From HERA to the LHC II

H. Jung (DESY)

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- Yesterday: HERA and the structure of the proton
- TODAY:
  - from inclusive x-section measurements to detailed investigations of QCD
    - measurements of hadronic final states:
    - ➔ lead to a detailed understanding of QCD
- QCD is challenging
  - ➔ implications and applications for LHC
  - ➔ PDFs, multiparton interactions, etc

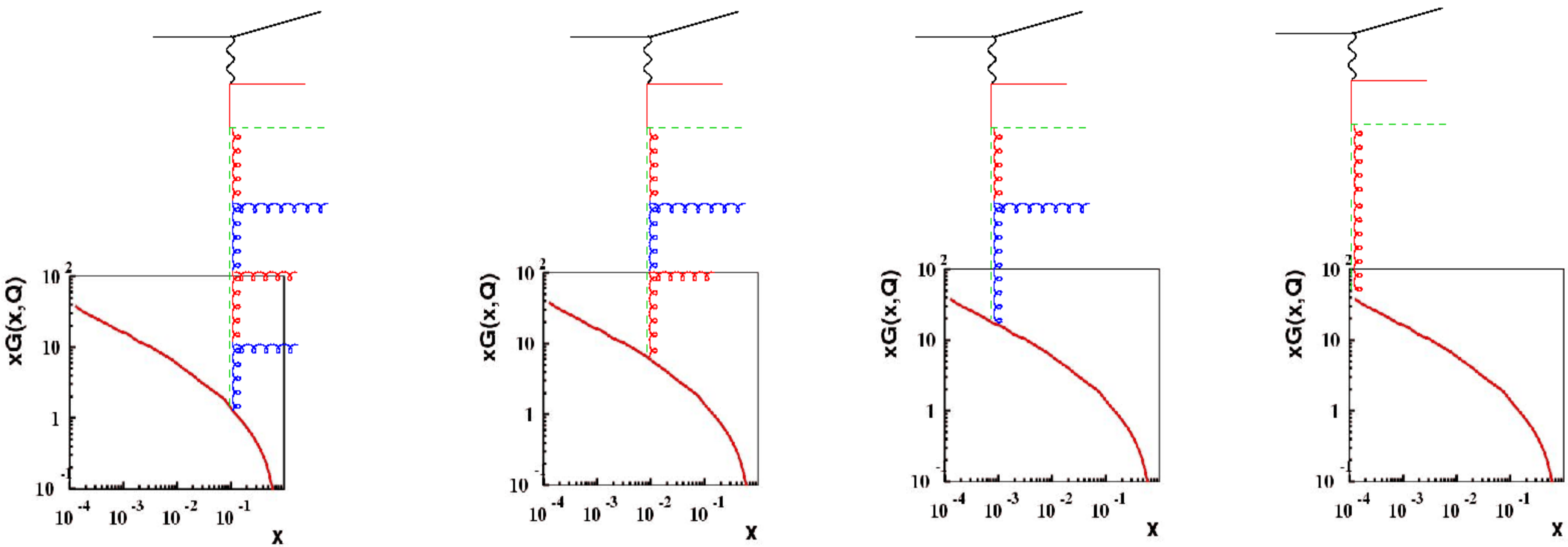
lectures based on lecture series:

"QCD & collider physics" H.Jung,J. Bartels University HH, 2005 -2007

Contributions to "HERA and the LHC" workshops: www,desy.de/~heralhc

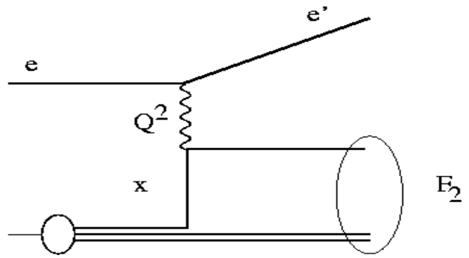
DGLAP evolution equation... again...

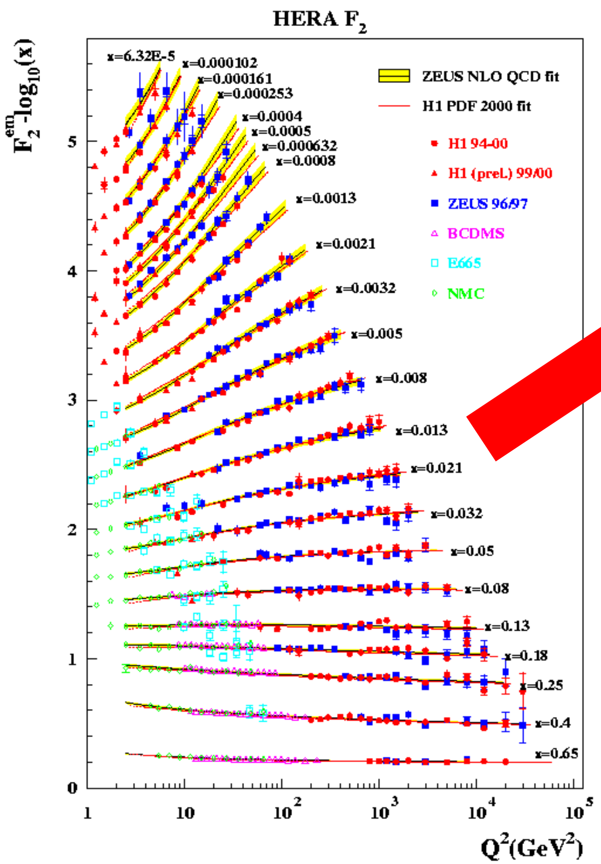
- for fixed x and Q^2 chains with different branchings contribute
- iterative procedure, spacelike parton showering



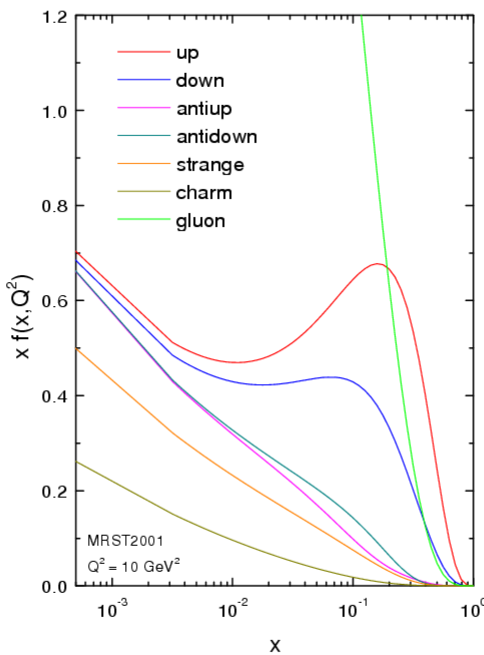
- $$f(x,t) = \sum_{k=1}^{\infty} f_k(x_k, t_k) + f_0(x, t_0)\Delta_s(t)$$

From HERA F_2 to Higgs at LHC



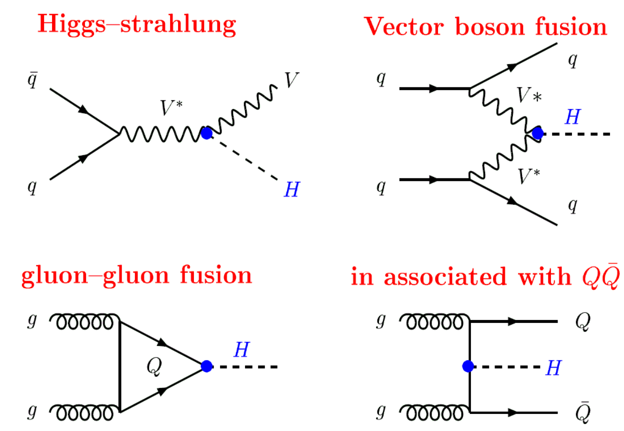


total x-section, F_2

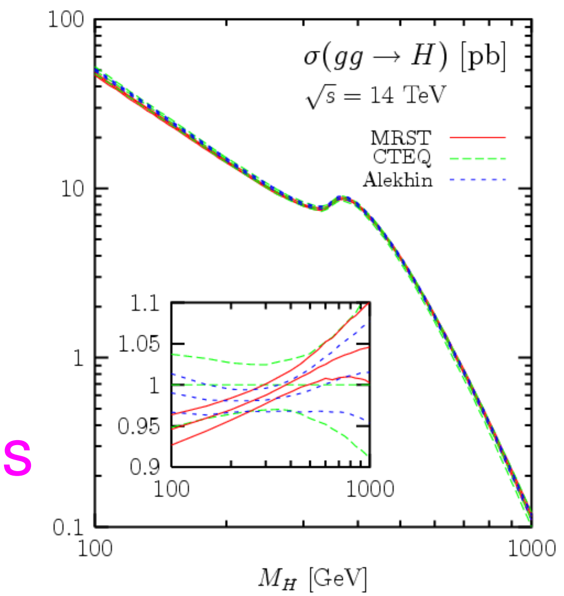


extract parton densities

from J. Stirling

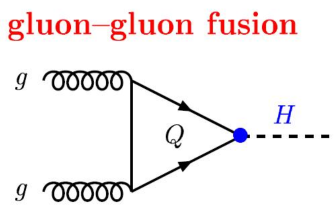


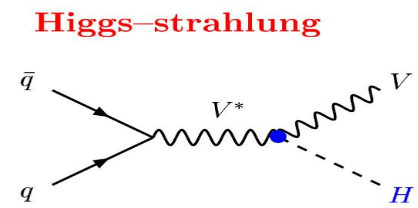
calculate Higgs prod

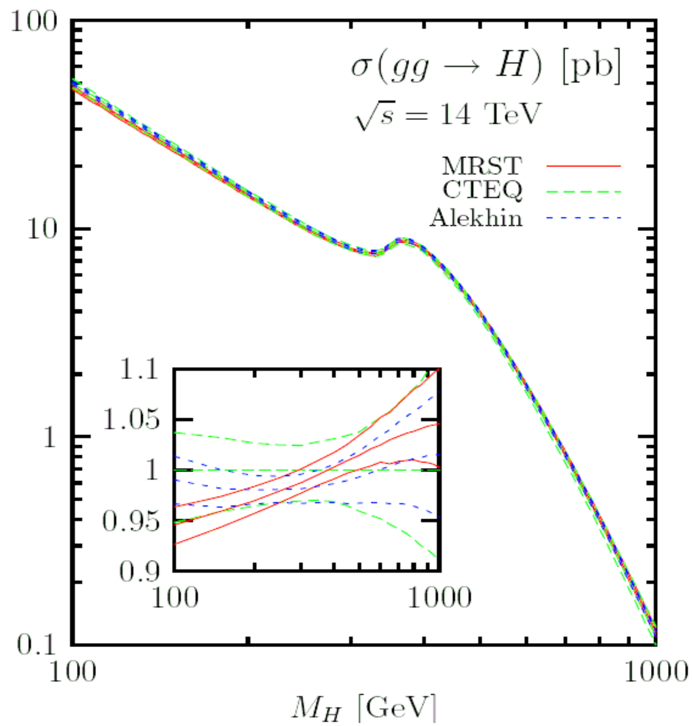


PDF uncertainty for Higgs prod.

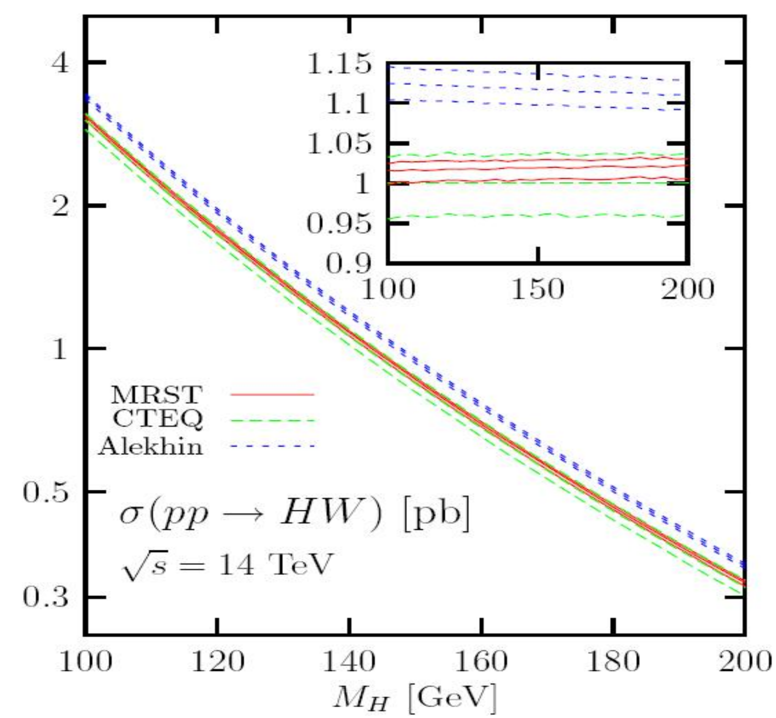
from Djouadi & Ferrag







Gluon induced... ~ 10 %

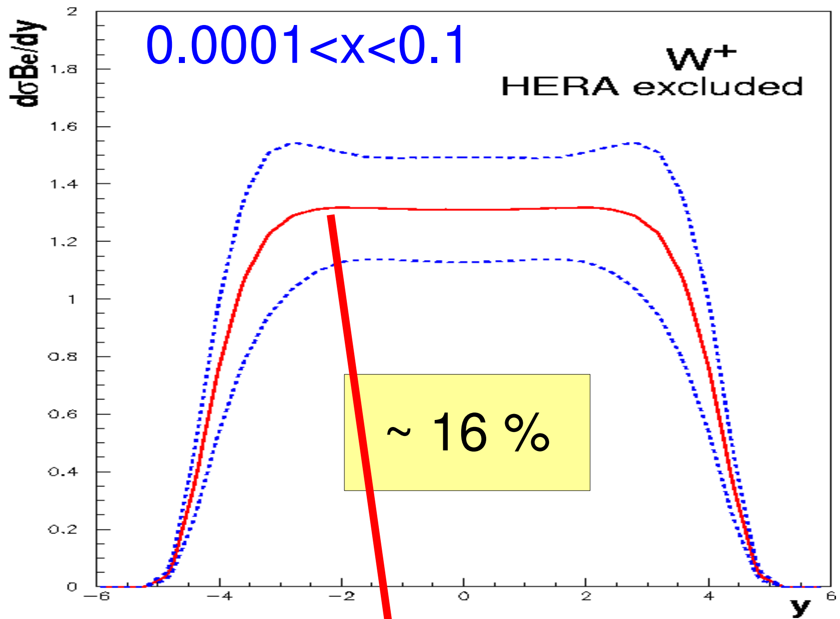


Quark induced ~ 10 % difference

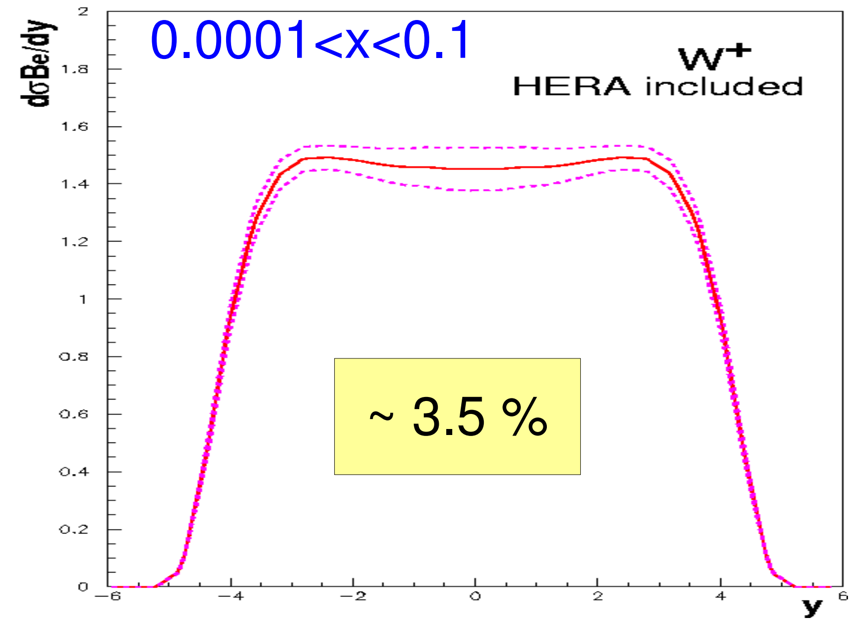
In 2004: PDFs did not agree within respective errors (J. Stirling) !!!!

Does LHC really need HERA ?

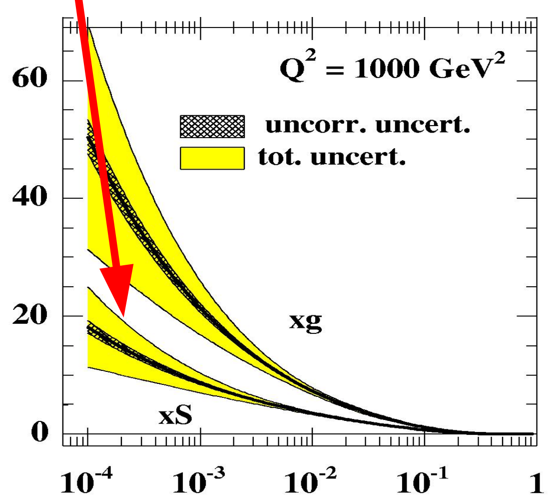
- W prod. at LHC without HERA:



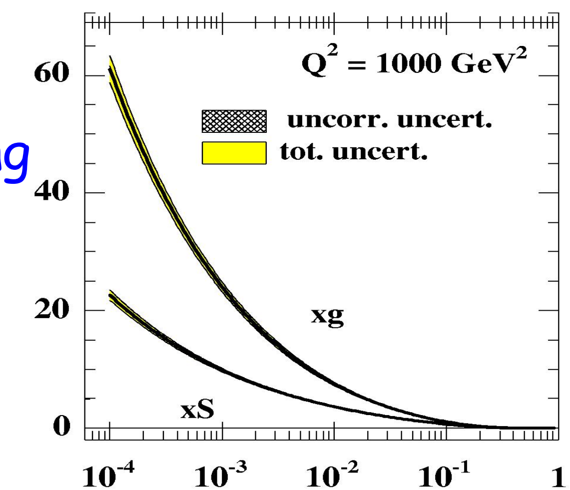
- W prod. at LHC including HERA



- PDFs withou HERA:



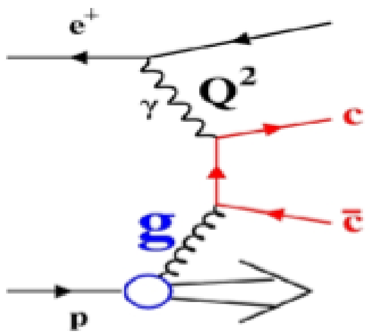
- PDFs including HERA:



Heavy Flavor measurements

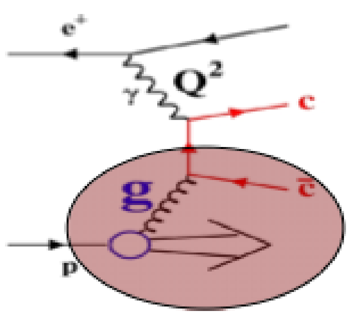
from O. Behnke, EPS07

Gluon via charm @ HERA



$Q^2 \sim m_c^2$

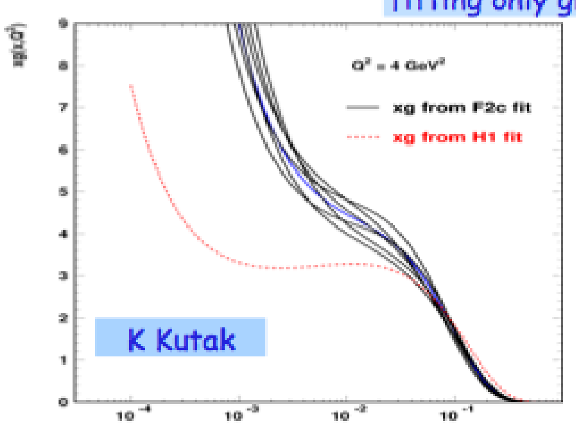
Massive c



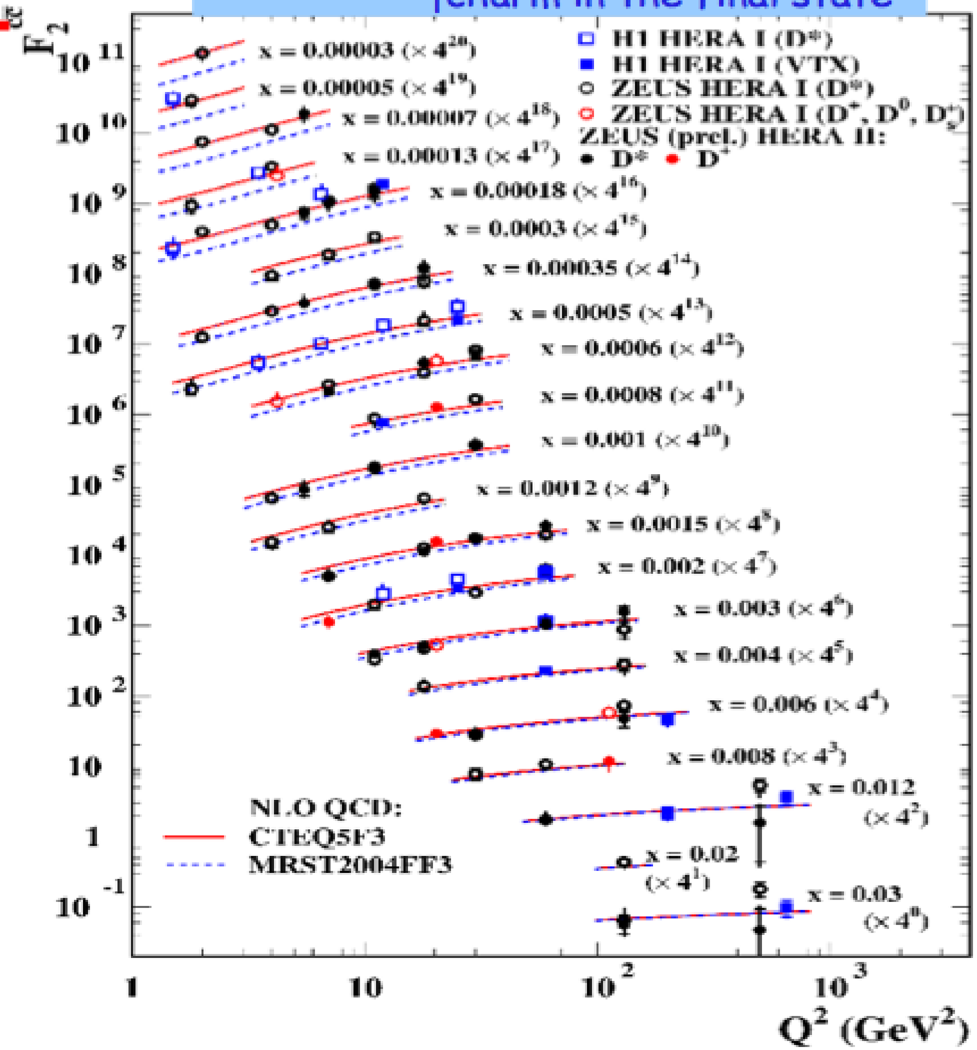
$Q^2 \gg m_c^2$

Massless c

NLO QCD fit using H1 F_2^{cc}, fitting only gluon

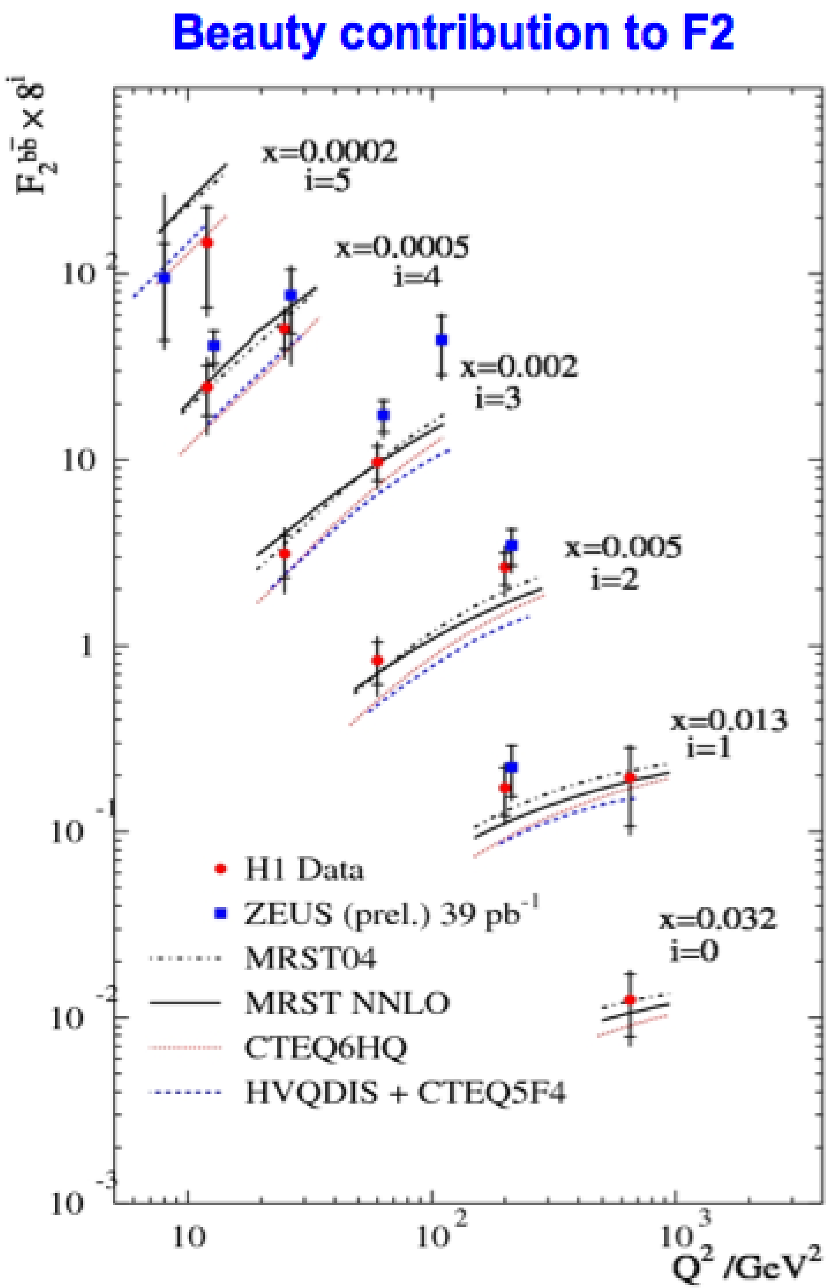


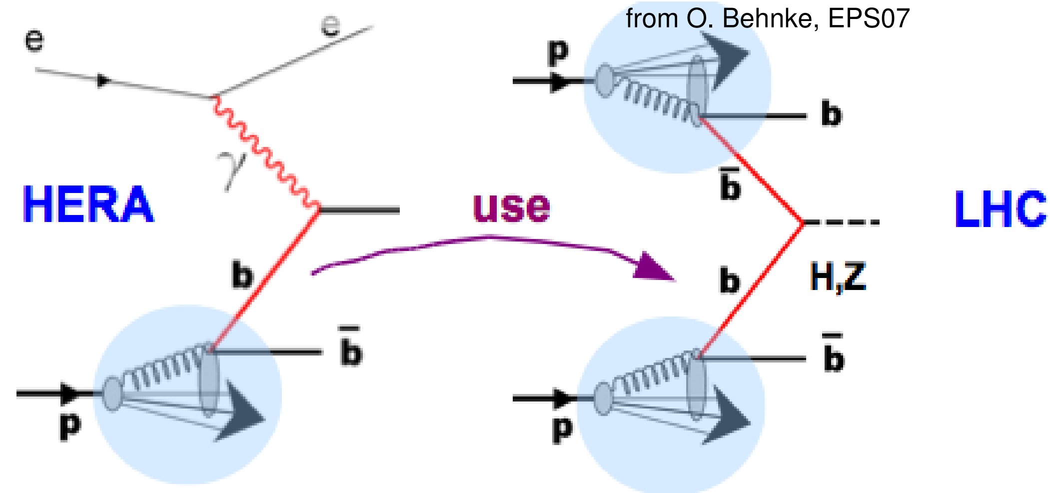
$F_2^{cc} = F_2|_{\text{charm in the final state}}$



➔ F_2^{cc} data can constrain the proton gluon density at small x

Heavy Flavor measurements



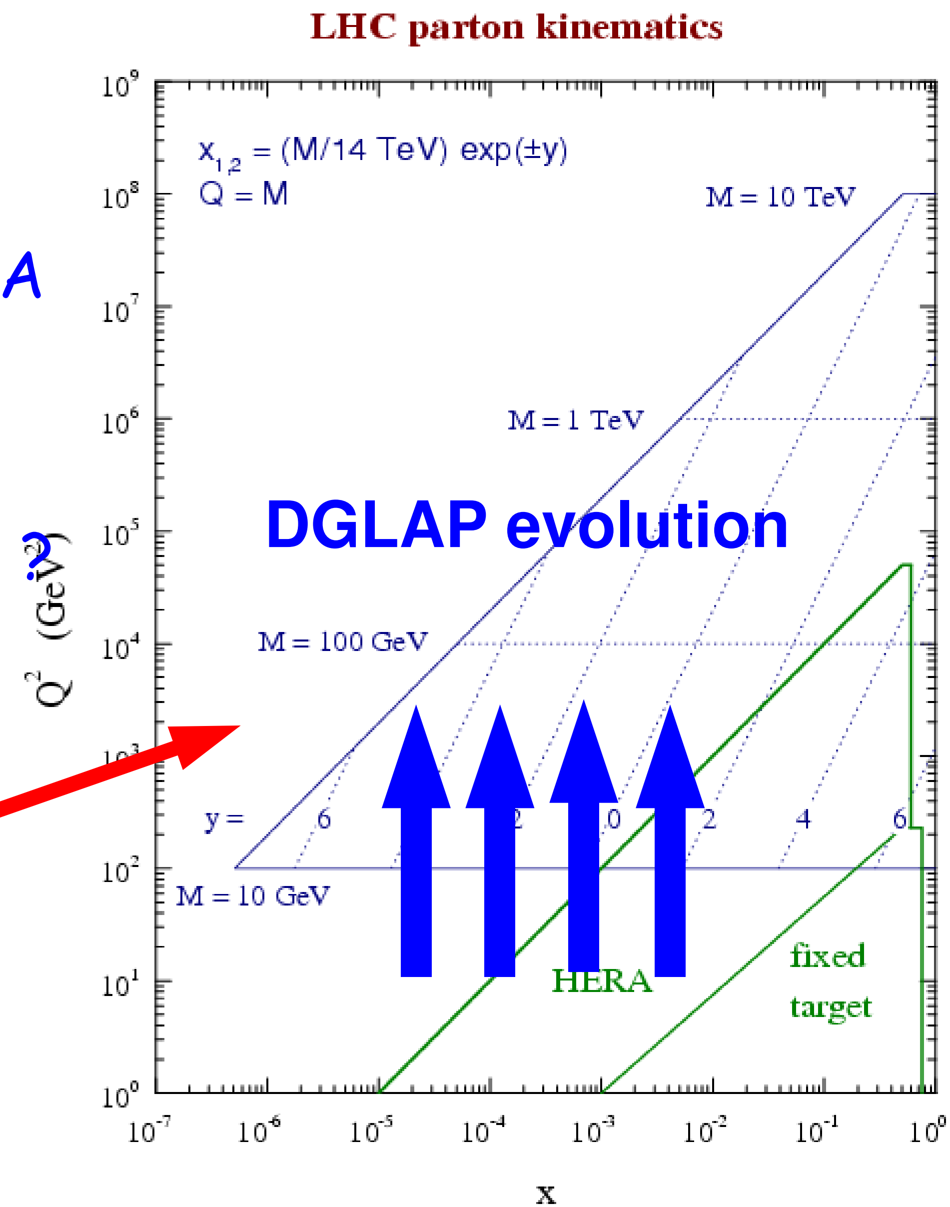


➔ 'Beautyful' new HERA II data

➔ Astonishing spread of model predictions!

Is DGLAP all ?????

