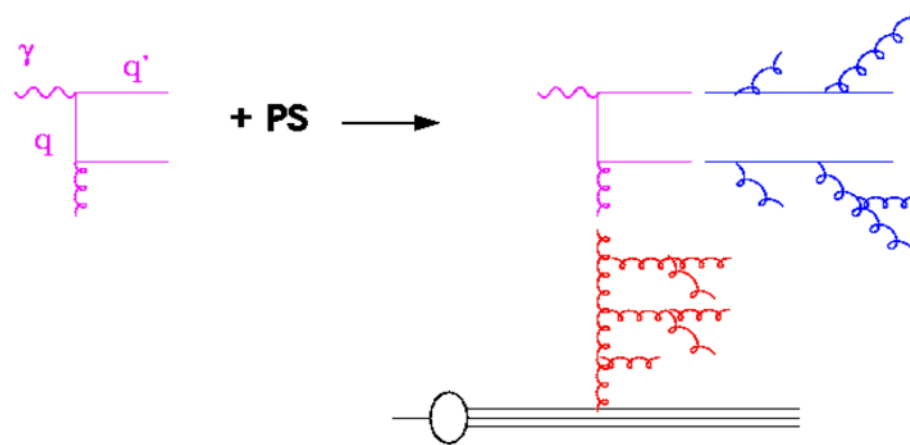# TMD PDFs for LHC

H. Jung (DESY, Uni Antwerp)

- Why TMDs?
- How can TMDs be determined ?
- Application to measurements at the LHC ?

Inconsistency: example from DIS

- **Collinear approach:** incoming/outgoing partons are on mass shell

$$(\gamma + q)^2 = q'^2, \; -Q^2 + xys = 0 \rightarrow x = Q^2/(ys)$$

- **BUT** final state radiation:

$$(\gamma + q)^2 = q'^2, \; -Q^2 + xys = m^2 \rightarrow x = (Q^2 + m^2)/(ys)$$

- **AND** initial state radiation:

$$(\gamma + q)^2 = q'^2, \; -Q^2 + xys + k^2 = 0 \rightarrow x = (Q^2 - k^2)/(ys)$$

Collinear approach: $q'^2 = k^2 = 0$ **, order by order .....**
NLO corrections... better treatment of kinematics... but still not all....

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

H. Jung, Transverse momentum dependent P
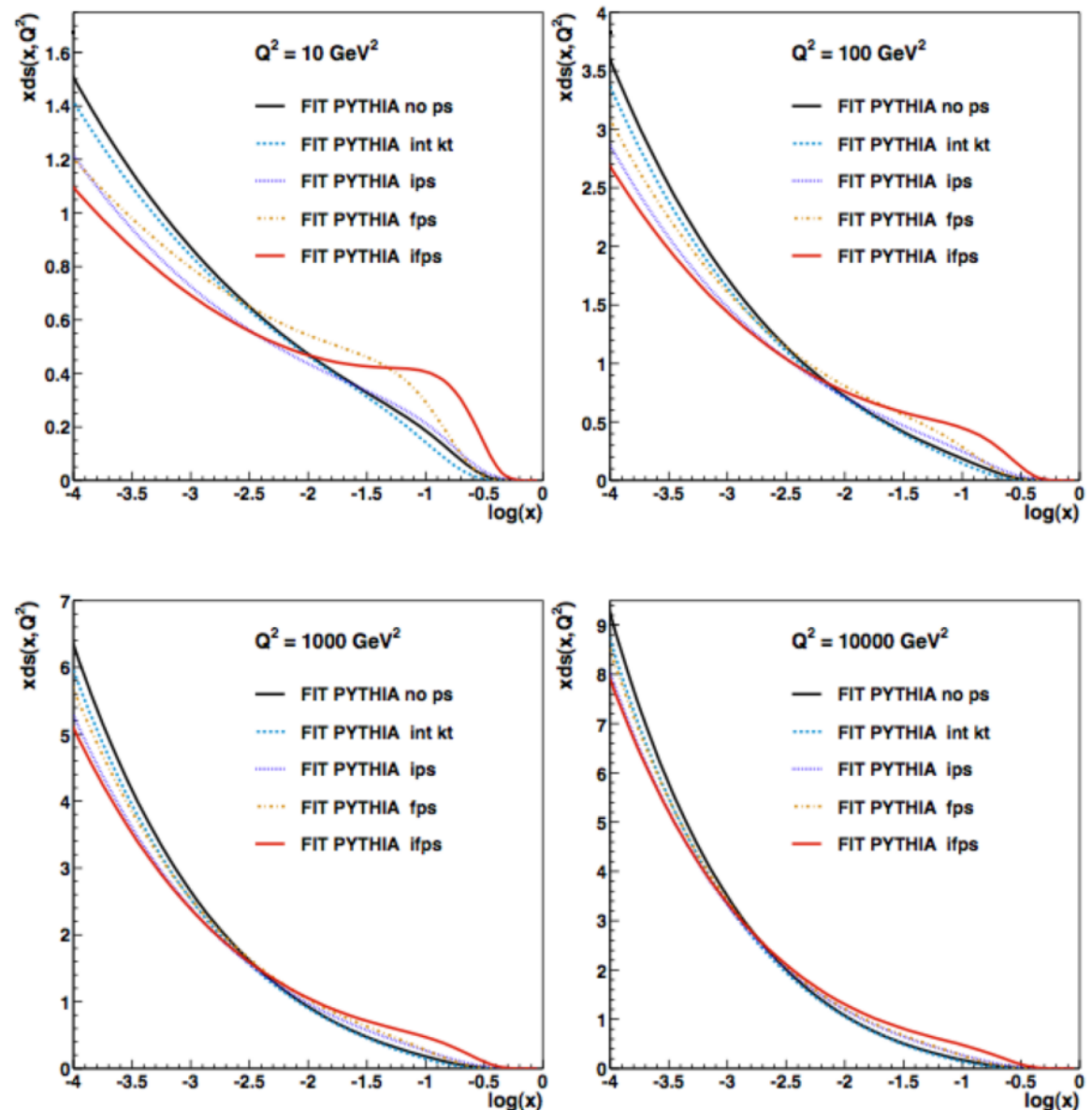
Transverse momentum effects in pp

S. Dooling, et al.
Longitudinal momentum shifts, showering and
nonperturbative corrections in matched
NLO-shower event generators.
Phys.Rev., D87:094009, 2013.

