

# MPI at hadron colliders

**Luca Rottoli**



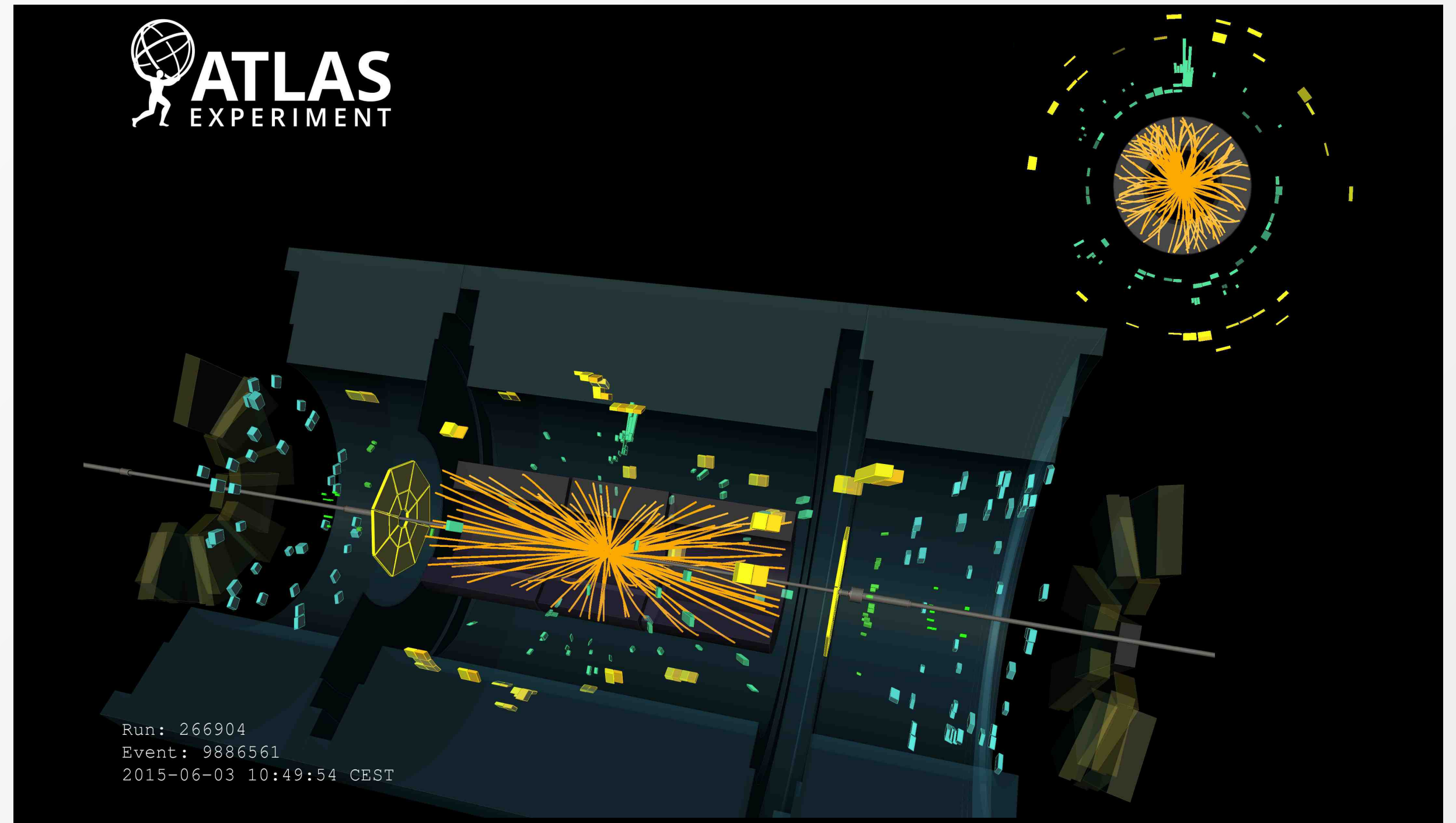
# Multi-parton interactions

Inelastic hadron-hadron collisions are dominated by **soft** (low- $p_T$ ) interactions, also known as **minimum bias (MB)**

Typically associated with the **inelastic non-diffractive component**  $\sigma_{nd}$  of the total cross section  $\sigma_{tot}$

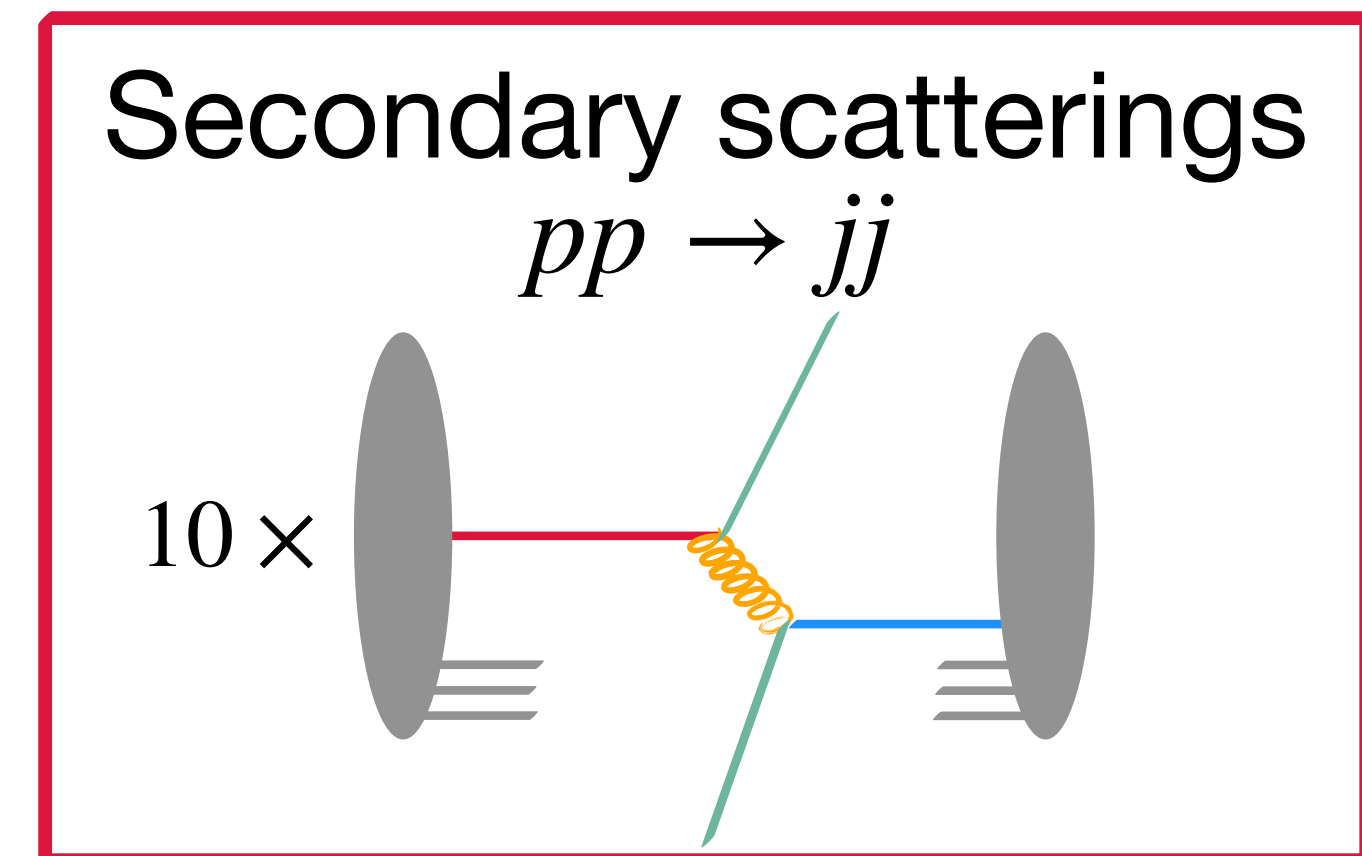
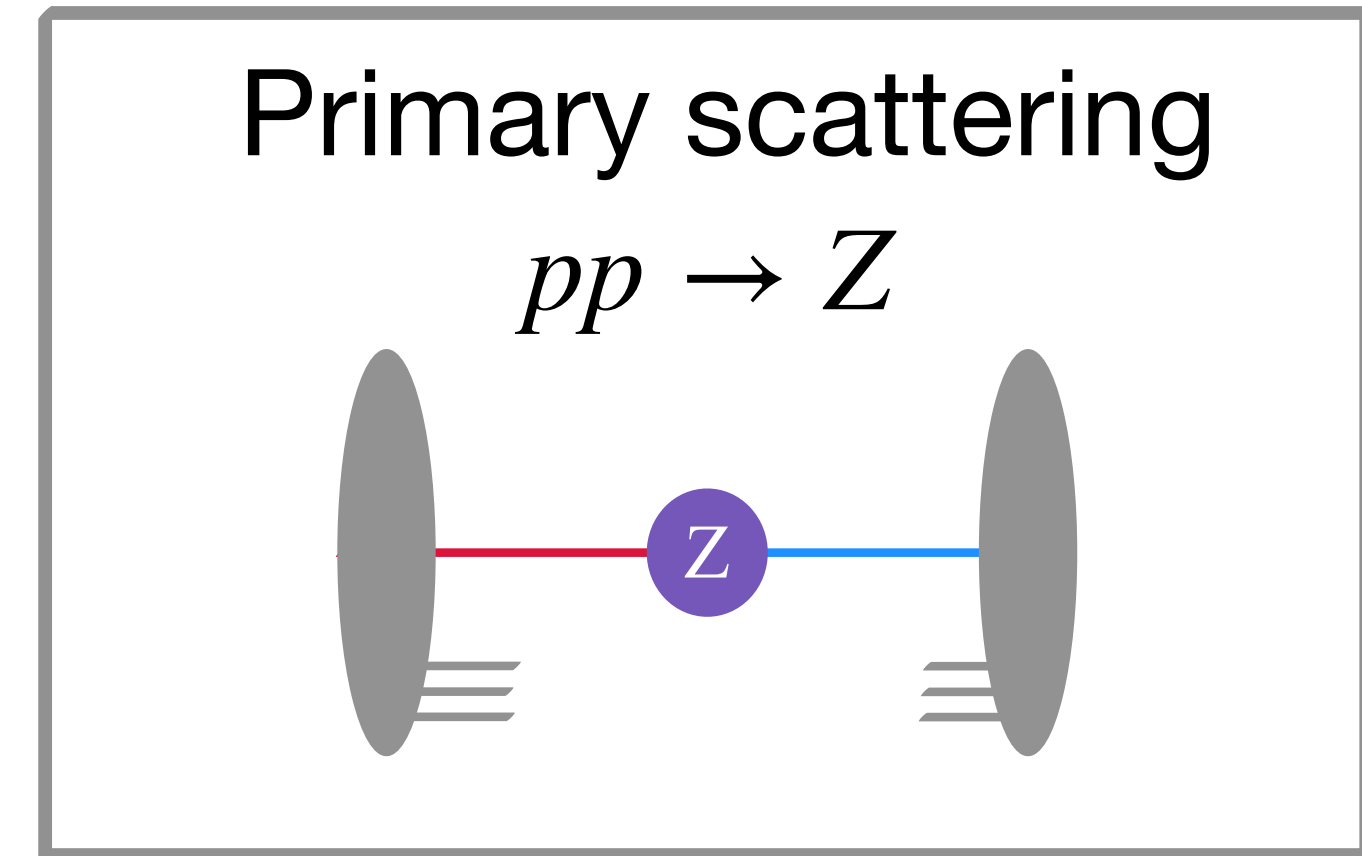
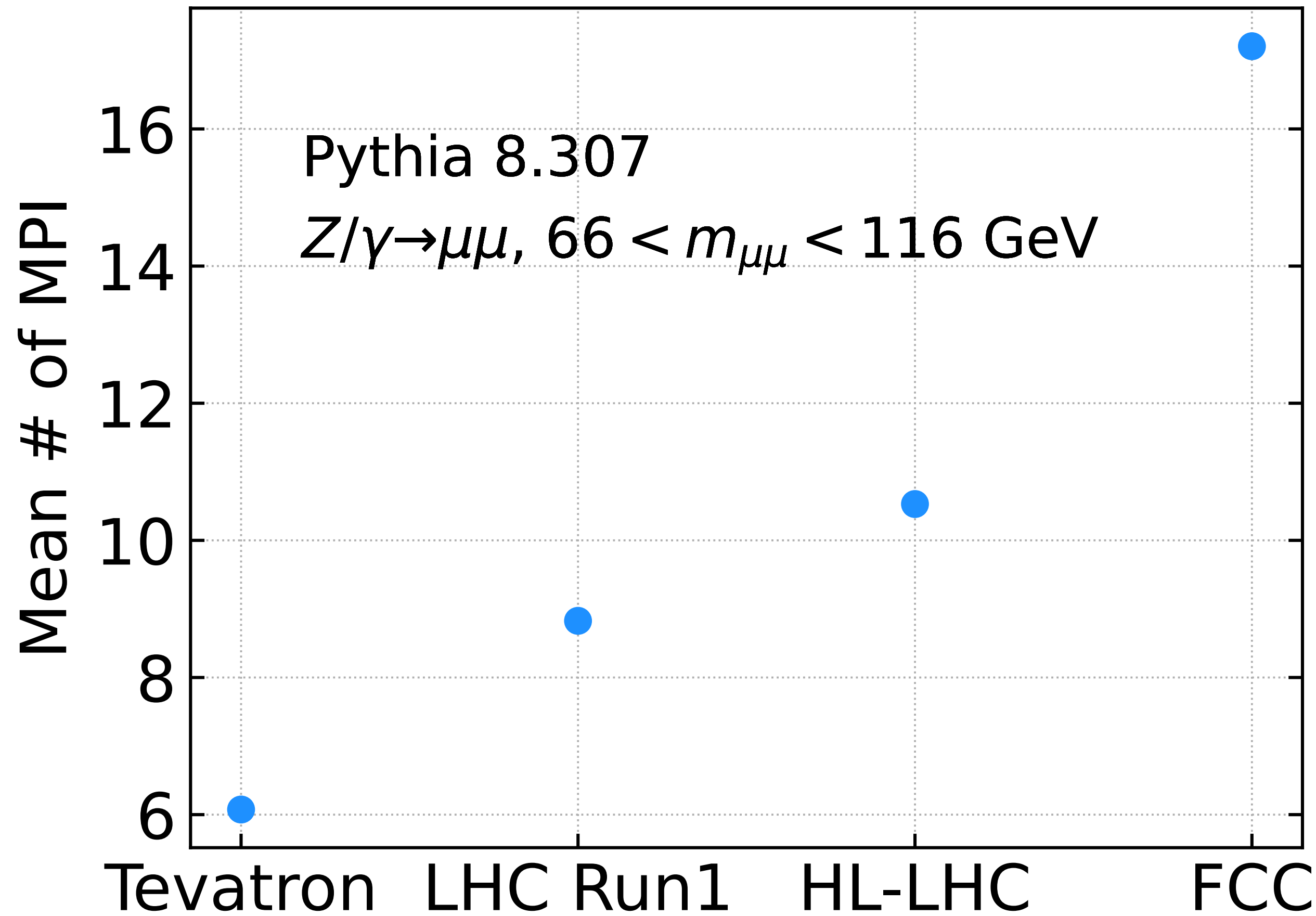
$$\sigma_{tot} = \sigma_{el} + \sigma_{sd} + \sigma_{dd} + \sigma_{nd}$$

Composite nature of hadrons implies that in such generic collisions **multi-parton interactions (MPI) are inevitable**



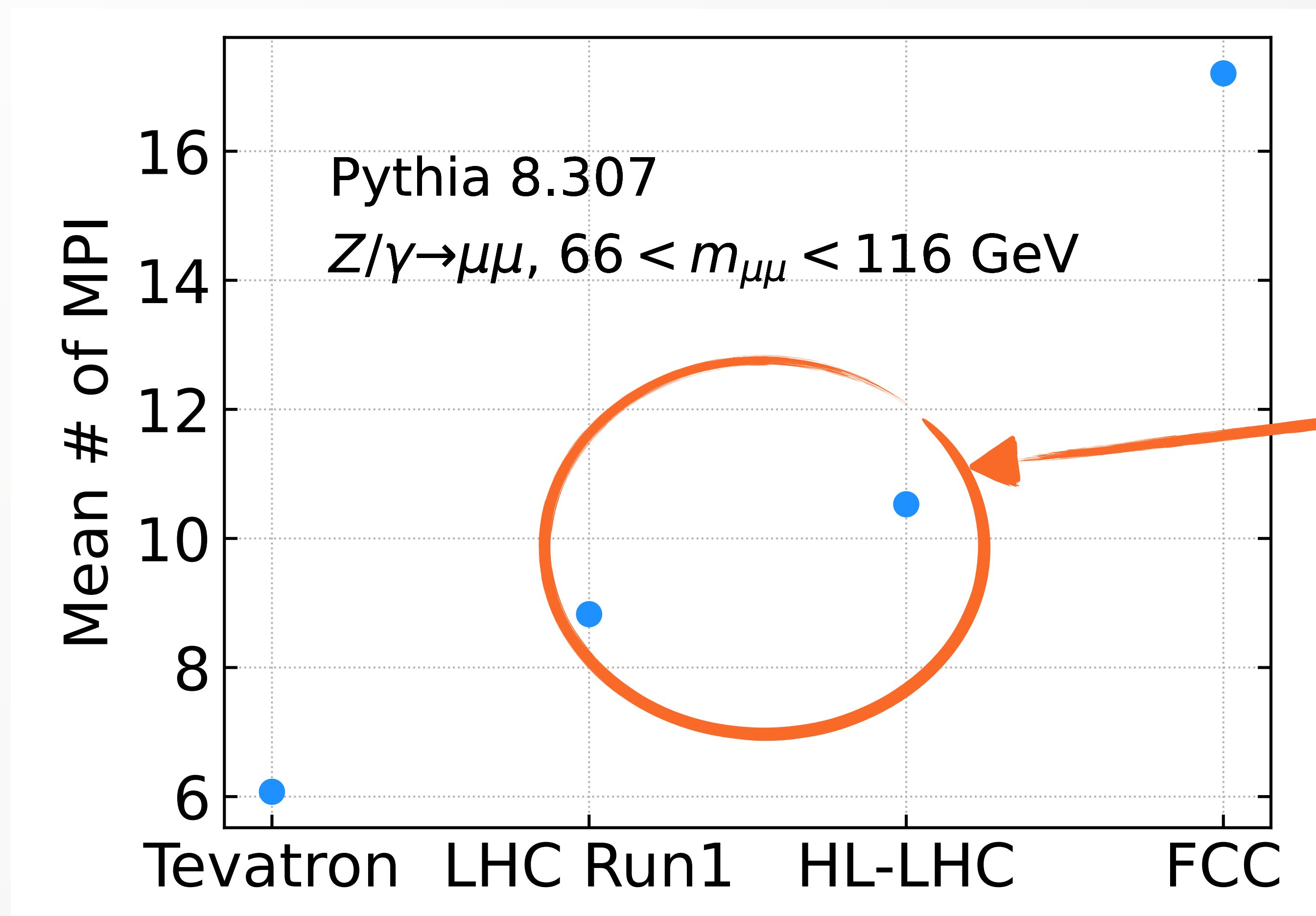
# Underlying event at hadron colliders

This **remains true also when selecting events where a hard collisions takes place**: these collisions at the LHC can be interpreted as a hard scattering between partons accompanied by an “**underlying event**” (UE) of additional soft interactions



