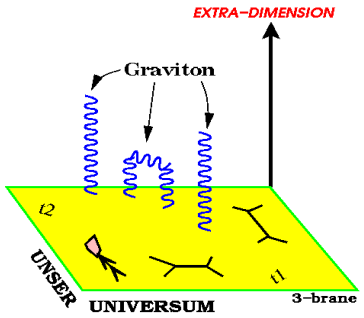
Discovery potential depends on precise PDFs



Supersymmetry?



Extra Dimensions?

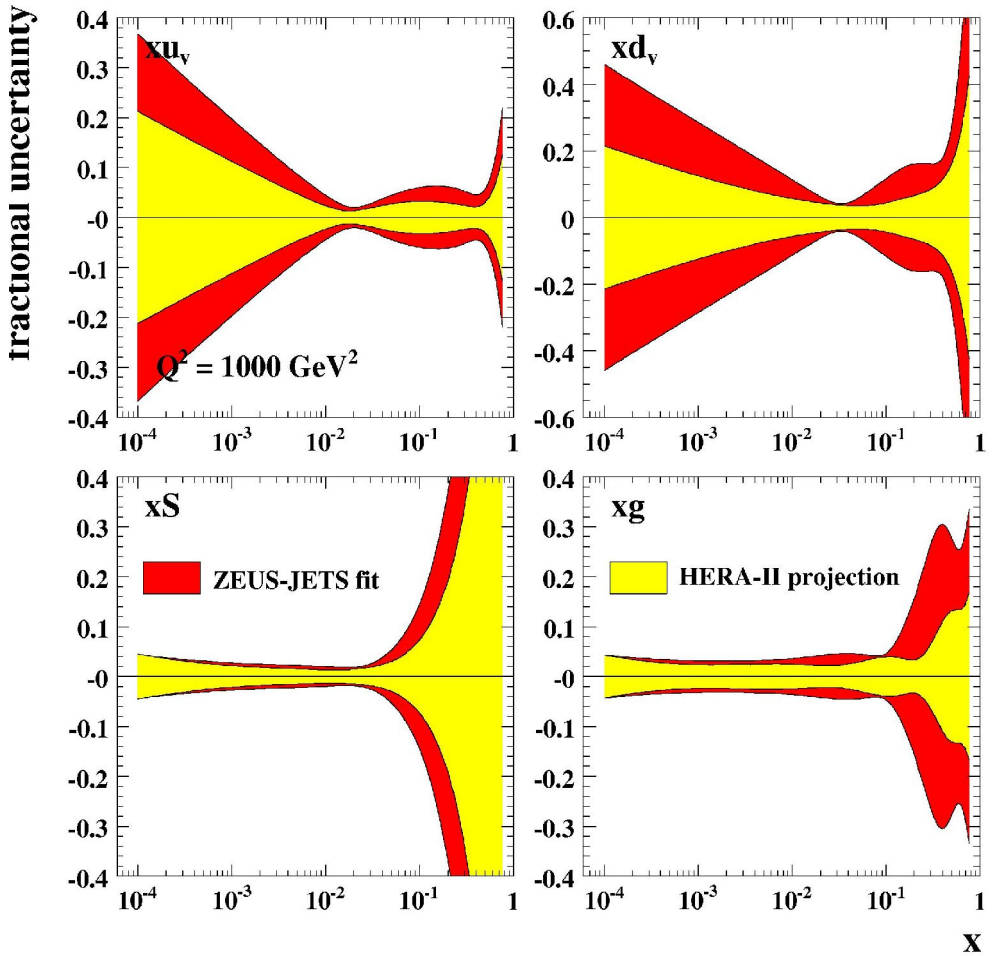


Precision determination of PDFs needed ...
understanding QCD is the key to new physics

PDF uncertainty: improvements

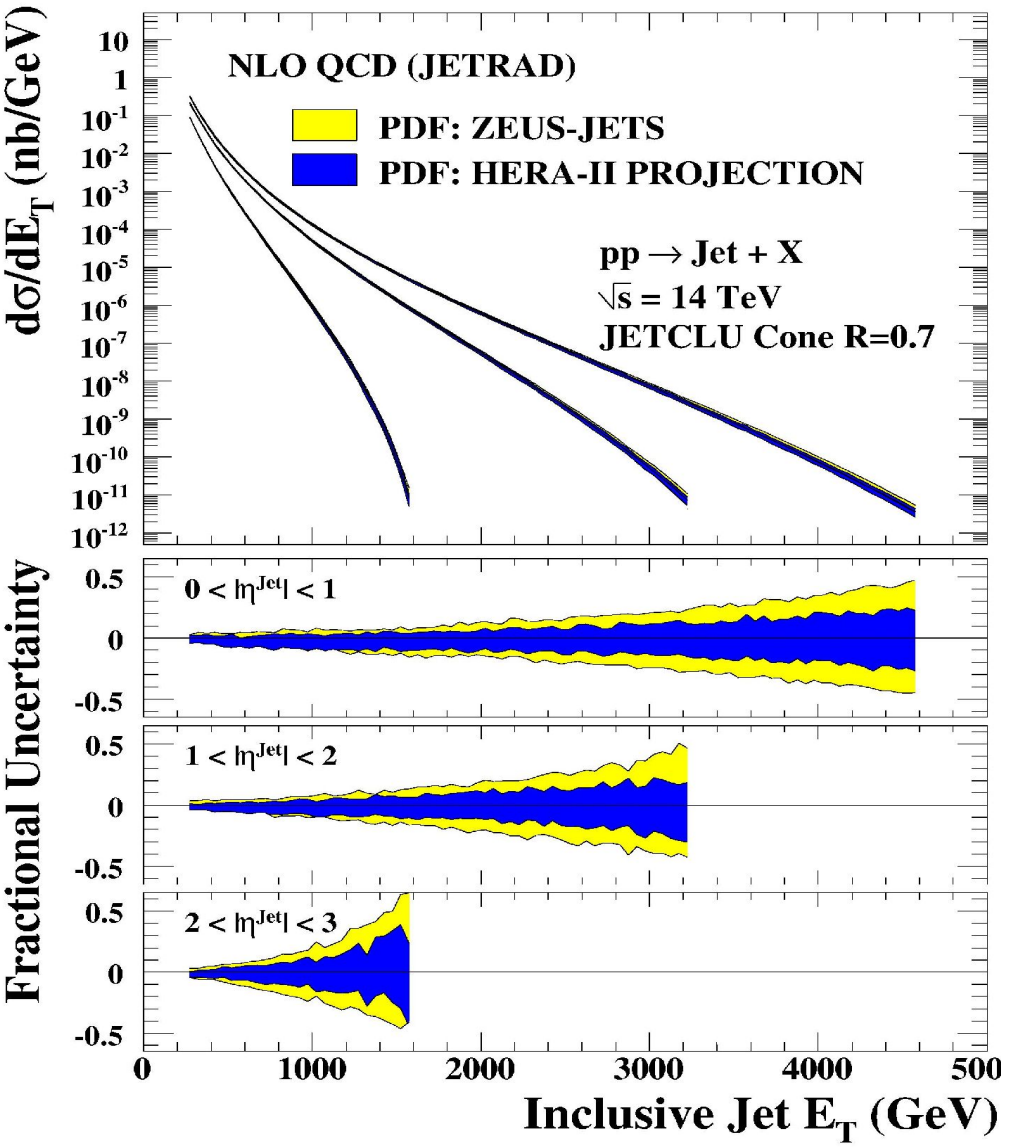
Using jets together with F_2 (at large Q^2)

quark and gluon uncertainties



high statistics from HERA II is important (assumed 700 pb^{-1})

from C. Gwenlan, A. Cooper-Sarkar, C. Targett-Adams

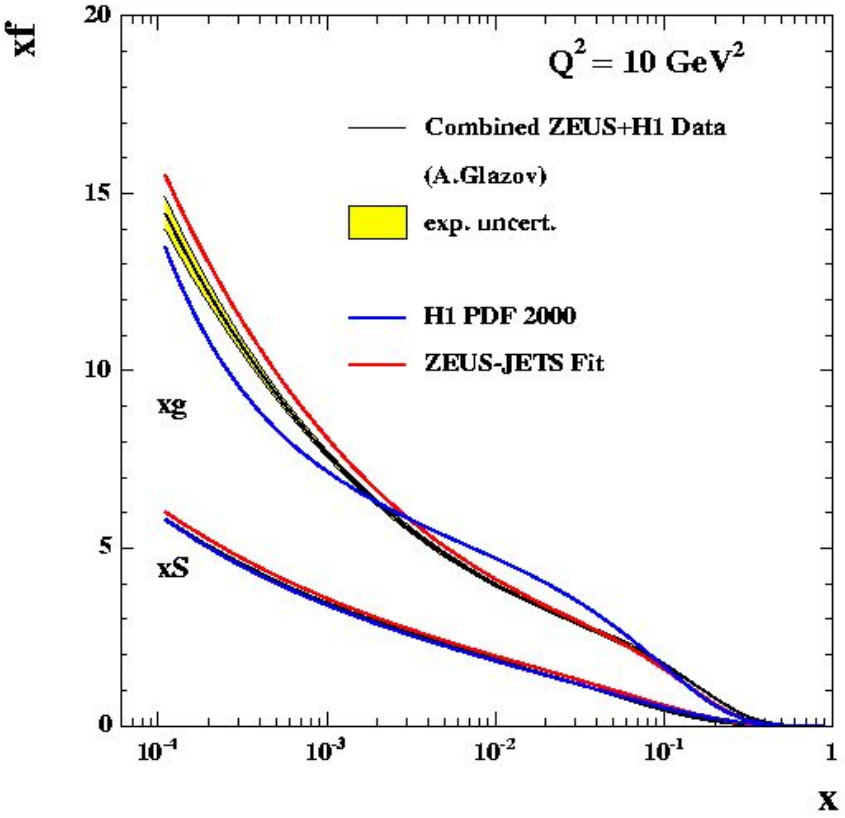


Error on LHC jet xsection reduced !!!

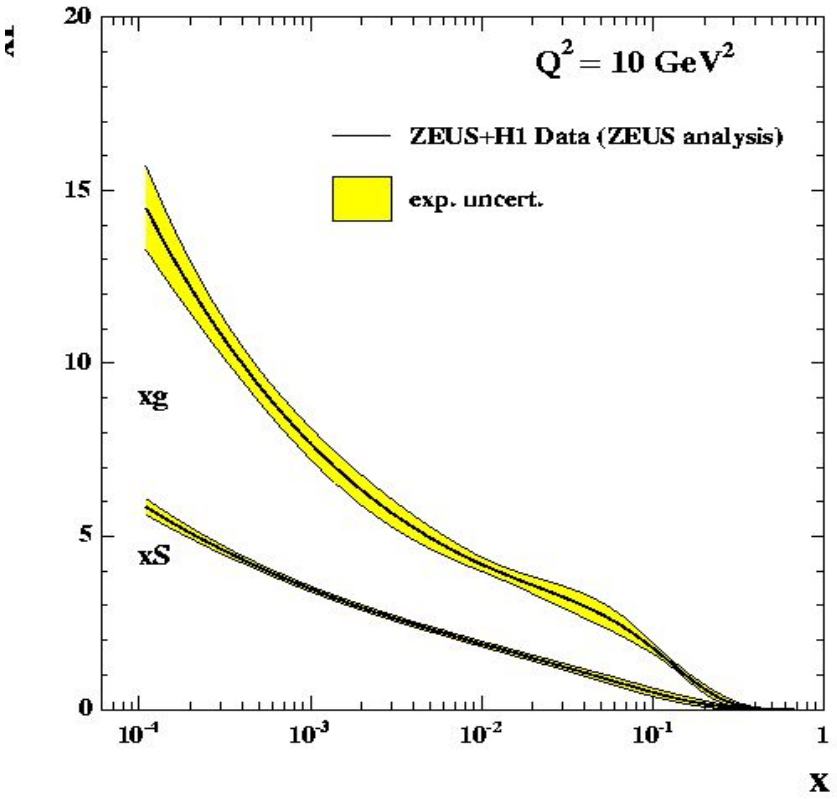
Average of HERA data

From M. Cooper-Sakar, C. Gwenlan and S. Glazov

- Average H1&ZEUS data sets



- Combined PDF fit to H1& ZEUS



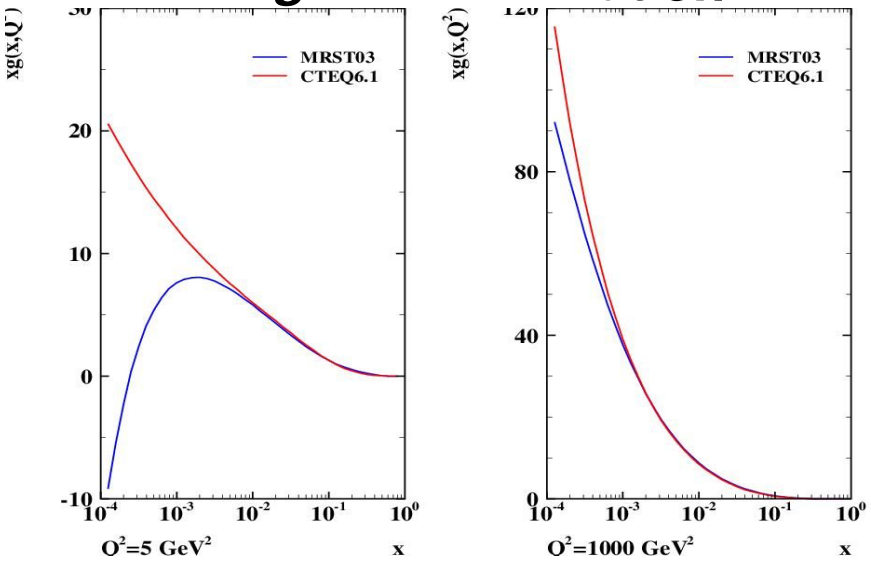
Much reduced uncertainties ....

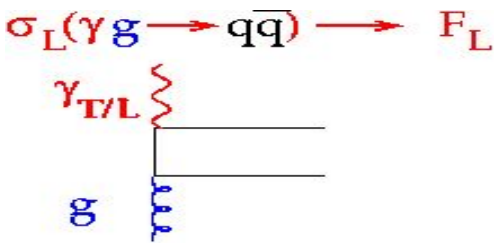
Model independent analysis of data desirable

Activities started to get HERA – PDF !!!!!

HERA future measurements: F_L

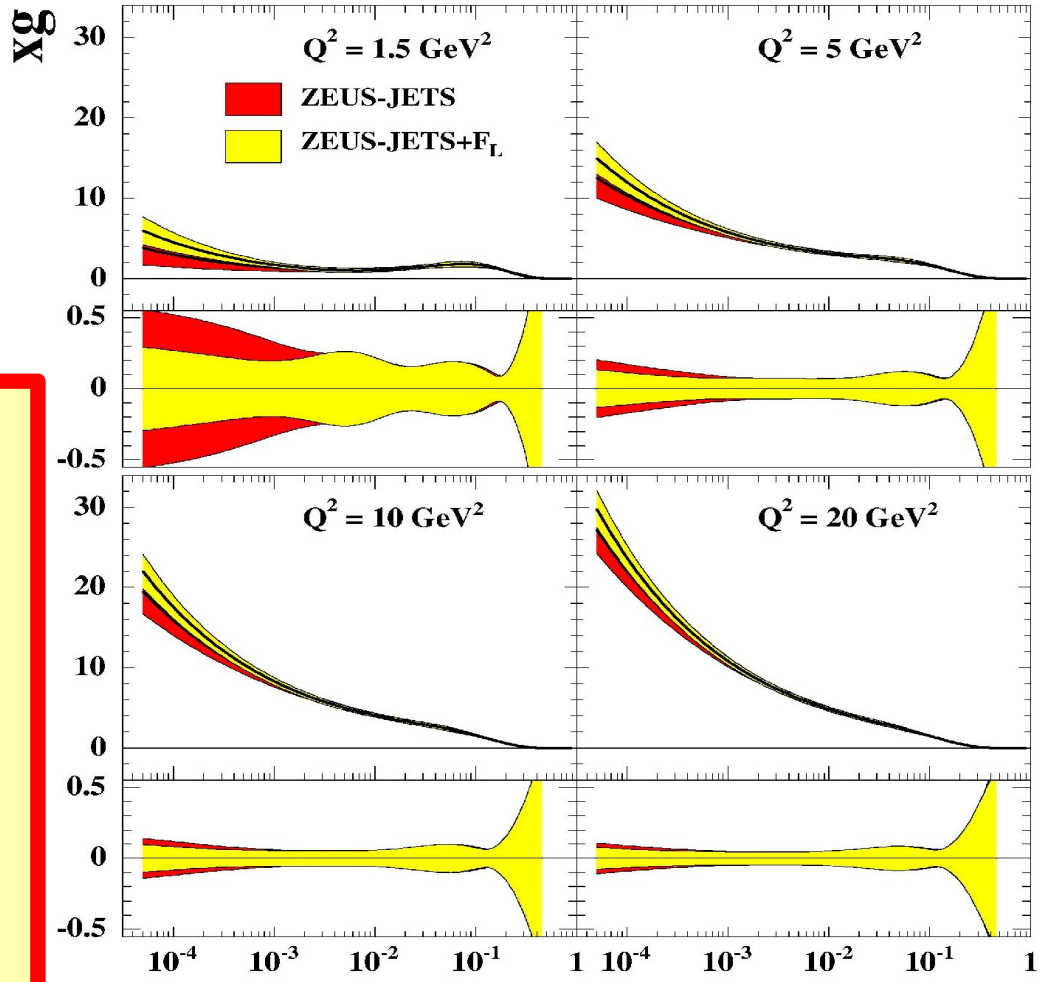
The gluon distribution





From J. Feltesse, C. Gwenlan, S. Glazov, M. Klein, S. Moch

$$F_L \propto \alpha_s x g(x, Q^2)$$



Precision measurement of F_L with lowered p-energies and 2-10 pb^{-1}

- cleanest for gluon
- crucial test of QCD at higher orders and consistency of theory

➔ where if not measured at HERA ?????

