Transverse momentum dependent gluon density from DIS precision data

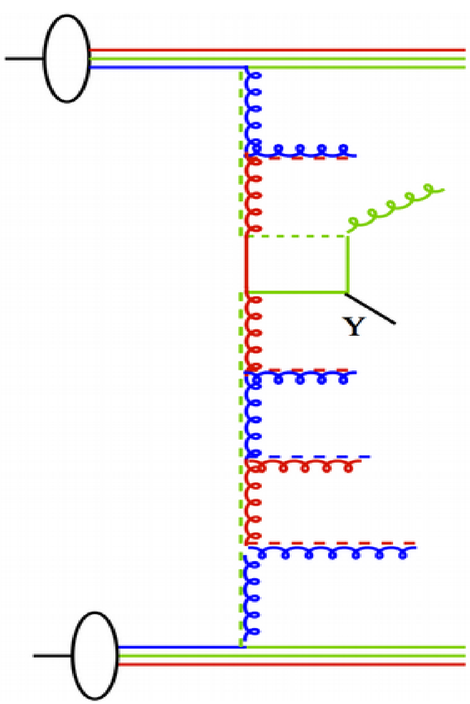
H. Jung (DESY, Uni Antwerp)
F. Hautmann (Uni Oxford)

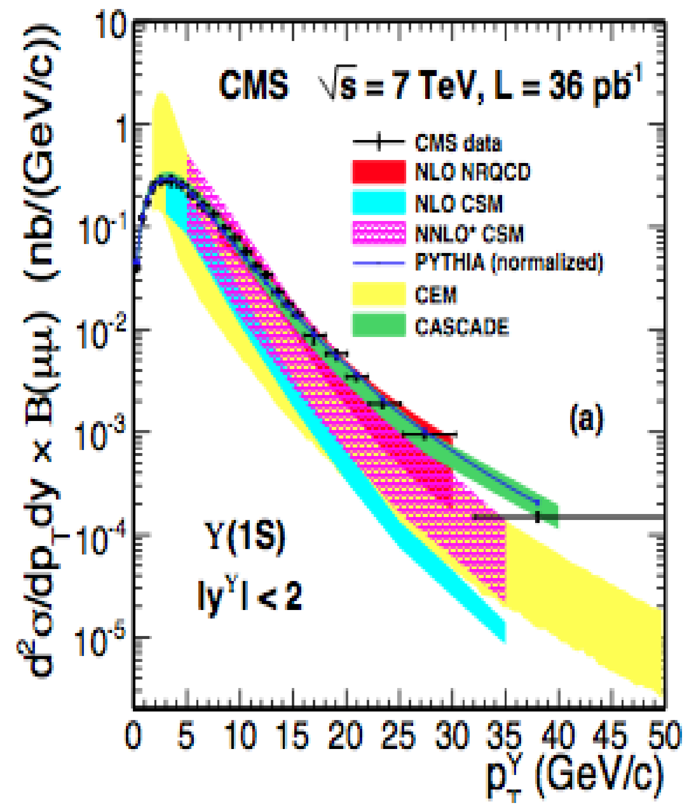
- Why gluon TMDs?
- How can gluon TMDs be determined ?
  - CCFM gluon uPDF
  - fits to inclusive DIS and uncertainties
- Description of hard processes at the LHC ?

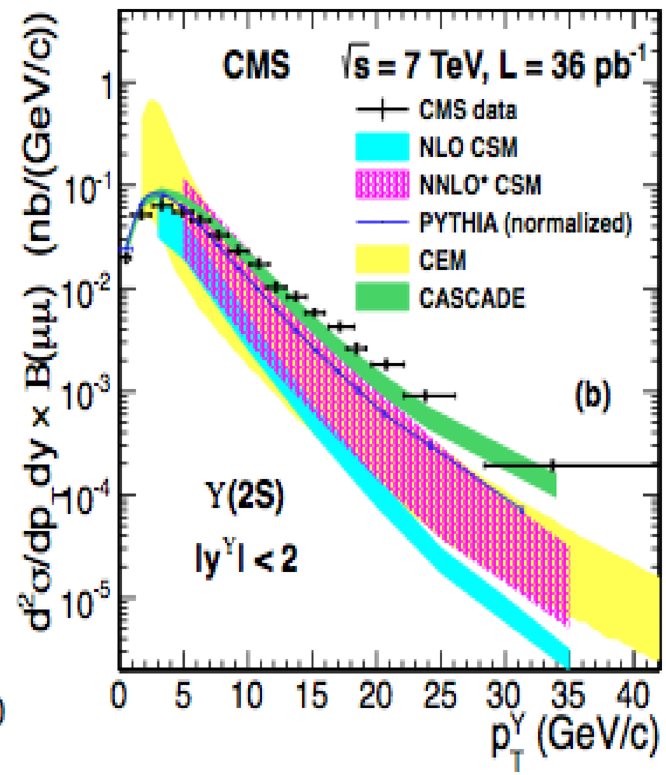
Upsilon production

$$g^* g^* \to \Upsilon g, \; g^* g^* \to \chi_b \to \Upsilon + X$$

CMS Phys.Lett. B727 (2013)101, 1303.5900
Measurement of the Υ(1S), Υ(2S), and Υ(3S) cross sections in pp collisions at s√ = 7 TeV





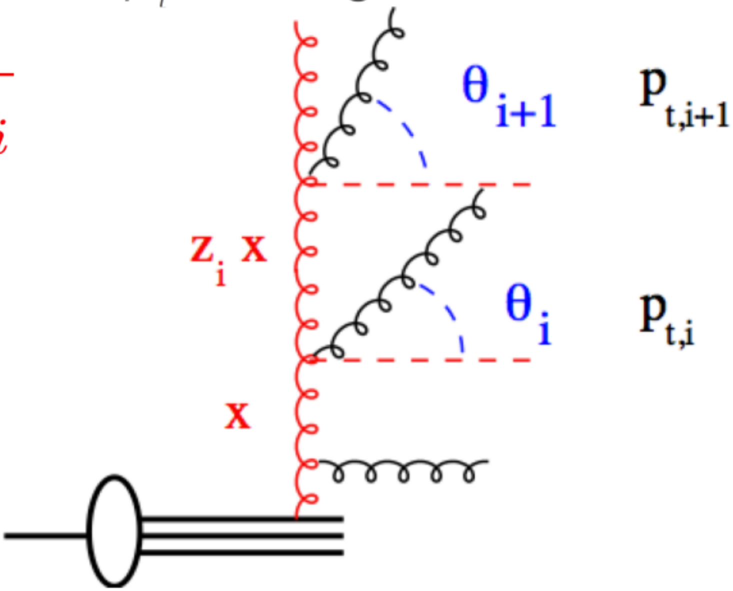


- Using TMDs with off-shell ME gives rather good description, without further tuning
- NNLO CSM is not as good !

How to obtain TMDs ? CCFM approach

- Color coherence requires angular ordering instead of p_t ordering …

$$q_i > z_{i-1} q_{i-1} \quad \text{with} \quad q_i = \frac{p_{ti}}{1 - z_i}$$



➔ recover DGLAP with q ordering
at medium and large x

➔ at small x, no restriction on q
p_{ti} can perform a random walk

➔ splitting fct:

$$\tilde{P}_g(z, q, k_t) = \bar{\alpha}_s \left[\frac{1}{1-z} - 1 + \frac{z(1-z)}{2} + \left(\frac{1}{z} - 1 + \frac{z(1-z)}{2} \right) \Delta_{ns}) \right]$$

$$\log \Delta_{ns} = -\bar{\alpha}_s \int_0^1 \frac{dz'}{z'} \int \frac{dq^2}{q^2} \Theta(k_t - q) \Theta(q - z' p_t)$$

➔ CataniCiafaloniFioraniMarchesini evolution forms a bridge between DGLAP and BFKL evolution

For precision predictions
need
precision (small x) TMDs
with
uncertainties !

