# Evaluations of Physics Performance for High Mass VBF Final States in the Presence of Pile-up

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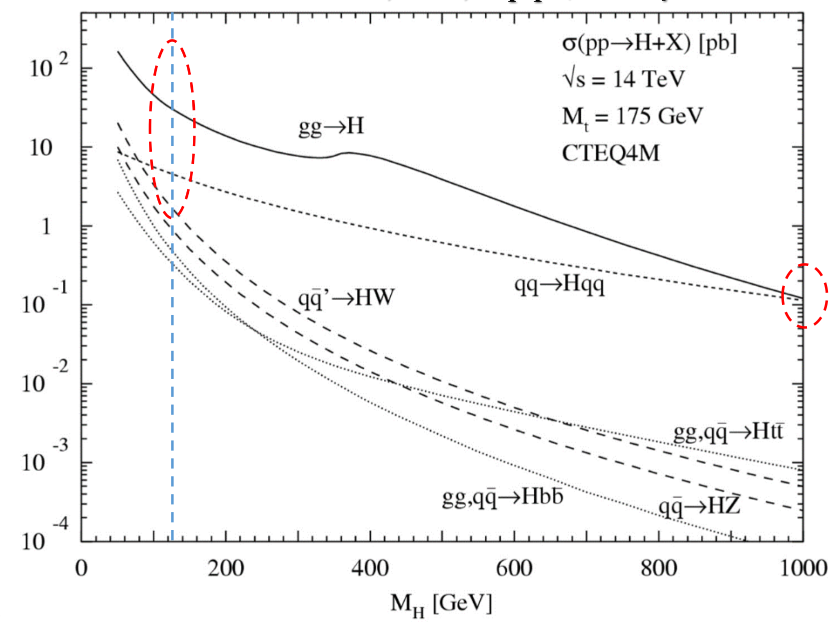
# Motivation and Goal

- Importance of forward calorimetry for searches with ATLAS at future (s/HiLum)LHC operations
  - VBF and VBS important production mechanism at $\sqrt{s} = 14$ TeV
    - Electroweak heavy resonance production
      - Heavy Higgs-like/excited Higgs states
    - Multiple boson production and coupling anomalies
      - SM: di-bosons, triple-bosons, quartic-bosons… - precision explorations in new kinematic domains, self-coupling including for Higgs
      - BSM: coupling anomalies
  - Distinctive quark jet pattern tag VBF/VBS
    - Two forward-going (tag) quark jets
      - $\Delta\eta_{\text{tag-jets}} \nearrow$ with $M \nearrow$ or $\sqrt{\hat{s}} \nearrow$
      - $\Delta\eta_{\text{tag-jets}} \nearrow$ with $\sqrt{s} \nearrow$

M. Mühlleitner, Diss., hep-ph/0008127




$\sigma_{qq\to Hqq}/\sigma_{gg\to H}$ is $O(10\%)$ @ $M_H = 125$ GeV

$\sigma_{qq\to H'qq}/\sigma_{gg\to H'}$ can be $O(1)$ @ $M_{H'} = 1$ TeV

General region of interest $\sqrt{\hat{s}}/\sqrt{s} \gtrsim 0.05$ (TeV scale)

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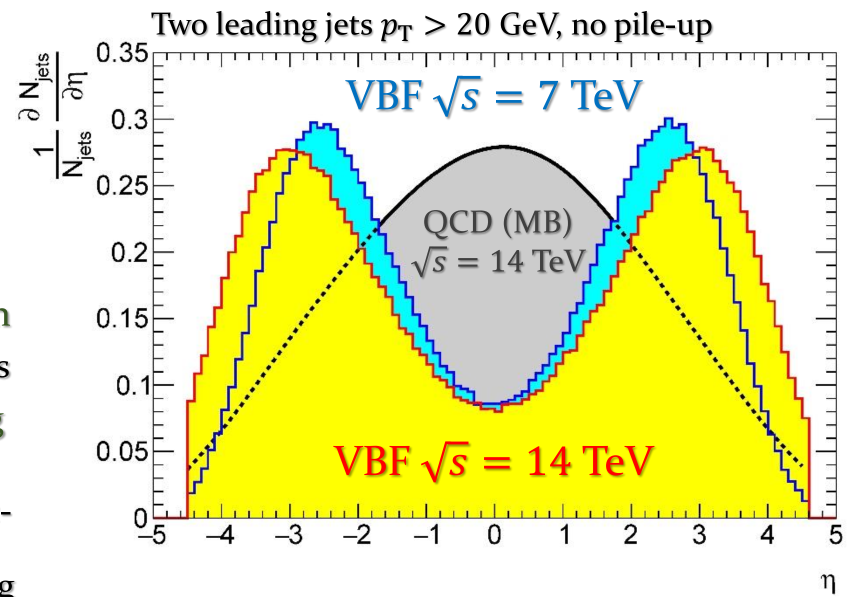
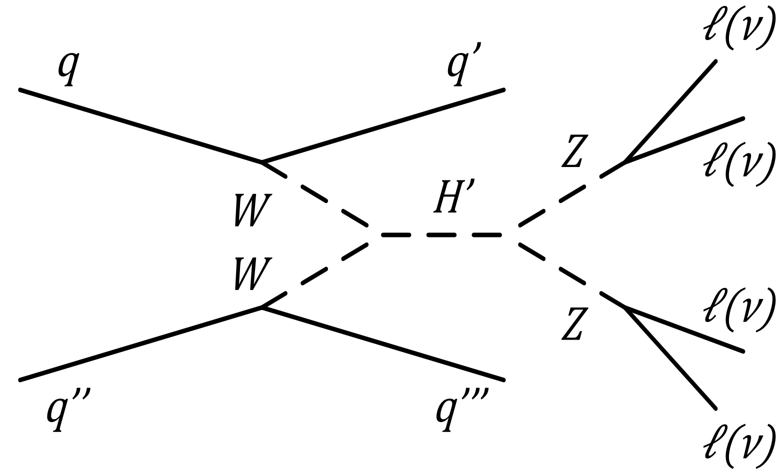


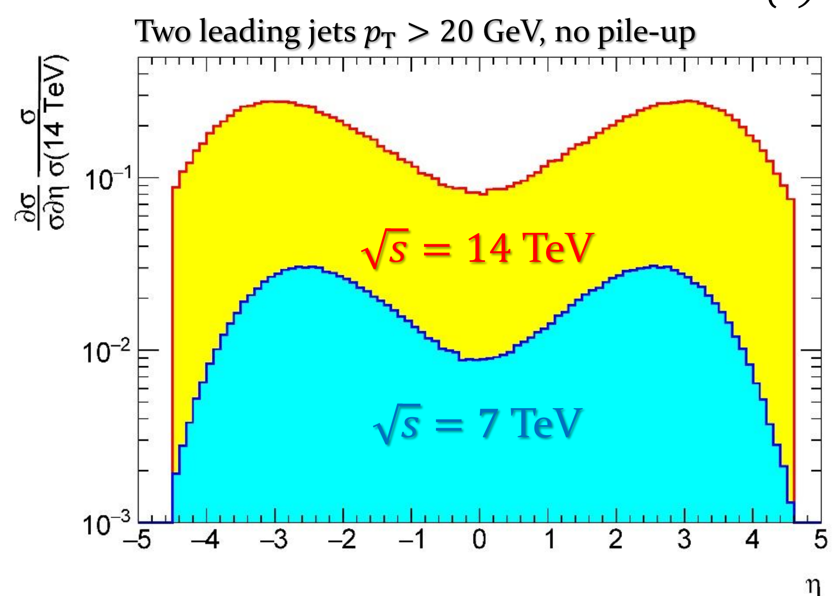

Leading & sub-leading jet $\eta$ in $qq \to qqH'$ with $M_{H'} = 1$ TeV (QCD jets from MB for reference)

General region of interest $\sqrt{\hat{s}}/\sqrt{s} \gtrsim 0.05$ (TeV scale)

# VBF Signatures in High Pile-up

- Example: new physics at TeV scale
  - Heavy Higgs-like particle $H'$ produced in longitudinal $WW$ scattering
    - Postulated mass $M_{H'} = 1$ TeV
    - Only considered decay is $H' \to ZZ,\ Z \to \ell\ell(\nu\nu)$
    - Associated tag jets produced by scattered quarks
  - Distinguished jet pattern
    - Two tag jets (widely) separated in $\eta$
    - Separation increases with increasing (1) $M_{H'}$ and (2) $\sqrt{s}$
    - Jets are typically low $p_T \sim 20-200$ GeV
  - Effects of pile-up (PU)
    - Disturbs distinguished jet pattern
    - Can fake one of the tag jets – especially the one sub-leading in $p_T$ (similar kinematic regime)
    - Can deteriorate the response of true signal jets – resolution and scale

