Vector boson + jets from k_t - dependent parton showers

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

- power - suppressed terms in k_t dependent shower
- W+n jet production using
  - new small x improved TMD gluon density including uncertainties
  - comparison with W+2 jet measurements
  - observables from double parton scattering

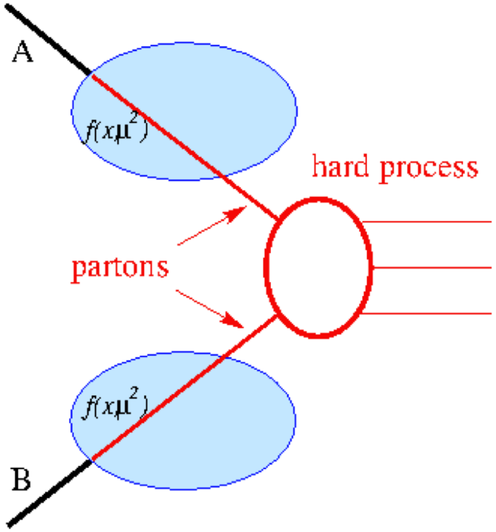
The past ...

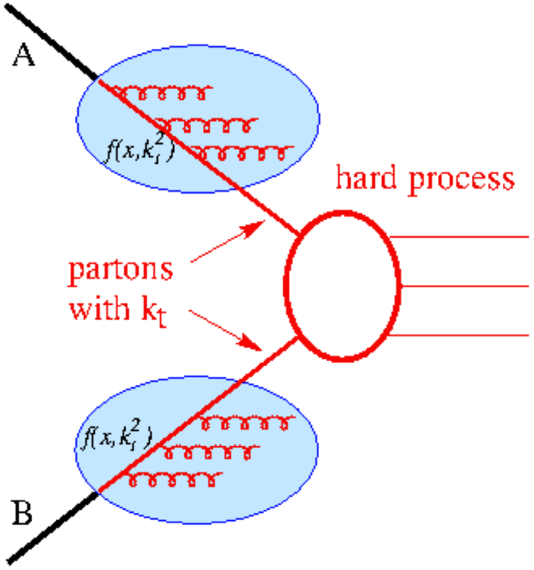
- The standard ansatz: collinear factorization

$$\sigma = f_i^A(x_1,\mu^2)\hat{\sigma}(i+j\to X)f_j^B(x_2,\mu^2)$$

- even at NLO kinematic constraints lead to inconsistencies (see talk by S. Dooling) especially away from central region.

- The extension: transverse momentum dependent factorization
  - factorization of TMDs proven by J. Collins (CUP 2011)
  - gluon TMD at small x determined, but it is still a challenge to include quarks



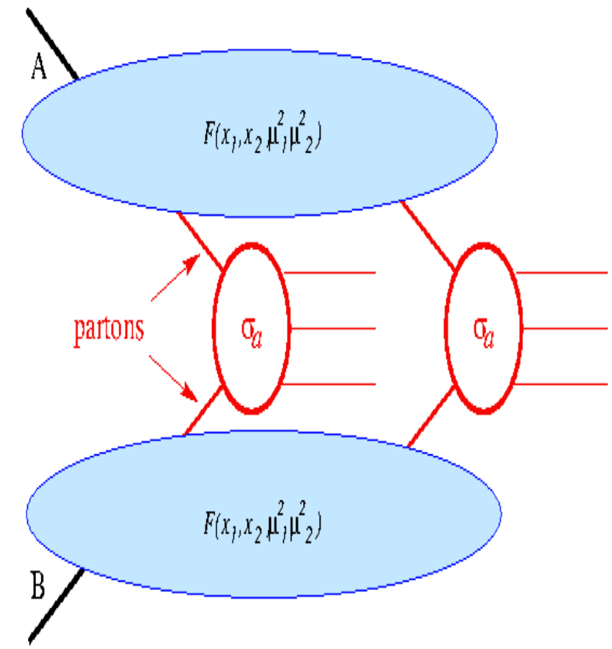


The past ...

- The limitations:

$$\sigma = c_1 f_g f_g + c_2 f_q f_q + c_3 f_g F + c_4 F F$$

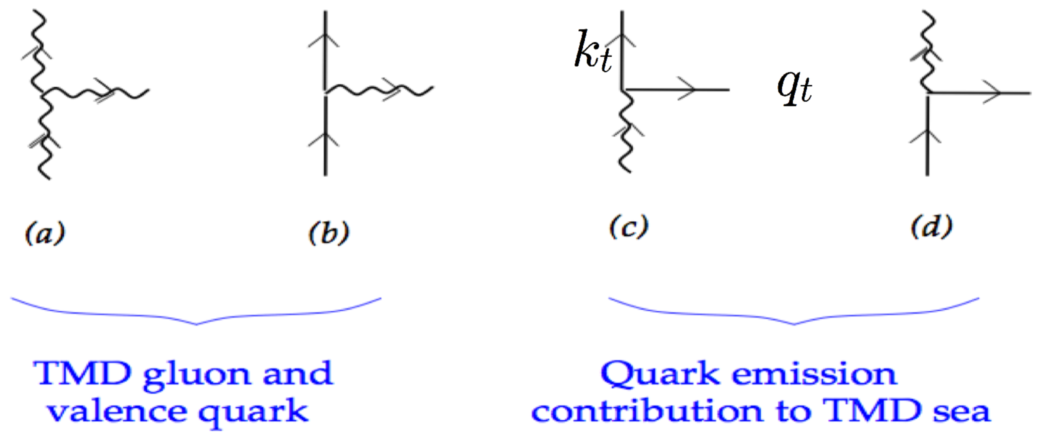
  - last terms are suppressed by powers of μ
  - ansatz of collinear factorization
    - inclusion of power suppressed terms leads to double parton scattering



- Can one do differently ?

Treatment of power suppressed terms

- un-integrated sea-quark distribution (see talk by M. Hentschinski *TMD quark distributions at small x* in Structure function session and Hautmann, Hentschinski, Jung, Nucl.Phys. B865 (2012) 54-66, arXiv 1205.6358)



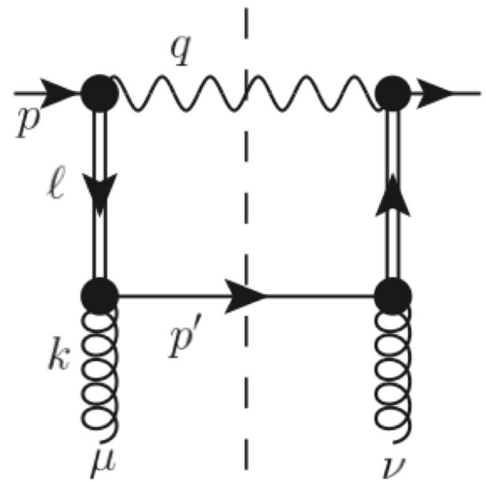
- quark sea: flavor singlet evolution coupled to gluons at small x via

$$\mathcal{P}_{g\to q}(z, q_t, k_t) = P_{qg,DGLAP}(z)\left(1 + \sum_{n=0}^{\infty} b_n(z)\left(\frac{k_t^2}{q_t^2}\right)^n\right)$$

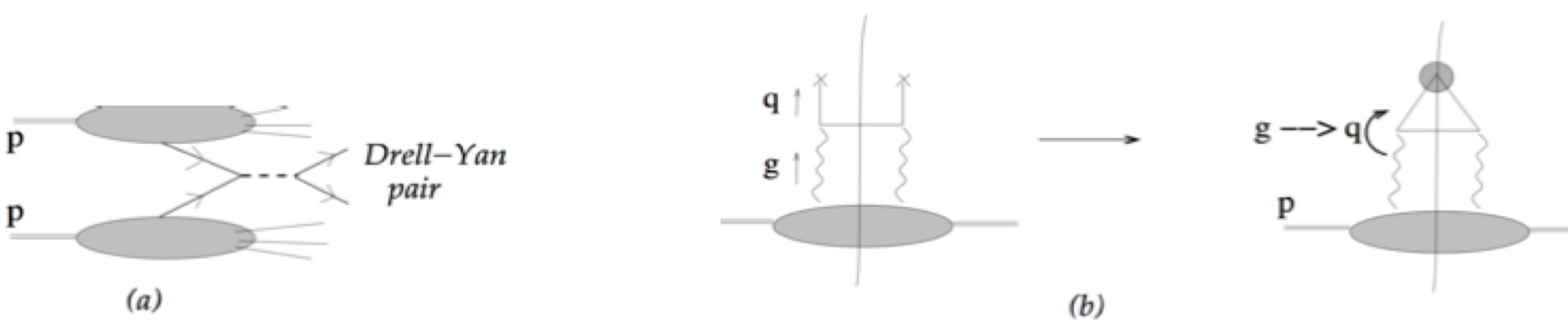
- → all b_n known: $\mathcal{P}_{g\to q}$ computed in closed form (pos definite) in Catani, Hautmann 1994, Ciafaloni et al 2005-2006 in small x factorization
- → Note: power suppressed terms only in small x improved TMDs (not covered by J. Collins factorization.)

