F Hautmann

CASCADE Monte Carlo for ep physics

Workshop on Future Physics with HERA Data

DESY, November 2014

Motivation

CASCADE

[H Jung et al, EPJ C 70 (2010) 1237
H Jung, Comput Phys Commun 143 (2002) 100
H Jung and G P Salam, EPJ C 19 (2001) 351]

is the first – and, so far, the only - parton shower Monte Carlo using transverse momentum dependent (TMD) initial-state parton distributions.

Motivation

TMDs

spin; low-energy data

Drell-Yan

DIS at high energy

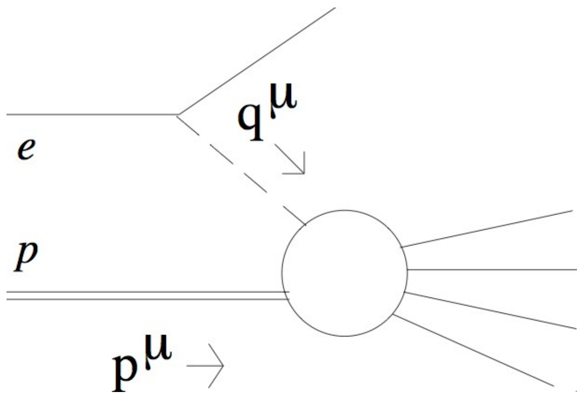
Outline

Hadron structure including
transverse momentum dependence

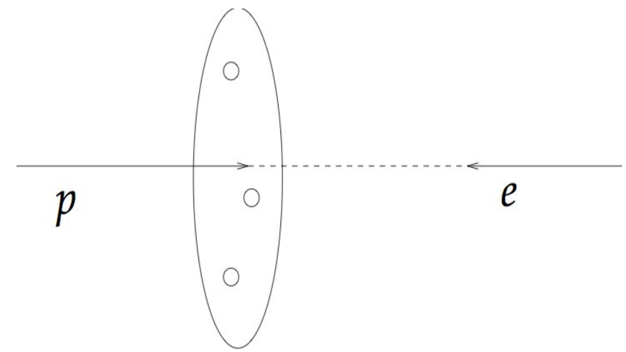
Precision DIS data
and applications at the LHC

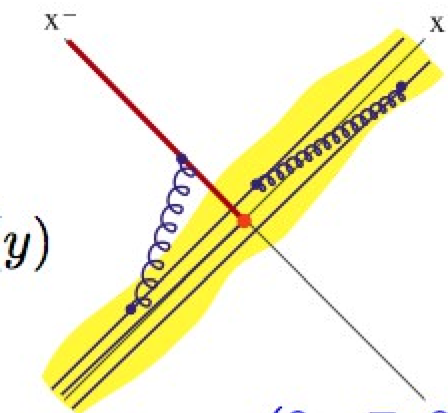
Final states in ep:
jets and particle multiplicities

The collinear parton density functions



DIS in
infinite momentum frame





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

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

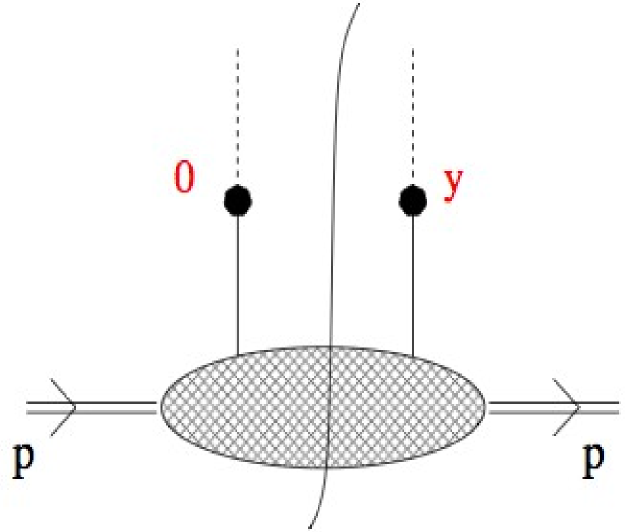
correlation of parton fields at lightcone distances

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

Transverse momentum dependent (TMD) parton density functions

J Collins,
Foundations of perturbative QCD
CUP 2011

Generalize matrix element to non-lightlike distances:



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

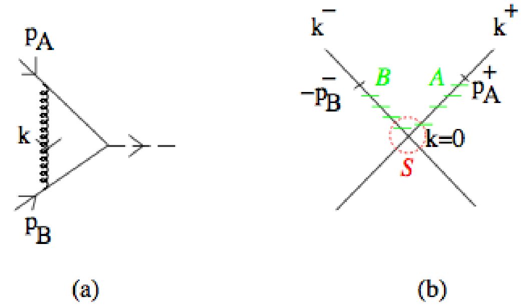
$$\tilde{f}(y) = \langle \, P \mid \overline{\psi}(y) \; V_y^\dagger(n) \; \gamma^+ \; V_0(n) \; \psi(0) \mid P \, \rangle \quad , \qquad y = (0, y^-, y_\perp)$$

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:

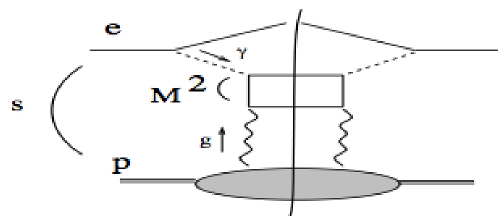


▷ entering Drell-Yan production, W/Z boson $q_\perp$ distribution, . . .

$\Rightarrow \partial S / \partial \eta = K \otimes S$ 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 $1/M$

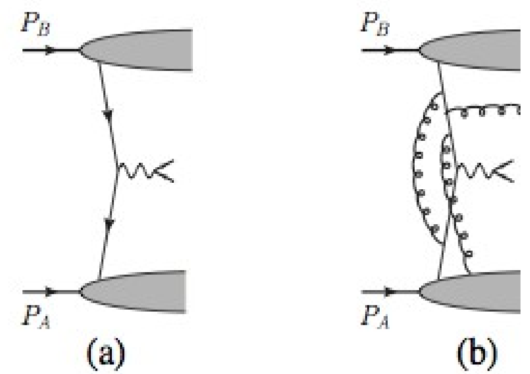
Classic motivations for TMDs (I)
Drell Yan hadroproduction pT spectra

- 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



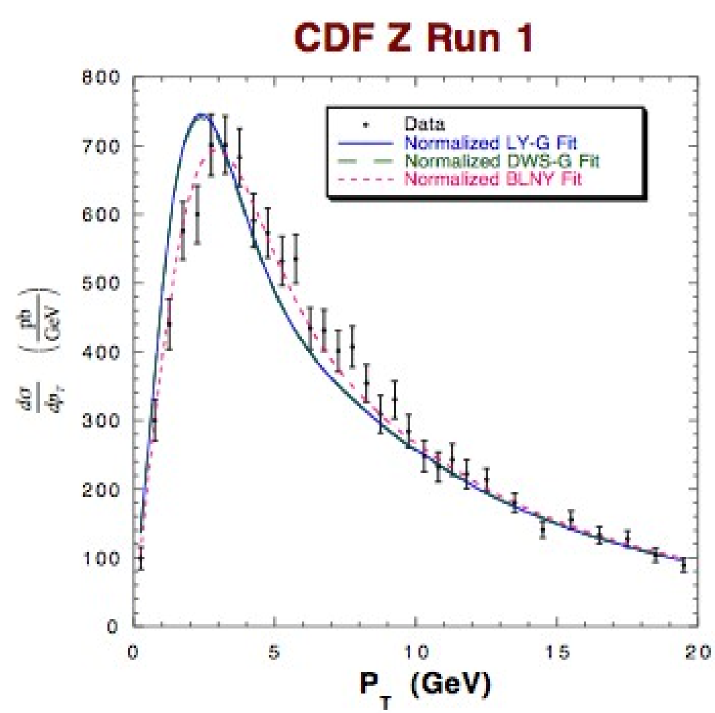
where $\dfrac{\partial \ln f}{\partial \ln \sqrt{\zeta}} = K(b_\perp, \mu)$ and $\dfrac{d \ln f}{d \ln \mu} = \gamma_f(\alpha_s(\mu), \zeta/\mu^2)$

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

cusp anomalous dimension

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

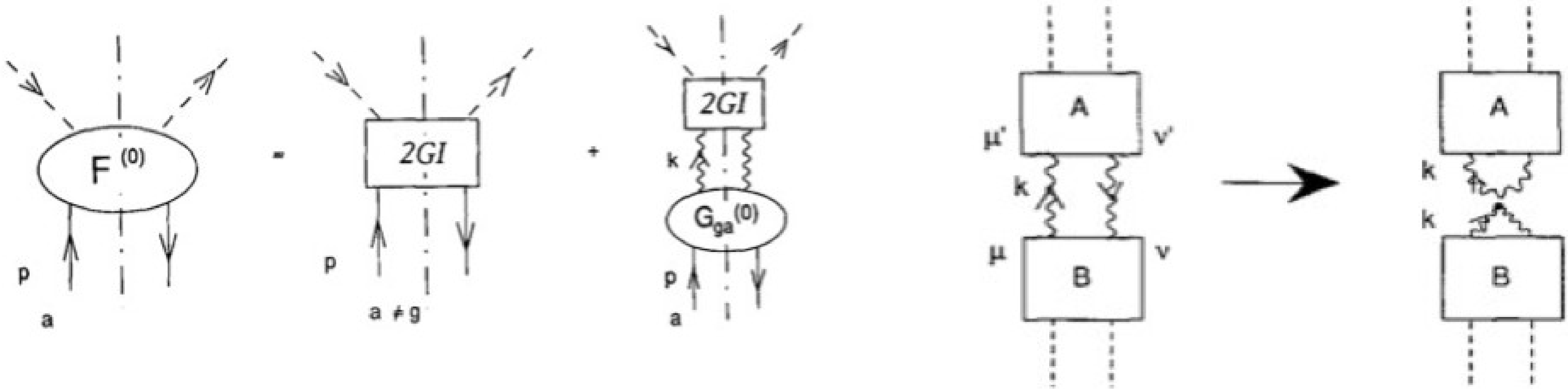
[Echevarria, Idilbi, Scimemi 2012; Chiu, Jain, Neill, Rothstein 2012; Becher, Neubert 2011; Mantry, Petriello 2011]



Landry et al. 2003

Classic motivations for TMDs (II)

DIS at x → 0 : large corrections to fixed order



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

↖ *unintegrated (TMD) gluon density*

↖ high-energy projector (spin and momentum)

"The TMDlib project" http://tmdlib.hepforge.org/

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

TMDlib and TMDplotter:
library and plotting tools for
transverse-momentum-dependent parton distributions
Version 1.0.0

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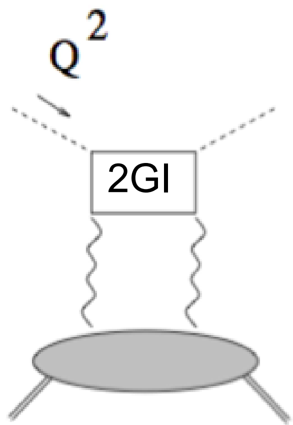
Abstract

Transverse-momentum-dependent distributions (TMDs) are central in high-energy physics from both theoretical and phenomenological points of view. In this manual we introduce the library, TMDlib, of fits and parameterisations for 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.

Example: flavor singlet evolution at small x



flavor non-singlet regular for x → 0

RG evolution :
$$\frac{d}{d\ln\mu^2}\begin{pmatrix}\Sigma\\ G\end{pmatrix} = \begin{pmatrix}\gamma_{qq} & \gamma_{qg}\\ \gamma_{gq} & \gamma_{gg}\end{pmatrix} \otimes \begin{pmatrix}\Sigma\\ G\end{pmatrix}$$

$$\gamma_{gg} = \underbrace{\sum_{k=1}^{\infty} a_k \alpha_s^k x^{-1} \ln^{k-1} x}_{L(x)\ [BFKL]} + (b_0 \alpha_s + \underbrace{\sum_{k=1}^{\infty} b_k \alpha_s \alpha_s^k x^{-1} \ln^{k-1} x}_{NL(x)}) + \dots$$

$$\gamma_{qg} = c_0 \alpha_s + \underbrace{\sum_{k=1}^{\infty} c_k \alpha_s \alpha_s^k x^{-1} \ln^{k-1} x}_{NL(x)} + \dots$$

- TMD factorization ⇒ well-defined resummation of $\alpha_s^n \ln^{n-m} x$ corrections to anomalous dim's (splitting functions) as well as DIS coefficient functions

Example: DIS F_2 coefficient function from TMD factorization

$$C^g_{2,N}(\alpha_s, Q^2/\mu^2) = \int_0^1 dx\, x^{N-1}\, C^g_2(x, \alpha_s, Q^2/\mu^2)$$

Mellin moments

$$C^g_{2,N}(\alpha_s, Q^2/\mu^2 = 1)$$
$$= \frac{\alpha_s}{2\pi} T_R N_f \frac{2}{3} \left\{ 1 + 1.49\, \frac{\overline{\alpha}_s}{N} + 9.71 \left(\frac{\overline{\alpha}_s}{N}\right)^2 + 16.43 \left(\frac{\overline{\alpha}_s}{N}\right)^3 + \mathcal{O}\left(\frac{\alpha_s}{N}\right)^4 \right\}$$

LO NLO NNLO (MVV 2004)

[Catani & H (1994)]

$$\alpha_s(\alpha_s/N)^k \leftrightarrow \alpha_s^2(\alpha_s \ln x)^{k-1}$$

Need for single-log resummations
[cf. double-log (x → 1, x → 0 timelike): e.g., A. Vogt, talk at DIS2012, Bonn]

What can we learn from high-precision deep inelastic scattering (DIS) data?

