Exploring high-purity multi-parton scattering at hadron colliders

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Based on arXiv:2307.05693 in collaboration with Jeppe Andersen, Pier Monni, Gavin Salam and Alba Soto-Ontoso

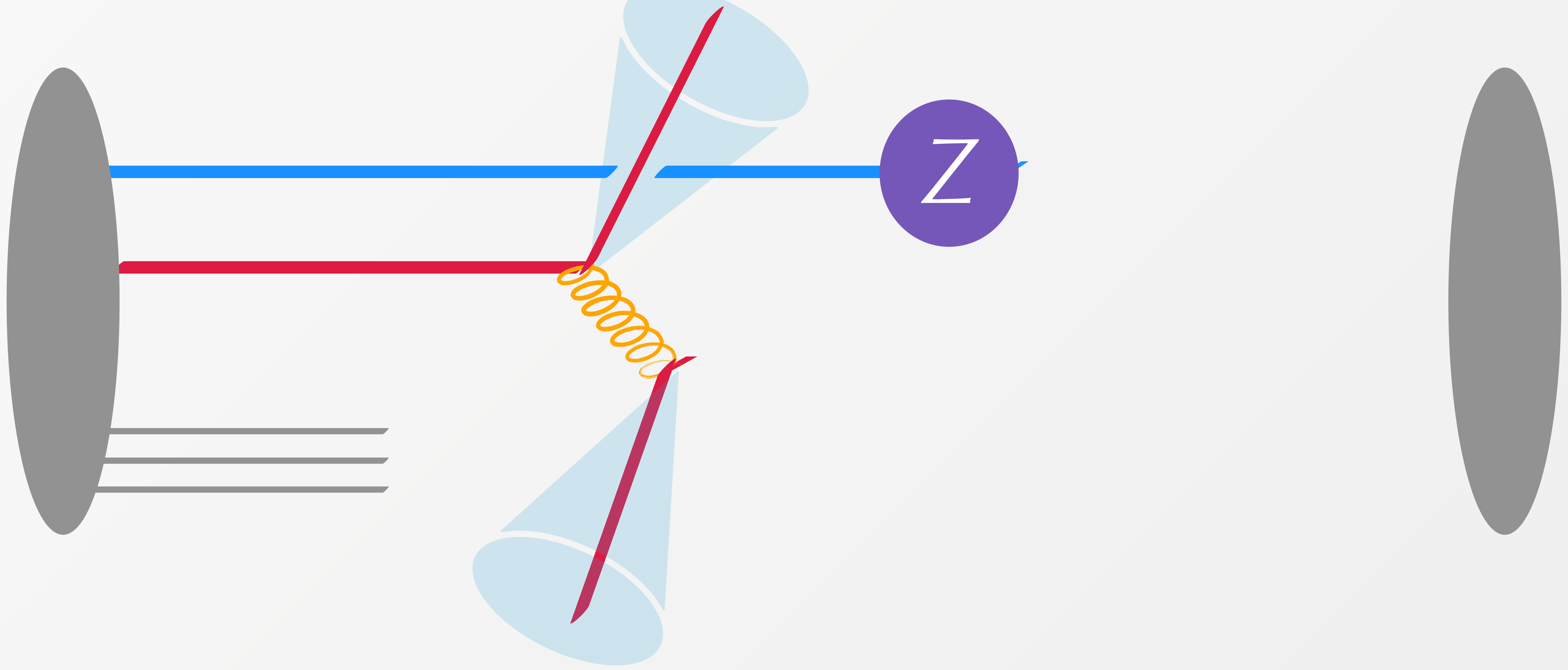
Challenges in MPI studies

Distinguishing two contributions:

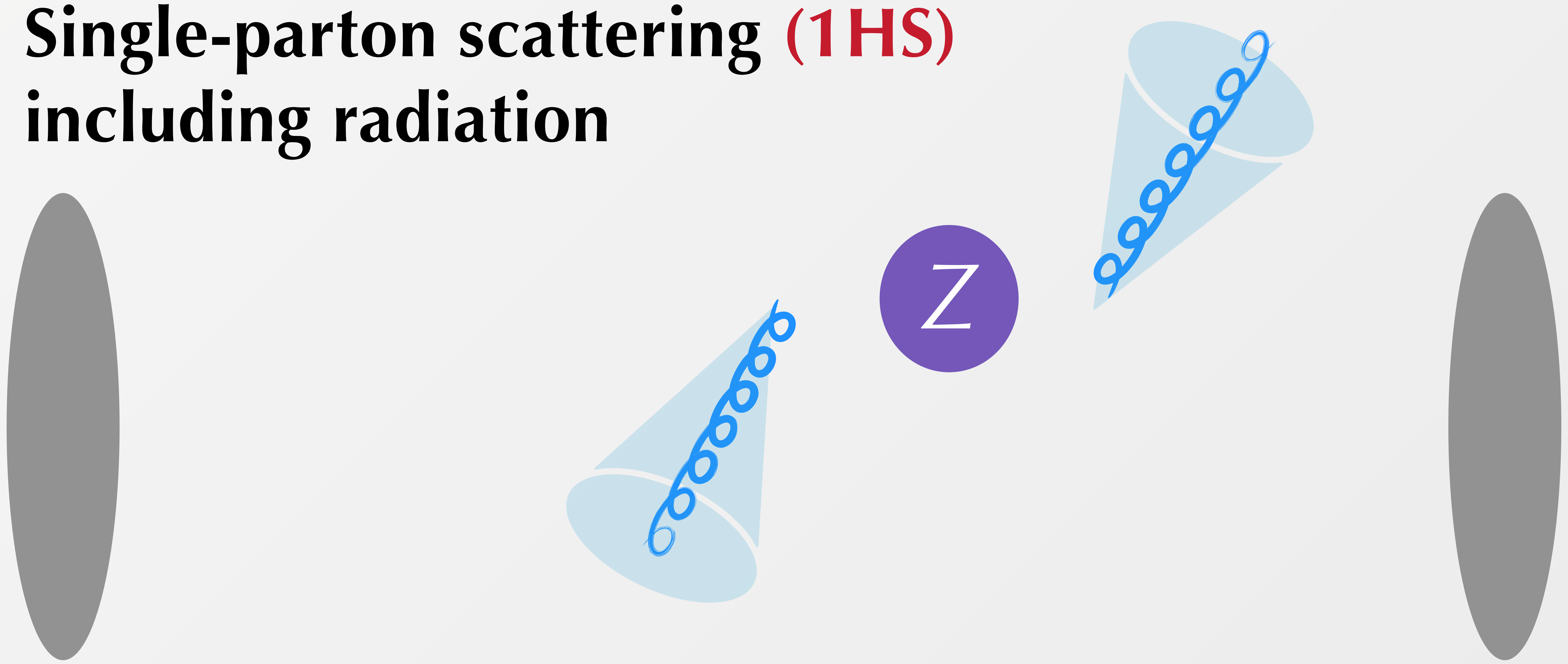
- two independent hard scatterings **(2HS)**
- a single hard scattering **(1HS)** with extra radiation

e.g. Z boson production: both contributions have experimental signature of Z boson ($\rightarrow$ 2 leptons) + jets

Double-parton scattering (2HS)



Background from Single-parton scattering (1HS) including radiation

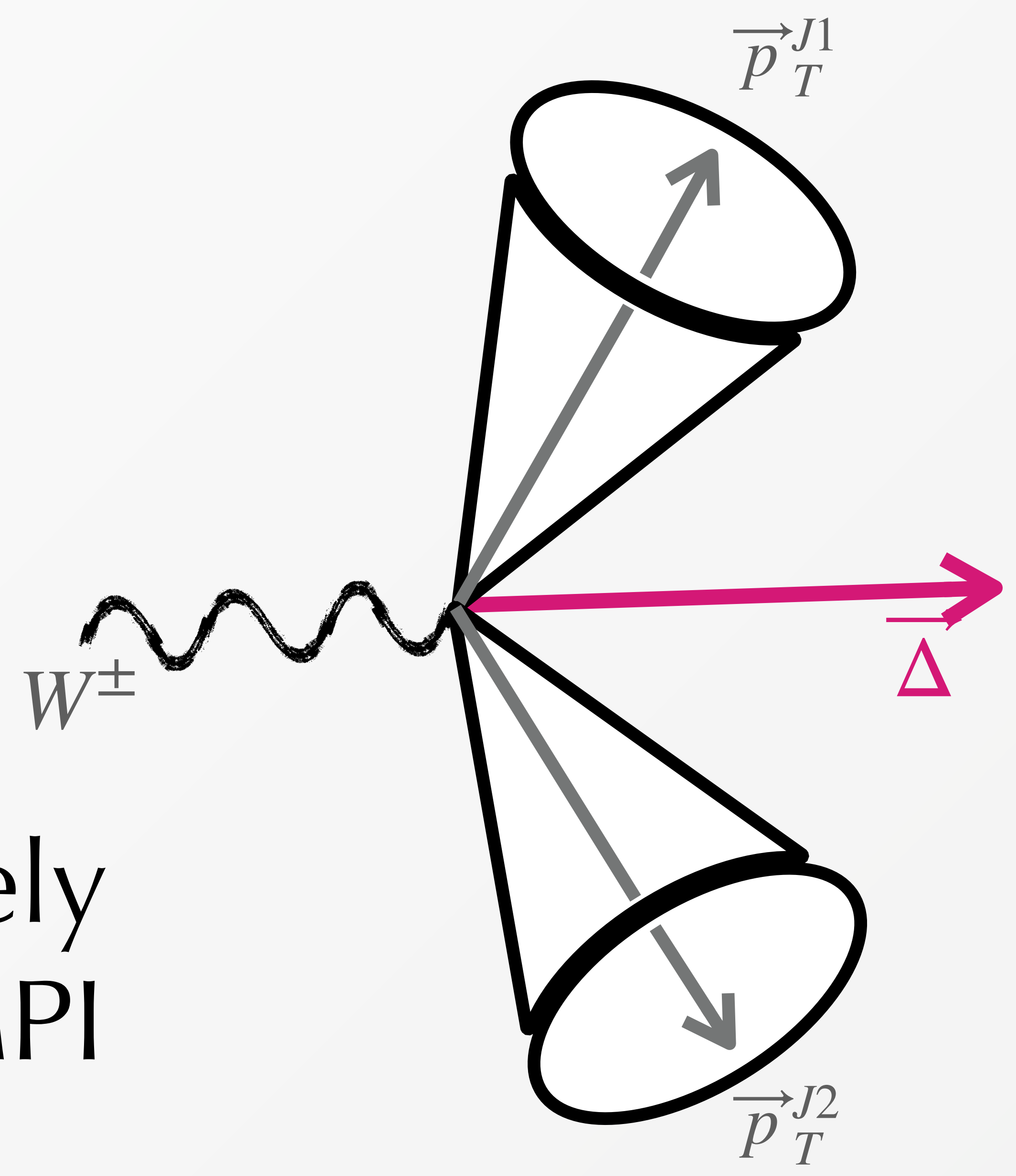


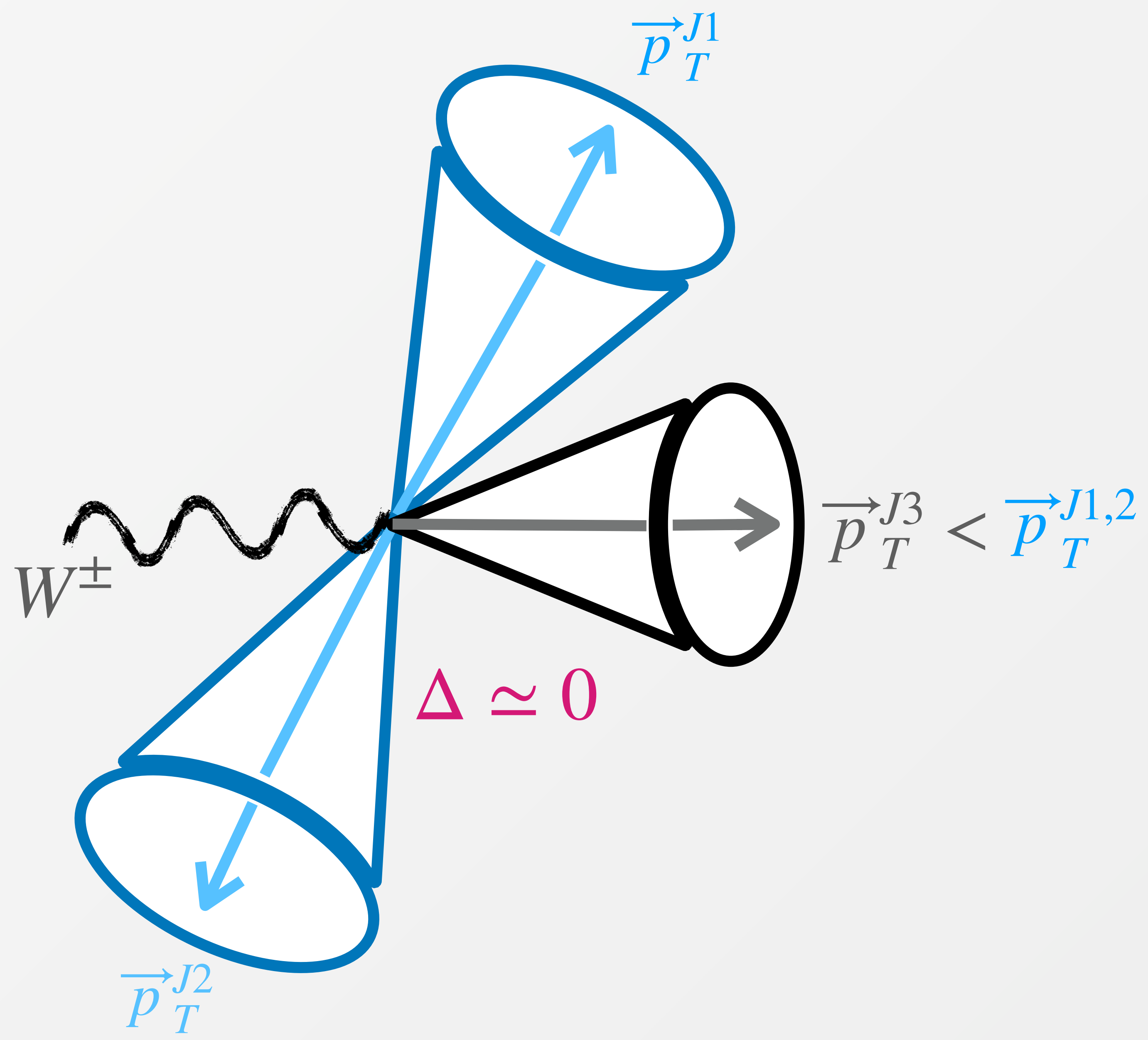
W+2-jets study

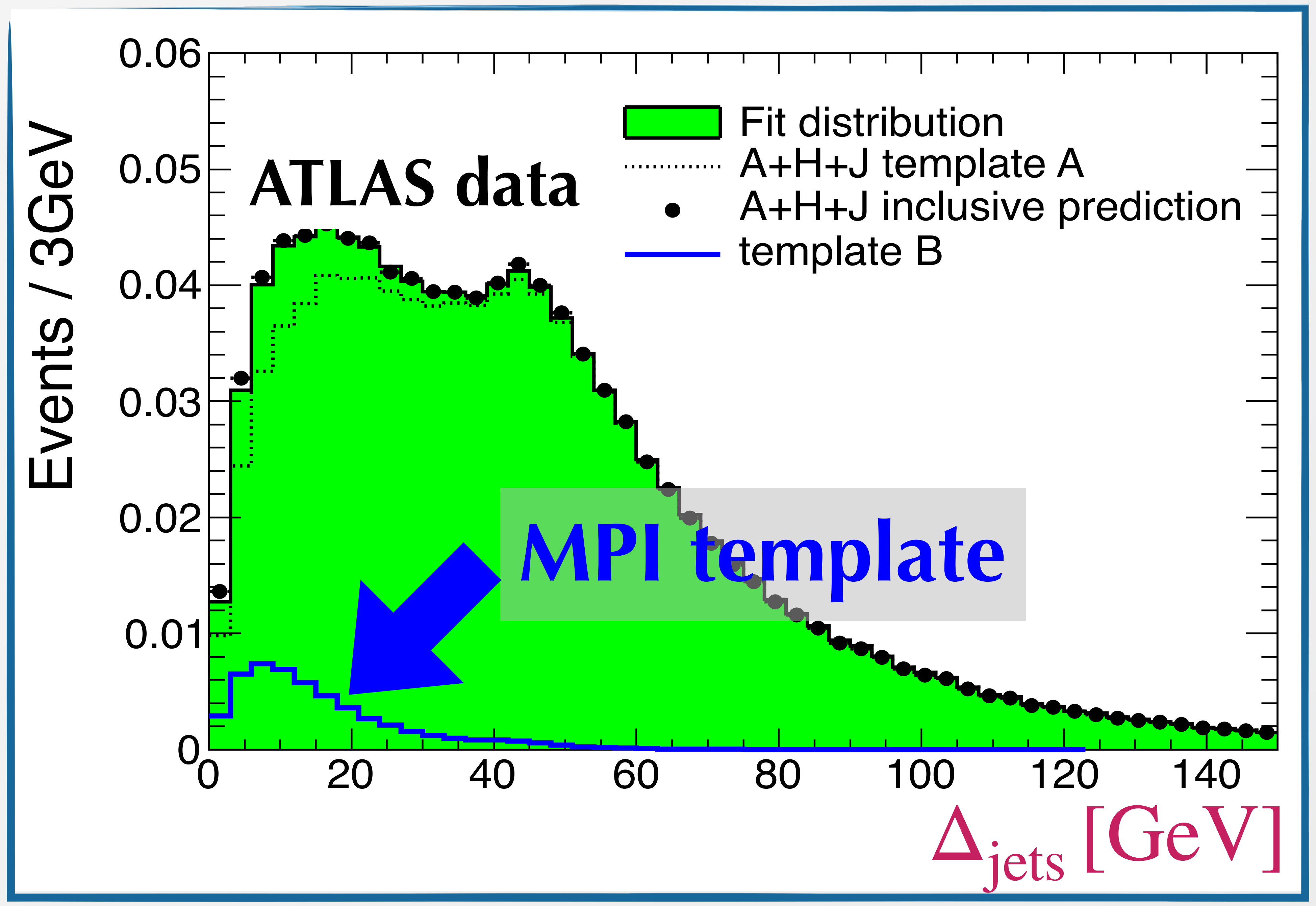
- E.g. ATLAS, $W \to \ell\nu + 2$ jets 1301.6872
- Exploits fact that MPI jet-pair more likely to balance than radiation jet pair, so MPI should be enhanced for

$$\Delta_{\text{jets}} = \left| \vec{p}_T^{\,J1} + \vec{p}_T^{\,J2} \right| \to 0$$

- That works to some extent, but relative MPI (2HS) fraction is moderate ($\lesssim 25\%$)
- Quantitative analysis requires very good understanding of radiation in single hard scattering (1HS)



