uPDFs in Monte Carlo generators

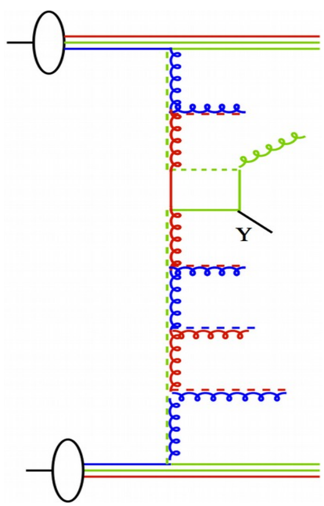
H. Jung (DESY, Uni Antwerp)
F. Hautmann (Uni Oxford)

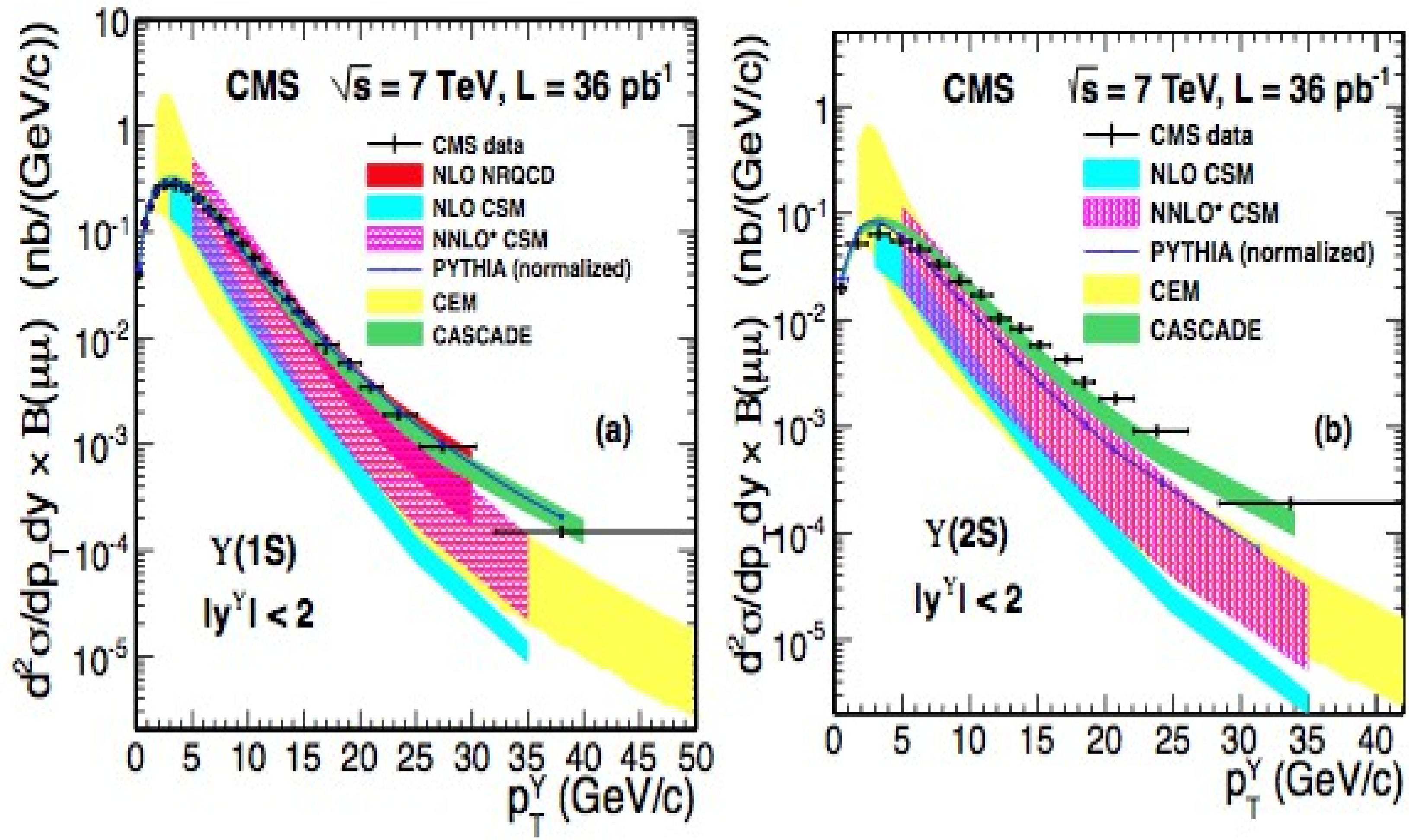
- uPDFs (TMDs) in MCs
  - why are they needed ?
  - how can they determined ?
    - CCFM gluon uPDF
      - fits to inclusive DIS and uncertainties
      - ➔ description of DIS at HERA
      - ➔ description of hard processes at the LHC ?
  - the small kt region at small x

Upsilon production

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

CMS arXiv:1303.5900
Measurement of the Y(1S), Y(2S), and Y(3S) cross sections in pp collisions at s√ = 7 TeV

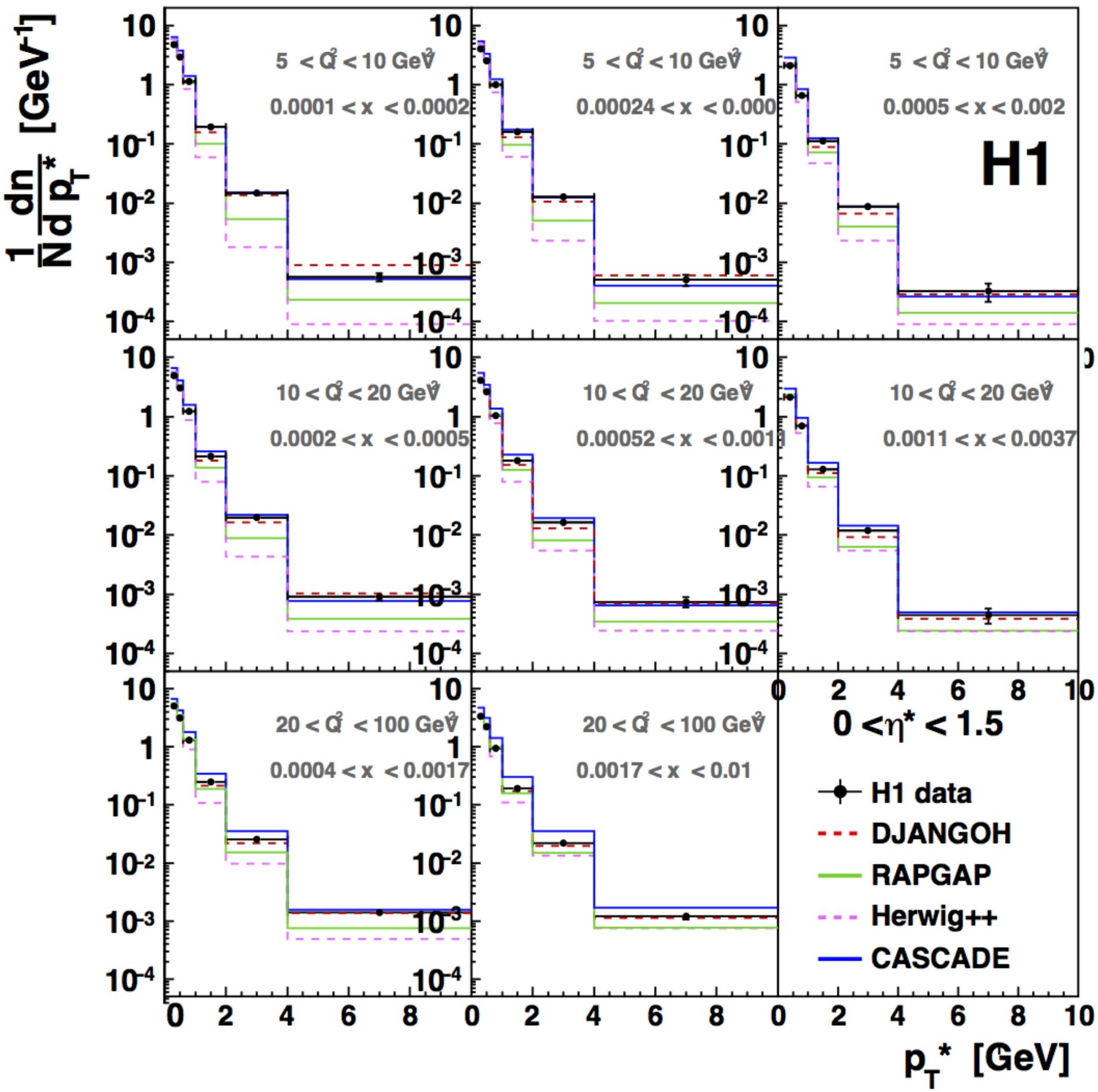




- Using TMDs with off-shell ME gives rather good description, without further tuning
- NNLO CSM is not as good !

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

H1 Coll. EPJC 73 (2013) 2406

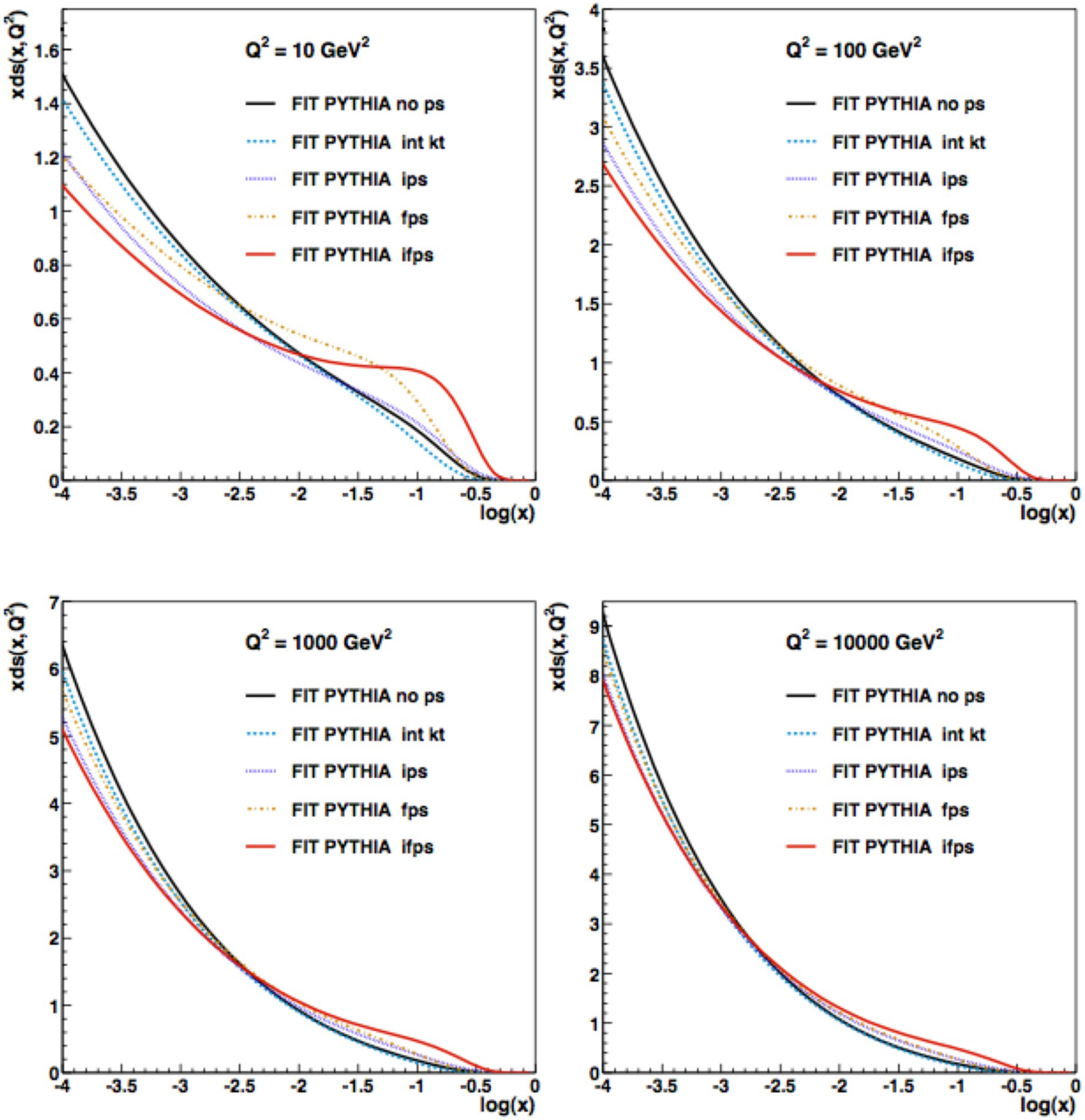


- particle spectra as fct of p^*_t give constraints on hardness of partons in parton shower
- collinear shower models (RAPGAP) generate too soft spectra compared to measurement
- small x improved (CCFM) shower (CASCADE) and CDM (DJANGOH) generate harder spectrum → closer to measurement at large p^*_t

