DESY

Terascale Physics Seminar

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QCD at high luminosity hadron colliders

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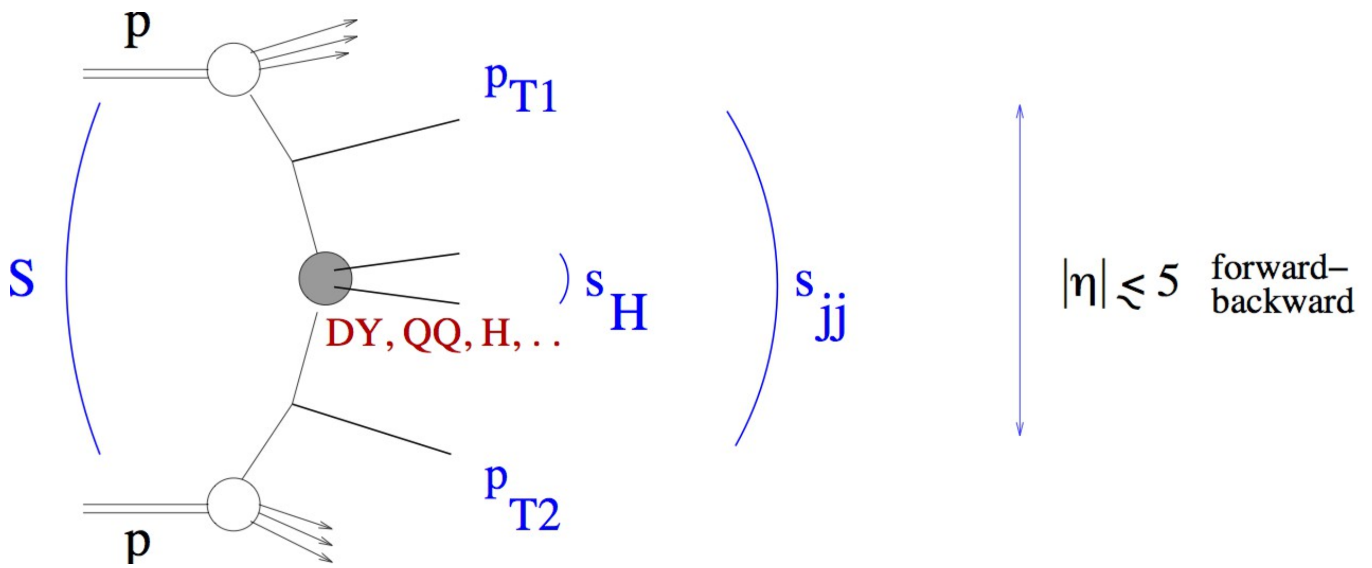
Many thanks to the DFG SFB 676 Program
“Particles, Strings and the Early Universe”

QCD at high luminosity hadron colliders



$s_{jj} \ll S \longrightarrow$ small-x pdf physics

$s_H \ll s_{jj} \longrightarrow$ high-energy log resummations of hard cross sections; multi-jets

HIGH-ENERGY

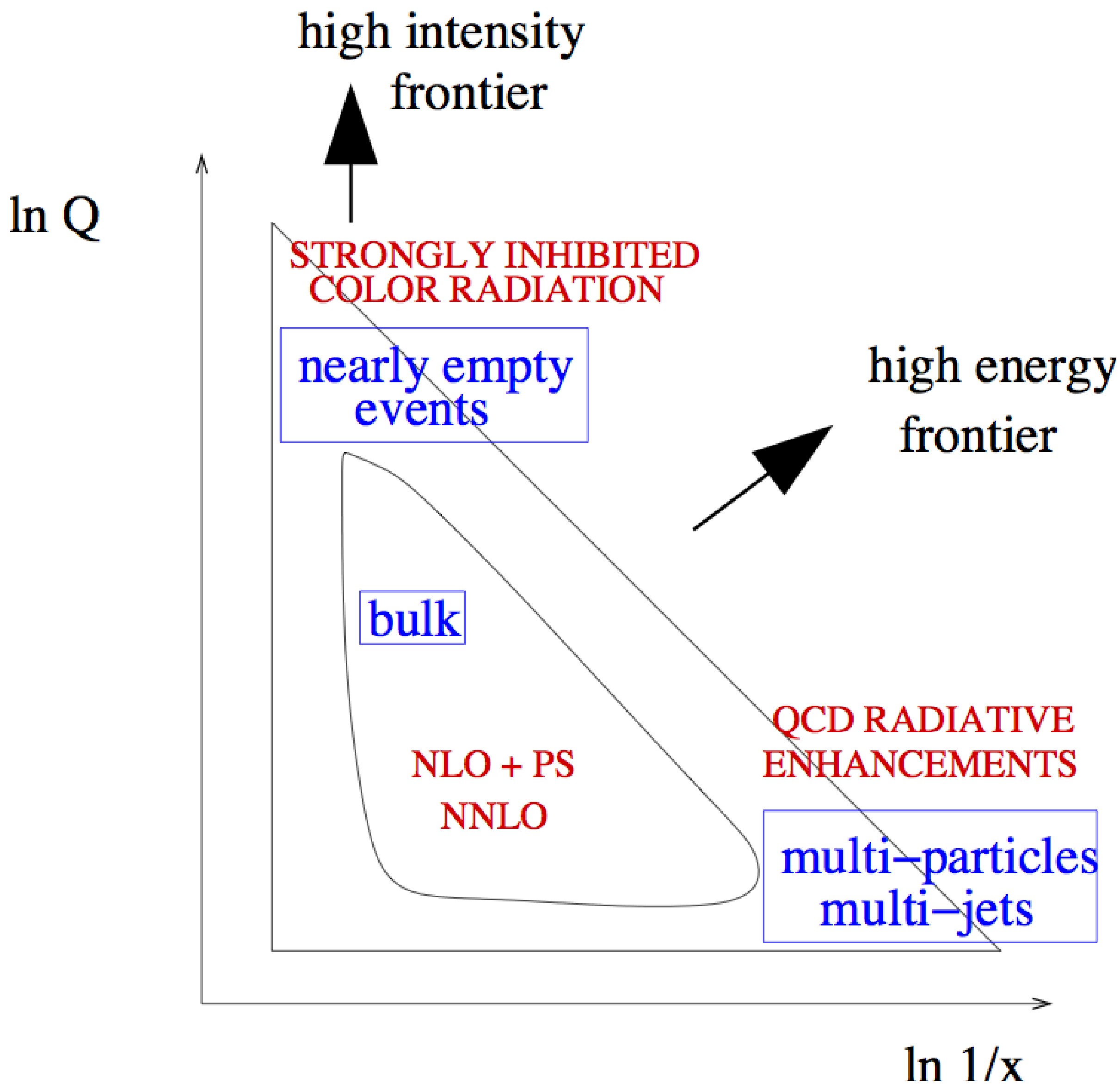
FACTORIZATION

- large sub-energy ratios approaching kinematic threshold

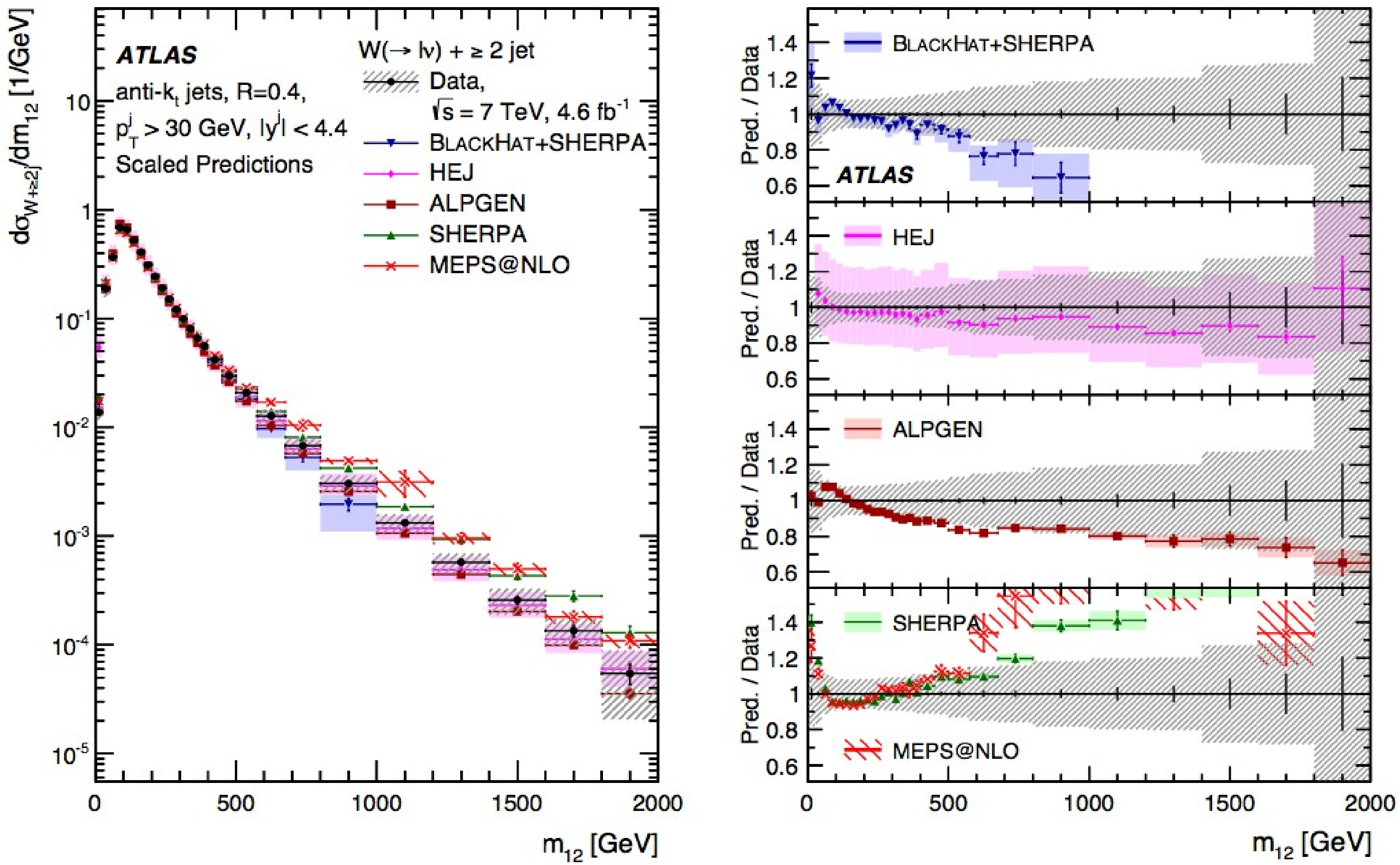
$\rightarrow$ strongly inhibited color radiation

INFRARED/ THRESHOLD RESUMMATION

QCD phase space at high energy colliders



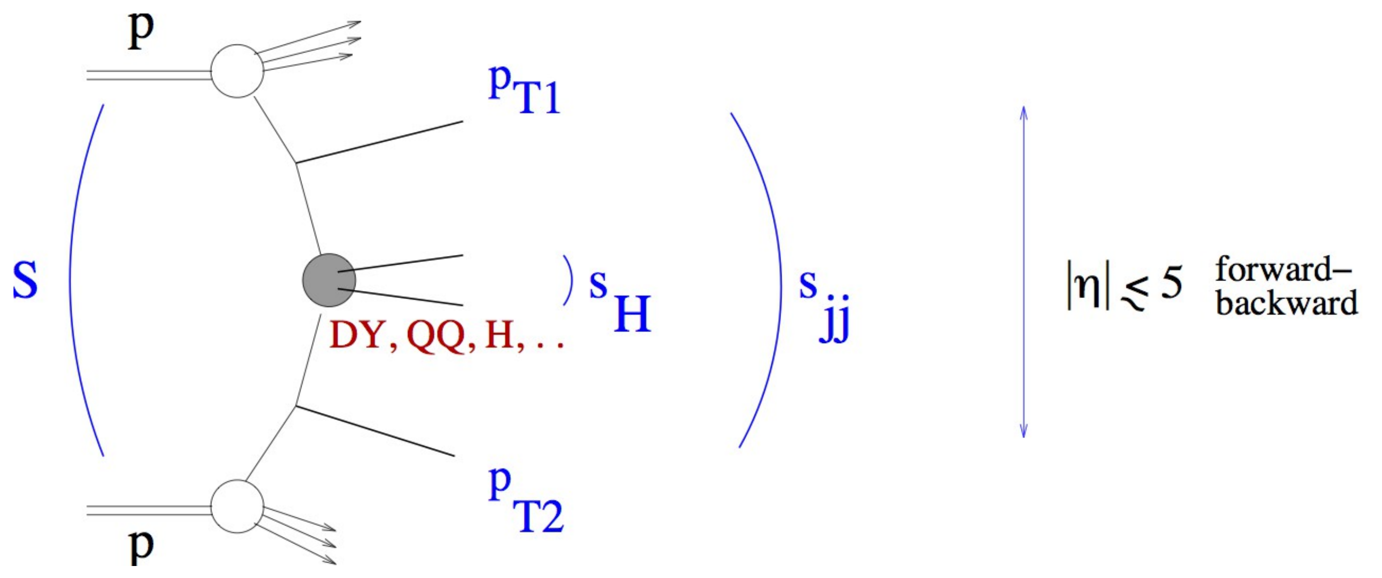
Motivation: high masses



Di-jet mass spectrum in W + 2 jets [ATLAS Coll., Eur. Phys. J. C 75 (2015) 82]

Large spread in Monte Carlo predictions around and above M_JJ ~ 400 – 600 GeV

QCD at high luminosity hadron colliders



high luminosity → high pile-up

large s_jj → forward/backward region → QCD resummation methods

heavy boson + jets cross sections

QCD at high luminosity hadron colliders:

Treating jet correlations in high pile-up

collaboration with H. van Haevermaet and H. Jung
arXiv:1508.07811

HIGH LUMINOSITY → HIGH PILE-UP

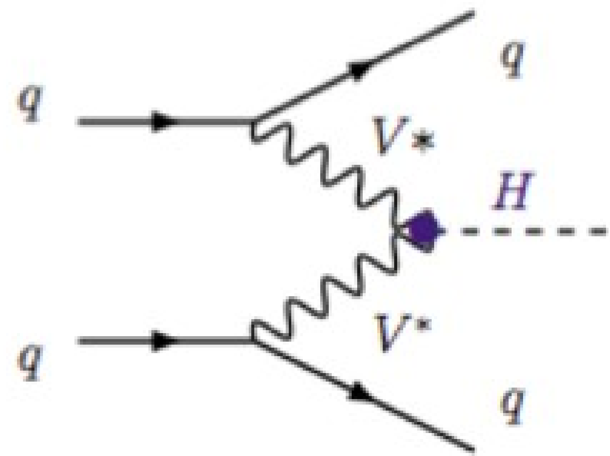
- In Run I: 20 pp collisions on average per bunch crossing
- Run II: pile-up up to the level of 50 collisions
- It increases for higher luminosity runs

Pile-up treatment:

- Precise vertex and track reconstruction in regions covered by tracking detectors
- Monte Carlo simulations including pile-up for comparison with data

Can one find data driven methods
to avoid dependence on Monte Carlo modeling

EXAMPLE: HIGGS BY VECTOR BOSON FUSION

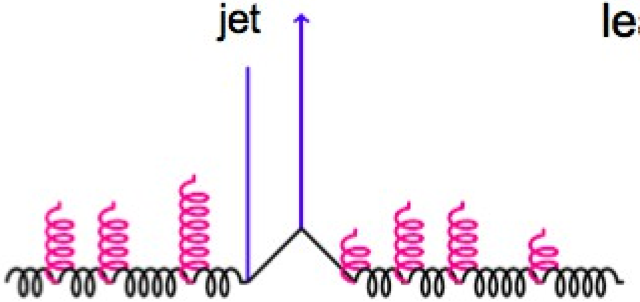


associated jets may be produced outside tracking detector acceptances

- Potentially non-negligible probability for jets with high pT from independent pile-up events (besides soft pile-up particles)
- Full pile-up simulation (at detector level) remains open question. Rather ask: how to extract physics signals with least dependence on pile-up simulation