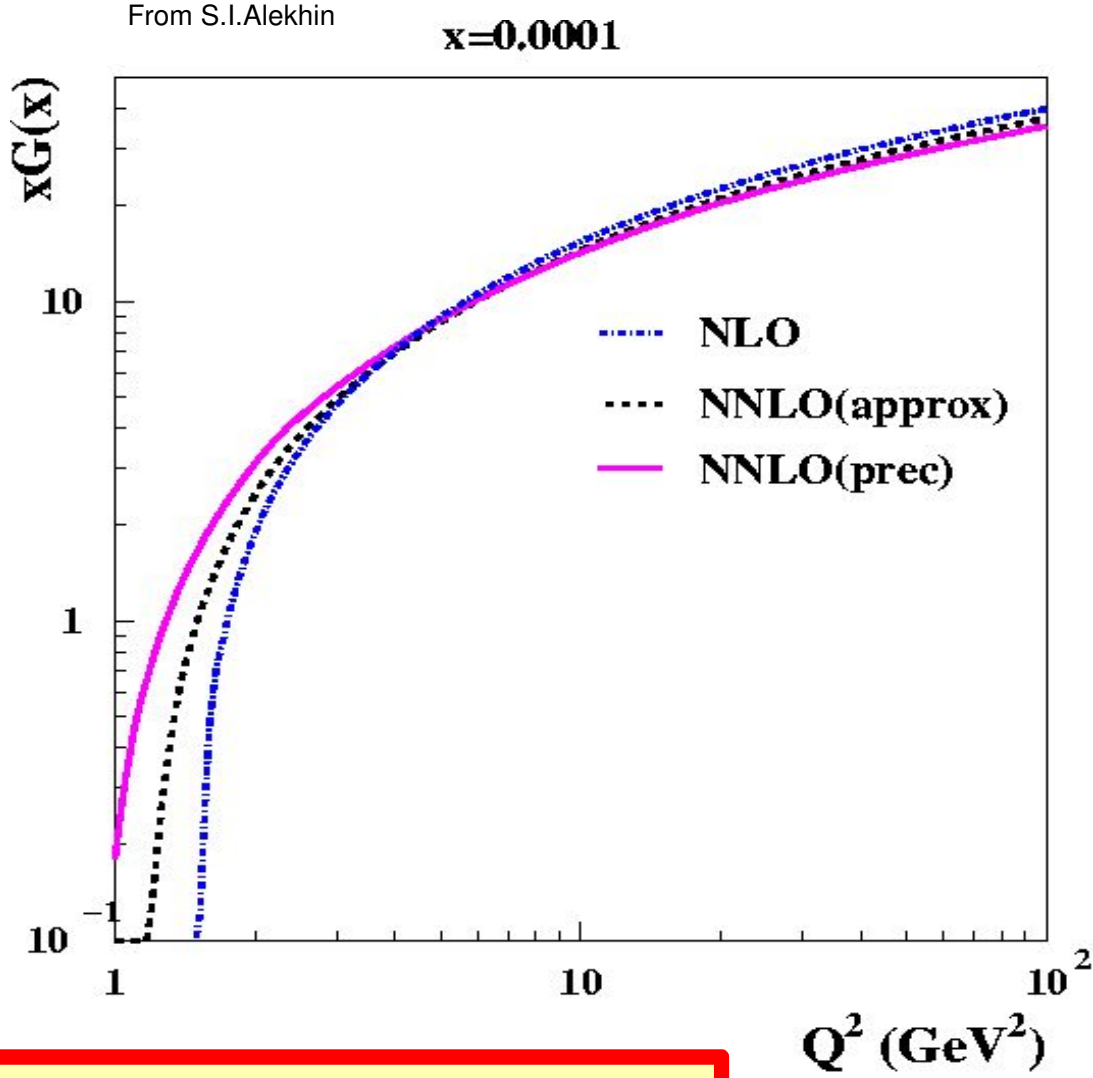
The gluon in NLO, NNLO

New theory development:

- 3-loop evolution kernels (NNLO) and 3-loop coefficient functions: NEW
- 2-loop evolution (NLO) known since long....

- Perform a full 3-loop (NNLO) fit to DIS .... obtain gluon...
  - ➔ Significant improvement at small Q^2
  - ➔ Change at large Q^2 (Higgs/W production) $\mathcal{O}(3-4\%)$

From S.I.Alekhin



Significant theoretical development: 3-loops for PDFs

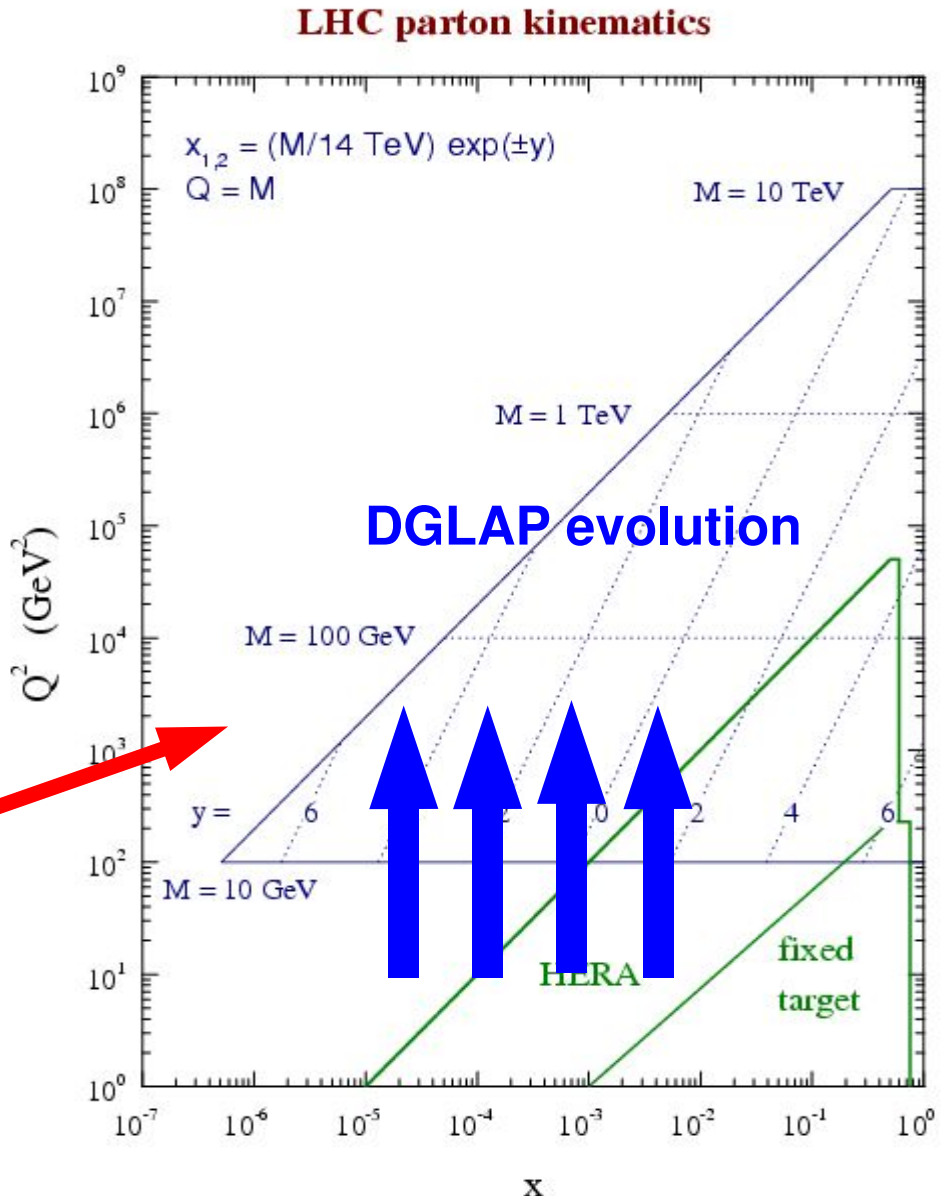
Is DGLAP all ????

Can we just assume that DGLAP is ok up to highest energies ?:

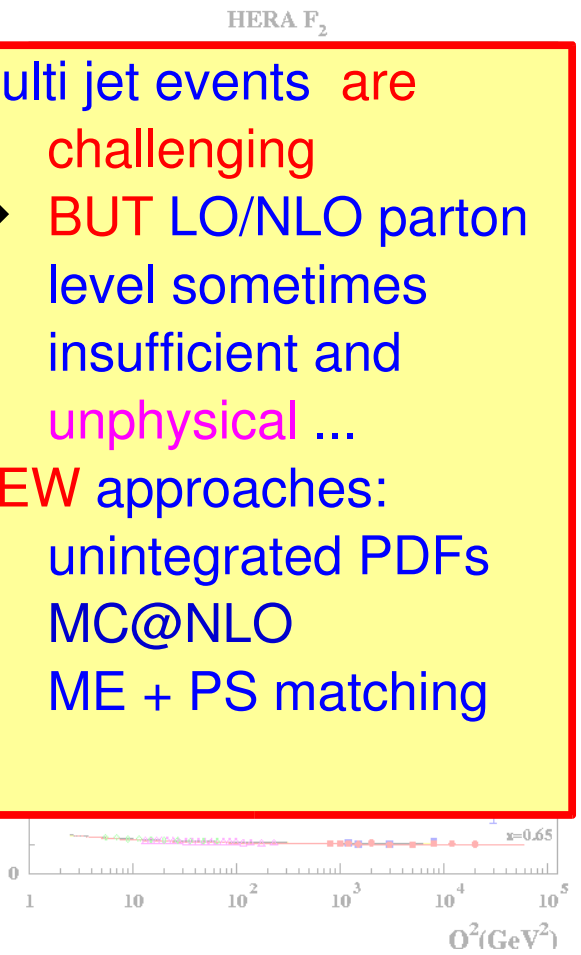
- Remember surprises from HERA
- Is collinear factorization valid ?
- Is linear evolution valid ?
- What about non-linear effects ?
- What about k_t-factorization ?

Is NLO (or NNLO) DGLAP sufficient at small x?
Are higher orders important ?

from J. Stirling



Topics of the workshop

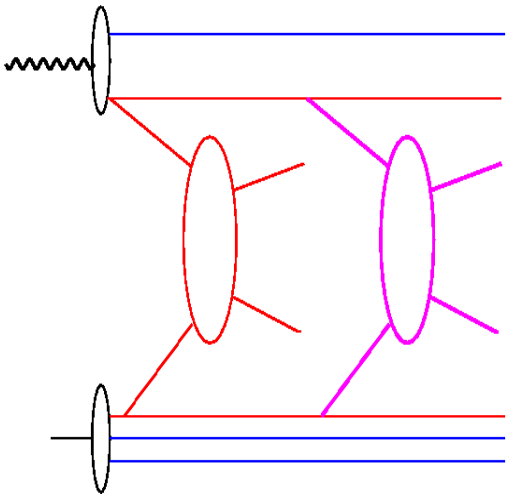


Multi jet events are challenging

➔ BUT LO/NLO parton level sometimes insufficient and unphysical ...

NEW approaches:

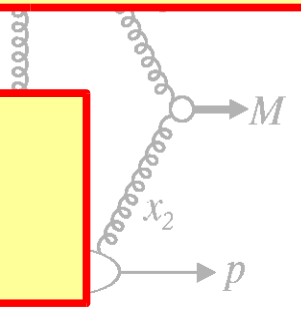
- unintegrated PDFs
- MC@NLO
- ME + PS matching



Multijets & final states
Underlying events,
un-integrated pdfs
LHC: event complexity,
jet x-section, Higgs

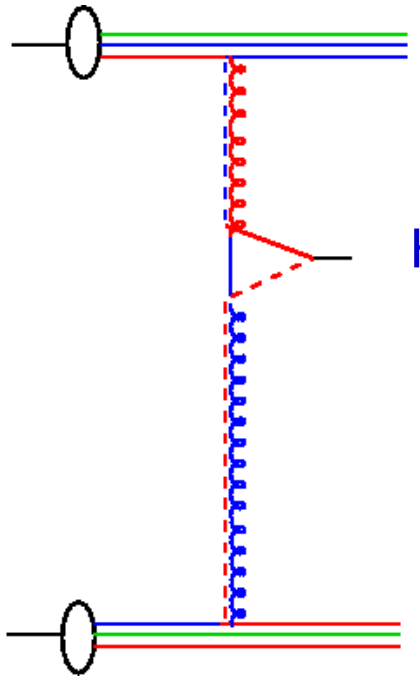
- Underlying event/minimum bias events
  - new models appeared during the workshop
  - tuned to *pp*
  - what about *ep ?*
  - connection to diffraction
  - what about saturation ?
- Gap survival
  - still not understood: Consequences for the LHC!
  - learn from HERA !

Structure f
parton dist
LHC: cross



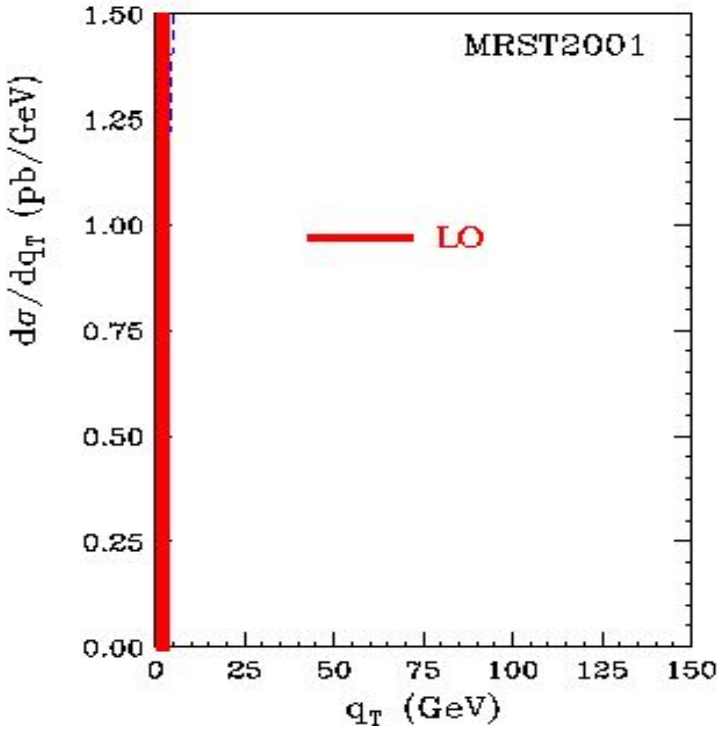
- Resummations for event shape variables
- Future parton shower developments
  - unintegrated parton correlation functions