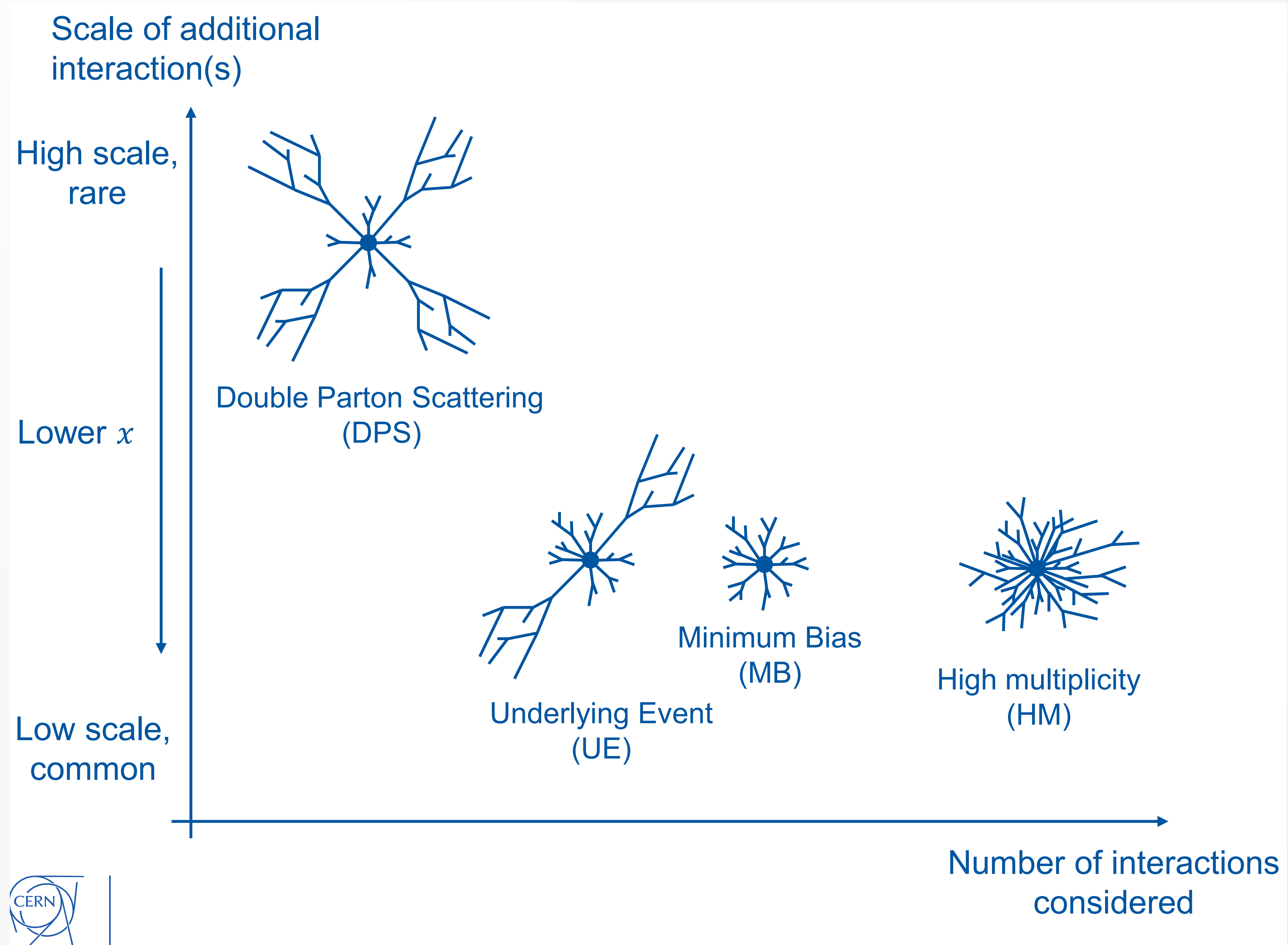
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$\mathcal{O}(10)$  additional parton-parton collisions per Drell-Yan event at the LHC

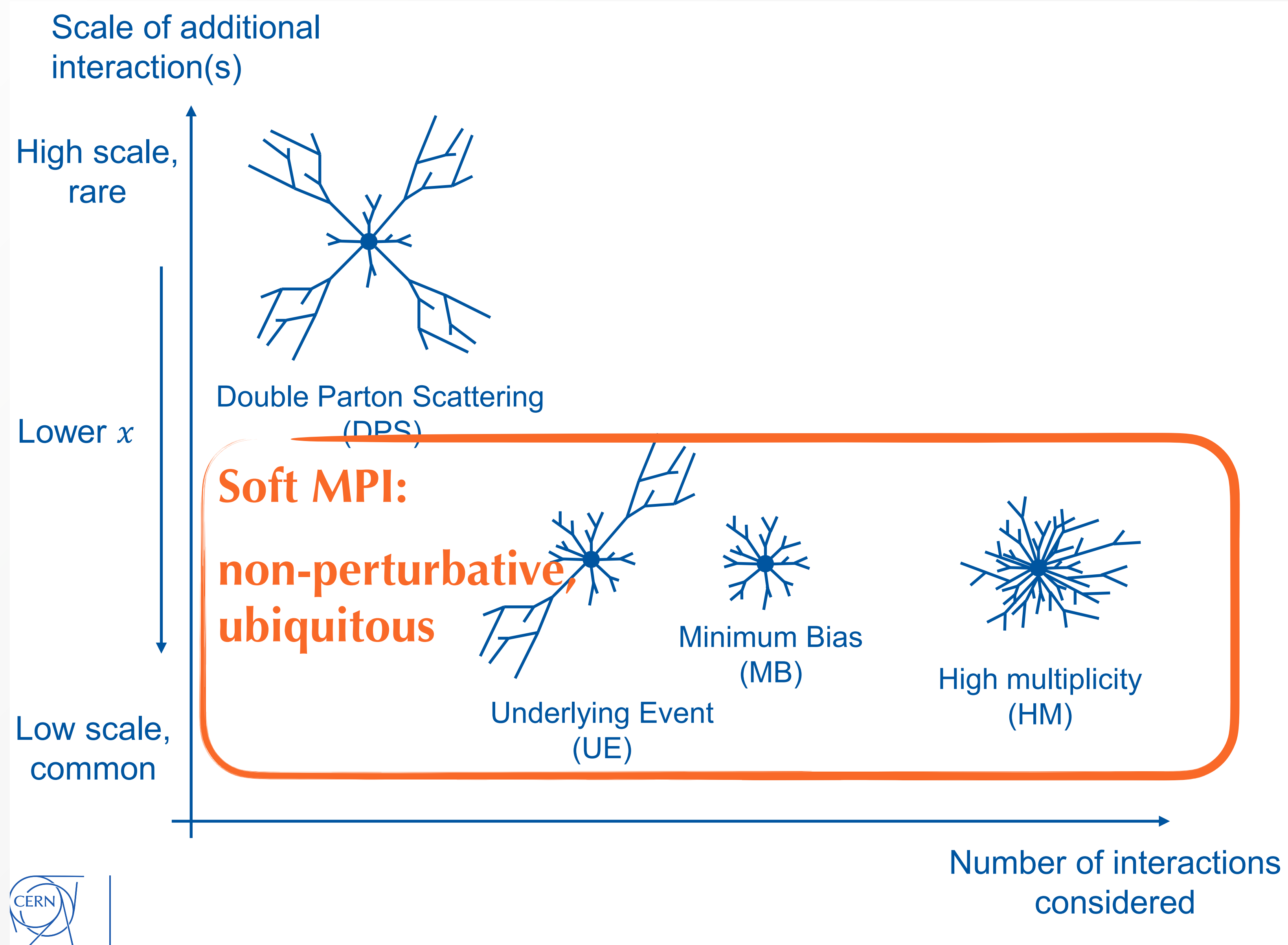
# MPI 'landscape'



Gaunt, Bartalini MPI@LHC 2018

Double Parton Scattering and the 3D structure of hadrons, Aussois, 14th January 2025

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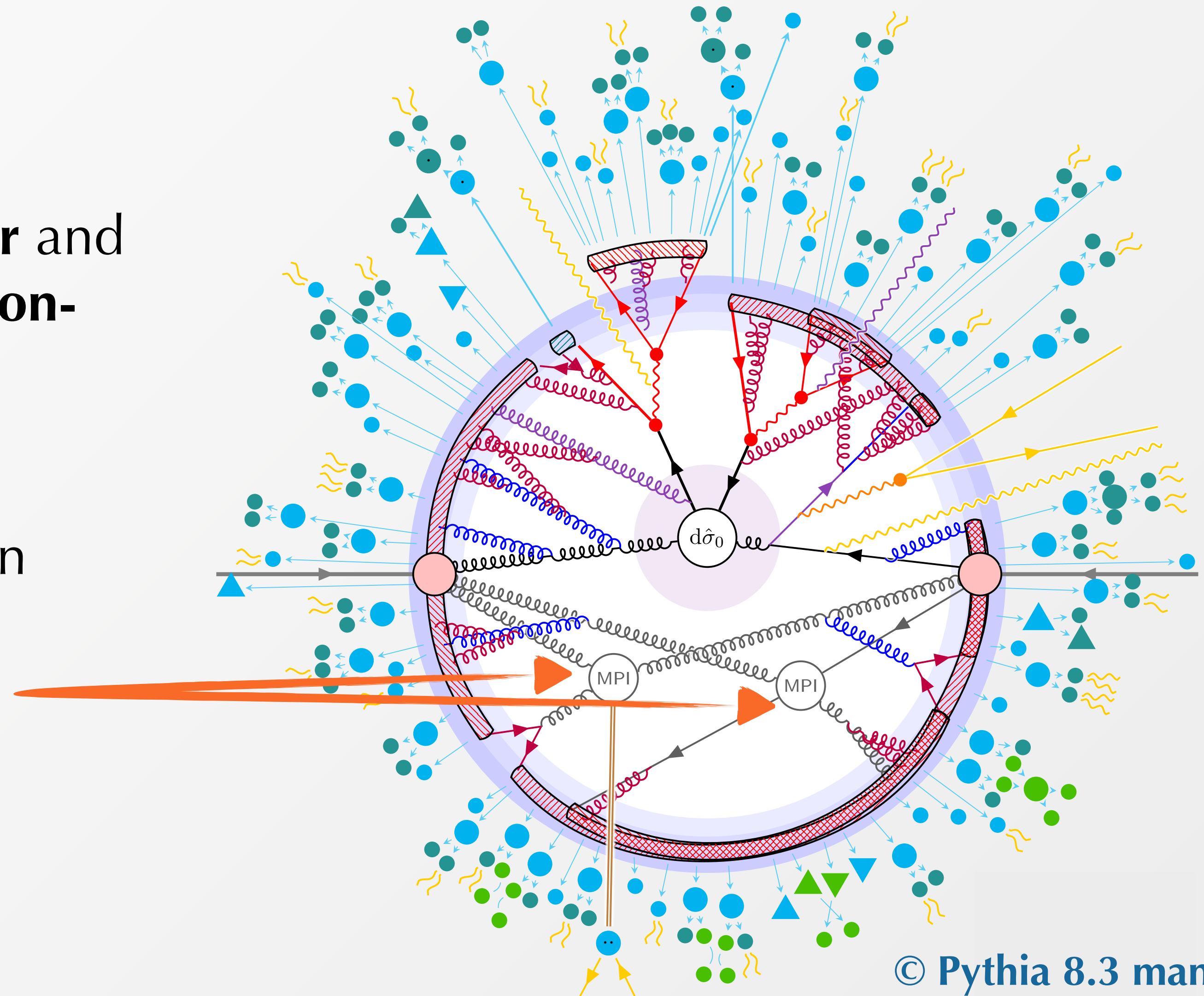
Gaunt, Bartalini MPI@LHC 2018

# MPI modelling in MC event generators

Accurate modeling of additional (**soft**) scatters is **crucial to ensure proper interpretation of hard events at hadronic colliders**

A complete description of the MPI is challenging due to their **large number** and complex interplay and their **chiefly non-perturbative nature**

At present soft MPI are modelled in an approximate way by **general-purpose Monte Carlo (MC) event generators**



© Pythia 8.3 manual

# Basics of MPI modelling

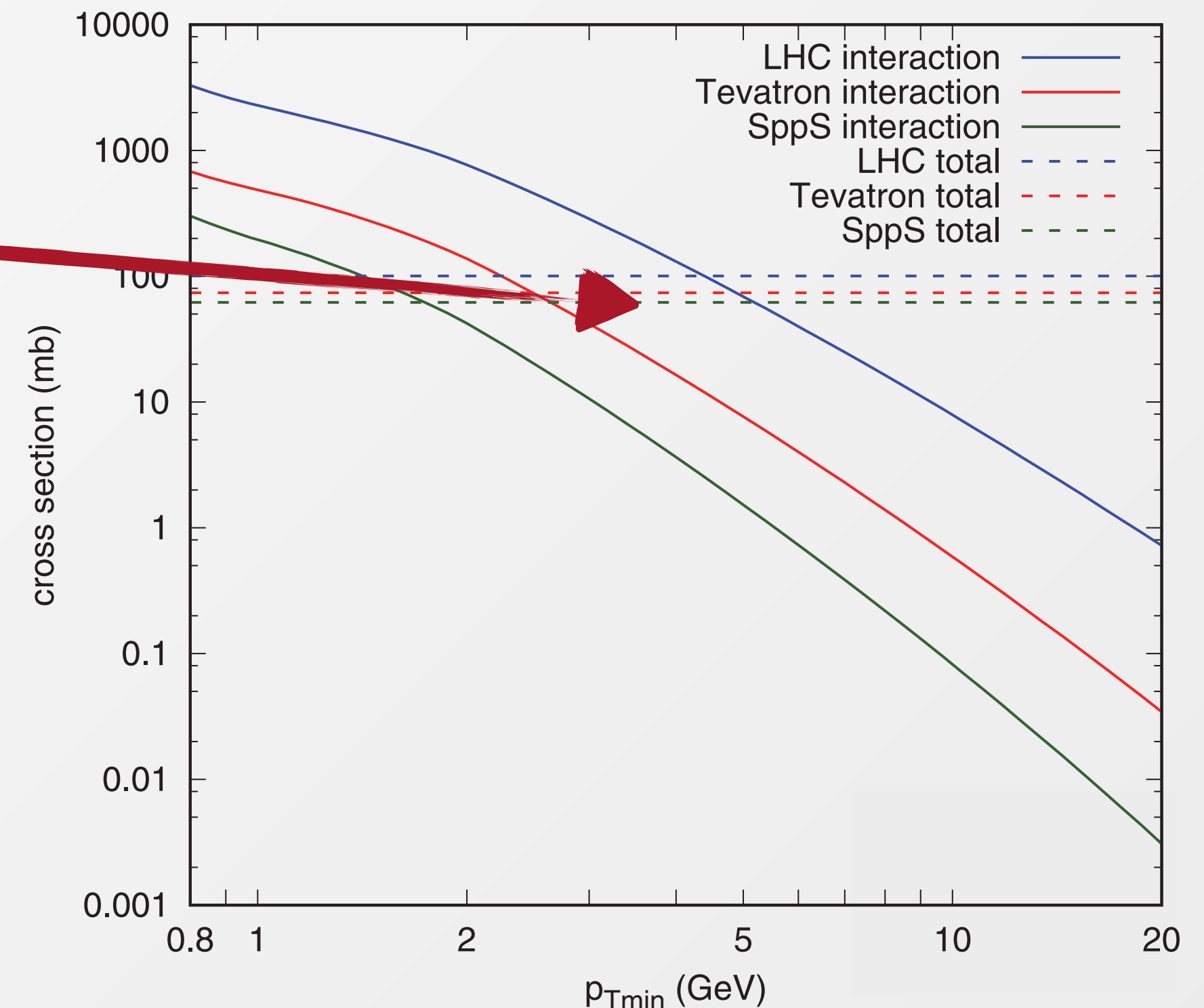
MC event generators such as Pythia, Herwig and Sherpa have refined and extended the modelling of MPI during the years, but all share the **same fundamental model** developed by T. Sjostrand and M. van Zijl in 1987 in the effort of improving the description of  $S\bar{p}pS$  data (different model used in tools like EPOS)

Starting point of the model is the differential perturbative QCD  $2 \rightarrow 2$  dijet cross section

$$\frac{d\sigma}{dp_T^2} = \sum_{i,j} \int f_i(x_1, Q^2) f_j(x_2, Q^2) \frac{d\hat{\sigma}_{ij}}{d\hat{t}} \delta(p_T^2 - \hat{t}\hat{u}/\hat{s}) dx_1 dx_2 d\hat{t}$$

The integrated cross section depends on the chosen  $p_{T,\min}$  scale and ultimately **exceeds the total cross section** even when  $p_{T,\min} \gg \Lambda_{\text{QCD}}$

$$\sigma_{\text{int}}(p_{T,\min}) = \int_{p_{T,\min}}^{\sqrt{s}/2} \frac{d\sigma}{dp_T} dp_T \sim \frac{1}{p_{T,\min}^2}$$



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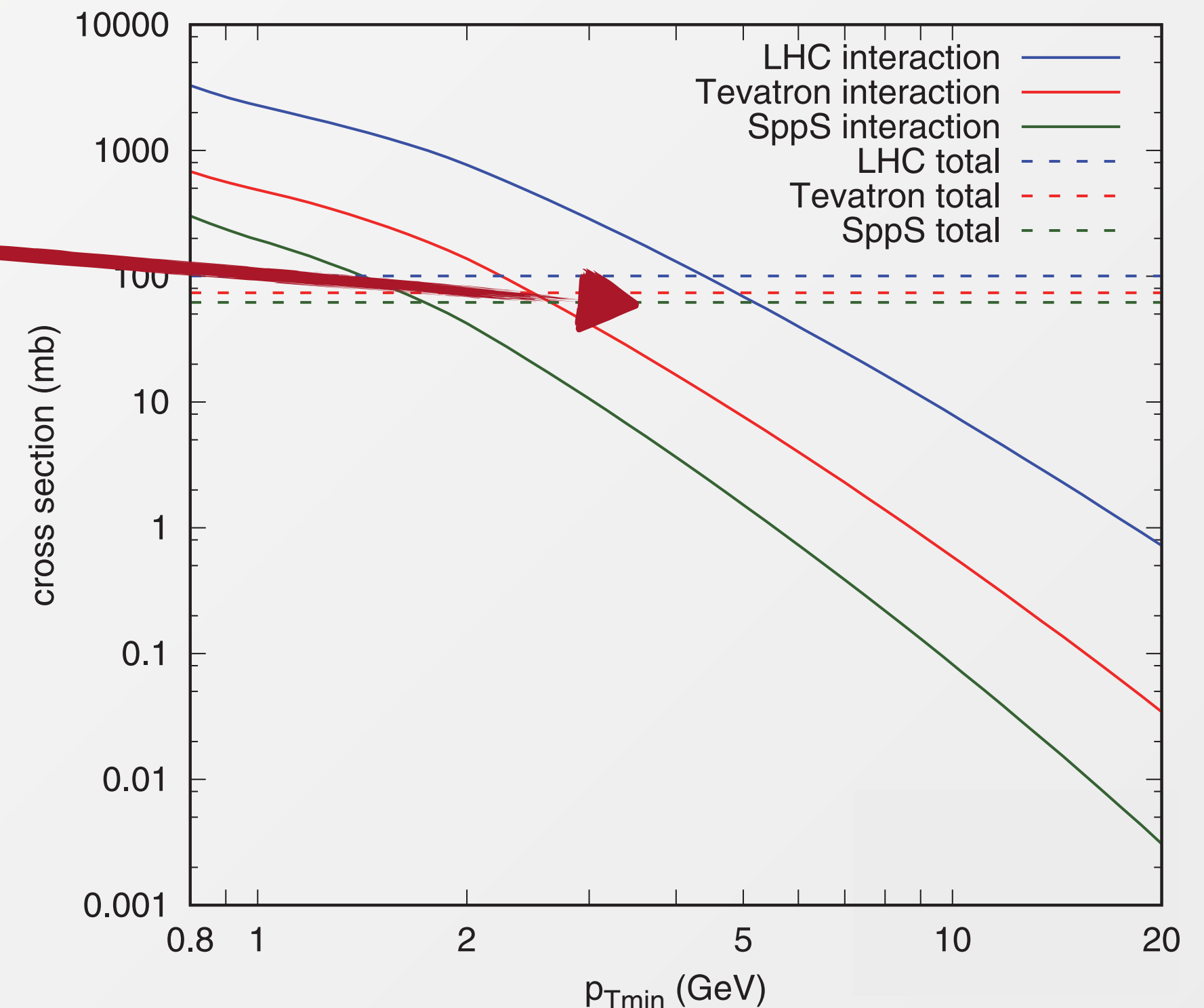
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**Interpretation: several parton-parton interactions per hadron-hadron interactions**

$$\langle n_{\text{MPI}}(p_{T,\min}) \rangle \simeq \frac{\sigma_{\text{int}}(p_{T,\min})}{\sigma_{\text{tot}}}$$