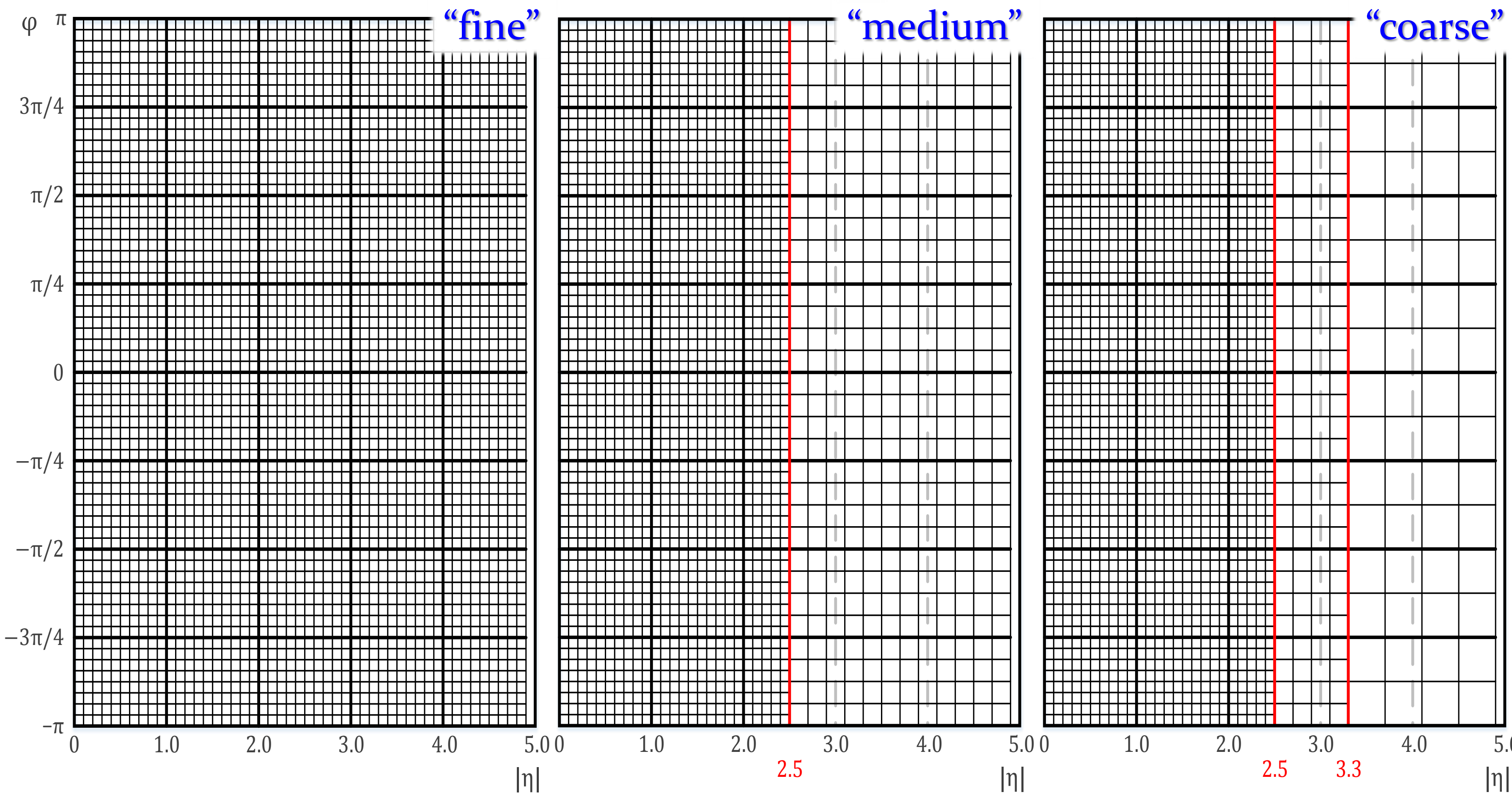


# Outline of Study

- Physics signal and background (pile-up) simulation
  - $H'$ (signal) production using Pythia8
    - Two center-of-mass energies – $\sqrt{s} = 7$ TeV and $\sqrt{s} = 14$ TeV
    - Record stable ($c\tau > 10$ mm) particles emerging from the interaction
  - Corresponding pile-up simulation
    - Dynamic overlay of generated minimum bias (MB) interactions at stable particle level
    - Number of MB interactions overlaid on a given signal interaction is sampled from Poisson distribution around central values $\langle\mu\rangle = 20$, $\langle\mu\rangle = 50$, $\langle\mu\rangle = 100$
- Signal definitions
  - $H'$ decay products removed from final state
    - Not relevant for present study
  - All remaining particles within $|\eta| < 5$
    - No further kinematic selection applied
  - Towers within $|\eta| < 4.9$
    - Simple detector model collects all remaining particles into towers in $(\eta, \varphi)$ space – various configurations (next slide)
    - No further kinematic selection applied
  - Jets are constructed from particles and tower configurations
    - Anti-$k_t$ jet clustering with distance parameter $R = 0.4$
    - Two samples: $p_{\mathrm{T}}^{\mathrm{jet}} > 20$ GeV, $p_{\mathrm{T}}^{\mathrm{jet}} > 40$ GeV

# Tower Configurations




$$\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$$

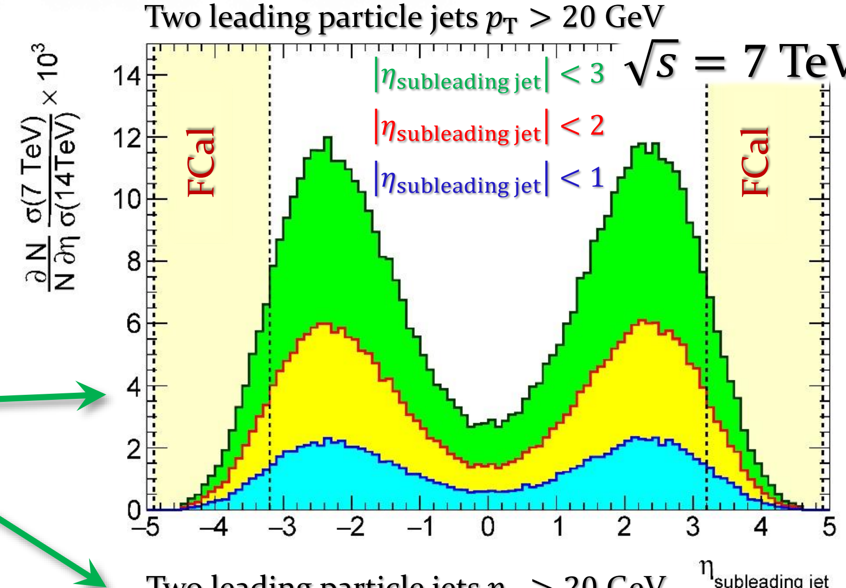
$$\Delta\eta \times \Delta\varphi = \begin{cases} 0.1 \times 0.1 & |\eta| < 2.5 \\ 0.2 \times 0.2 & |\eta| > 2.5 \end{cases}$$

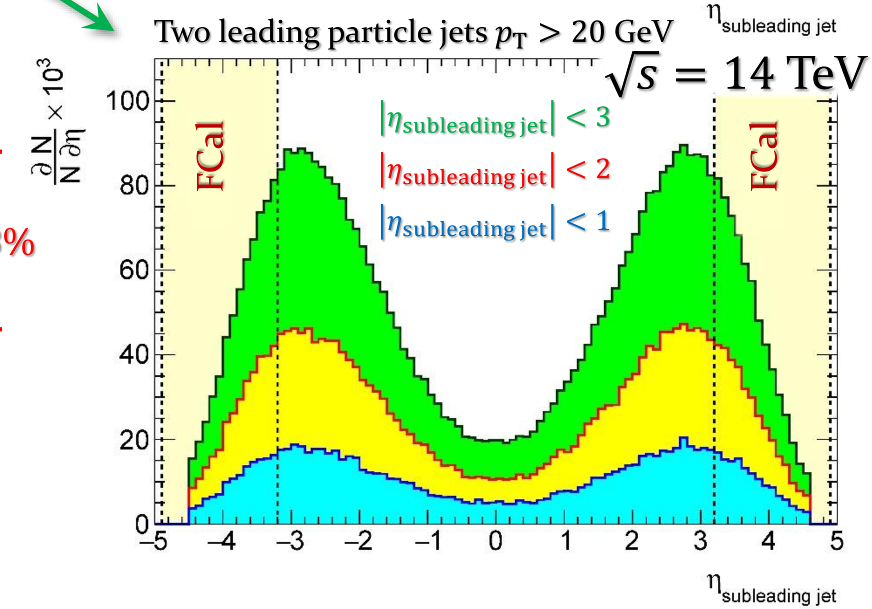
$$\Delta\eta \times \Delta\varphi = \begin{cases} 0.1 \times 0.1 & |\eta| < 2.5 \\ 0.2 \times 0.2 & 2.5 < |\eta| < 3.3 \\ 0.4 \times 0.4 & |\eta| > 3.3 \end{cases}$$

