

# Transverse momentum dependent gluon density from DIS precision data

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H. Jung (DESY, Uni Antwerp)

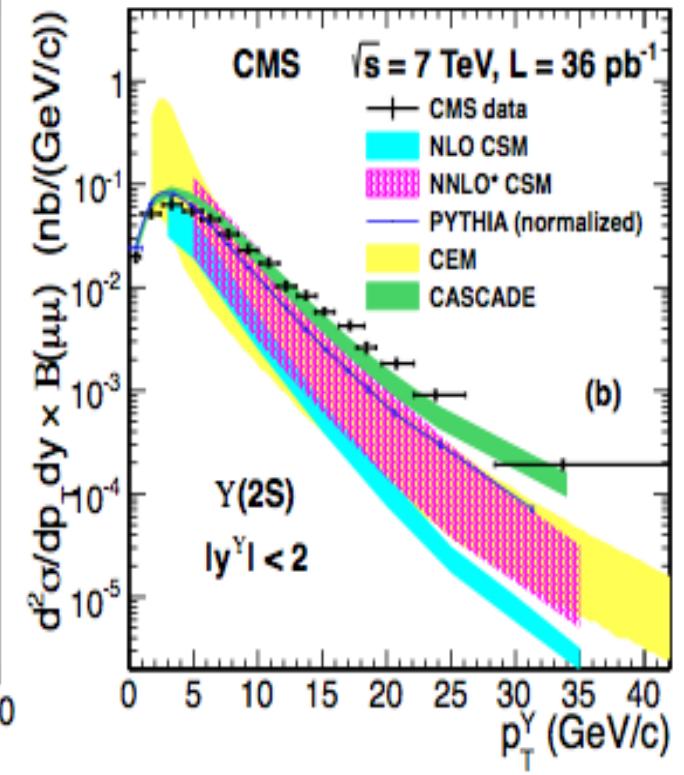
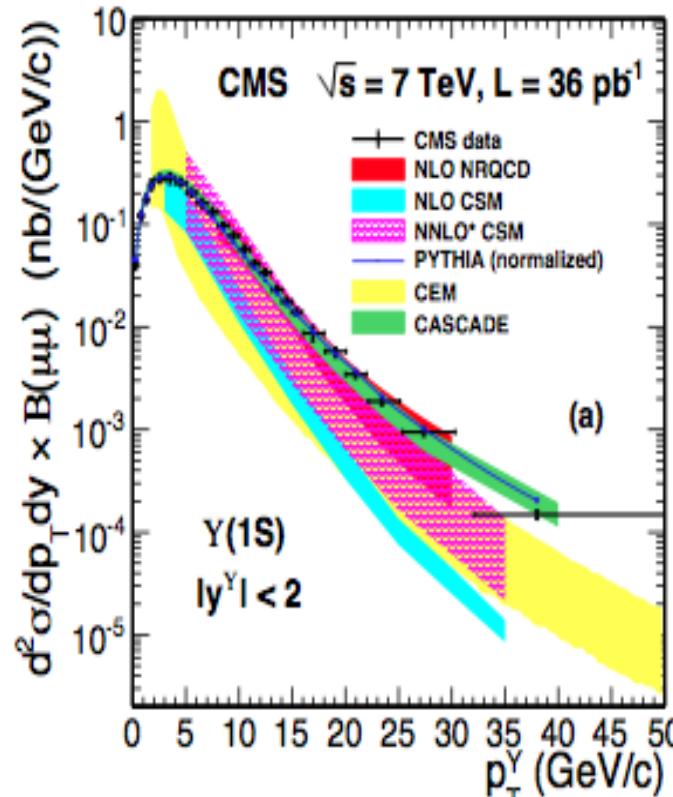
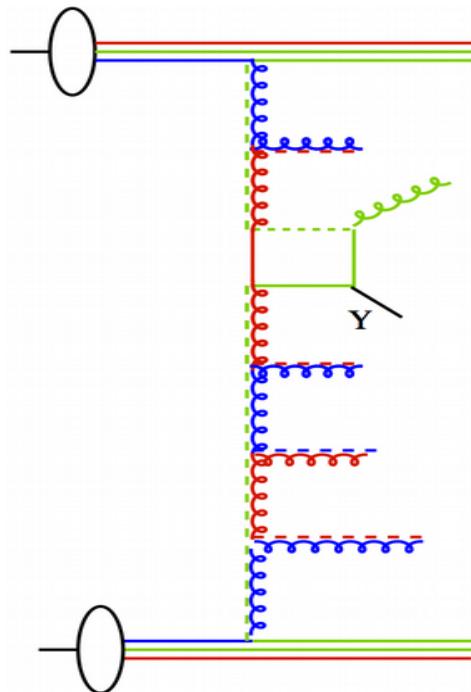
F. Hautmann (Uni Oxford)

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

# Upsilon production

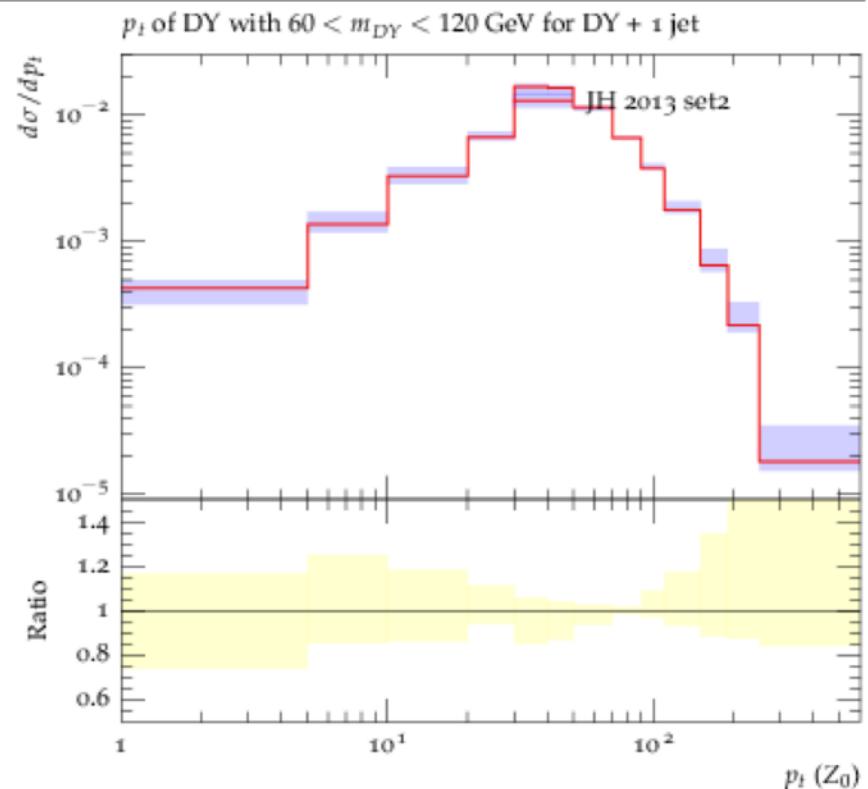
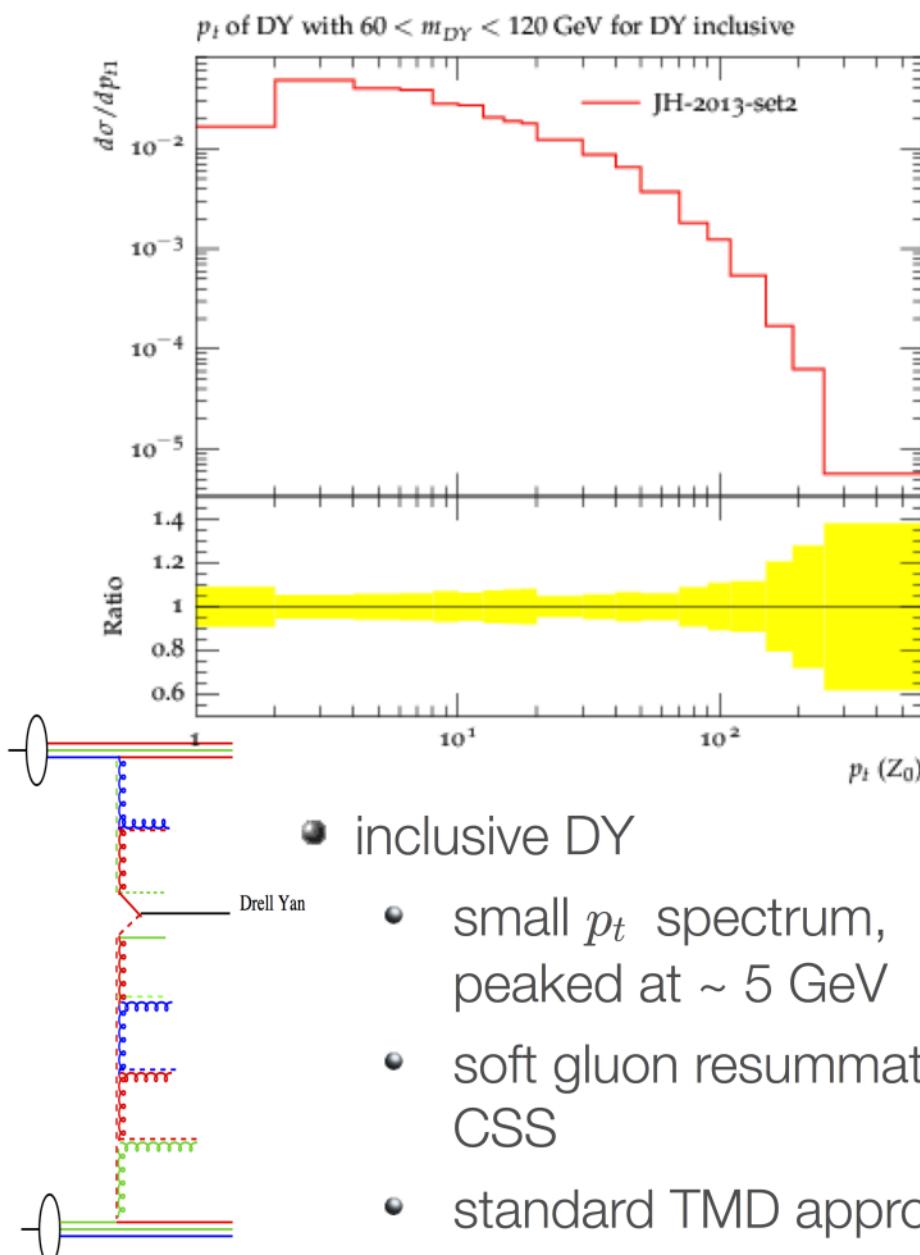
$$g^* g^* \rightarrow \Upsilon g, \quad g^* g^* \rightarrow \chi_b \rightarrow \Upsilon + X$$