Kinematic effects in PDF determination

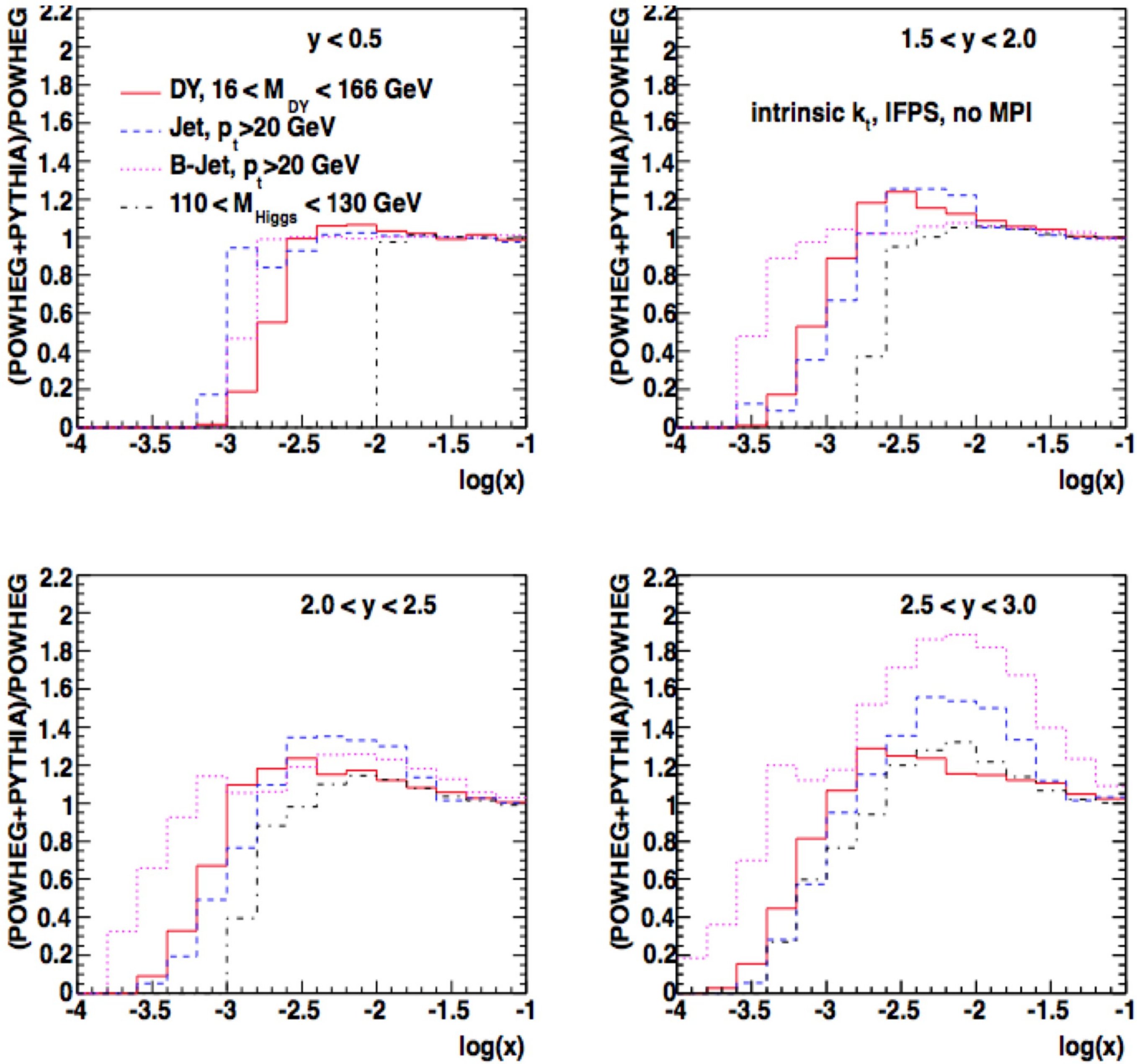
Determination of parton density functions using Monte Carlo event generator Federicon Samson-Himmelstjerna /afs/desy.de/group/h1/psfiles/theses/h1th-516.pdf

- 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



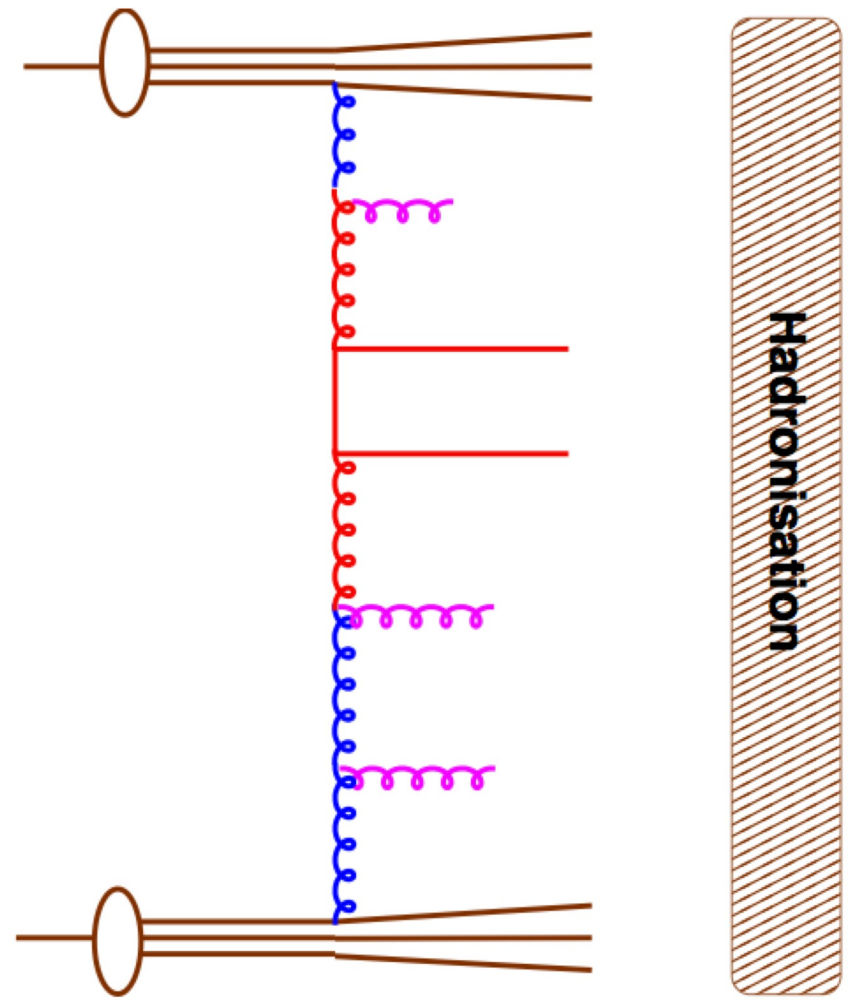
Transverse momentum effects in pp

- 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*



uPDFs, x-sections and MCs

- 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

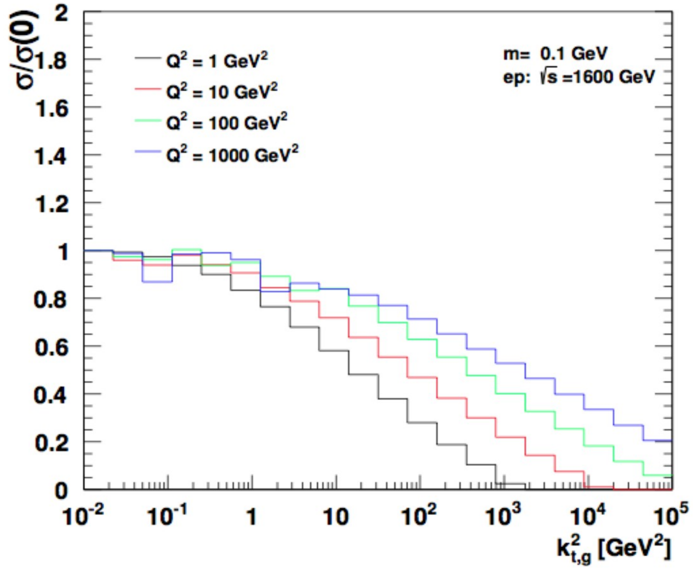


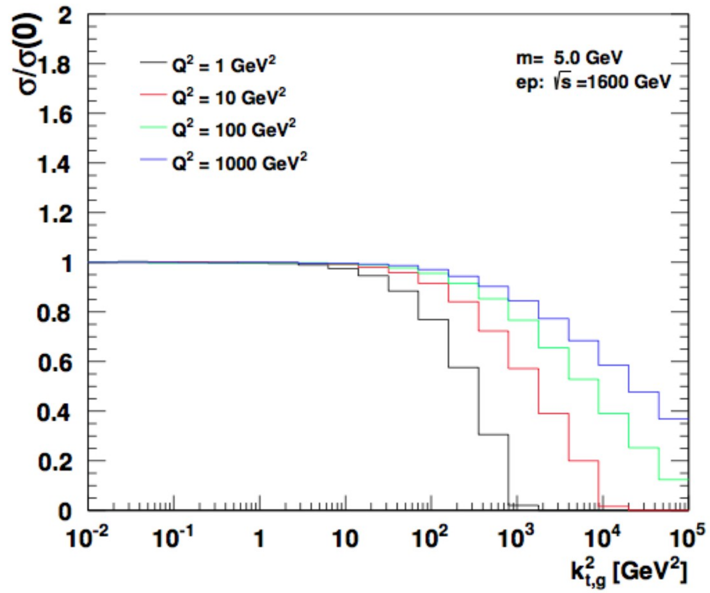
$$\sigma(pp \to q\bar{q} + X) = \int \frac{dx_{g1}}{x_{g1}} \frac{dx_{g2}}{x_{g2}} \int d^2k_{t1} d^2k_{t2} \hat{\sigma}(\hat{s}, k_t, \bar{q}) \times x_{g1} \mathcal{A}(x_{g1}, k_{t1}, \bar{q}) x_{g2} \mathcal{A}(x_{g2}, k_{t2}, \bar{q})$$

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

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





Which uPDFs ?

- 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:

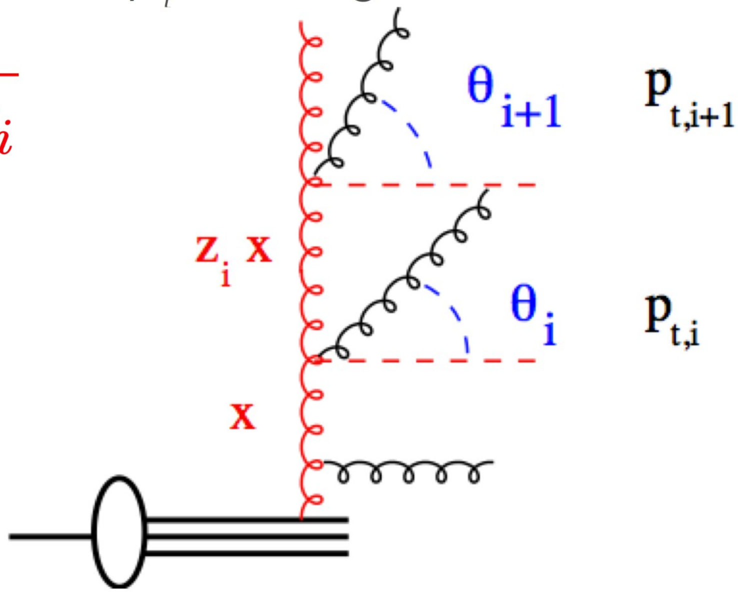
$$f(x,k_\perp^2,\mu^2) \quad = \quad \frac{dg(x,\mu^2)}{d\mu^2} \exp\left(-\int_{k_\perp^2}^{\mu^2} \frac{\alpha_s}{2\pi} d\log k_\perp^2 \sum_i \int_0^1 P(z')dz'\right)$$

  - ➔ generated from integrated PDF, only last emission generates transverse momentum via sudakov form factor.
- appropriate form DGLAP with strong ordering....
- this is what is done in all standard parton shower MCs

Which uPDFs ? 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:

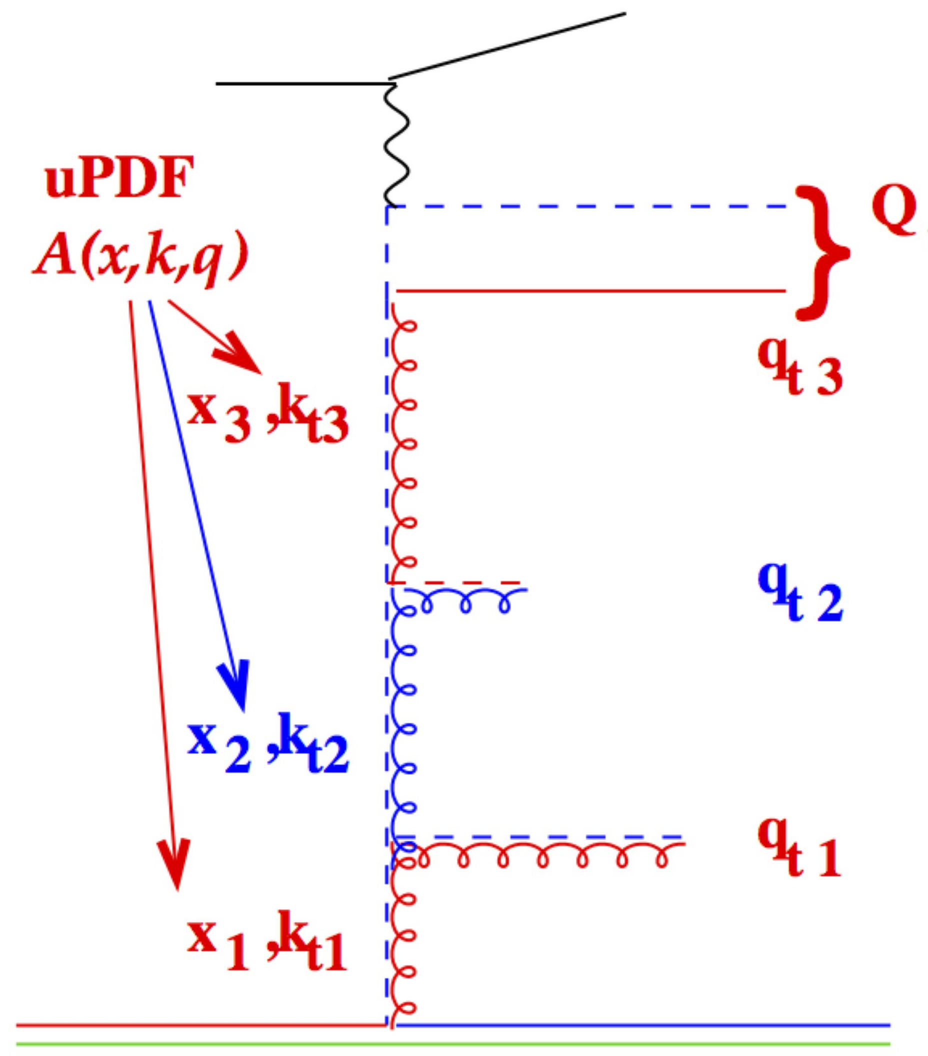
$$\tilde{P}_g(z, q, k_t) = \bar{\alpha}_s \left[\frac{1}{1-z} - 1 + \frac{z(1-z)}{2} + \left(\frac{1}{z} - 1 + \frac{z(1-z)}{2} \right) \Delta_{ns}) \right]$$

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

➔ CataniCiafaloniFioraniMarchesini evolution forms a bridge between DGLAP and BFKL evolution

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



For precision predictions
need
precision uPDFs
with
uncertainties !

Evolution equation and uPDFs

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

- solve integral equation via iteration:

from q′ to *q* w/o branching

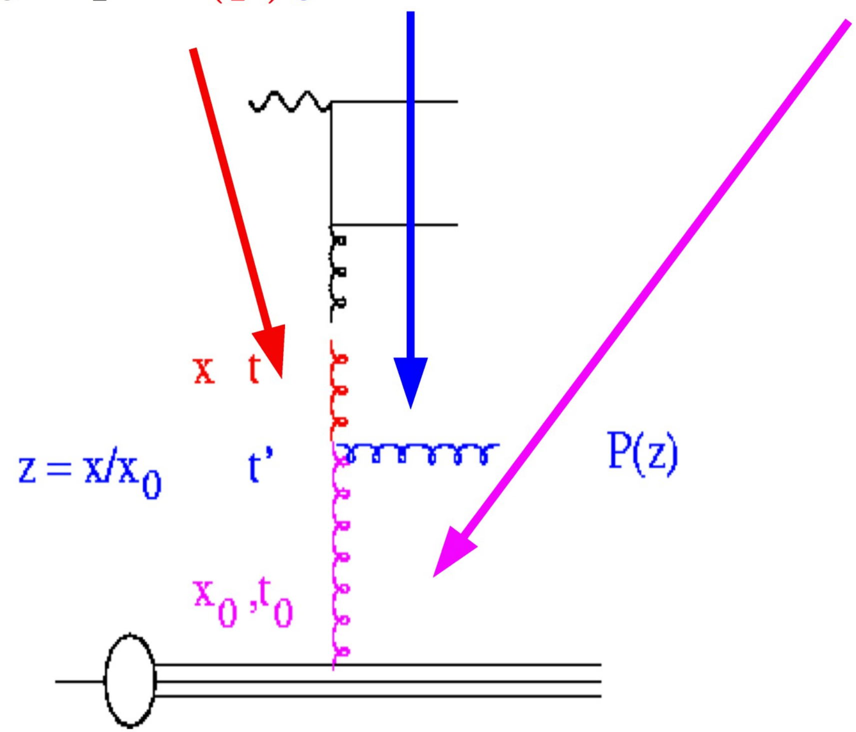
branching at q′

from q_0 to q′ w/o branching

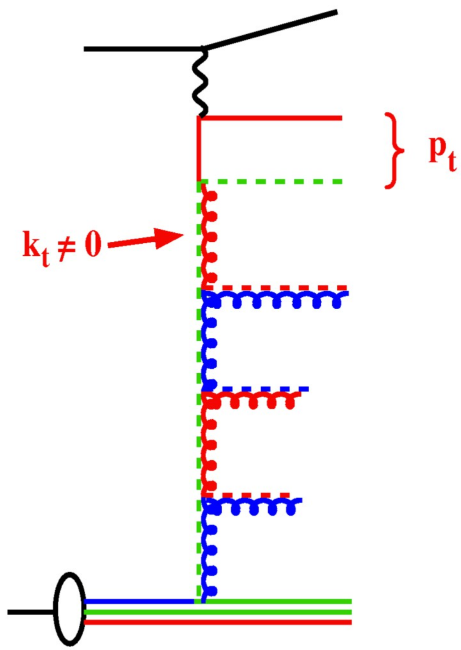
$$x\mathcal{A}_0(x,k_t,q) = x\mathcal{A}(x,k_t,q_0)\Delta(q)$$

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

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



uPDFs from $F_2(x,Q^2)$ at small x – general case



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

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

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

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

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

Determination of uPDFs (TMDs)

- 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 :

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

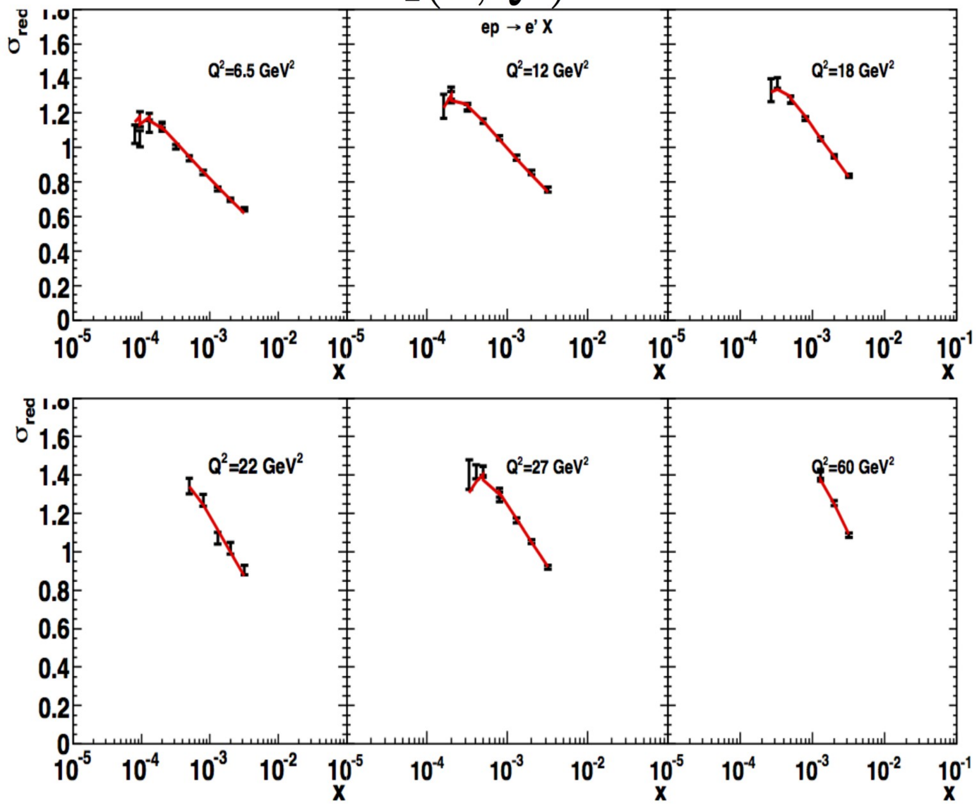
- starting distribution for valence quarks at q_0:

$$\begin{aligned} xQ_{v0}(x, k_t, p) &= xQ_{v0}(x, k_t, q_0)\Delta_s(p, q_0) \\ xQ_{v0}(x, k_t, q_0) &= xQ_{v\,\mathrm{CTEQ66pdf}}(x, q_0)\ \exp[-k_t^2/\sigma^2] \end{aligned}$$

