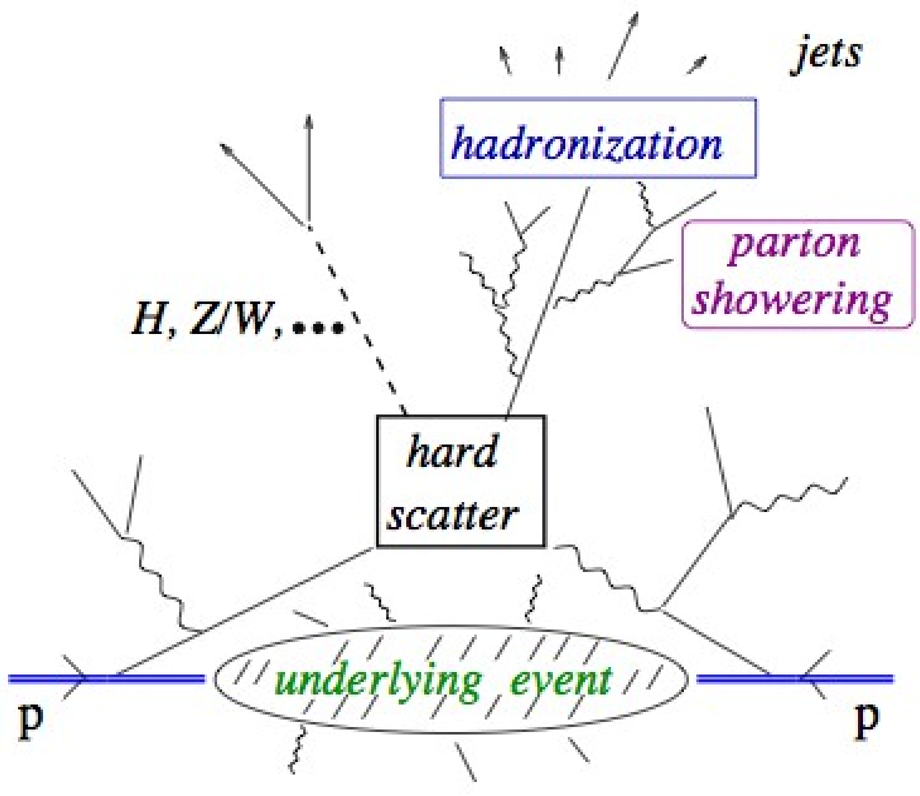
F Hautmann

QCD IN HIGH MULTIPLICITY FINAL STATES AT THE LHC

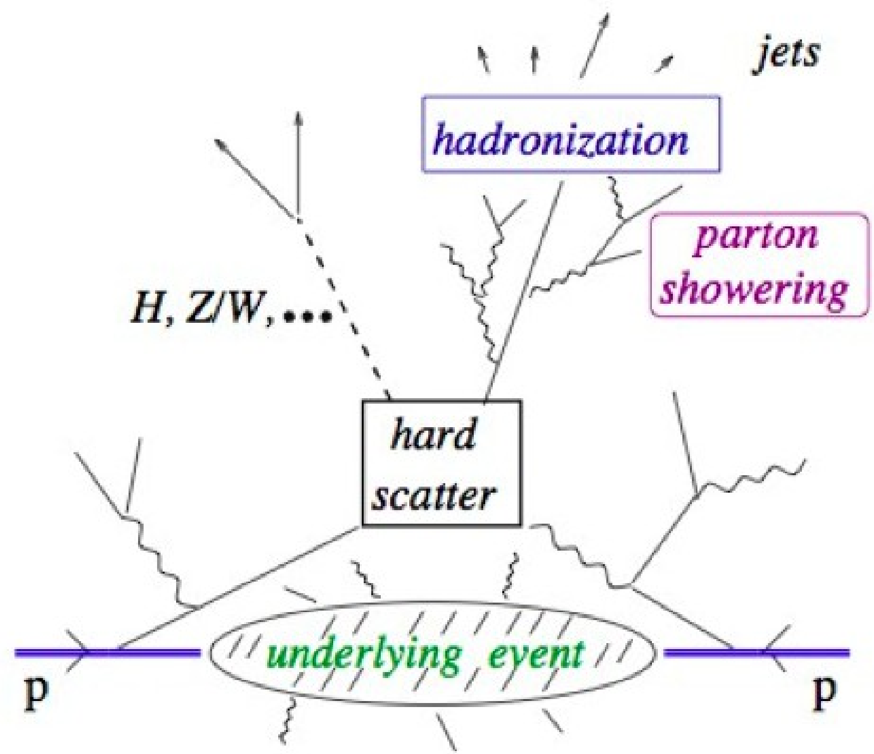


Work in collaboration with S Dooling, P Gunnellini, H Jung

PRD 87 (2013) 094009,

PLB 736 (2014) 293 + in progress

Motivation

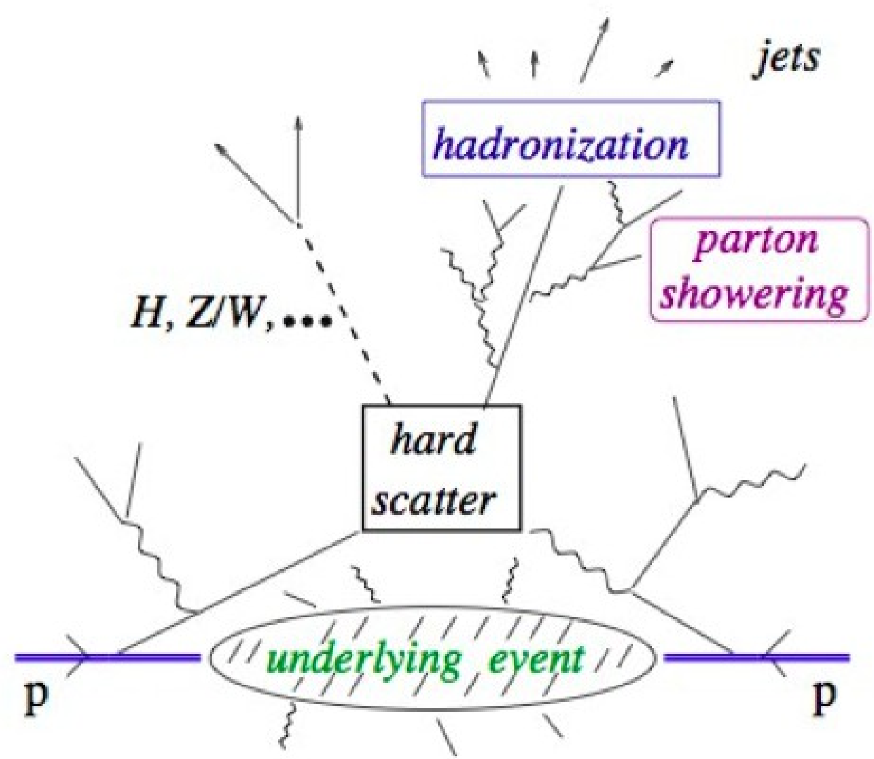


♠ Complex jet final states associated with massive SM / BSM states:

- background to searches
- detailed understanding of QCD physics

(QCD tuning of MC event generators;
QCD factorization, parton shower evolution, all-loop resummations)

Motivation



Baseline predictions:

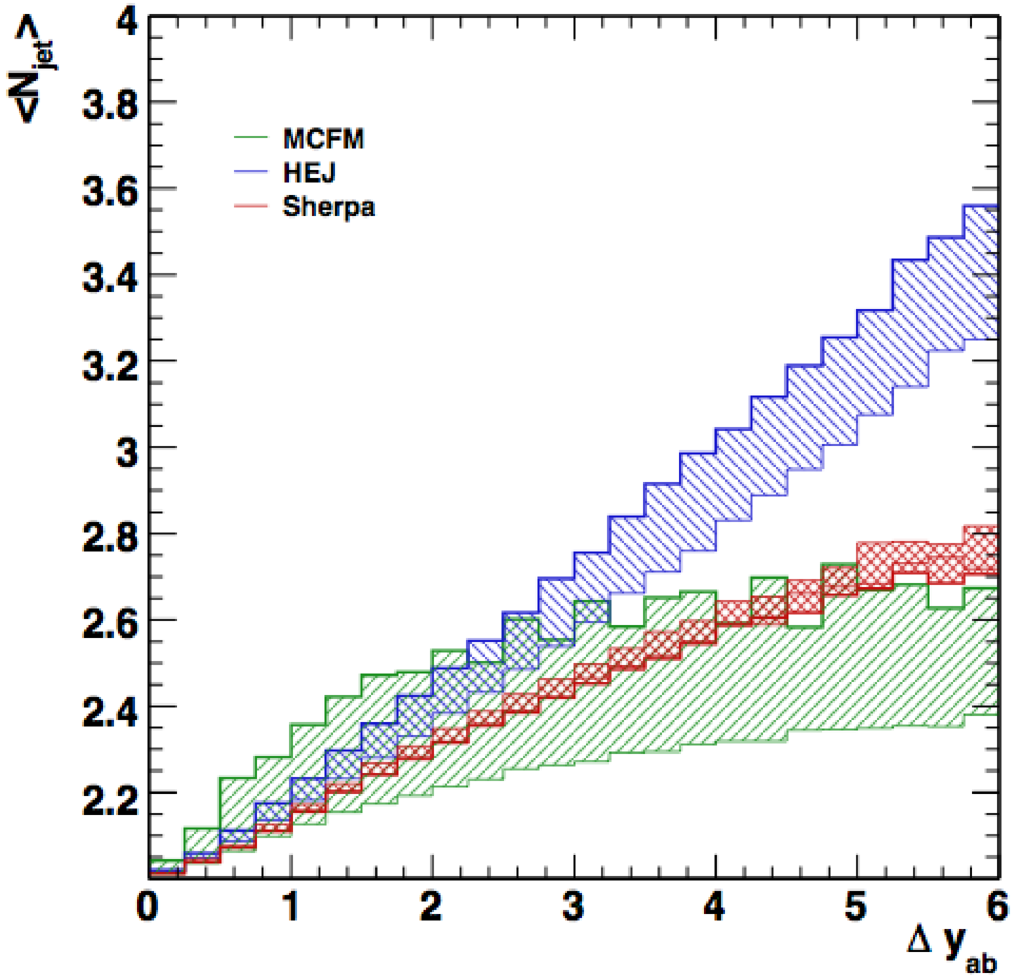
NLO QCD calculations + collinear evolution of QCD parton showers

Motivation

- However, when this approach is pushed to increasingly high energies new effects arise due to soft but finite-angle multigluon radiation.

- More recently, additional effects of kinematical origin have been pointed out which arise from combining collinearity approximations in the QCD showers with energy-momentum conservation constraints.

Higgs boson + jets



J.R. Andersen, J. Campbell, S. Höche, arXiv:1003.1241

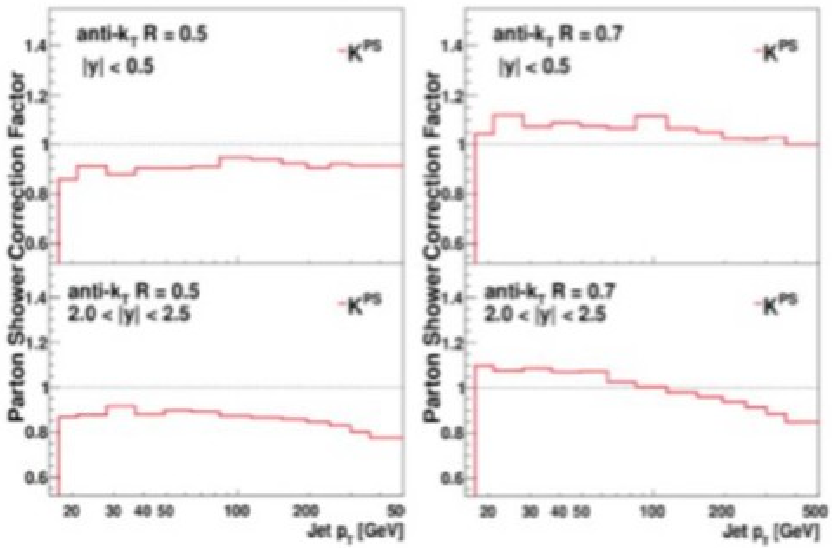
h+dijets (at least 40GeV). Δy_{ab}: Rapidity difference between most forward and backward hard jet

Compare NLO (green), CKKW matched shower (red), and High Energy Jets (blue).

All models show a clear increase in the number of hard jets as the rapidity span Δy_{ab} increases.