# Example: MPI modelling in Pythia

See talk by Lawrie Smith

Assuming that each interaction is independent:  $\langle n_{\text{MPI}}(p_{T,\text{min}}) \rangle$  follows a Poissonian distribution

A naive approach does not take into account even basic correlations (e.g. energy–momentum conservation): the sum of interaction energies may exceed the total CM energy

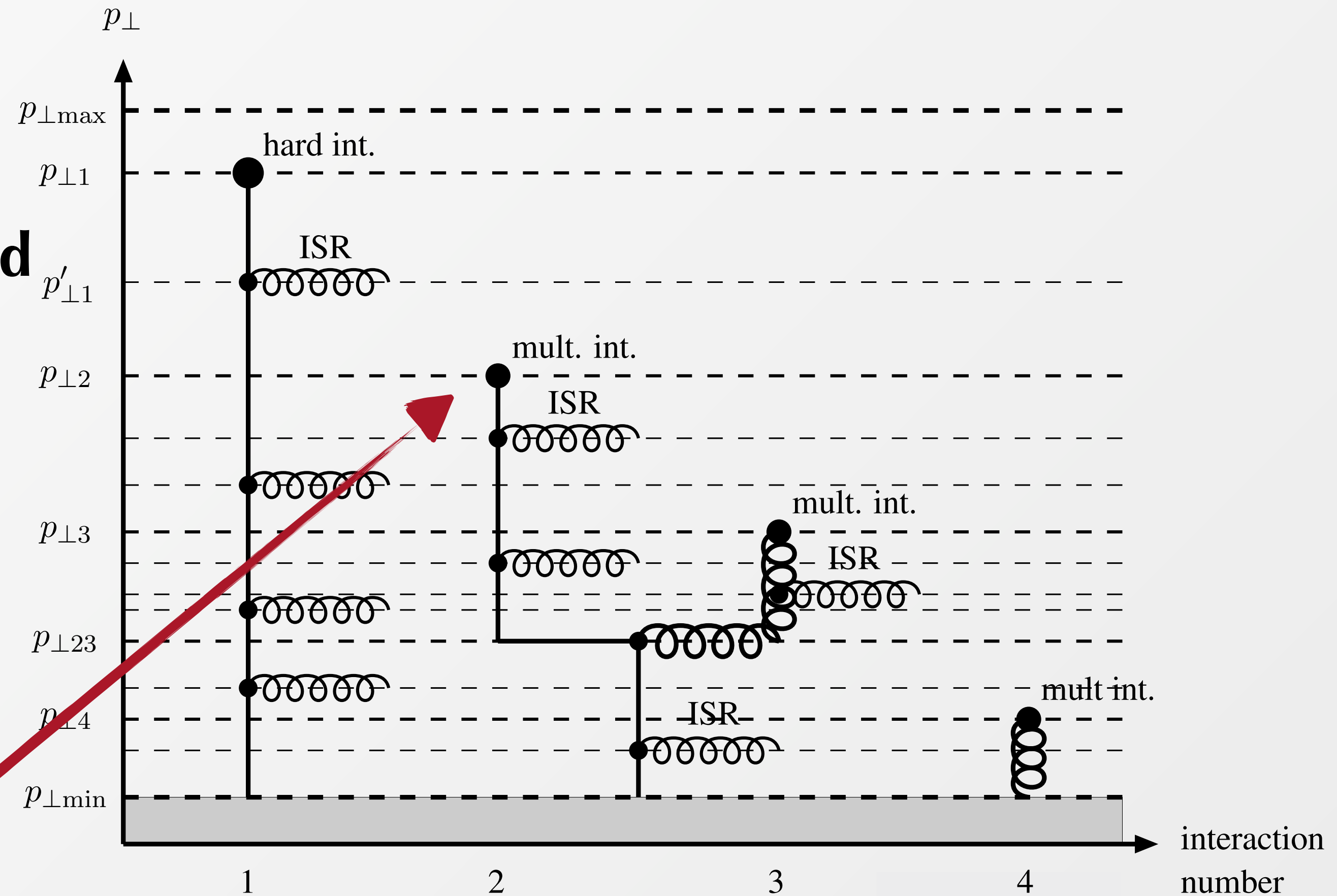
Solution to the problem comes by recasting MPI as a **Sudakov-style evolution**

Generation of MPI formulated as a **downward evolution in  $p_T$**  with probability

$$\frac{d\mathcal{P}}{dp_{T,i}} = \frac{1}{\sigma_{\text{tot}}} \frac{d\sigma}{dp_{T,i}} \exp\left(-\int_{p_{T,i}}^{p_{T,i-1}} \frac{1}{\sigma_{\text{tot}}} \frac{d\sigma}{dp_T} dp_T\right)$$

Interleave of MPI, ISR and FSR evolution in **one common sequence** in  $p_T$

[Sjostrand, Skands 2005][Sjostrand, Cork 2011]

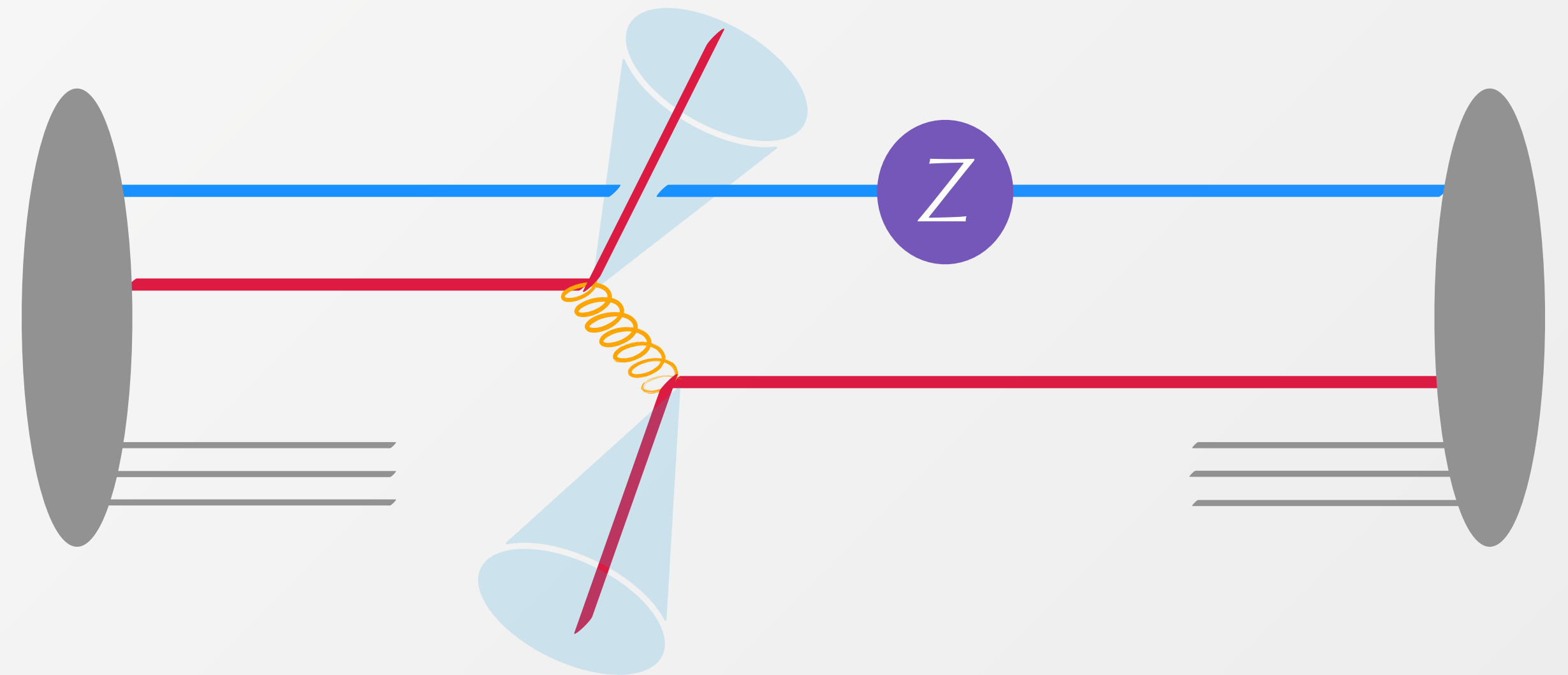


# Soft MPI: summary

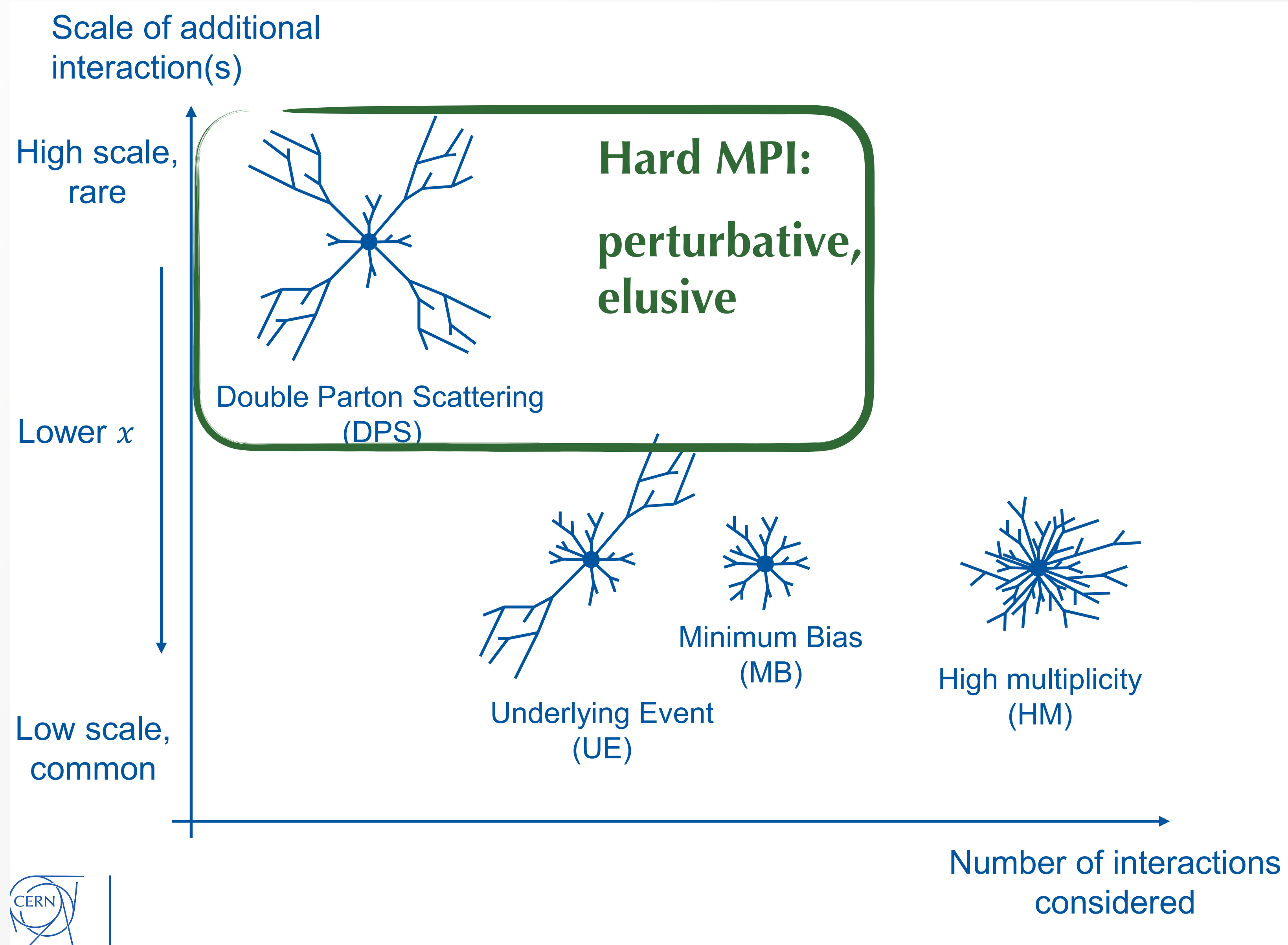
Monte Carlo models seek an unified description of hard jets, UE and MB

Although inspired by theoretical ideas, the development of MPI models is **rather decoupled from detailed theoretical calculations** due to the complexity of the environment with  $\mathcal{O}(10)$  soft MPIs

An alternative approach to study MPI physics in a **much cleaner environment** is in events with two (or more) separate **hard processes** in an individual hadron-hadron collisions: double- or triple-parton scattering (DPS, TPS), more amenable to first-principle theoretical approaches



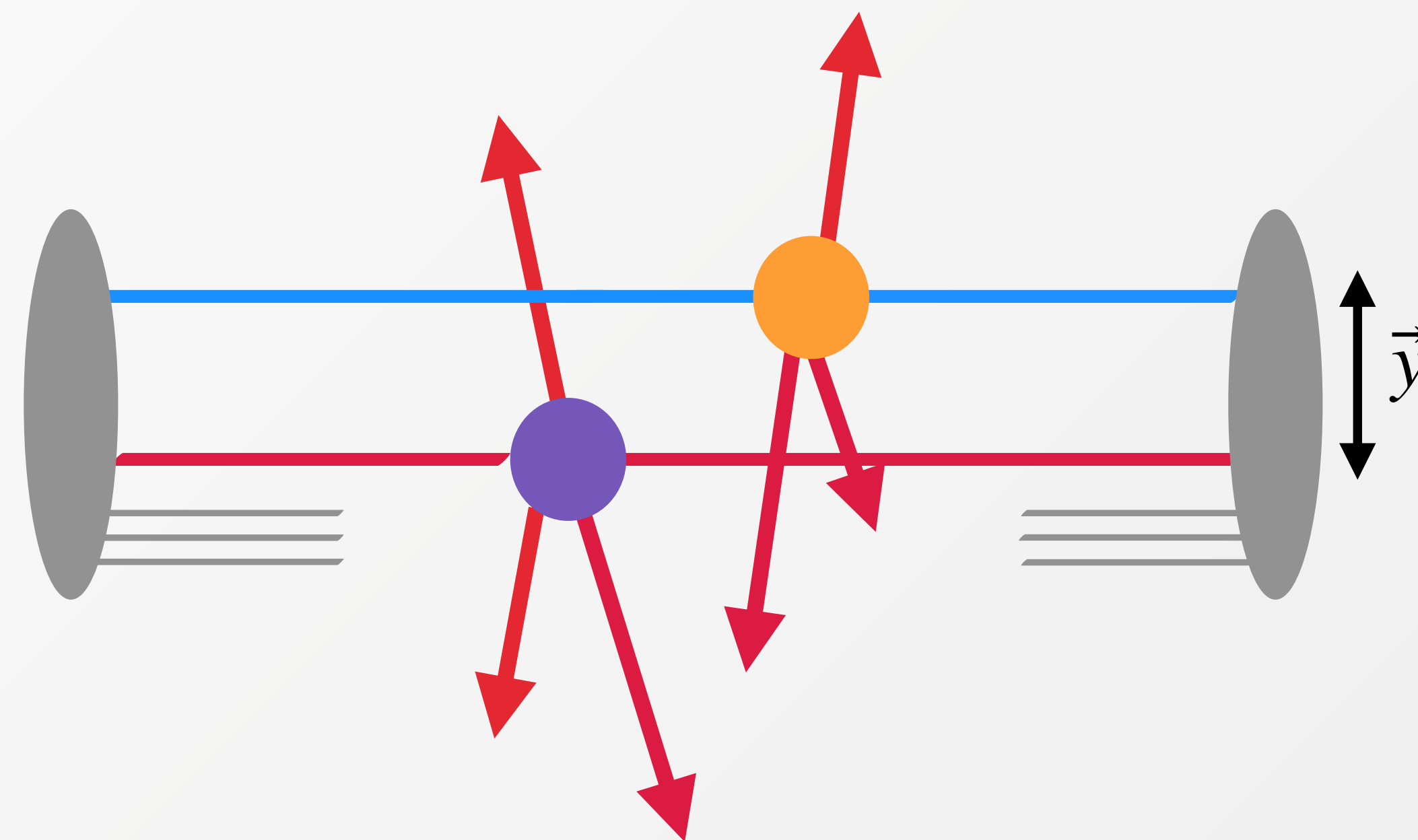
# MPI 'landscape'



Gaunt, Bartalini MPI@LHC 2018

# Double parton scattering: basic features

**Two** separate **hard interactions** in a **single** proton-proton collision



Postulated factorisation formula for integrated DPS cross section based on parton model / low order Feynman diagrams considerations

## Parton level cross sections

$$\sigma^{A,B} = \frac{m}{2} \sum_{i,j,k,l} \int F_h^{ik}(x_1, x_2, \vec{y}, Q_A, Q_B) F_h^{jl}(x'_1, x'_2, \vec{y}, Q_A, Q_B) \times \hat{\sigma}_{ij}^A(x_1, x'_1) \hat{\sigma}_{kl}^B(x_2, x'_2) dx_1 dx'_1 dx_2 dx'_2 d^2\vec{y}$$

**Collinear double-parton distributions**

[Paver, Treleani 1982]

[Mekhfi, 1985]

[Blok, Dokshitzer, Frankfurt, Strikman 2011]

[Diehl, Ostermeier, Schaefer 2012]

# Double parton scattering: simplified assumptions

If **correlations between partons** are ignored

$$F_h^{ik}(x_1, x_2, \vec{y}) = \int d^2\vec{b} D^i(x_1, \vec{b}) D^j(x_1, \vec{b} + \vec{y}) \quad D: \text{impact-parameter dependent PDFs}$$

Justified at small  $x$  given the large population of partons

Often the further approximation  $D^i(x_1, \vec{b}) = D^i(x_1)G(\vec{b})$  is made, leading to the **pocket formula**

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

where  $\sigma_{\text{eff}} \sim O(20 \text{ mb})$  is a normalisation factor roughly connected with area over which partons are concentrated in the proton.