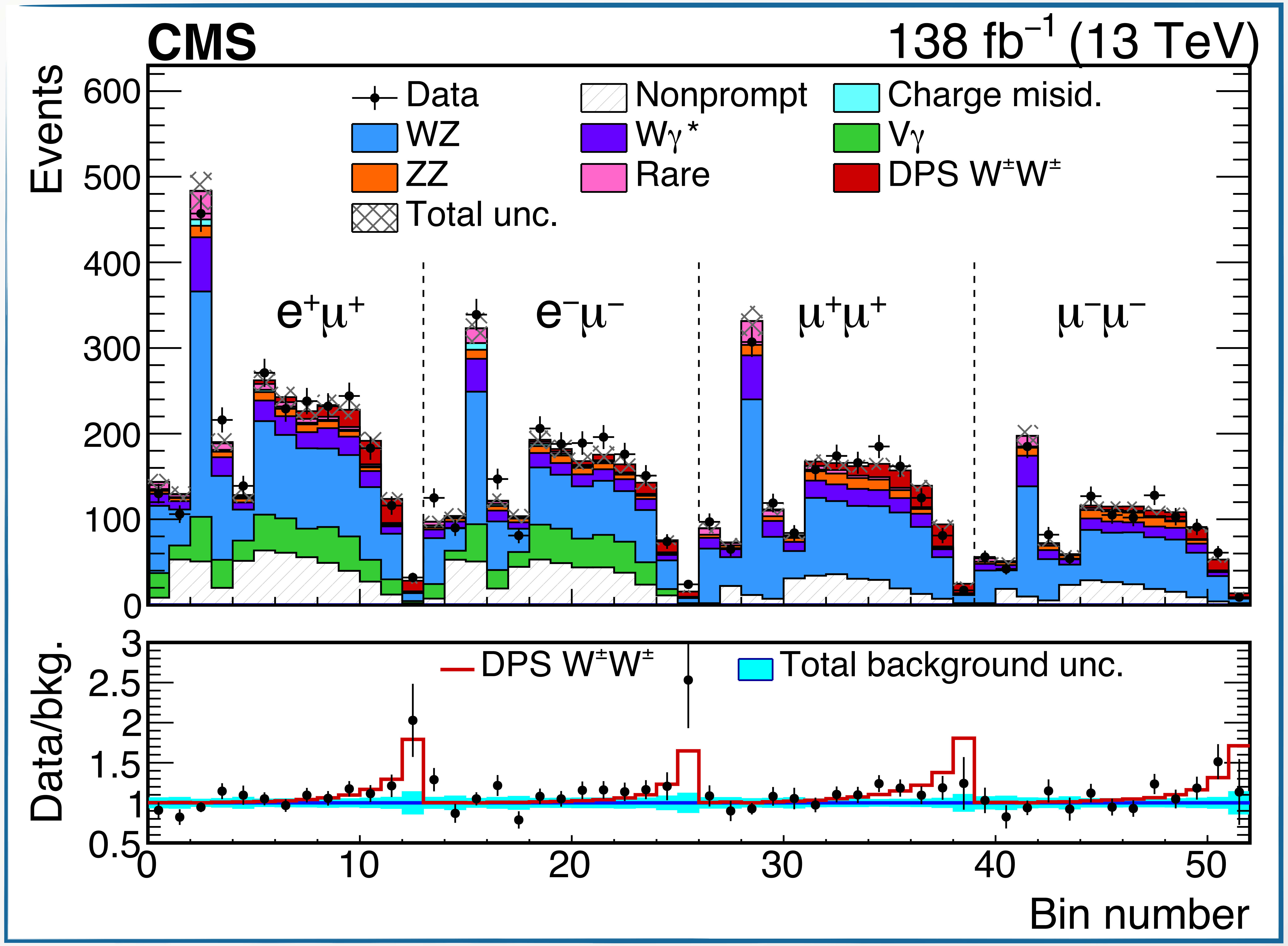




[ATLAS 1301.6872]

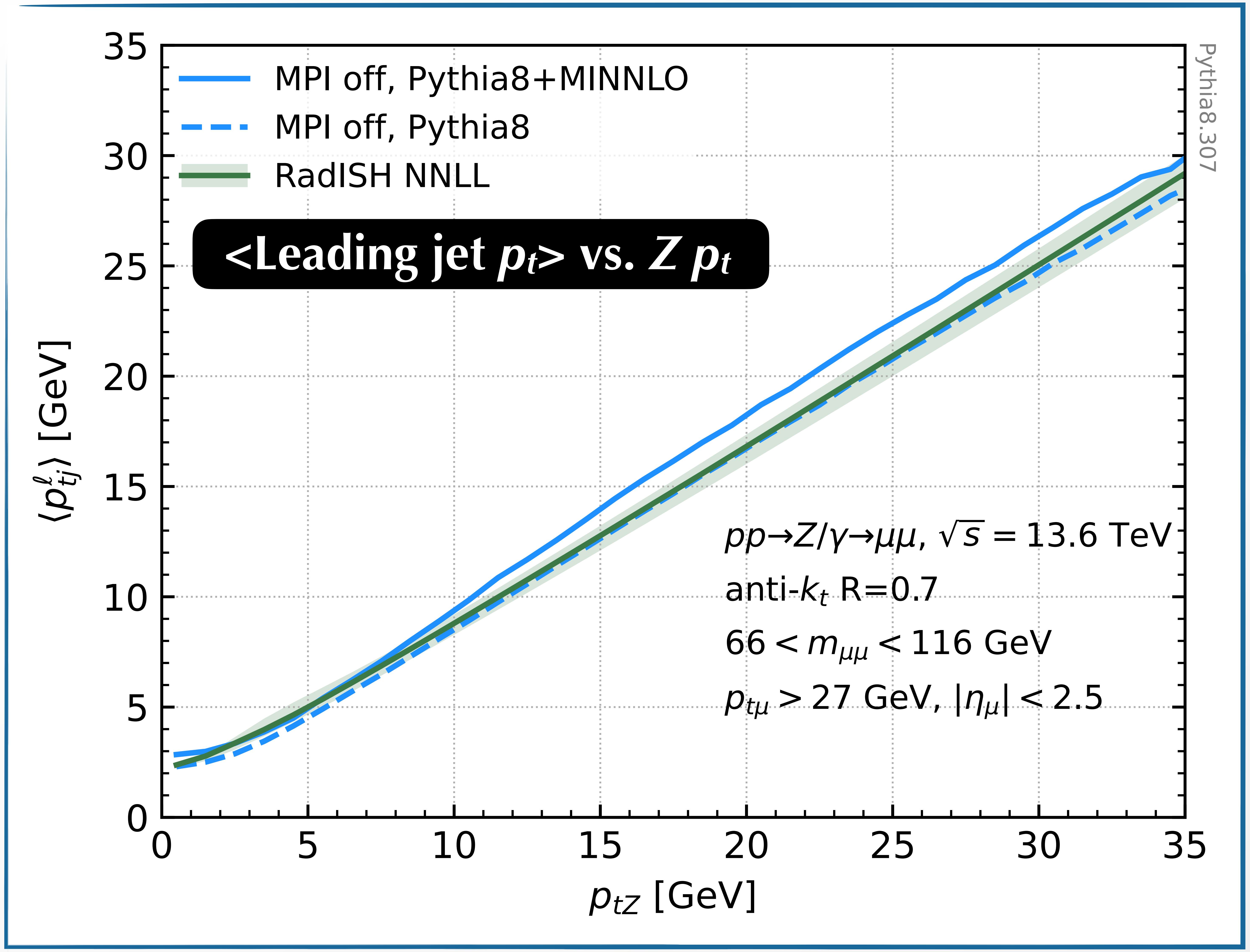
Avoid radiation issue: same-sign *WW*

- even traditional "gold-plated" MPI processes are difficult
- Here $W^{\pm}W^{\pm} \to$ same-sign leptons, CMS 2206.02681
- many other backgrounds: need for BDT makes it difficult to study MPI physics
- 6.2σ observation with full Run 2 dataset



[CMS 2206.02681]

$pp \to Z + X$: can we constrain radiation from Z scattering?



- Consider process with **MPI simulation turned off** (i.e. just 1HS)
- Look at avg. p_t of leading jet (p_{tj}^{ℓ}) as a function of Z p_t (p_{tZ})

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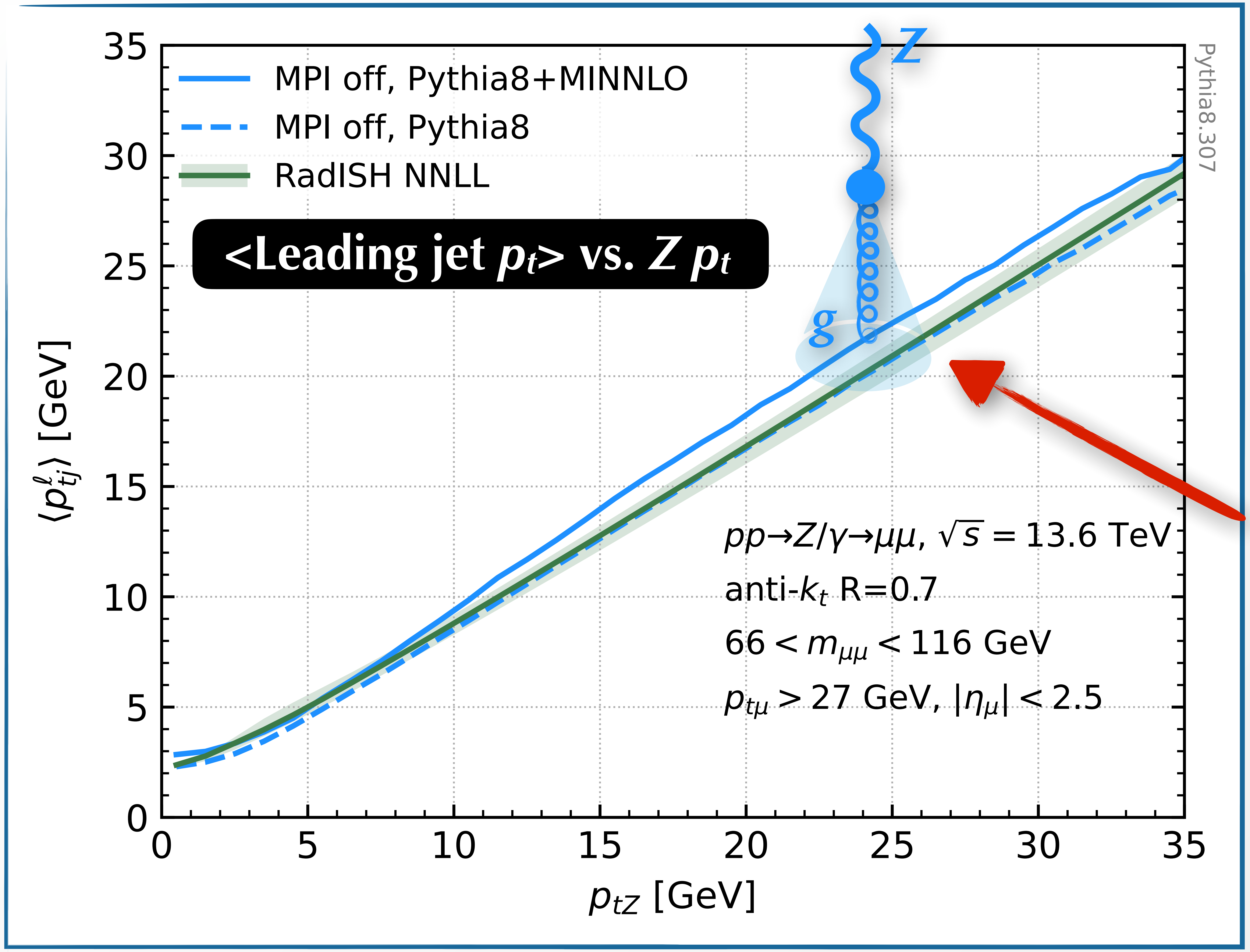

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- **Most of p_{tZ} range:** almost perfect linear correlation, since **leading jet balances p_{tZ}**

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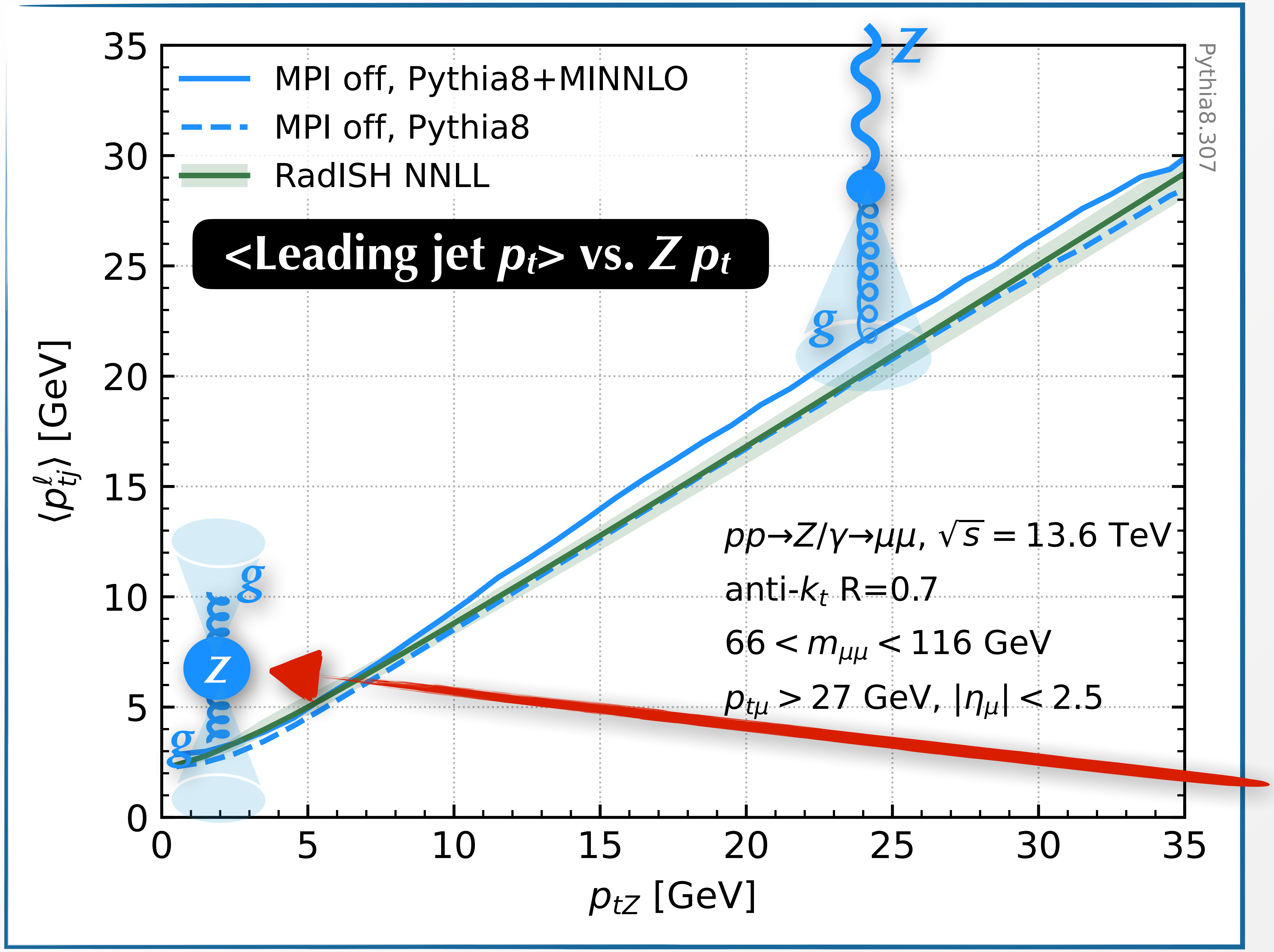

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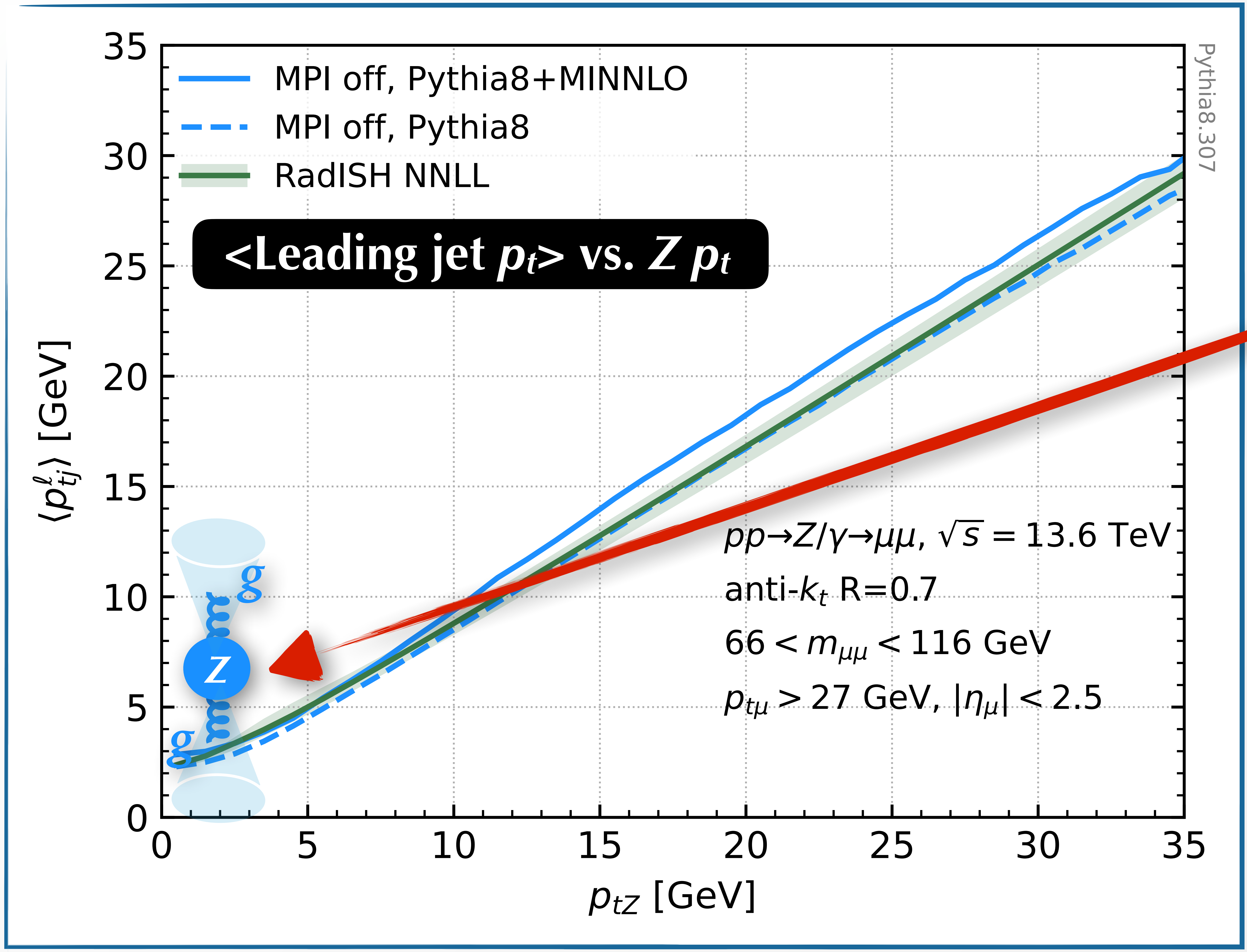
- **Most of p_{tZ} range:** almost perfect linear correlation, since **leading jet balances p_{tZ}**
- **For $p_{tZ} \to 0$:** $\langle p_{tj}^{\ell} \rangle$ saturates at about 2–3 GeV: **two (or more) soft jets balance each other**

$pp \to Z + X$: can we constrain radiation from Z scattering?

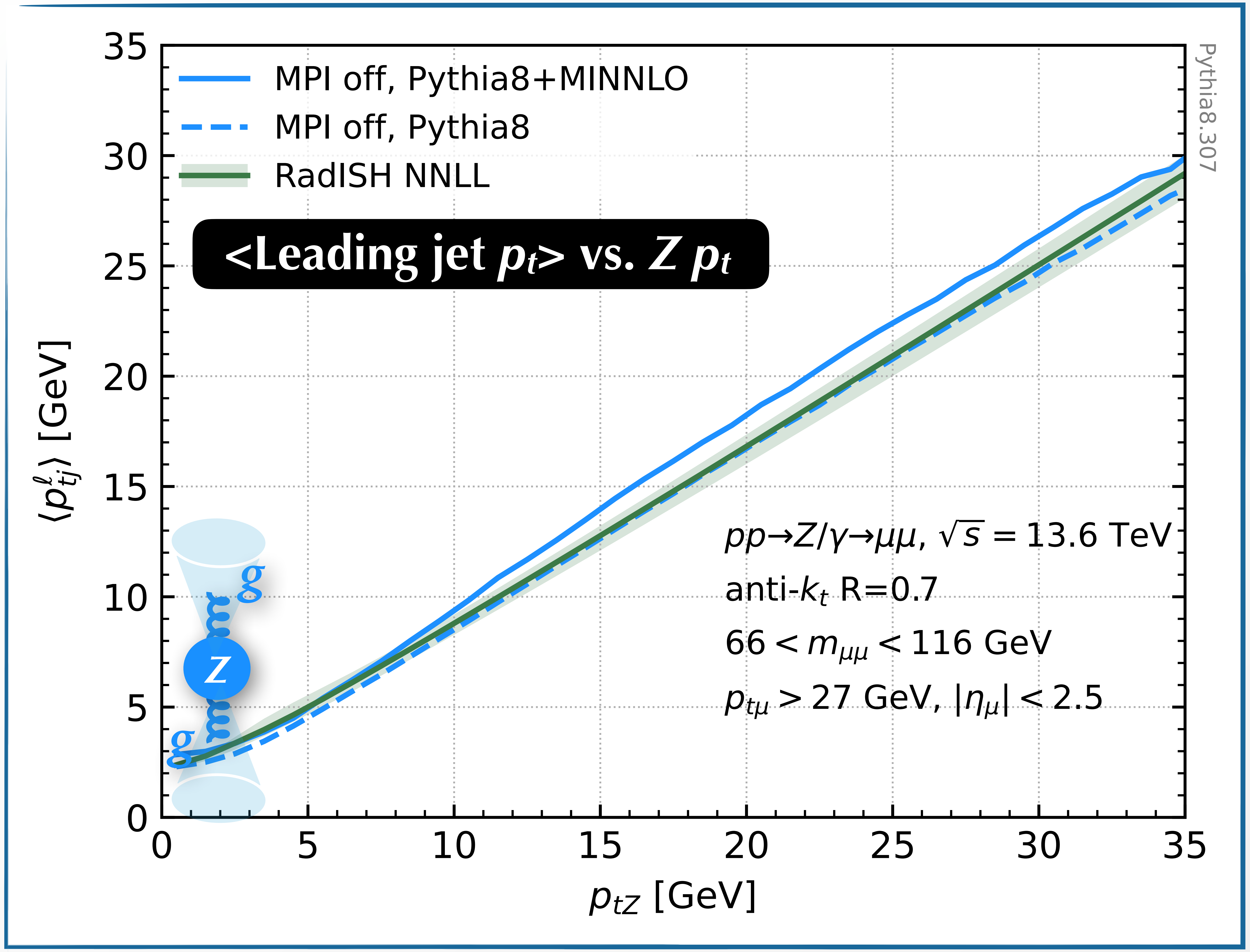


Average leading jet p_T can be calculated from **resummation** in the limit $p_{tZ} \to 0$ **[Monni, LR, Torrielli '19]**

$$\langle p_{tj}^{\ell} \rangle_{p_{tZ} \to 0} \sim \Lambda_{QCD} \left(\frac{m_Z}{\Lambda_{QCD}} \right)^{\kappa \ln \frac{2+\kappa}{1+\kappa}}$$

$$\sim 2 - 3\,\text{GeV} \qquad \kappa = \frac{2C_F}{\pi \beta_0}$$

$pp \to Z + X$: can we constrain radiation from Z scattering?