Andersen, Terascale MC School, DESY 2015

Kinematic correction from showering to associated jets

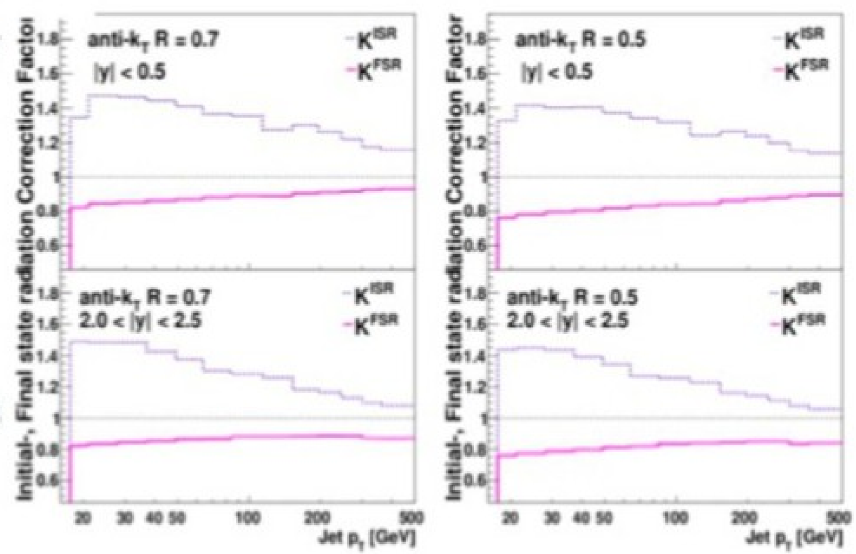


$$K^{PS} = K^{(ps)}_{NLO-MC} / K^{(0)}_{NLO-MC}$$

- 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

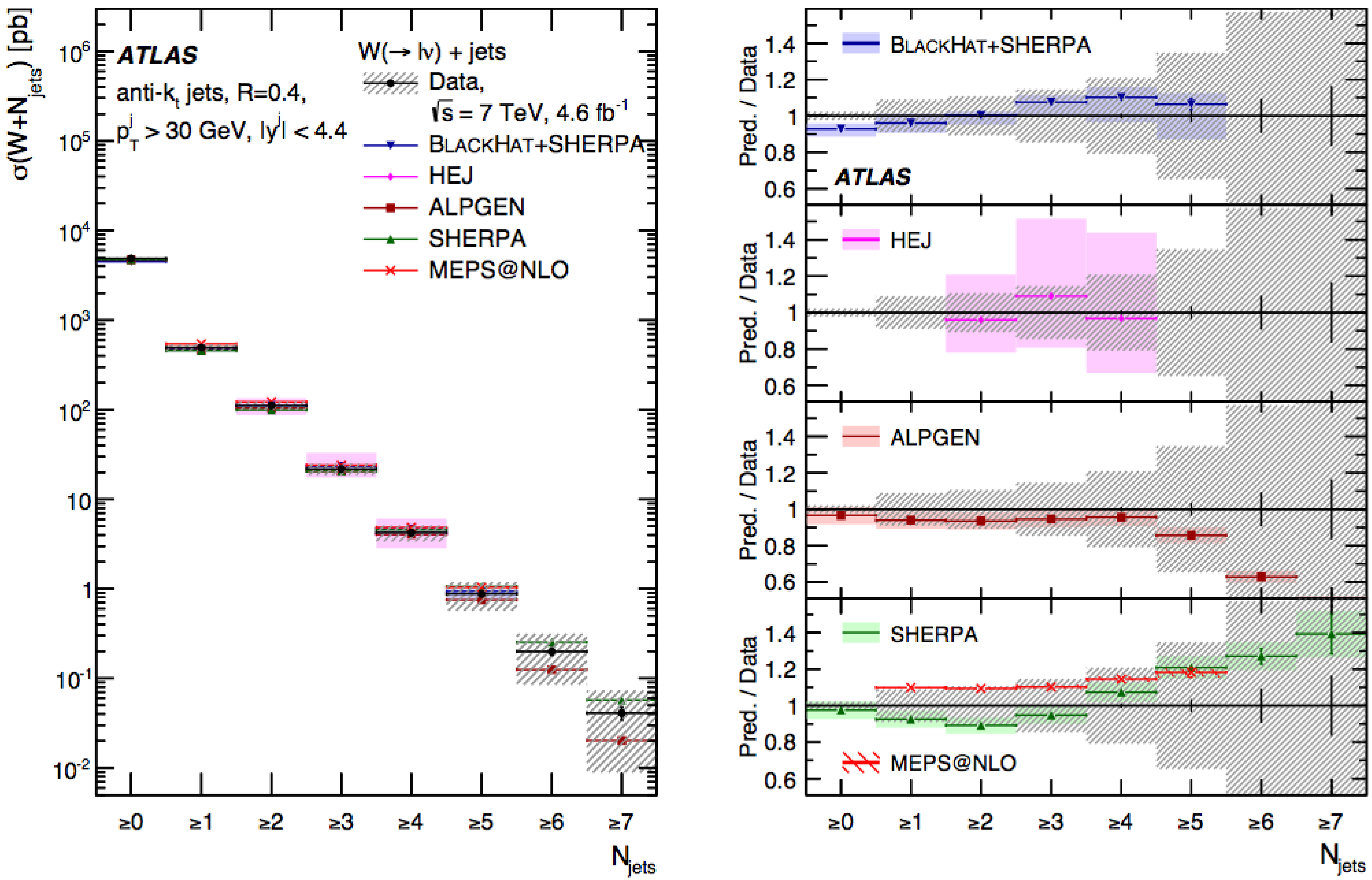
[S. Dooling, talk at DIS 2013]



Dooling et al., arXiv:1212.6264

W + jets

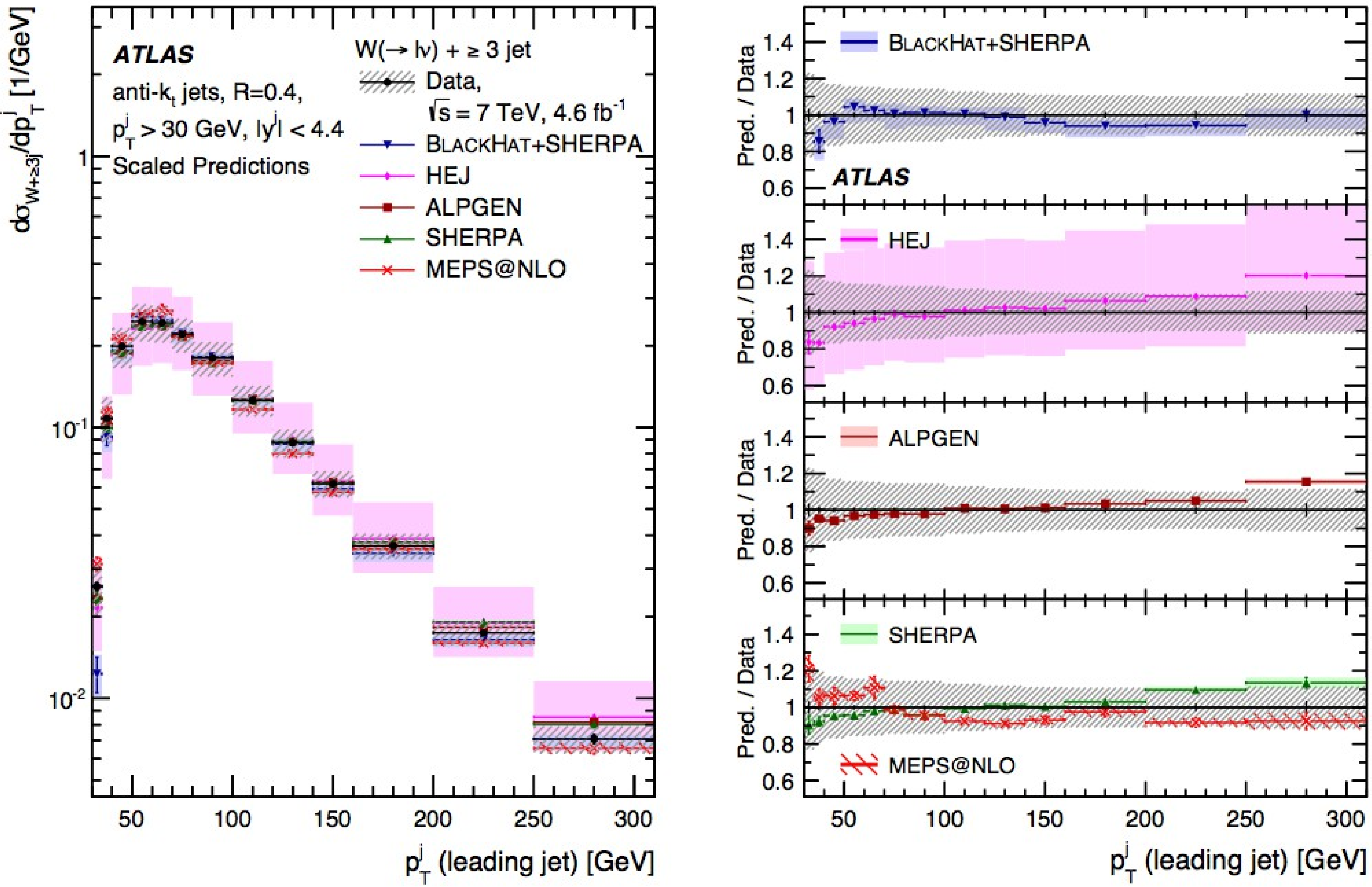
ATLAS, EPJC 75 (2015) 82



Rapidity phase space opens up as s increases → relevant for Run II

W + jets

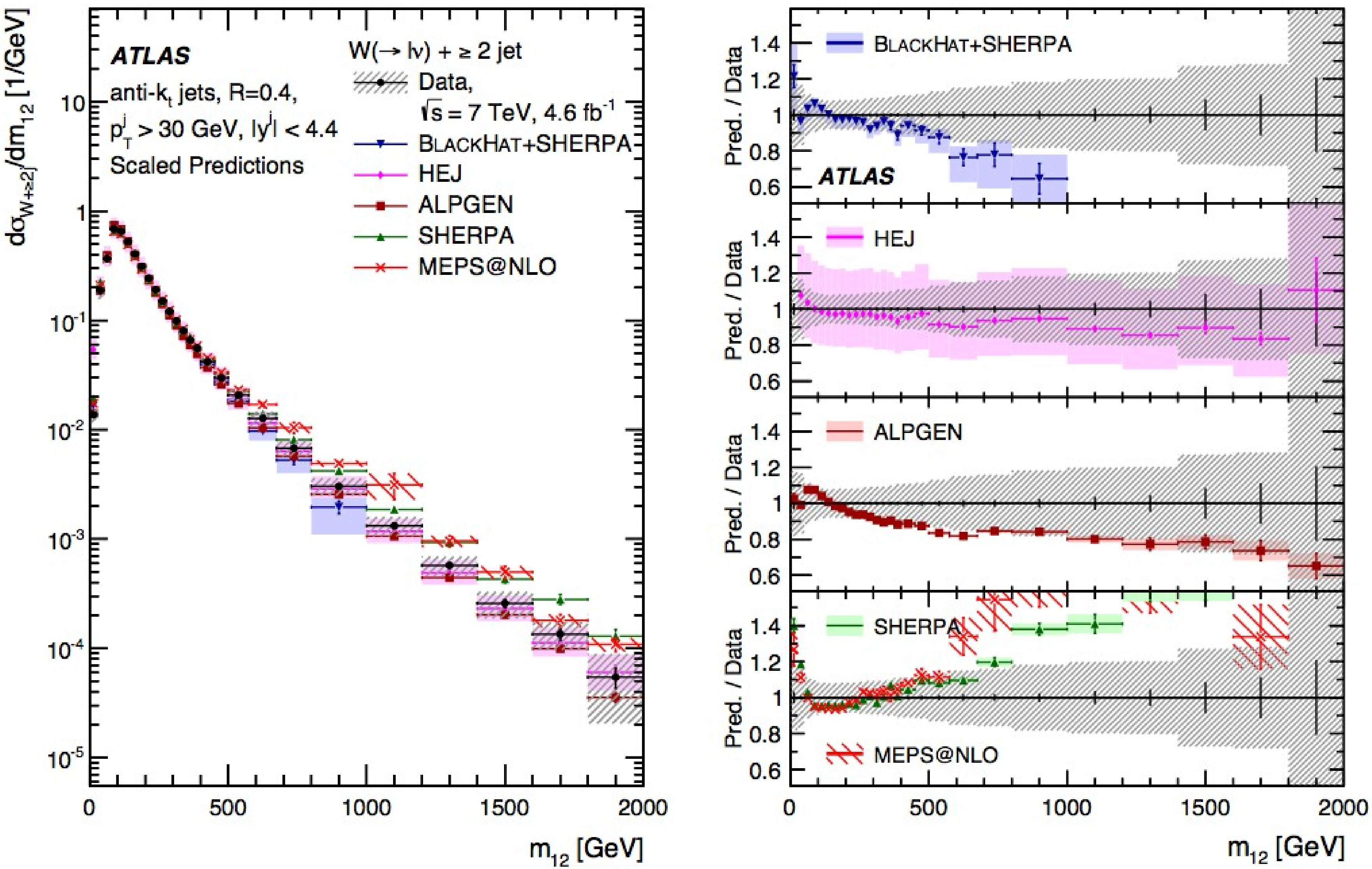
ATLAS, EPJC 75 (2015) 82



Good agreement between all predictions and data for inclusive observables

W + jets

ATLAS, EPJC 75 (2015) 82



Large spread in predictions for invariant mass spectrum

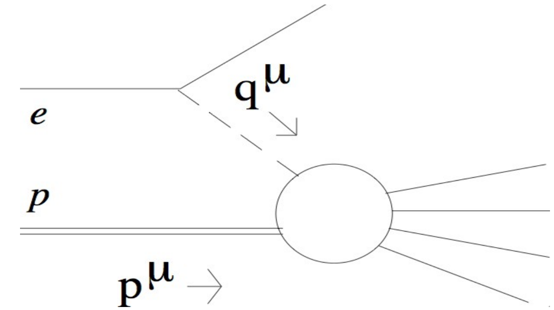
M_JJ ~ 400 – 600 GeV

OUTLINE OF THE REST OF THE TALK:

- Generalized factorization theorems in QCD

- Examples in high-multiplicity final states

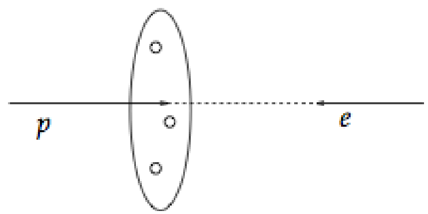
QCD FACTORIZATION



A) Single-scale scattering

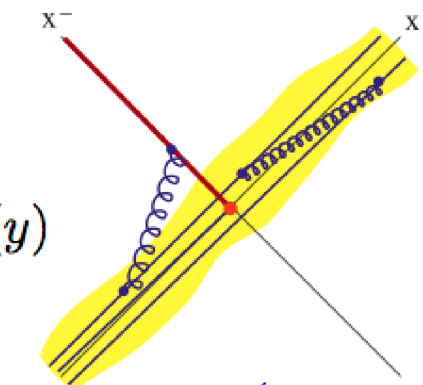
- necessarily sensitive to long timescales, BUT

$$\sigma(Q,m) = C(Q, \text{parton momenta } > \mu) \otimes f(\text{parton momenta } < \mu, m)$$



$\delta t_{\text{scatter}} \ll \tau_{\text{parton}}$ in "infinite-momentum" frame

The collinear parton density functions:



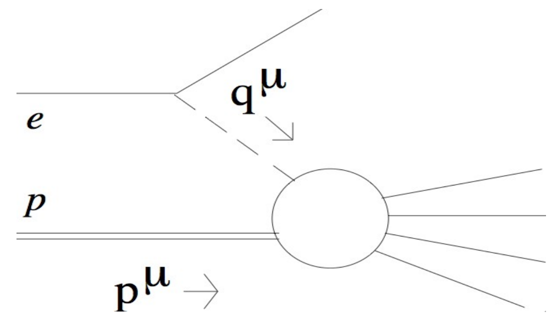
$$\text{Pdf's}: \quad f(x,\mu) = \int \frac{dy^-}{2\pi} \, e^{-ixp^+y^-} \, \widetilde{f}(y)$$

$$\widetilde{f}(y) = \langle \, P \mid \overline{\psi}(y) \, V_y^\dagger(n) \, \gamma^+ \, V_0(n) \, \psi(0) \mid P \, \rangle \quad , \qquad y = (0, y^-, 0)$$

$$V_y(n) = \mathcal{P} \exp \left(i g_s \int_0^\infty d\tau \; n \cdot A(y + \tau \, n) \right)$$

↖ correlation of parton fields at lightcone distances

Single-scale scattering.
E.g.: DIS



◇ Renormalization group invariance ⇒

$$\frac{d}{d\ln\mu}\sigma = 0 \quad \Rightarrow \quad \frac{d}{d\ln\mu}\ln f = \gamma = -\frac{d}{d\ln\mu}\ln C$$

↪ RG evolution equations

$$f = f_0 \times \exp \int \frac{d\mu}{\mu}\,\gamma(\alpha_s(\mu))$$

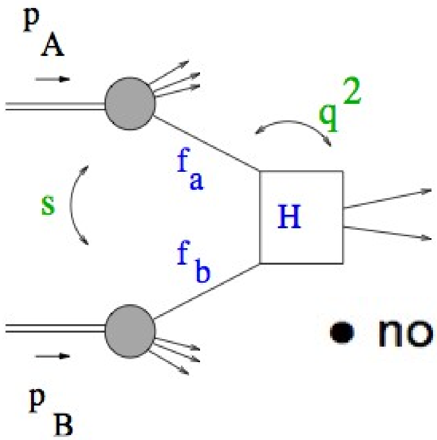
↗ resummation of $[\alpha_s \ln(Q/\Lambda_{\rm QCD})]^n$ to all orders in PT

Note: expansions $\gamma \simeq \gamma^{(LO)}\,(1 + b_1\alpha_s + b_2\alpha_s^2 + \ldots)$

$$C \simeq C^{(LO)}\left(1 + c_1\alpha_s + c_2\alpha_s^2 + \ldots\right)$$

give LO, NLO, NNLO, ... logarithmic corrections

B) Multi-scale hard scattering at LHC energies



$$s \gg q_1^2 \gg \cdots q_n^2 \gg \Lambda^2_{\rm QCD}$$

- nonperturbative components probed near kinematic boundaries $(x \to 0,\ 1 - x \to 0)$

- more complex, potentially large corrections to all orders in α_s, $\sim \ln^k(q_i^2/q_j^2)$

$$e.g.\ \ C \simeq C^{(LO)}\,(1 + c_1\alpha_s + \ldots + c_{n+m}\alpha_s^m(\alpha_s\ L)^n + \ldots)\ ,\ L = \text{“large log”}$$

$\hookrightarrow$ yet summable by QCD techniques that

▷ generalize RG factorization

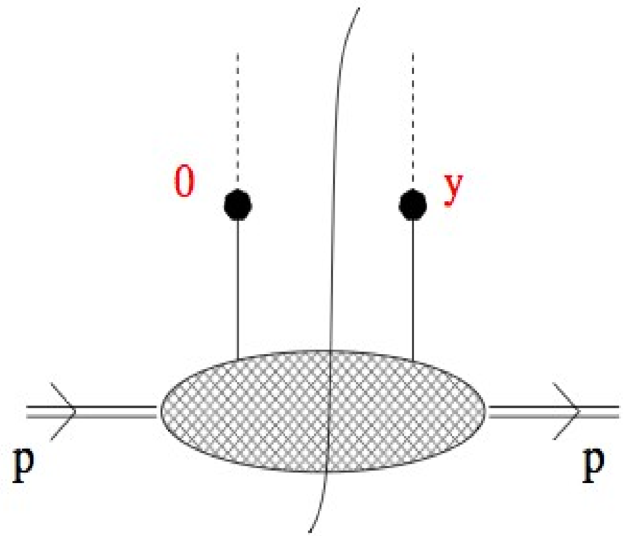
▷ extend parton correlation functions off the lightcone

$\Rightarrow$ unintegrated (or TMD) pdf's

♠ new nonperturbative information; generalized evolution equations

Transverse momentum dependent (TMD) parton density functions

Generalize matrix element to non-lightlike distances:



J Collins,
Foundations of perturbative QCD
CUP 2011

$$p = (p^+ , m^2 / 2 p^+ , 0_\perp)$$

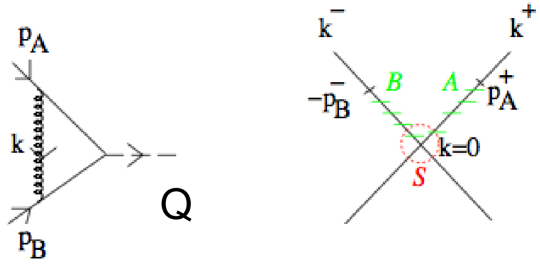
$$\tilde{f}(y) = \langle \, P \mid \overline{\psi}(y) \, V_y^\dagger(n) \, \gamma^+ \, V_0(n) \, \psi(0) \mid P \, \rangle \quad , \qquad y = (0, y^-, y_\perp)$$

TMD pdf's:

$$f(x, k_\perp) = \int \frac{dy^-}{2\pi} \frac{d^{d-2} y_\perp}{(2\pi)^{d-2}} e^{-ixp^+ y^- + ik_\perp \cdot y_\perp} \, \tilde{f}(y)$$

Examples: generalized evolution equations

- Sudakov form factor S:



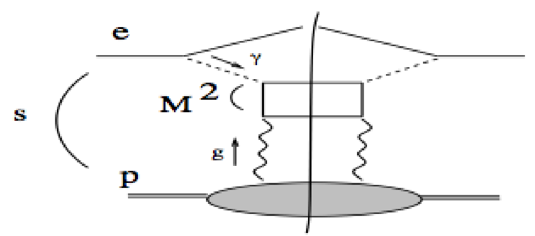
(a) (b)

▷ entering Drell-Yan production, W/Z boson $q_\perp$ distribution, . . .

$\Rightarrow \partial S/\partial\eta = K \otimes S$ **CSS evolution equations** [Collins-Soper-Sterman]

↖ resums $\alpha_s^n \ln^m Q/q_T$

- High-energy resummation: $s \gg M^2 \gg \Lambda^2_{\rm QCD}$



◇ energy evolution: **BFKL equation** [Balitsky-Fadin-Kuraev-Lipatov]

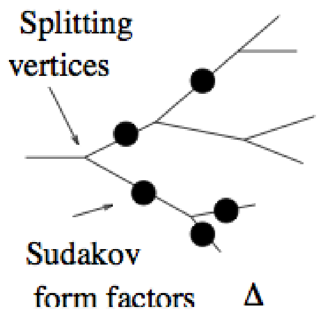
↖ resums $(\alpha_s \ln \sqrt{s}/M)^n$

↪ corrections down by $1/\ln s$ rather than $1/M$

FROM QCD TO MONTE CARLO EVENT GENERATORS

- Factorizability of QCD x-sections $\longrightarrow$ probabilistic branching picture

  ◇ QCD evolution by "parton showering" methods:

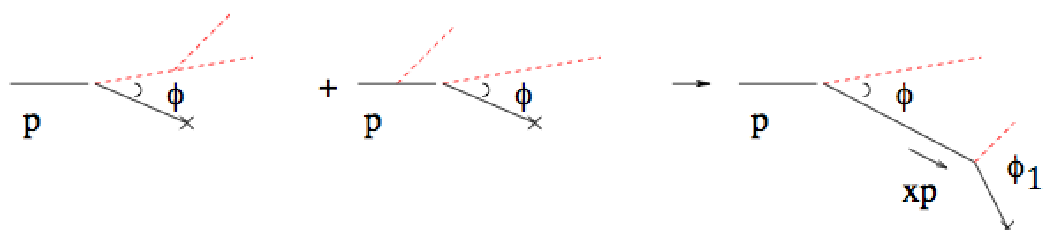


$$dP = \int \frac{dq^2}{q^2} \int dz\, \alpha_S(q^2)\, P(z)\, \Delta(q^2, q_0^2)$$

$\hookrightarrow$ collinear, incoherent emission

◇ Soft emission $\longrightarrow$ interferences $\longrightarrow$ ordering in decay angles:

$\hookrightarrow$ gluon coherence for $x \sim 1$



◇ Gluon coherence for $x \ll 1$ $\Rightarrow$ corrections to angular ordering:

$\hookrightarrow$ $k_\perp$-dependent parton showers

CCFM equation is TMD branching equation which contains both Sudakov physics and BFKL physics

CCFM exclusive evolution

→ Catani-Ciafaloni-Fiorani-Marchesini (1990's)