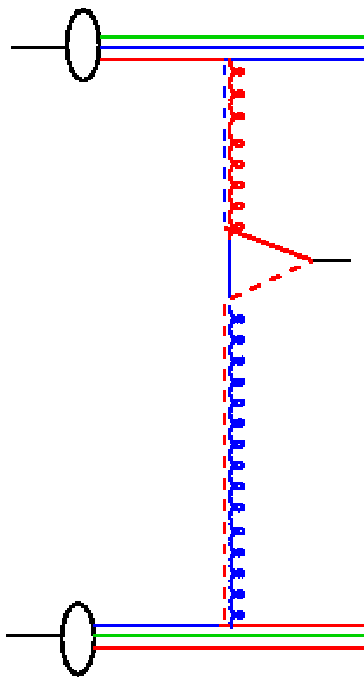
from J. Stirling



- Can we just assume DGLAP
- is ok also at highest energies ?
- remember surprises from HERA
- Is factorization valid ?
- What about k_t-factorization ?
- What about non-linear effects ?

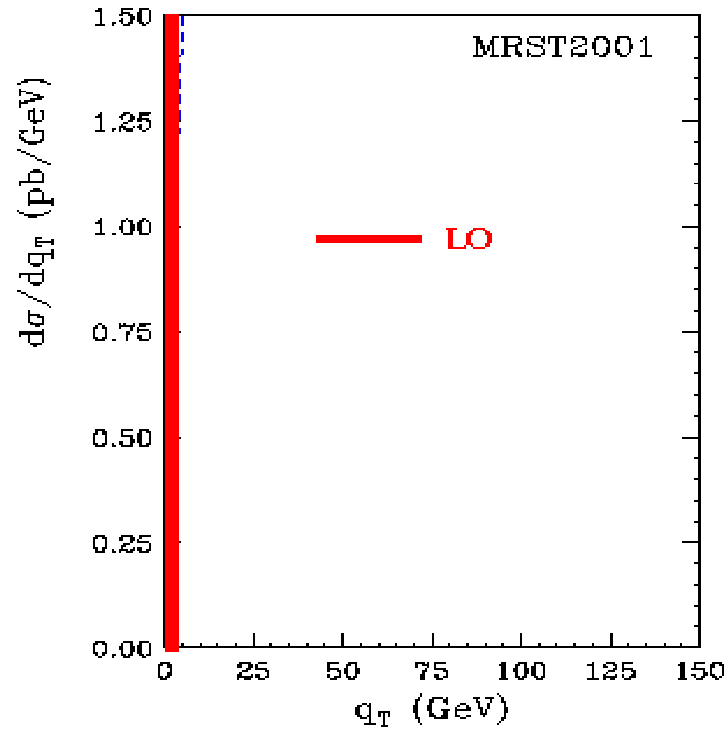
Is NLO (or NNLO) DGLAP sufficient at small x?
Are higher orders important ?

k_t effects at HERA and LHC

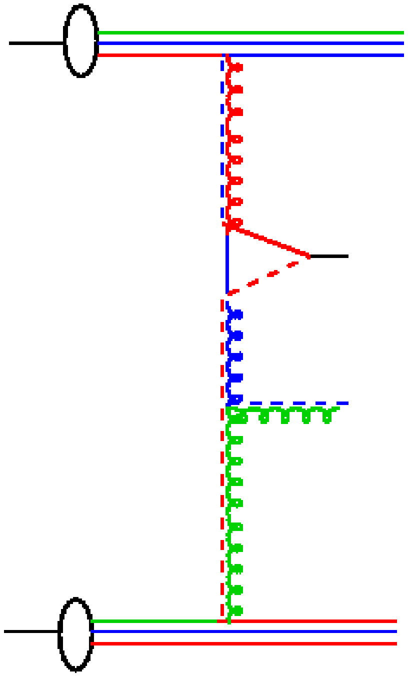


Higgs

LO pretty bad

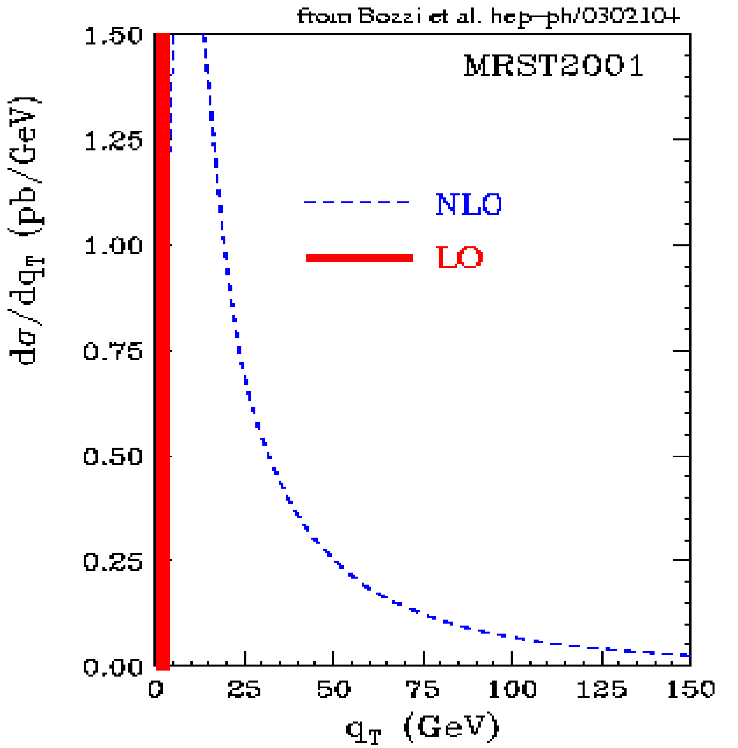


k_t effects at HERA and LHC

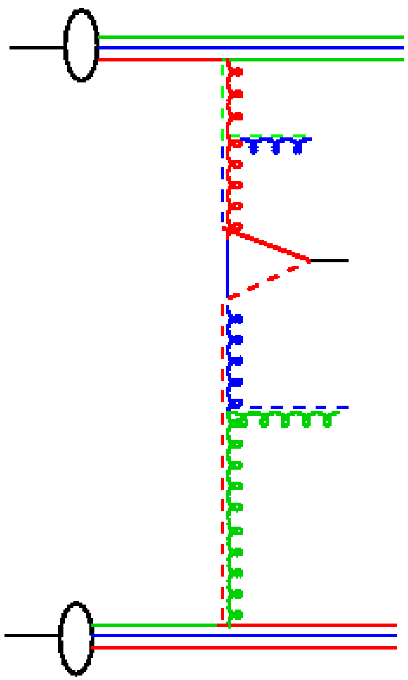


Higgs

NLO better

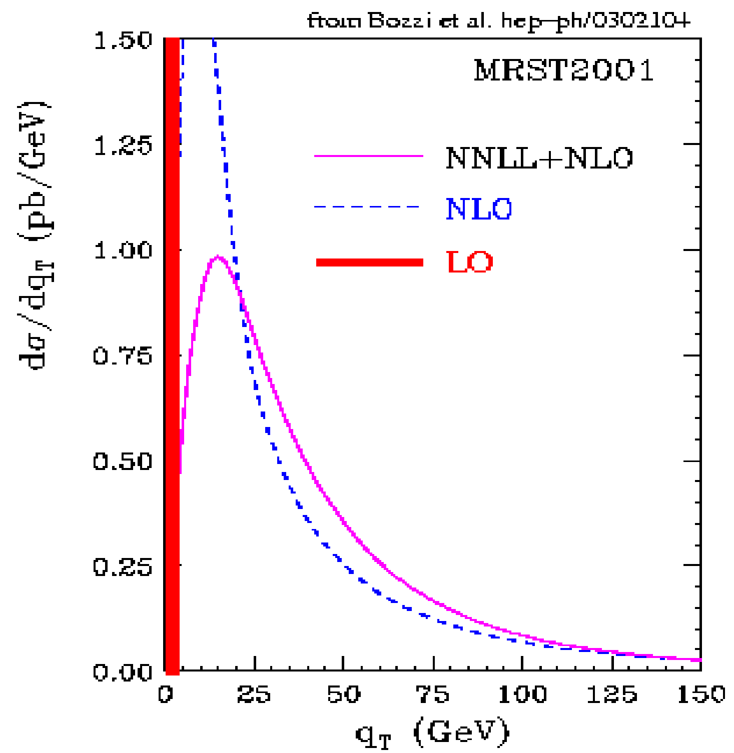


k_t effects at HERA and LHC



Higgs

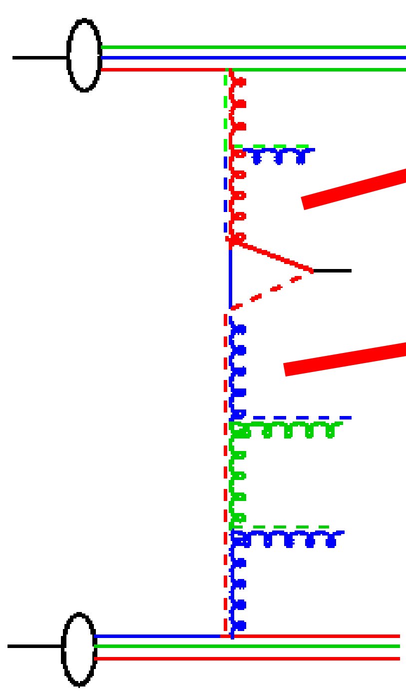
NNLO betttter

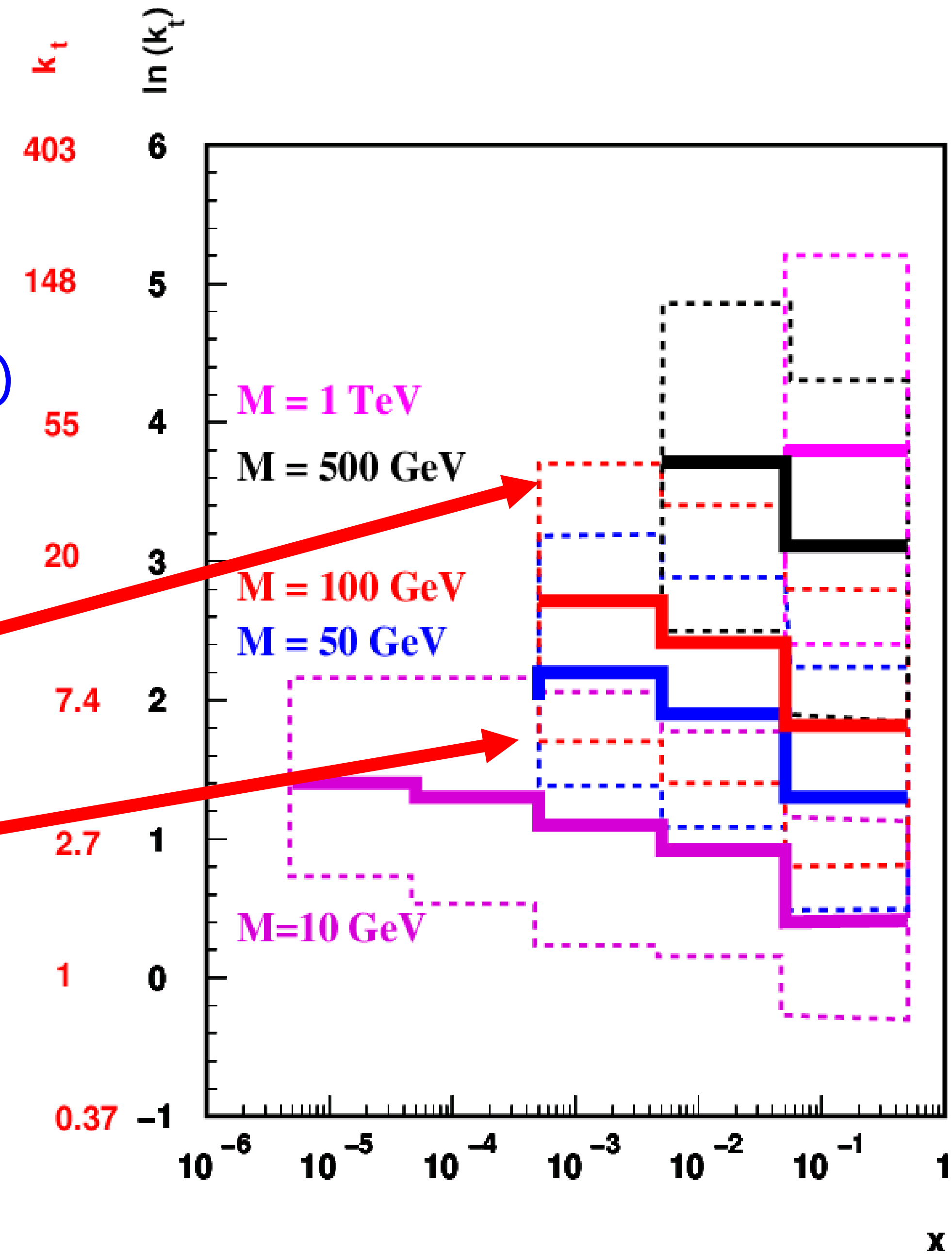


Parton Density Functions and all that

- collinear PDFs
- uPDFs (single and double unintegrated)

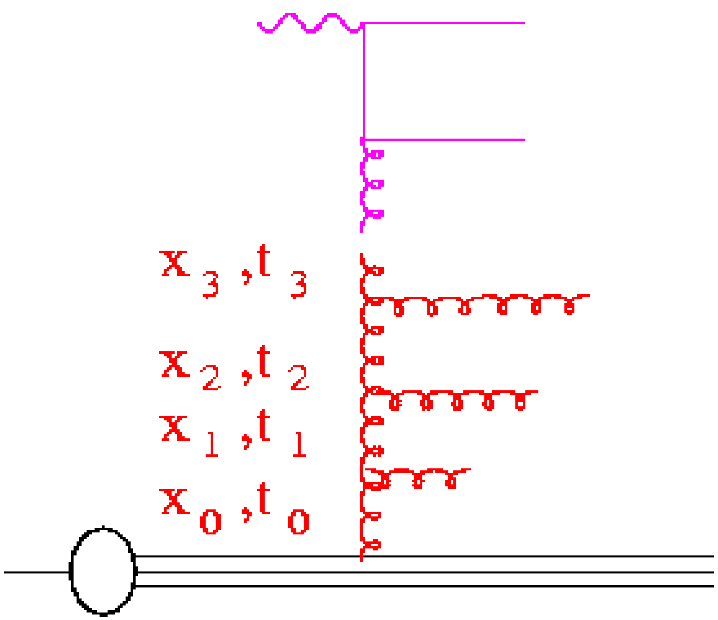
Higgs production et al





Approximations so far ....

- Only inclusive quantities were considered:
  - nothing was said about "real" emissions of gluons or quarks although implicitly assumed....
  - in deriving DGLAP splitting functions we assumed: $\hat{t} \ll \hat{s}$
  - and also in the small *t* limit: $\hat{t} \sim \frac{-k_t^2}{1-z}$



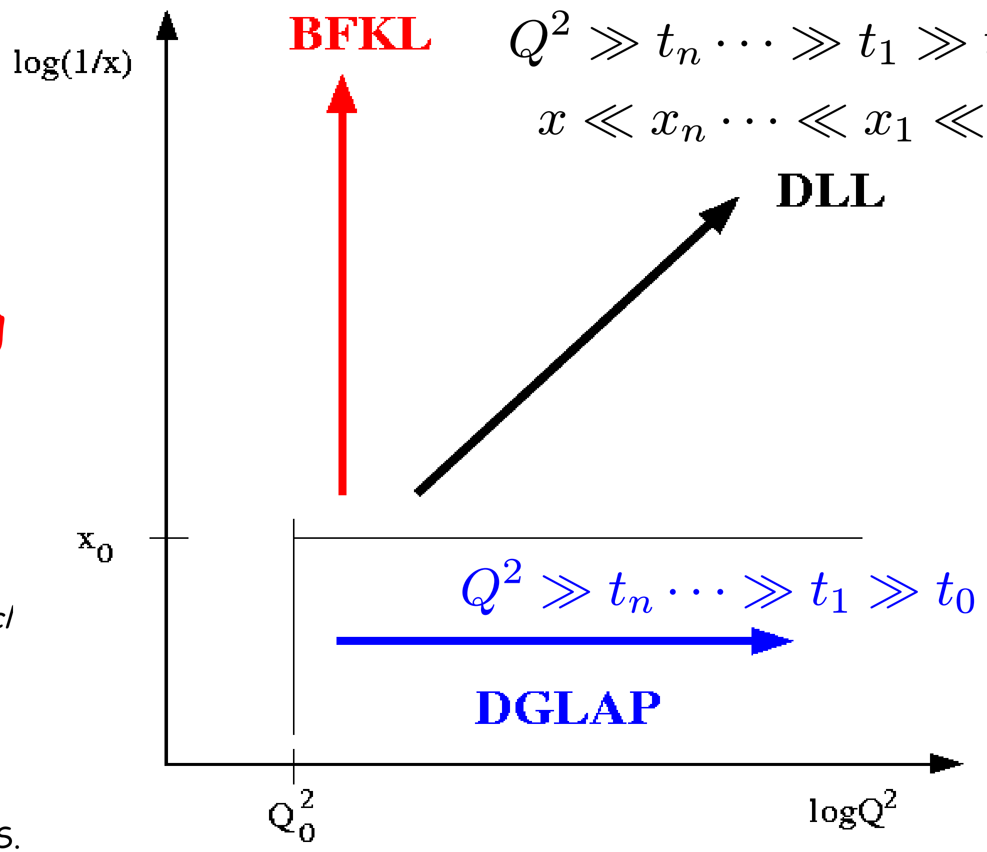
- neglect *t* in previous branchings
  $t_0 \ll t_1 \ll t_2 \ll t_3 \cdots \ll \mu^2$
  - strong ordering condition
  - strong ordering: neglect all kinematics of previous branchings...
- ordering in *x*

  $x_0 > x_1 > x_2 > x_3$

Kinematic regions: new evolution ..

- DGLAP:
  strong ordering in t
- DLL:
  strong ordering in t
  strong ordering in x
- what happens if strong t ordering relaxed ?
  - **B**alitskii**F**adin**K**uraev**L**ipatov evolution
    E. Kuraev, L. Lipatov, V.Fadin, *Sov. Phys. JETP* 44 (1976),443., E. Kuraev, L. Lipatov, V. Fadin, *Sov. Phys. JETP* 45,(1977),199., Y. Balitskii, L. Lipatov, *Sov. J. Nucl Phys.* 28,(1978), 822.
  - **C**atani**C**iafaloni**F**iorani**M**archesini evolution
    M. Ciafaloni, Nucl. Phys. B 296,(1988),49. S. Catani, F. Fiorani, G. Marchesini, Phys. Lett. B 234, (1990), 339, S. Catani, F. Fiorani, G. Marchesini, Nucl. Phys. B 336, (1990),18, G. Marchesini, Nucl. Phys. B 445, (1995), 49.

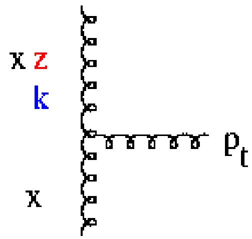
$x \ll x_n \ll \cdots \ll x_1 \ll 1$



Approximations to higher orders ...

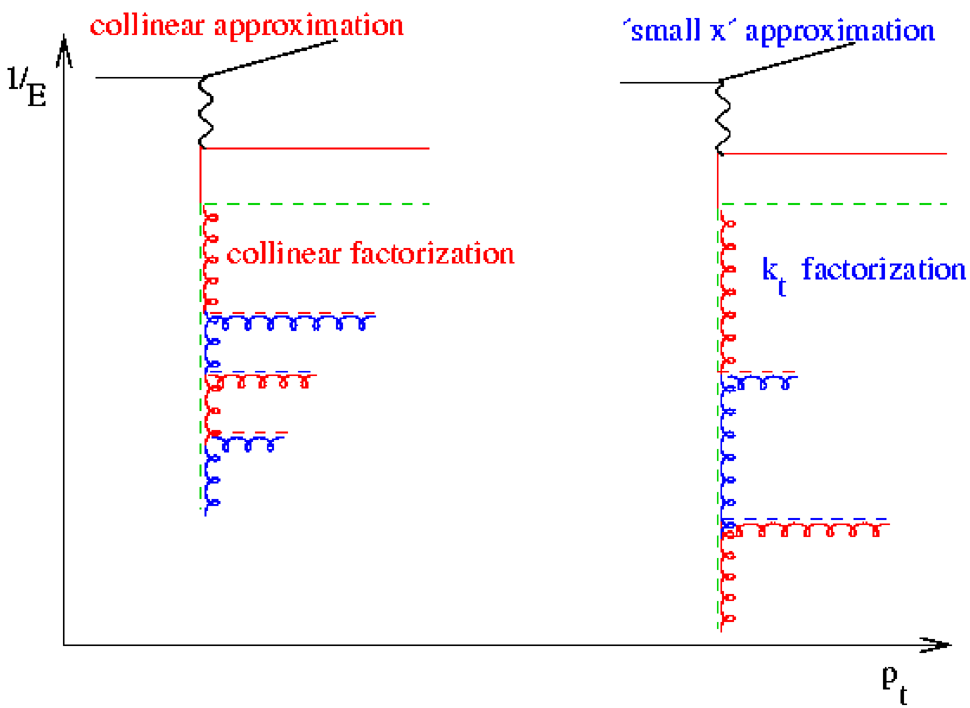
gluon bremsstrahlung

$$\sim \frac{1}{k^2}\left(\frac{1}{z} + \cdots\right)$$



Dokshitzer **G**ribov **L**ipatov **A**ltarelli **P**arisi

- collinear singularities factorized in pdf $\quad Q^2 \sim k^2, \text{ or } k_t^2 \text{ or } ?$
- evolution in
- $$\sigma = \sigma_0 \int \frac{dz}{z} C^a\left(\frac{x}{z}\right) f_a(z, Q^2)$$



Balitski **F**adin **K**uraev **L**ipatov

- k_t dependent pdf → unintegrated pdf
- evolution in x
- $$\sigma = \int \frac{dz}{z} d^2 k_t \hat{\sigma}\left(\frac{x}{z}, k_t\right) \mathcal{F}(z, k_t)$$

The problem of asymptotia

DGLAP is great
at highest $Q^2 \to \infty$
for **inclusive quantities**

BUT has problems

- heavy quarks
- jets
- particle spectra
- small x processes

BFKL is great
at small $x \to 0$
or highest $W \to \infty$
for **inclusive quantities**

BUT has problems

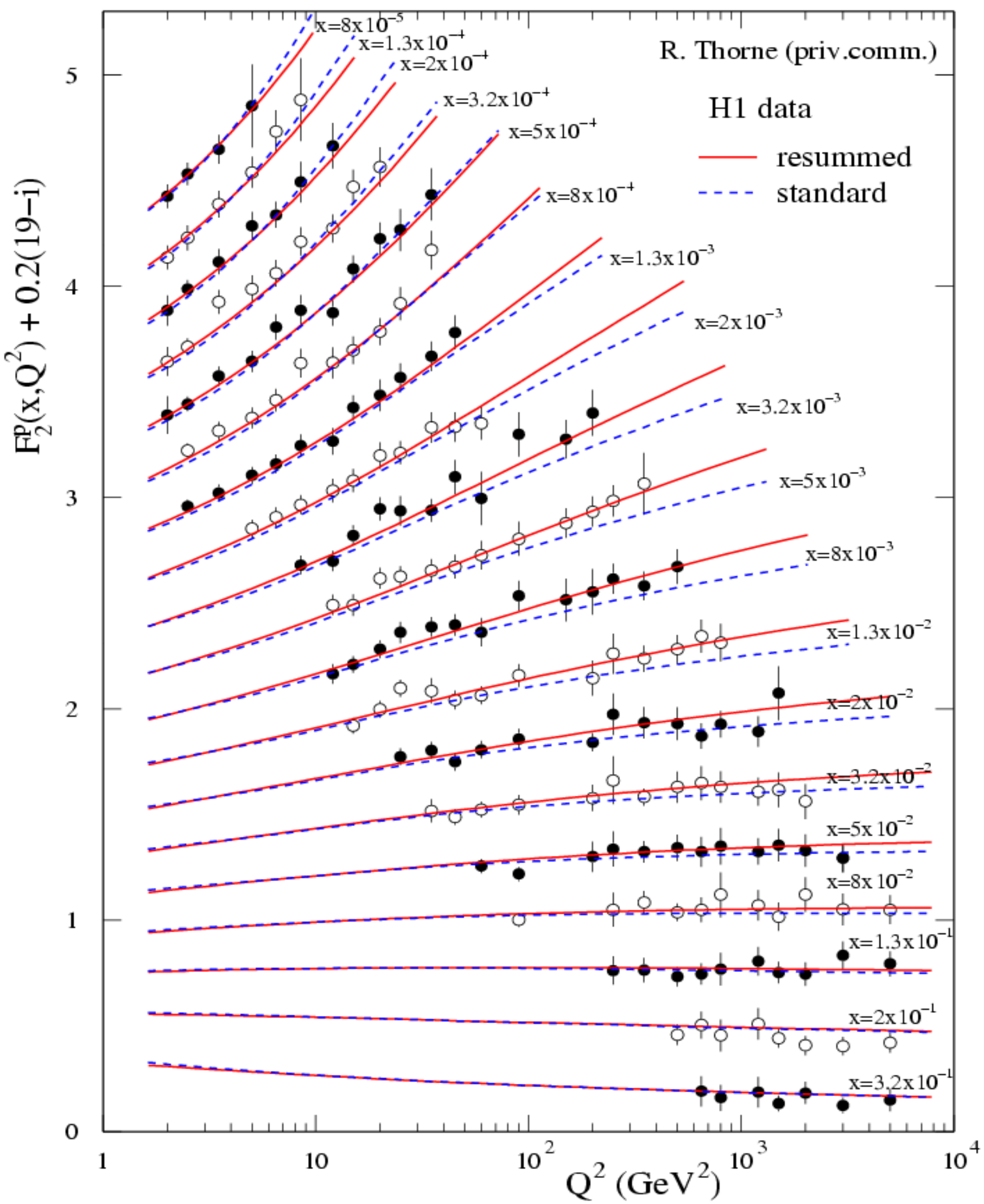
- finite x
- NL corrections
- final states

BUT asymptotia still far away
even for LHC or cosmic energies

From asymptotia to total x-section

- Description of inclusive processes:
  - DGLAP for high Q^2
  - BFKL for small x
- matched DGLAP/BFKL for F_2

  (R. Thorne, Kimber,Martin,Stasto, etc)
  - resummed gives better fit
  - .... not a big effect at HERA !!!
- where is asymptotia ?



From asymptotia to exclusivity

- Description of inclusive processes:
  - DGLAP for high Q^2
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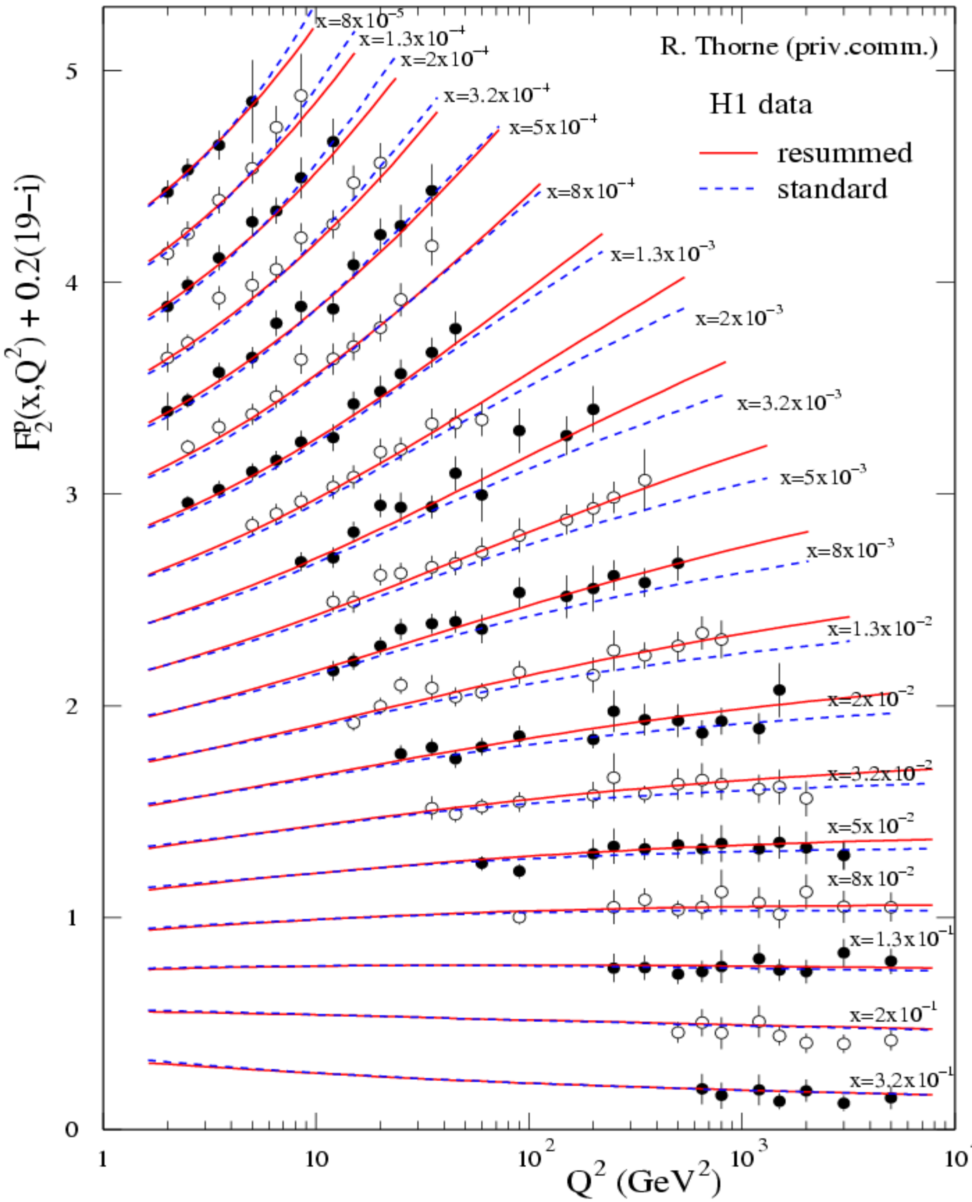
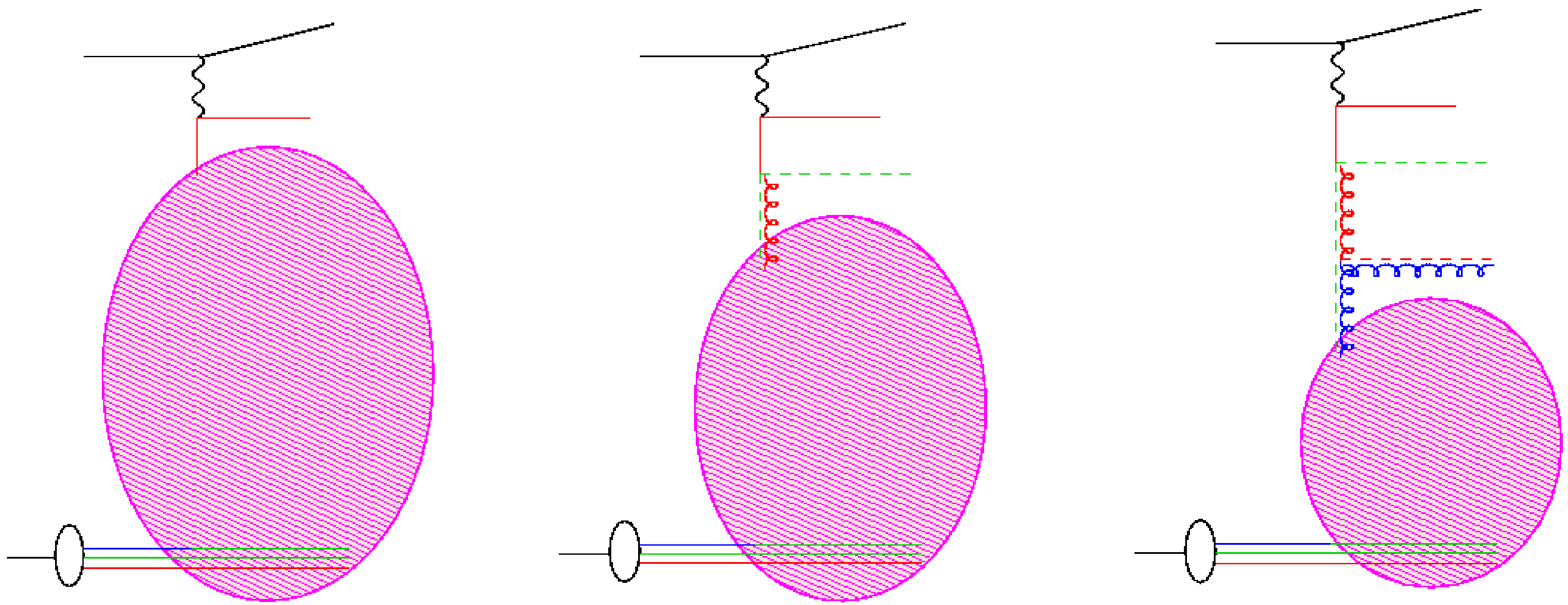


Building up the final states

- Monte Carlo event generators
- fixed order parton level calculations at NLO

Howto investigating in detail small x behavior ?

