Photon 2013, Paris, May 2013

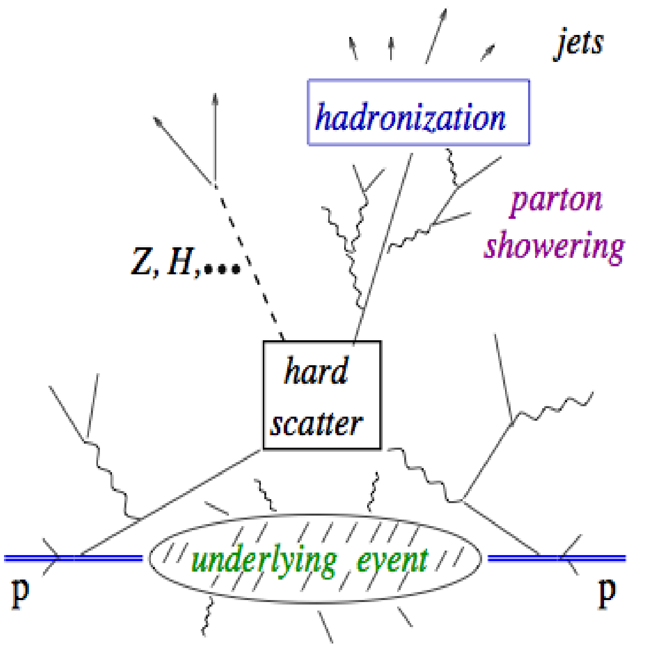
Vector Boson and Jet Production: Theoretical Aspects

F. Hautmann

- Thanks to S. Dooling, P. Gunnellini, M. Hentschinski and H. Jung for collaboration

Nucl. Phys. B865 (2012) 54; Eur. Phys. J. C72 (2012) 2254;
arXiv:1212.6164 [hep-ph]

MOTIVATION



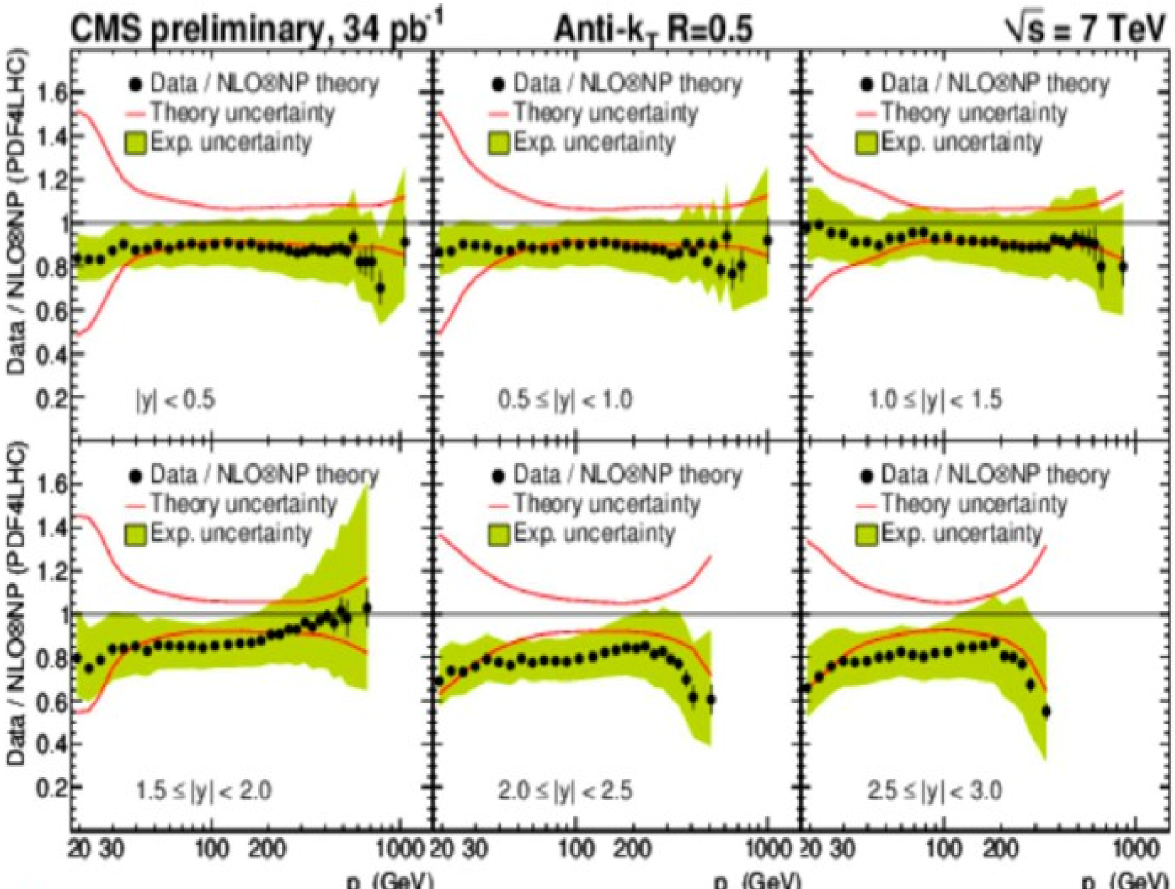
♠ Complex jet final states associated with massive SM / BSM states:

- new physics searches and backgrounds
- detailed understanding of QCD physics

⇒ QCD factorization; parton shower evolution; resummations; MC event generators

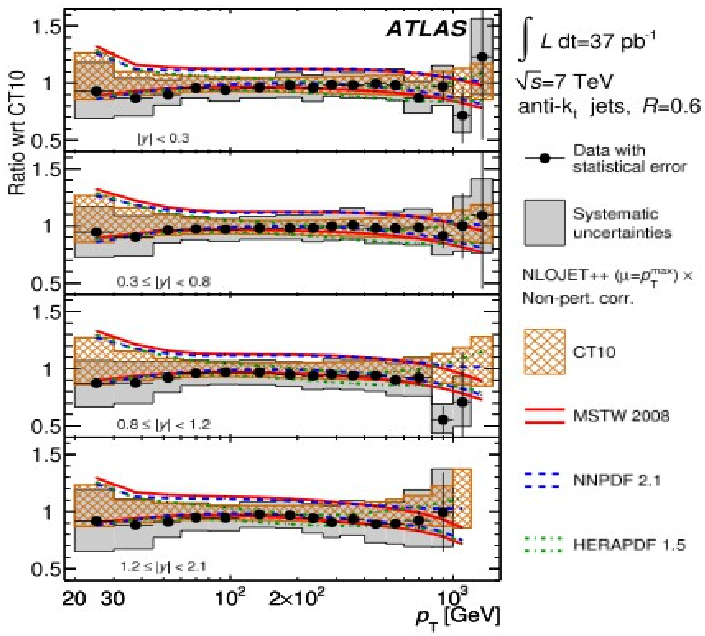
CONTENTS

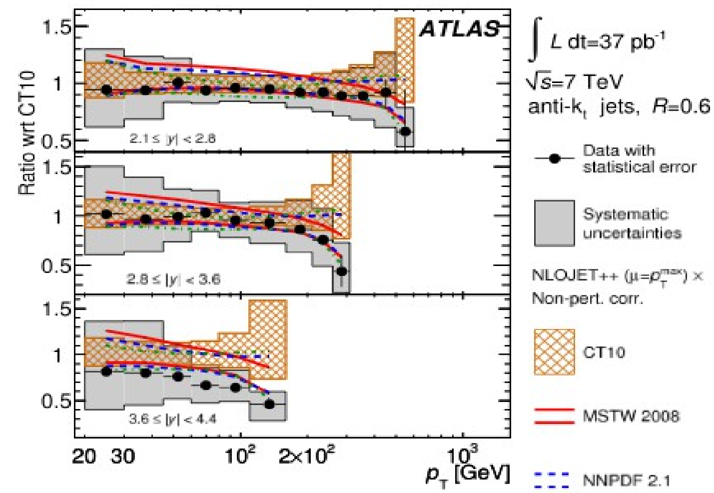
Inclusive Jet Production



- Jet measurement over a much larger kinematic range than previous collider experiments
- Comparison of NLO⊗NP with data shows good agreement at central rapidities, but
- Large differences at higher rapidity

Inclusive jet production

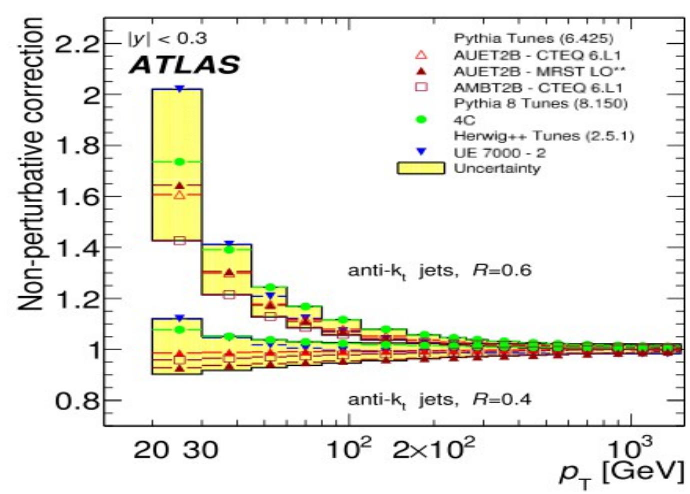




[ATLAS, PRD86 (2012) 014022]

NP correction

- hadronization $\oplus$ underlying events



NONPERTURBATIVE (NP) AND SHOWERING (PS) CORRECTIONS

- Estimates using leading order (LO-MC):

$$K_0^{NP} = N_{LO-MC}^{(ps+mpi+had)} / N_{LO-MC}^{(ps)}$$

[CMS, PRL 107 (2011) 132001; ATLAS, PRD86 (2012) 014022]

— natural definition with LO-MC

— but affected by potential inconsistency if combined with NLO parton-level results

- Alternatively, assign NP correction factors by using NLO-MC:

[Dooling, Gunnellini, Jung & H, arXiv:1212.6164 [hep-ph]]