k_t effects at HERA and LHC

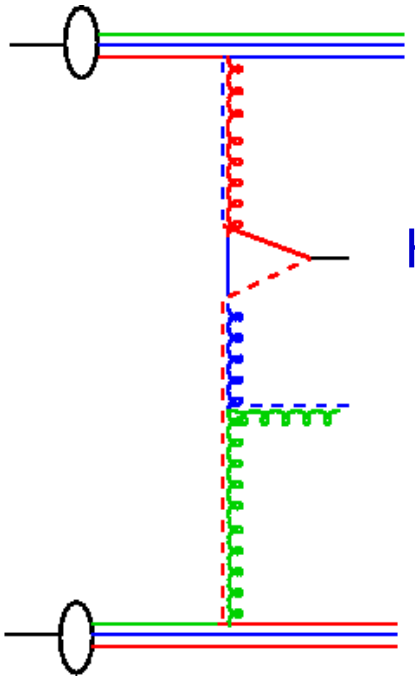


Higgs

LO pretty bad

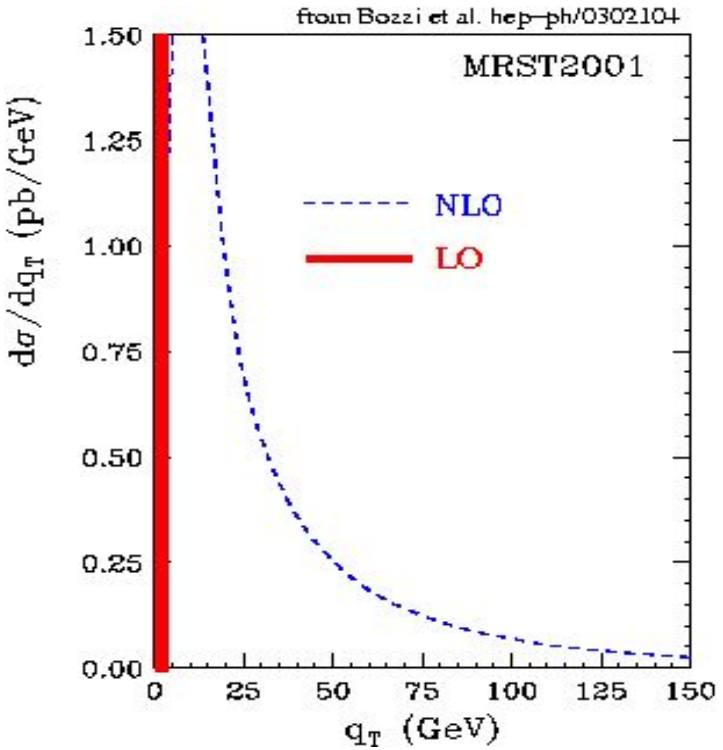


k_t effects at HERA and LHC

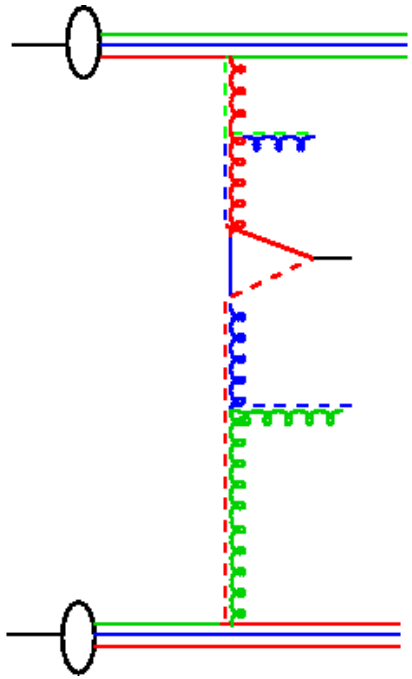


Higgs

NLO better

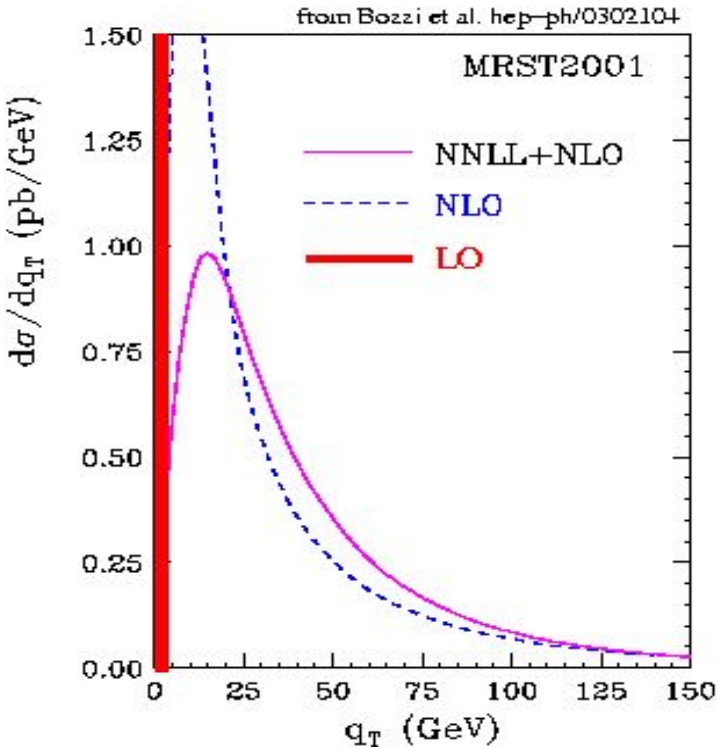


k_t effects at HERA and LHC

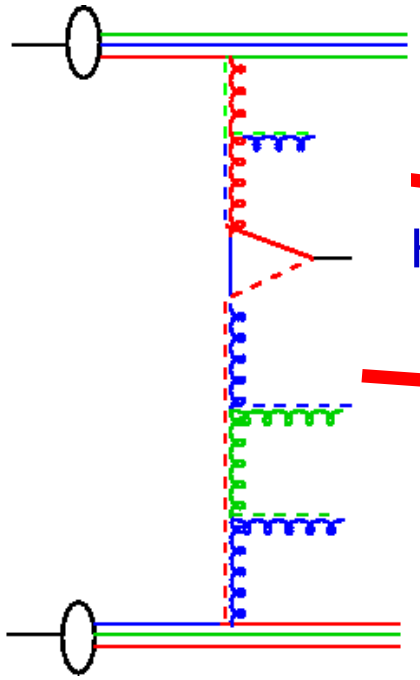


Higgs

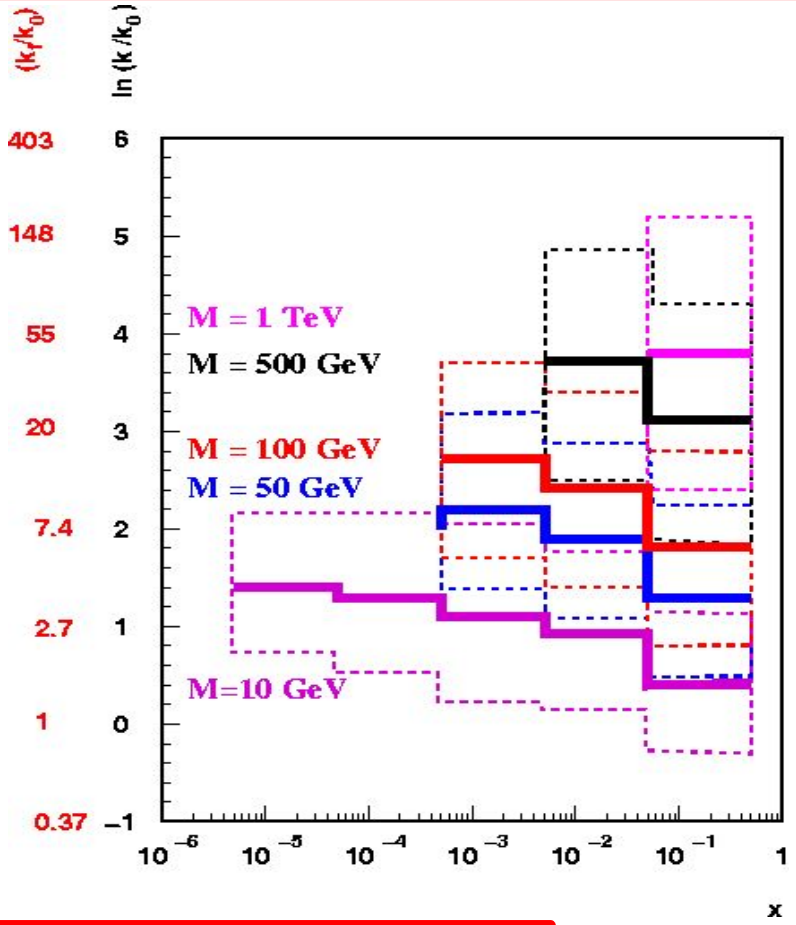
NNLO betttter



k_t effects at HERA and LHC



Higgs

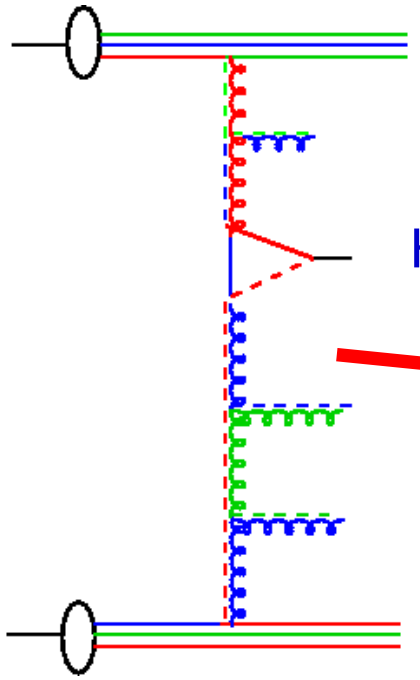


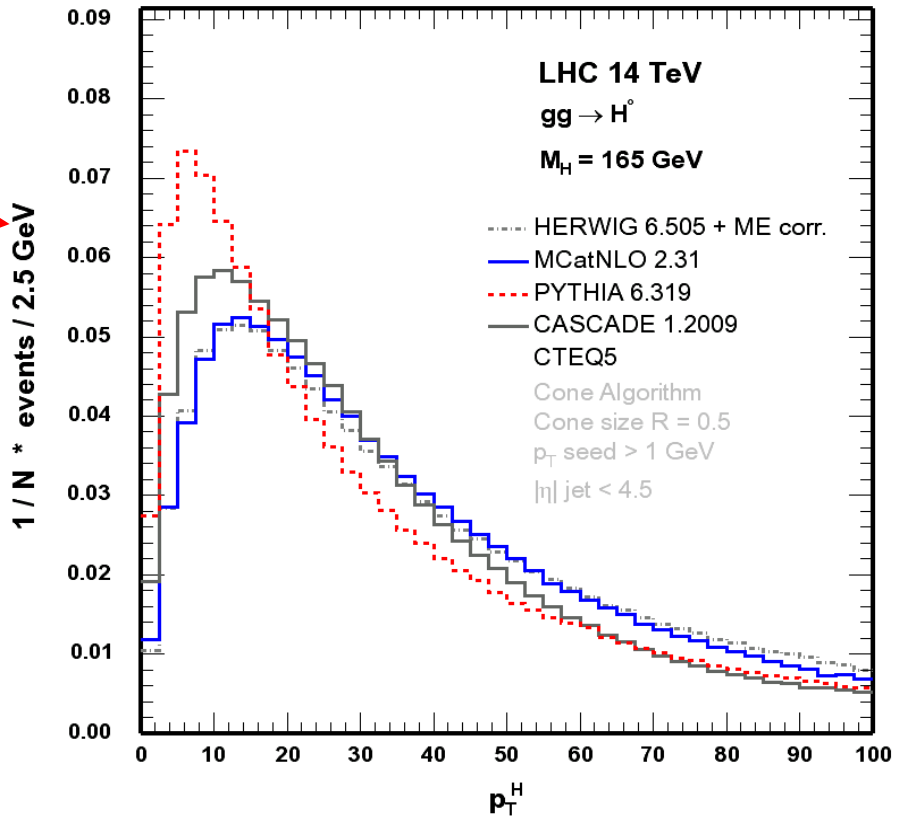
- $\langle k_t \rangle$ can be large .... collinear approach not best
- unintegrated (k_t - dependent) PDFs will be needed
  - to be constrained from HERA
  - Using more the just F_2 ... jets, heavy quarks

k_t effects at HERA and LHC

from G. Davatz

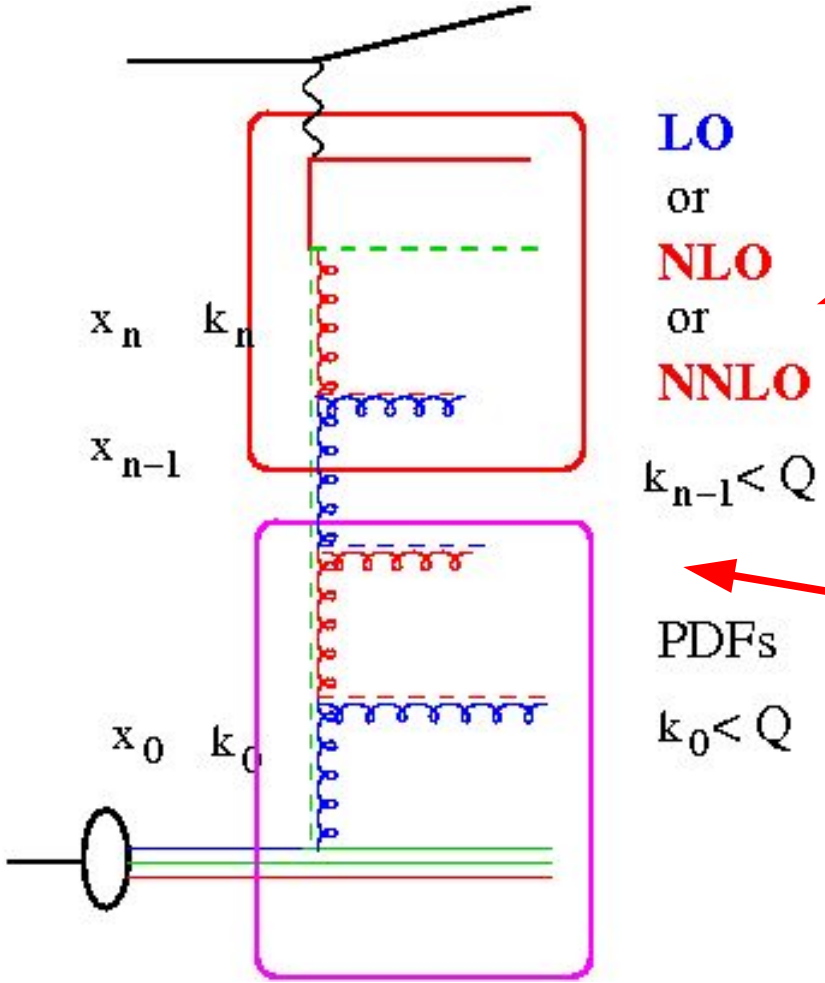
- Do we understand the p_t spectrum of Higgs at LHC?
- Important for the $gg \to \mathrm{Higgs} \to W^+W^- \to l^+\bar{\nu}l^-\nu$ to understand the jet-veto for *tt* suppression...





<k_t> large ....
➔ unintegrated parton PDFs will be needed
➔ Need to be better constrained
at HERA with final states

Integrated PDFs and kinematics



LO
or
NLO
or
NNLO

$k_{n-1} < Q$

PDFs

$k_0 < Q$

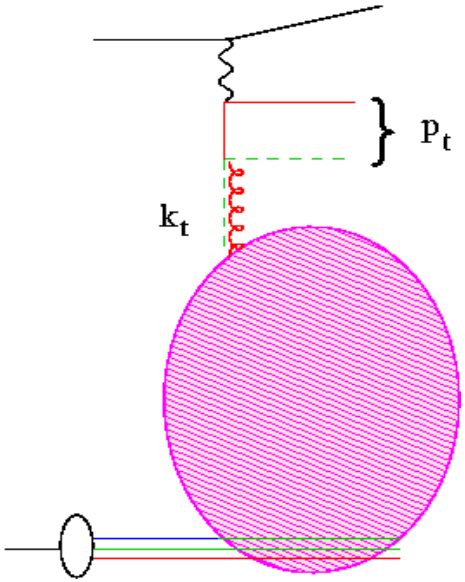
treatment of kinematics important for final state

integrated up to factorization scale Q

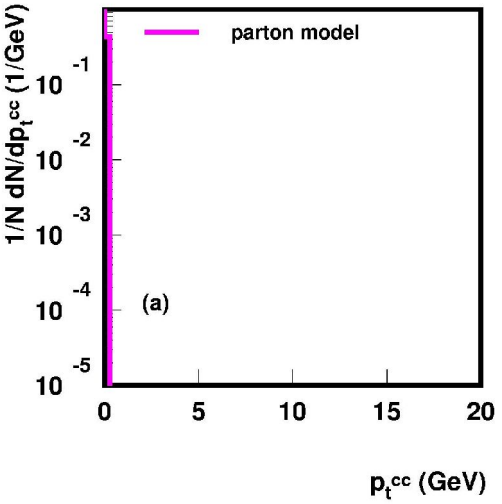
Need for unintegrated PDFs

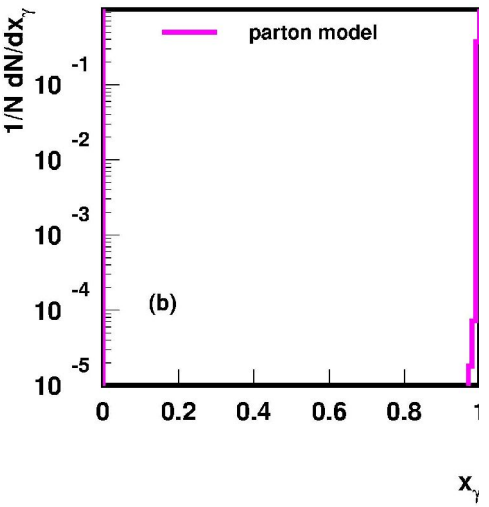
Define:

- $p_{Tq\bar{q}}$
- $x_\gamma = \frac{\sum_{i=q,\bar{q}}(E_i - p_{z\,i})}{2yE_e} = \frac{p^-_{q\bar{q}}}{q^-}$



J. Collins, H. Jung



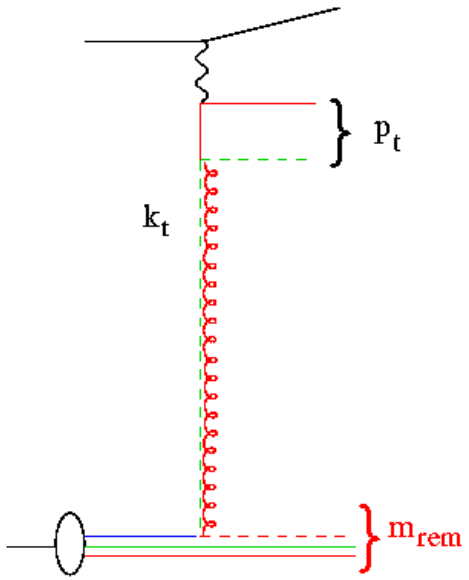


- parton kinematics

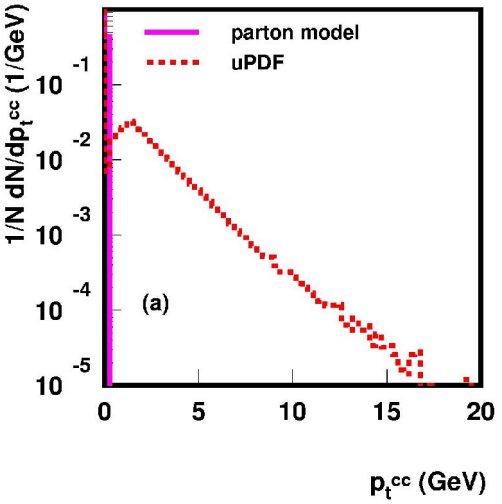
Need for unintegrated PDFs

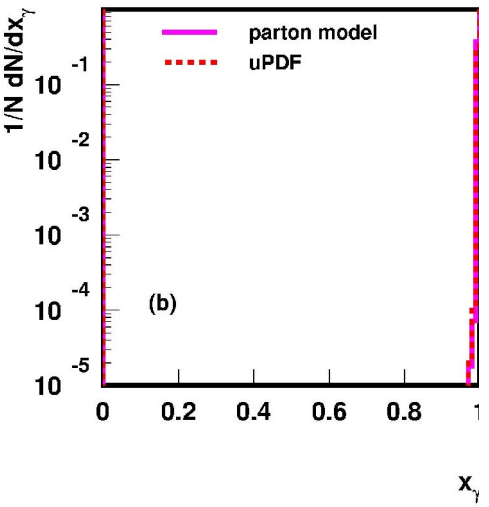
Define:

- $p_{T q\bar{q}}$
- $x_\gamma = \frac{\sum_{i=q,\bar{q}}(E_i - p_{z\,i})}{2yE_e} = \frac{p^-_{q\bar{q}}}{q^-}$