- 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
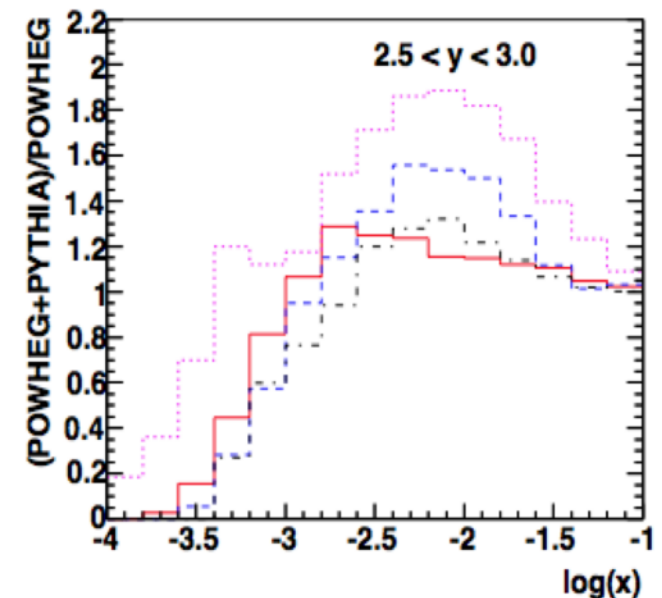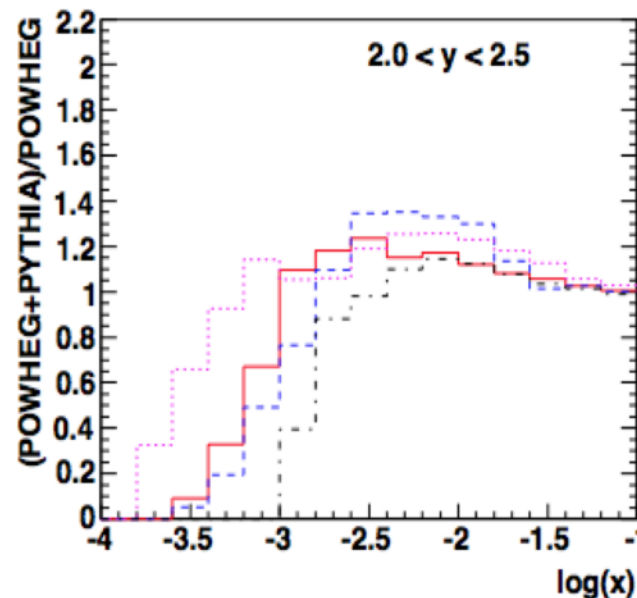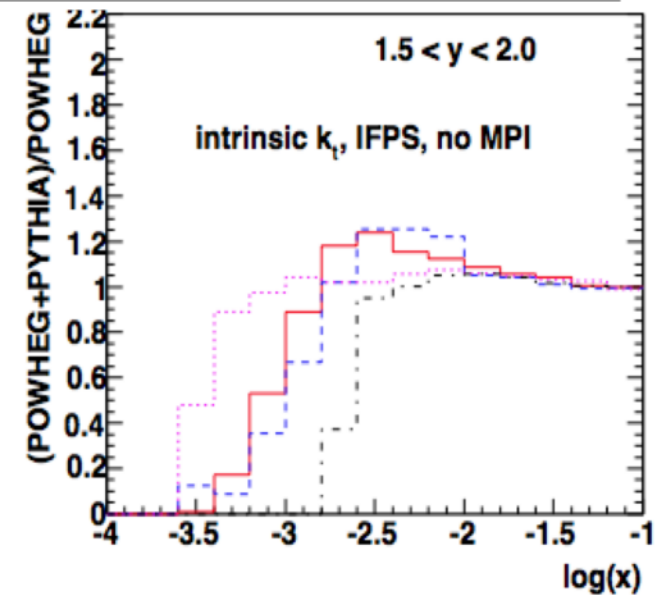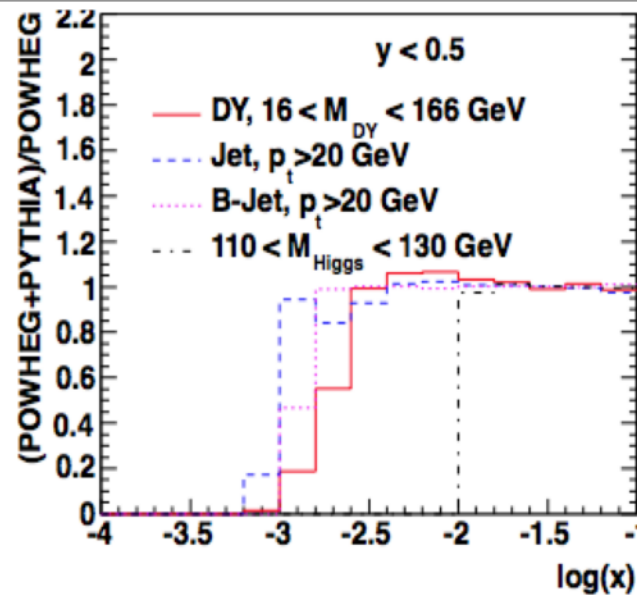
For precision predictions need precision TMDs with uncertainties !

small x TMDs from $F_2(x, Q^2)$ – general case
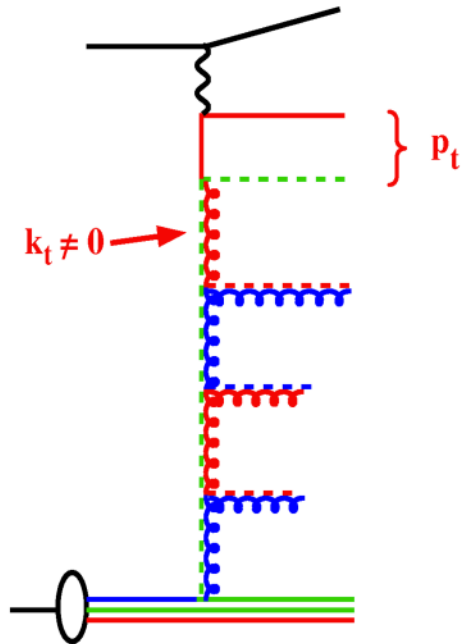
- $$\frac{d\sigma}{dx\,dQ^2} = \int dx_g \left[dk_\perp^2\, x_g \mathcal{A}_i(x_g, k_\perp^2, p) \right]$$
  $$\times \hat{\sigma}(x_g, k_\perp^2, x, \mu_f^2, Q^2)$$

  $\hat{\sigma}(x_g, k_\perp^2, x, \mu_f^2, Q^2)$ 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

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

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

Determination of TMDs (uPDFs)

- 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 :

$$x\mathcal{A}_0(x, k_\perp) \;=\; N x^{-B} \cdot (1-x)^C \left(1 - Dx + E\sqrt{x}\right) \exp[-k_t^2/\sigma^2]$$
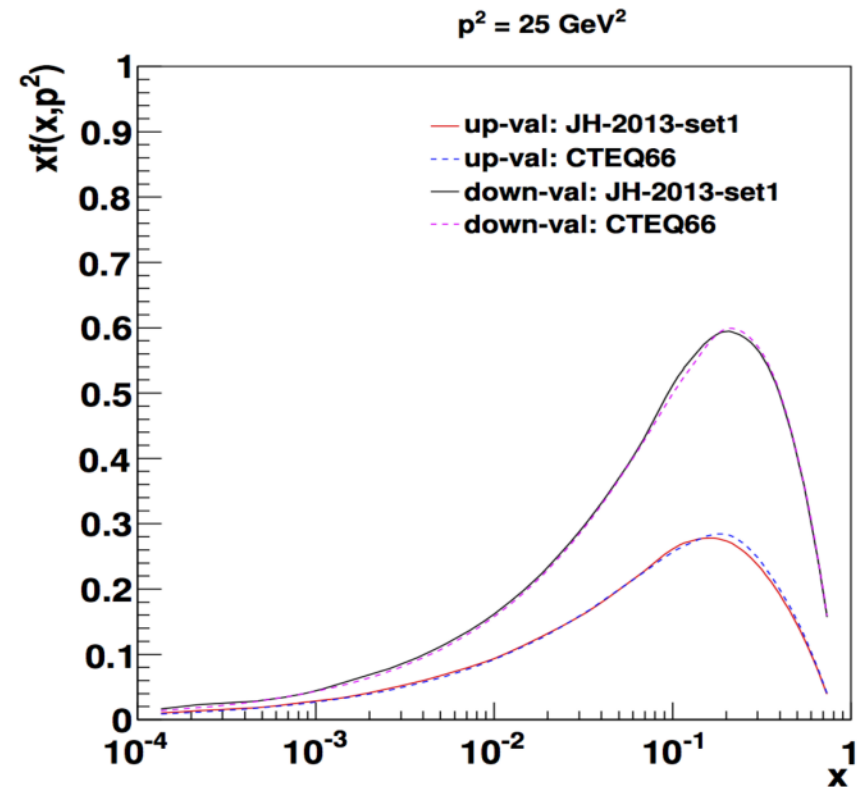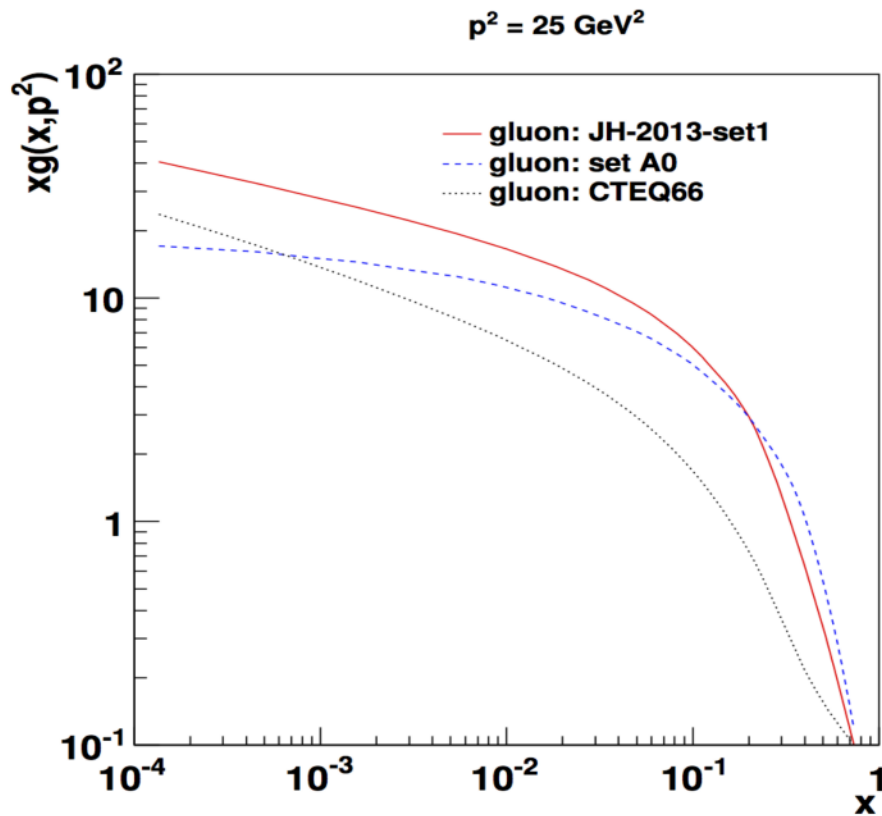
- starting distribution for valence quarks at q_0:

$$x Q_{v0}(x, k_t, p) \;=\; x Q_{v0}(x, k_t, q_0) \Delta_s(p, q_0)$$
$$x Q_{v0}(x, k_t, q_0) \;=\; x Q_{v\,\mathrm{coll.pdf}}(x, q_0) \; \exp[-k_t^2/\sigma^2]$$
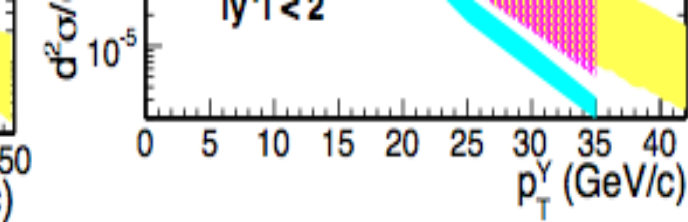
with $\sigma^2 = q_0^2/2$

TMD - integrated

CCFM gluon is different from standard collinear gluon, since no sea quarks are directly included in fit (treated only via $g \to q\bar{q}$)
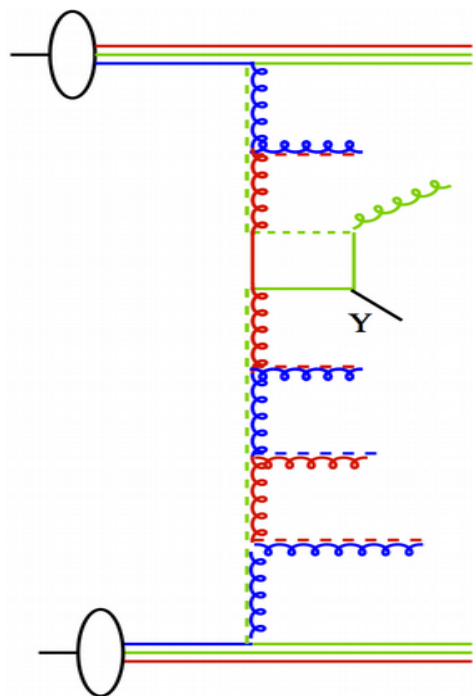
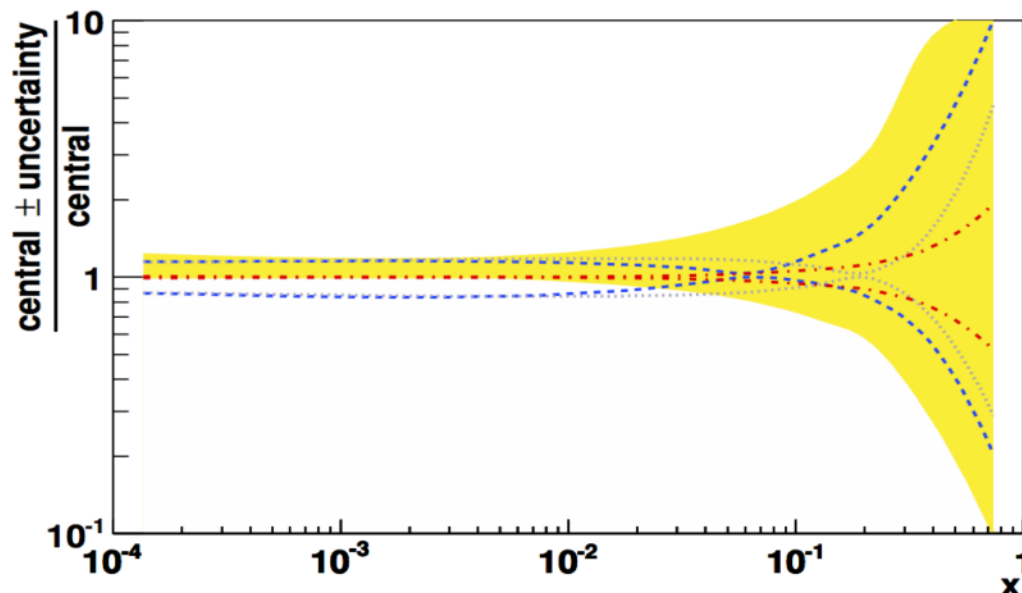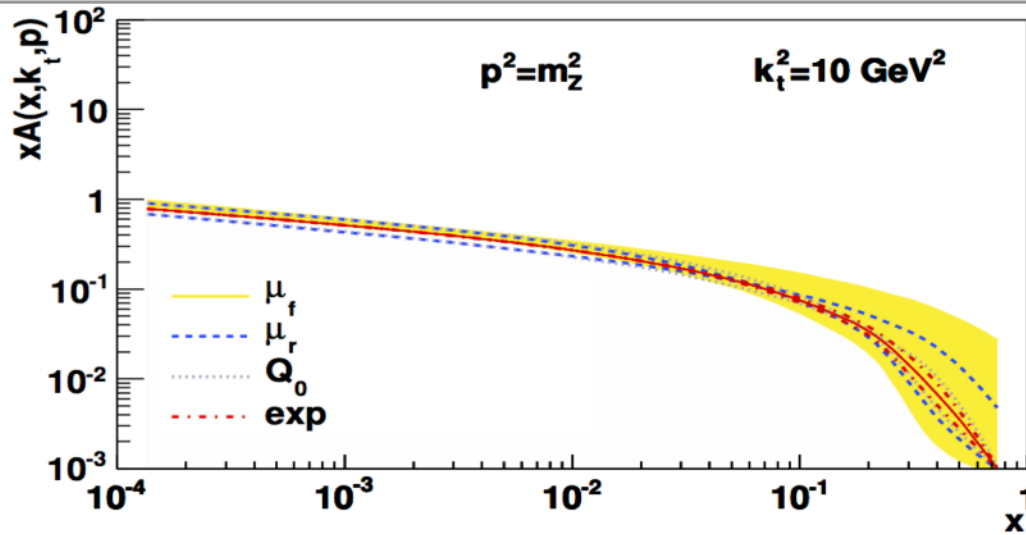- valence quarks in CCFM are similar to CTEQ, but evolution is different due to different α_s

ction

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

CMS Phys.Lett. B727 (2013)101, 1303.5900
Measurement of the Y(1S), Y(2S), and Y(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 !