PILE-UP EFFECTS: Z + JET CASE STUDY

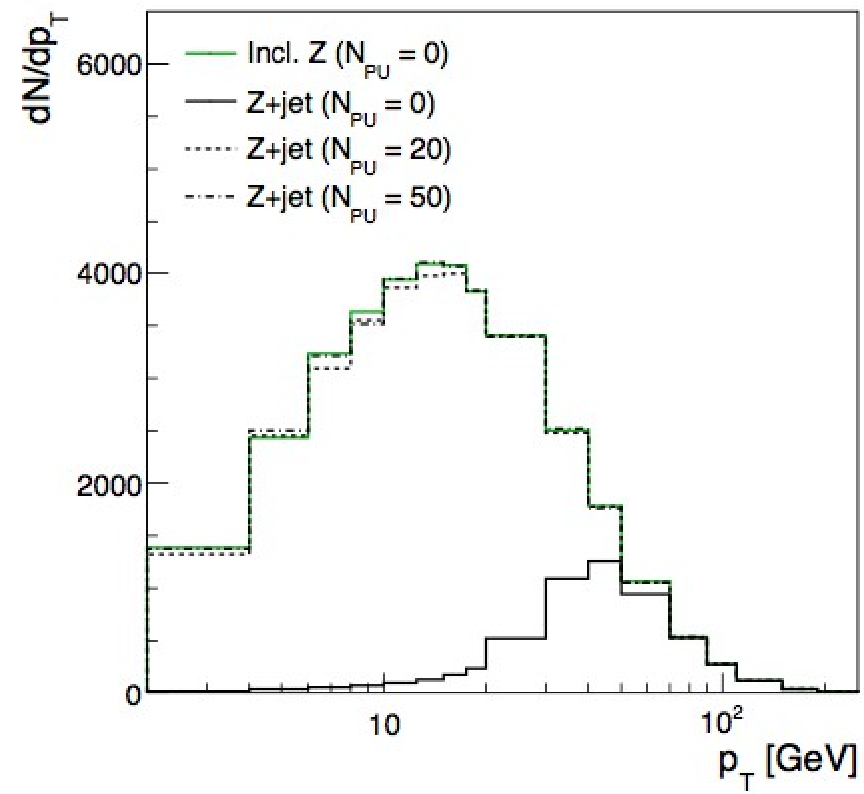
- Additional pp collisions (pile-up): large effect on Z + jet correlations



Z boson: 60 < M < 120 GeV
leading jet: p_T > 30 GeV; $|\eta|$ < 4.5

- p_T spectrum shifts to lower values (inclusive spectrum)

  ➔ jet p_T > 30 GeV: no longer sufficient
  ➔ signal process drowns in pile-up

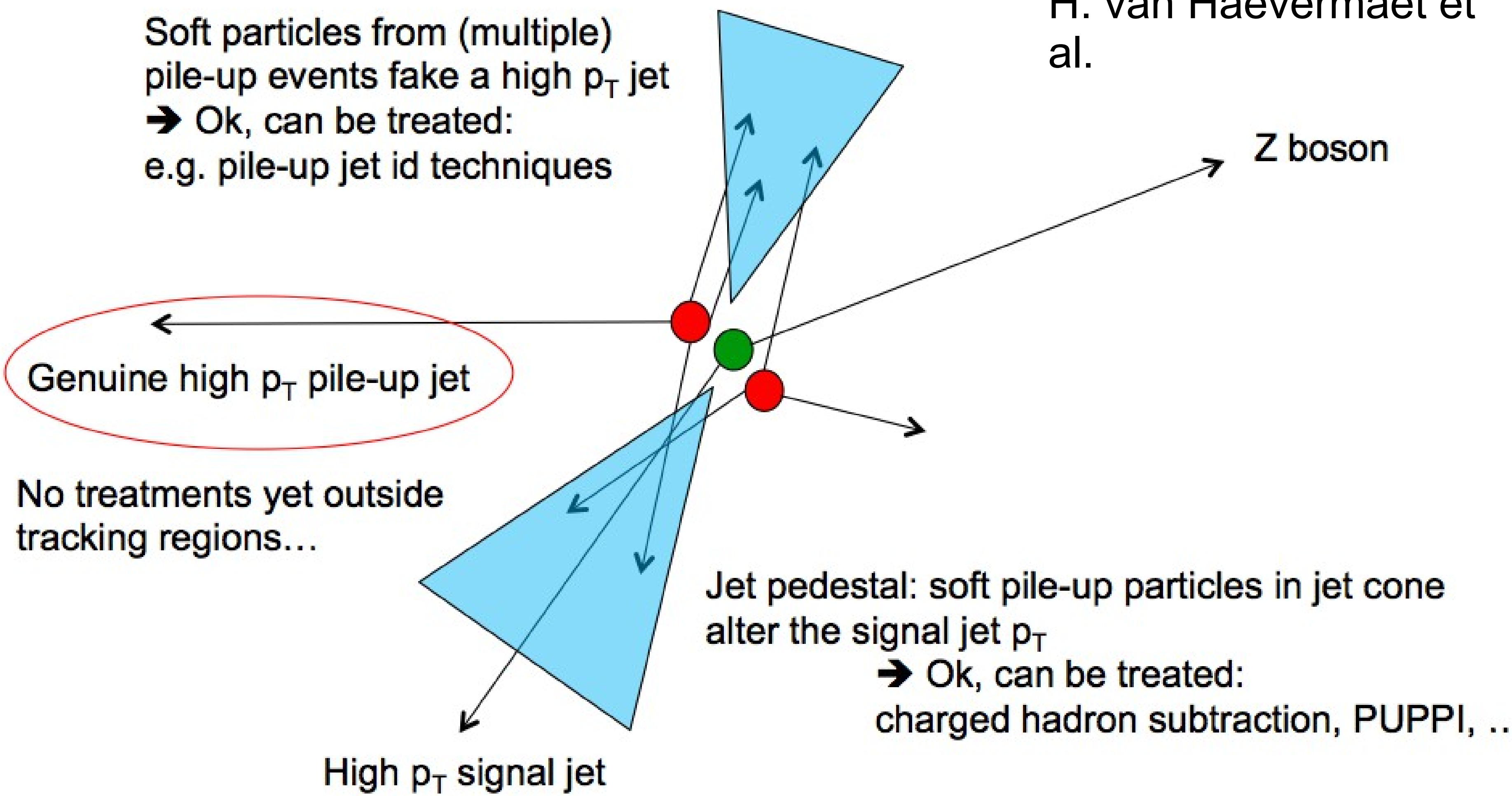


H. van Haevermaet et al.
arXiv:1508.07811

THE DIFFERENT CONTRIBUTIONS FROM PILE-UP

- Z + jet correlations are affected by:

H. van Haevermaet et al.



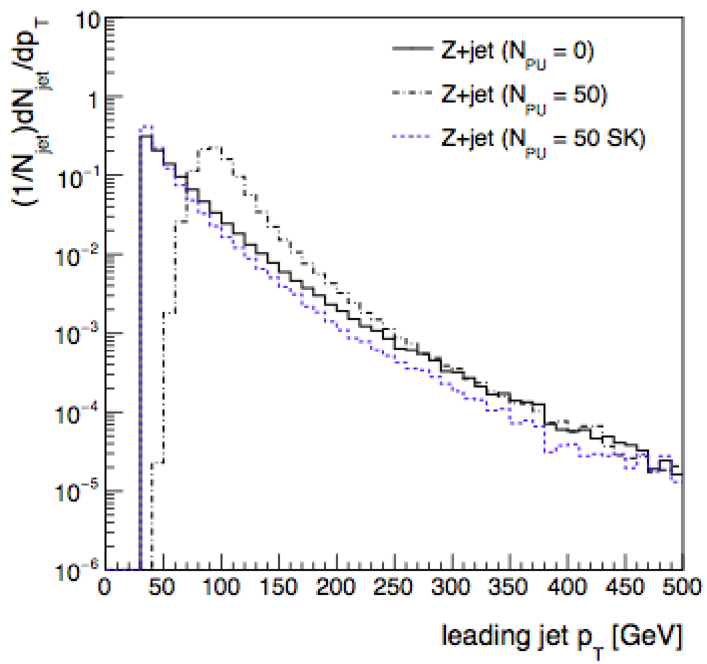
CORRECTING THE JET PT PEDESTAL

- **Can be done with several existing methods for central jets**

  e.g. Charged Hadron Subtraction (CHS): H. Kirschenmann et al. CERN-CMS-CR-2013-325.
  PUPPI: Bertolini D. et al. JHEP 1410 (2014) 59
  SoftKiller: Cacciari, M. et al. Eur.Phys.J. C75 (2015) 2

Jet cleansing: D. Krohn et al.
Phys. Rev. D90 (2014) 065020

- **Apply SoftKiller method: also works more forward**



Principle:
- remove particles below a p_T cutoff
- minimal value that ensures that the event-wide estimate of p_T flow density (ρ) = 0
- re-cluster jets (Anti-k_T, R = 0.5)

Can be used with calorimeter information only

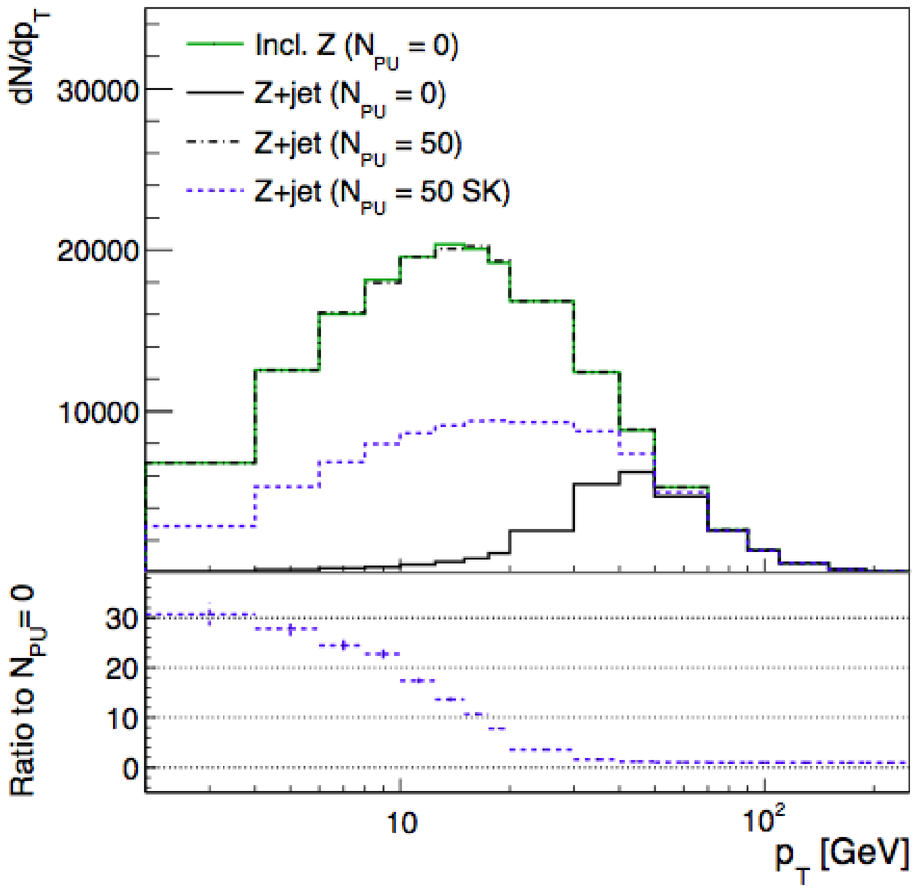
$$\rho = \underset{i \in \text{patches}}{\text{median}} \left\{ \frac{p_{ti}}{A_i} \right\}$$

Cacciari, Salam, Soyez
Eur. Phys. J. C 75 (2015) 2

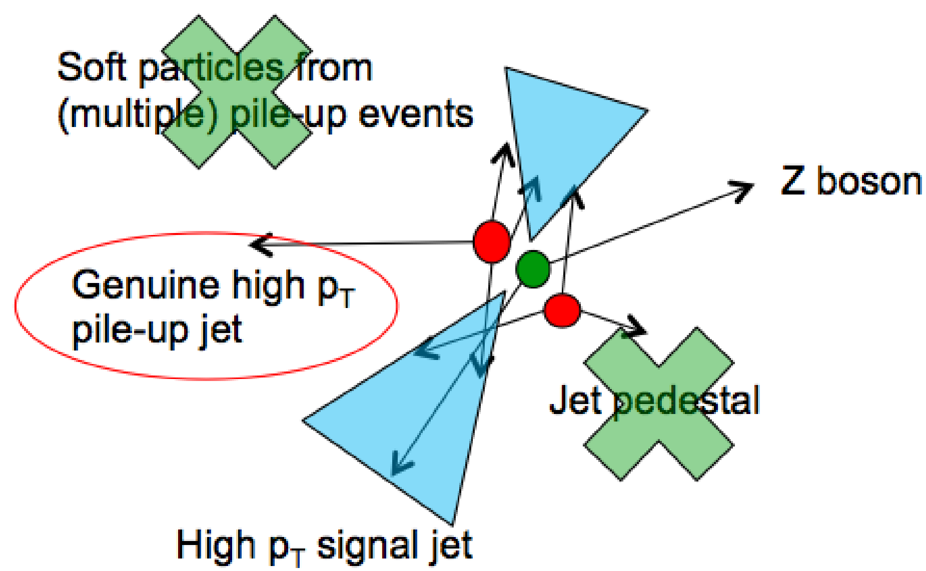
- correct for transverse momenta of individual objects but not for any misidentification

APPLY SOFTKILLER TO Z-BOSON PT SPECTRUM

> SoftKiller correction on Z boson + jet p_T spectra:



- At high p_T values no need for corrections
- At low p_T still large contribution from misidentified pile-up jets



- mistagged pile-up jets are not corrected for
  → need to be properly treated

TREATING EFFECTS BEYOND SOFT PARTICLES AND THE JET PT PEDESTAL

Data-driven pile-up treatment

- Obtain signal using a jet mixing technique
- Minimum bias sample of real data in high pile-up
- Mix this independent sample with signal events without pile-up
- Extract unbiased signal without the use of MC

TREATING EFFECTS BEYOND SOFT PARTICLES AND THE JET PT PEDESTAL

- Jet mixing techniques using uncorrelated event samples

$$\mathcal{M} \otimes T = \mathcal{D}$$

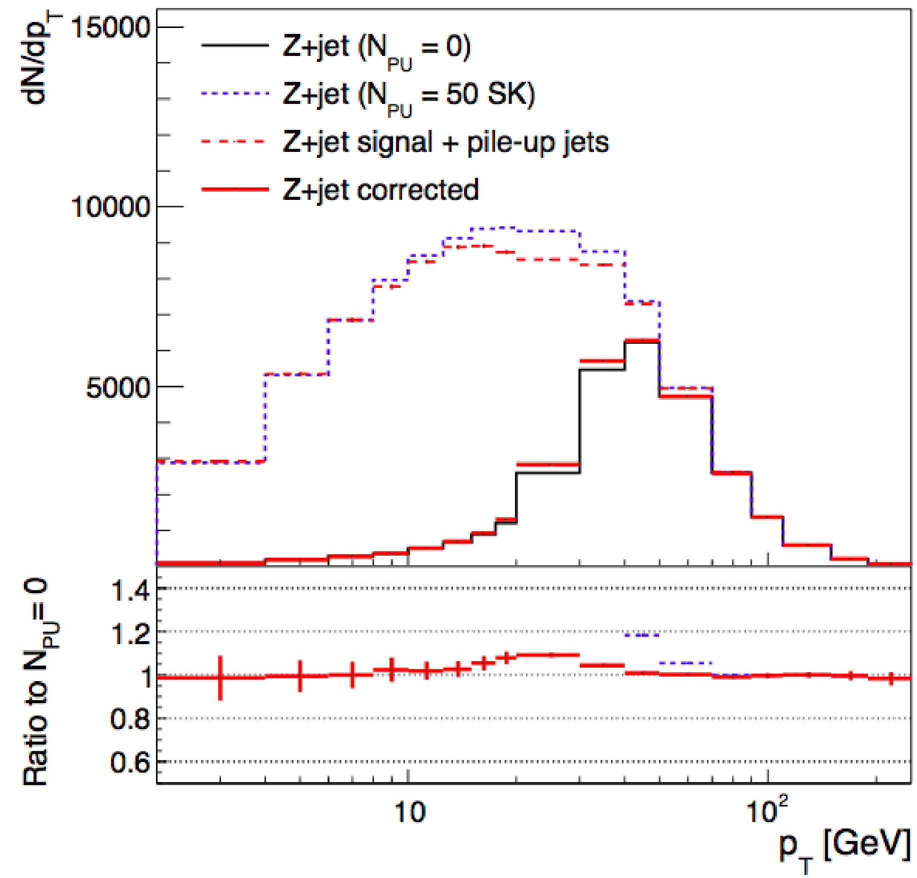
↗ ↑ ↖

mixing matrix "true" data

To identify contribution of high-pT jets
from independent pile-up events,
construct signal + pile-up scenario
In a data-driven manner.