J. Collins, H. Jung



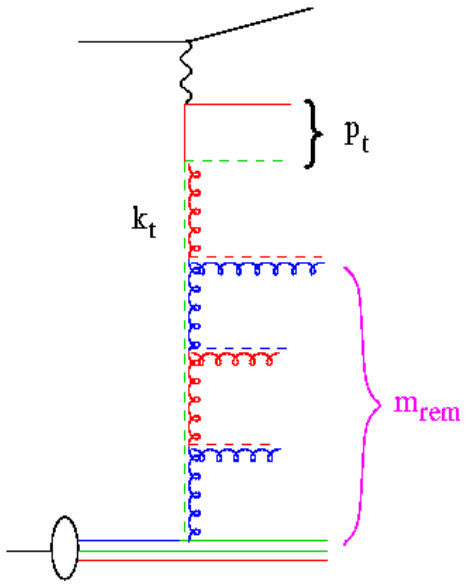


- parton kinematics
- uPDFs

Need for unintegrated PDFs

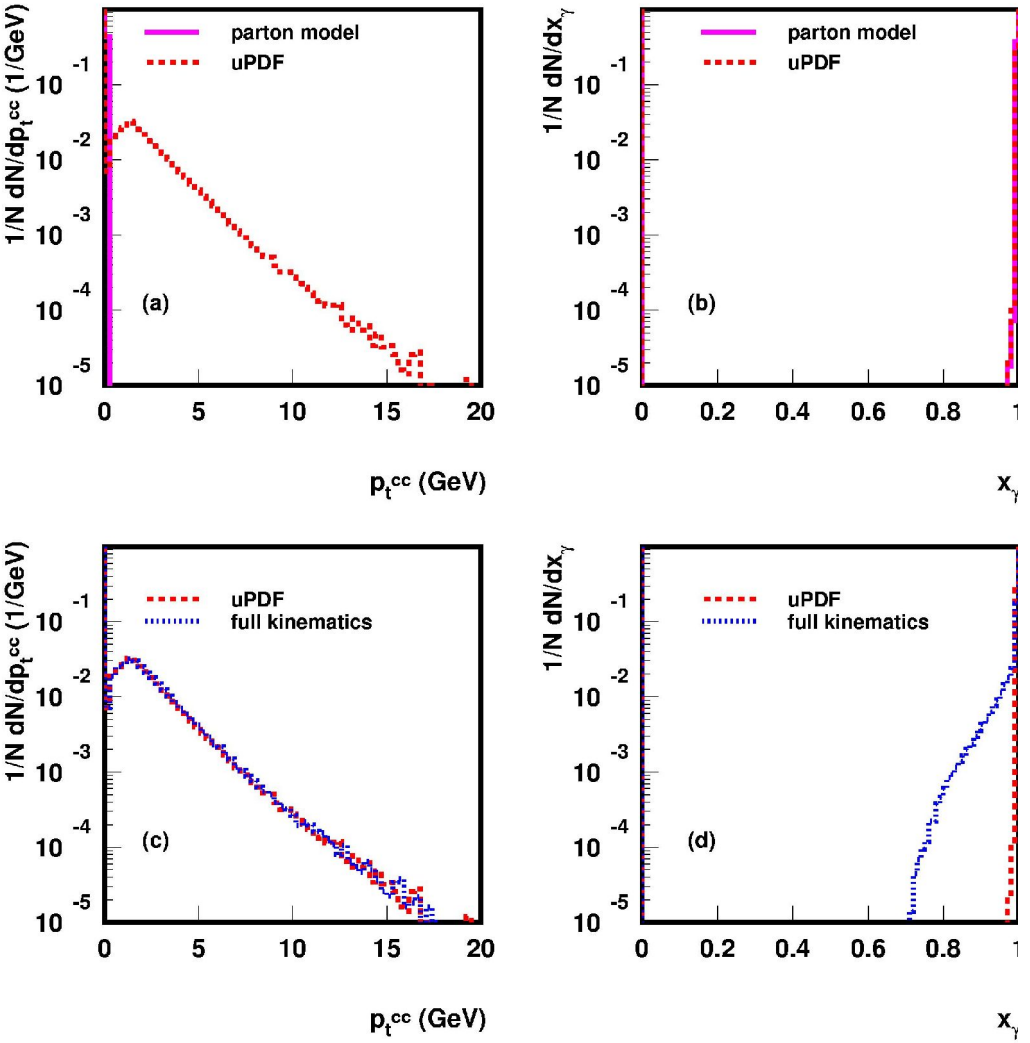
Define:

- $p_{Tq\bar{q}}$
- $x_\gamma = \frac{\sum_{i=q,\bar{q}}(E_i - p_{z\,i})}{2yE_e} = \frac{p^-_{q\bar{q}}}{q^-}$



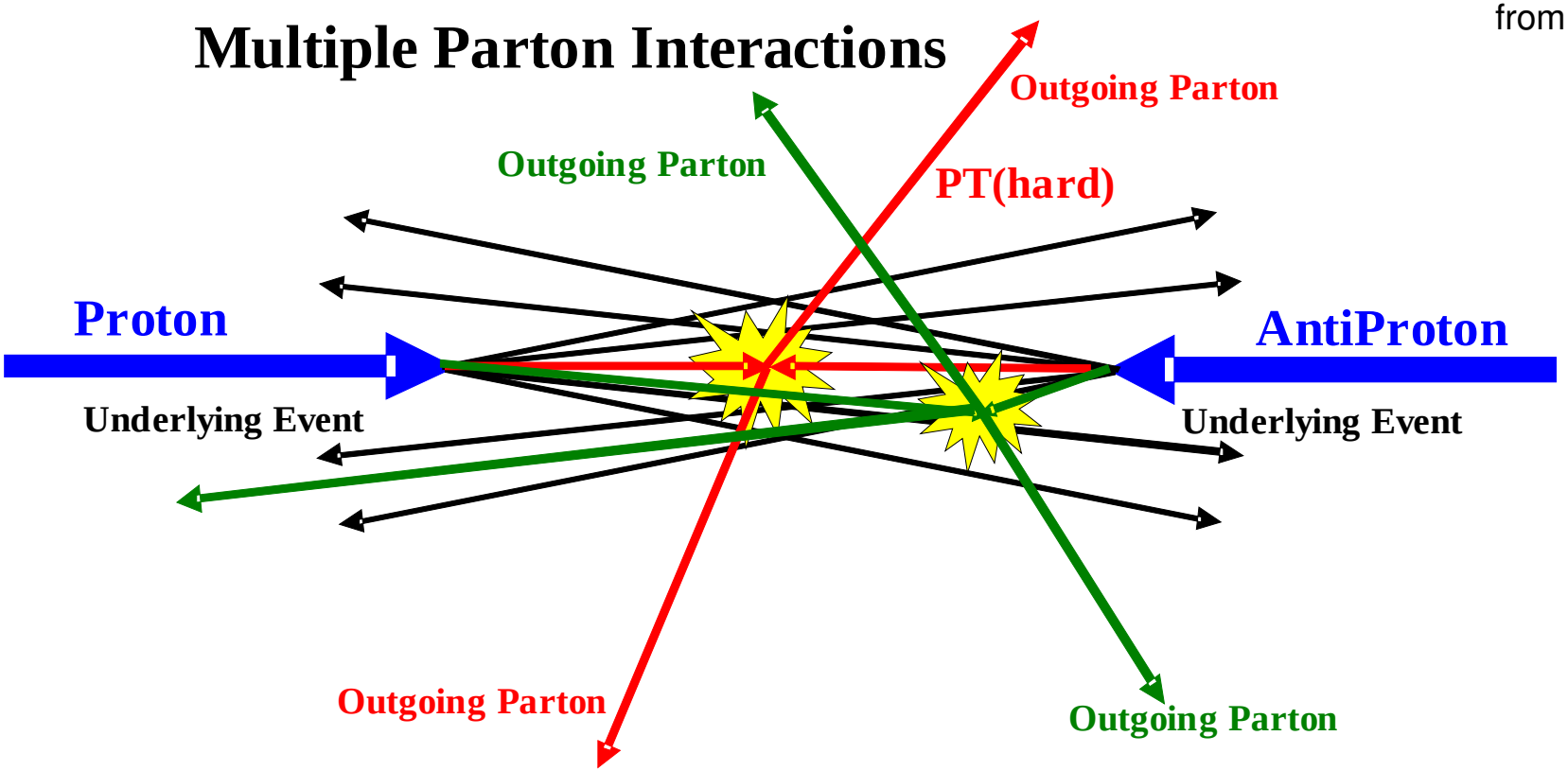
- parton kinematics
- uPDFs
- full kinematics

J. Collins, H. Jung



Multiple Parton Interactions in pp

from R. Field



What is the underlying event (UE), multiple parton interactions (MI)?

➔ *Everything, except the LO process we're currently interested in*

- *parton showers*
- *additional remnant – remnant interactions*

✗ NOT pile-up events (luminosity dependent)

Underlying event – Multiple Interaction

- Basic partonic perturbative cross section

$$\sigma_{\rm hard}(p^2_{\perp \rm min}) = \int_{p^2_{\perp \rm min}} \frac{d\sigma_{\rm hard}(p^2_\perp)}{dp^2_\perp} dp^2_\perp$$

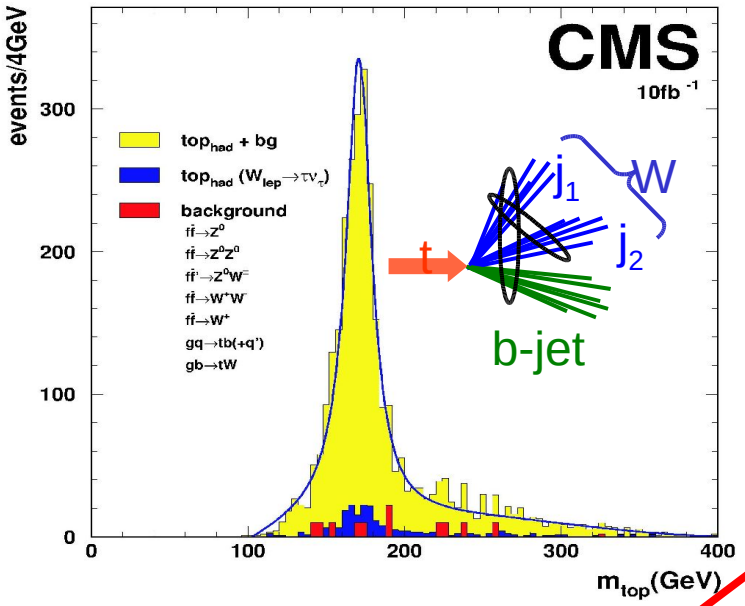
➔ diverges faster than $1/p^4_{\perp \rm min}$ as $p_{\perp \rm min} \to 0$ and exceeds eventually total inelastic (non-diffractive) cross section, resulting in more than 1 interaction per event (multiple interactions, MI).

➔ Average number of interactions per event is given by:

$$\langle n \rangle = \frac{\sigma_{\rm hard}(p_{\perp \rm min})}{\sigma_{nd}}$$

- It depends how soft interactions are treated, ***BUT*** also on the parton densities and factorization scheme !!!!!!!

Multiple Interactions and top mass

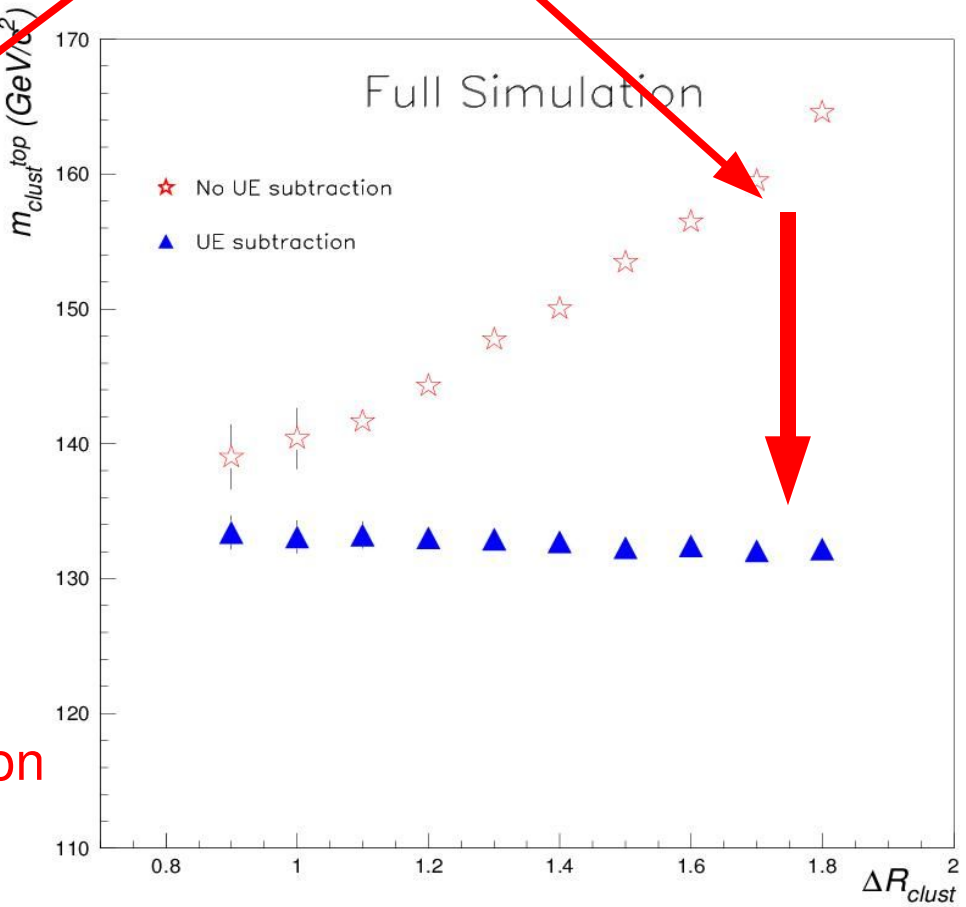


Source of error in GeV	Lepton+jets inclusive sample	Lepton+jets large clusters sample	Dilepton	All jets high pT sample
Energy scale				
Light jet energy scale	0.2	-	-	0.8
b-jet energy scale	0.7	-	0.6	0.7
Mass scale calibration	-	0.9	-	-
UE estimate	-	1.3	-	-
Physics				
Background	0.1		0.2	0.4
b-quark fragmentation	0.1	0.3	0.7	0.3
Initial state radiation	0.1	0.1	0.1	0.4
Final state radiation	0.5	0.1	0.6	2.8
PDF		-	1.2	-

from M. Mangano

hep-ex/04003021

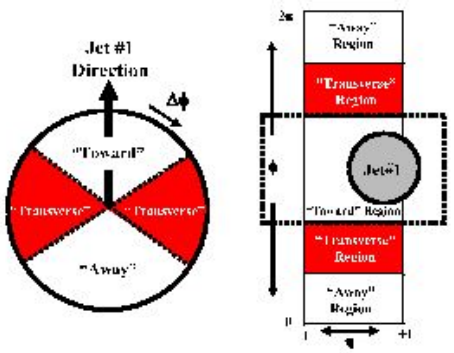
Are we sure ?



- Multiple Interactions
- Jet fragmentation properties, jet profiles
- Final state QCD radiation
- B-fragmentation

Significant effects on top mass determination
Better understand them !!!

Multiple Interactions at LHC

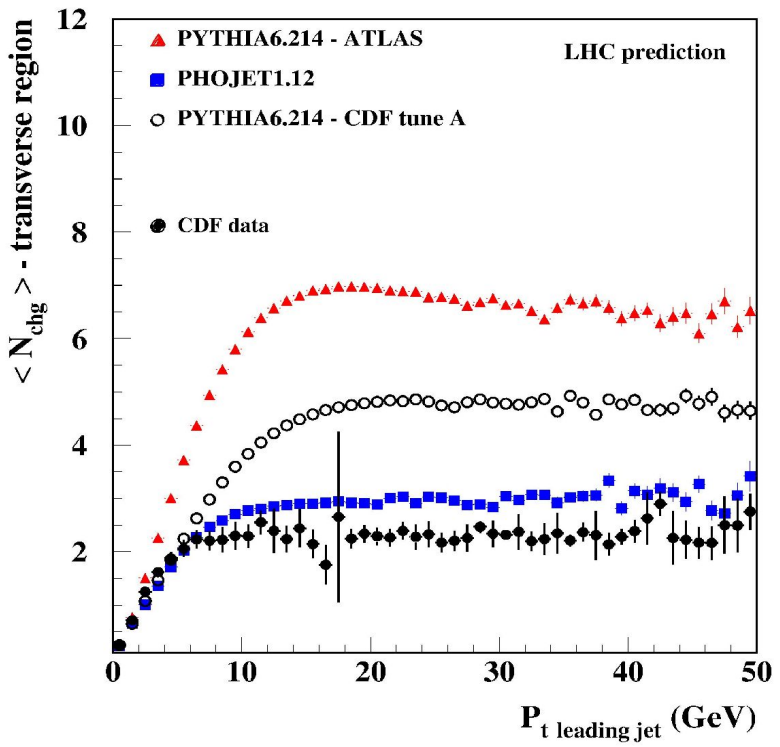


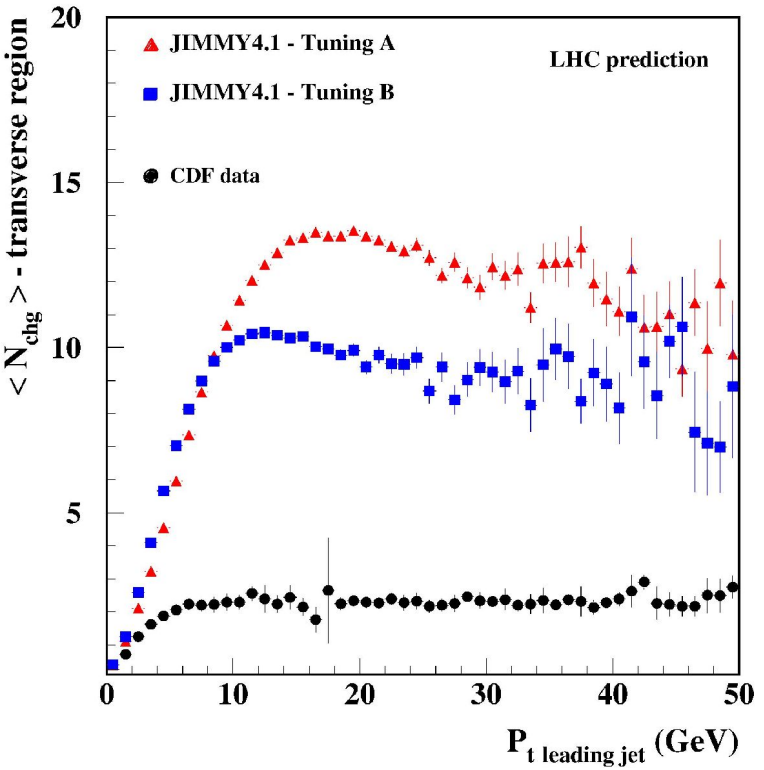
Charged multiplicities in transverse region