Phenomenological applications require matching small-x contributions with medium and large x

Beyond x → 0: CCFM exclusive evolution

→ Catani-Ciafaloni-Fiorani-Marchesini

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

- solve integral equation via iteration:

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

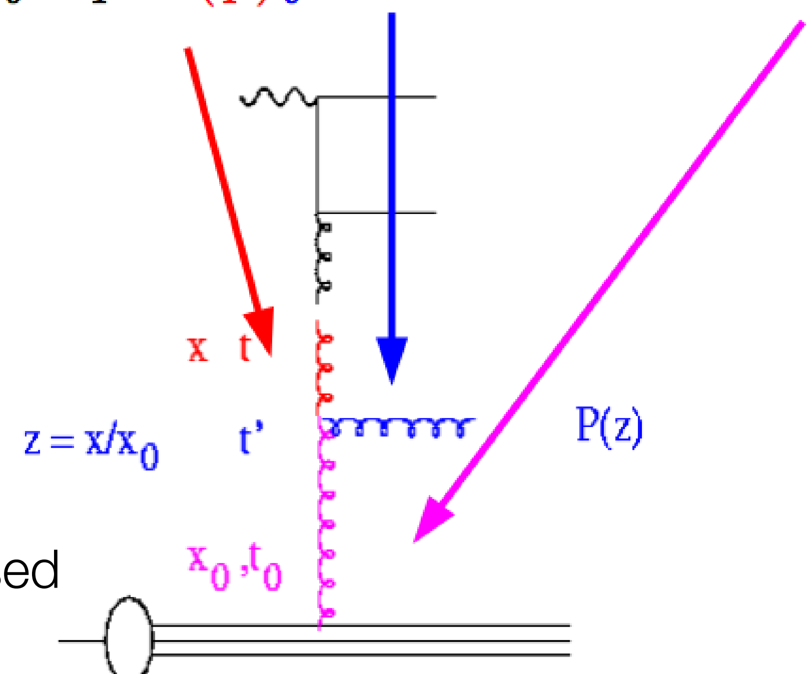
$$x\mathcal{A}_1(x,k_t,q) \quad = \quad x\mathcal{A}(x,k_t,q_0)\Delta(q) + \int \frac{dq'}{q'}\frac{\Delta(q)}{\Delta(q')}\int dz\tilde{P}(z)\frac{x}{z}\mathcal{A}(x/z,k_t',q_0)\Delta(q')$$

from q' to *q* w/o branching

branching at q'

from q_0 to q' w/o branching

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

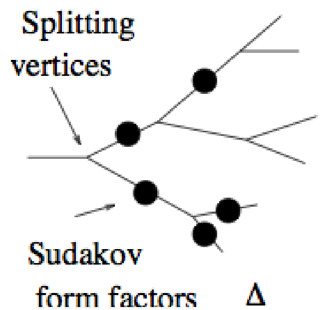


- evolution code uPDFevolv publicly released [Jung, Taheri Monfared & H, EPJ C 74 (2014) 3082 [arXiv:1407.5935]]

Physical interpretation in terms of parton showers

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

$\diamondsuit$ QCD evolution by “parton showering” methods:

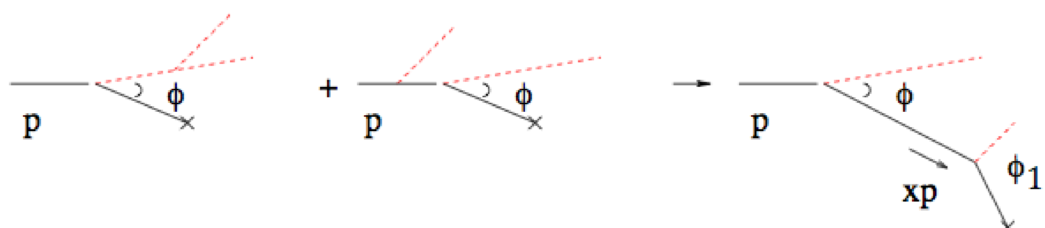


$$d\mathcal{P} = \int \frac{dq^2}{q^2} \int dz \, \alpha_S(q^2) \, P(z) \, \Delta(q^2, q_0^2)$$

$\hookrightarrow$ collinear, incoherent emission

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

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

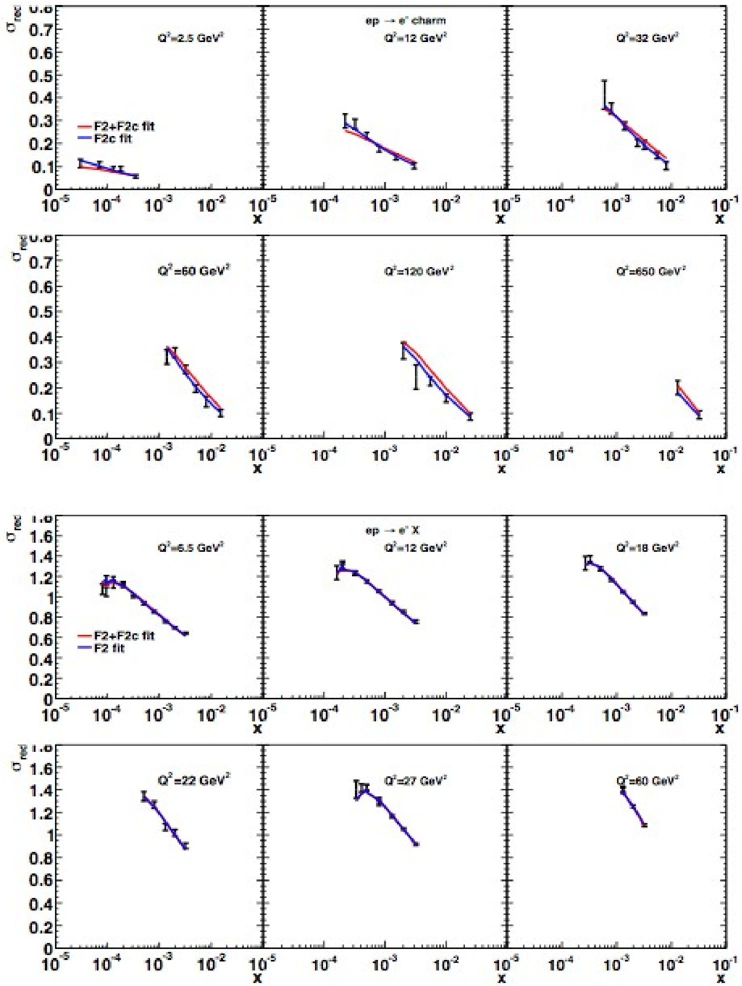


$\diamondsuit$ Gluon coherence for $x \ll 1$ $\Rightarrow$ corrections to angular ordering:

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

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

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 arXiv:1410.4412 [hep-ph] https://www.herafitter.org/

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

kT-dependent gluon density from precision DIS data

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

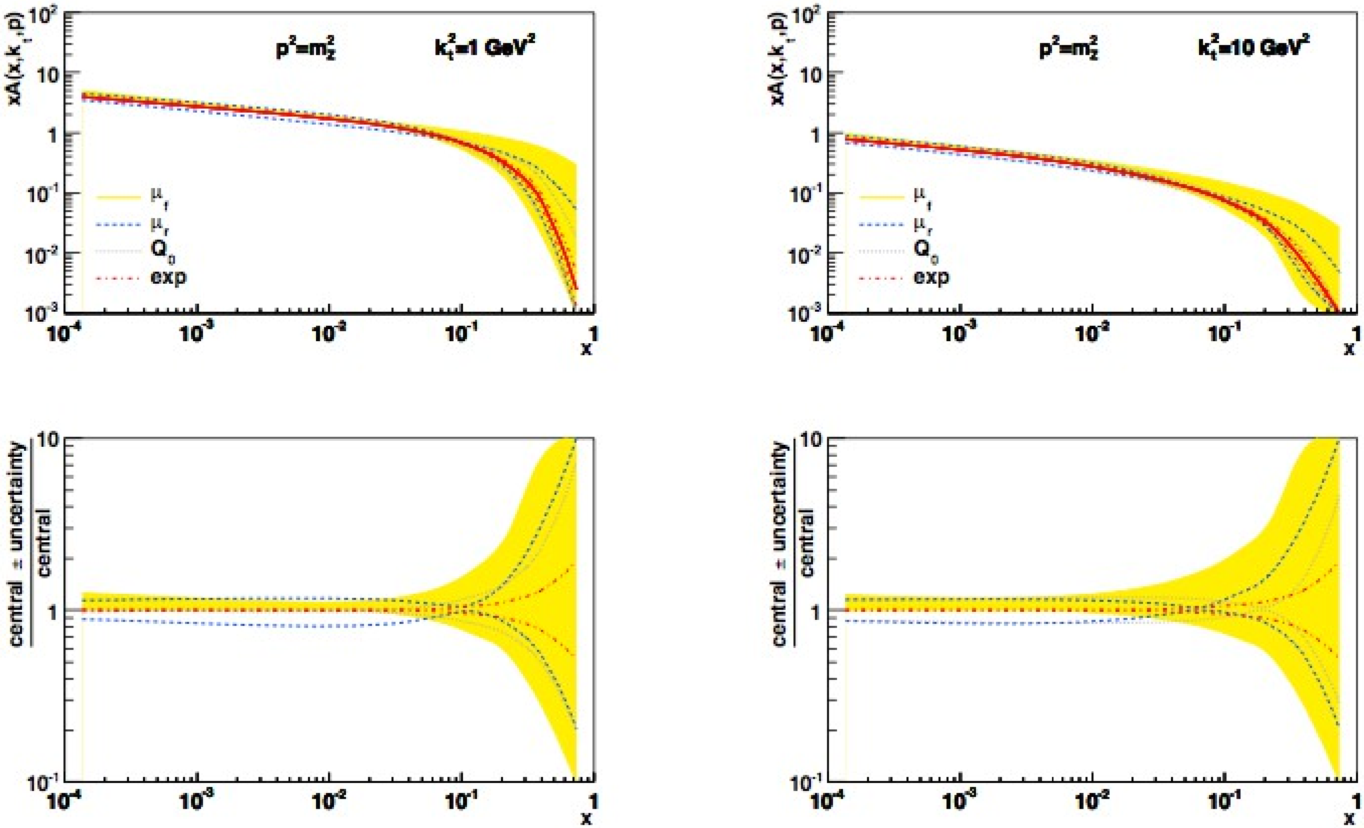


FIG. 6. *Experimental and theoretical uncertainties of the unintegrated TMD gluon density versus x for different values of transverse momentum at $p^2 = m_Z^2$. The yellow band gives the uncertainty from the factorization scale variation; the curves indicate the uncertainties from the other sources.*

Can we go to large transverse momenta?

Applications to LHC final states

Application to vector bosons + jets

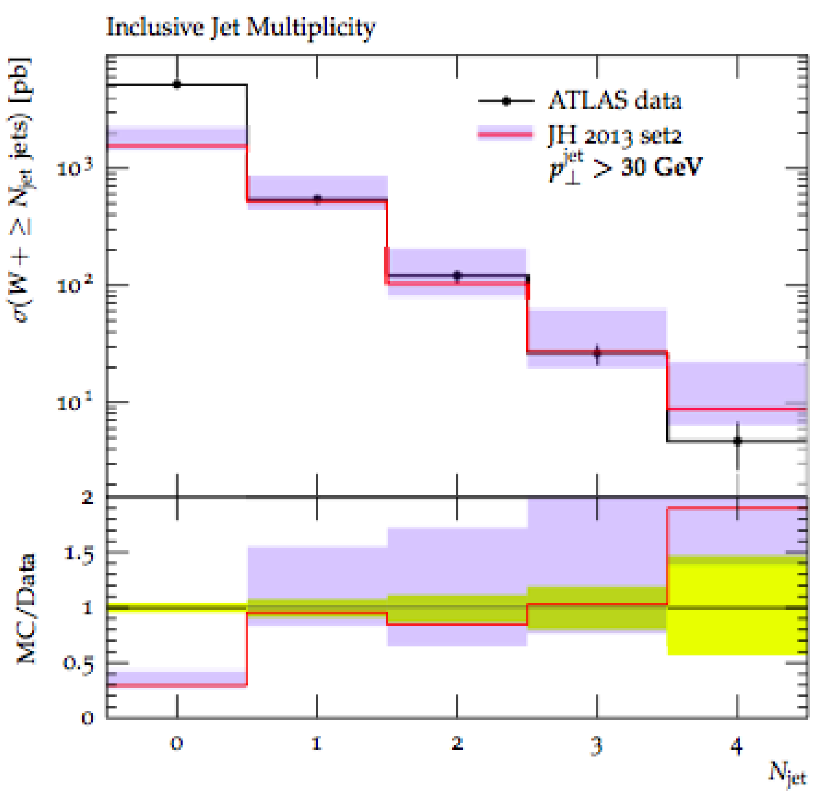
- Motivation: effects of not only collinear-ordered emissions but also non-ordered region which opens up at high s / pt^2 (and large pt).
- Finite angle multi-gluon radiation.
- Push limits of high-energy expansion beyond small-x region.