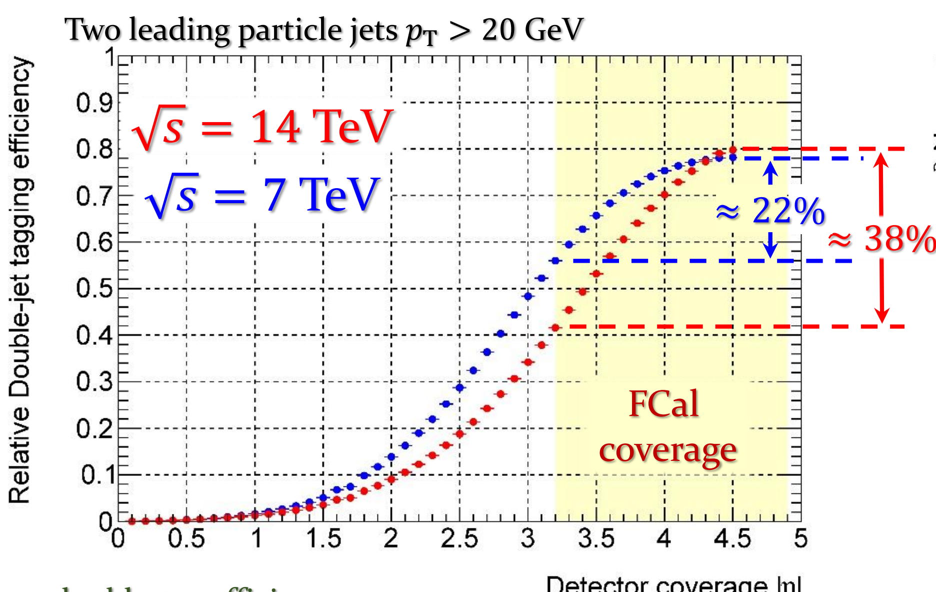
No pile-up!

# Relevance of the FCal

- Leading jets in VBF
  - Two highest $p_T$ jets tag $WW$ scattering
    - Most often true in leptonic final states
  - Leading jet tag
    - Tagged central sub-leading jet pushes leading tag jet forward – even more so at higher beam energies
  - Good forward coverage improves double-tag efficiency



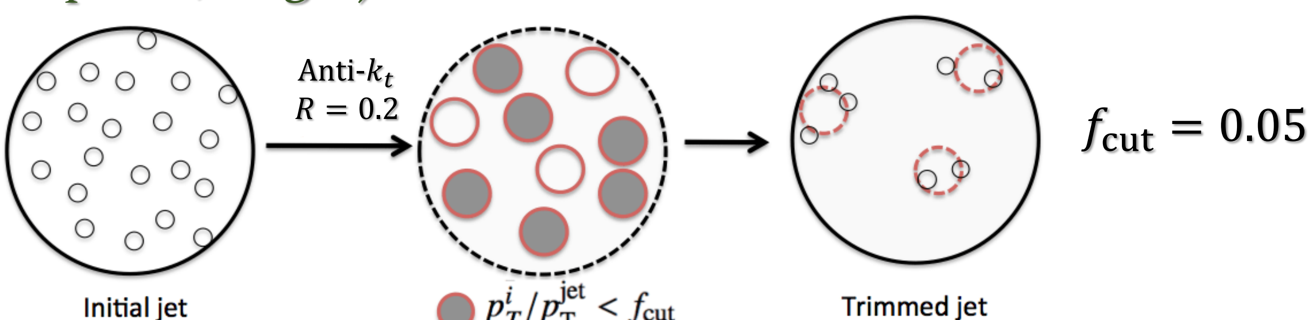




Maximum double-tag efficiency
affected by limited detector acceptance $|\eta| < 4.9$ and jet $p_T$-threshold!

# Pile-up Mitigation

- Jet grooming techniques considered for pile-up mitigation
  - Subtraction of pile-up contribution from $p_{\mathrm{T}}^{\mathrm{jet}}$
    - Employs jet area technique $p_{\mathrm{T,corr}}^{\mathrm{jet}} = p_{\mathrm{T,raw}}^{\mathrm{jet}} - \rho A^{\mathrm{jet}}$
    - $\rho = \frac{\partial^2 p_{\mathrm{T}}}{\partial\eta\partial\varphi}$ measured by median transverse momentum density of event – reflects softer event $p_{\mathrm{T}}$-flow induced by pile-up (dominant) and underlying event activity
  - Trimming of remaining jet
    - Removes small sub-jets from reconstructed jets – improves jet response, single jet mass measurement etc.




D.Krohn, J.Thaler, L.Wang, *JHEP* **02** (2010) 84

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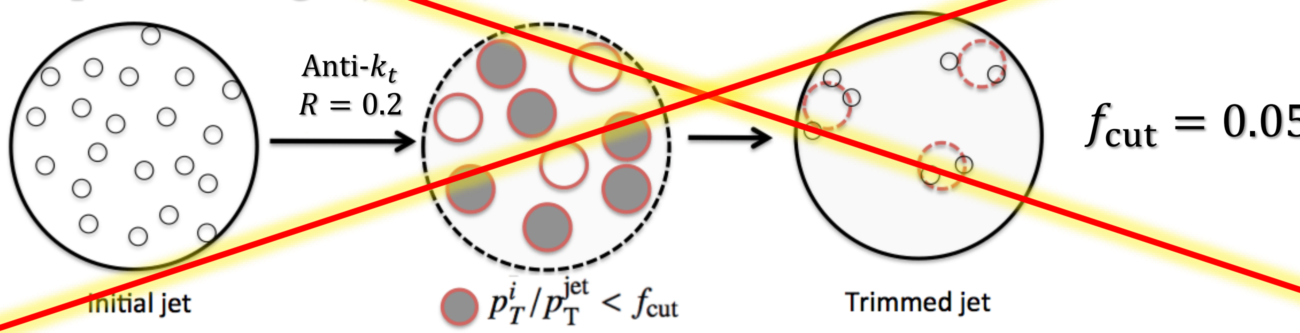


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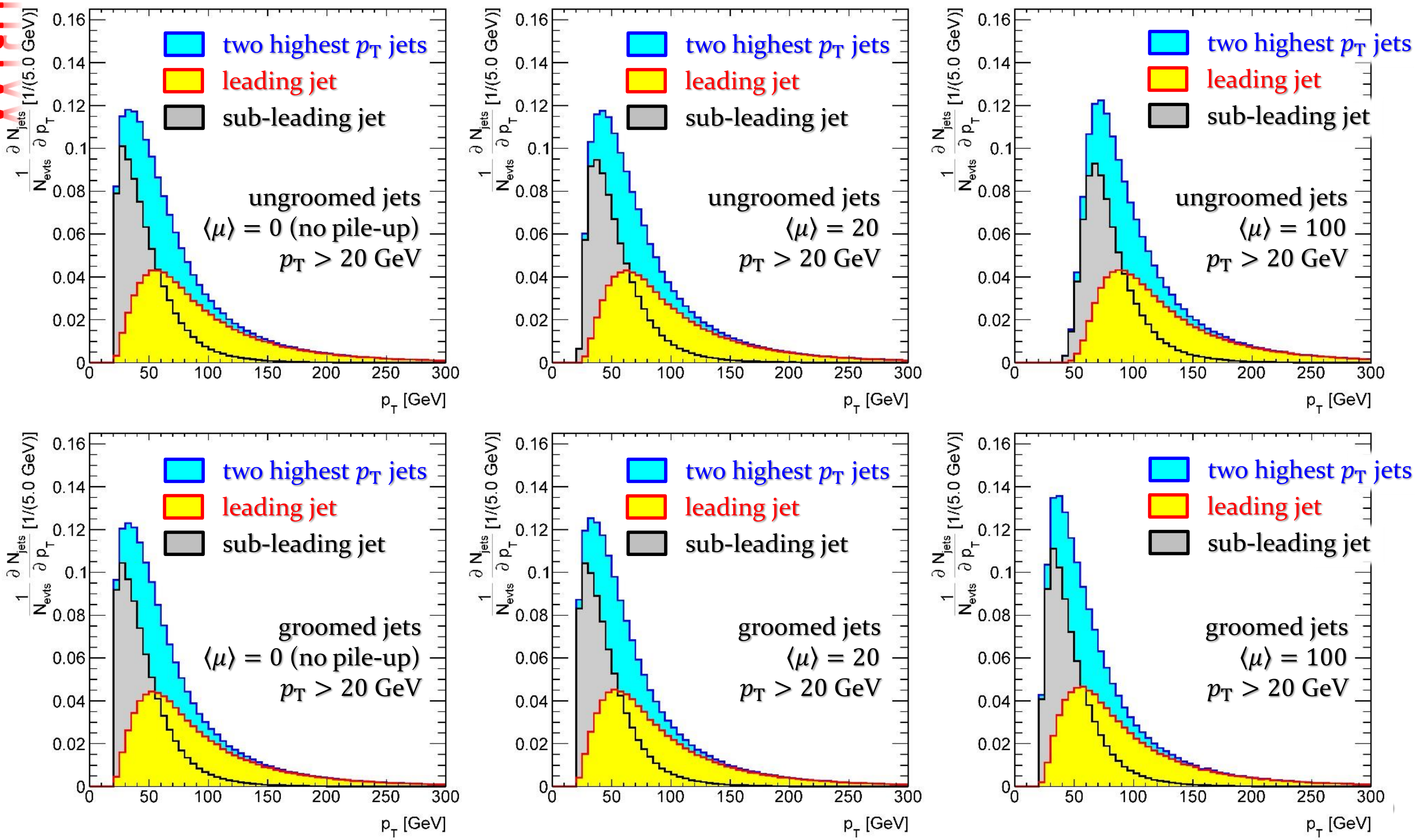
With pile-up!