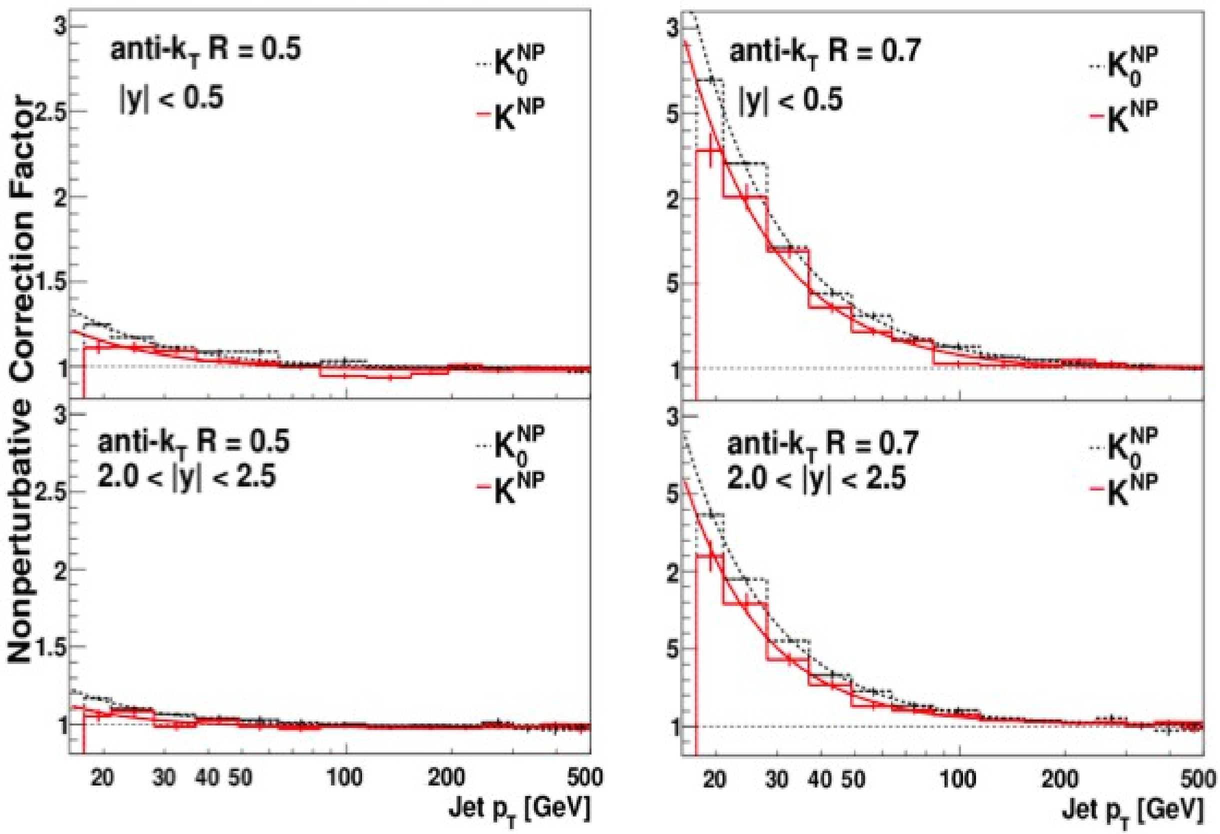
$$K^{NP} = N_{NLO-MC}^{(ps+mpi+had)} / N_{NLO-MC}^{(ps)}$$

$$K^{PS} = N_{NLO-MC}^{(ps)} / N_{NLO-MC}^{(0)}$$

♣ K^{NP} differs from K_0^{NP}

♣ K^{PS} is new

Nonperturbative Correction



$$K_0^{NP} = K_{LO-MC}^{(ps+mpi+had)} / K_{LO-MC}^{(ps)}$$

$$K^{NP} = K_{NLO-MC}^{(ps+mpi+had)} / K_{NLO-MC}^{(ps)}$$

Dooling et al.
arXiv:1212.6264

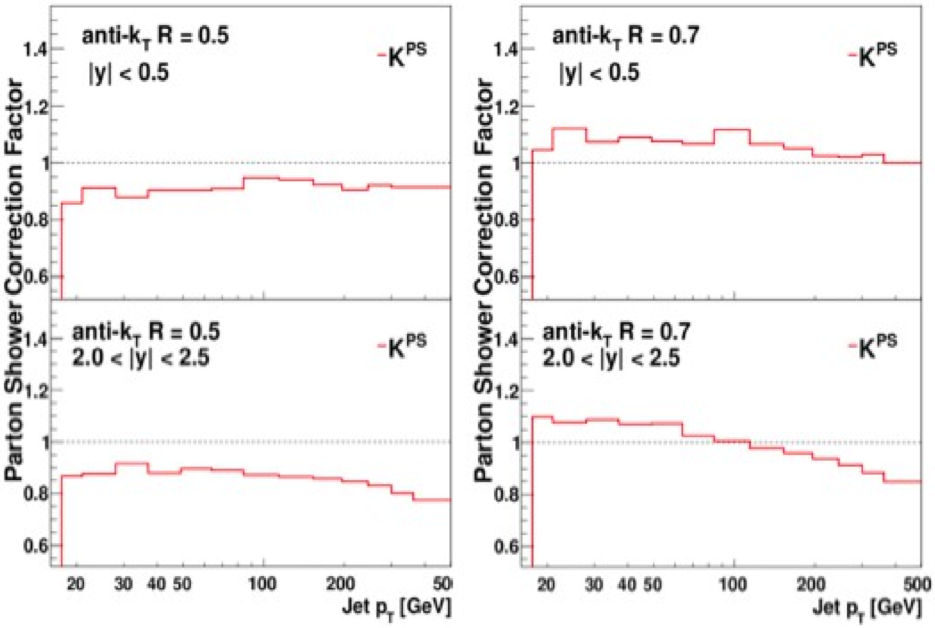
Non-negligible effect from nonperturbative effects at small p_T

Difference between LO and NLO correction

- Matching of MPI to the NLO calculation because the MPI p_T scale is different in LO and NLO

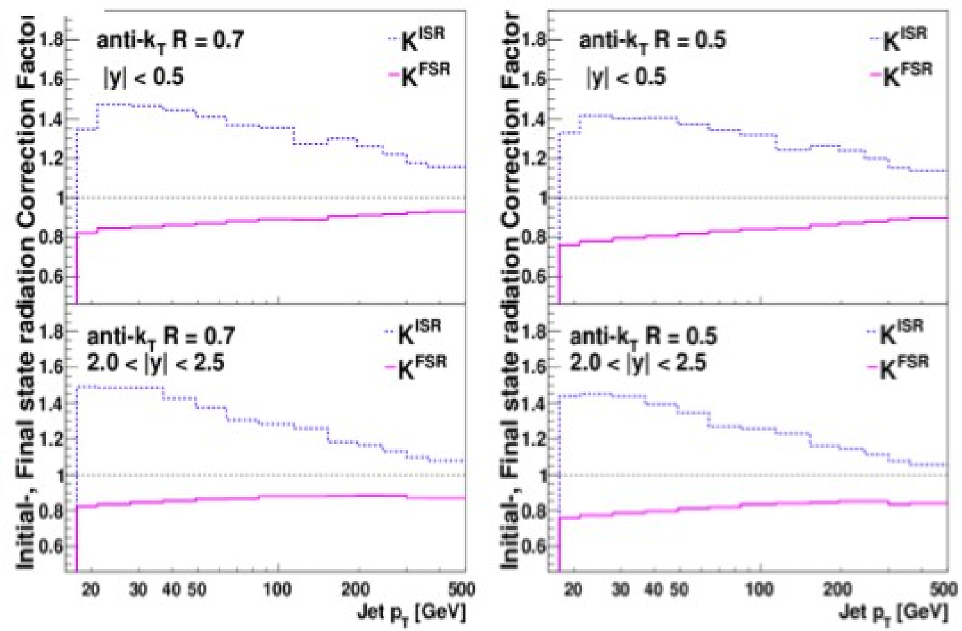
Parton Shower Correction

Dooling et al.
arXiv:1212.6264



$$K^{PS} = K^{(ps)}_{NLO-MC} / K^{(0)}_{NLO-MC}$$

- Depends on rapidity and p_T especially in the forward region
- Finite effect also at large p_T



- Initial and Final State Parton Shower considered independently
- But they are interconnected:

The combined effects cannot be obtained by adding the individual contributions

- ISR largest at low p_T, FSR significant for all p_T

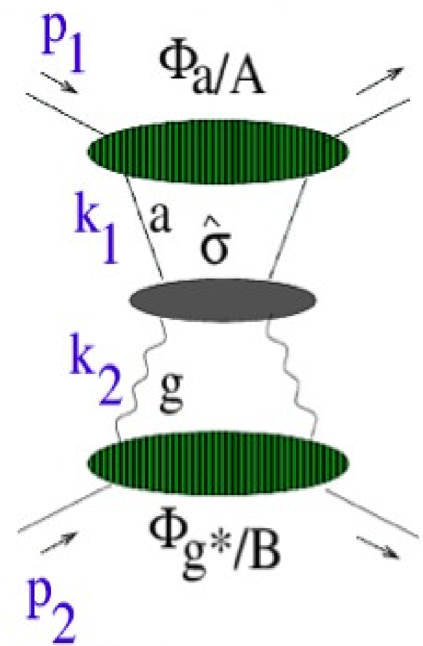
Longitudinal Momentum Shift

Dooling et al.
arXiv:1212.6264

In SMC:

hard subprocess is generated with full 4-momentum for the external lines

Factorized jet cross section at high rapidity



Momentum of the partons initiating the hard scatter: $k_j^{(0)} = x_j p_j$ on-shell and fully collinear with the incoming momenta

Applying shower algorithm

Complete final states: $k_j \neq x_j p_j$ no longer collinear

Energy momentum conservation ▷ Reshuffling in x_j (long. mom fraction)

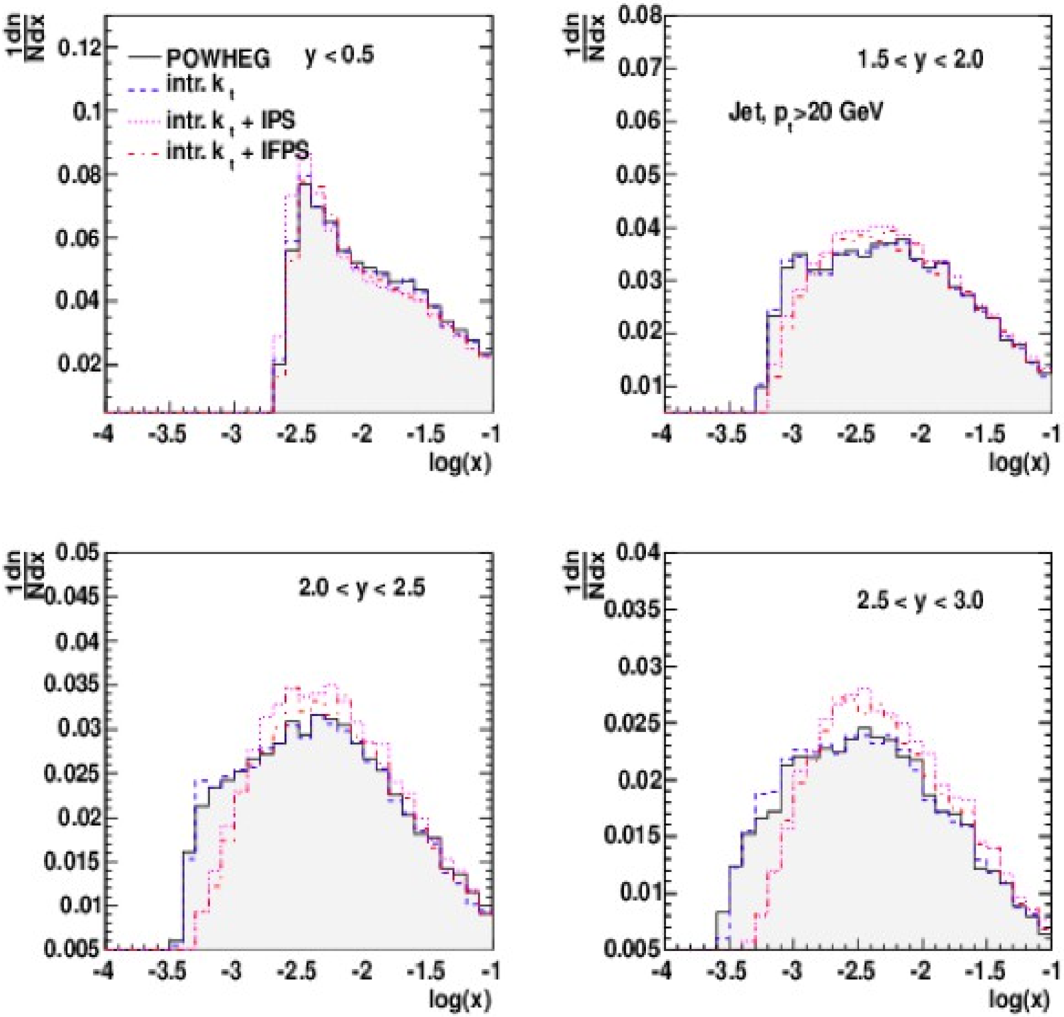
Collinear approximation ⊗ energy momentum conservation