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

- Jet multiplicities associated with W boson production

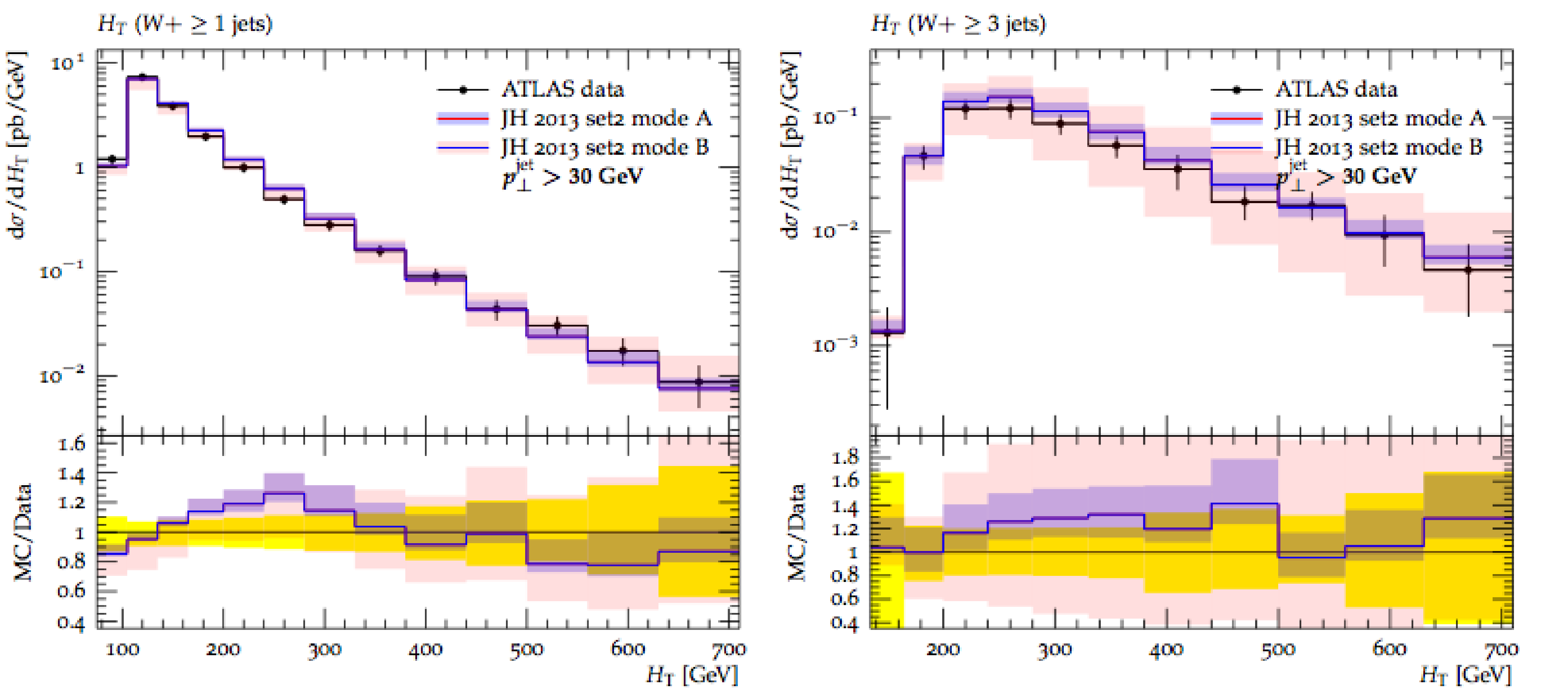
Atlas data PRD85 (2012) 092002: jet | y | < 4.4

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

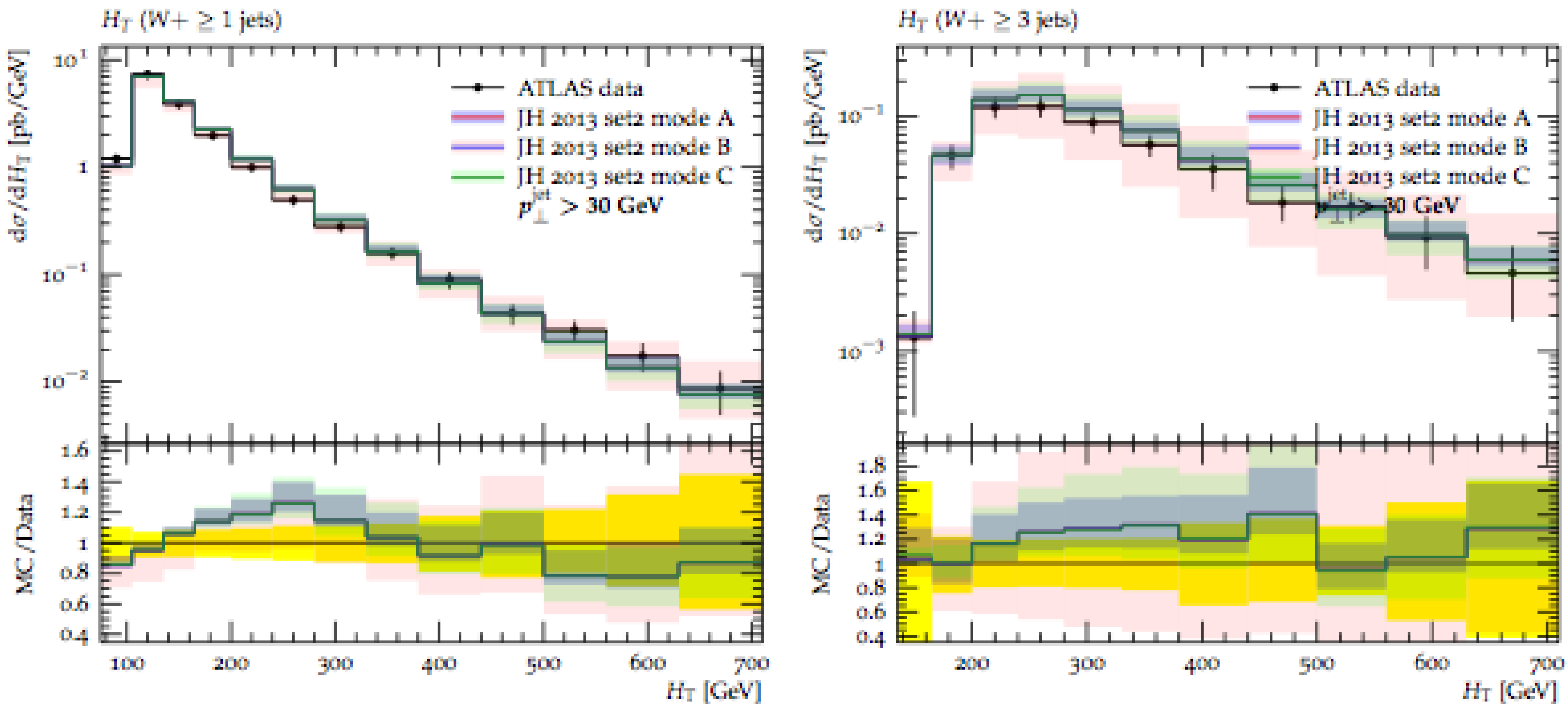
Dooling, Jung & H, Phys. Lett. B736 (2014) 293



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

mode B: include factorization scale uncertainties

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



mu^2 = m^2 + qT^2

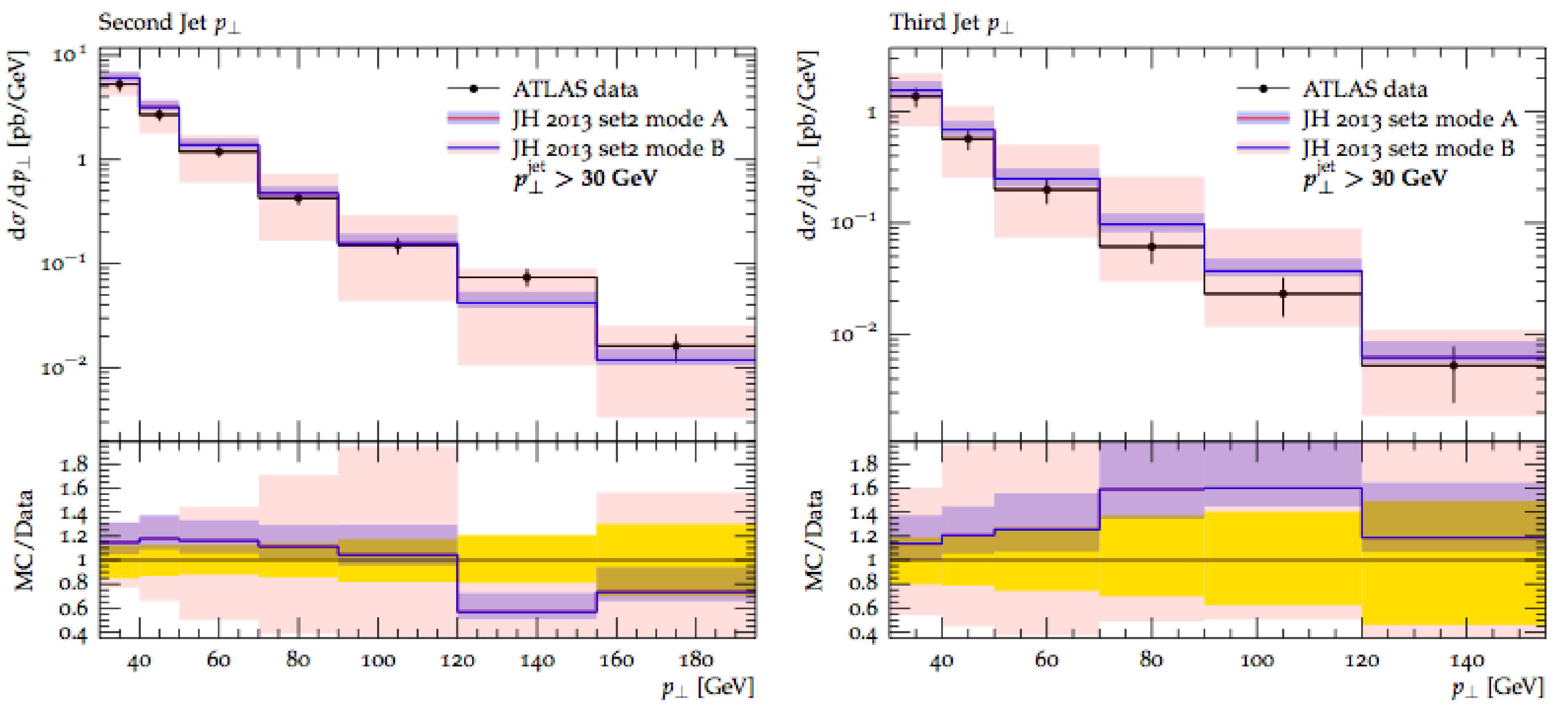
Dooling, Jung & H, Phys. Lett. B736 (2014) 293

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 subleading jets

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



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

What do we gain?

- Uses of TMD pdfs + kt-dependent shower:

  matching with 2 → n off-shell parton calculations

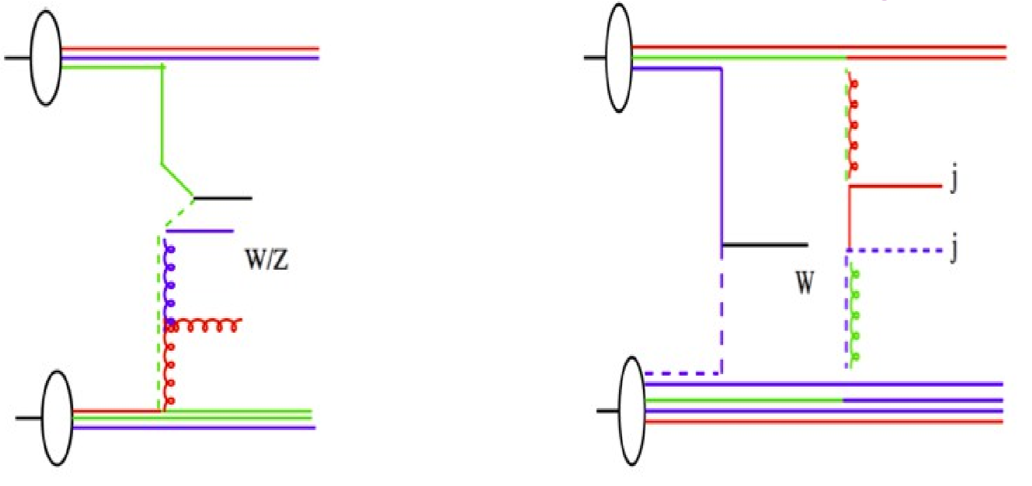
  (automated method, see van Hameren, Kotko & Kutak JHEP 1301 (2013) 078)

- 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

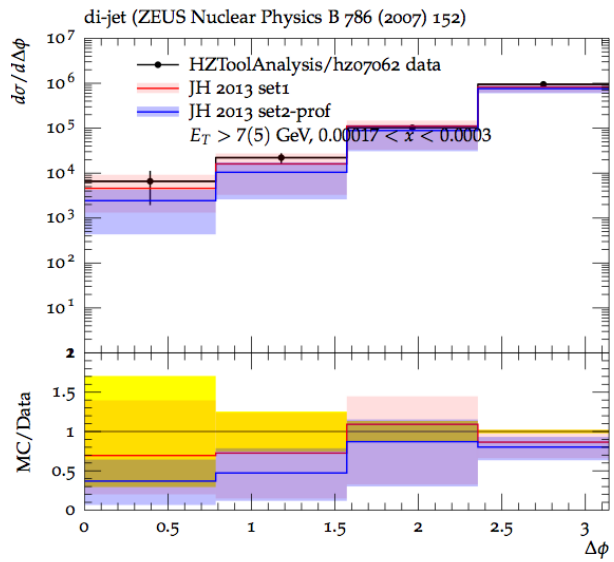
Going to lower pT in ep final states:

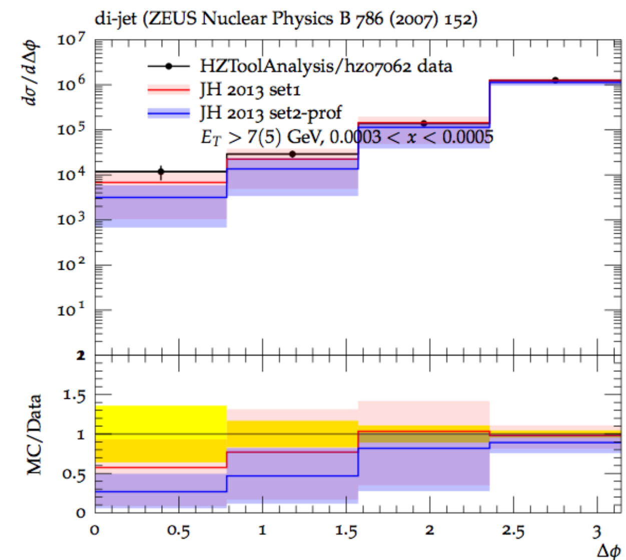
DIS jets

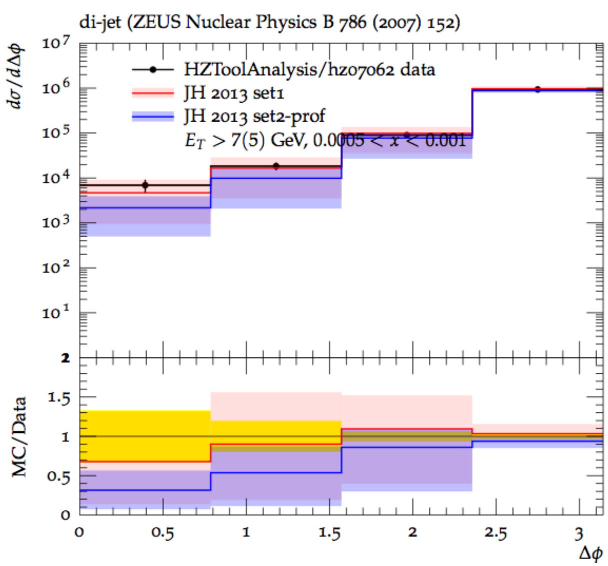
charged particle multiplicities

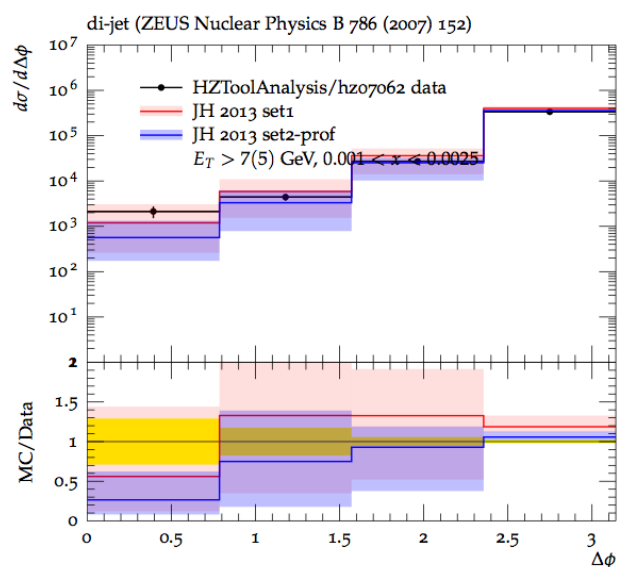
DIS dijet azimuthal distribution

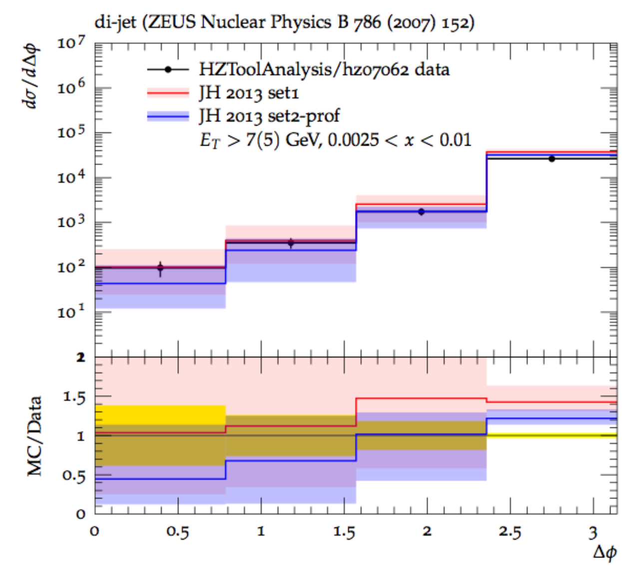
- CASCADE with new TMD pdfs from precision F2 and F2-charm data
- ZEUS 2007 jet measurements





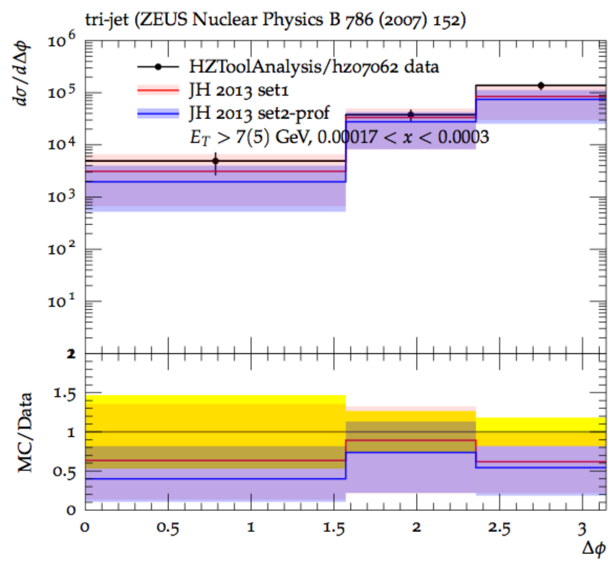


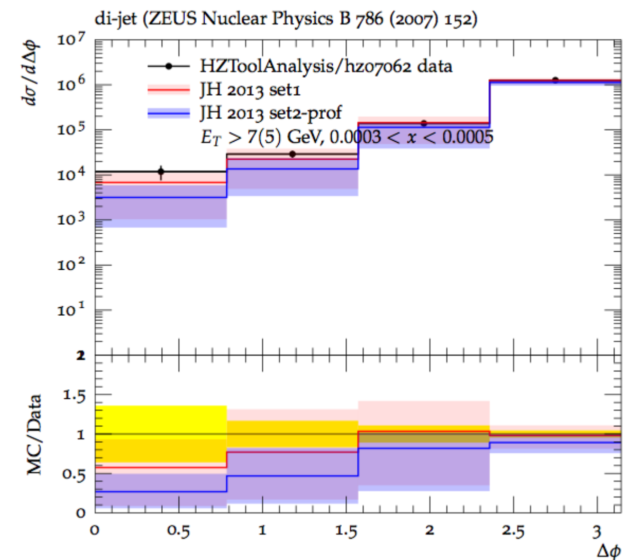


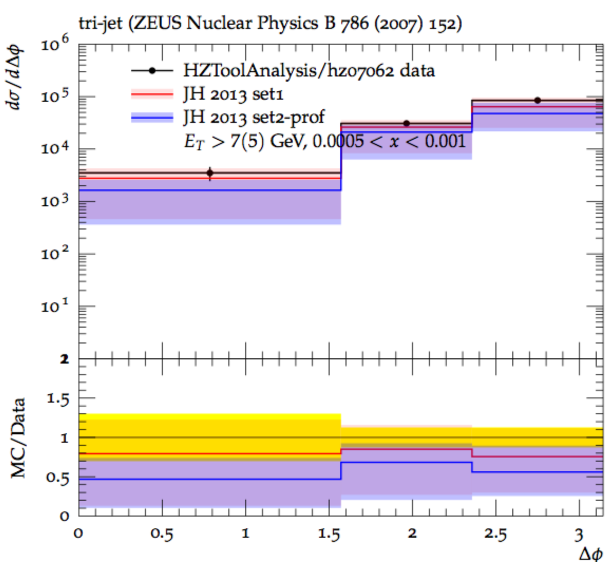


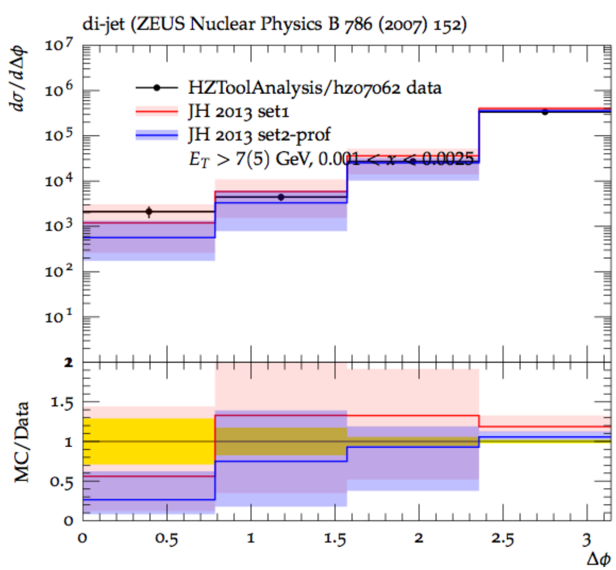
DIS 3-jet production

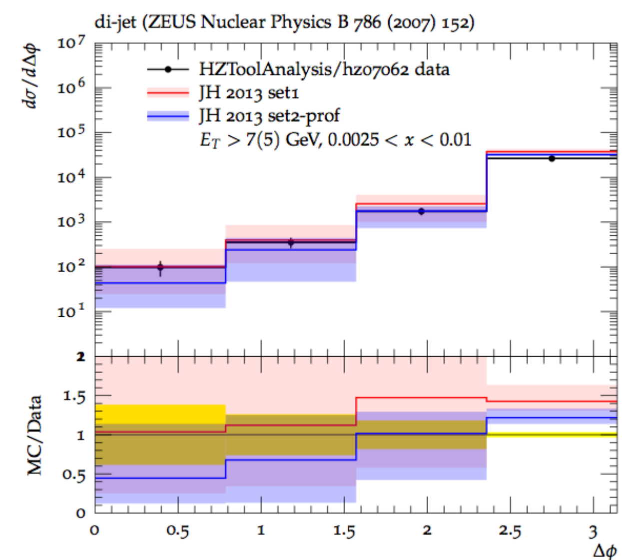
- CASCADE with new TMD pdfs from precision F2 and F2-charm data
- ZEUS 2007 jet measurements





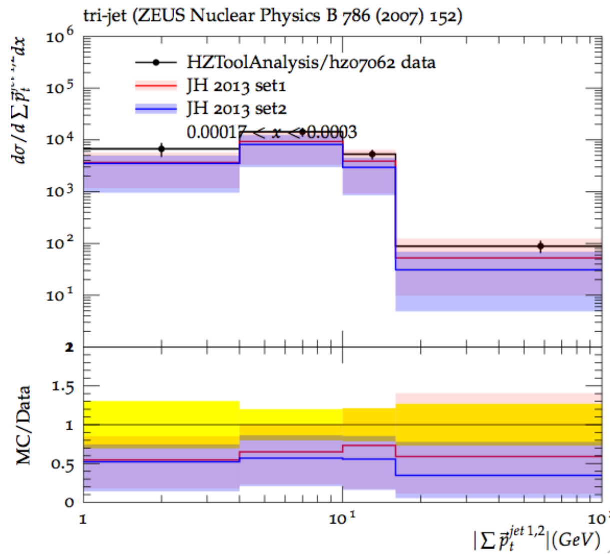


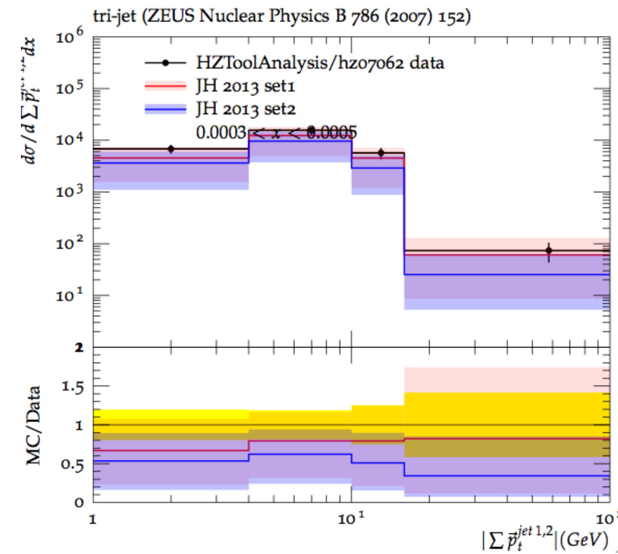


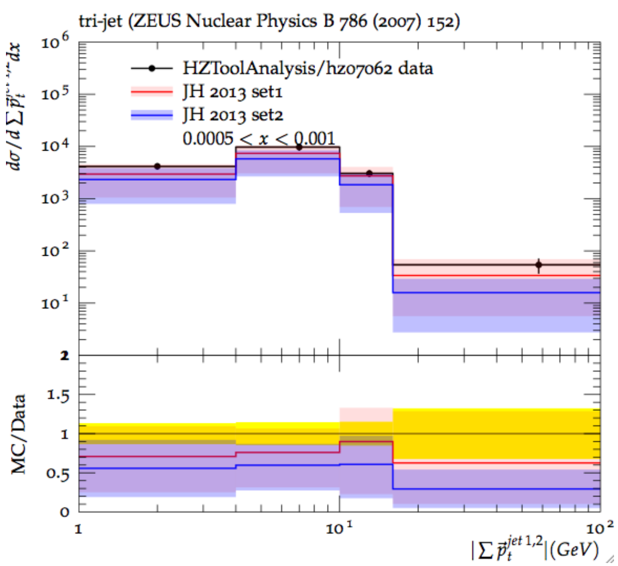


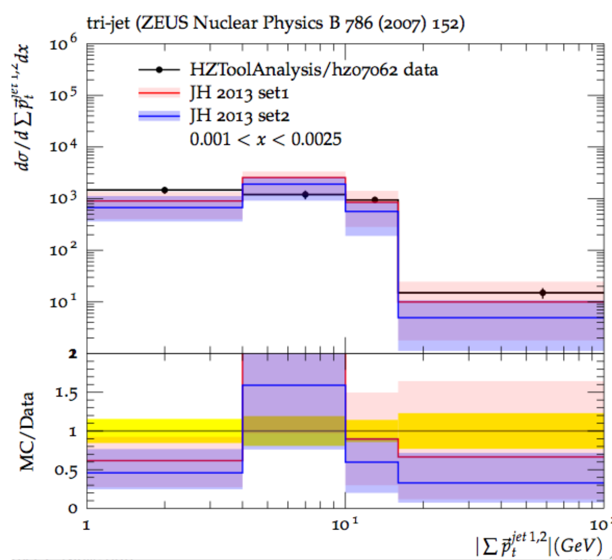
Momentum correlations $|\sum p_T^{1,2}|$

