Determination of TMDs from HERA

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Outline:

- TMDs from HERA
  - all loop CCFM gluon TMD
    - Fits to F_2
    - uncertainties
  - one loop mode
    - inclusion of quarks
    - Fits to F_2

Evolution equation and TMDs

$$xA(x,k_t,q) = xA(x,k_t,q_0)\Delta_s(q) + \int dz \int \frac{dq'}{q'} \cdot \frac{\Delta_s(q)}{\Delta_s(q')} \tilde{P}(z,k_t,q') \frac{x}{z} A\left(\frac{x}{z}, q'\right)$$

- solve integral equation via iteration:

from q′ to q w/o branching

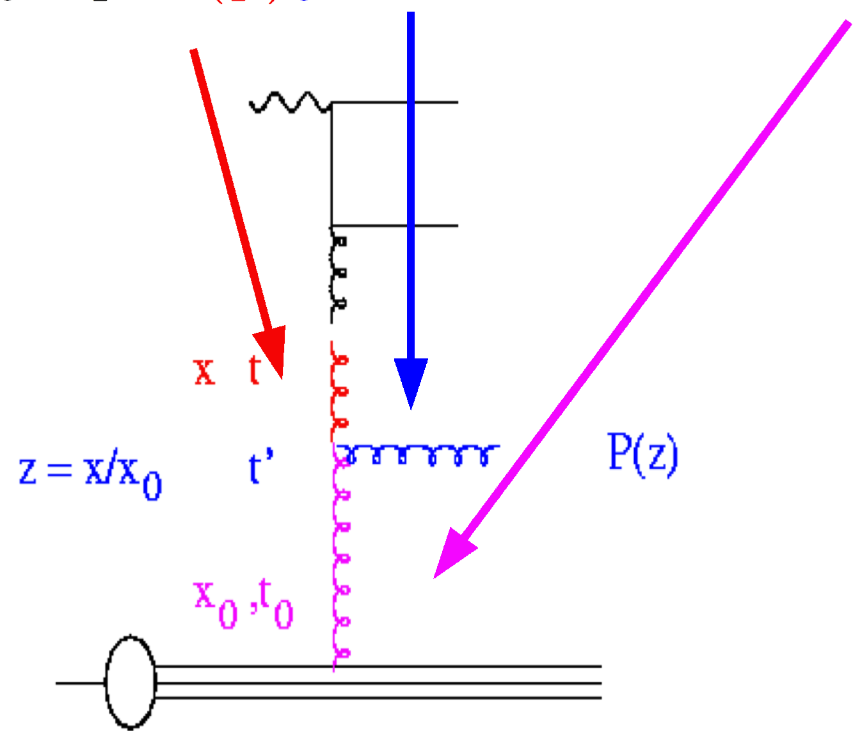
branching at q′

from q_0 to q′ w/o branching

$$xA_0(x,k_t,q) = xA(x,k_t,q_0)\Delta(q)$$

$$xA_1(x,k_t,q) = xA(x,k_t,q_0)\Delta(q) + \int \frac{dq'}{q'} \frac{\Delta(q)}{\Delta(q')} \int dz \tilde{P}(z) \frac{x}{z} A(x/z, k_t', q_0)\Delta(q')$$

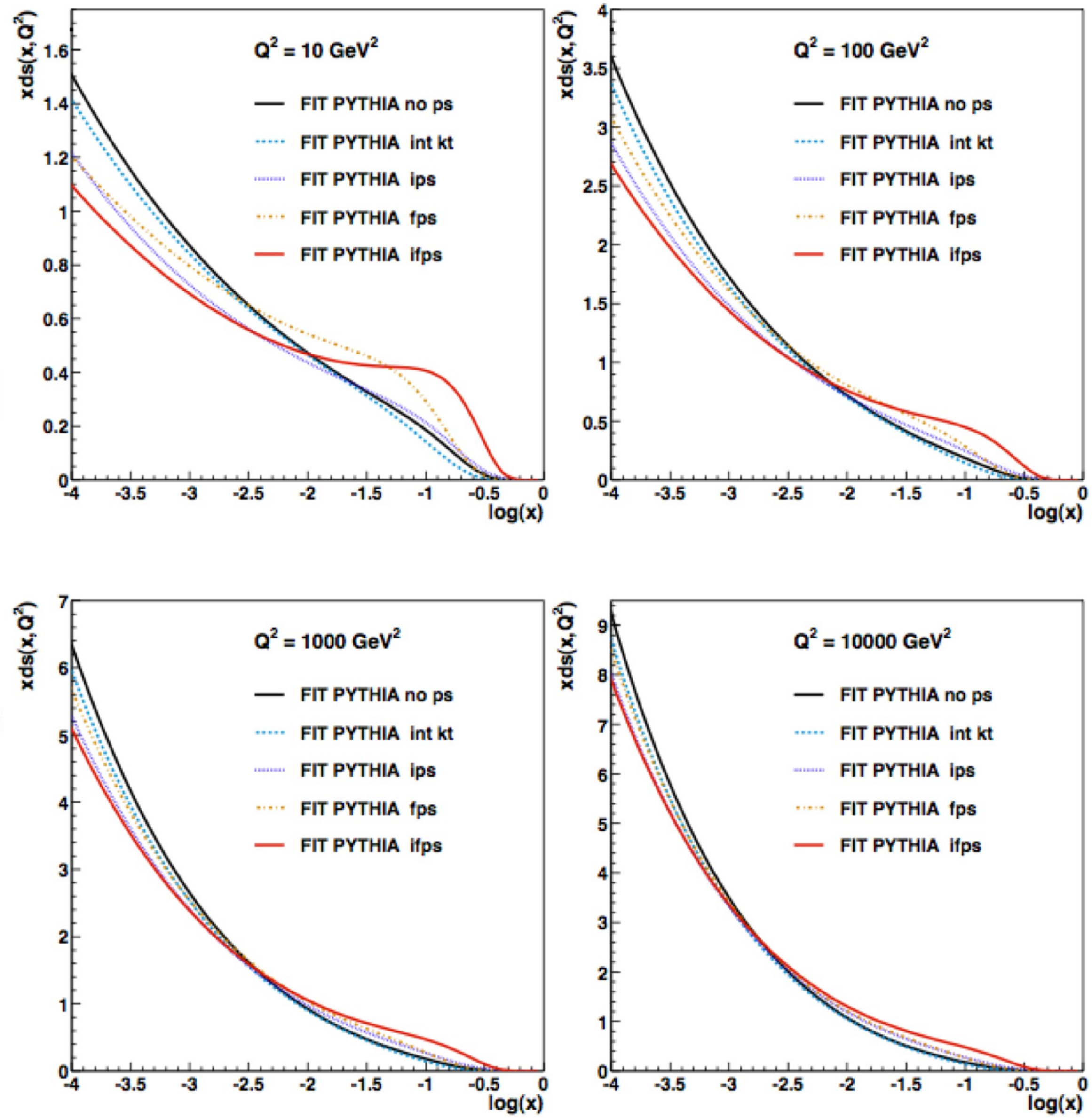
- Note: evolution equation formulated with Sudakov form factor is equivalent to “plus” prescription, but better suited for numerical solution for treatment of kinematics



Are TMDs really necessary ?