Vector bosons + jets at high energies

- Partonic matrix elements (gauge invariant, despite off-shell parton)
  (see Ball & Marzani NPB814 (2009) 246, Hautmann, Hentschinski, Jung NPB865 (2012) 54)



- DY production and $g \to q$ splitting contribution to sea quark distribution



CCFM evolution and k_t – dependent shower

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

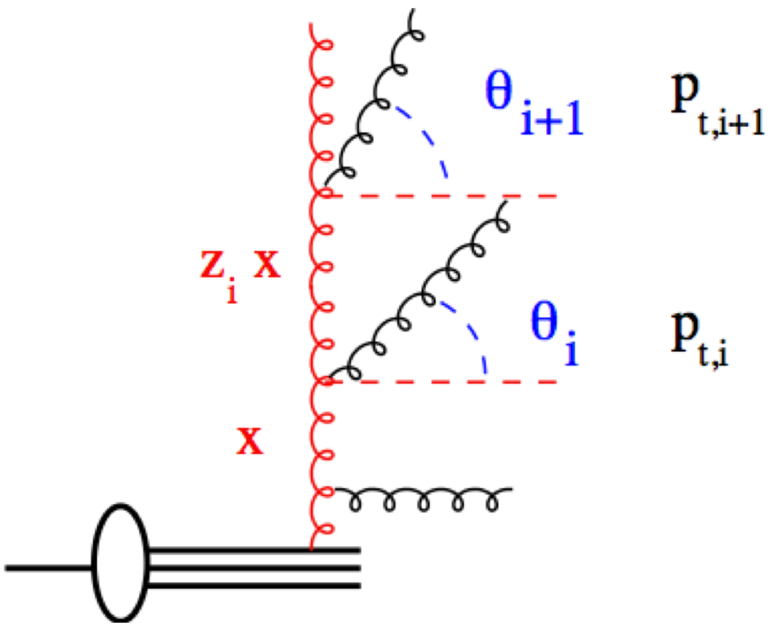
$$q_i > z_{i-1} q_{i-1} \quad \text{with} \quad q_i = \frac{p_{ti}}{1 - z_i}$$

➔ recover DGLAP with *q* ordering at medium and large *x*

➔ HERWIG uses: $q_i > q_{i-1}$

➔ at small x, no restriction on *q*

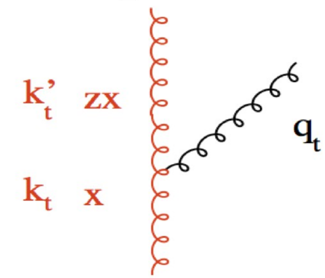
p_{ti} can perform a random walk

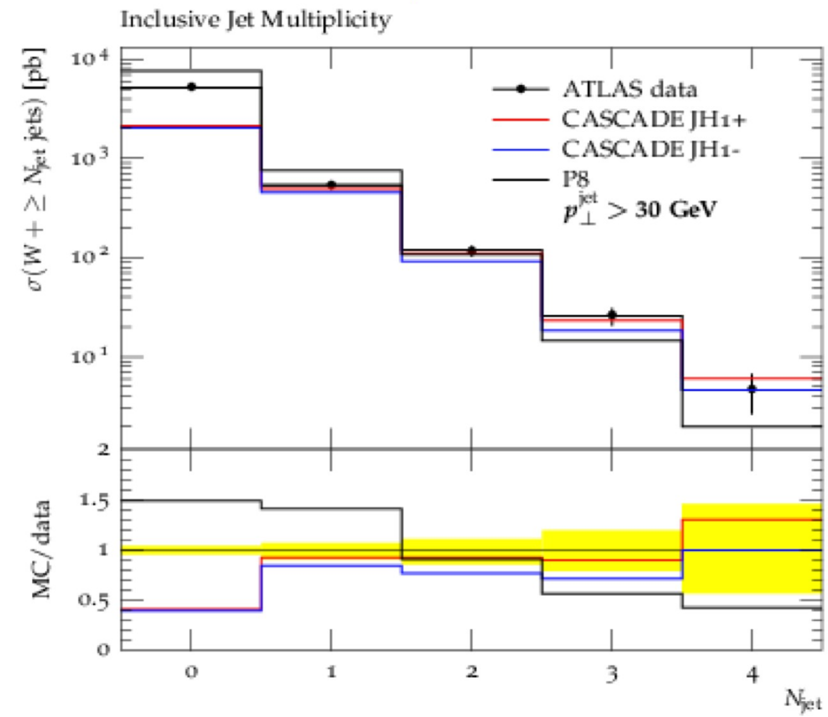


➔ CataniCiafaloniFioraniMarchesini evolution forms a bridge between DGLAP and BFKL evolution

W + jets

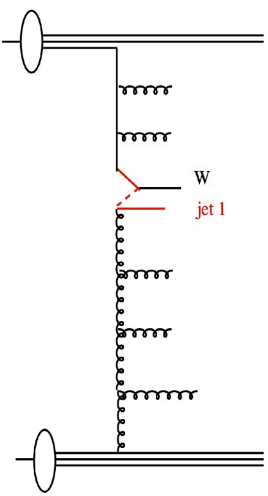
- using CCFM gluon TMD, determined from HERA F_2 including experimental and model uncertainties
- initial parton shower according to CCFM evolution in angular ordered phase space
  - $q_i > z_{i-1} q_{i-1}$ with $q_i = \frac{p_{ti}}{1-z}$
  - → no p_t constraint at small x
  - → jets can have large p_t