CMS Phys.Lett. B727 (2013)101, 1303.5900  
 Measurement of the  $\Upsilon(1S)$ ,  $\Upsilon(2S)$ , and  $\Upsilon(3S)$   
 cross sections in pp collisions at  $s\sqrt{s} = 7$  TeV



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

# Drell Yan production in pp



- inclusive DY

- small  $p_t$  spectrum, peaked at  $\sim 5$  GeV
- soft gluon resummation, CSS
- standard TMD approach

- DY + jet,  $p_{t,jet} > 30$  GeV

- peak shifted to larger  $p_t$
- “mini-jet” resummation
- need TMDs in truly perturbative region

Talk by S. Dooling, WG2, Wednesday

# How to obtain TMDs ?

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- take derivative of integrated PDF:

$$f(x, k_\perp^2) = \frac{dg(x, k_\perp^2)}{dk_\perp^2} = \left[ \frac{\alpha_s}{2\pi} \int_x^{1-\delta} P(z) g\left(\frac{x}{z}, k_\perp^2\right) dz \right]$$

- KMR approach:

$$f(x, k_\perp^2, \mu^2) = \frac{dg(x, \mu^2)}{d\mu^2} \exp \left( - \int_{k_\perp^2}^{\mu^2} \frac{\alpha_s}{2\pi} d \log k_\perp^2 \sum_i \int_0^1 P(z') dz' \right)$$

- generated from integrated PDF, only last emission generates transverse momentum via sudakov form factor.
- TMD with evolution in hard scale in CSS formalism (<http://tmd.hepforge.org/>)  
**TMD Project**

Webpage maintained by: Ted Rogers, Andrea Signori

This is the development page for the TMD project. The purpose of this project is to organize a repository for theoretical and phenomenological studies of transverse-momentum-dependent parton distribution functions (TMD PDFs) and fragmentation functions (TMD FFs). We provide access to parametrizations and fits of TMDs, with and without taking into account the perturbative QCD evolution.

# How to obtain TMDs ? CCFM approach

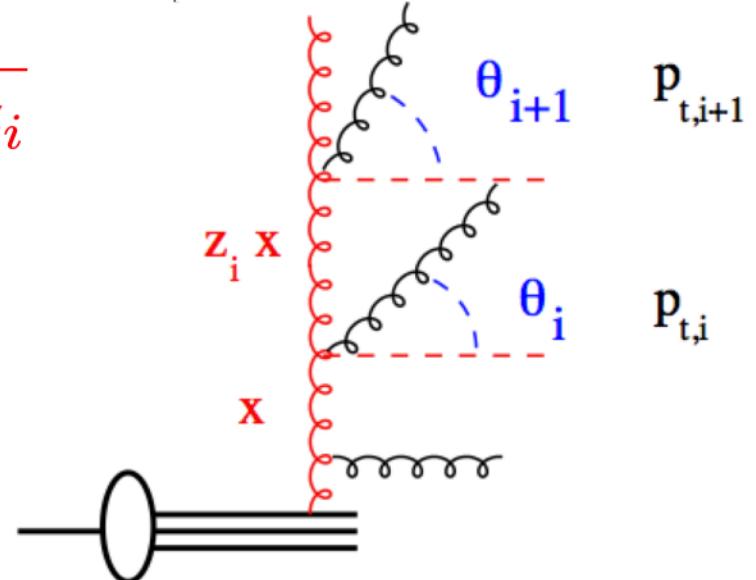
- Color coherence requires angular ordering instead of  $p_t$  ordering ...

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

→ 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:



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

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

→ Catani Ciafaloni Fiorani Marchesini evolution forms a bridge between DGLAP and BFKL evolution

# TMDlib and TMDplotter

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- combine and collect different ansaetze and approaches:

<http://tmd.hepforge.org/> and  
<http://tmdplotter.desy.de>

- TMDlib: a library of parametrization of different TMDs and uPDFs (similar to LHApdf)

- started by F. Hautmann, H. Jung, P. Mulders, A. Signori, T. Rogers

- easily callable from C++ or Fortran

```
TMDinit(name)  
TMDpdf(x,xbar,kt,mu, uval, dval,  
sea, charm, bottom, gluon);
```

- first release within next weeks

DESY 14-059  
April 2014

**TMDlib and TMDplotter:  
library and plotting tools for  
Transverse Momentum Dependent parton distributions  
Version 0.1.02**

F. Hautmann<sup>1,2,3</sup>, H. Jung<sup>4,5</sup>, M. Krämer<sup>4</sup> P. Mulders<sup>6,7</sup>, T. Rogers<sup>8</sup>,  
A. Signori<sup>6,7</sup>

<sup>1</sup> Dept. of Physics and Astronomy, University of Sussex, UK

<sup>2</sup> Rutherford Appleton Laboratory, UK

<sup>3</sup> Dept. of Theoretical Physics, University of Oxford, UK

<sup>4</sup> DESY, Hamburg, FRG

<sup>5</sup> University of Antwerp, Belgium

<sup>6</sup> Department of Physics and Astronomy, VU University Amsterdam, the Netherlands

<sup>7</sup> Nikhef, the Netherlands

<sup>8</sup> C.N. Yang Institute for Theoretical Physics, Stony Brook University, USA

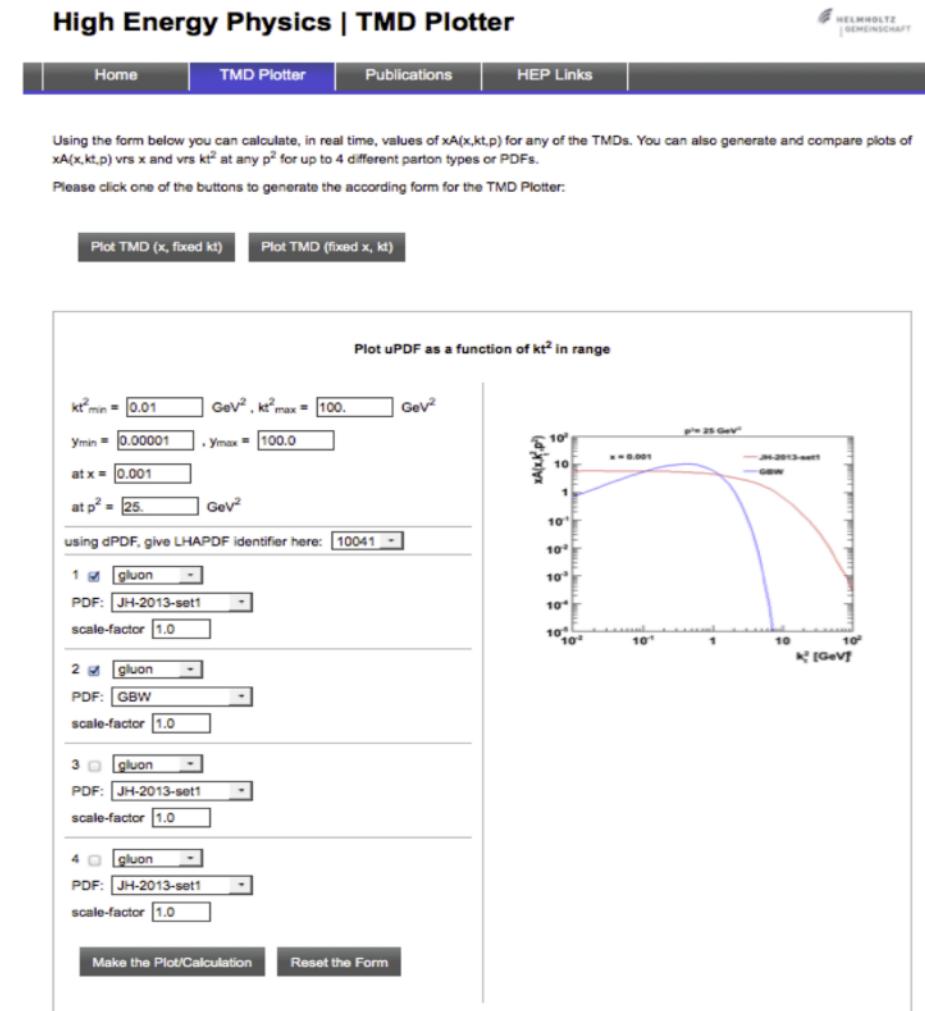
## Abstract

Transverse-momentum-dependent distributions (TMDs) play a crucial role in high-energy physics from the theoretical and phenomenological point of view. The library of transverse-momentum-dependent parton distribution functions (TMD PDFs) and fragmentation functions (TMD FFs) TMDlib is described together with the online plotting tool TMDplotter.

A detailed program description is given, with emphasis on parameters the user wants to change.