Howto investigate this ?

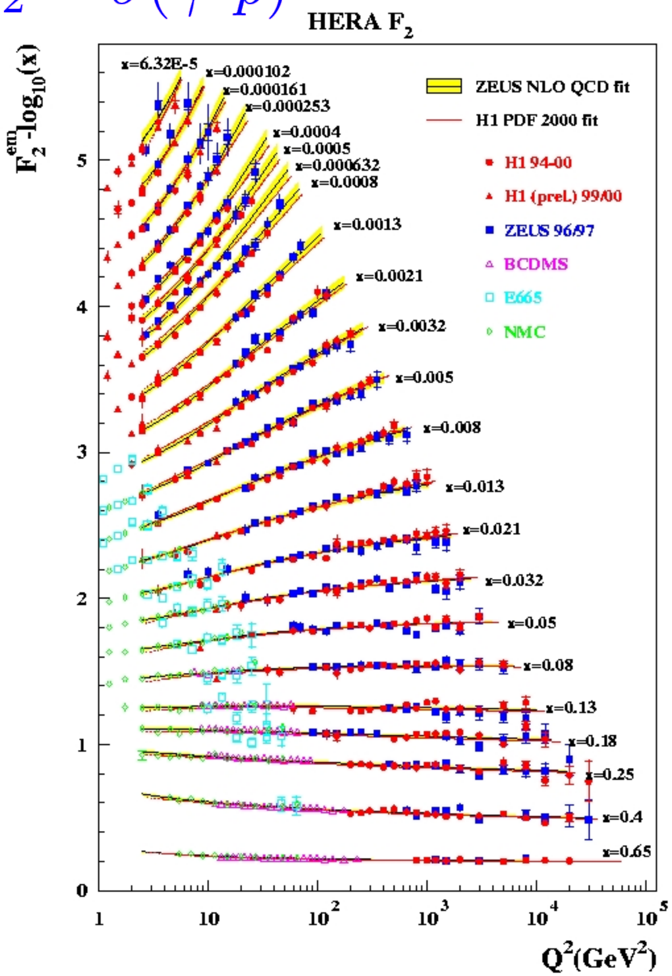


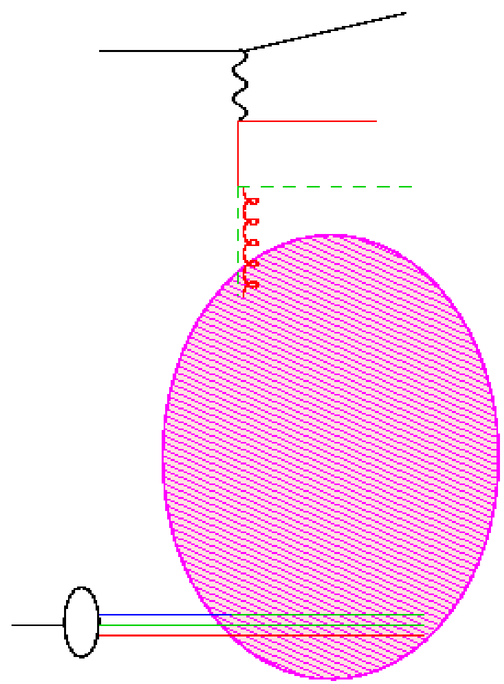
QPM process
total x-section

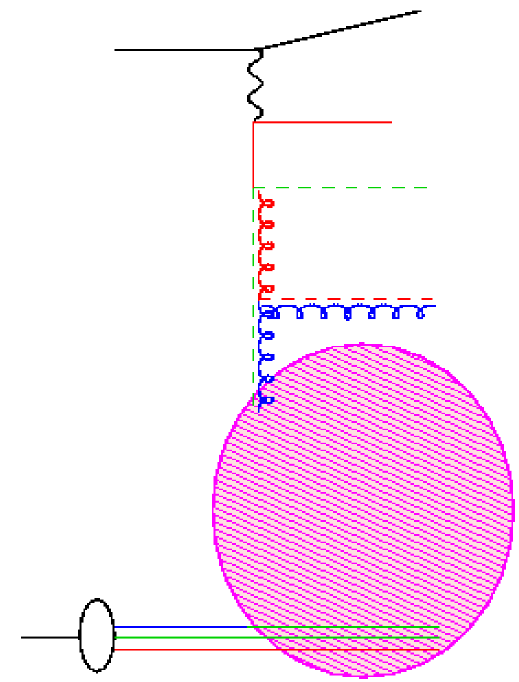
BGF $\mathcal{O}(\alpha_s)$ process $\mathcal{O}(\alpha_s^2)$ process
heavy quarks (charm & bottom)
2-jet 3-jet

Howto investigate this ?

$F_2 \sim \sigma(\gamma^* p)$







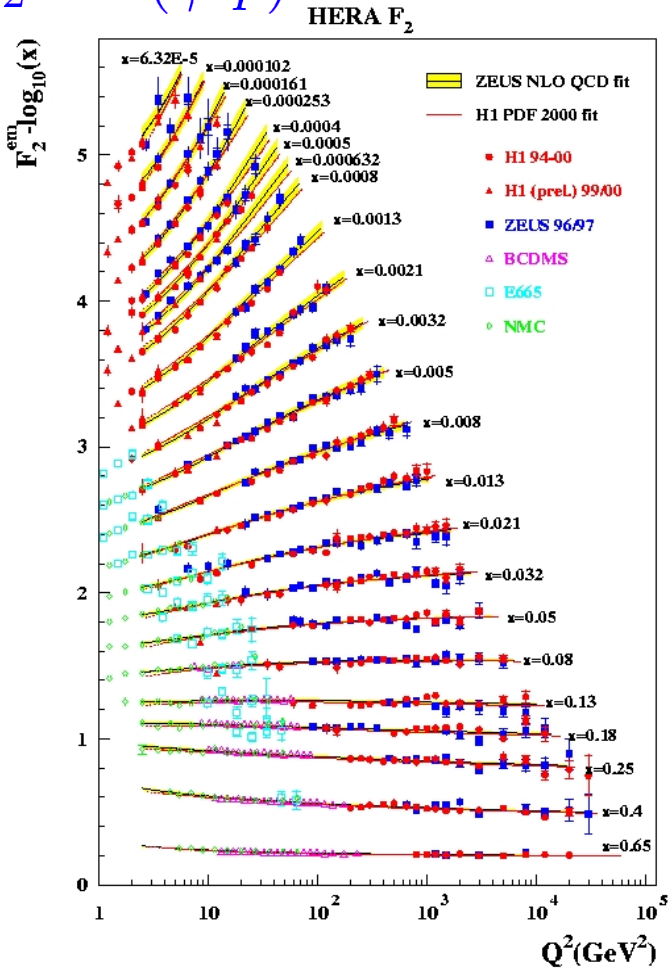
QPM process | BGF $\mathcal{O}(\alpha_s)$ process | $\mathcal{O}(\alpha_s^2)$ process

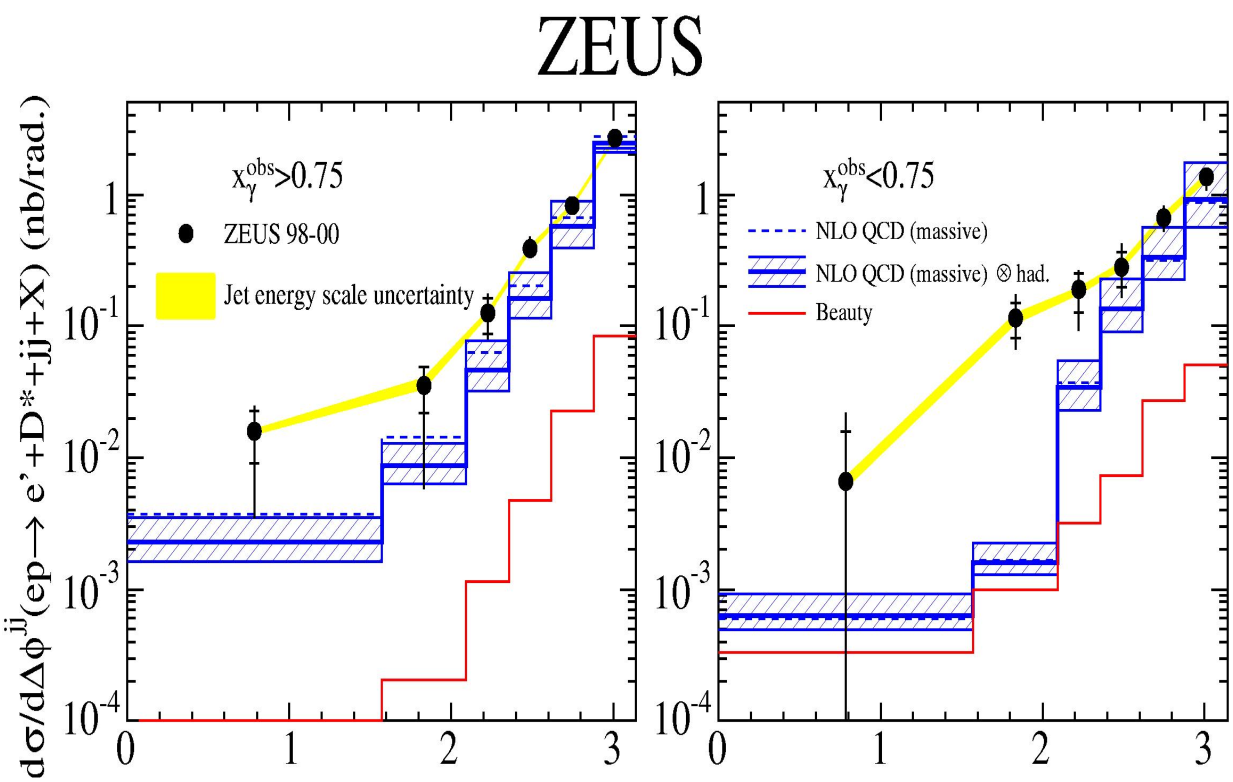
total x-section | heavy quarks (charm & bottom)

2-jet | 3-jet

Howto investigate this ?

$F_2 \sim \sigma(\gamma^* p)$





QPM process

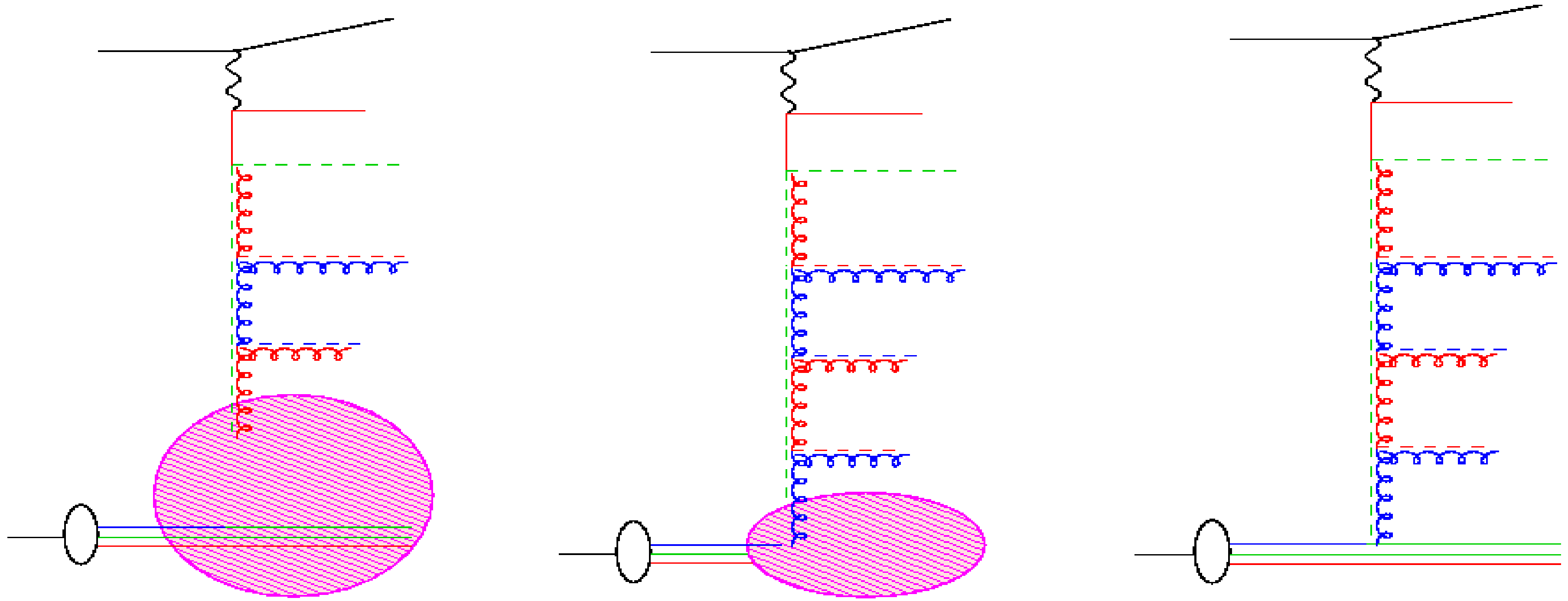
total x-section

BGF $\mathcal{O}(\alpha_s)$ process $\mathcal{O}(\alpha_s^2)$ process

heavy quarks (charm & bottom)

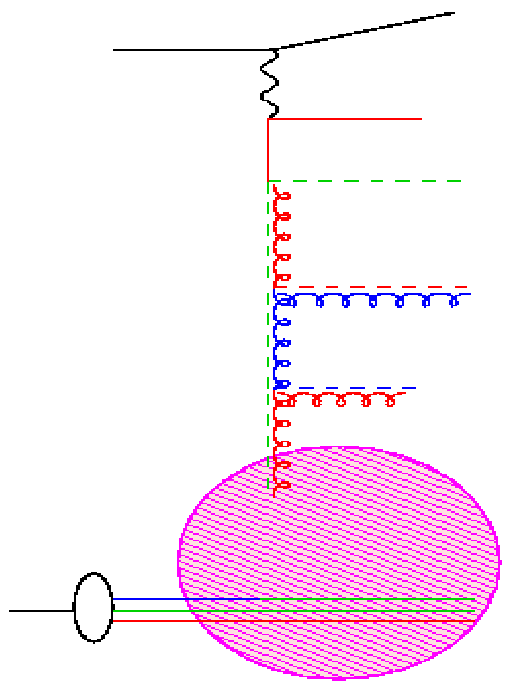
2-jet 3-jet

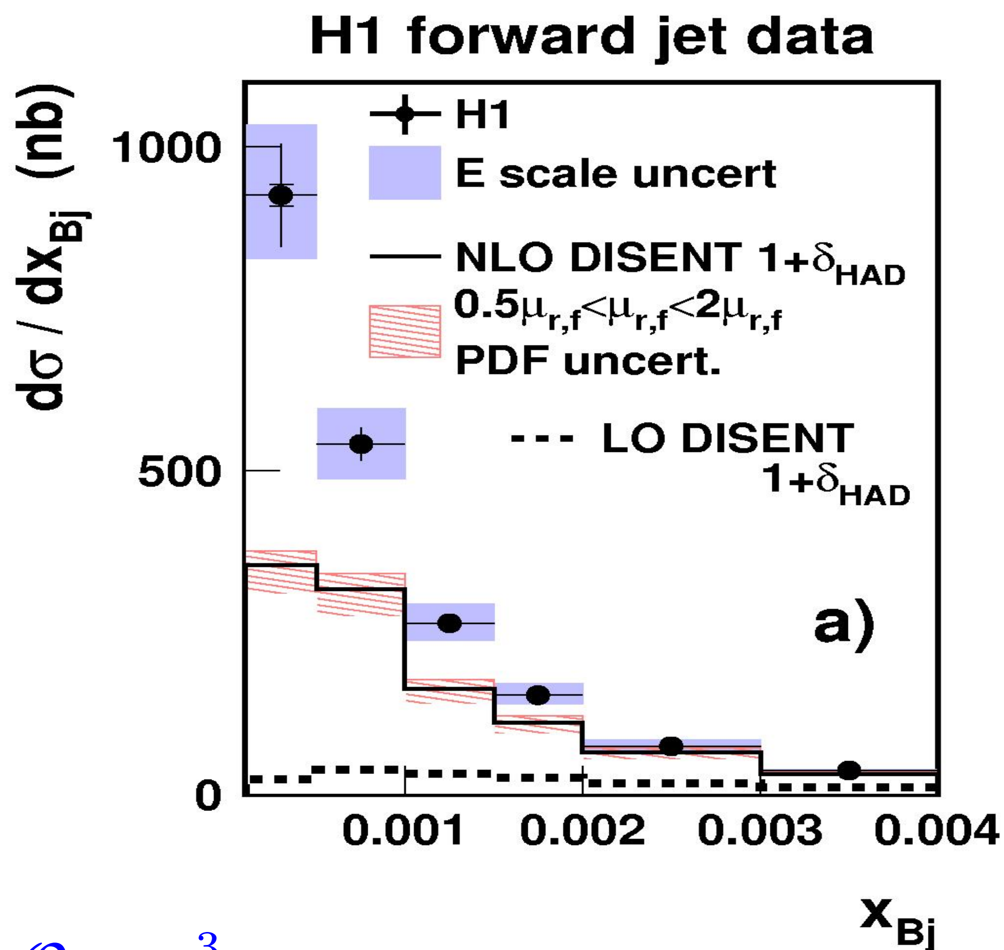
Howto investigate this ?



- processes of $\mathcal{O} > \alpha_s^3$ have not yet been calculated ...
- interesting to go closer to outgoing proton remnant

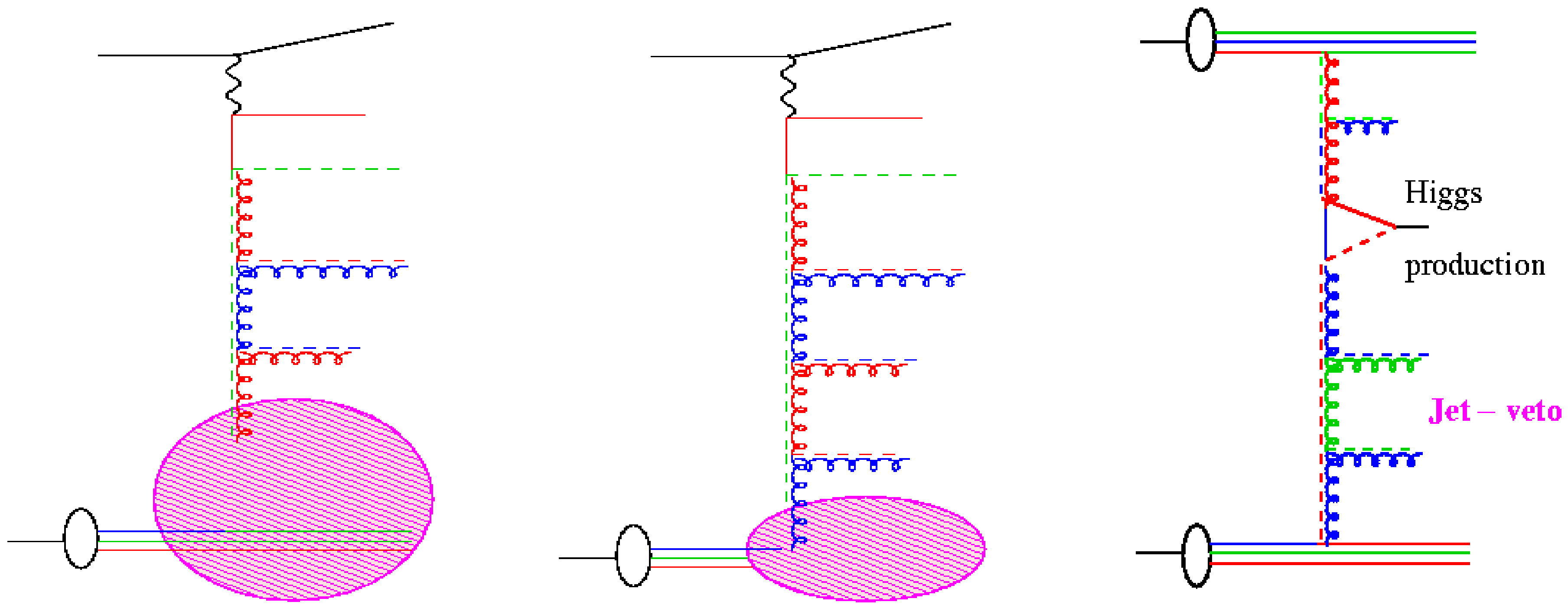
Howto investigate this ?





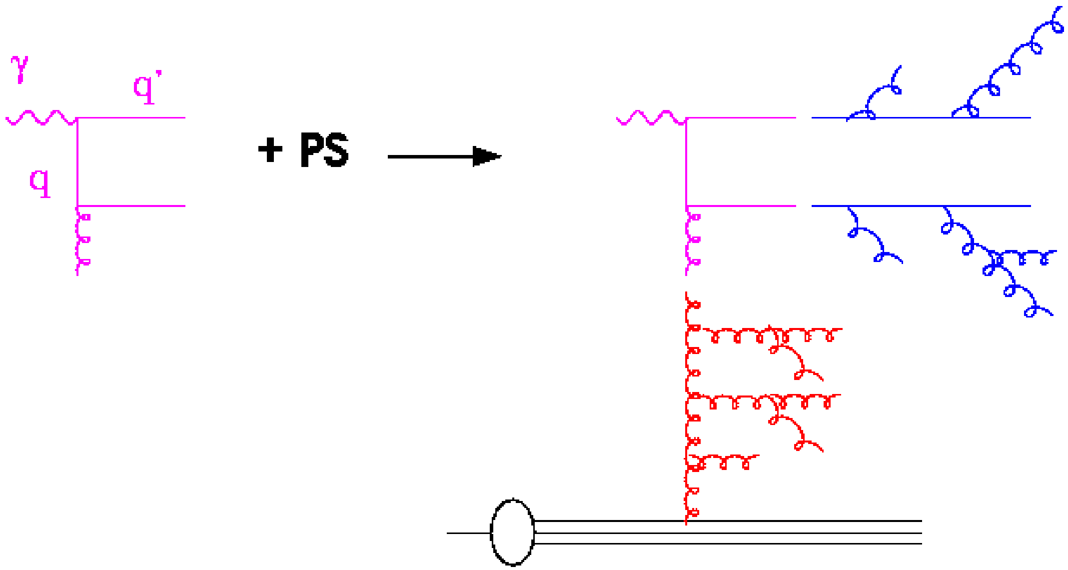
- processes of $\mathcal{O} > \alpha_s^3$ have not yet been calculated ...
- interesting to go closer to outgoing proton remnant
- forward jets

Howto investigate this ?



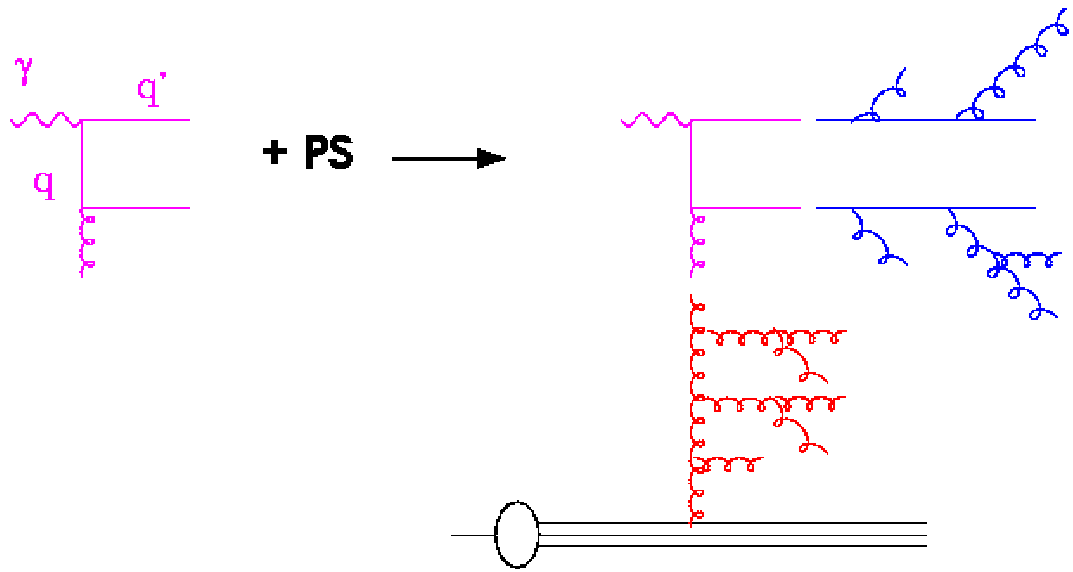
- processes of $\mathcal{O} > \alpha_s^3$ have not yet been calculated ...
- interesting to go closer to outgoing proton remnant
- jet veto in Higgs production at LHC

DGLAP Monte Carlo event generators



- use LO (NLO) matrix elements
- apply initial and final state parton showers
  - a la DGLAP or BFKL/CCFM
  - matching of ME with parton showers
- apply hadronization
- obtain cross sections fully differential in any observable
- **BUT:**
  - mainly LO (attempts to include NLO: Collins et al, MC@NLO, etc)

Inconsistency: example from HERA



- **Collinear approach:** incoming/outgoing partons are on mass shell
  $(\gamma+q)^2 = q'^{\,2}$, $-Q^{\,2} + x\,y\,s = 0 \rightarrow$ $x= Q^{\,2}/(ys)$
- **BUT** final state radiation:
  $(\gamma+q)^2 = q'^{\,2}$, $-Q^{\,2} + x\,y\,s = m^2 \rightarrow$ $x= (Q^{\,2}+m^2)/(ys)$
- **AND** initial state radiation:
  $(\gamma+q)^2 = q'^{\,2}$, $-Q^{\,2} + x\,y\,s + q^{\,2} =0 \rightarrow$ $x= (Q^{\,2}-q^{\,2})/(ys)$
- **Collinear approach: $q'^{\,2} = q^2 = 0$, order by order ....**
- Well known.... since years....
- NLO corrections... better treatment of kinematics... but still not all....

Arguments for PDF4MC

Campbell, Huston Stirling
Rep.Prog.Phys 70 (2007) 89

In addition, it is often useful to examine variations in acceptances in Monte Carlos using the families of NLO error pdfs; thus, it is important to also compare with the predictions using the central (NLO) pdf. It is our recommendation, then, that NLO pdfs be used for predictions at the LHC, even with LO matrix element programs and parton shower Monte Carlos. There are two consequences: (1) the pdfs must be positive-definite in the kinematic regions of interest as they will be used to develop the initial-state showering history and (2) underlying event tunes must be available using the NLO pdfs. An underlying event model that uses multiple-parton interactions depends strongly on the slope of the low x gluon distribution. The NLO gluon distribution tends to have a much shallower slope than does the LO gluon and thus a different set

Is that the end of the story ?

Which PDFs to be used in MC's ?

arguments by T. Sjostrand

General purpose event generators provide

$$\hat{\sigma}(\mathrm{LO}) \otimes \mathrm{PDF(LO)} \otimes \mathrm{showers}$$

Each component separately is positive

BUT ...

- PDF fits using LO are bad
- no uncertainty estimate for LO PDFs
- Often NLO PDFs are used....

BUT

- PDFs are not physical observables ... not necessarily positive
- $\hat{\sigma}(\mathrm{LO}) \otimes \mathrm{PDF(NLO)}$ may be grap

- Different solutions proposed
- determine new LO* PDFs by relaxing momentum sum rule
  - ..... hack .....
- use NLO PDFs for hard process, and LO PDFs for showering
  - .... hack ....
- determine special PDFs: PDF4MC

PDFs after fitting F_2 with PYTHIA

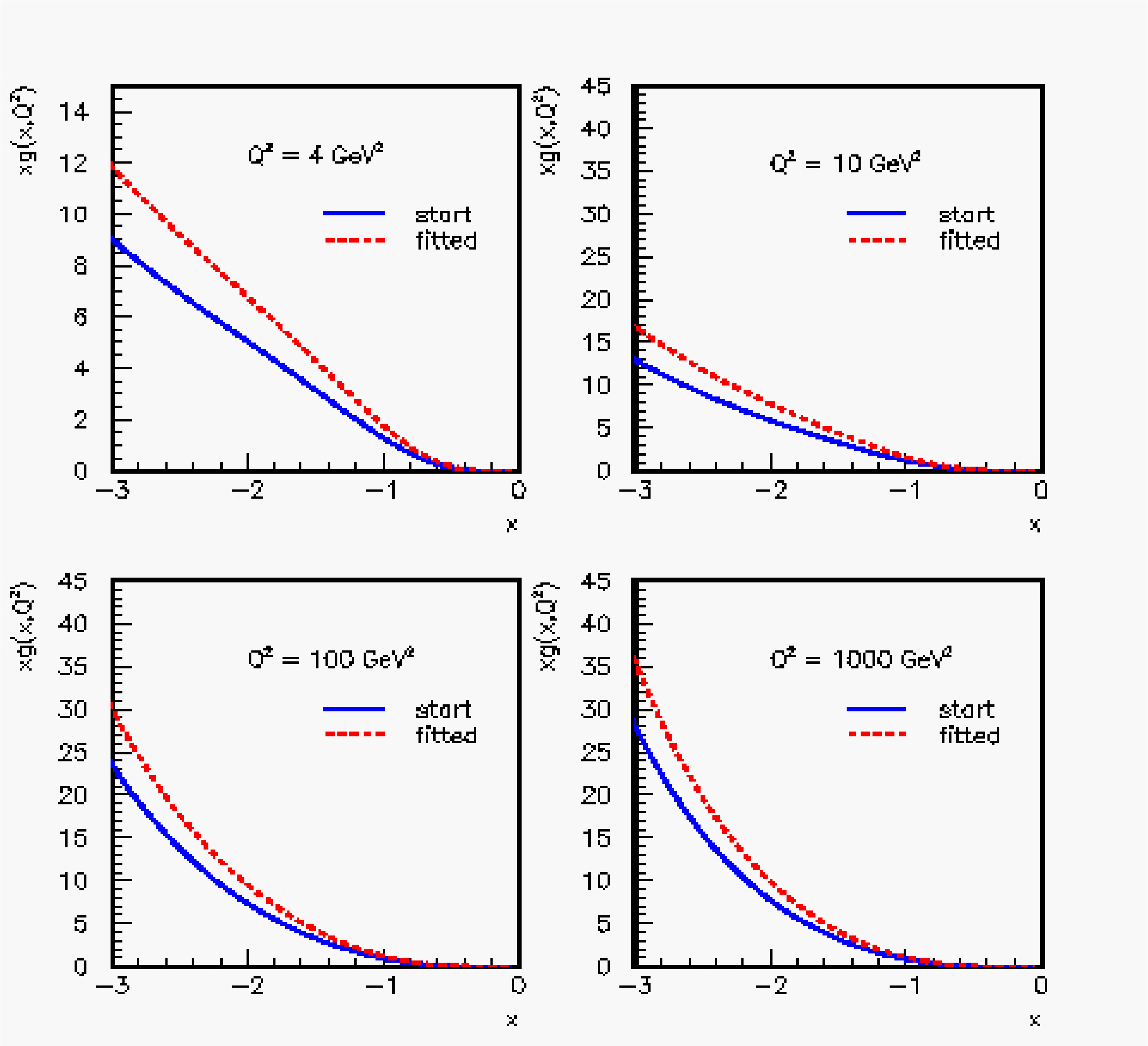
- Use LO fit....
- Fit F_2 by varying

$$xg(x,\mu) = A_0 x^{A_1} \ldots$$

and $\alpha_s(\mu)$

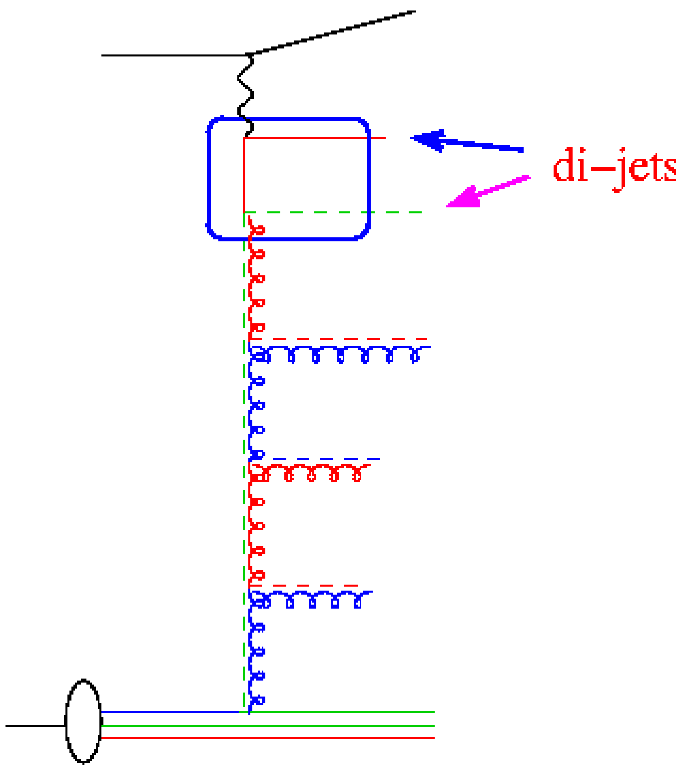
- Fit changes normalization and slope of gluon ... as seen in the scan....
- χ^2/ndf improves...., but can still be better....