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:
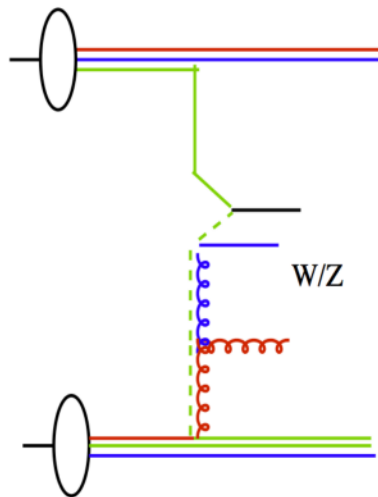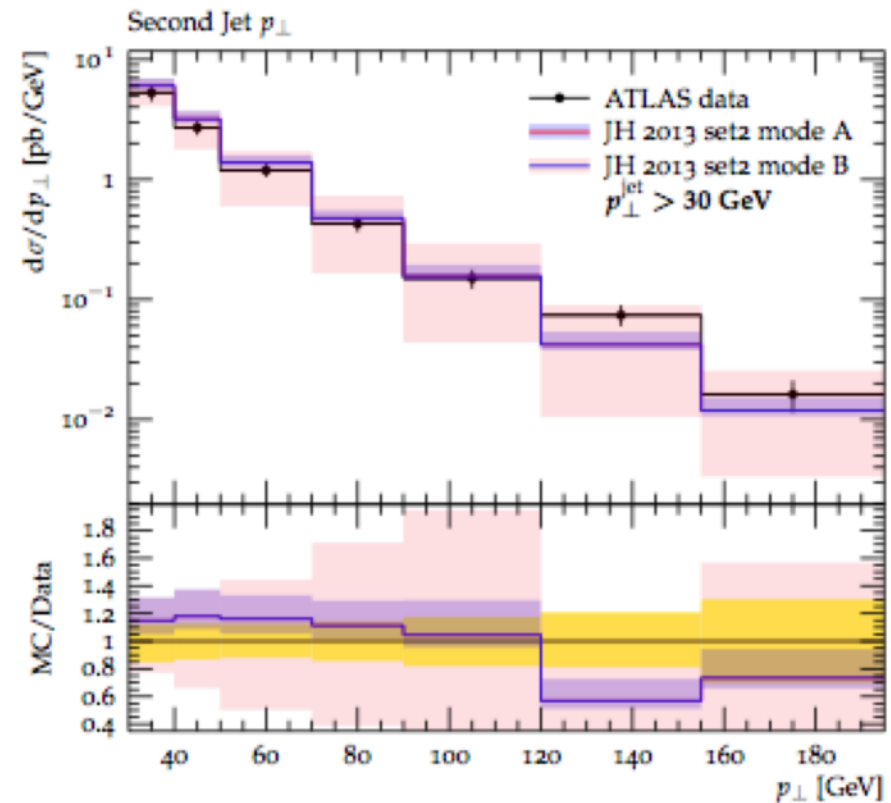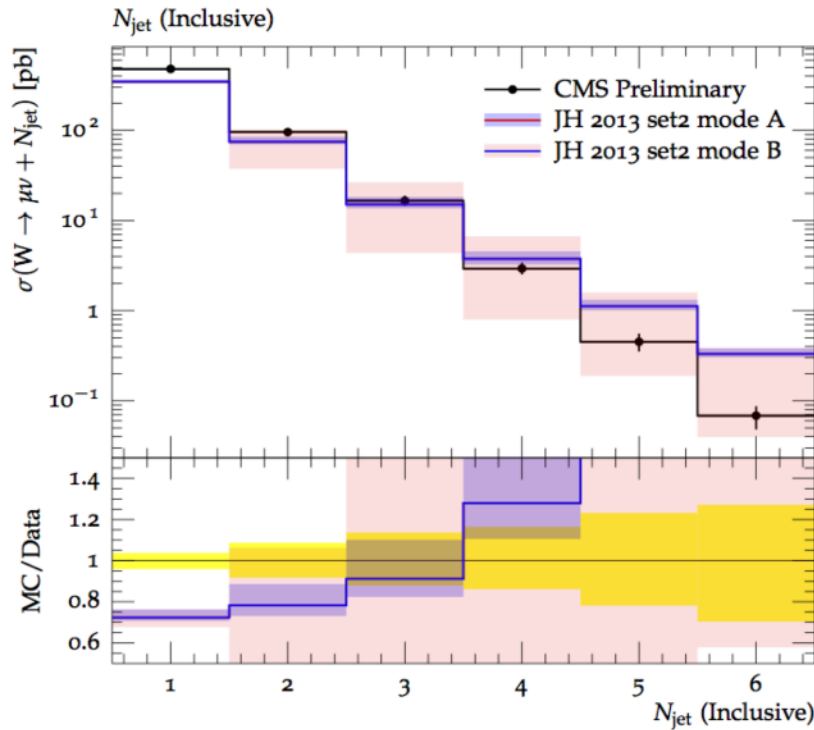 - Matrix Elements:
    - ➜ on shell/off shell
  - PDFs
    - ➜ TMD PDFs
  - Parton Shower
    - ➜ angular ordering
- Proton remnant and hadronization
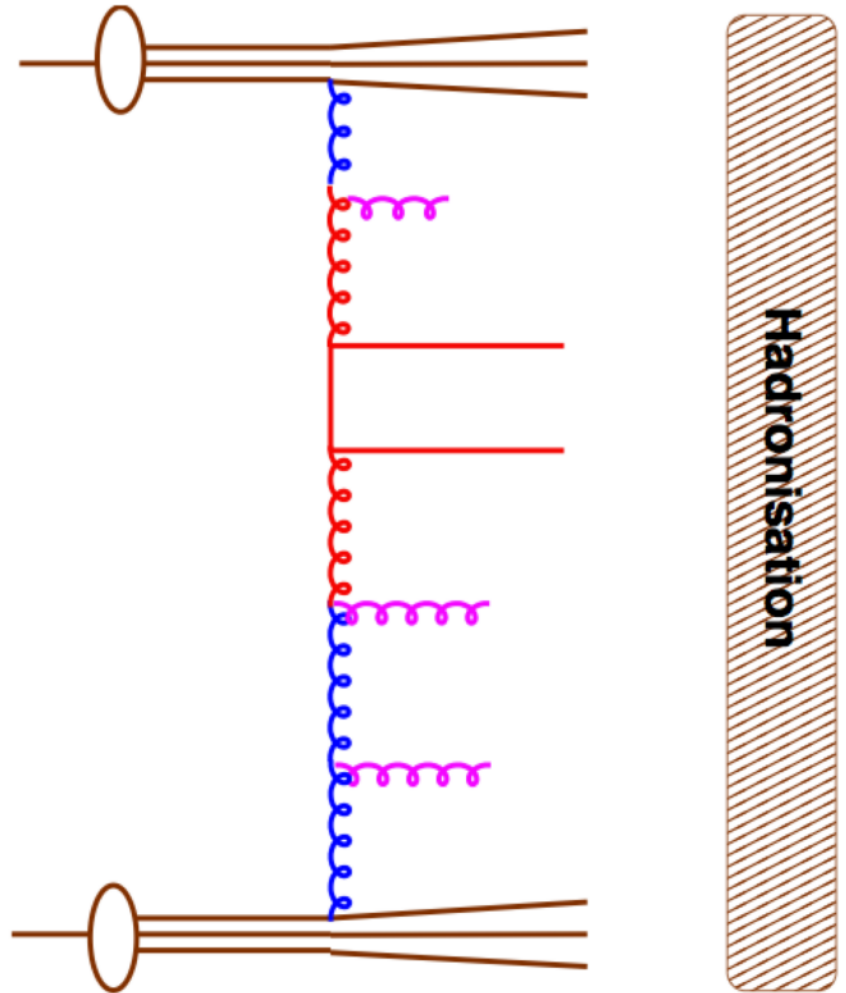
$$\sigma(pp \to q\bar{q} + X) \;=\; \int \frac{dx_{g1}}{x_{g1}} \frac{dx_{g2}}{x_{g2}} \int d^2 k_{t1} d^2 k_{t2} \hat{\sigma}(\hat{s}, k_t, \bar{q})$$