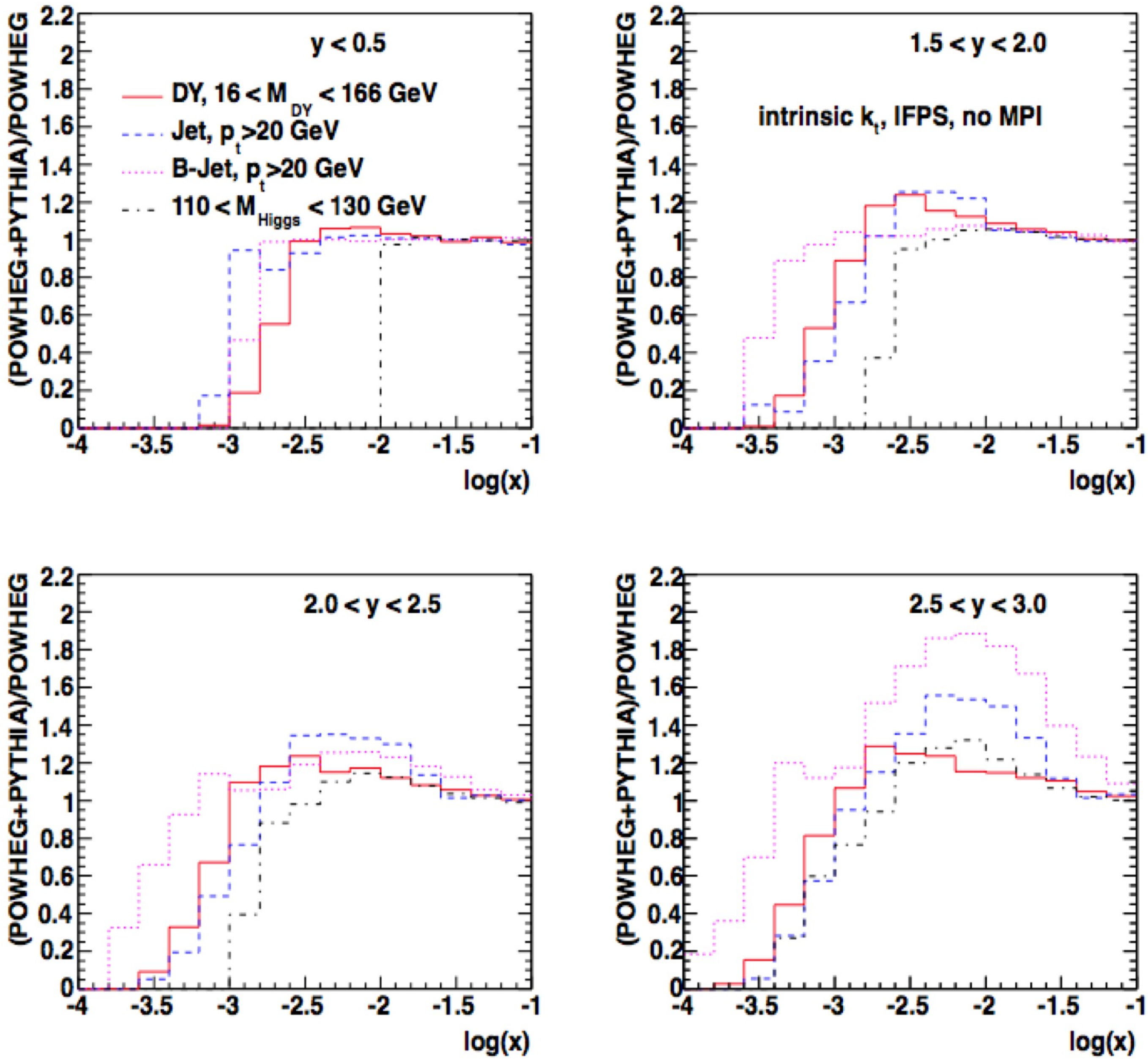
Determination of parton density functions using Monte Carlo event generator Federicon Samson-Himmelstjerna /afs/desy.de/group/h1/psfiles/theses/h1th-516.pdf

- perform fits to F_2 using a Monte Carlo event generator which includes parton showers and intrinsic k_t
- the resulting PDFs agree with standard LO ones if no PS and intrinsic k_t is applied.
- the final PDFs are different because of kinematic effects coming from transverse momenta of PS and intrinsic k_t



TMD effects in pp

- TMDs are relevant for many processes at LHC
- parton shower matched with NLO (POWHEG) generates additional k_t, leading to energy-momentum mismatch
- detailed discussion by S.Dooling: *Non-perturbative and Parton Shower corrections in matched NLO-shower event generators* n WG4 QCD and HFS

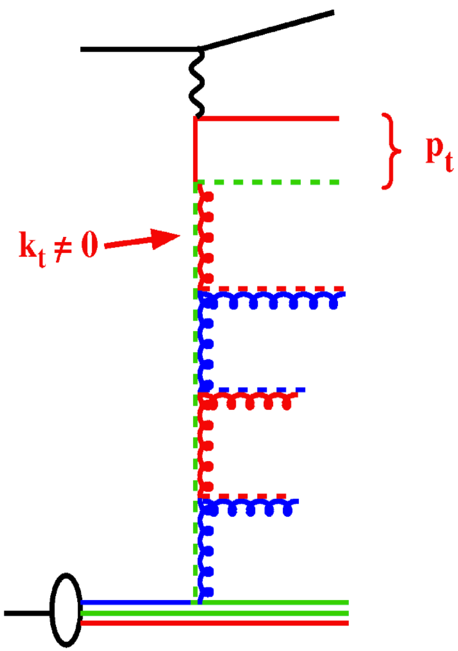


Determination of TMDs

- Apply formalism to describe HERA F_2 measurements
  - start with gluon only for small x
    - in “all loop” mode (CCFM with full angular ordering $\rightarrow$ no k_t ordering at small x)
    - in “one loop” mode (with angular ordering $\rightarrow$ p_t ordering at small x)
  - include valence quarks (for large x)
  - include $g \rightarrow q\bar{q}$ splitting
    - apply GRV approach (for technical reasons)
    - only gluons and valence quarks at q_0
      - sea-quarks only from gluon splitting

      ➔ need only determination of parameters for gluon

TMDs from $F_2(x,Q^2)$ – general case



- $$\frac{d\sigma}{dx dQ^2} = \int dx_g \left[dk_\perp^2 x_g \mathcal{A}_i(x_g, k_\perp^2, p)\right] \times \hat{\sigma}(x_g, k_\perp^2, x, \mu_f^2, Q^2)$$