Taking  $\sigma_A$  “**hard**” and  $\sigma_B$  “**soft**” (i.e. large cross section, likely to be produced as MPI), DPS contribution becomes important when  $\sigma_B/\sigma_{\text{eff}}$  is similar to the perturbative suppression of process  $pp \rightarrow (A + B)$  over  $pp \rightarrow A$

# Challenges in hard MPI studies

Distinguishing two contributions:

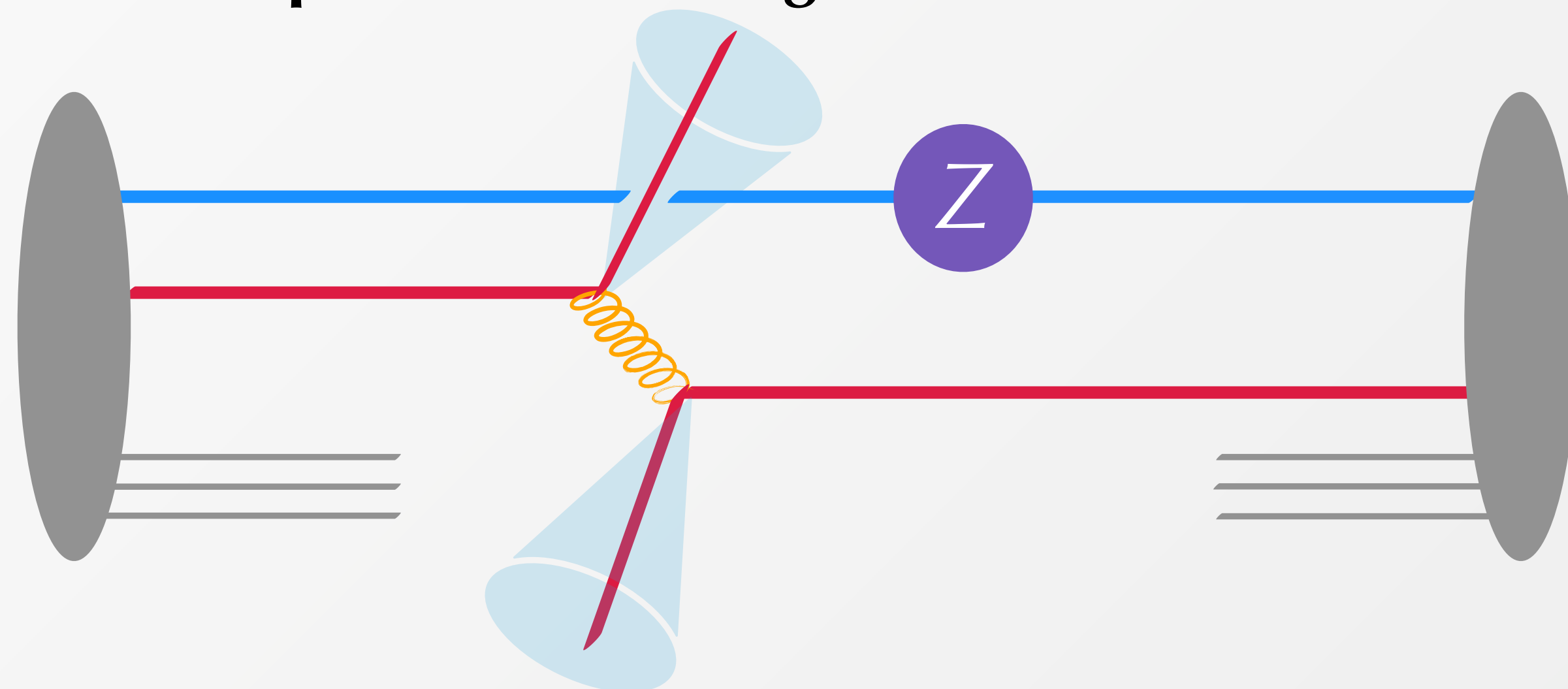
- two independent hard scatterings **(2HS)**
- a single hard scattering **(1HS)** with extra radiation

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

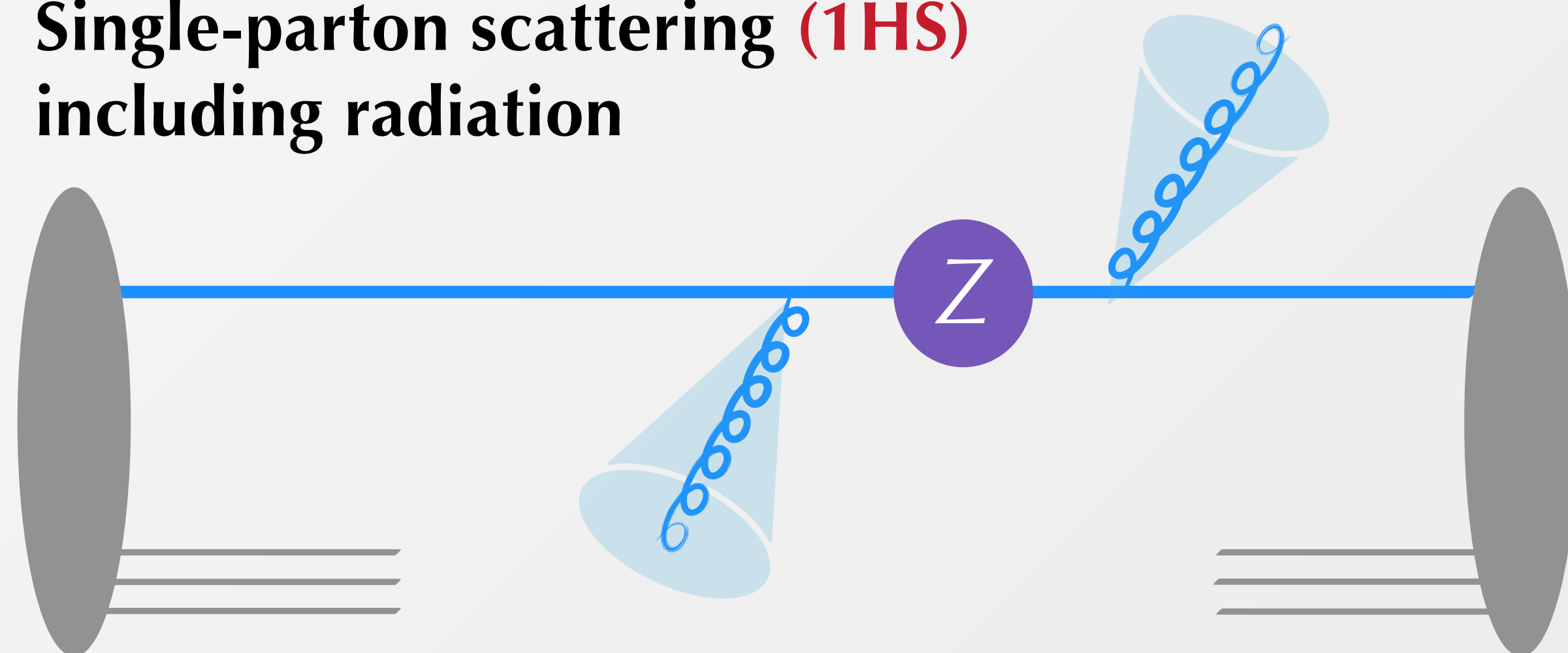
At the level of the total cross section, 2HS mechanism is power suppressed with respect to 1HS

$$\sigma_{2HS}/\sigma_{1HS} \sim \Lambda^2/Q^2$$

## Double-parton scattering **(2HS)**

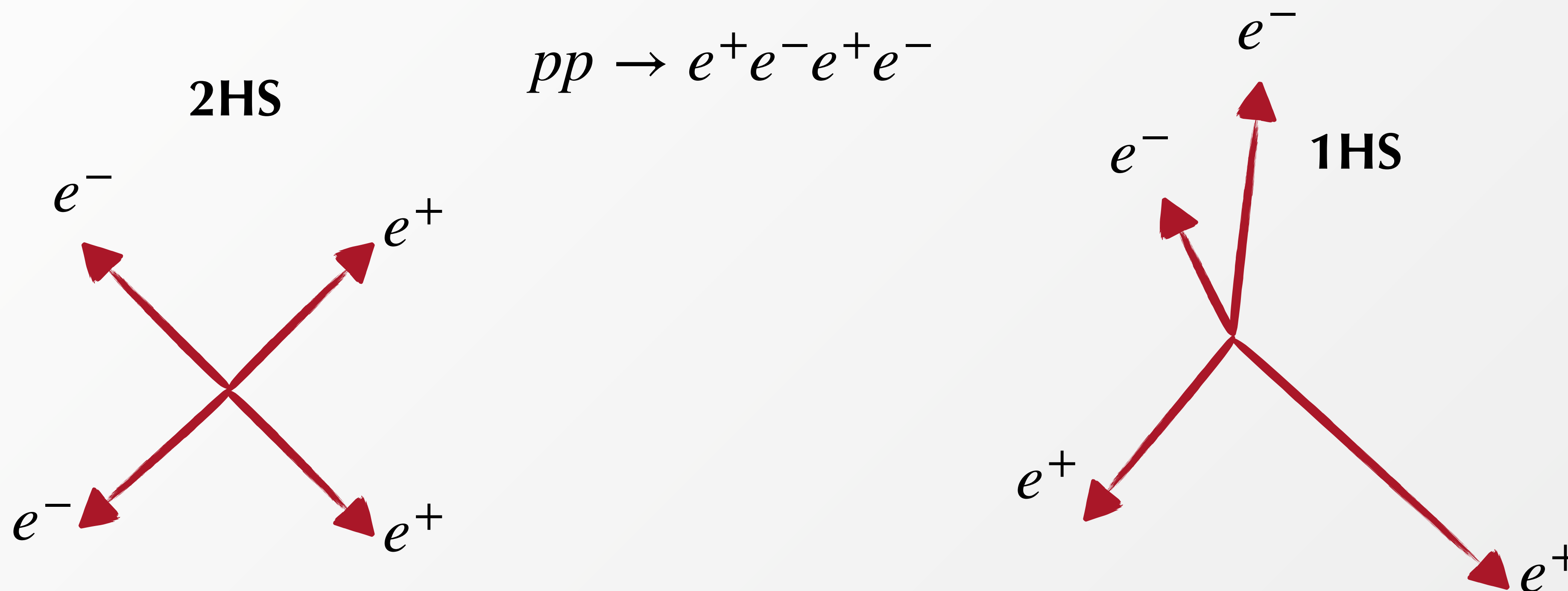


## Background from Single-parton scattering **(1HS)** including radiation



# Strategy A

DPS populates the final state phase space in a different way from 1HS. In particular, for processes A and B it tends to populate the region of small  $\vec{q}_A, \vec{q}_B$



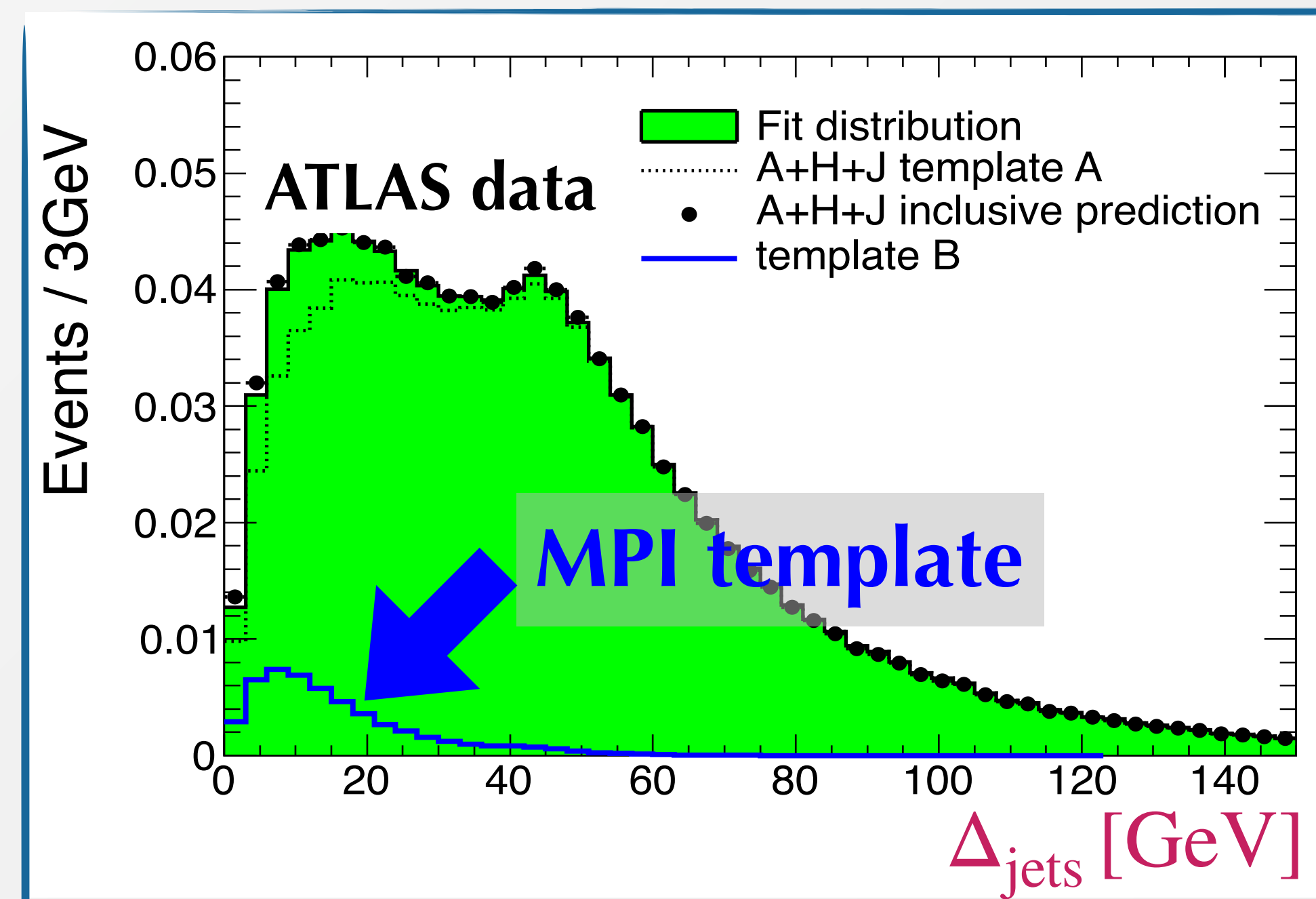
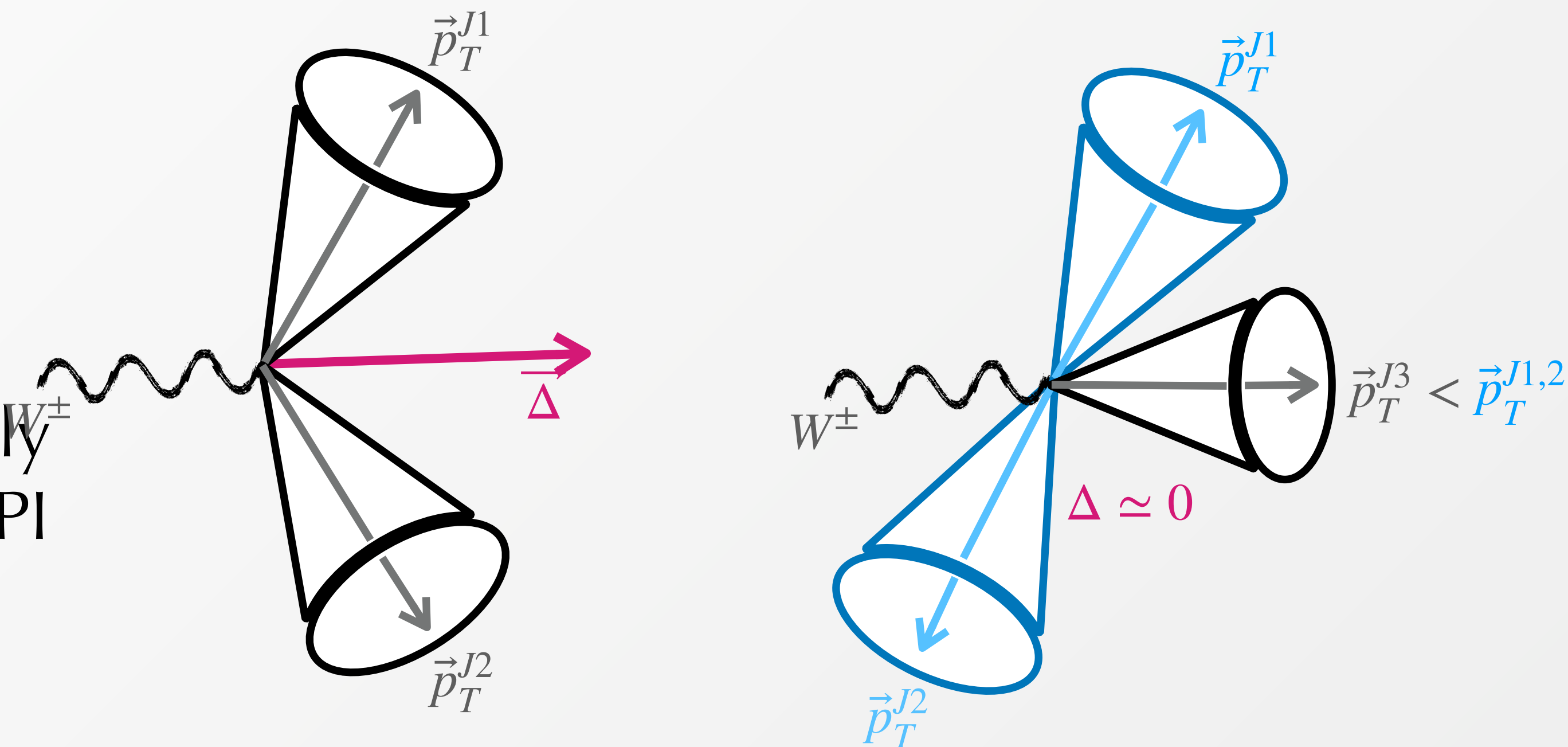
# W+2-jets study