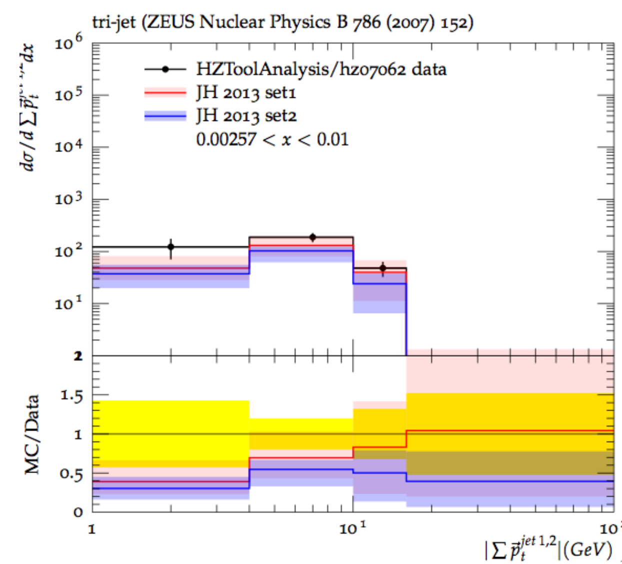
- pT imbalance in trijets





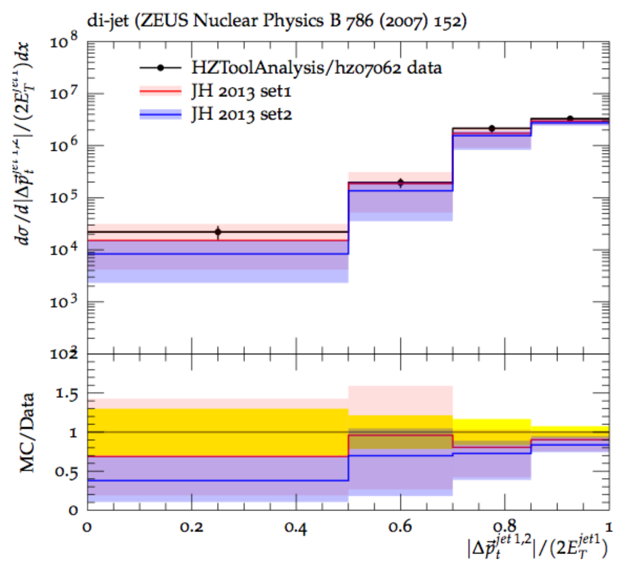


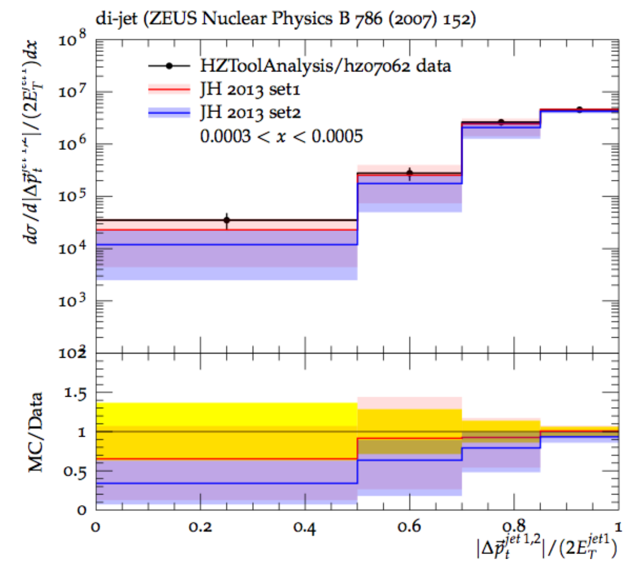


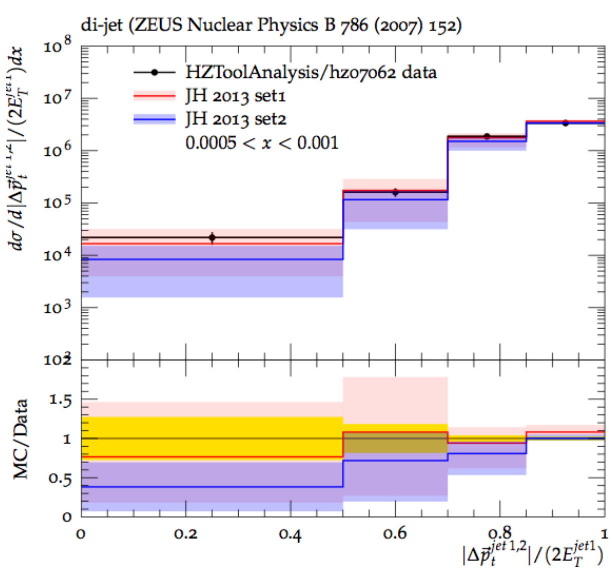


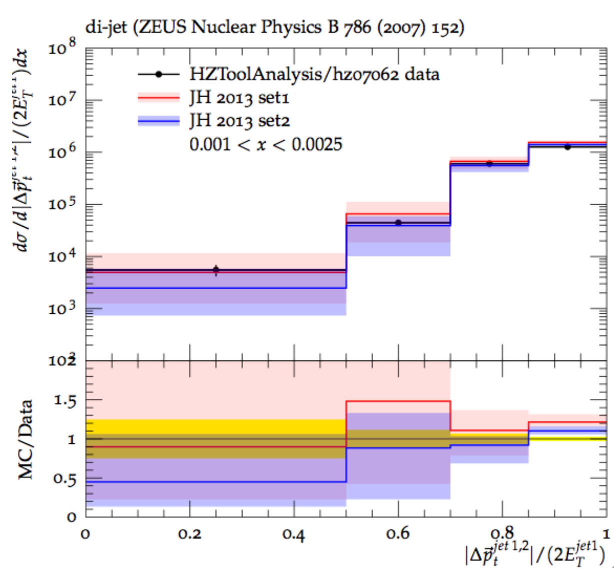
Momentum correlations $|\Delta p_T^{1,2}|/(2E_T^1)$

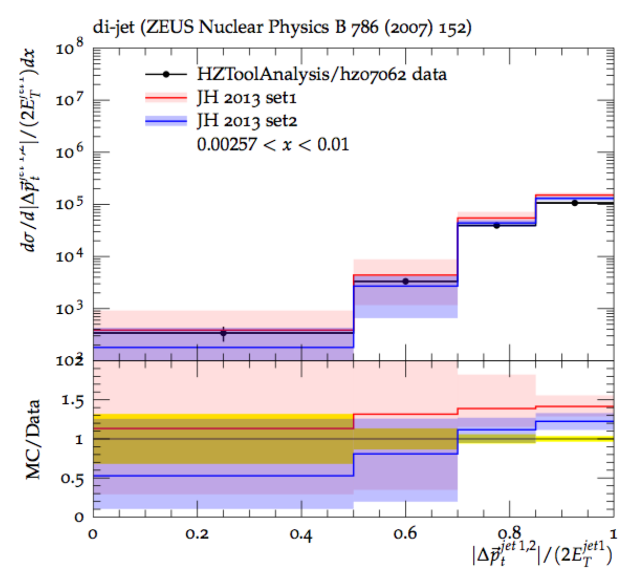
- pT imbalance in dijets



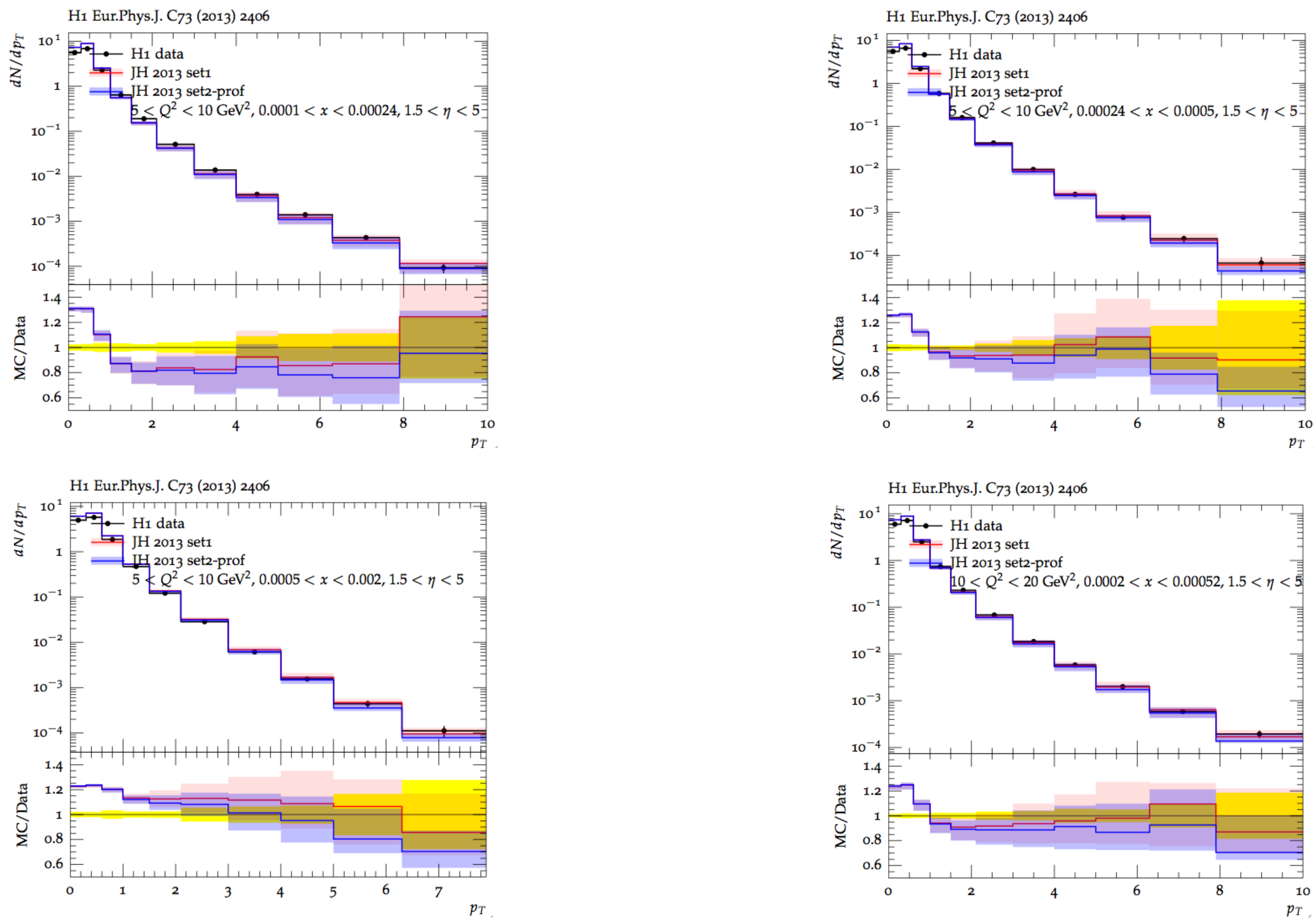






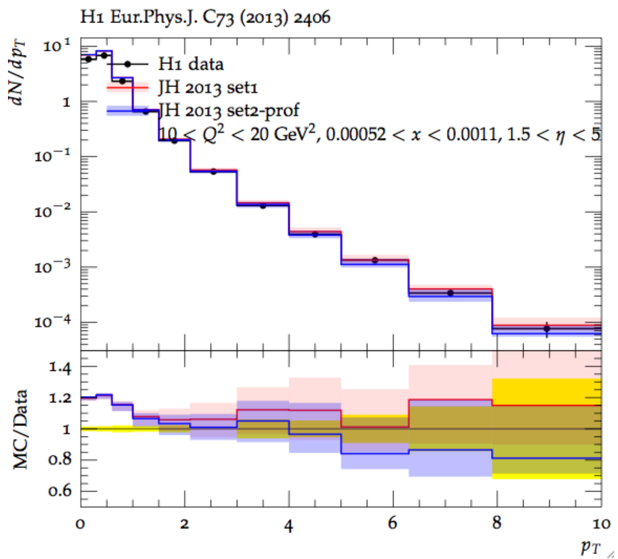


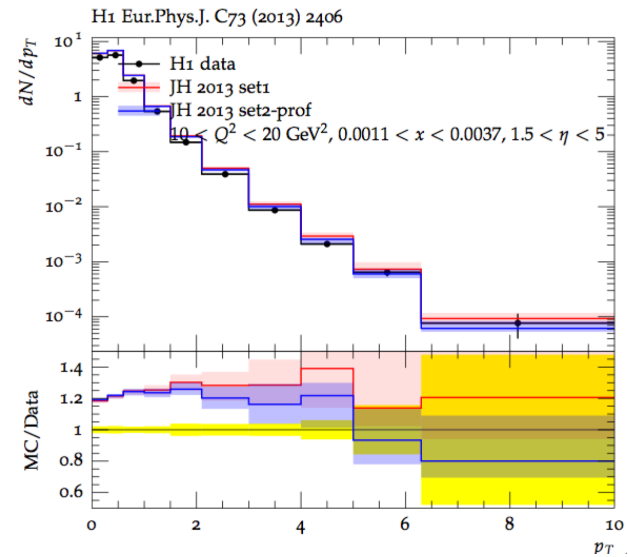
Charged particle spectra in the central region

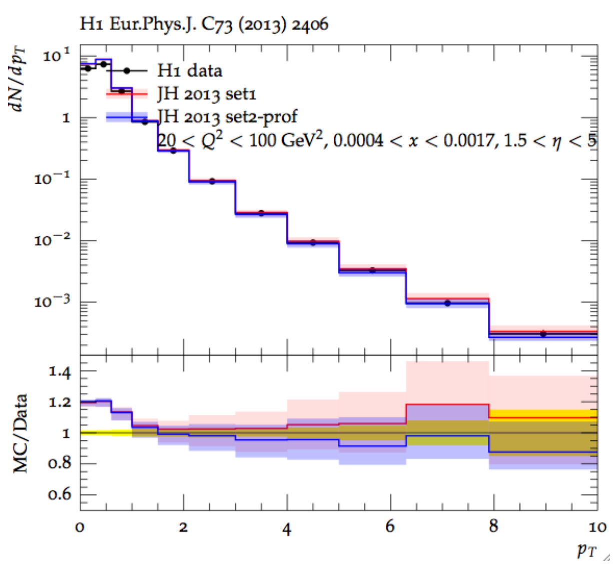


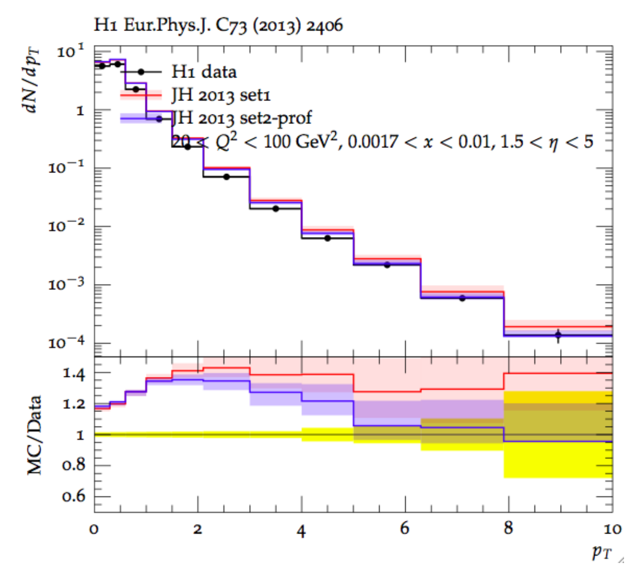
Could this be used to constrain TMD pdfs at low transverse momenta?