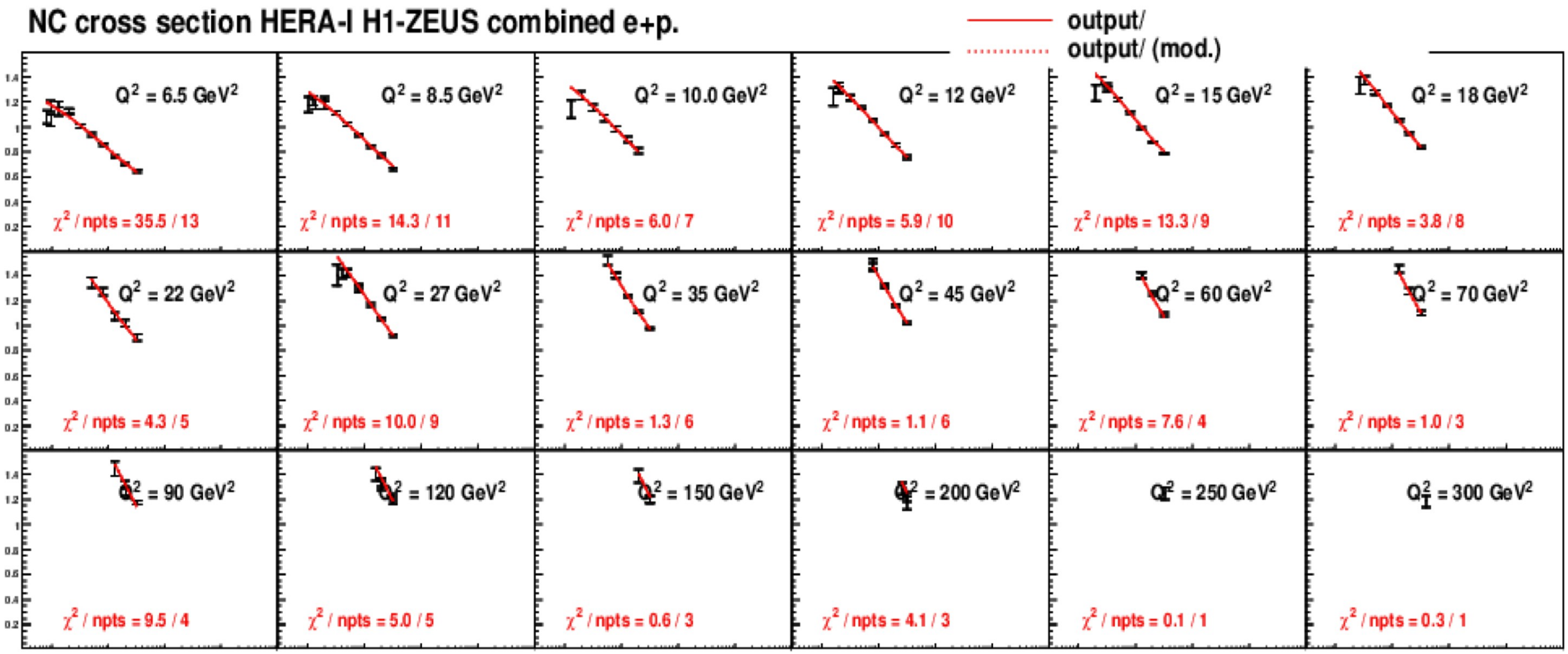
$\hat{\sigma}(x_g, k_\perp^2, x, \mu_f^2, Q^2)$ is (off-shell, k_t -dependent) hard scattering cross section

- until now, only gluon TMDs were determined
- valence quarks from starting distribution of HERAPDF1.5

$$\begin{aligned} xQ_v(x,k_t,p) &= xQ_{v0}(x,k_t,p) + \int \frac{dz}{z} \int \frac{dq^2}{q^2}\, \Theta(p - zq) \\ &\times \Delta_s(p,zq) P(z,k_t)\; xQ_v\left(\frac{x}{z}, k_t + (1-z)q, q\right) \end{aligned}$$

$$P(z,k_t) = \bar{\alpha}_s\left(k_t^2\right) \frac{1+z^2}{1-z}$$

σ_r from HERA and small x improved gluon TMD

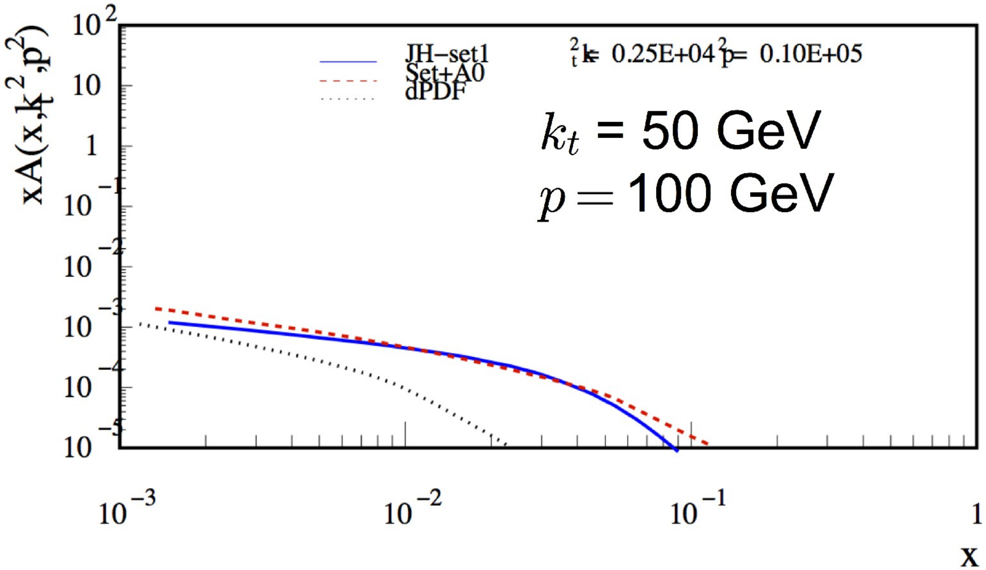


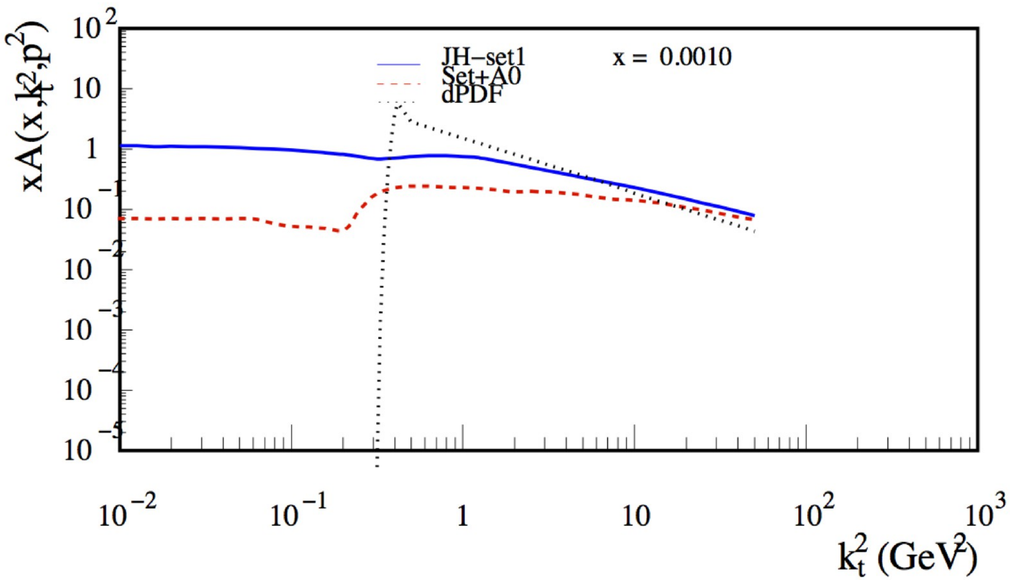
- fit performed with `herafitter` package in range:

$$Q^2 > 5 \text{ GeV}, \quad x < 0.005$$

➔ $\chi^2/ndf \sim 1.2$

CCFM gluon from F_2 fit





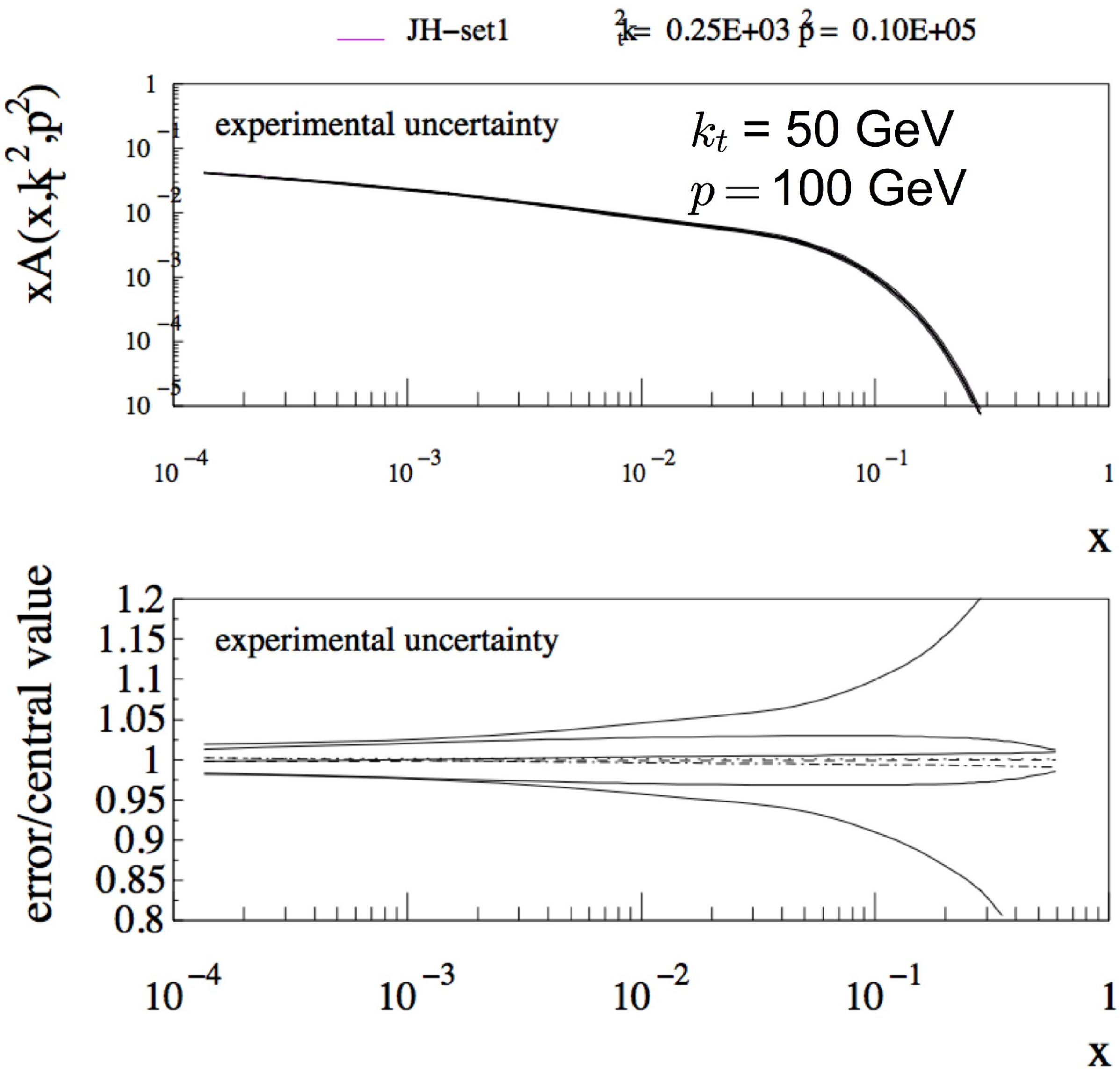
- Fit function:

$$\mathcal{A}_0(x) = N_g x^{-B_g}(1-x)^{C_g} \times (1 - D_g x + E_g\sqrt{x} + F_g x^2)$$

- 2-loop α_s
- gluon splitting function with non-singular terms
- $Q^2 > 5$ GeV, x < 0.005

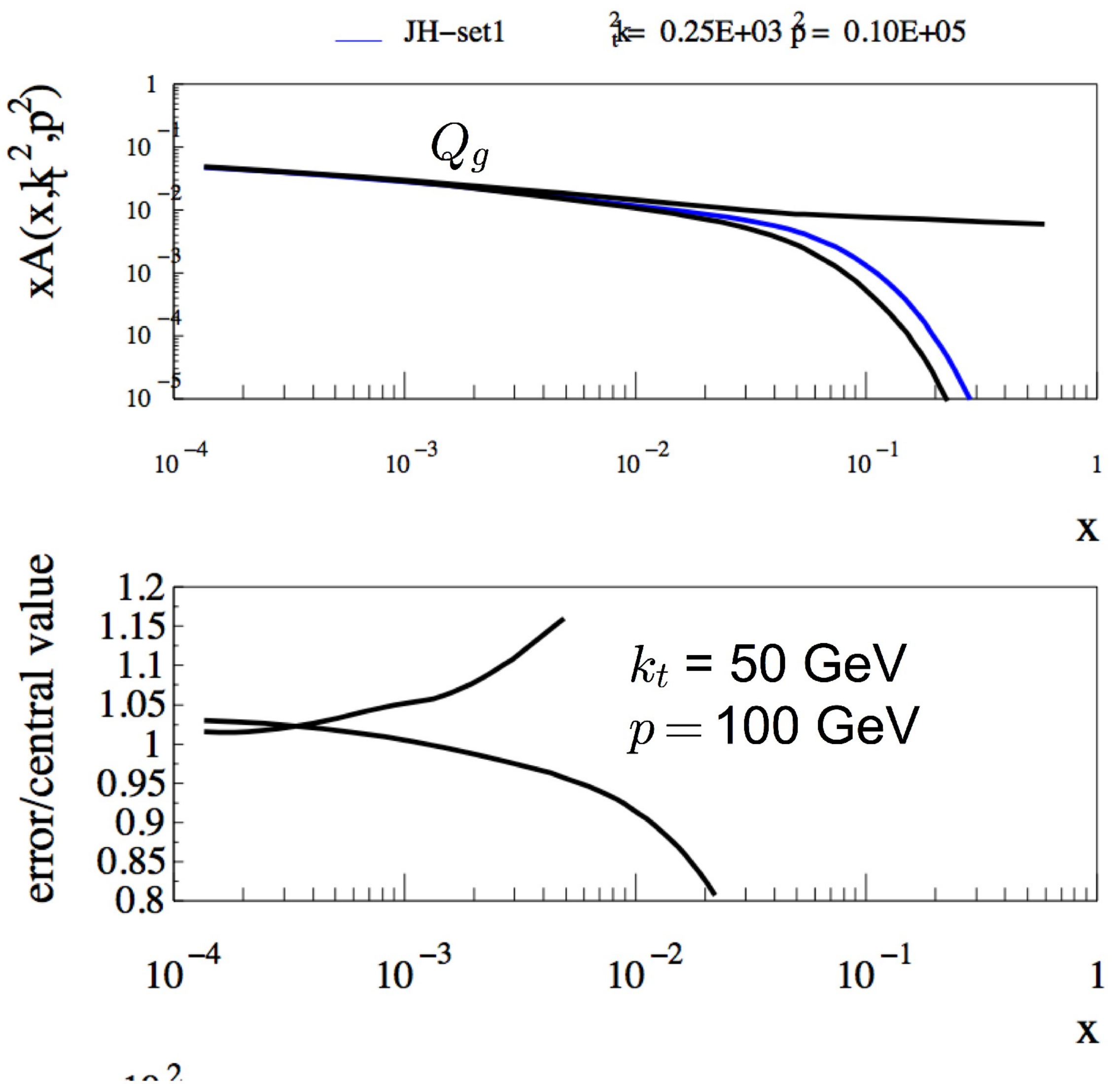
  new fit gives $\chi^2/ndf \sim 1.2$
  - depending on number of parameters
- details are different from previous uPDF set A_0 and from derivative of collinear gluon with CTEQ6