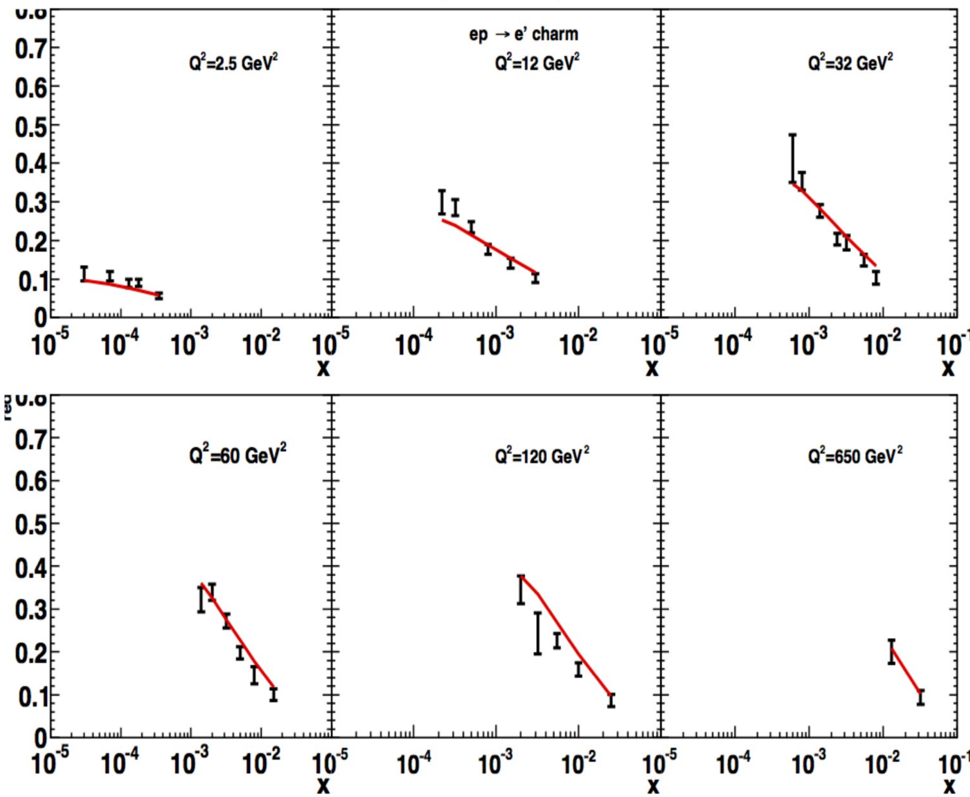
with $\sigma^2 = q_0^2/2$

From HERA: small x improved gluon uPDF

$F_2(x,Q^2)$

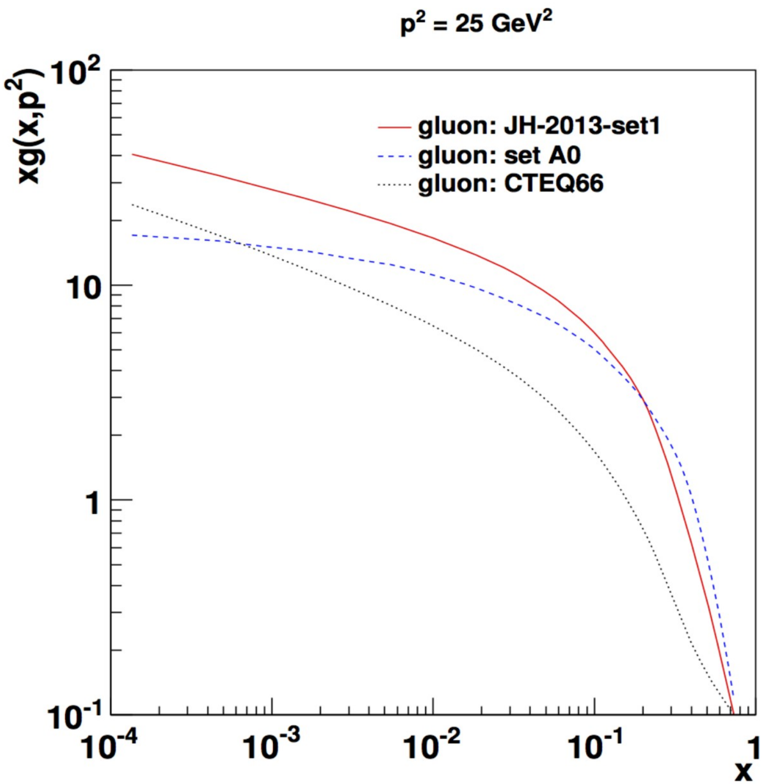


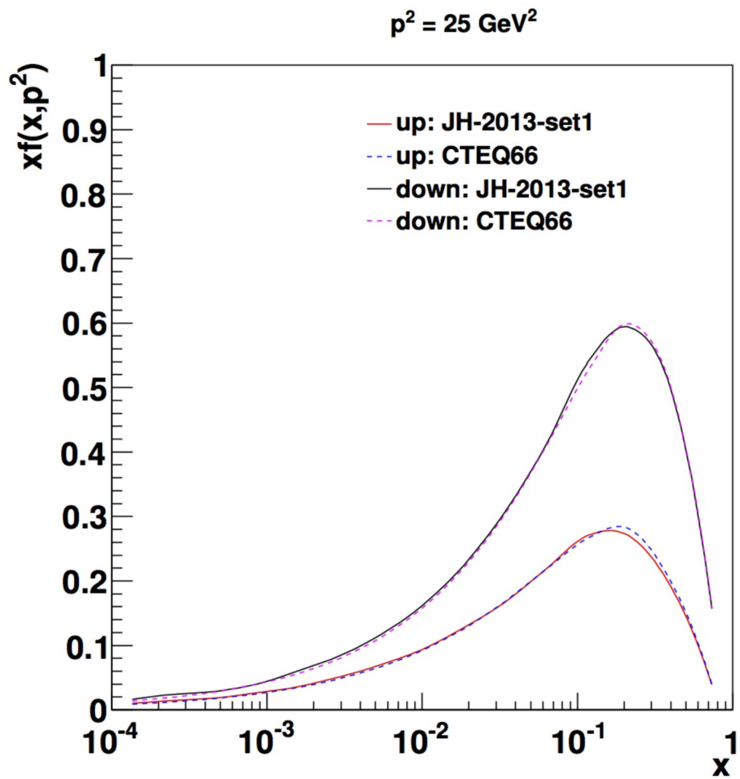
$F_2{}^c(x,Q^2)$



- 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
- very good χ^2/ndf obtained (~ 1)

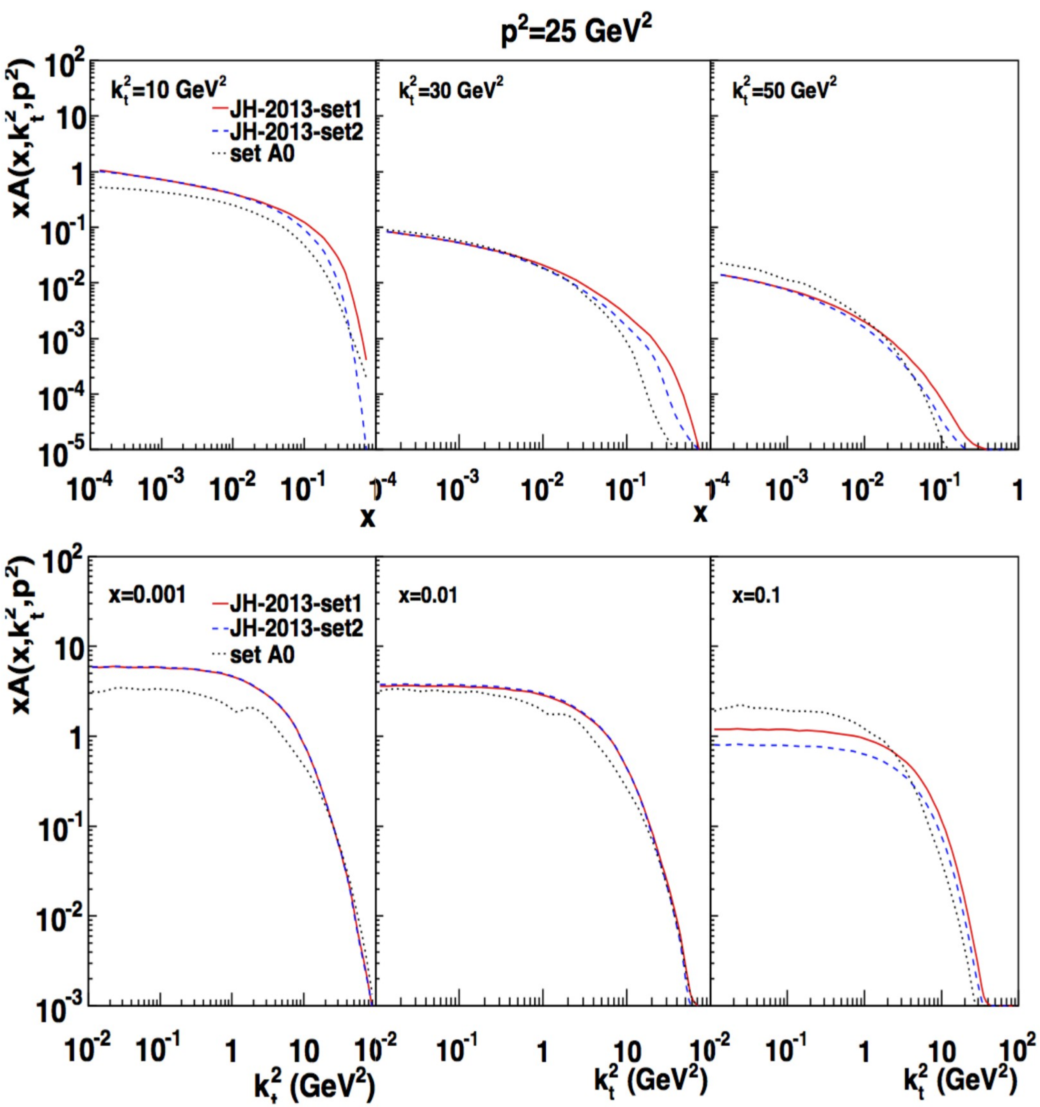
uPDF - integrated





- CCFM gluon is different from standard collinear gluon, since no sea quarks are included in fit
- 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

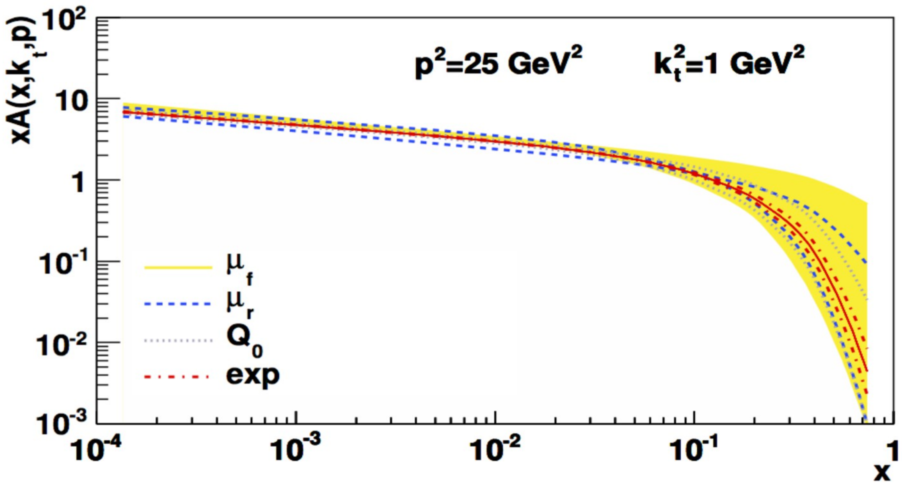


- Fit function:

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

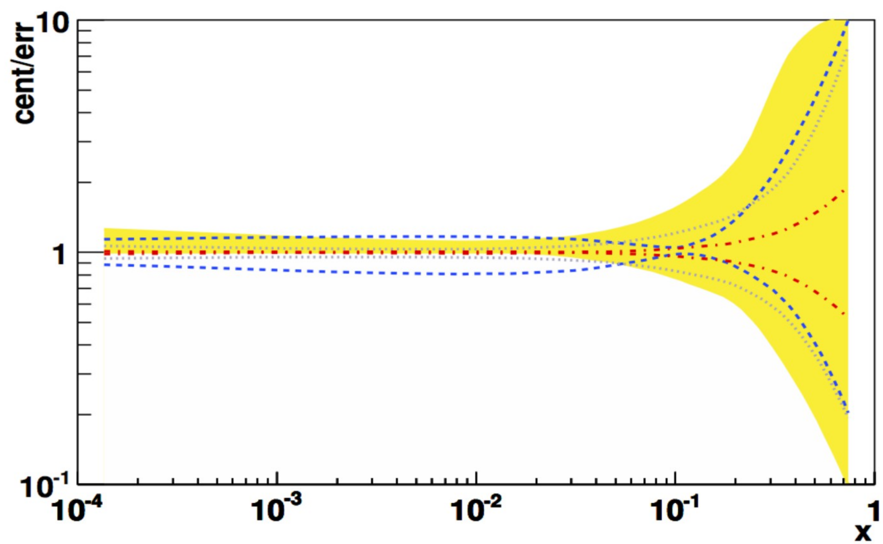
- 2-loop α_s
- gluon splitting function with non-singular terms
- fits:
  - set 1 F_2 : $Q^2 > 5$ GeV, $x \leq 0.005$
  - set 2 - F_2 & F_2^c: $Q^2 > 2.5$ GeV
- new fit gives χ^2/ndf ~ 1.2
- details are different from previous uPDF set A_0