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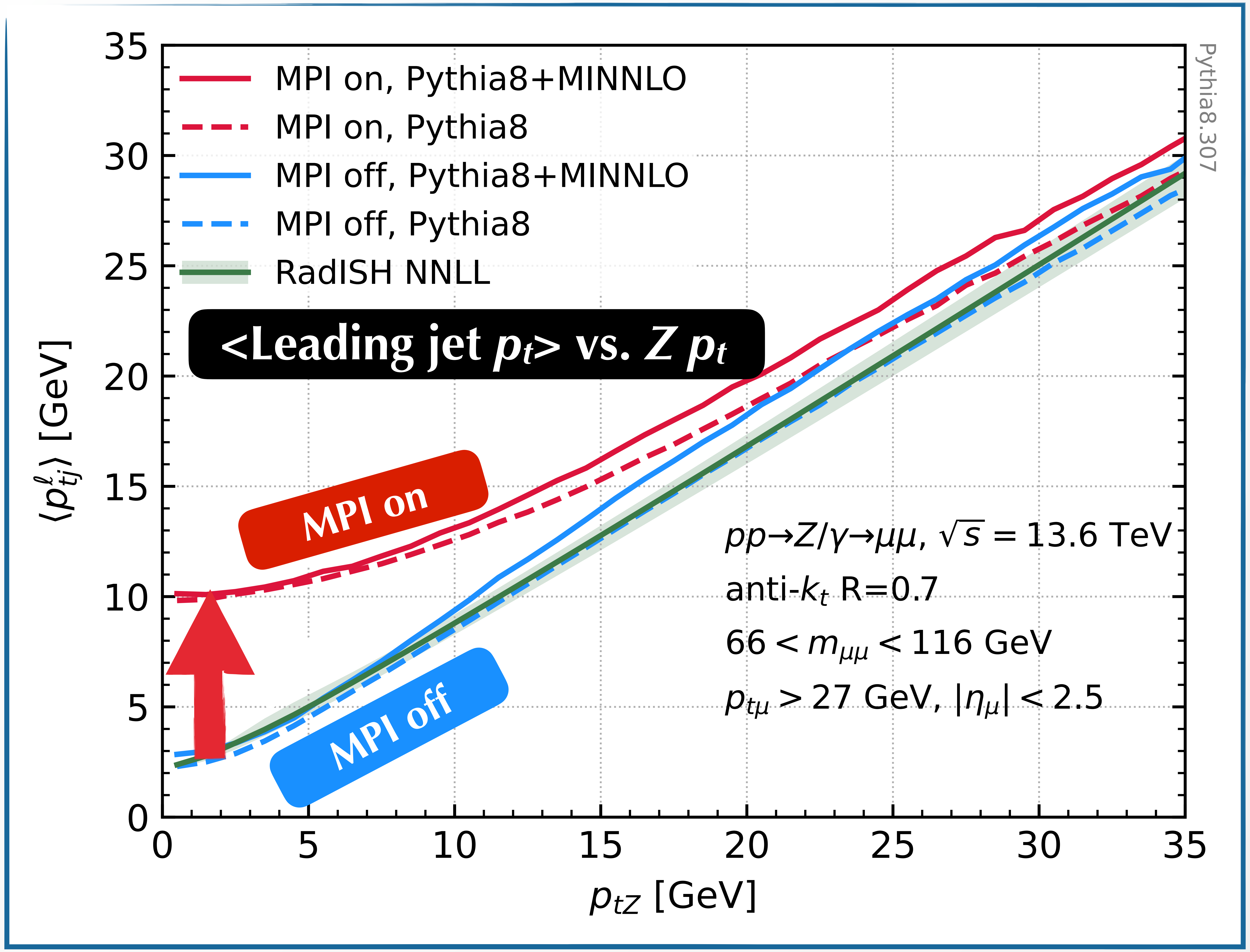
By **constraining** p_{tZ} we can **forbid most radiation** above this characteristic 2–3 GeV scale

[classic Parisi-Petronzio '79]

$pp \to Z + X$: can we constrain radiation from Z scattering?



What happens when turning on MPI?

- for $p_{tZ} \to 0$, leading jet p_t is now ~10 GeV instead of 2–3 GeV
- Why? Because there is almost always an MPI jet that is much harder than the soft jets from Z-process NB: Current models in Pythia/Herwig/ Sherpa simulate MPI as semi-hard scatterings

→Peter Skand's talk

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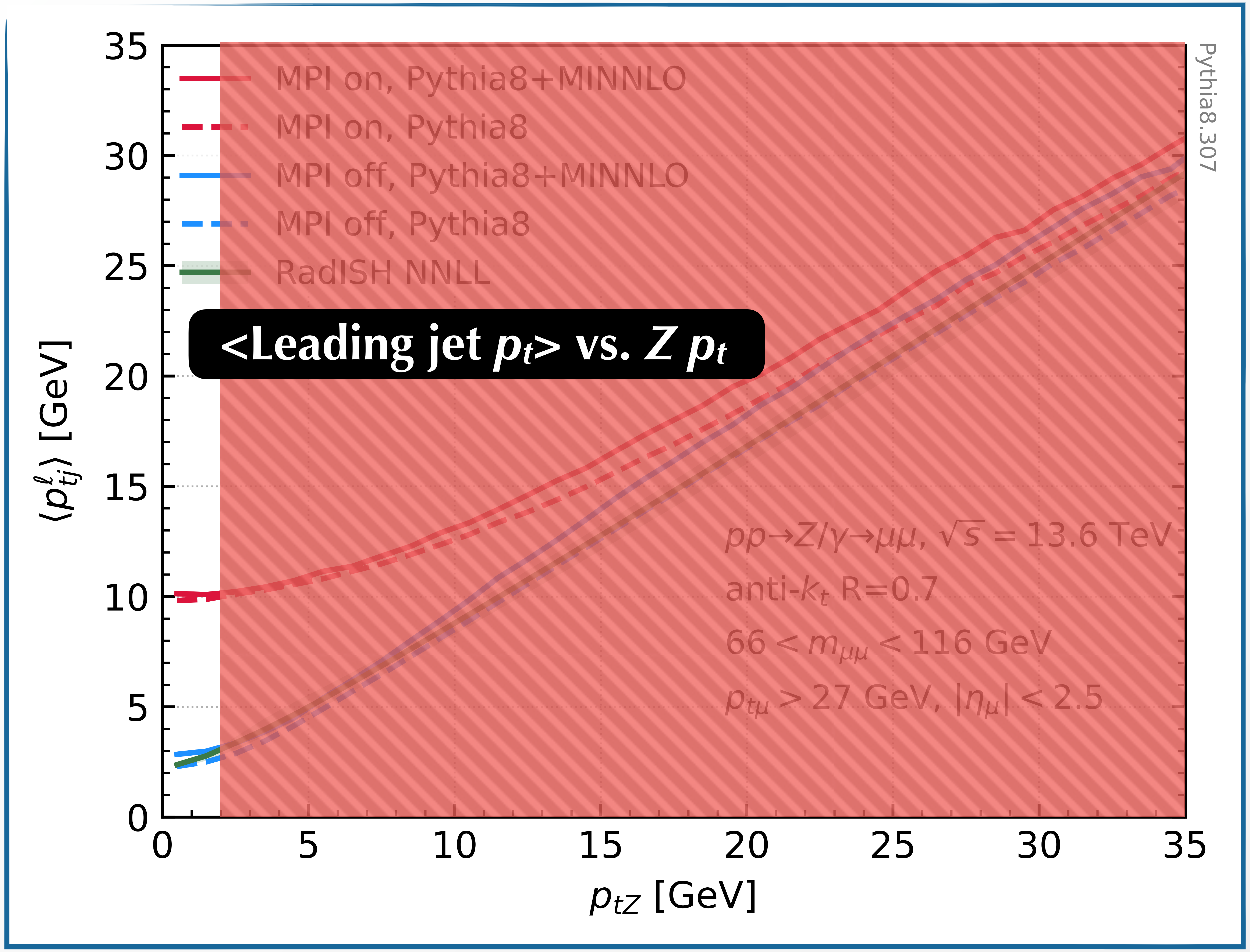

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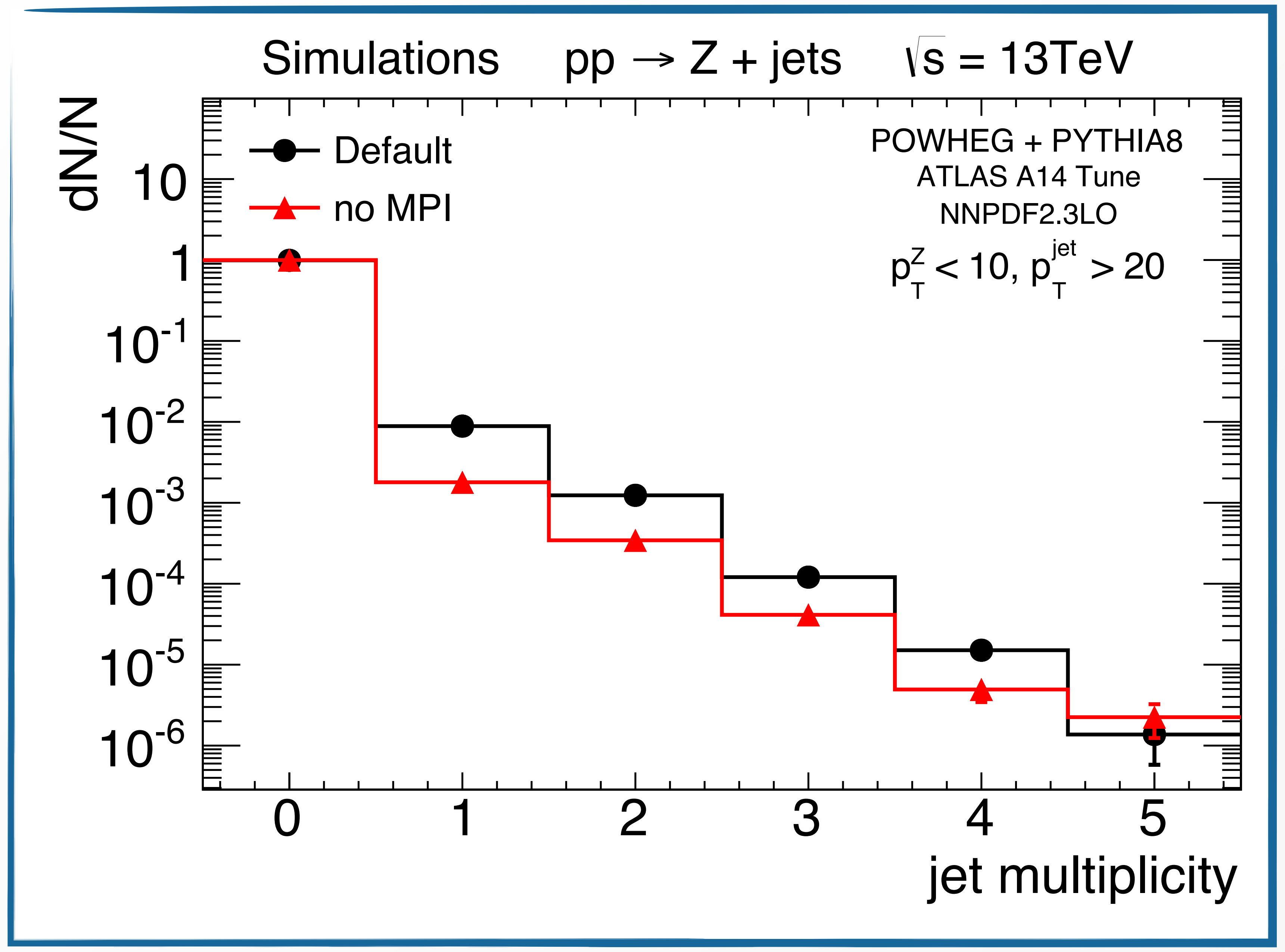
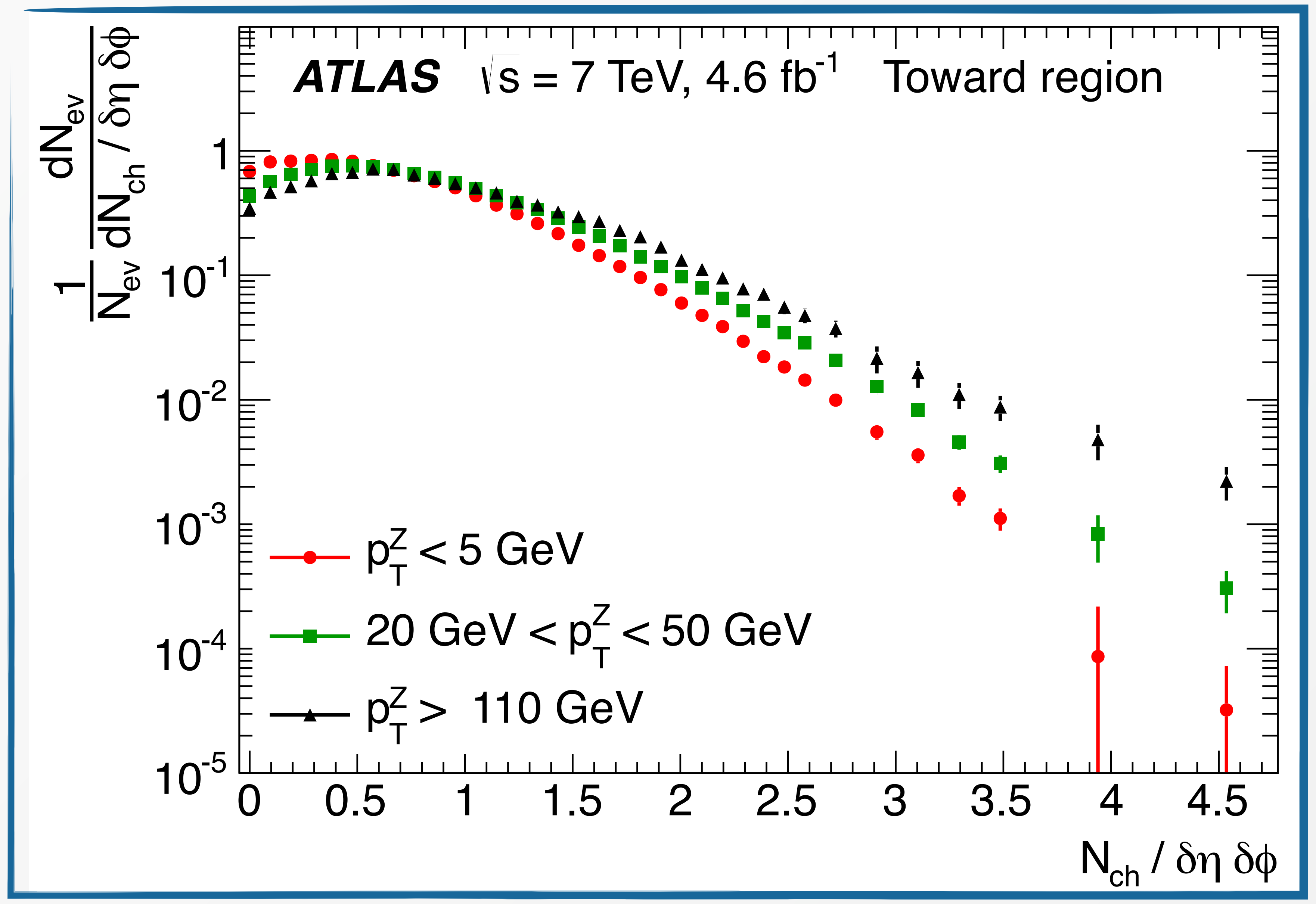
Suggests we should study MPI with **help of a tight cut on p_{tZ}**

Past MPI studies with cuts on p_{tZ}

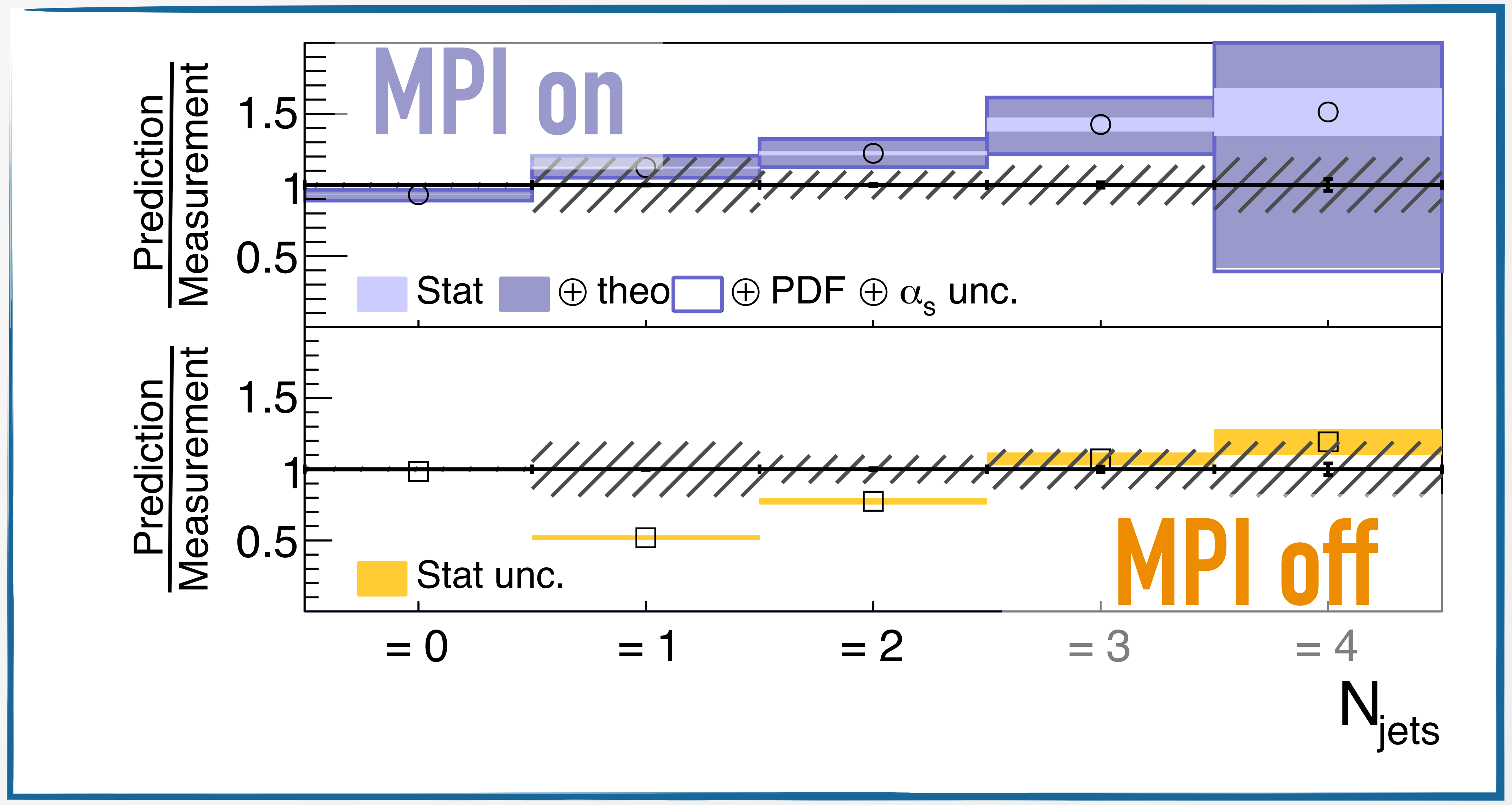


Bansal, Bansal, Kumar, Singh 1602.05392 suggested MPI studies with $p_{tZ} < 10\,\text{GeV}$ for improved MPI purity