uncertainties of CCFM gluon



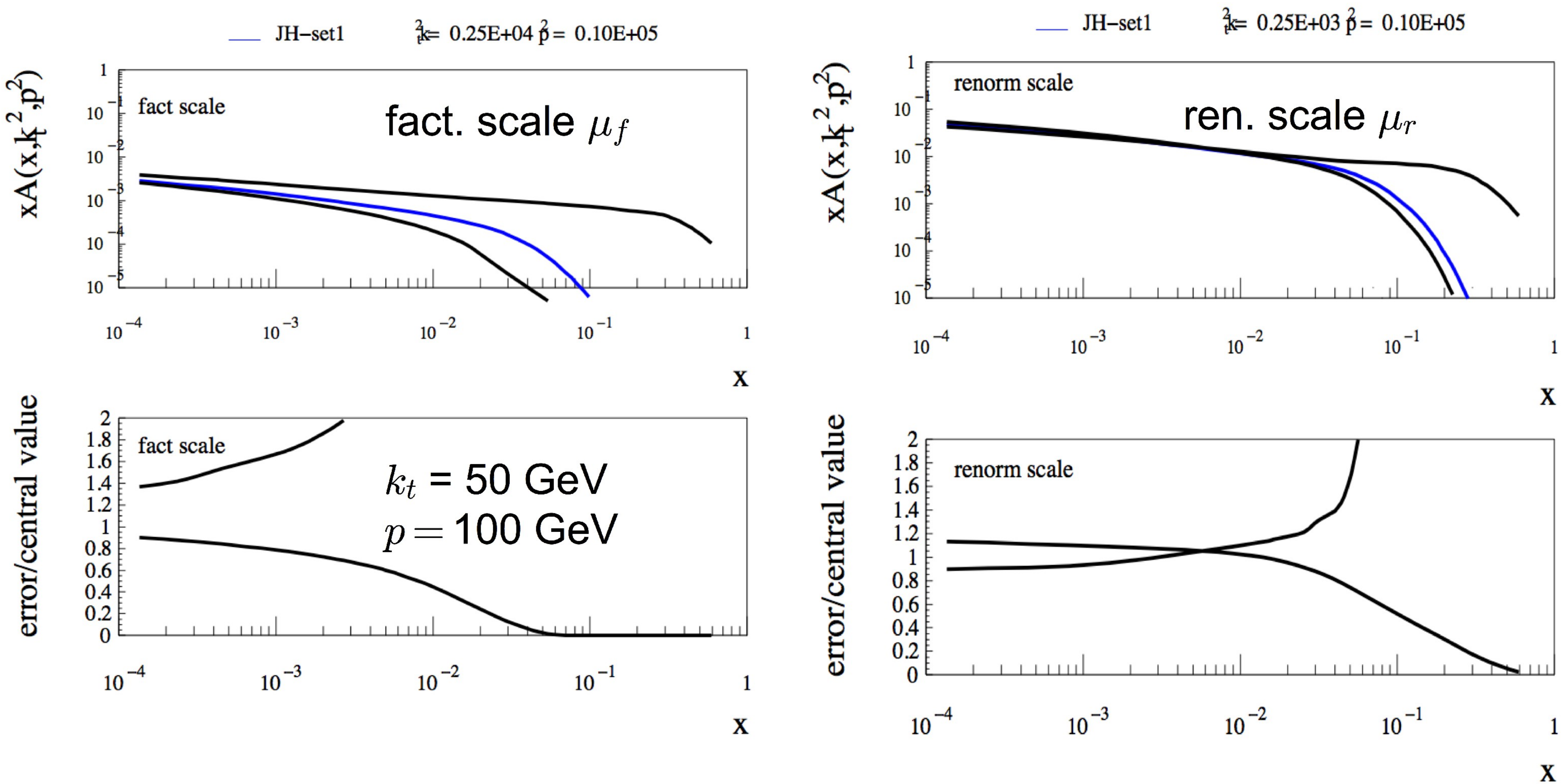
- experimental uncertainties result in 10-20 % for gluon uncertainty at medium and large x
- uncertainties at small x very small

uncertainties of CCFM gluon



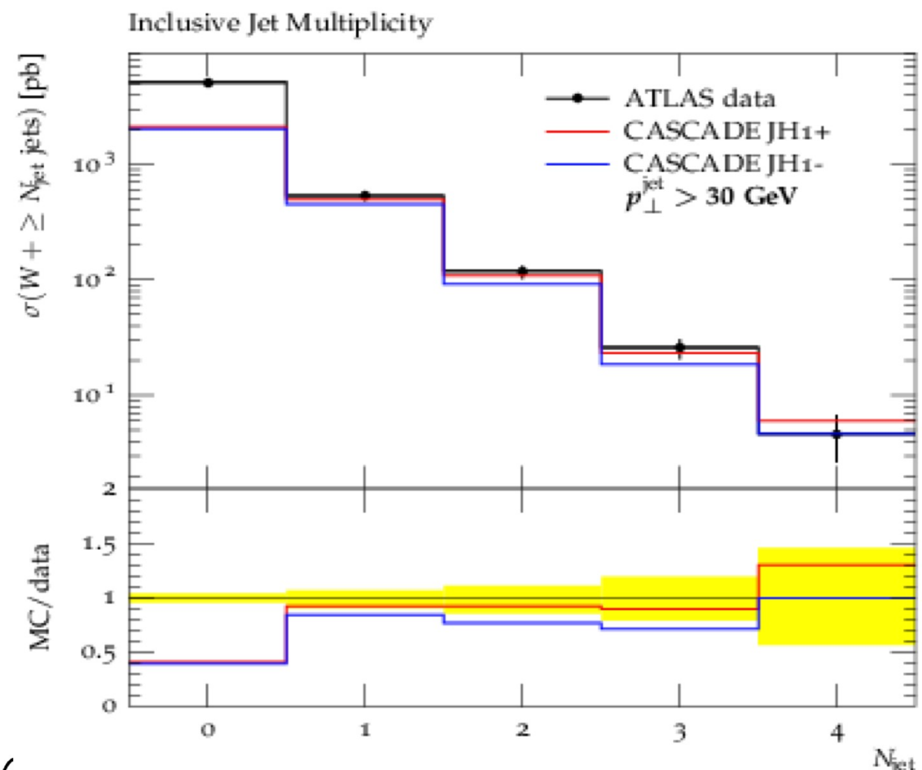
- for the first time: estimation theory uncertainties in TMDs
- uncertainties from starting scale Q_g
  - small at small x
  - explode at large x, because of no constraint from data: $Q^2 > 5$ GeV, x < 0.005