uncertainties of CCFM gluon

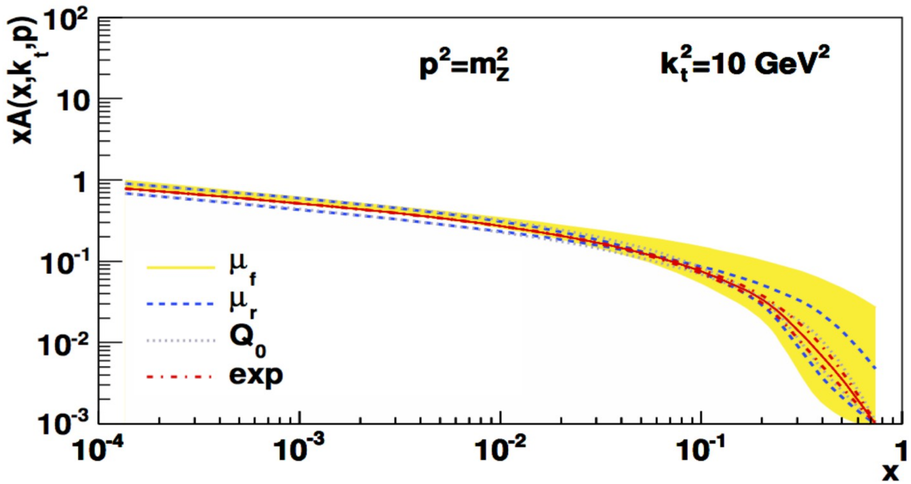


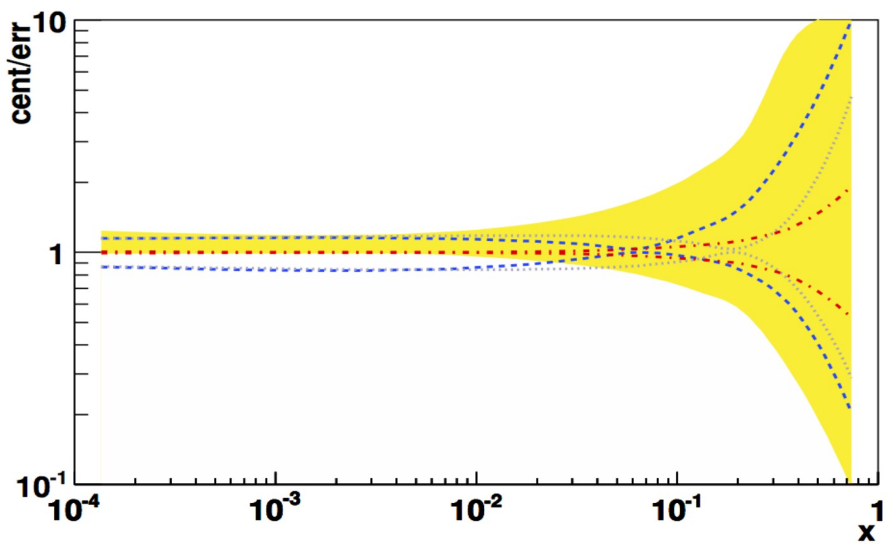
small k_t, small p^2

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



uncertainties of CCFM gluon

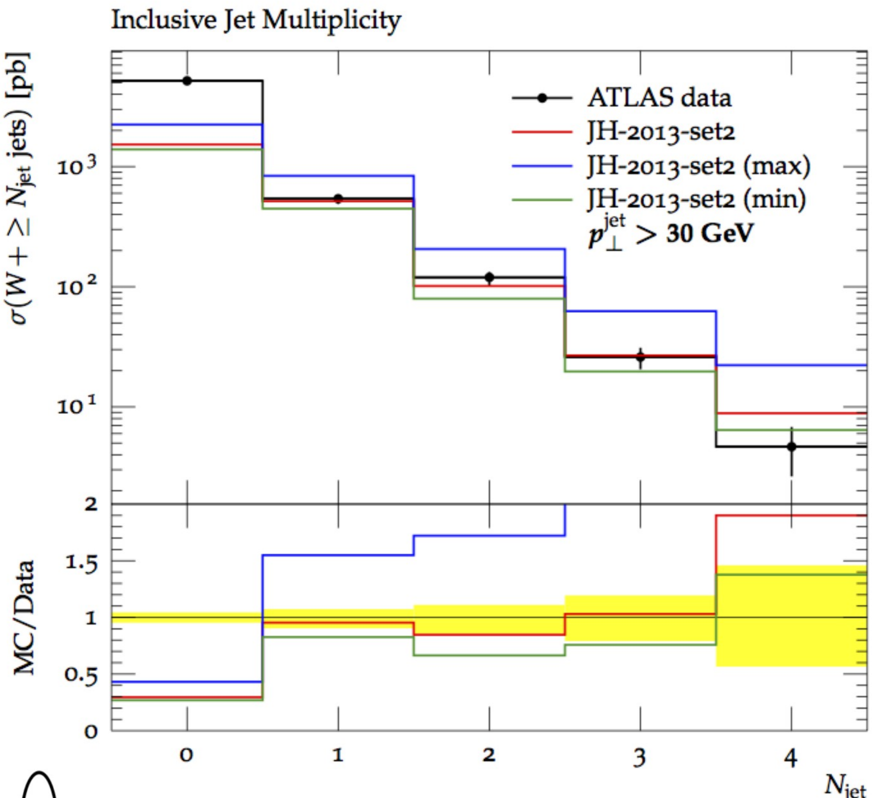


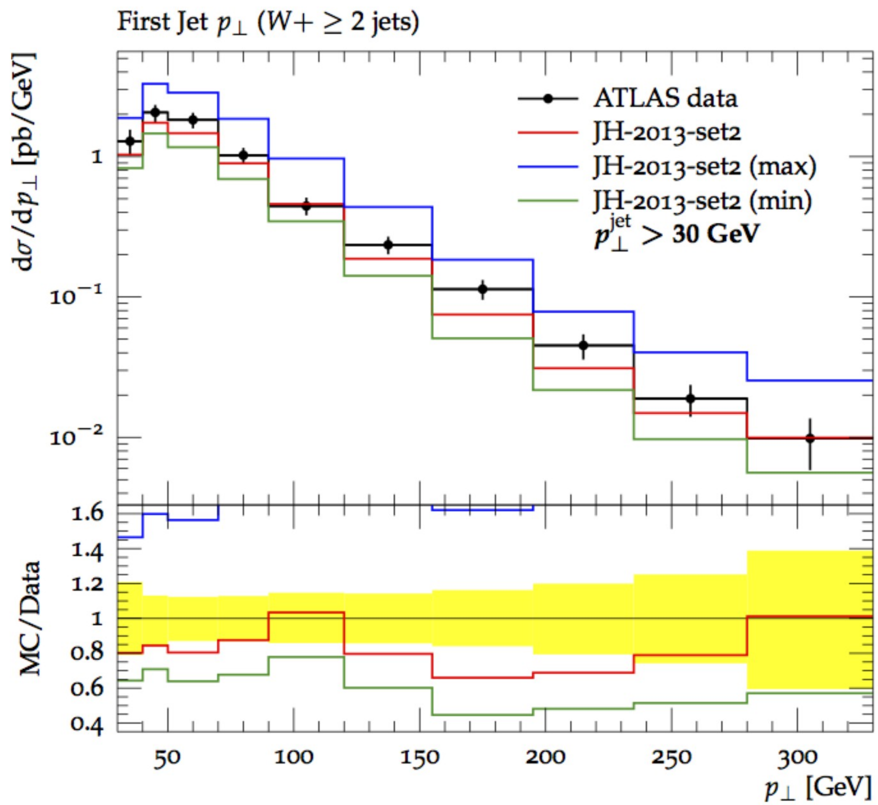


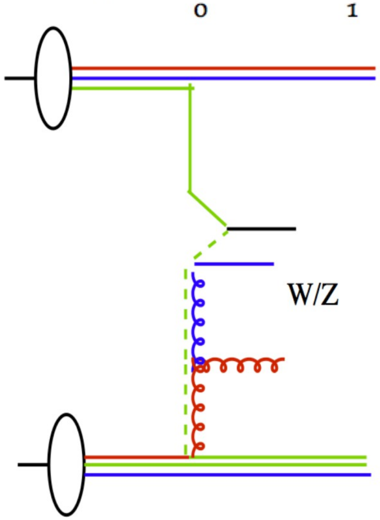
large k_t, large p^2

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

Application to W + jet production at LHC

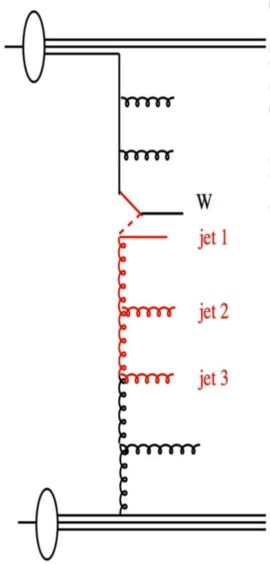


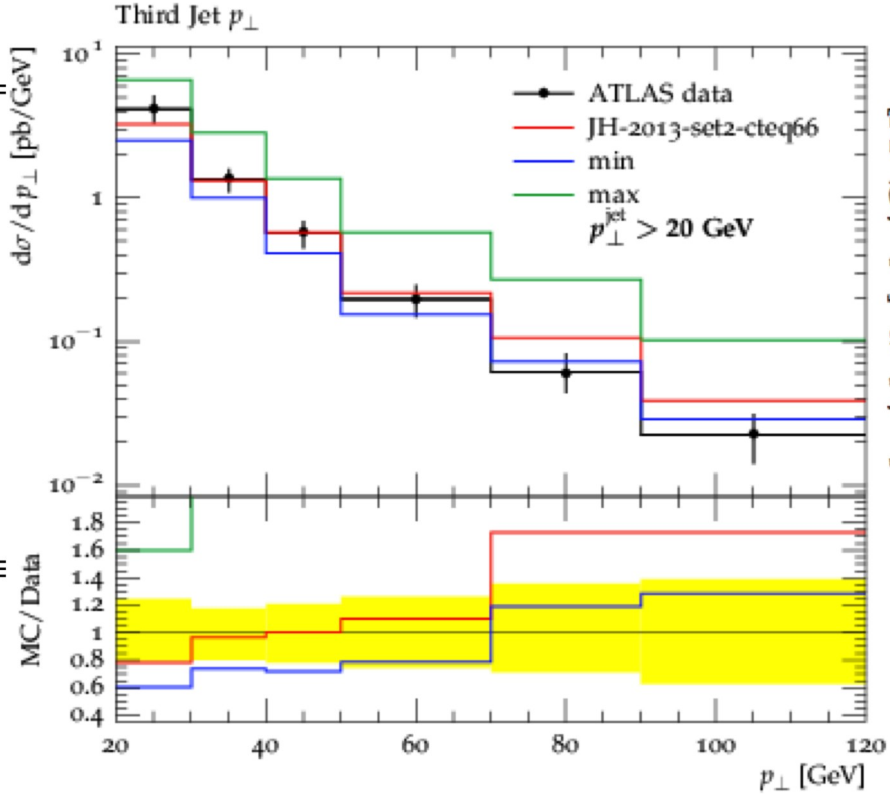




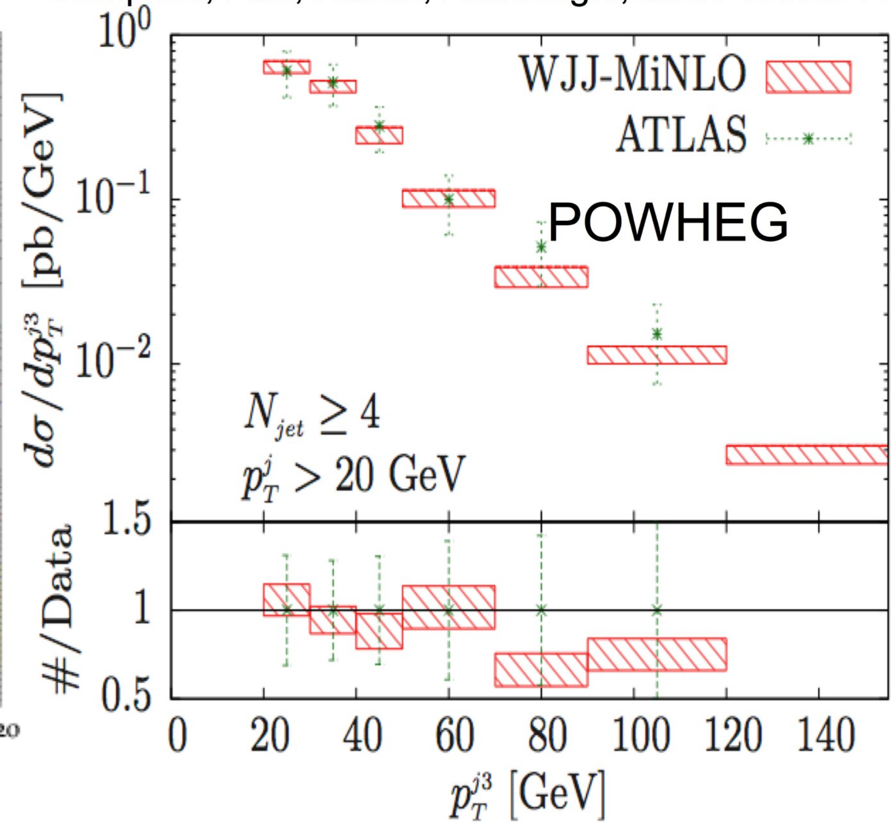
- use valence quarks and CCFM gluon convoluted with off-shell ME
- compare with W+jet measurement