Evolution equation and TMDs

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

- solve integral equation via iteration:

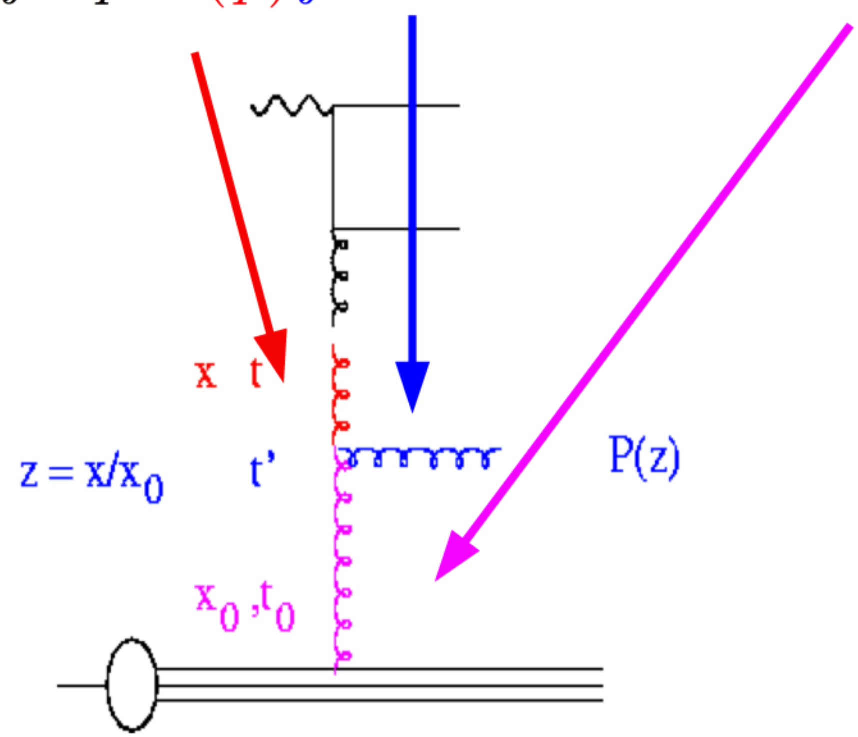
from q′ to q w/o branching

branching at q′

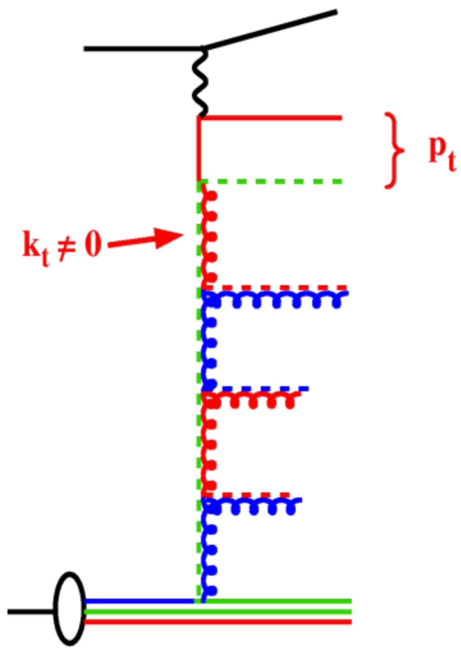
from q_0 to q′ w/o branching

$$\begin{aligned} x\mathcal{A}_0(x,k_t,q) &= x\mathcal{A}(x,k_t,q_0)\Delta(q) \\ x\mathcal{A}_1(x,k_t,q) &= x\mathcal{A}(x,k_t,q_0)\Delta(q) + \int \frac{dq'}{q'} \frac{\Delta(q)}{\Delta(q')} \int dz \tilde{P}(z) \frac{x}{z} \mathcal{A}(x/z, k'_t, q_0)\Delta(q') \end{aligned}$$

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



small x 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 HERAPDF or CTEQ6

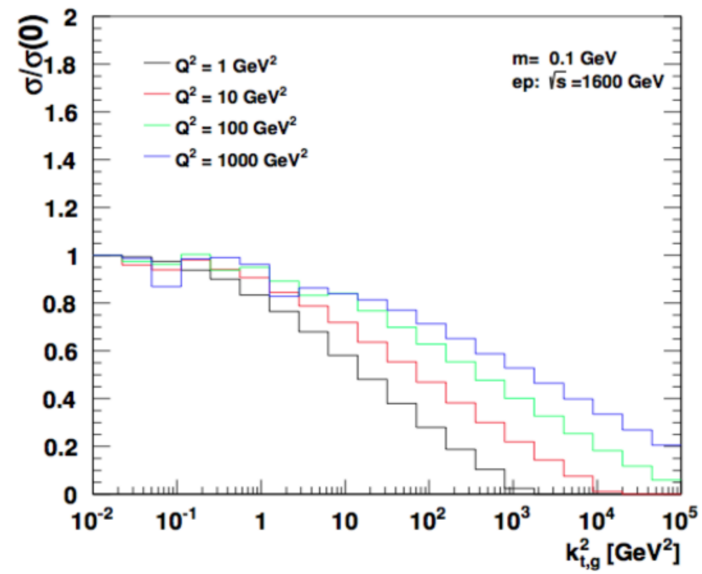
$$xQ_v(x, k_t, p) = xQ_{v0}(x, k_t, p) + \int \frac{dz}{z} \int \frac{dq^2}{q^2} \Theta(p - zq) \times \Delta_s(p, zq) P(z, k_t)\ xQ_v\left(\frac{x}{z}, k_t + (1-z)q, q\right)$$

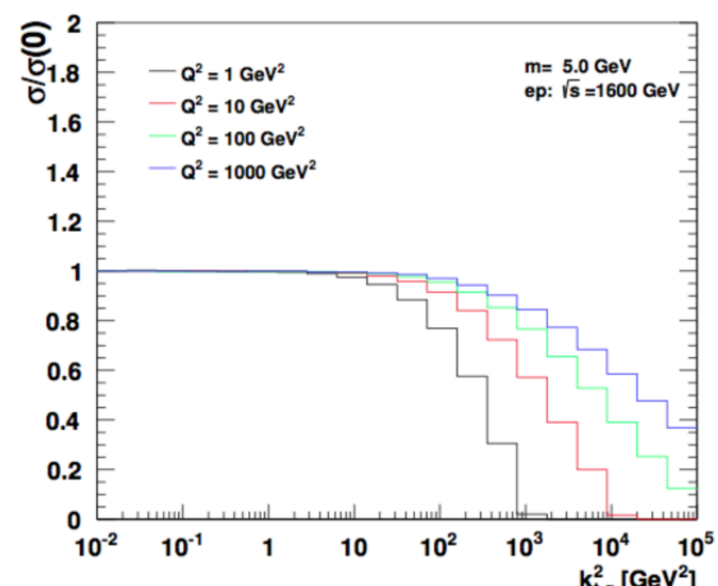
$$P(z, k_t) = \bar{\alpha}_s\left(k_t^2\right) \frac{1+z^2}{1-z}$$

Why off-shell matrix elements ?

- Behavior of ME as function of k_t:
  - for small k_t converges to collinear result
  - for large k_t has suppression
  - → suppression appears at "standard factorization scale": $Q^2 + 4\,m^2$
  - collinear factorization: $\mu^2 \sim Q^2 + 4\,m^2$:

$$\int_0^{\mu^2} dk_\perp \hat{\sigma}(k_\perp, \ldots)$$





Determination of TMDs (uPDFs)

F. Hautmann and H. Jung. Transverse momentum dependent gluon density from DIS precision data. arXiv 1312.7875 Nuclear Physics B, 883:1, 2014.