# TMDlib and TMDplotter

- combine and collect different ansaetze and approaches
  - from <http://tmd.hepforge.org/> and <http://tmdplotter.desy.de>
- TMDlib: a library of parametrization of different TMDs and uPDFs (similar to LHApdf)
  - started by F. Hautmann, H. Jung, P. Mulders, A. Signori, T. Rogers
- platform for online plotting of TMDs using TMDlib
- <http://tmdplotter.desy.de>



Contact Imprint

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

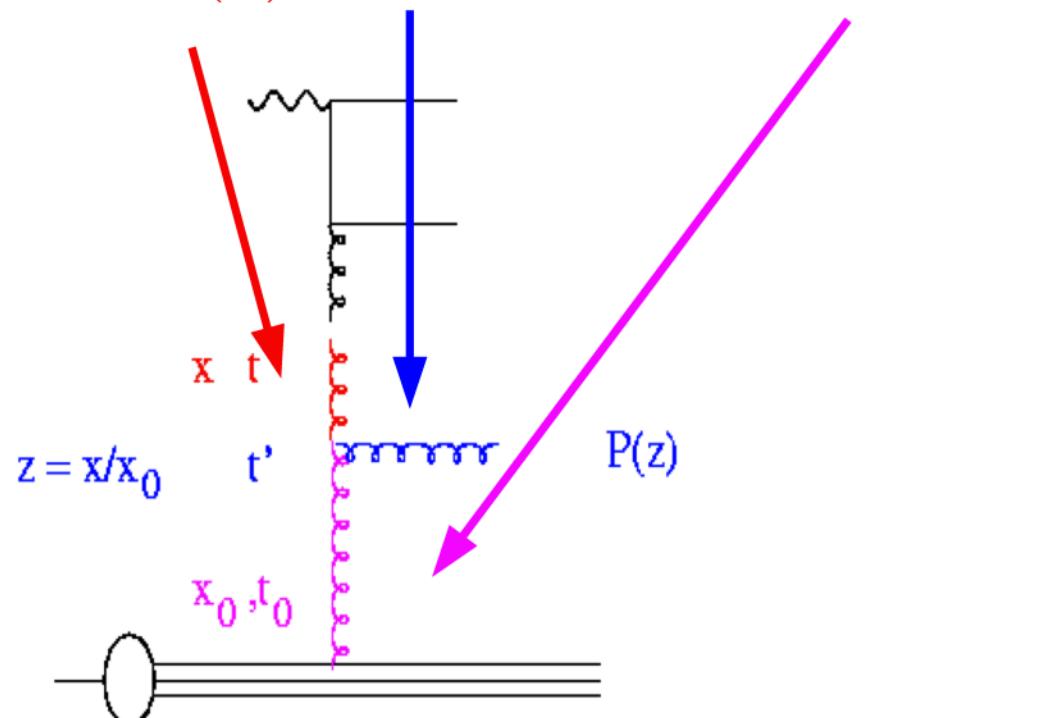
# Evolution equation and TMDs

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

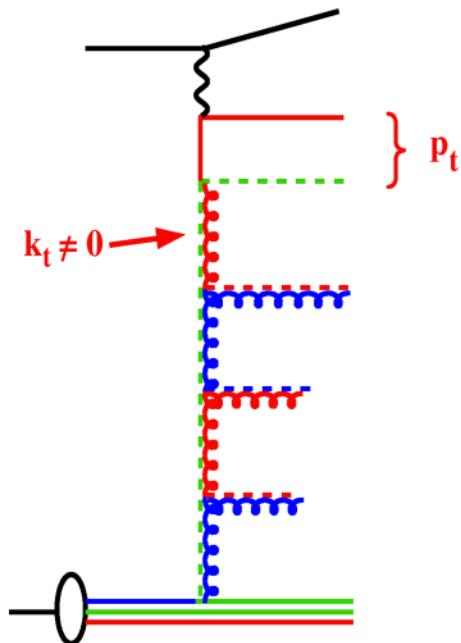
- solve integral equation via iteration:

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

- 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



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

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

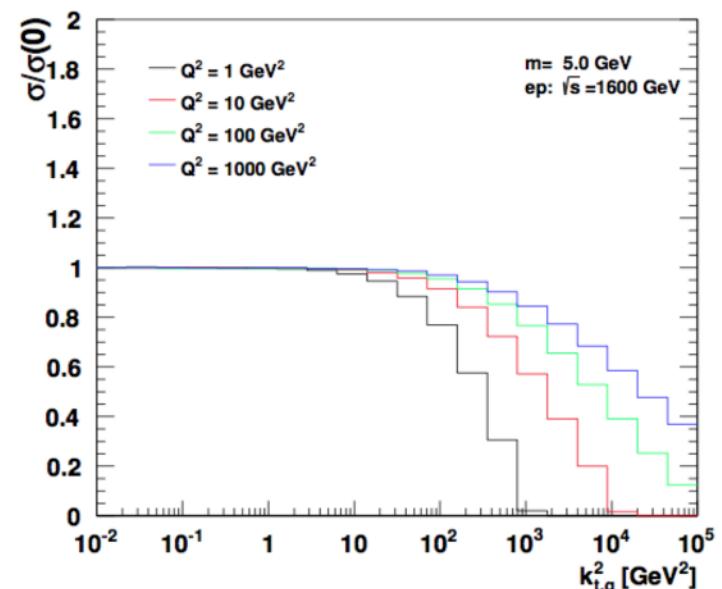
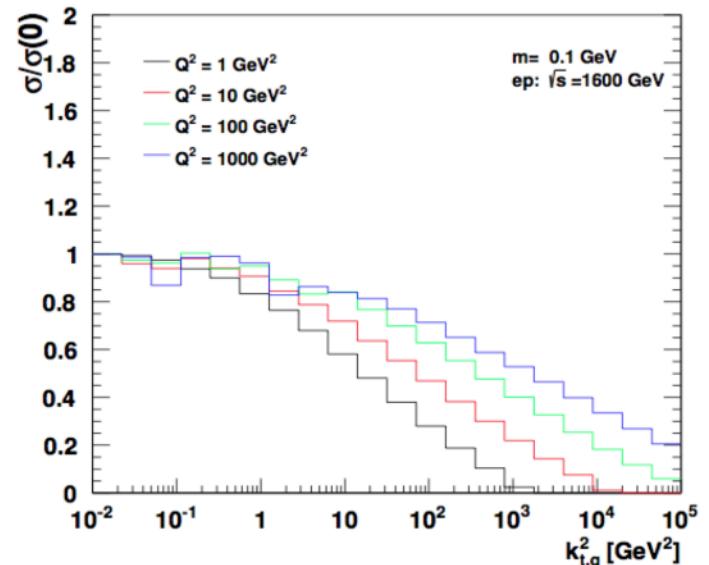
- until now, only gluon TMDs were determined
- valence quarks from starting distribution of HERAPDF or CTEQ6

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

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

# 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:  $\mu^2 \sim Q^2 + 4 m^2$ :
$$\int_0^{\mu^2} dk_{\perp} \hat{\sigma}(k_{\perp}, \dots)$$



# 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  $\rightarrow$  no  $k_t$  ordering at small  $x$
  - include valence quarks (for large  $x$ )

- starting distribution for gluon at  $q_0$ :

$$x\mathcal{A}_0(x, k_\perp) = Nx^{-B} \cdot (1-x)^C (1 - Dx + E\sqrt{x}) \exp[-k_t^2/\sigma^2]$$

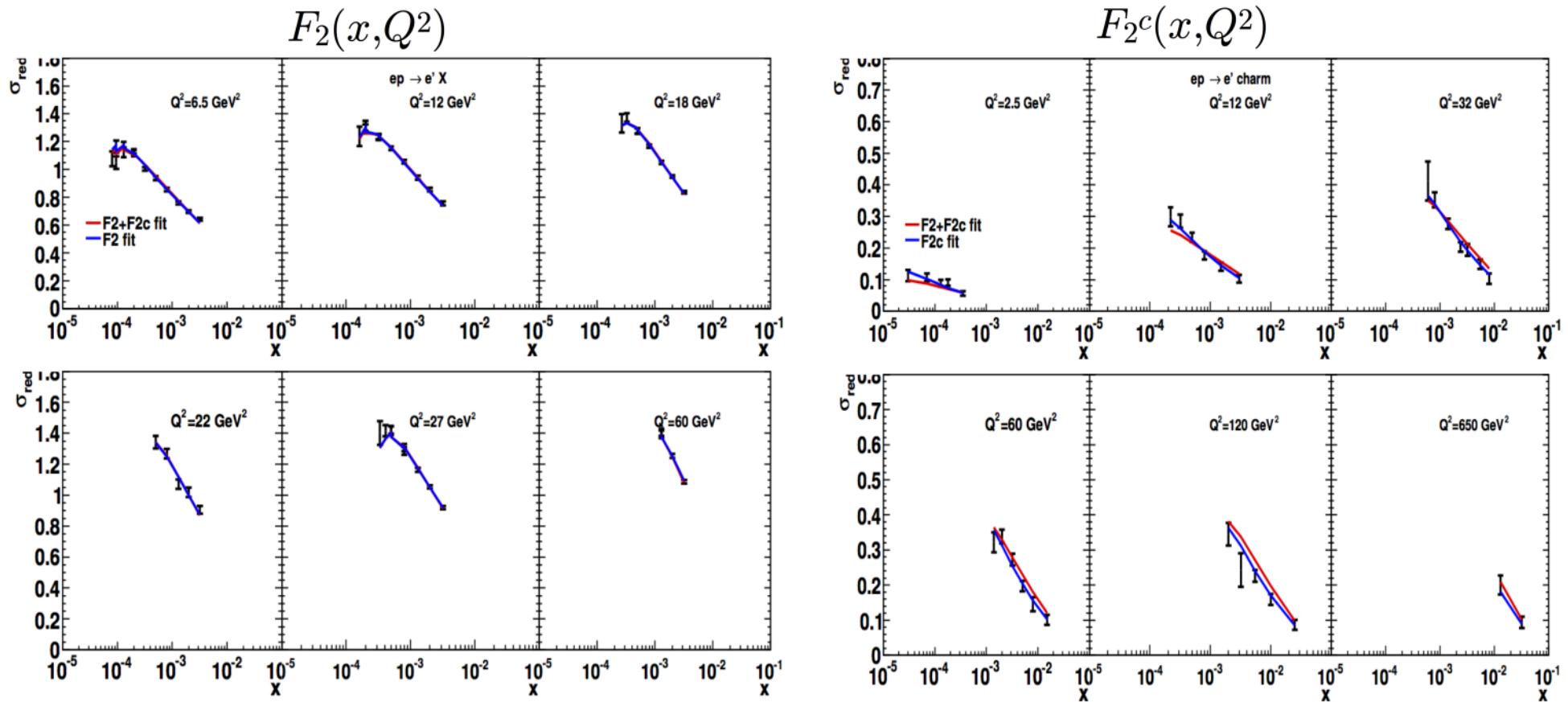
- starting distribution for valence quarks at  $q_0$ :