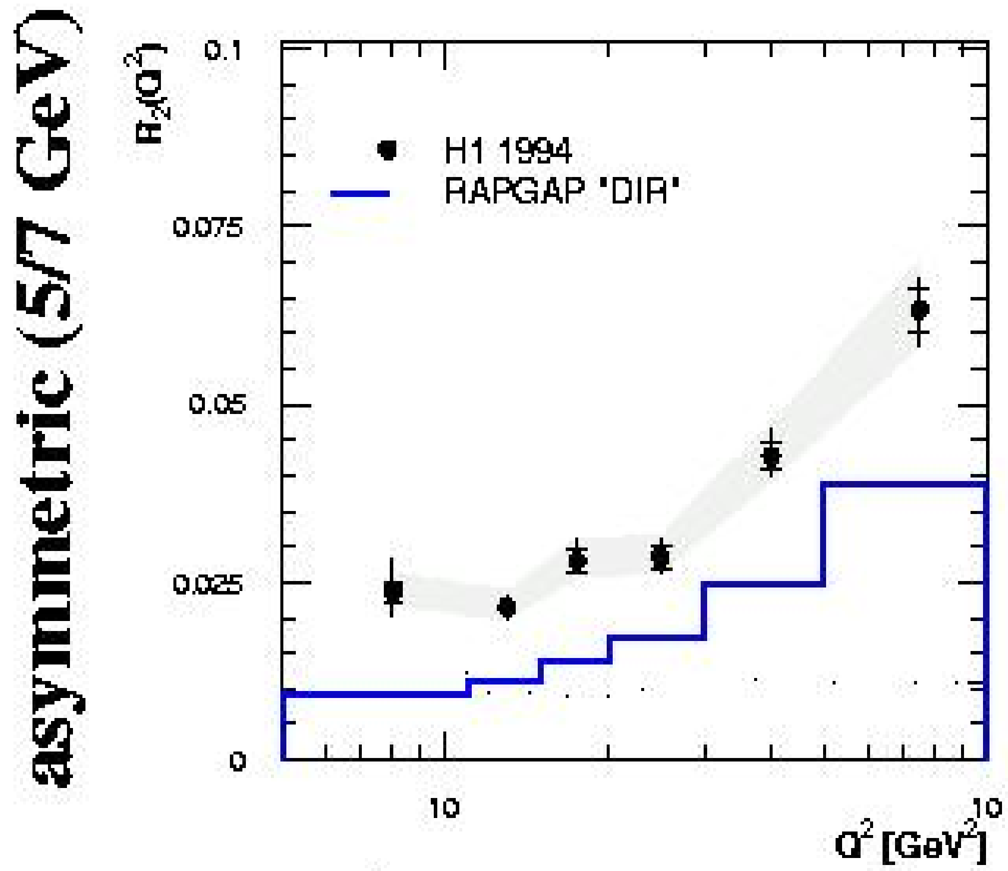
➔ Seems to be a bit different ...



How well do we understand the hadronic final state ?

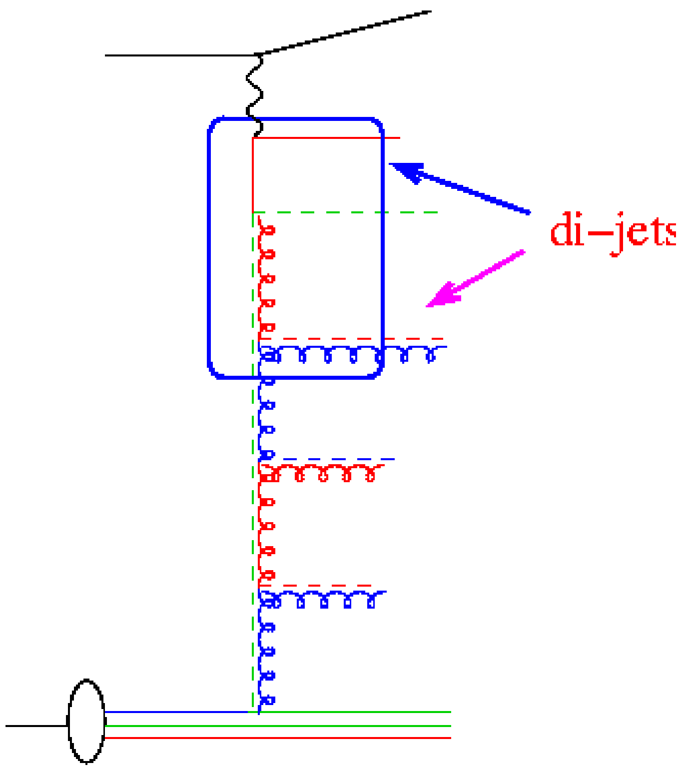
Do we understand di-jet production?

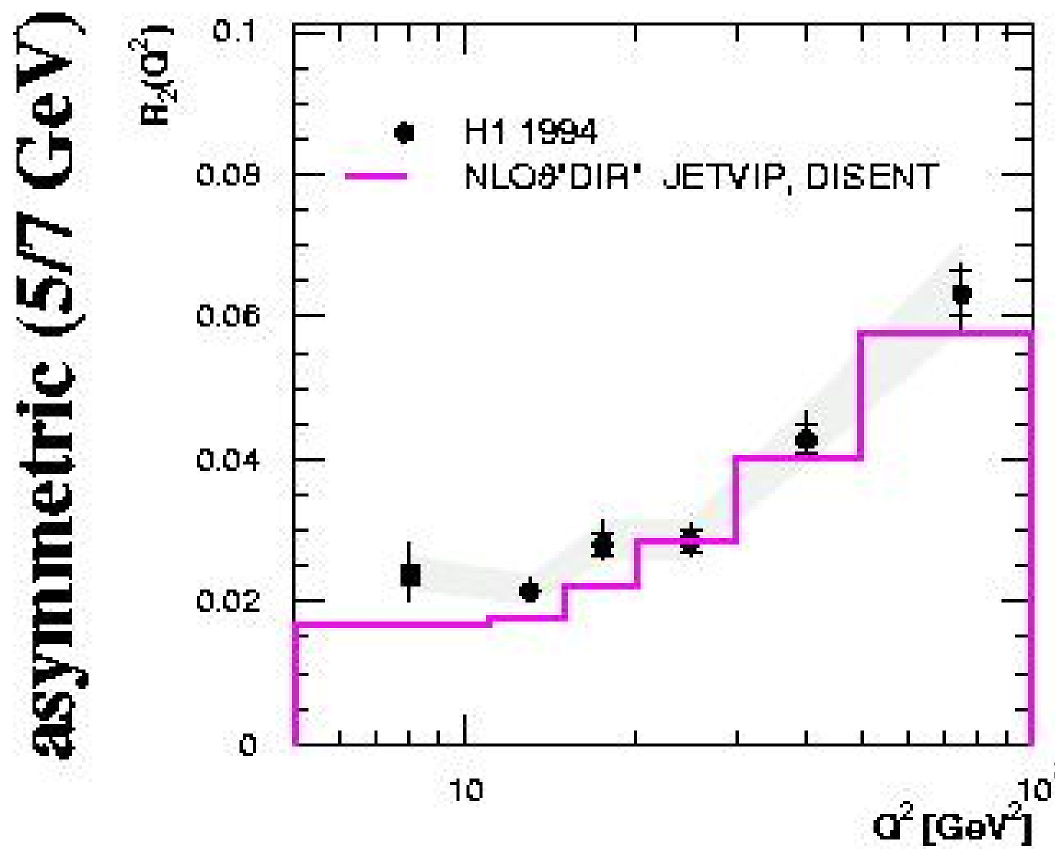




- (2+remnant) jets in DIS for $Q^2 > 5$ GeV^2, $p_t^{jets} > 5$ GeV
- use perturbative expansion: $\sigma_{true} = \sigma\left(\mathcal{O}(\alpha_s)\right) + \sigma\left(\mathcal{O}(\alpha_s^2)\right) + \cdots$
- $\mathcal{O}(\alpha_s)$ processes not enough
  - ➔ need higher order contributions

Doing better for di-jets ...



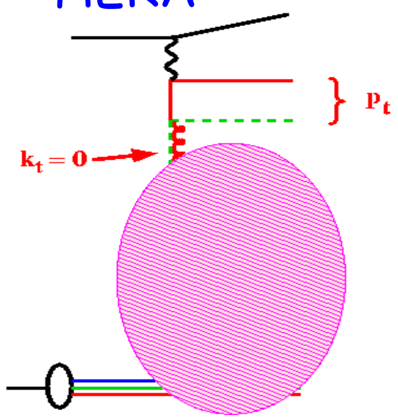


- (2+remnant) jets in DIS for $Q^2 > 5$ GeV^2, $p_t^{jets} > 5$ GeV
- use perturbative expansion: $\sigma_{true} = \sigma\left(\mathcal{O}(\alpha_s)\right) + \sigma\left(\mathcal{O}(\alpha_s^2)\right) + \cdots$
- NLO calculations are ok, if $p_{t1} \neq p_{t2}$

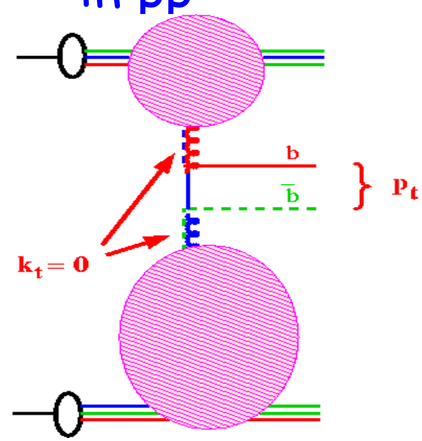
Problems in Collinear Approximation

J. Collins, H. Jung hep-ph/0508280

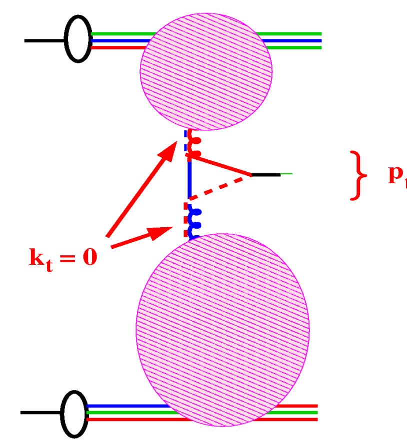
Jets/ heavy quarks at HERA

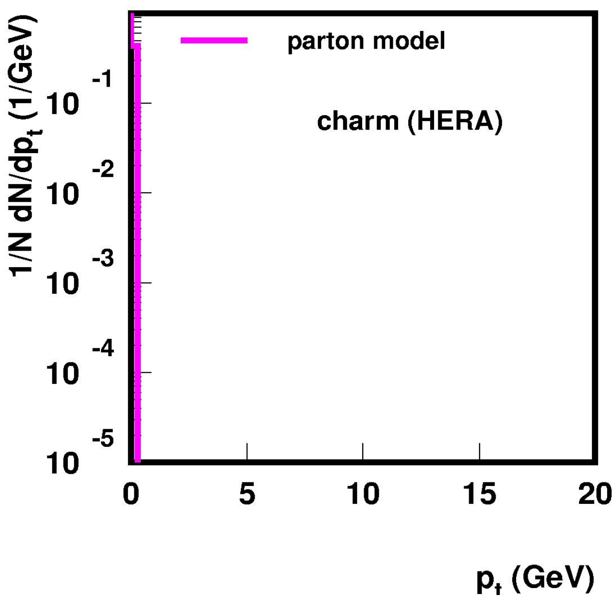


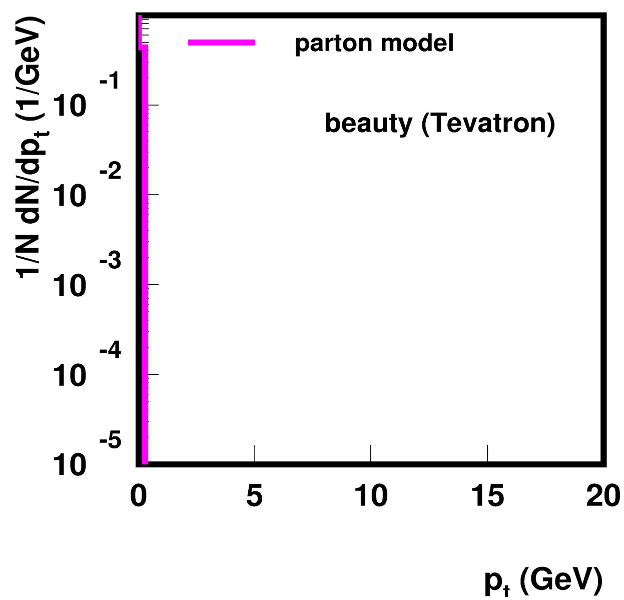
Jets/ heavy quarks in pp

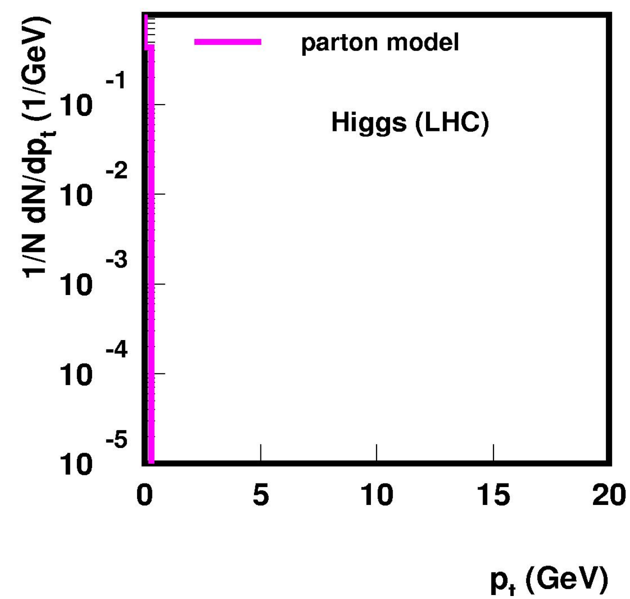


Higgs in pp







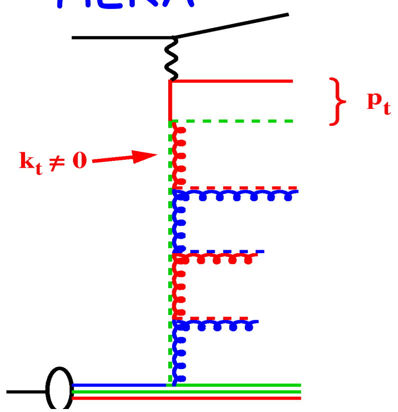


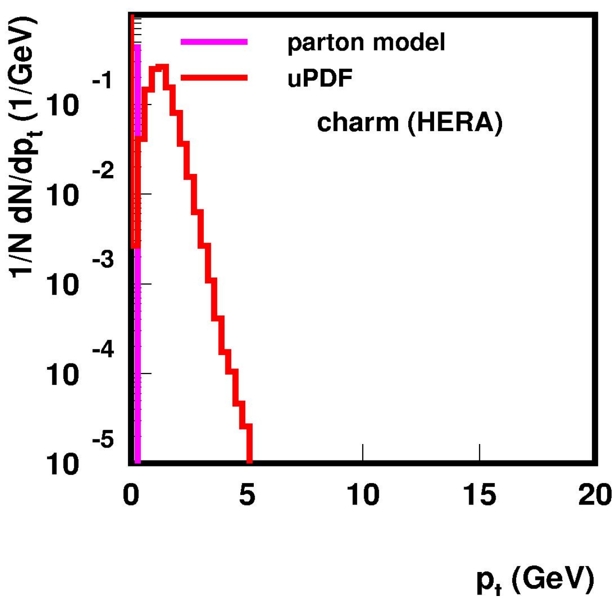
➔ NLO corrections will be very large for these LO processes .....

Doing much better with uPDFs ...

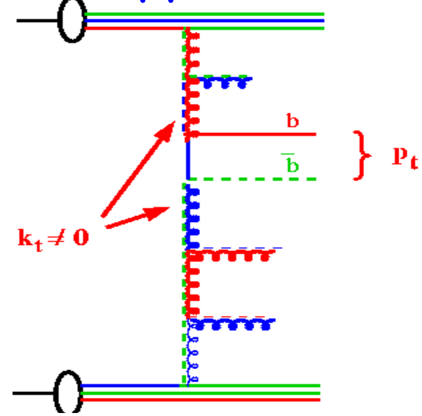
J. Collins, H. Jung hep-ph/0508280

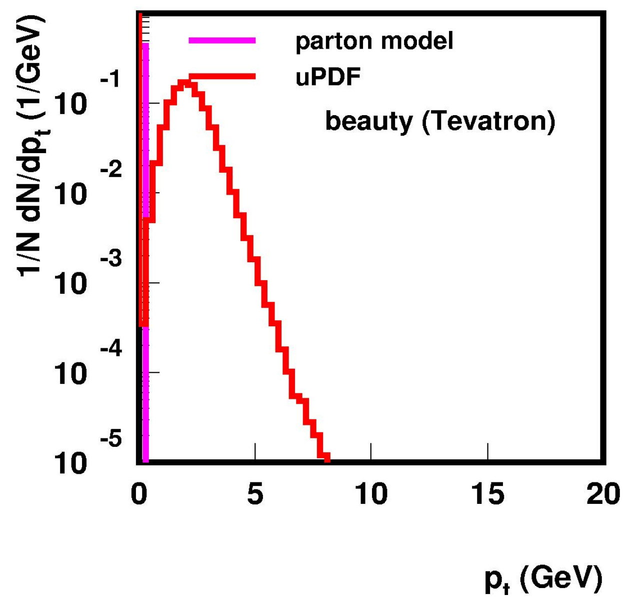
Jets/ heavy quarks at HERA



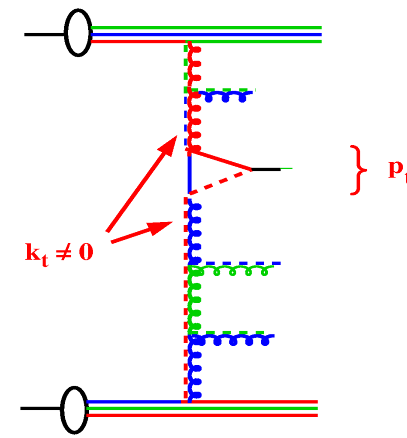


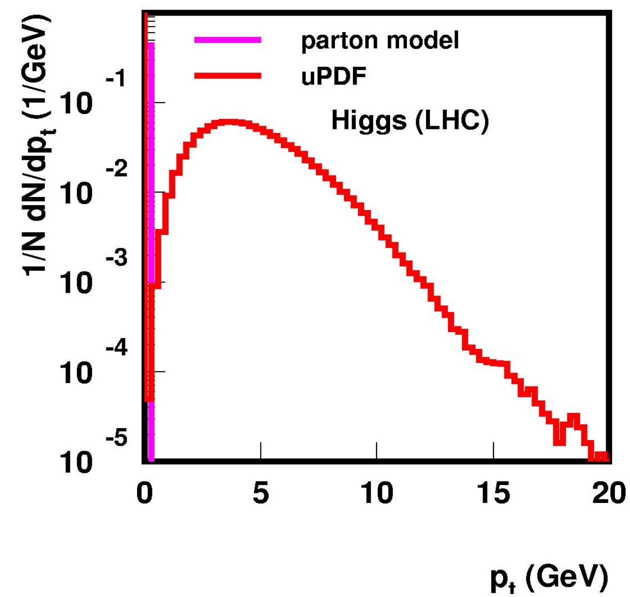
Jets/ heavy quarks in pp





Higgs in pp



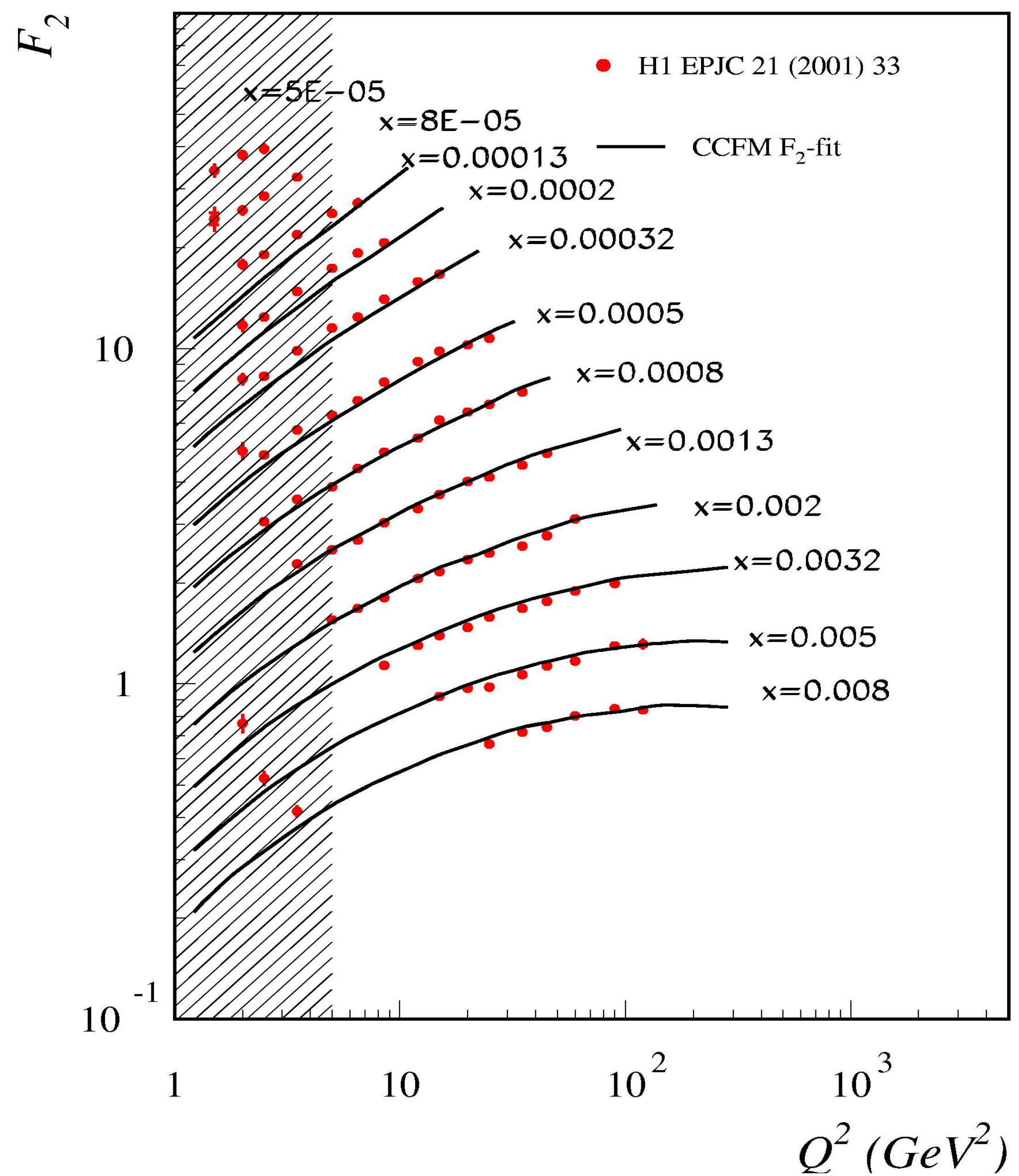


➔ doing kinematics correct at LO, reduces NLO corrections ... NEED uPDFs !!!!

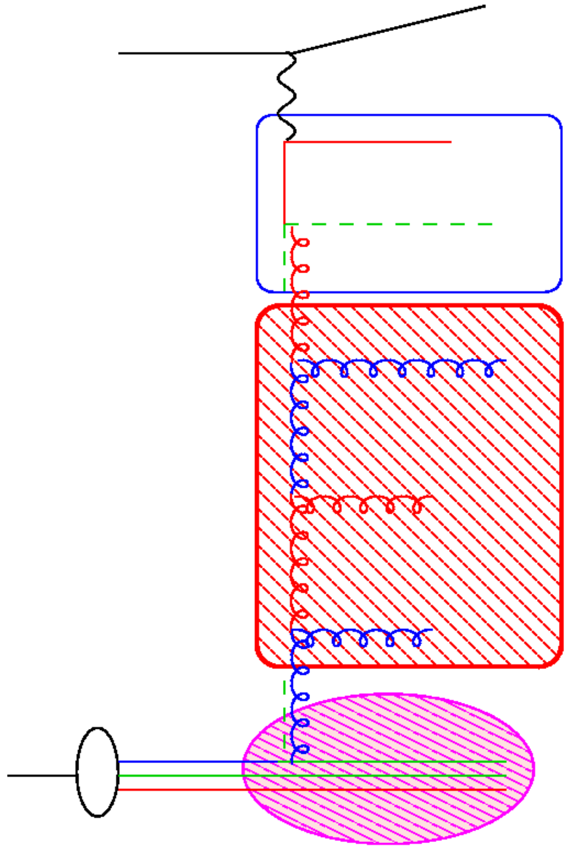
uPDF fit to F_2 HERA data

- fit parameters of starting distribution
  $$x\,g(x,\mu_0^2) = N x^{-B_g} \cdot (1-x)^4$$
- using F_2 data
  (H1 Eur. Phys. J. C21 (2001) 33-61, DESY 00-181)
  $$x < 0.05 \quad Q^2 > 5\ \mathrm{GeV}^2$$
- parameters: $\mu_r^2 = p_t^2 + m_{q,Q}^2$
  $$m_q = 250\,\mathrm{MeV}\,,\, m_c = 1.5\ \mathrm{GeV}$$
- Fit (only stat+uncorr):
  $$\frac{\chi^2}{\mathrm{ndf}} = \frac{111.8}{61} = 1.83$$

➔ similar to NLO DGLAP fits (~1.5)



CASCADE – Catani C iafaloni F iorani M archesini evolution



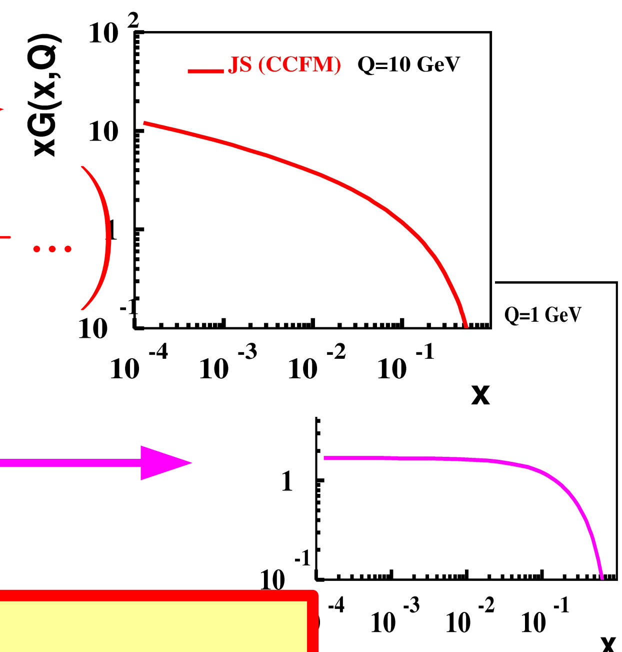
BGF matrix element
off shell

evolution of parton cascade:

$$\tilde{P} = \bar{\alpha}_s \left(\frac{1}{1-z} + \frac{1}{z}\Delta_{ns} + \ldots \right)$$

initial distribution
~ flat

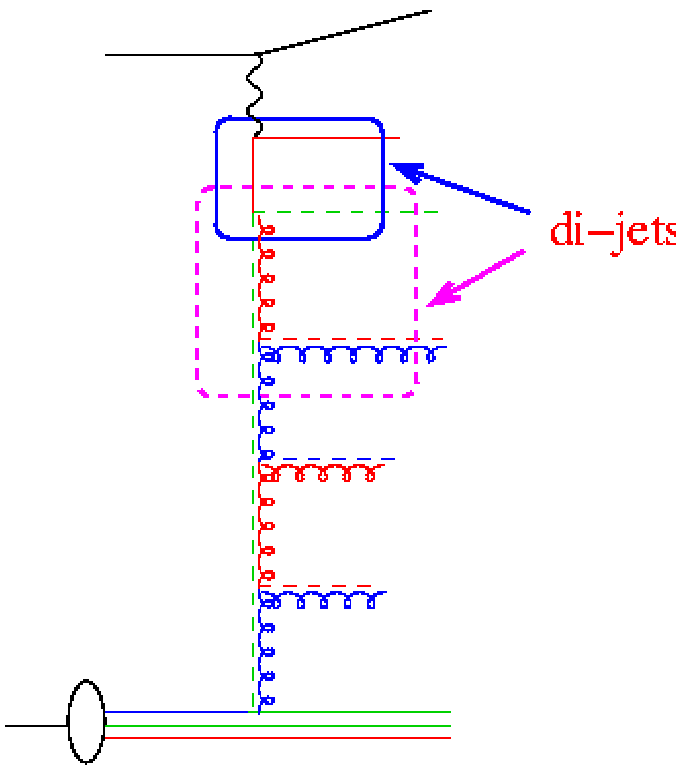
CCFM (all loops)
- angular ordering
- non – Sudakov Δ_{ns}

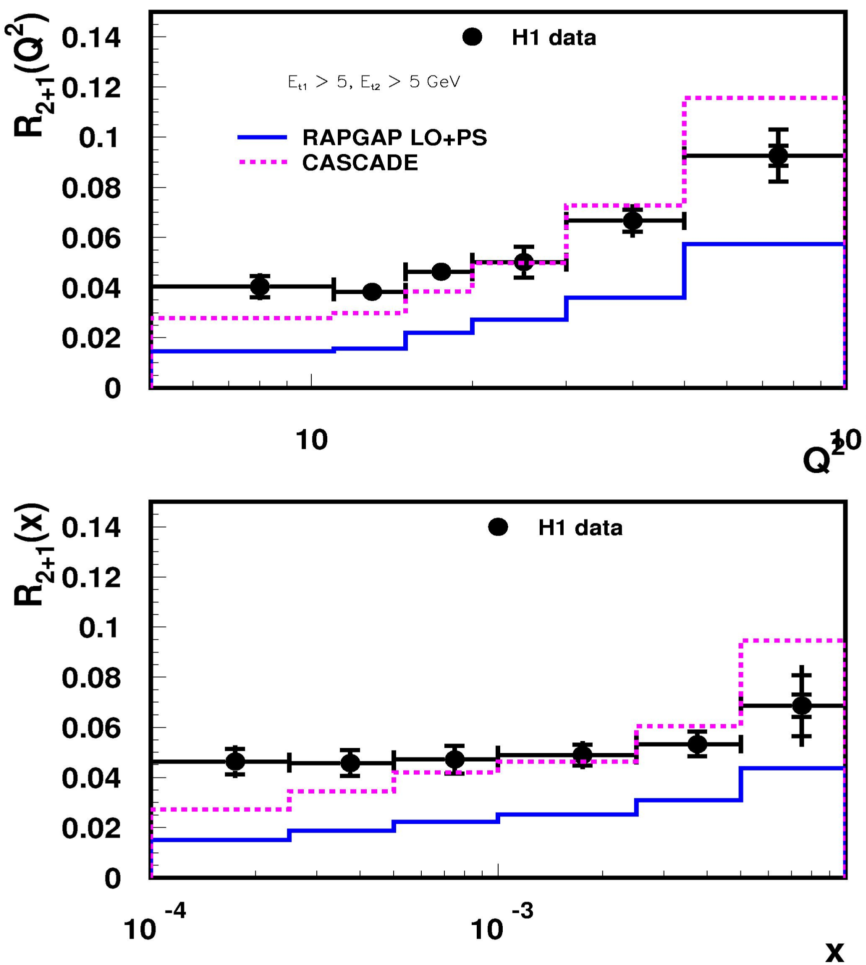


$$\sigma(ep \to e'q\bar{q}) = \int \frac{dy}{y} d^2Q \frac{dx_g}{x_g} \int d^2k_t \hat{\sigma}(\hat{s}, k_t, Q) x_g \mathcal{A}(x_g, k_t, \bar{q})$$

$$\int d^2k_t x_g \mathcal{A}(x_g, k_t, \bar{q}) \simeq x_g G(x_g, Q^2)$$

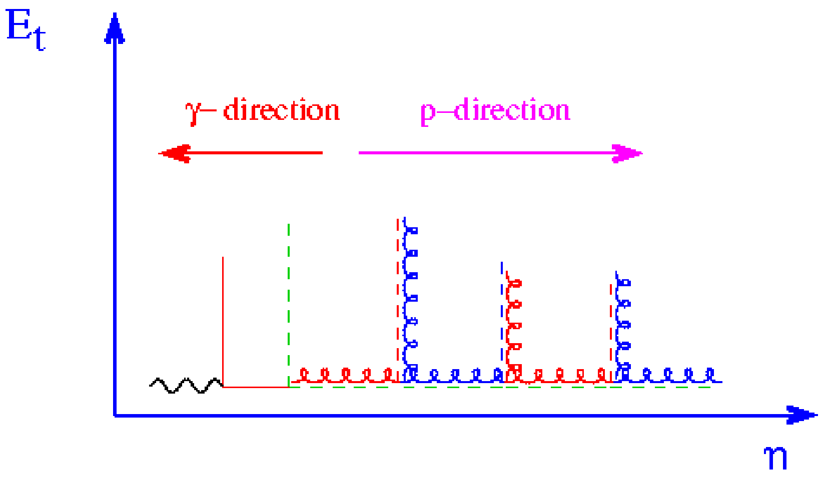
Doing easier for dijets ...

