ECT*
Workshop on Linear and Future Colliders

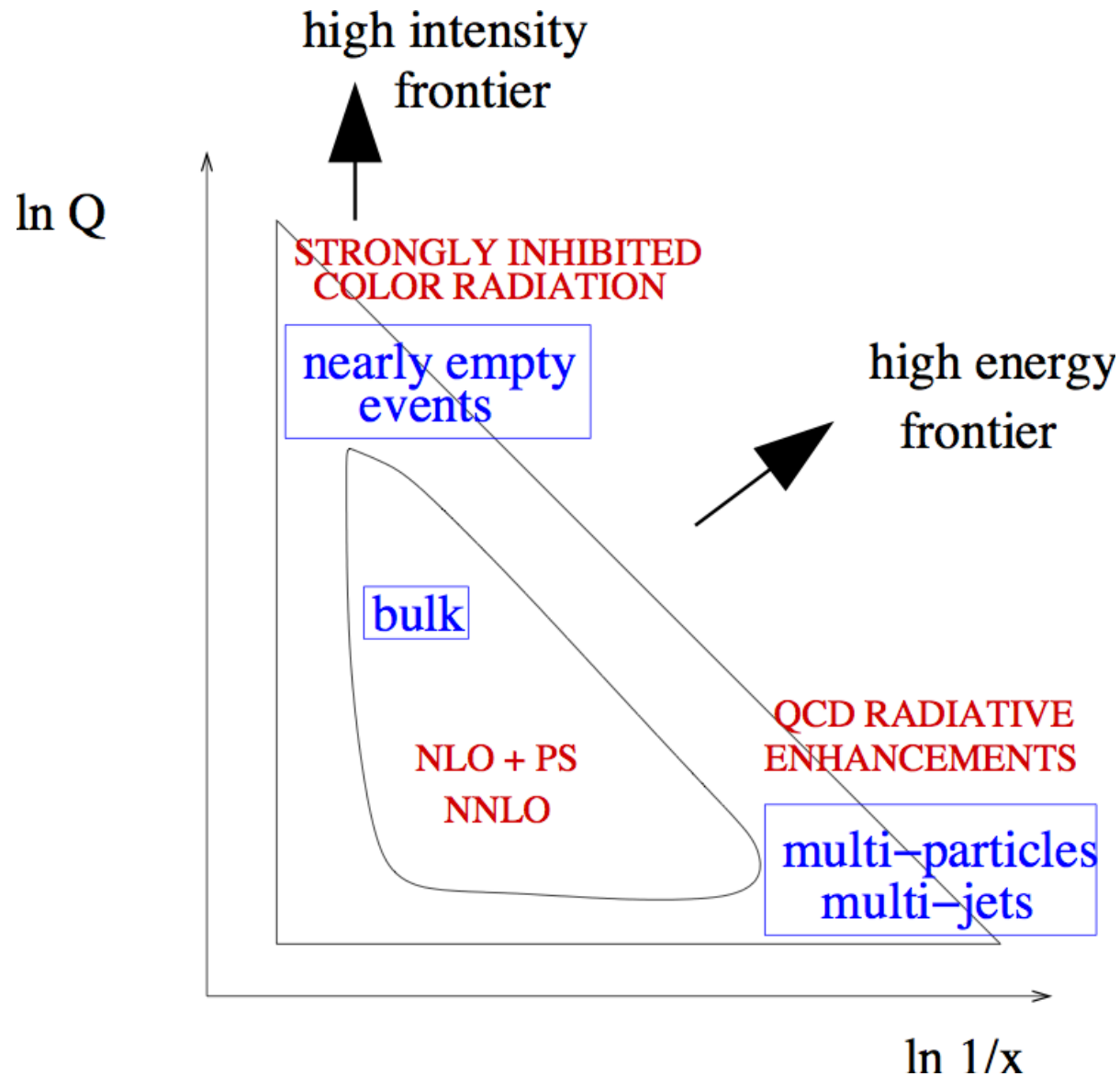## Trento, September 2015

F Hautmann

QCD at high luminosity hadron colliders:

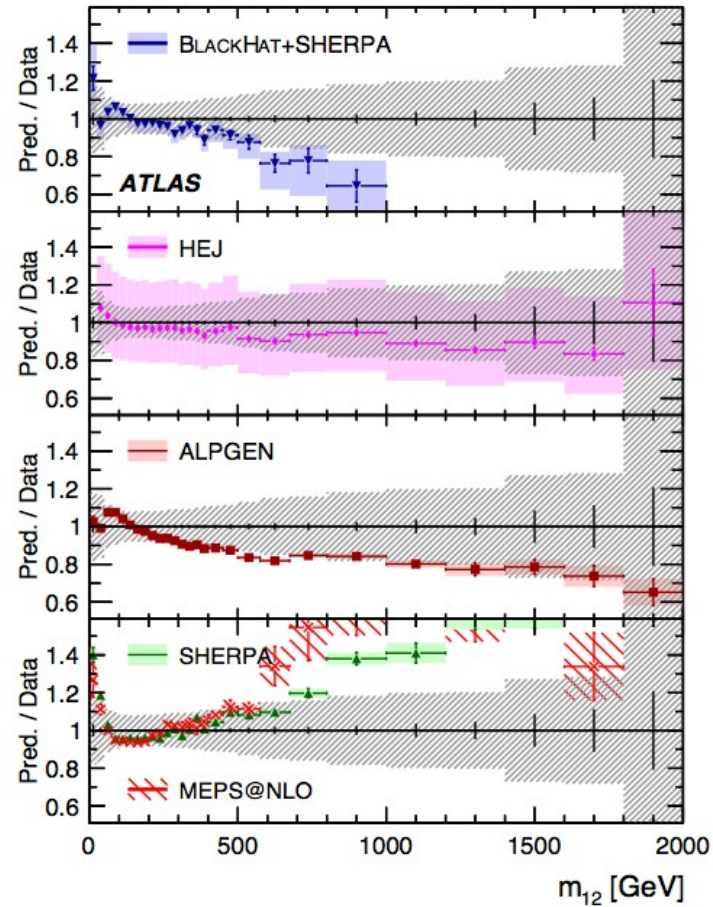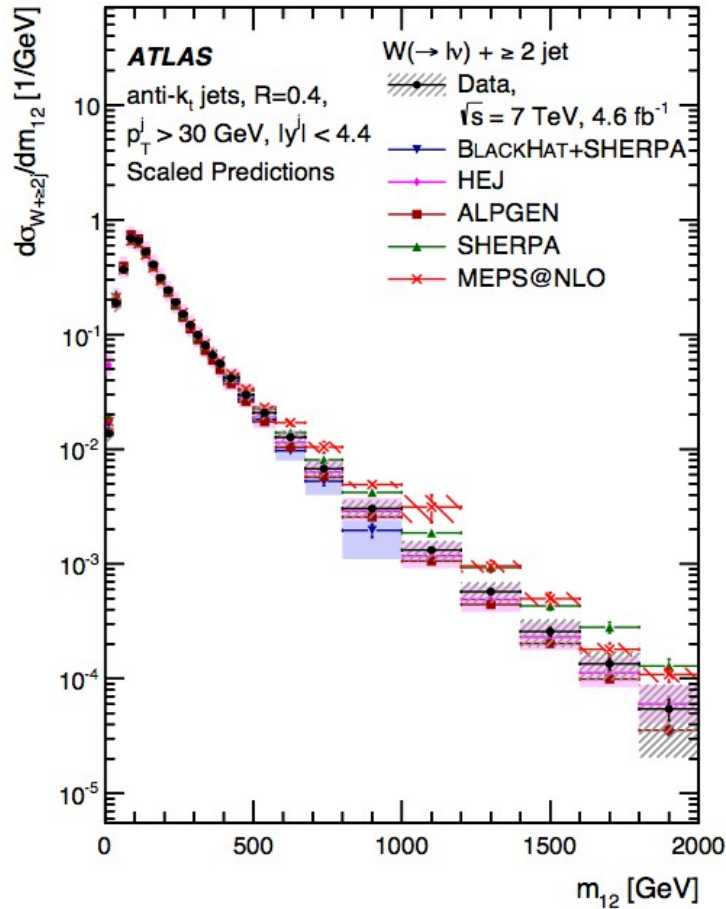## *Treating jet correlations in high pile-up*