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

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

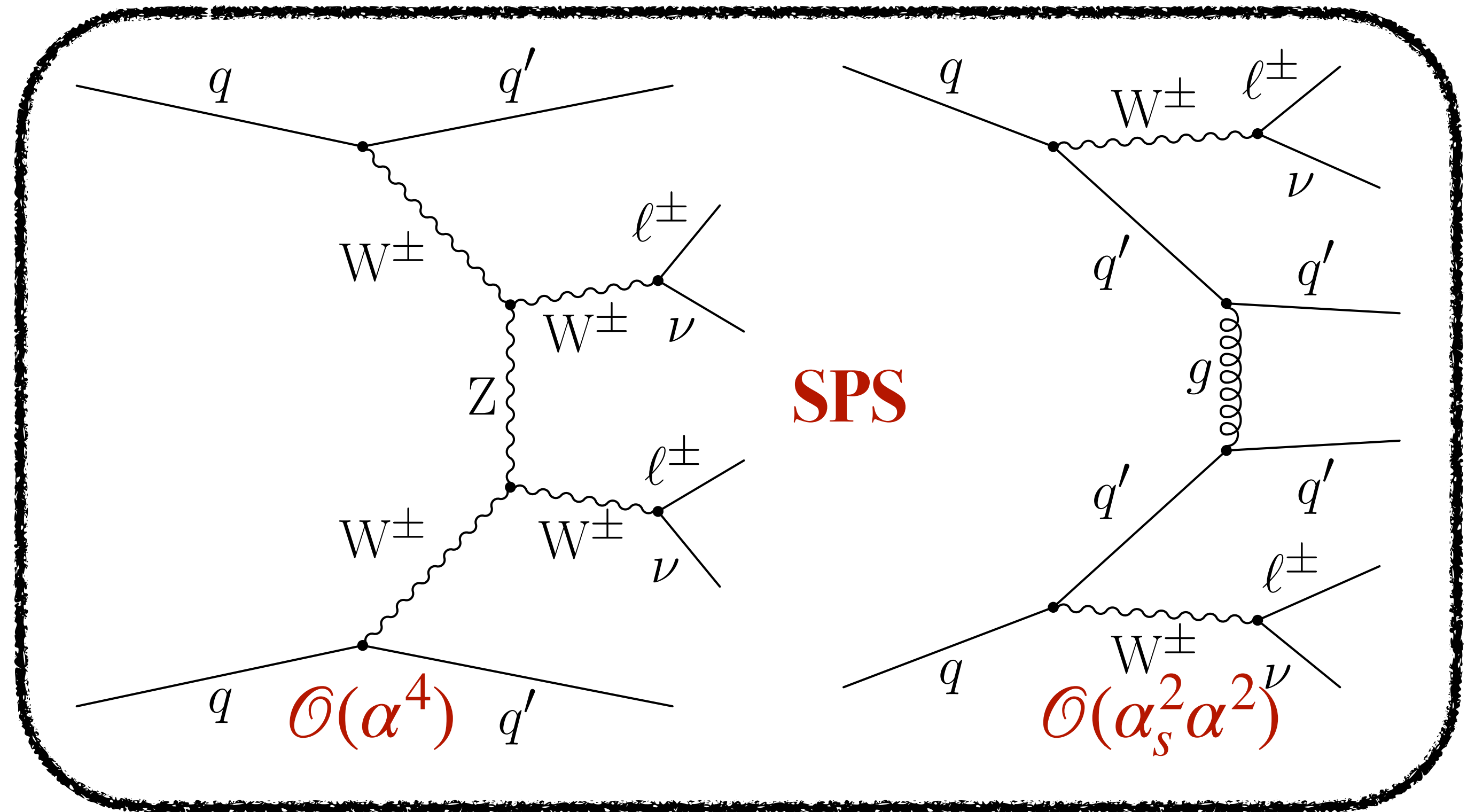
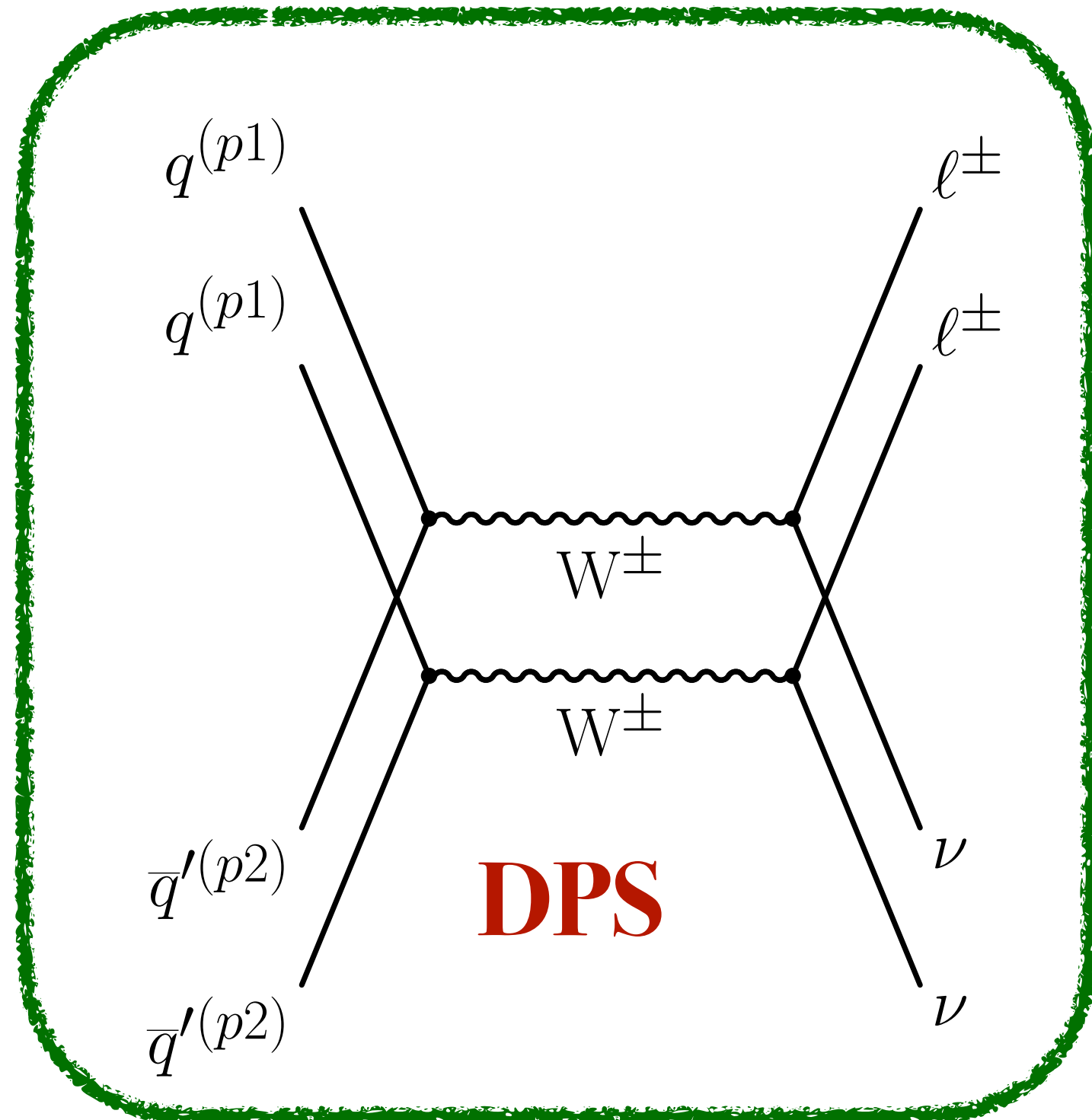
- That works to some extent, but relative MPI (2HS) fraction is moderate ( $\lesssim 10\%$ )
- Quantitative analysis requires very good understanding of radiation in single hard scattering (1HS)

See talk by Yue Xu



# Strategy B

Identify processes where **1HS mechanism is suppressed** (e.g. small couplings)



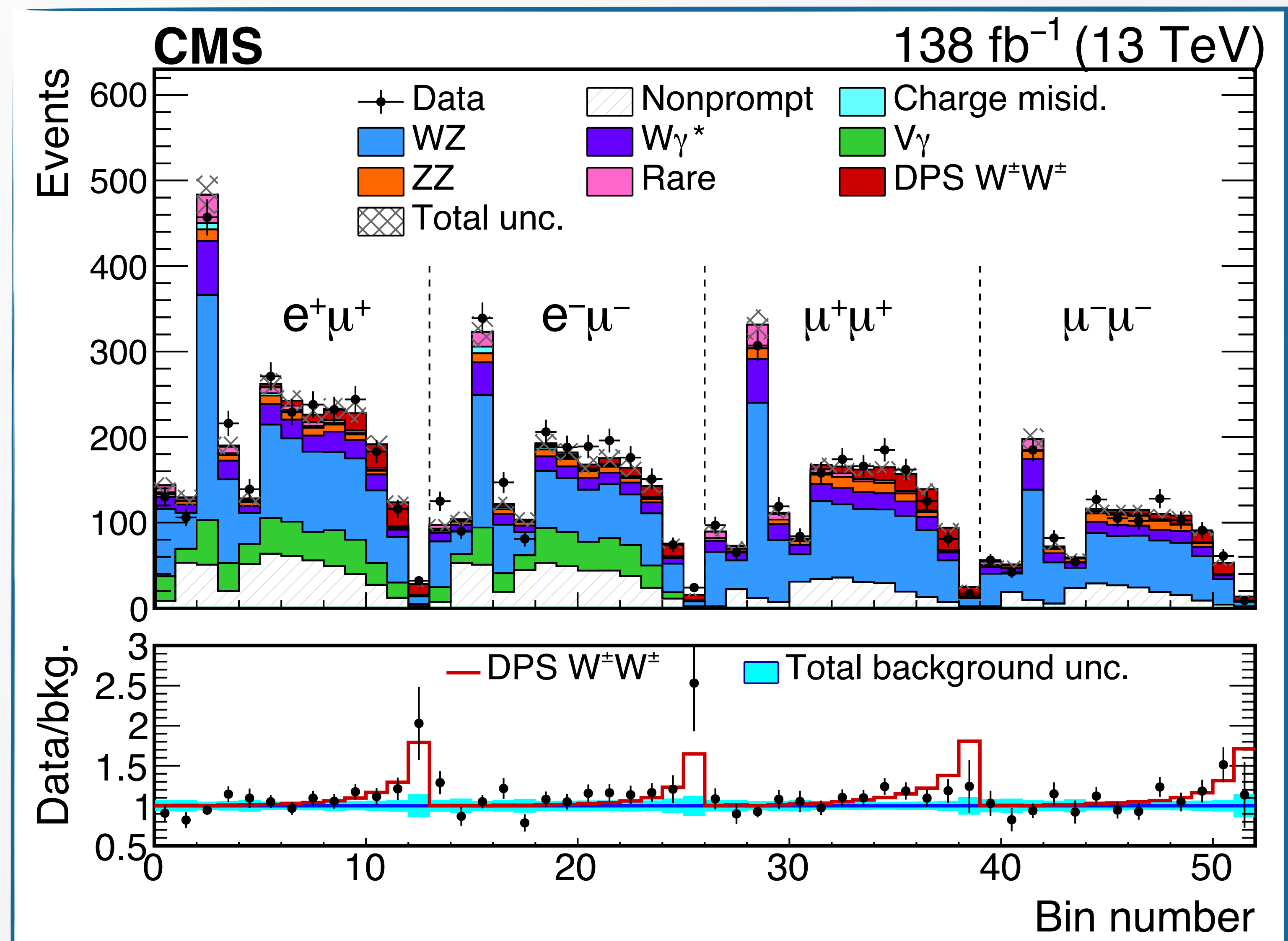
*See talk by Ankita*

# Avoid radiation issue: same-sign $WW$ See talk by Ankita

- Here  $W^\pm W^\pm \rightarrow$  same-sign leptons, CMS 2206.02681
- many other backgrounds: need for BDT makes it difficult to study MPI physics
- $6.2\sigma$  observation with full Run 2 dataset

See also triple  $J/\psi$  production  
[Shao, Zang 2019][CMS 2023]

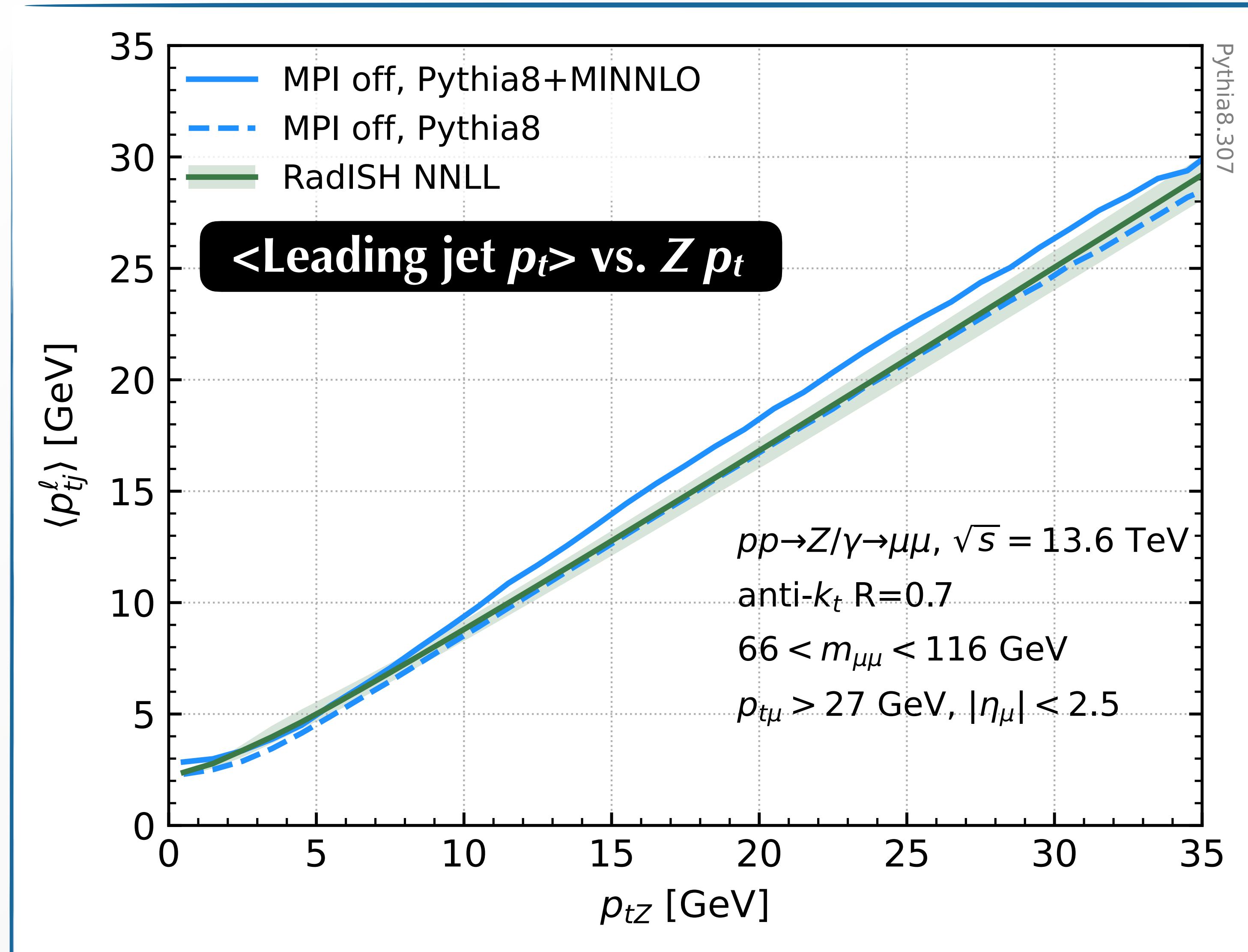
*See talk by Maria Elena*



[CMS 2206.02681]

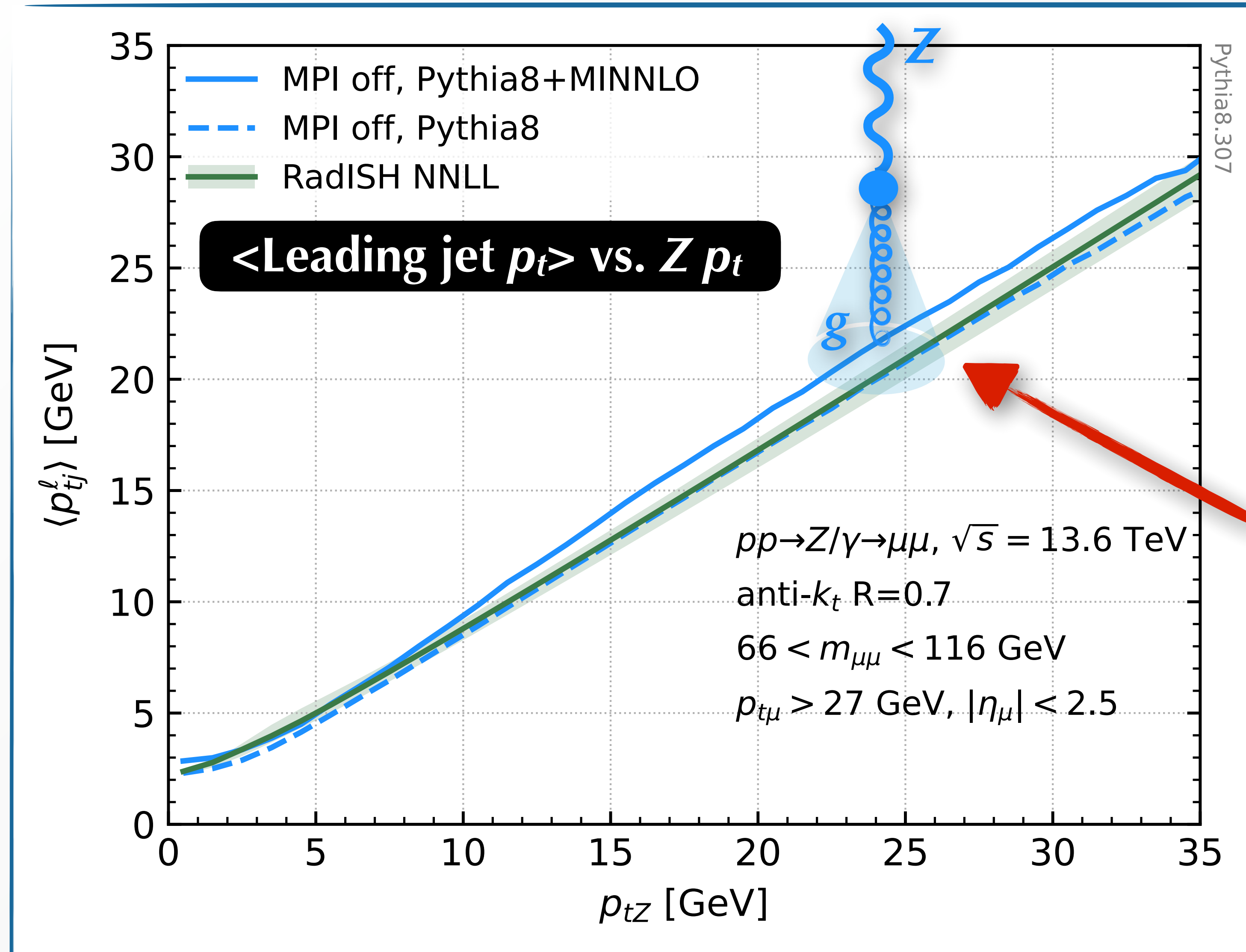
# Alternative route: can we study MPI in $Z$ scattering?