- Apply formalism to describe HERA F_2 measurements
  - start with gluon only for small x
  - CCFM with full angular ordering → no k_t ordering at small x
  - include valence quarks (for large x)
- starting distribution for gluon at q_0 :

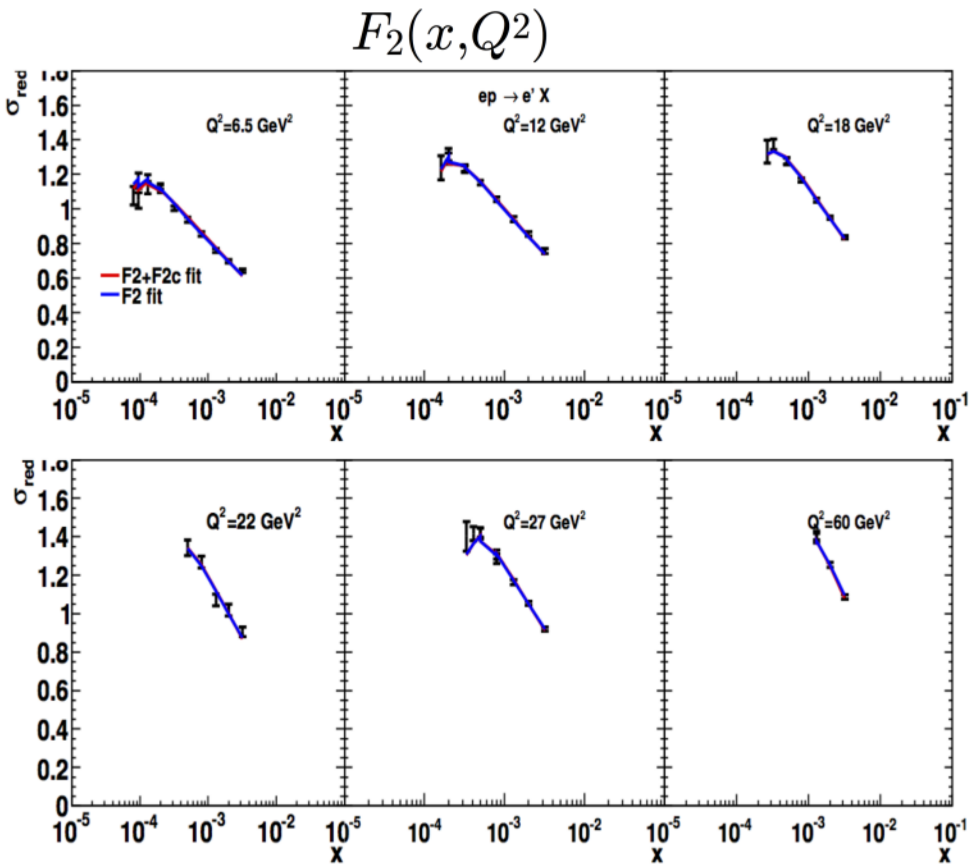
$$xA_0(x,k_\perp) \quad = \quad Nx^{-B} \cdot (1-x)^C \left(1 - Dx + E\sqrt{x}\right) \exp[-k_t^2/\sigma^2]$$

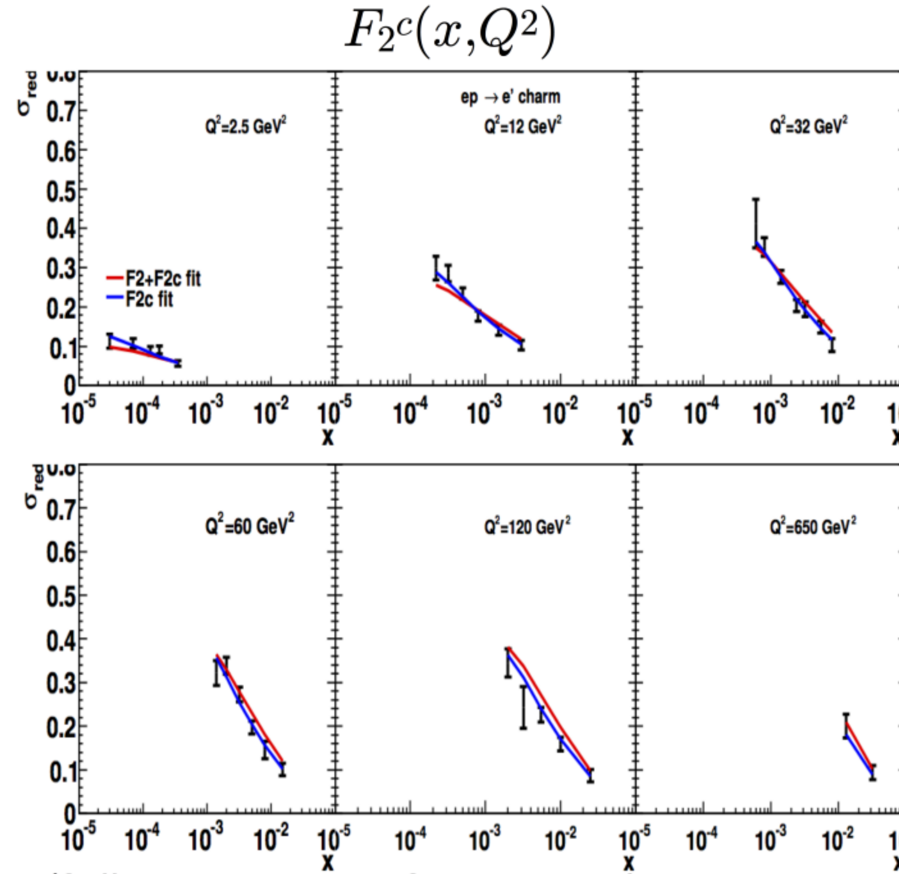
- starting distribution for valence quarks at q_0:

$$\begin{aligned} xQ_{v0}(x,k_t,p) &= xQ_{v0}(x,k_t,q_0)\Delta_s(p,q_0) \\ xQ_{v0}(x,k_t,q_0) &= xQ_{v\,\mathrm{coll.pdf}}(x,q_0)\ \exp[-k_t^2/\sigma^2] \end{aligned}$$