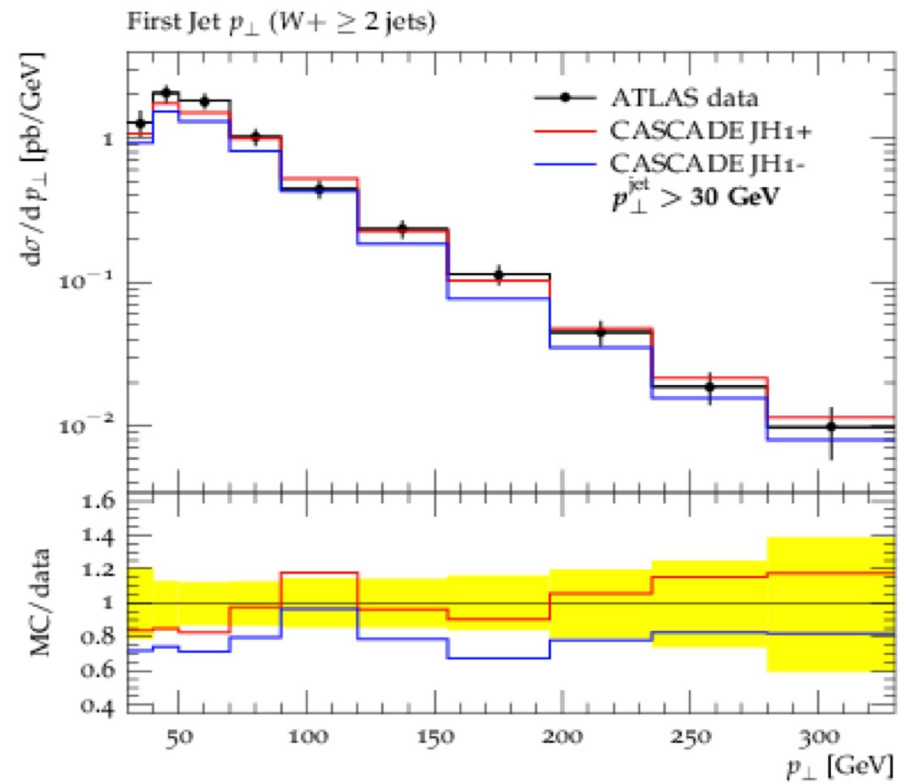
model uncertainties of CCFM gluon

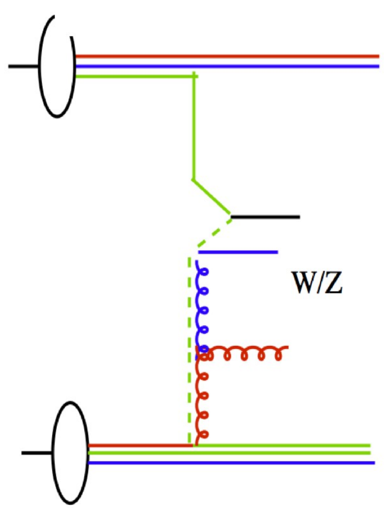


- factorization scale and renormalization scale varied by factor 2
  - what matters is x-section (convolution of σ with pdf !
  - at large x no constraint (since x < 0.005)

Application to W + jet production at LHC

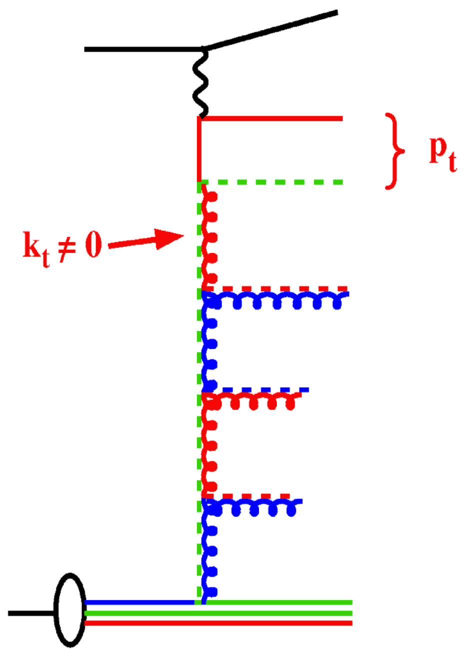




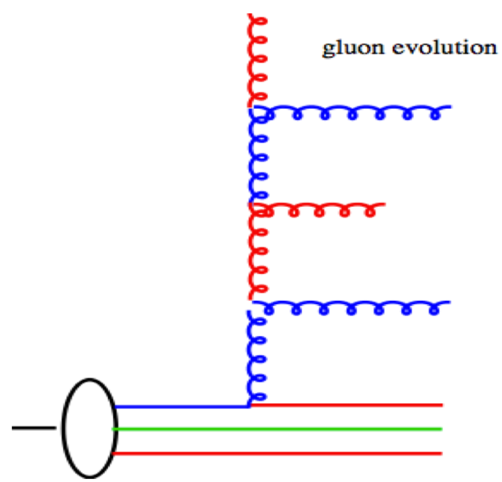


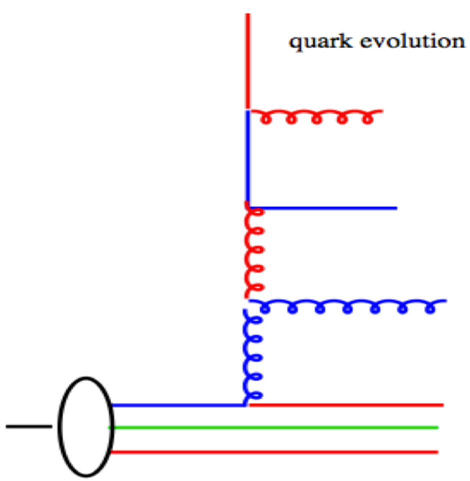
- use valence quarks and CCFM gluon convoluted with off-shell ME
- compare with W+jet measurement
  - for more details see: *Vectorboson+jet talk in QCD & HFS session*