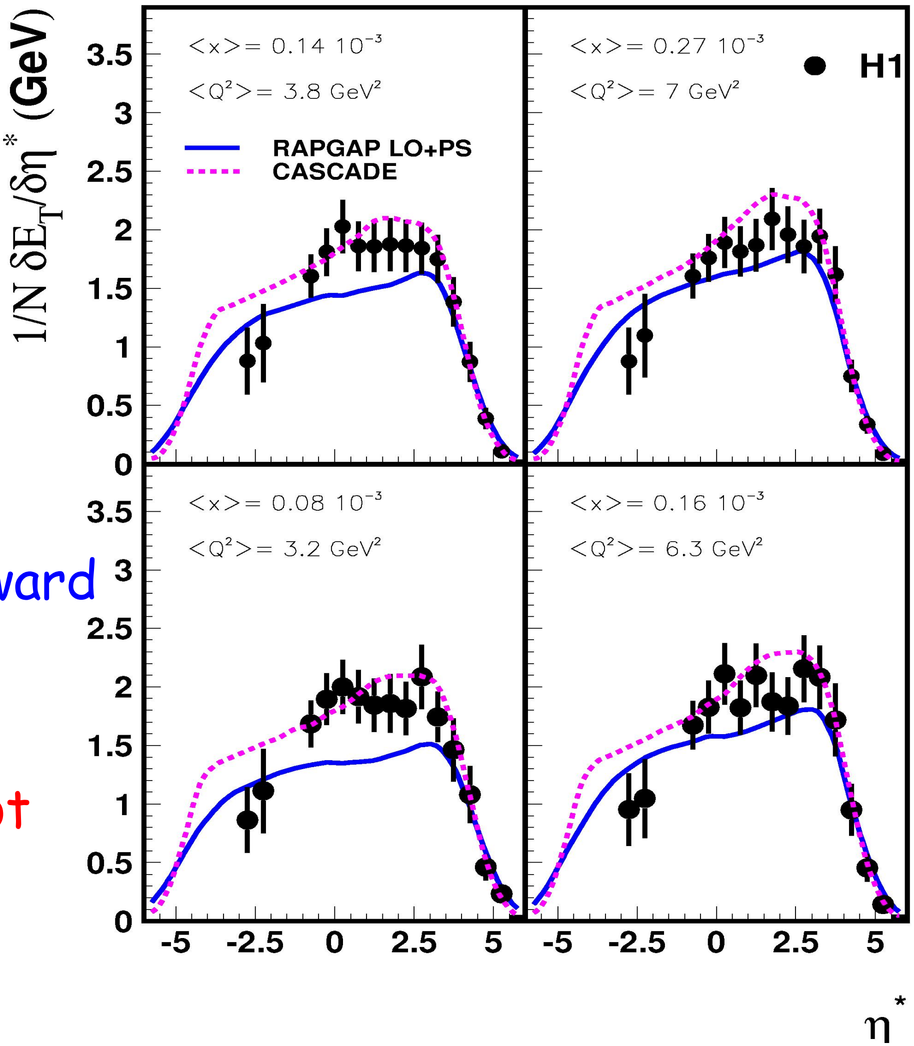




- (2+remnant) jets in DIS for $Q^2 > 5\ GeV^2$, $p_t^{jets} > 5$ GeV
- $\mathcal{O}(\alpha_s)$ processes not enough
  - ➔ needs $\mathcal{O}(\alpha_s^2)$ NLO calculations .... or ....
  - ➔ using uPDFs is as good as NLO !!!

Hadronic final state: Energy flow



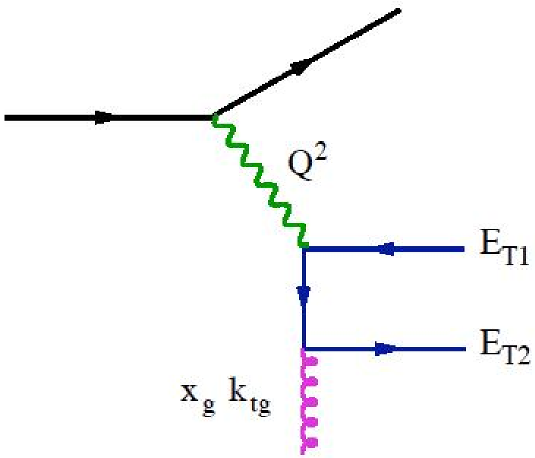


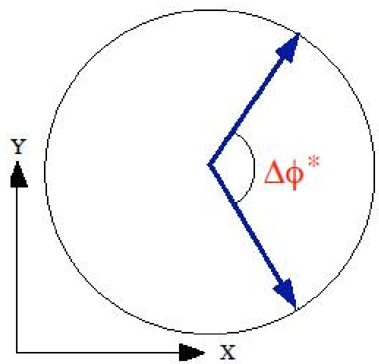
- Et flow in DIS at small x and forward angle (p-direction):
  - ➔ $\mathcal{O}(\alpha_s)$ processes not enough
  - ➔ even DGLAP parton showers do not help

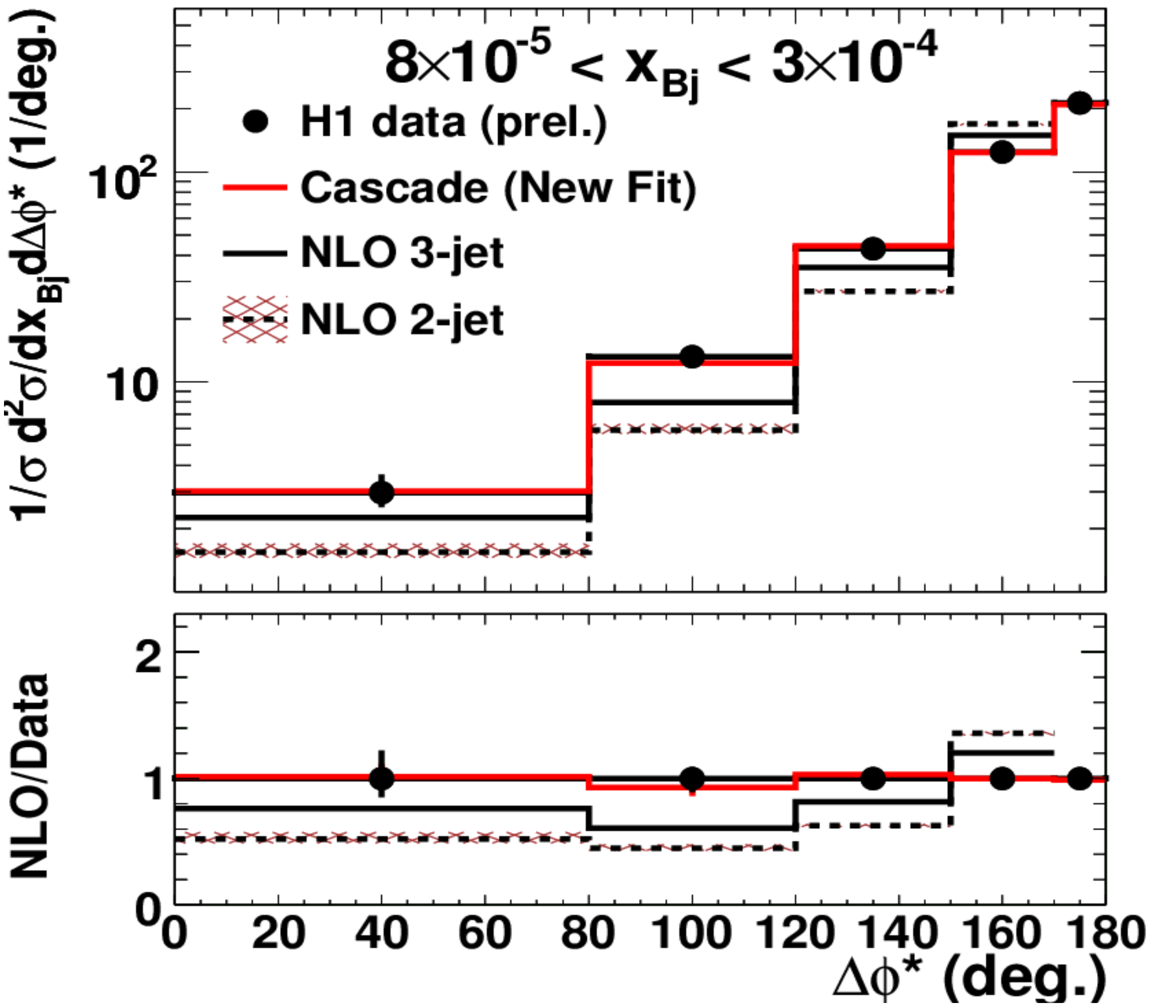
- need higher order contributions...
- using uPDFs with detailed parton showers ala CCFM very good !!!!!

Dijets and uPDFs: azimuthal correlations

M. Hansson (Lund)

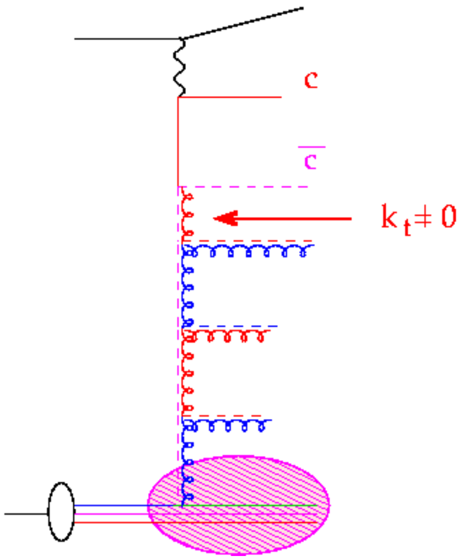


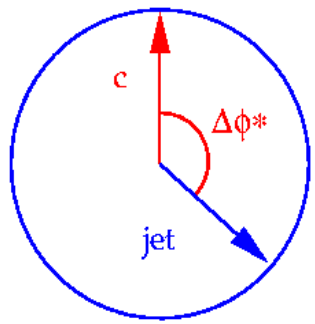


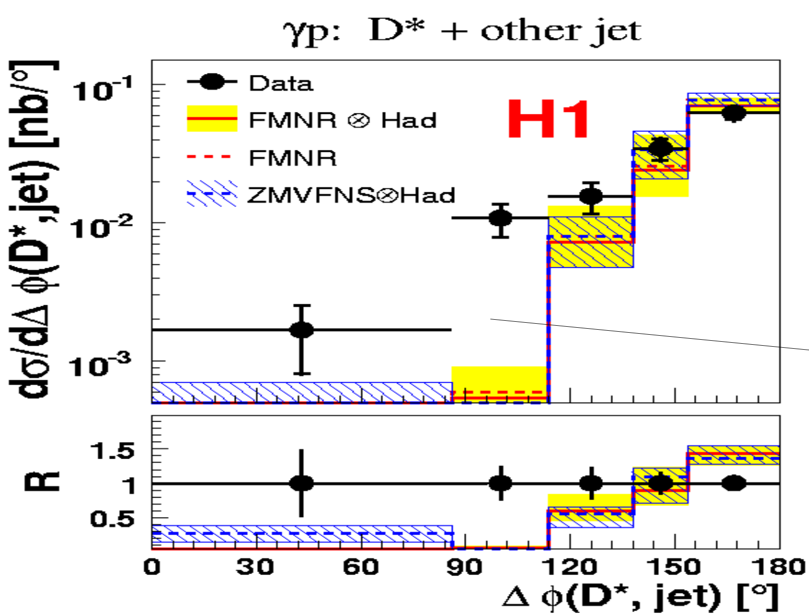


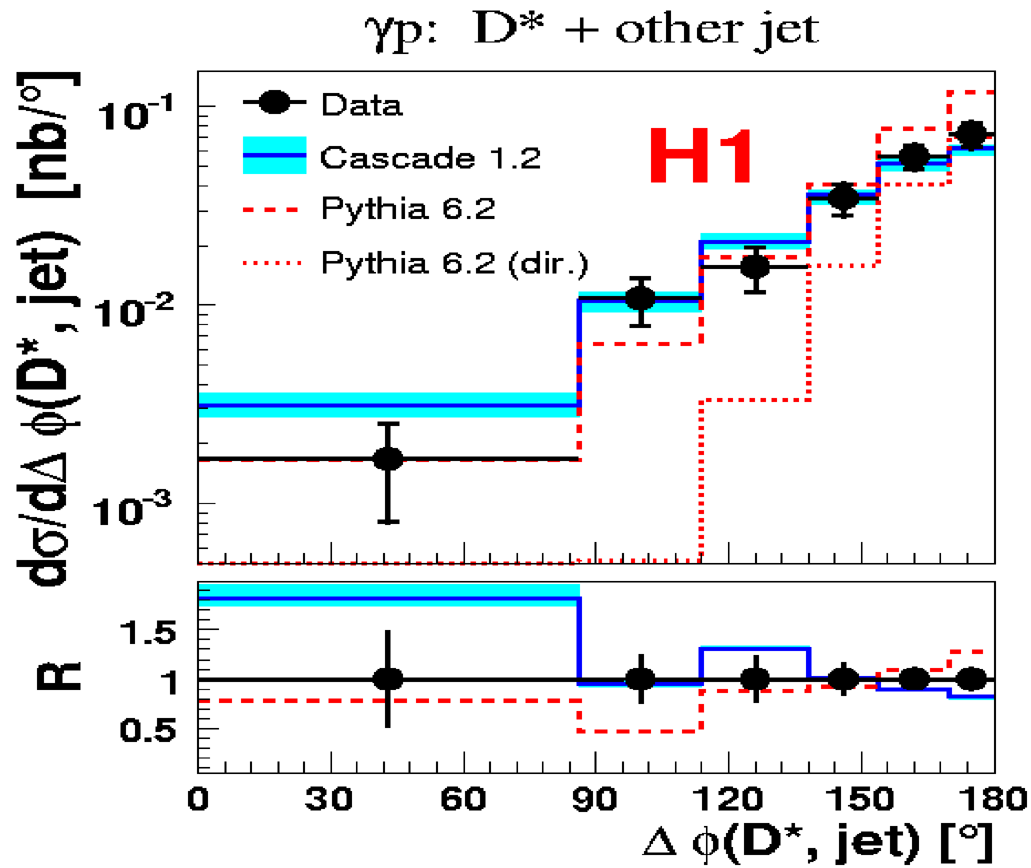
- uPDF is much better than NLO calculations !!!!

Charm production: another problem



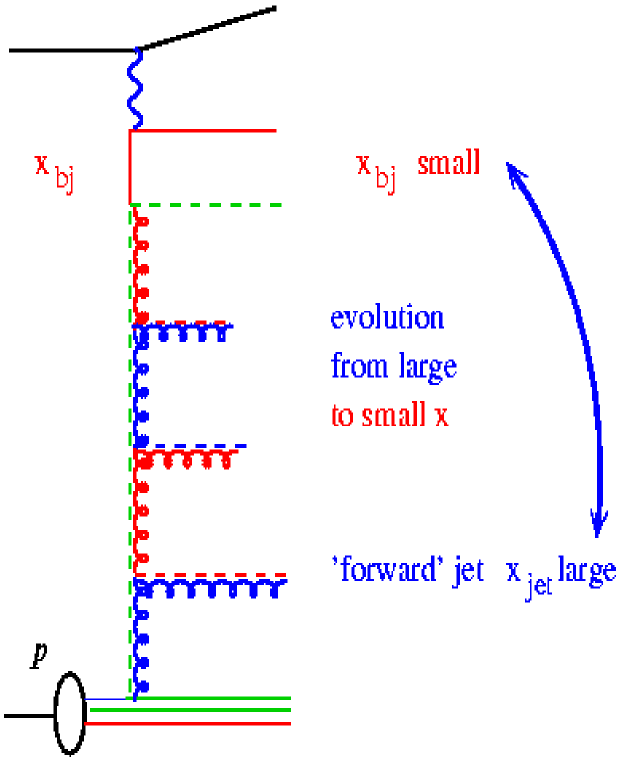


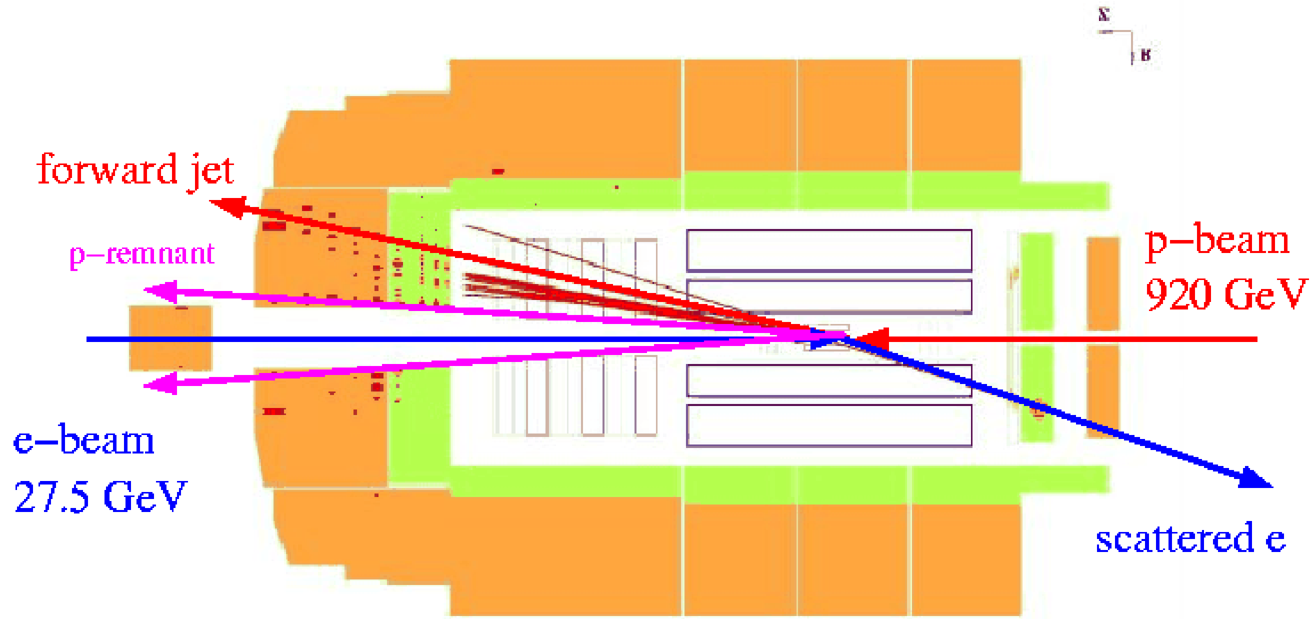




- problems at small and large $\Delta\phi$ in NLO calc.
- $\Delta\phi$ x-section better described by MC event generators and uPDFs !

forward jets: another problem





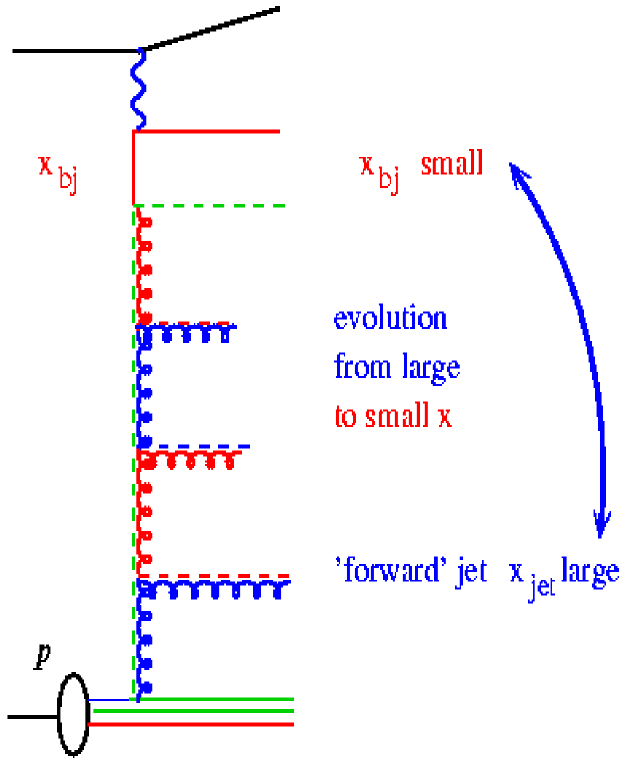
- DIS and forward jet:

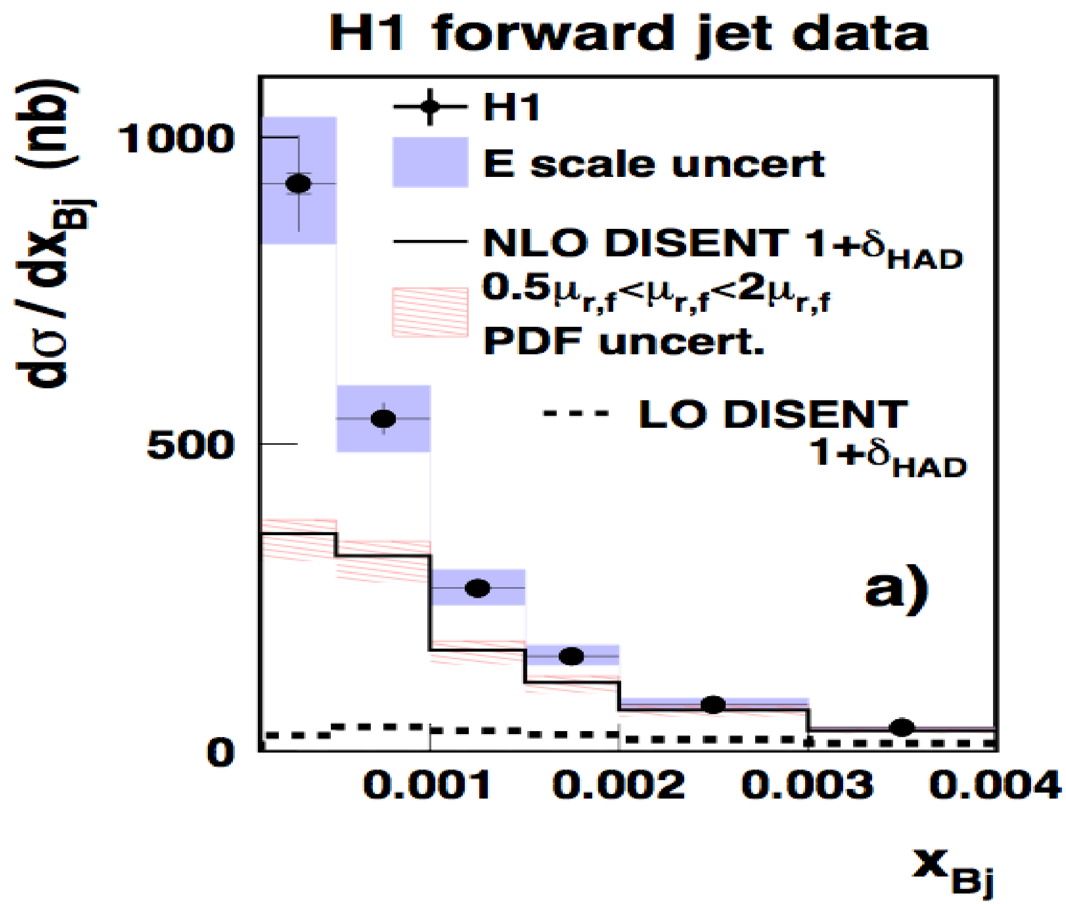
  $1.7 < \eta_{jet} < 2.8$

  $x_{jet} > 0.035$

  $$0.5 < \frac{p_{t\ jet}^2}{Q^2} < 5$$

forward jets: another problem





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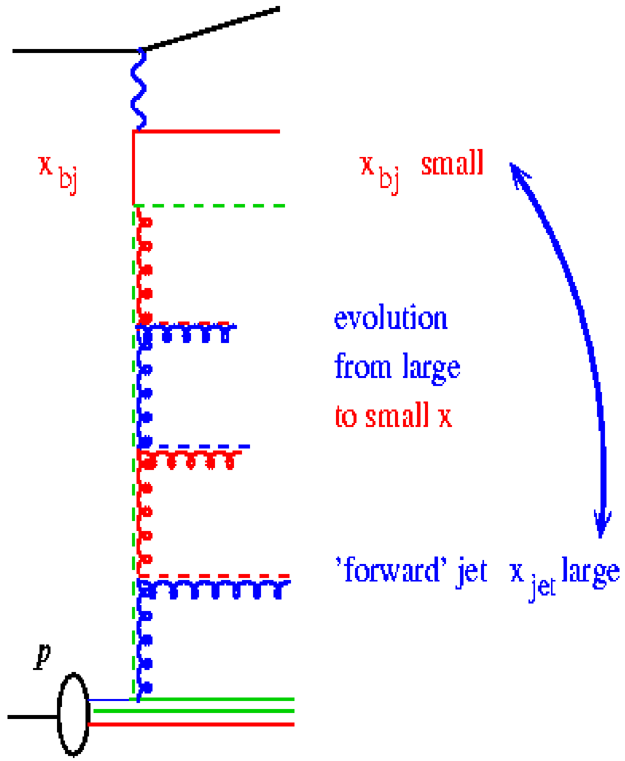
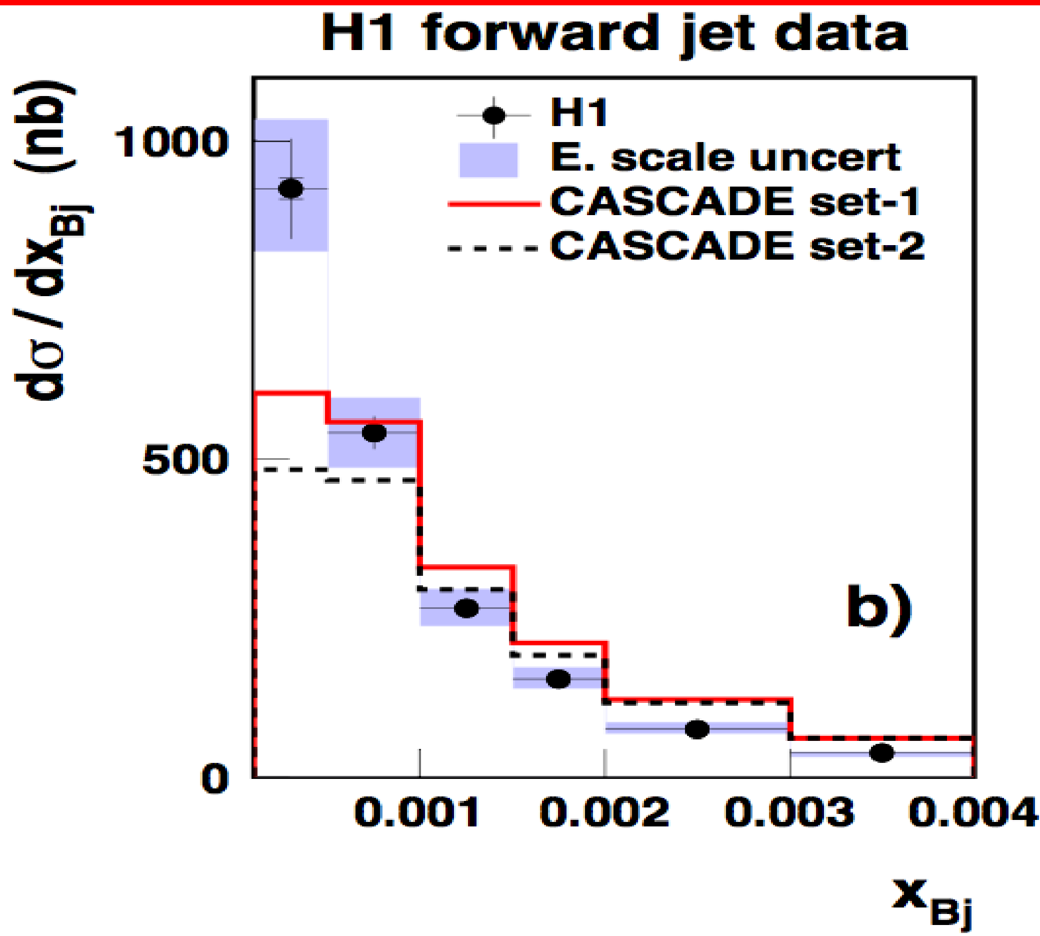
- "NLO" too low

forward jets: another problem





- DIS and forward jet:
  $1.7 < \eta_{jet} < 2.8$
  $x_{jet} > 0.035$
  $0.5 < \frac{p_{t\ jet}^2}{Q^2} < 5$

- "NLO" too low
- Detailed modeling of parton cascades still challenging ...

Hadronic final states at HERA

Is that all from HERA

???

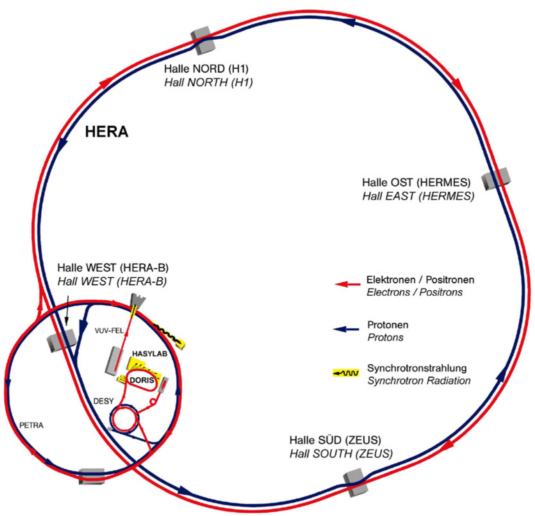
Implications for LHC

!!!!!

Why HERA and LHC ?