# VBF Jets with Pile-up (1)

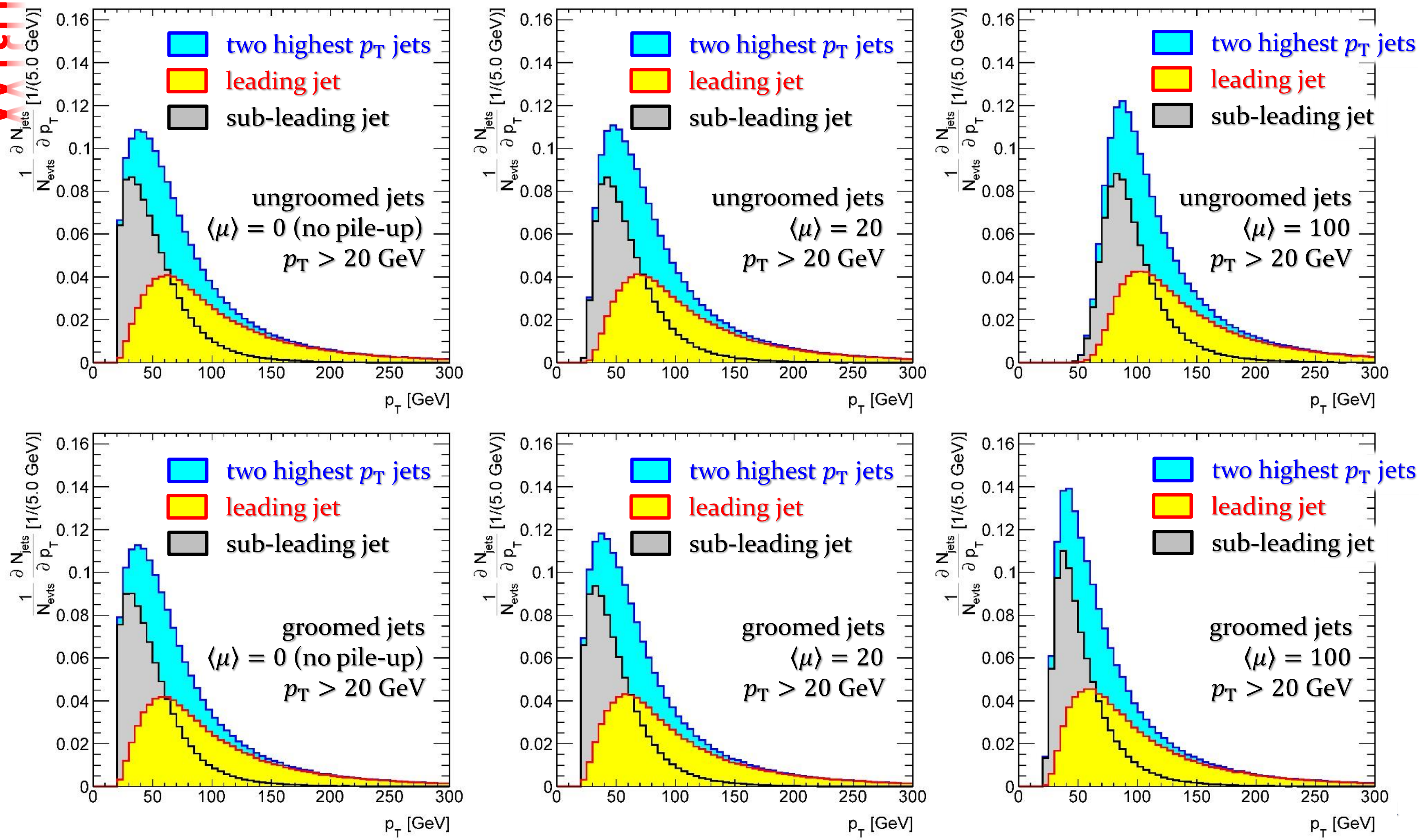
- Leading and sub-leading jet kinematics at $\sqrt{s} = 7$ TeV



With pile-up!

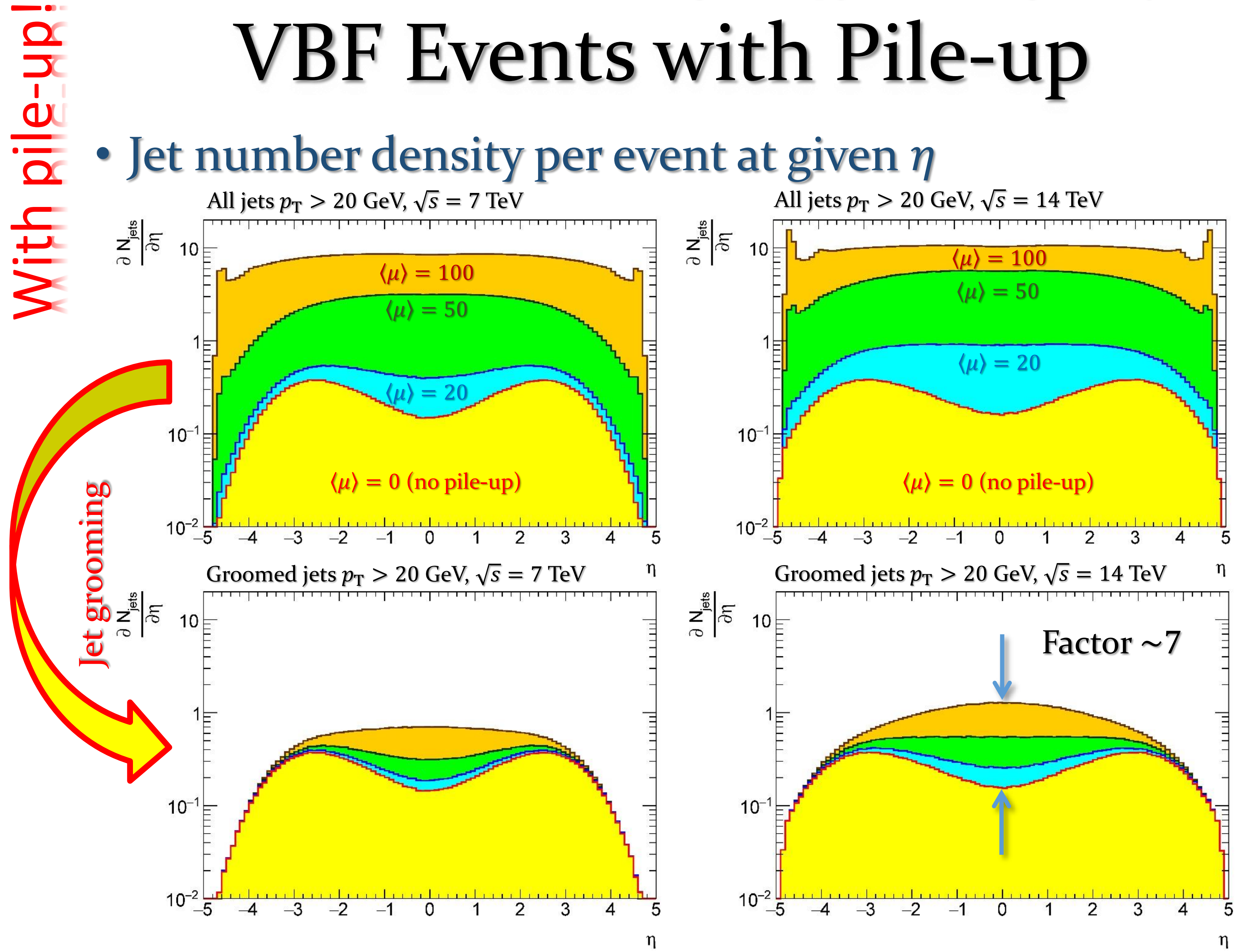
# VBF Jets with Pile-up (2)