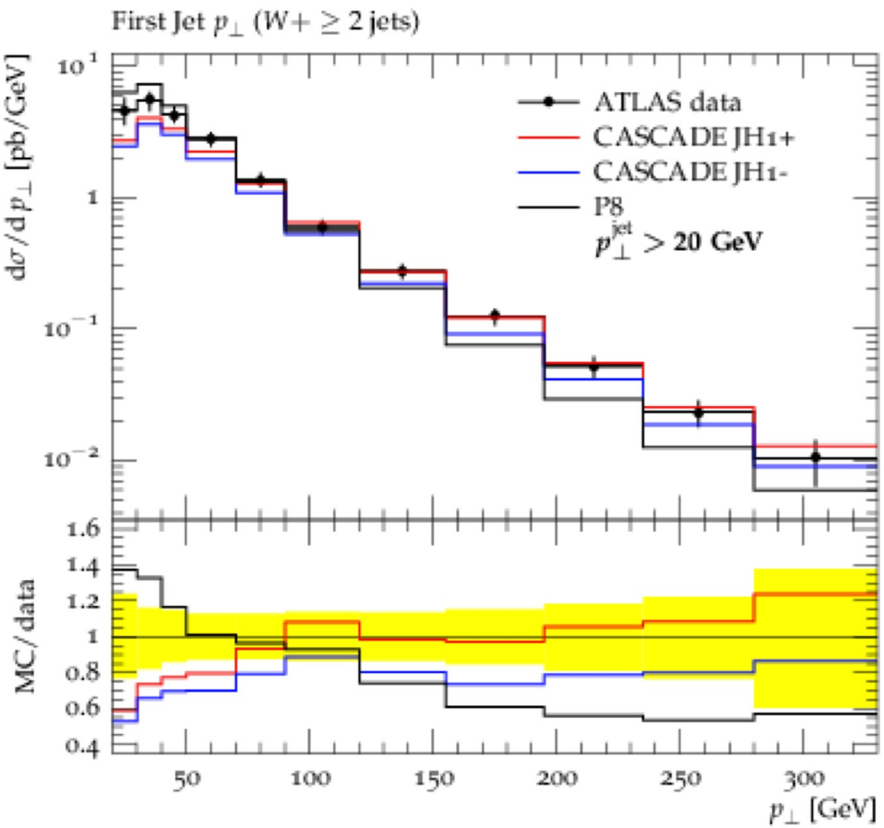




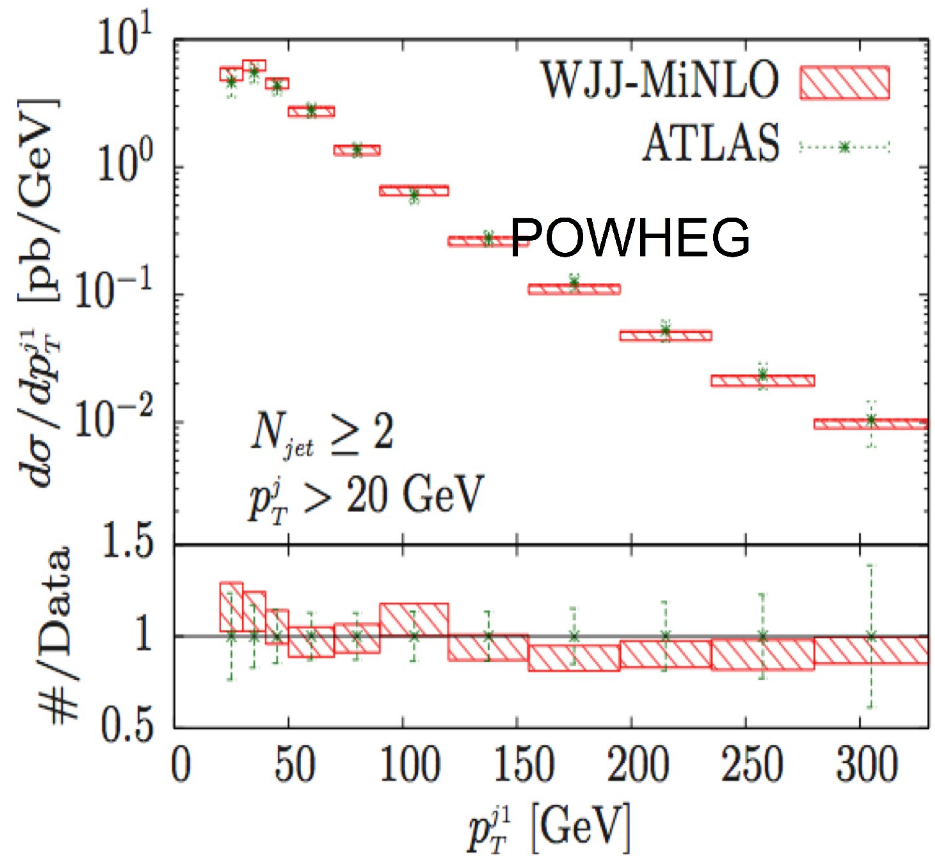
- Jet multiplicities are reproduced
  - 1 jet → from ME
  - 2-4 jets from shower
- Note: PYTHIA with p_t -ordered shower cannot predict higher jet multiplicities

W + n-jets: k_t shower vrs NLO



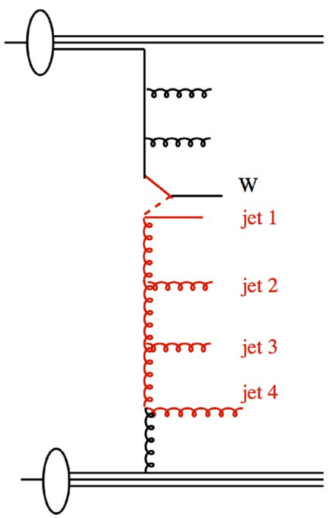


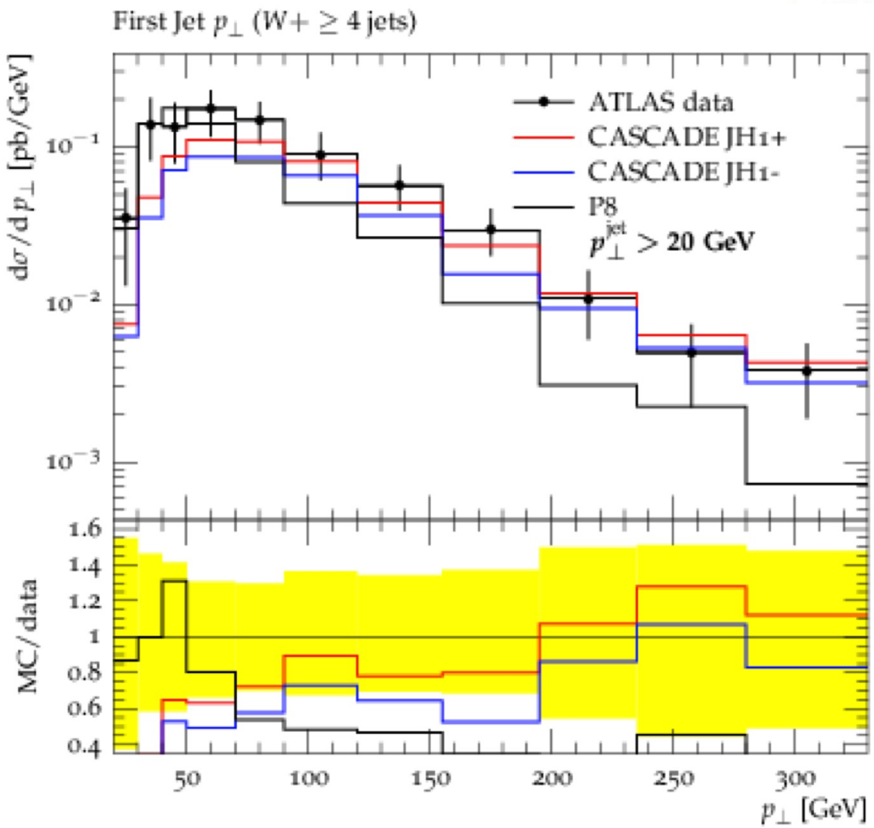
Campbell, Ellis, Nason, Zanderighi, arXiv 1305.5447



- 1st jet in W+> 2jet events:
  - off shell ME + CCFM k_t - shower (CASCADE) comparable with NLO W+2jet (POWHEG)
  - uncertainties studied in CASCADE: pdf and scale uncertainties
  - PYTHIA + shower starts to fail at large pt