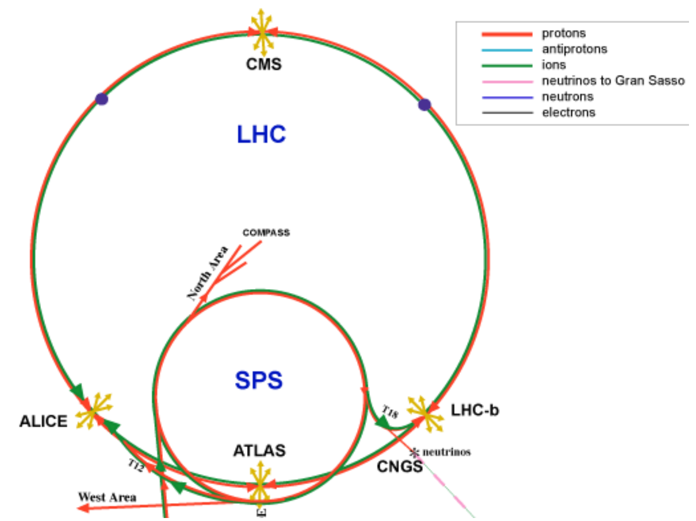
electron proton collider HERA
√s = 320 GeV

proton proton collider LHC
√s = 14 TeV



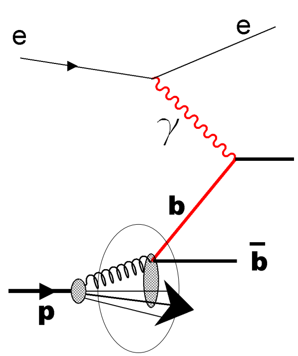
typical range

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



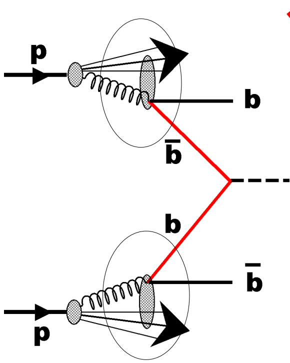
HERA: QCD
structure of the proton

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



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

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



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

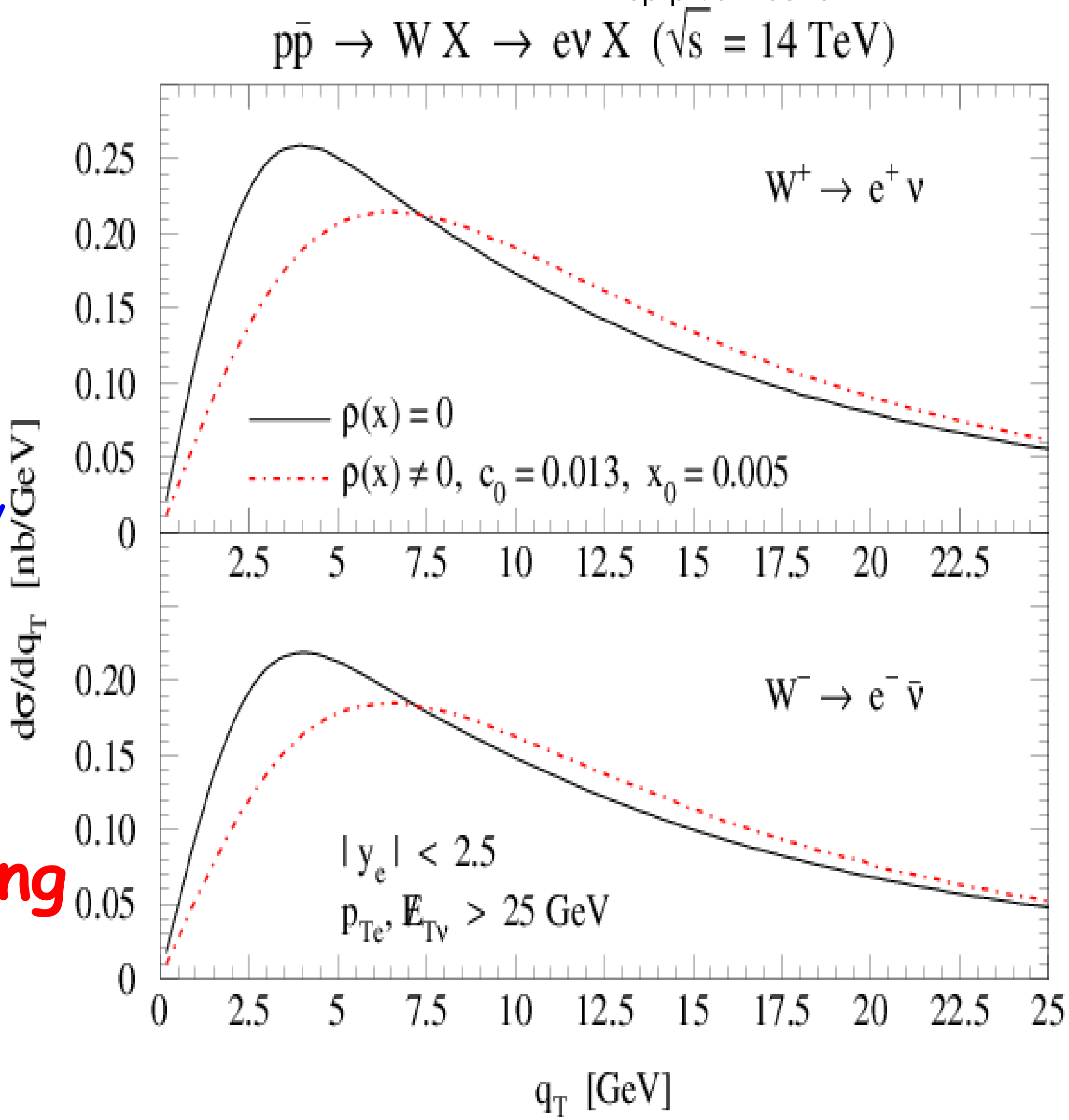
for $M \sim 140\ \mathrm{GeV}$

Qt spectrum: small x improved ...

Berge, Nadolsky, Olness, Yuan
hep-ph/0410375

- in standard p_t resummation, no small x effects are included.
- at large energies (small x) BFKL effects might play a role... diffusion of transverse momenta, qt broadening...
- obtain effective pt-broadening by HERA data on transverse energy flow... include that for qt spectra of W/Z (Berge, Nadolsky, Olness, Yuan hep-ph/0410375)

➔ **Interesting physics coming with hard QCD processes !!!!**

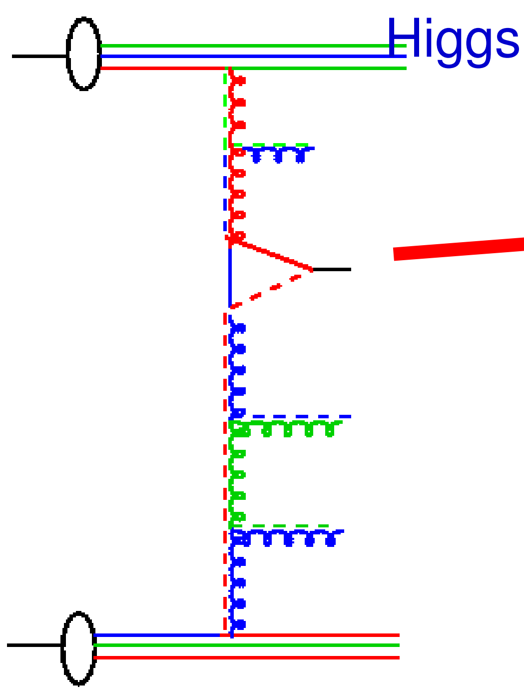


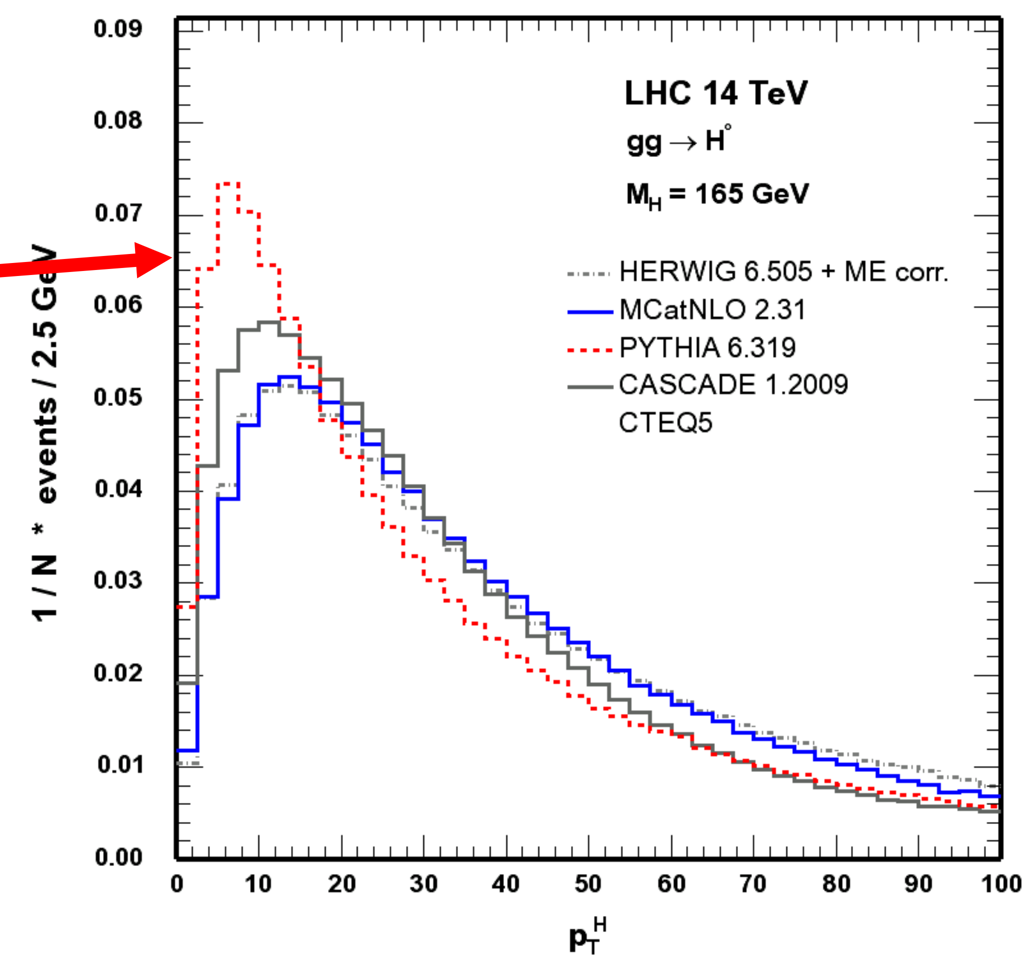
k_t effects at HERA and LHC

from G. Davatz

Do we understand the p_t spectrum of Higgs at LHC?

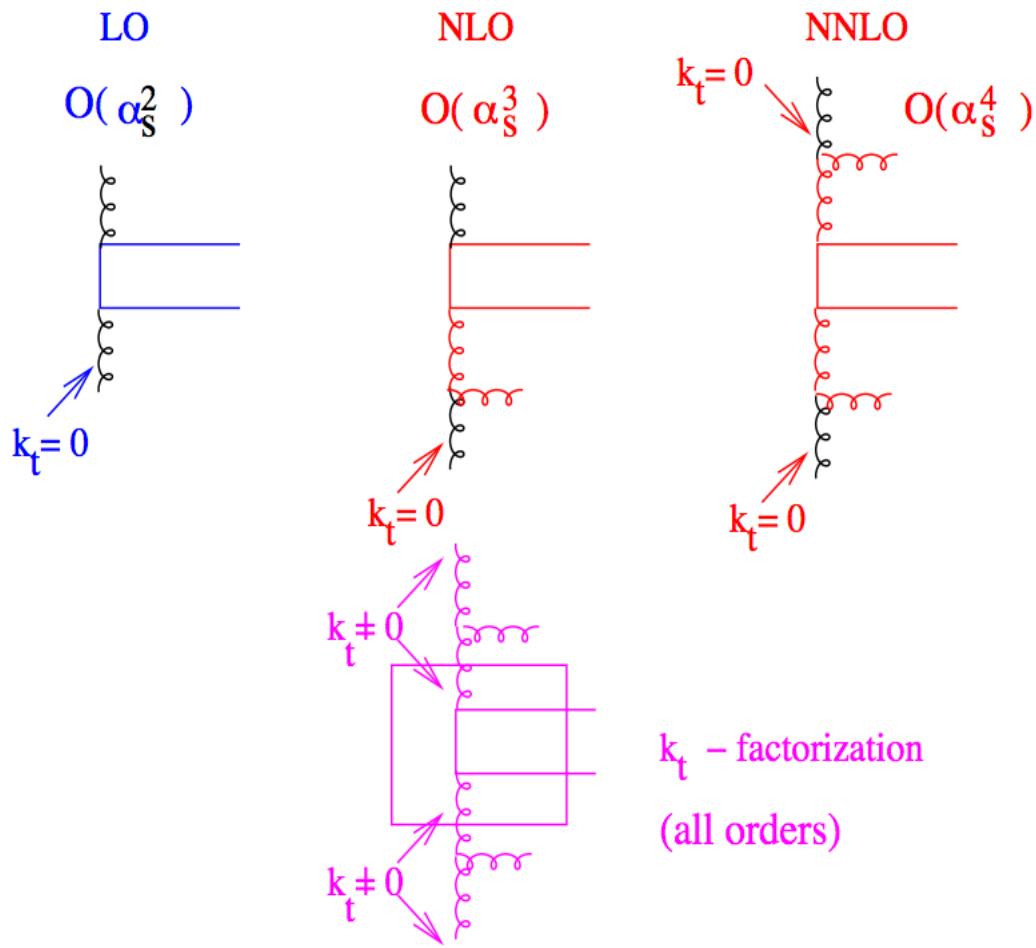
Important for the *gg* → Higgs → *WW* → $l\nu$ $l\nu$ to understand the jet-veto for *tt* suppression...





uPDFs and NLO calculations

- fit of uPDF to inclusive structure functions /x-sections used to determine normalization
  - ➔ includes "all-orders" !!!!
- off-shell matrix element simulates part of real NLO corrections
  - ➔ study of scale dependence
  - ➔ compare to coll. NLO calculations
  - ➔ check with benchmark x-sections

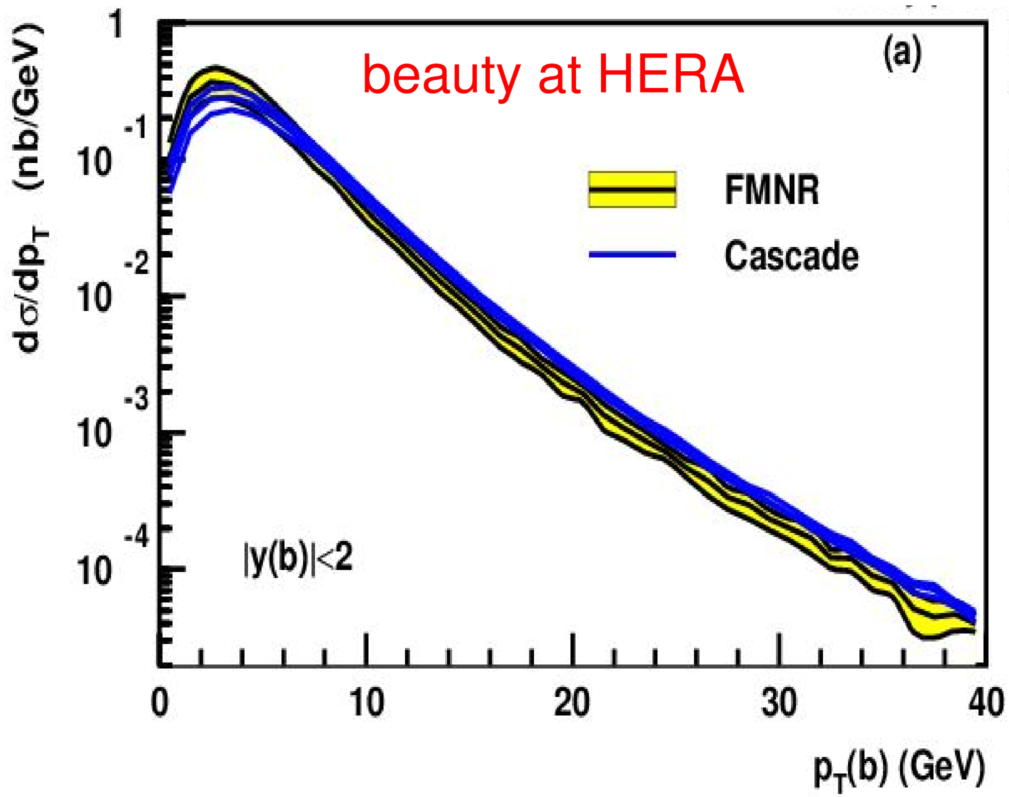


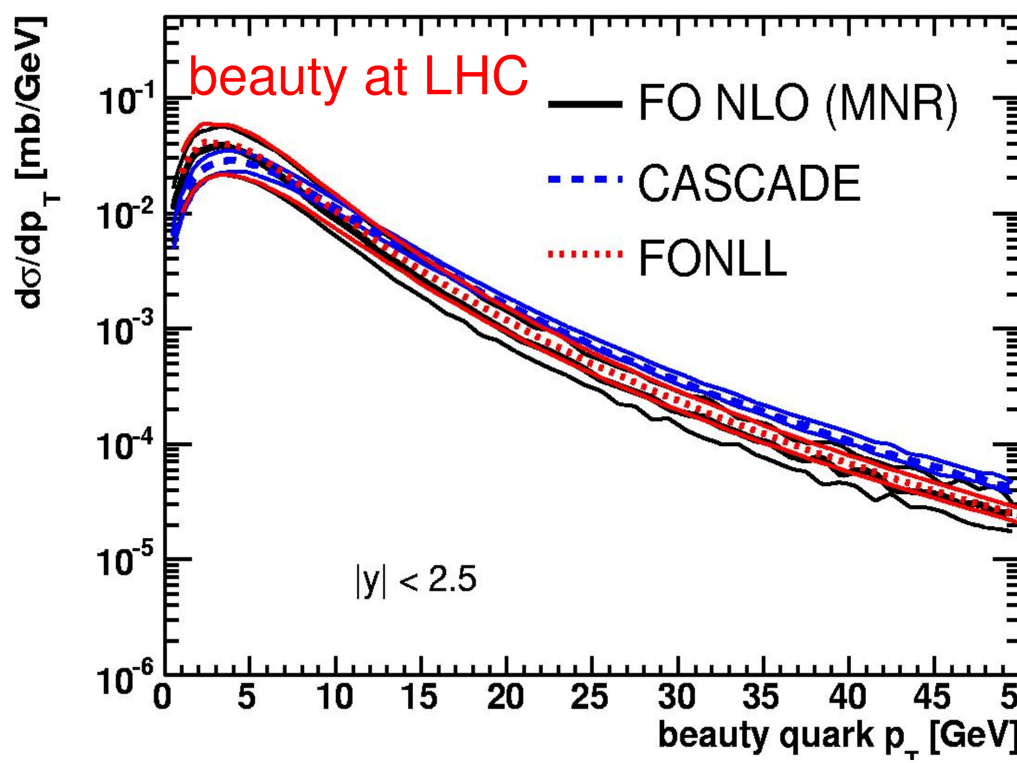
Benchmarks: beauty at HERA and LHC

from Proceedings of the HERA-LHC workshop hep-ph/0601013

Cross sections at parton level in central region

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





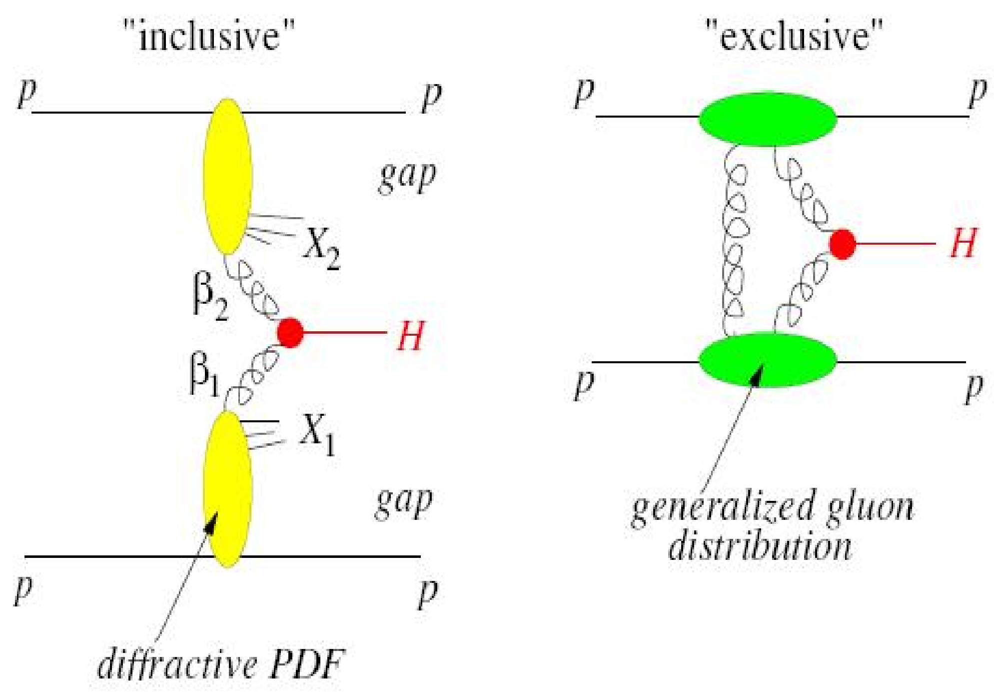
"Perfect" agreement of NLO(FMNR) calculation with CASCADE using uPDFs !!!

Do we have now all parton densities considered ?

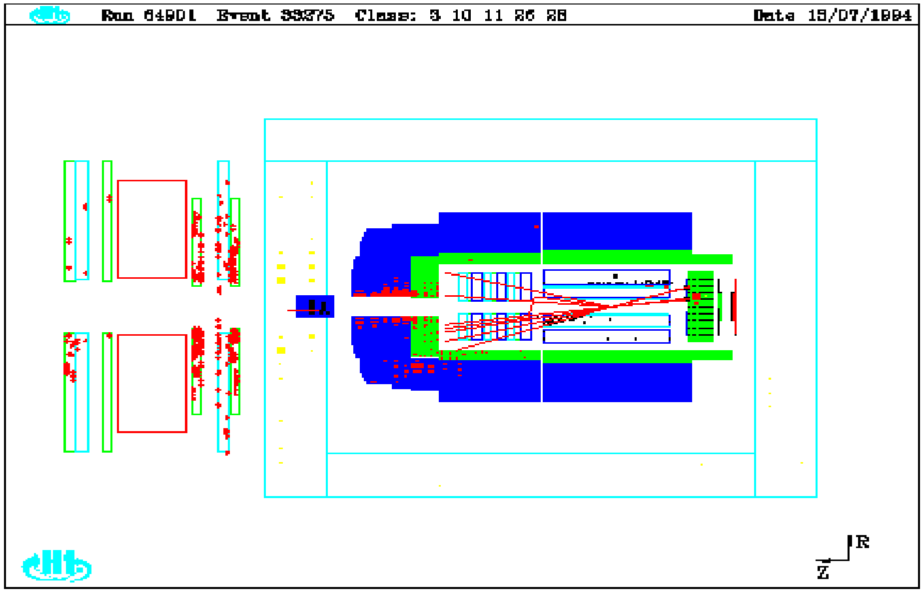
Parton Density Functions and all that

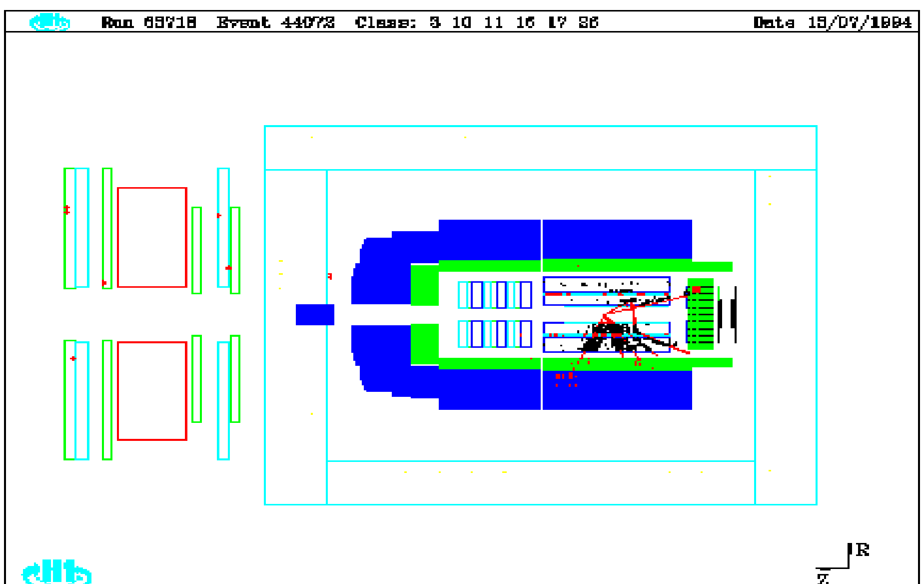
- collinear PDFs
- uPDFs (single and double unintegrated)
- diffractive and generalized PDFs

Exclusive Higgs production

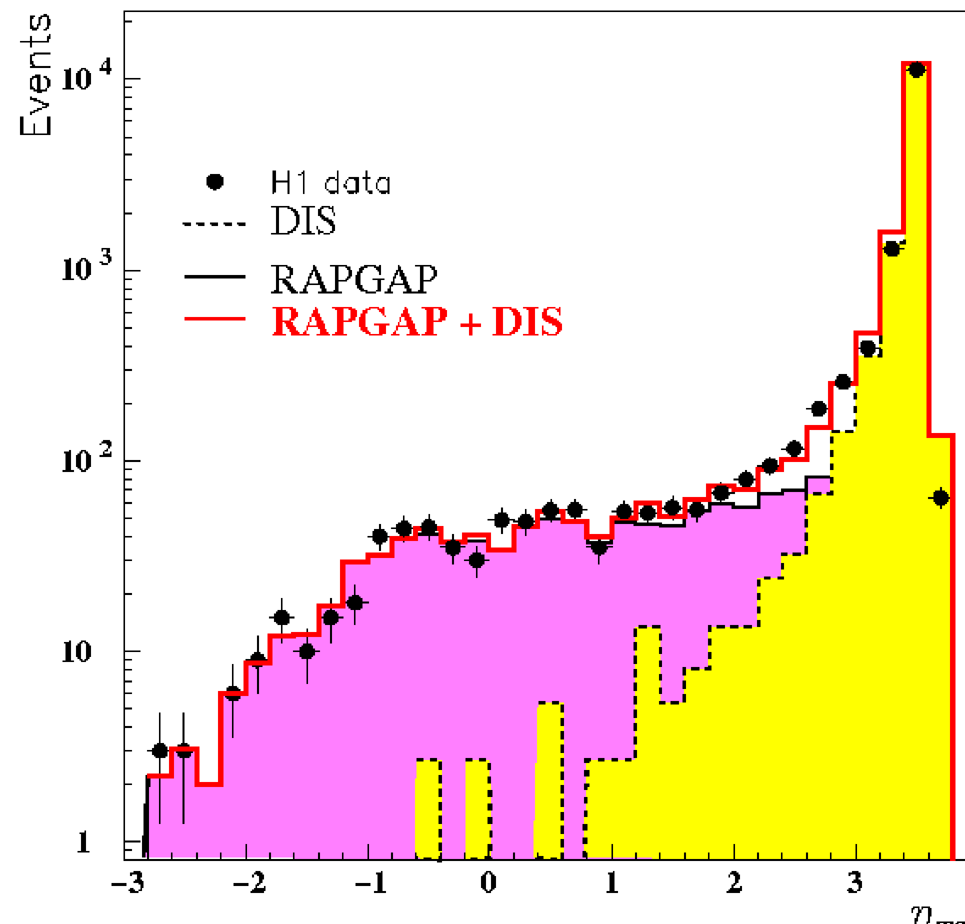


Rapidity Gap Events





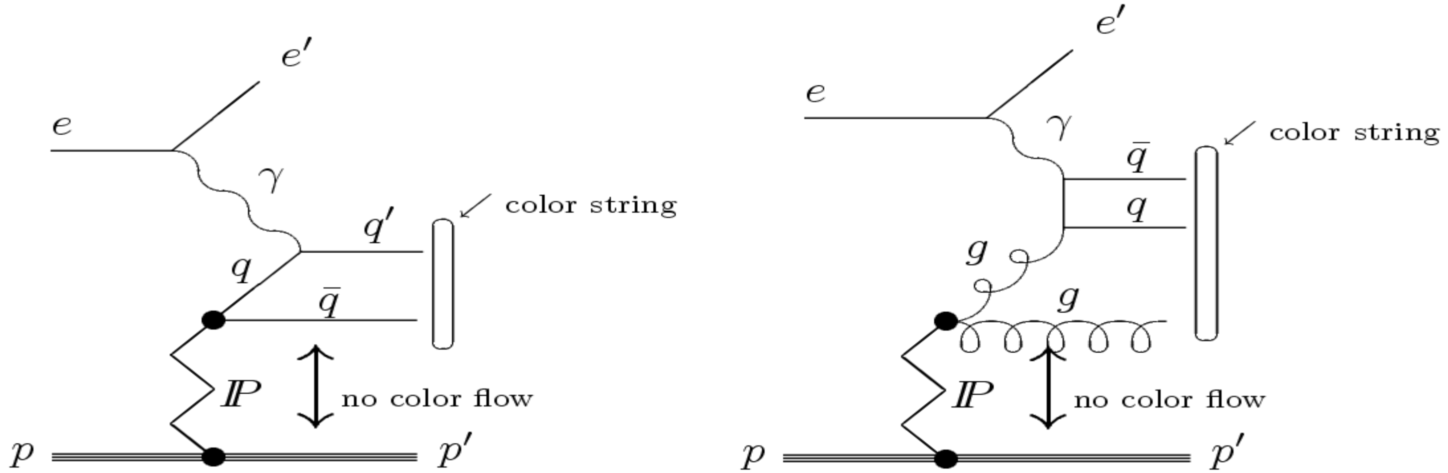
H1 Collaboration, desy 94-133



- **(Re)Discoveries at HERA**
  .... in 1994 ..
- **Diffraction in DIS !!!!!!**

The Ingelman-Schlein of diffraction

- Ingelman Schlein (IS) model for diffractive DIS



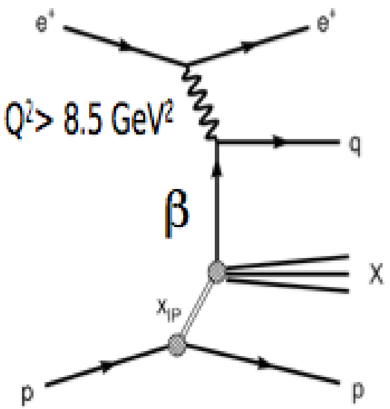
- use hard processes as in non-diffractive DIS
- use diffractive PDFs (example pomeron flux and F_2^{pom})
- additional variables:

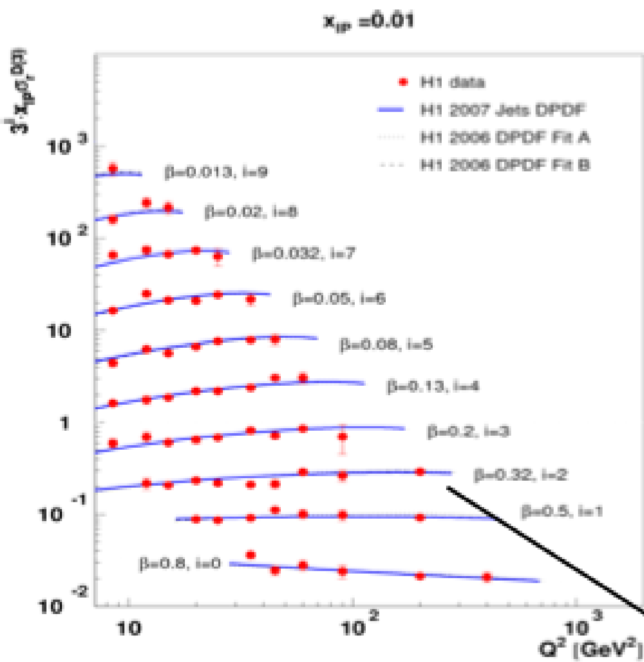
$$x_{I\!P}\beta = x_{Bj} = \frac{Q^2}{2p.q}$$

Diffractive PDF

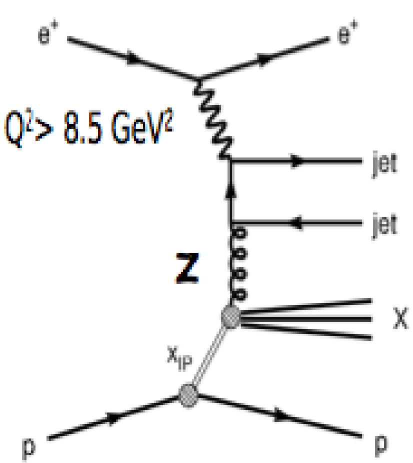
from O. Behnke, eds07

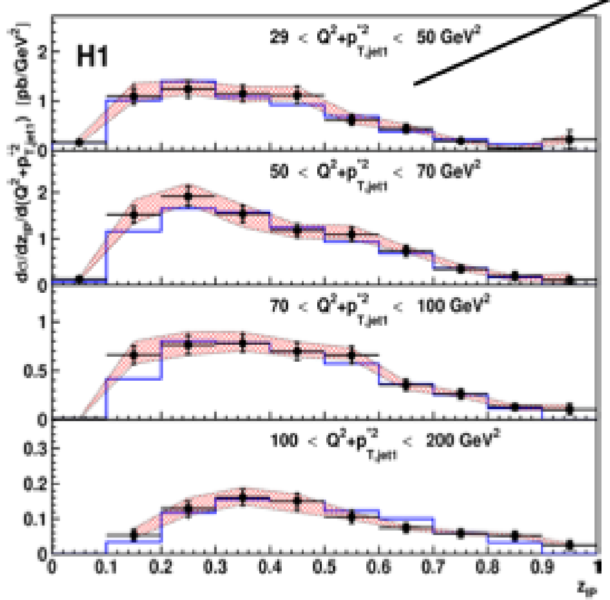
Inclusive diffr.