$p_t > 0.5$ GeV; $|\eta| < 1$

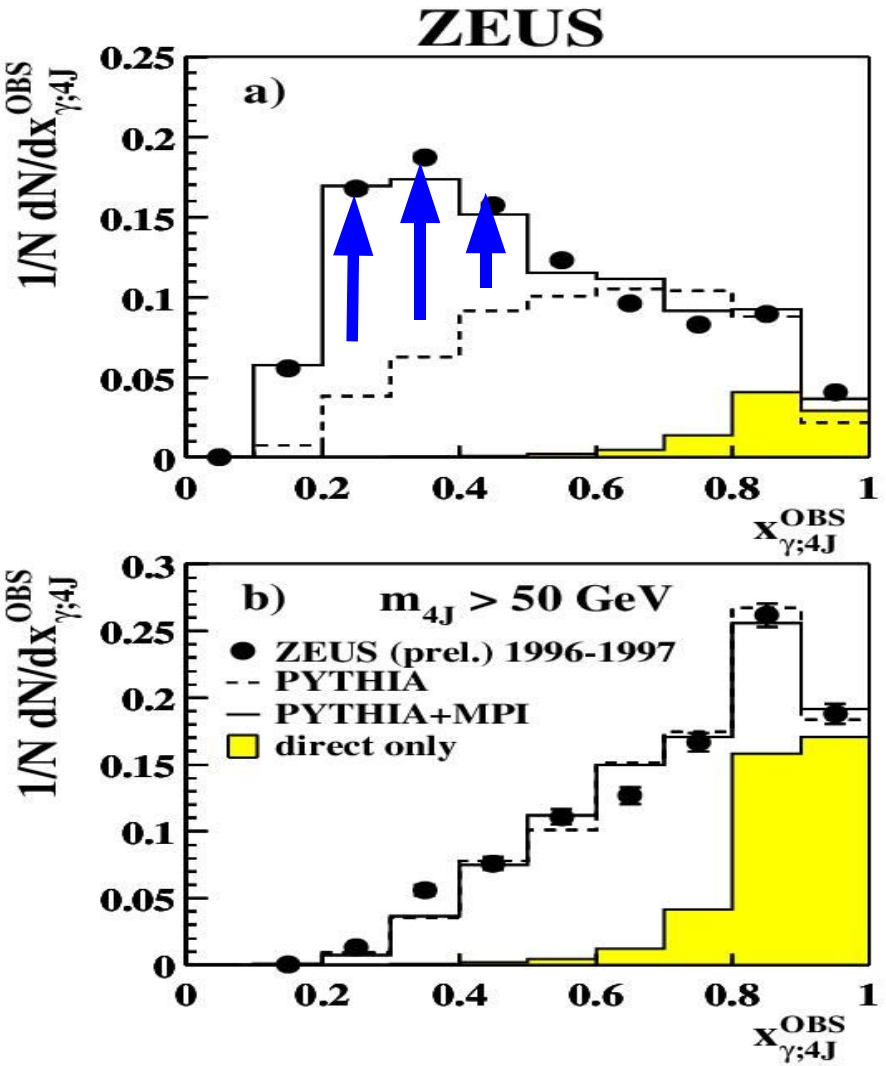
C. Buttar et al

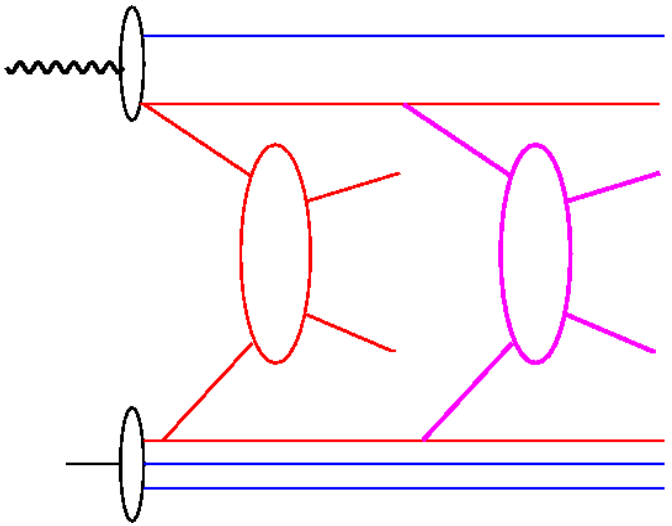
- Models tuned to TeVatron data
- ➔ give **HUGE** differences at LHC ...
- ➔ **better understand multiple interactions ...**





Multiple Interactions at HERA



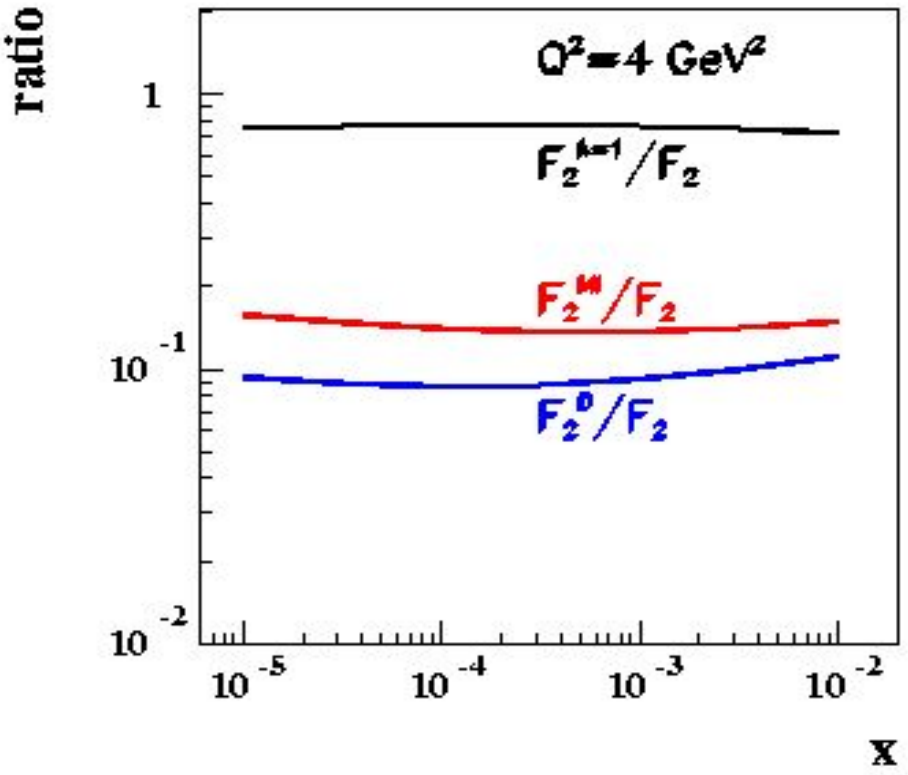


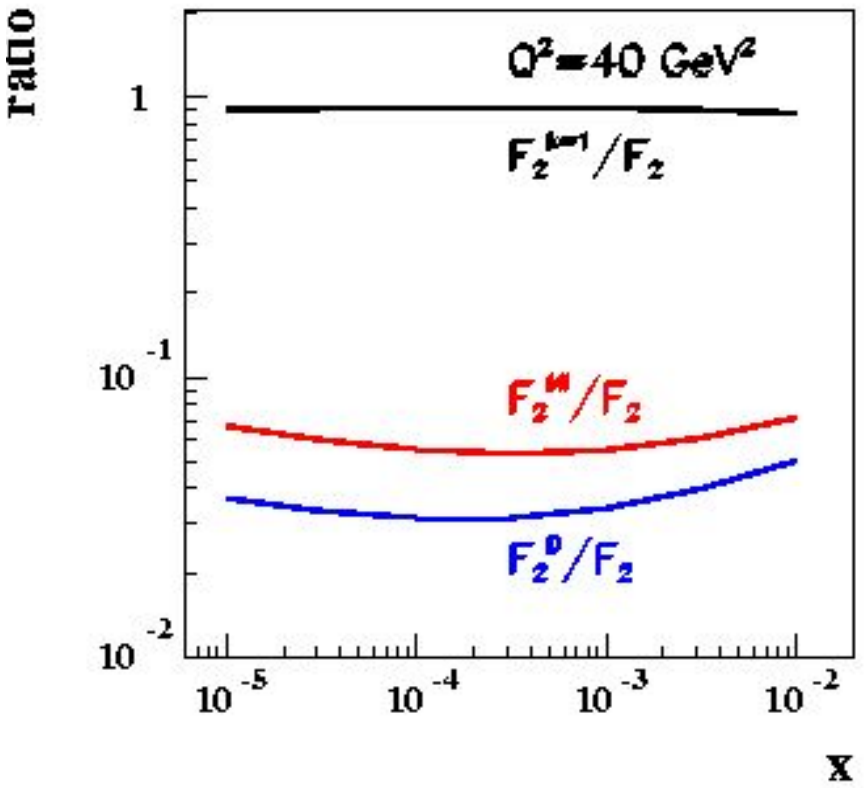
photoproduction is effectively hadron-hadron production...

Test and understand multiple interactions at HERA !!!

Multiple Interactions in F_2

from H. Kowalski



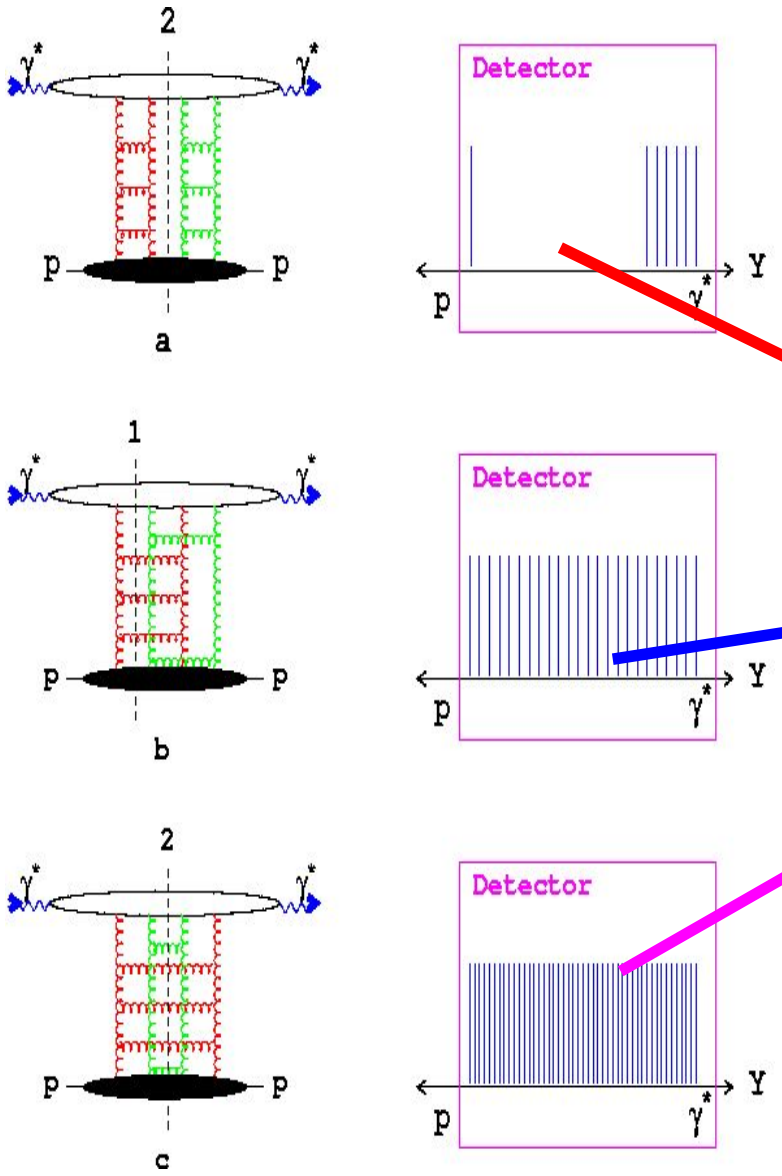


- Color dipole model predict a large contribution of MI to F_2

➔ of similar size as **diffraction**

➔ Need to understand that ... AGK cutting rules in QCD and all that

Towards understanding of MI



Bartels, Kowalski, Sabio-Vera

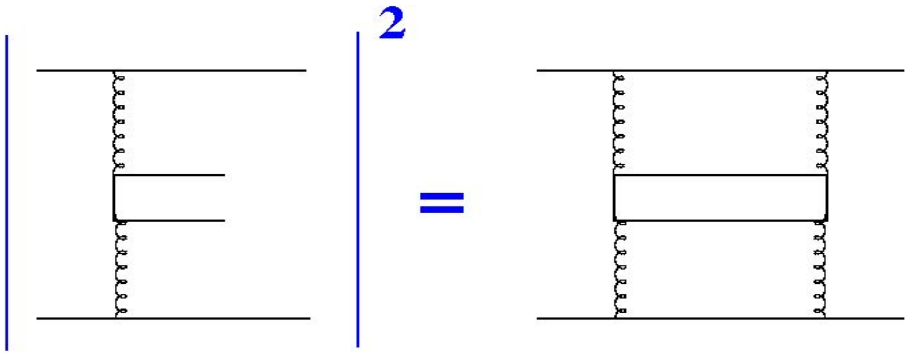
- Cutting rules (AGK) extended to QCD
- Relate diffraction, saturation and multiple scatterings
- All from the same amplitude, but different factors:
  - +1 Diffraction
  - - 4 Saturation
  - +2 Multiple Interactions
- Extended now also to pp !!!!
  - further work needed ...

➔ HERA is the place to understand MI !!!!
(TeVatron to tune MC !!!)

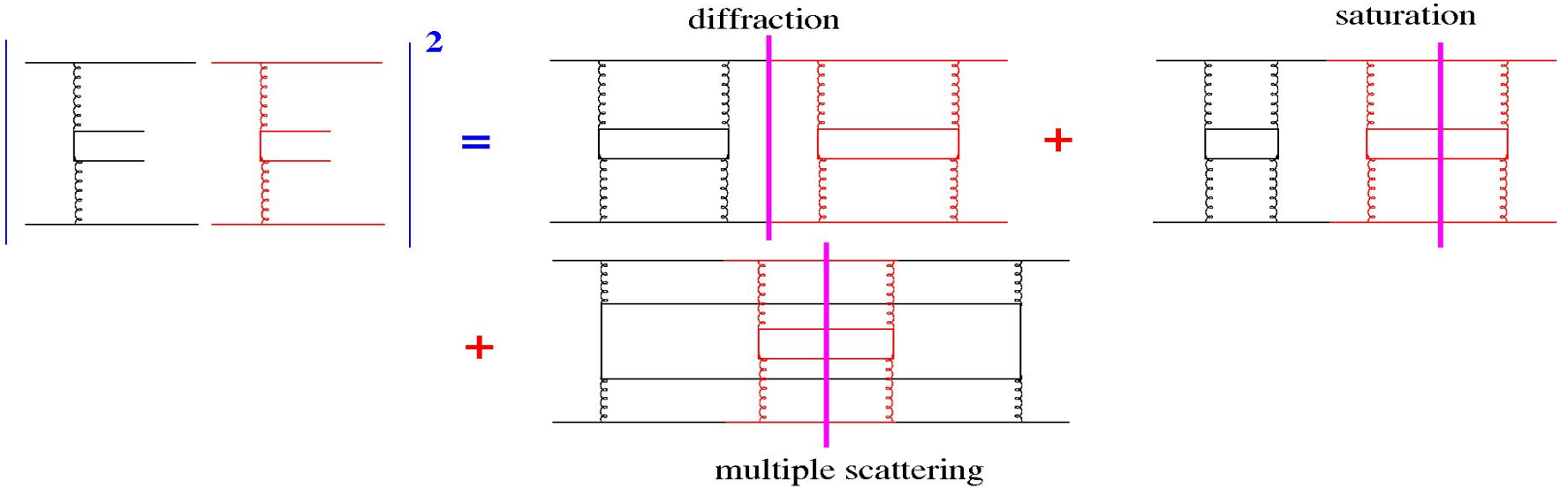
➔ Towards the description of *"everything"* !!!!!

Toy Model for AGK

- where is relation of diffraction – multiple scatterings – saturation coming from ?
- single parton exchange:



- 2-parton exchange:



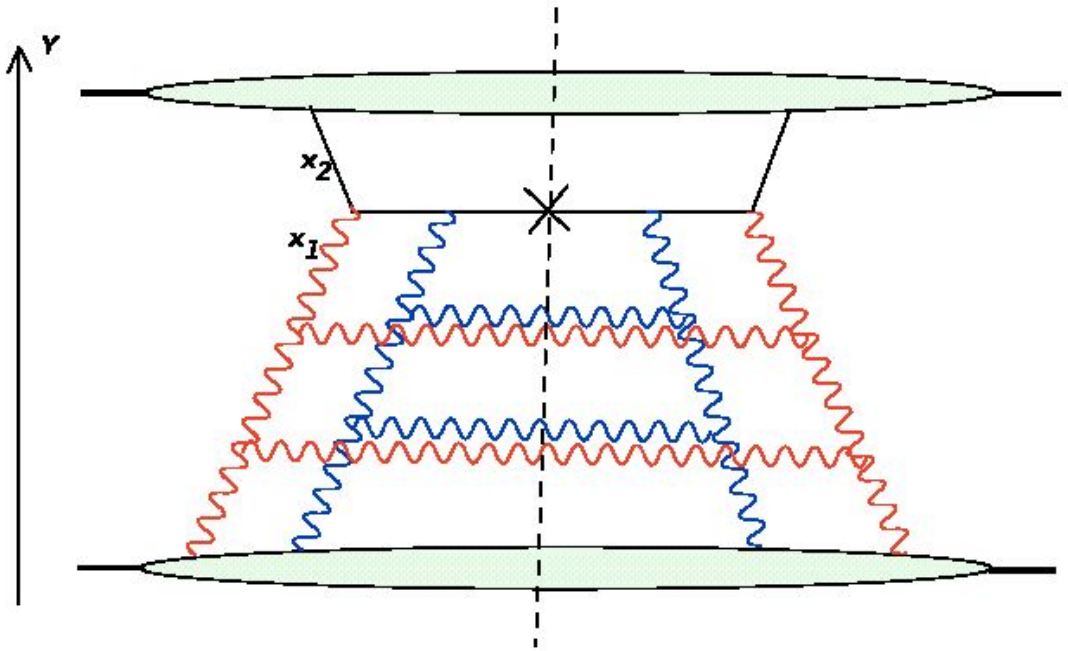
Multiple Interactions

- Measurements in forward region

➔ observe Multiple Interactions –

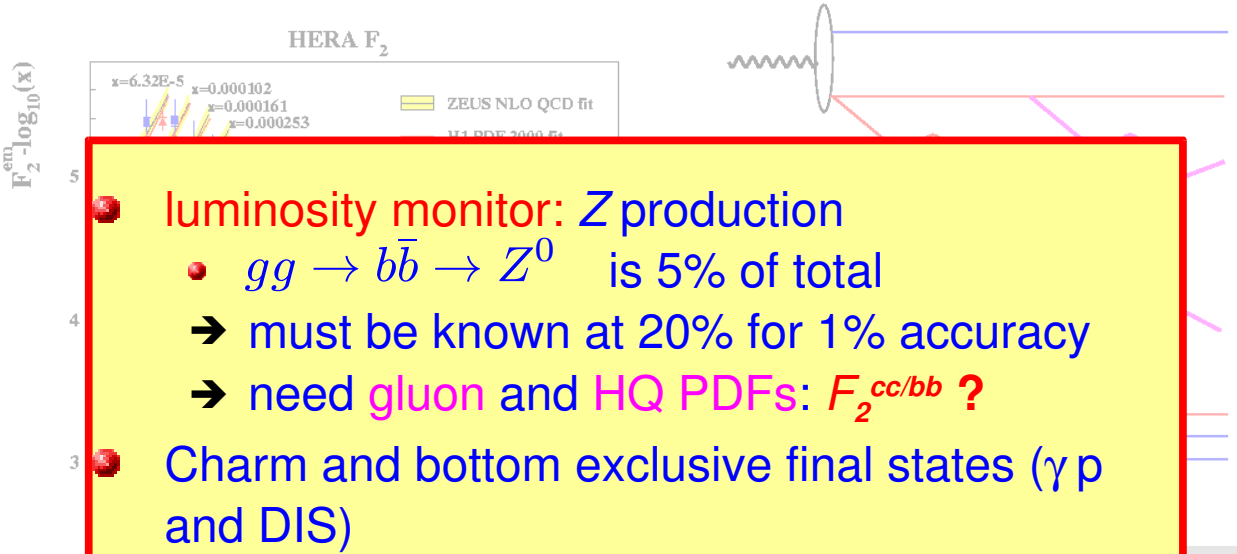
Breaking of standard linear QCD factorization !!!