Application to W + jet production at LHC



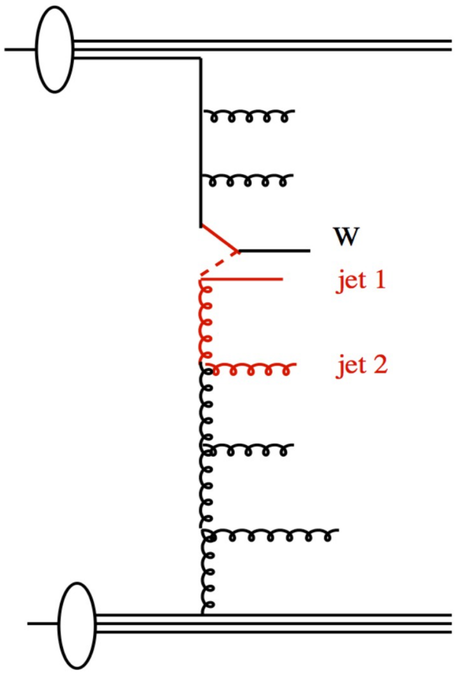


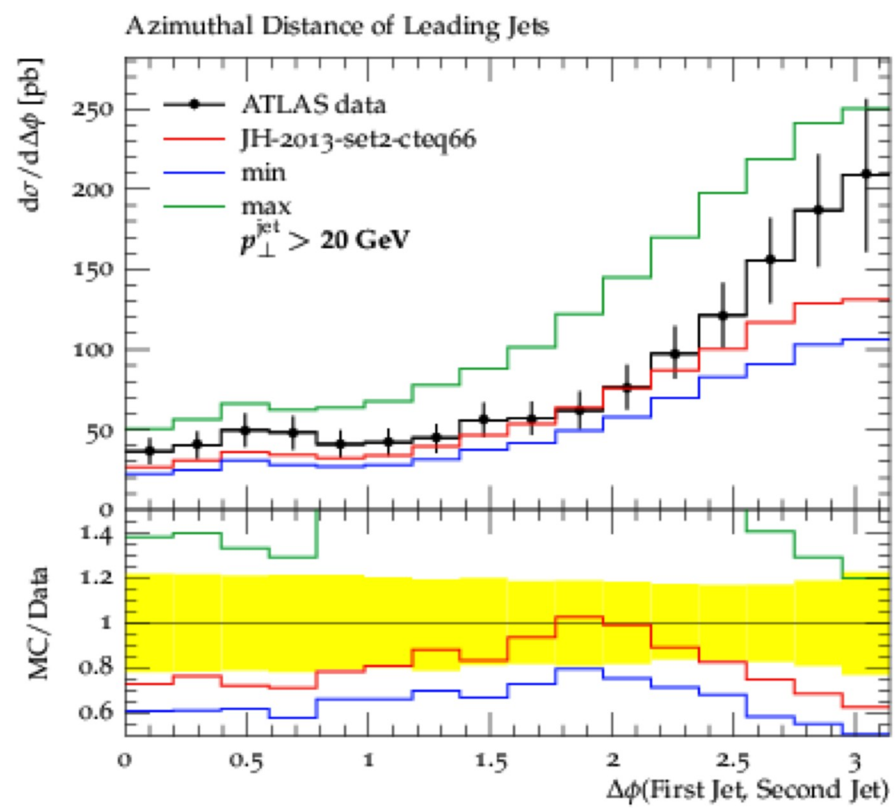
Campbell, Ellis, Nason, Zanderighi, arXiv 1305.5447



- off-shell ME + CCFM k_t - shower predicts correct x-section and shape for 3rd jet (similar to NLO W+2jet) !
  - 3rd jet comes from CCFM k_t - shower

W + n-jets: k_t shower vrs NLO



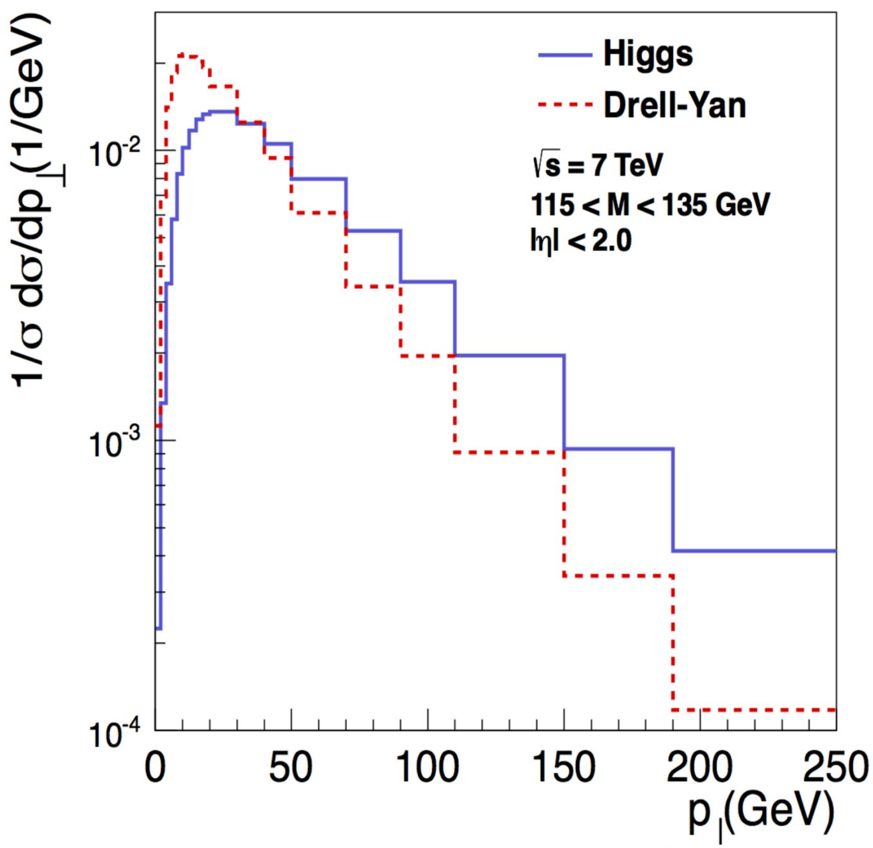


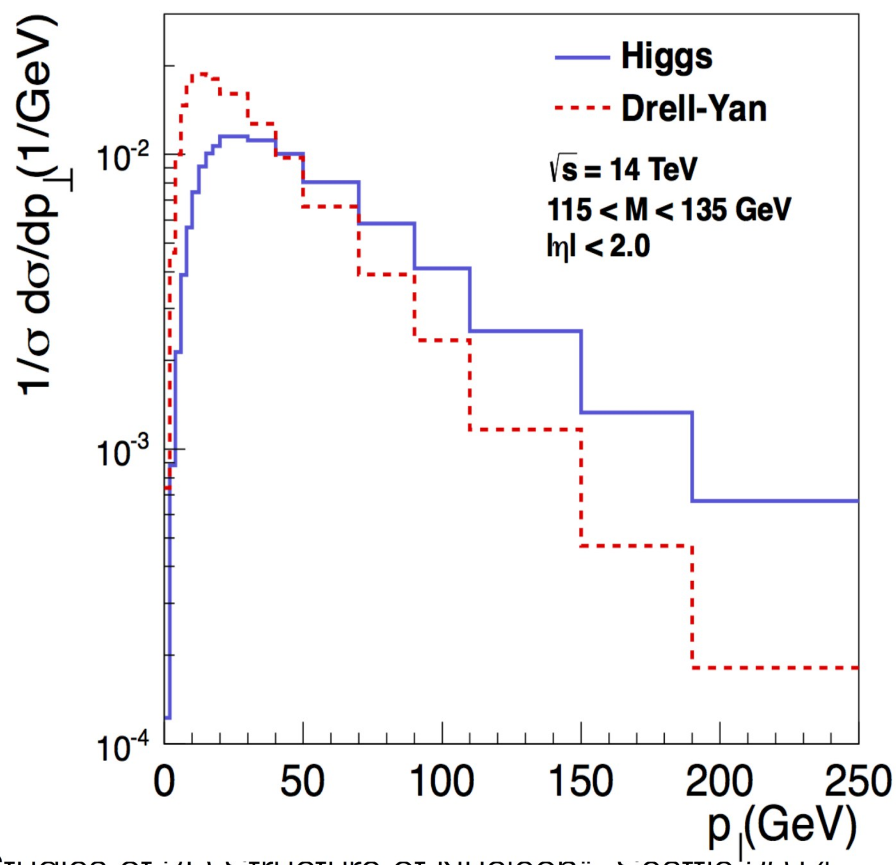
- off-shell ME + CCFM k_t - shower for x-section and shape for $\Delta\,\phi$ between first 2 jets agrees with measurements within uncertainties:
  - sensitive probe of shower:
    - decorrelation region well reproduced !

How to determine directly TMD of gluon ?

- Higgs as gluon trigger

  P. Cipriano, S. Dooling, A. Grebenyuk, P. Gunnellini, F. Hautmann, H. Jung, P. Katsas (arXiv:1308.1655 and Phys. Rev. D 88, 097501 (2013)
- comparison with DY production at same mass range
- p_T spectrum of DY and Higgs: difference in soft gluon resummation



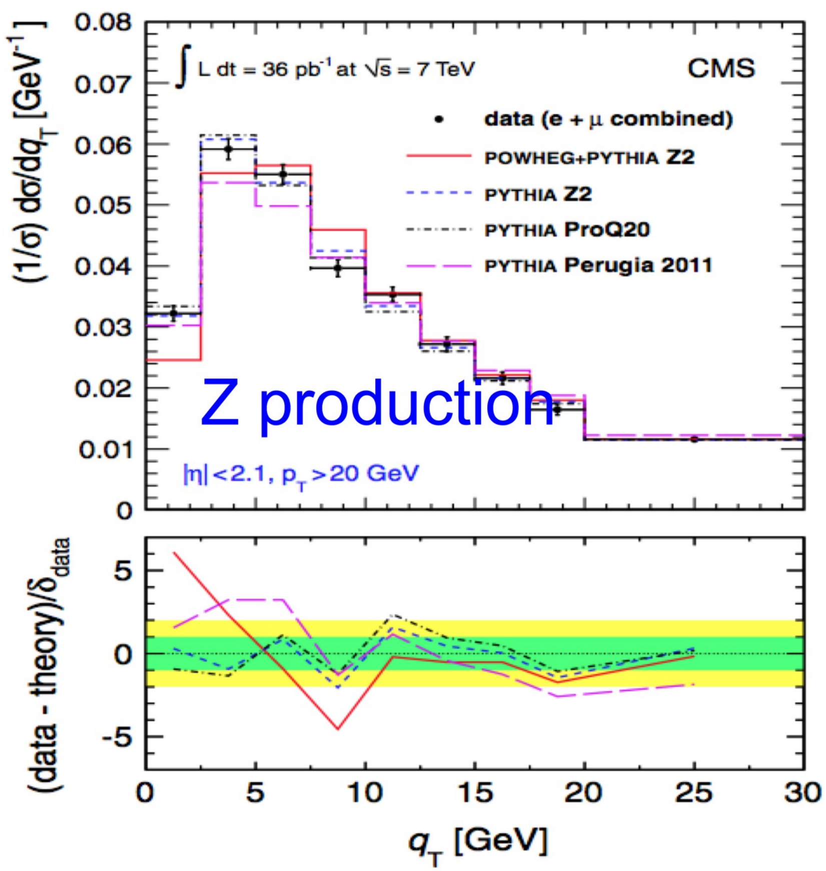


How to determine directly TMD of gluon ?

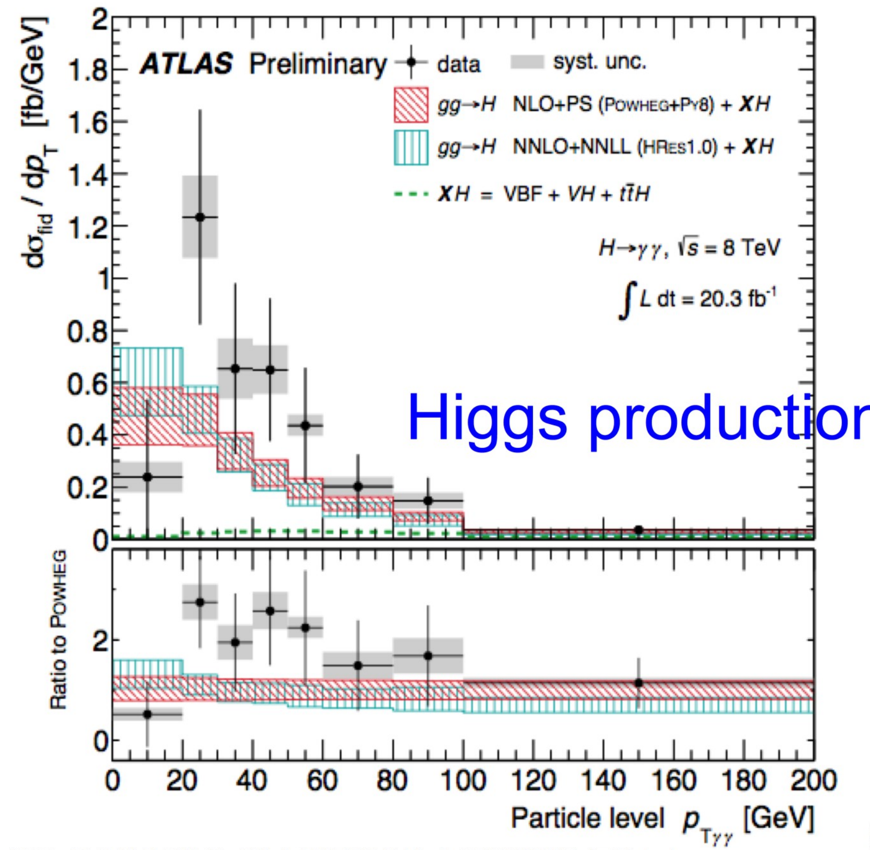
Until last year, perspectives for QCD studies at HL LHC were rather bad.....