TMDs from $F_2(x,Q^2)$ – one loop mode

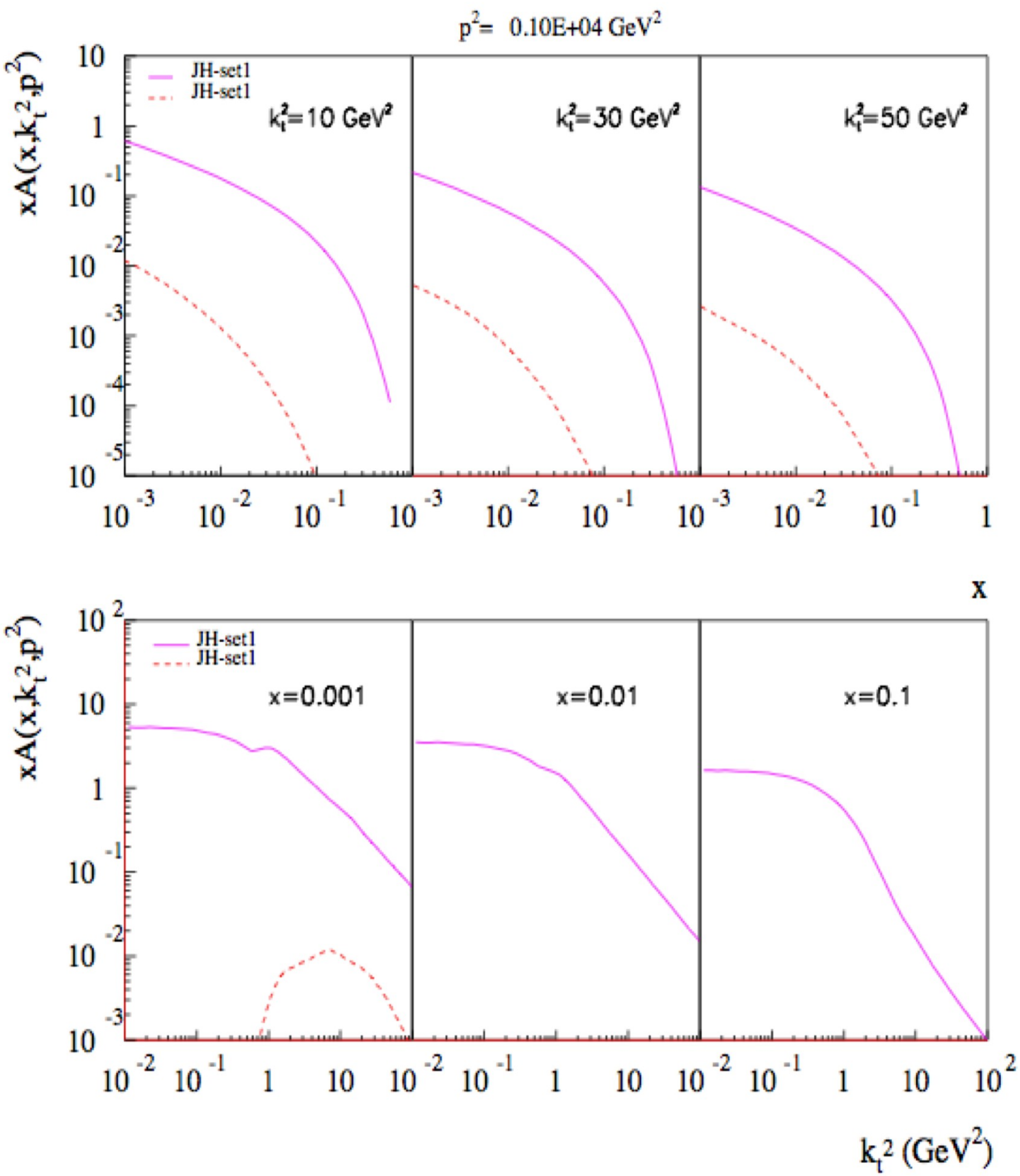


- $$\frac{d\sigma}{dx dQ^2} = \int dx_g \left[dk_\perp^2 x_g \mathcal{A}_i(x_g, k_\perp^2, p) \Theta(k_\perp^2 - \mu_f^2) \right] \times \hat{\sigma}(x_g, 0, x, \mu_f^2, Q^2)$$
- $\hat{\sigma}(x_g, 0, x, \mu_f^2, Q^2)$ is (on-shell, kt independent) hard scattering cross section
- only gluon → leads to bad $\chi^2/ndf \sim 6$
- first attempt to include quarks (a la GRV: only gluons and valence quarks at starting scale → for technical reasons)





1-loop: gluon and quark TMD from F_2

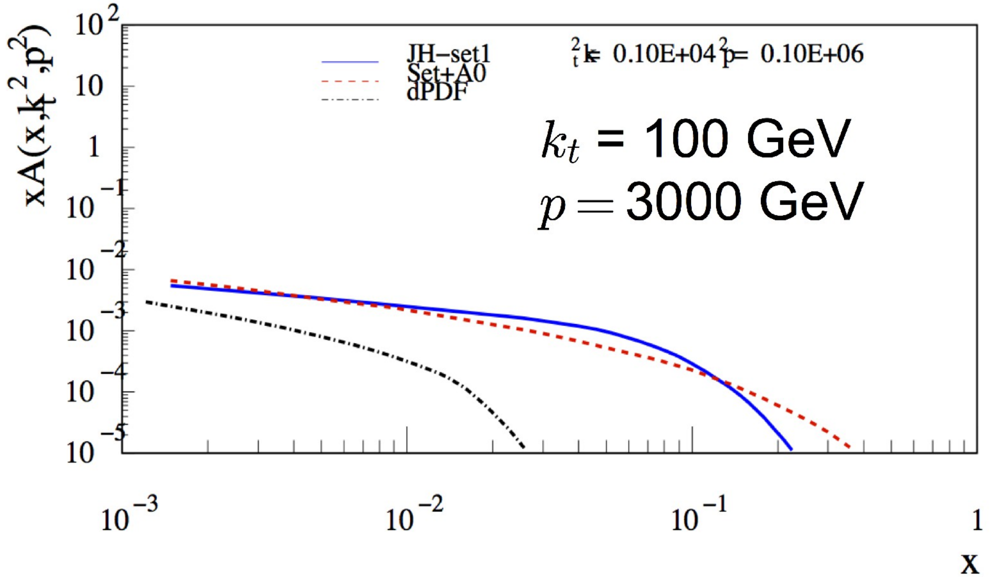


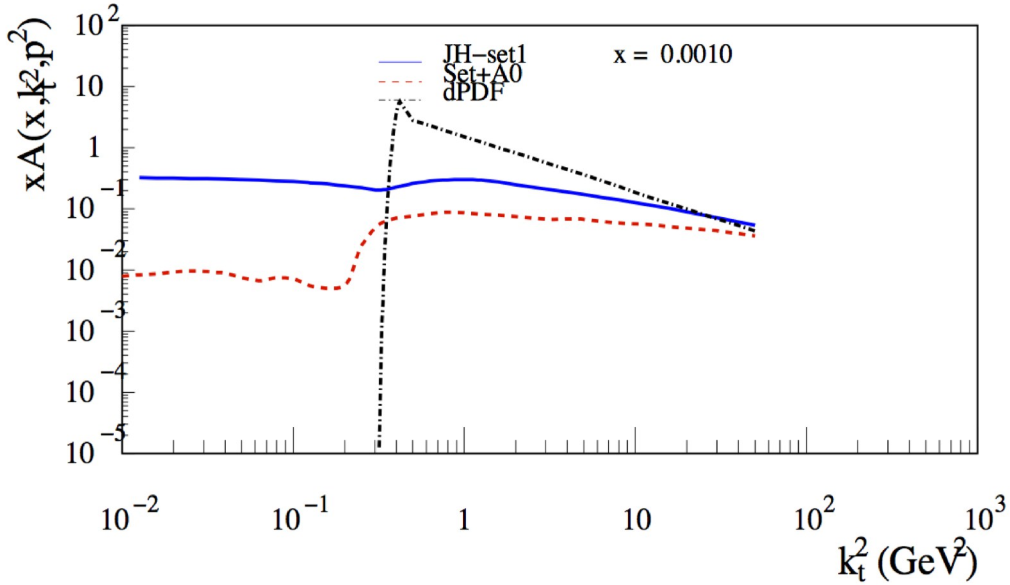
- only gluon at starting scale
- quarks only from $g \rightarrow q\,q$ splitting
  - using standard one loop splitting functions
  - evolution driven by Sudakov form factor
- q can appear only with perturbative splitting with $k_t > Q_g \sim$ 1 GeV
  - no quarks with small k_t
  - …. would come only from intrinsic q distribution
- similar result, if starting from q only and generating gluon perturbatively
- suppression of q (or g) at small k_t
  - shape similar to what is expected from saturation → vanishing at small k_t

Summary

- TMDs are necessary to account for proper kinematics even at NLO !
- TMDs determined with HERA F_2
    - all loop gluon TMD including uncertainties:
        - experimental
        - model uncertainties
            - small at small x but sizable at larger x
    - using gluon and valence quark TMD $\rightarrow$ good description of W+ jets at LHC obtained !!!
- first attempt to determine gluon and quark TMD from HERA F_2
    - method a la GRV: gluons and valence-quarks only at starting scale
    - perturbatively generated sea-quarks have finite $k_t > Q_g$
- first steps towards a complete TMD determination including uncertainties
    - combined with k_t dependent CCFM shower and off-shell ME gives many opportunities for LHC phenomenology