LHC: jet near the beam directions ($x_1 \ll x_2$)

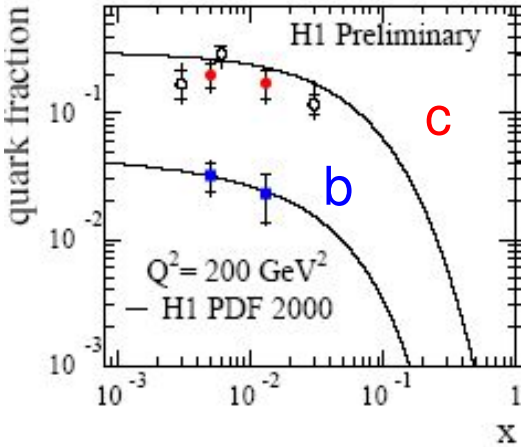


Multiple interaction across large rapidity intervals.

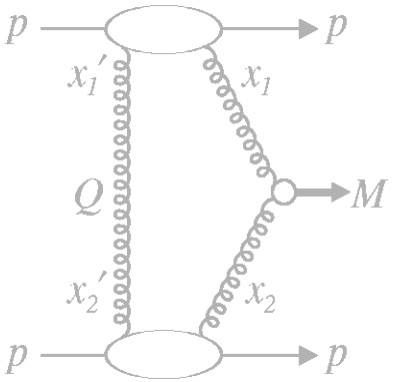
Topics of the workshop



- luminosity monitor: Z production
  - $gg \to b\bar{b} \to Z^0$ is 5% of total
  - ➔ must be known at 20% for 1% accuracy
  - ➔ need gluon and HQ PDFs: $F_2^{cc/bb}$?
- Charm and bottom exclusive final states (γ p and DIS)
  - Cross sections
  - Fragmentation universality
  - Contribution from higher charm resonances
- x-section precision
  - LO/NLO
  - Resummation
  - unintegrated PDFs
  - Benchmark x-section
- Non-linear effects/saturation



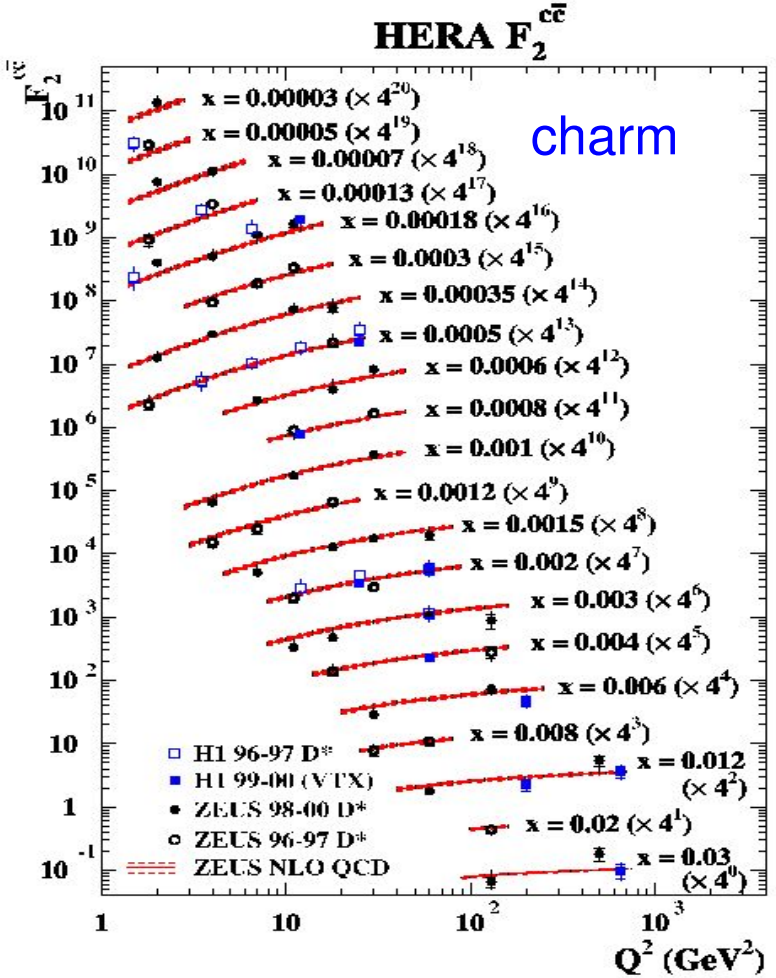
Heavy quarks:
B quark PDFs of the proton, fragmentation fct, uPDFs
LHC: cross sections, non-linear evol., Higgs

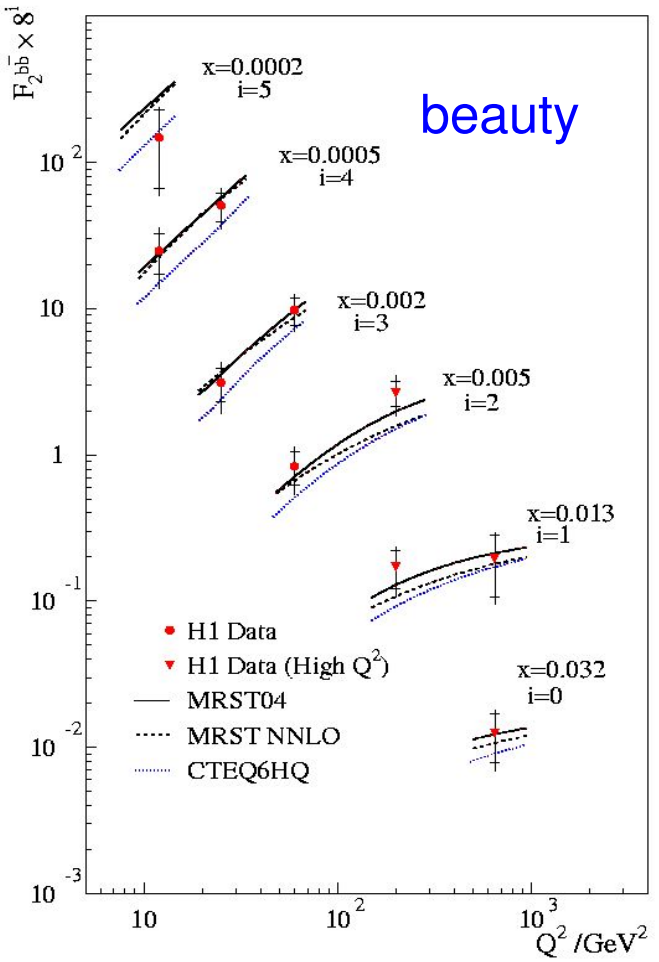


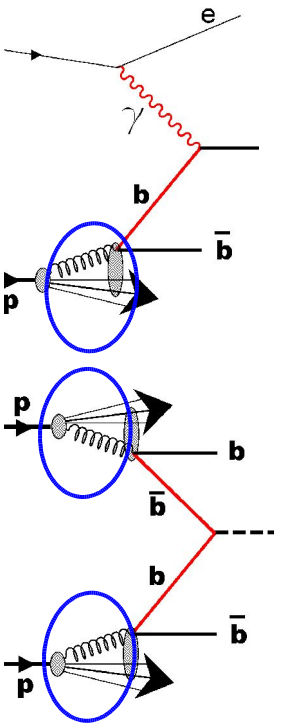
HERA: Heavy Quark PDFs at large Q^2

- Current H1 (HERA I) analysis

From O.Behnke, A. Geiser, A. Meyer, M. Wing







- HERA II analysis (expect factor 10 more), larger kinematic range, both exp. with CST/MVD

➔ Understand *b*-production mechanism (...remember *b*-puzzle at the TeVatron...)

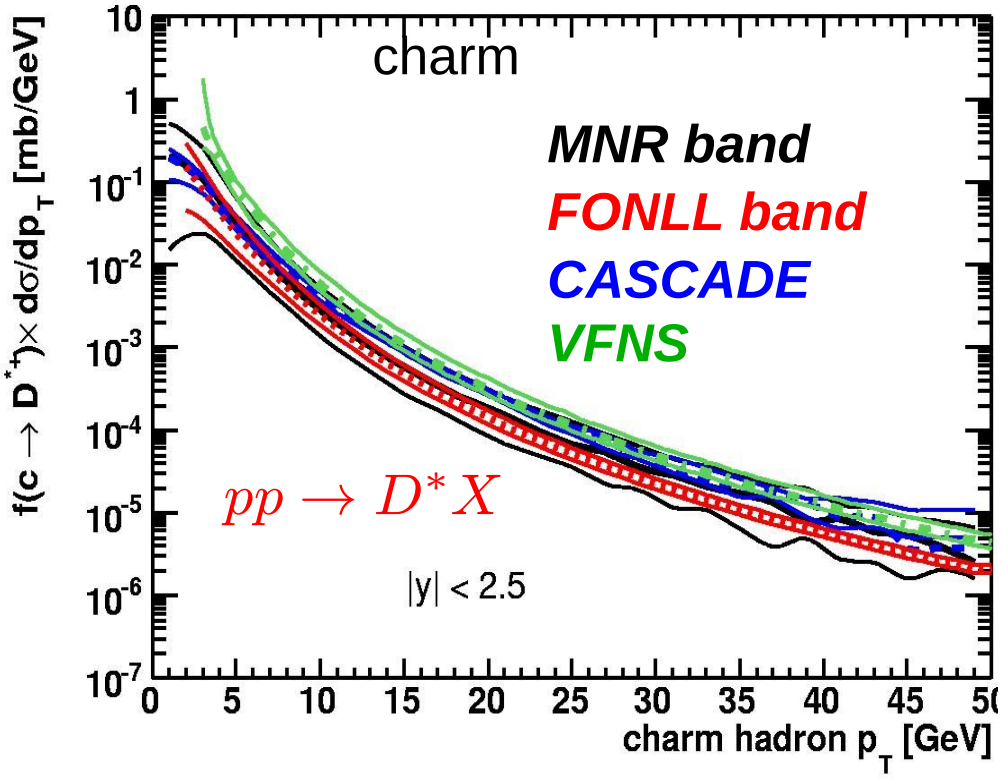
➔ **NOTE:** gluon drives heavy quark PDFs .... transverse momenta ????

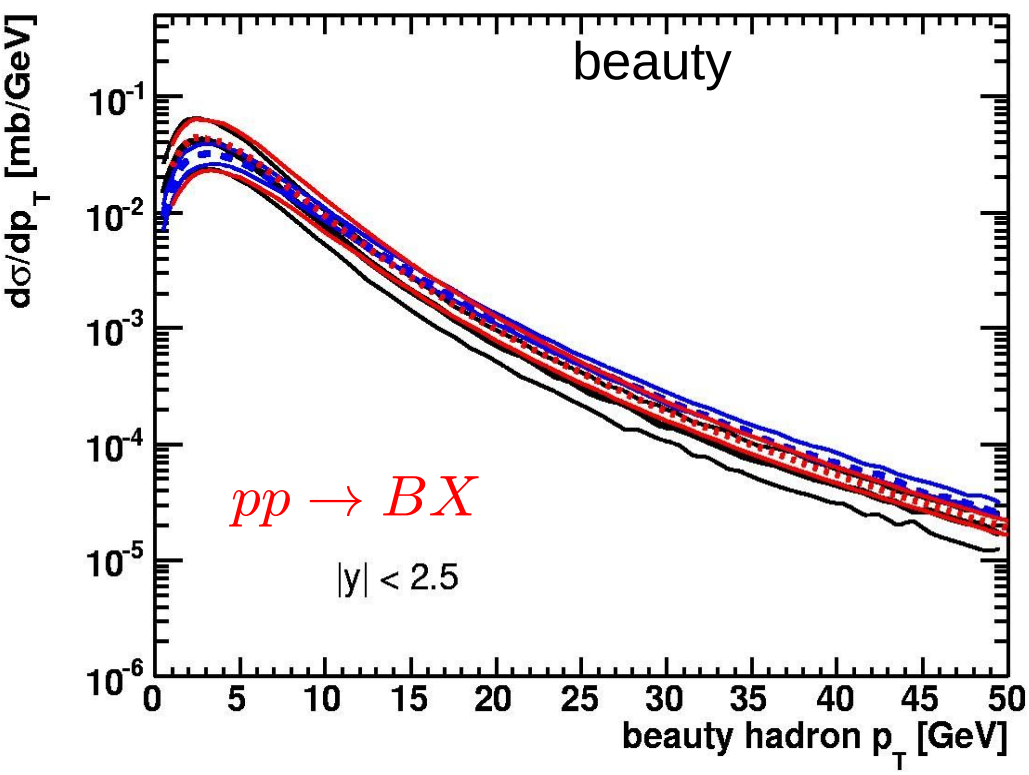
Charm and Beauty at the LHC

from O. Behnke et al

Benchmarks at hadron level in central region

MNR (massive NLO) – FONLL (matched NLL) – CASCADE (uPDF) - VFNS



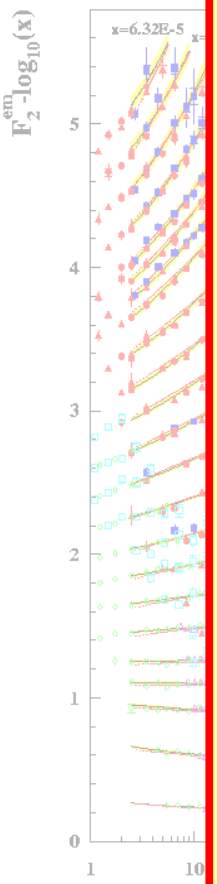


CASCADE agrees well with **MNR** and **FONLL** for charm and beauty.

VFNS is larger for charm at small p_t ...

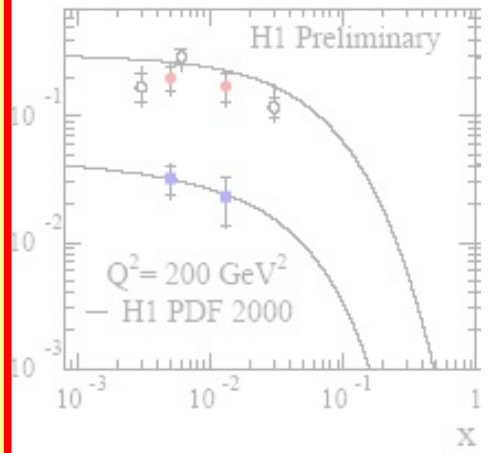
All agree reasonably well ... success **!!!**

Topics of the workshop



- Forward proton tagging for NEW PHYSICS
  - Higgs, ???
- Diffractive Higgs production
  - Theory of exclusive (diffractive) Higgs production
  - Trigger, forward tagging
  - Backgrounds to diffractive Higgs
- Diffractive PDFs and combing HERA experiments
  - New measurements e.g F_L^D
- Diffractive factorization breaking
  - Dijet/Charm production
- Saturation effects and relation to MI/gap survival

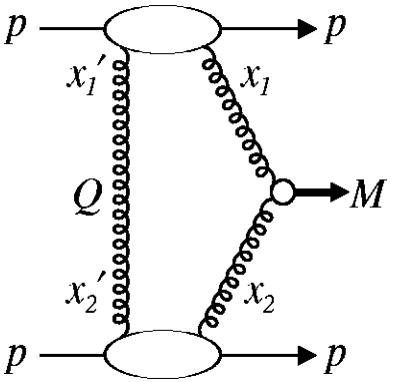
- Large part of the activities was transfer of experience of the knowledge and design and operation of detectors for forward physics from HERA to the LHC



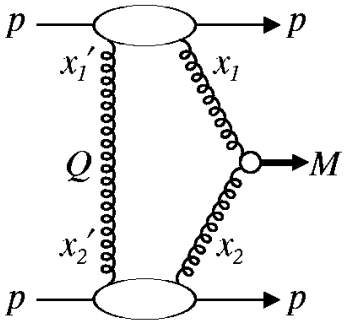
y quarks:
rk PDFs of the proton,
entation fct, uPDF
Higgs production

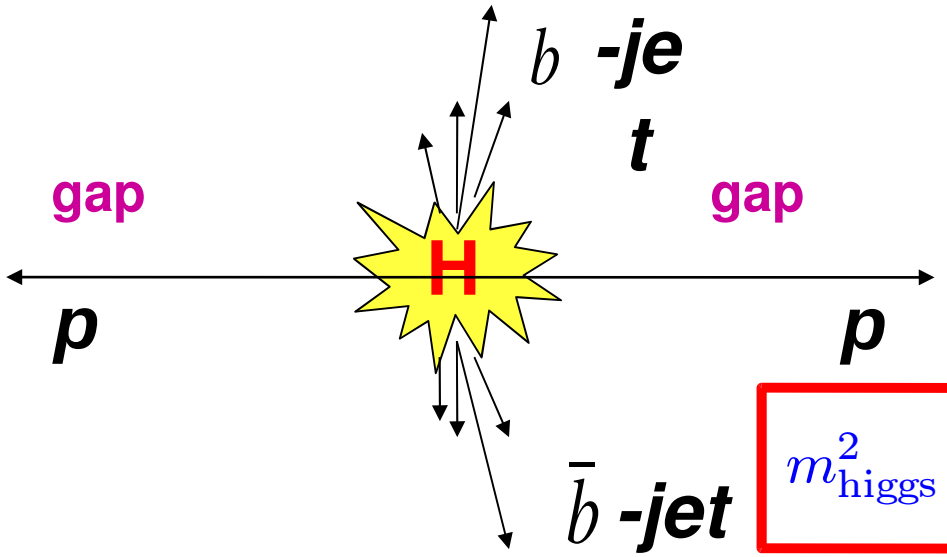
Structure functions and
parton distributions
LHC: cross sections/precision