$$\times x_{g1} \mathcal{A}(x_{g1}, k_{t1}, \bar{q}) x_{g2} \mathcal{A}(x_{g2}, k_{t2}, \bar{q})$$

Application to W + jet production at LHC

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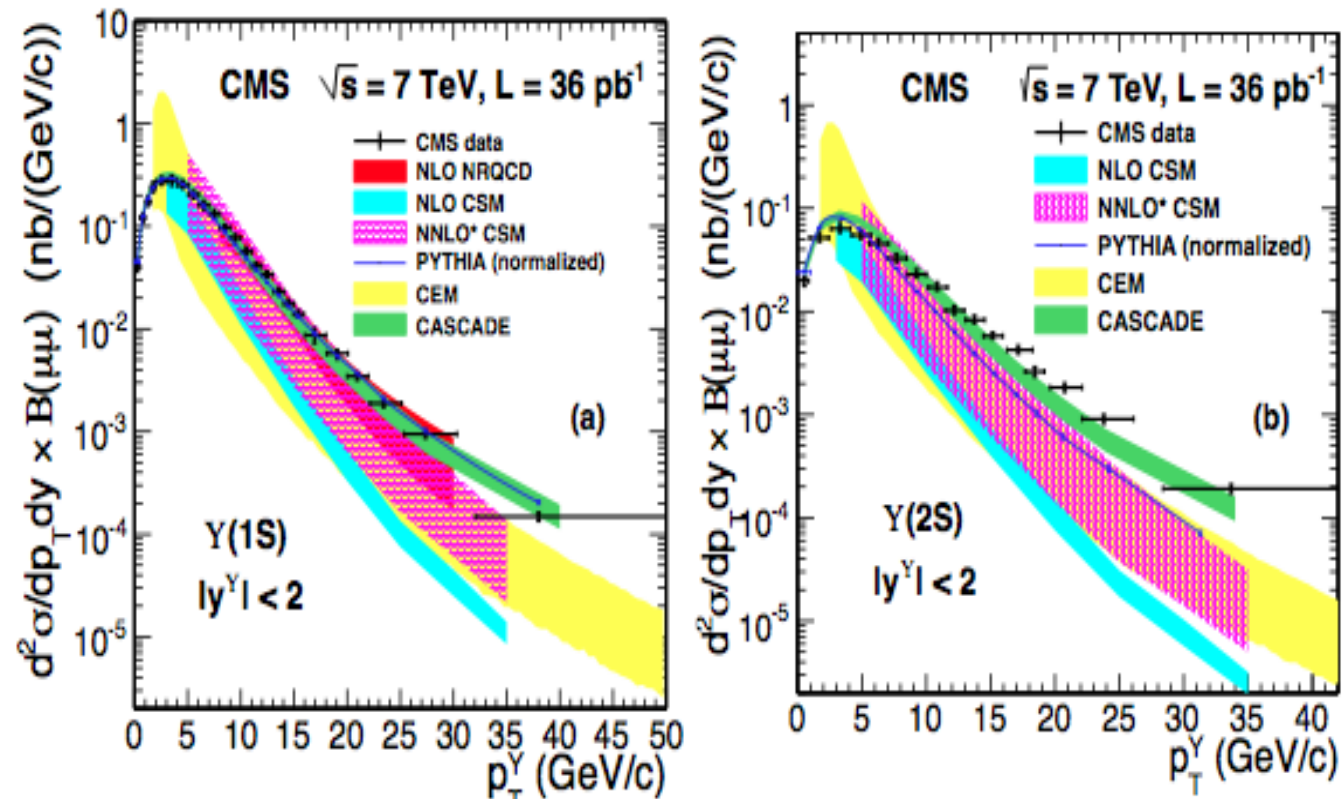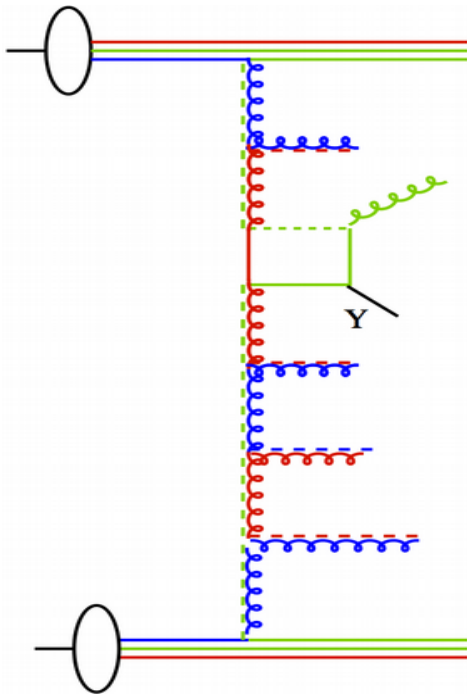S. Dooling, F. Hautmann, H. Jung arXiv:1406.2994

- TMD PDFs with parton shower → successful describing hard process at LHC
- uncertainty can be estimated, large but no compensation of scale variation yet !

Upsilon production

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

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

TMDlib and TMDplotter

- 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)

TMDlib and TMDplotter: library and plotting tools for transverse-momentum-dependent parton distributions, *F. Hautmann et al.* arXiv 1408.3015, submitted to EPJC.

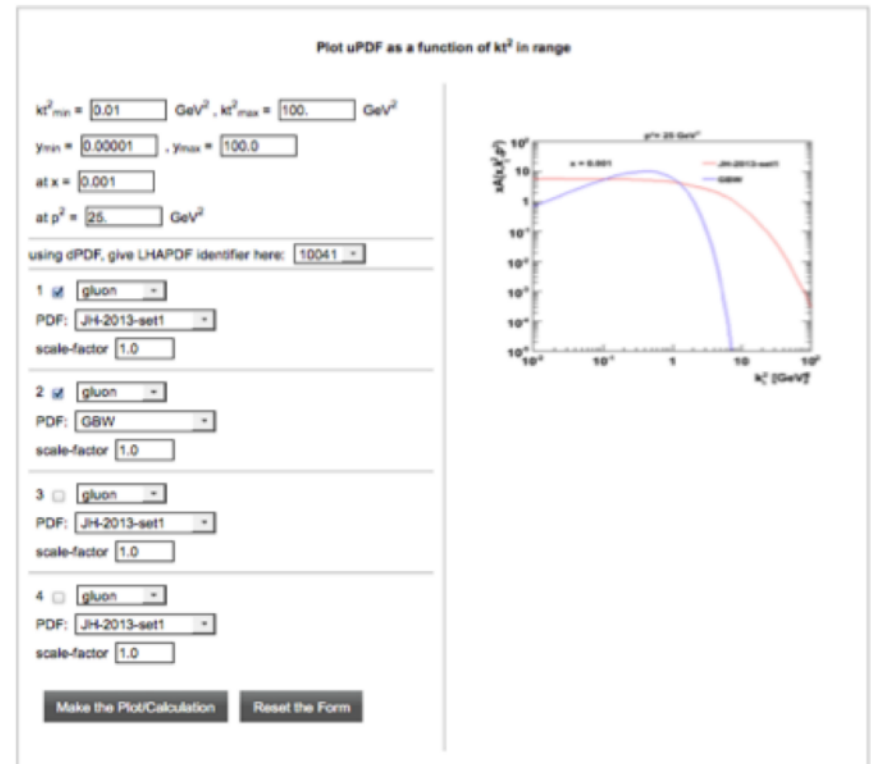**High Energy Physics | TMD Plotter**

| Home | TMD Plotter | Publications | HEP Links |

Using the form below you can calculate, in real time, values of xA(x,kt,p) for any of the TMDs. You can also generate and compare plots of xA(x,kt,p) vrs x and vrs kt² at any p² for up to 4 different parton types or PDFs.