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

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

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
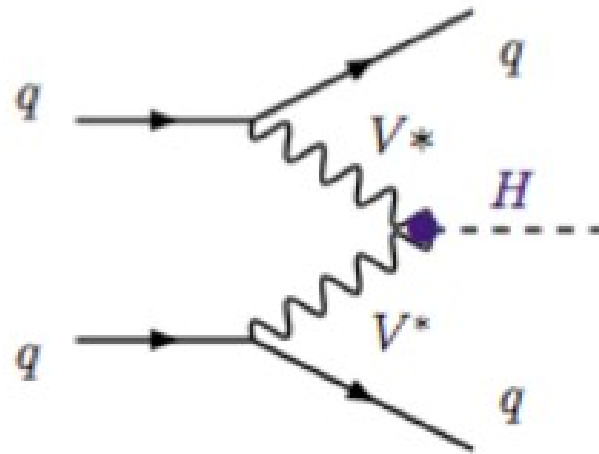
associated jets may be produced outside tracking detector acceptances

- 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
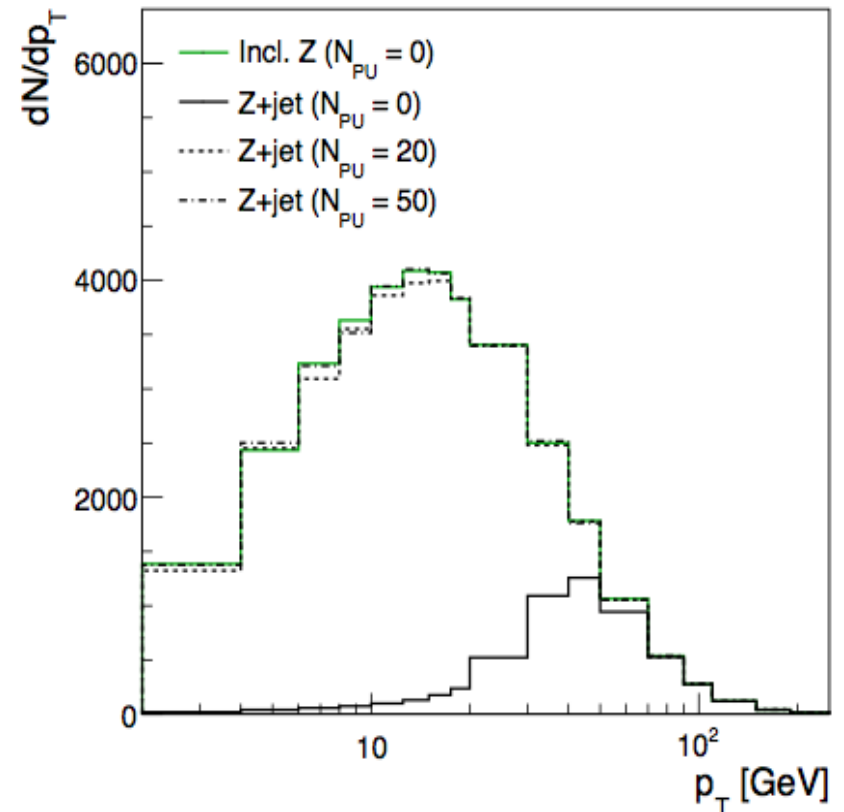
Pile-up effects: Z + jet case study

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

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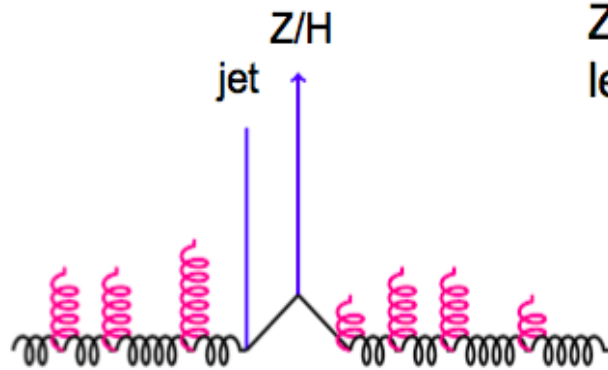
Z boson: $60 < M < 120$ GeV
leading jet: $p_T > 30$ GeV; $|\eta| < 4.5$

> p_T spectrum shifts to lower values (inclusive spectrum)