$$xQ_{v0}(x, k_t, p) = xQ_{v0}(x, k_t, q_0)\Delta_s(p, q_0)$$

$$xQ_{v0}(x, k_t, q_0) = xQ_{v\text{coll.pdf}}(x, q_0) \exp[-k_t^2/\sigma^2]$$

$$\text{with } \sigma^2 = q_0^2/2$$

# From HERA: small $x$ improved gluon TMD

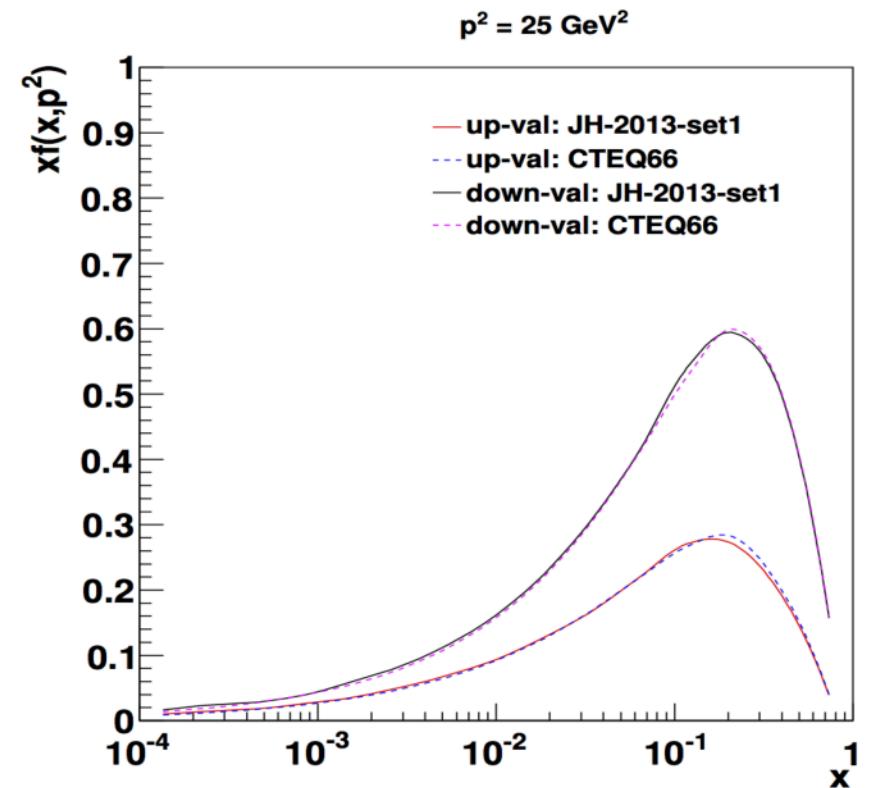
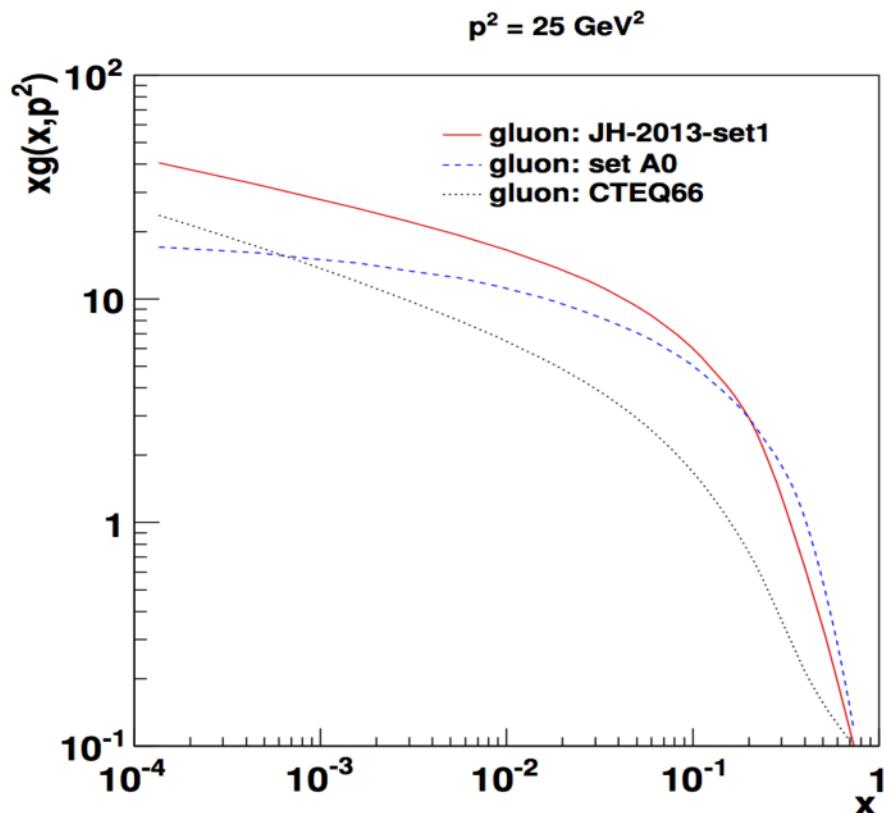


- fit performed with `herafitter` package (full treatment of corr. and uncorr. uncertainties)
  - $F_2^c(x, Q^2)$ :  $Q^2 \geq 2.5 \text{ GeV}$
  - $F_2(x, Q^2)$ :  $x \leq 0.005$ ,  $Q^2 \geq 5 \text{ GeV}$
- very good  $\chi^2/ndf$  obtained ( $\sim 1$ )

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

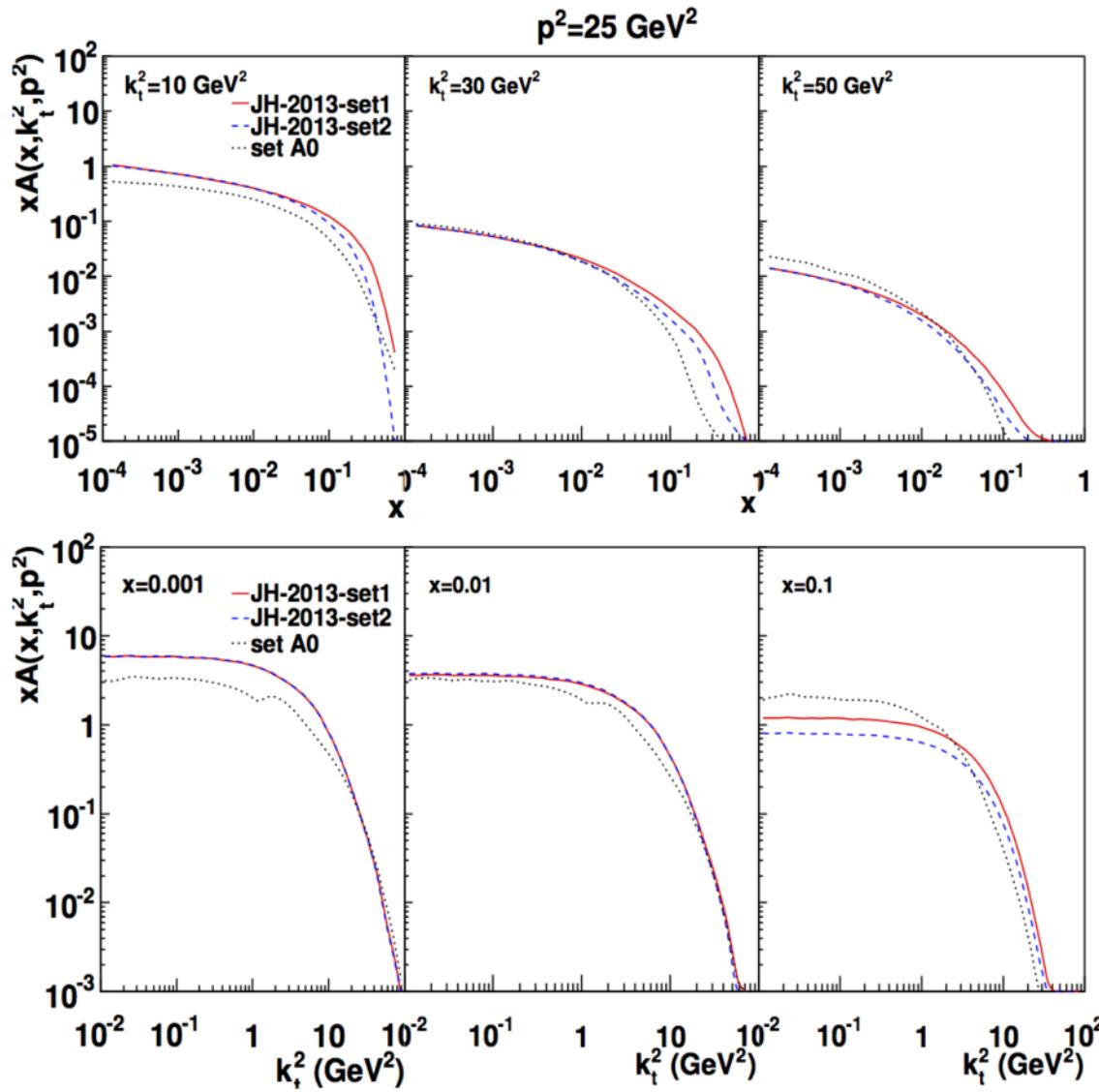
F. Hautmann and H. Jung. Transverse momentum dependent gluon density from DIS precision data. arXiv 1312.7875 Nuclear Physics B, 883:1, 2014.