Charged particle spectra in the central region









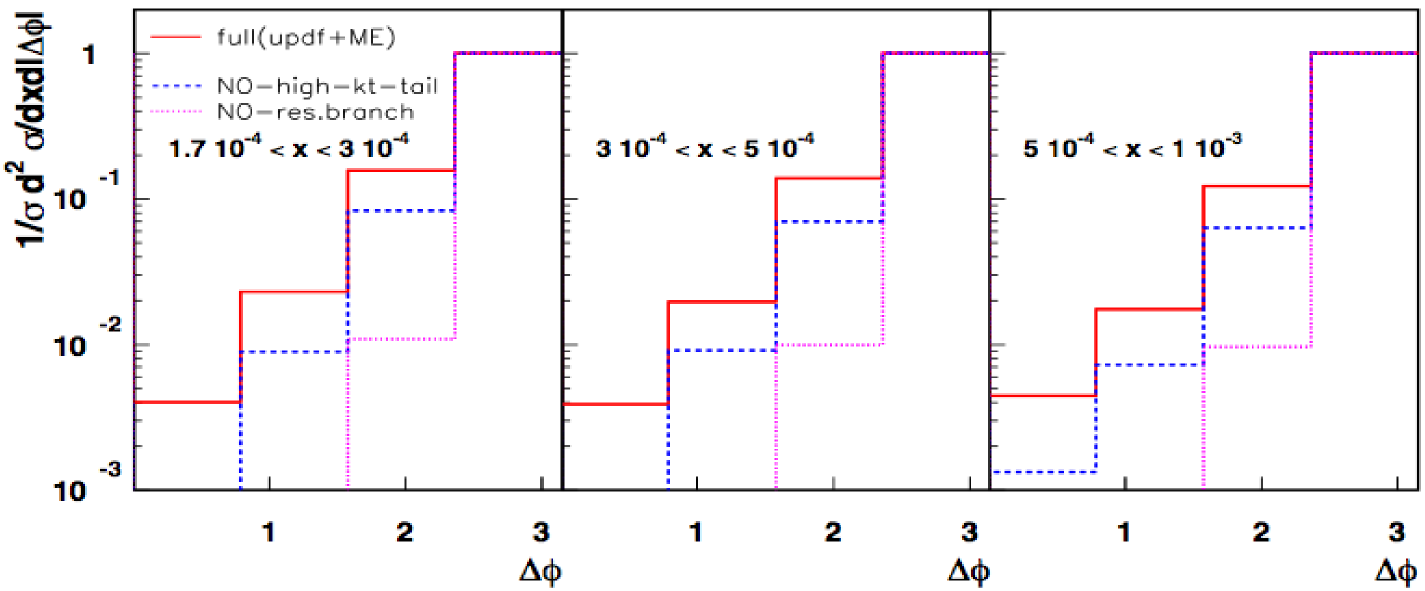
Could this be used to constrain TMD pdfs at low transverse momenta?

Conclusion

- TMD proton structure 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 [→ 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

Extra slides

Normalize to the back-to-back cross section:



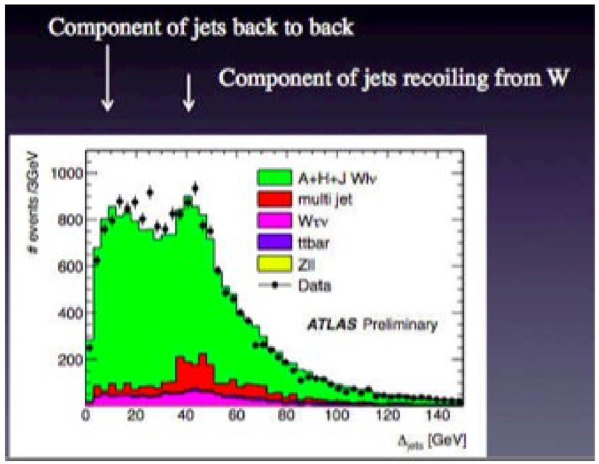
——— updf $\oplus$ ME

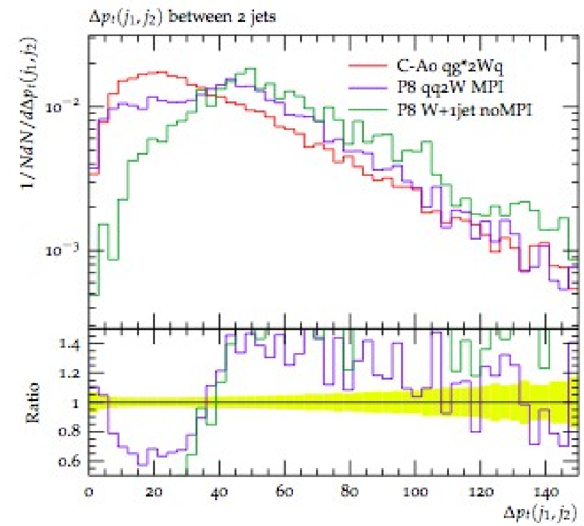
- - - updf $\oplus$ ME$_{collin.}$: $\mathcal{M} \to \mathcal{M}_{collin.}(k_T) = \mathcal{M}(0_\perp)\ \Theta(\mu - k_T)$

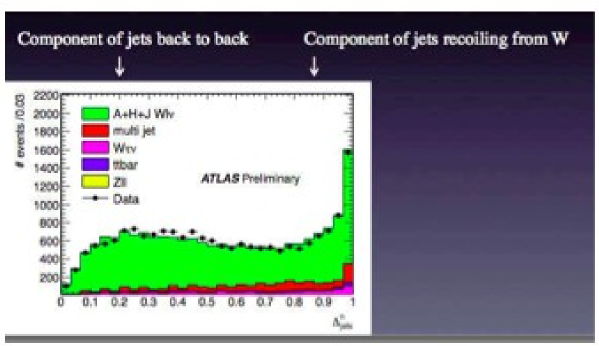
· · · · · · no resolved branching : $\mathcal{A} \to \mathcal{A}_{no-res.}(x, k_T, \mu) = \mathcal{A}_0(x, k_T, Q_0)\ \Delta(\mu, Q_0)$

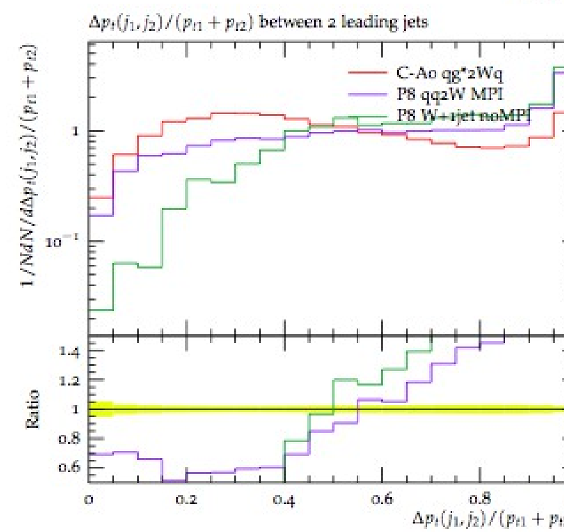
▷ high-$k_\perp$, coherent effect essential for correlation at small $\Delta\phi$

W + 2 jets: signal for double parton interactions?







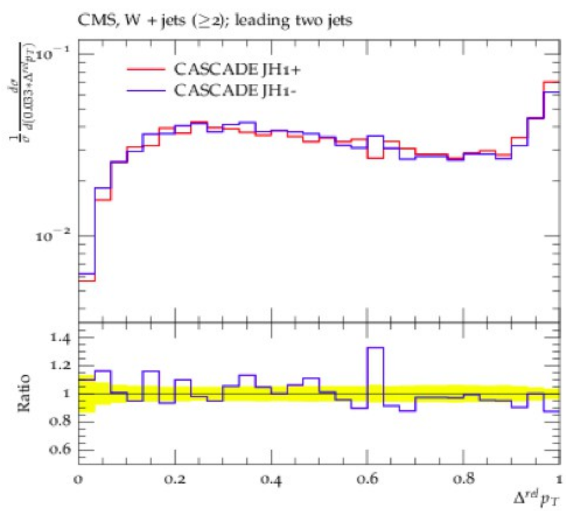


[E. Dobson, talk at MPI-TAU Workshop, October 2012]

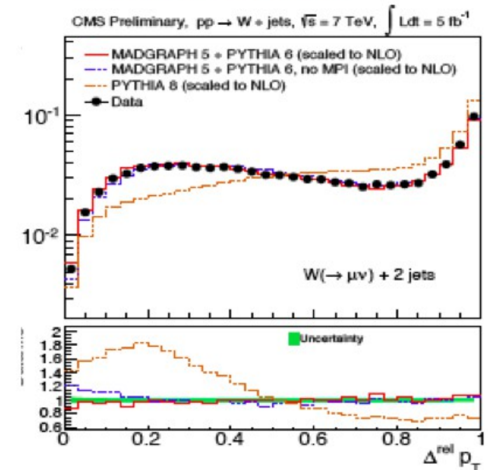
ATLAS, New J Phys 15 (2013) 033038

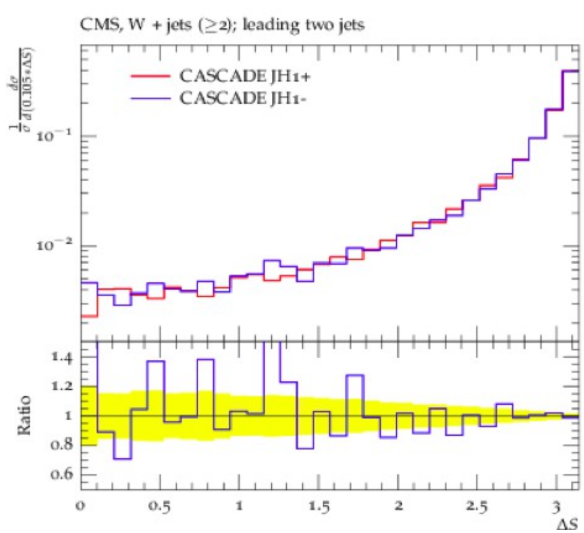
For jet pT = O(20 GeV) effects from higher orders in kt-shower significant

W + 2 jets: signal for double parton interactions?



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





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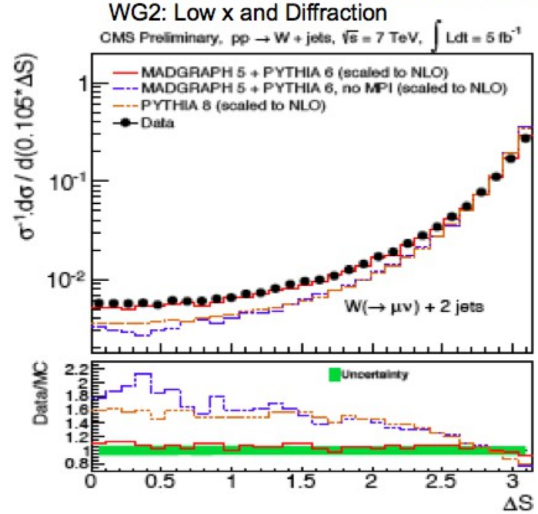


How much room is left for DPI in the framework of kt-shower?

Kinematic effects in parton shower evolution

S. Dooling, talk at DIS 2013, Marseille

Longitudinal Momentum Shift

Dooling et al.
arXiv:1212.6264

In SMC:

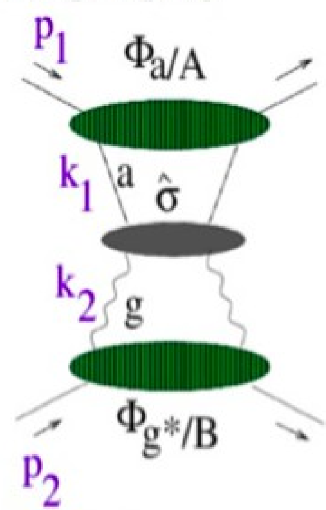
hard subprocess is generated with full 4-momentum for the external lines

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

Factorized jet cross section at high rapidity



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

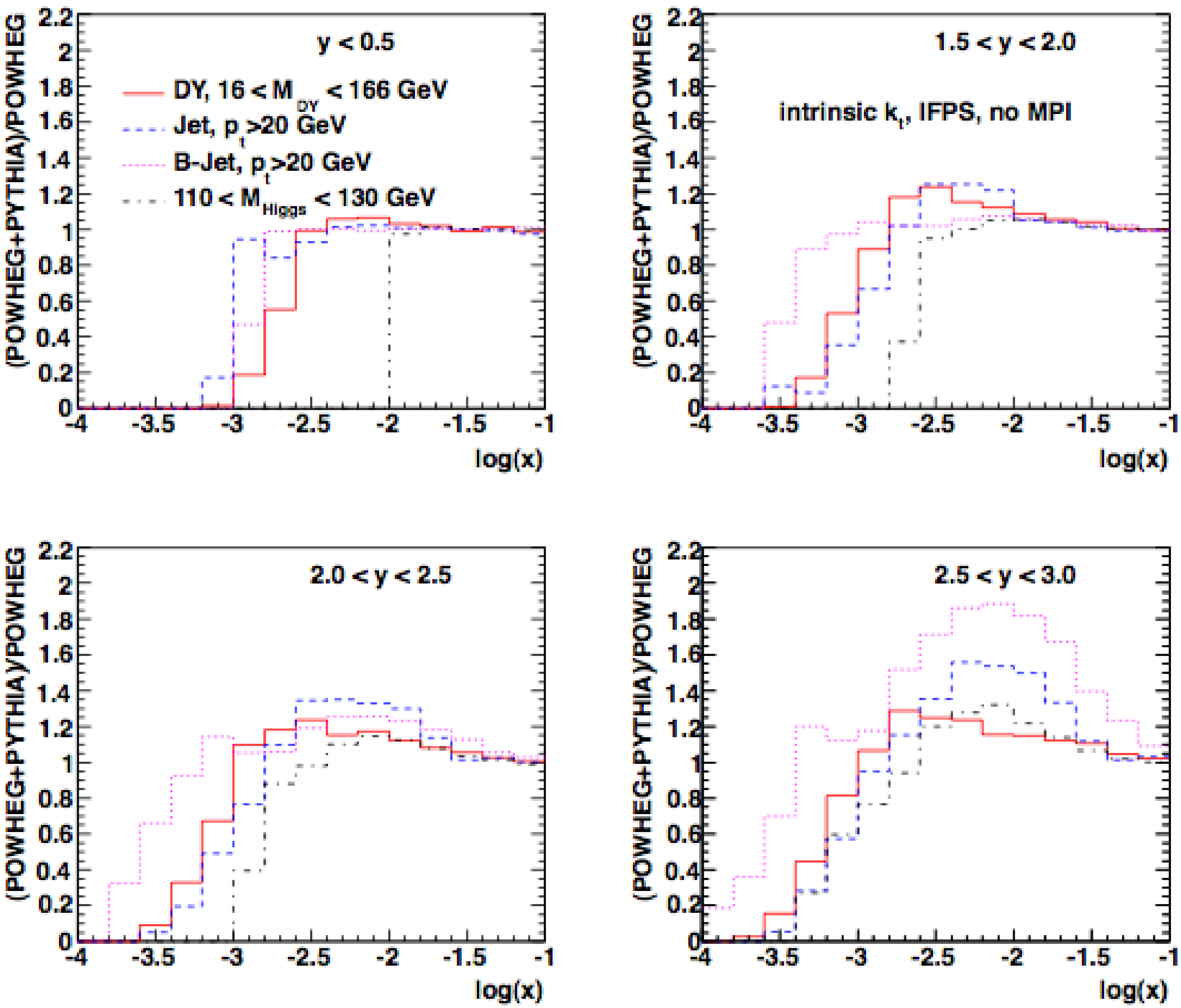
Collinear approximation ⊗ energy momentum conservation