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

- solve integral equation via iteration:

from q' to q w/o branching

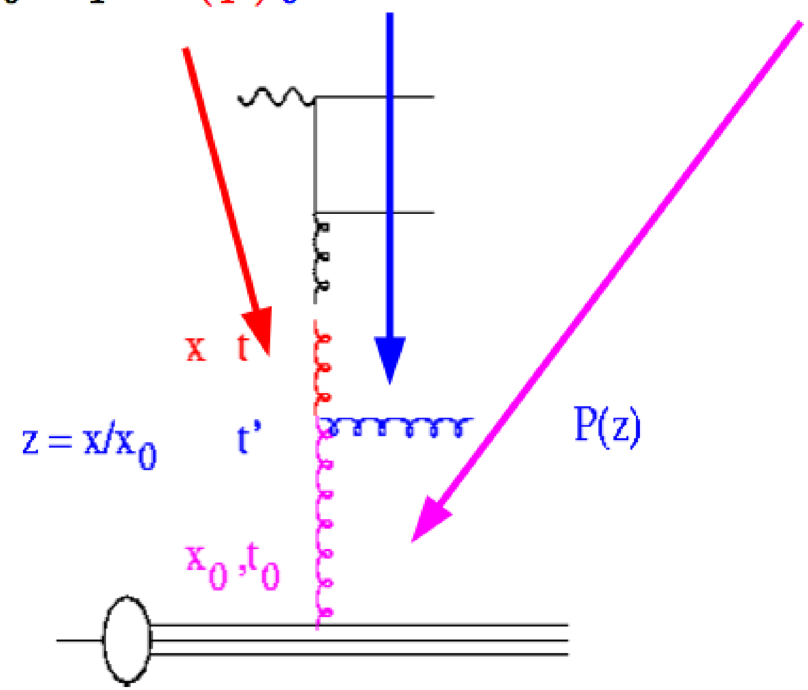
branching at q'

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



- evolution code uPDFevolv [Jung, Taheri Monfared & H, arXiv:1407.5935]

“The TMDlib project” http://tmdlib.hepforge.org/

- a platform for theory and phenomenology of TMD pdfs
- library of fits and parameterizations LHApdf style

EPJC 74 (2014) 3220

DESY 14-059
NIKHEF 2014-024
RAL-P-2014-009
YITP-SB-14-24
Dec 2014

arXiv:1408.3015v2 [hep-ph] 23 Dec 2014

TMDlib and TMDplotter:
library and plotting tools for
transverse-momentum-dependent parton distributions

F. Hautmann[1,2], H. Jung[3,4], M. Krämer[3],
P. J. Mulders[5,6], E. R. Nocera[7], T. C. Rogers[8,9], A. Signori[5,6]

[1] Rutherford Appleton Laboratory, UK
[2] Dept. of Theoretical Physics, University of Oxford, UK
[3] DESY, Hamburg, FRG
[4] University of Antwerp, Belgium
[5] Department of Physics and Astronomy, VU University Amsterdam, the Netherlands
[6] Nikhef, the Netherlands
[7] Università degli Studi di Genova and INFN Genova, Italy
[8] C.N. Yang Institute for Theoretical Physics, Stony Brook University, USA
[9] Department of Physics, Southern Methodist University, Dallas, Texas 75275, USA

Abstract

Transverse-momentum-dependent distributions (TMDs) are extensions of collinear parton distributions and are important in high-energy physics from both theoretical and phenomenological points of view. In this manual we introduce the library TMDlib, a tool to collect transverse-momentum-dependent parton distribution functions (TMD PDFs) and fragmentation functions (TMD FFs) together with an online plotting tool, TMDplotter. We provide a description of the program components and of the different physical frameworks the user can access via the available parameterisations.

EXAMPLES:
VECTOR BOSON + JETS
FINAL STATES

Application to vector bosons + jets

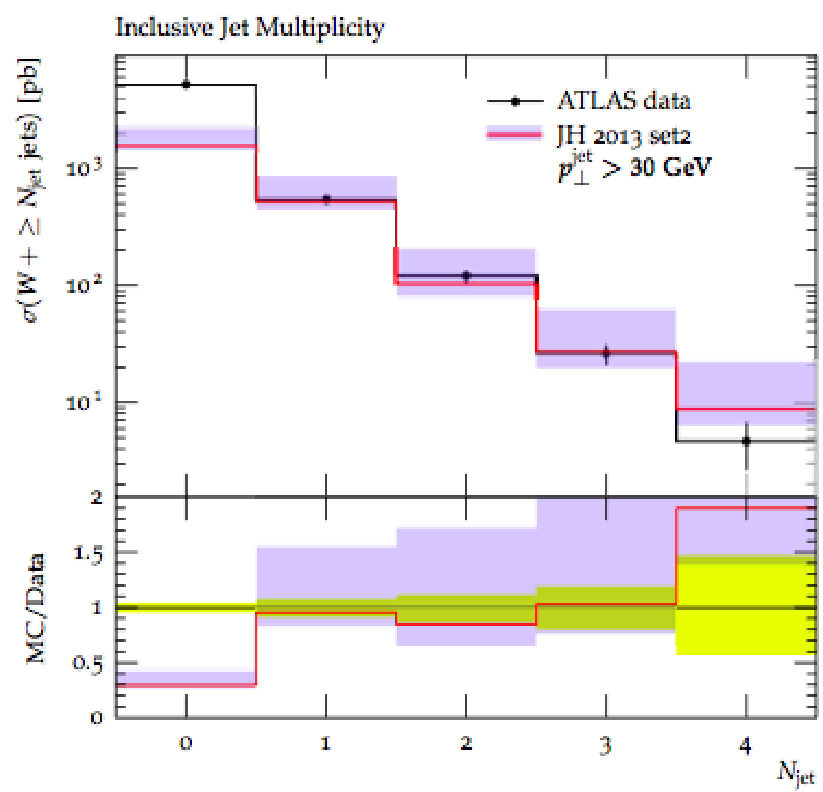
- Motivation: effects of not only collinear-ordered emissions but also non-ordered region which opens up at high s / pt^2 (and large pt).
- Finite angle multi-gluon radiation.
- Push limits of high-energy expansion beyond small-x region.

- Role of transverse-momentum kinematics on jets produced at moderately non-central rapidities

- Jet multiplicities associated with W boson production

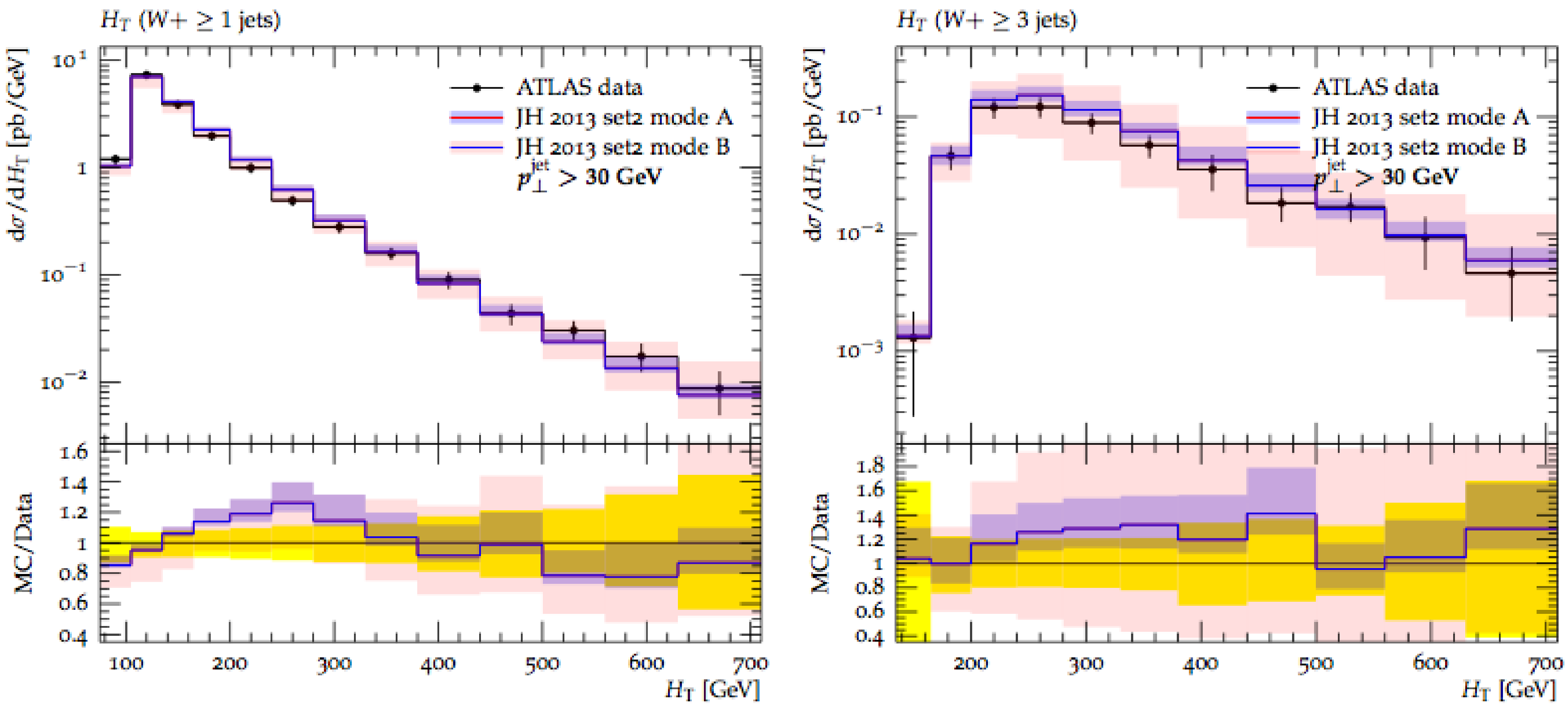
Atlas data PRD85 (2012) 092002:
jet | y | < 4.4

Note: pt-ordered shower (eg, Pythia) cannot predict higher jet multiplicities



Can we go to large transverse momenta?
Total H_T distribution in
W + n jets final states at the LHC