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

- valence quarks in CCFM are similar to CTEQ, but evolution is different due to different  $\alpha_s$

# CCFM gluon from $F_2$ and $F_2 \& F_2^c$ fit

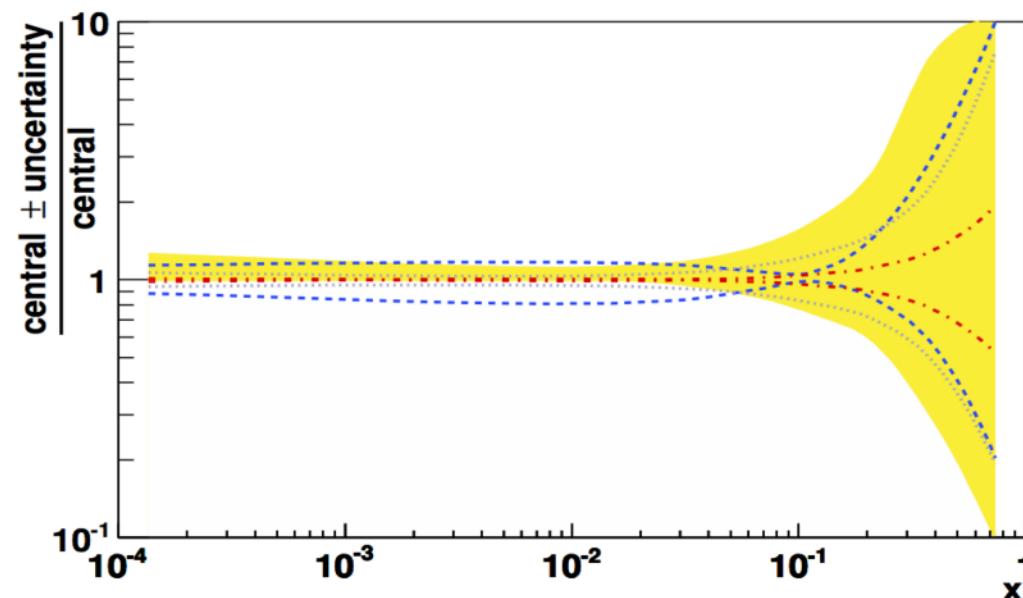
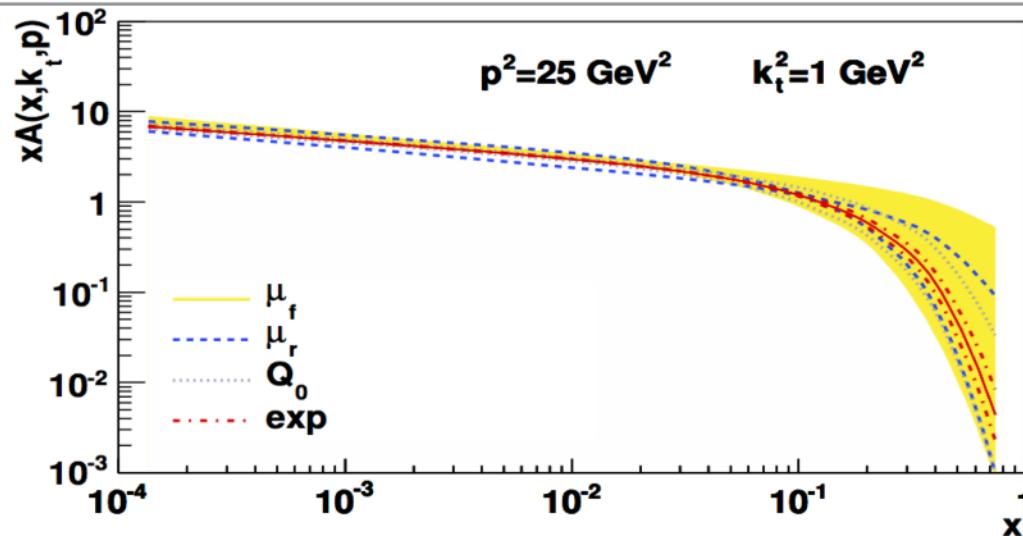


- Fit function:

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

- only 3 params used in fit: no significant change for more params
- 2-loop  $\alpha_s$
- gluon splitting function with non-singular terms
- fits:
  - set 1:  $F_2$  :  $Q^2 > 5$  GeV,  $x \leq 0.005$
  - set 2:  $F_2 \& F_2^c$ :  $Q^2 > 2.5$  GeV
- new fit gives  $\chi^2/ndf \sim 1.2$
- details are different from previous uPDF set A<sub>0</sub>

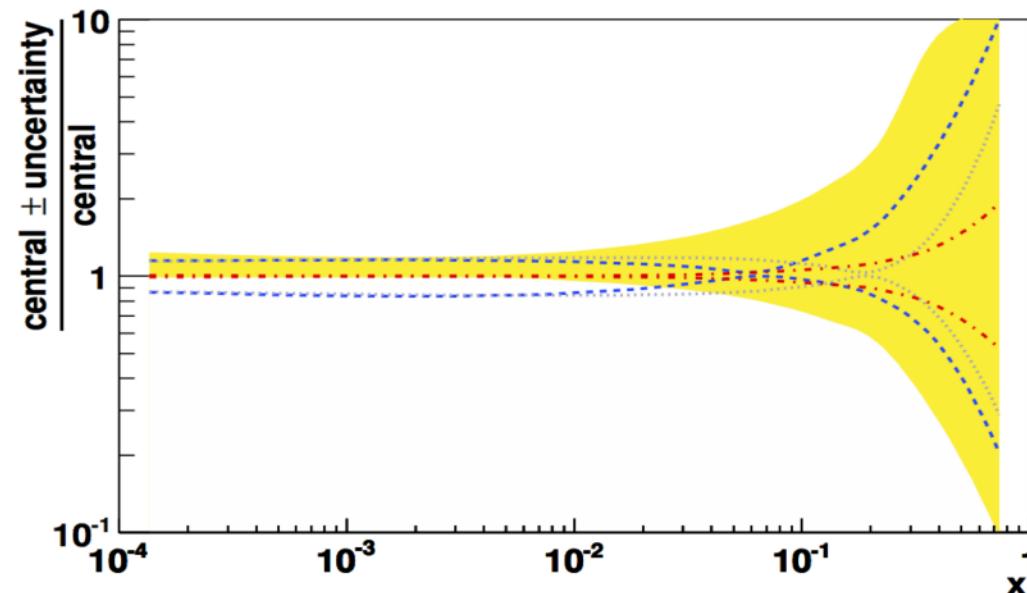
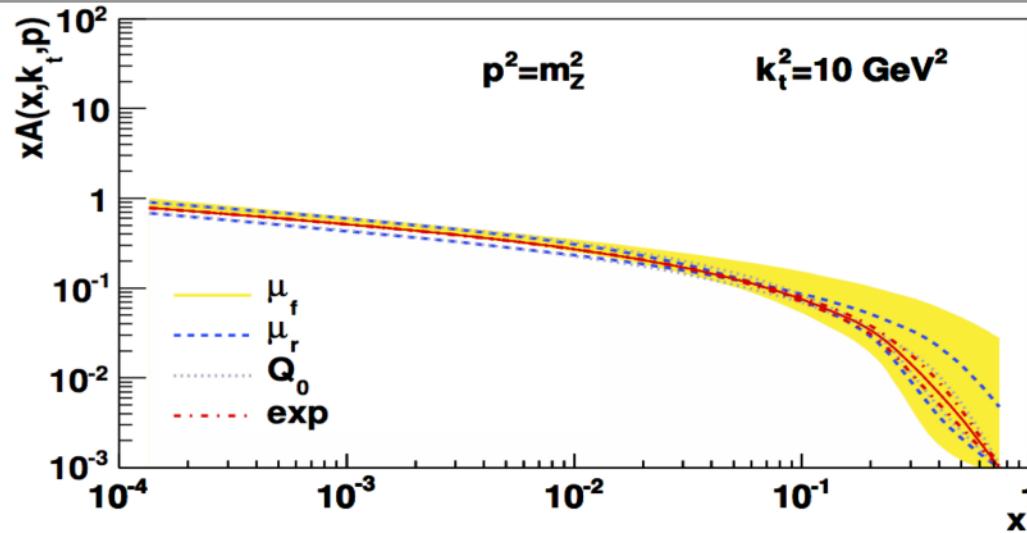
# uncertainties of CCFM gluon



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:  
 $x < 0.005, Q^2 > 5 \text{ GeV}^2$
  - dominant uncertainties

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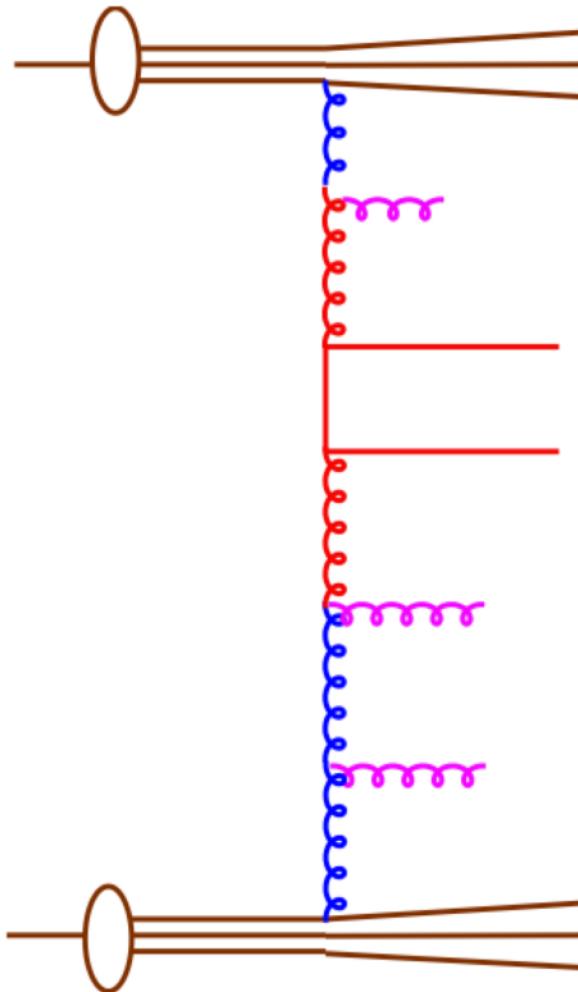
# CCFM evolution code

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- CCFMuPDF: CCFM evolution code (based on SMALLX code by G. Marchesini & B. Webber)
  - fast Monte Carlo forward evolution including full treatment of kinematics in each splitting
  - choices for:
    - kinematic constraints
    - splitting functions
    - scales
    - $k_t$  dependent starting distribution
  - applicable for gluon and valence quark evolution
  - sea quark evolution coming soon
- already used in **herafitter** package
- public release May 2014