See also Alioli, Bauer, Guns, Tackmann, 1605.07192



ATLAS 1409.3433 mostly an underlying-event study, used $p_{tZ} < 5\,\text{GeV}$



CMS 2210.16139:

results with $p_{tZ} < 10\,\text{GeV}$, confirming some MPI enhancement

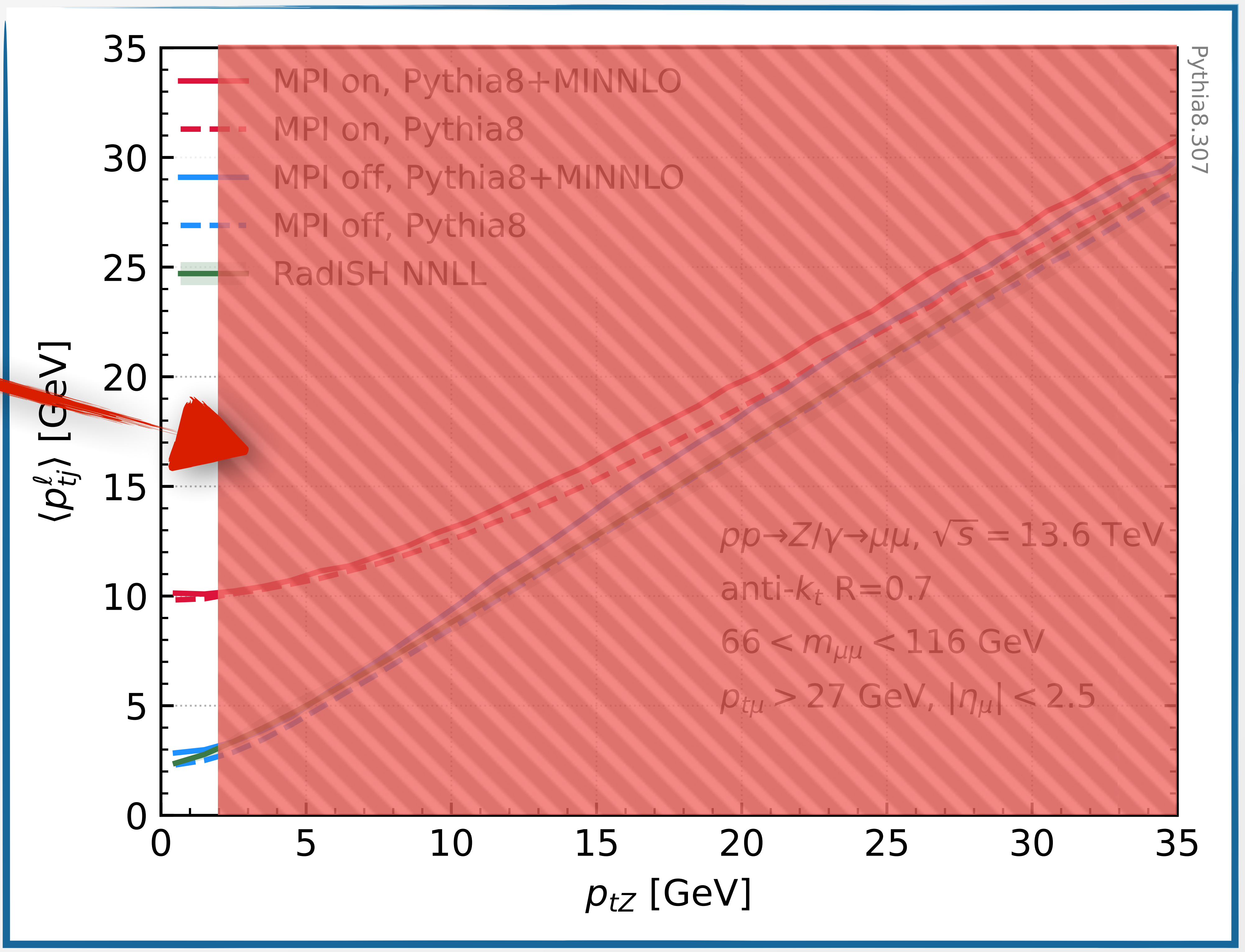
This study: establish what cut to use, explore opportunities that open up

Need **balance** between

- **maximising statistics** (favours loose cut on Z)
- **minimising radiation** from Z hard system (favours tight cut on Z)

From $\langle p_{tj}^{\ell} \rangle$ vs. p_{tZ} plot optimum requirement is $p_{tZ} \lesssim 2\,\mathrm{GeV}$

- Smaller cut does not reduce scale of soft radiation from Z process and lower stats
- Higher cut increases average p_T of radiation
- Feasible given current experimental resolution



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ptZ < 2 GeV cut retains 4 – 5% of Z-pole Drell-Yan events

For $Z \to \mu^+\mu^-$ residual cross section is ~40pb

~12 million events for 300fb^{-1} in Run 3

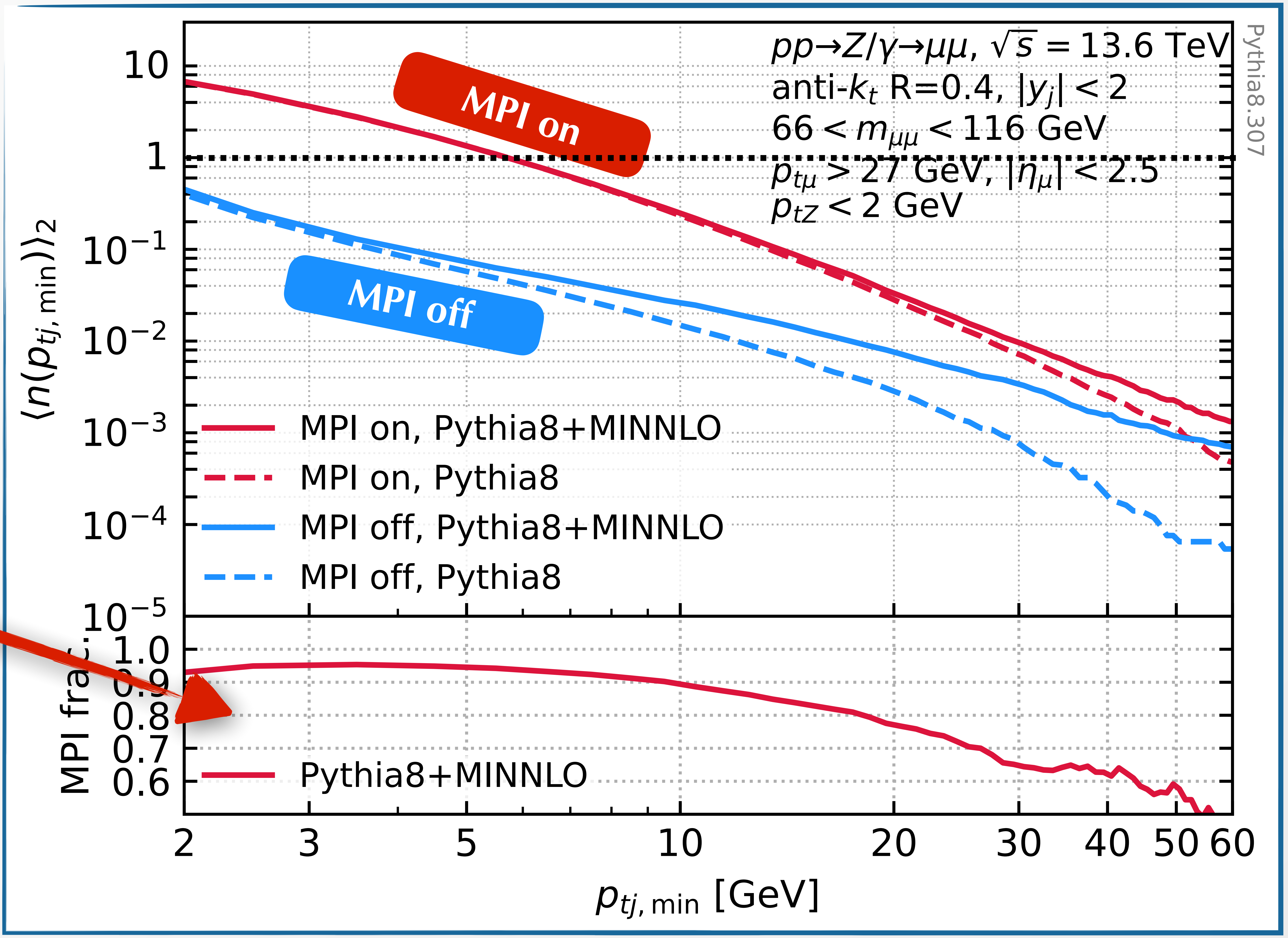
Simplest observable: cumulative inclusive jet spectrum for $p_{tZ} < 2$ GeV

Linear sum (for small jet radius) of

- cumulative jet spectrum from 1HS process
- cumulative jet spectrum from any additional hard scatters (dominant!)

MPI purity remains significant also at relatively high values of $p_{tj,\min}$

$p_{tj,\min}$	MPI purity
10 GeV	90%
20 GeV	78%
40 GeV	60%



Connection with "pocket formula" (σ effective)

Pocket formula says that cross section for two processes A and B to happen simultaneously is

$$\sigma_{AB} = \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}}$$

where σ_{eff} is a normalisation factor roughly connected with area over which partons are concentrated in the proton.

Connection with "pocket formula" (σ effective)

$\langle n(p_{tj,\min})\rangle_{C_Z}$ = average number of jets above $p_{tj,\min}$ for a given cut C_Z on p_{tZ}

$$\langle n(p_{tj,\min})\rangle_{C_Z} = \frac{1}{\sigma(p_{tZ} < C_Z)} \int_{p_{tj,\min}} dp_{tj} \frac{d\sigma_{\text{jet}}(p_{tZ} < C_Z)}{dp_{tj}}$$

Pure MPI part extracted by subtracting no-MPI calculation (thanks to linearity)

$$\langle n(p_{tj,\min})\rangle_{C_Z}^{\text{pure-MPI}} \equiv \langle n(p_{tj,\min})\rangle_{C_Z} - \langle n(p_{tj,\min})\rangle_{C_Z}^{\text{no-MPI}}$$

In σ_{eff} picture, pure-MPI part can be connected with jet rate in min-bias events (i.e. no Z)

NB: can be directly measured on data, identical systematics (e.g. with charge-track jets at low p_{tj})

$$\langle n(p_{tj,\min})\rangle_{C_Z}^{\text{pure-MPI}} \simeq \frac{1}{\sigma_{\text{eff}}} \int_{p_{tj,\min}} dp_{tj} \frac{d\sigma_{\text{jet}}^{\text{min-bias}}}{dp_{tj}}$$

Some questions

Within pocket formula picture

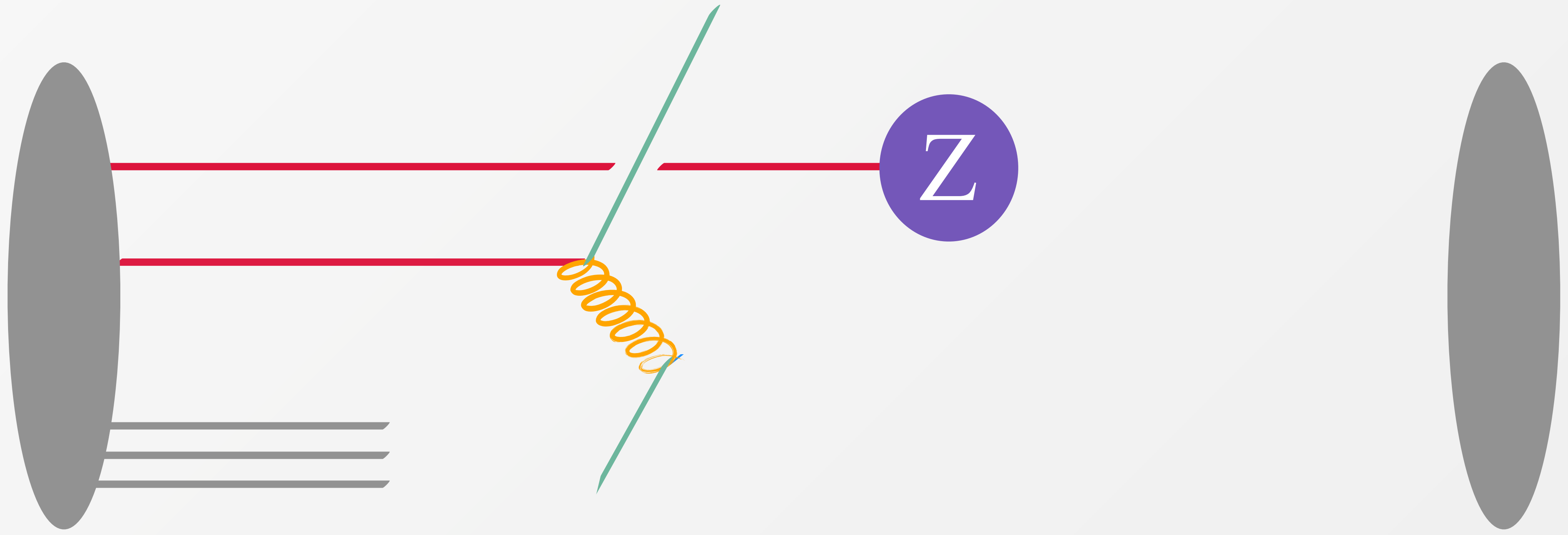
- how does σ_{eff} depend on kinematics of the jets? ($\rightarrow$ in Pythia, $\sigma_{\text{eff}} \simeq 30\,\text{mb}$, fairly independently of jet p_t)

Beyond DPS pocket formula

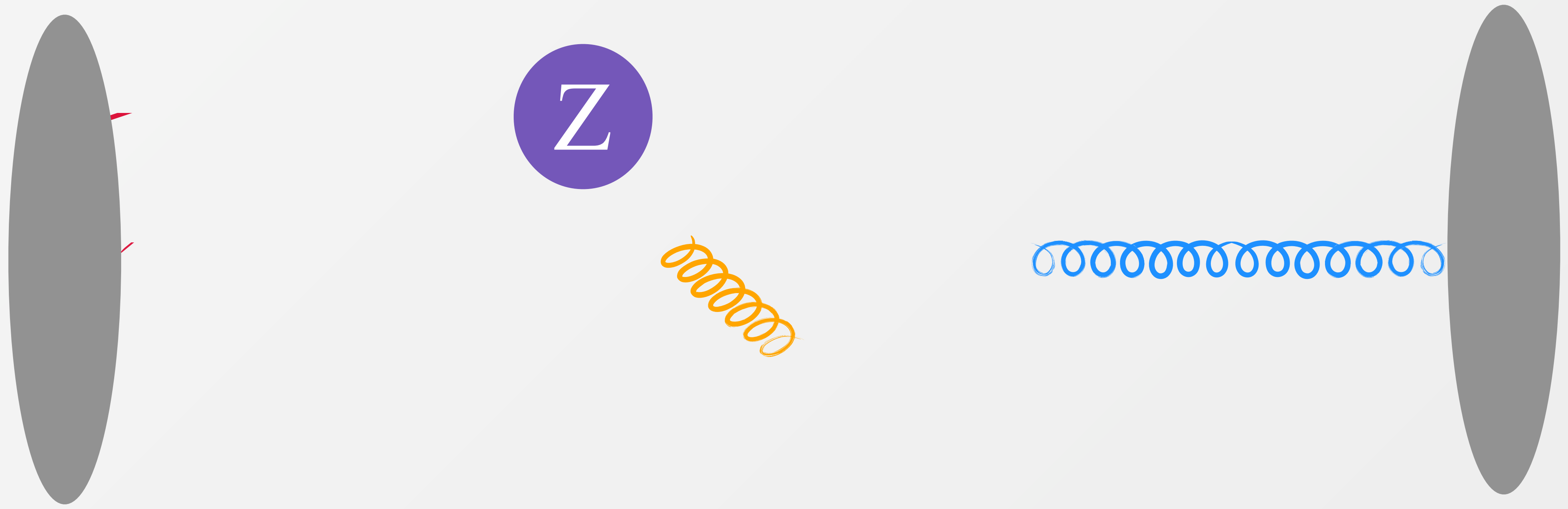
- QFT effects & potential breakdown of pocket formula?
- can one use this to measure 3HS, etc.? (cf. d'Enterria and Snigirev 1612.05582)
- …

Beyond the pocket formula

- Pocket formula is based on independent scatterings, with some effective transverse size over which partons are spread



- But we expect some partons to come from splitting of common parents, "**perturbative interconnection**"
- Such splittings tend to give more p_t to the partons → higher p_{tZ}



- **We should see an change of MPI jet rate if we relax the p_{tZ} cut**

Interconnection studies: Diehl & Schafer 1102.3081; Blok, Dokshitzer, Frankfurt & Strikman 1106.5533; Diehl, Gaunt & Schönwald, 1702.06486

Can one see effect of perturbative interconnection?

Measure cumulative jet rate with two p_{tZ} cuts:

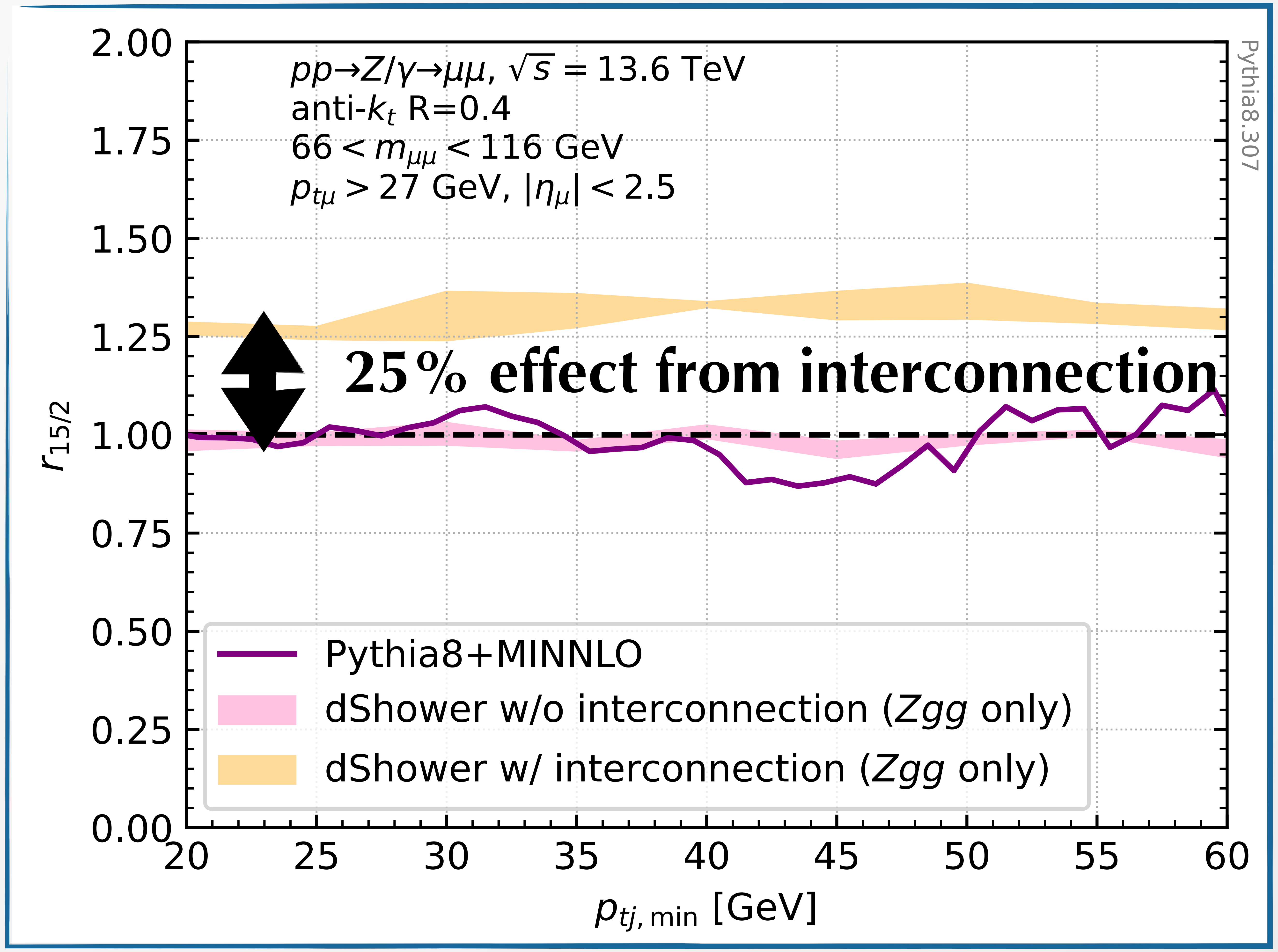
- tight (2 GeV)
- loose (15 GeV)