with $\sigma^2 = q_0^2/2$

From HERA: small x improved gluon TMD



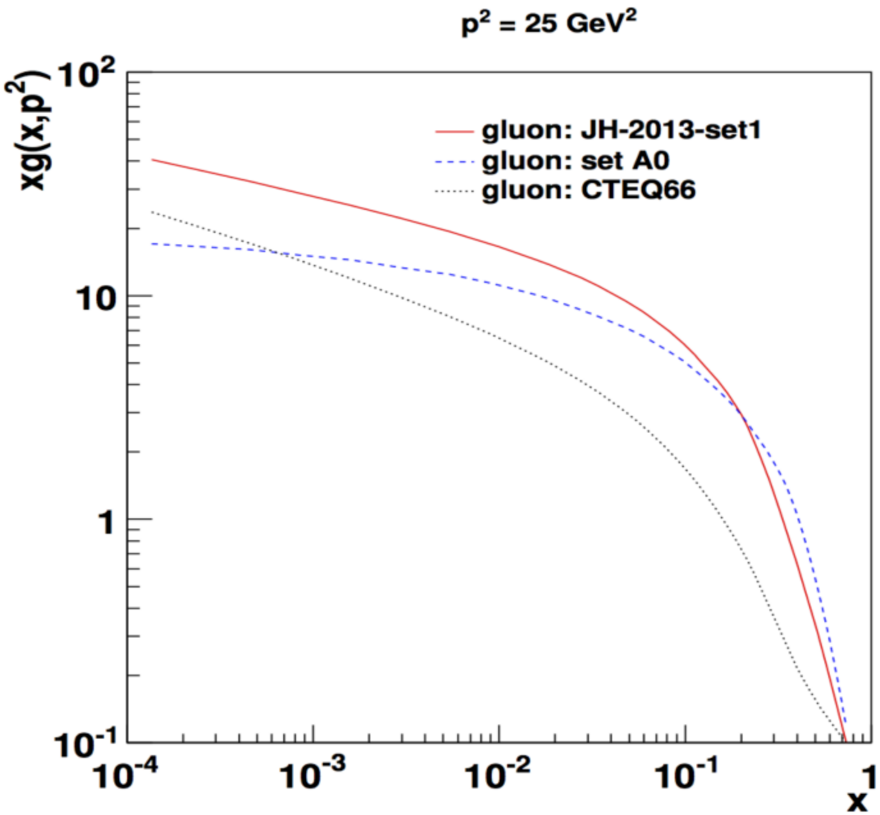


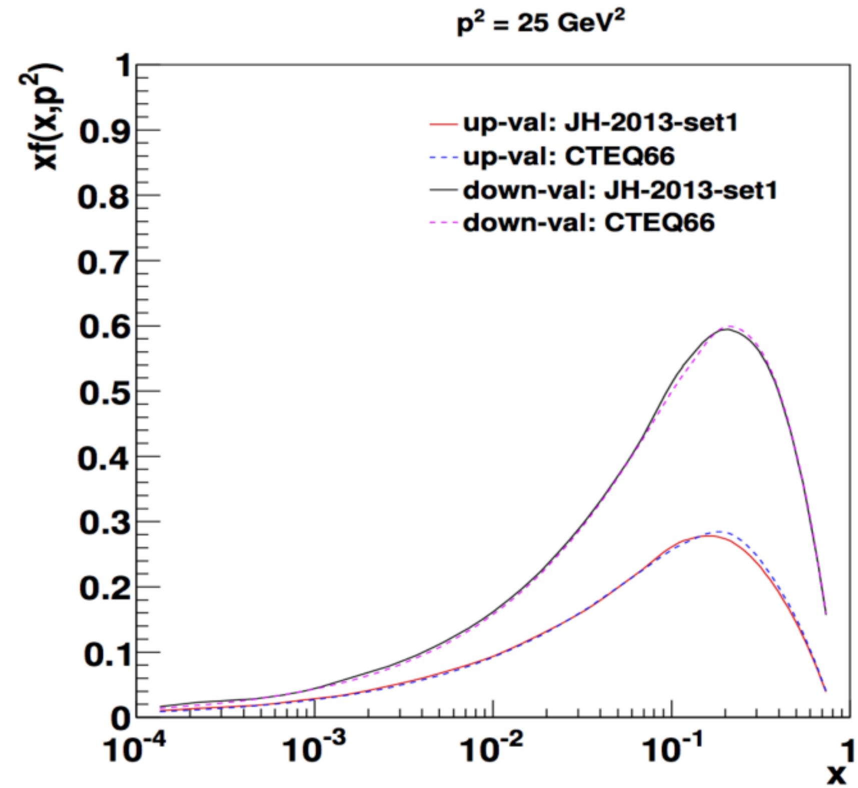
- fit performed with `herafitter` package (full treatment of corr. and uncorr. uncertianties)
  - $F_2^c(x,Q^2)$: $Q^2 \geq 2.5$ GeV
  - $F_2(x,Q^2)$: $x \leq 0.005,\ Q^2 \geq 5$ GeV
- very good χ^2/ndf obtained (~ 1)

F. Hautmann and H. Jung. Transverse momentum dependent gluon density from DIS precision data. arXiv 1312.7875 Nuclear Physics B, 883:1, 2014.

TMD - integrated

F. Hautmann and H. Jung. Transverse momentum dependent gluon density from DIS precision data. arXiv 1312.7875 Nuclear Physics B, 883:1, 2014.

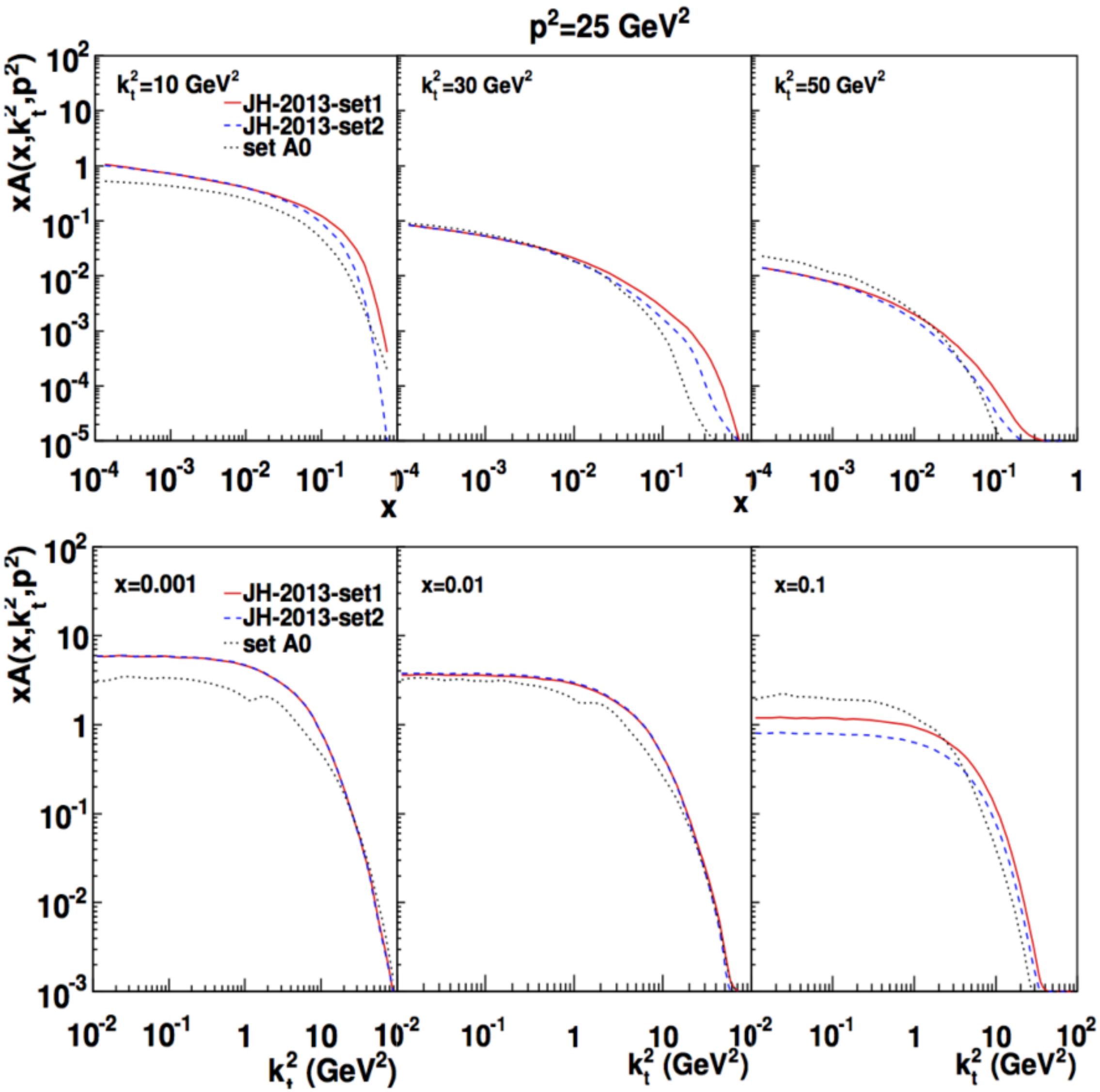




CCFM gluon is different from standard collinear gluon, since no sea quarks are directly included in fit (treated only via $g \to qq$)