Dooling, Jung & H, Phys. Lett. B736 (2014) 293

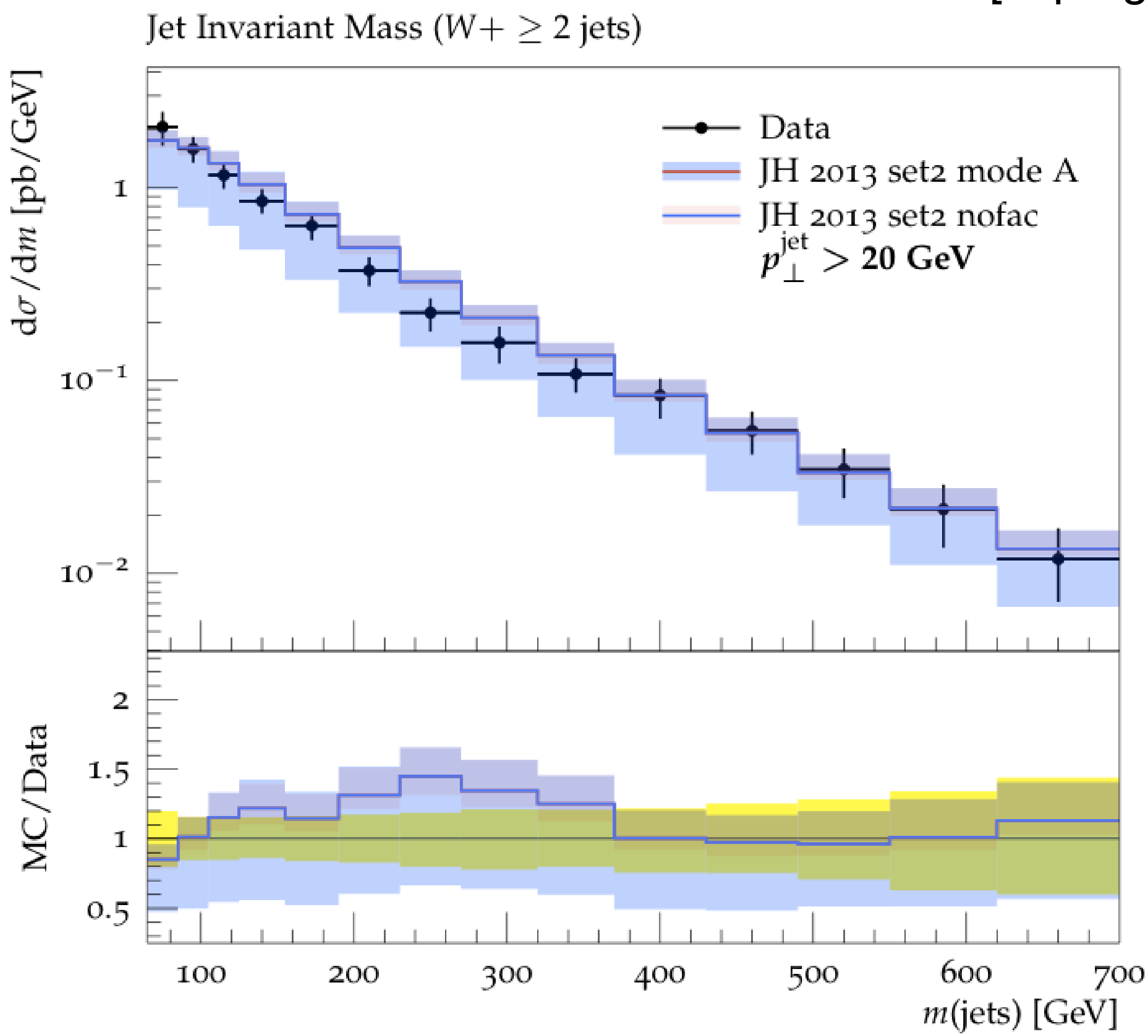


mode A: uncertainties from renorm. scale, starting evol. scale, expt. errors

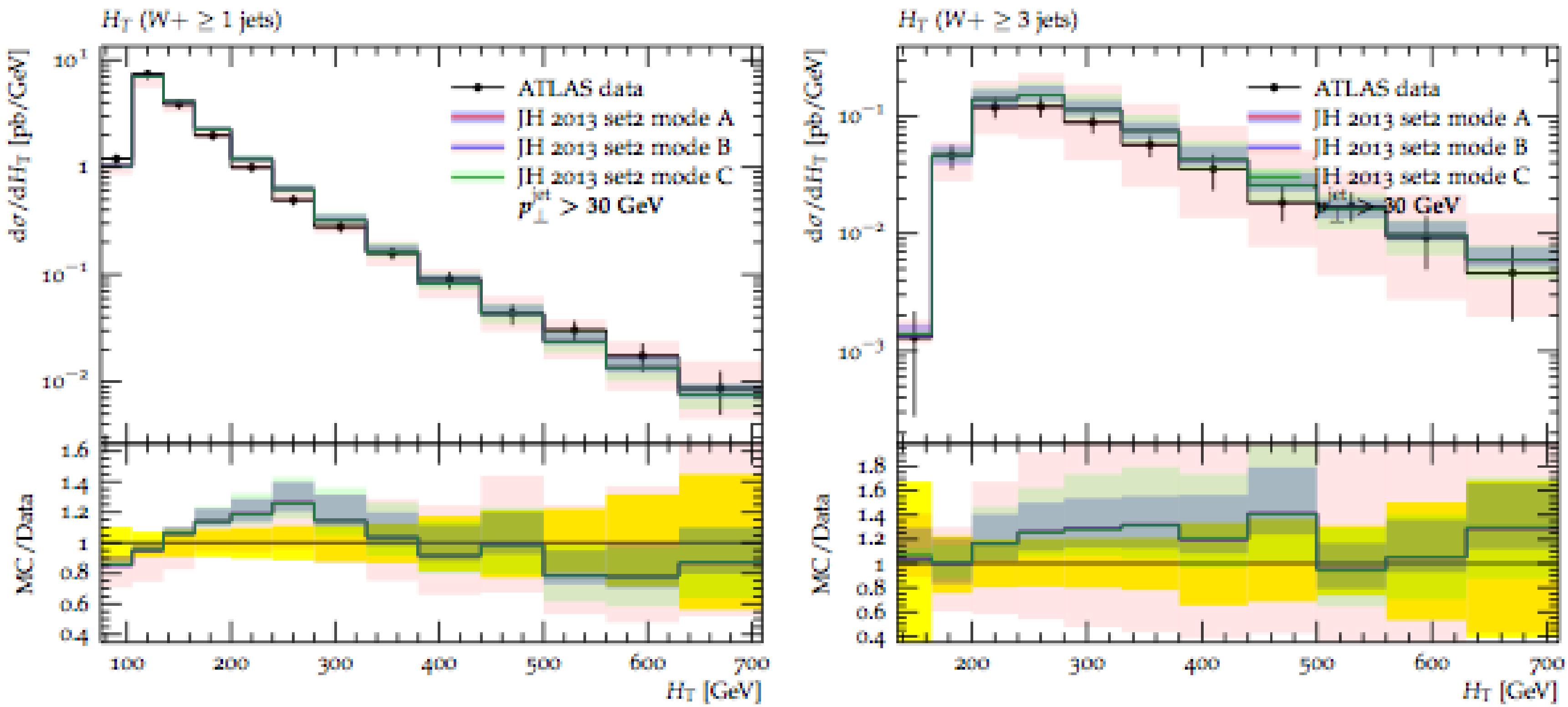
mode B: include factorization scale uncertainties

W + n jets: Invariant mass spectra

[in progress]



Theoretical uncertainties larger for larger H_T (increasing x) and, at fixed H_T, for higher jet multiplicities



mu^2 = m^2 + qT^2

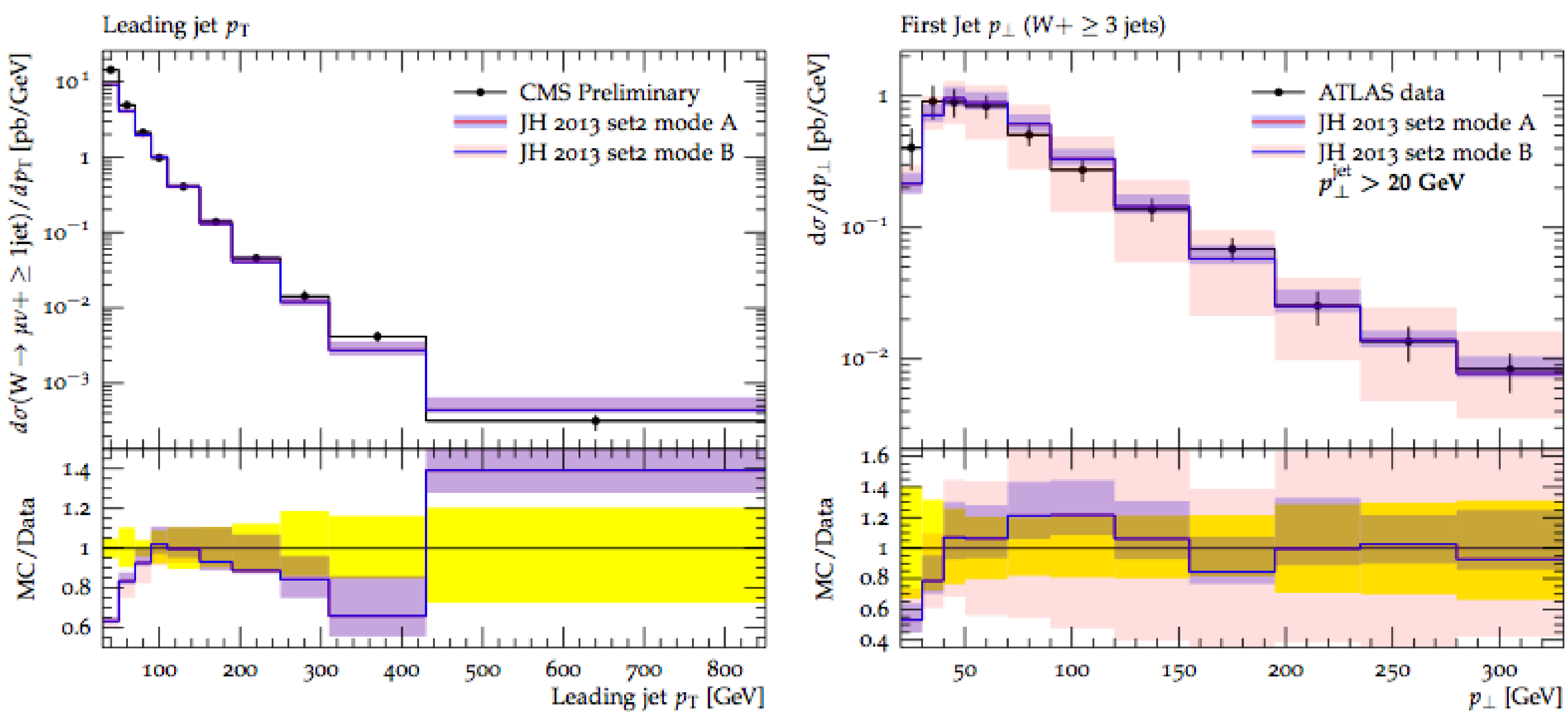
Dooling, Jung & H, Phys. Lett. B736 (2014) 293

Mode C: vary transverse part of mu^2 by factor 2 above and below central value
(more closely related to standard collinear calculations)

Mode B: include variation of longitudinal component
(more conservative estimate – unlike standard collinear approximations)

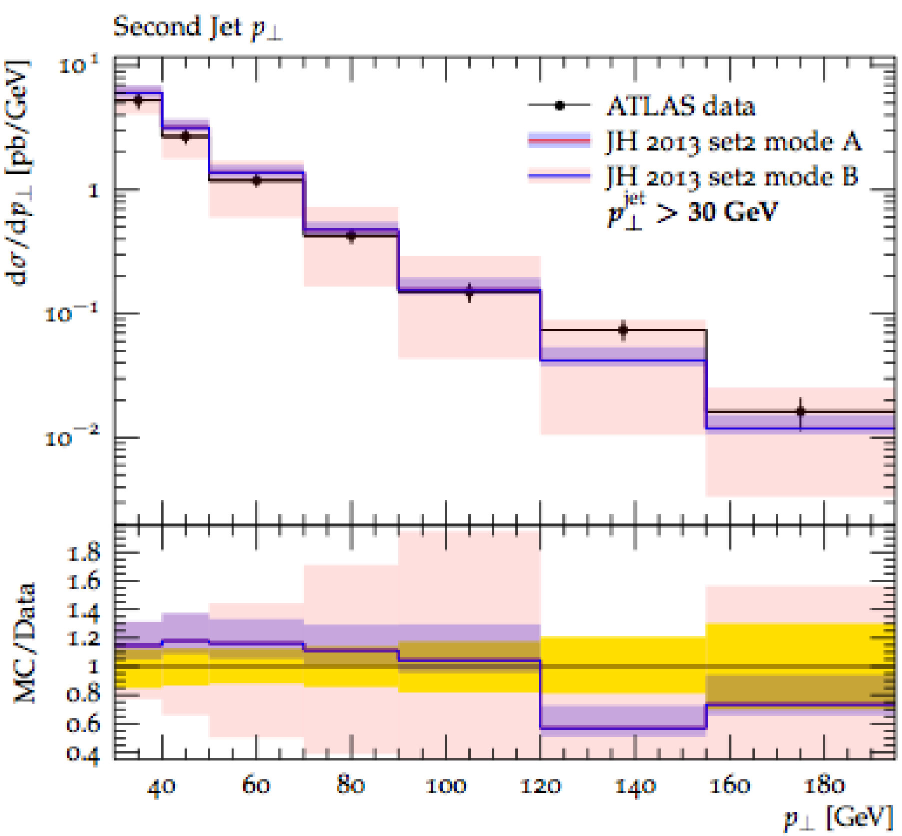
W + n jets final states at the LHC: pT spectra of the jets

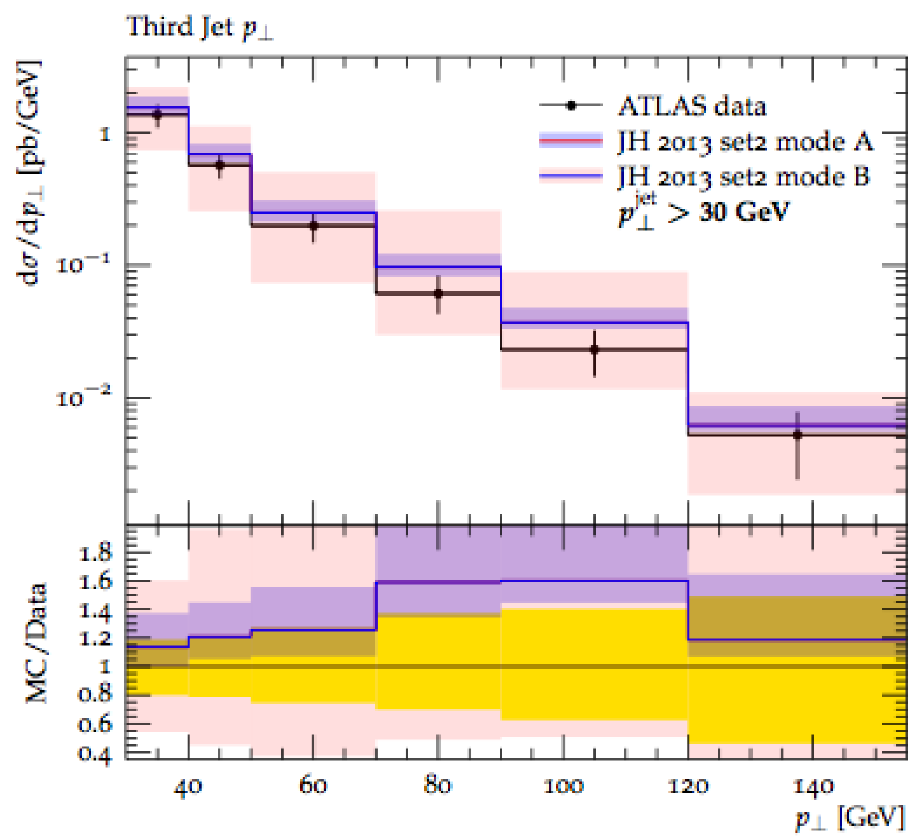
Dooling, Jung & H, Phys. Lett. B 736 (2014) 293