Valid for high pile-up:

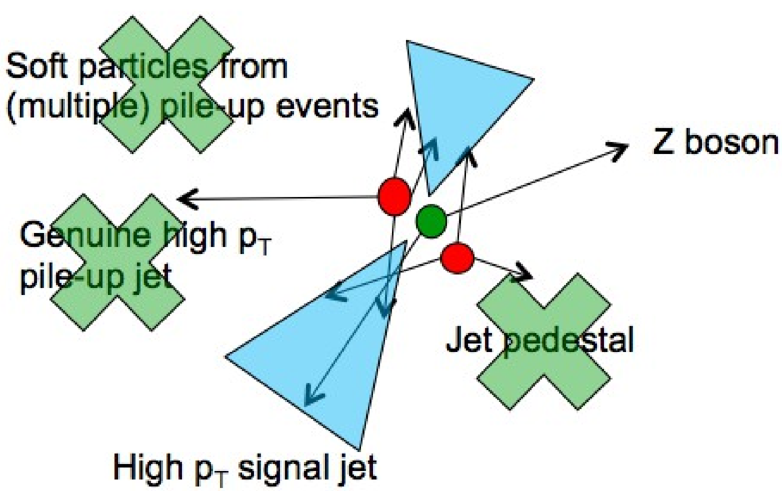
$$(N_{\mathrm{PU}} + 1)/N_{\mathrm{PU}} \approx 1$$

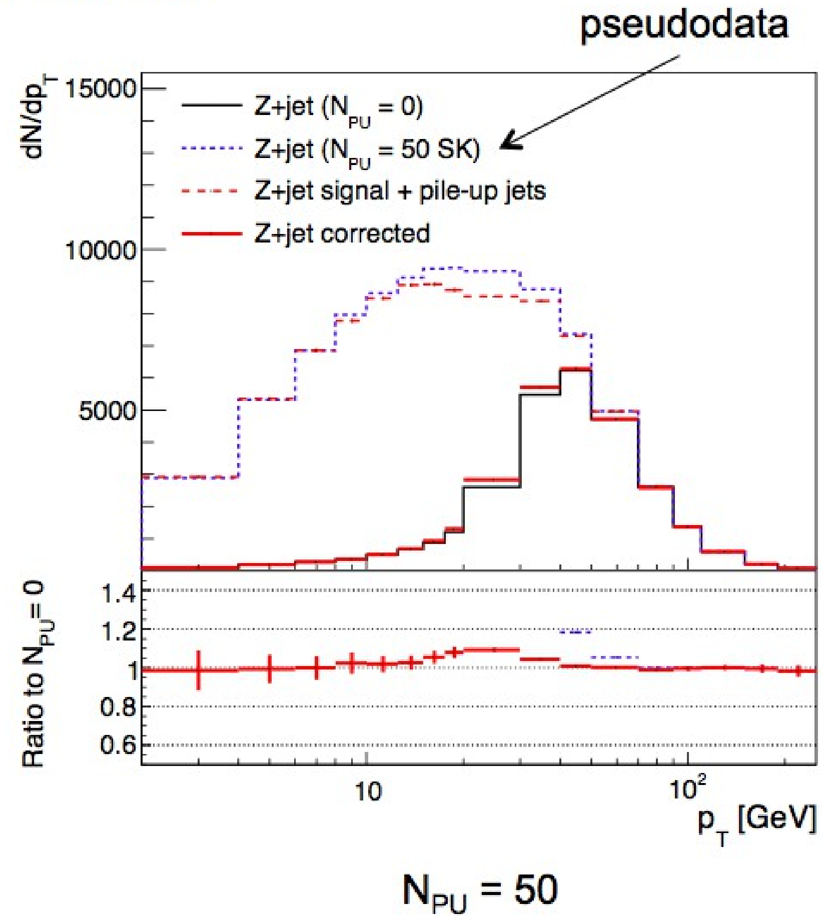


Without appealing to any Monte Carlo method, true signal extracted nearly perfectly from mixed sample

Z-BOSON PT SPECTRUM IN Z + JET WITH JET MIXING APPLIED

- Extract signal without relying on Monte Carlos
- From mixed sample can extract true signal succesfully
- Advantages:
  - ➔ works in high N_{PU} regime
  - ➔ no data at low pile-up needed
  - ➔ no Monte Carlo needed





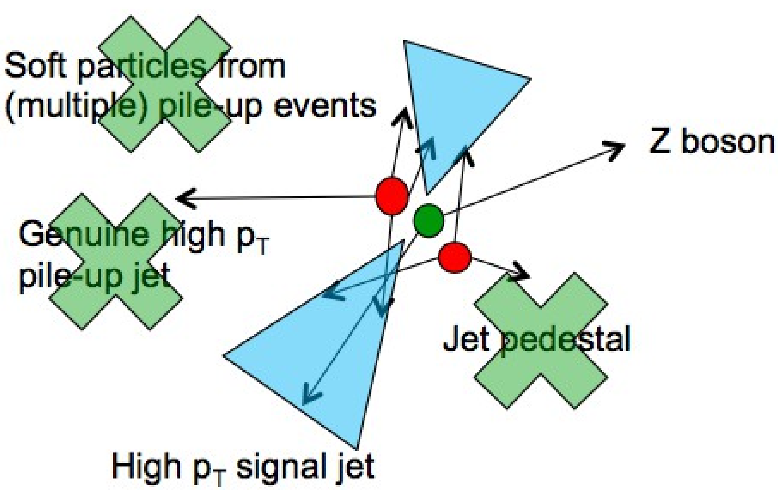
H. Van Haevermaet | QCD@LHC 02/09/2015 | Page 8

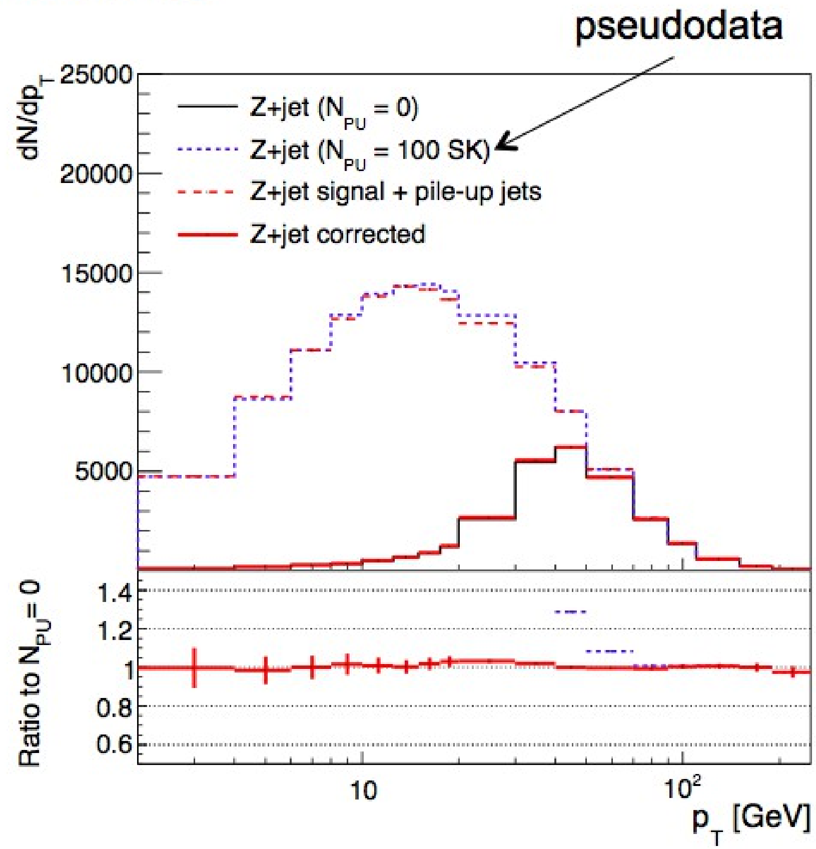
THE CASE OF VERY HIGH PILE-UP: N_PU = 100

> Extract signal without relying on Monte Carlos

> From mixed sample can extract true signal succesfully

> Advantages:
➔ works in high N_{PU} regime
➔ no data at low pile-up needed
➔ no Monte Carlo needed





N_{PU} = 100

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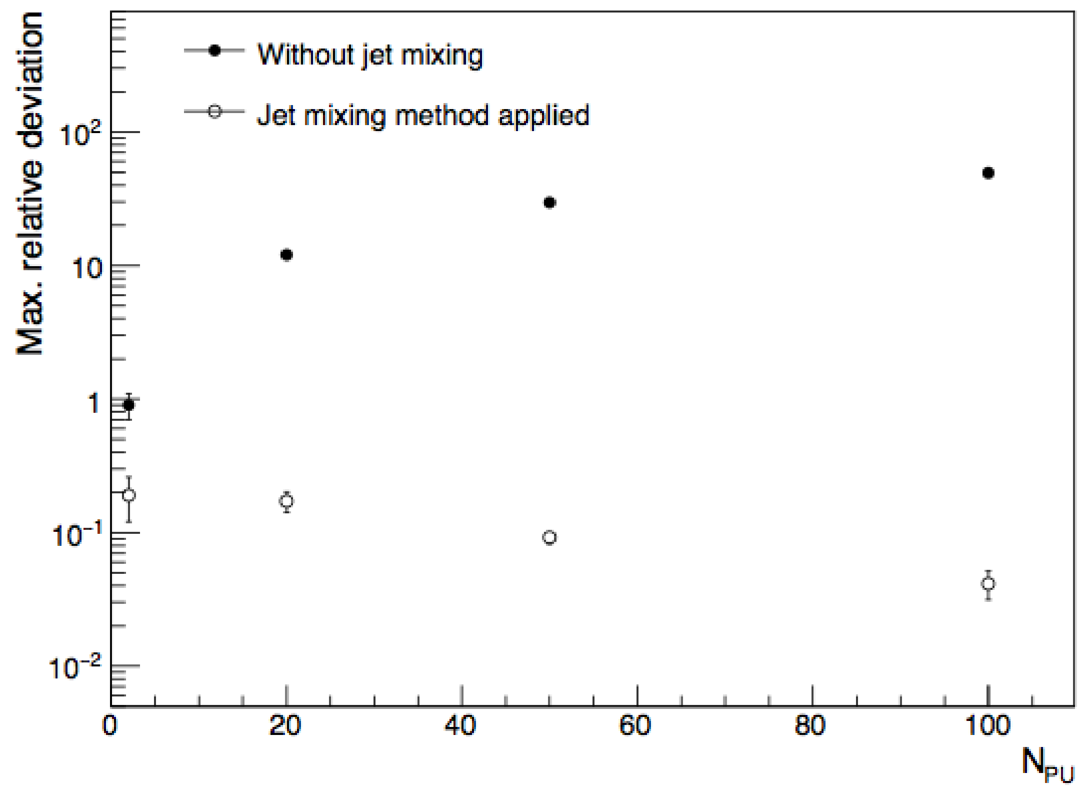
ACCURACY OF CORRECTIONS IN LOW PILE-UP AND HIGH PILE-UP

- Behaviour of maximum relative deviation as function of N_{PU}

- (corrected - true) / true

- Without jet mixing: deviation larger at high N_{PU}

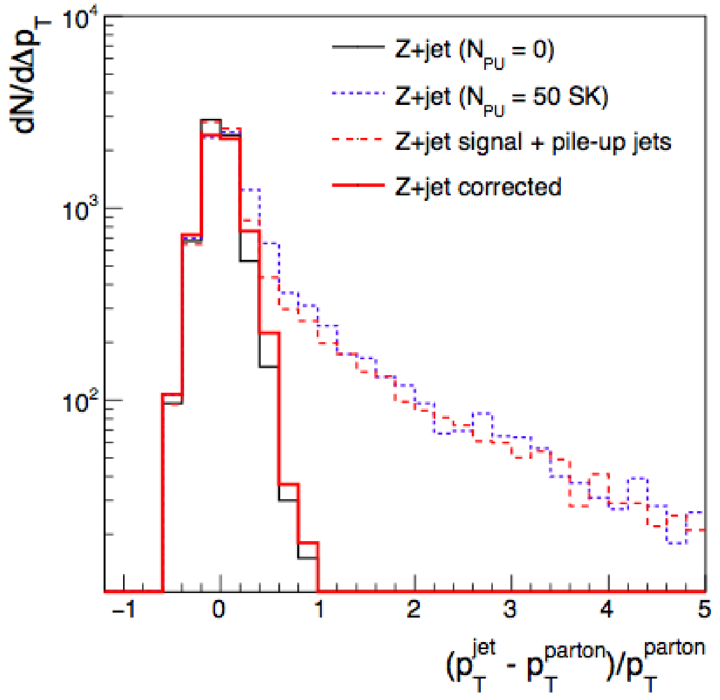
- With jet mixing: improvement with increasing N_{PU}

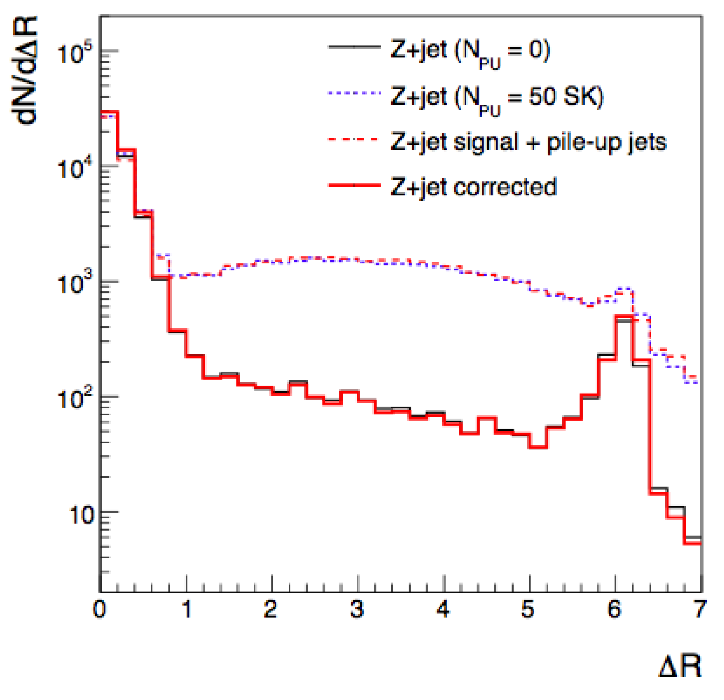


- Approach designed to treat high N_{PU} region: $(N_{PU} + 1) / N_{PU} \approx 1$

IMPROVEMENT IN JET RESOLUTION FROM APPLYING JET MIXING METHOD

- Control checks with p_T resolution and $\Delta R = \sqrt{(\Delta\phi^2 + \Delta\eta^2)}$



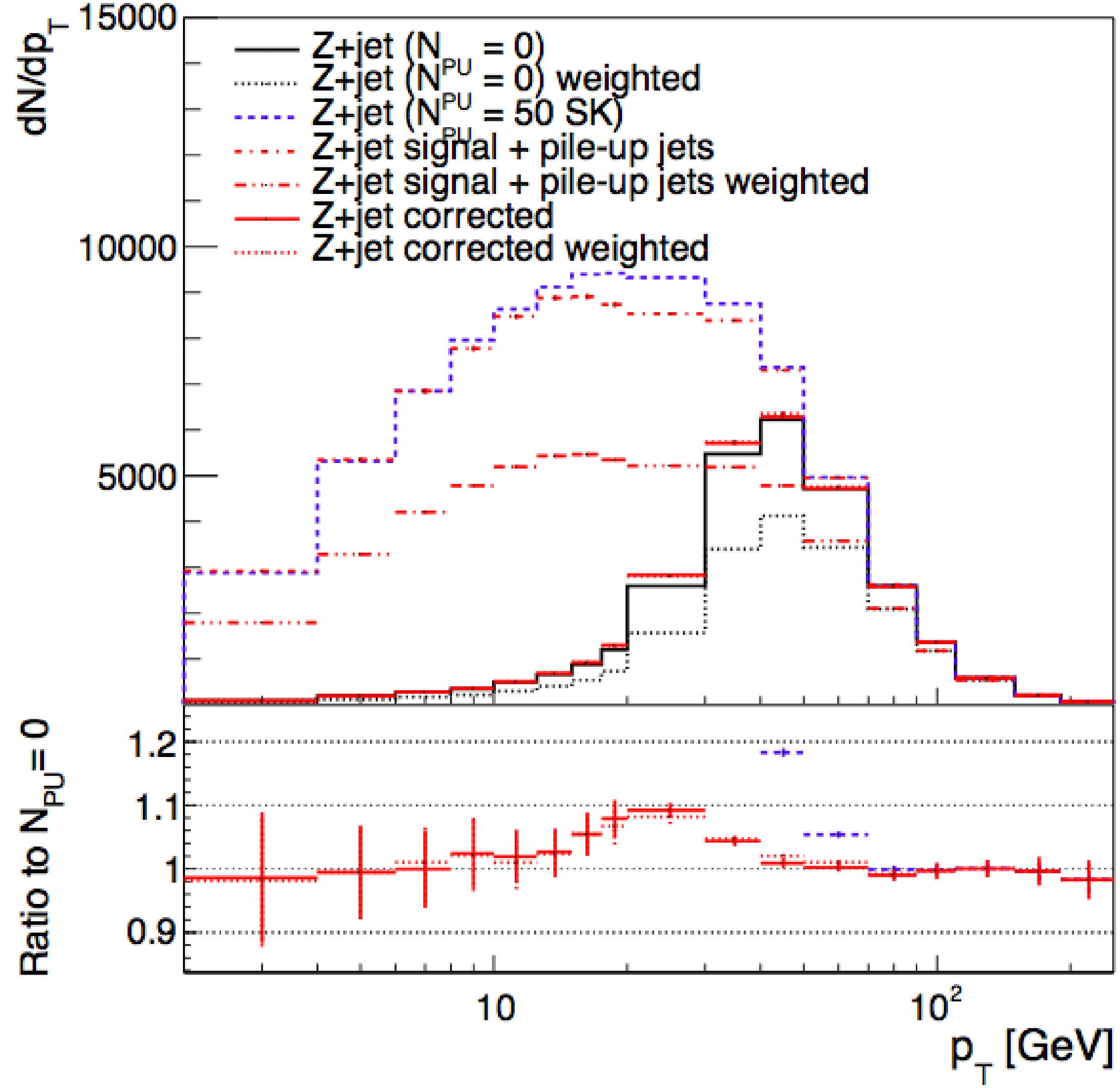


➔ true signal reproduced

COMMENT: WHAT IF THE MIXING IS DONE WITH THE "WRONG" ANSATZ FOR THE SIGNAL?