=

kinematic shift in longitudinal momentum distribution due to showering

Longitudinal Momentum Shift – Inclusive Jets

Jet measurement in the rapidity range $y < 2.5$



Compute x_j from POWHEG before parton showering and after parton showering (using PYTHIA6)

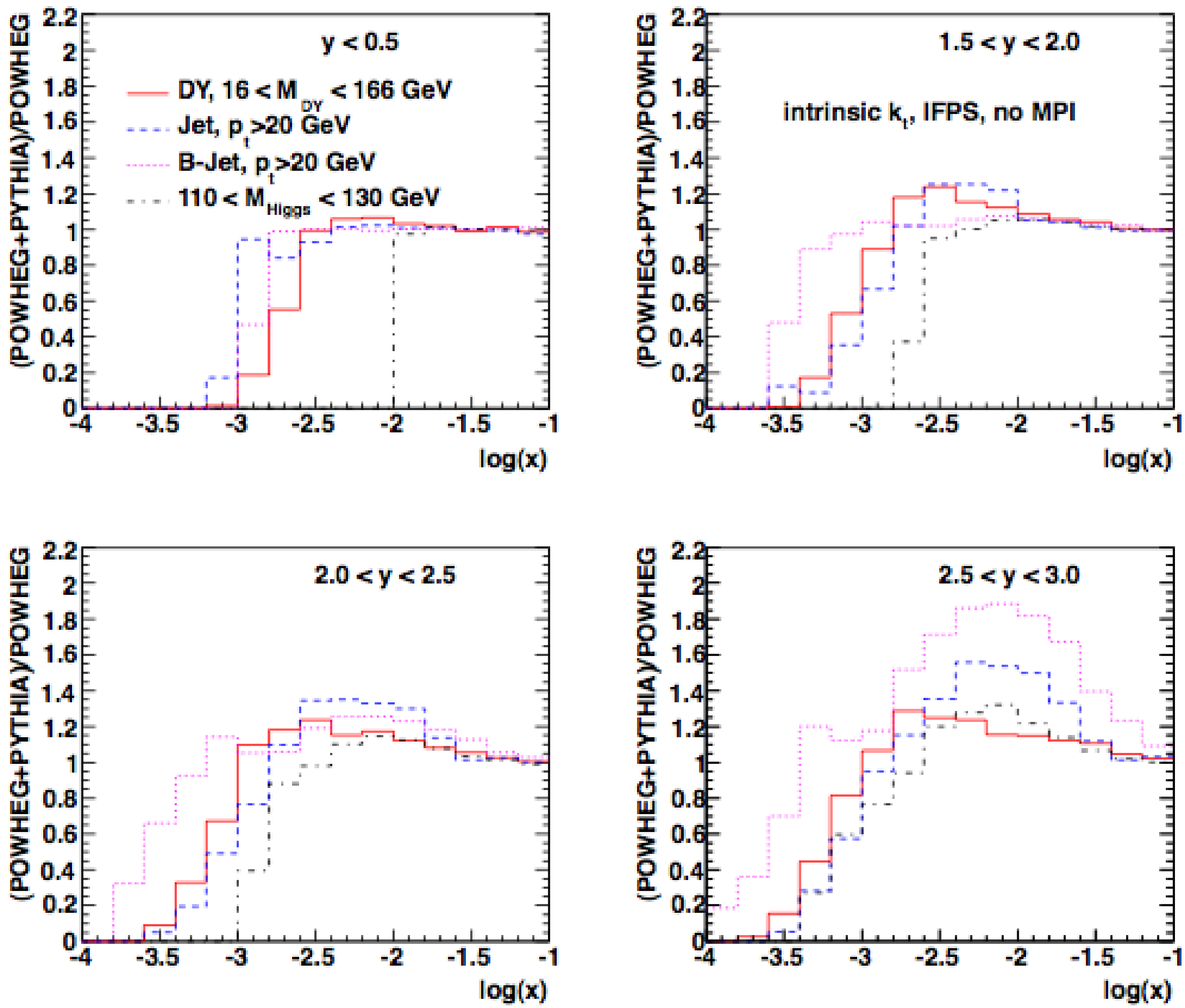
Kinematic reshuffling in x is negligible for central rapidities but becomes significant for $y > 1.5$

- Kinematic shift can affect predictions through the PDFs

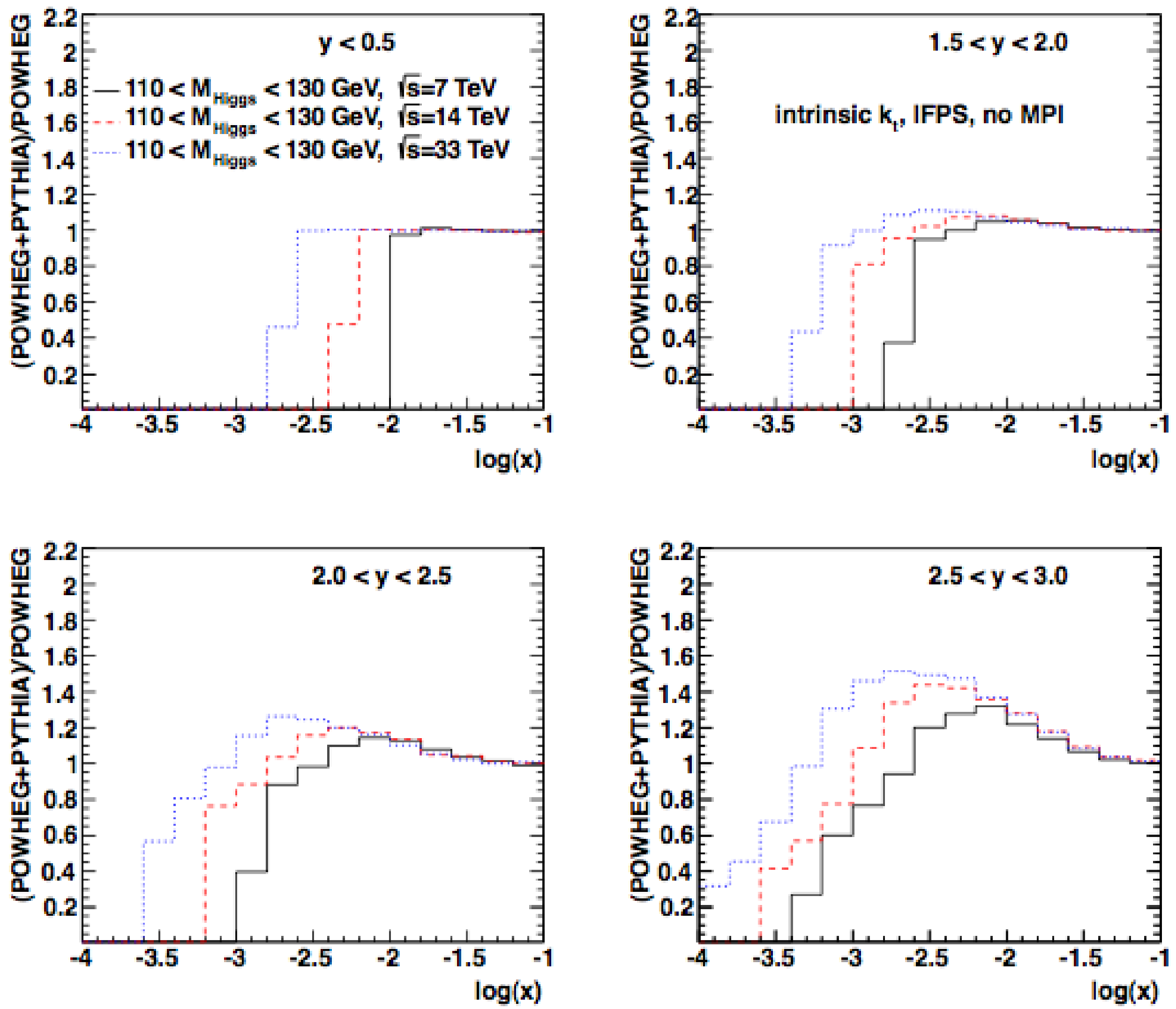
Dooling et al.
arXiv:1212.6264

TMD effects in pp collisions

- Transverse momentum dependent (TMD) effects are relevant for many processes at the LHC
- parton shower matched with NLO generates additional k_t, leading to energy-momentum mismatch
- avoided by using formulation with TMD distributions from the outset



Longitudinal momentum shift: Higgs



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

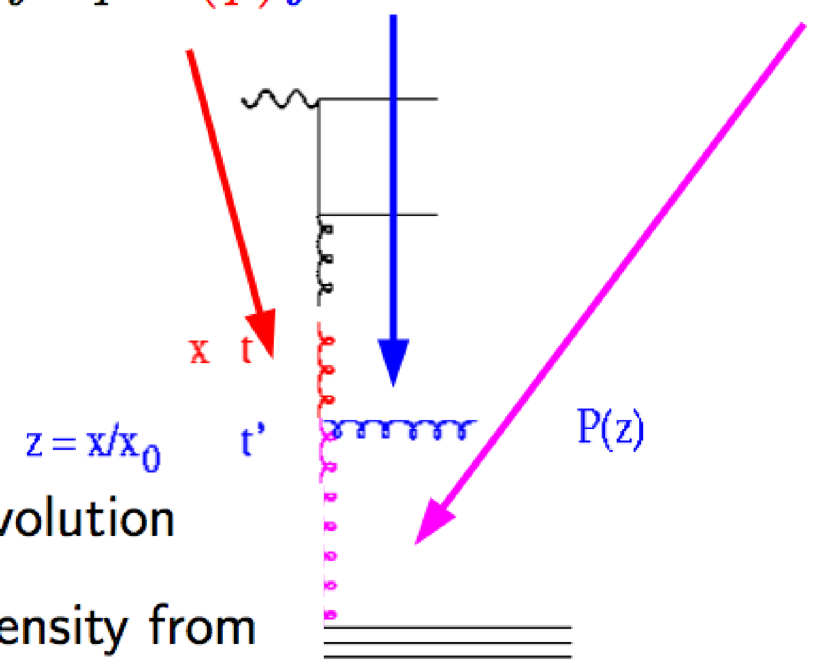
branching at q'

from q_0 to q' w/o branching

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

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

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

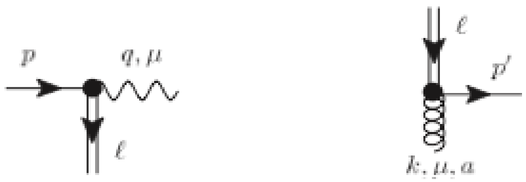


- k_t-dependent shower by CCFM evolution

- new determination of TMD gluon density from DIS precision data [Jung & H, arXiv:1206.1796, and in preparation]

Vector bosons + jets at high energy

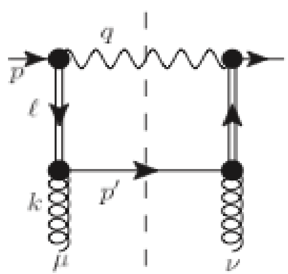
- High-energy effective theory → effective vertices



[Bogdan & Fadin, NPB740 (2006) 36]