Take ratio of pure-MPI jet rates

$$r_{15/2} = \frac{\langle n(p_{tj,\min})\rangle_{15}^{\text{pure-MPI}}}{\langle n(p_{tj,\min})\rangle_{2}^{\text{pure-MPI}}}$$

Compare to

- **Pythia (+MiNNLO)**: no interconnection (expect $r = 1$)
- **dShower**: with option of interconnection
  [Cabouat, Gaunt, Ostrolenk, 1906.04669; Cabouat, Gaunt, 2008.01442]

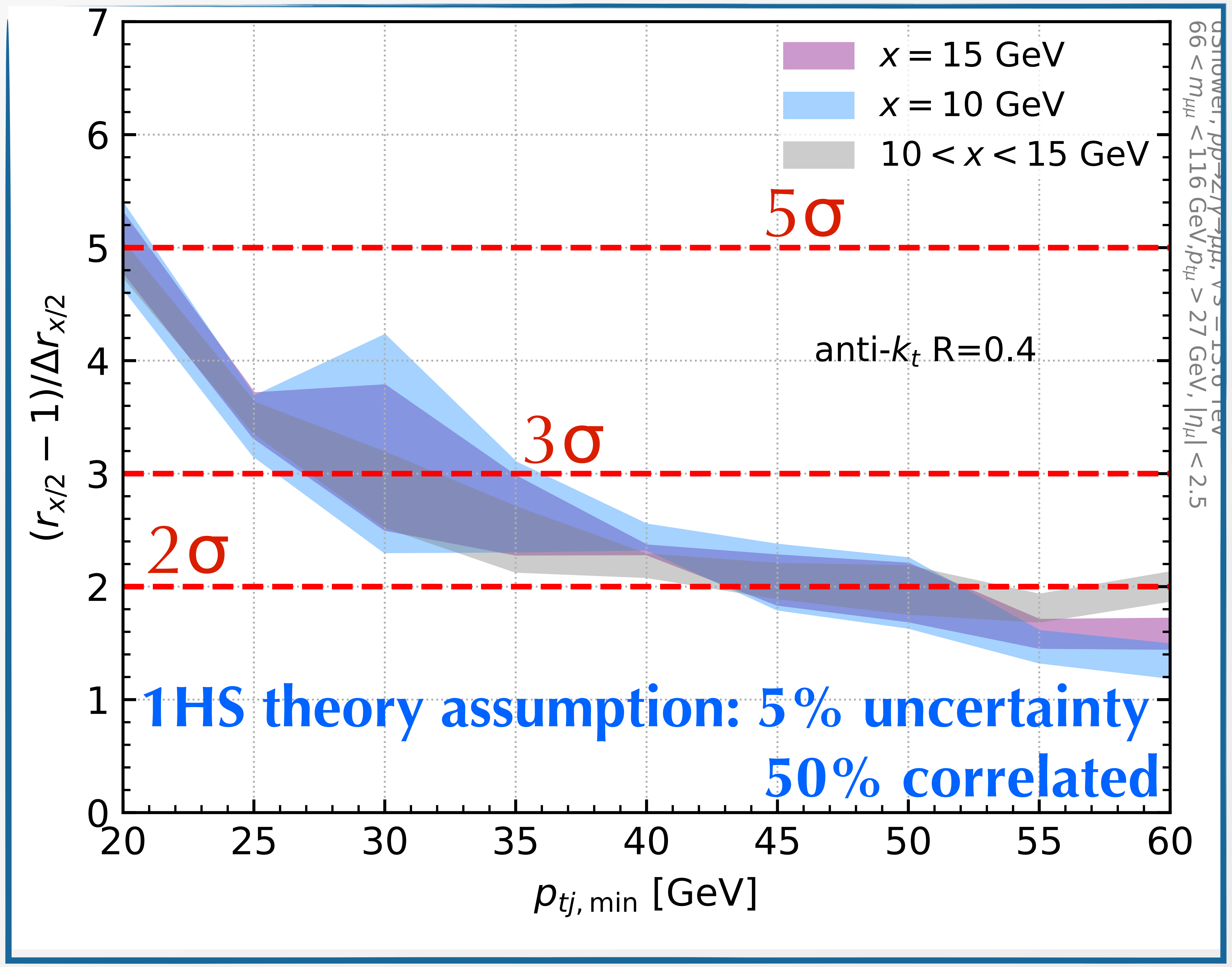


Interplay of significance with MPI purity

Significance of signal of perturbative interconnection in simulation, for dShower-sized effect vs. $p_{tj,\min}$ depends on assumptions for sizes of **theory uncertainties** on 1HS subtraction + **their correlation** between the two p_{tZ} cuts

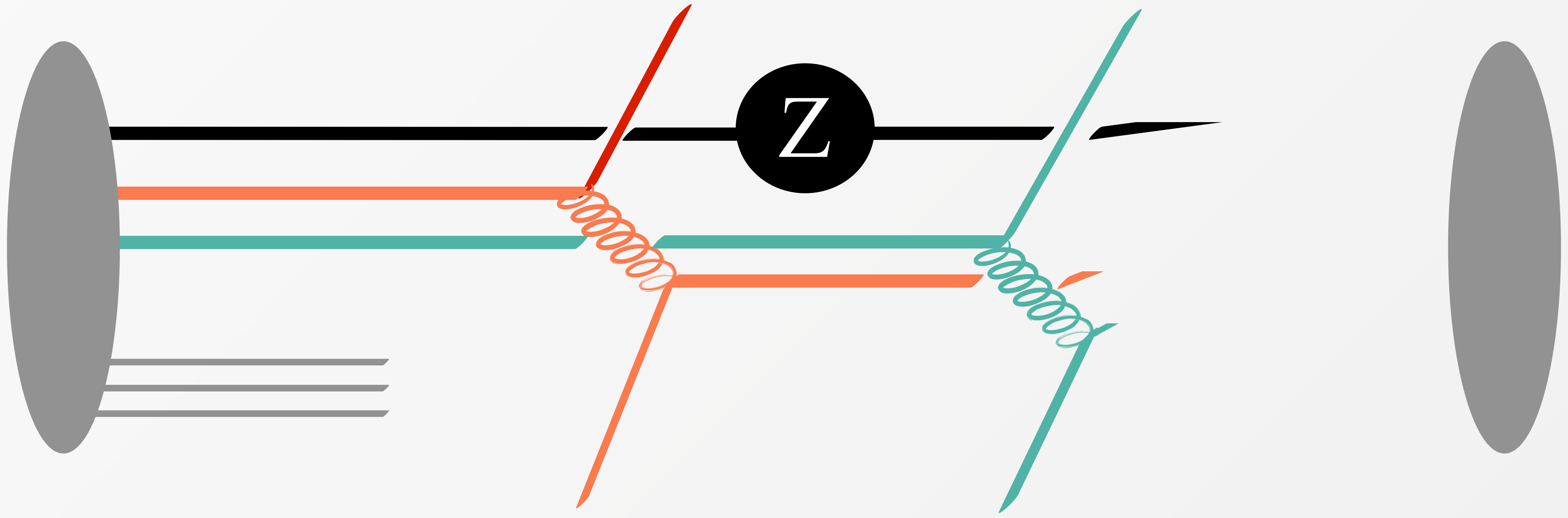
- **Just barely feasible?**
- motivates NNLO (matched) *Z+2j* calculations to reduce current theory uncertainty (10-20%)

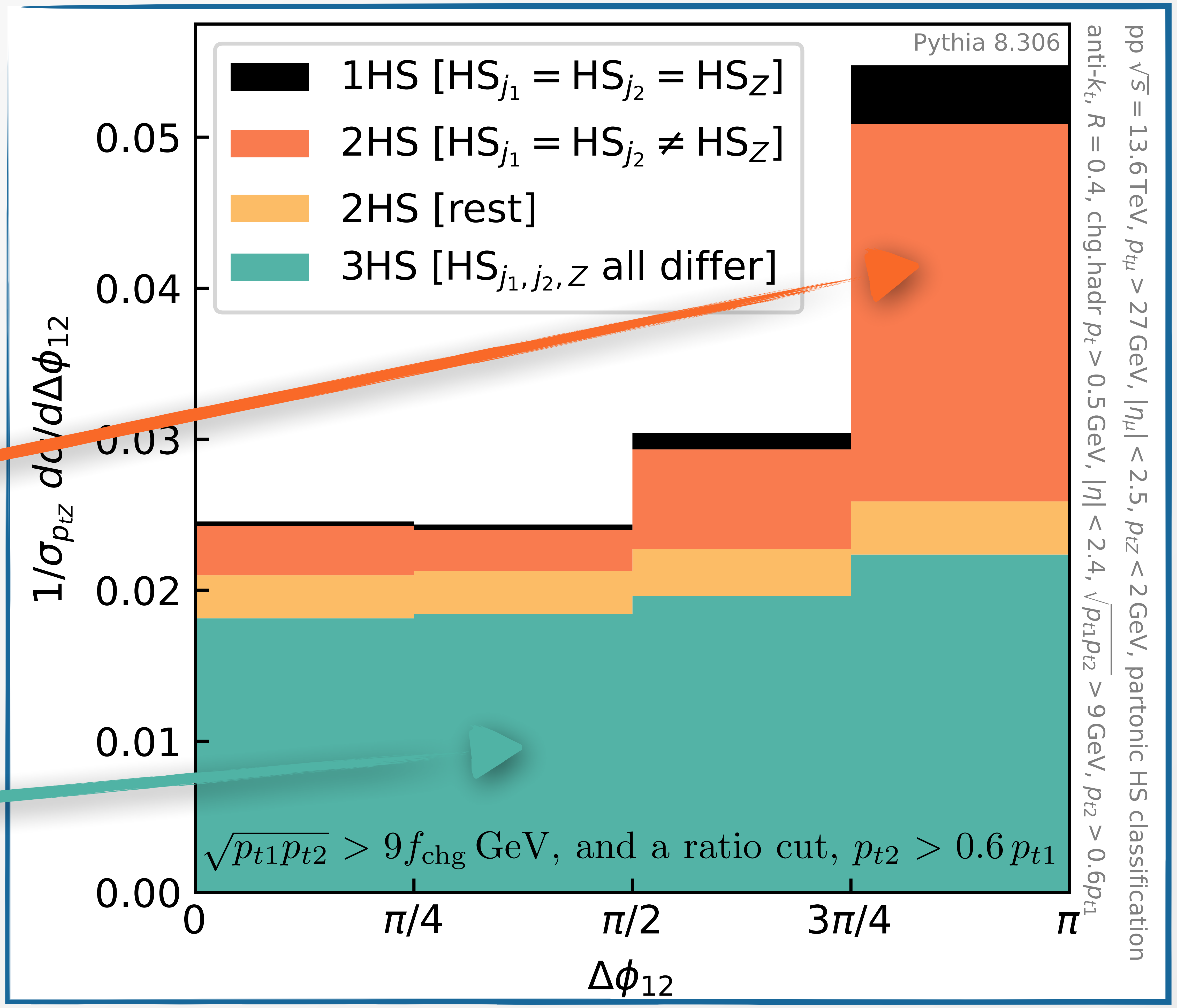
significance of signal
of perturbative interconnection



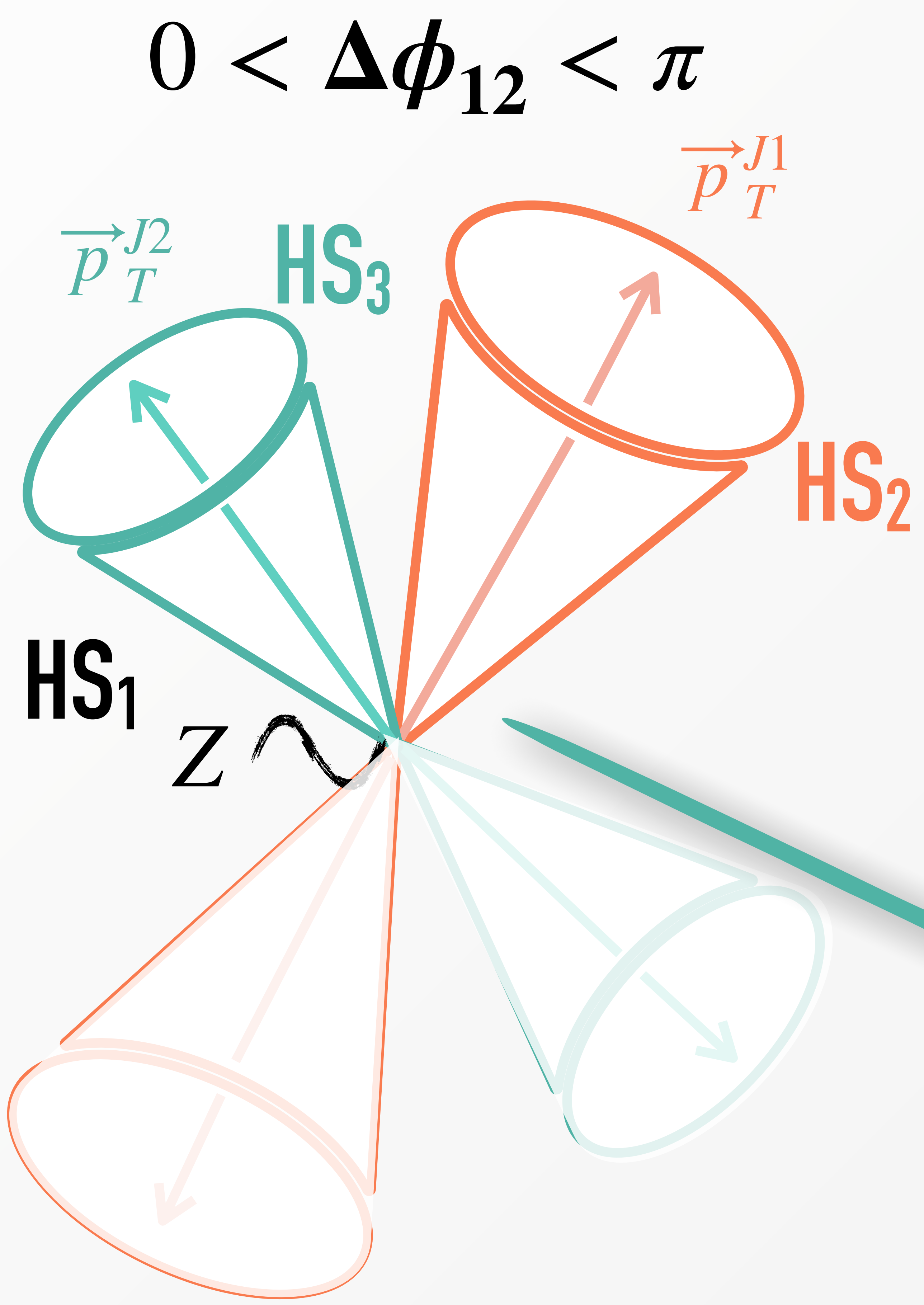
Beyond 2HS

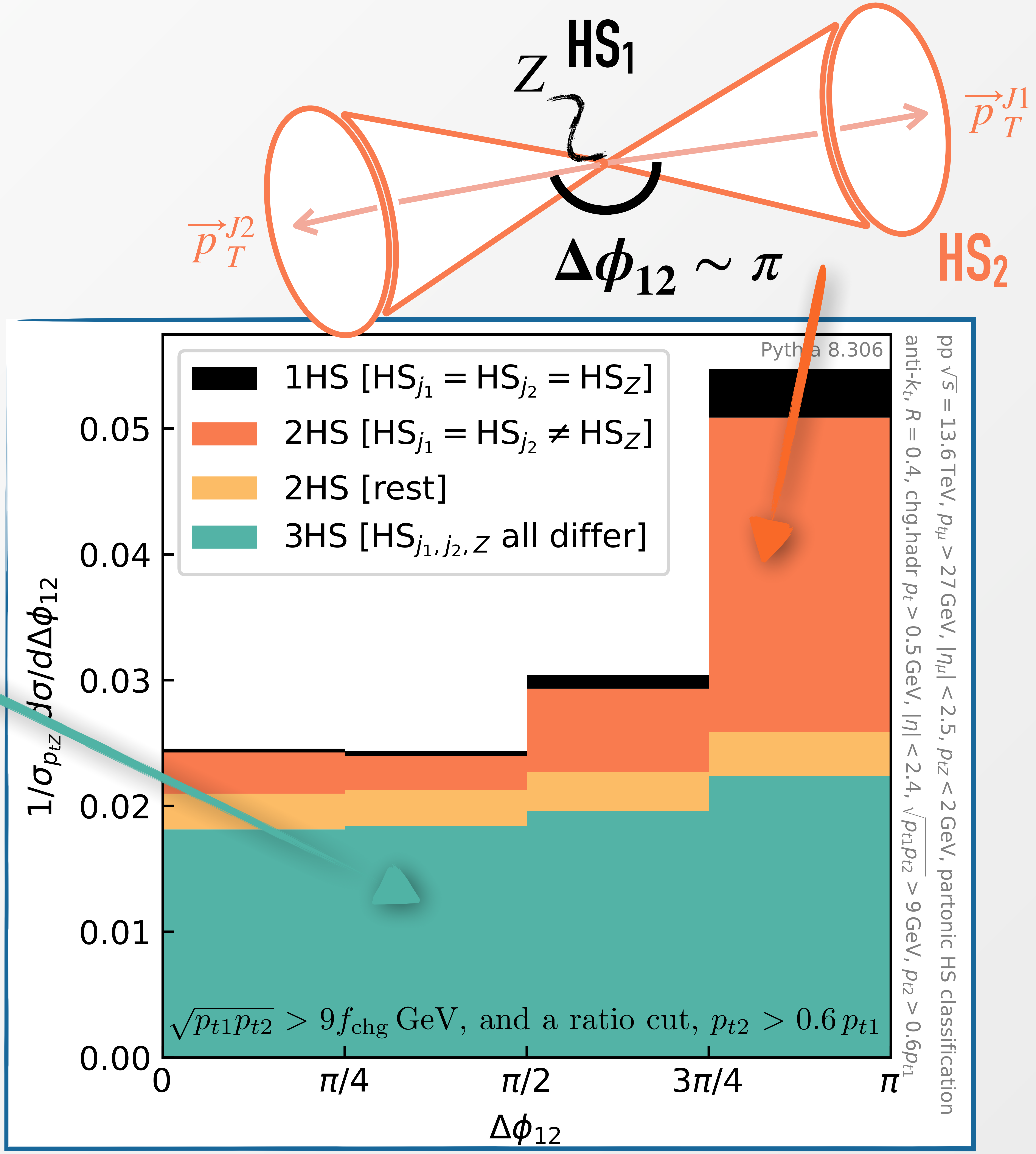
- Only measurements of 3HS are in J/ψ production, which is a difficult process to interpret even with just 1HS! →**Huasheng Shao's talk**
- Instead, put tight $p_{tZ} < 2\,\mathrm{GeV}$ cut and look at $\Delta\phi$ between two leading charged-track jets, with low p_{tj} cuts (~ 5 GeV on charged-track sum)
- gives clear **2HS** peak at $|\Delta\phi| \simeq \pi$
- gives distribution ~independent of $|\Delta\phi|$, when the Z and the 2 jets each come from different hard scatters **(total of 3HS)**





Beyond 2HS





More challenging: repeating analysis examining $|\Delta\phi_{34}|$ to access **4HS contribution**

Conclusion

Study of Drell-Yan events with tight cut on p_{tZ} opens door to numerous new MPI studies:

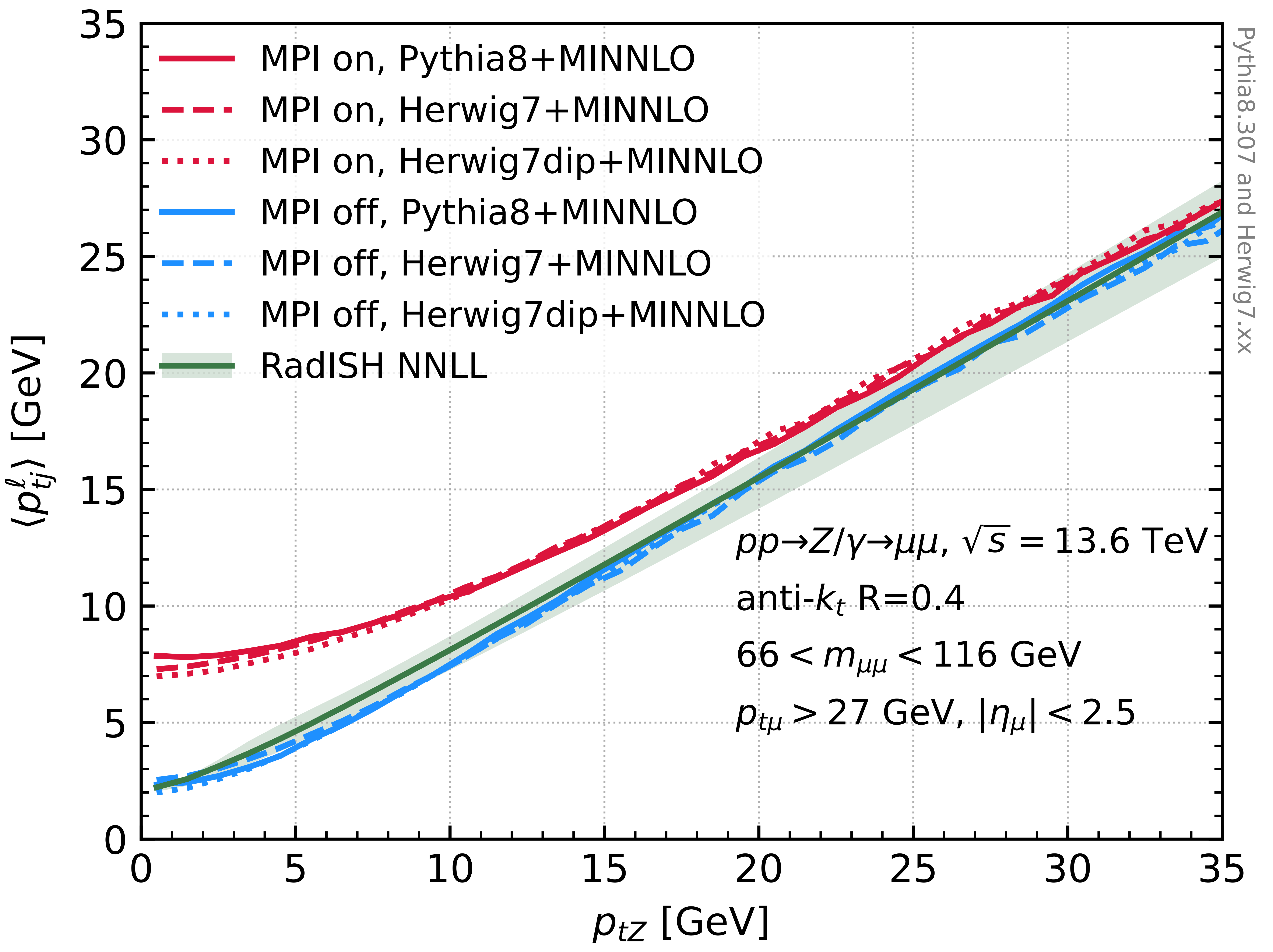
- high-purity 2HS samples
- QFT effects that interconnect primary and secondary hard scatters
- easy 3HS studies (maybe even 4HS, more challenging)
- perhaps still more (flavour, $\gamma\gamma \to \ell^+\ell^-$ off Z-peak, *p*Pb collisions…)?

Overall

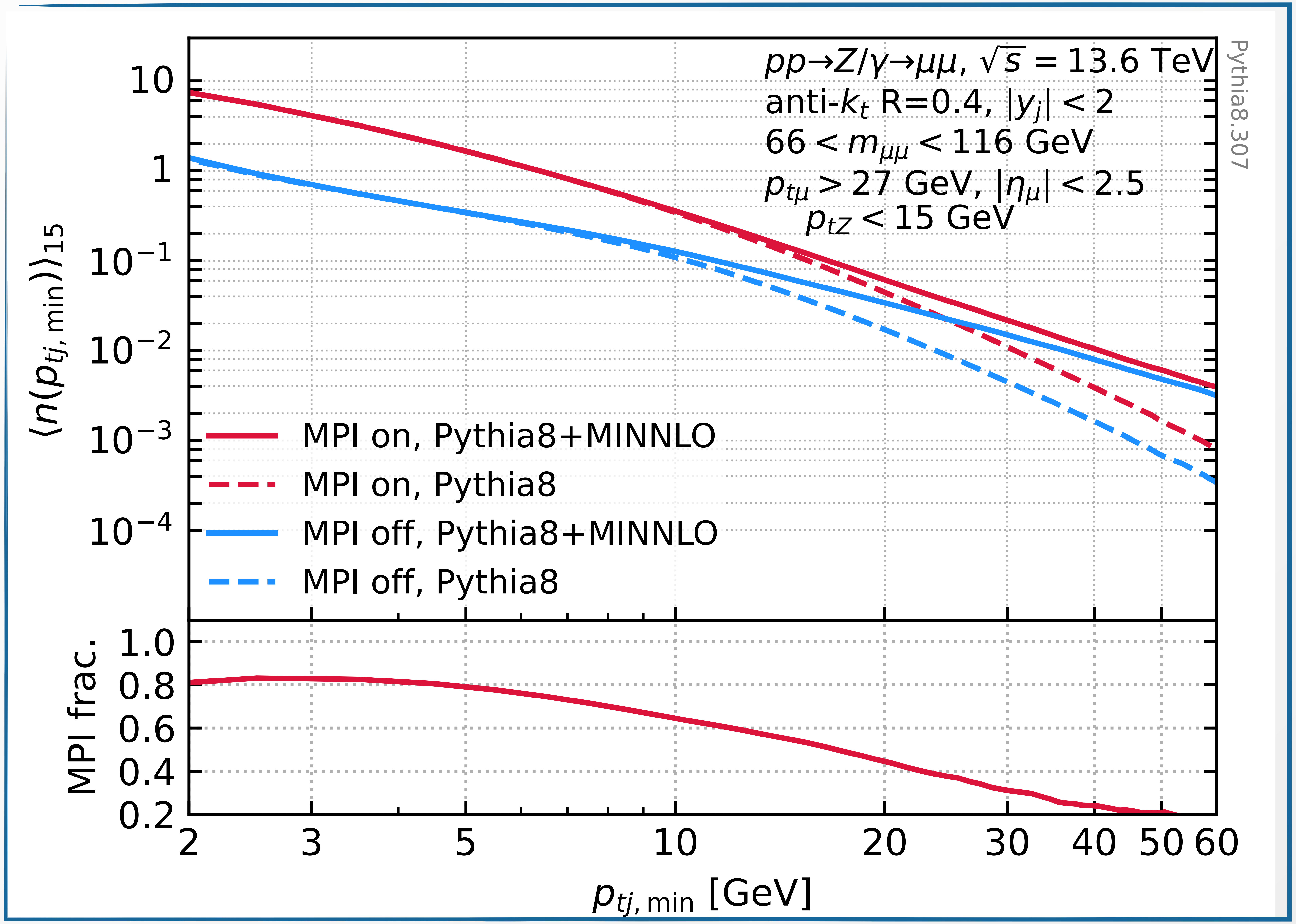
potential for significant impact on conceptual and quantitative understanding of MPI

Backup

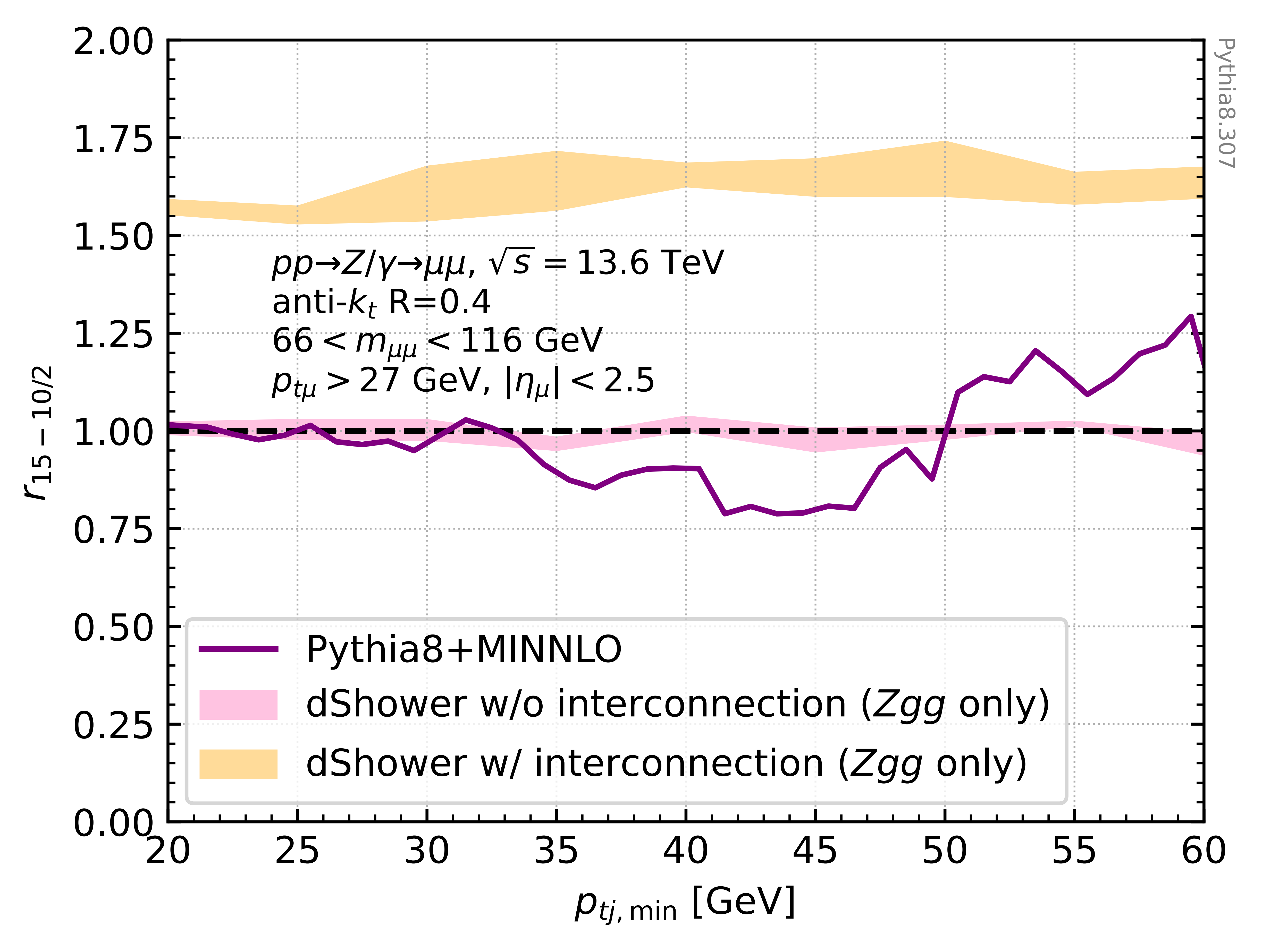
HERWIG results

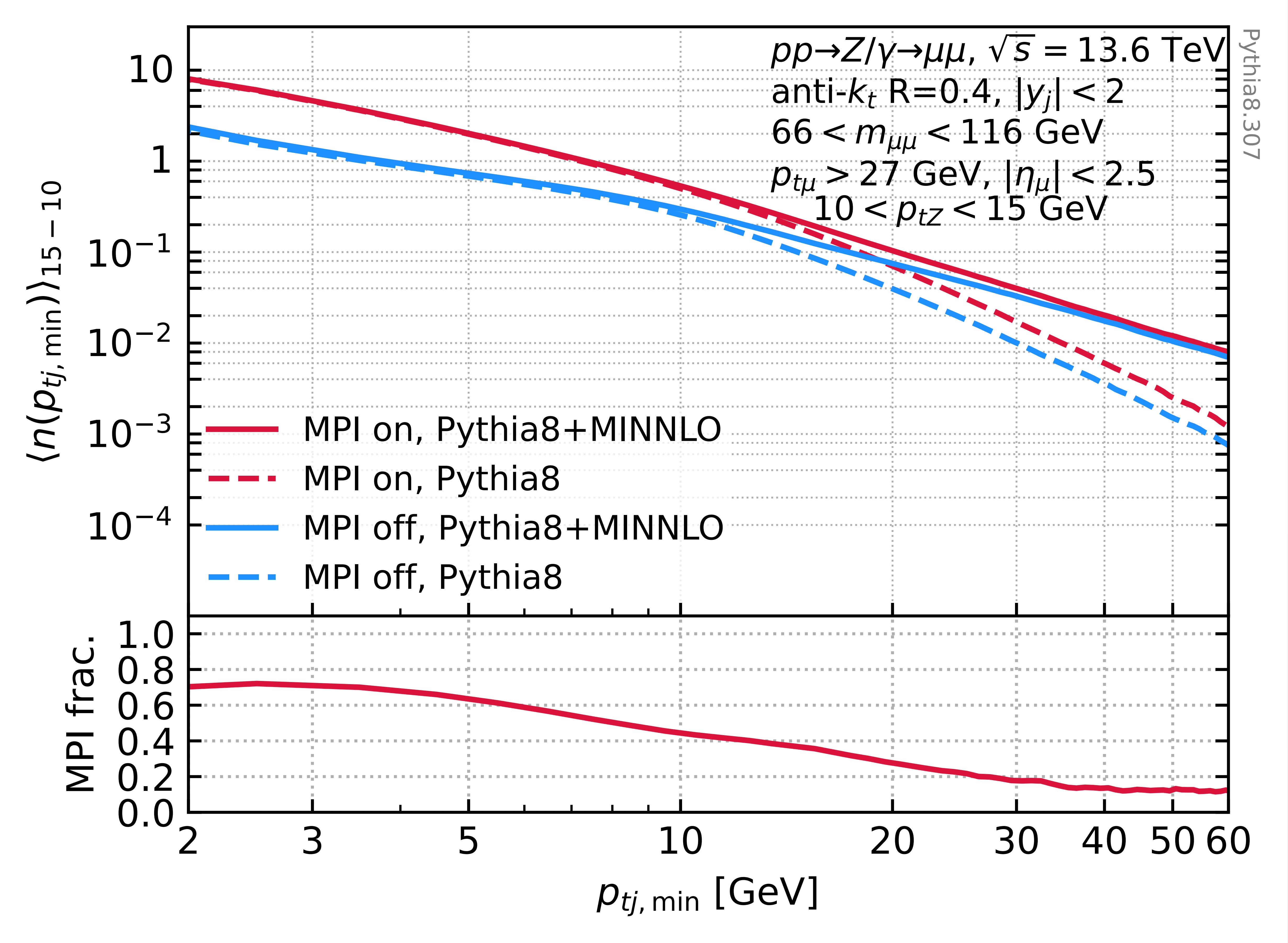


MPI purity with 15 GeV cut on p_{tZ}

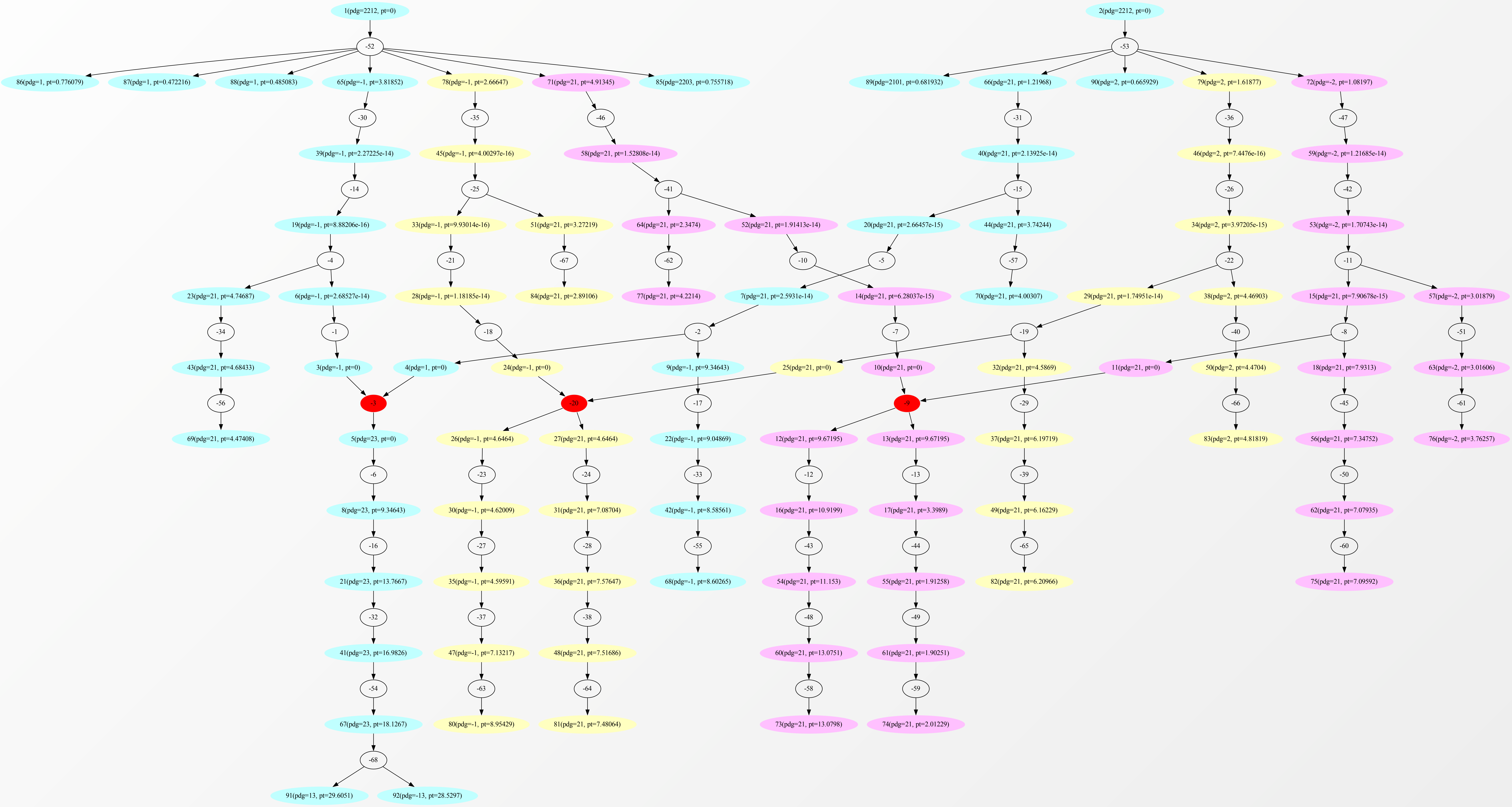


10 < p_{tZ} < 15 GeV for the loose sample: increases interconnection, reduces purity