- Leading and sub-leading jet kinematics at $\sqrt{s} = 14$ TeV



# VBF Events with Pile-up

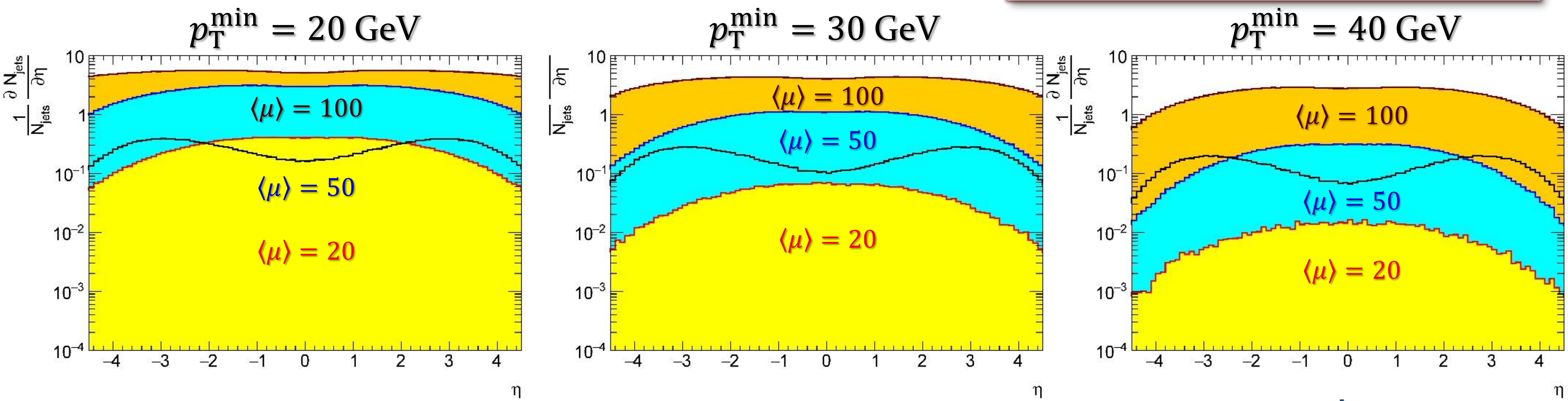
- Jet number density per event at given $\eta$



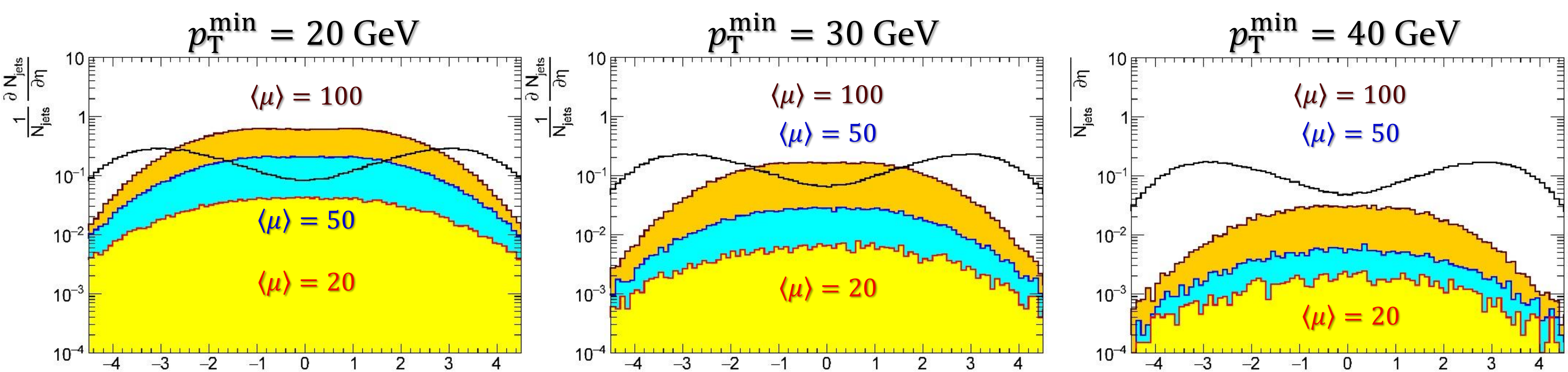
# Jets From Pile-Up at $\sqrt{s} = 14$ TeV

VBF signal jets with $p_T > p_T^{min}$

- All jets with $p_T > p_T^{min}$



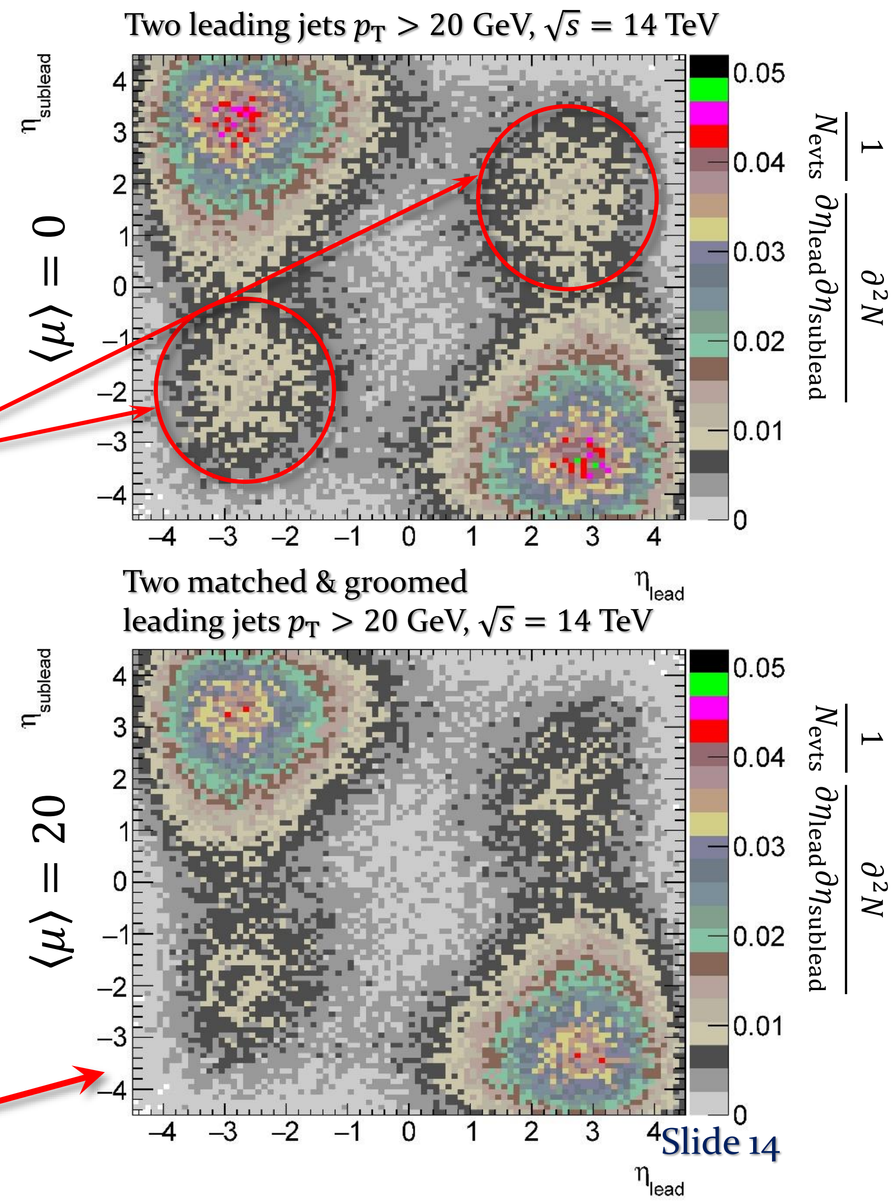

- Leading and sub-leading groomed jet with $p_T > p_T^{min}$



# Efficiency of Pile-Up Suppression

- Jets with pile-up are matched with signal jets
  - Signal jets are particle level jets without pile-up ($\langle\mu\rangle = 0$. "truth")
    - Only the two leading jets considered – maybe not sufficient for signal selection (additional cuts on di-jet angles and/or mass, include third jet)
    - Radiation patterns are observed where two leading jets are relatively close
  - Jets with pile-up are groomed
    - PU subtraction only – standard ATLAS correction for Run I and Run II
  - Matching is geometric
    - Jets are matched if $\Delta R < 0.1$

With pile-up!