=

kinematic shift in longitudinal momentum distribution due to showering

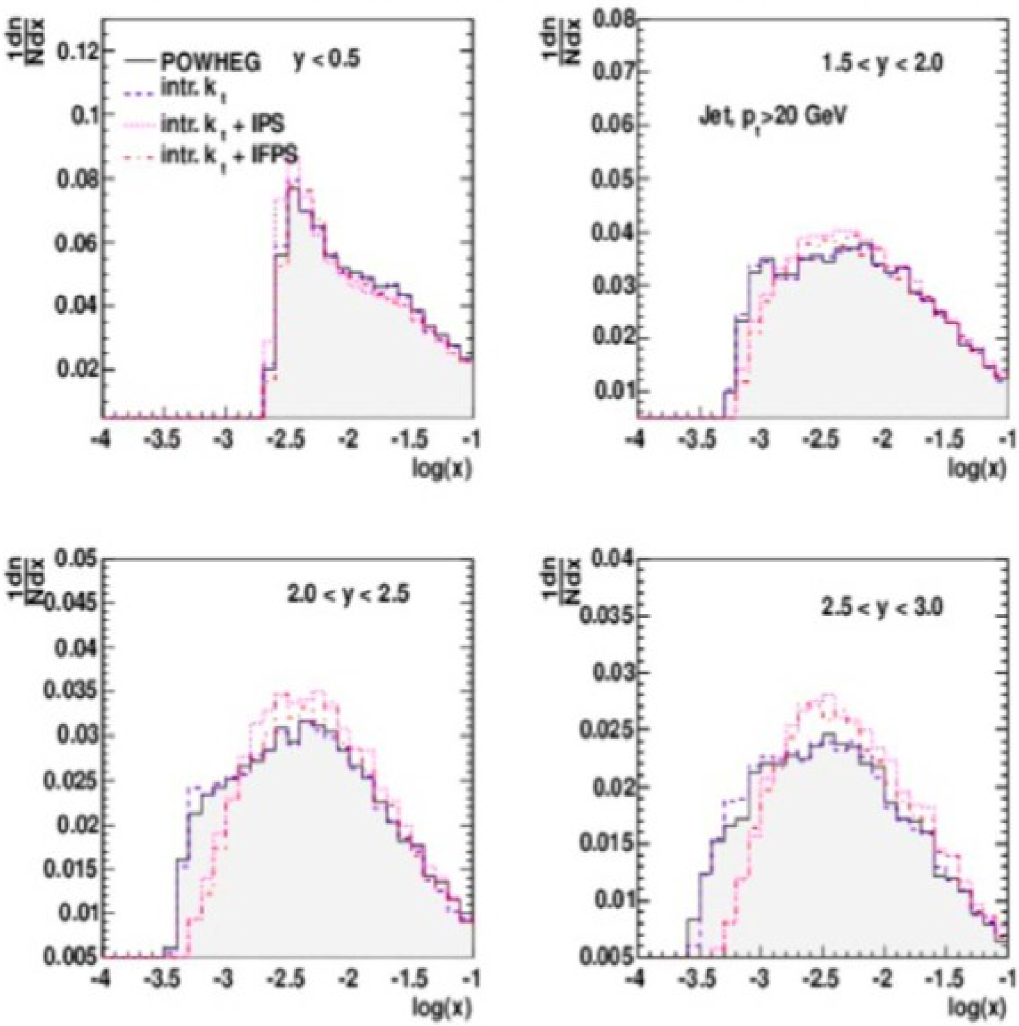
Kinematic effects in parton shower evolution

- Longitudinal momentum shifts due to energy-momentum conservation combined with collinearity approximation [S. Dooling et al., arXiv:1212.6264]
- Non-negligible effect especially in data/theory comparisons for high rapidity jets.



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

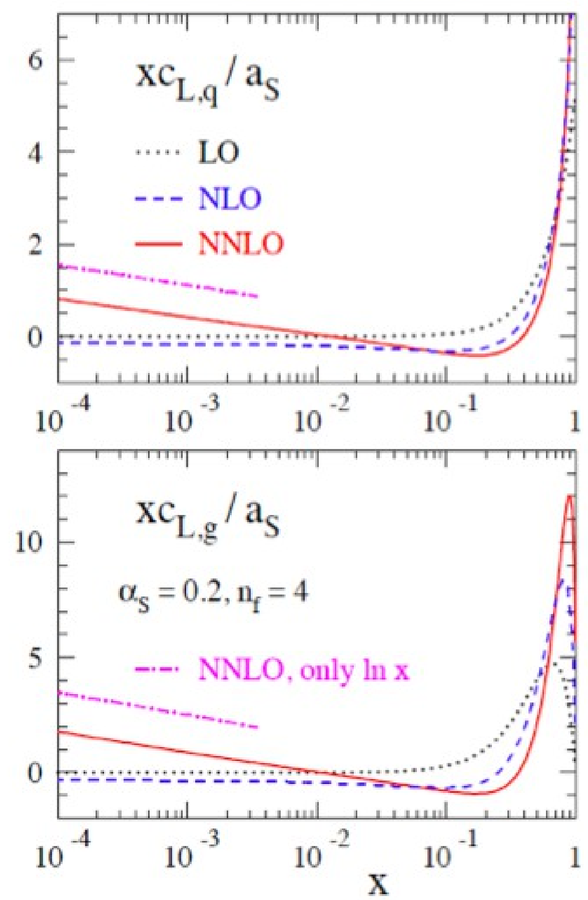
[S. Dooling, talk at DIS 2013]

Classic motivations for TMDs (II)

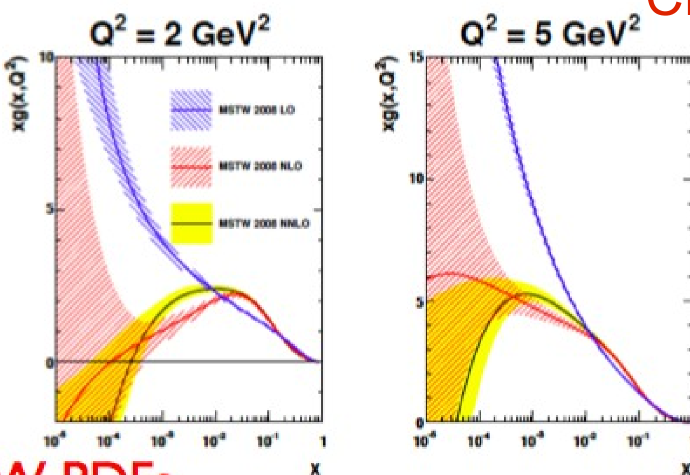
DIS at x → 0 : large corrections to fixed order

A Stasto, talk at VHECR2014, CERN, Aug 2014

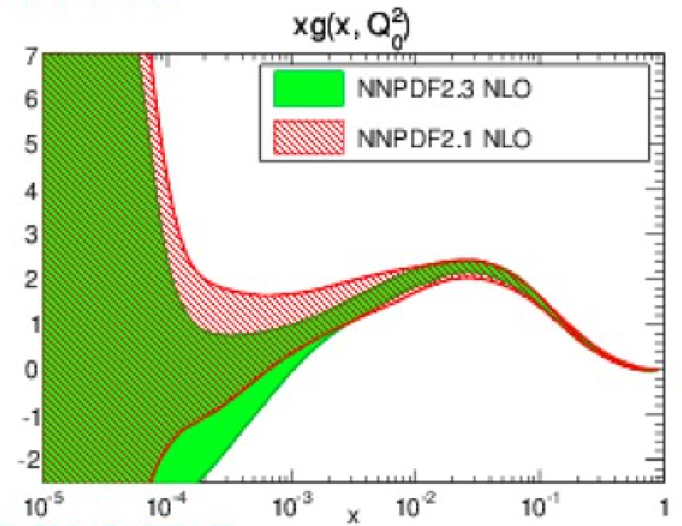
$$x^{-1}F_L = C_{L,\mathrm{ns}} \otimes q_{\mathrm{ns}} + \langle e^2 \rangle \left(C_{L,q} \otimes q_s + C_{L,g} \otimes g \right)$$



Moch, Vermaseren, Vogt



MSTW PDFs



NNPDF2.3 PDFs

kT-dependent gluon density from precision DIS data

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

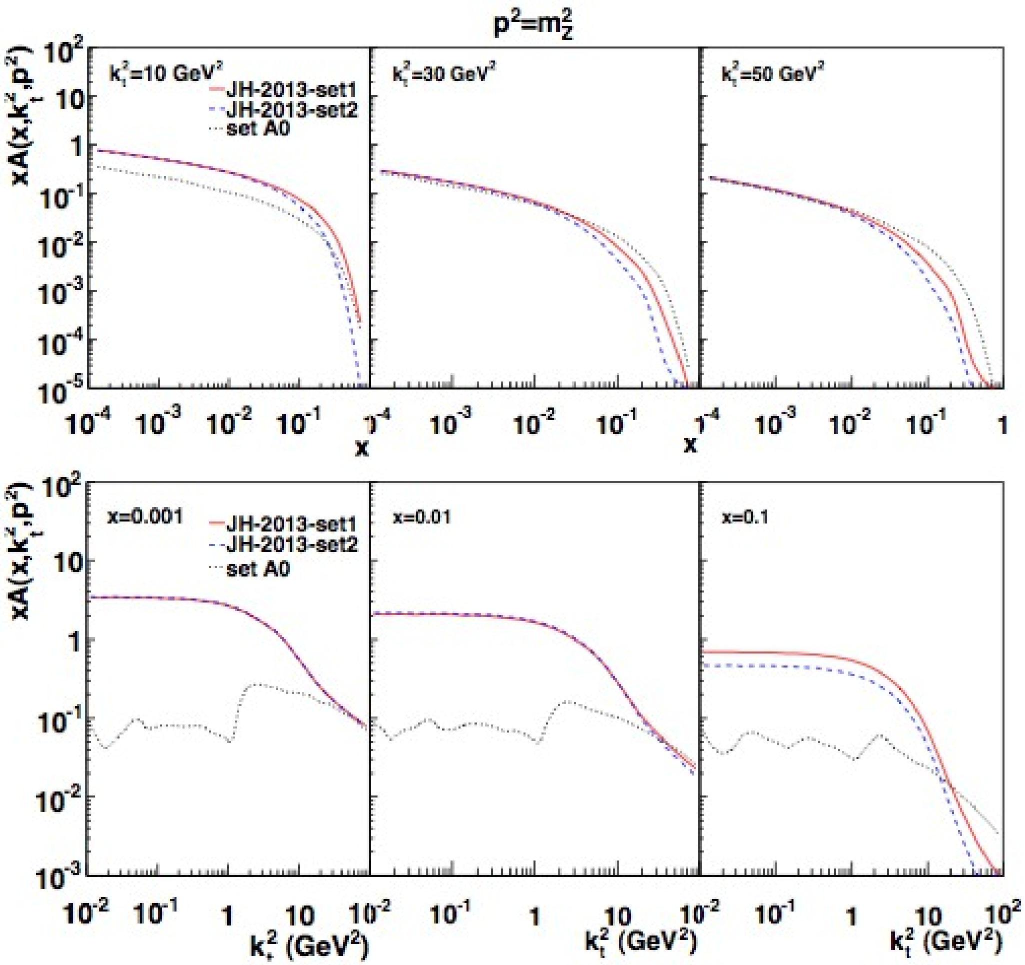


FIG. 4. *Unintegrated TMD gluon density (JH-2013-set1 and JH-2013-set2) at evolution scale equal to the Z-boson mass, $p^2 = m_Z^2$: (top) as a function of x for different values of k_t^2; (bottom) as a function of k_t^2 for different values of x. The results are compared with set A0 [35].*