CCFM gluon from F_2 fit





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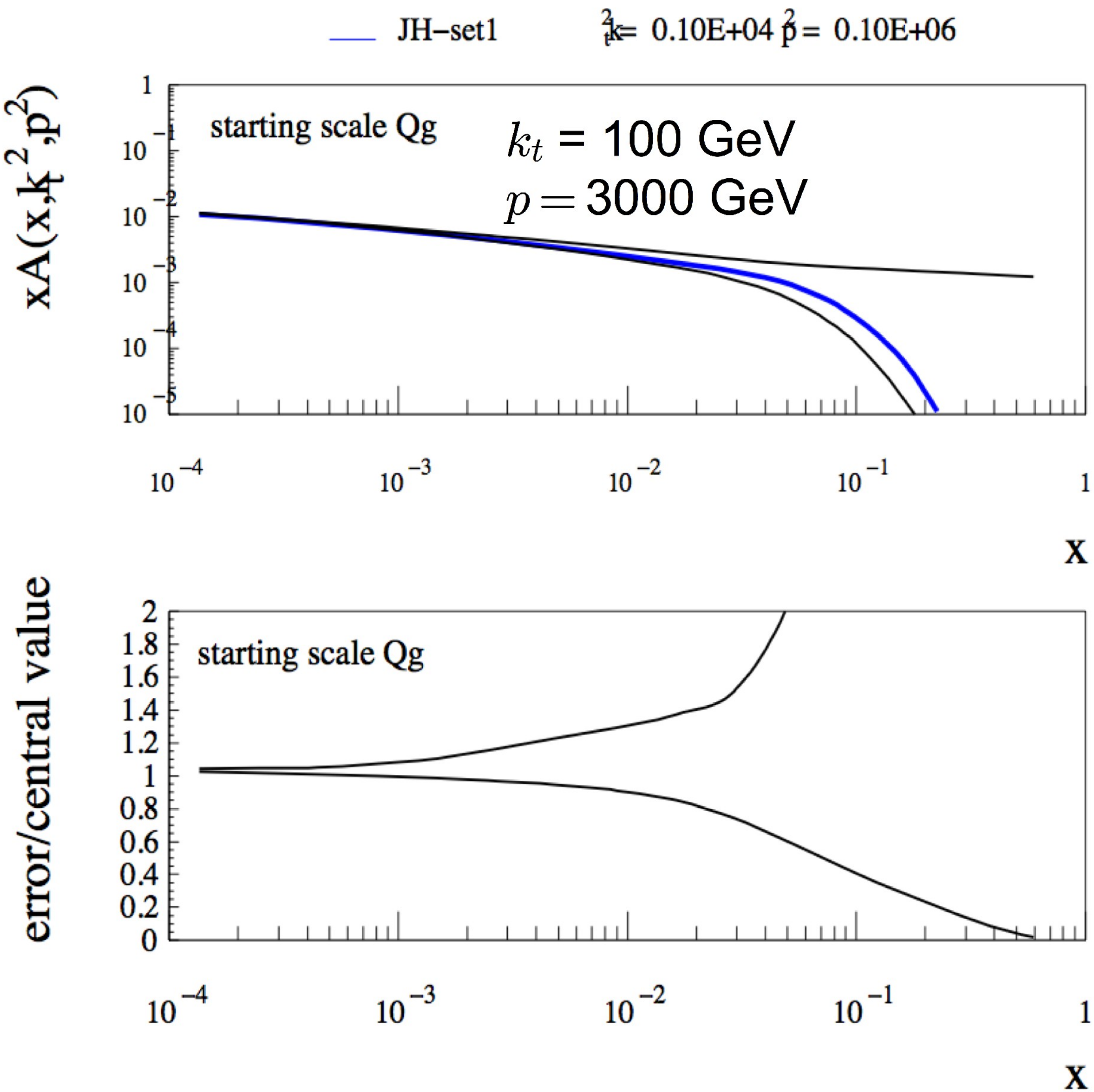
uncertainties of CCFM gluon



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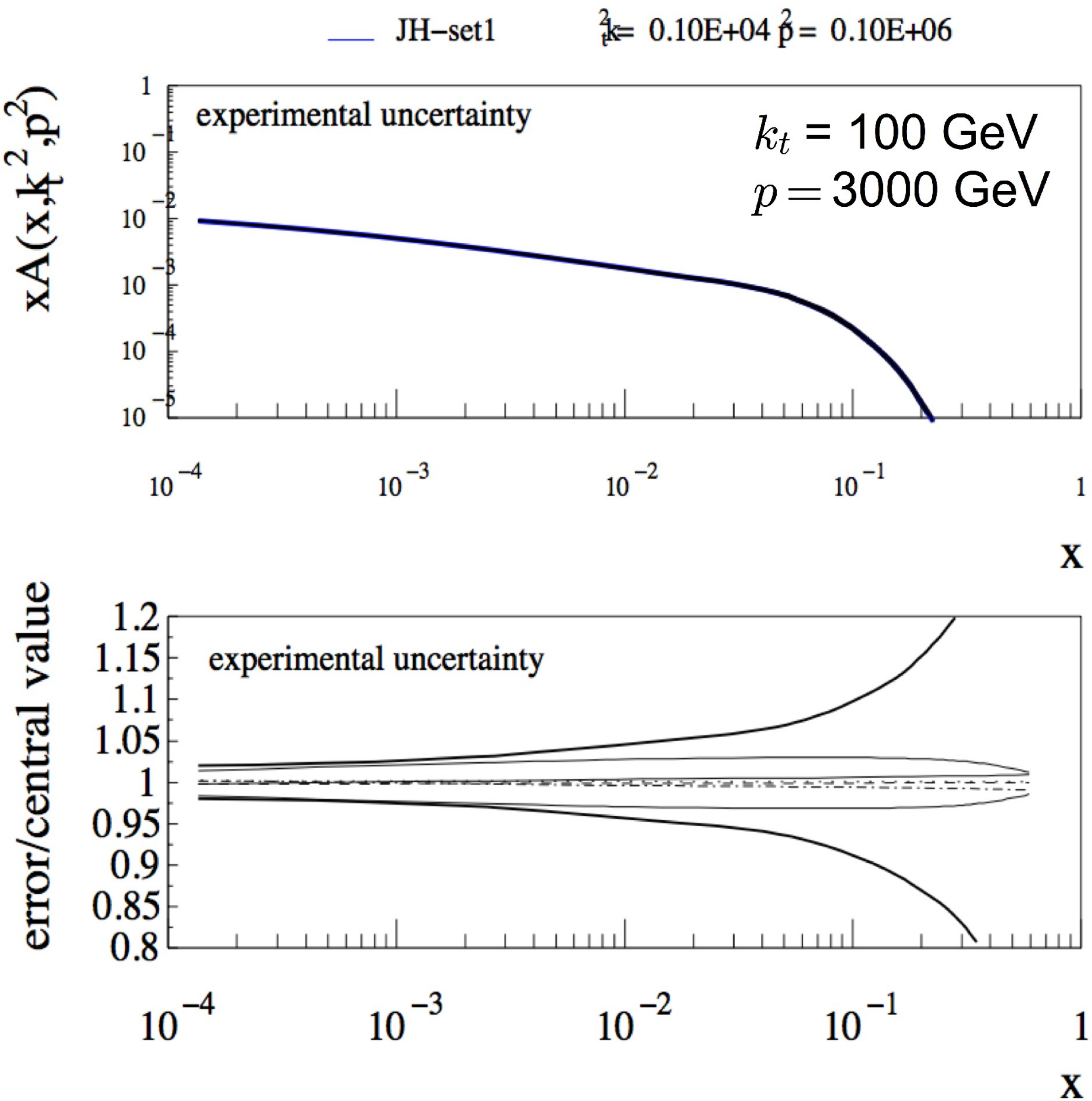

- for illustration calculated largest scales and large k_t
- experimental uncertainties result in 10-20 % for gluon uncertainty at medium and large x
- uncertainties at small x very small
- uncertainties for HERA or typical LHC scales larger