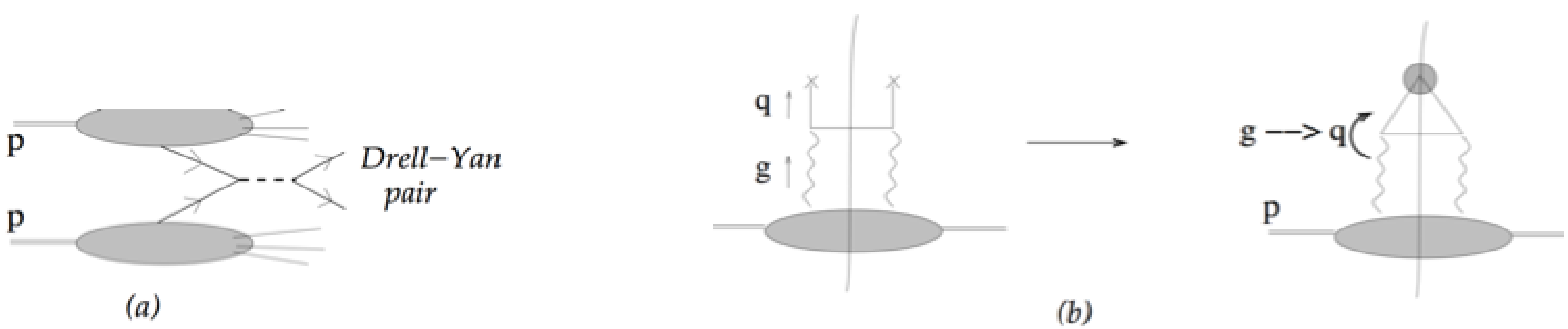
[Lipatov & Vyazovsky, NPB597 (2001) 399]

- Parton matrix elements (gauge-invariant, despite off-shell parton)



[Ball & Marzani, NPB814 (2009) 246]

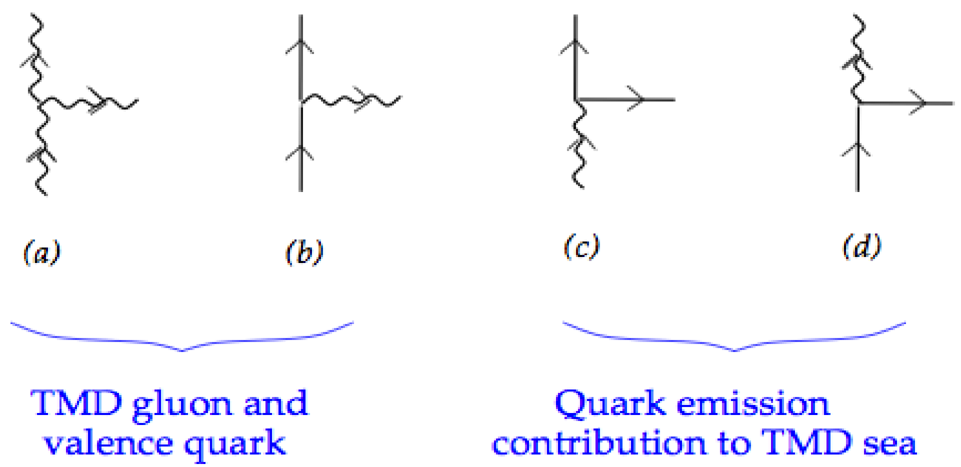
[Hentschinski, Jung & H, NPB865 (2012) 54]



a) $\bar{q}q$ Drell-Yan production; (b) $g \to q$ splitting contribution to sea quark distribution

Beyond quenched approximation: unintegrated quark evolution

[Hentschinski, Jung & H, arXiv:1205.1759; arXiv:1205.6358]



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

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

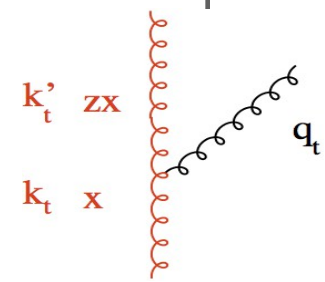
all b_n known; $\mathcal{P}_{g\to q}$ computed in closed form (positive-definite)

in *[Catani & H, 1994; Ciafaloni et al., 2005-2006]* by small-x factorization

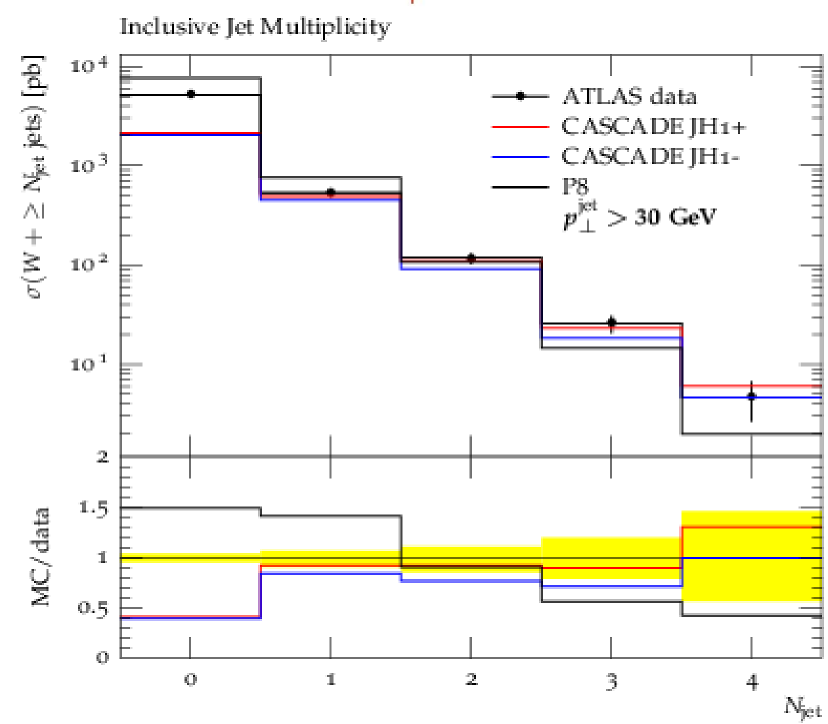
- valence: independent evolution (dominated by soft gluons x $\to$ 1)

Application to W + jets at the LHC

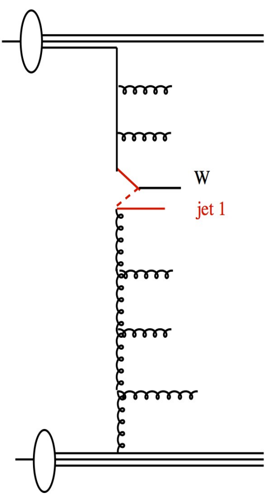
- use valence quarks and CCFM gluon (from DIS precision data), convoluted with off-shell high-energy matrix elements
- initial parton shower by CCFM evolution in angular ordered phase space:
  - $q_i > z_{i-1} q_{i-1}$ with $q_i = \dfrac{p_{ti}}{1-z}$
  - → no p_t constraint at small x
  - → jets can have large p_t

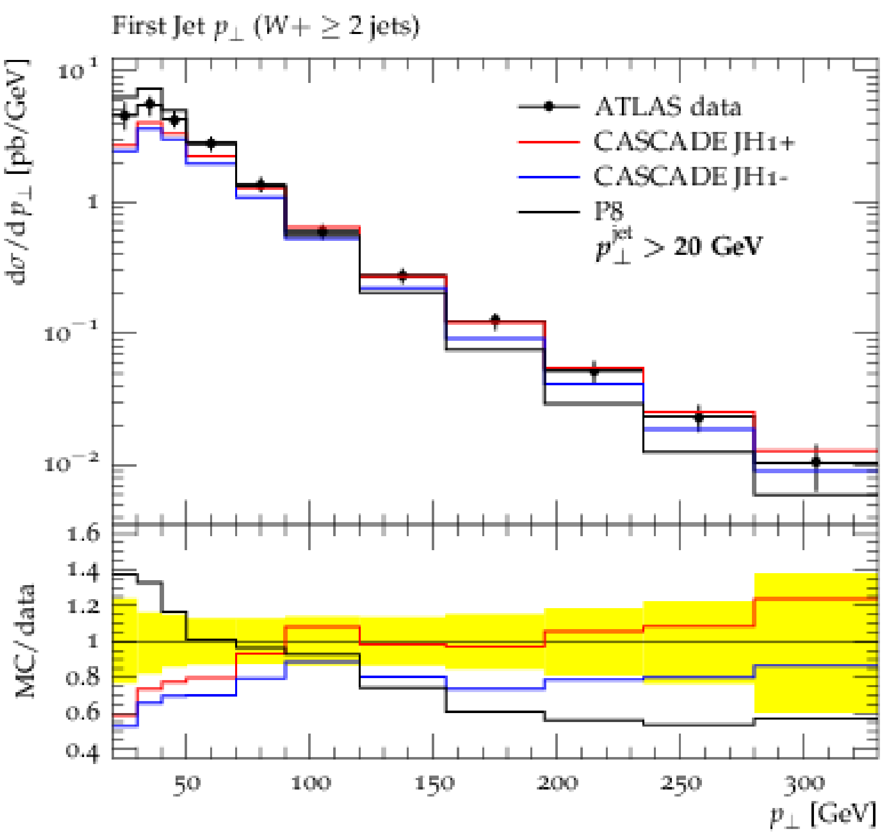


- Compare with W + jets measurements
- Jet multiplicities are reproduced:
  - 1 jet $\longrightarrow$ from ME
  - 2-4 jets from shower
- Note: PYTHIA with p_t -ordered shower cannot predict higher jet multiplicities

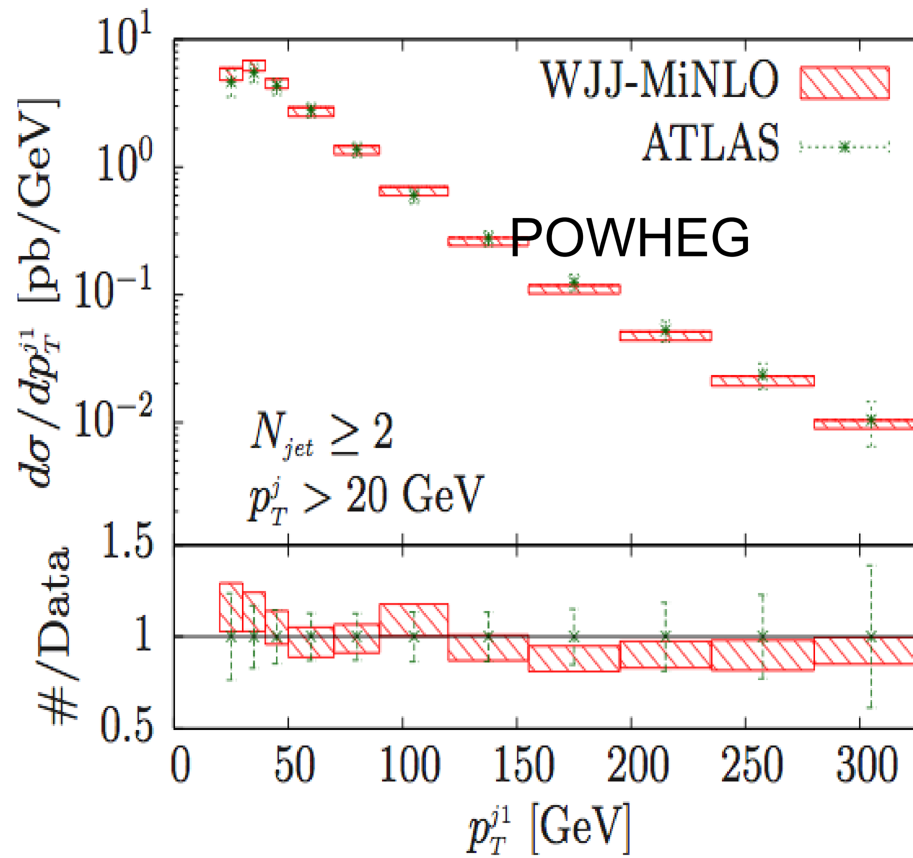


W + 2 jets: k_t-shower vs. NLO-matched





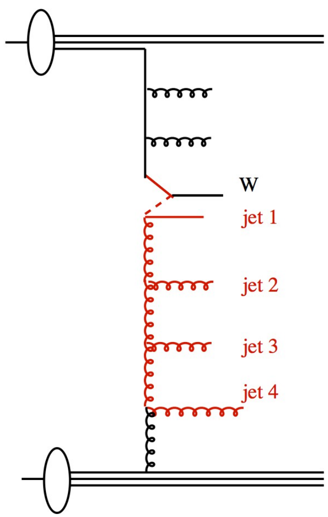
Campbell, Ellis, Nason, Zanderighi, arXiv 1303.5447