- valence quarks in CCFM are similar to CTEQ, but evolution is different due to different α_s

CCFM gluon from F_2 and F_2 & $F_2{}^c$ fit

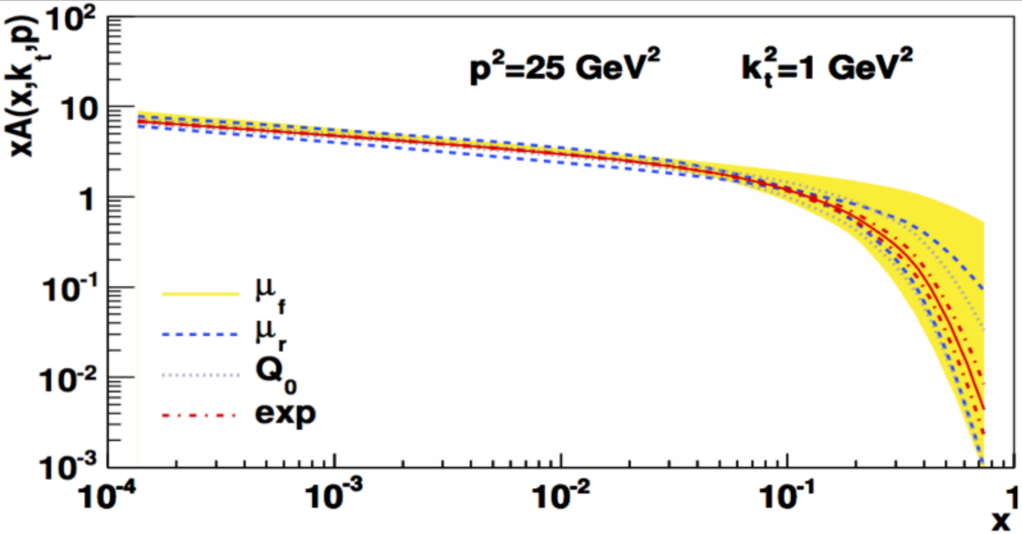


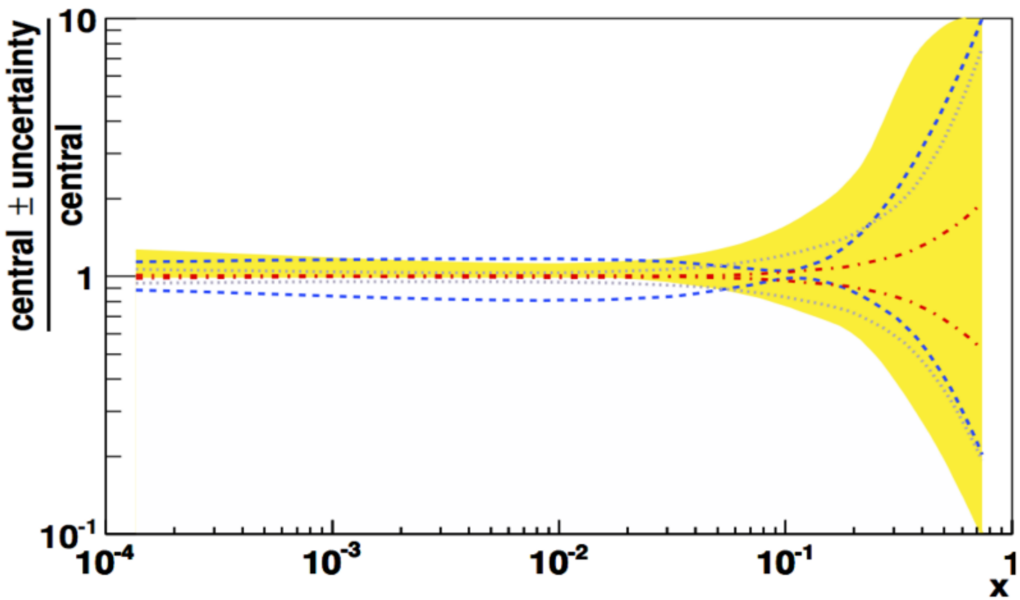
- Fit function:

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

  - only 3 params used in fit: no significant change for more params
- 2-loop α_s
- gluon splitting function with non-singular terms
- fits:
  - set 1: F_2 : Q² > 5 GeV, $x \leq 0.005$
  - set 2: F_2 & $F^c{}_2$: Q² > 2.5 GeV
- new fit gives χ^2/ndf ~ 1.2
- details are different from previous uPDF set A_0

uncertainties of CCFM gluon

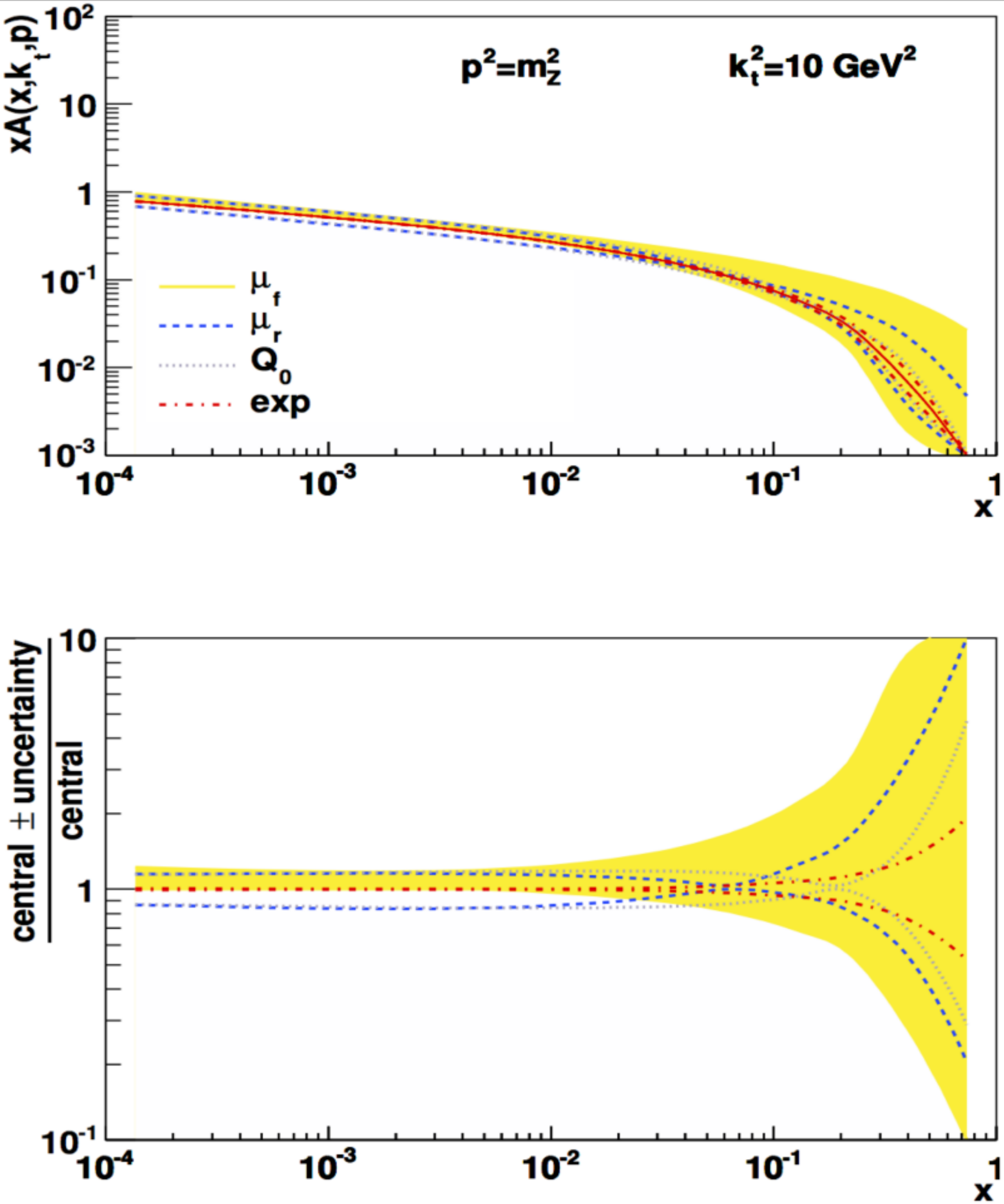




small k_t, small p^2

- experimental uncertainties result in 10-20 % for gluon uncertainty at medium and large x
- small uncertainties at small x
- NEW: factorization and renormalisation scale uncertainties
  - fit with shifted scales
  - large at large x, since no constrain from data: $x<0.005$, Q^2 > 5 GeV^2
  - → dominant uncertainties