- BUT now, with Higgs, we have new and exciting options, which opens up a completely new world for QCD studies
- gluon fusion processes with color singlet final state at large masses

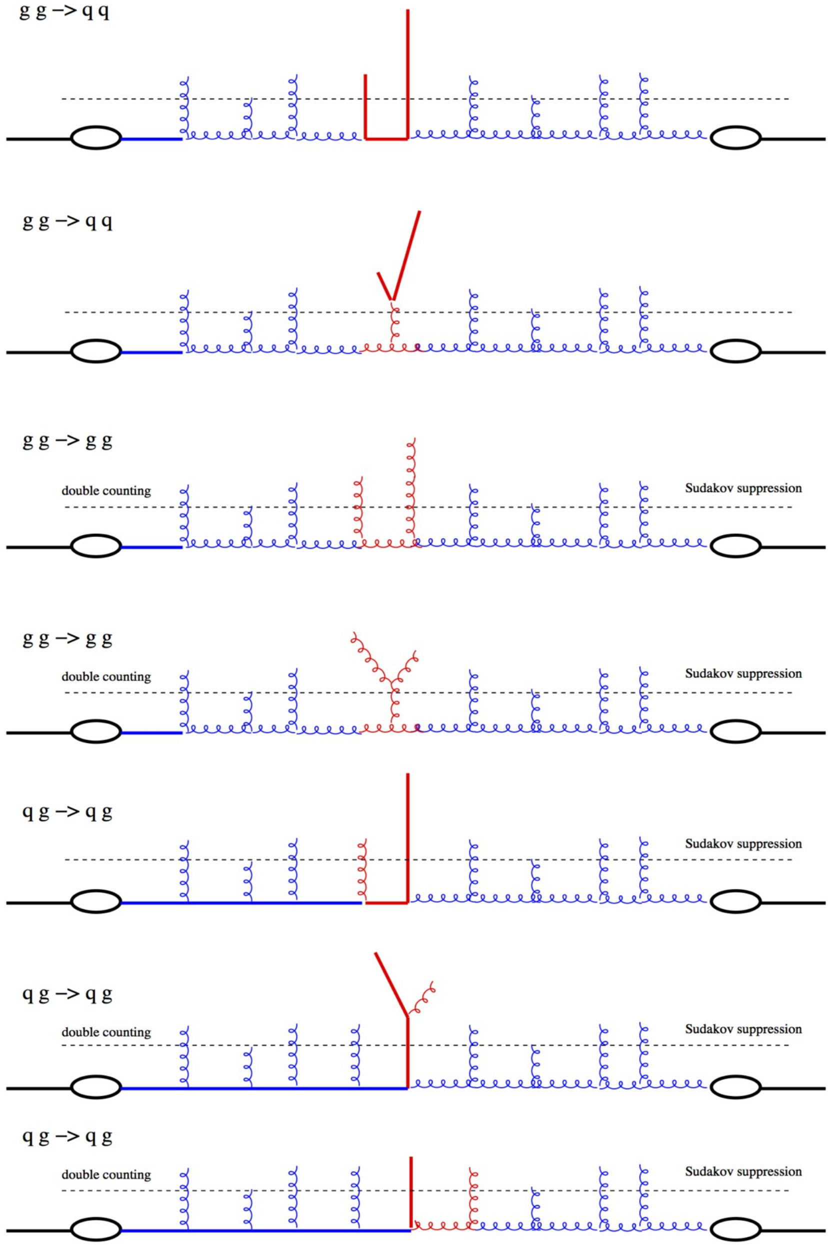
CMS Coll., PRD 85, 032002 (2012)



Differential cross sections of the higgs boson measured in the diphoton decay channel using 8 TeV pp collisions. ATLAS-CONF-2013-072,



pp: factorization issues



- k_t of initial partons a priori not restricted, extends to large k_t
- factorization at small x proven for heavy flavor production or gauge boson production
- with k_t of initial partons, identification of hard scattering no longer trivial for light partons

What happens
at small x and small k_t ?

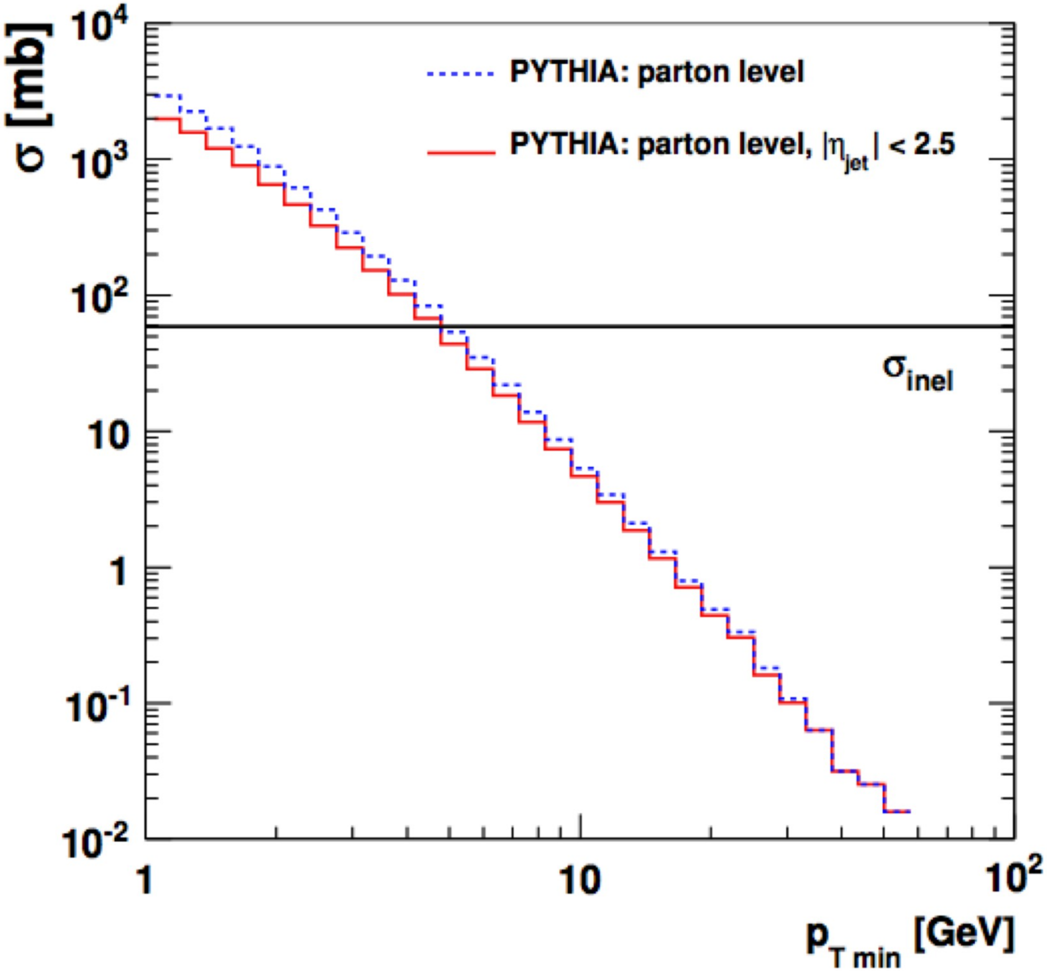
Accessing low p_t and low k_t region

- Basic partonic perturbative cross section

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

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

- mechanism needed which tames rise:
- damping of xsection
  - **saturation effects ?**
  - **Multiparton Interactions ?**



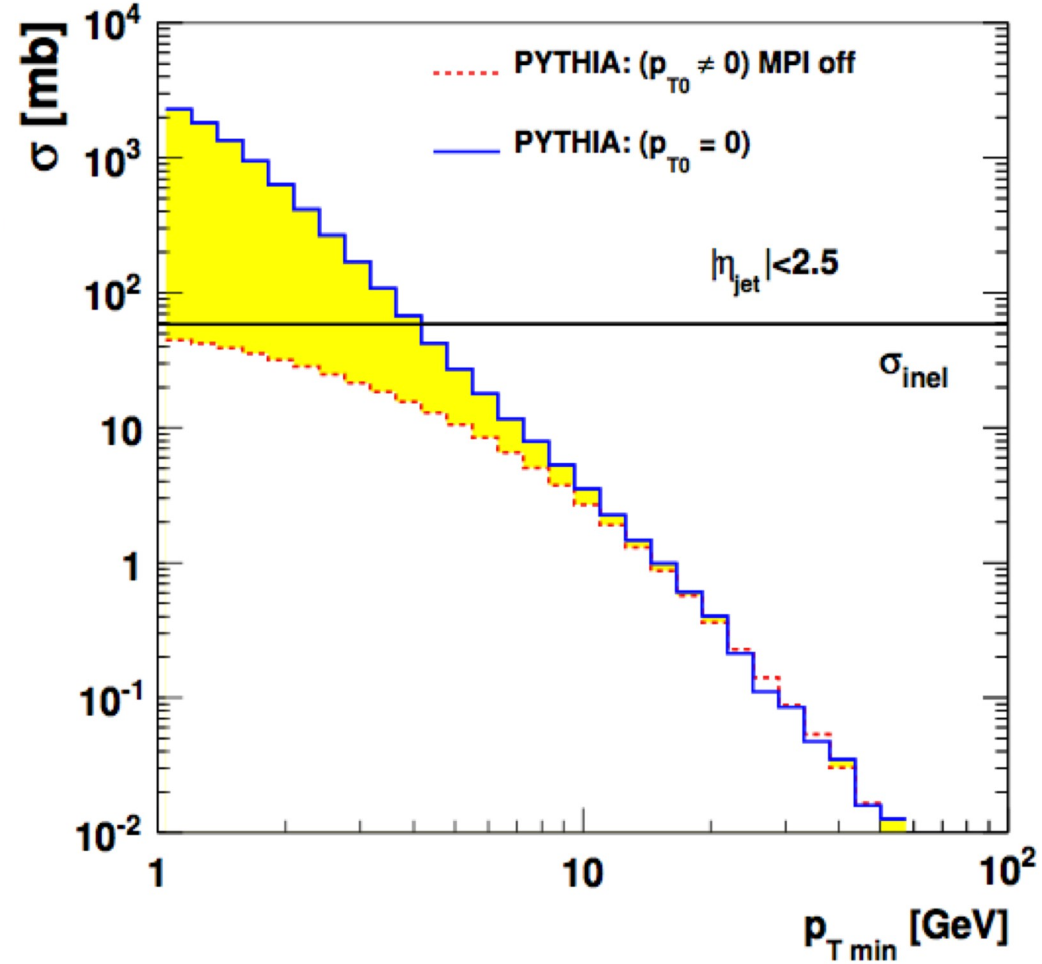
already in η range accessible by experiment

Taming of x-section in PYTHIA

- taming of xsection ($\propto 1/{p_t}^4$) in PYTHIA:

$$\sigma \to \sigma \times \frac{\alpha_s(p_t + p_{t0})}{\alpha_s(p_t)} \frac{p_t^4}{\left(p_t^2 + p_{t0}^2\right)^2}$$