Leading jet pT: (left) inclusive; (right) n>=3

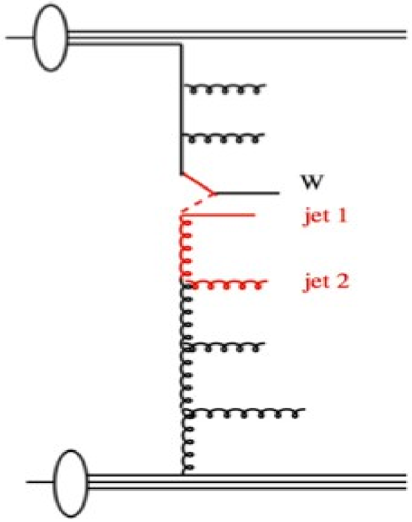
W + n jets final states at the LHC: pT spectra of subleading jets

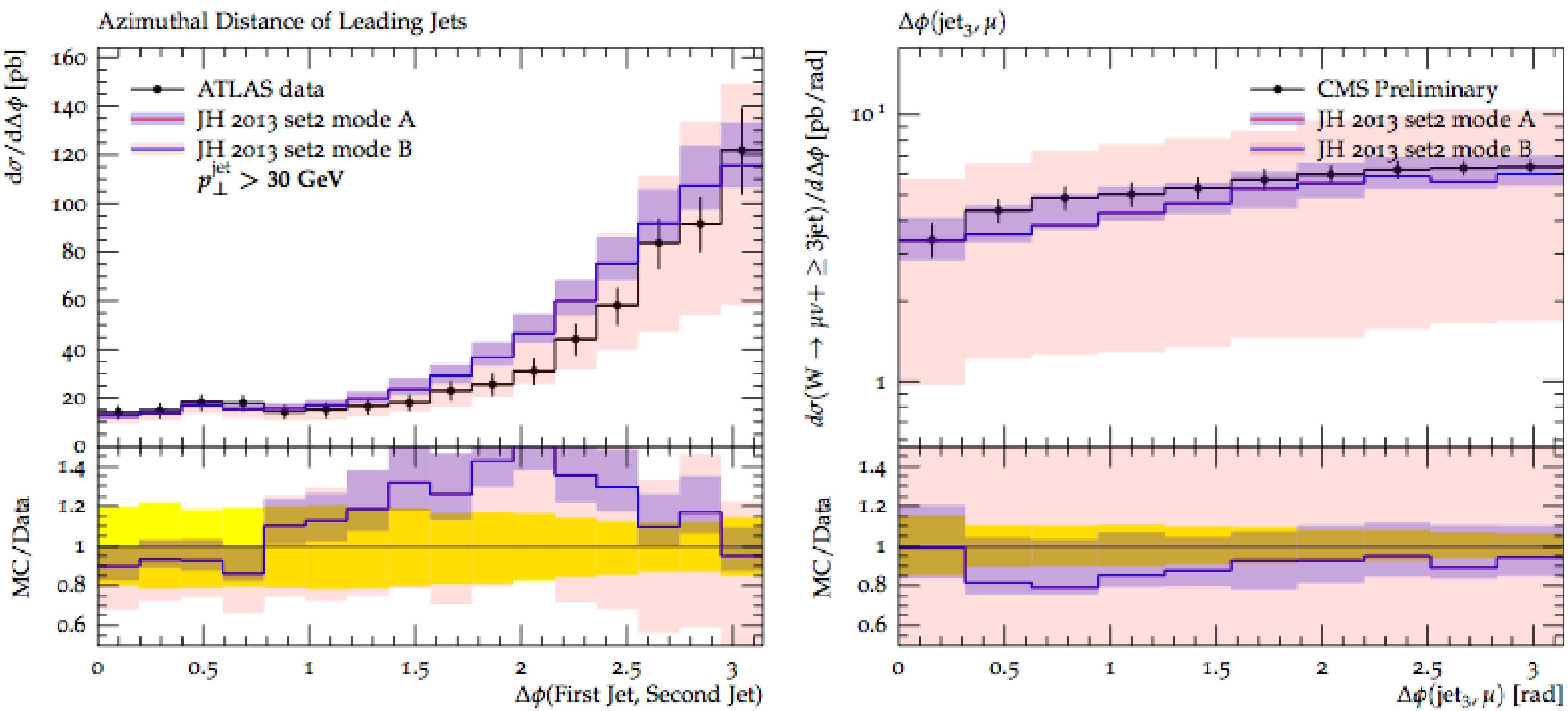




Subleading jets: (left) second jet pT; (right) third jet pT

Angular correlations in W + n jets final states





(left) Delta-phi between two hardest jets; (right) vector boson - third jet correlation

Conclusion: What do we gain?

- Uses of TMD pdfs + kt-dependent shower:

  matching with 2 $\longrightarrow$ n off-shell parton calculations

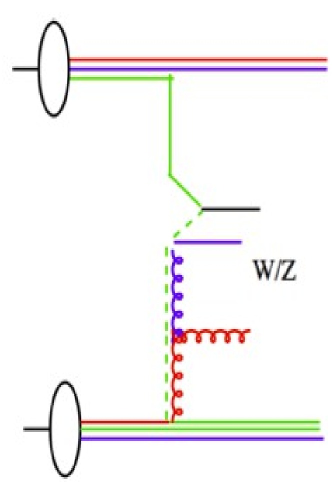
  (automated method, see van Hameren, Kotko & Kutak JHEP 1301 (2013) 078)

- Opens possibility for full LHC phenomenology of QCD, EWK and BSM processes

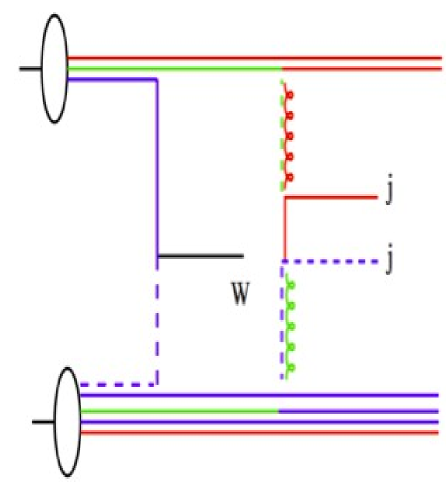
W + 2 jets as signal of double parton interactions

- Influence of TMD corrections to shower evolution on analysis of DPI?

- Formalism interpolates from low pT to high pT
- Incorporates experimental information from high-precision DIS measurements
- Takes into account transverse momentum kinematics without approximations in the branching



Single chain



Double chain

EXTRA SLIDES

EXAMPLES:

TMD kinematic effects in parton shower evolution

Kinematic effects in parton shower evolution

S. Dooling, talk at DIS 2013, Marseille

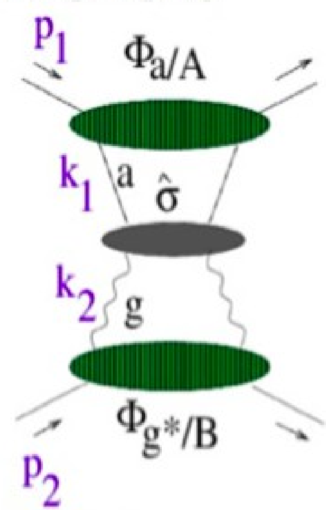
Longitudinal Momentum Shift

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)

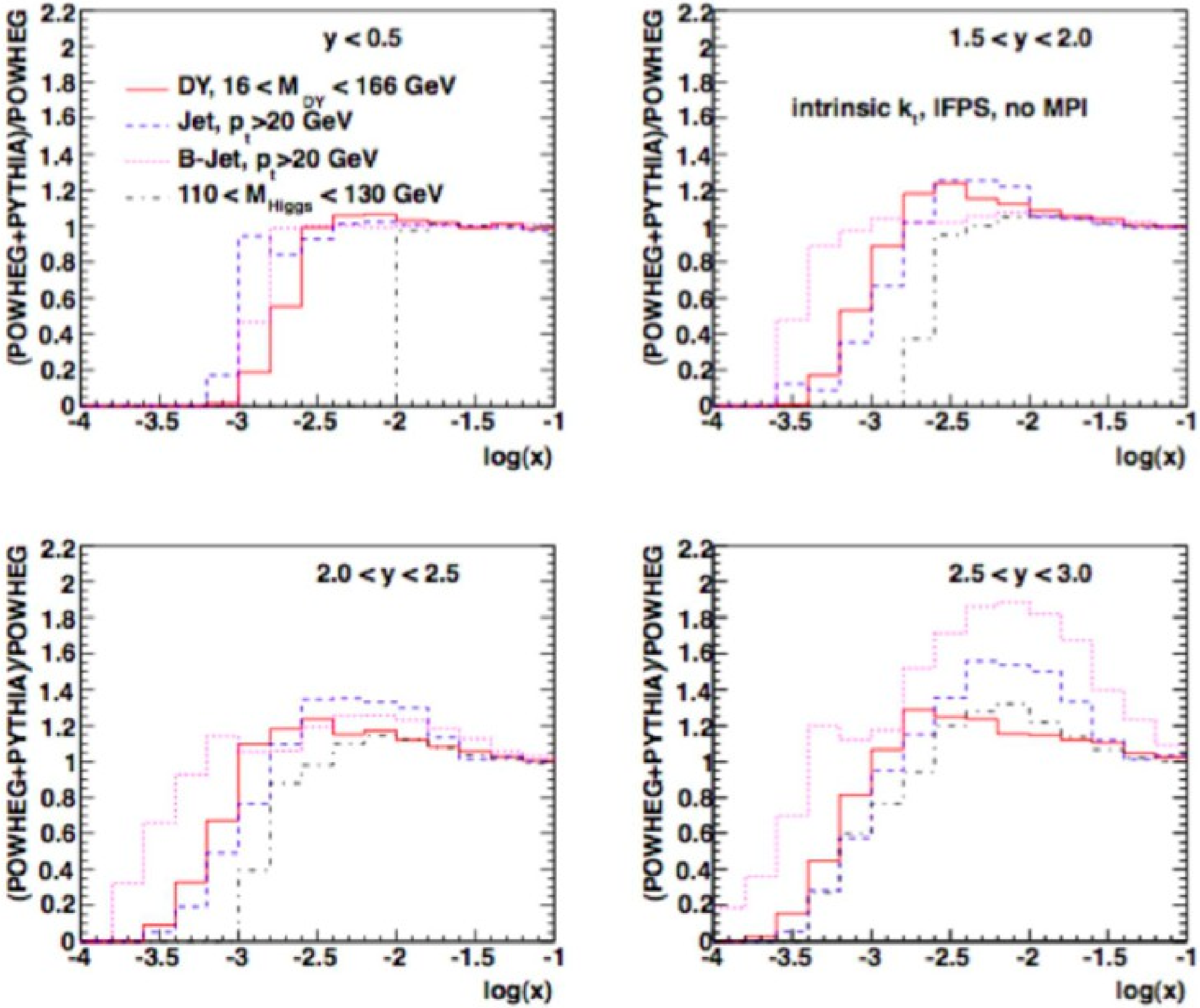
Collinear approximation ⊗ energy momentum conservation

=

kinematic shift in longitudinal momentum distribution due to showering

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



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]]