Model independence:

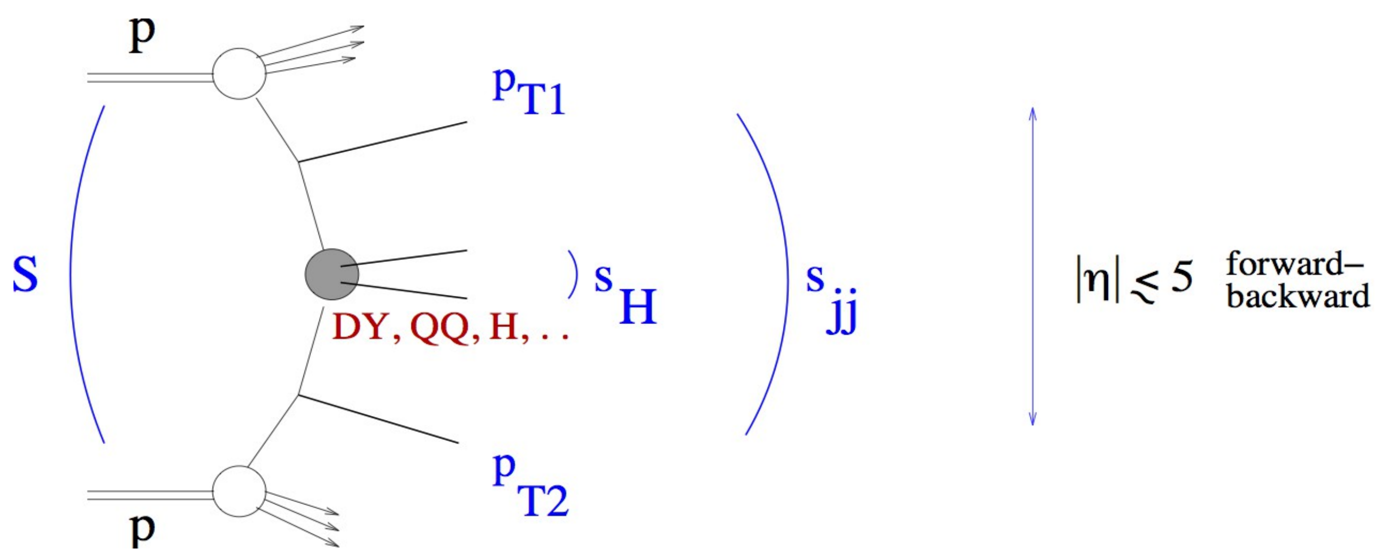
Test jet mixing method with different starting signal distribution



mixed sample now far off pseudodata – but true signal still recovered from unfolding!

TO SUM UP

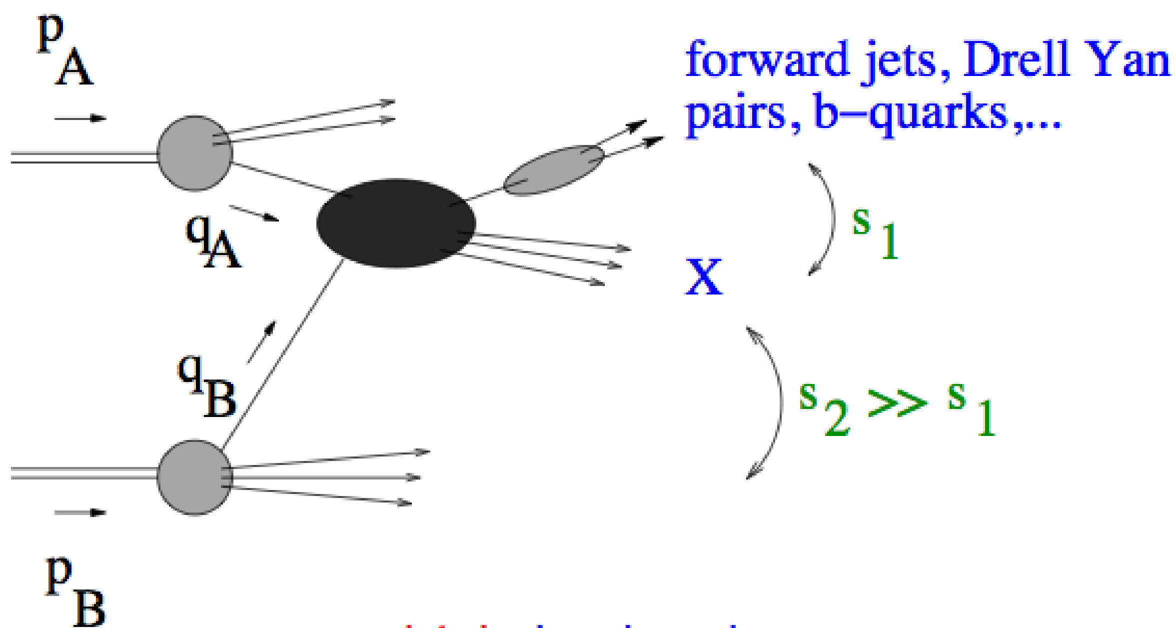
- Effects of pile-up beyond the jet pT pedestal:
  mistagging of high-pT jets from
  independent pile-up events
- Treatment by data-driven methods, not
  dependent on Monte Carlo generators
- Relevant especially for regions outside tracker
  acceptances, where vertexing techniques
  cannot be relied on to identify pile-up jets.
  Example: Higgs by vector boson fusion
- No need for low pile-up runs – no loss in
  luminosity



QCD at high luminosity hadron colliders:

High-pT production over large rapidity intervals

HIGH PT PRODUCTION OVER LARGE RAPIDITY INTERVALS



- multiple hard scales

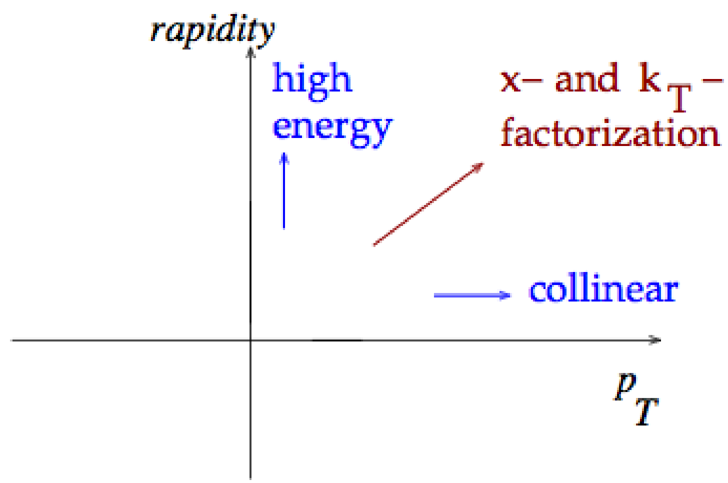
- asymmetric parton kinematics $x_A \rightarrow 1, \ x_B \rightarrow 0$

◊ Are finite-order QCD calculations reliable in the forward region?

◊ Perturbative QCD resummations?

HIGH PT PRODUCTION OVER LARGE RAPIDITY INTERVALS: RESUMMATION FORMALISM

- Large logarithmic corrections are present both in the hard p_T and in the rapidity interval



$\longrightarrow$ Both kinds of log contributions can be summed consistently to all orders of perturbation theory via QCD factorization at fixed k_T

- Valid to single-logarithmic accuracy [Deak, Jung, Kutak & H, JHEP 09 (2009) 121]
- Extended to forward DY [Hentschinski, Jung & H, Nucl. Phys. B 865 (2012) 54]

QCD FACTORIZATION AT FIXED TRANSVERSE MOMENTUM

$$\frac{d\sigma}{dQ_t^2 d\varphi} = \sum_a \int \phi_{a/A} \otimes \frac{d\widehat{\sigma}}{dQ_t^2 d\varphi} \otimes \phi_{g^*/B}$$

▷ needed to resum consistently both logs of rapidity and logs of hard scale *Deak, Jung, Kutak & H, JHEP 09 (2009) 121*

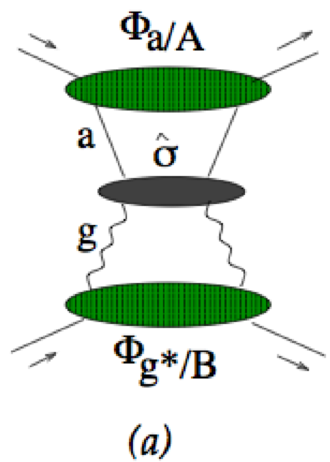


Figure 1: Factorized structure of the cross section.

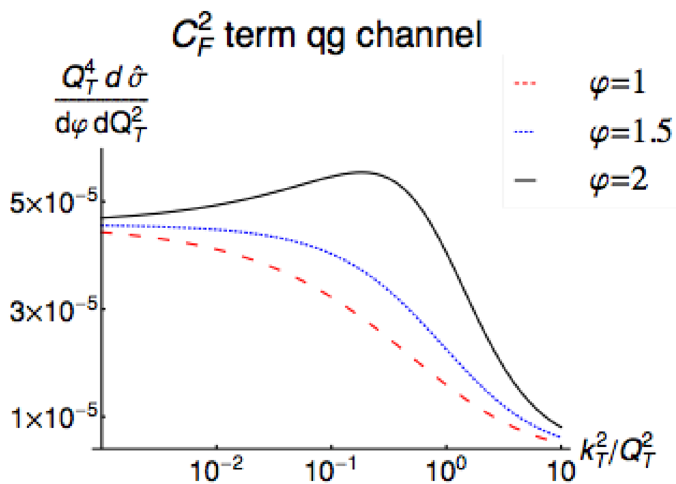
◇ ϕ_a near-collinear, large-x; ϕ_{g^*} $k_\perp$-dependent, small-x

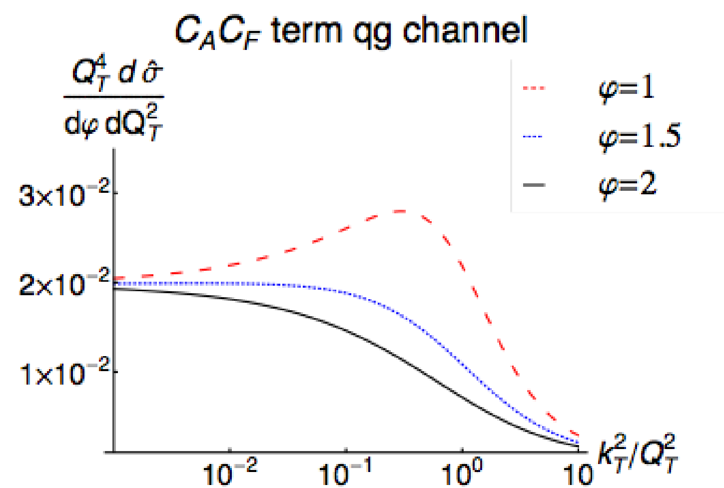
◇ $\widehat{\sigma}$ off-shell (but gauge-invariant) continuation of hard-scattering matrix elements *[Catani et al., 1991; Ciafaloni, 1998]*

QCD FACTORIZATION AT FIXED TRANSVERSE MOMENTUM: FULLY EXCLUSIVE MATRIX ELEMENTS

Q_t = final-state transverse energy (in terms of two leading jets p_t's)

k_t = transverse momentum carried away by extra jets





- dynamical cut-off at $k_t \sim Q_t$, set by higher-order radiative effects
    - non-negligible terms from finite k_t tail
- $C_F C_A$ contribution to qg dominates at high energies $s/Q_t^2 \gg 1$

QCD FACTORIZATION AT FIXED TRANSVERSE MOMENTUM: FULLY EXCLUSIVE MATRIX ELEMENTS

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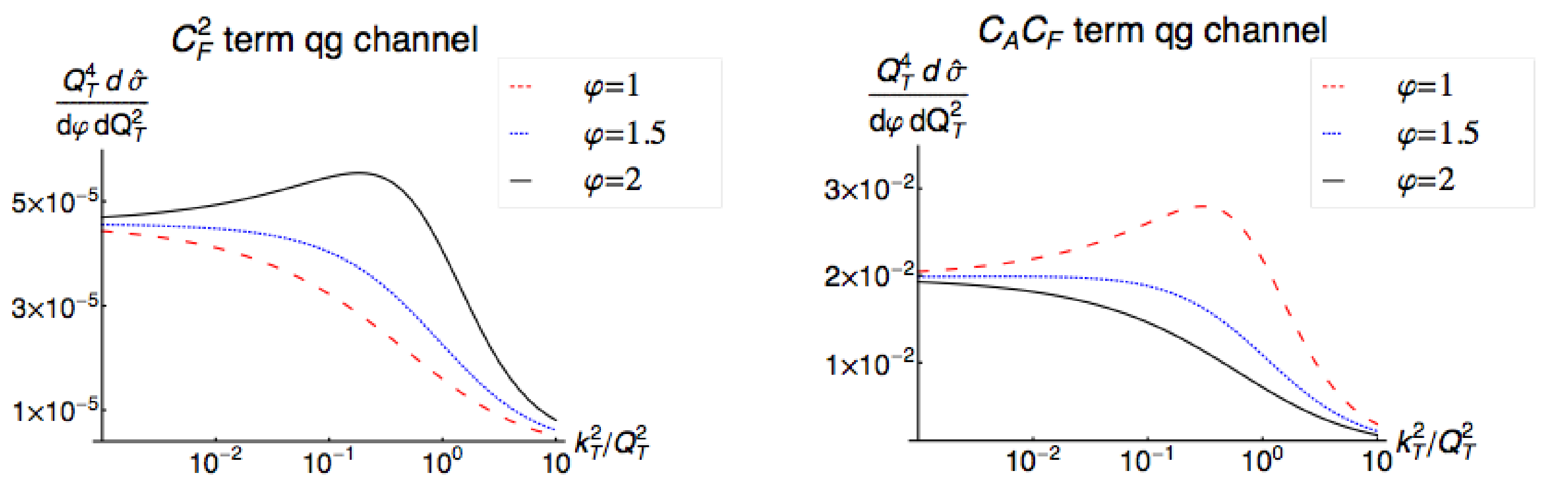


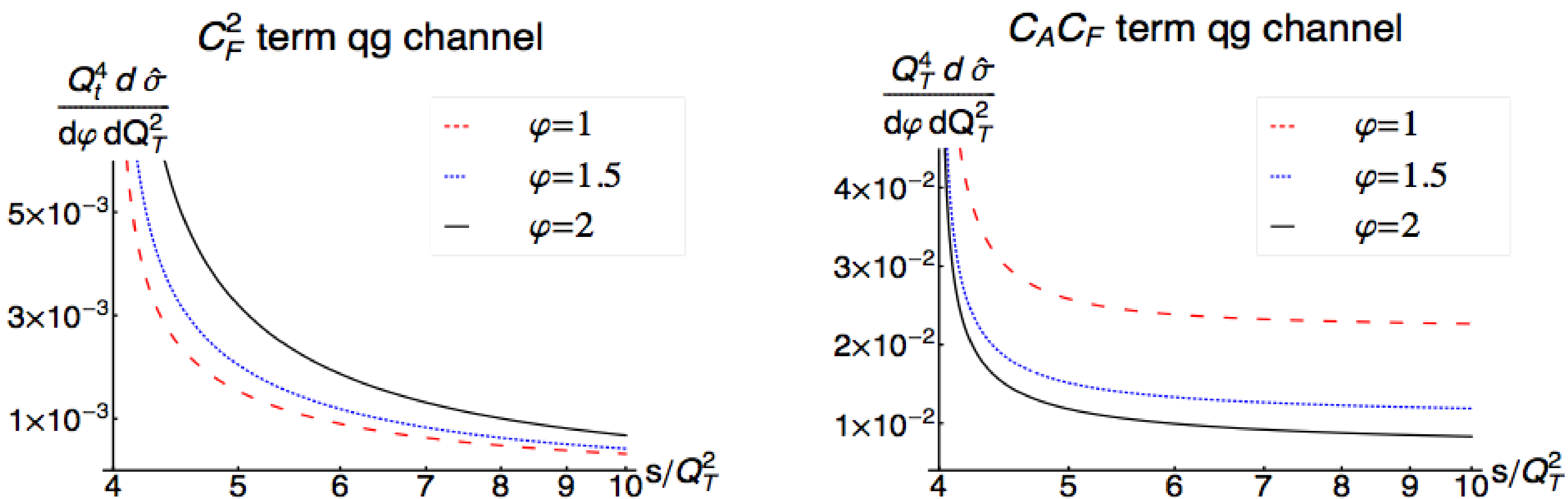
- Matrix elements factorize for high energy
  not only in collinear region but also at finite angle