Diffraction
LHC: exclusive
Higgs production



Diffractive Higgs Production





E.g. V. Khoze et al
M. Boonekamp et al.
B. Cox et al. …

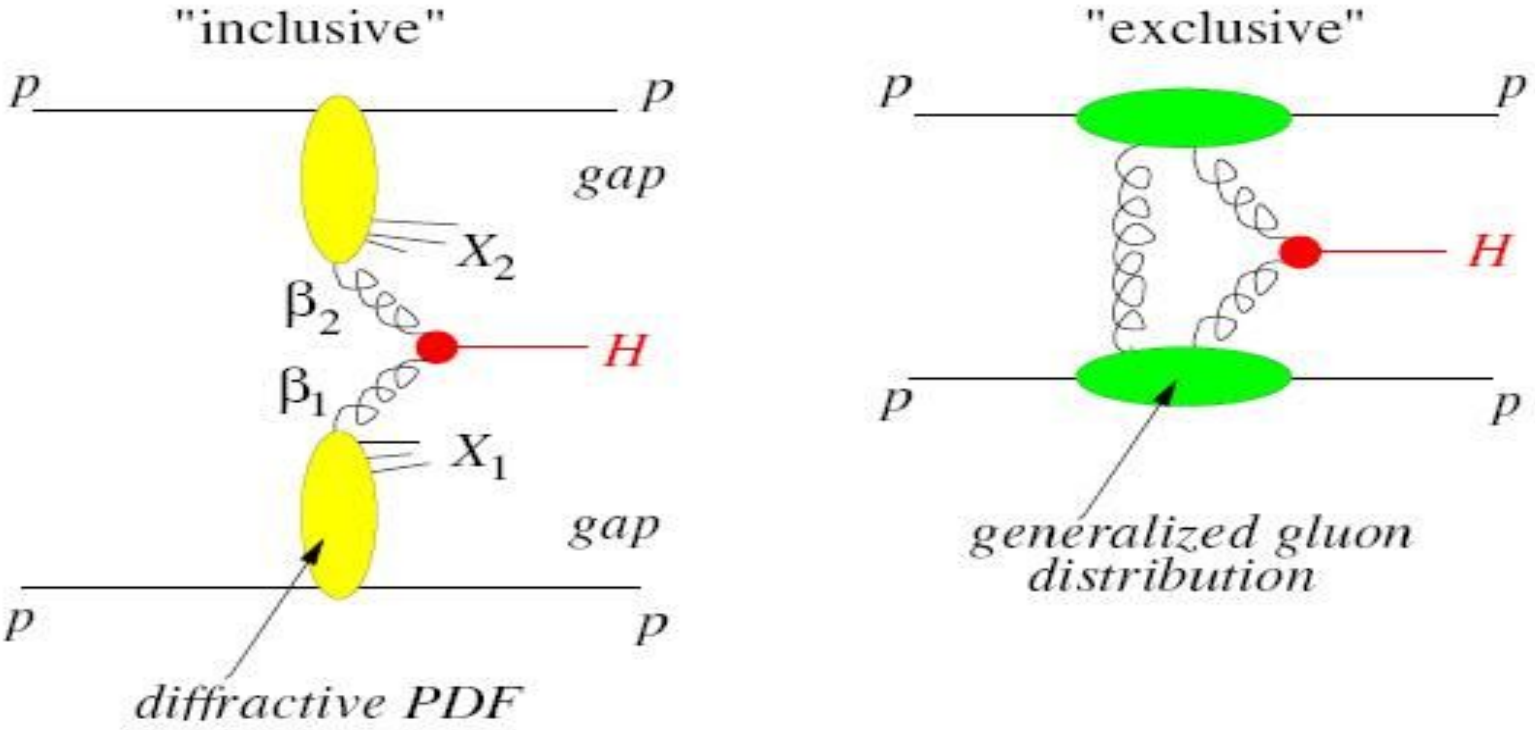
$$m^2_{\text{higgs}} = (p + \bar{p} - p' - \bar{p}')$$

- Exclusive diffractive Higgs production $p + p \to p + H + p$ 2-10 fb
- Inclusive diffractive Higgs production $pp \to p + X + H + Y + p$ O(100) fb

- Advantages:
  - Mass resolution
    from energy of protons determine mass,precise mass determination
  - Quantum numbers
    central system produced in $J_z=0$, C and P even state
- Sensitive to unintegrated PDFs

Exclusive Higgs and diffraction at HERA

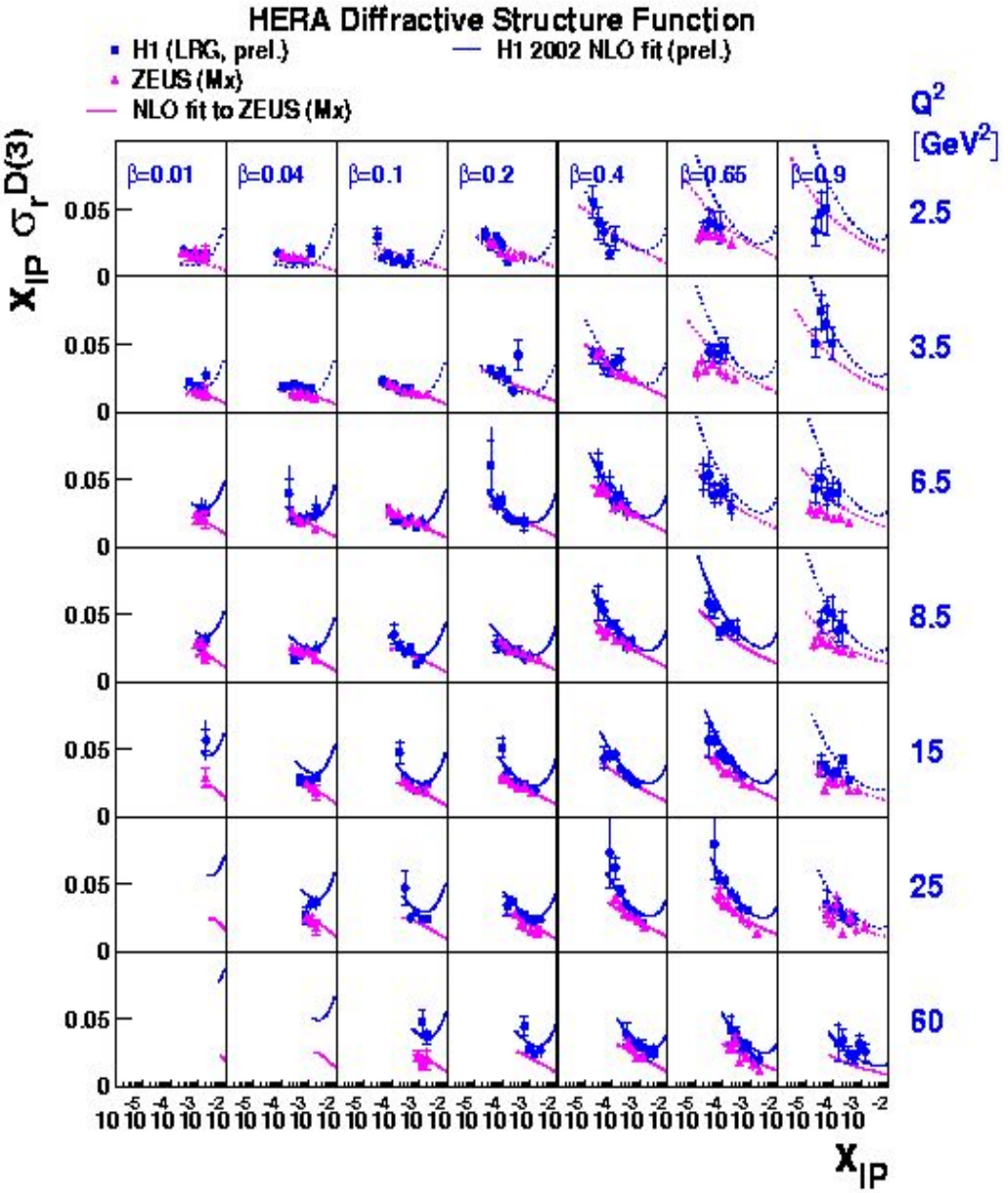
from M. Diehl



- Inclusive diffractive events become background to exclusive ones, when remnant systems X become soft...
- relevant region for diffractive PDFs:
  $\beta \to 1$ and $Q^2 \sim M^2_{\rm higgs}$
- diffractive PDF at highest Q^2 and highest β is needed, in addition to the whole range....

F_2^D summary at HERA

From FP Schilling, P.Newman



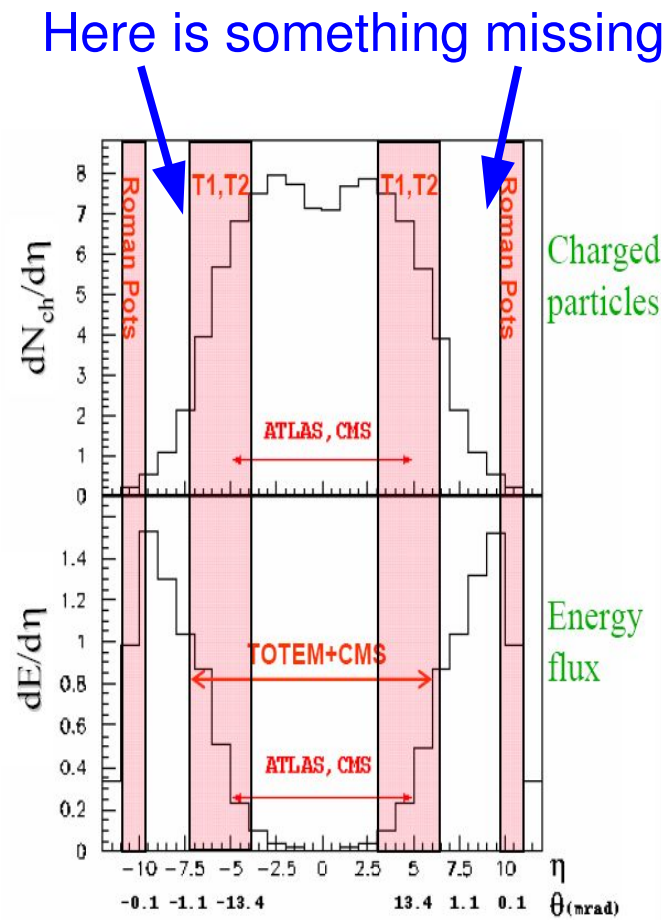
F_2^D is crucial for understanding Color Singlet Exchange (CSE) in hadronic interactions:

➔1st step was made towards final, combined F_2^D from HERA!

Present status: In unified analysis of measured cross-sections reasonable global agreement between H1 & ZEUS is found, and regions of discrepancies identified.

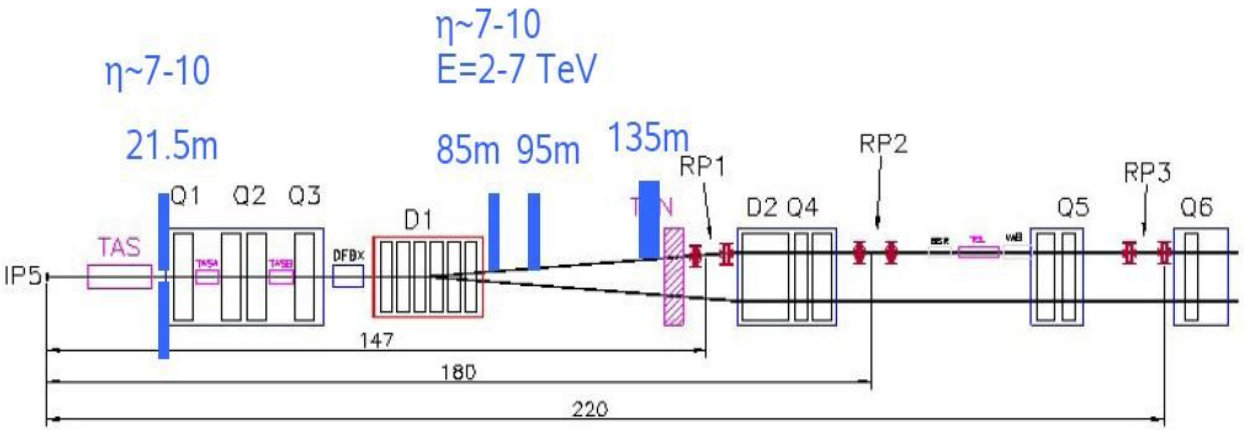
- **get the best out of HERA**
- **precise determination of diffractive PDFs needed !!!**

Ideas for upgrading forward region

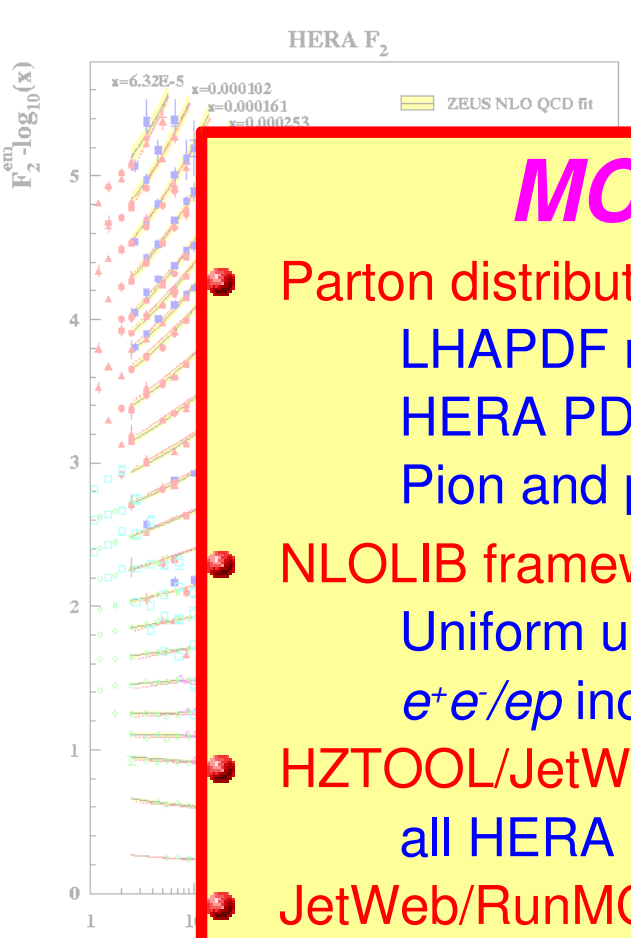


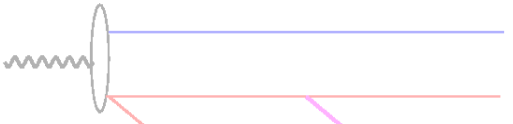
from V. Andreev, A. Buniatian, L. Lytkine, M. Kapishin, H.J.

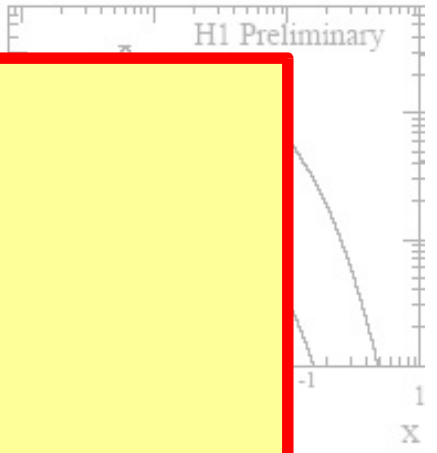
- important for UHECR (hadron showers at E ~ 10^{17} eV)
- important region for small x QCD: MI – saturation – diffraction – gap-survival
- possibilities:
  - ➔ small angle tagging: micro-stations
  - ➔ calorimetry



Topics of the workshop







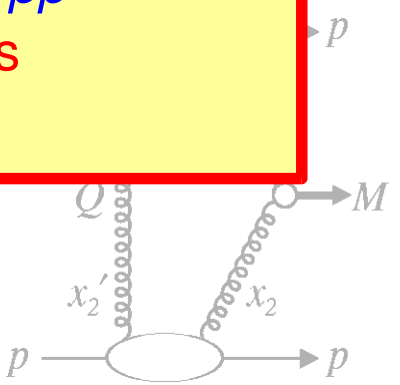
MC&Tools WG *(V. Lendermann)*

- Parton distribution library:
  - LHAPDF now official carrier of the PDFs
  - HERA PDFs have been added
  - Pion and photon added, F_2^D next?
- NLOLIB framework for NLO QCD programs
  - Uniform user interface/interface to HZTOOL
  - e^+e^-/ep included, pp can be added (but not done yet?)
- HZTOOL/JetWeb/RunMC/Cedar for tuning
  - all HERA results included, important ones from pp
- JetWeb/RunMC graphical interface to MC generators
- NEW MC developments

proton,
PDF
on

Structure functions and
parton distributions
LHC: cross sections/precision

Diffraction
LHC: exclusive
Higgs production



What did HERA teach us now ????

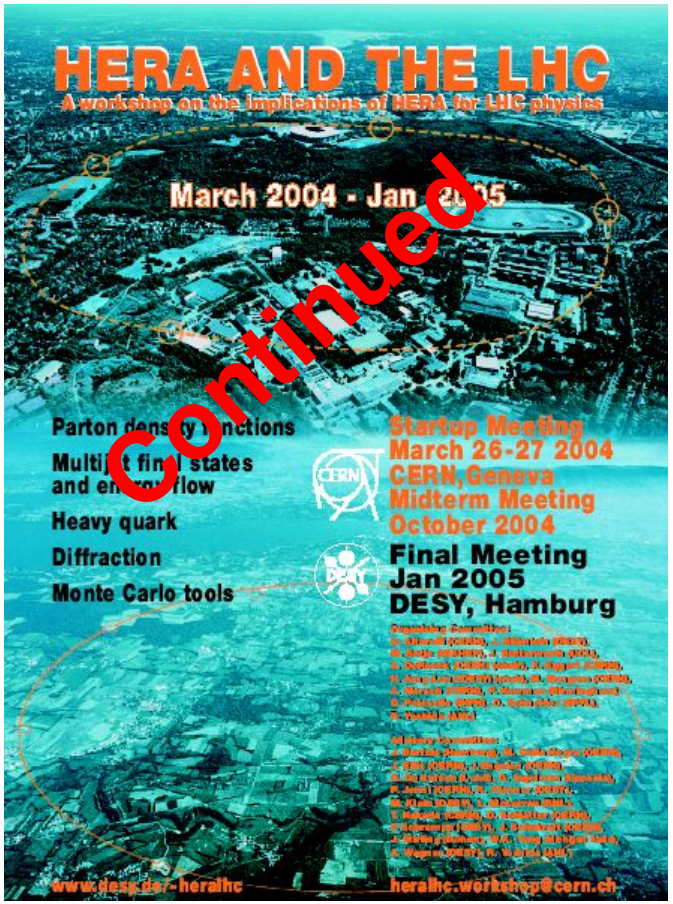
- Understanding QCD is a MUST for all searches
- HERA measurements are crucial for the physics reach at LHC
  - without HERA, NO search for Higgs and SUSY would be possible...
  - precise measurement of PDFs
  - hadronic final states are as well important
    - multiple interactions can only be understood in HERA environment
    - saturation – diffraction – multiple interaction is triggered from HERA
    - theoretical and phenomenological development triggered by precise HERA results
- J. Ellis: *We do not know what the LHC will find - maybe there will be no supersymmetry and we will observe mini-black-hole production instead!*

➔ BUT we know there will be QCD in the central and forward regions ...