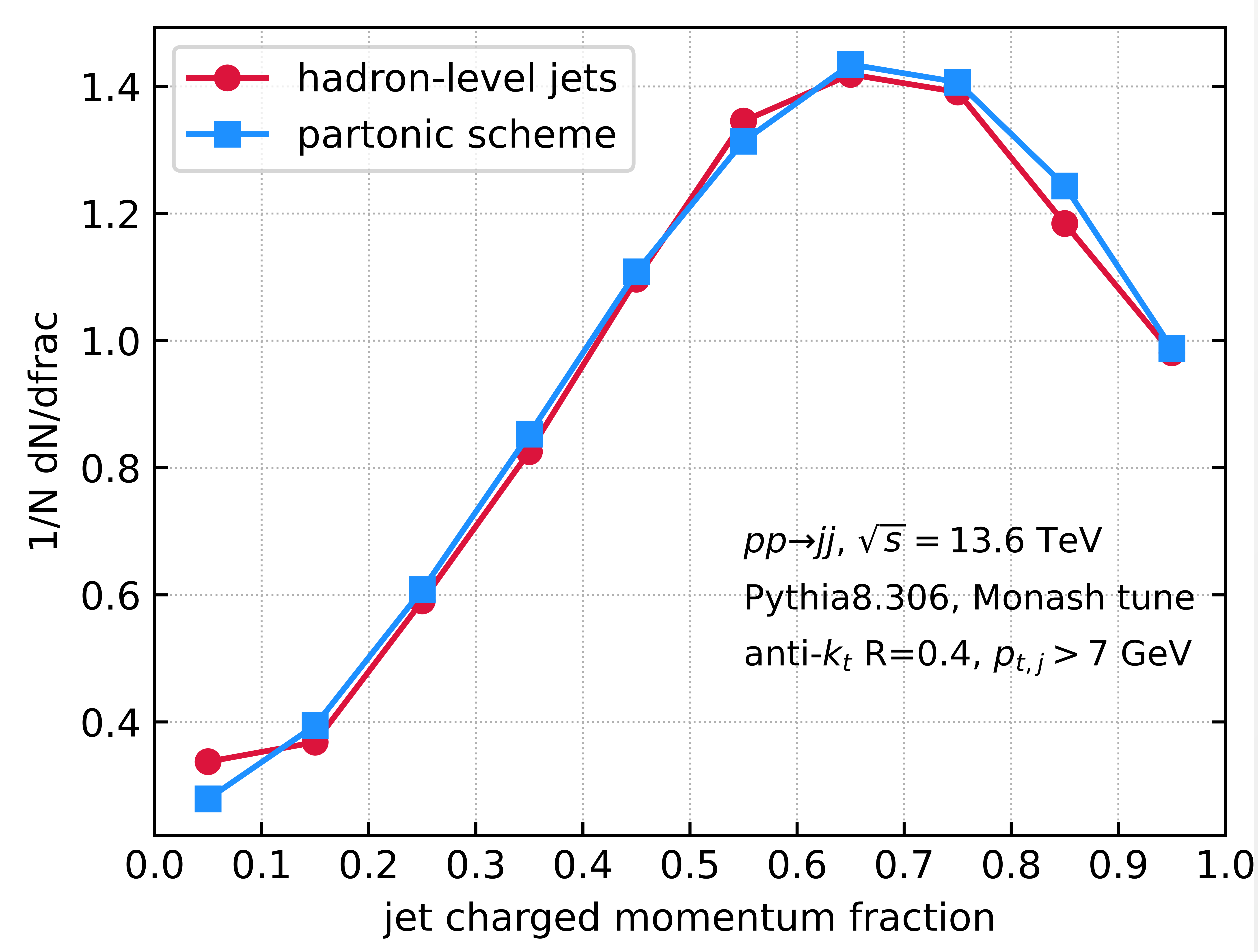




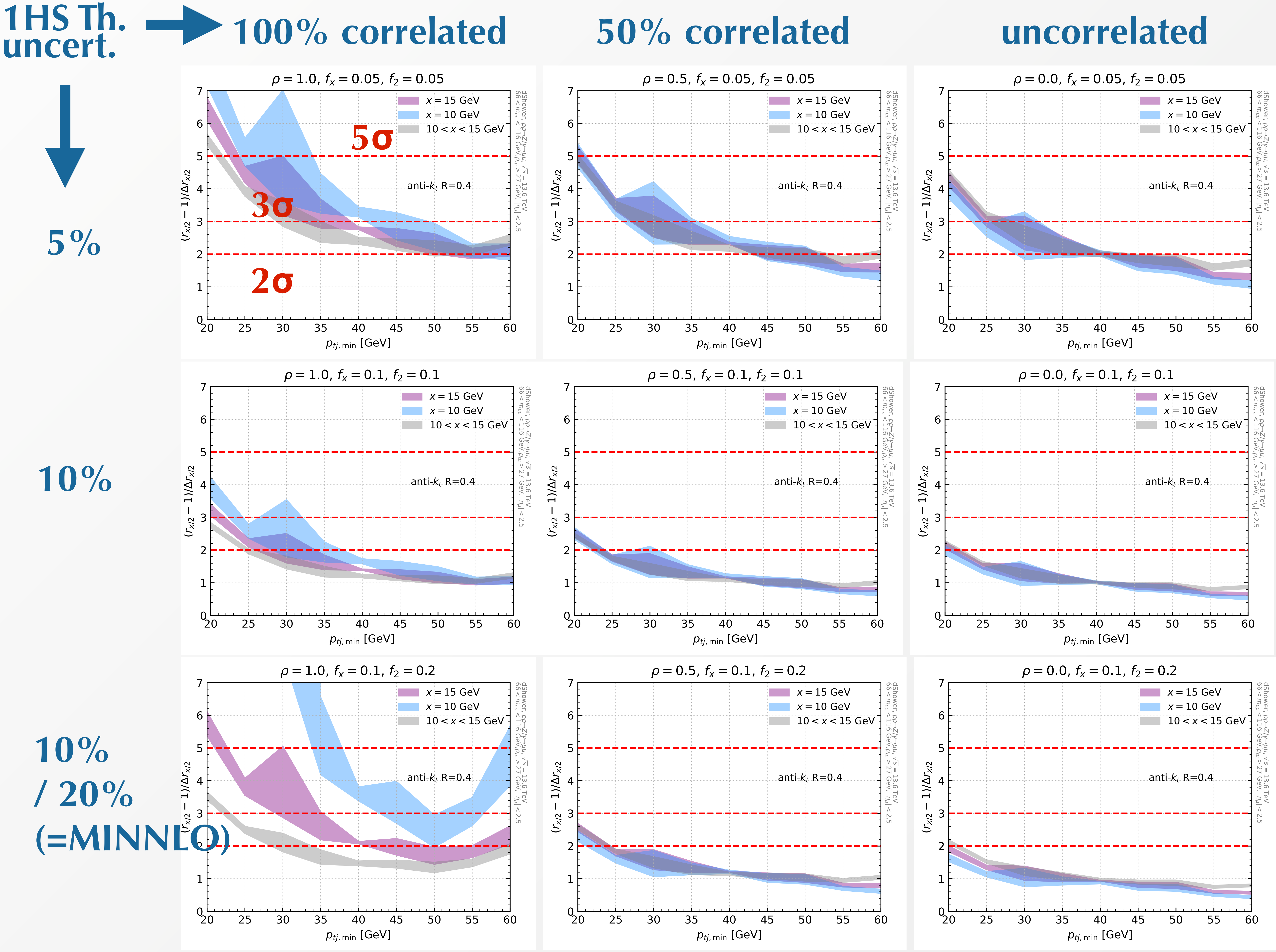
Extracting partonic hard-scattering classification from Pythia (via HepMC)



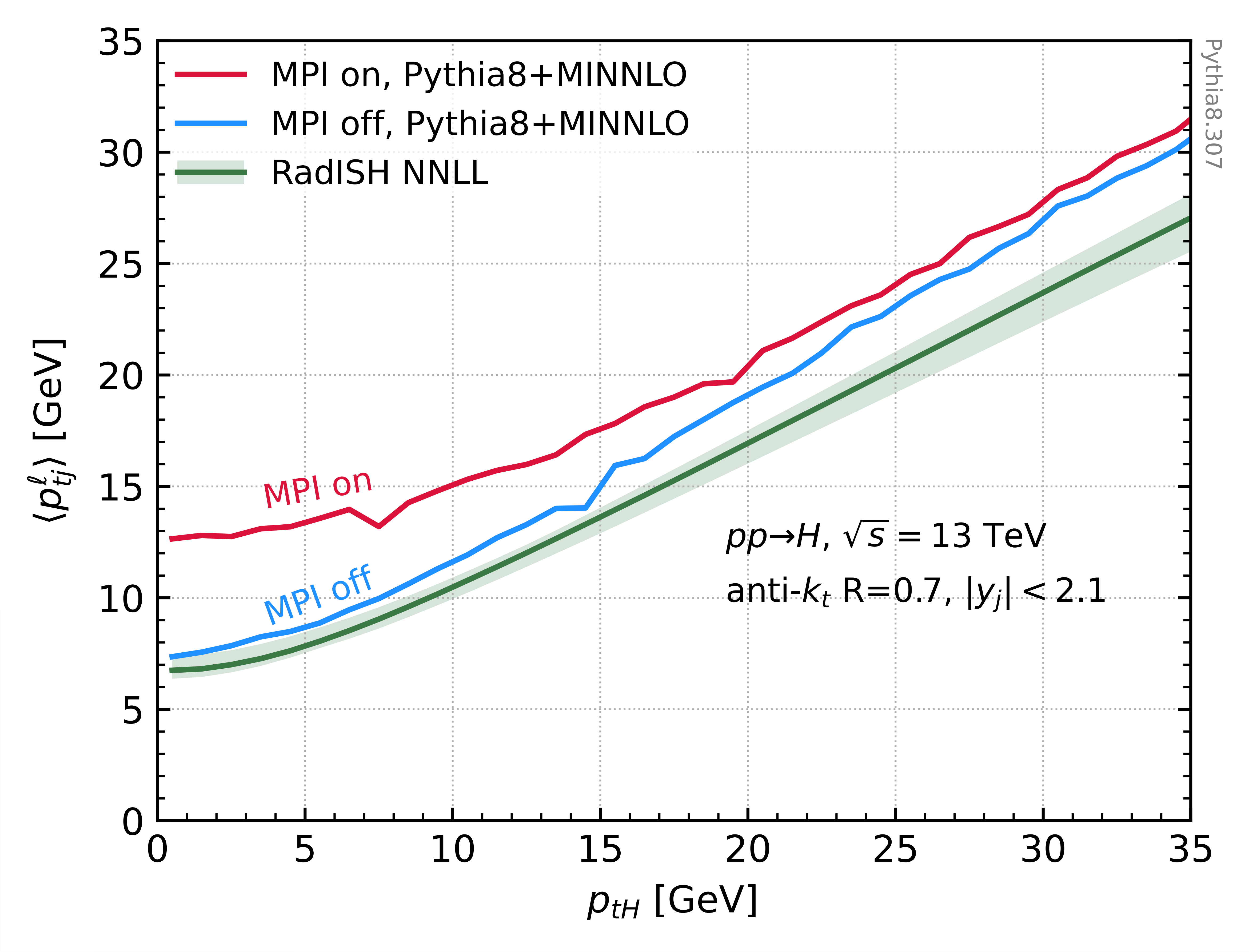
Validation of simple parton → charged hadron conversion for hard-scatter classification

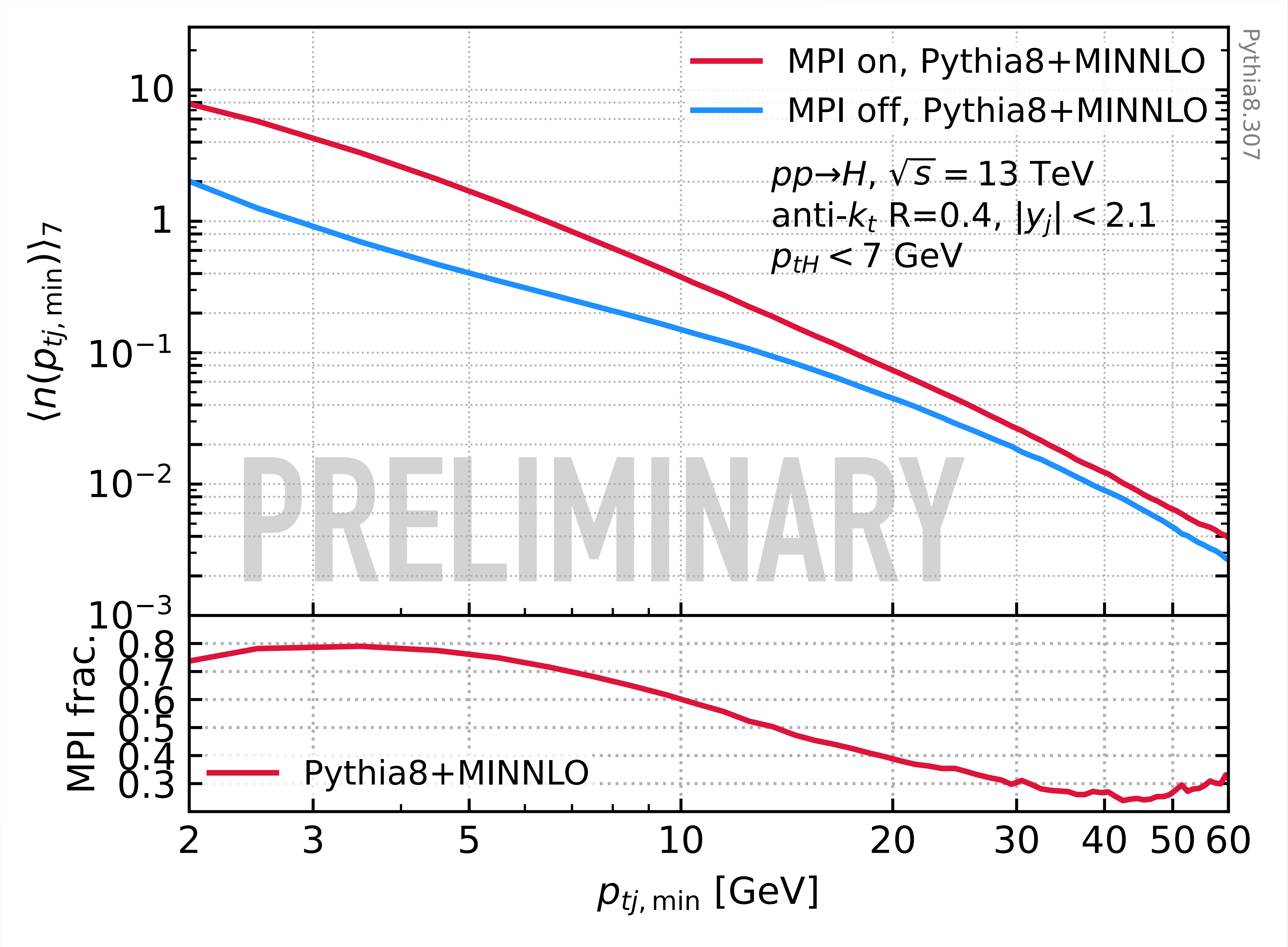


Interplay of significance with MPI purity in different scenarios



Higgs production (gg channel said to have smaller σeff, mainly from J/ψ)





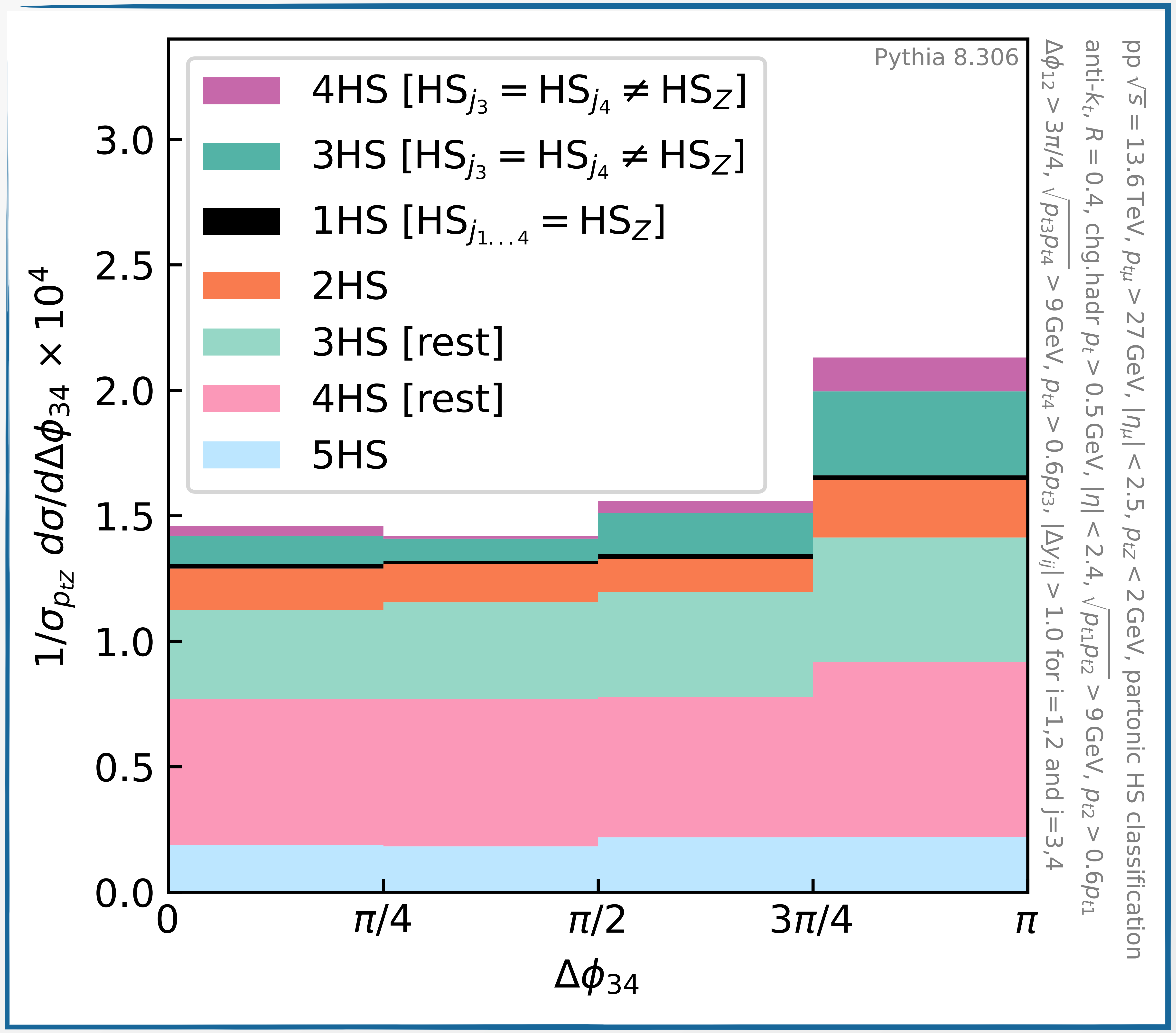
Optimal cut is $p_{t\mathrm{H}} \lesssim 7$ [GeV]

~10% of events H events pass this cut

(with $p_{t\mathrm{H}}$ cut, full run 2+3 stats in H→ZZ*→4ℓ c. 50–100 events)

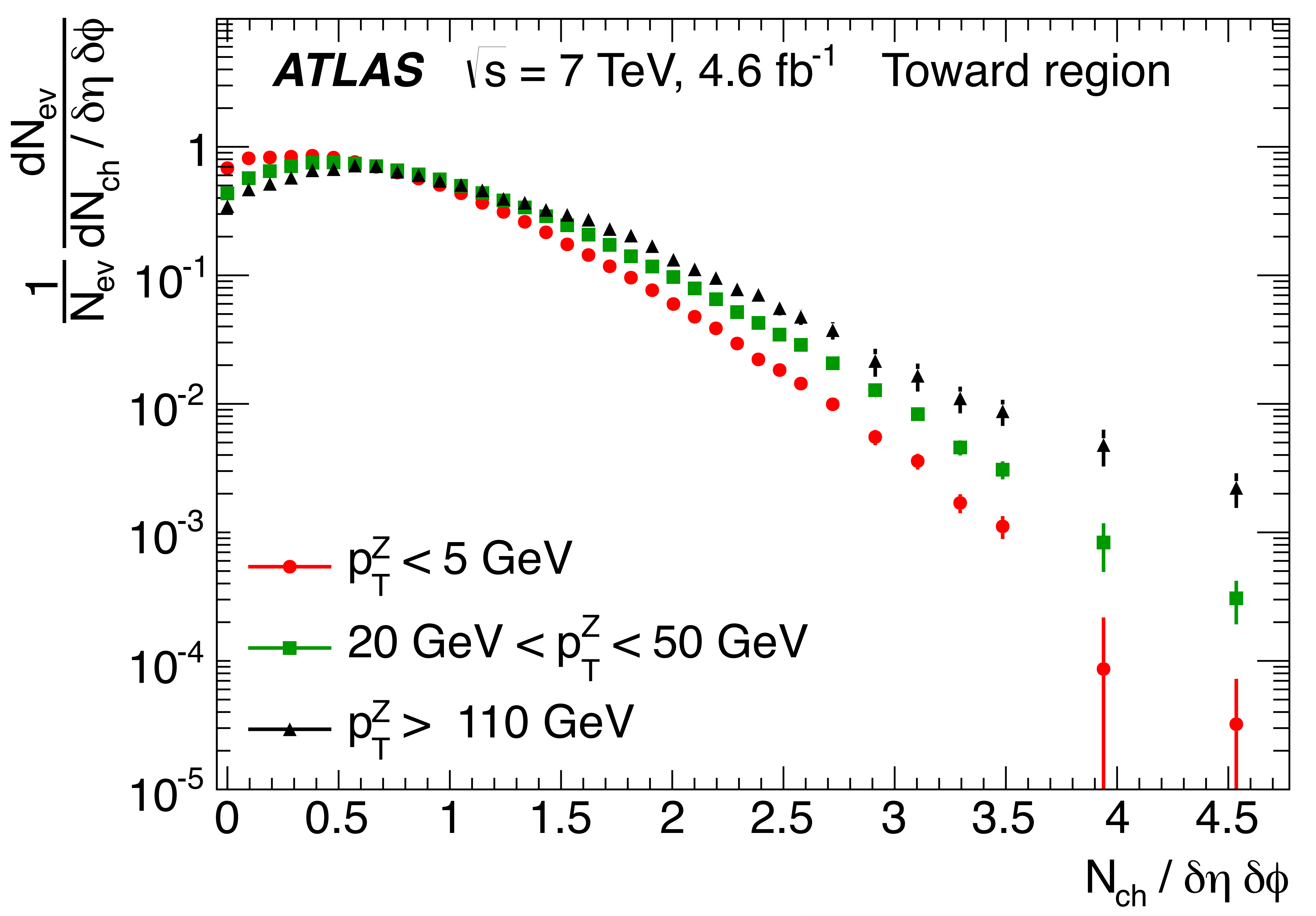
Beyond 3HS?