W + n-jets: k_t shower vrs NLO





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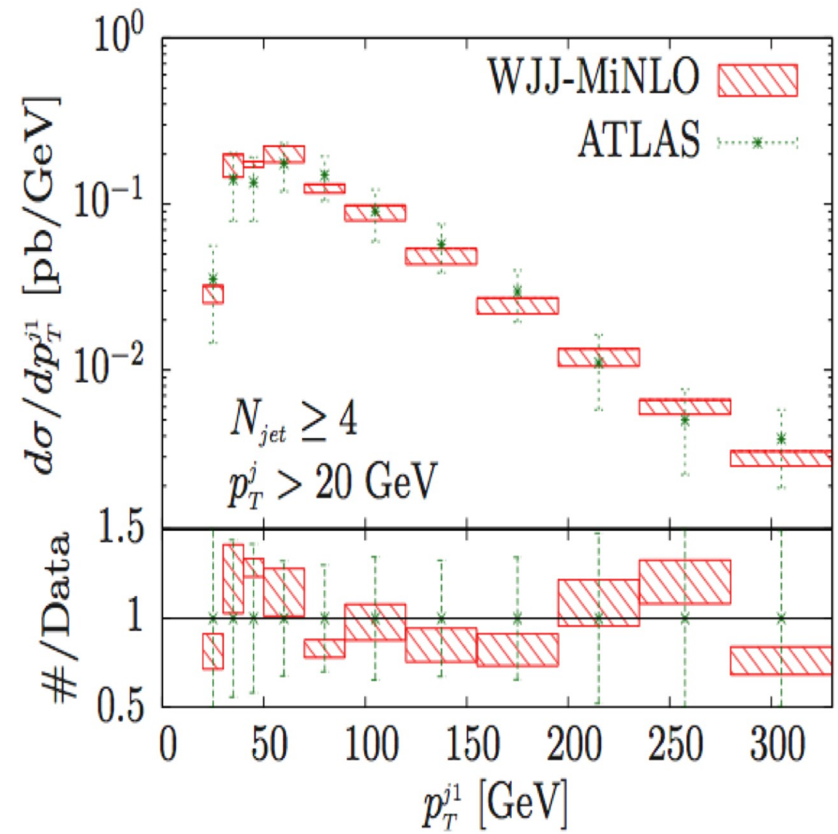
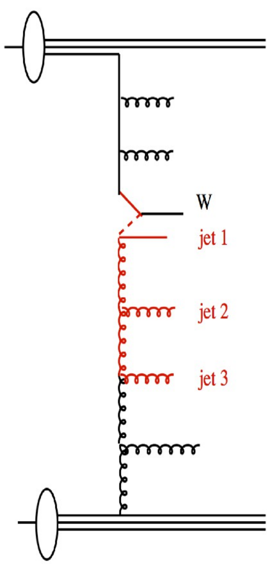
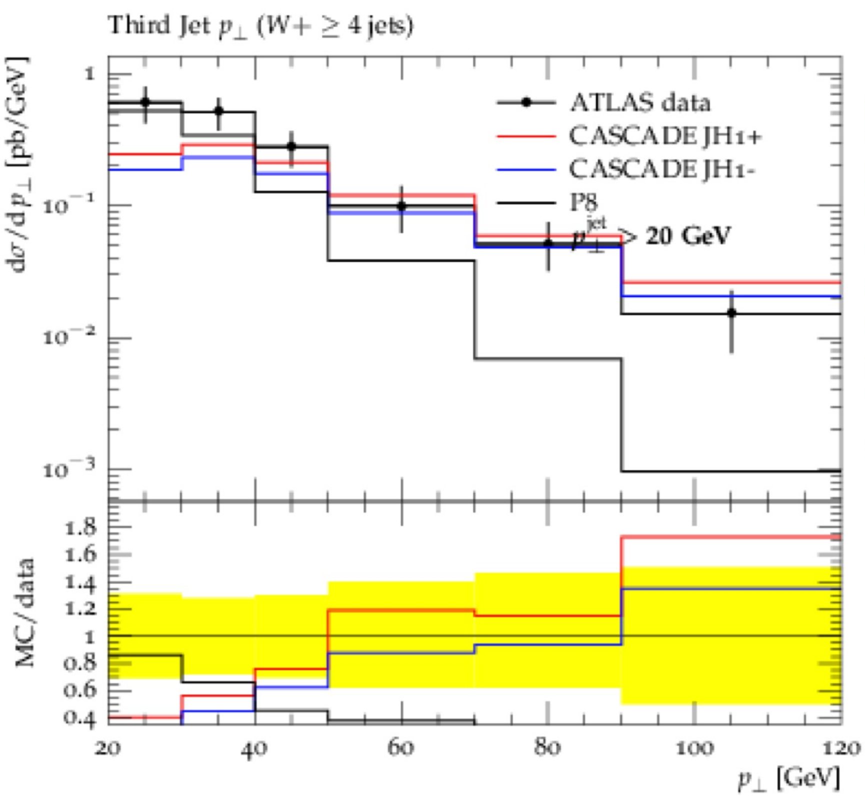


- off-shell ME + CCFM k_t - shower (CASCADE) comparable with NLO W+4jet
- first jet comes from hard process, other jets partially from shower
  - CCFM k_t - shower works fine even for high pt
  - P8 shower cannot describe shape

W + n-jets: k_t shower vrs NLO





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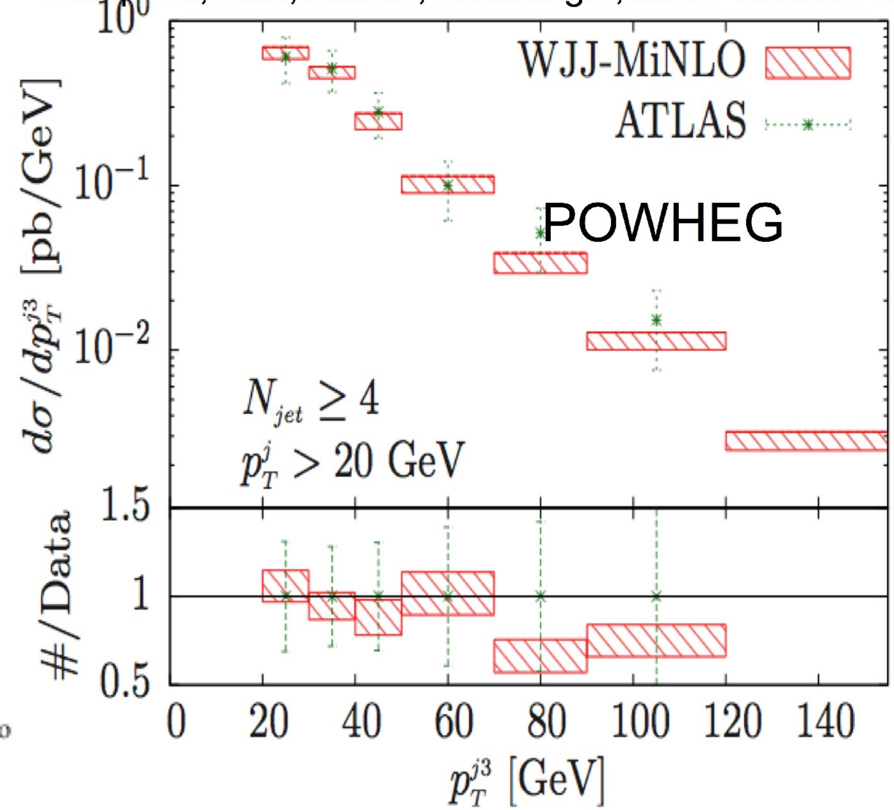
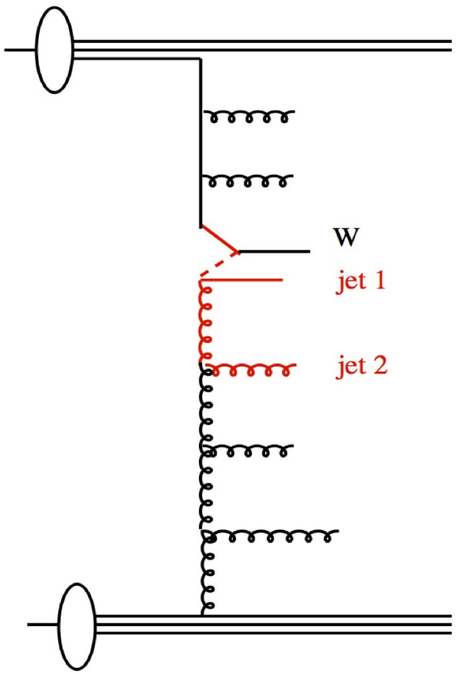
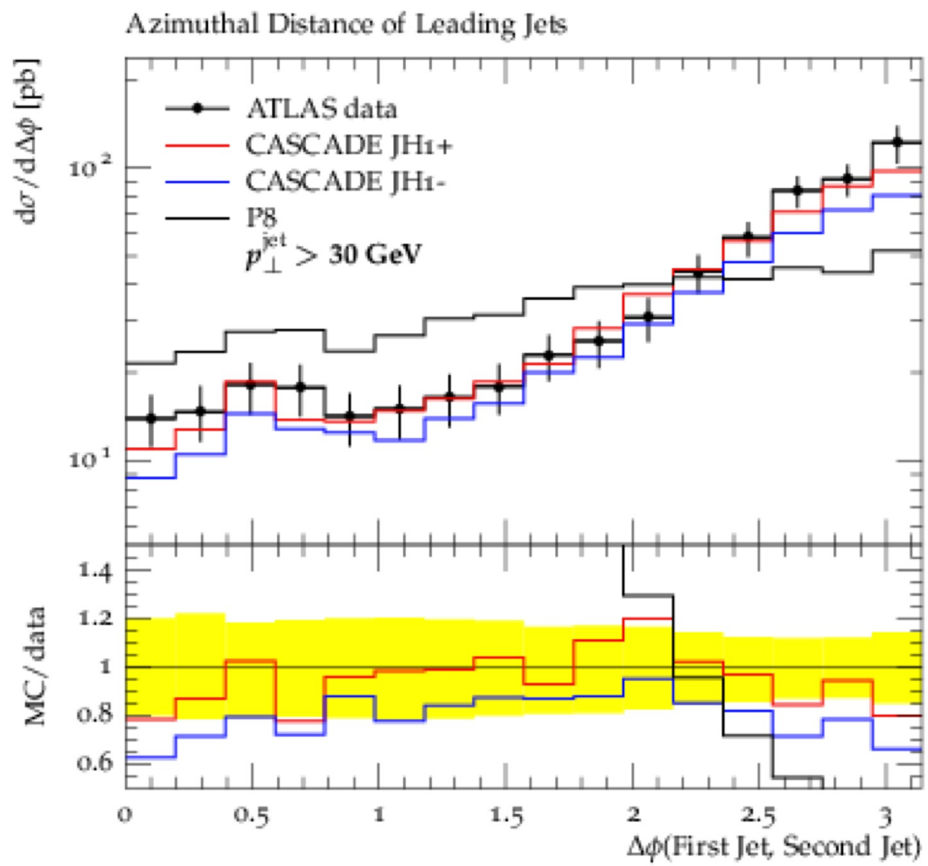