uncertainties of CCFM gluon

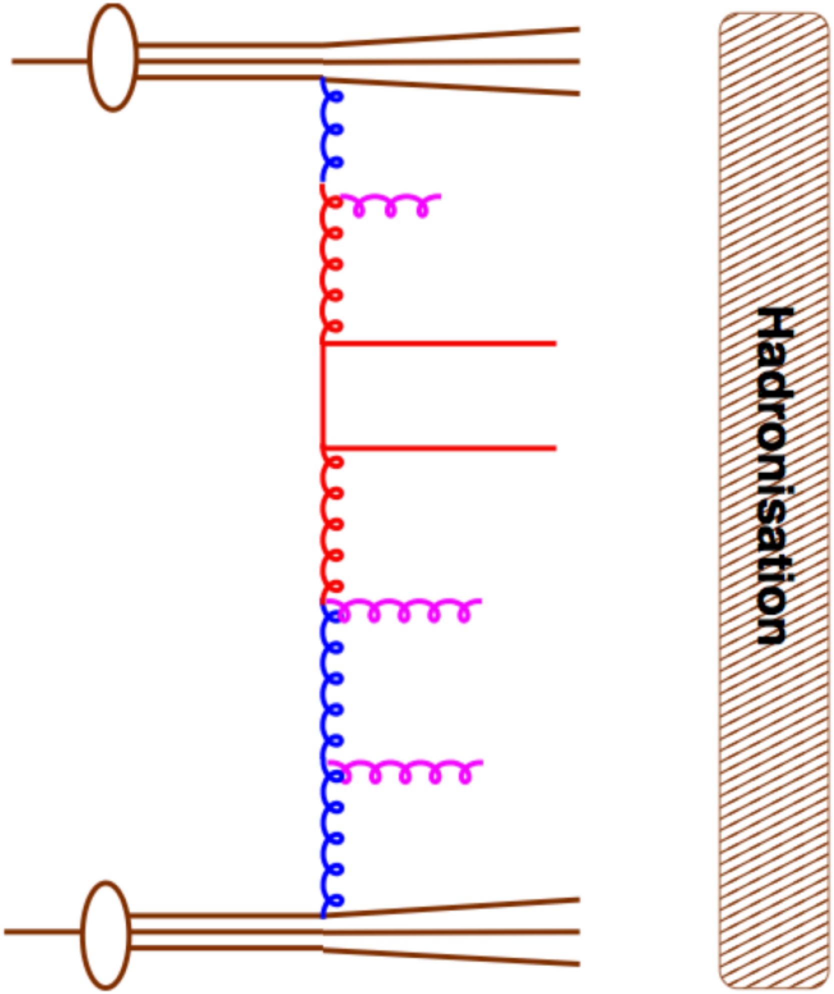


large k_t, large p^2

- experimental uncertainties result in 10-20 % for gluon uncertainty at medium and large x
- small uncertainties at small x
- NEW: factorization and renormalisation scale uncertainties
  - fit with shifted scales
  - large at large x, since no constrain from data: $x<0.005$, $Q^2 > 5$ GeV^2
  - ➔ dominant uncertainties

TMDs and the general pp case

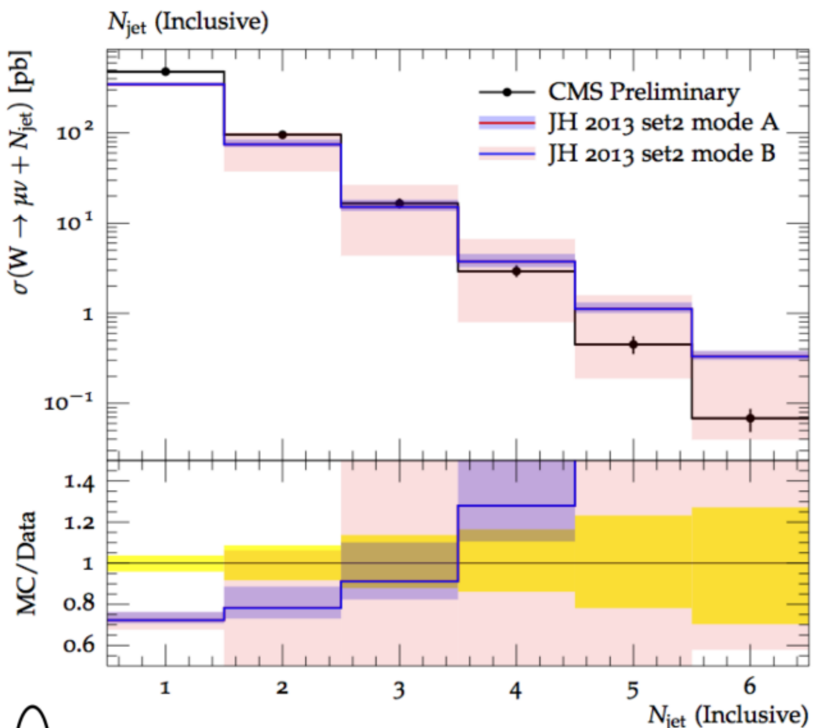
- basic elements are:
  - Matrix Elements:
    - ➔ on shell/off shell
  - PDFs
    - ➔ unintegrated PDFs
  - Parton Shower
    - ➔ angular ordering (CCFM)
- Proton remnant and hadronization handled by standard hadronization program, e.g. PYTHIA