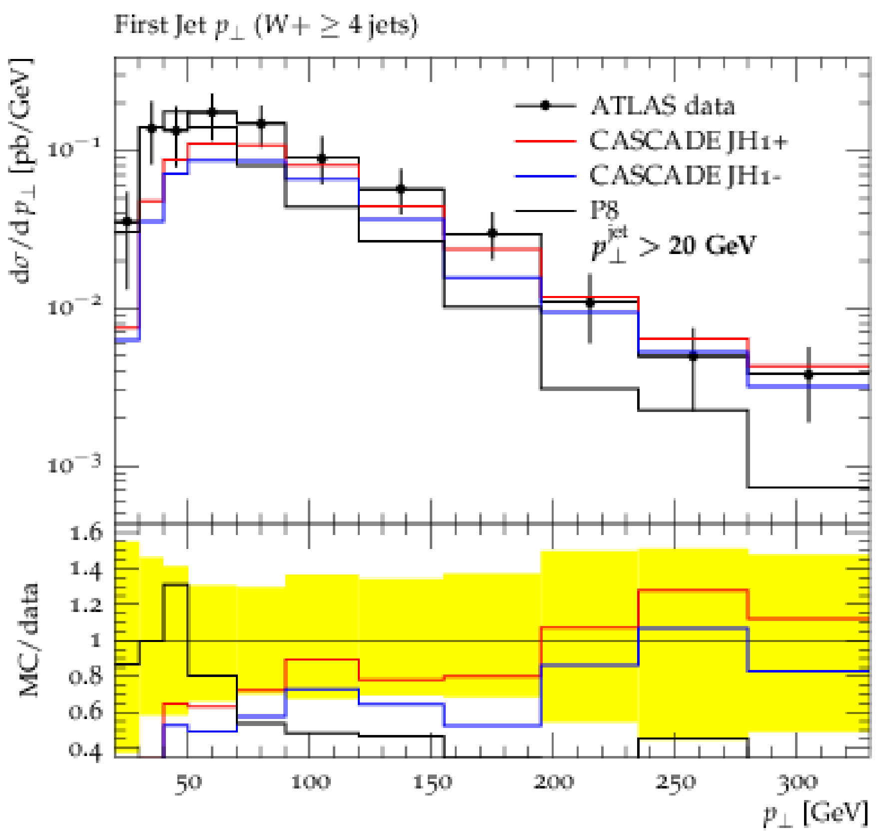


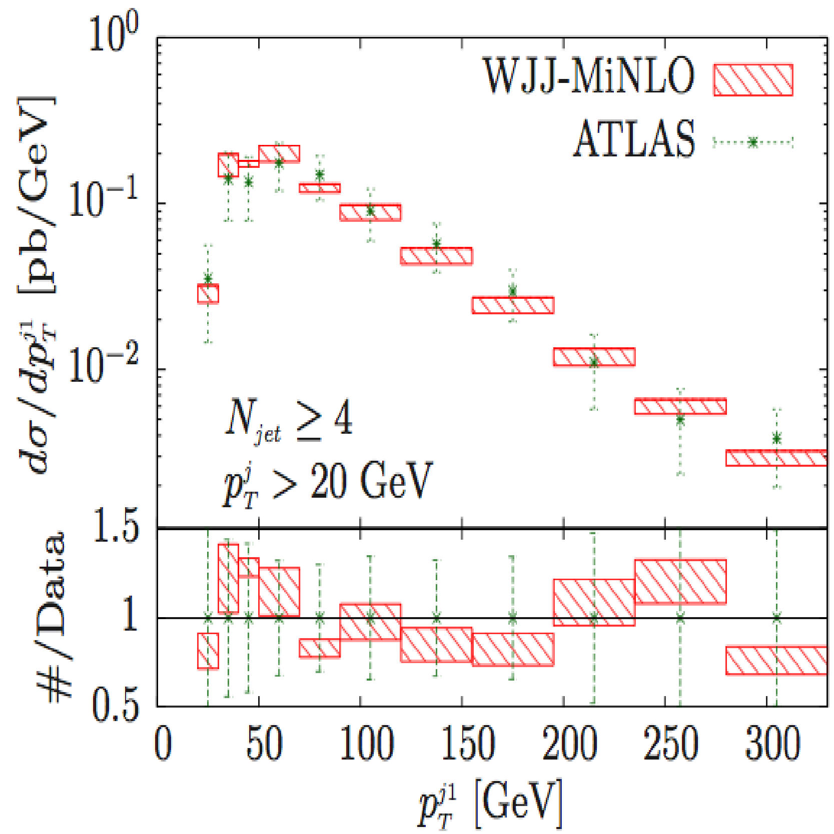
- 1st jet in W + (> 2) jet events:
  - off shell ME + CCFM k_t - shower (CASCADE) comparable with NLO W + 2 jet (POWHEG)
  - uncertainties studied in CASCADE: pdf and scale uncertainties
  - PYTHIA P8 shower starts to fail at large pt

W + n jets: k_t-shower vs. NLO-matched

Campbell, Ellis, Nason, Zanderighi, arXiv 1303.5447

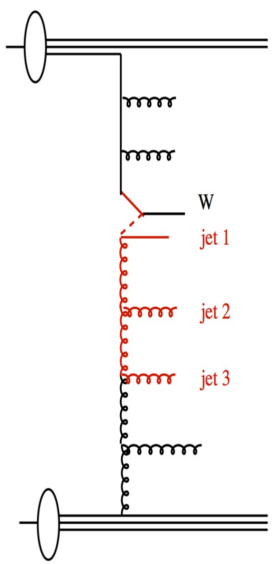


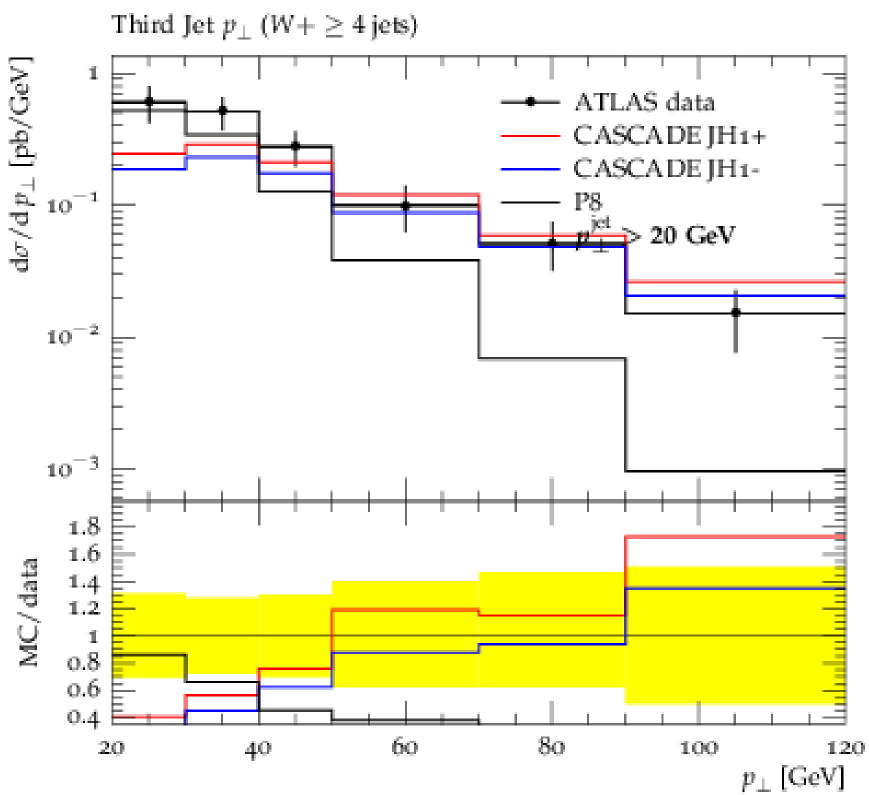




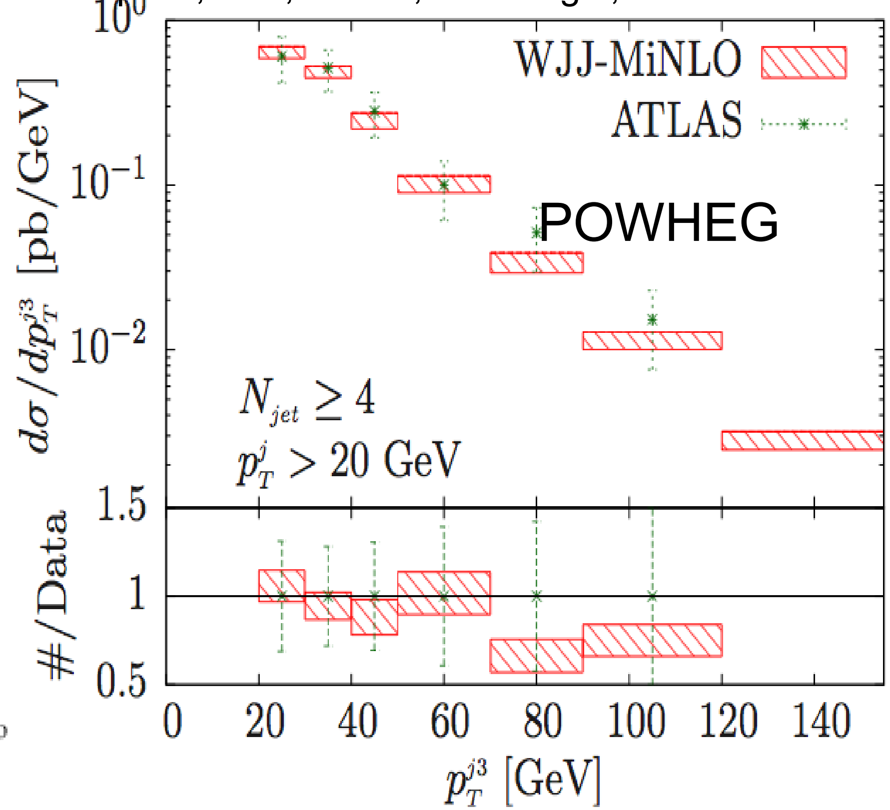
- off-shell ME + CCFM k_t - shower (CASCADE) comparable with NLO W+4jet
- first jet comes from hard process, other jets partially from shower
  - CCFM k_t - shower works fine even for high pt
  - P8 shower cannot describe shape