- off-shell ME + CCFM k_t - shower predicts correct x-section and shape for 3rd jet (similar to NLO W+2jet) !
  - 3rd jet comes from CCFM k_t - shower
  - collinear shower pt ordered shower (PYTHIA) fails to describe shape

W + n-jets: k_t shower vrs NLO





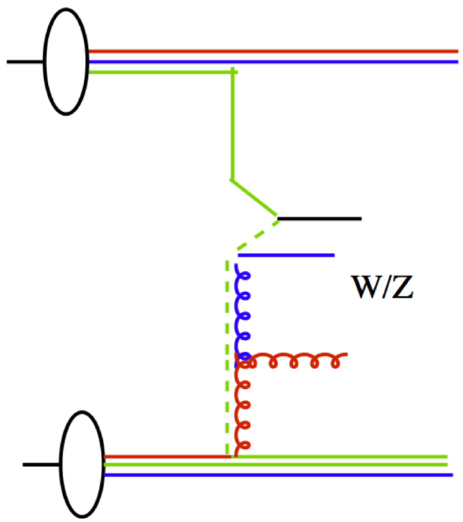
- off-shell ME + CCFM k_t- shower for x-section and shape for $\Delta\,\phi$ between first 2 jets agrees with measurements within uncertainties:
  - sensitive probe of shower:
    - back to back region and decorrelation region well reproduced !
    - not described by collinear shower pt ordered shower (PYTHIA)

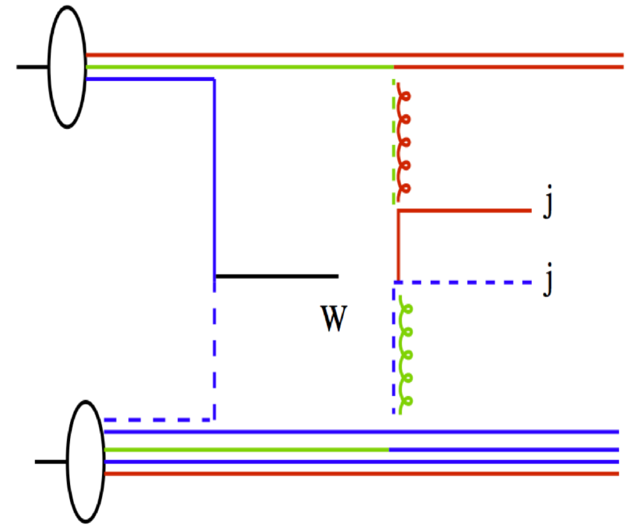
What is the gain ?

- CCFM gluon TMD and k_t dependent shower with off shell ME give similar results as NLO matched with collinear shower
- calculation arranged in a very efficiency way → fast calculation
- jet production from TMD and k_t dependent shower extendable to any number of jets without further adjustment and tuning
  - CCFM + k_t dependent shower describes well high pt jet production

- Advantage of CCFM+k_t dependent shower:
  - matching with 2 →n off-shell parton calculation (automated method, *see talk by A. van Hameren, small x session*)
  - opens possibility for full LHC phenomenology of QCD, EWK and BSM processes

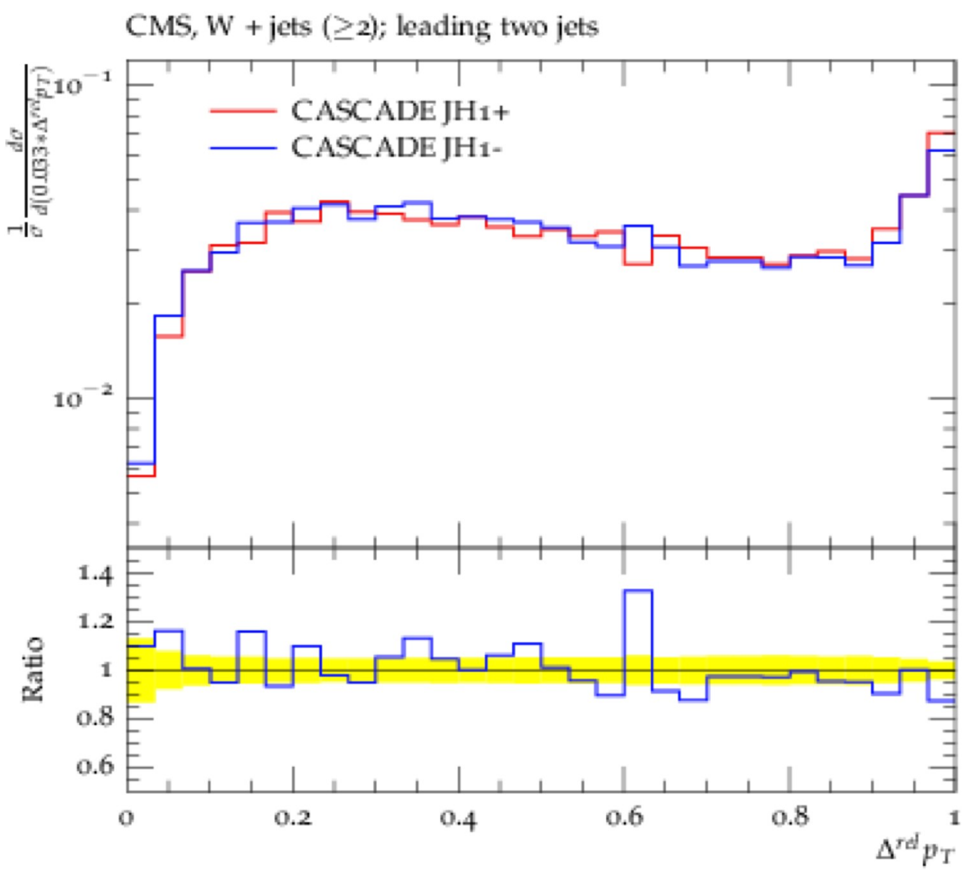
W + 2 jet: signal for double-parton scattering ?