Please click one of the buttons to generate the according form for the TMD Plotter:

Plot TMD (x, fixed kt)   Plot TMD (fixed x, kt)

Plot uPDF as a function of kt² in range

kt^2_{min} = 0.01 GeV² , kt^2_{max} = 100. GeV²
y_{min} = 0.00001 , y_{max} = 100.0
at x = 0.001
at p^2 = 25. GeV²

using dPDF, give LHAPDF identifier here: 10041

1 ☑ gluon
PDF: JH-2013-set1
scale-factor 1.0

2 ☑ gluon
PDF: GBW
scale-factor 1.0

3 ☐ gluon
PDF: JH-2013-set1
scale-factor 1.0

4 ☐ gluon
PDF: JH-2013-set1
scale-factor 1.0

Make the Plot/Calculation   Reset the Form

Contact   Imprint

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ERC application (DESY): TMD-MCatLHC

- develop MC using TMDs: TMD-MCatLHC
- Needs:
  - TMDs for gluon, sea and valence quarks
  - full parton shower following exactly the TMD evolution
  - TMD fragmentation functions
  - (off-shell) matrix-elements for all possible processes → automated calculation
  - systematic investigations of factorization issues

- Advantages:
  - consistency form beginning: no kinematic reshuffling needed
  - small higher order corrections
  - scaleable to any jet multiplicity
    - via parton shower
  - soft gluon resummation included from beginning, no extra factors are needed
  - fast calculation
- Applications:
  - DY+jet, Higgs - production
  - $t\bar{t}$ -(and heavy flavor) production
  - jets
  - searches

Conclusion

- TMD PDFs are important
  - effects form transverse momentum in small x processes (Υ production etc) but also in higher scale processes (W+2jets, etc)
  - precision determination TMD-gluon from inclusive DIS HERA data
    - now with model- and experimental uncertainties

- TMD PDFs can give a consistent recipe for initial state parton shower
  - no kinematic corrections are needed

- The big challenges:
  - TMD determination over full range in x and μ including quarks
  - Systematic extension to higher orders
  - Full TMD-MC including automated process calculation matched with TMD-parton shower
  - TMD factorization in hadronic processes

# Backup Slides

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:

$$x\mathcal{A}_0(x, k_t, q) = x\mathcal{A}(x, k_t, q_0)\Delta(q)$$

| from q′ to q w/o branching |

| branching at q′ |

| from q₀ to q′ w/o branching |

$$x\mathcal{A}_1(x, k_t, q) = x\mathcal{A}(x, k_t, q_0)\Delta(q) + \int \frac{dq'}{q'} \frac{\Delta(q)}{\Delta(q')} \int dz \tilde{P}(z)\frac{x}{z}\mathcal{A}(x/z, k_t', q_0)\Delta(q')$$

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

$$x \quad t$$

$$z = x/x_0 \qquad t'$$

$$P(z)$$

$$x_0, t_0$$
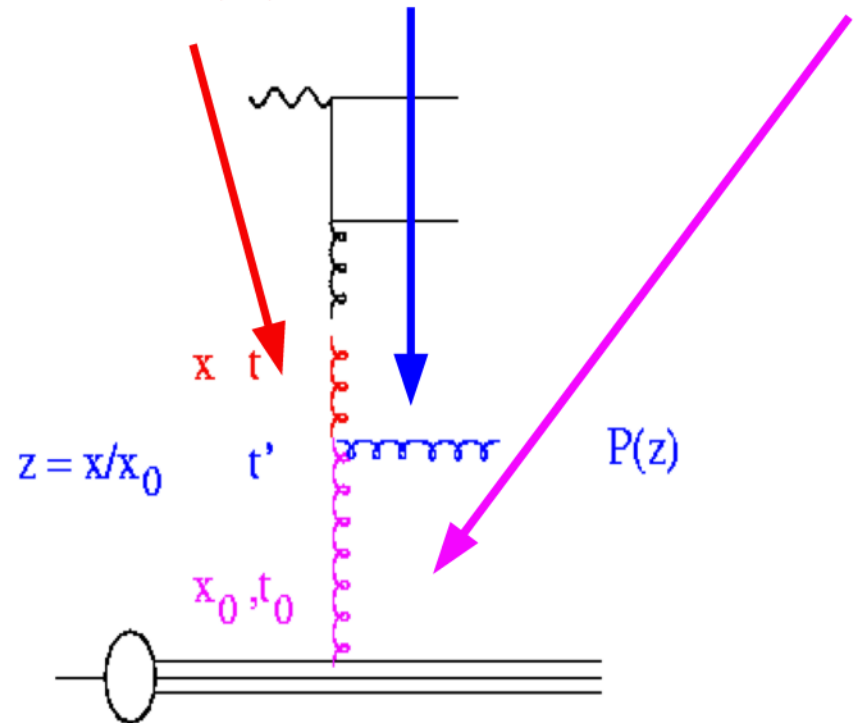
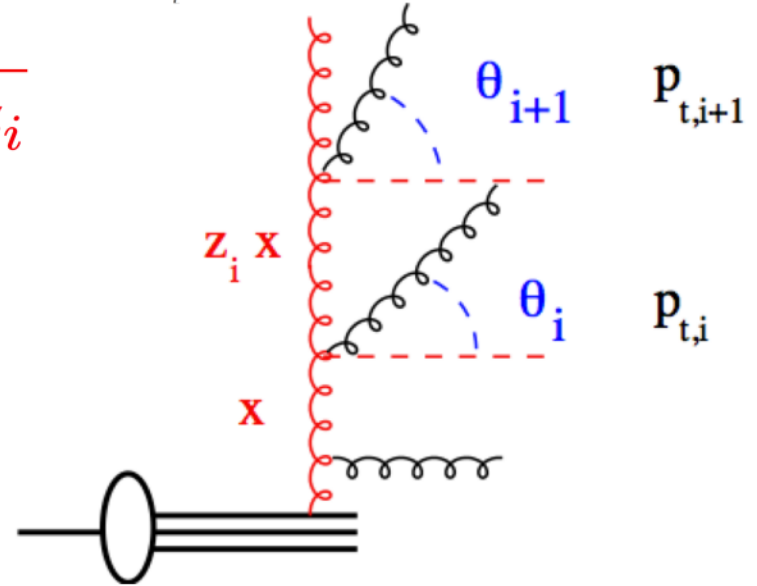# How to obtain TMDs ? CCFM approach