W + n jets: pt spectrum of third jet



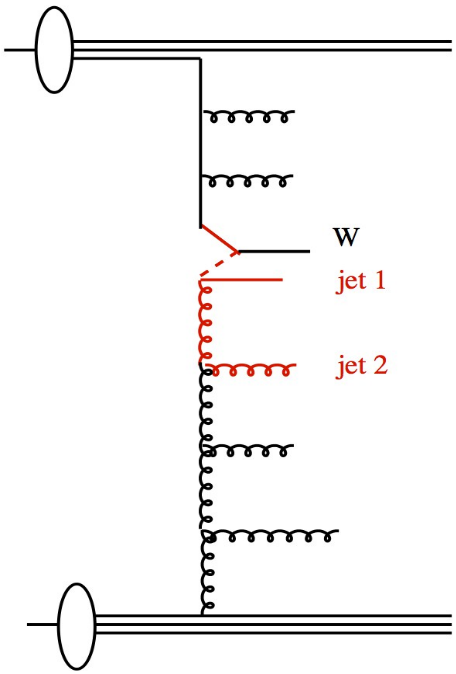


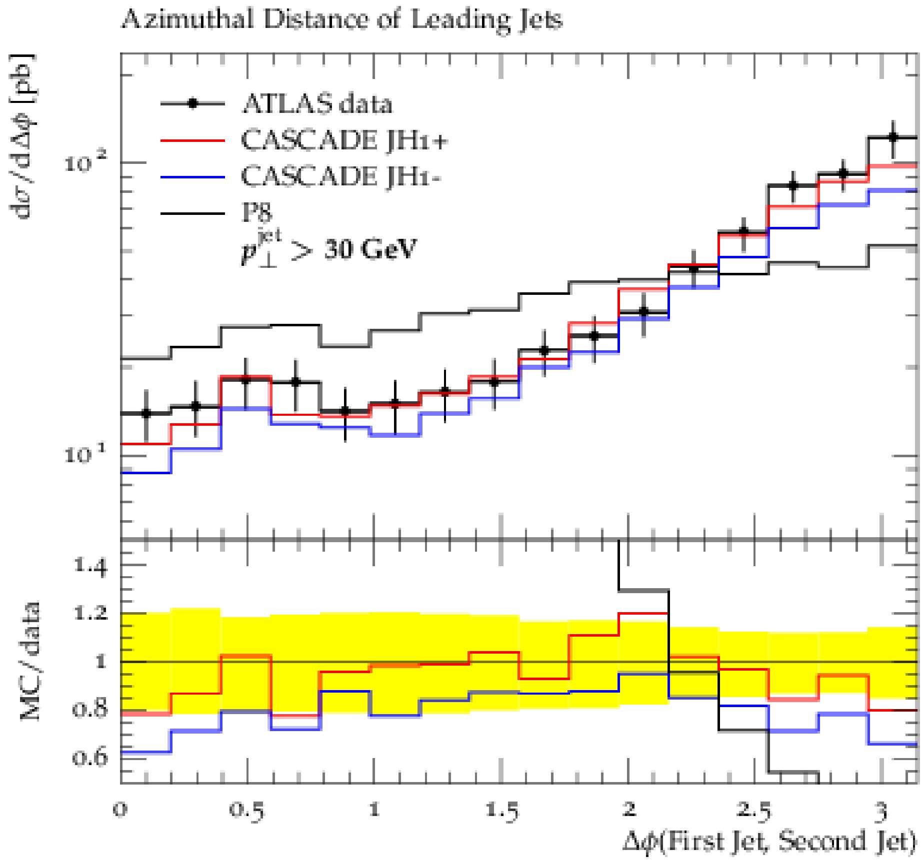
Campbell, Ellis, Nason, Zanderighi, arXiv 1303.5447



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

Application to angular correlations in W + n jets production





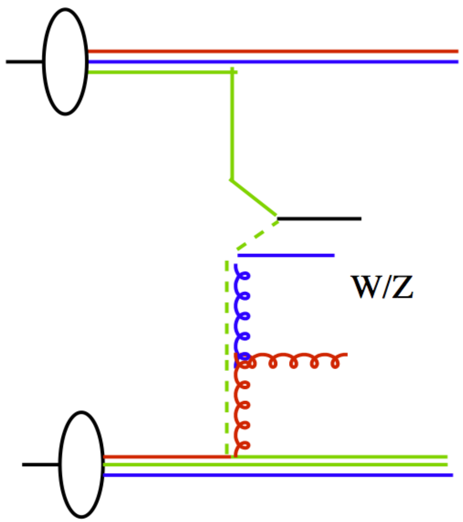
- off-shell ME + CCFM k_t - shower for x-section and shape for $\Delta\,\phi$ between first 2 jets agrees with measurements within uncertainties:
  - sensitive probe of shower:
    - back to back region and decorrelation region well reproduced !
    - not described by collinear pt ordered shower PYTHIA

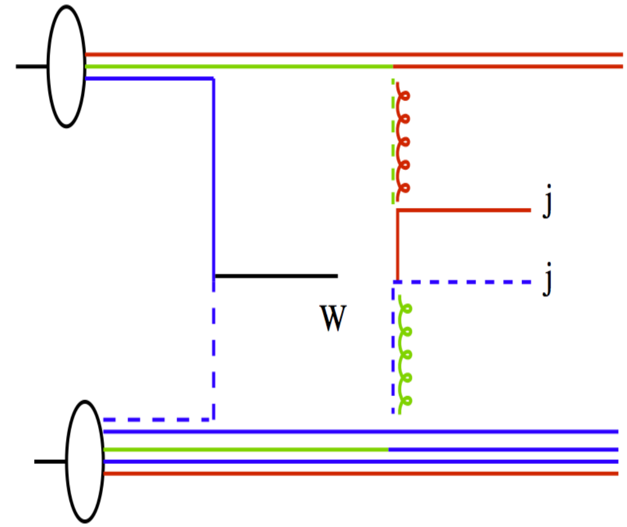
What is the gain ?

- 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 $\longrightarrow$ 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 $\longrightarrow$n off-shell parton calculation (automated method, *see A. van Hameren, P. Kotko and K. Kutak, JHEP1301(2013)078.*)
  - opens possibility for full LHC phenomenology of QCD, EWK and BSM processes

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

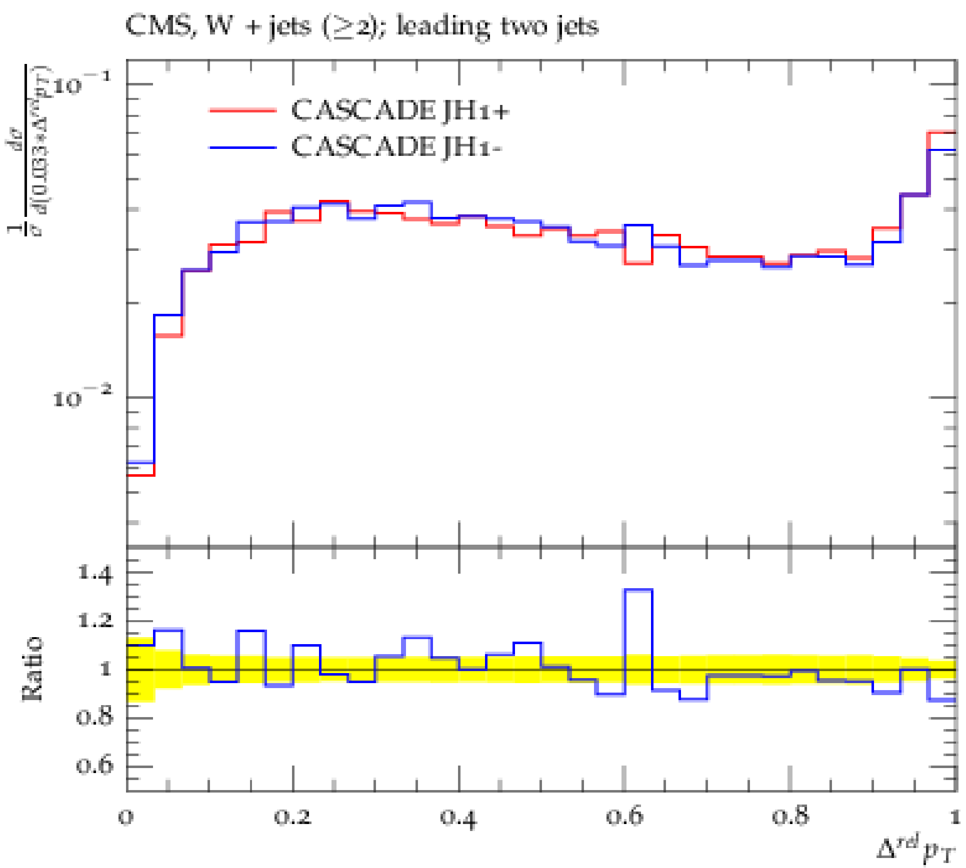


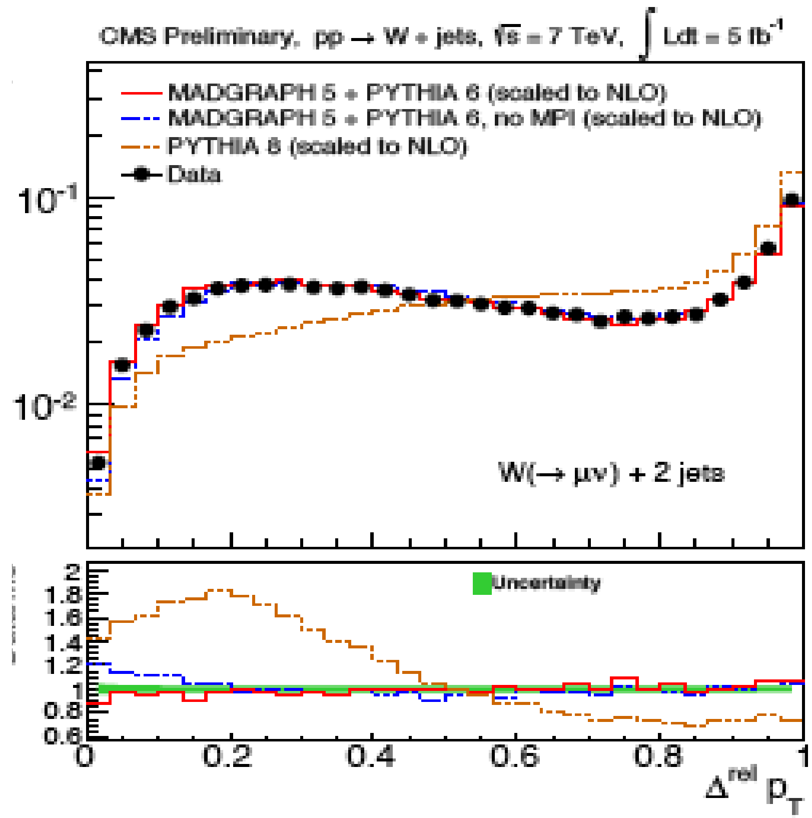


- DPS signal: de-correlated jets compared to W
    - what is the contribution from single chains ?
    - are jets coming from power-like terms in shower evolution or are they coming from independent scatterings ?