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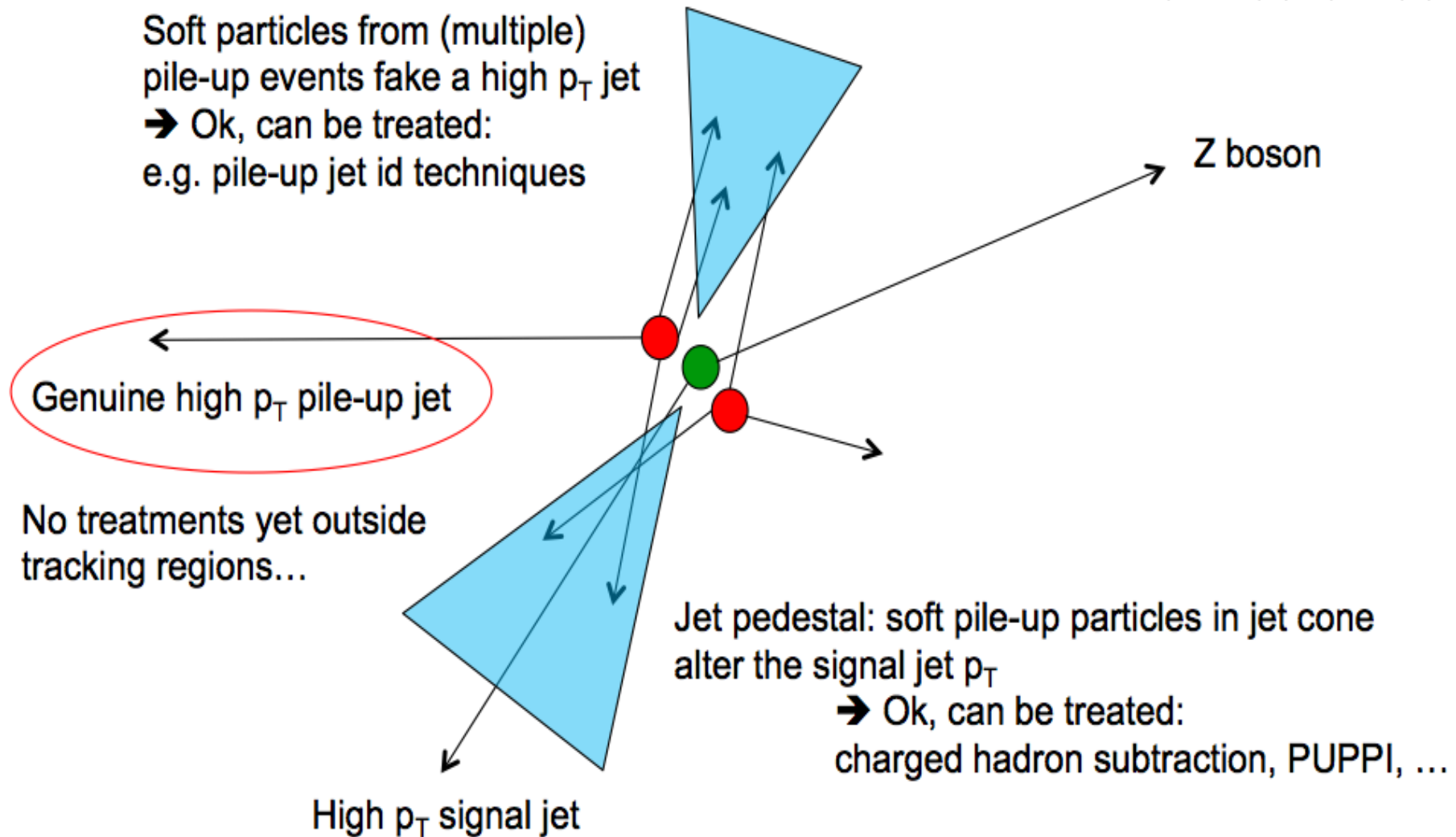→ signal process drowns in pile-up

H. van Haevermaet et al.
arXiv:1508.07811

> Z + jet correlations are affected by:

H. van Haevermaet et al.

Soft particles from (multiple)
pile-up events fake a high p_T jet
➔ Ok, can be treated:
e.g. pile-up jet id techniques

Z boson

Genuine high p_T pile-up jet

No treatments yet outside
tracking regions...

Jet pedestal: soft pile-up particles in jet cone
alter the signal jet p_T
➔ Ok, can be treated:
charged hadron subtraction, PUPPI, ...

High p_T signal jet

Correcting the jet p_T pedestal

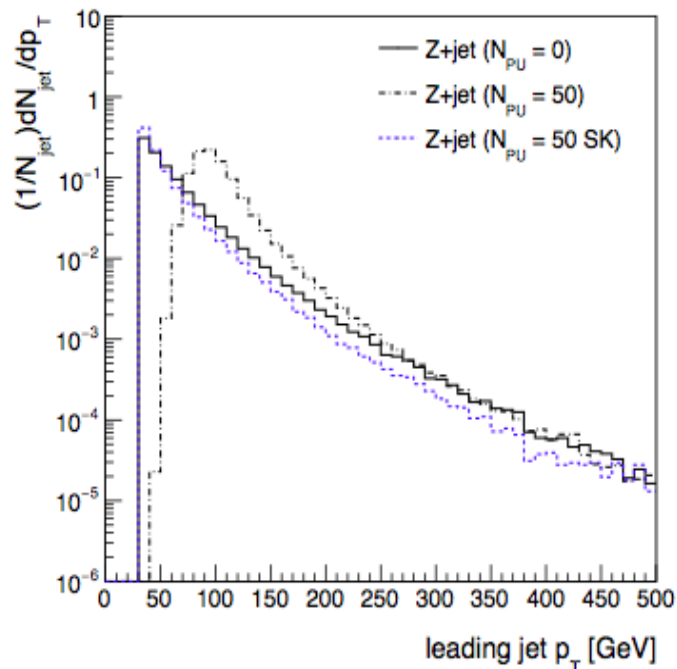> **Can be done with several existing methods for central jets**

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. D 90 (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

$$\rho = \underset{i \in \text{patches}}{\text{median}} \left\{ \frac{p_{ti}}{A_i} \right\}$$
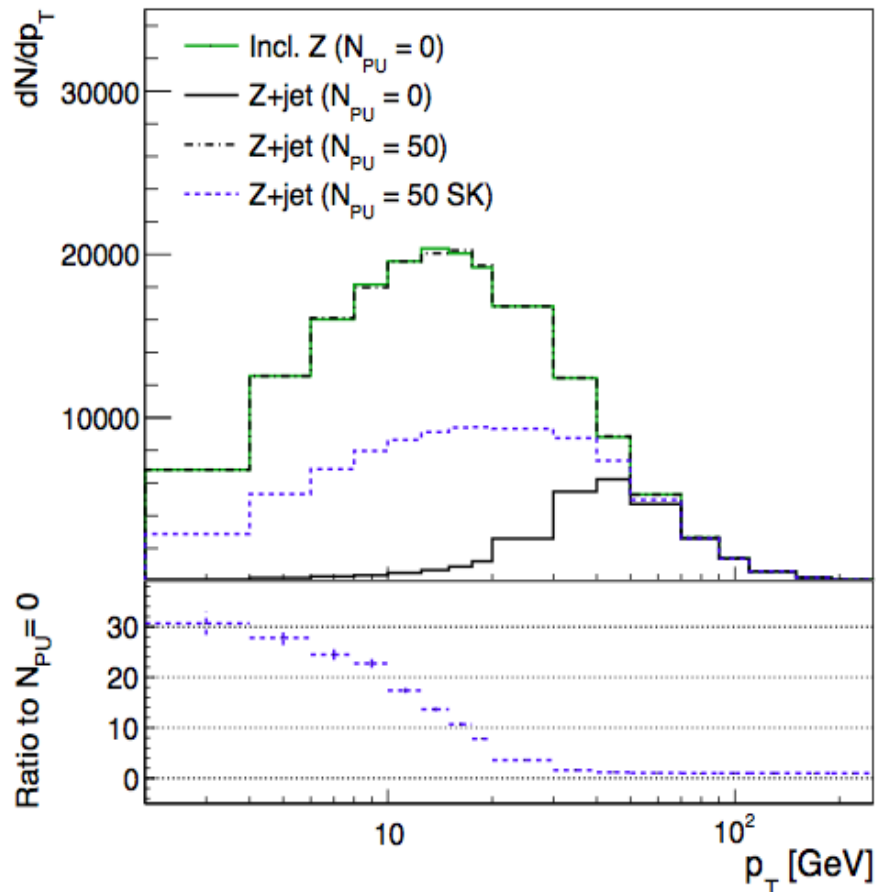
Cacciari, Salam, Soyez
Eur. Phys. J. C 75 (2015) 2