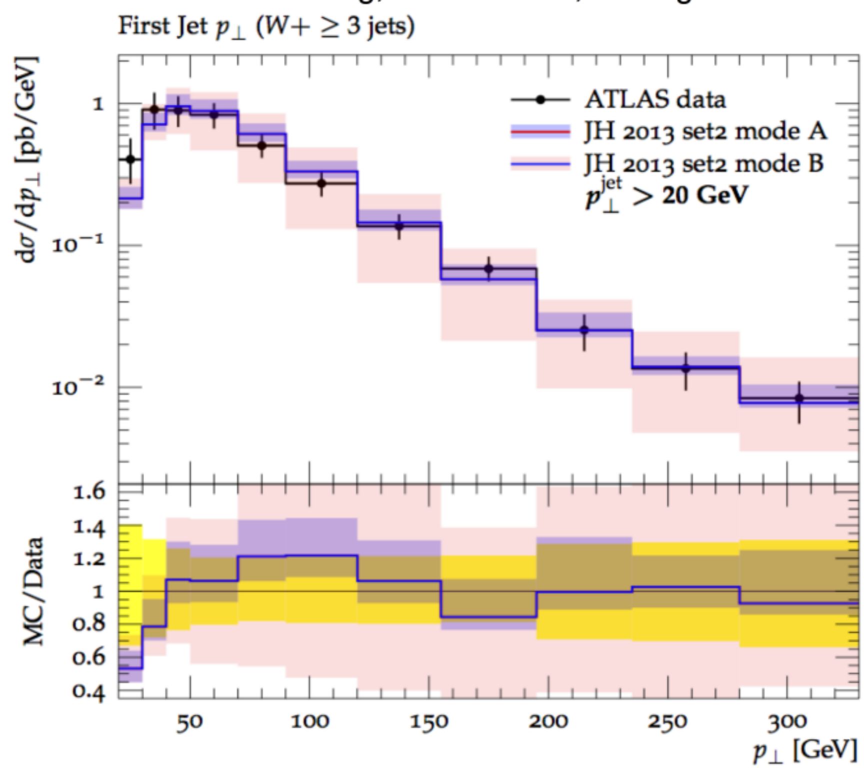


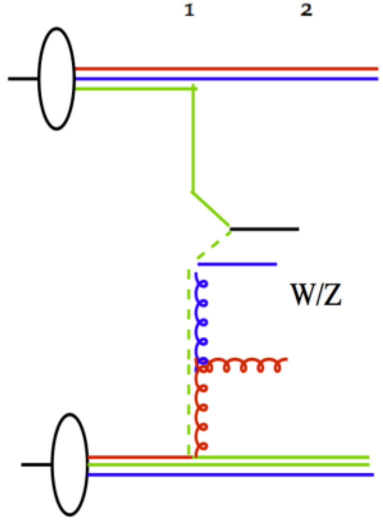
$$\sigma(pp \to q\bar{q} + X) \quad = \quad \int \frac{dx_{g1}}{x_{g1}} \frac{dx_{g2}}{x_{g2}} \int d^2 k_{t1} d^2 k_{t2} \hat{\sigma}(\hat{s}, k_t, \bar{q})$$
$$\times x_{g1} \mathcal{A}(x_{g1}, k_{t1}, \bar{q}) x_{g2} \mathcal{A}(x_{g2}, k_{t2}, \bar{q})$$

Application to W + jet production at LHC

Hadroproduction of electroweak gauge boson plus jets and TMD parton density functions
S. Dooling, F. Hautmann, H. Jung arXiv:1406.2994







- use CCFM gluon convoluted with off-shell ME
- uncertainty from pdf on 1st jet is small → ME !
  - **uncertainty In multijets becomes sizeble**
- agrees reasonably well with W+jet measurement

Conclusion

- TMD – uPDFs are important
  - effects form transverse momentum in small x processes (Υ production etc) but also in higher x processes (W+2jets, etc)
  - precision determination of CCFM TMD-gluon from inclusive DIS HERA data
    - now with model- and experimental uncertainties
- CCFM TMD gives a consistent recipe for initial state parton shower
  - no kinematic corrections are needed

Backup Slides

TMD and small x factorization

M. Diehl
INT workshop Seattle 2014
"Parton distributions: concepts..."

Small-x factorization

high-energy/low-x factorization		hard-scattering factorization (collinear or TMD)
	separate dynamics according to	
rapidity		virtuality/transverse mom.
	expand in	
log(1/x)		1/(hard scale)

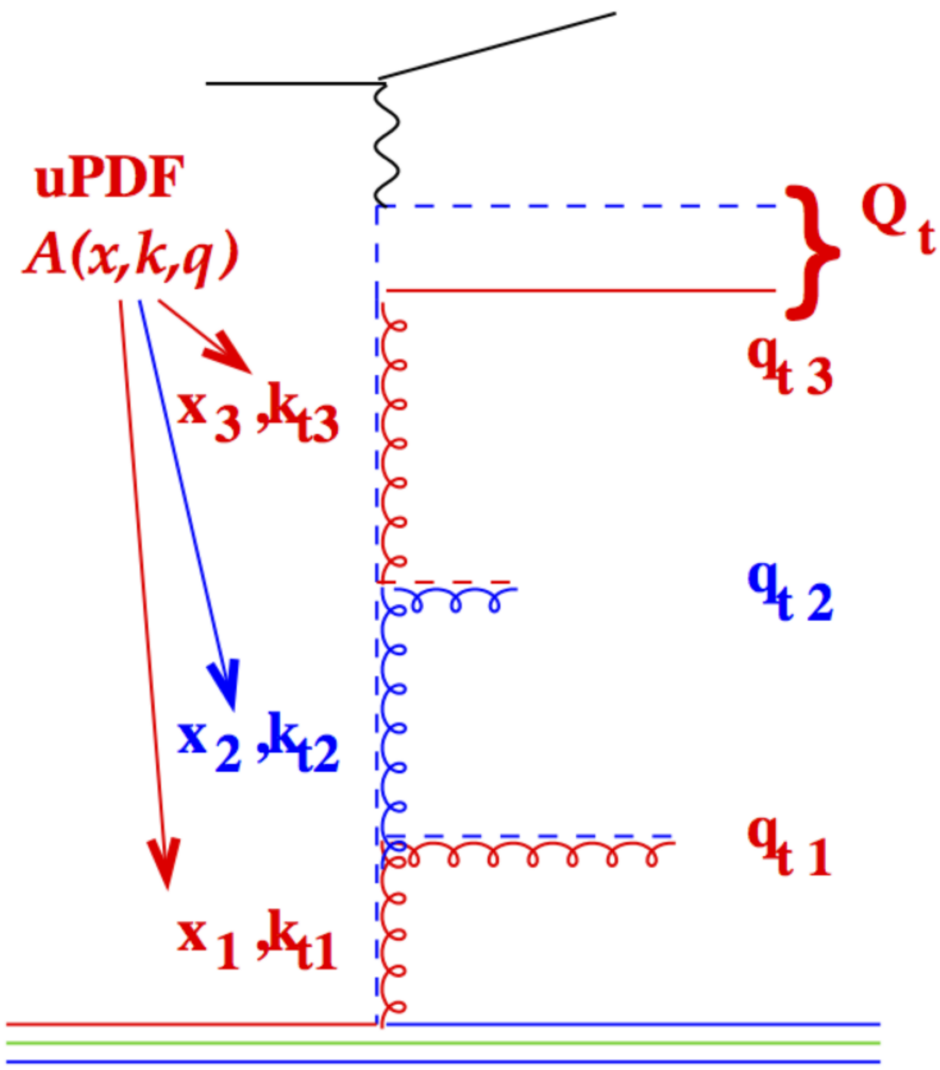
small-x formalism(s):

- evolution equations in log(1/x) ~ rapidity
  - ★ BFKL, CCFM
- gluon saturation → nonlinear evolution: BK, JIMWLK
- primary quantities are not parton distributions, but
  - ★ impact factors, BFKL kernel, dipole scattering amplitude and generalizations (formulated in terms of Wilson lines)