$\Rightarrow$ effects of coherence across large rapidity intervals not associated with small angles

- Coupling to parton showers via merging scheme defined by factorization at high energy

QCD FACTORIZATION AT FIXED TRANSVERSE MOMENTUM: FULLY EXCLUSIVE MATRIX ELEMENTS

$Q_t =$ final-state transverse energy (in terms of two leading jets p_t's)



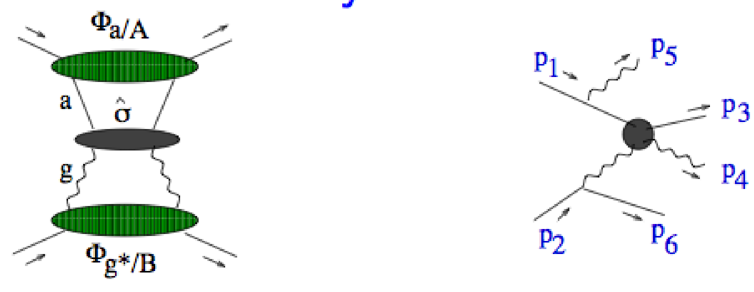
▷ $C_F C_A$ contribution to qg dominates large $\hat{s}/Q_t^2$ (constant at large energy)

QCD FACTORIZATION AT FIXED TRANSVERSE MOMENTUM: FULLY EXCLUSIVE MATRIX ELEMENTS

- High-energy matrix elements factorize not only in the collinear emission region but also at finite angle

◇ once coupled to distributions for parton branching at fixed $k_\perp$, can serve to take into account effects of coherence across large rapidity intervals, not associated with small angles

◇ Merging scheme defined by the factorization at high energy



(a) (b)

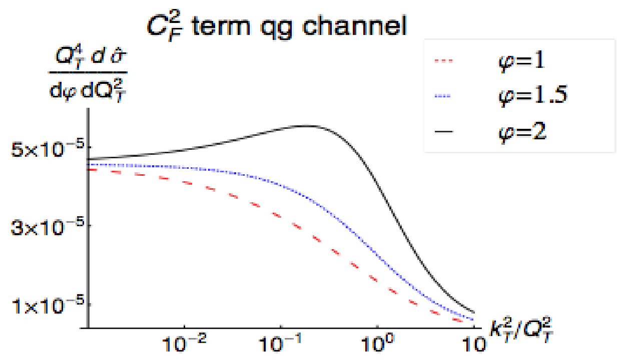
$$p_1 - p_5 = k_1 = \xi_1 p_1 + k_{\perp 1} + \bar{\xi}_1 p_2 \quad , \quad p_2 - p_6 = k_2 = \xi_2 p_2 + k_\perp + \bar{\xi}_2 p_1$$

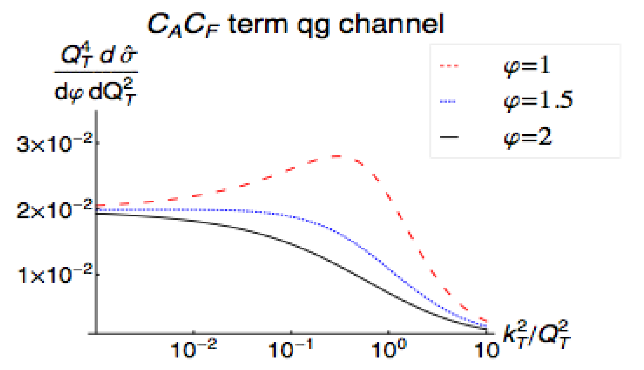
Forward region: $(p_4 + p_6)^2 \gg (p_3 + p_4)^2$, $k_1 \simeq \xi_1 p_1$, $k_2 \simeq \xi_2 p_2 + k_\perp$

$$\Rightarrow \quad p_5 \simeq (1 - \xi_1) p_1 \quad , \quad p_6 \simeq (1 - \xi_2) p_2 - k_\perp \quad , \quad \xi_1 \gg \xi_2$$

$$Q_T = (1 - \nu) p_{T4} - \nu p_{T3} \quad , \quad \text{where} \quad \nu = (p_2\, p_4)/[(p_2\, p_1) - (p_2\, p_5)]$$

RESUMMATION OF HIGH-RAPIDITY LOGARITHMS





- small-angle limit:

$$\frac{Q_T^4\ d\hat\sigma}{dQ_T^2 d\varphi} \to \alpha_s^2 f^{(0)}(p_T^2/s) \quad , \quad Q_T \to p_T = |p_{T3}| = |p_{T4}|$$

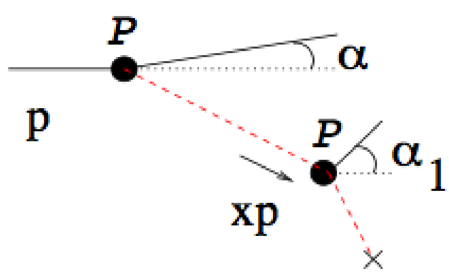
$$f^{(0)}(z) = \frac{1}{16\sqrt{1-4z}} \ \left[C_F^2 z(1+z) + 2C_F C_A (1 - 3z + z^2) \right]$$

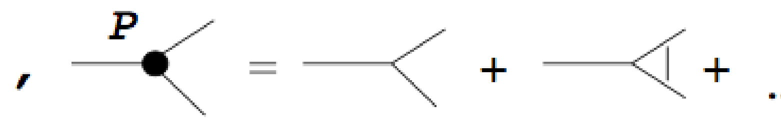
- summation of logs for large $y \sim \ln s/p_T^2$ achieved by convolution with unintegrated splitting functions

$$\int d^2 k_T \ \left(\frac{1}{k_T^2} \right)_+ \ \hat\sigma(k_T) = \int d^2 k_T \ \frac{1}{k_T^2} \ \left[\hat\sigma(k_T) - \Theta(\mu - k_T)\ \hat\sigma(0_T) \right]$$

RESUMMATION OF HIGH-RAPIDITY LOGARITHMS

$$\mathcal{G}(x, k_T, \mu) \;=\; \mathcal{G}_0(x, k_T, \mu) + \int \frac{dz}{z} \int \frac{dq^2}{q^2}\, \Theta(\mu - zq) \times \underbrace{\Delta(\mu, zq)}_{\text{Sudakov}} \; \underbrace{\mathcal{P}(z, q, k_T)}_{\text{unintegr. splitting}} \; \mathcal{G}(x/z, k_T + (1-z)q, q)$$





▷ CCFM evolution equation

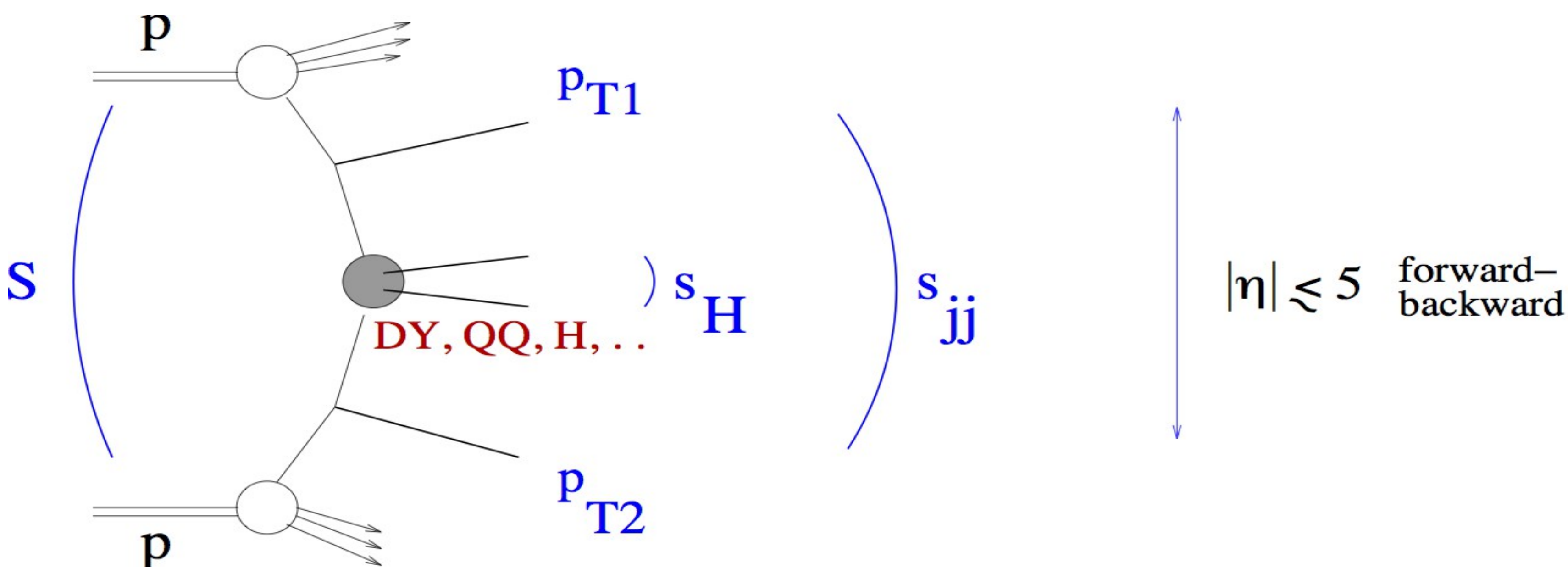
▷ Monte Carlo implementations CASCADE, LDC, ...

Merging PS and ME

- Merging in high-energy limit can be done using

$$\gamma \, \frac{1}{k_\perp^2} \left(\frac{k_\perp^2}{\mu^2} \right)^{\gamma} \stackrel{\gamma \ll 1}{=} \delta(k_\perp^2) + \gamma \left(\frac{1}{k_\perp^2} \right)_{\mathrm{R}} + \gamma^2 \left(\frac{1}{k_\perp^2} \ln \frac{k_\perp^2}{\mu^2} \right)_{\mathrm{R}} + \dots$$

where $\int dk_\perp \, (G(k_\perp, \mu))_{\mathrm{R}} \, \varphi(k_\perp) = \int dk_\perp \, G(k_\perp, \mu) [\varphi(k_\perp) - \Theta(\mu - k_\perp) \, \varphi(0)]$



Applications to 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

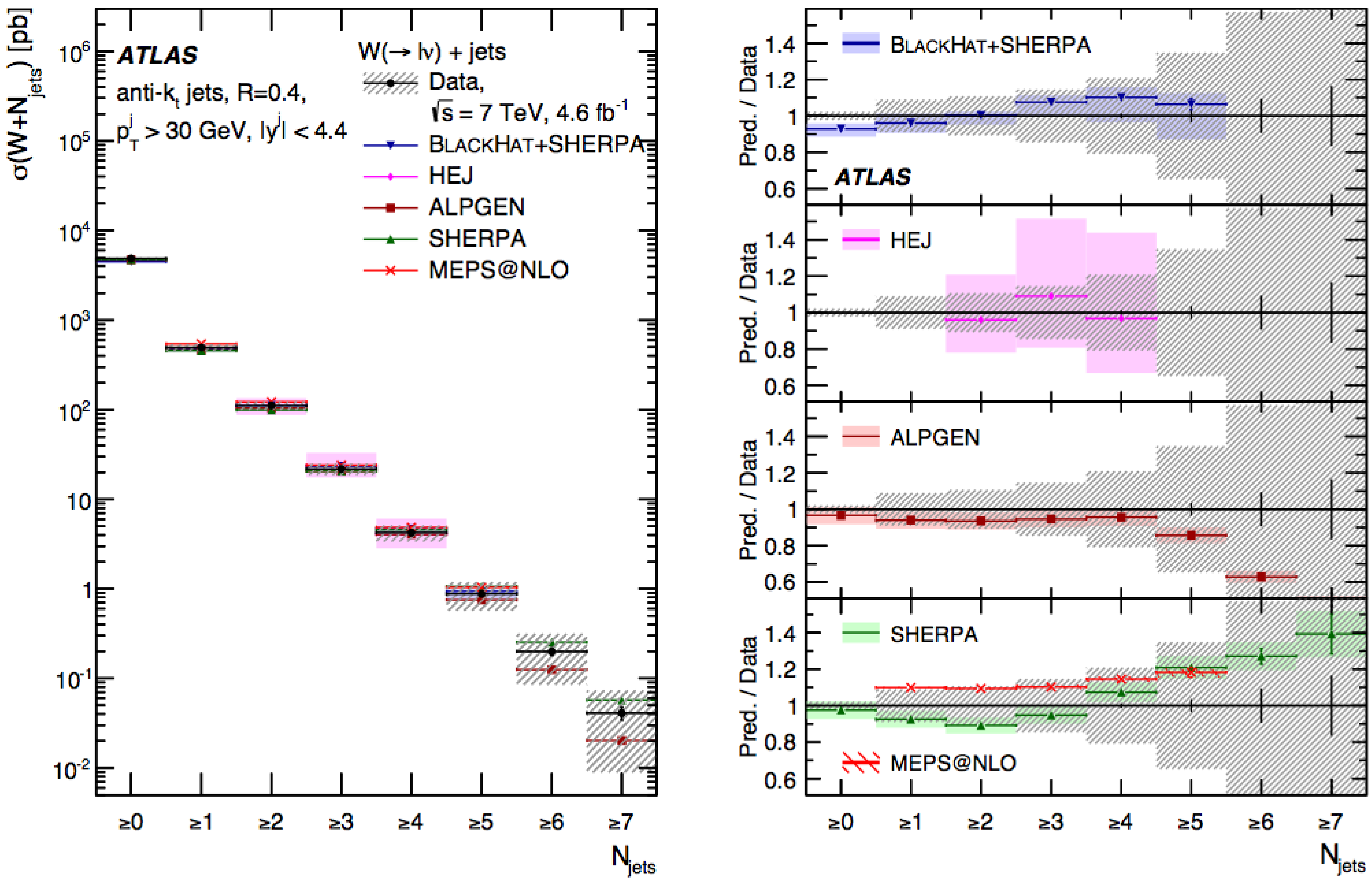
- Jet multiplicities associated with W boson production