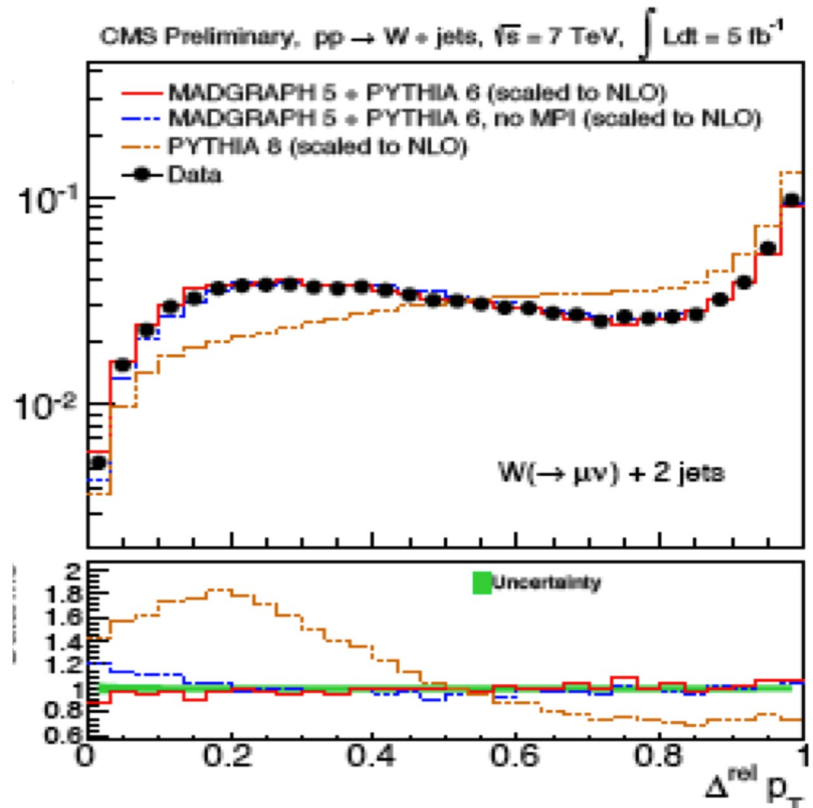


- DPS signal: de-correlated jets compared to W
  - what is the contribution from single chains ?
  - are jets just power-suppressed terms from evolution or do they come from independent scatterings ?

W+2 jet: signal for double-parton scattering ?



From P. Bartalini: MPI and DPS studies at CMS
WG2: Low x and Diffraction



- off-shell ME & CCFM + k_t shower predict a similar shape as seen in latest CMS measurement

W+2 jet: signal for double-parton scattering ?

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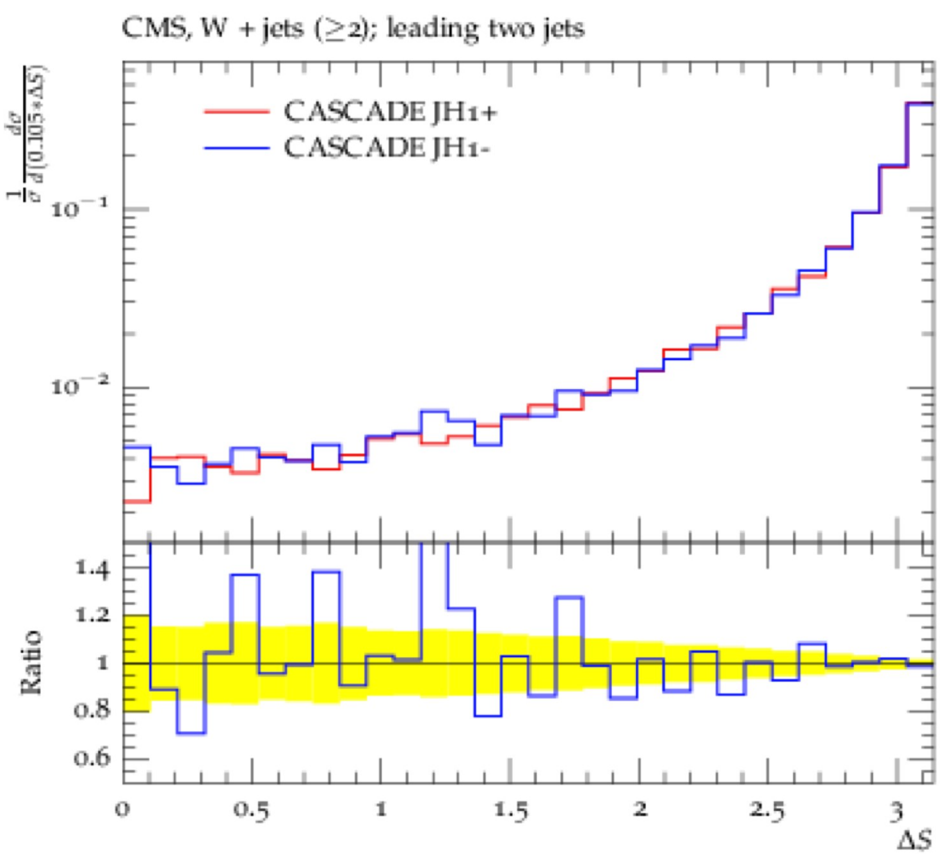
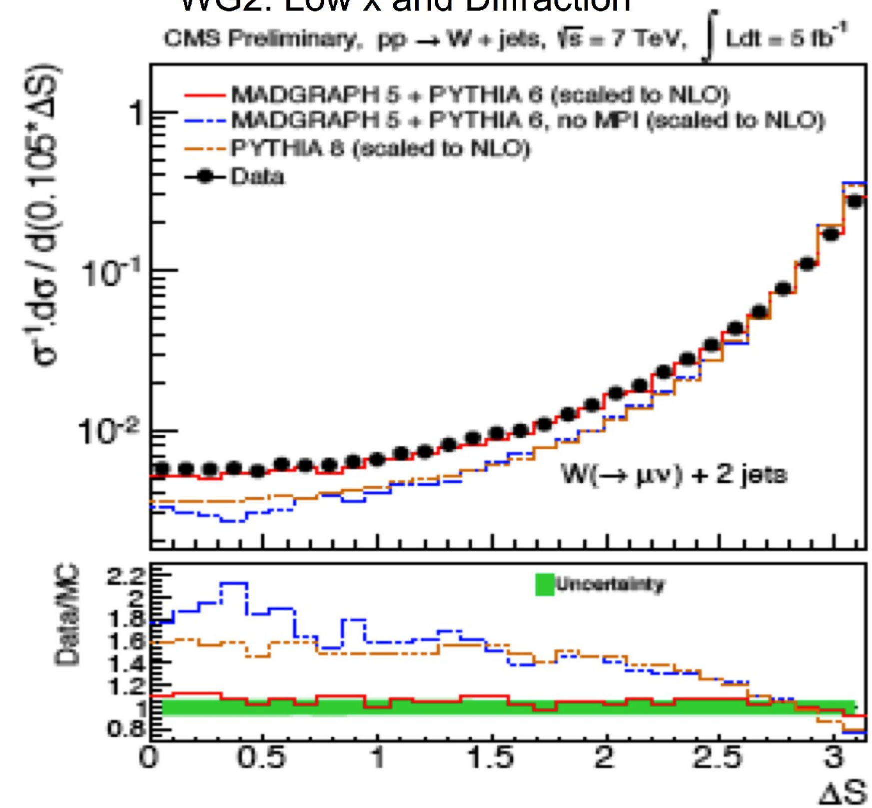