# TMDs and the general pp case

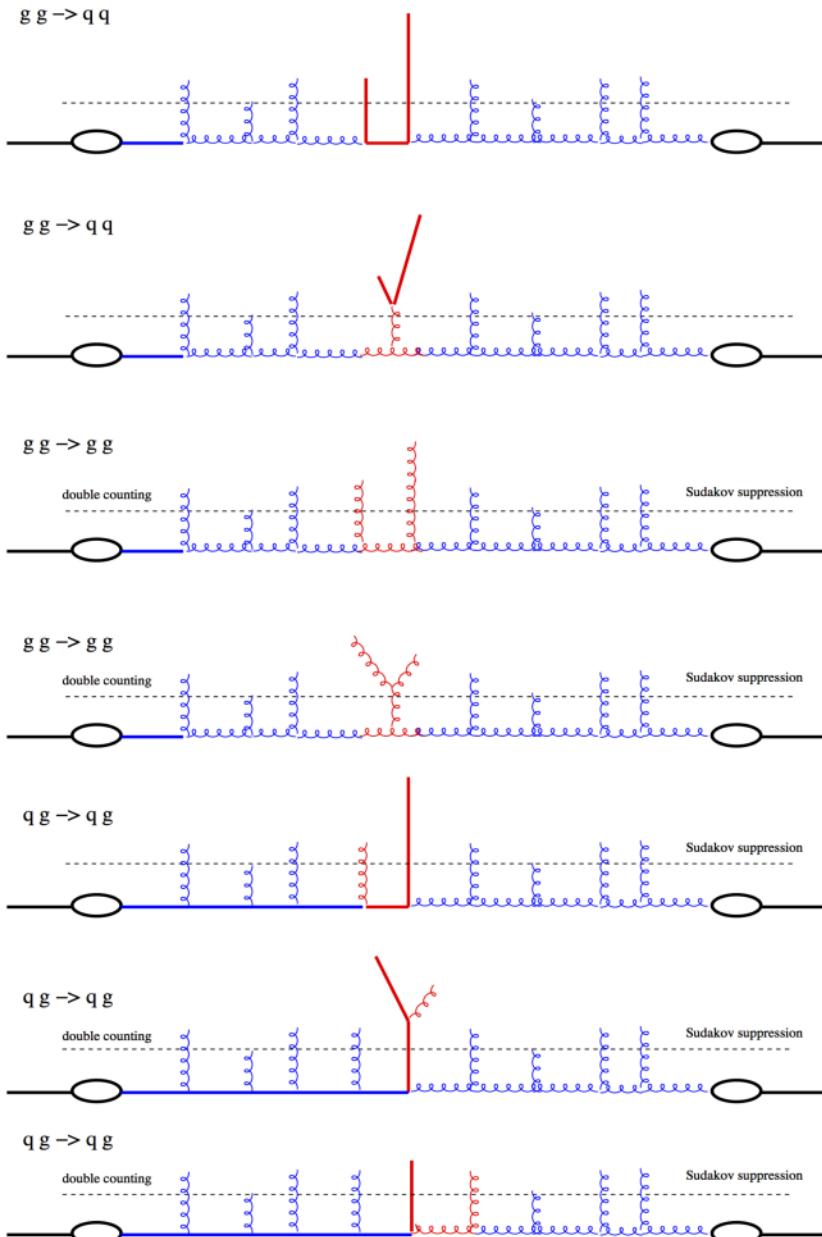
- basic elements are:
  - Matrix Elements:
    - on shell/off shell
  - PDFs
    - unintegrated PDFs
  - Parton Shower
    - angular ordering (CCFM)
- Proton remnant and hadronization handled by standard hadronization program, e.g. PYTHIA



Hadronisation

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

# TMDs and pp: factorization issues



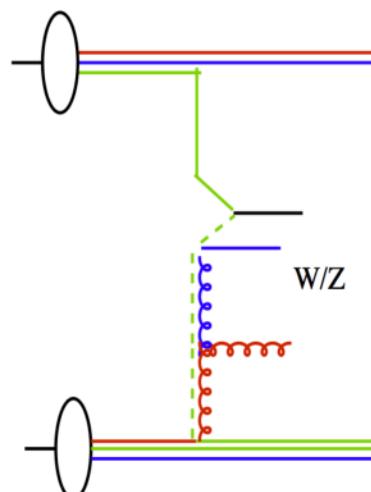
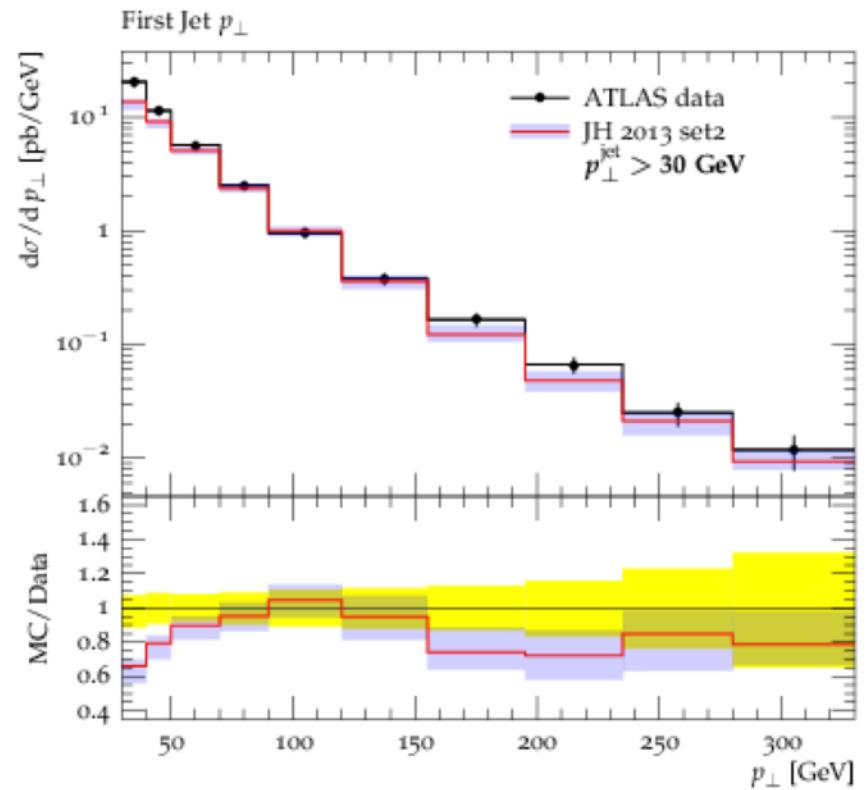
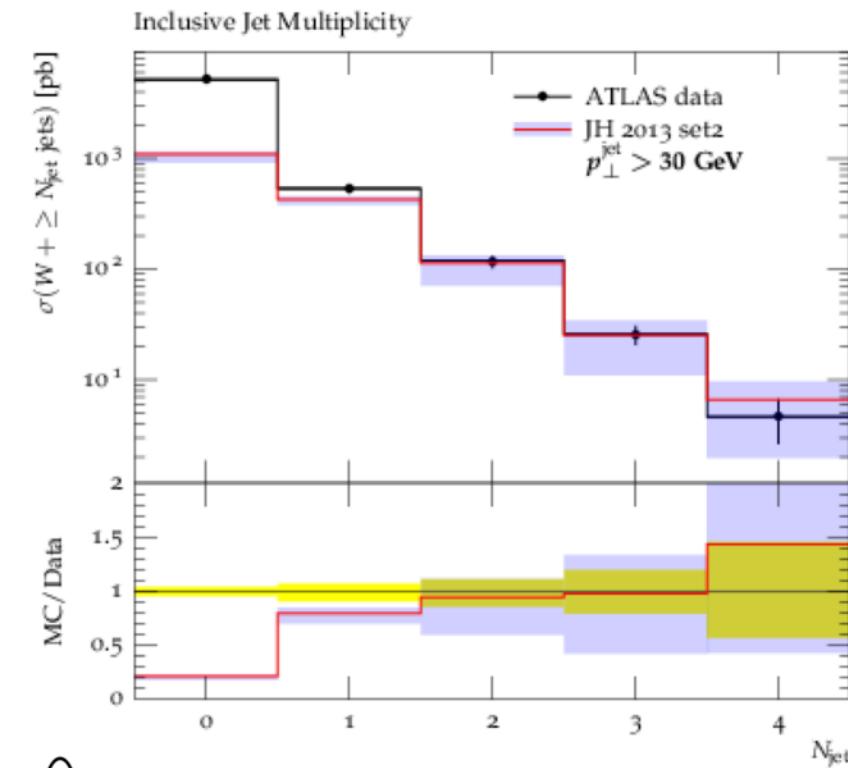
- $k_t$  of initial partons a priori not restricted, extends to large  $k_t$
- with  $k_t$  of initial partons, identification of hard scattering **no longer trivial for light partons**
- double counting issues (factorization) within and crossed process chains:  $gg \rightarrow gg$  partially included in  $gg \rightarrow qq$

# Factorization issues for TMDs in pp

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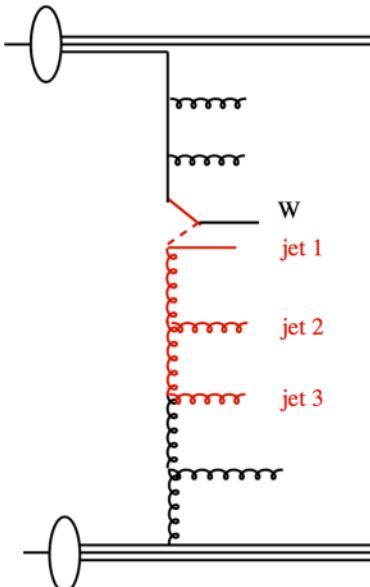
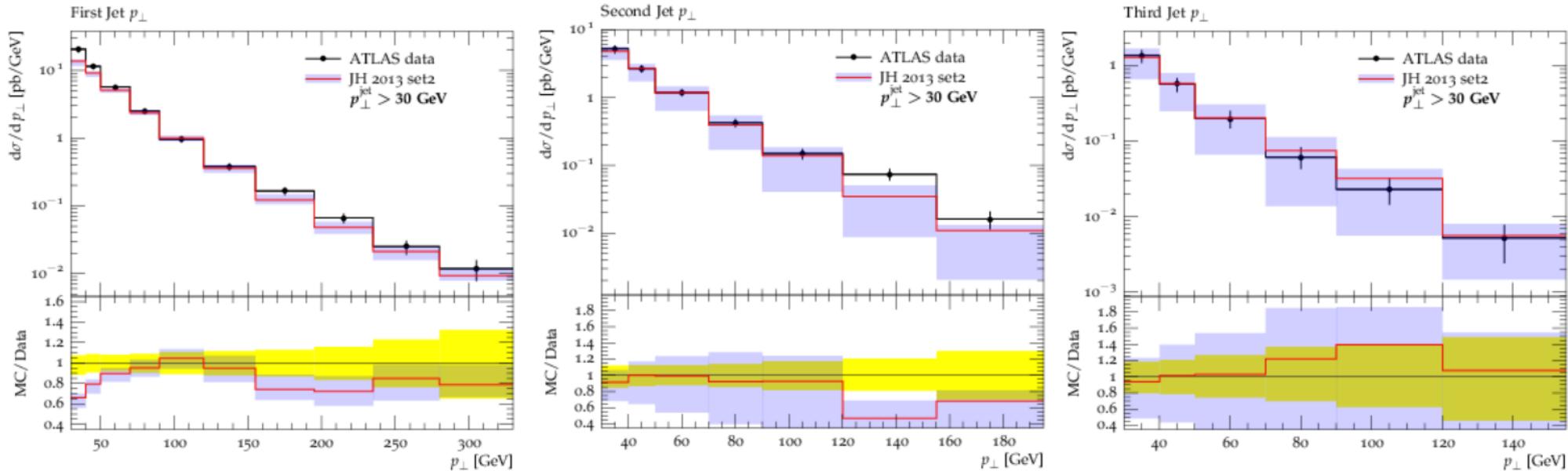
- High energy factorization proven for
  - DIS at small  $x$
  - heavy quark production in pp
  - Boson ( $Z,W,H$ ) production in pp
- TMD factorization proven for
  - (semi)-inclusive DIS
  - Boson production in pp
- Factorization breaking in
  - back-to-back di-hadron (di-jet) production in pp
  - how large ?
  - problems also in non back-to-back region ?
- Test first application of CCFM TMD-gluon to  $W+jet$  production in pp