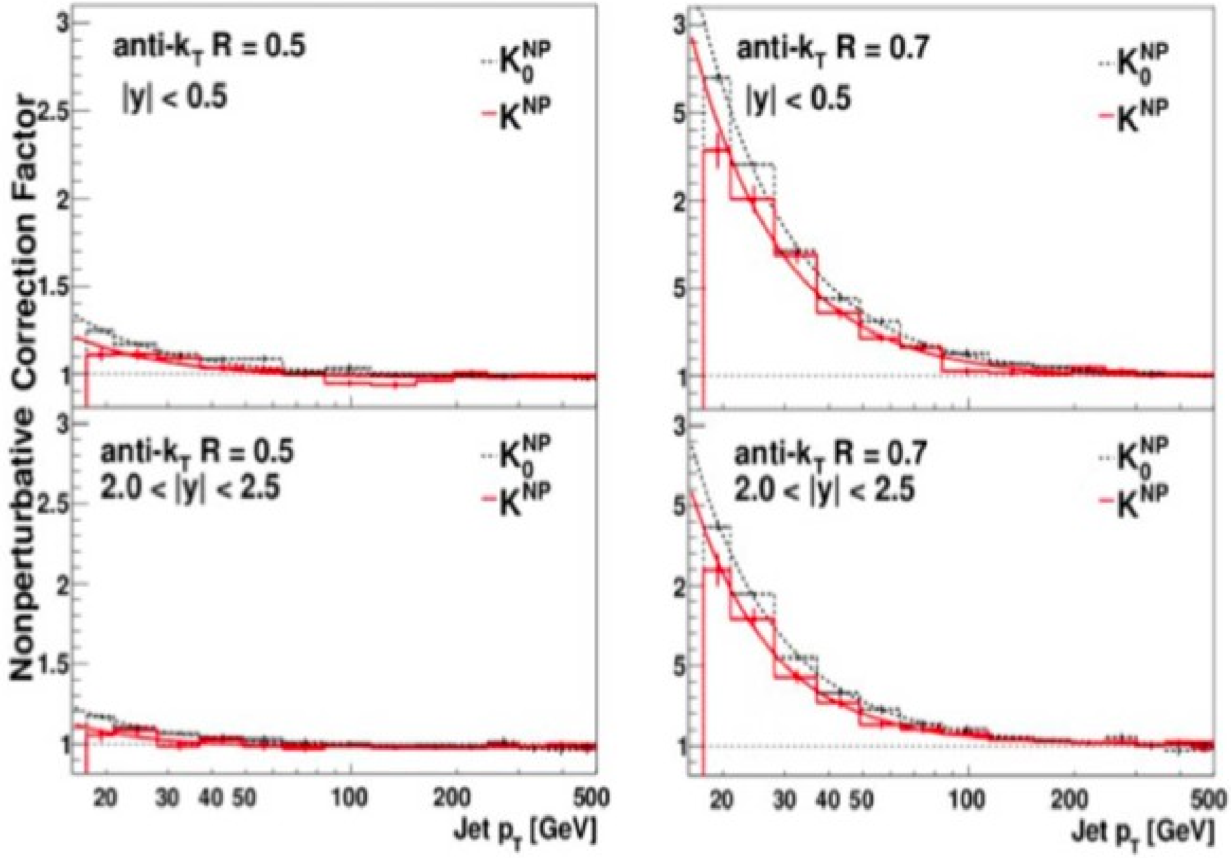
$$K^{NP} = N_{NLO-MC}^{(ps+mpi+had)} / N_{NLO-MC}^{(ps)}$$

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

♣ K^{NP} differs from K_0^{NP}

♣ K^{PS} is new

Nonperturbative Correction



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

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

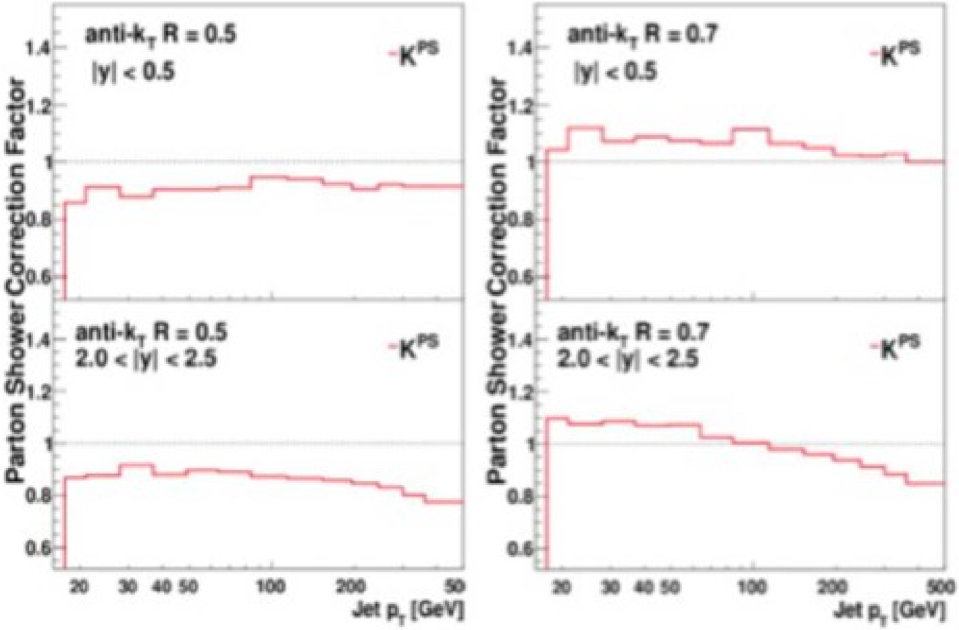
$$K^{NP} = K_{NLO-MC}^{(ps+mpi+had)} / K_{NLO-MC}^{(ps)}$$

Dooling et al.
arXiv:1212.6264

S. Dooling, talk at DIS 2013, Marseille

Parton Shower Correction

Dooling et al.
arXiv:1212.6264

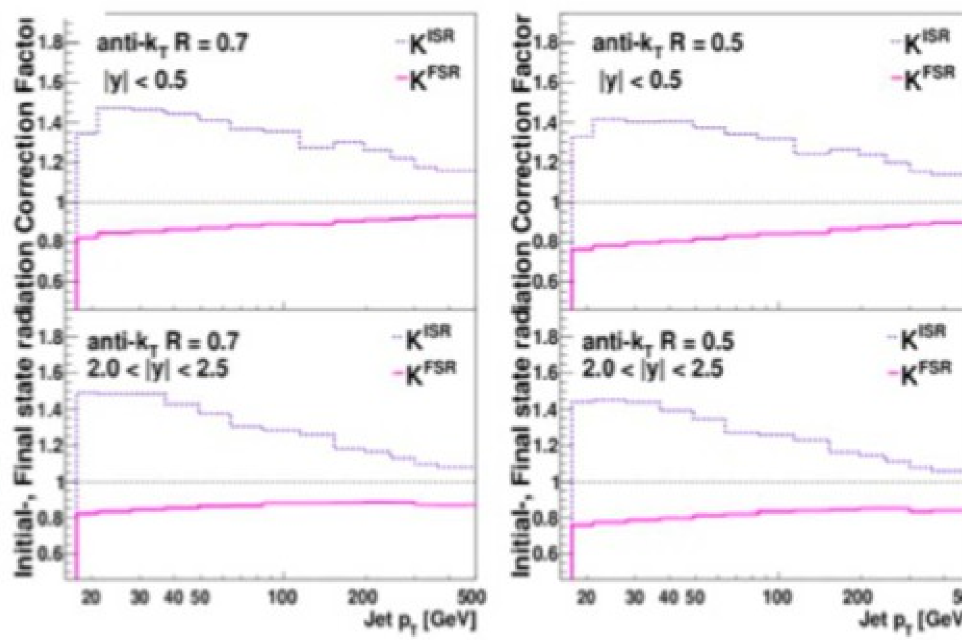


$$K^{PS} = K^{(ps)}_{NLO-MC} / K^{(0)}_{NLO-MC}$$

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

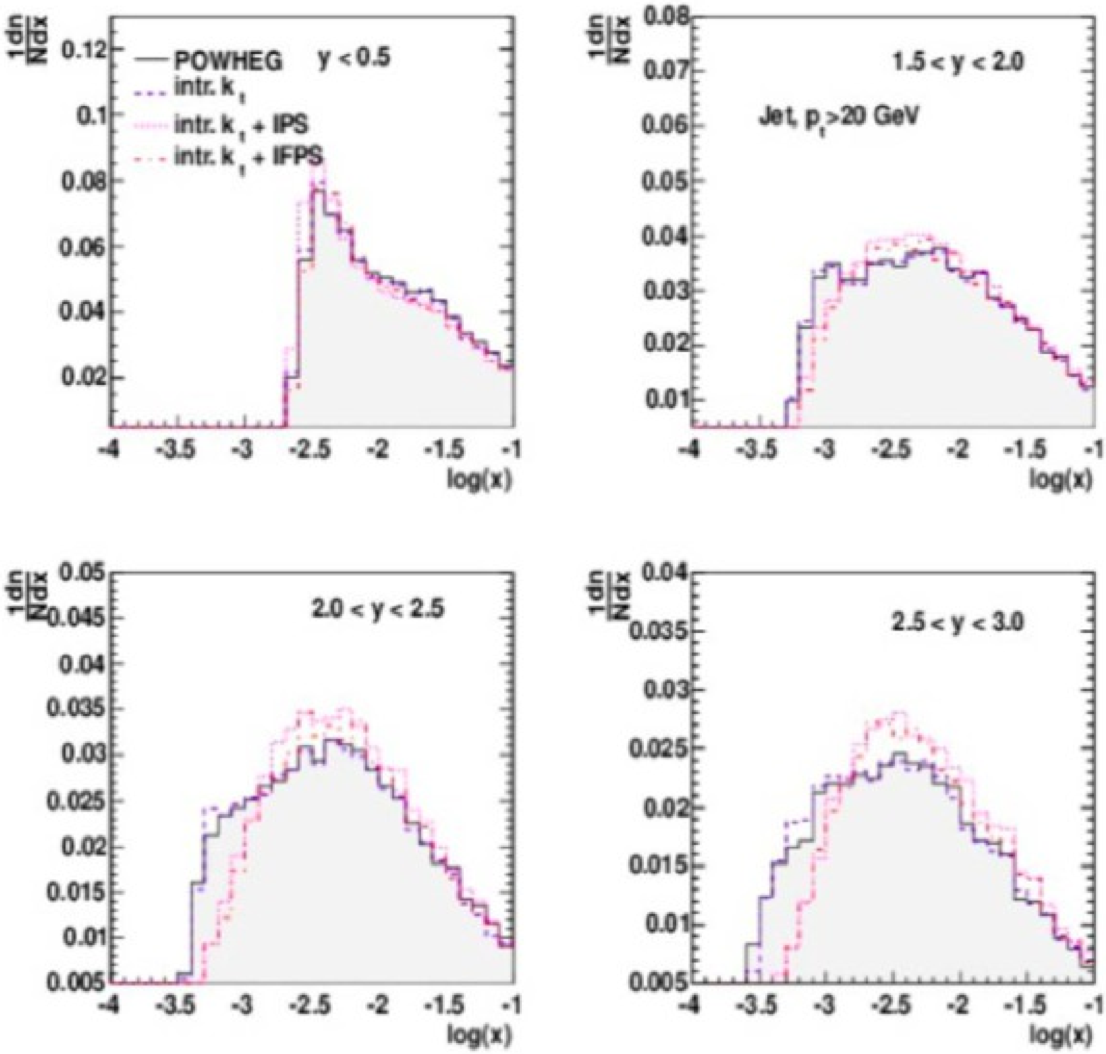
- Initial and Final State Parton Shower considered independently
- But they are interconnected: The combined effects cannot be obtained by adding the individual contributions
- ISR largest at low p_T, FSR significant for all p_T

[S. Dooling, talk at DIS 2013]



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)

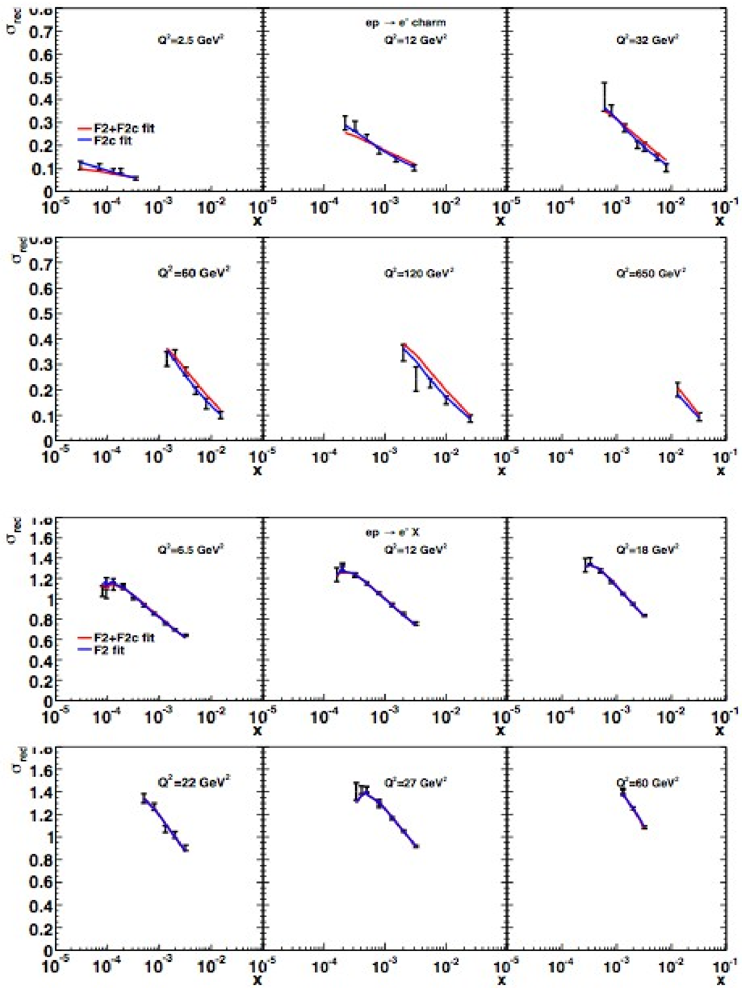
Kinematic reshuffling in x is negligible for central rapidities but becomes significant for y > 1.5