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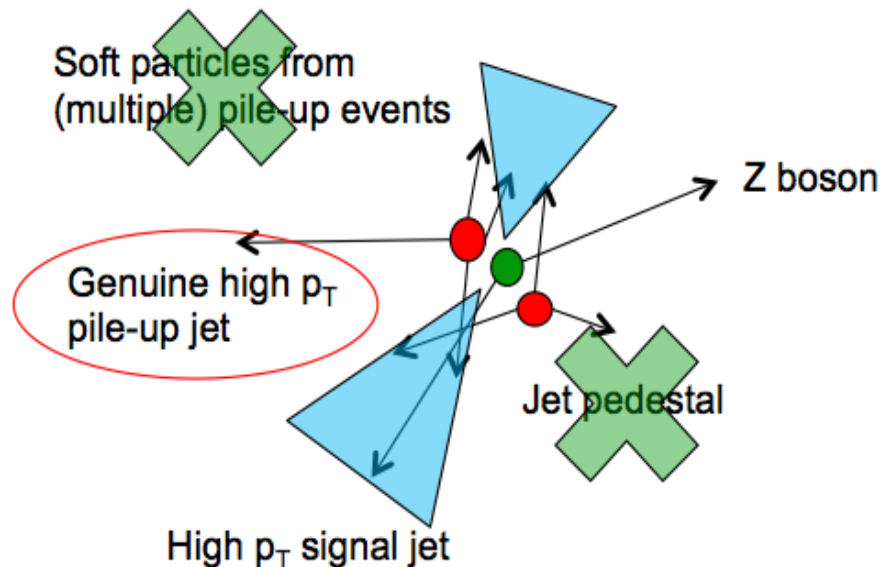but not for any misidentification

Apply SoftKiller to Z boson p_T 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

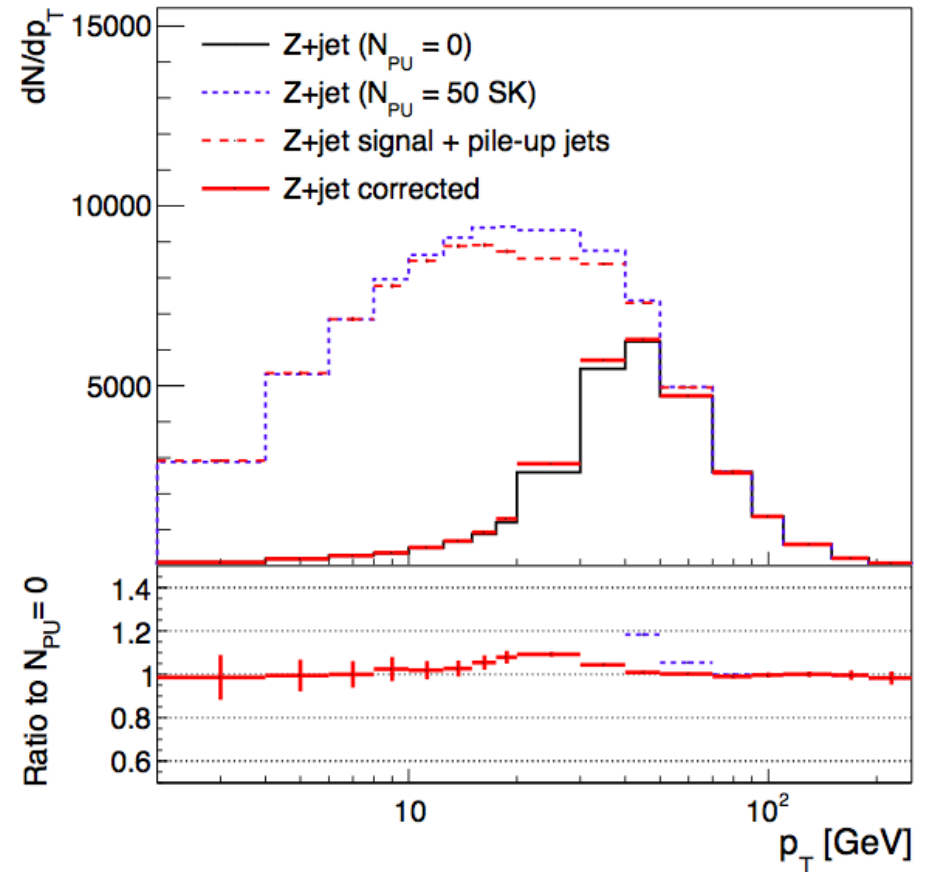# Treating effects beyond soft particles and the jet pT pedestal

- Jet mixing techniques using uncorrelated event samples

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

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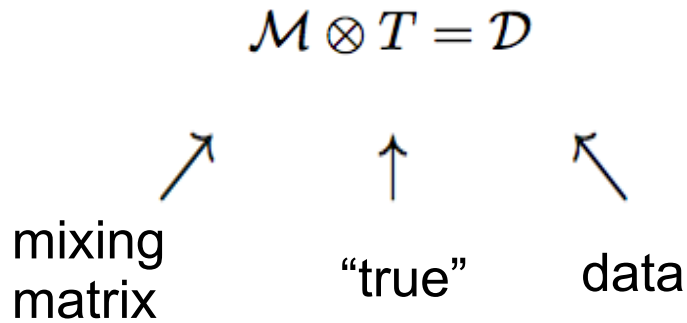
To identify contribution of high-pT jets from independent pile-up events, construct signal + pile-up scenario In a data-driven manner.

Valid for high pile-up:

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

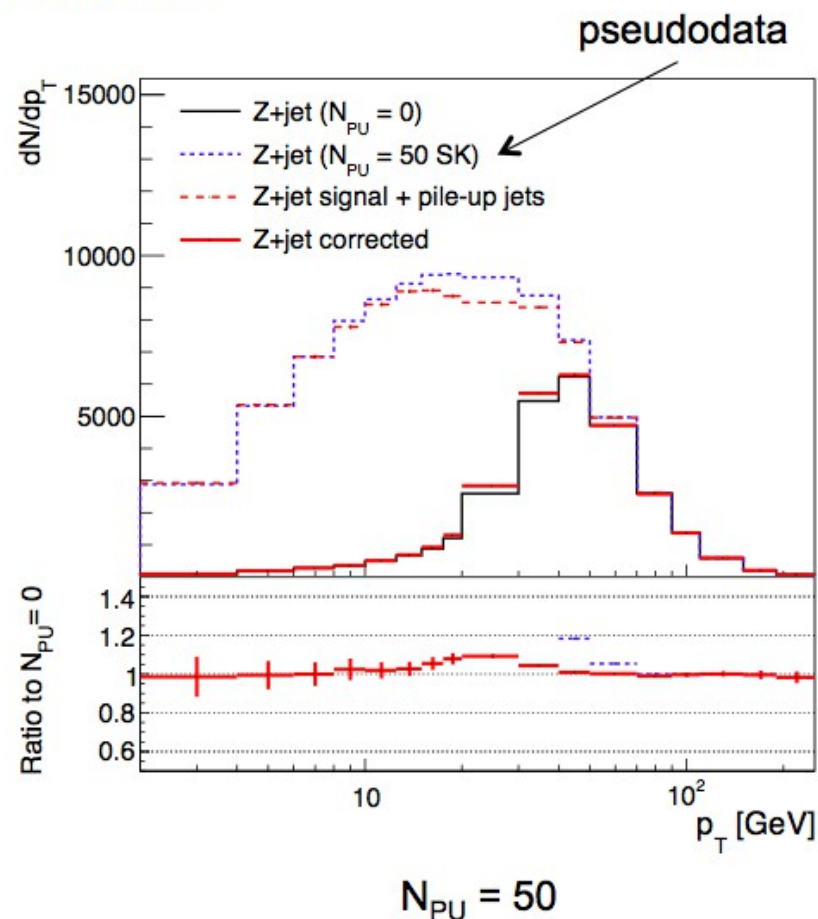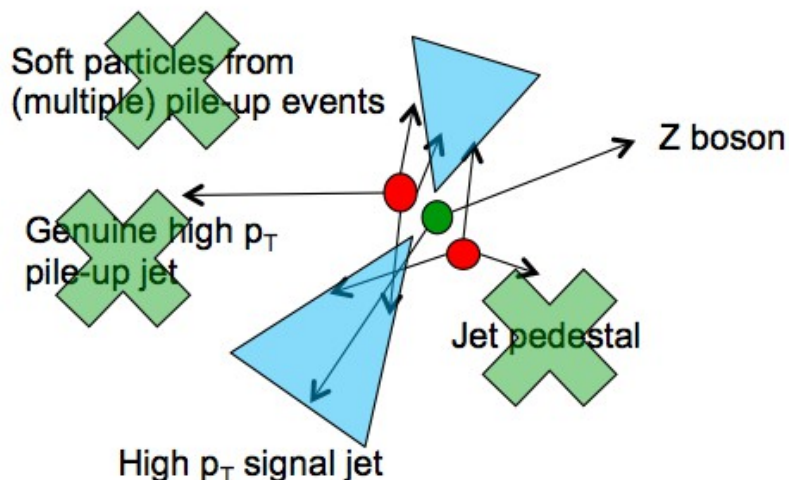Without appealing to any Monte Carlo method, true signal extracted nearly perfectly from mixed sample

Z-boson pT spectrum in Z + jet with jet mixing applied

> Extract signal without relying on Monte Carlos
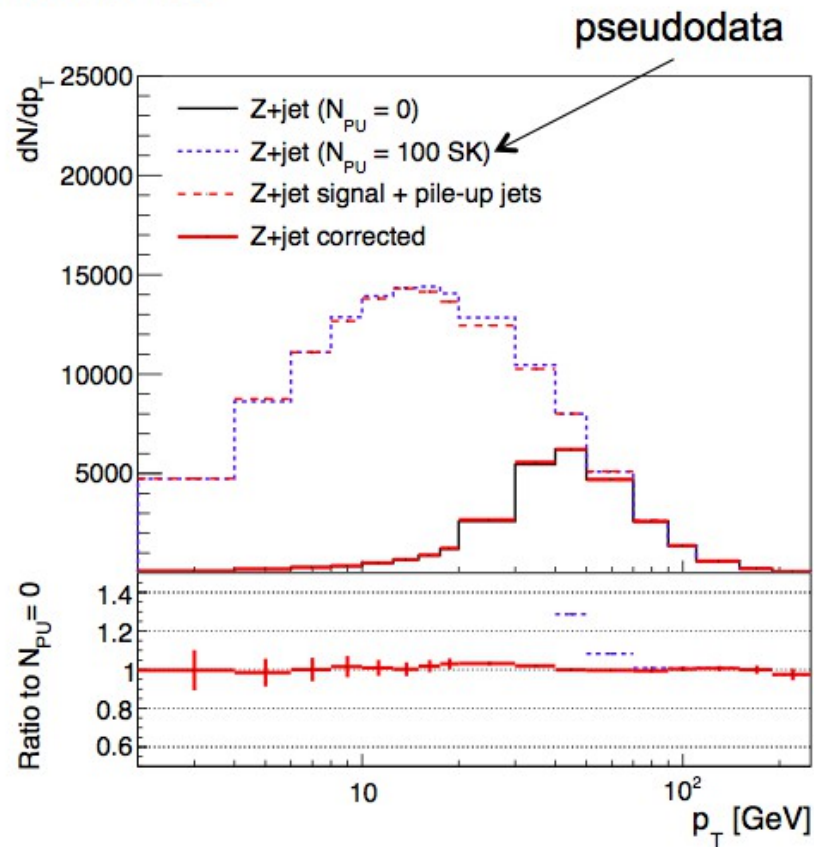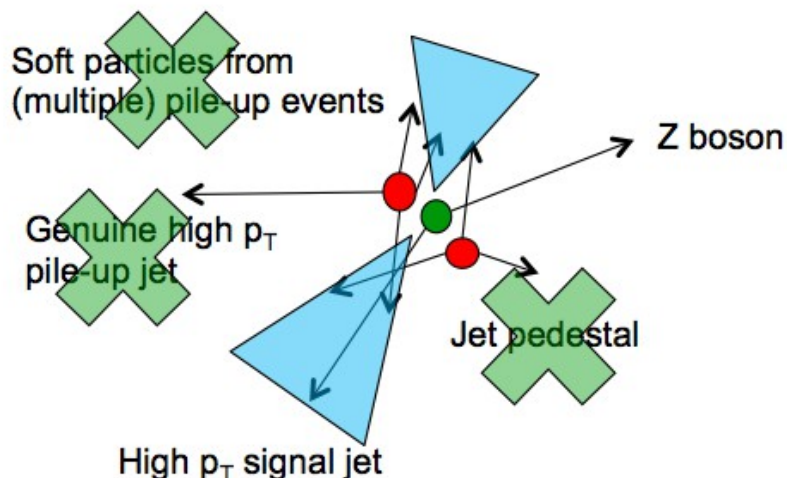
> From mixed sample can extract true signal succesfully

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

Soft particles from (multiple) pile-up events

Genuine high p_T pile-up jet

Z boson

Jet pedestal

High p_T signal jet

pseudodata

dN/dp_T

- Z+jet (N_{PU} = 0)
- Z+jet (N_{PU} = 50 SK)
- Z+jet signal + pile-up jets
- Z+jet corrected

Ratio to N_{PU}=0

p_T [GeV]

N_{PU} = 50

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

Soft particles from (multiple) pile-up events

Genuine high p_T pile-up jet

Jet pedestal

Z boson

High p_T signal jet

pseudodata

dN/dp_T

- Z+jet ($N_{PU} = 0$)
- Z+jet ($N_{PU} = 100$ SK)
- Z+jet signal + pile-up jets
- Z+jet corrected

Ratio to $N_{PU}= 0$

p_T [GeV]