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

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

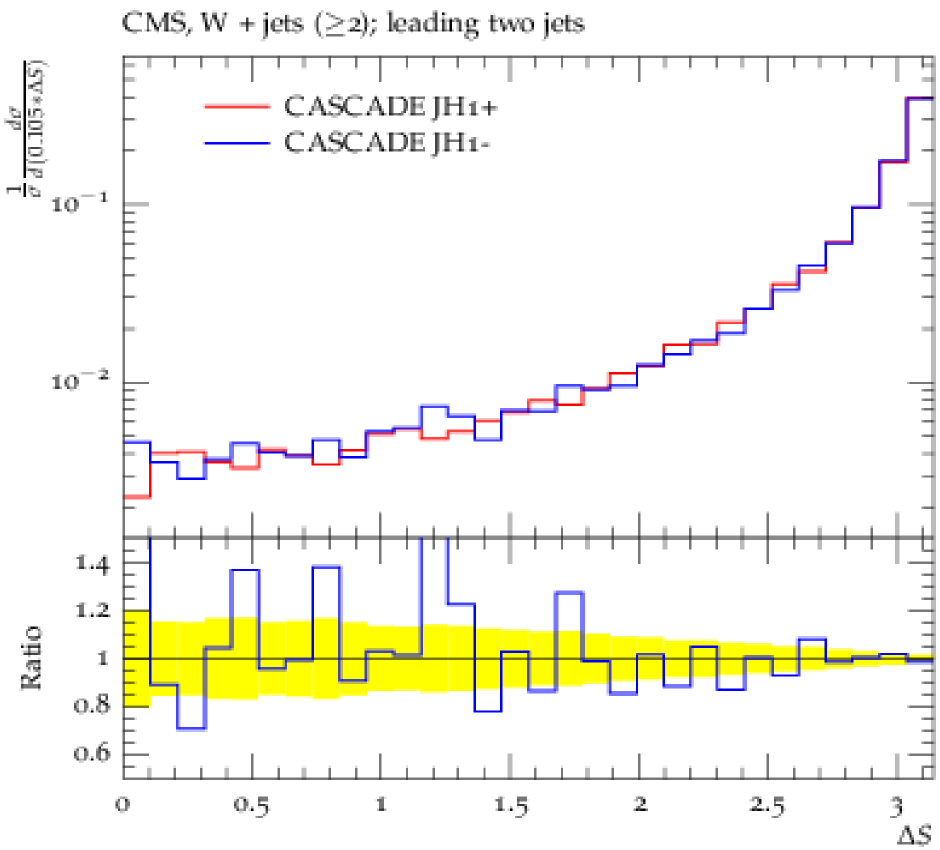


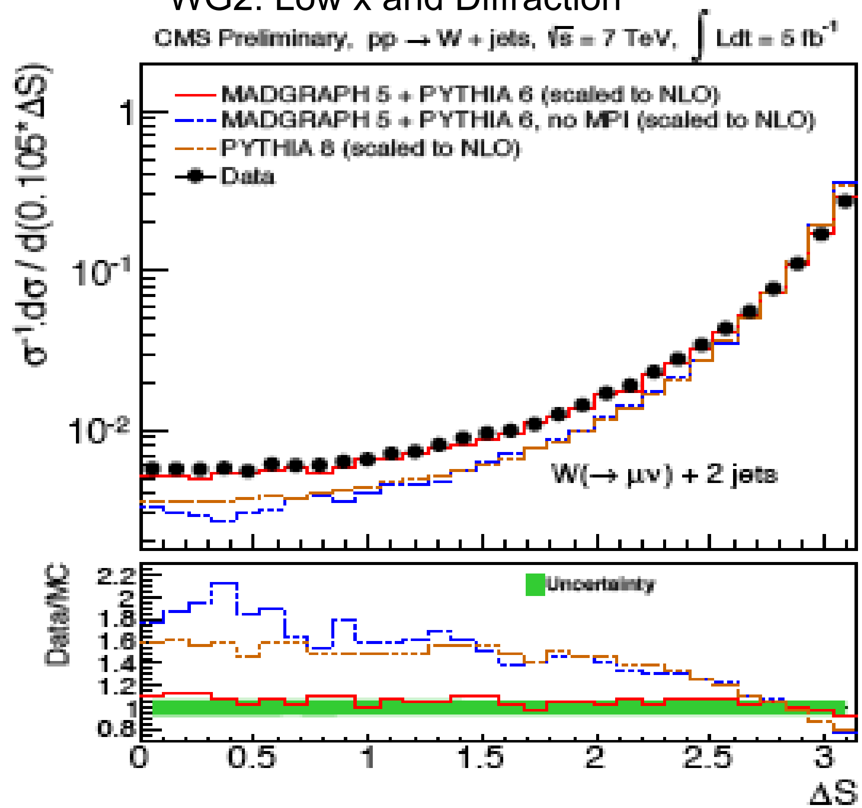


- off-shell ME & CCFM + k_t shower predict a similar shape as seen in latest CMS measurement

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

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.
  - how much room for DPS is left in the framework of high-energy factorization?

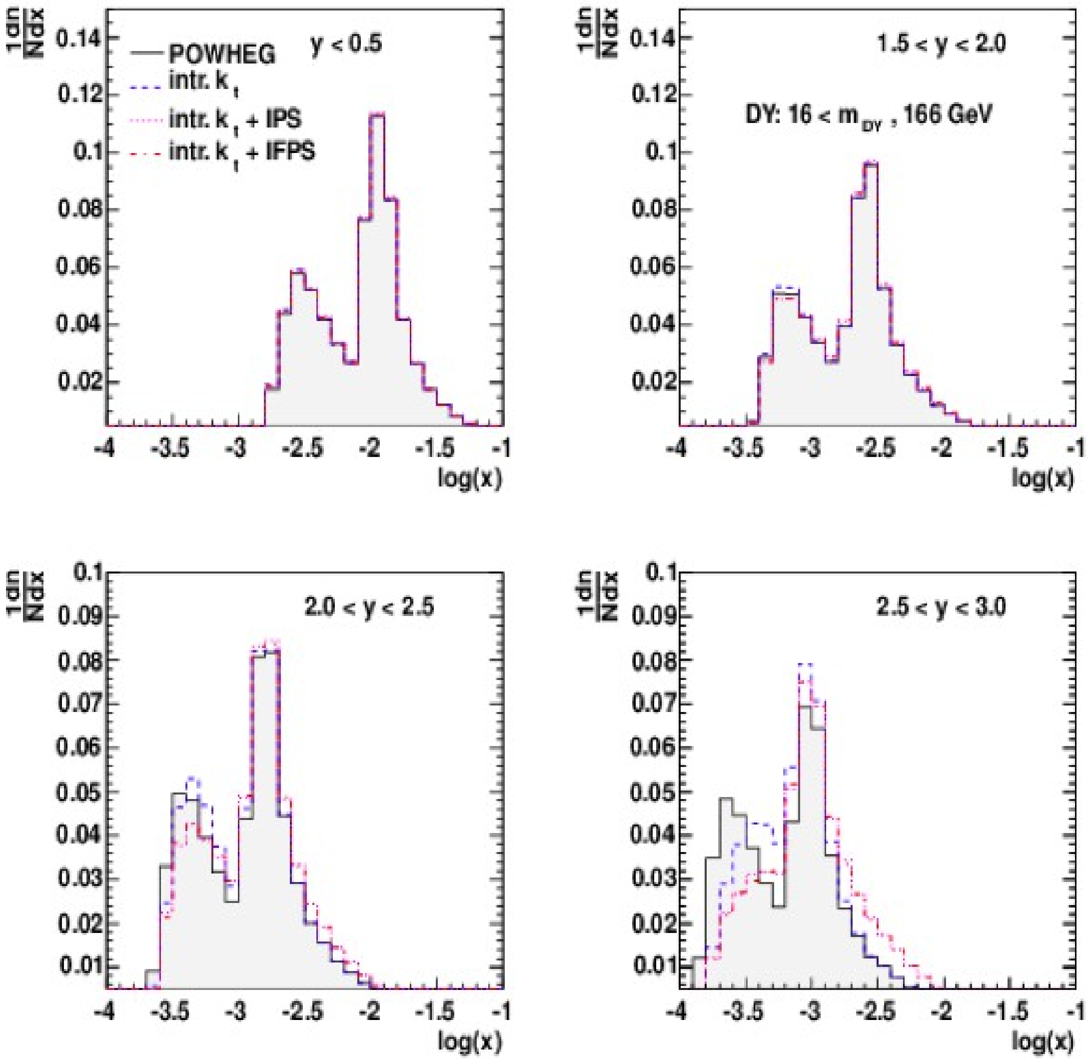
Conclusion

- collinear approximation + energy conservation ---> longitudinal momentum shifts in shower algorithms
  - keep track of non-collinear momentum components from the outset
  - using high energy factorization and latest TMD gluon densities: reasonable description of W+n jet observables is obtained; description is similar to W+2 jet NLO-matched
  - approach to low-pt jets? (mini-jet / leading track measurements [CMS PAS FSQ-12-026])
- 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 – including angular correlations
  - off-shell ME + k_t dependent CCFM shower predicts shape of double-parton scattering variables close to latest measurements

Extra slides

Longitudinal Momentum Shift – Drell-Yan

x distribution before and after showering of DY production in 16 < m < 166 GeV



Double peak structure comes from the continuum DY production in addition to the Z_0

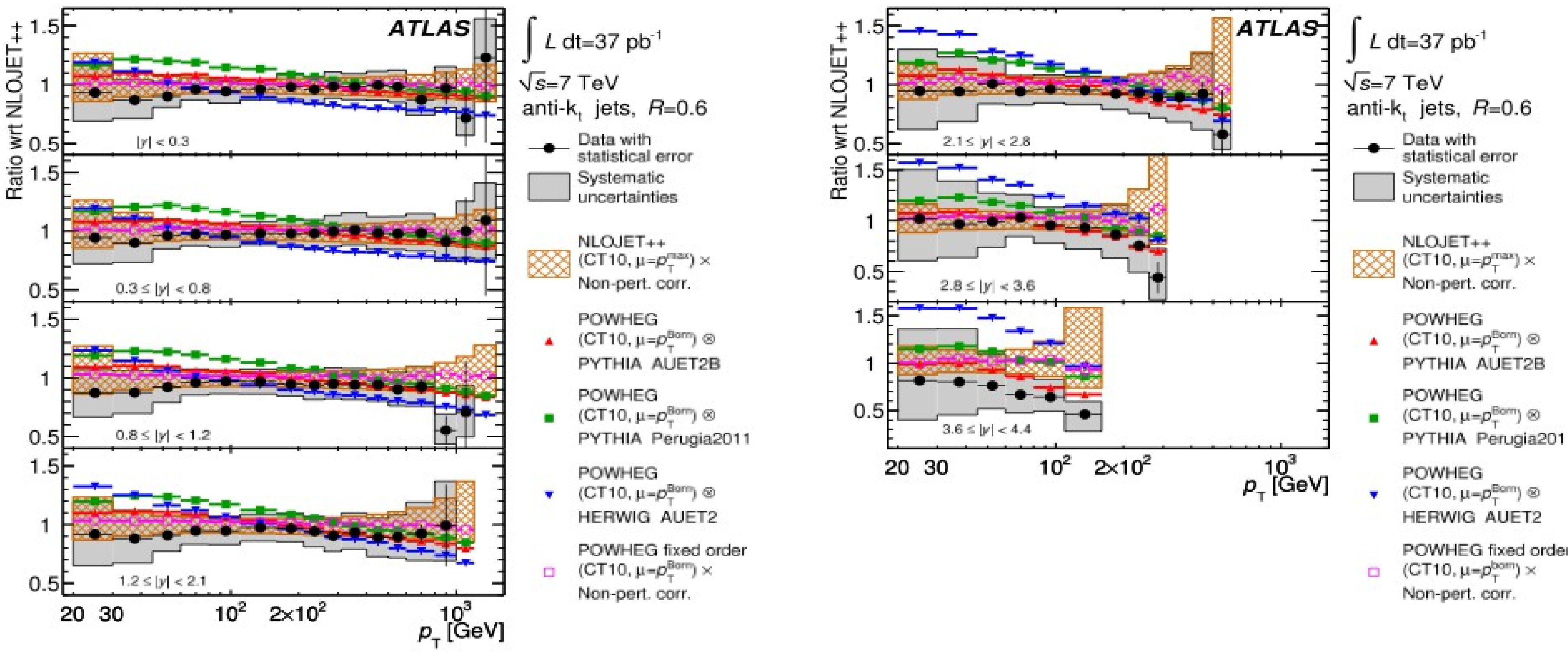
▷ Kinematic reshuffling in x for forward Drell-Yan production is not negligible