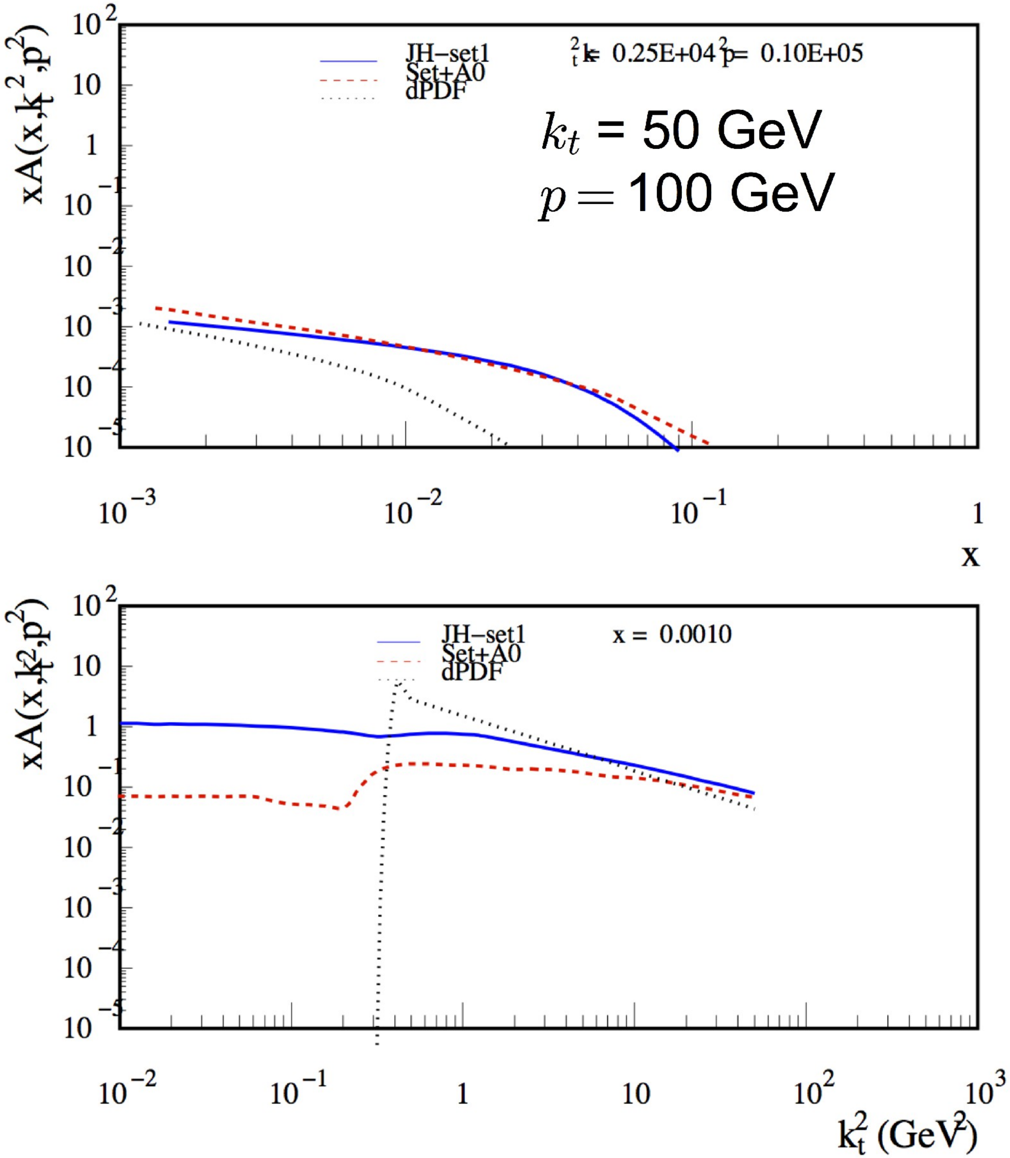


- off-shell ME & CCFM + k_t shower predict a similar shape as seen in latest CMS measurement.
  - how much room for DPS is left in frame of high-energy factorization ?

Conclusion

- terms which are neglected in collinear factorization can be important:
  - some are included in high energy factorization and small x improved TMD gluon densities
- using latest gluon TMD including uncertainties
  - reasonable description of W+n jet observables are obtained
  - description is similar to W+2 jet NLO
- k_t dependent CCFM shower is appropriate for multi-jet kinematics
  - shape and p_t x-sections of 4 hard jets (most coming from shower) are well reproduced
- off-shell ME + CCFM TMD with k_t dependent CCFM shower predicts shape of double-parton scattering variables close to latest measurements

CCFM gluon from F_2 fit



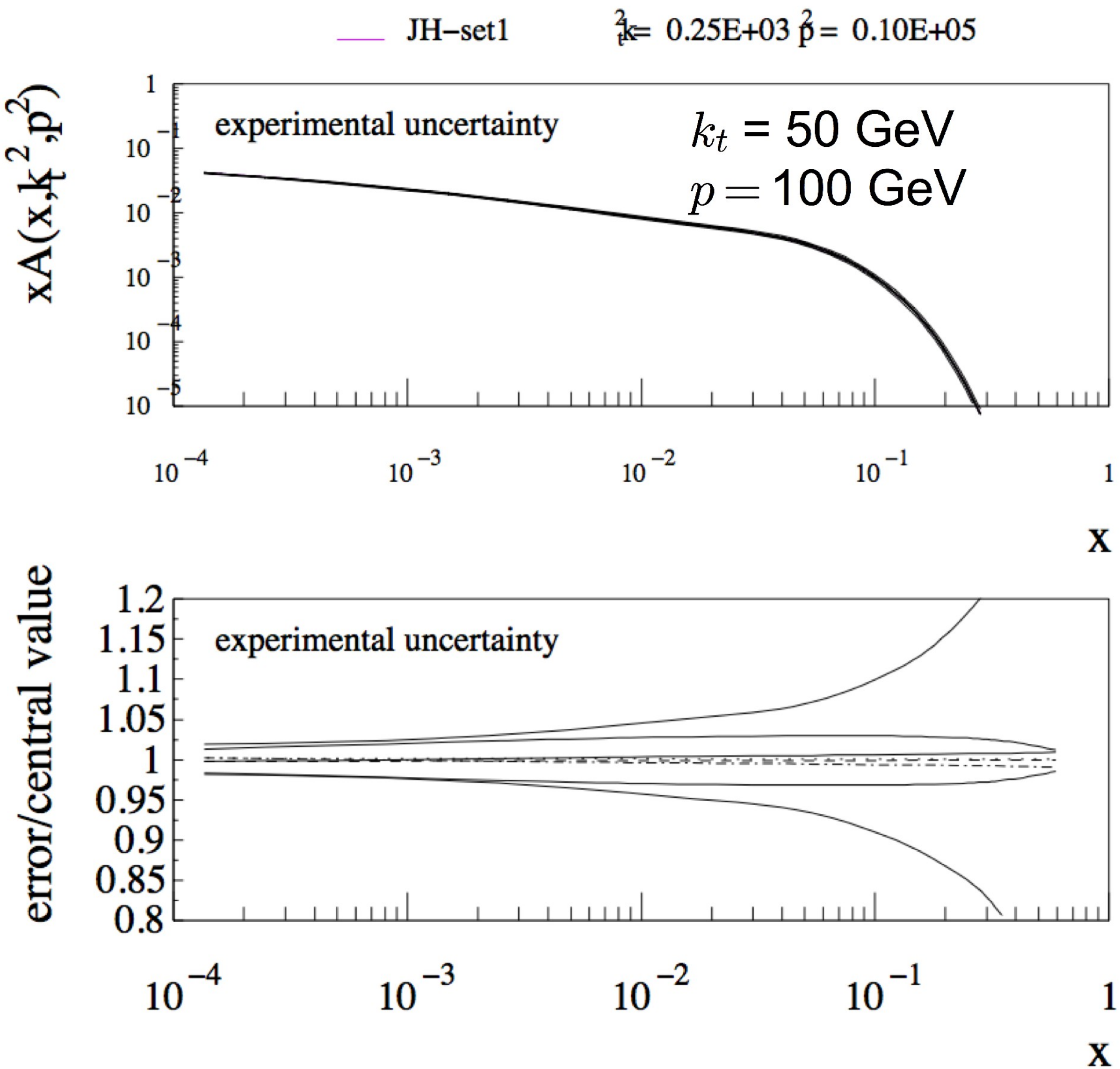
- Fit function:

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

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

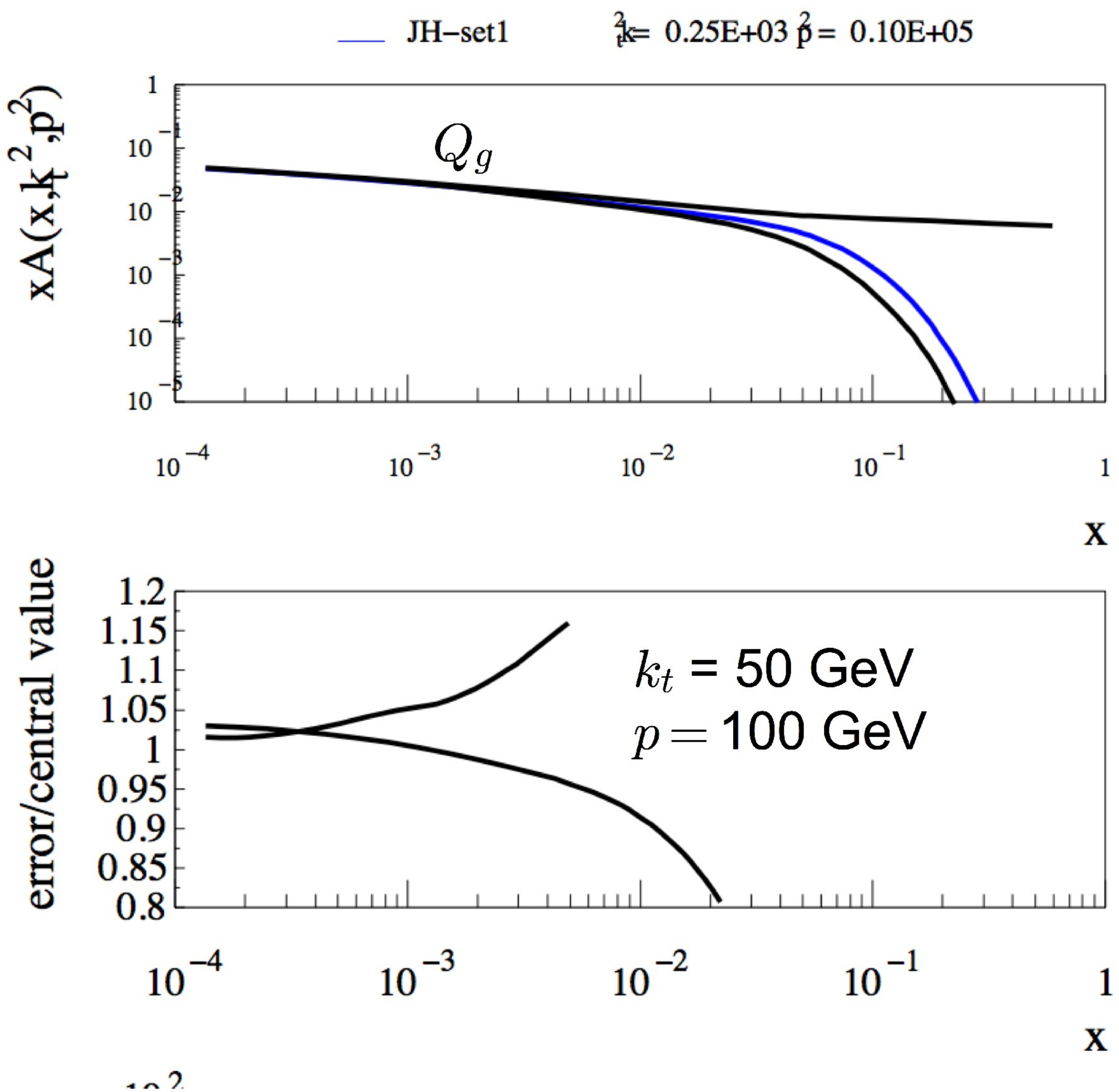
  new fit gives $\chi^2/ndf \sim 1.2$
  - depending on number of parameters
- details are different from previous uPDF set A_0 and from derivative of collinear gluon with CTEQ6

uncertainties of CCFM gluon



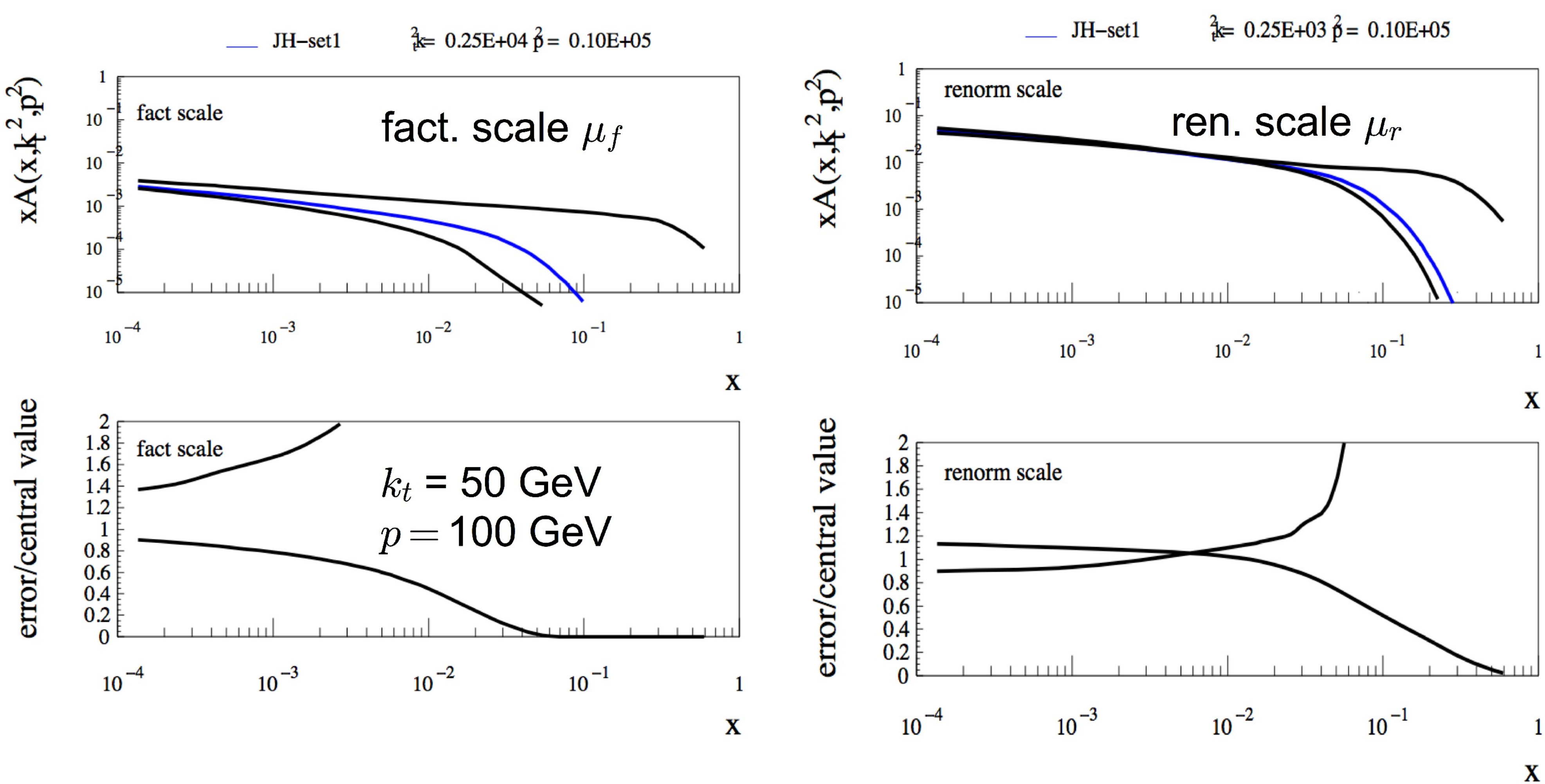
- experimental uncertainties result in 10-20 % for gluon uncertainty at medium and large x
- uncertainties at small x very small

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)