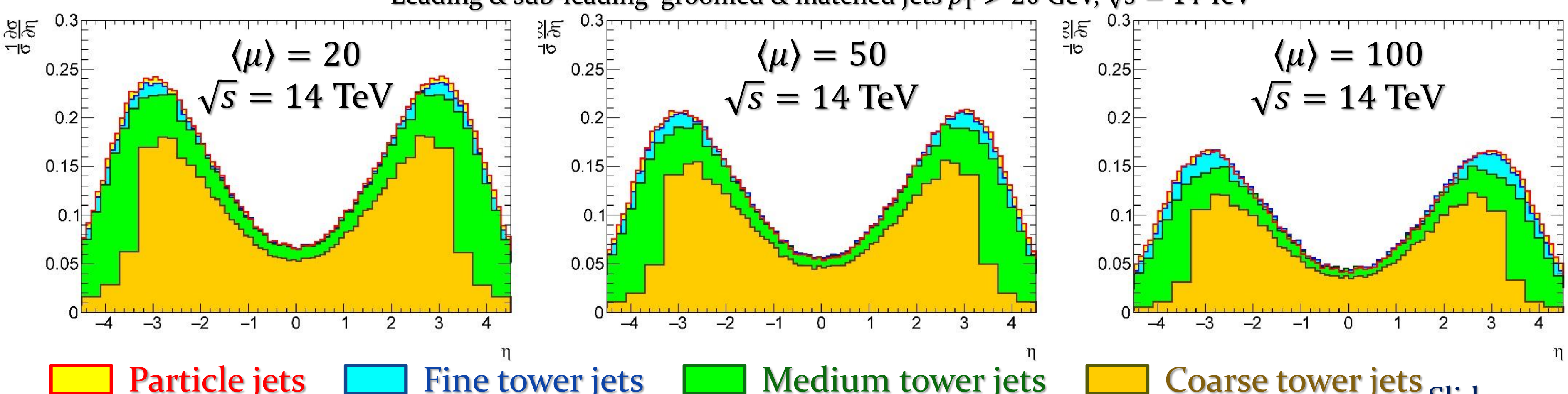


With pile-up!

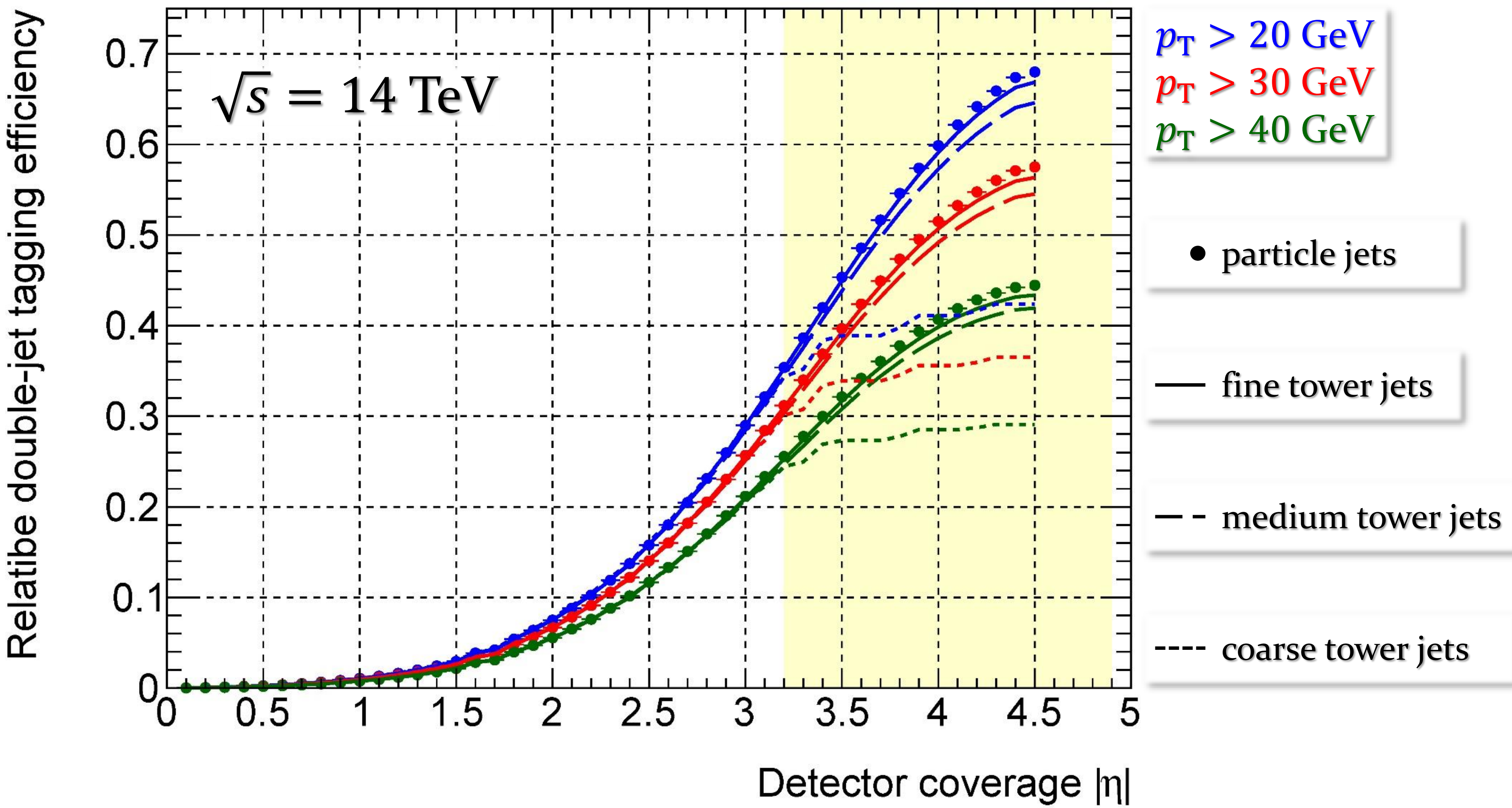
# Effect of Granularity

- Reconstruct jets with different tower grids
  - No towers (particle level), fine grid, medium grid, coarse grid
    - See earlier slide "Tower Configurations"
  - All jets are reconstructed with pile-up
    - **Groomed** and **matched** with "truth" signal jet reconstructed with $\langle\mu\rangle = 0$
  - Findings
    - Fine tower grid very similar to particle level – expected
    - Medium grid (~ATLAS FCal) has reduced efficiency for $|\eta| > 2.5$
    - Coarse grid (worse than ATLAS FCal) significant efficiency losses