[PRL 132 (2024) 4, 041901 Andersen, Monni, LR, Salam, Soto-Ontoso]



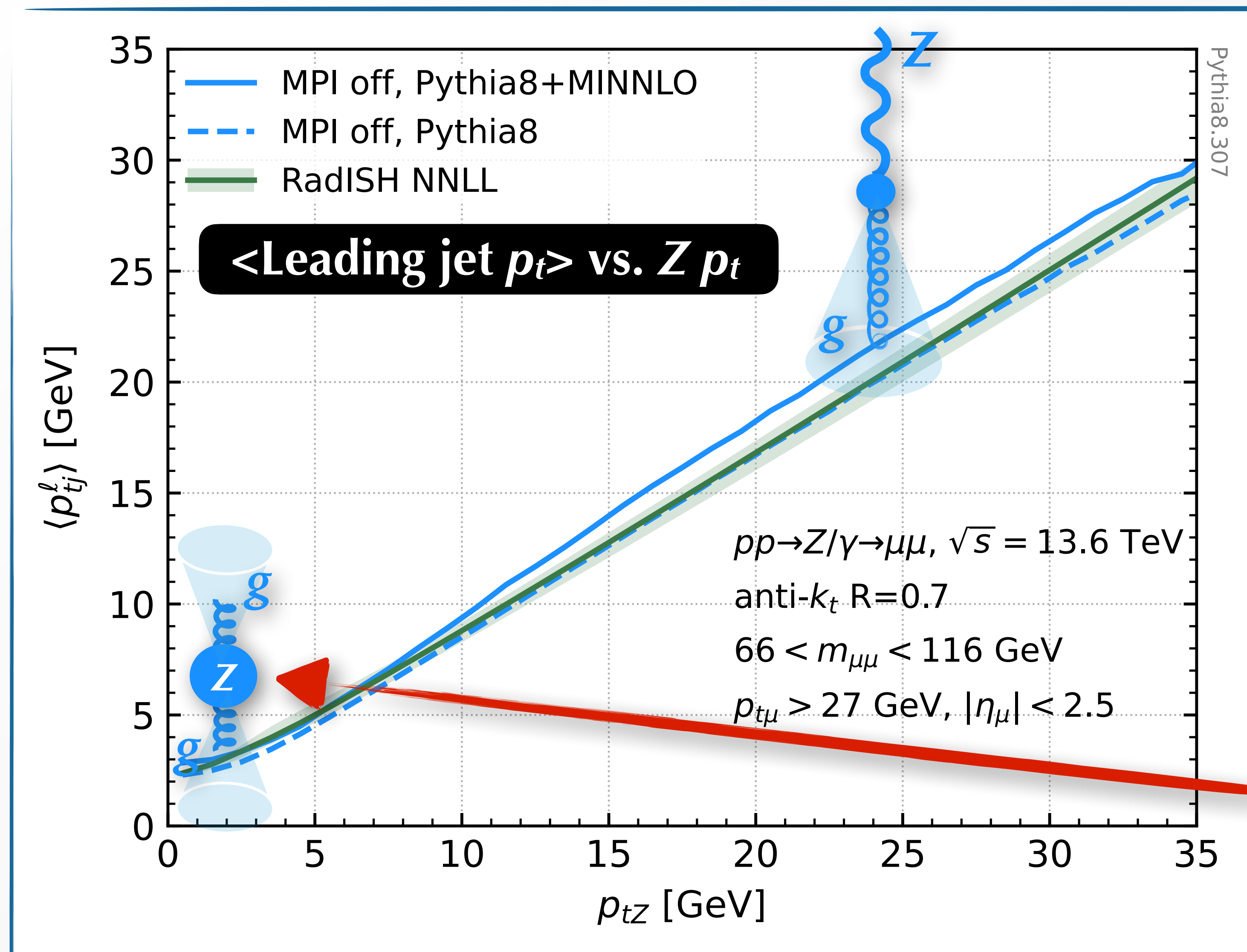
- Consider process with **MPI simulation turned off** (i.e. just 1HS)
- Look at avg.  $p_t$  of leading jet ( $p_{tj}^\ell$ ) as a function of  $Z p_t$  ( $p_{tZ}$ )

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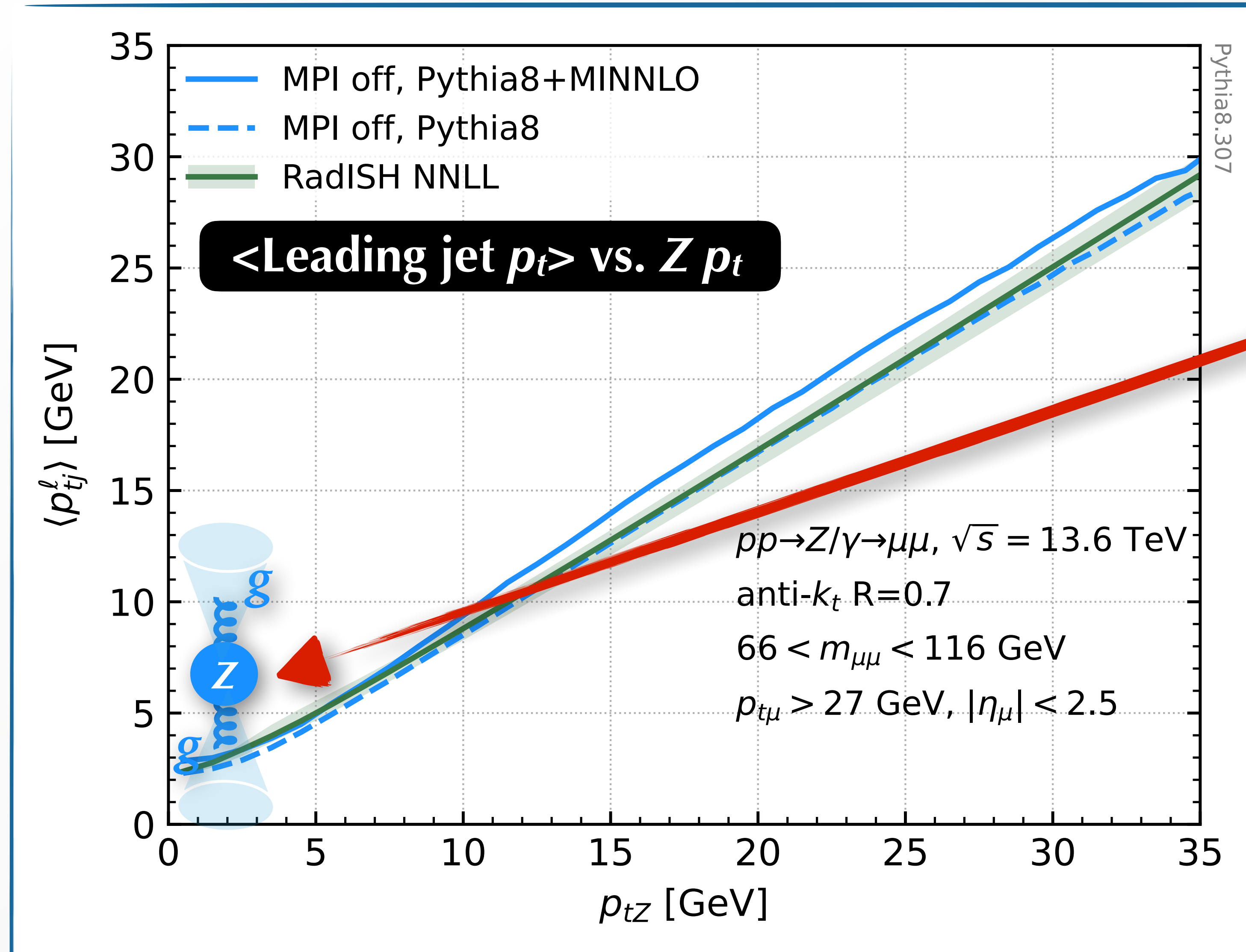
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- **For  $p_{tZ} \rightarrow 0$ :**  $\langle p_{tj}^\ell \rangle$  saturates at about 2–3 GeV: **two (or more) soft jets balance each other**

# Alternative route: can we study MPI in $Z$ scattering?

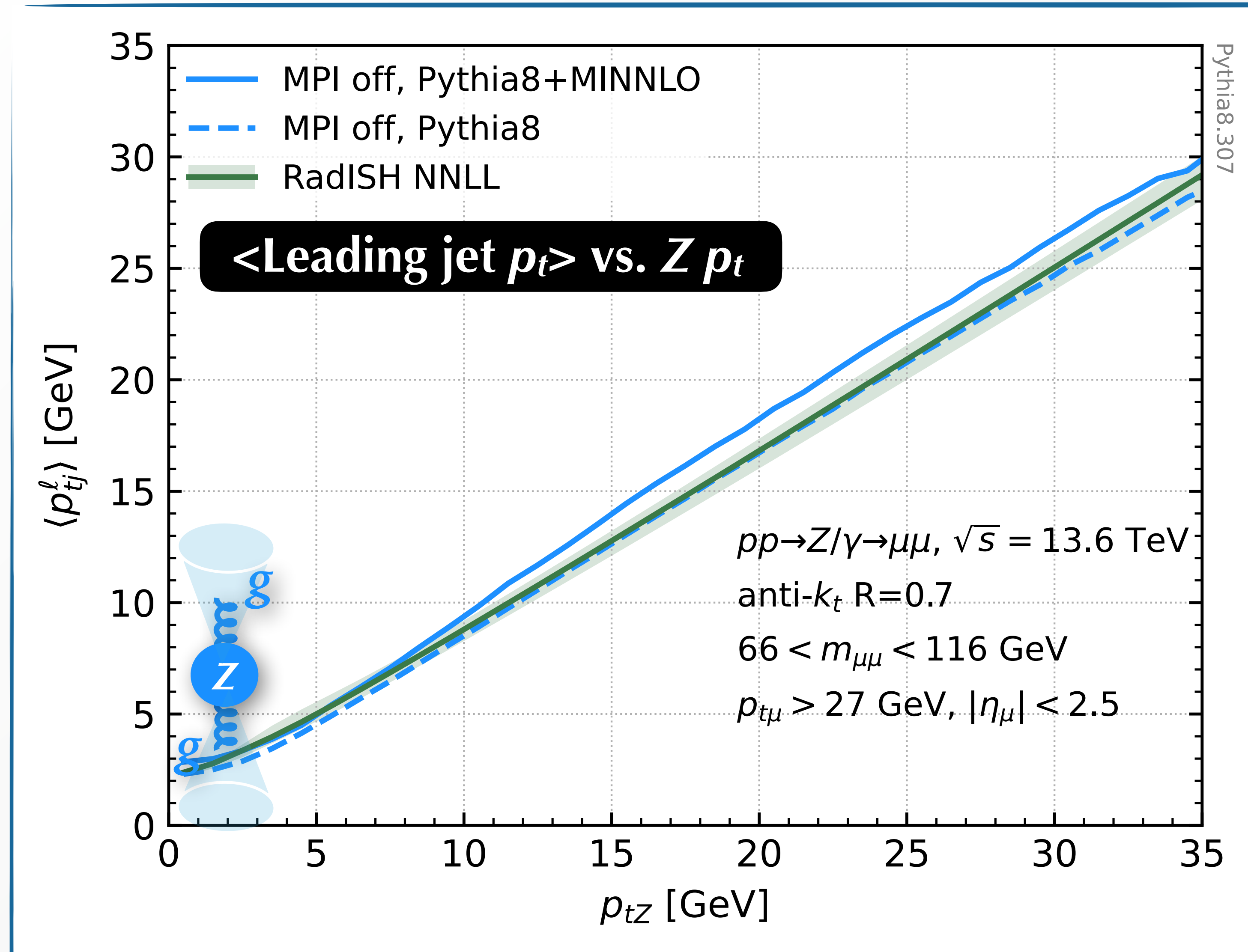


Average leading jet  $p_T$  can be calculated from **resummation** in the limit  $p_{tZ} \rightarrow 0$  [Monni, LR, Torrielli '19]

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

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

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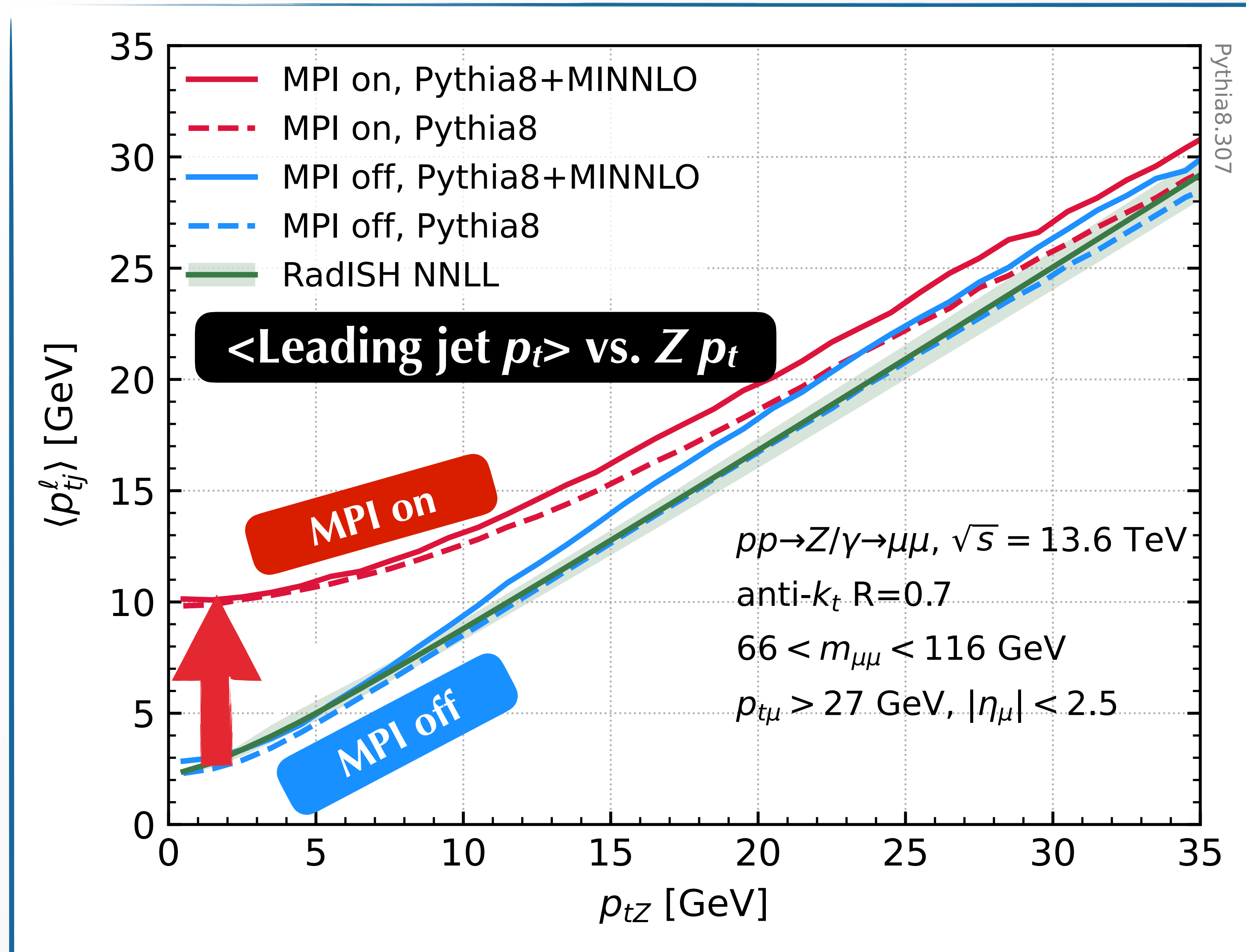
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By constraining  $p_{tZ}$  we can forbid most radiation above this characteristic 2–3 GeV scale

[classic Parisi-Petronzio '79]

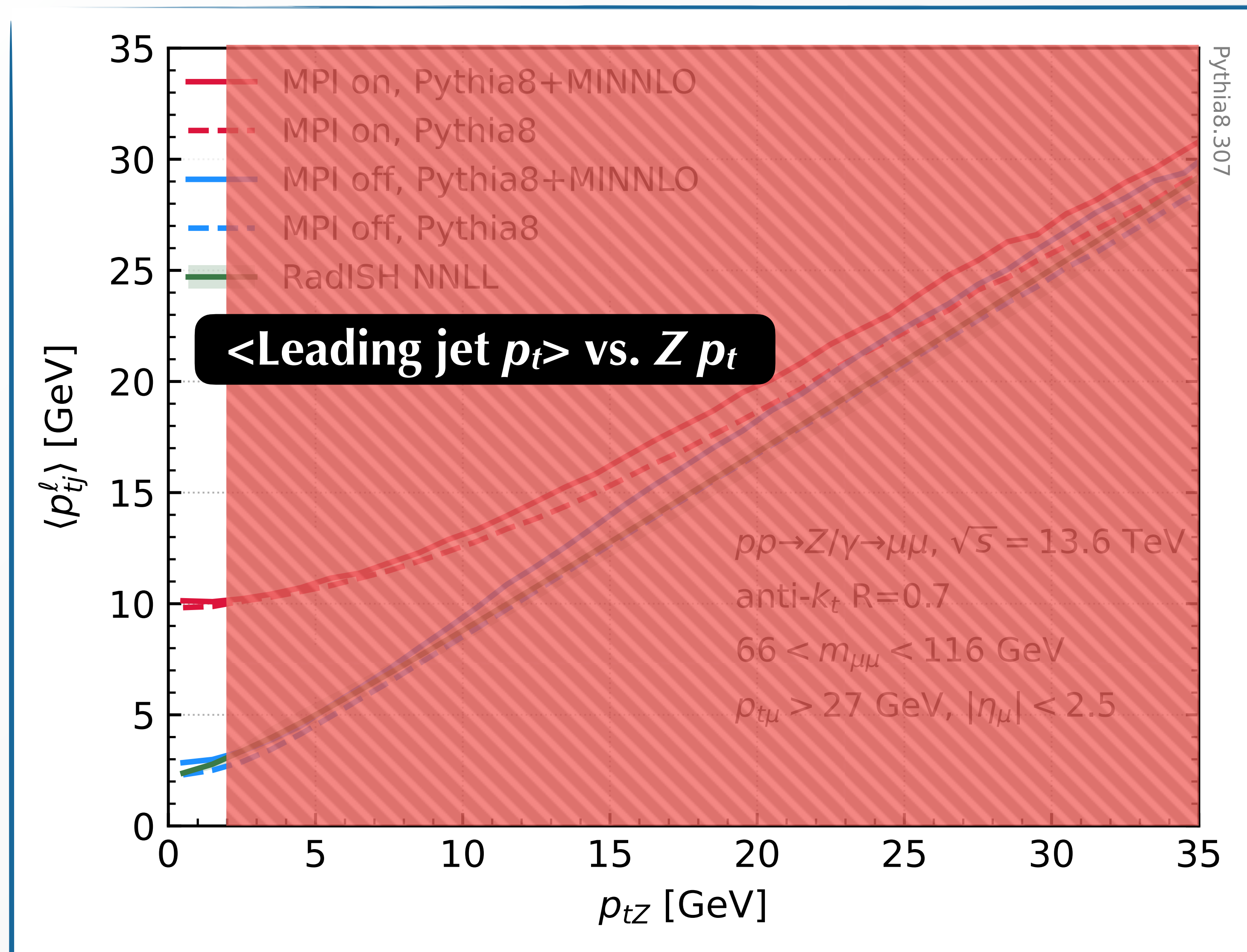
# Alternative route: can we study MPI in $Z$ scattering?