M. Diehl Parton distributions 26

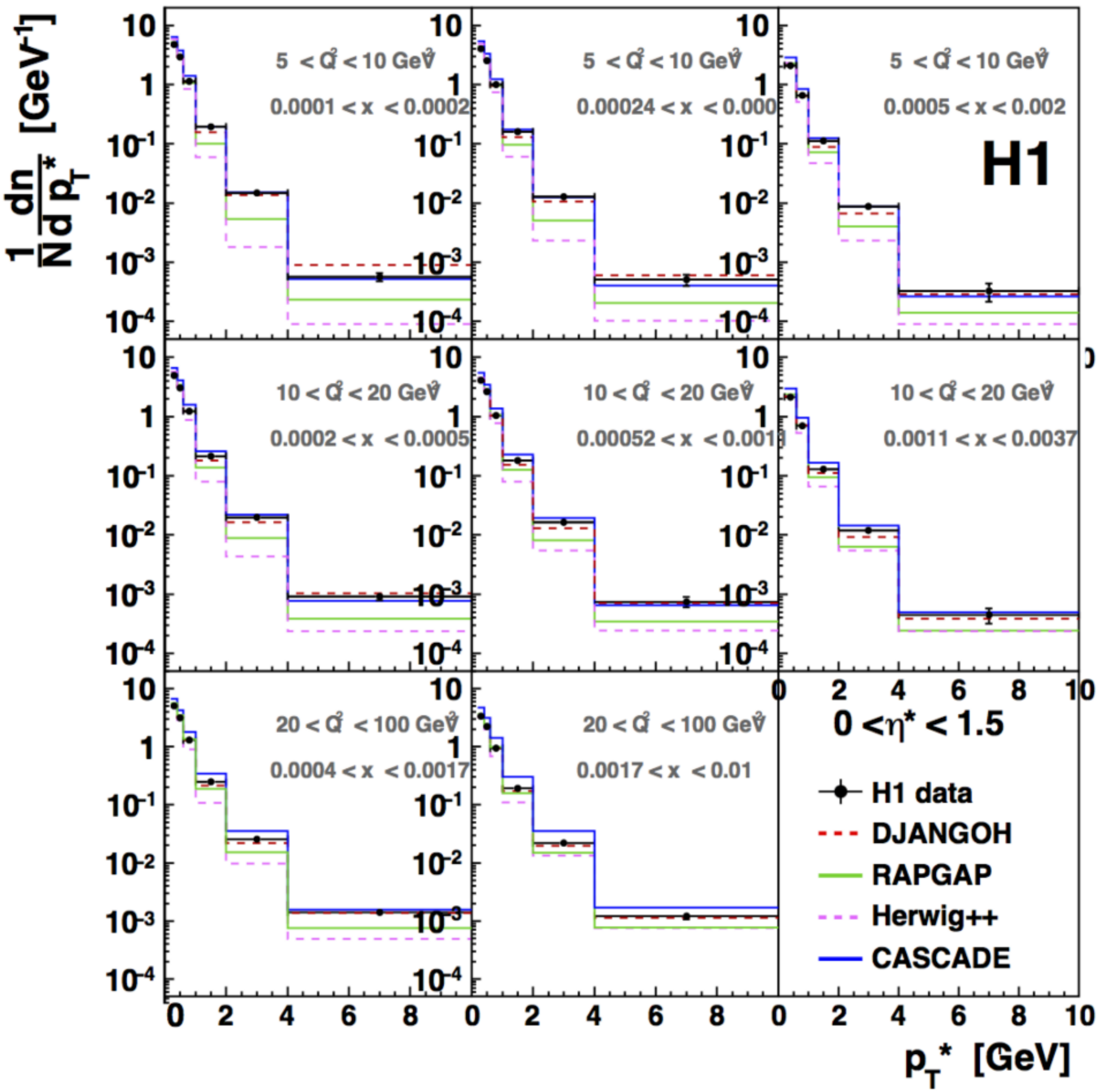
Initial state parton showers using uPDFs

- Backward evolution from hard scattering towards proton
- No change in kinematics of hard scattering, since k_t of initial state partons treated by uPDF
- In all branchings kinematics are constraint by uPDF
- using the same frame for uPDF evolution and parton shower, no free or additional parameters are left for shower



Charged particle spectra as fct of p^*_t in DIS

H1 Coll. EPJC 73 (2013) 2406

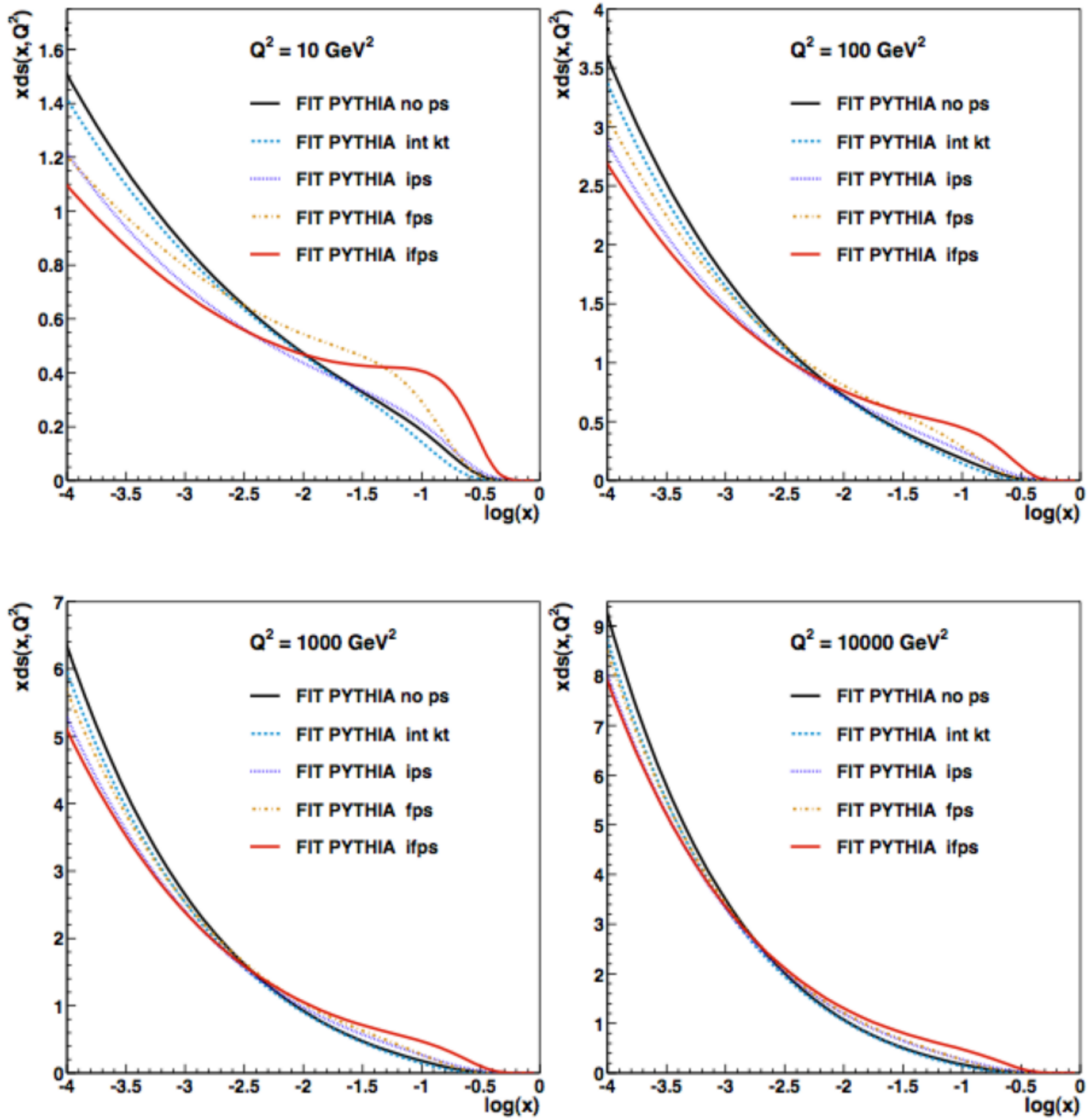


- particle spectra as fct of p^*_t give constraints on hardness of partons in parton shower
- collinear shower models (RAPGAP) generate too soft spectra compared to measurement
- small x improved (CCFM) shower (CASCADE) and CDM (DJANGOH) generate harder spectrum → closer to measurement at large p^*_t

Kinematic effects in PDF determination

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



Transverse momentum effects in pp

- Transverse momentum effects are relevant for many processes at LHC
- parton shower matched with NLO (POWHEG) generates additional k_t , leading to energy-momentum mismatch
- Transverse momentum effects are visible in high p_t processes, not only at small *x*