Leading & sub-leading groomed & matched jets $p_T > 20$ GeV, $\sqrt{s} = 14$ TeV

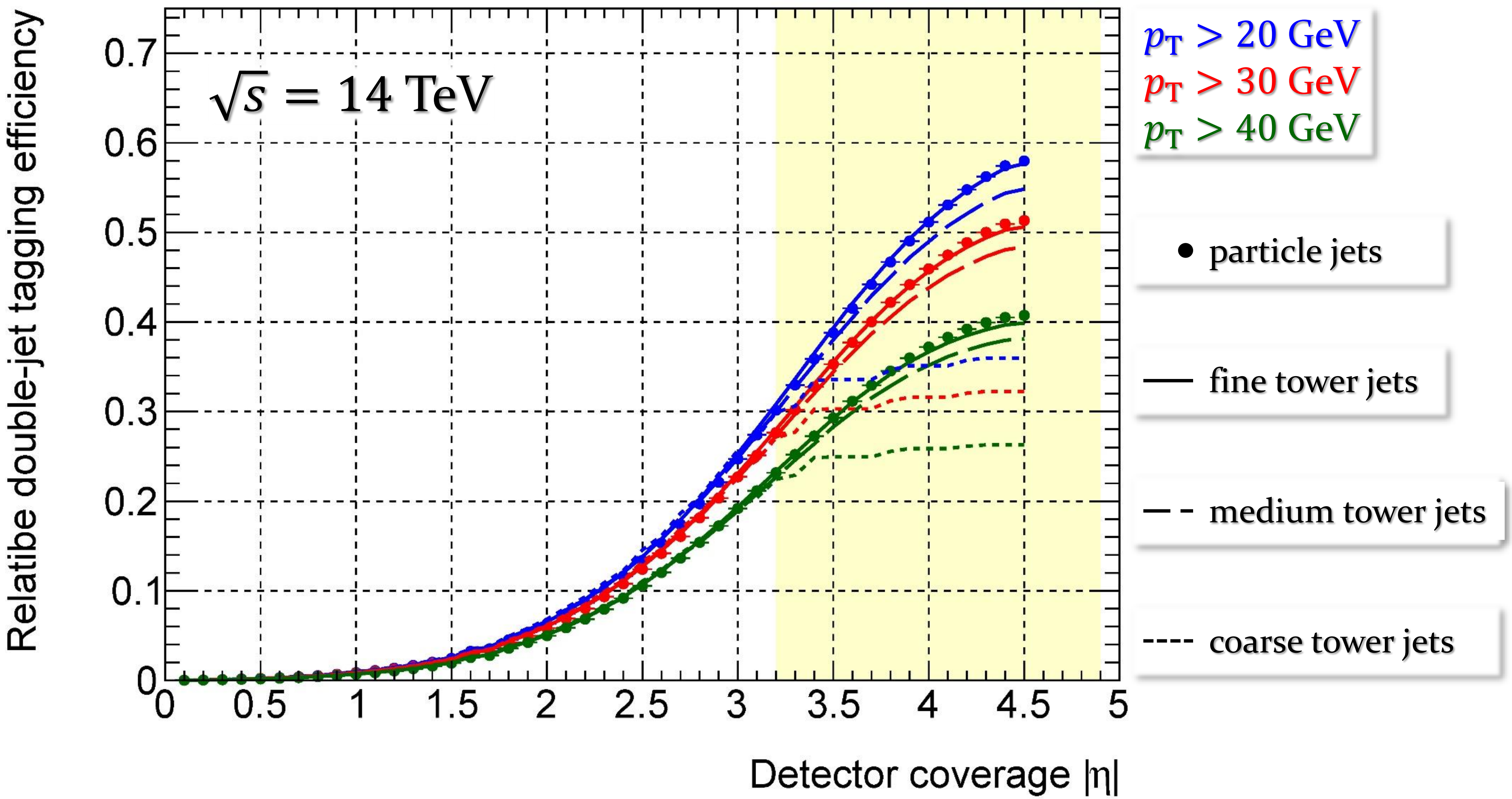


# Efficiency Estimate $\langle \mu \rangle = 20$



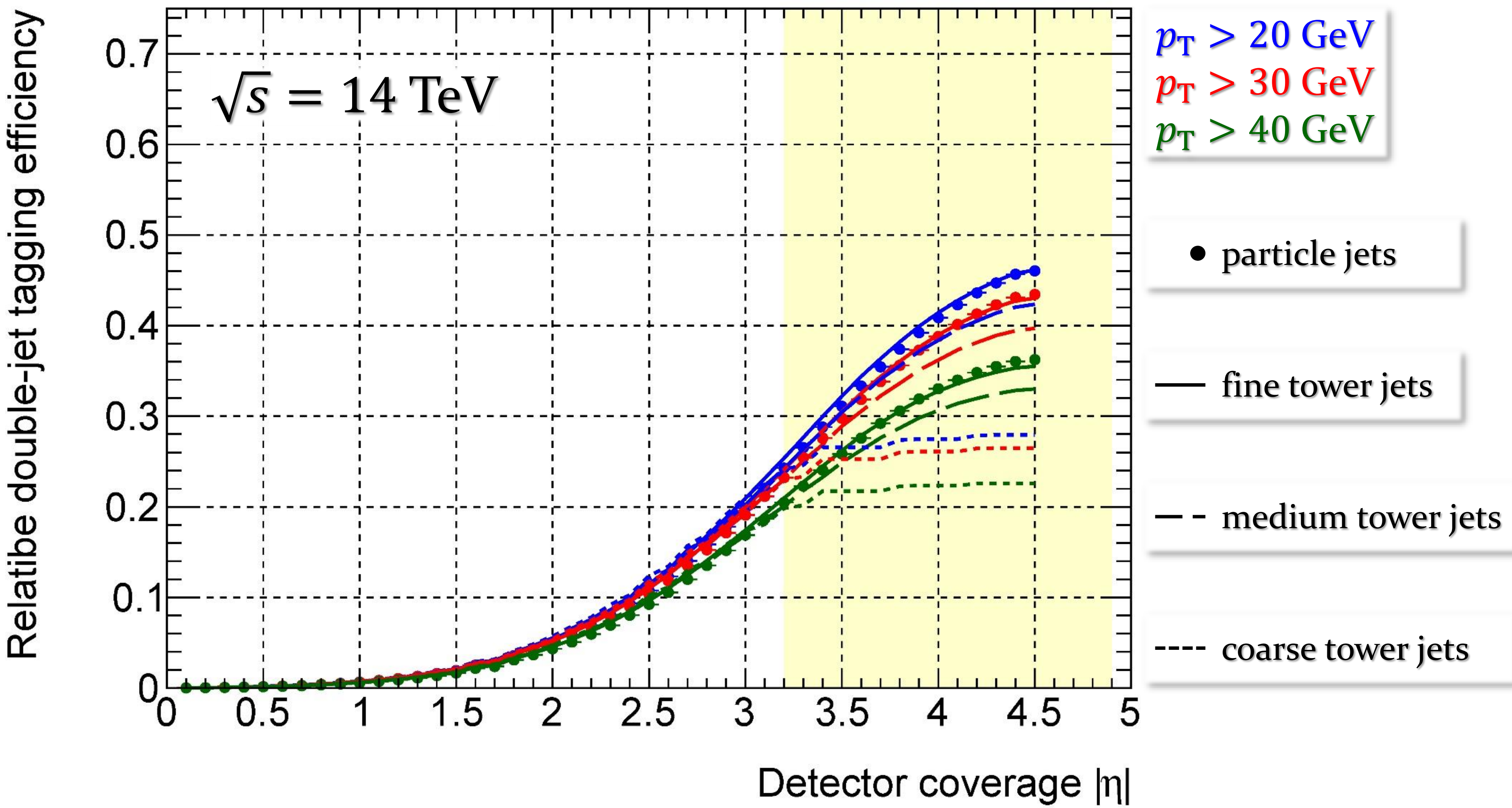

With pile-up!

# Efficiency Estimate $\langle\mu\rangle = 50$




With pile-up!

# Efficiency Estimate $\langle\mu\rangle = 100$




With pile-up!

# Conclusion (1)

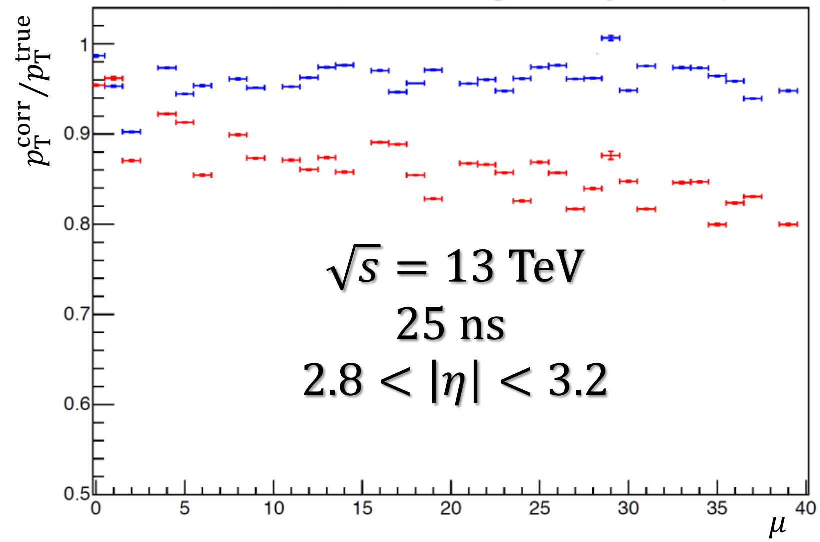
- Efficient VBF/VBS tagging requires largest $\eta$-coverage
  - Tag jets will be important discovery tools
    - Higher $\sqrt{s}$ pushes jets more forward at a ~fixed $\sqrt{\hat{s}}$ – as does corresponding higher reach in $\sqrt{\hat{s}}$
    - EW production of new particles and multi-boson final states at high $\sqrt{\hat{s}}$ is VBF/VBS driven – makes tagging jets at high $|\eta|$ much more important
  - Small cross-sections of prospective VBF-produced heavy particles requires highest detection efficiency
  - Present and future pile-up interferes with VBF tagging
    - Fake jets
    - Loss of precision of jet kinematics measurement
- Higher FCal granularity
  - First impression: better performance
    - Full evaluation needs detector effects – Sven Menke/Walter Lampl are working on FullSim of highly granular FCal for sLHC/HiLum
  - Potential particle flow with forward tracking
    - Improved pile-up suppression for low $p_{\mathrm{T}}$ jets – higher signal efficiency