## What happens when turning on MPI?

- for  $p_{tZ} \rightarrow 0$ , leading jet  $p_t$  is now  $\sim 10$  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 cfr. current models in Pythia/Herwig/Sherpa which simulate MPI as semi-hard scatterings

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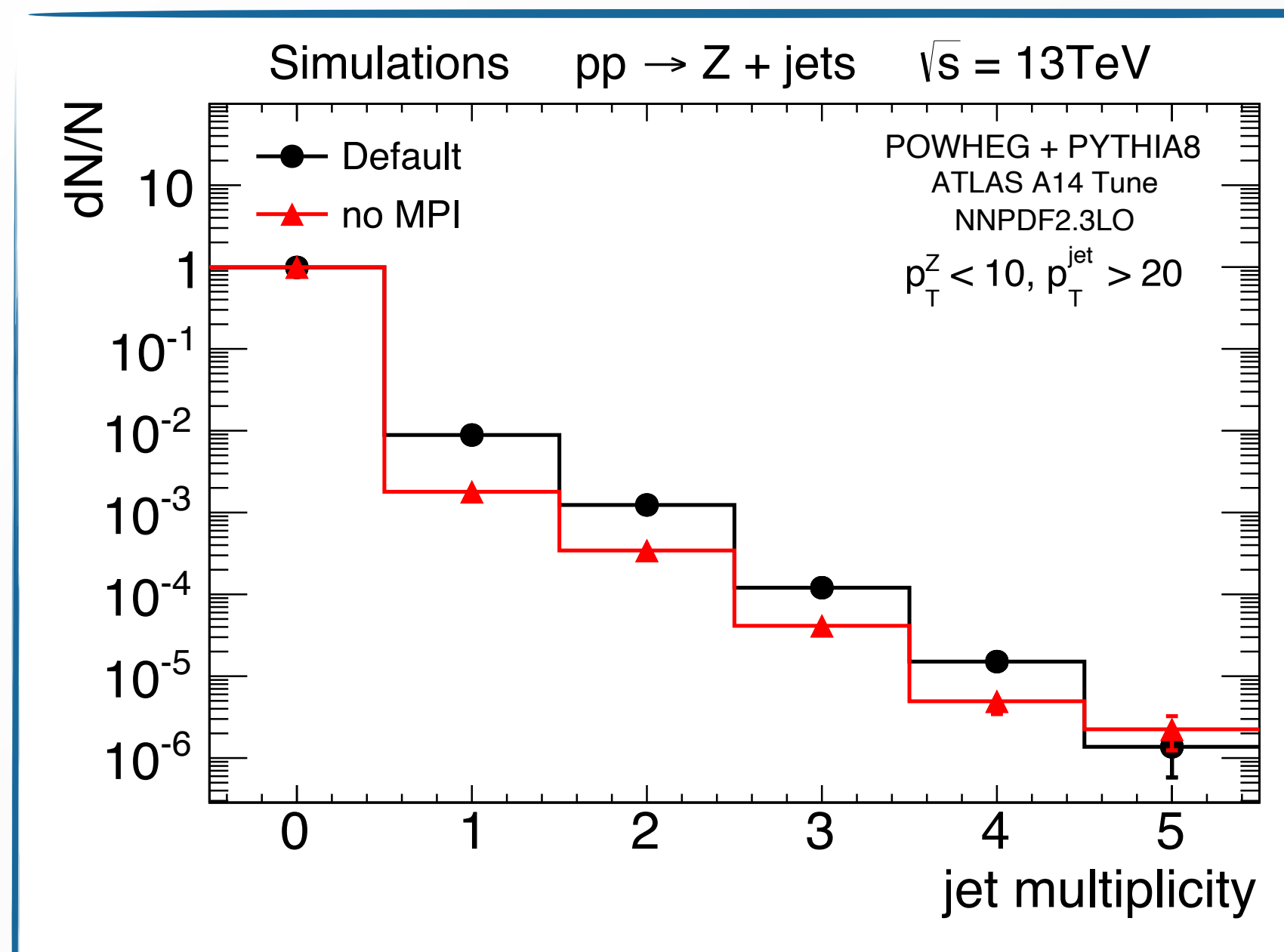


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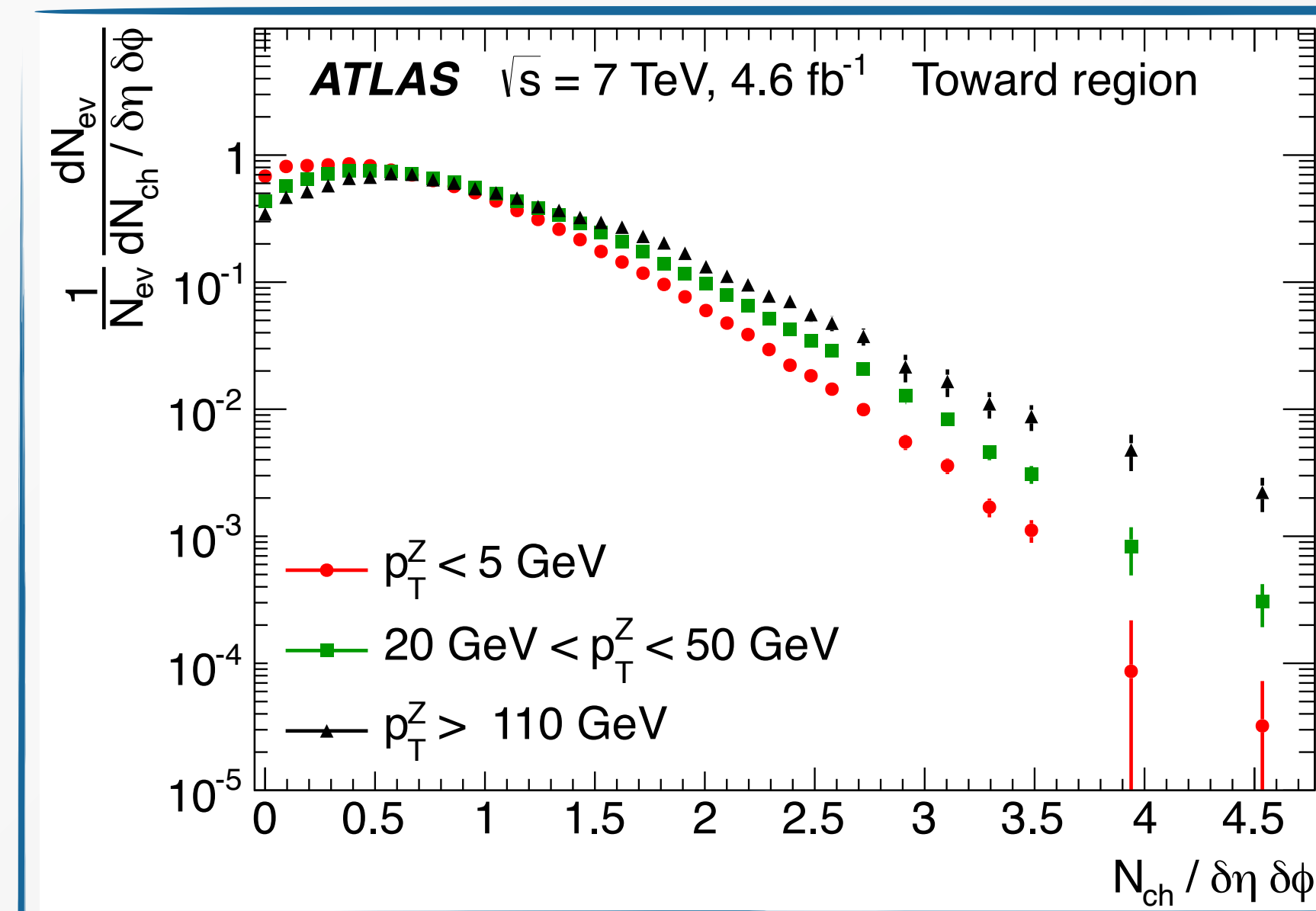
Suggests we should study MPI with help of a tight cut on  $p_{tZ}$

# Past MPI studies with cuts on $p_{tZ}$

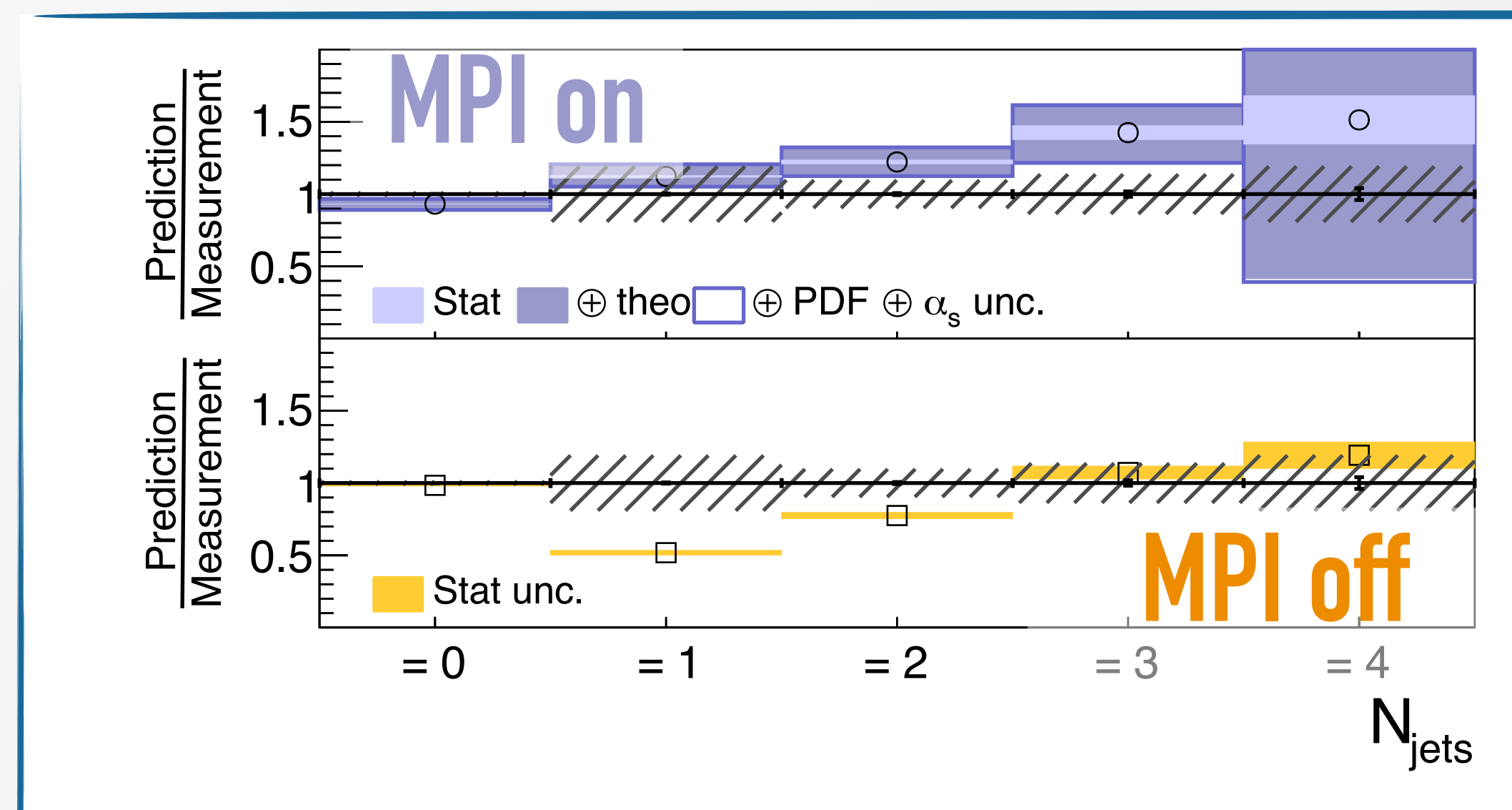


Bansal, Bansal, Kumar, Singh 1602.05392 suggested MPI studies with  $p_{tZ} < 10$  GeV for improved MPI purity

See also Alioli, Bauer, Guns, Tackmann, 1605.07192



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



CMS 2210.16139: results with  $p_{tZ} < 10$  GeV, confirming some MPI enhancement

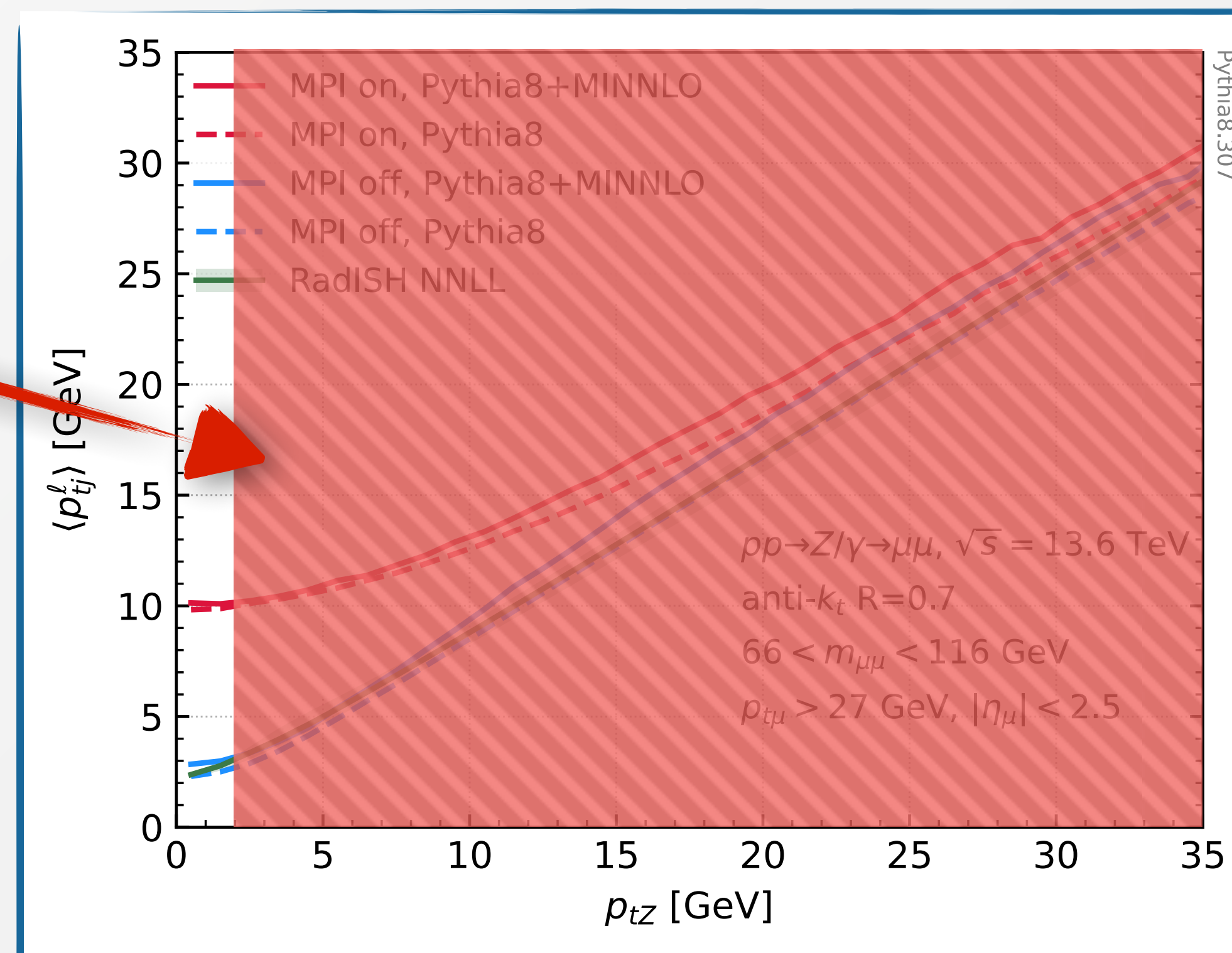
# Our study: establish what cut to use, explore opportunities that open up

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  $p_{tZ} \lesssim 2 \text{ GeV}$

- 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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**$p_{tZ} < 2 \text{ GeV}$  cut retains 4 – 5% of Z-pole Drell-Yan events**

**For  $Z \rightarrow \mu^+ \mu^-$  residual cross section is  $\sim 40 \text{ pb}$**

**$\sim 12$  million events for  $300 \text{ fb}^{-1}$  in Run 3**

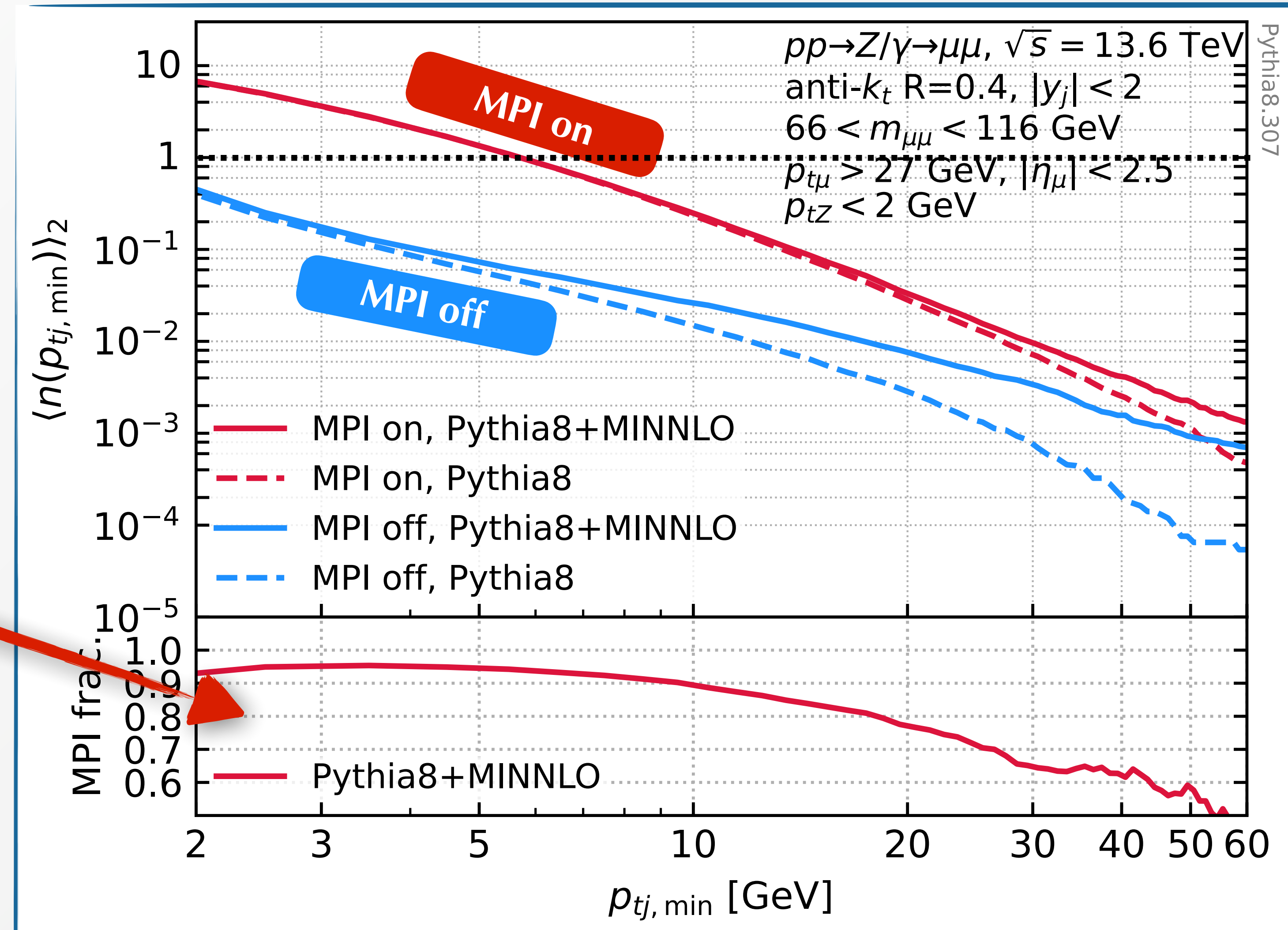
# Simplest observable: cumulative inclusive jet spectrum for $p_{tZ} < 2$ GeV