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

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

W + jets

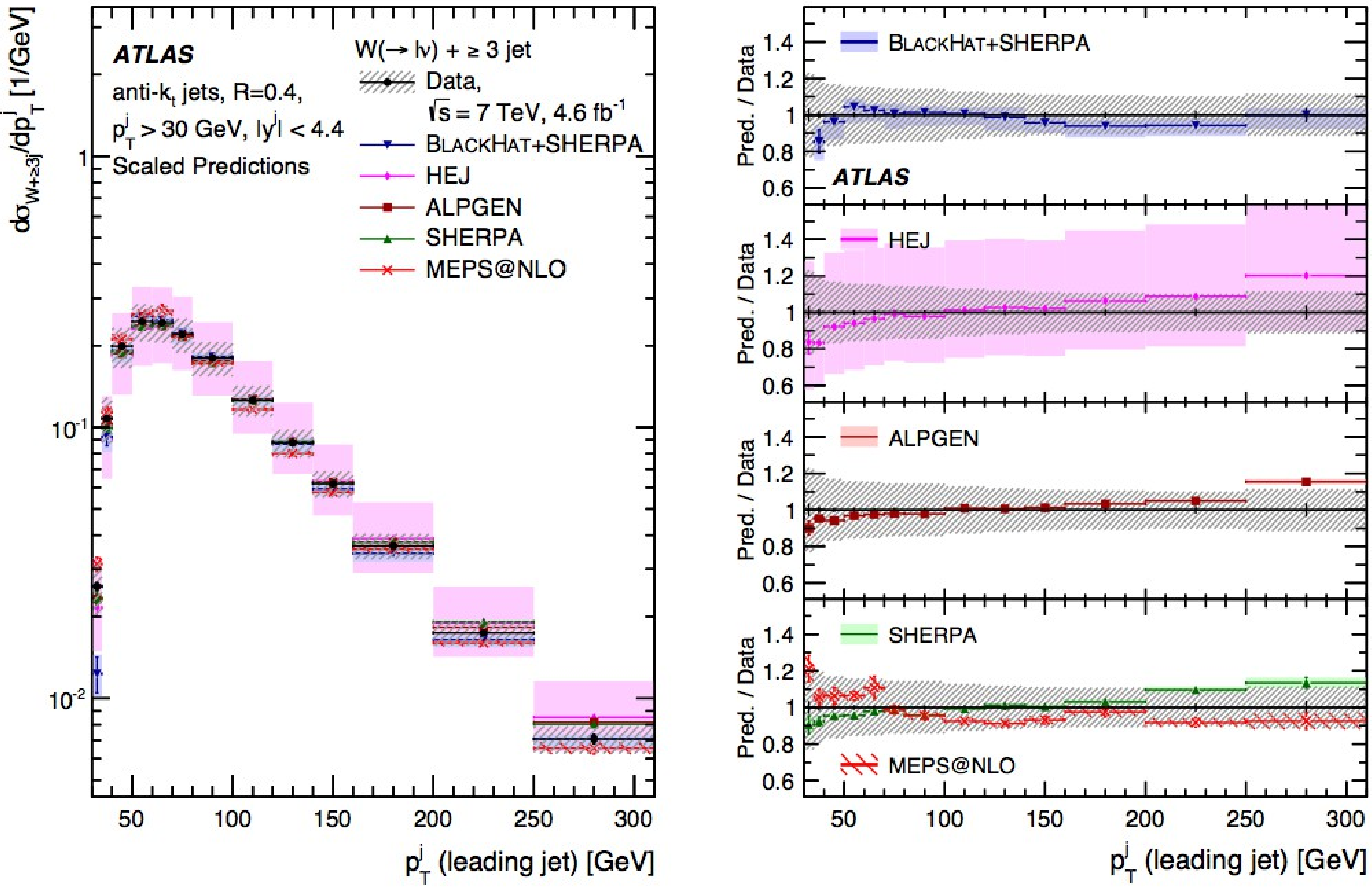
ATLAS, EPJC 75 (2015) 82



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

W + jets

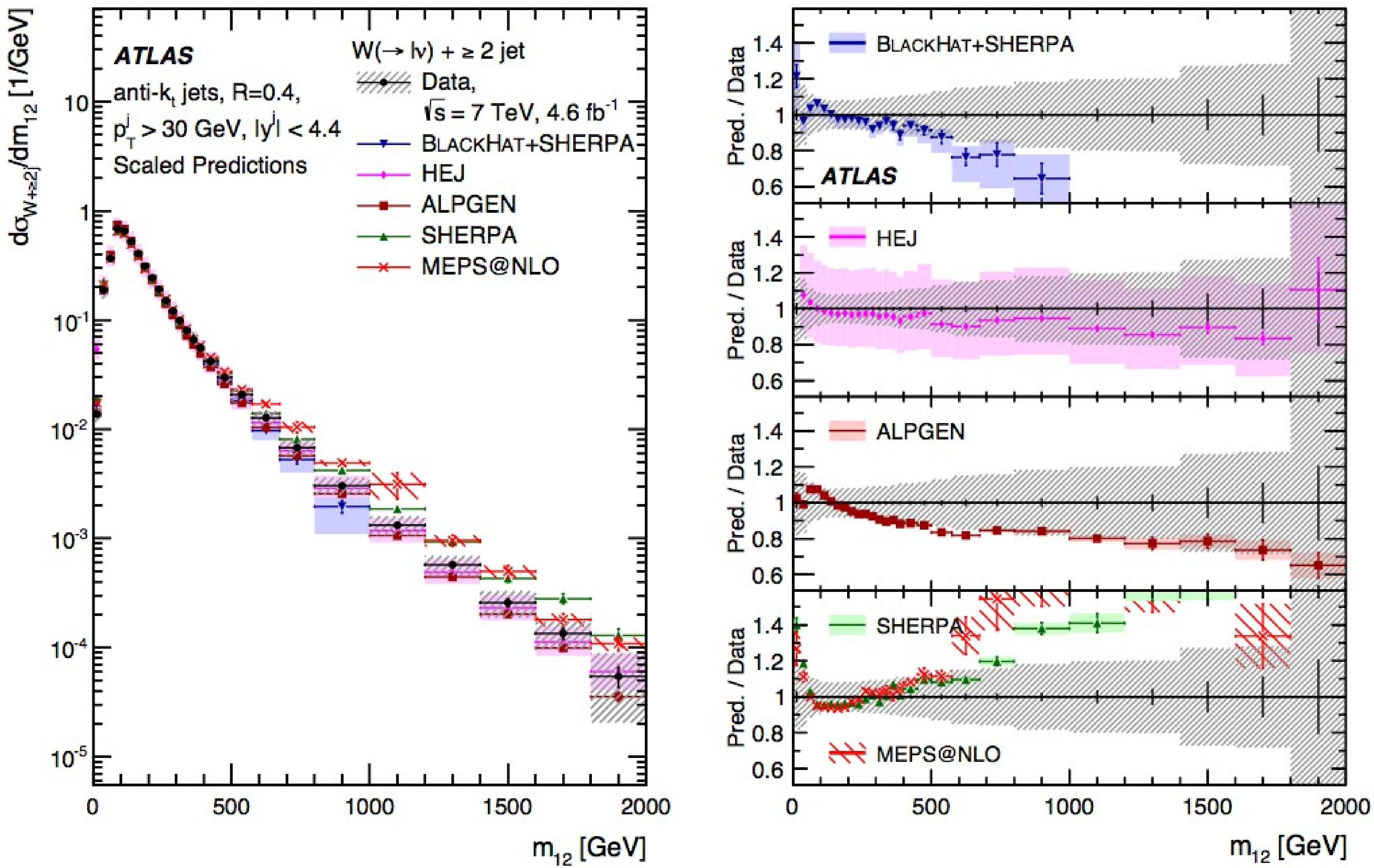
ATLAS, EPJC 75 (2015) 82



Good agreement between all predictions and data for inclusive observables

W + jets

ATLAS, EPJC 75 (2015) 82

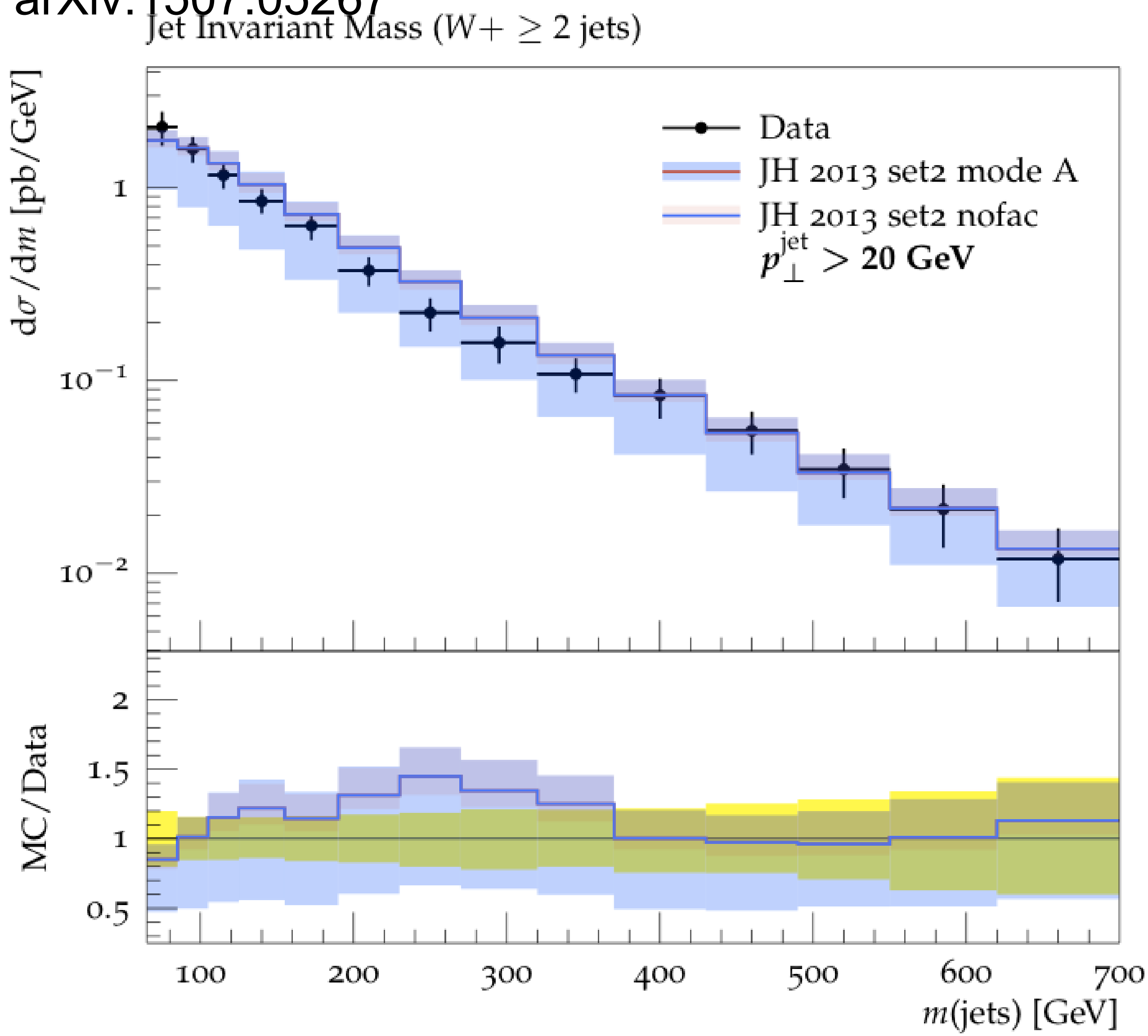


Large spread in predictions for invariant mass spectrum

M_JJ ~ 400 – 600 GeV

W + n jets: dijet mass spectra from TMD-resummed approach

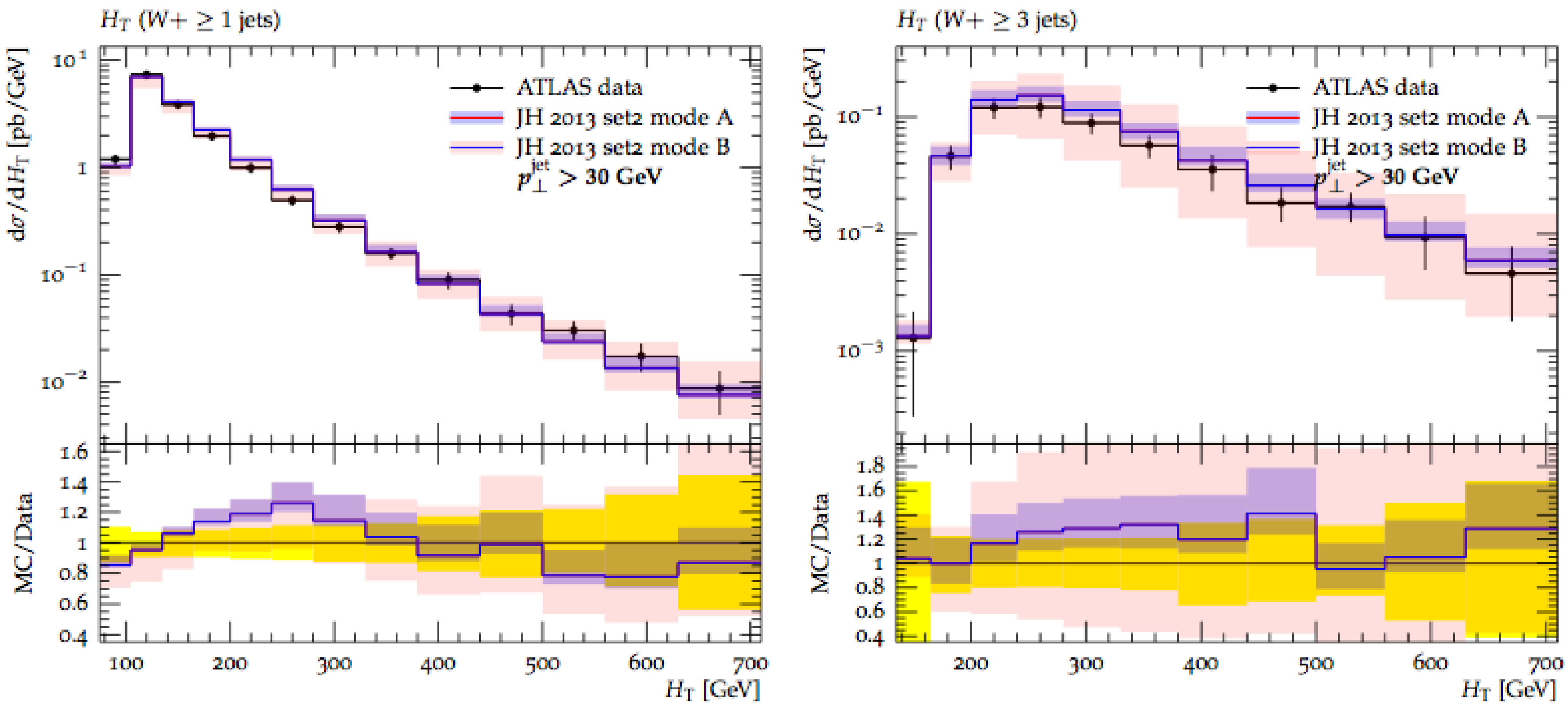
R. Angeles-Martinez et al., arXiv:1507.05267



- 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.

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

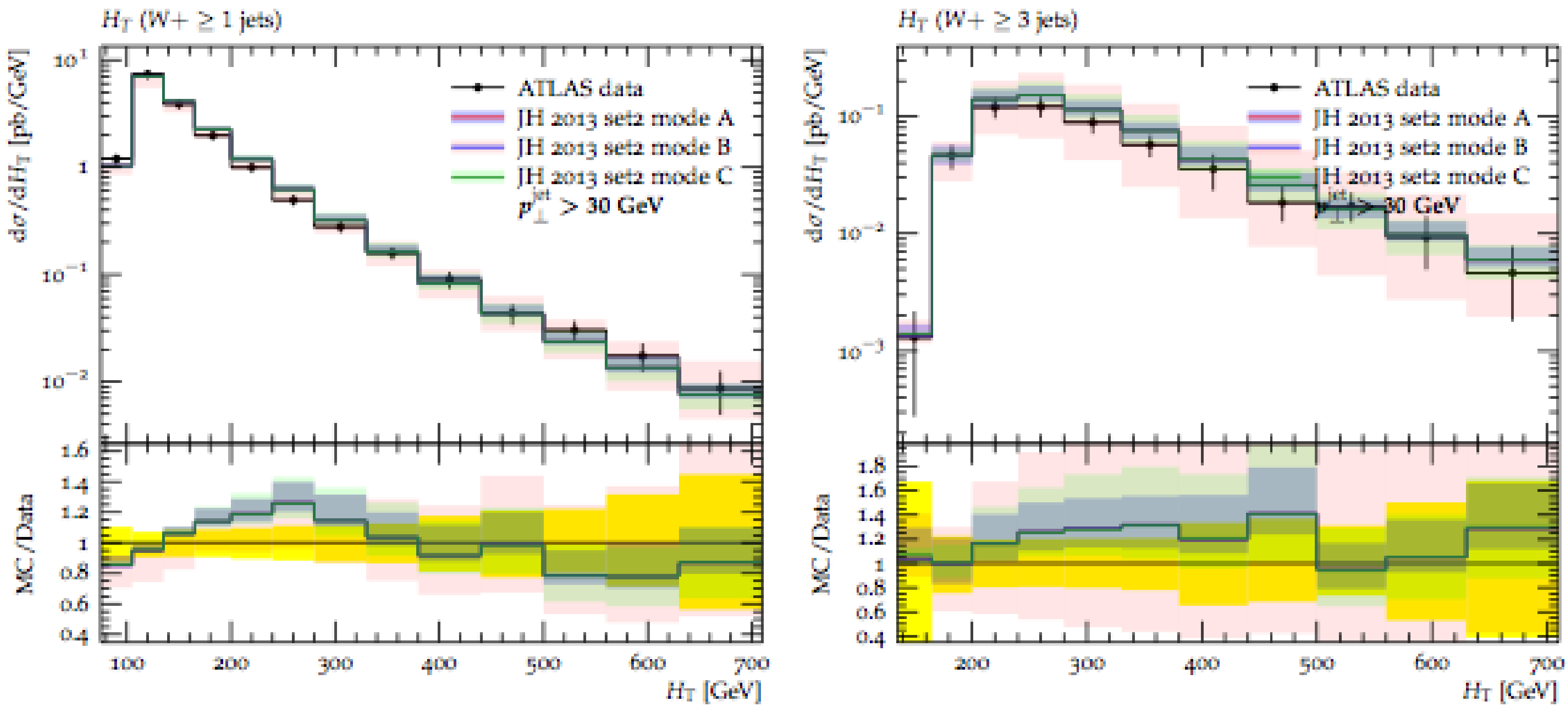
Dooling, Jung & H, Phys. Lett. B736 (2014) 293