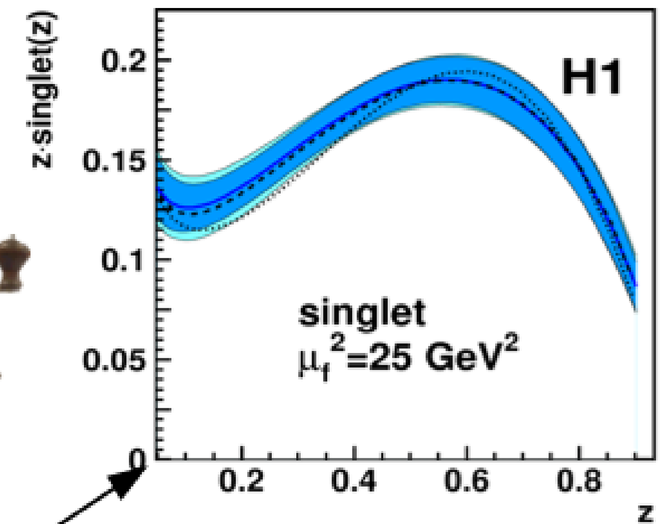


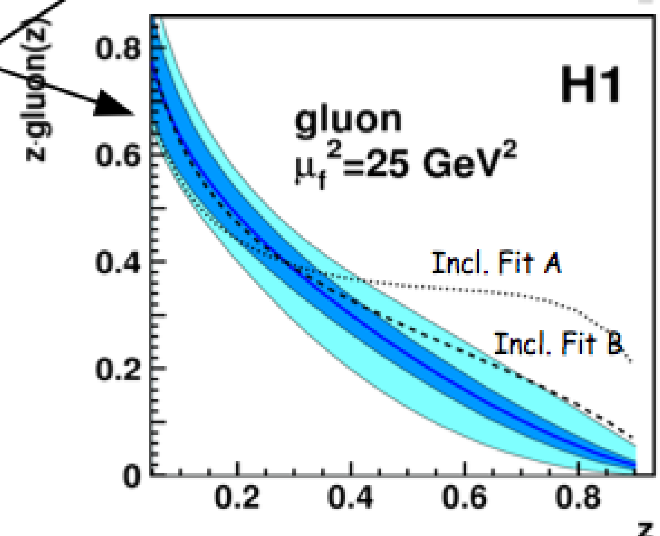
New: add info from diffractive dijets





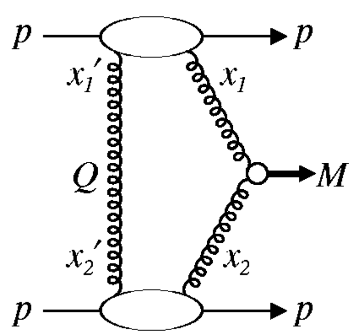
NLO FIT

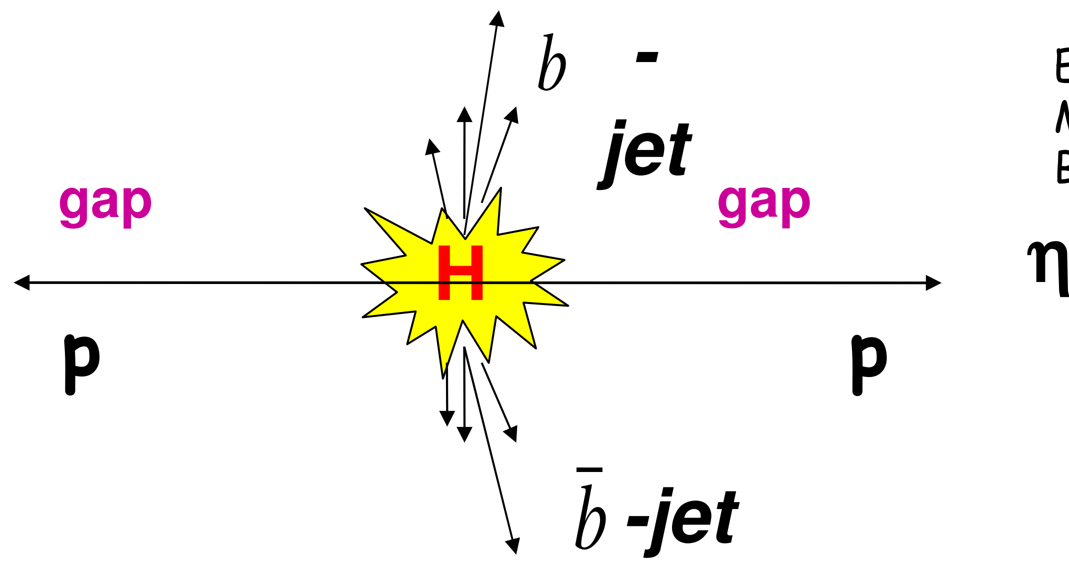




➔ Consistent picture, improved gluon density

Diffractive Higgs Production





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

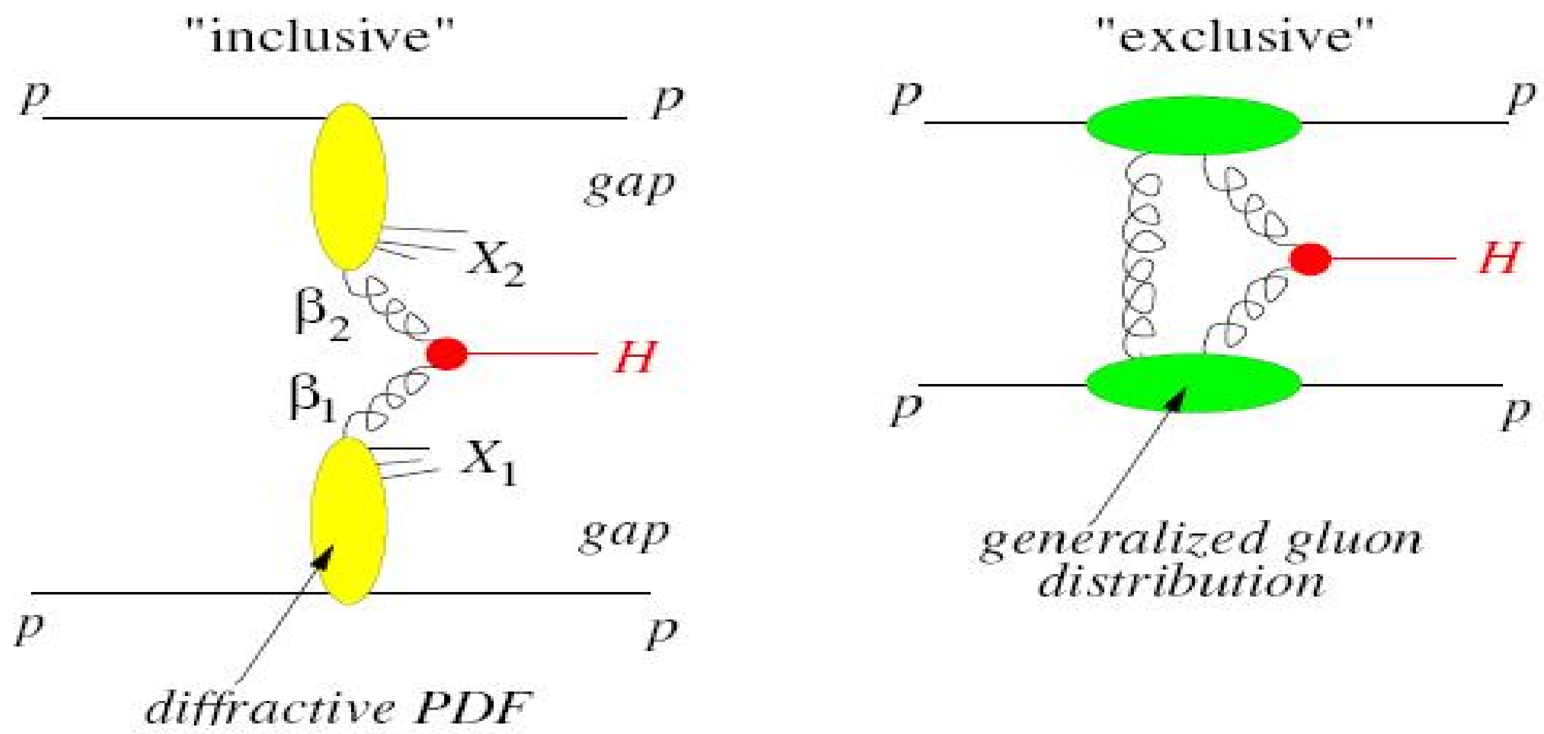
$$M_H^2 = (p + \bar{p} - p' - \bar{p}')^2$$

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

- Advantages: Mass resolution
  - from energy of protons determine mass
  - precise mass determination
- Sensitive to un-integrated pdfs

Exclusive Higgs and diff. at HERA

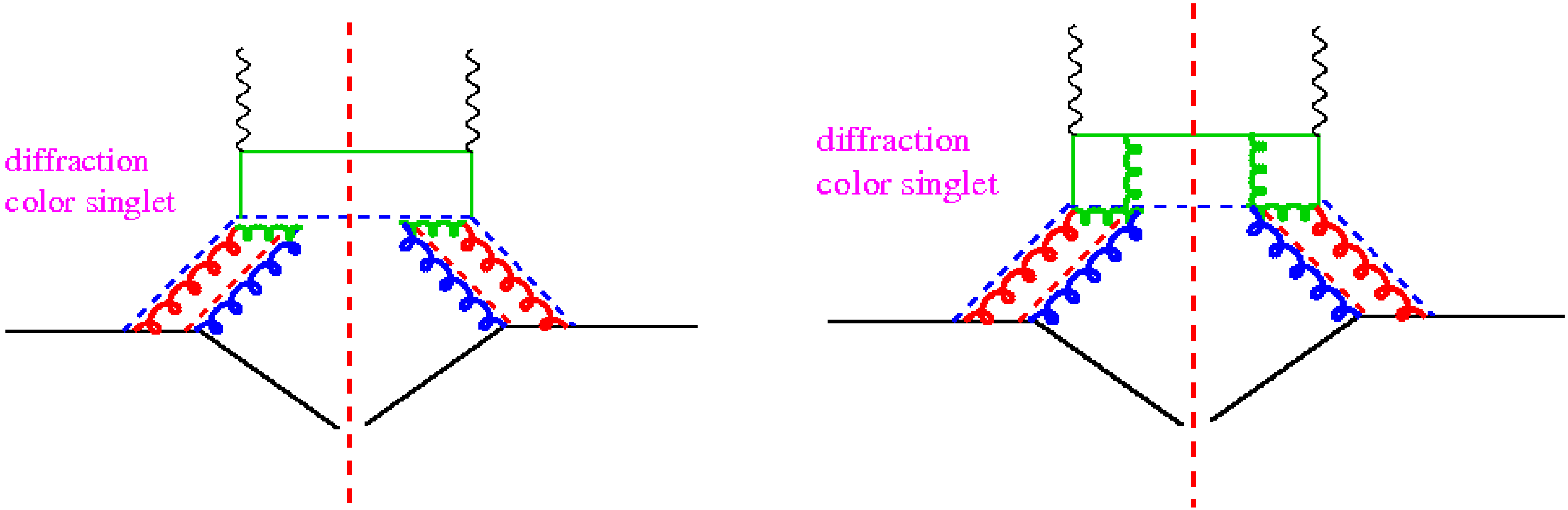
from M. Diehl



- Inclusive diff. events become background to exclusive one, when remnant systems X become soft...
- relevant region for diff. Pdfs:
- $\beta \to 1$ and $Q^2 \sim M^2_h$
- measure diff pdf at highest Q^2 and highest β ....

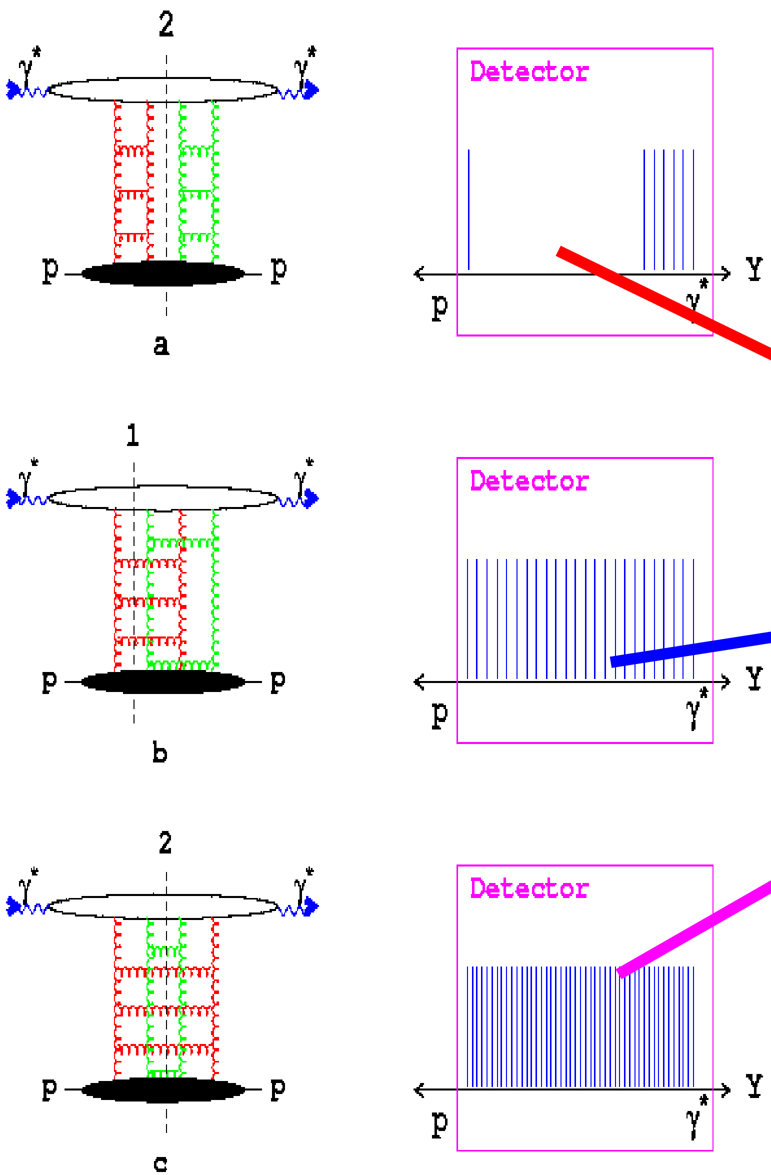
Understanding diffraction

- simplest model for Pomeron: 2 gluon system



Why we need to care about diffraction and all that ?

Towards understanding of all that ...



Bartels, Kowalski, Sabio-Vera

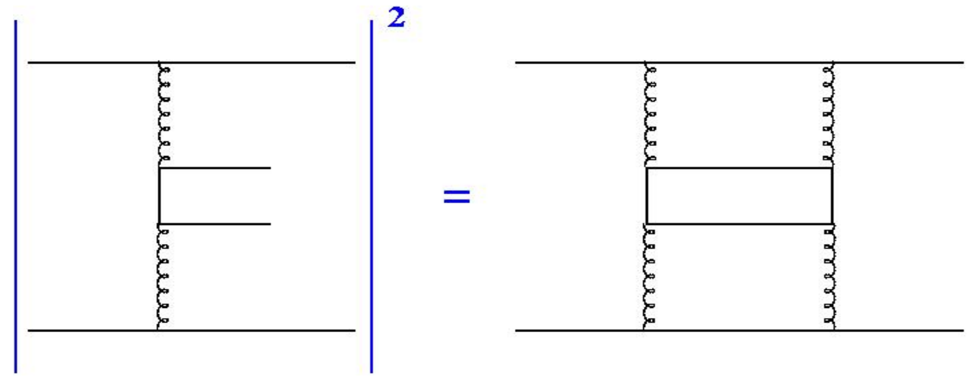
- Cutting rules (AGK) extended to QCD
- Relate diffraction, saturation and multiple scatterings
- All from the same amplitude, but different factors:
  - +1 Diffraction
  - - 4 Saturation
  - +2 Multiple Interactions
- Extended now also to pp !!!!
  - further work needed ...

➔ HERA is the place to understand MI !!!!

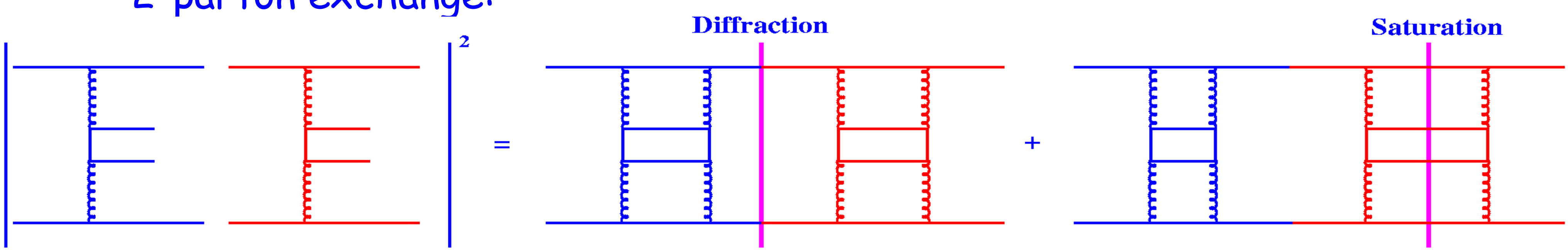
➔ Towards the description of *"everything"* !!!!!

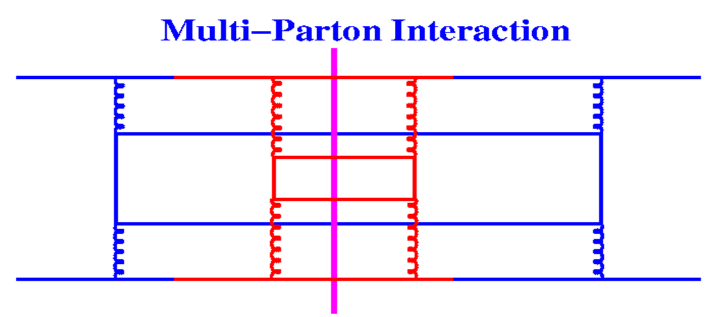
Toy Model for multi-parton scattering

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



- 2-parton exchange:

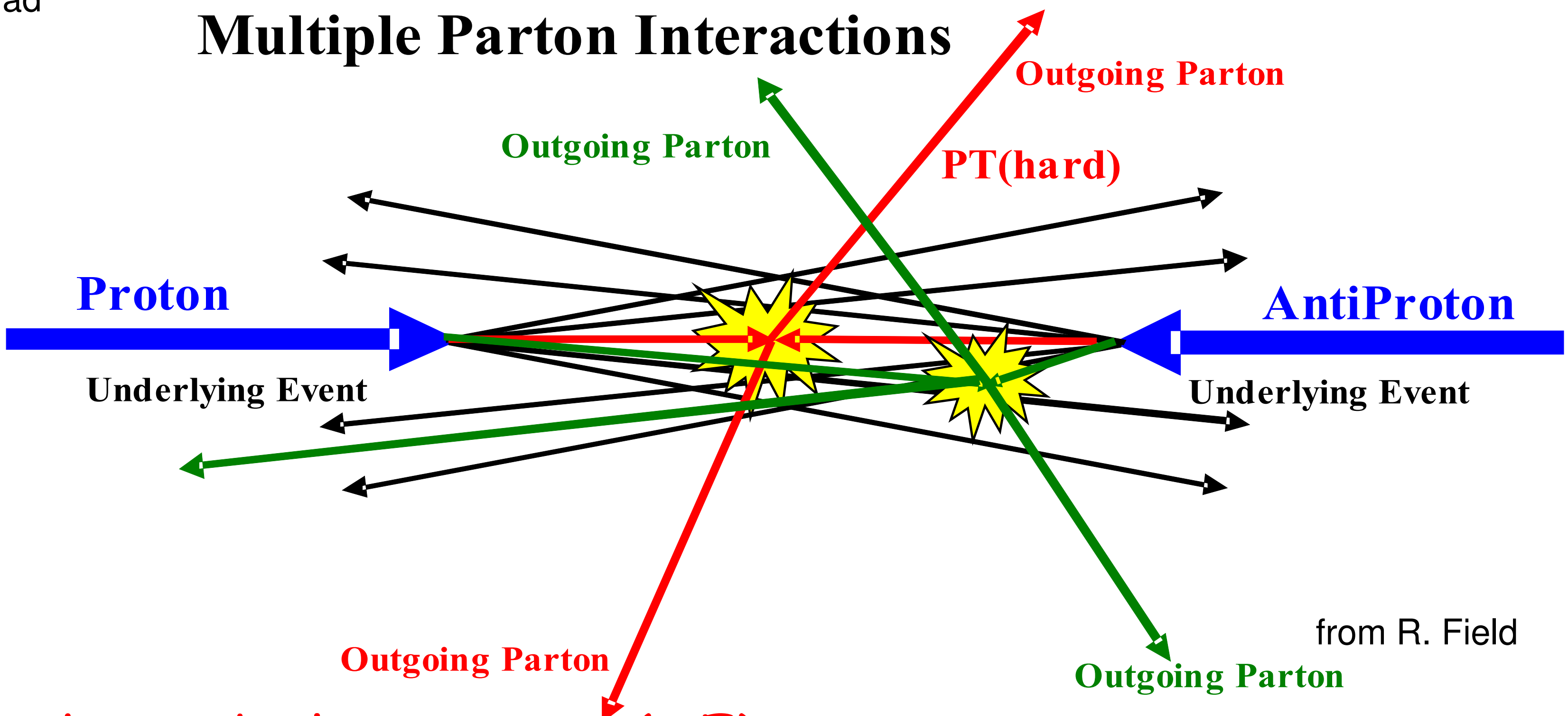




Is this at all relevant at LHC?

Multiparton Interactions

from L. Loennblad



from R. Field

What is the underlying event (UE)?

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

- *parton showers*
- *additional remnant – remnant interactions (multi-parton interactions,soft/hard)*

✗ NOT pile-up events (luminosity dependent)

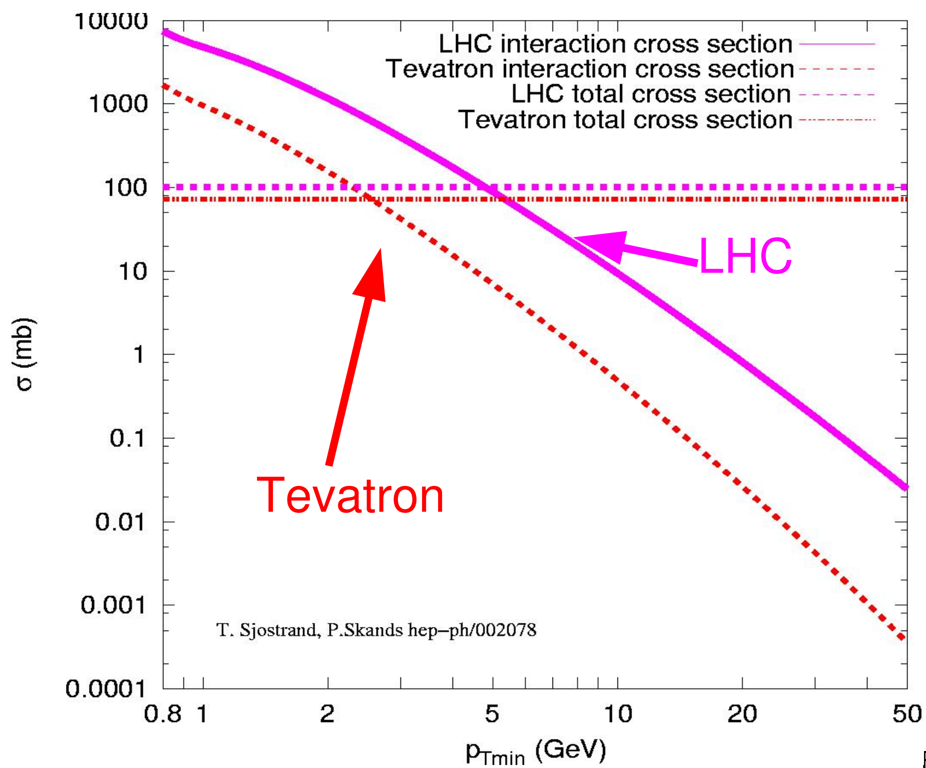
Underlying event – Multiple Interaction

- Basic partonic perturbative cross section

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

➔ diverges faster than $1/p^2_{\perp\min}$ as $p_{\perp\min} \to 0$ and exceeds eventually total inelastic (non-diffractive) cross section

- Interaction x-section exceeds total xsection
- happens well above λ_{QCD}
- still in perturbative region



Underlying event–Multiparton Interaction

- Basic partonic perturbative cross section

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

➔ diverges faster than $1/p^2_{\perp\min}$ as $p_{\perp\min} \to 0$ and exceeds eventually total inelastic (non-diffractive) cross section, resulting in more than 1 interaction per event (multiparton interactions, MI).

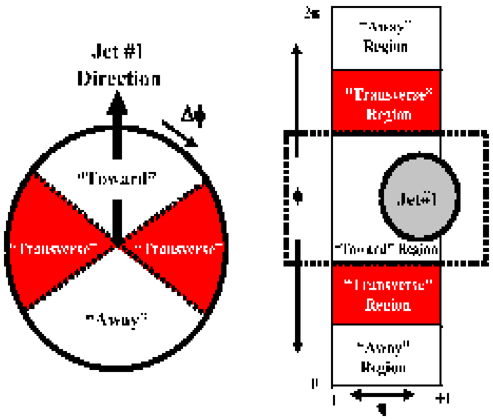
➔ Average number of interactions per event is given by:

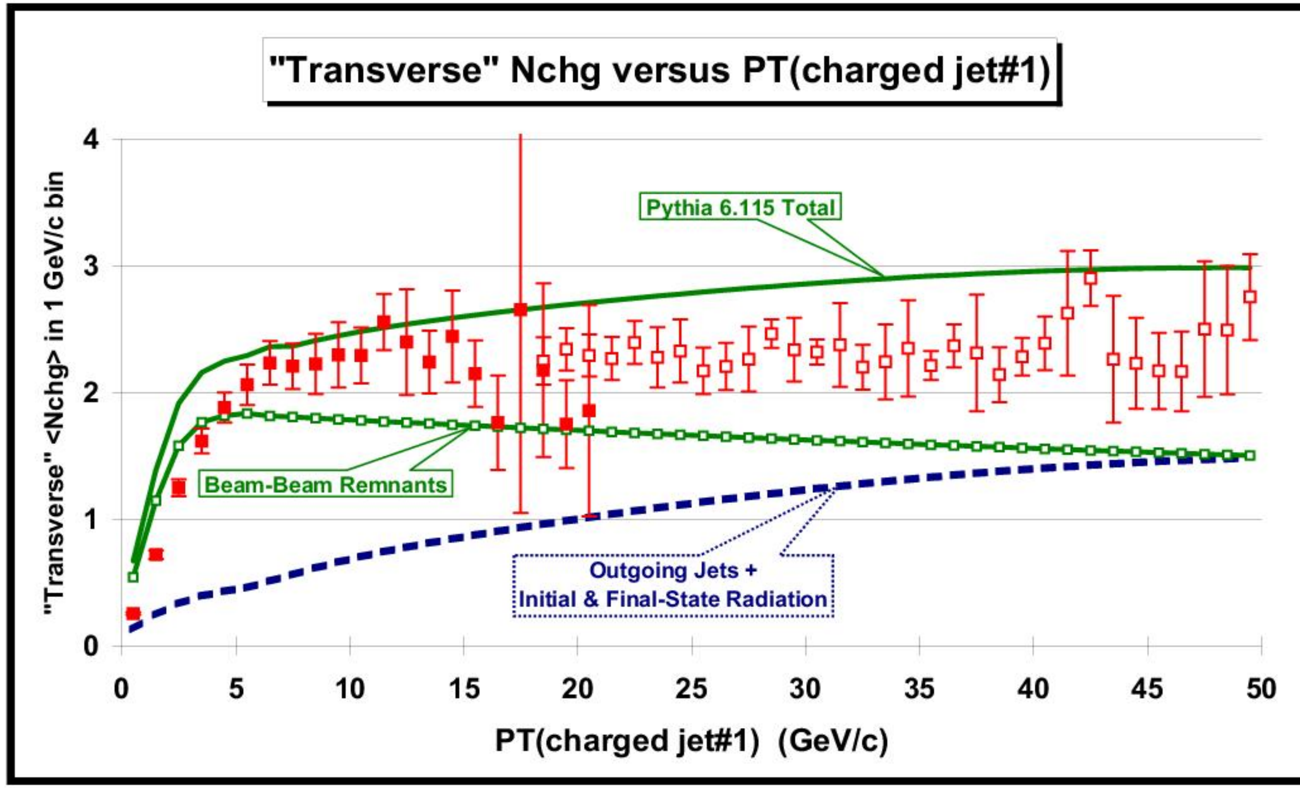
$$\langle n \rangle = \frac{\sigma_{\text{hard}}(p_{\perp\min})}{\sigma_{nd}}$$

- It depends on how soft interactions are treated, ***BUT*** also on the parton densities and factorization scheme, parton evolution (DGLAP/BFKL) !!!!!!!!