- Remember, HERA was planned to also find lepto-quarks .....

But wait, this is not the end.....

.... this is not the end



- Phase I of this workshop is over and will be concluded with the proceedings
- However an important link between communities has been established.

We should not just let it fade away, but strongly exploit it, to the benefit of both communities.

Therefore this is not THE END

Proceedings are out in Dec 2005

available on hep-ph/0601012-13

Keep momentum with one HERA-LHC meeting per year

NEXT 6-9 June 2006 CERN

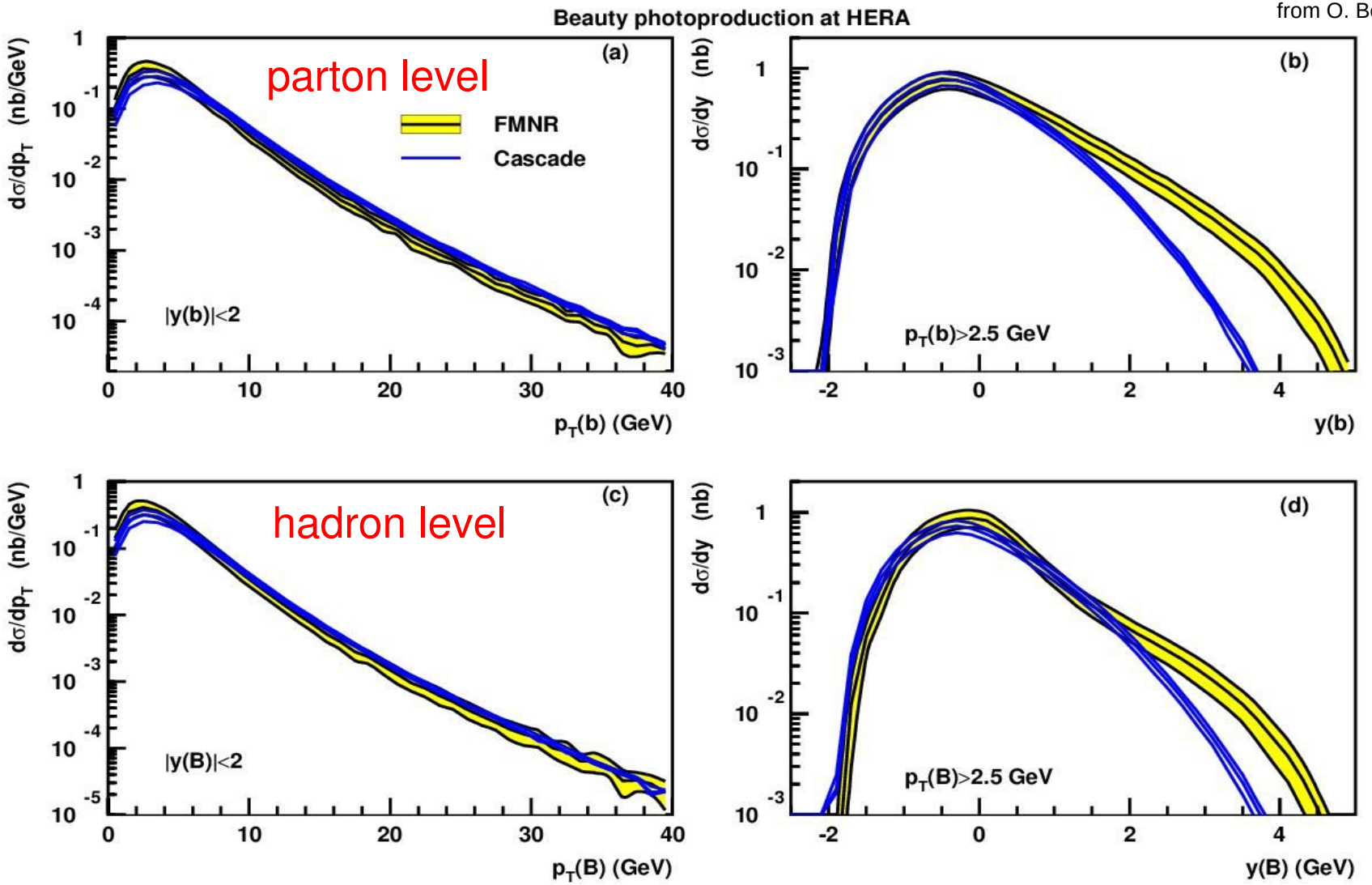
Spring 2007 DESY
Spring 2008 CERN… (first physics @ LHC!?!)

HERA and the LHC

This will be the beginning of a beautiful friendship !

Beauty at HERA

from O. Behnke et al



"Perfect" agreement of NLO(FMNR) calc with CASCADE on quark and hadron level for x<0.01(y>2)

!!!

Deviations: non-linear effects ?

GribovLevinRyskin-MuellerQiu equation:

$$\frac{\partial x\, g(x,Q^2)}{\partial \log Q^2} = \left.\frac{\partial x\, g(x,Q^2)}{\partial \log Q^2}\right|_{DGLAP} - \frac{9\pi\alpha_s^2}{2Q^2}\int_x^1 \frac{dy}{y} y^2 G^{(2)}(y,Q^2)$$

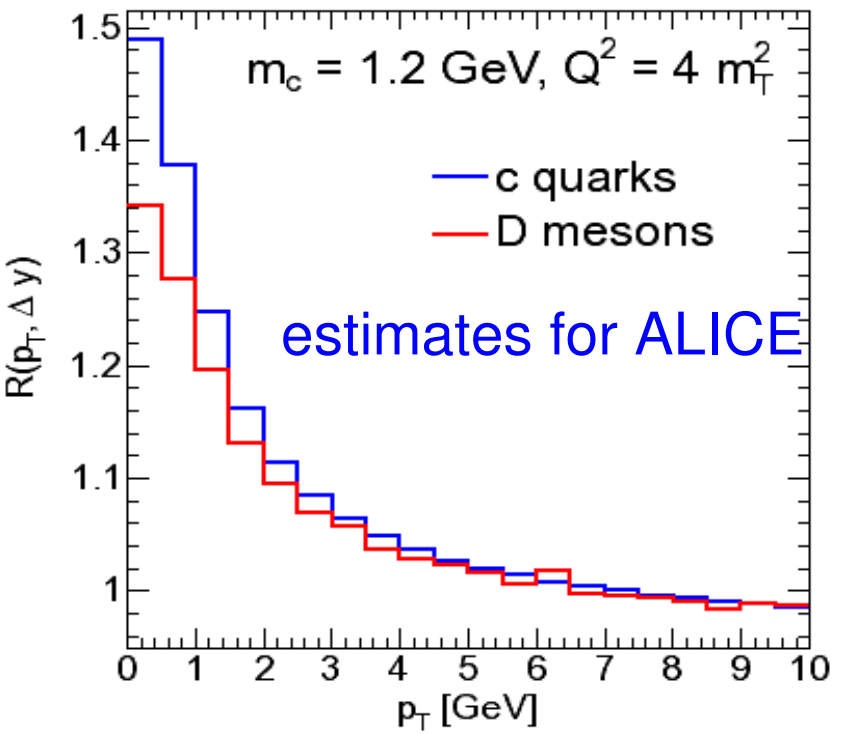
$$x^2 G^{(2)}(x,Q^2) = \frac{1}{\pi R^2}\left(x\, g(x,Q^2)\right)^2$$

- non-linear (quadratic) correction has "–" sign Q^2 evolution is ***slower***

- refit HERA F_2 data, reduces F_2^{DGLAP} at low x and moderate Q^2

- $xg(x,Q^2)$ at low Q^2 (<10 GeV^2) and x (<10^{-3}) is larger than in DGLAP

A. Dainese et al



➔ Get these non-linear effects better understood from HERA !

➔ Precise HERA data important !!!

➔ connection to MI, diffraction ...

Non-linear effects at LHC

Nonlinear evolution equation for uPDF:
(Balitsky-Kovchegov equation)

$$f(x,k^2) = \tilde{f}^{(0)}(x,k^2) + K^1 \otimes f - K^2 \otimes f^2$$

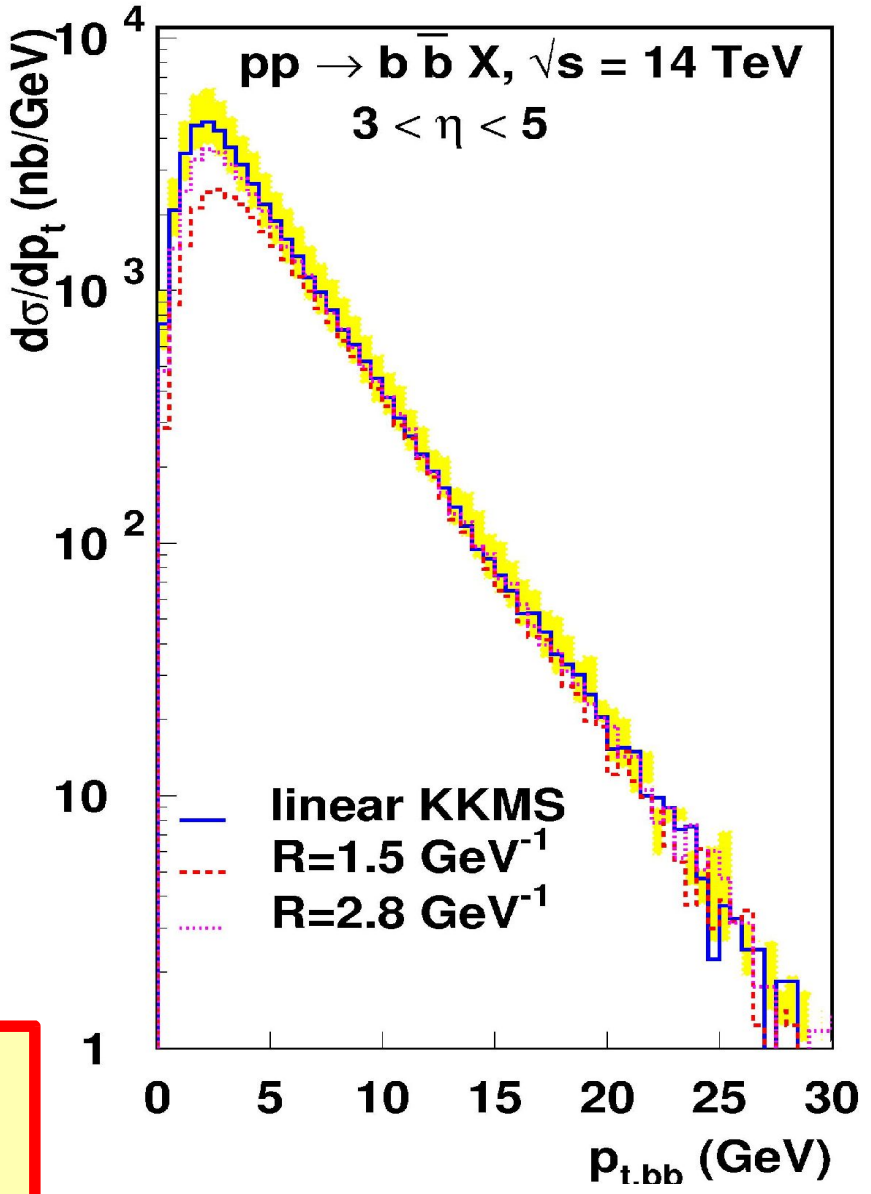
$$\tilde{f}^{(0)}(x,k^2) \rightarrow \text{input}$$

$$K^1 \otimes f \rightarrow \text{BFKL}$$

$$K^2 \otimes f^2 = \left(1 - k^2 \frac{d}{dk^2}\right)^2 \frac{k^2}{\bar{R}^2} \times$$

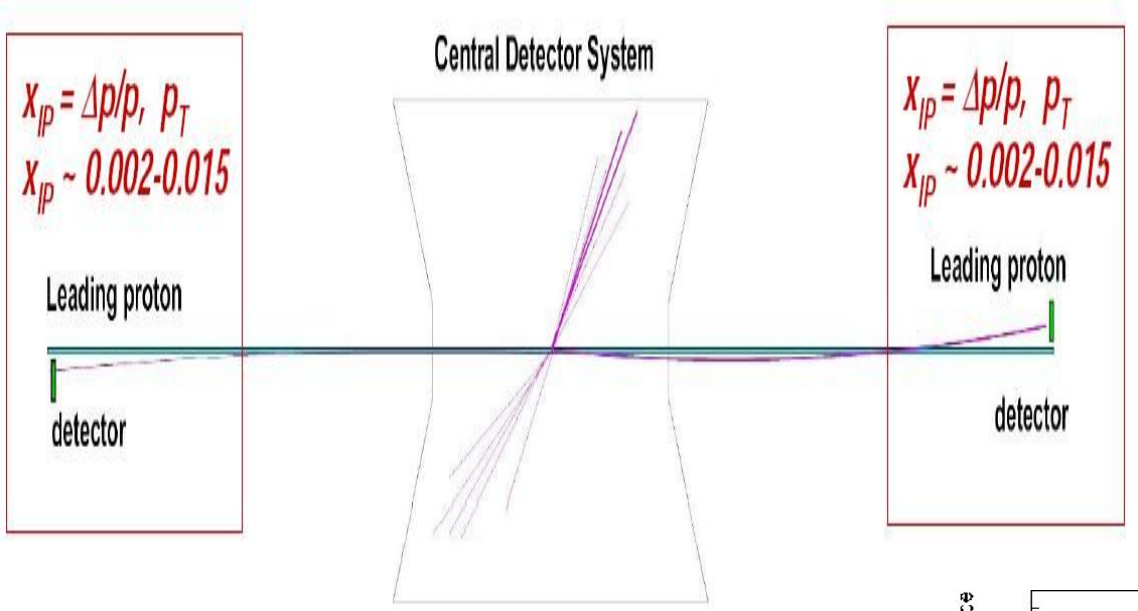
$$\int_x^1 \frac{dz}{z} \left[\int_{k^2}^{\infty} \frac{dk'^2}{k'^4} \alpha_s(k'^2) ln\left(\frac{k'^2}{k^2}\right) f(z,k'^2)\right]^2$$

Bottom suppression due to non-linear effects in BK



- Significant effects...
- up to factor of 2 in hot spot scenario
- factorization still ok ?

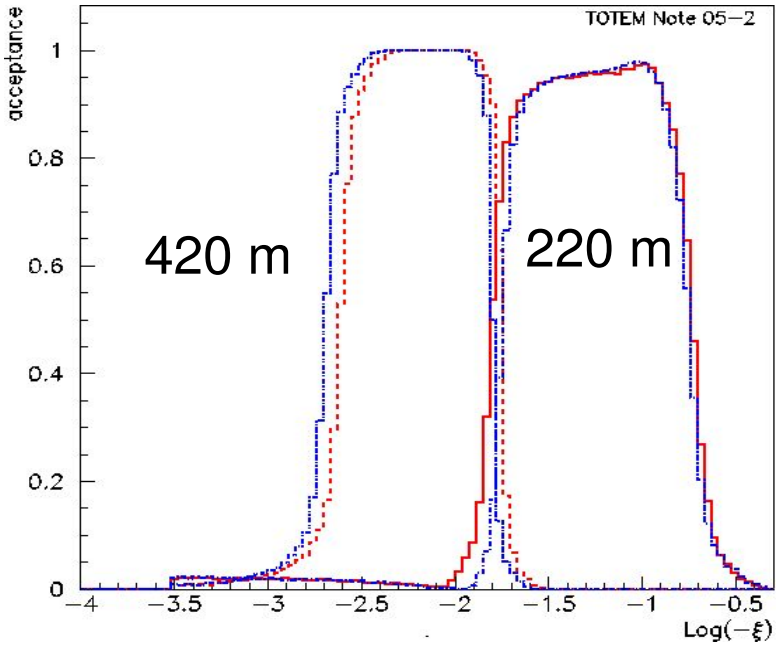
Measurement of exclusive Higgs



B. Cox, M Grothe, H. Kowalski et al.

- Detector stations at 220 m and 420 m from Interaction point
- 420 m station is in cold region.... – *Hamburg pipe*

- goal: mass resolution 1 GeV for Higgs with $m_{\mathrm{Higgs}} = 160\ \mathrm{GeV}$
- 420 m stations are needed for low mass Higgs $m_{\mathrm{Higgs}} < 200\ \mathrm{GeV}$
- other issues:
  - triggers
  - gap-survival
  - rates



Absorptive Corrections from diffraction

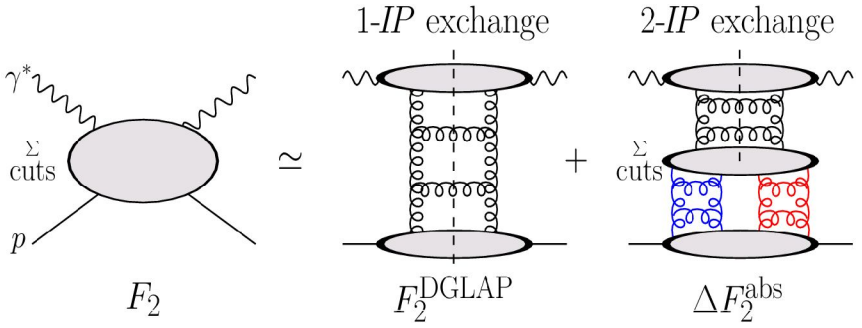
- Non-linear evolution from diffraction:

from G. Watt, A. Martin, M. Ryskin

$$F_2(x,Q^2) = F_2^{\mathrm{DGLAP}}(x,Q^2) + \Delta F_2^{\mathrm{abs}}(x,Q^2)$$

- Improved version of GLR-MQ equation:

$$\frac{\partial x\, g(x,Q^2)}{\partial \ln Q^2} = \frac{\alpha_S}{2\pi} \sum_{a'=q,g} P_{ga'} \otimes a' \; - \frac{9}{16}\,\frac{\alpha_S^2(Q^2)}{B_D\, Q^2} \int_x^1 \frac{dx_{I\!P}}{x_{I\!P}} \left[x_{I\!P}\, g(x_{I\!P}, Q^2)\right]^2$$



- Connection of Diffraction with F_2
- improves small x behavior of gluon (negative gluon starts later...)
- **further investigations are needed to understand gluon PDF !!!**