$N_{PU} = 100$

Accuracy of corrections in low and high pile-up

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

> (corrected - true) / true

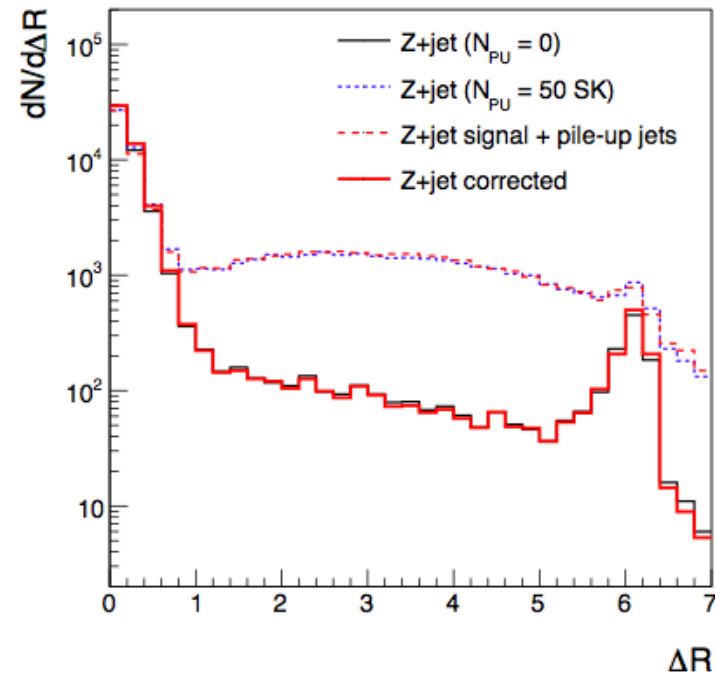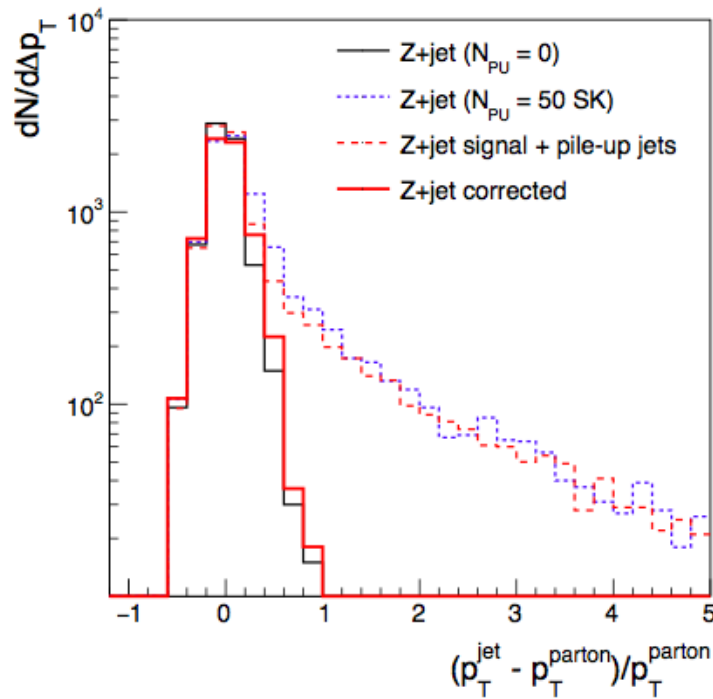> Without jet mixing: deviation larger at high N_{PU}

> With jet mixing: improvement with increasing N_{PU}
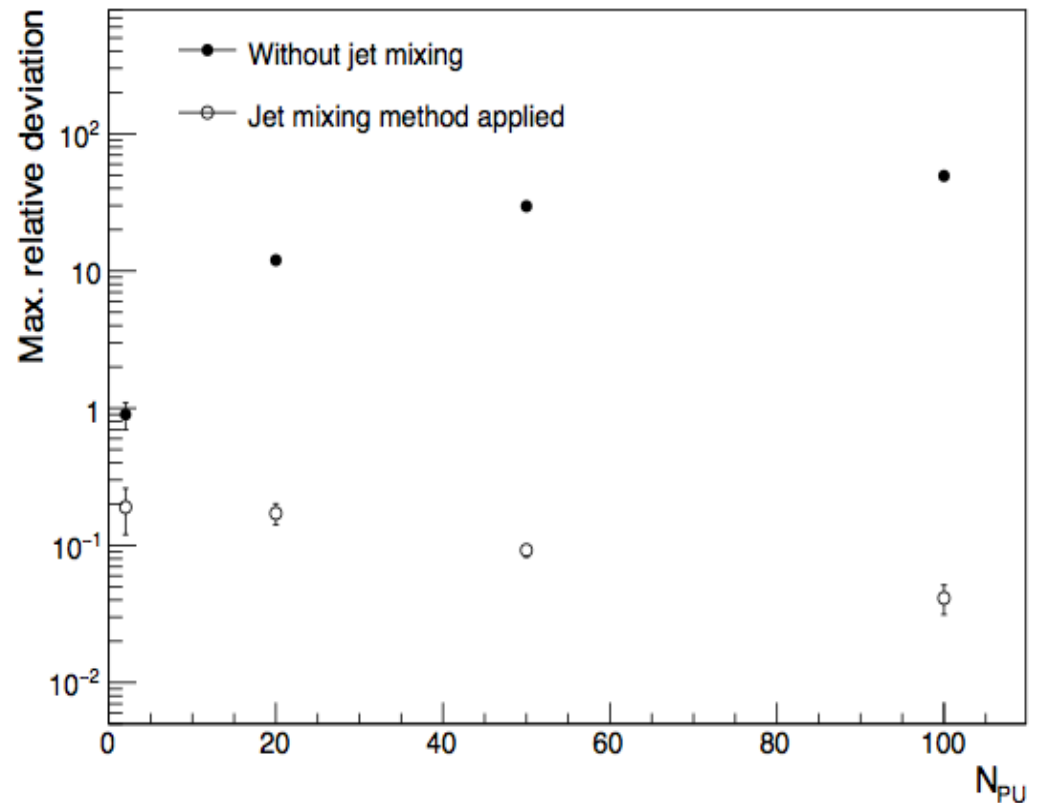
> Approach designed to treat high N_{PU} region: $(N_{PU} + 1) / N_{PU} \approx 1$