Integrated pdfs

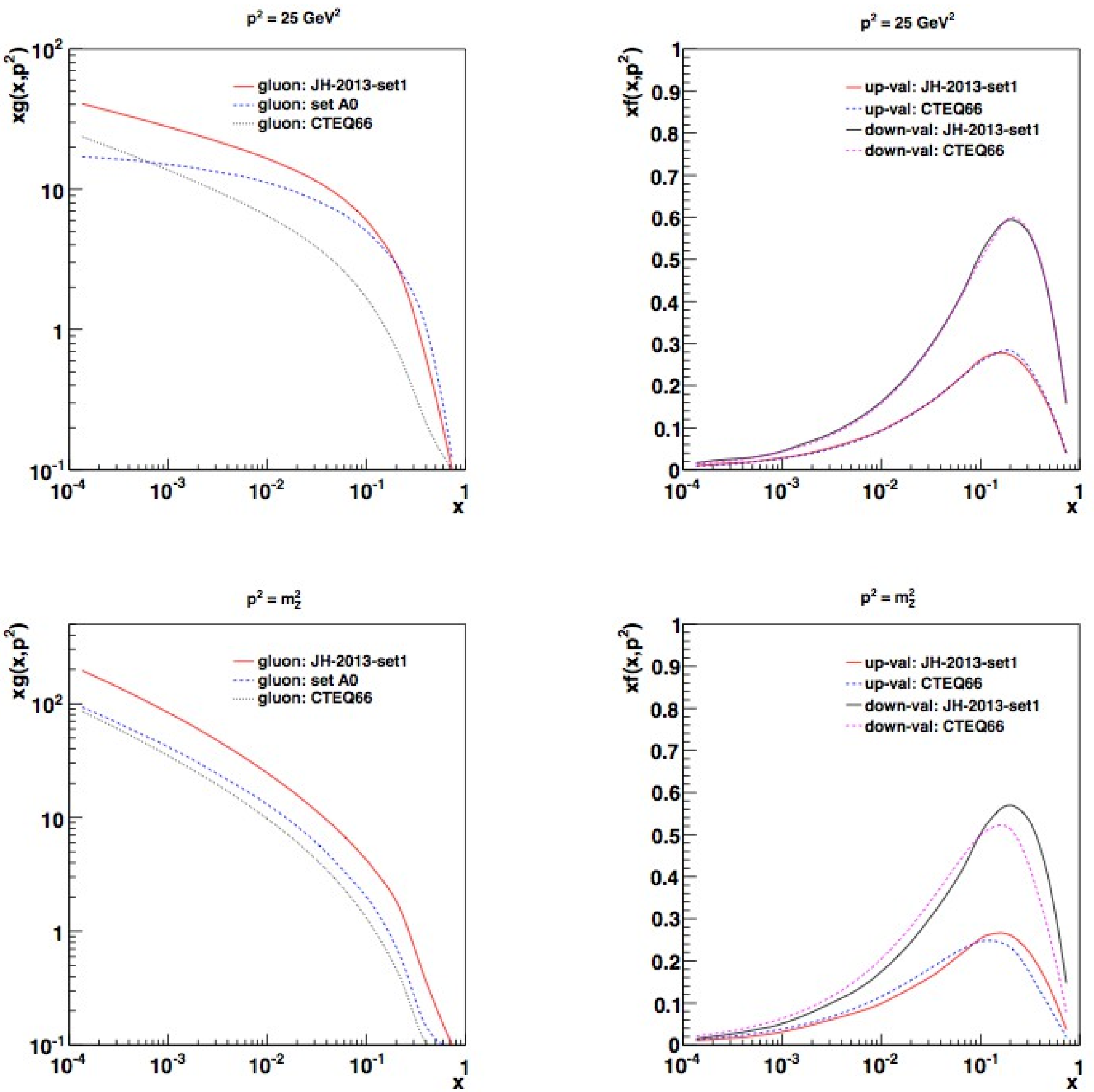
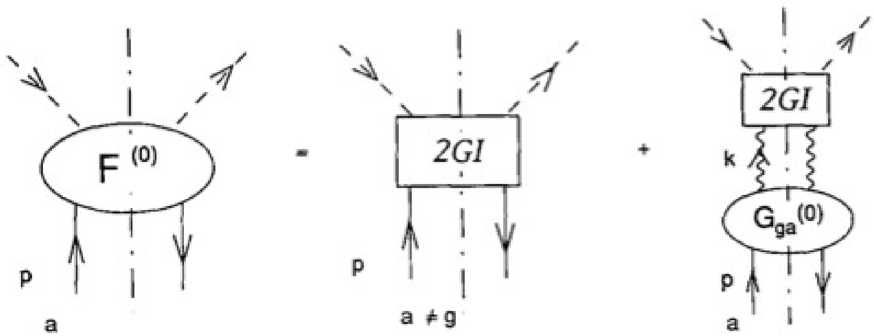


FIG. 8. *Integral over transverse momenta of the TMD distributions for (left) gluon and (right) valence quark at different evolution scales: (top)* $p^2 = 25$ GeV^2*; (bottom)* $p^2 = m_Z^2$.

Comment on scheme dependence: The renormalization group R factor



$$\int^{\mu} dk_{\perp}\ \mathcal{F}(k_{\perp}, \mu)\ =\ R\ \otimes\ f^{\overline{\rm MS}}(\mu)$$

- Perturbative expansion ($x \to 0$):

$$R(x) - \delta(1-x) \simeq 1.40\ \alpha_s^3\ \ln^2 x - 0.11\ \alpha_s^4\ \ln^3(1/x) + \ldots$$

- Relationship with RG evolution:

$$\mathcal{F}_N(k_{\perp}, \mu) = \underbrace{R_N\ [\gamma_N\ \frac{1}{k_{\perp}^2}\ \left(\frac{k_{\perp}^2}{\mu_F^2}\right)^{\gamma}_N]}_{\varepsilon \to 0}\ \underbrace{\Gamma_N(\frac{\mu_F^2}{\mu^2})}_{\text{series of poles } 1/\varepsilon}$$

γ_N = anomalous dimension
μ_F = factorization scale

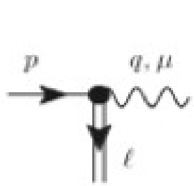
Application to vector bosons + jets at high energy

→ Use exclusive CCFM evolution

→ Determine TMD pdf from high-precision DIS data

→ Obtain predictions for final states associated with Drell-Yan using high-energy off-shell matrix elements

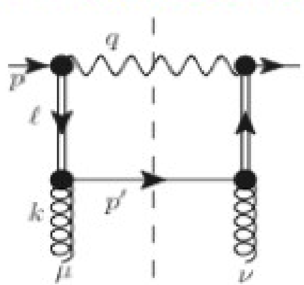
- High-energy effective theory → effective vertices



[Bogdan & Fadin, NPB740 (2006) 36]

[Lipatov & Vyazovsky, NPB597 (2001) 399]

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

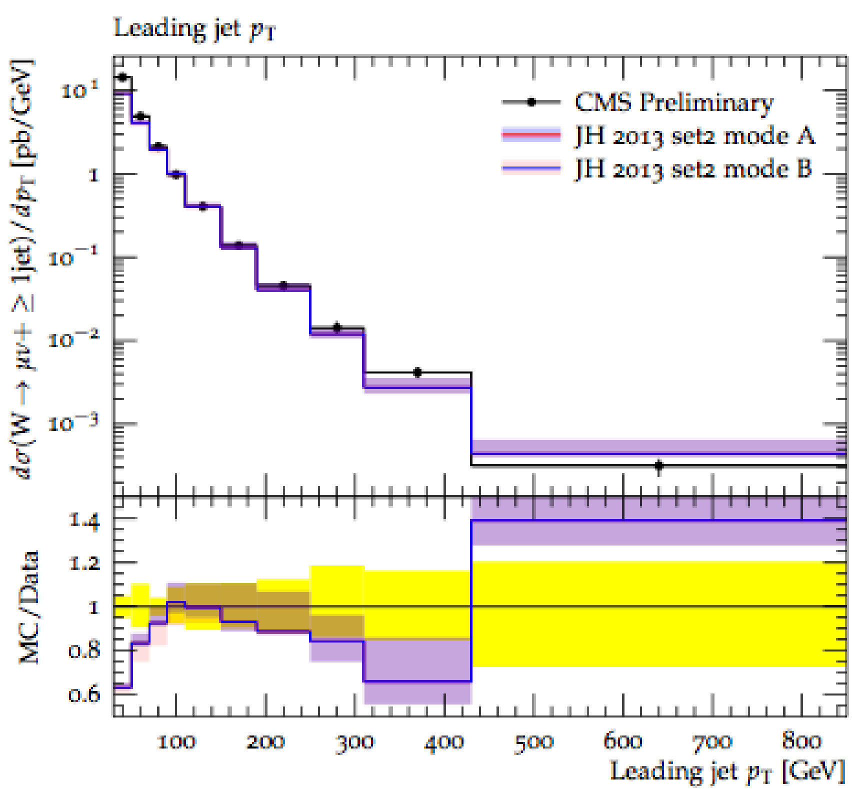


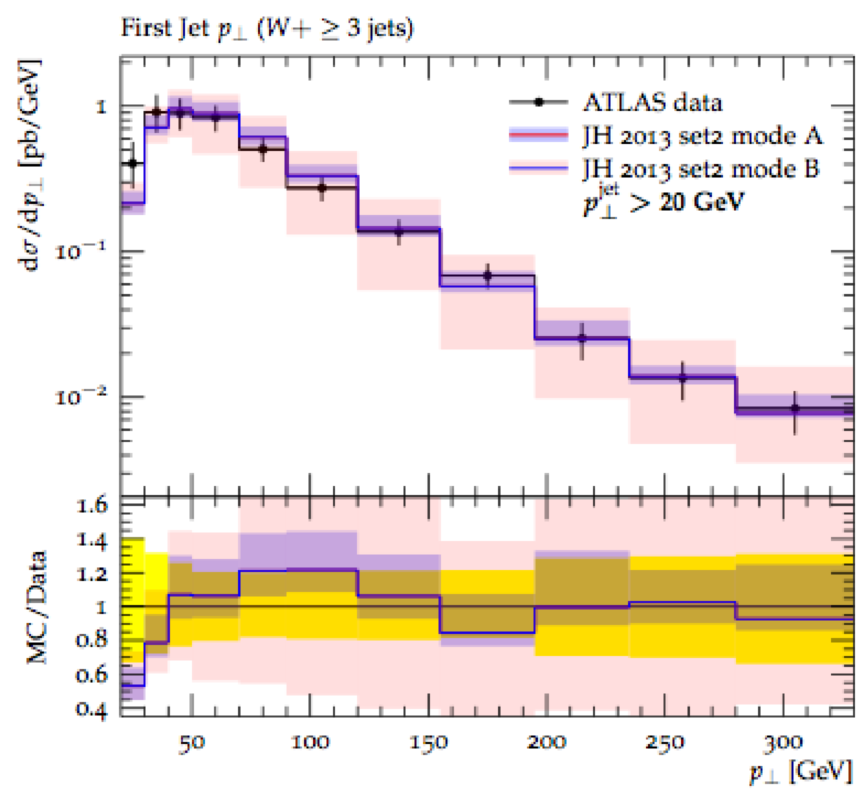
[Ball & Marzani, NPB814 (2009) 246]

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

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

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

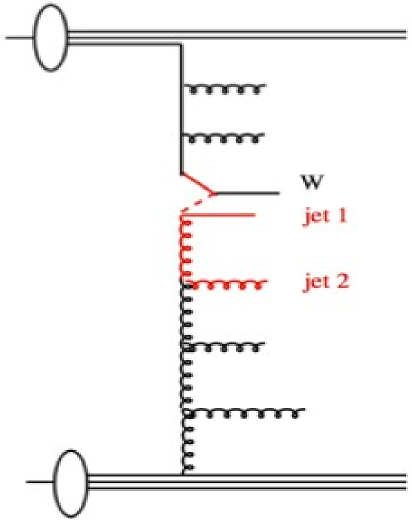


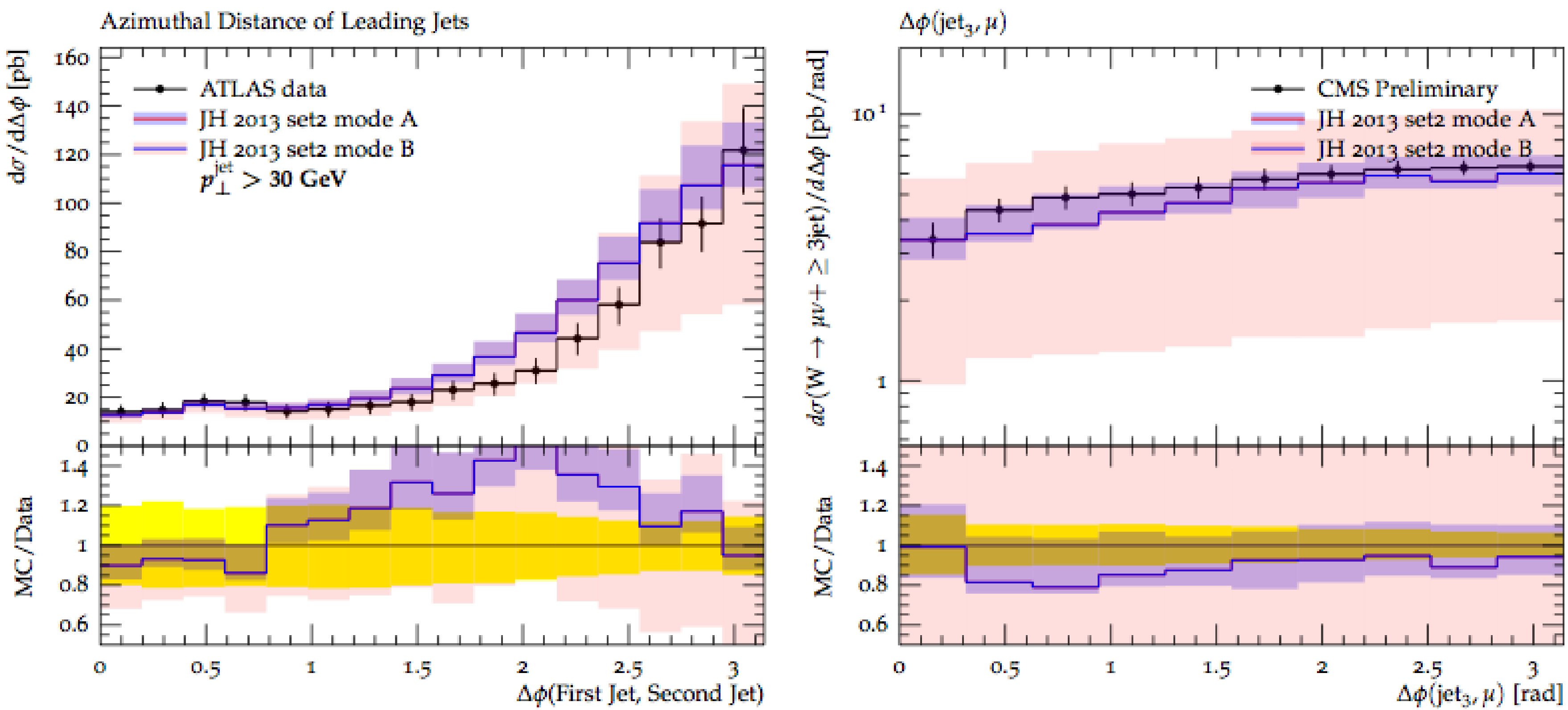


Leading jet pT: (left) inclusive; (right) n>=3

Angular correlations in W + n jets final states

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





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