- Color coherence requires angular ordering instead of p_t ordering …

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

➜ recover DGLAP with q ordering
  at medium and large x

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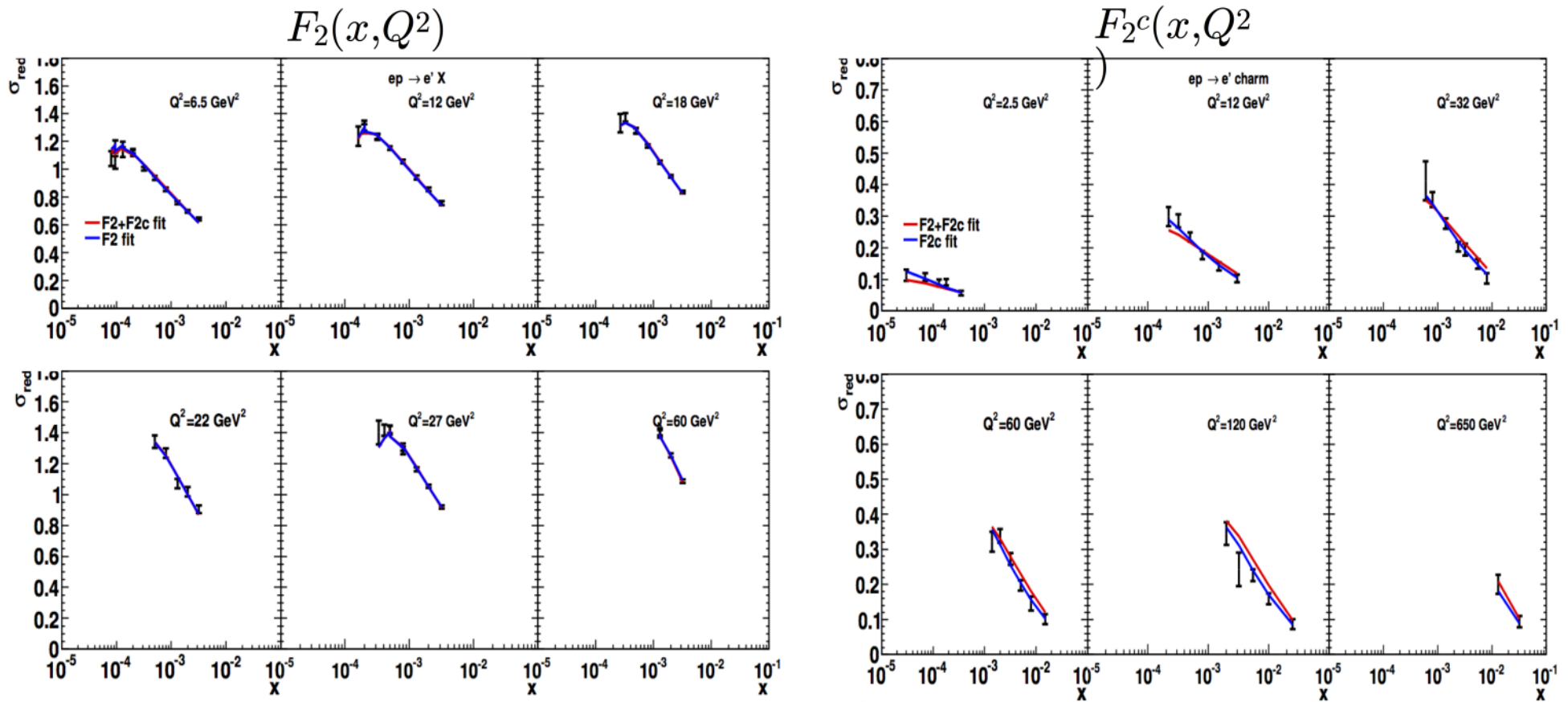 p_{ti} can perform a random walk

➜ 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

From HERA: small x improved gluon TMD

$F_2(x,Q^2)$ $F_2^c(x,Q^2)$

- 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

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

- **very good χ^2/ndf obtained (~ 1)**

# CCFM gluon from F_2 and F_2 & F_2^c fit
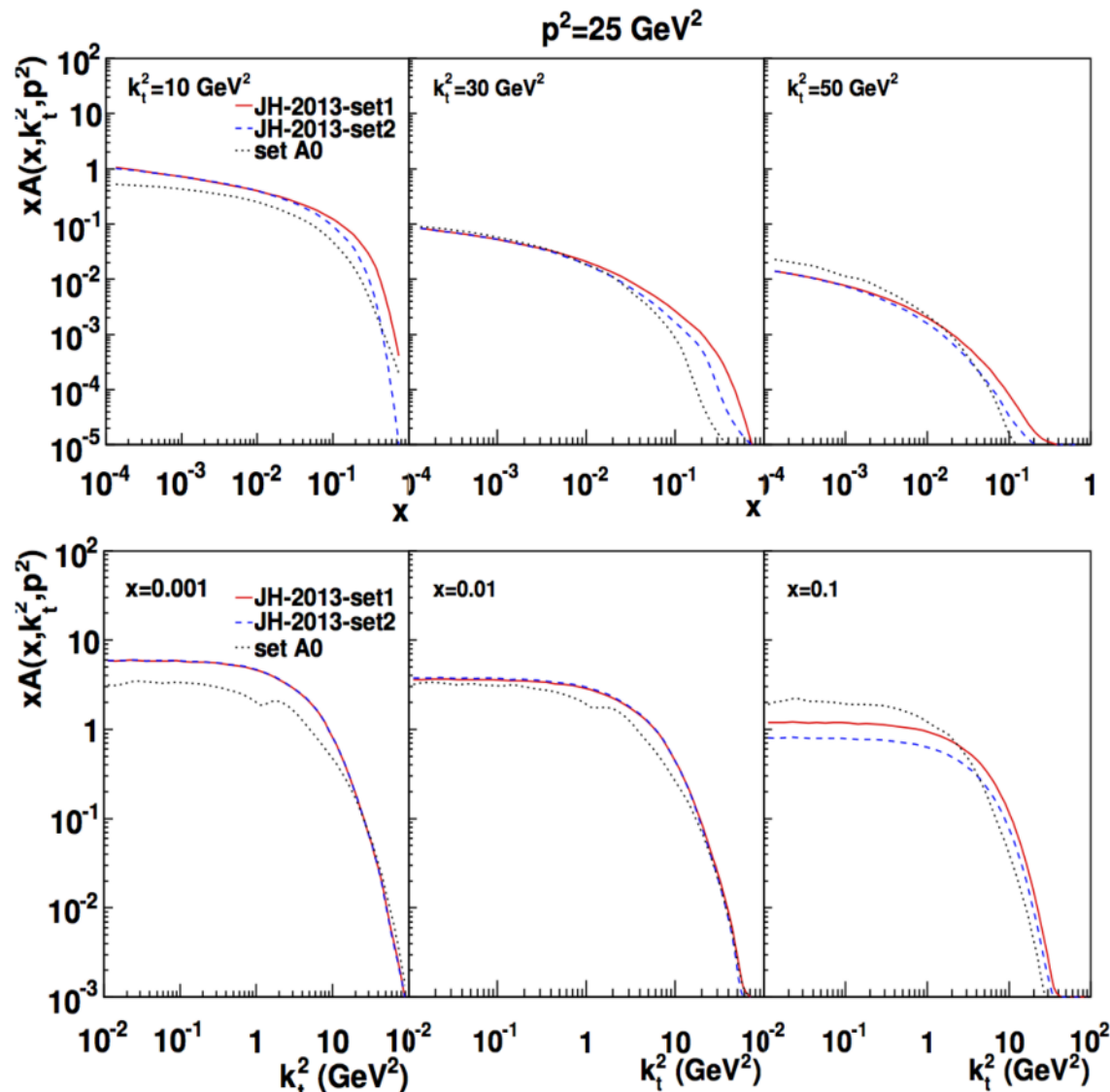
- Fit function:

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

- 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, $x \le 0.005$
  - 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