- p_{to} **is a free parameter !**

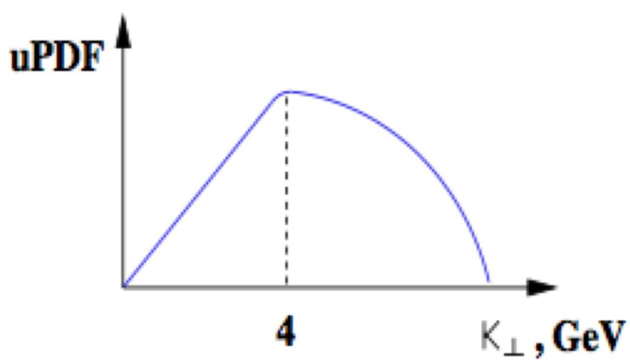


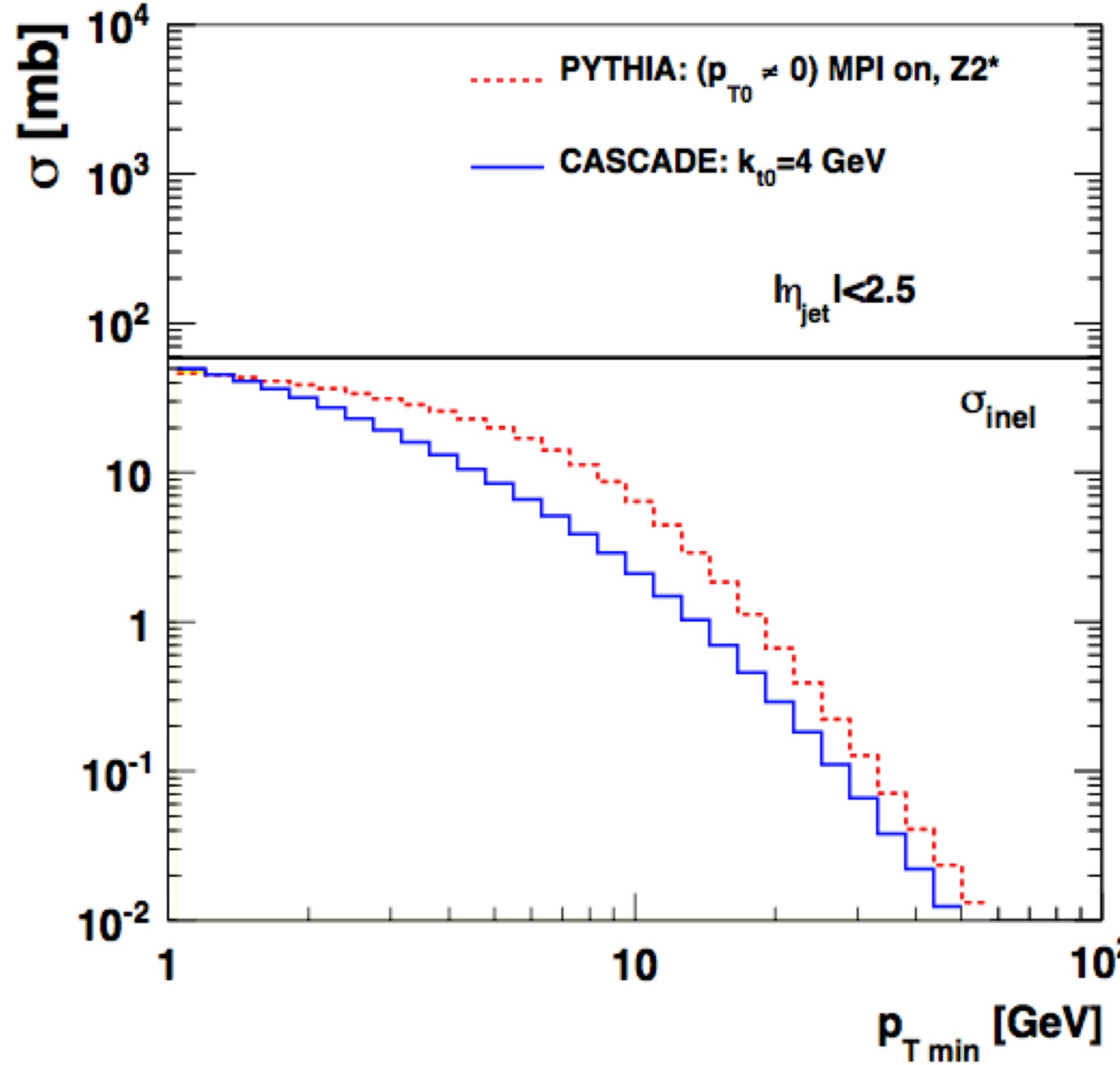
Relation to saturation and TMDs

- using TMDs
  - saturation happens at small k_t
  - gluon density vanishes

A. Grebenyuk, DIS2013, Marseille

Modification of unintegrated PDF such that it goes to zero for $k_T \to 0$:

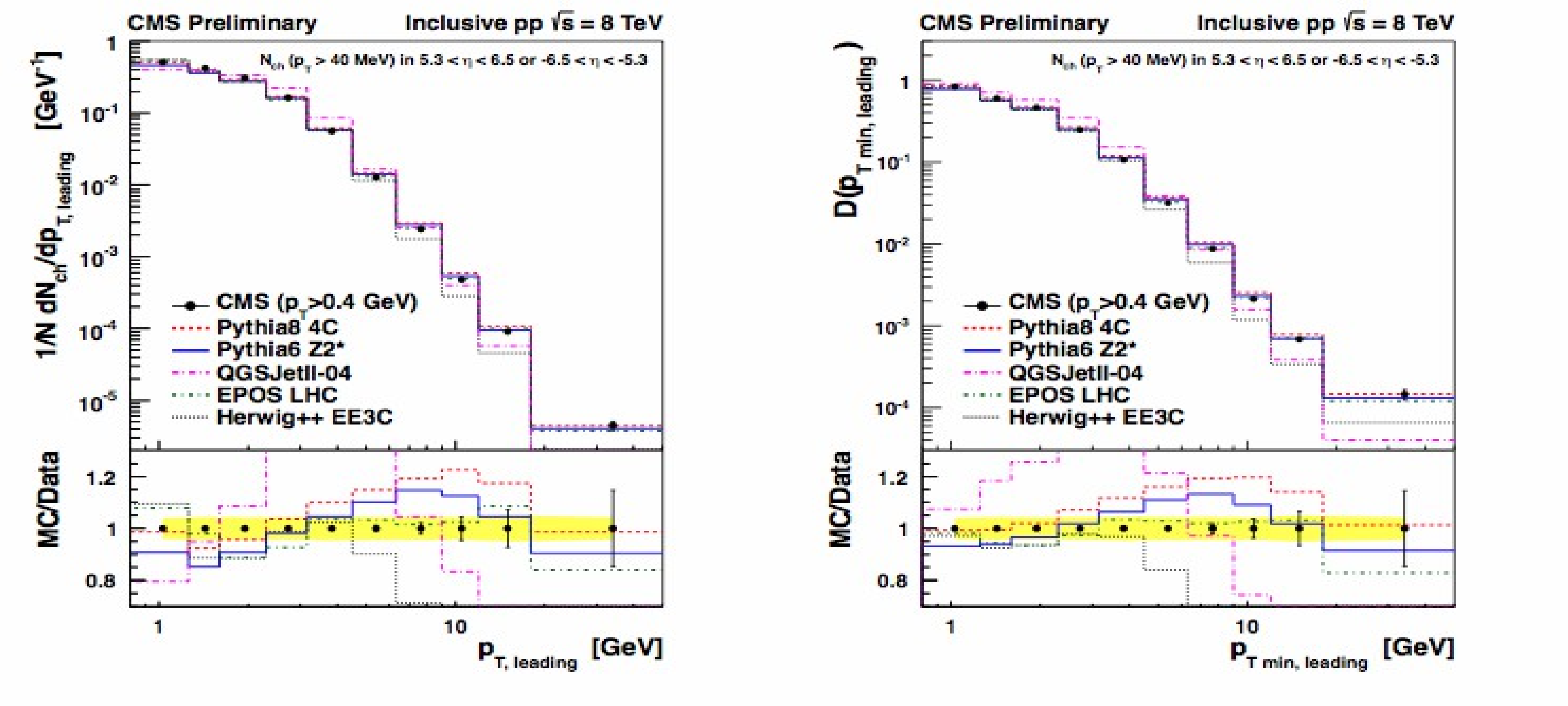




- using TMDs with saturation at small k_t gives correct behavior of xsection

Comparison with CMS measurement

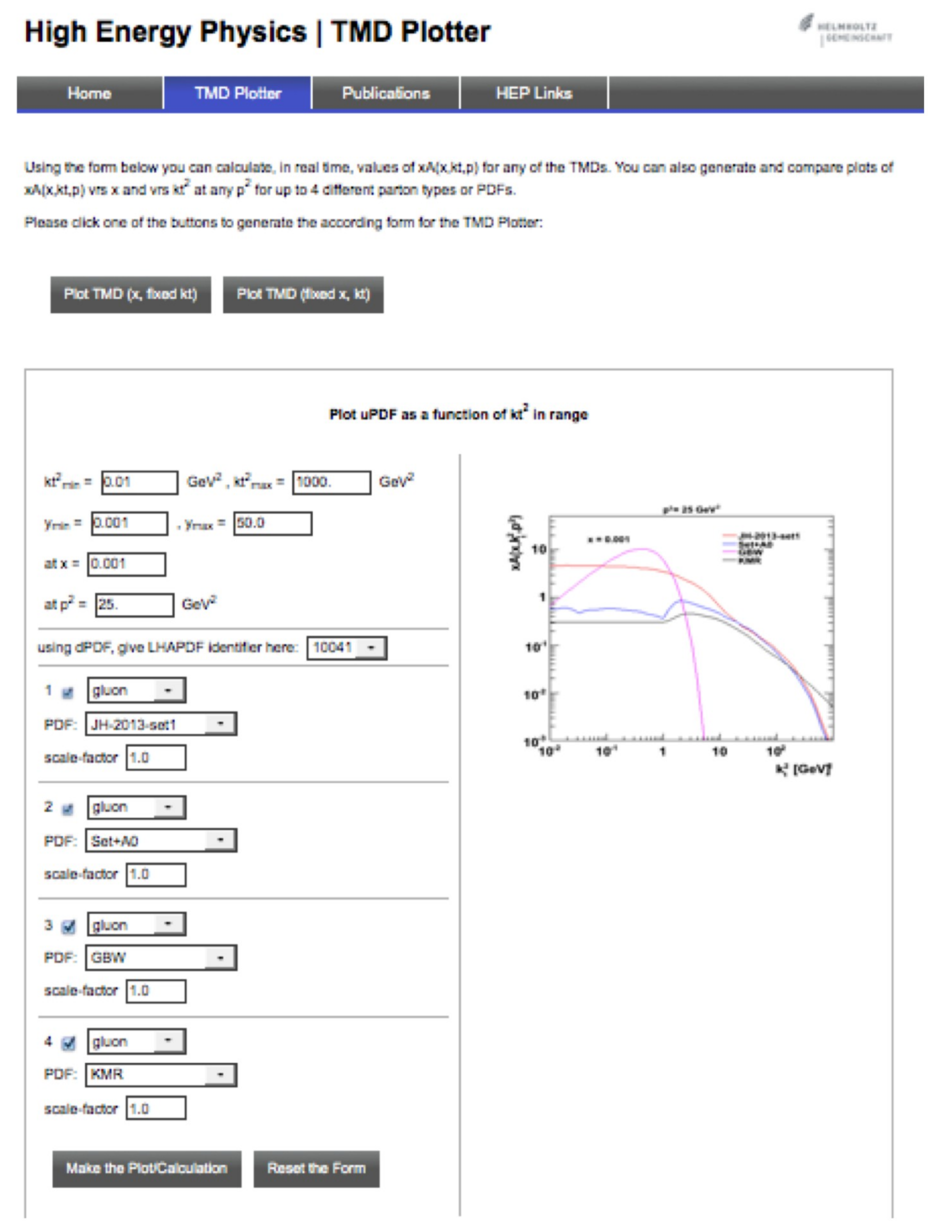
P. Katsas (CMS), DIS2013, Marseille



- QGSJETII-04 and Herwig++ fail to describe the measurements
- EPOS LHC in good agreement with the data

TMDplotter and TMDlib

- combine and collect different ansaetze and approaches
  - ➔ library of parametrizations of different TMDs and uPDFs similar to LHApdf
    - started by F. Hautmann, H. Jung, P. Mulders, A. Signori, T. Rogers
  - ➔ plotter for easy comparison of different TMDs and uPDFs: http://tmdplotter.desy.de
- support, contributions and help for TMDplotter and TMDlib projects are very welcome !



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 TMD-gluon from inclusive DIS HERA data
    - now with model- and experimental uncertainties

- TMD – uPDF gives a consistent recipe for initial state parton shower
  - no kinematic corrections are needed

- very small x processes
  - saturation comes naturally from TMDs vanishing at small k_t and small x and can be implemented in MCs

- TMD – uPDF together with off-shell ME applied to ep and pp scattering