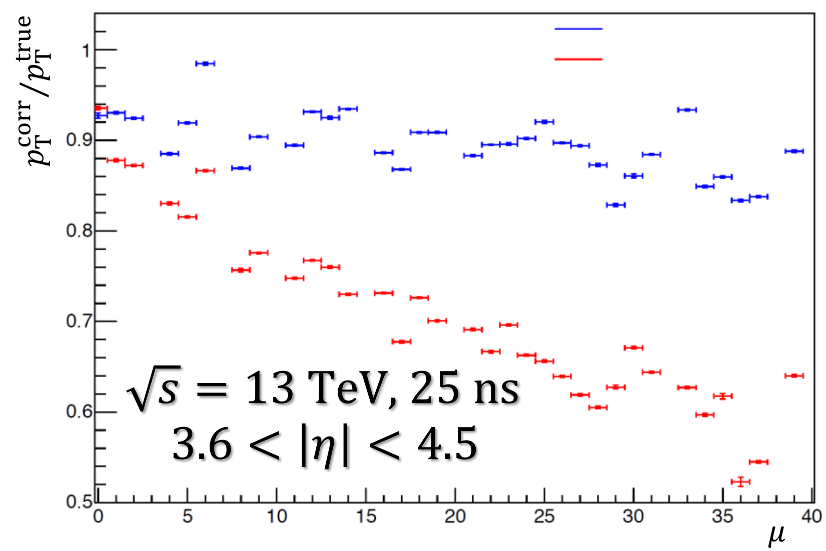
# Conclusions (2)

- Run II
  - IBL services may degrade FCal jet performance
    - Tag jets are low in $p_T$!
  - Tag efficiency may be problematic
    - We need FullSim with Run II conditions to study this
  - Pile-up may be less of a concern for 25 ns running
    - Jet-area-based subtraction expected to work (blue) – without the additional out-of-time pile-up correction needed for $|\eta| > 2.5$ (in red)
    - Statistically limited, **very preliminary plots!**

Jet-area-based pile-up subtraction based on $\rho$
Additional correction for out-of-time pile-up (essential in Run I at 50 ns)

Fabrice Balli (JES/JER meeting January 20, 2015)

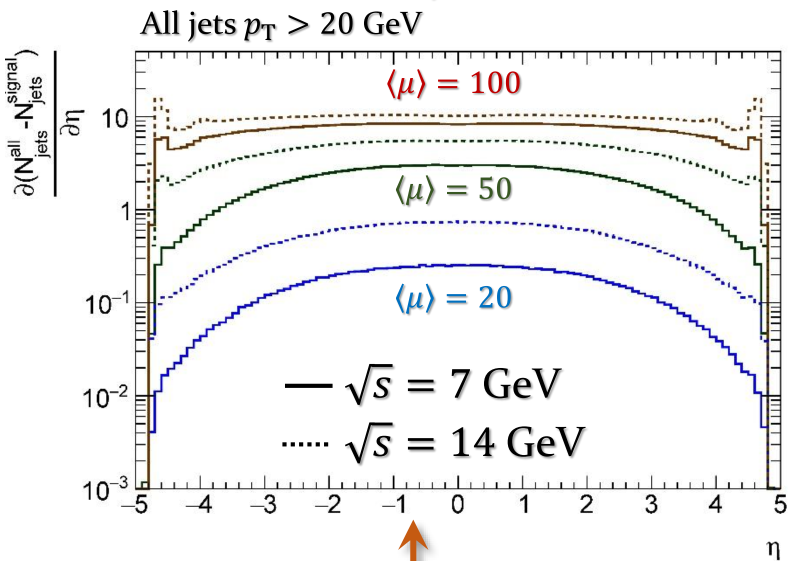


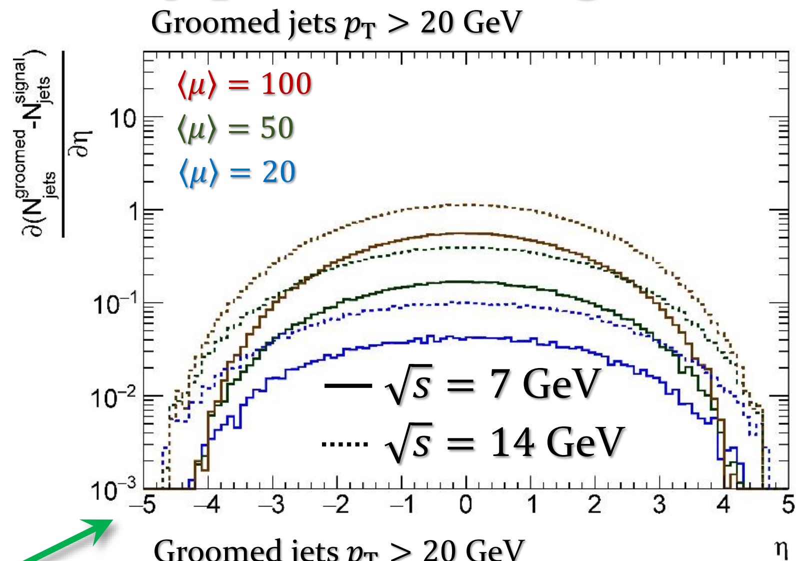



# Backup Material

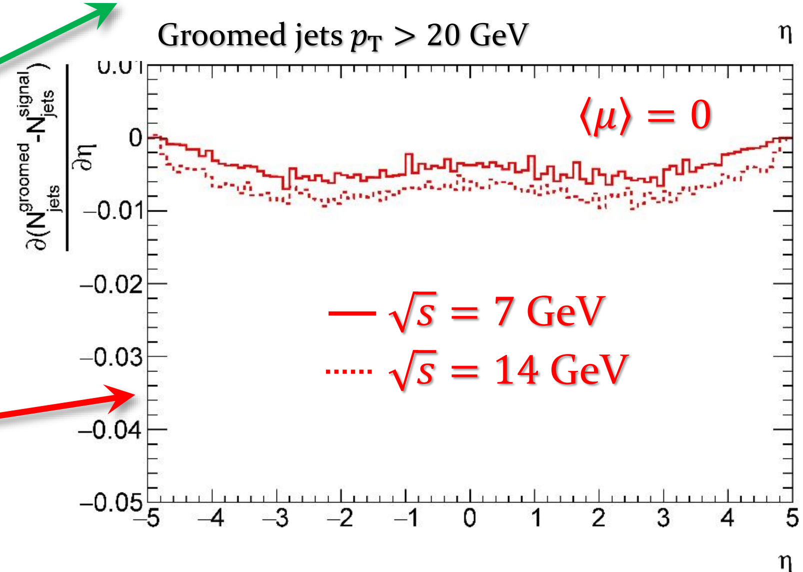
# More on Effect of Jet Grooming

- Difference in jet number density per event at given $\eta$




Difference in number of jets per event and unit $\eta$ between pile-up and no-pile-up (ungroomed and groomed)




Loss of signal jets per event and unit $\eta$ by application of grooming in events w/o pile-up

# Signal & Pile-up Generation

- Signal
  - Pythia8.165
    - $M_{H'} = 1$ TeV, $\sigma_{M_{H'}} \approx 520$ GeV (default settings for $H' \to ZZ \to \ell^{\pm}\ell^{\mp}(\nu\nu)$)
    - CTEQ6.1 LO PDF
    - Underlying event tune 4C
  - 500,000 signal events for each center-of-mass
    - $\sqrt{s} = 7$ TeV & $\sqrt{s} = 14$ TeV
- Minimum bias for pile-up
  - Pythia8.165
    - CTEQ6.1 LO PDF
    - Underlying event tune 4C
  - 100,000,000 MB events available
    - Need approximately $N_{\text{signal events}} \times \left(\langle\mu_{\max}\rangle + (3-4) \times \sqrt{\langle\mu_{\max}\rangle}\right) \approx 70{,}000{,}000$ MB events (at least) for completely independent and non-repetitive pile-up sample
- Output
  - All stable particles from signal and MB
    - $c\tau \geq 10$ mm