- Select four leading jets
- Pair them up (first two, next two)
- Require first two to be back-to-back
- Require $|\Delta y| > 1$ rapidity separations between first two and next two
- examine $|\Delta\phi_{34}|$
- see small peak around $|\Delta\phi_{34}| = \pi$ (3HS)
- **continuum includes substantial 4HS contribution!**



ATLAS 1409.3433

- mostly a UE study
- uses $p_T^Z < 5\,\mathrm{GeV}$



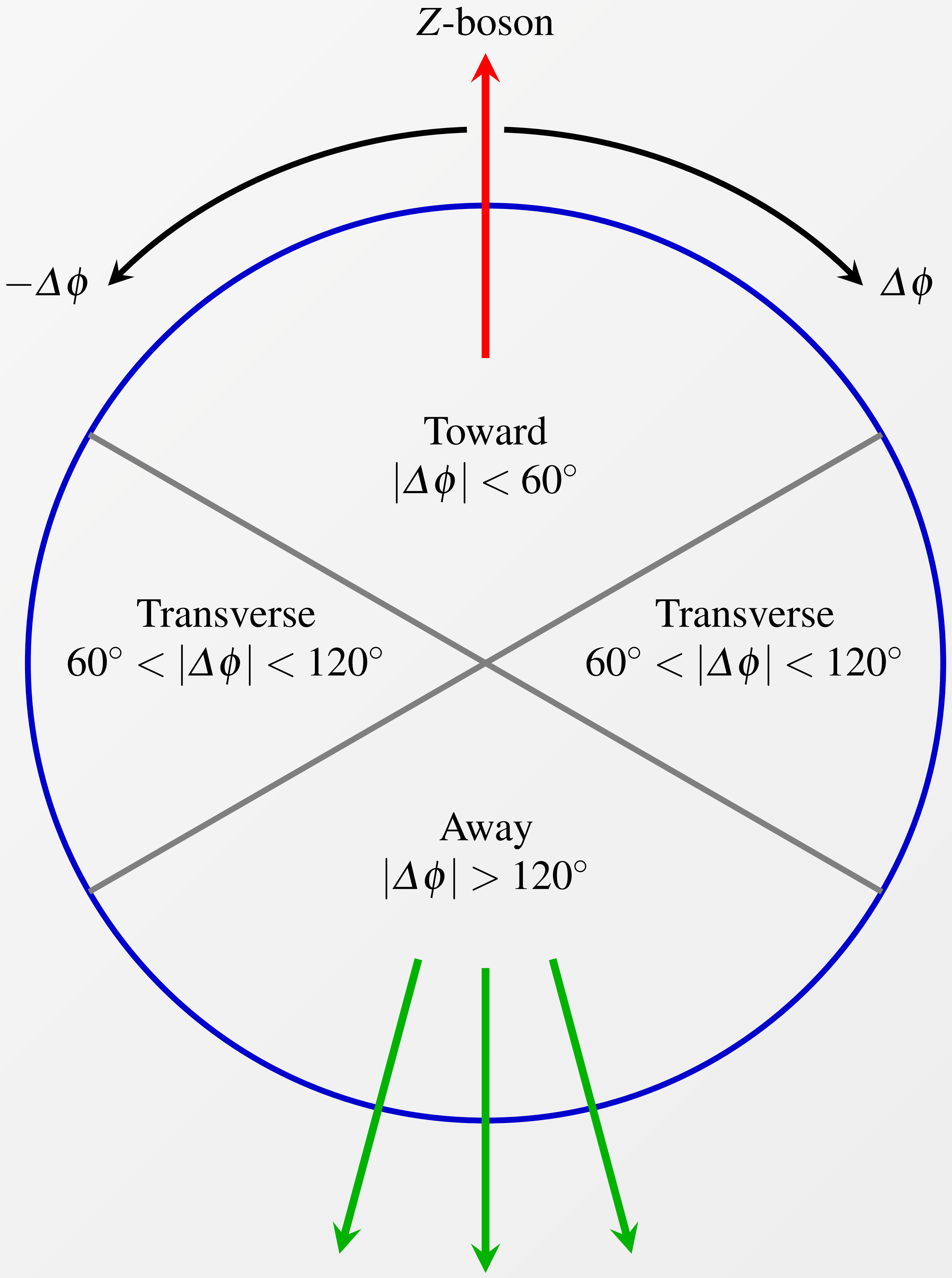


Fig. 1 Definition of UE regions as a function of the azimuthal angle with respect to the Z-boson.

CMS 1711.04299

- mostly a UE study
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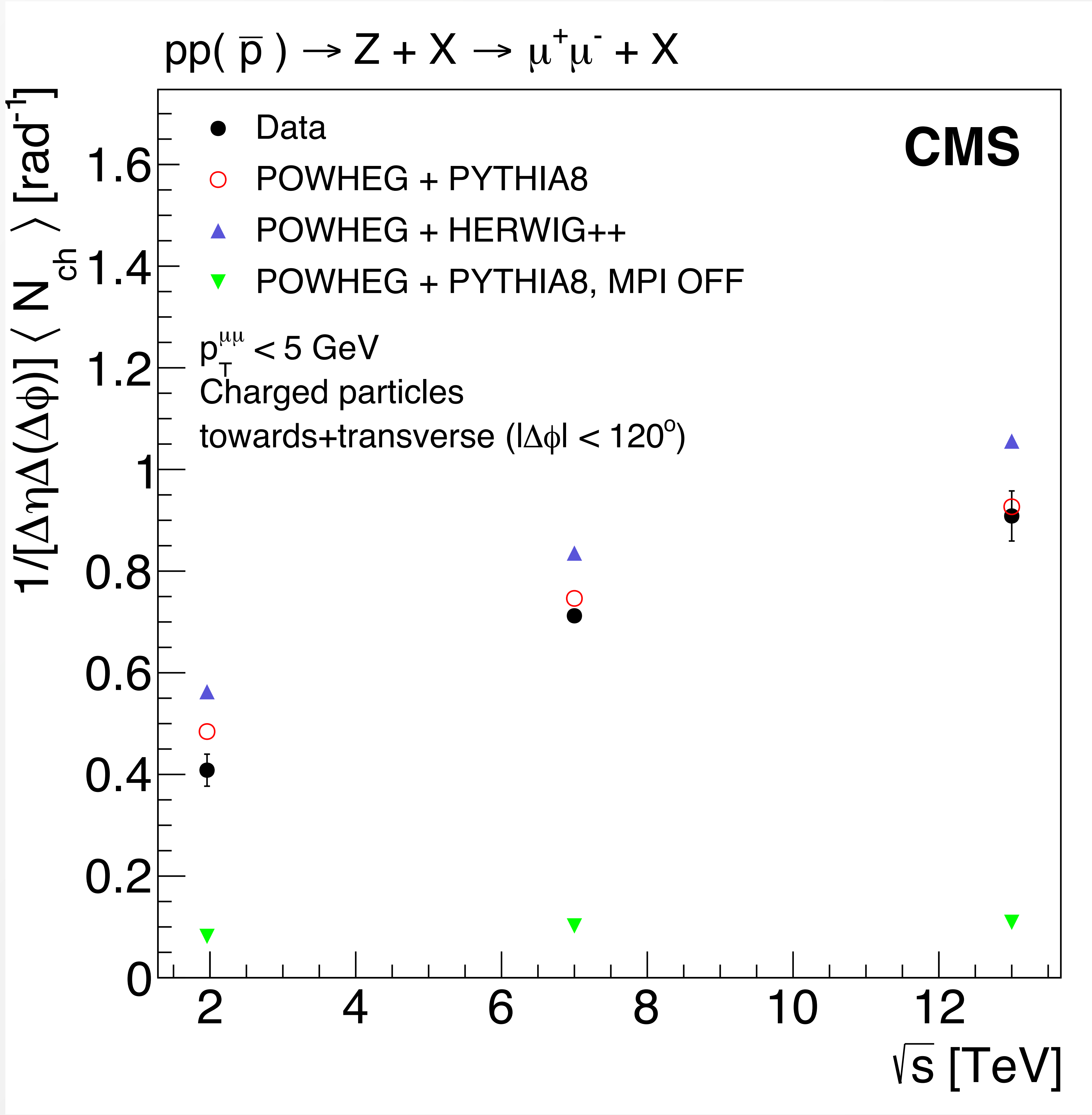
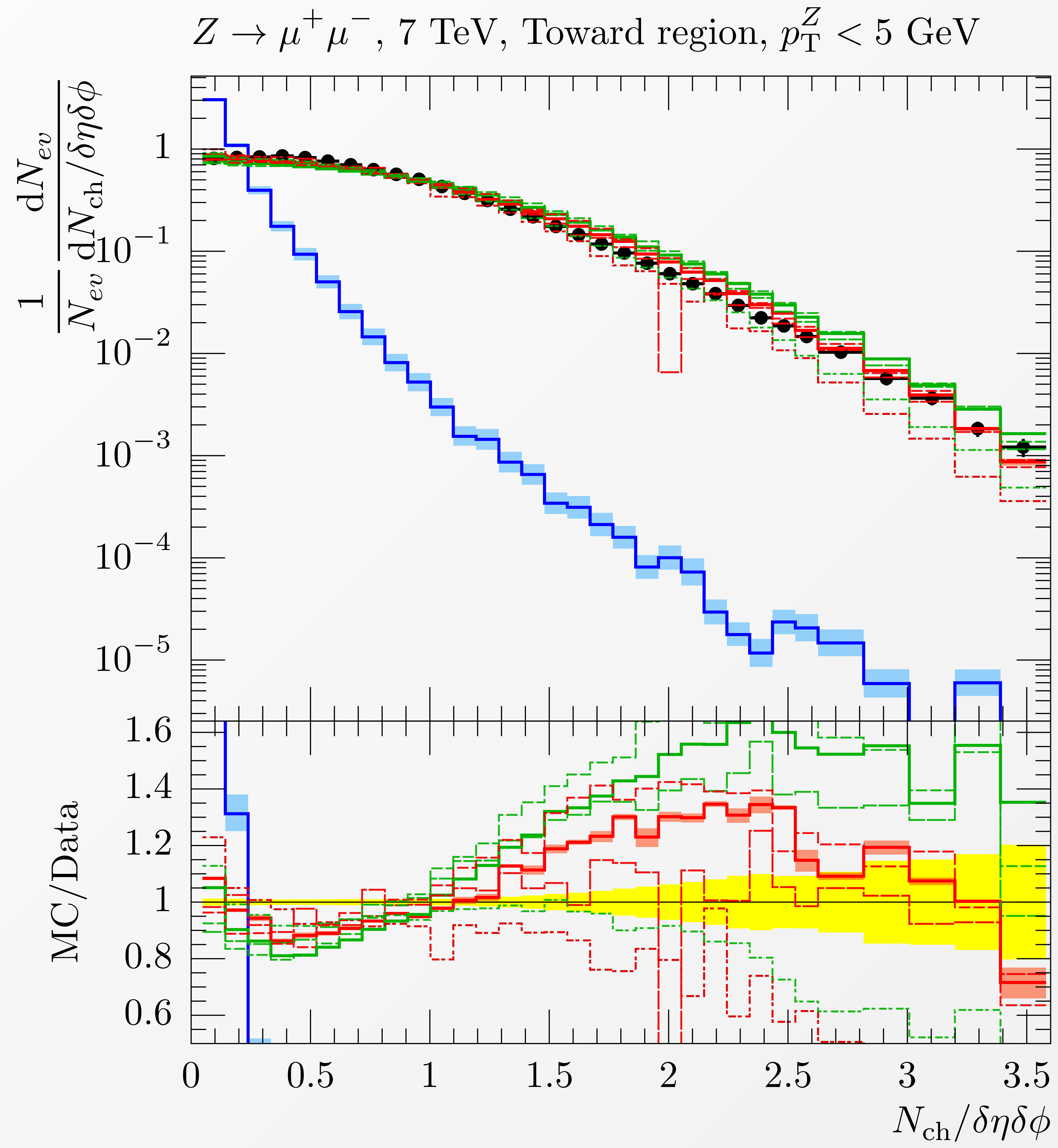
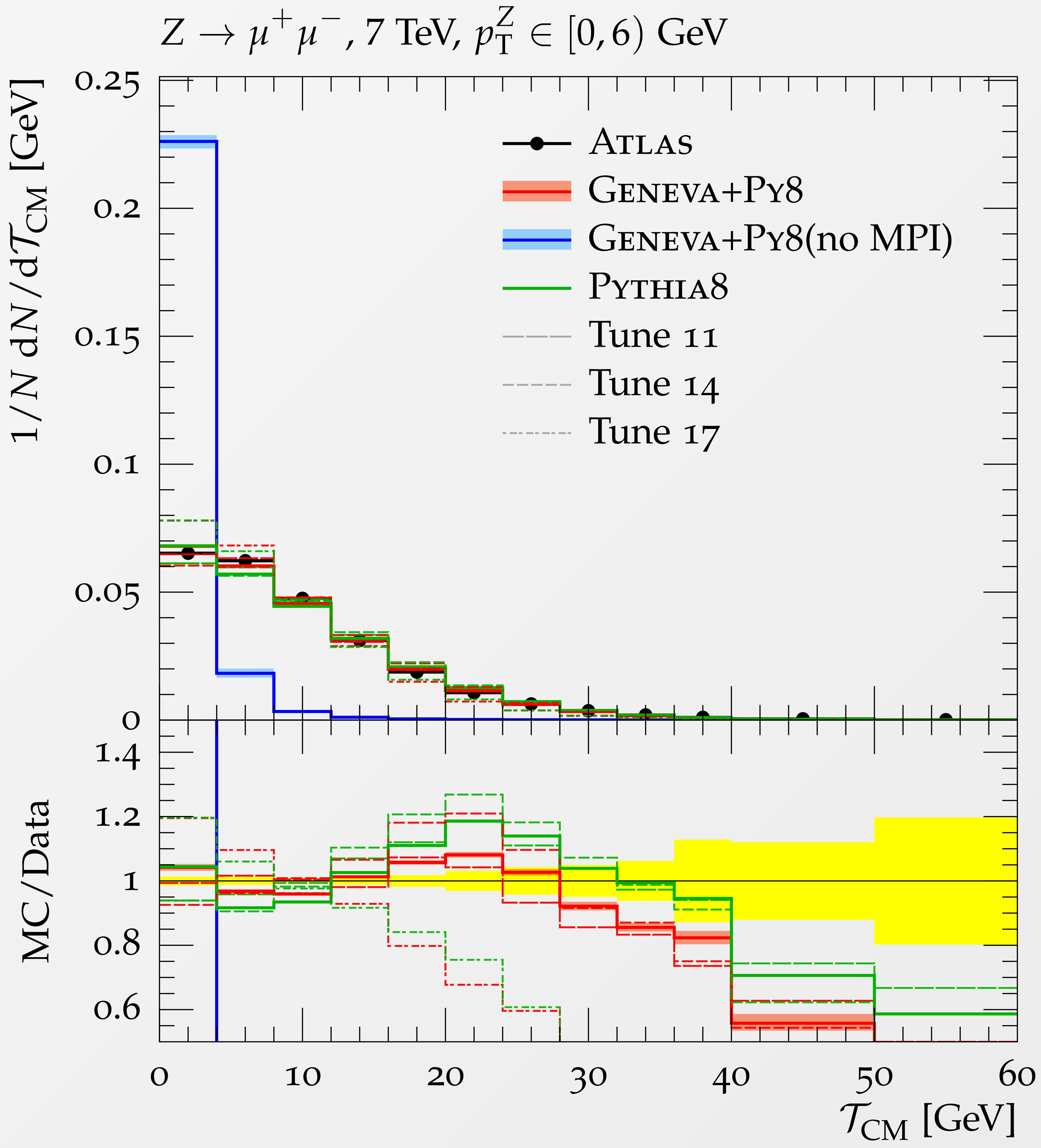


Alioli, Bauer, Guns, Tackmann, 1605.07192

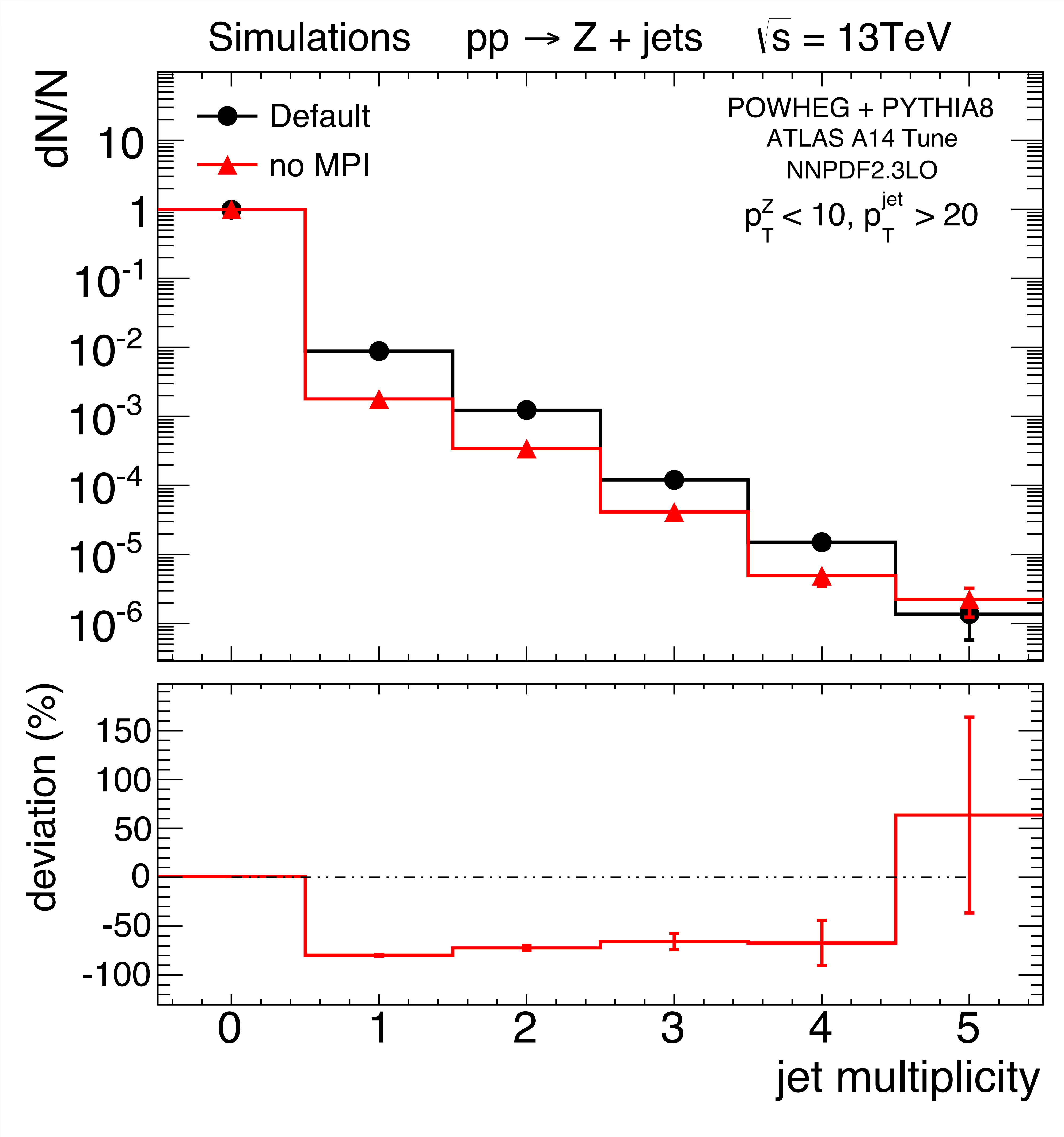
- explores $p_T^Z < 5\,\text{GeV}$
- mainly a "UE" study





Bansal, Bansal, Kumar, Singh 1602.05392

- explores $p_T^Z < 10\,\mathrm{GeV}$ as central part of their study
- explores various jet cuts, including $p_T^{\mathrm{jet}} > 5\,\mathrm{GeV}$



CMS 2210.16139

- includes $p_T^Z < 10\,\text{GeV}$ bin, with 25-50% MPI contribution for jets with $p_T^J > 30\,\text{GeV}$
- includes $\Delta\phi_{j_1j_2}$, though high p_T^J cut means only 2HS