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

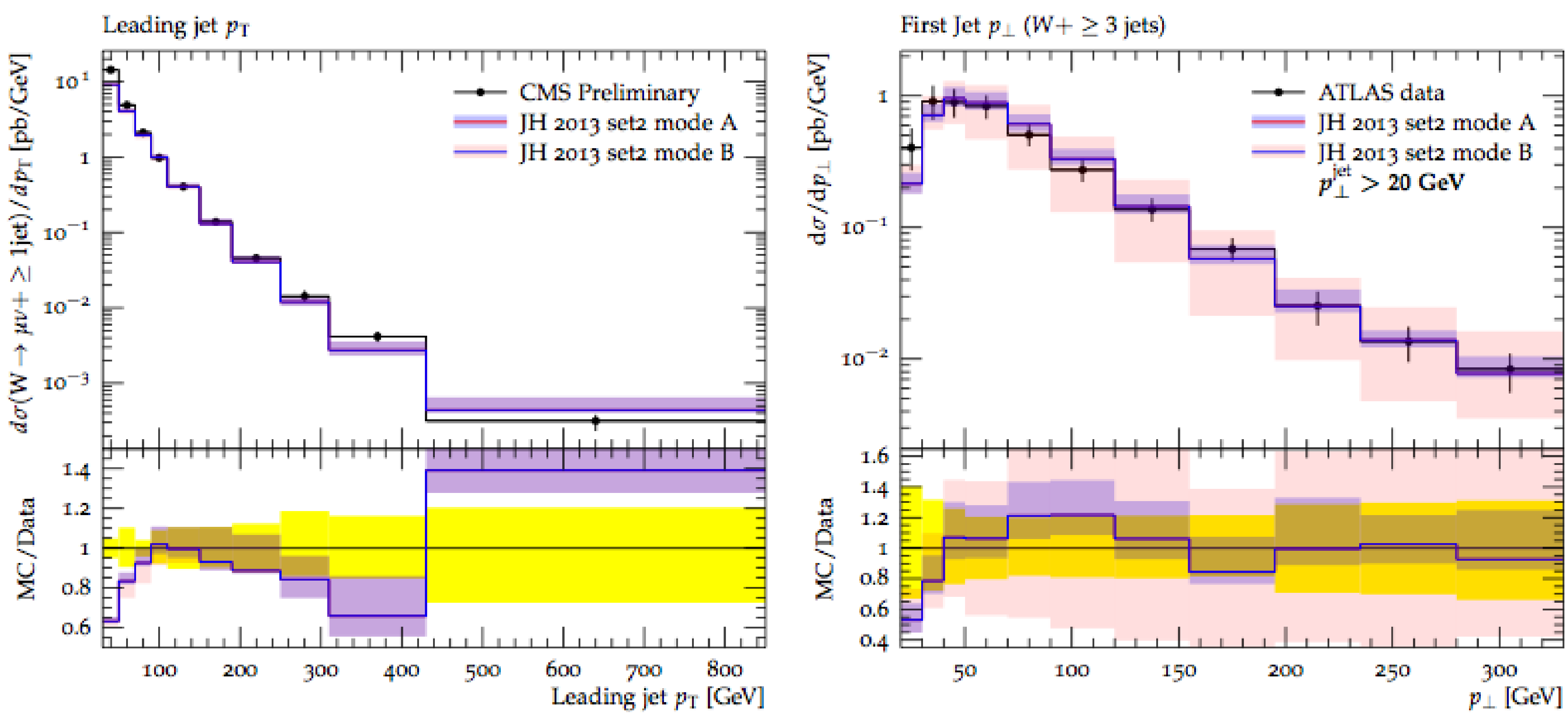
Dooling, Jung & H, Phys. Lett. B736 (2014) 293

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)

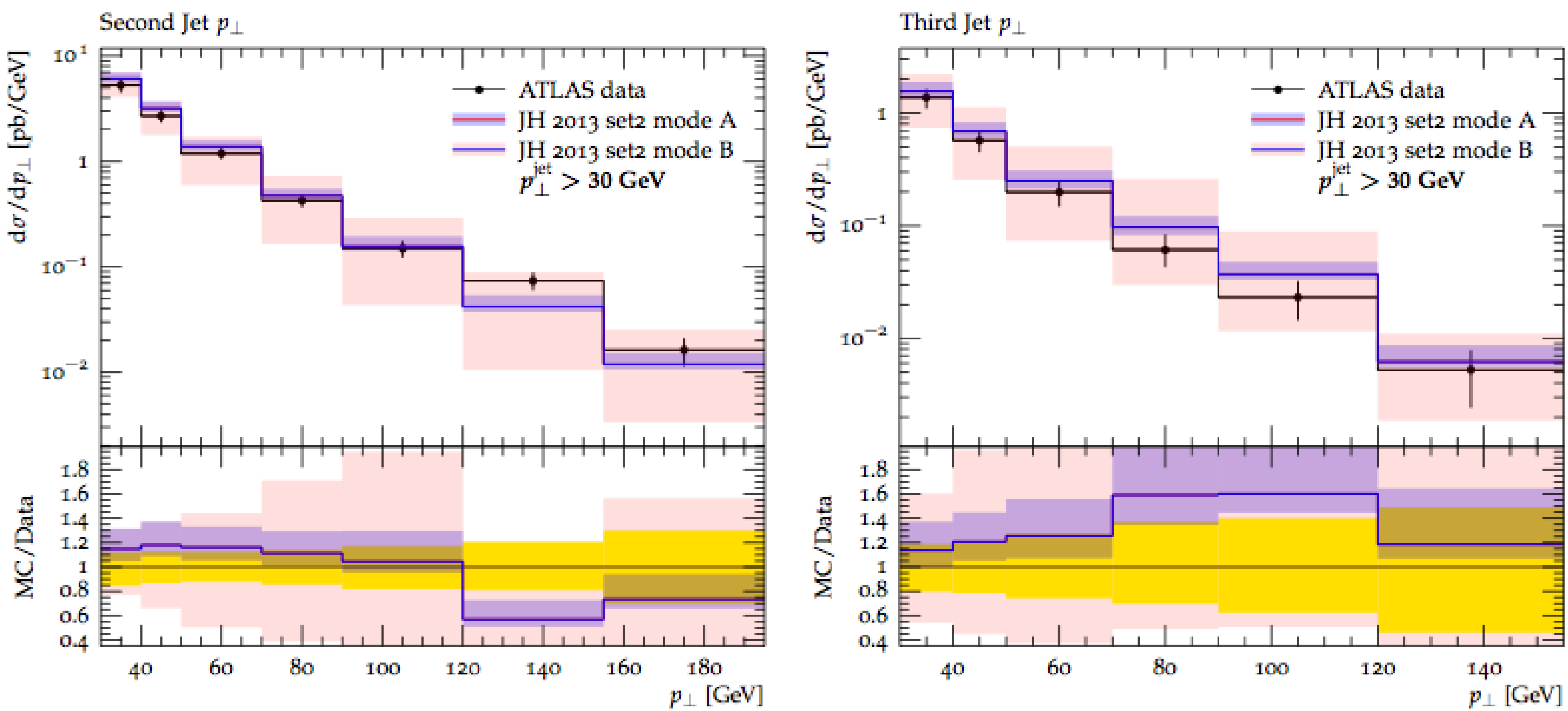
W + n jets final states at the LHC: pT spectra of the jets

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

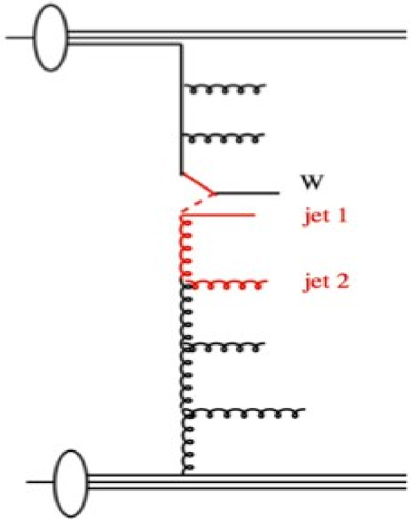


Leading jet pT: (left) inclusive; (right) n>=3

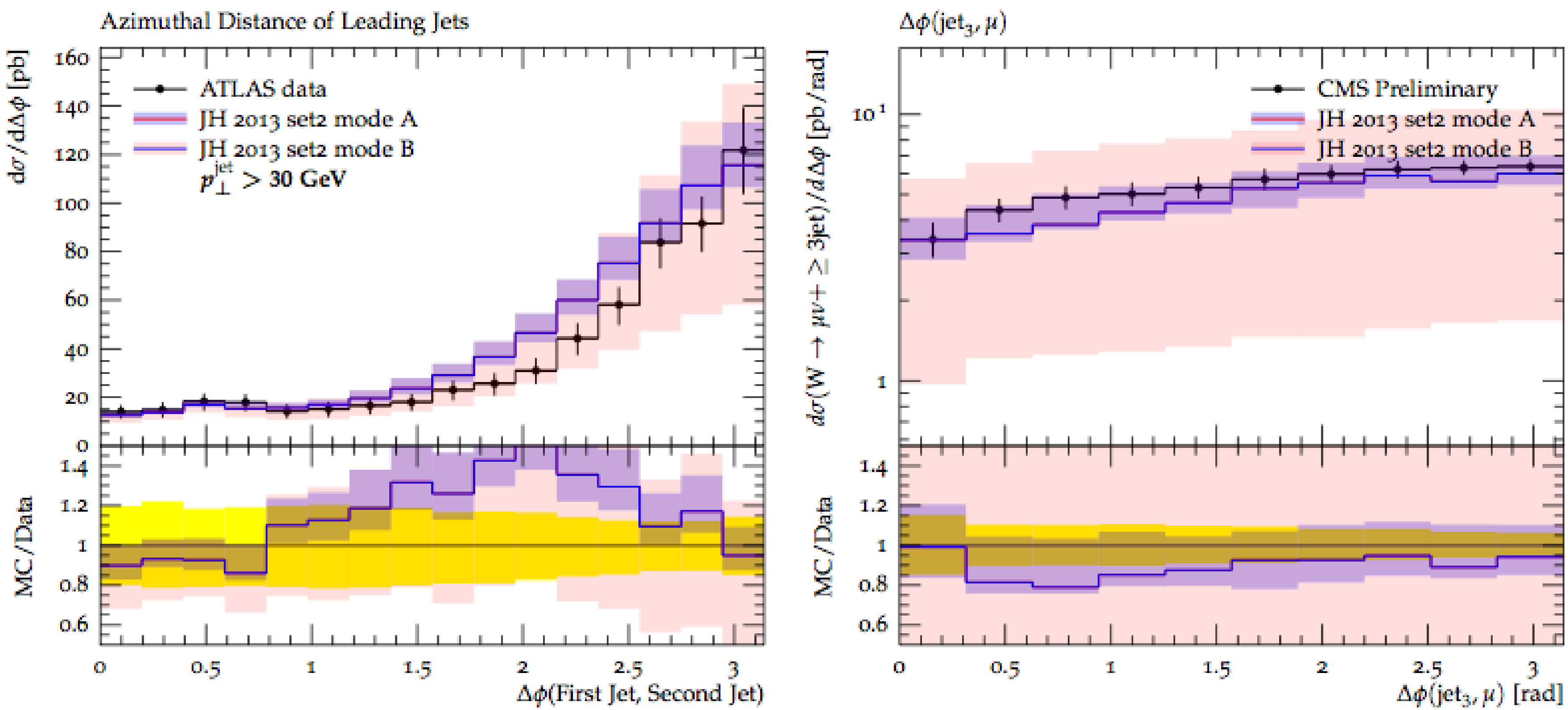
W + n jets final states at the LHC: pT spectra of subleading jets



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

What do we gain?

- Uses of TMD pdfs + kt-dependent shower:

  matching with 2 → n off-shell parton calculations

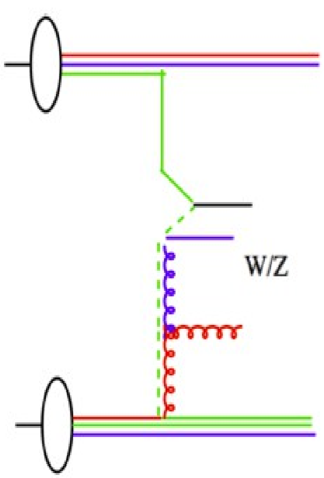
  (automated method, see van Hameren, Kotko & Kutak JHEP 1301 (2013) 078)

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

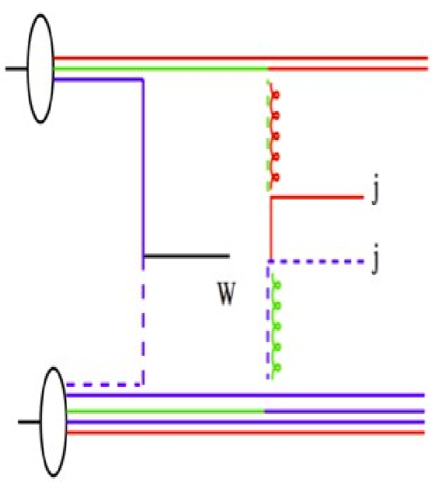
W + 2 jets as signal of double parton interactions

- 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

How can we reduce theoretical uncertainties?

- Work in progress on TMD evolution
- Threshold resummation from shower solution

  (coherent branching)

Reformulation of evolution equations

- ~~Sea quark evolution including gluons from sea quarks:~~

$$
\begin{aligned}
\mathcal{S}^s(x,k_\perp,p) &= \mathcal{S}^s_0(x,k_\perp,p) \\
&+ \int \frac{dz}{z} \int \frac{dq^2}{q^2}\, \Theta(p-zq)\ \Delta_s(p,zq) P_{qg}(z,q,k_\perp)\ \mathcal{A}^s\left(\frac{x}{z}, k_\perp + (1-z)q, q\right) \\
&+ \int \frac{dz}{z} \int \frac{dq^2}{q^2}\, \Theta(p-zq) \Delta_s(p,zq) P_{qq}(z,q,k_\perp)\ \mathcal{S}^s\left(\frac{x}{z}, k_\perp + (1-z)q, q\right)
\end{aligned}
$$

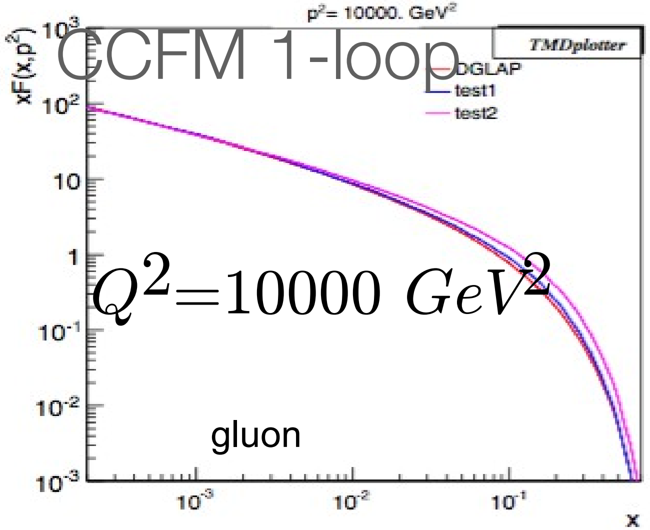
$$
\begin{aligned}
\mathcal{A}^g(x,k_\perp,p) &= \mathcal{A}^g_0(x,k_\perp,p) \\
&+ \int \frac{dz}{z} \int \frac{dq^2}{q^2}\, \Theta(p-zq) \Delta_s(p,zq) P_{gg}(z,q,k_\perp)\ \mathcal{A}^g\left(\frac{x}{z}, k_\perp + (1-z)q, q\right) \\
&+ \int \frac{dz}{z} \int \frac{dq^2}{q^2}\, \Theta(p-zq) \Delta_s(p,zq) P_{gq}(z,q,k_\perp)\ \mathcal{S}^g\left(\frac{x}{z}, k_\perp + (1-z)q, q\right)
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{S}(x,k_\perp,p) &= \mathcal{S}^s(x,k_\perp,p) + \mathcal{S}^g(x,k_\perp,p) \\
\mathcal{A}(x,k_\perp,p) &= \mathcal{A}^s(x,k_\perp,p) + \mathcal{A}^g(x,k_\perp,p)
\end{aligned}
$$

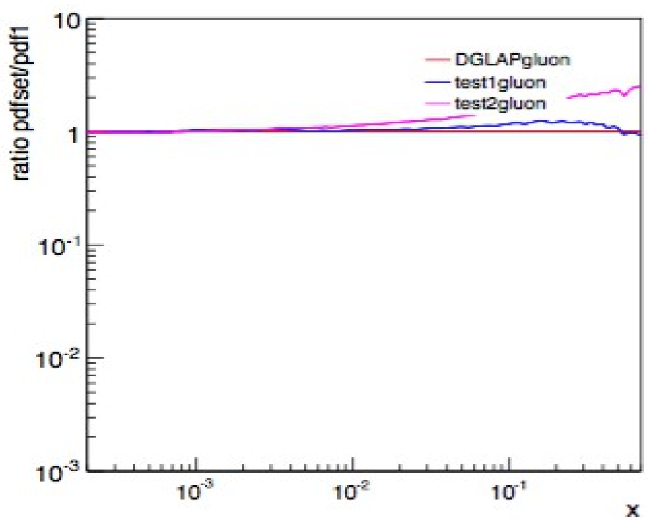
- strategy (to avoid double counting and avoid missing contributions):
  - determine 2 kernels: for gluon and sea separately