▷ Kinematic shift can affect predictions through the PDFs

Dooling et al.
arXiv:1212.6264

[S. Dooling, talk at DIS 2013]

kT-dependent gluon density from precision DIS data



[Jung & H, Nucl. Phys. B 883 (2014) 1]

- Good description of inclusive DIS data with TMD gluon
- Sea quark yet to be included at TMD level
- Fit performed with herafitter package https://www.herafitter.org/ arXiv:1410.4412 [hep-ph]

	$\chi^2/ndf\,(F_2^{(\mathrm{charm})})$	$\chi^2/ndf\,(F_2)$	$\chi^2/ndf\,\left(F_2 \text{ and } F_2^{(\mathrm{charm})}\right)$
3-parameter	0.63	1.18	1.43
5-parameter	0.65	1.16	1.41

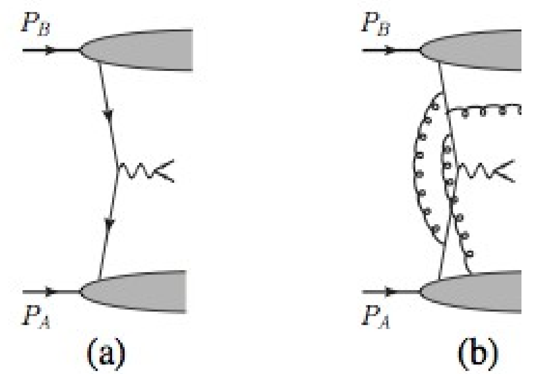
Example I:
Drell Yan hadroproduction of electroweak gauge bosons

- CSS formalism

$$\frac{d\sigma}{d^4q} = \sum_{ij} H_{ij}(Q^2/\mu^2, \alpha_s(\mu)) \int d^2b_\perp \, e^{iq_\perp \cdot b_\perp} \, f_i(x_1, b_\perp; \zeta_1, \mu) \, f_j(x_2, b_\perp; \zeta_2, \mu)$$

$$+ \, Y\text{-term} \, + \, \mathcal{O}\left(\Lambda^2_{\rm QCD}/Q^2\right)$$

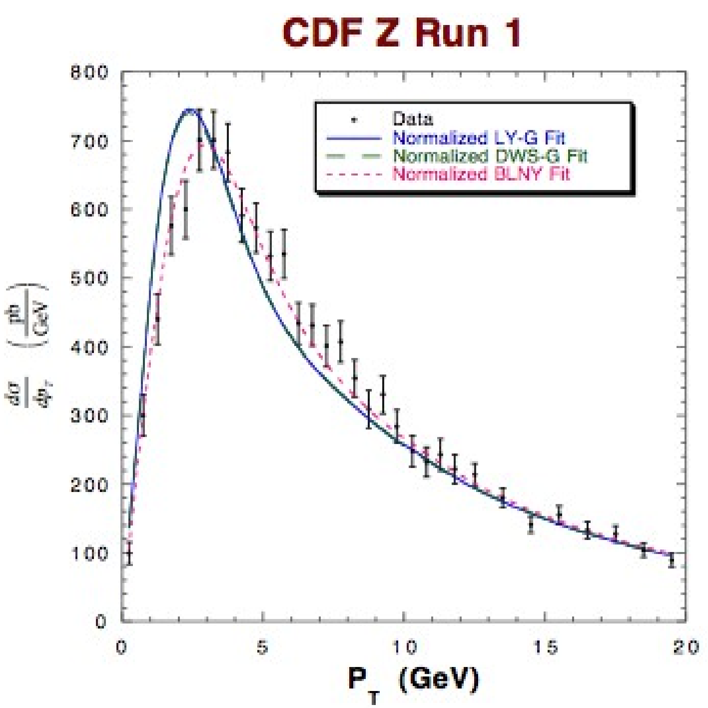
TMD factorization



where $\displaystyle\frac{\partial \ln f}{\partial \ln \sqrt{\zeta}} = K(b_\perp, \mu)$ and $\displaystyle\frac{d \ln f}{d \ln \mu} = \gamma_f(\alpha_s(\mu), \zeta/\mu^2)$

$$\frac{dK}{d\ln\mu} = -\gamma_K(\alpha_s(\mu))$$

cusp anomalous dimension



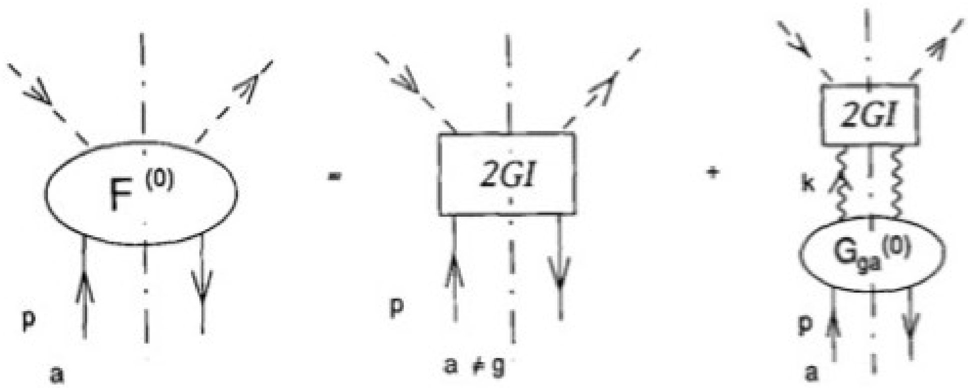
Landry et al.

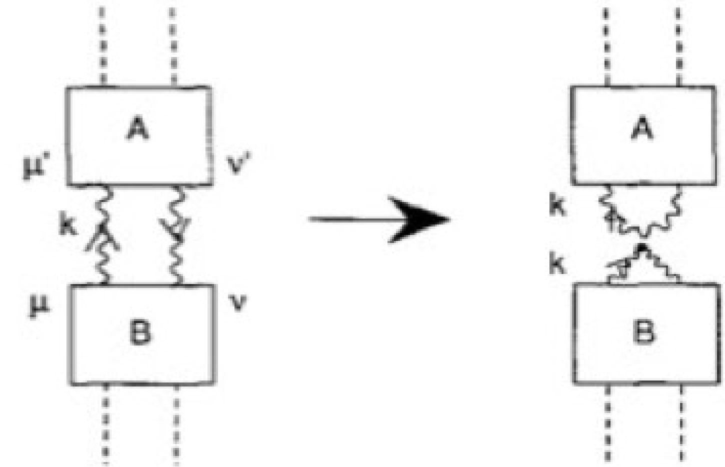
- Soft Collinear Effective Theory (SCET) provides alternative approach to comparable results

[Echevarria, Idilbi, Scimemi 2012; Chiu, Jain, Neill, Rothstein 2012; Becher, Neubert 2011; Mantry, Petriello 2011]

Example II:

DIS at high energies





transverse momentum dependent
high-energy factorization :

$$F_j(x,Q^2) = \int_x^1 \frac{dz}{z} \int d^{2+2\varepsilon}\mathbf{k}\ \underbrace{\hat{\sigma}_j\left(x/z, \mathbf{k}/Q, \alpha_s(Q/\mu)^\varepsilon, \varepsilon\right)}_{2GI\ kernel}\ \mathcal{A}(z,\mathbf{k},\mu,\varepsilon) \qquad j = 2, L$$

where $\quad \mathcal{A}(z,\mathbf{k},\mu,\varepsilon) = \int \frac{dk^2}{2(2\pi)^{4+2\varepsilon}}\ P^{(H)}_{\mu\nu}\ G^{\mu\nu}(k,p)$

↖ *unintegrated (TMD) gluon density*

↖ high-energy projector (spin and momentum)

Conclusion

- TMD parton distributions and showers relevant to both large pT and small pT processes, high x and low x:

  TMDlib platform http://tmdlib.hepforge.org/

- First determination of TMD gluon from combined high-precision DIS data, including uncertainties [$\longrightarrow$ herafitter]

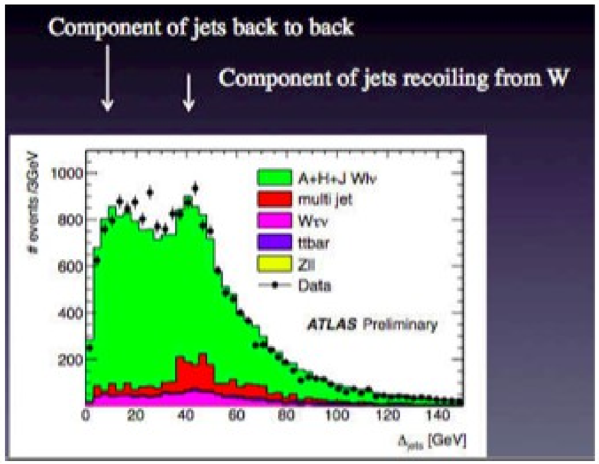
- The approach has far reaching implications for LHC physics:

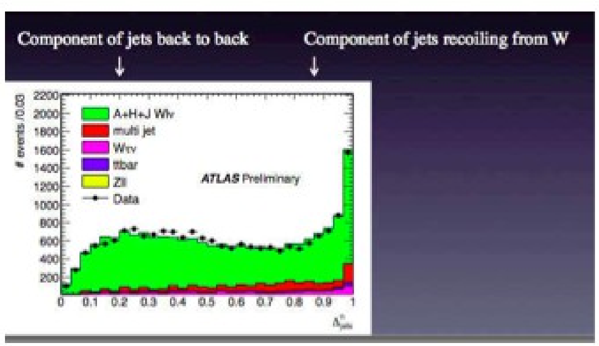
  treatment of kinematic corrections to parton showers;

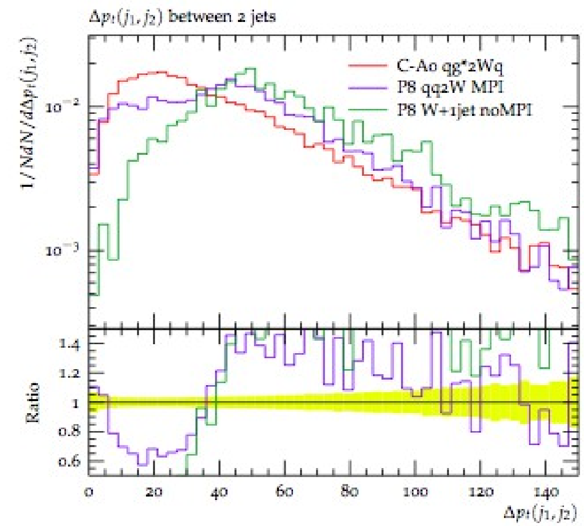
  studies of theor uncertainties in multi-particle final states;

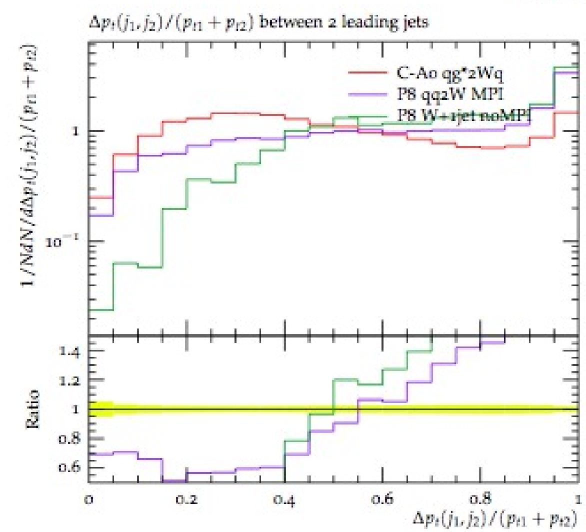
  ex.: W + jets pT spectra and angular correlations

W + 2 jets: signal for double parton interactions?









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

ATLAS, New J Phys 15 (2013) 033038

For jet pT = O(20 GeV) effects from higher orders in kt-shower significant