▷ Kinematic effect influences quark induced processes

Dooling et al.
arXiv:1212.6264

Inclusive jet data vs. NLO-matched

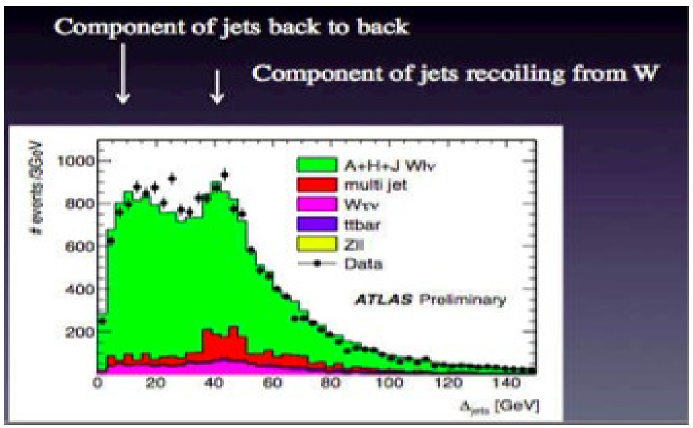
Inclusive jets *[ATLAS, Phys. Rev. D86 (2012) 014022 [arXiv:1112.6297]]*

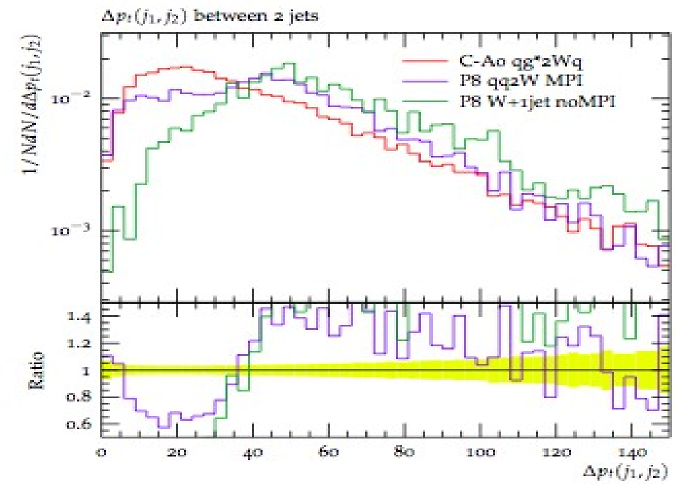


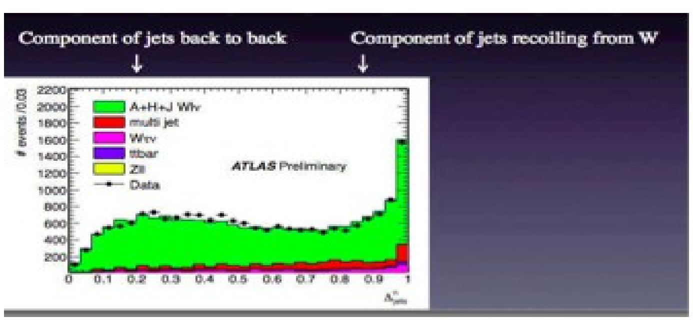
- higher order radiation from parton shower in POWHEG significant
- large differences between POWHEG/ PYTHIA and POWHEG/ HERWIG at forward rapidities

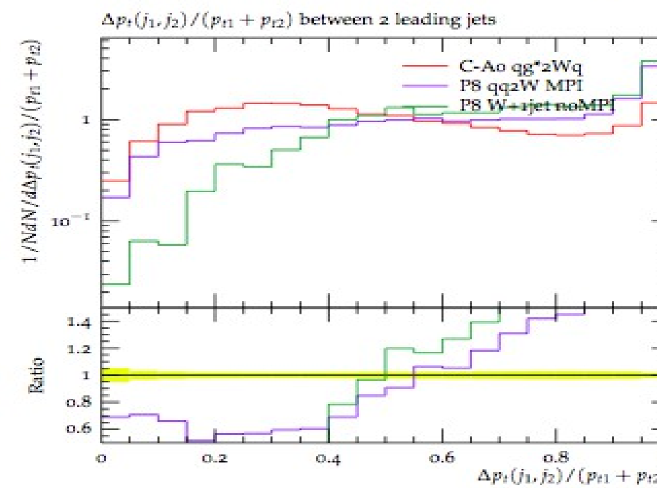
W + 2 jets as a DPS signal

W + 2 jets









[E. Dobson, talk at MPI-TAU Workshop, October 2012]

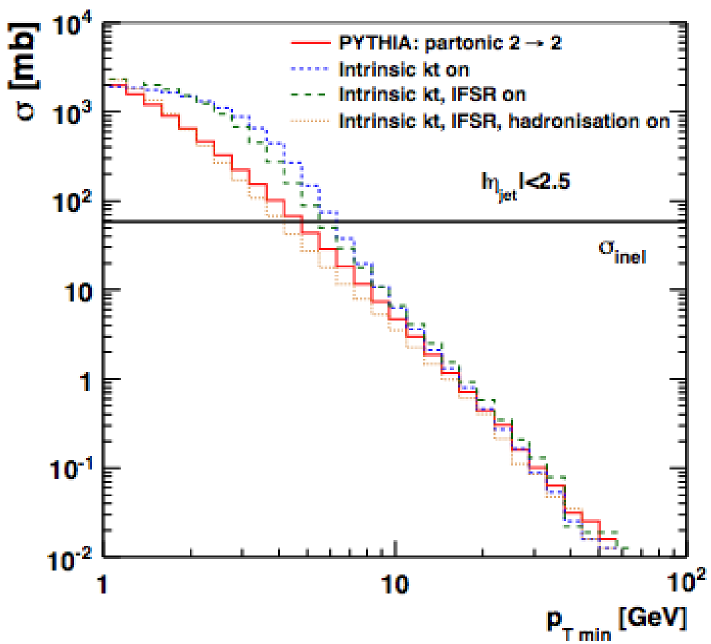
Jets, MPI and the inelastic cross section

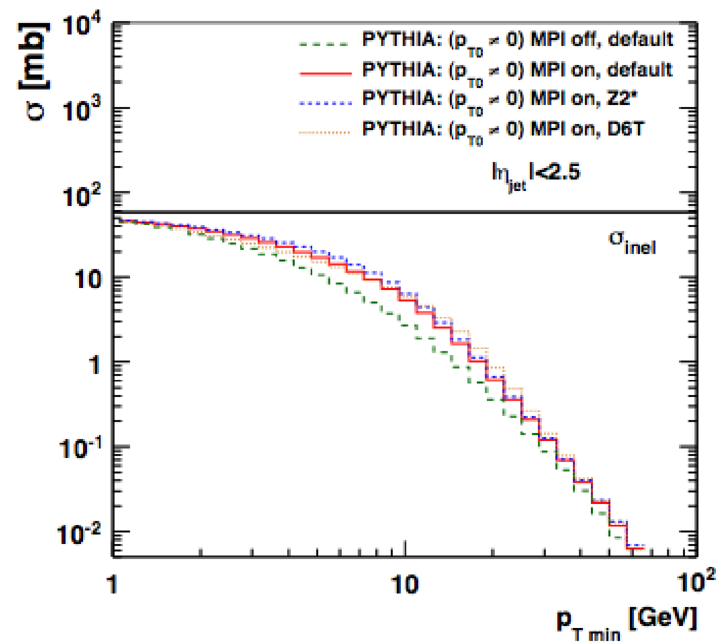
- Extend central jet measurements to lower $p_\perp$

$\Rightarrow$ visible jet cross section sensitive to bound from inelastic σ_{pp}

[ATLAS Coll., Nature Commun. 2 (2011) 46

CMS Coll., CMS PAS QCD-11-002]





(Left) cross section from purely partonic 2→2 process, including intrinsic k_t-effects, initial and final state parton showers (IFSR), hadronization;

(Right) result of applying $p_{T0} \neq 0$ and MPI with different UE tunes of PYTHIA.

[Grebenyuk et al., arXiv:1209.6265]

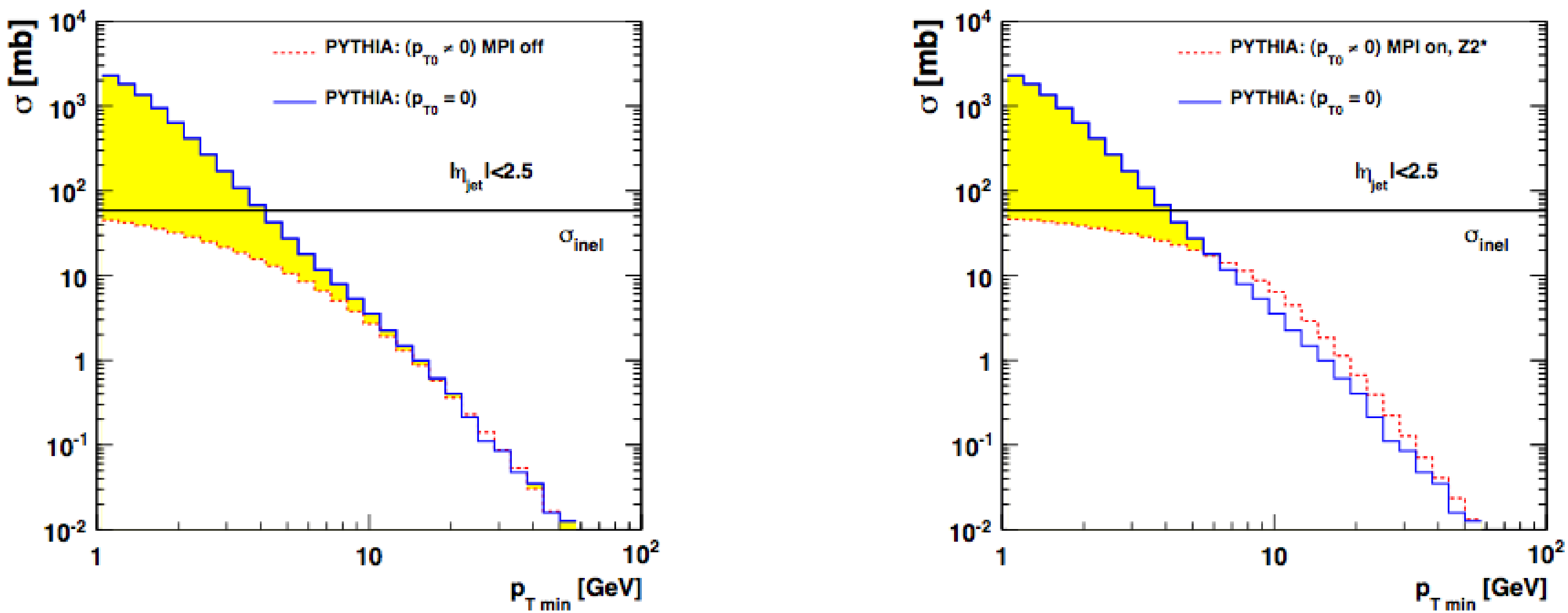
• low-p_T model in collinear framework (Pythia):

$$\sigma \to \sigma \times \frac{\alpha_s^2(p_{T0}^2 + p_T^2)}{\alpha_s^2(p_T^2)} \frac{p_T^4}{(p_{T0}^2 + p_T^2)^2}$$

• k_T factorized: low-p_T behavior results from

— ME dependence (standard low-p_T rise for $k_T \ll p_T$, slower rise for $k_T \simeq p_T$)

— unintegrated pdf (suppression of the low-k_T region)



Left: without MPI. Right: including MPI

[Grebenyuk et al., arXiv:1209.6265]