# Application to W + jet production at LHC



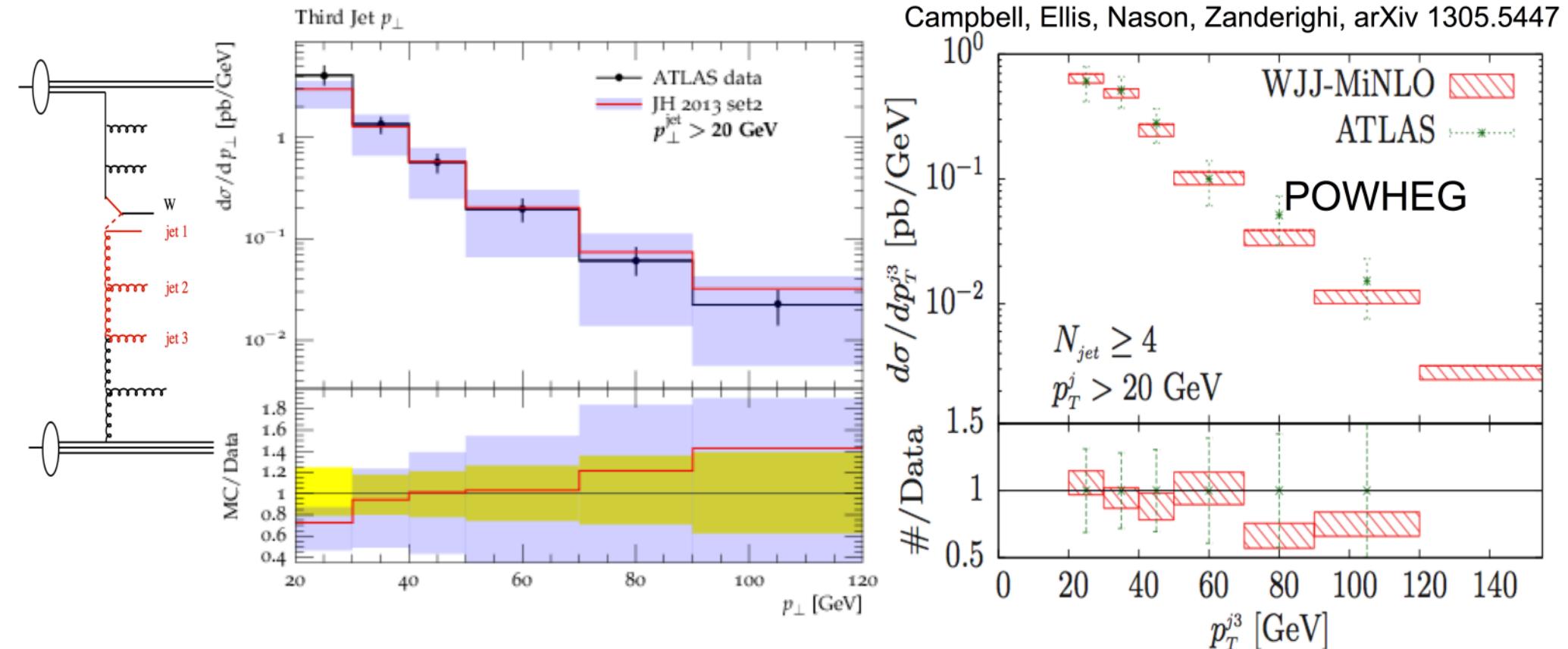
- use CCFM gluon convoluted with off-shell ME
- uncertainty from pdf (including scale variation) on 1st jet is small → ME !
- agrees reasonably well with W+jet measurement

# Application to W + jet production at LHC



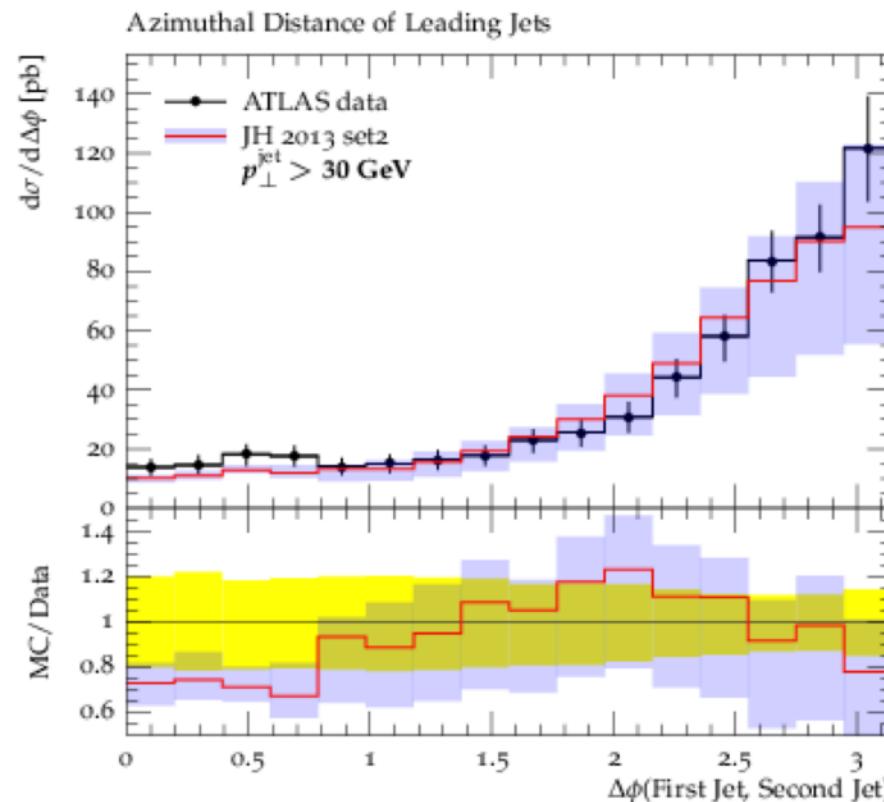
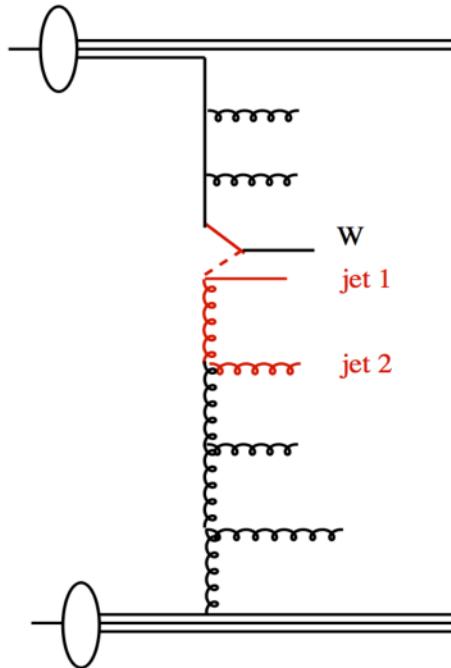
- off-shell ME + CCFM  $k_t$  - shower can predict multi-jet production
  - $p_t$  spectra reasonable
  - multi jets come from CCFM  $k_t$  - shower
  - uncertainty from pdf (including scale variation) increases with jet multiplicity !
    - dominant is scale variation

# Application to W + jet production at LHC



- off-shell ME + CCFM  $k_t$  - - shower for 3rd jet (similar to NLO W+2jet) !
  - 3rd jet comes from CCFM  $k_t$  - - shower
  - uncertainty from pdf (including scale variation) is larger → jets from shower at different scales !!!

# $W + n\text{-jets}$ : $k_t$ shower vrs NLO



- off-shell ME + CCFM  $k_t$  - shower for x-section and shape for  $\Delta\phi$  between first 2 jets agrees with measurements within uncertainties:
  - sensitive probe of shower:
    - decorrelation region well reproduced !
    - uncertainty from pdf in back-to-back region non-negligible → shower !

# Conclusion

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- TMD – uPDFs are important
  - effects from transverse momentum in small  $x$  processes ( $\Upsilon$  production etc) but also in higher  $x$  processes ( $W+2\text{jets}$ , 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
- CCFM TMD together with off-shell ME give good description of Boson + multi-jets in pp !