Improvement in jet resolution from applying event mixing method

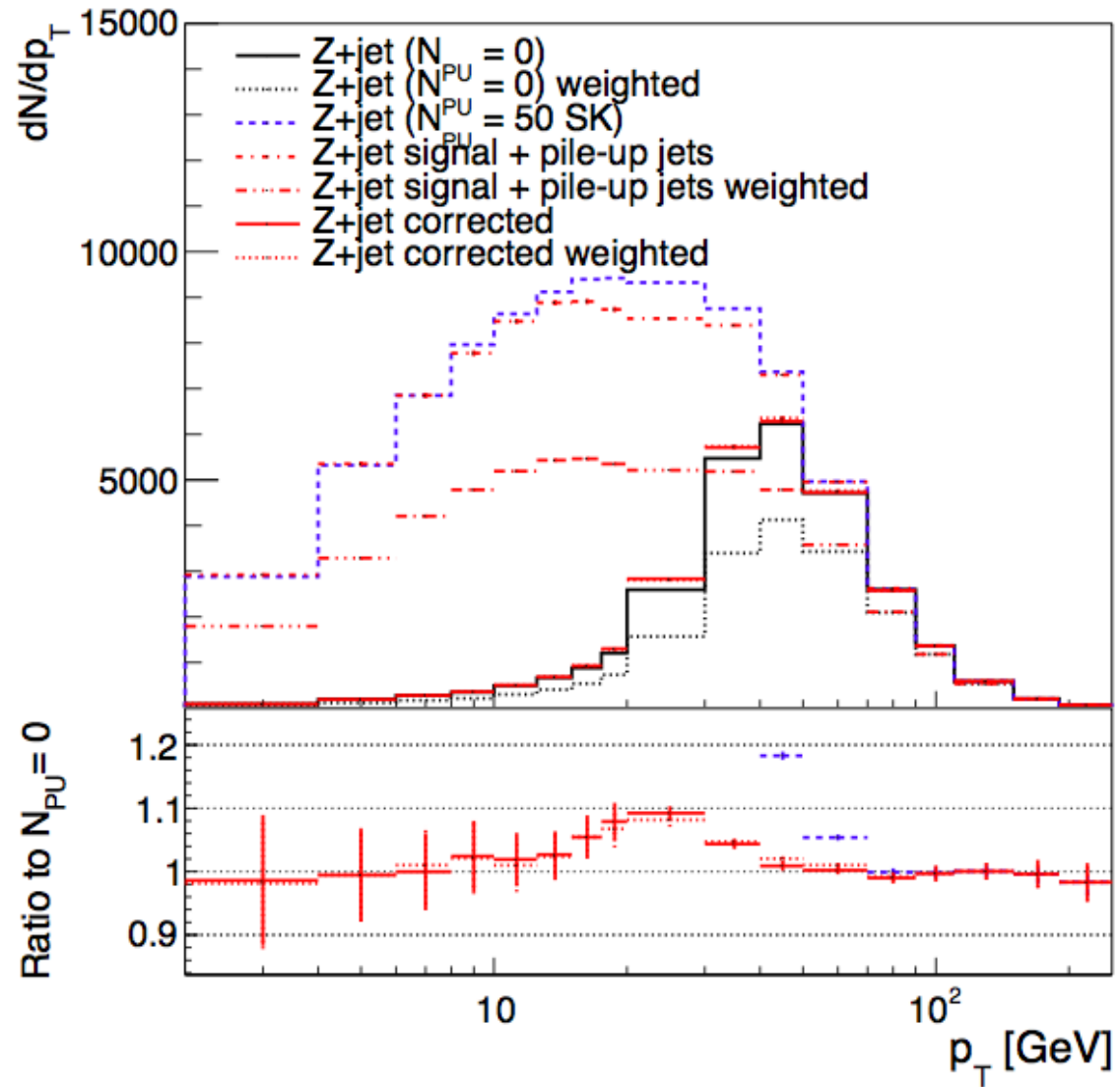> Control checks with p_T resolution and $\Delta R = \sqrt{(\Delta\phi^2 + \Delta\eta^2)}$

➜ 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

Legend:
- Z+jet ($N_{PU} = 0$)
- Z+jet ($N_{PU} = 0$) weighted
- Z+jet ($N_{PU} = 50$ SK)
- Z+jet signal + pile-up jets
- Z+jet signal + pile-up jets weighted
- Z+jet corrected
- Z+jet corrected weighted

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

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?**
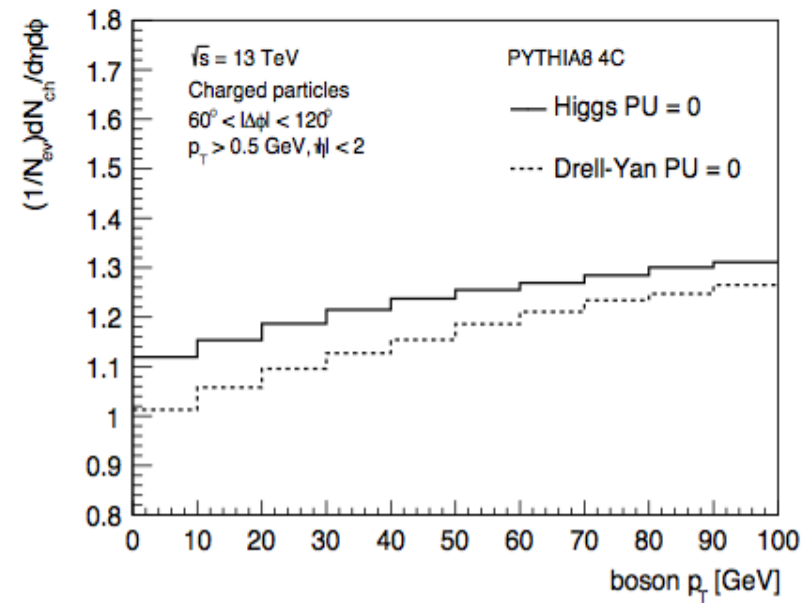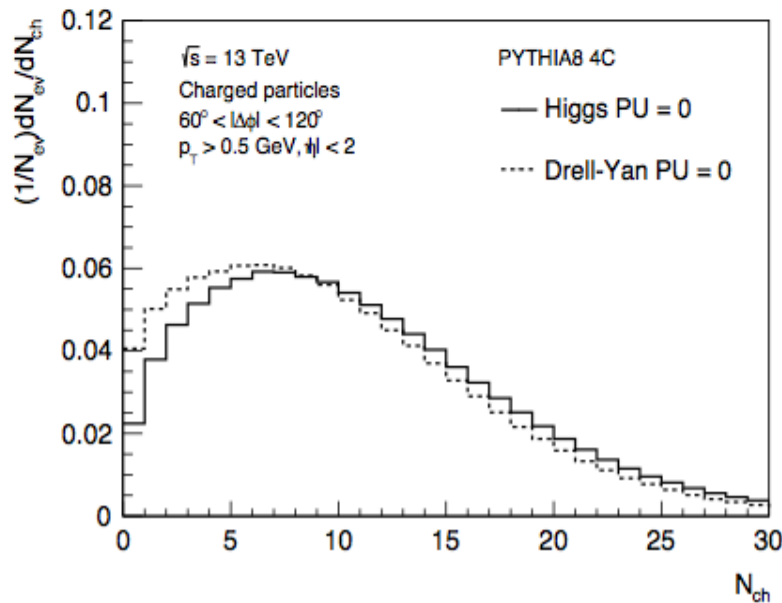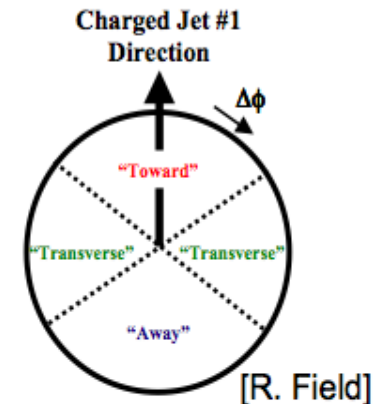
Charged Jet #1
Direction