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:
      $\mu^2 \sim Q^2 + 4\, m^2$:

$$\int_0^{\mu^2} dk_\perp \hat\sigma(k_\perp, ...)$$
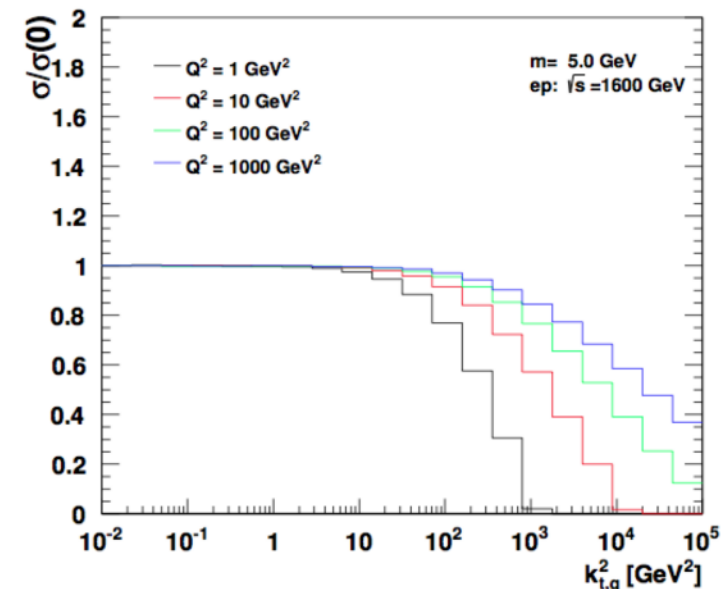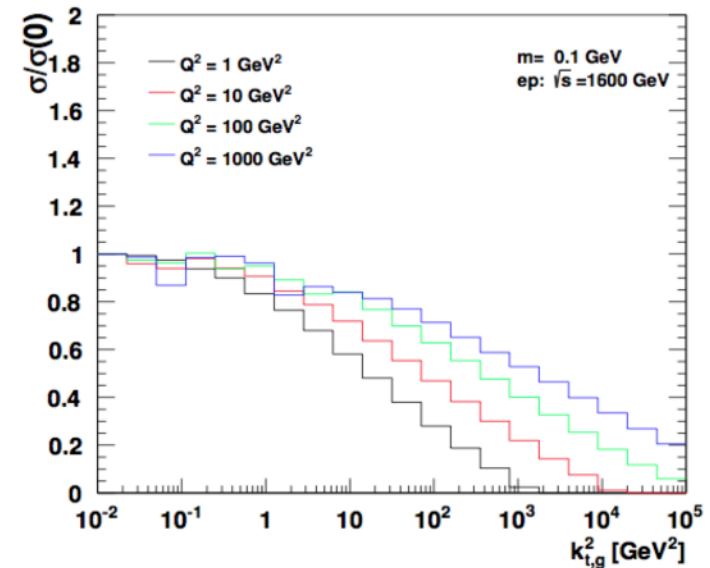
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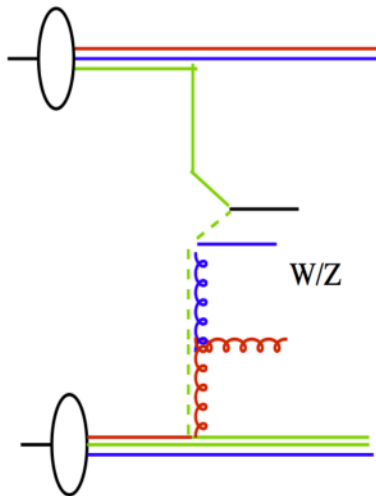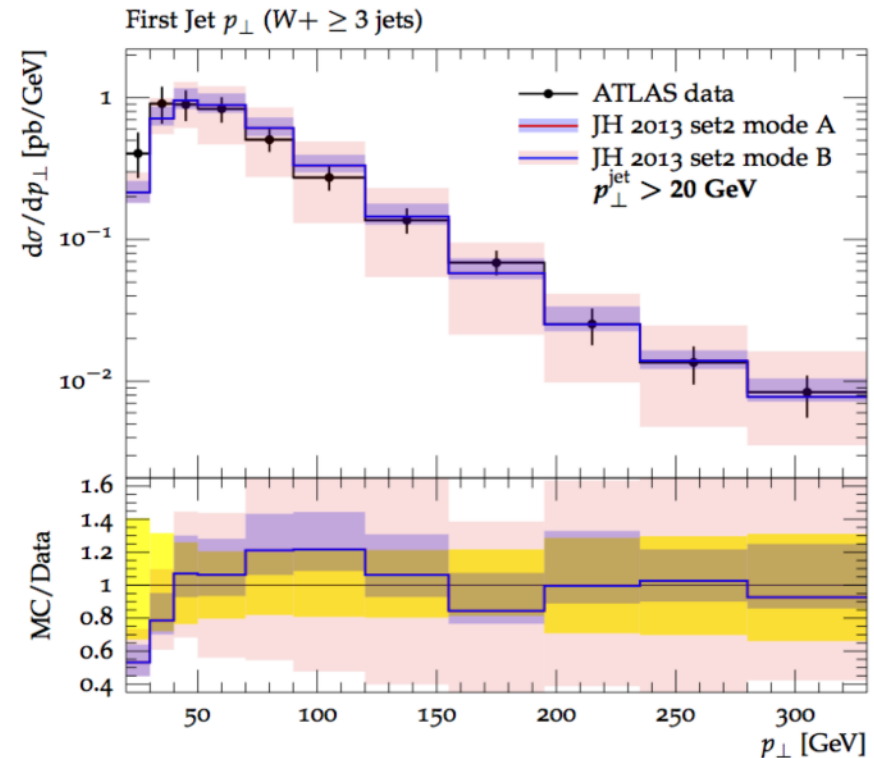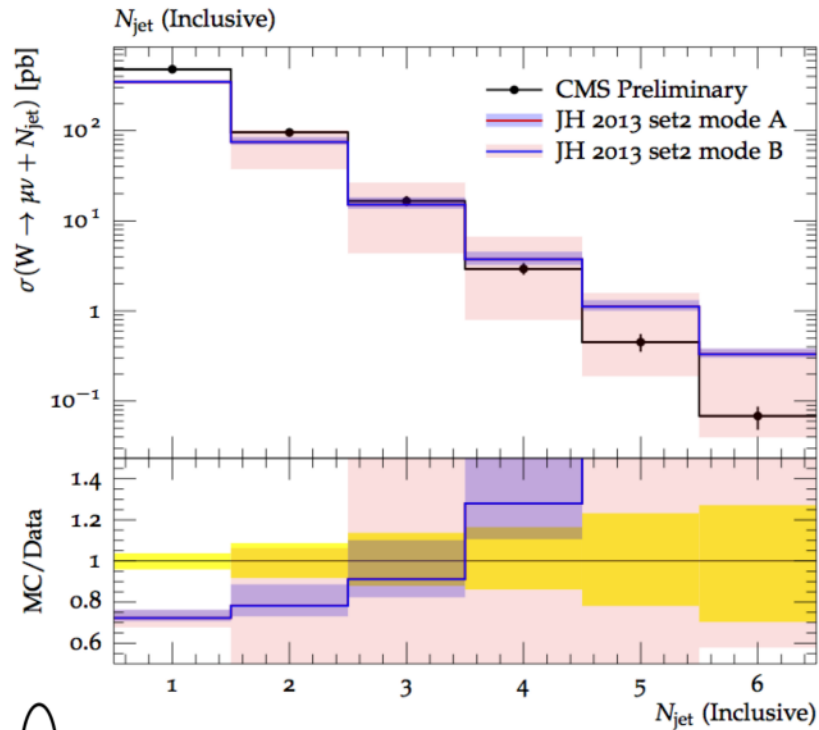
- use CCFM gluon convoluted with off-shell ME
- uncertainty from pdf on 1st jet is small → ME !

- agrees reasonably well with W+jet measurement