Multiparton Interactions at CDF

CDF coll. PRD 65, 092002 (2002)





- Multiplicity distribution in region transverse to jet can only be described by adding multi-parton interactions (Remnant- Remnant Interactions)

Tuning to CDF data... Color flow in MI

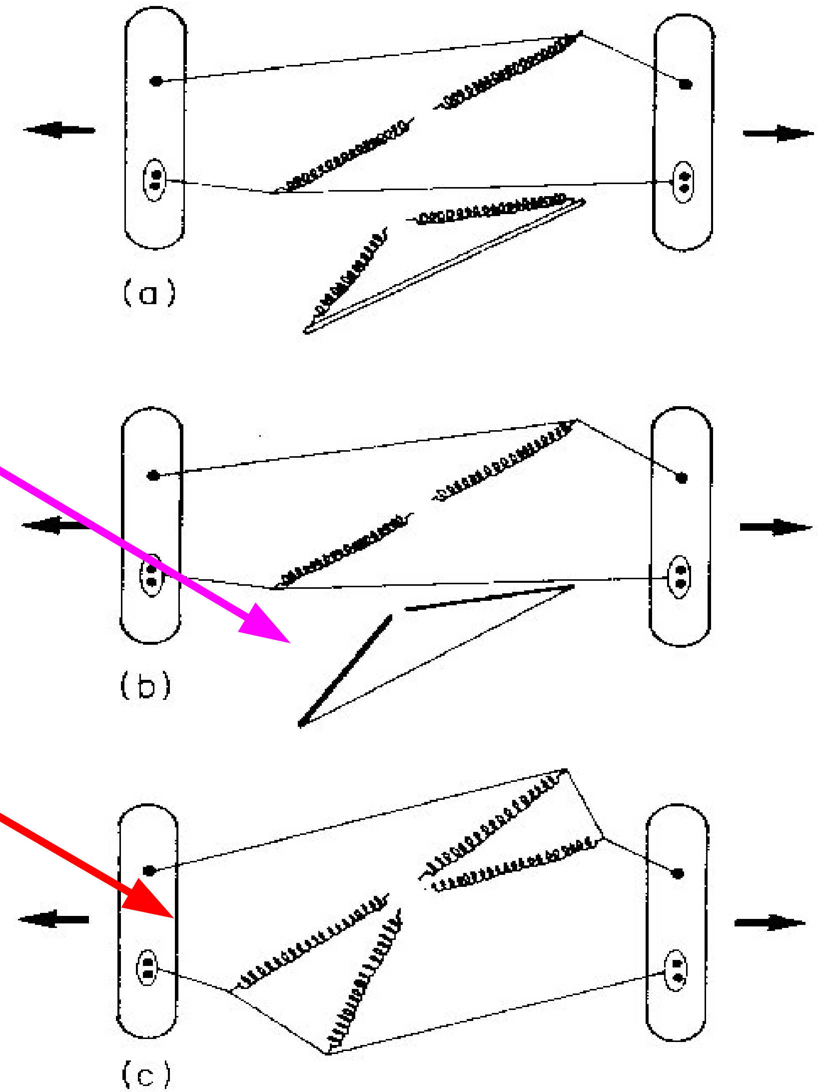
T. Sjostrand, M. Zijl
PRD 36 (1987) 2019

- possible scenarios for color string connection in multiparton events
- to describe underlying events.... need (CDF Tune A)

  5 % quarks (default 33 %)
  95 % gluons (default: 66%)
  out of which 90 %
  (default 33 %) are

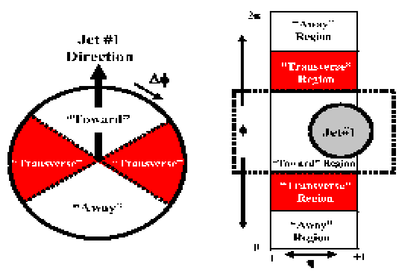
➔ smaller multiplicity
  with large transverse energy

- Are there good phyiscs reasons for this mix ???
- **Highly nontrivial to describe multiplicity AND transverse energy distributions ...**



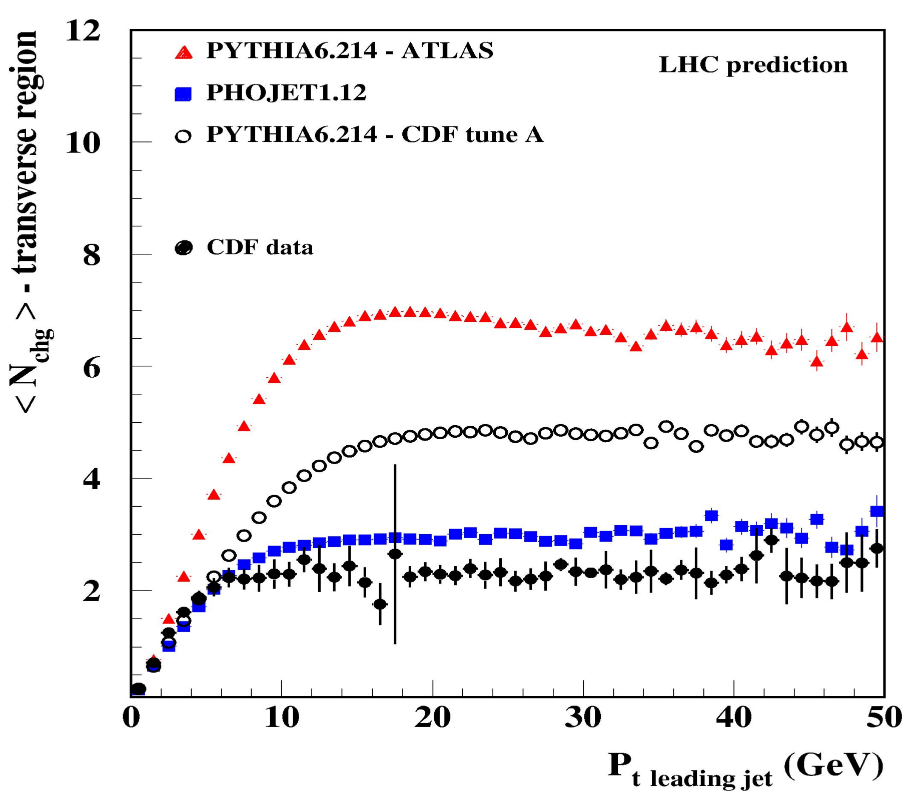
Multiparton Interactions at LHC

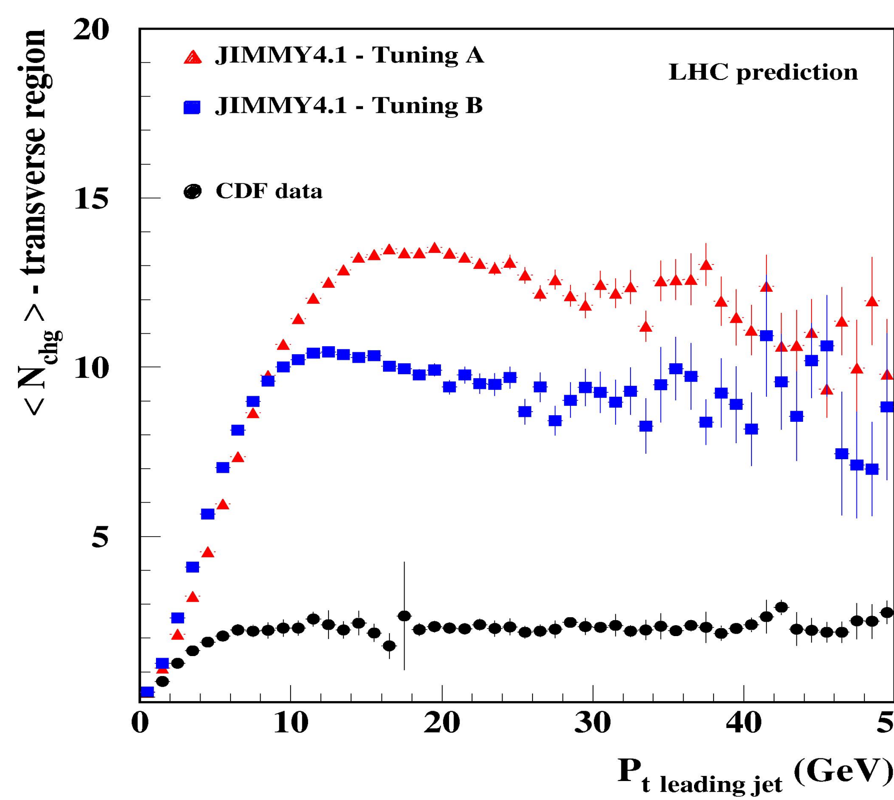
C. Buttar et al in HERA – LHC workshop proceedings hep-ph/0601012



Charged multiplicities in transverse region

- Models tuned to TeVatron data
  - ➔ give **HUGE** differences at LHC ...
  - ➔ **better understand multiple interactions ...**
    - ➔ photo-production of jets at HERA T. Namsoo

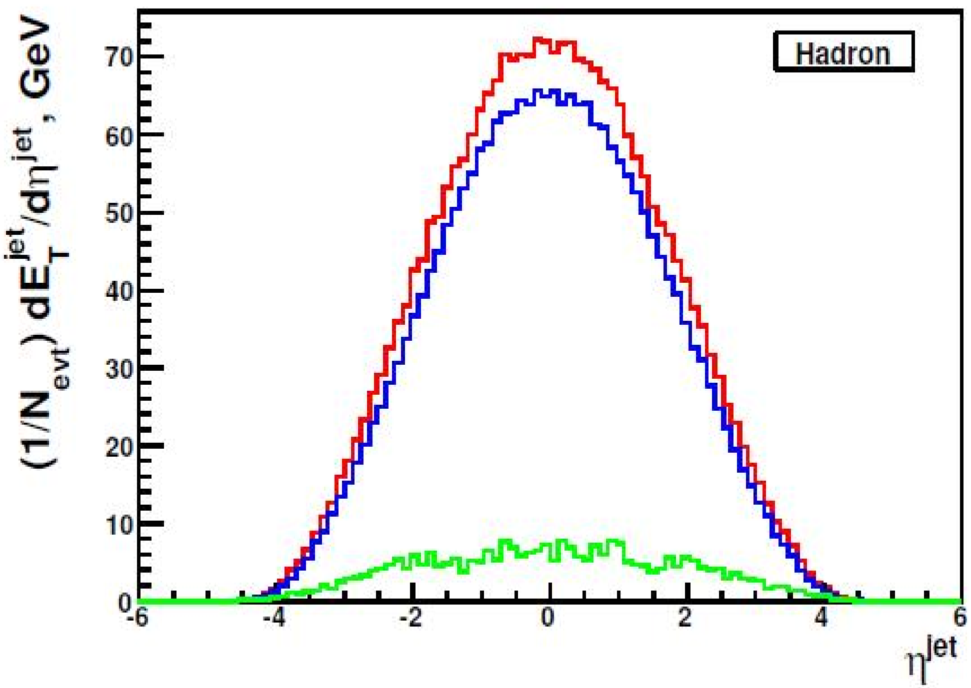


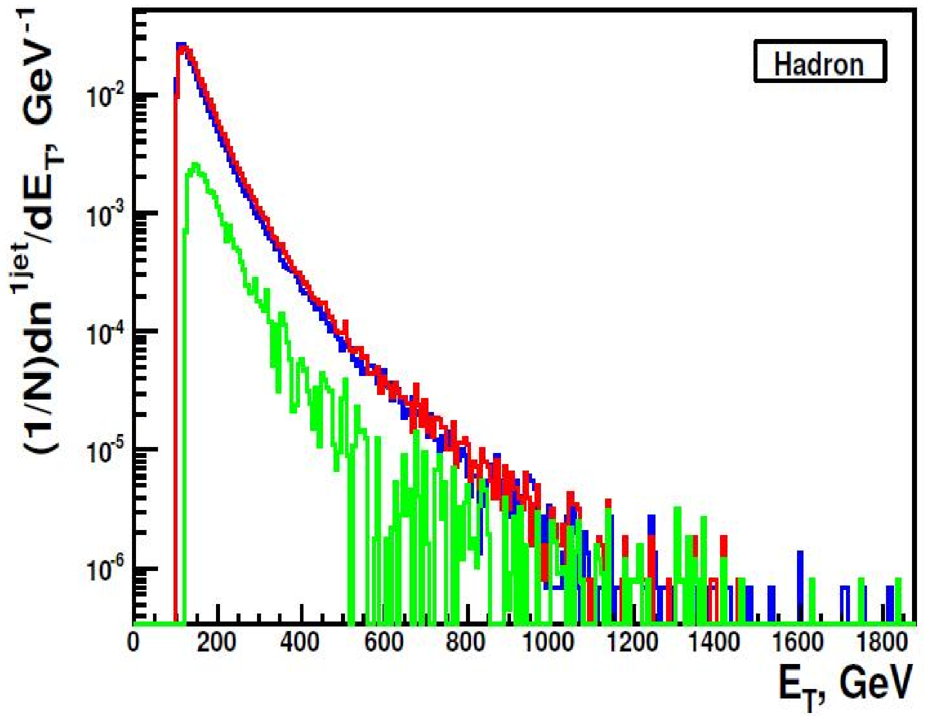


Multiparton Interactions and Jets

P. Starovoitov, T. Carli
HERA-LHC WS, June 2006

- SHERPA: $E_T > 100\,\mathrm{GeV}, |\eta| < 5$



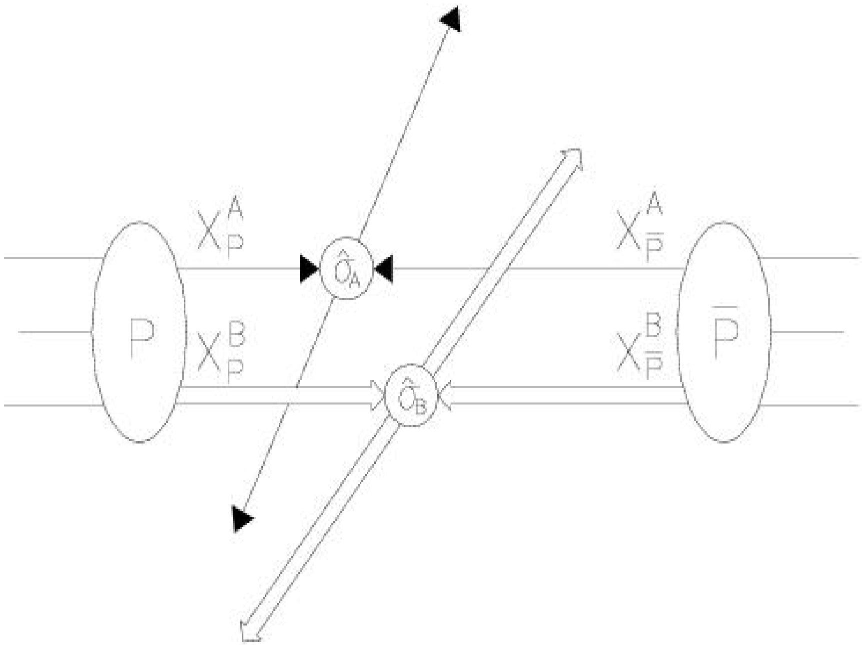


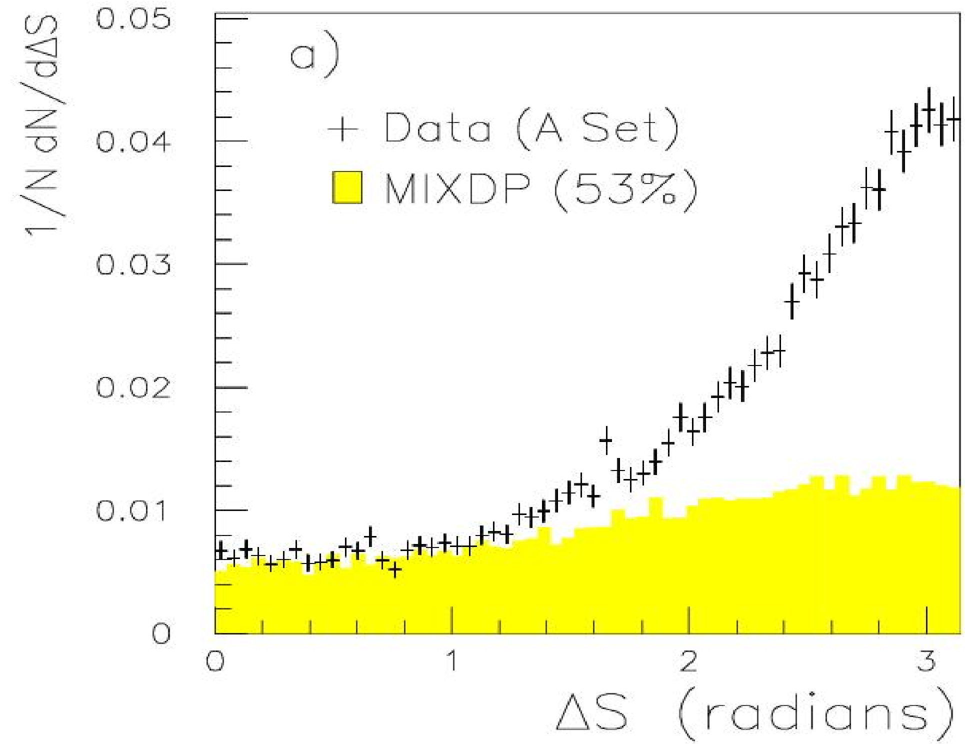
Hard Scale, HS+UE, Difference

- UE contributes ~ 10 - 30 % to Jets, even at large E_t !!!!
- **need reliable model for UE**
- **Factorization ??!!??**

Evidence for Multi-Parton Interactions

CDF coll. PRD 56, 3811 (1997)





- look at $\gamma + 3$ Jets with

$$E_T^{\gamma} > 16 GeV$$
$$E_T^{Jets} > 5 GeV$$

- angular correlation of jet/photon pairs ΔS
- compare to $\gamma + 3$ Jets calculation
- **Need > 50 % double parton interaction to describe data**

Double-Parton Interactions at LHC

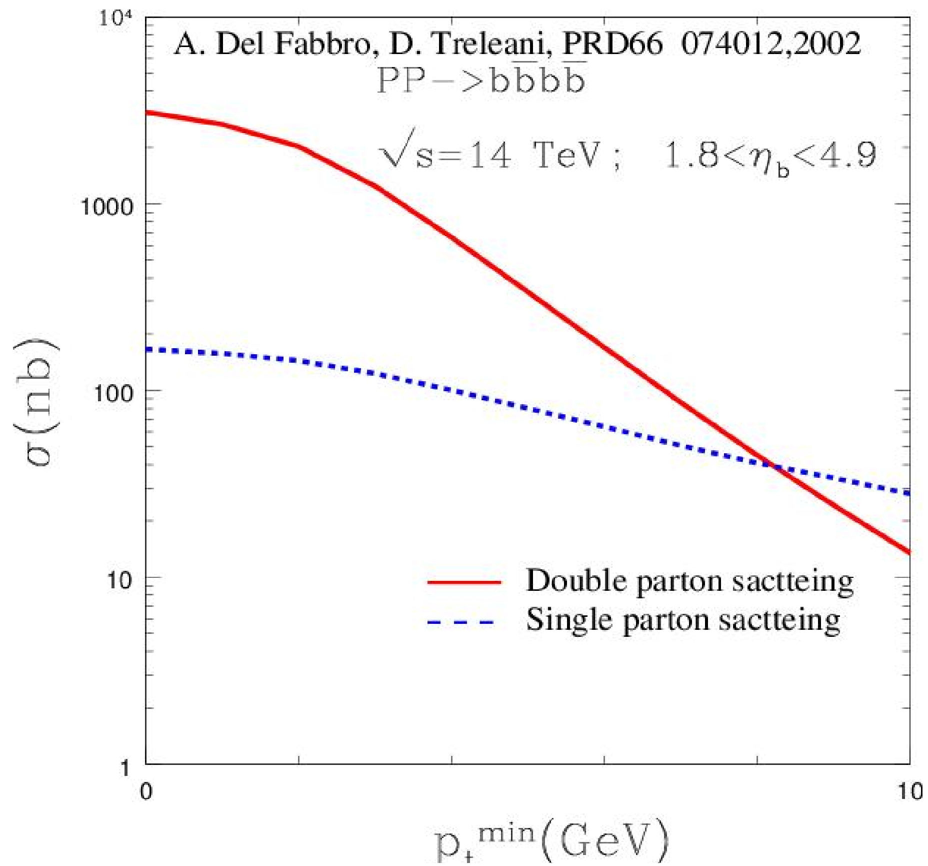
- xsection for $p + p \to b\bar{b}b\bar{b}$

  single parton exchange (SP)

  $\sigma^{SP} \sim f^2 \hat{\sigma}(2 \to 4)$

  double parton exchange (DP)

  $\sigma^{DP} \sim f^4 \hat{\sigma}^2(2 \to 2)$



- PYTHIA predictions:

  $\sigma^{DP} = 0.8 \cdots 11.1\ \mu b$

➔ Depending on model for underlying event/muli-parton interactions...

Multi-Parton Interactions at LHC

- Higgs: $p+p \to W+H+X$

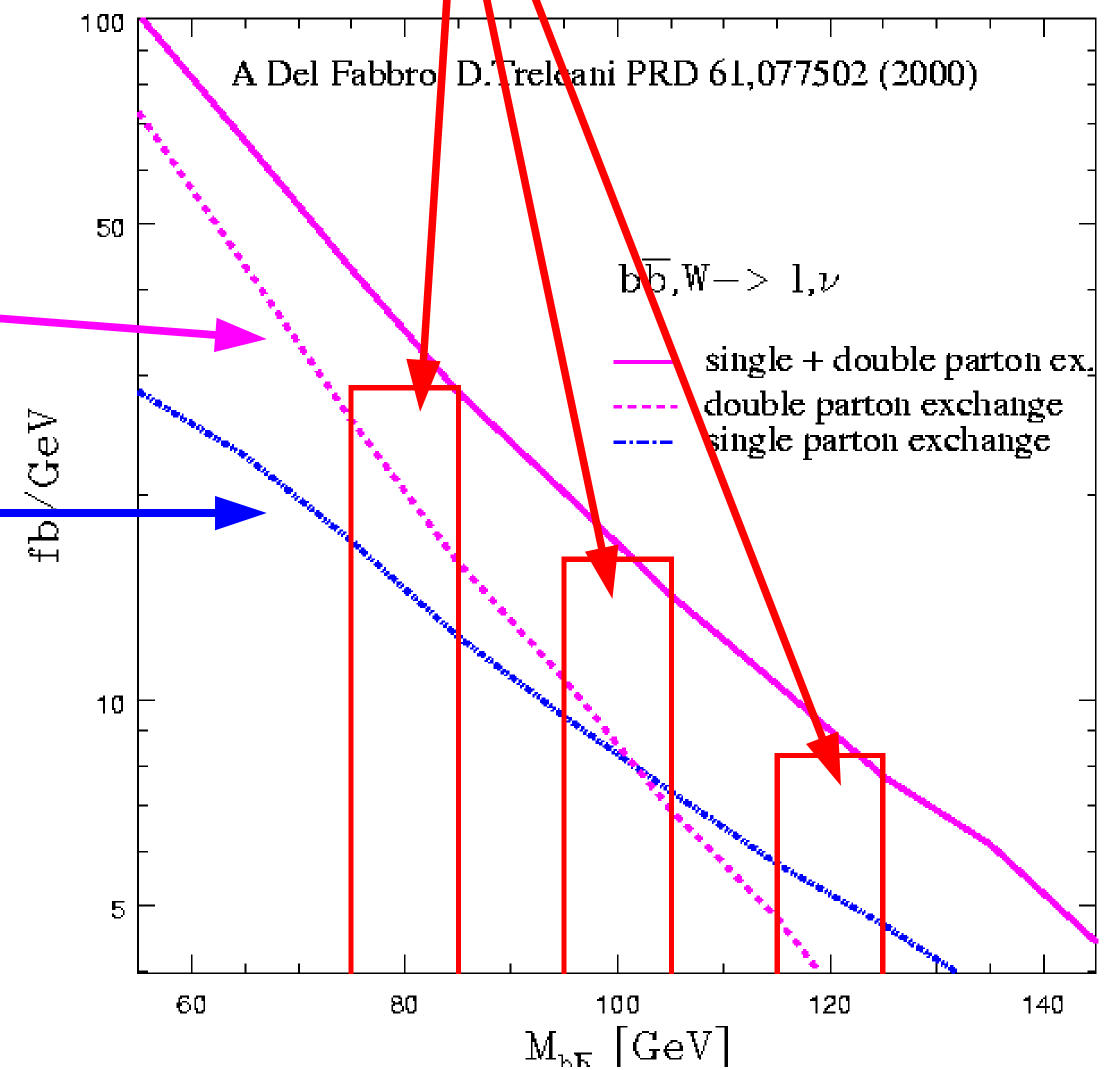
  with $W \to l\nu, \;\; H \to b\bar{b}$
- Double parton scattering:

➔ $p+p \to b\bar{b}X$

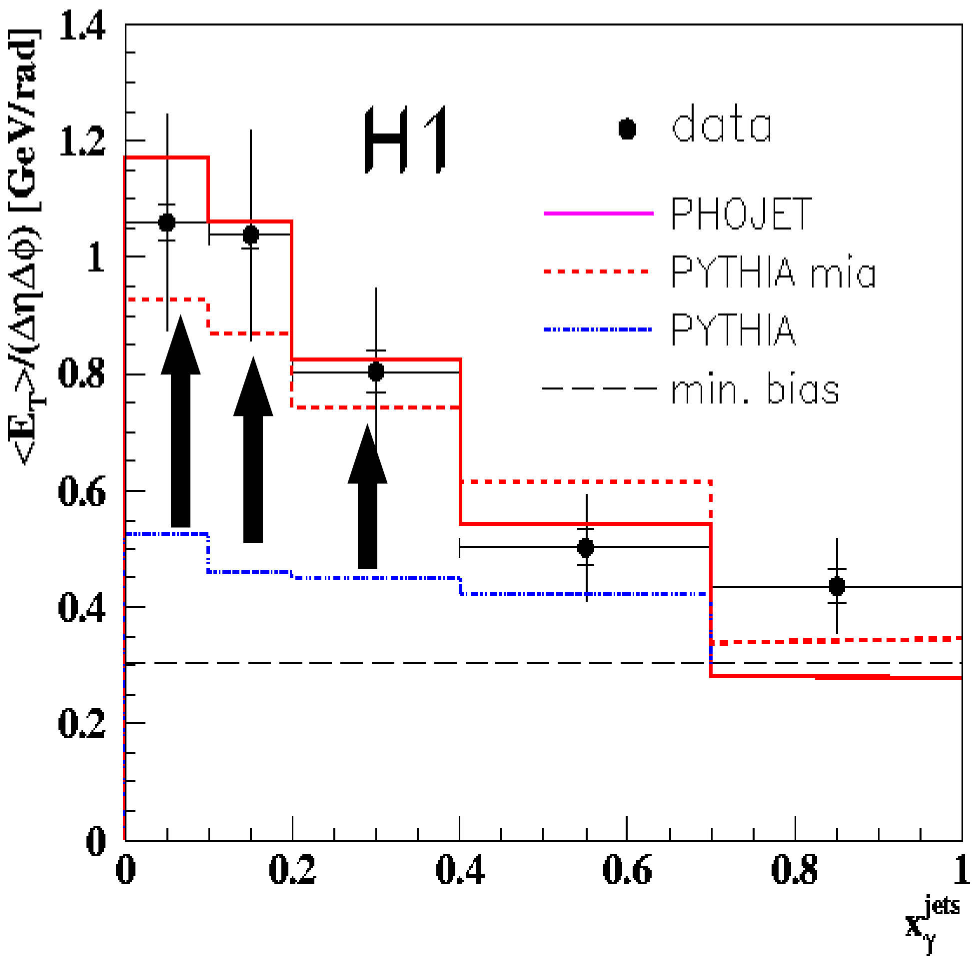
$p+p \to W+X$

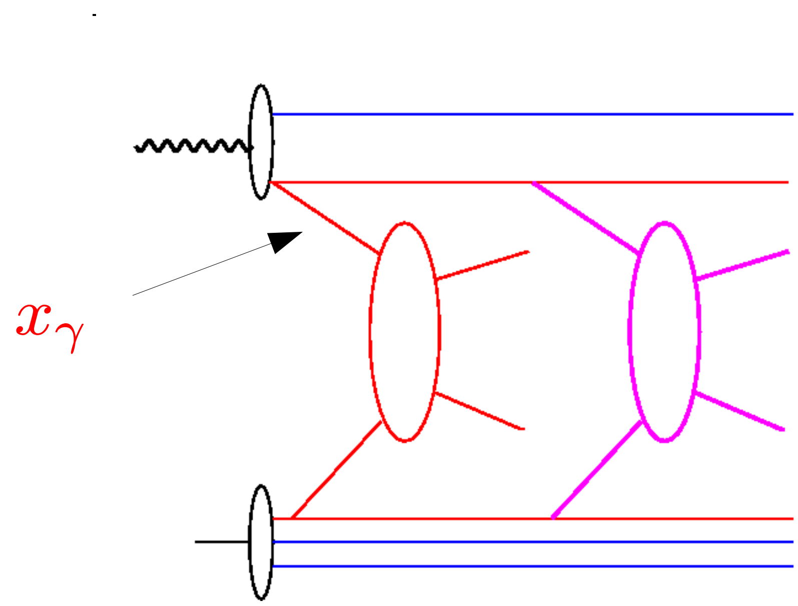
- $p+p \to W+b\bar{b}+X$

$p+p \to W+H+X$



Multiple Interactions at HERA

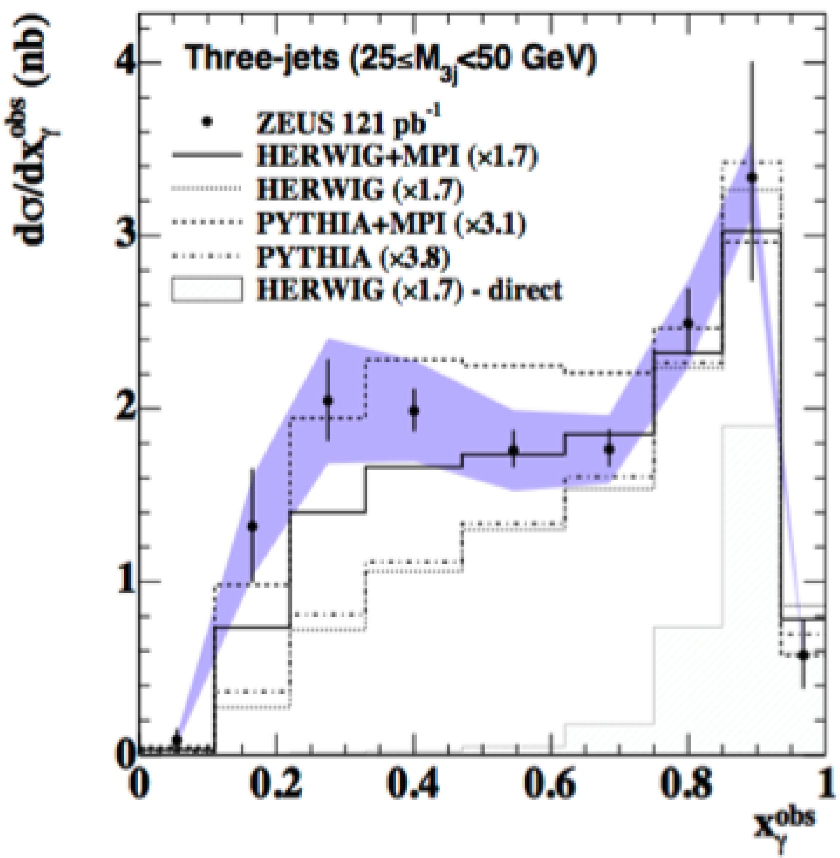




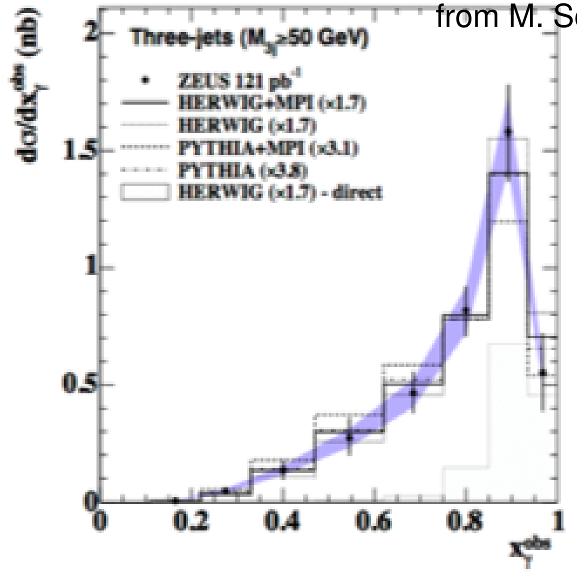
photoproduction is effectively hadron-hadron production...

Test and understand multiple interactions at HERA !!!

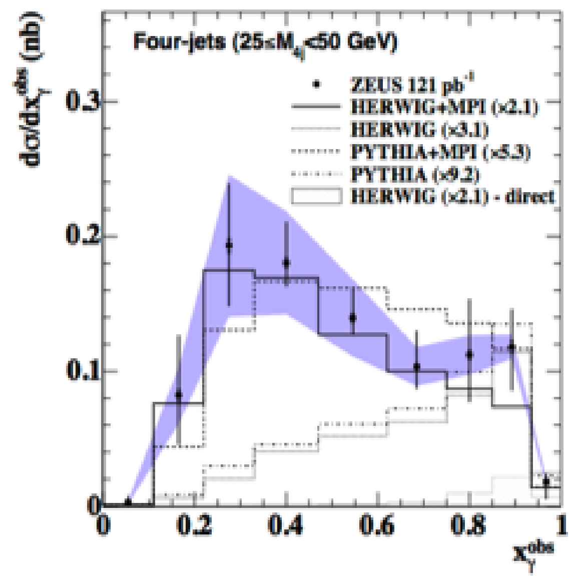
Multiple Interactions at HERA



from M. Soares, EPS07



General improvement
adding MPIs to LO MC



EPS07 Multijet production at HERA

Multiparton Interactions at LHC

- Multiparton Interactions play a role in soft **BUT** also in high pt processes
- Theoretical description is tricky ...
- Models can be tuned to describe TeVatron measurements
  - at the price of "just reasonable" parameters
- **Extrapolation to LHC:**
  - questionable, because of high parton densities at small x
  - possible non-linear effects: saturation, small x increase
  - Color flow is far from clear...
  - Stay tuned to surprises ...

Conclusions

- HERA physics is very rich:
  - from inclusive x-section measurements to detailed investigations of QCD
  - measurements of hadronic final states:
    - jets, heavy flavors
    - ➔ leads to a detailed understanding of QCD
    - ➔ new issues addressed:

      integrated PDFs, uPDFs, etc ...

      saturation, diffraction, multi-parton interactions...
- HERA implications for LHC
  - ➔ PDFs, small x, multiple interactions, diffraction

It all comes from the high gluon density ....

Understanding of QCD at high energies is still challenging !