$\Delta\phi$

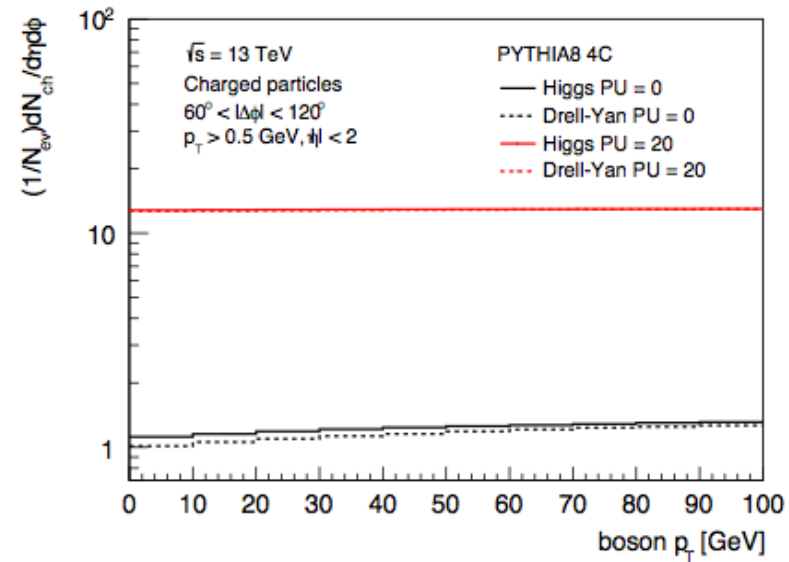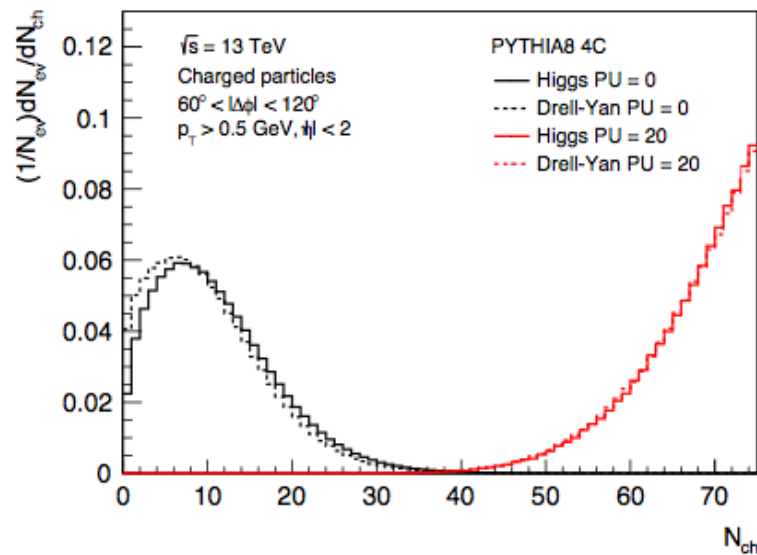"Toward"

"Transverse"   "Transverse"

"Away"

[R. Field]

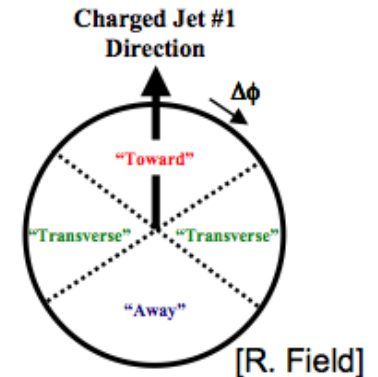
H van Haevermaet et al., in progress

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:

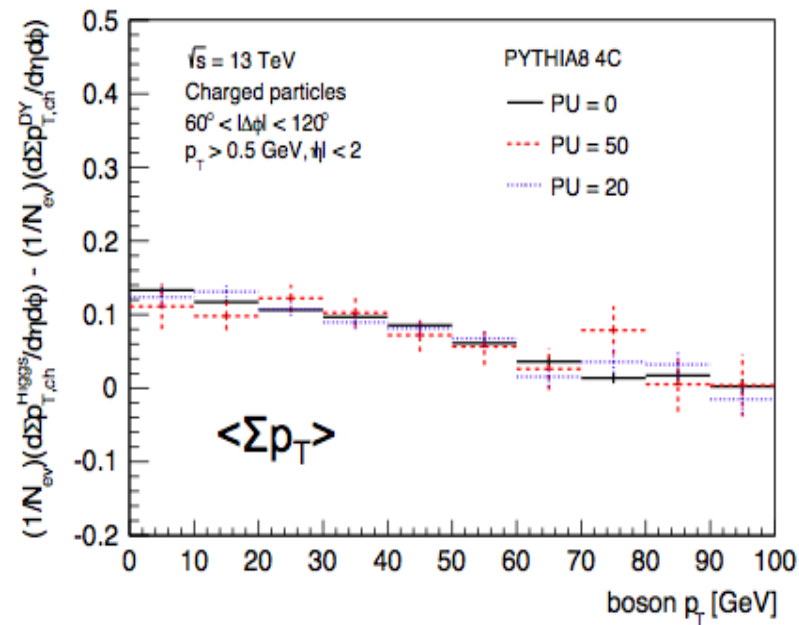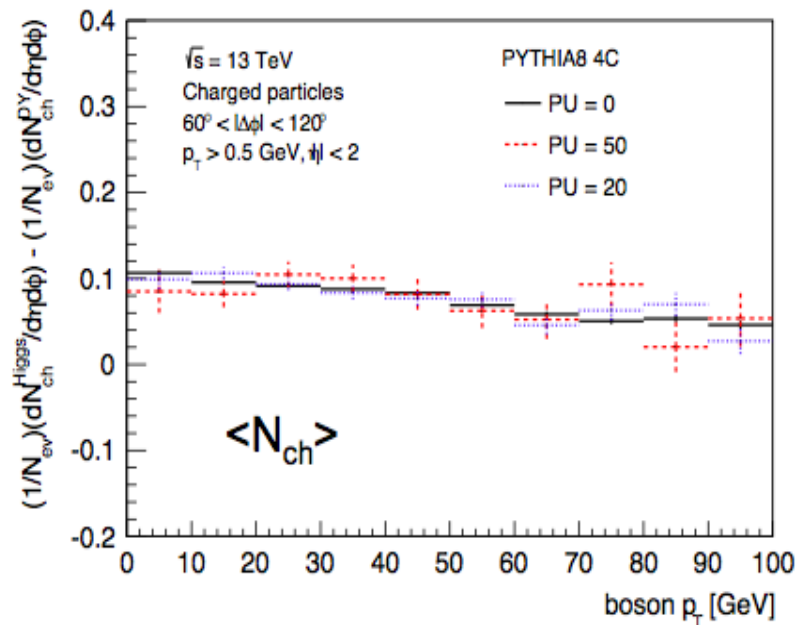$$\frac{dn}{dp_T}(H-DY) = \frac{dn}{dp_T^H} + \frac{dn}{dp_T^{PU}} - \left(\frac{dn}{dp_T^{DY}} + \frac{dn}{dp_T^{PU}} \right)$$

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