# Backup Slides

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# 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

$\log(1/x)$

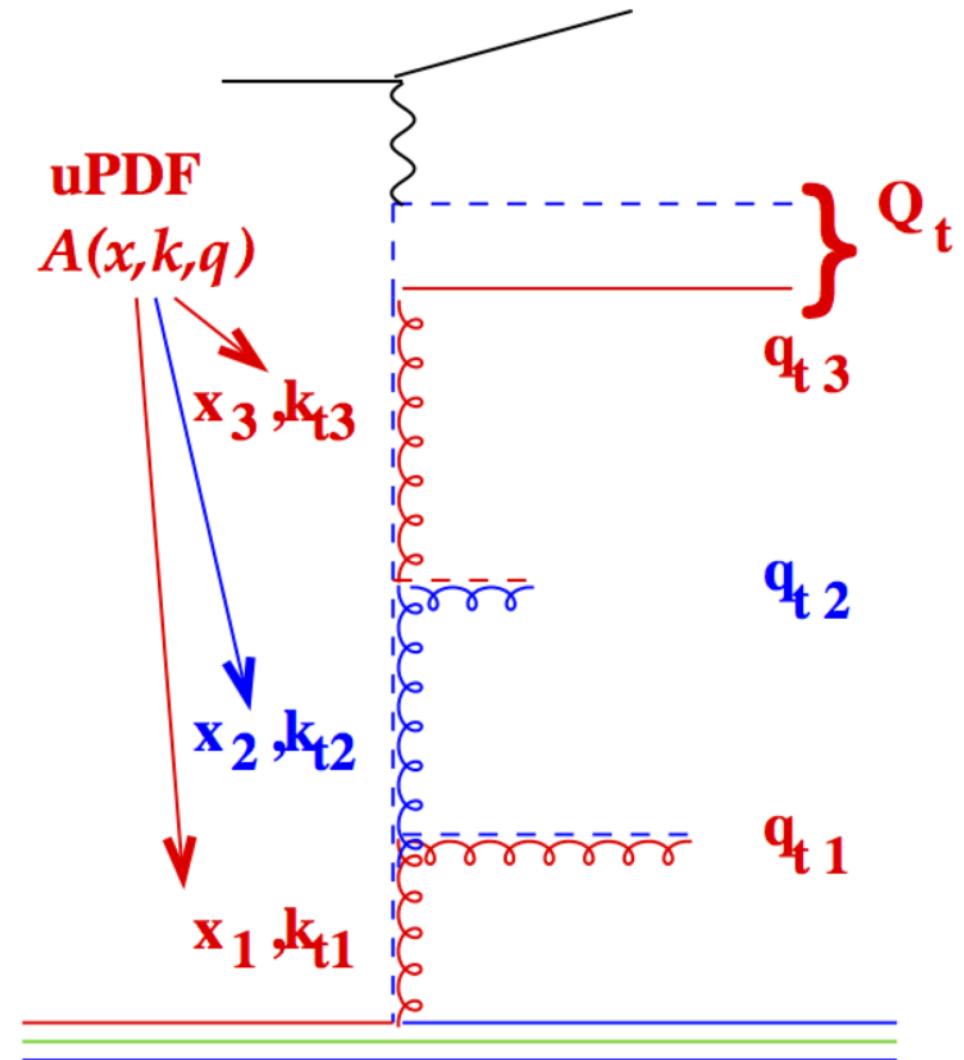
$1/(\text{hard scale})$

### small-x formalism(s):

- evolution equations in  $\log(1/x) \sim$  rapidity
  - ★ BFKL, CCFM
- gluon saturation  $\rightarrow$  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**)

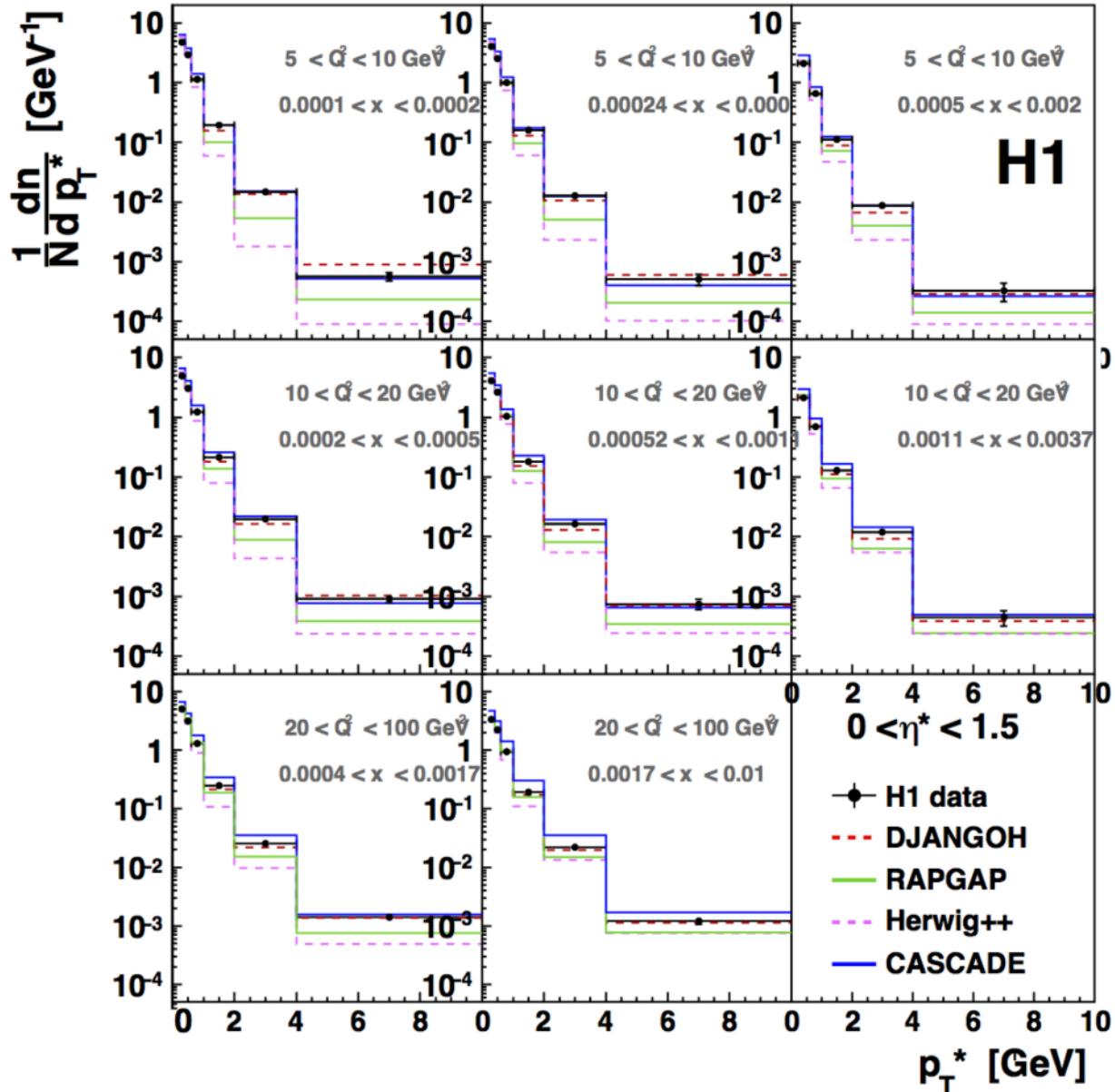
# Initial state parton showers using uPDFs

- 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

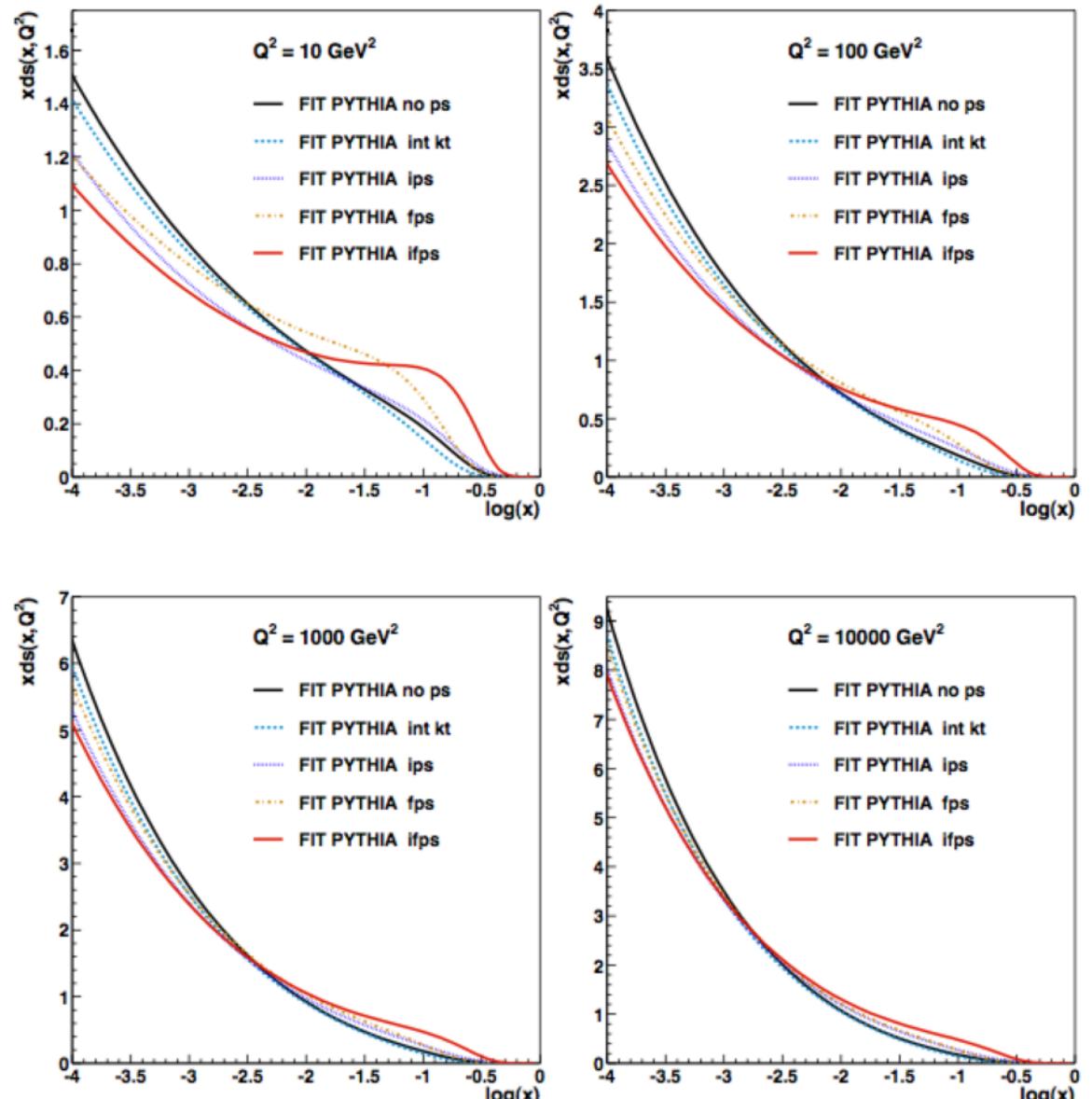


- particle spectra as fct of  $p^*_t$  give constraints on hardness of partons in parton shower
- collinear shower models (RAPGAP) generate too soft spectra compared to measurement
- small  $x$  improved (CCFM) shower (CASCADE) and CDM (DJANGOH) generate harder spectrum → closer to measurement at large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

# 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  $x$