Validation of procedure with LO DGLAP evolution

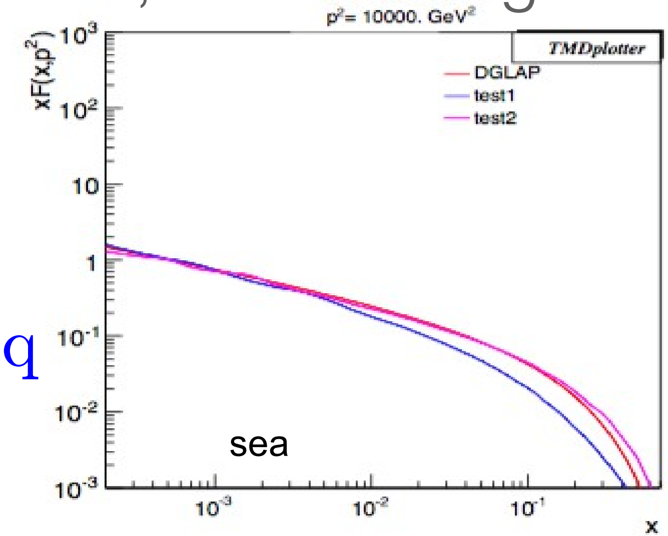
- use HERAPDF1.5 LO as starting distribution, evolve using CCFM 1-loop

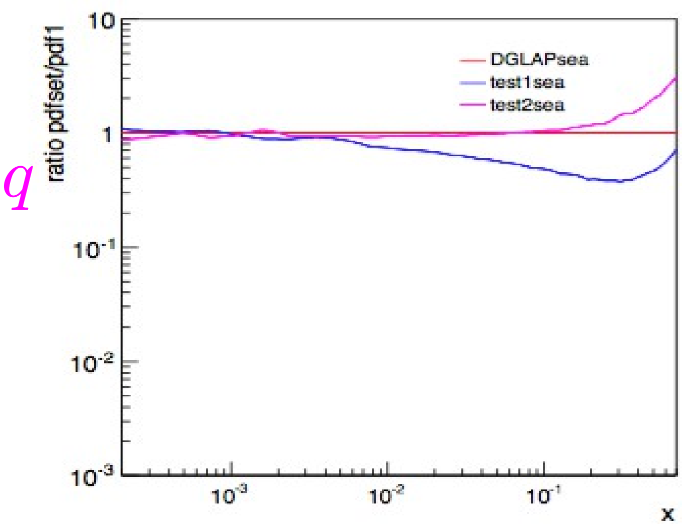


$Q^2 = 10000\ GeV^2$

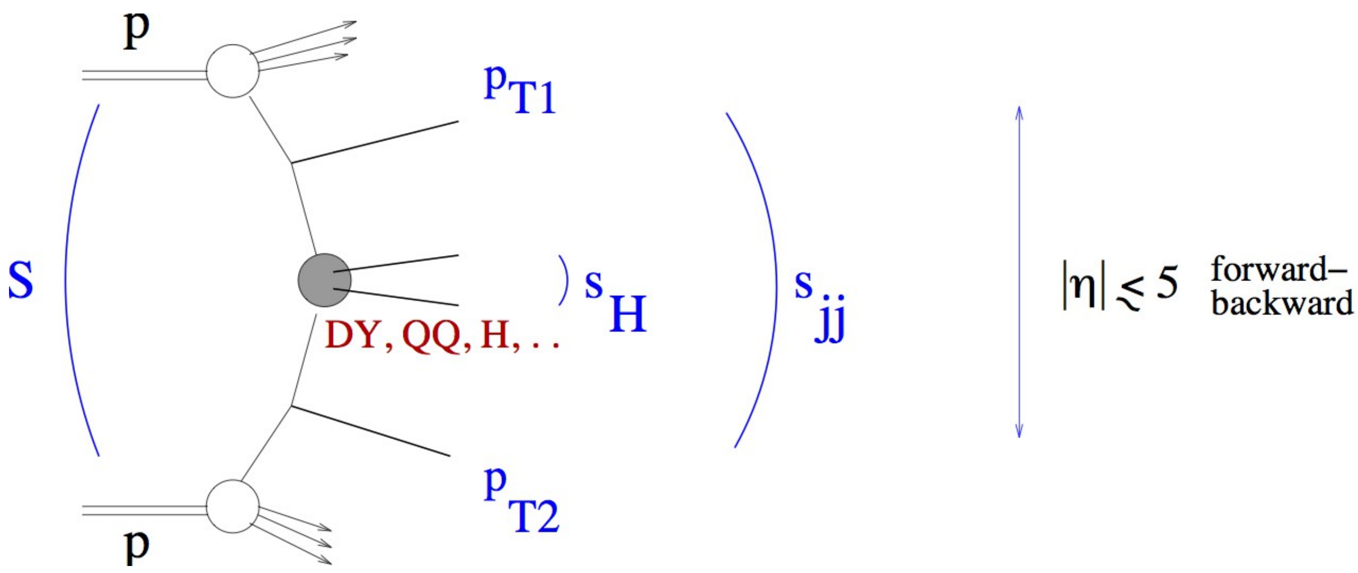


- test1:
  - angular ordering $z_{max} = 1 - (q_0/q)^2$
- test2:
  - strict q ordering
  - $z_{max} = 1 - q_0/q$





CONCLUSION



high luminosity → high pile-up

large s_jj → forward/backward region → QCD resummation methods

heavy boson + jets cross sections

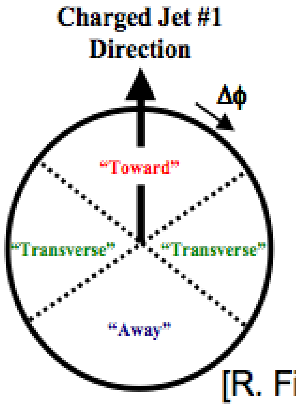
full TMD evolution and shower solution – in progress

threshold resummation by coherent branching – in progress

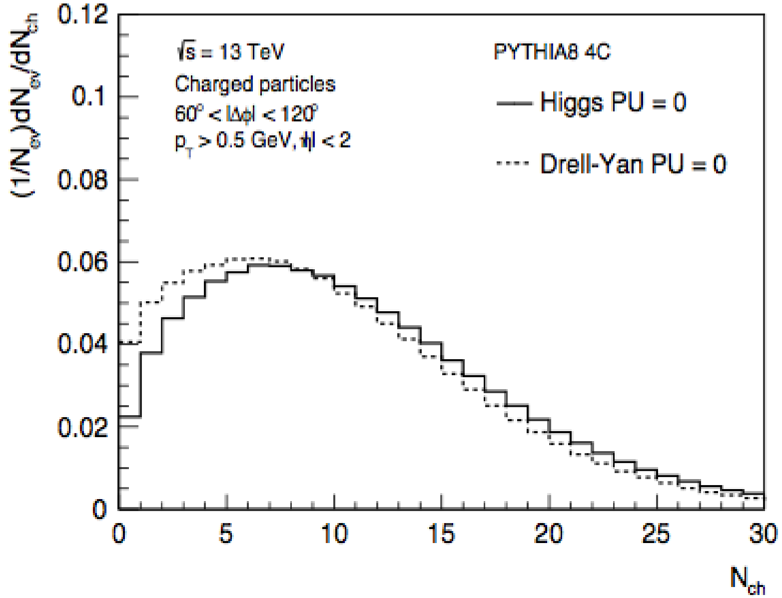
EXTRA SLIDES

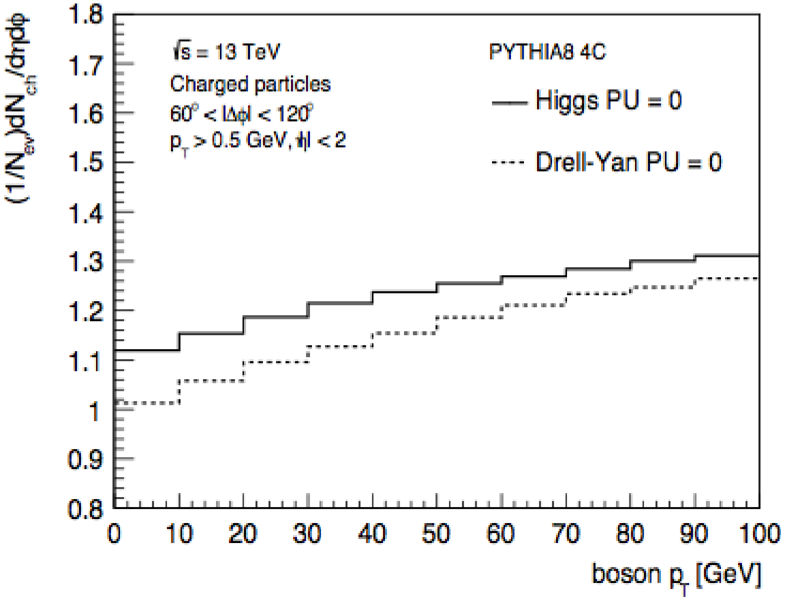
The underlying event in high pile-up environments

- UE studies typically measure the number of charged particles (or Σp_T) in the transverse plane
- As function of the hard scale in the event
- Compare UE of Higgs vs DY production
  ➔ clean final state ➔ only initial state radiation (ISR) + MPI
- Can one perform UE studies in high PU environments?



[R. Field]



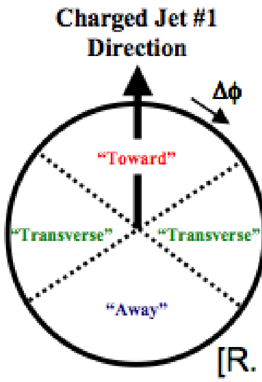


H van Haevermaet et al., in progress

The underlying event in high pile-up environments

- UE studies typically measure the number of charged particles (or Σp_T) in the transverse plane
- Activity scales with number of additional PU events
- But one can subtract PU contribution:

$$\frac{dn}{dp_T}(\mathrm{H}-\mathrm{DY}) = \frac{dn}{dp_T^{\mathrm{H}}} + \frac{dn}{dp_T^{\mathrm{PU}}} - \left(\frac{dn}{dp_T^{\mathrm{DY}}} + \frac{dn}{dp_T^{\mathrm{PU}}}\right)$$



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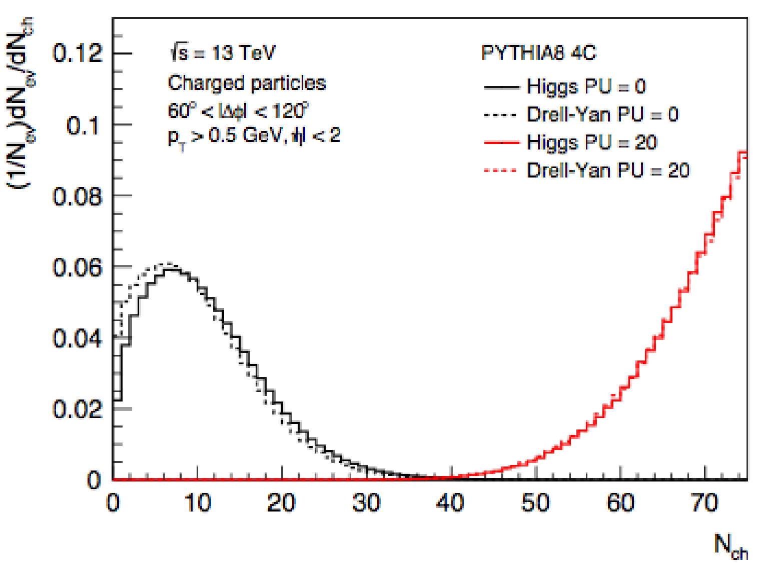
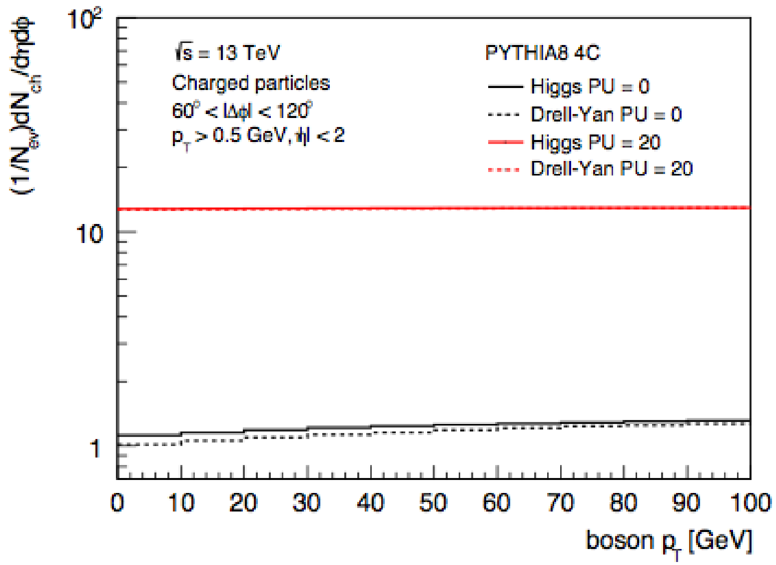
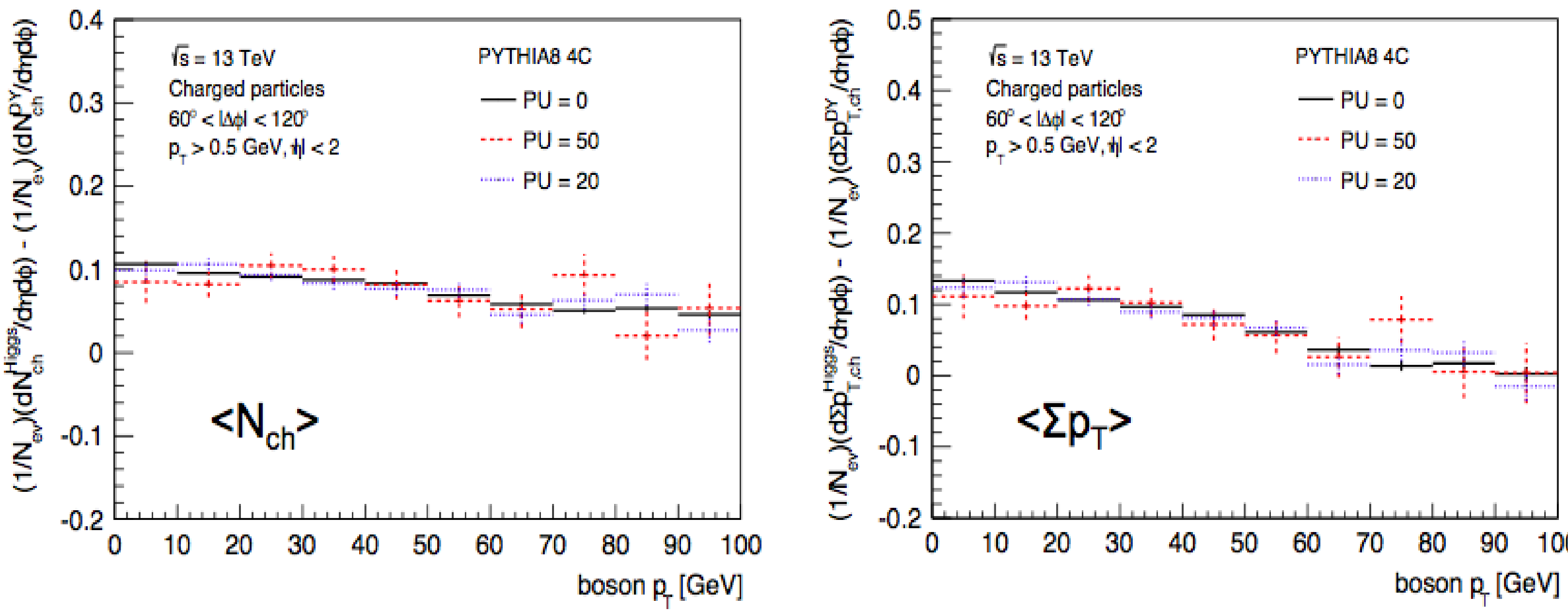




H van Haevermaet et al., in progress

The underlying event in high PU environments: 13 TeV

- After subtraction of activity in DY from activity in Higgs production:



- PU contribution cancels
- Access to small-p_T QCD physics
- Probe directly difference of quark vs gluon induced UE activity!
  ➔ access to colour decomposition/structure of ISR

Conclusions

- Many interesting measurements in LHC high-luminosity runs are hampered by high pile up
- Especially topologies that exploit the correlation between final state products
  - ➔ e.g. Drell-Yan or Higgs + jet production
- Main pile-up effects present in such measurements:
  1. large bias in jet p_T due to added pile-up particles in jet cone
     - ➔ several methods exist to correct for this (e.g. CHS, PUPPI, SoftKiller)
  2. mis-tagging of high p_T jets from independent pile-up events
     - ➔ not properly treated yet
- Proposed new method of jet mixing to treat pile-up:
  - ➔ use data recorded at high pile-up
  - ➔ no Monte Carlo dependence
- Good prospects for precision SM studies & BSM searches in high pile-up