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%



Pythia8.307

## Connection with “pocket formula” ( $\sigma$ 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  $\sigma_{\text{eff}}$  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  $p_{tj}$ )

$$\langle n(p_{tj,\min}) \rangle_{C_Z}^{\text{pure-MPI}} \simeq \frac{1}{\sigma_{\text{eff}}} \int_{p_{tj,\min}} dp_{tj} \frac{d\sigma_{\text{jet}}^{\text{min-bias}}}{dp_{tj}} \quad \begin{array}{l} \text{Independent on } C_Z \\ \text{(Within pocket formula)} \end{array}$$

# Some questions

## Within pocket formula picture

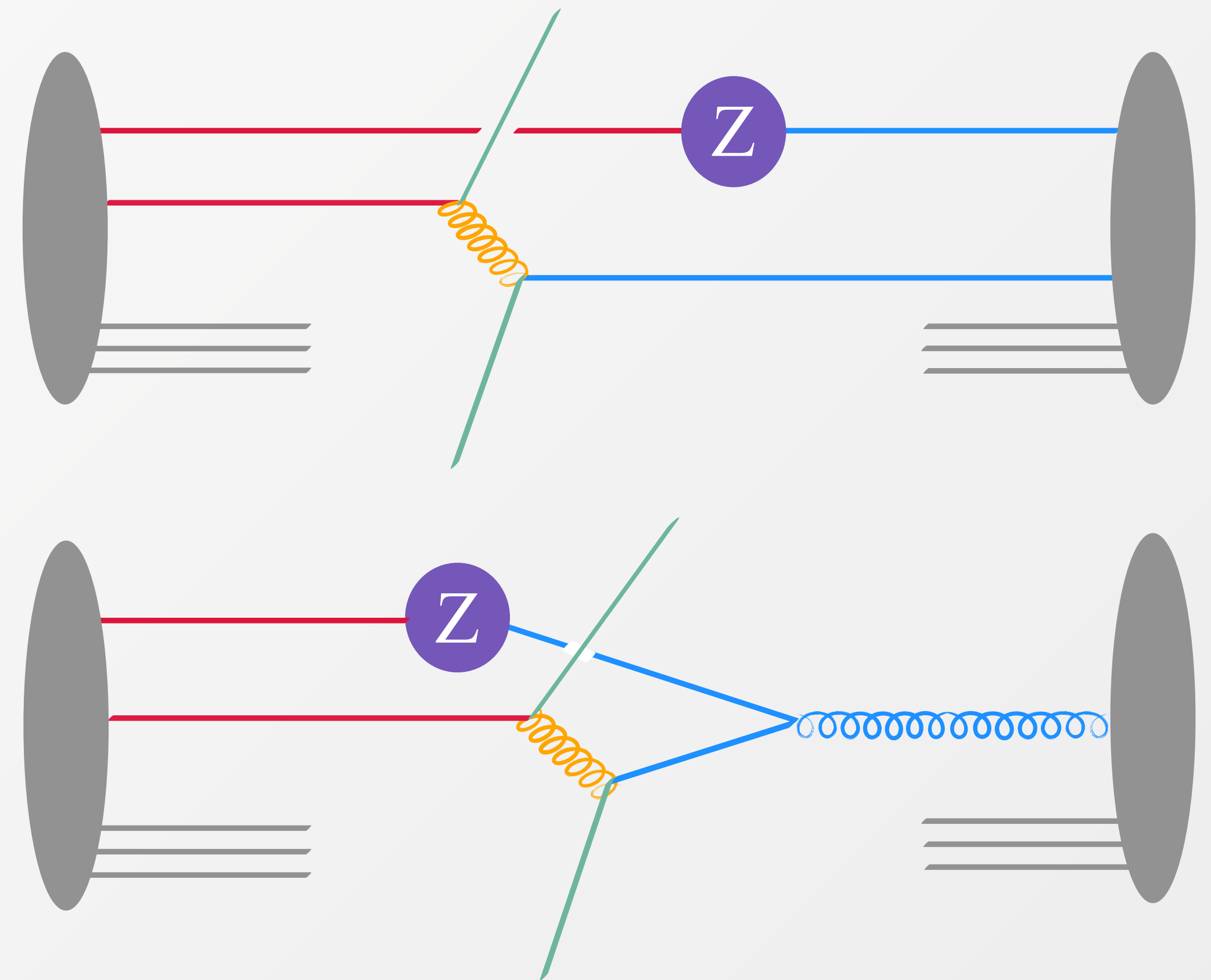
- how does  $\sigma_{\text{eff}}$  depend on kinematics of the jets? ( $\rightarrow$  in Pythia,  $\sigma_{\text{eff}} \simeq 30 \text{ mb}$ , fairly independently of jet  $p_t$ )

## 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  $\rightarrow$  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:

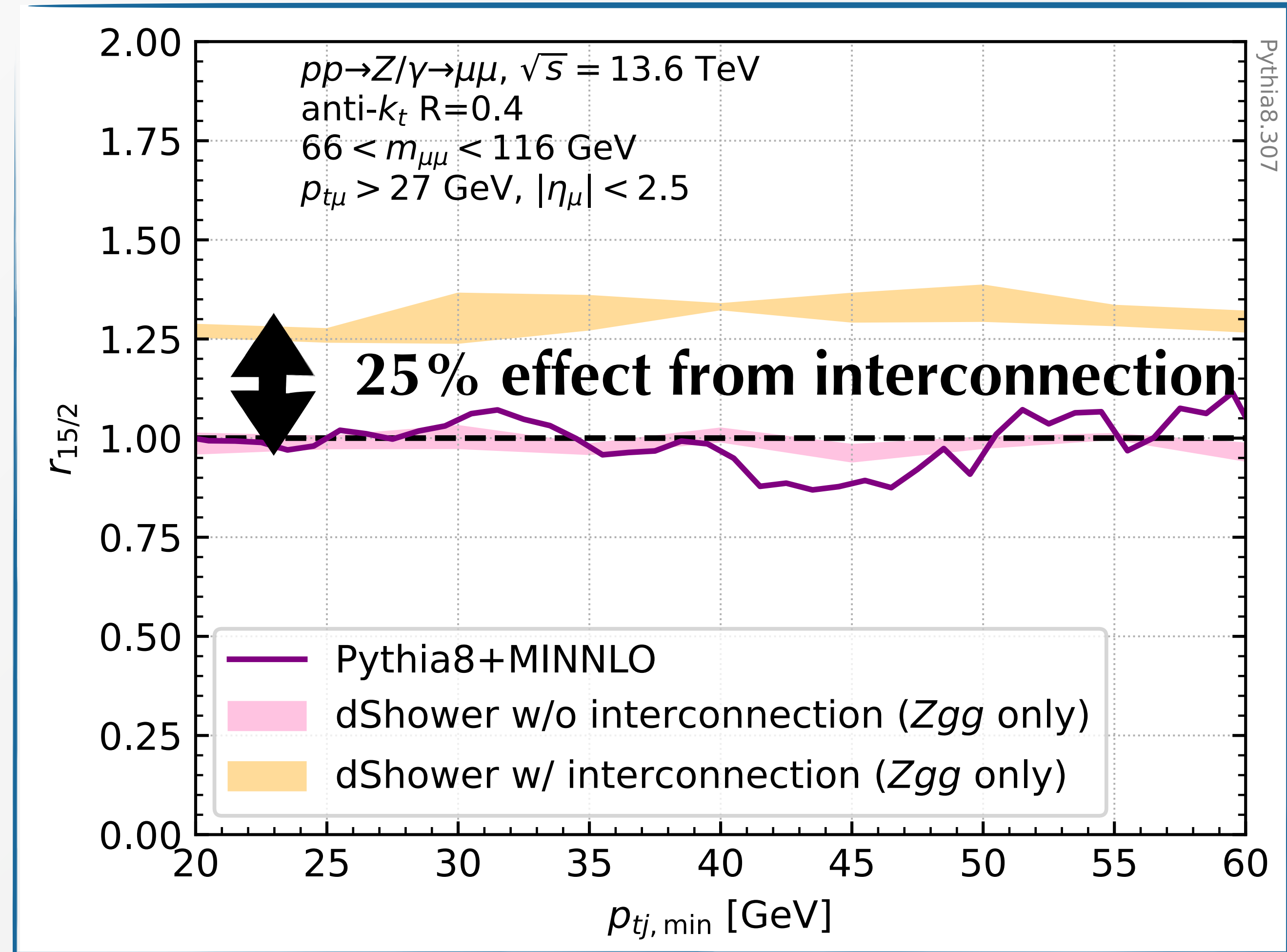
- tight (2 GeV)
- loose (15 GeV)

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]

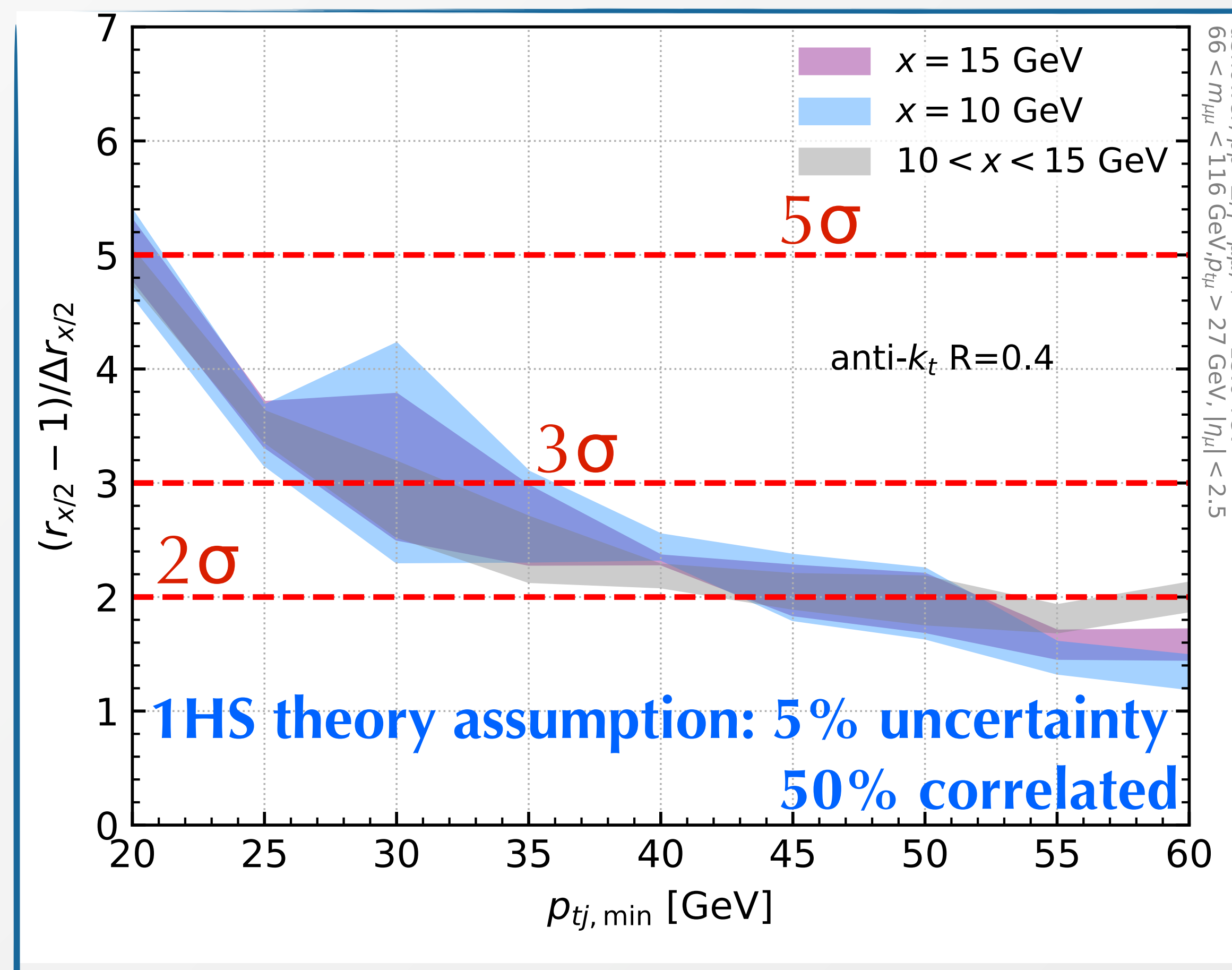


# Interplay of significance with MPI purity

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

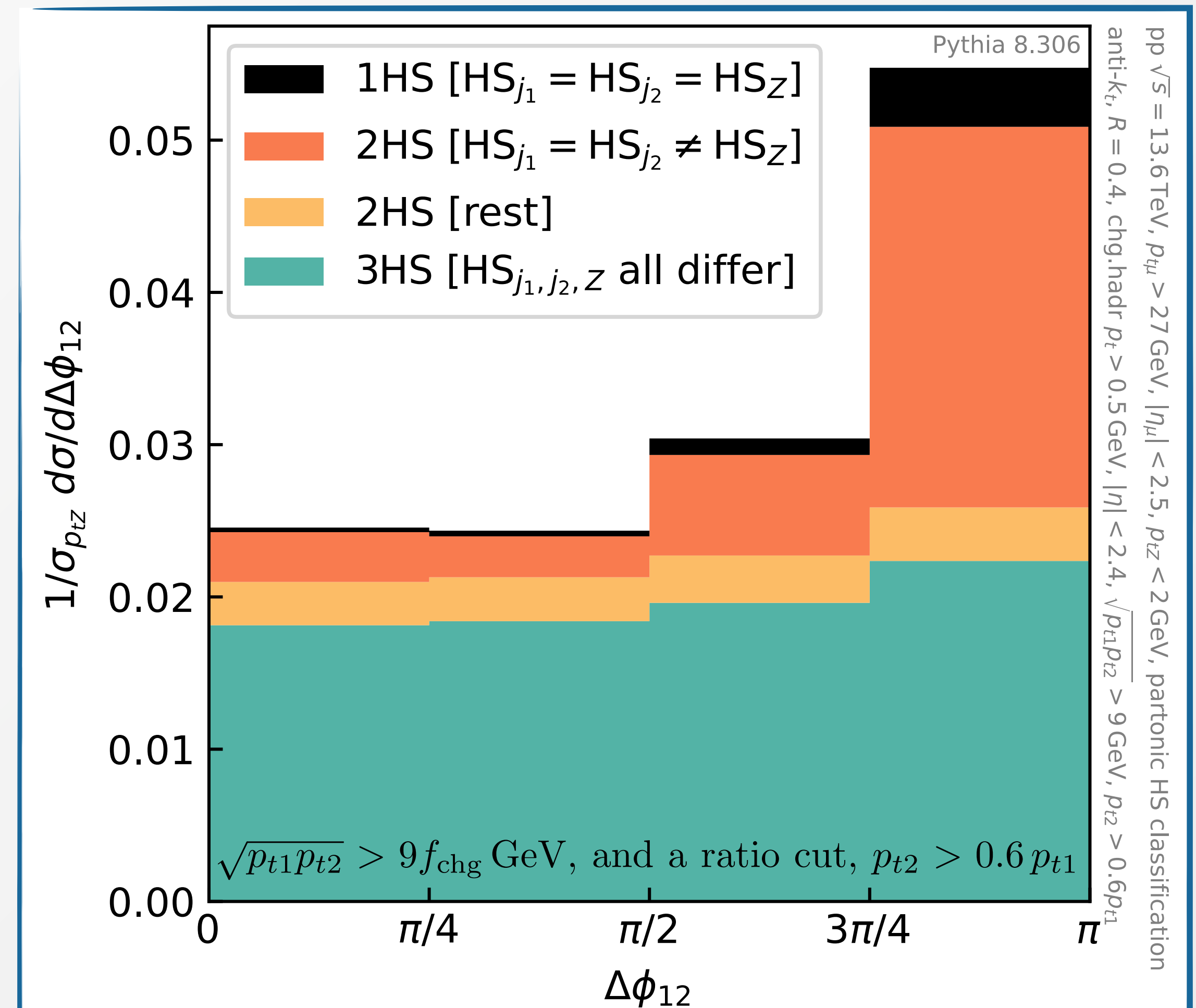
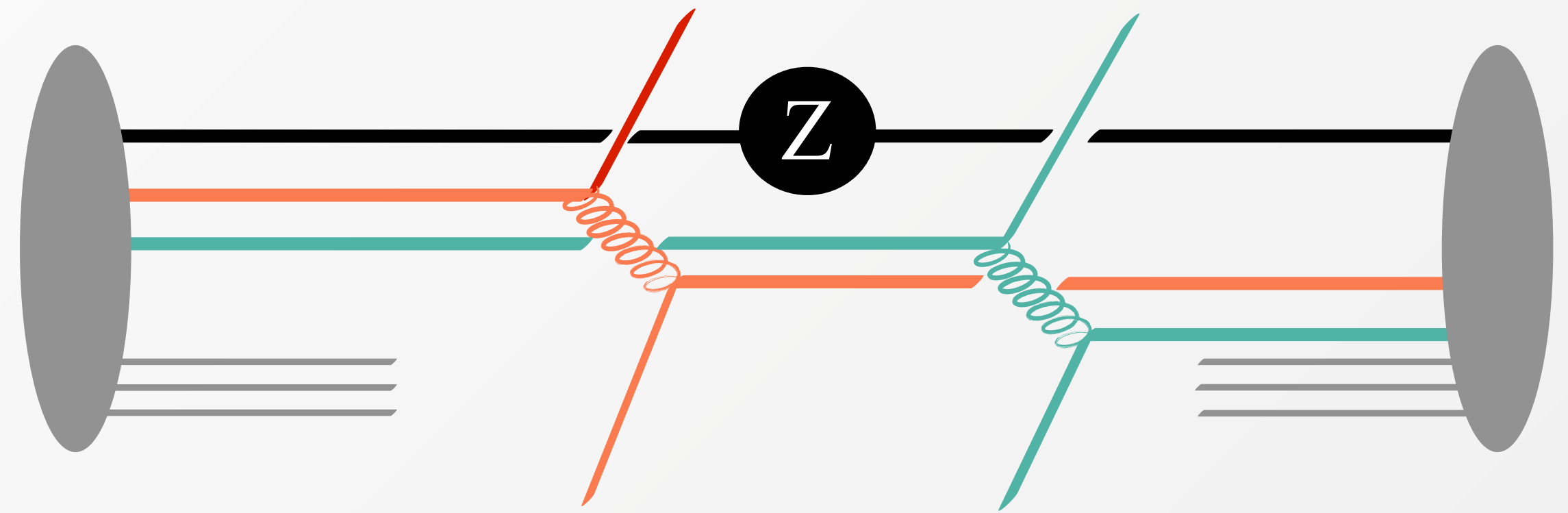
- **Just barely feasible?**
- motivates NNLO (matched)  $Z+2j$  calculations to reduce current theory uncertainty (10-20%)

## significance of signal of perturbative interconnection



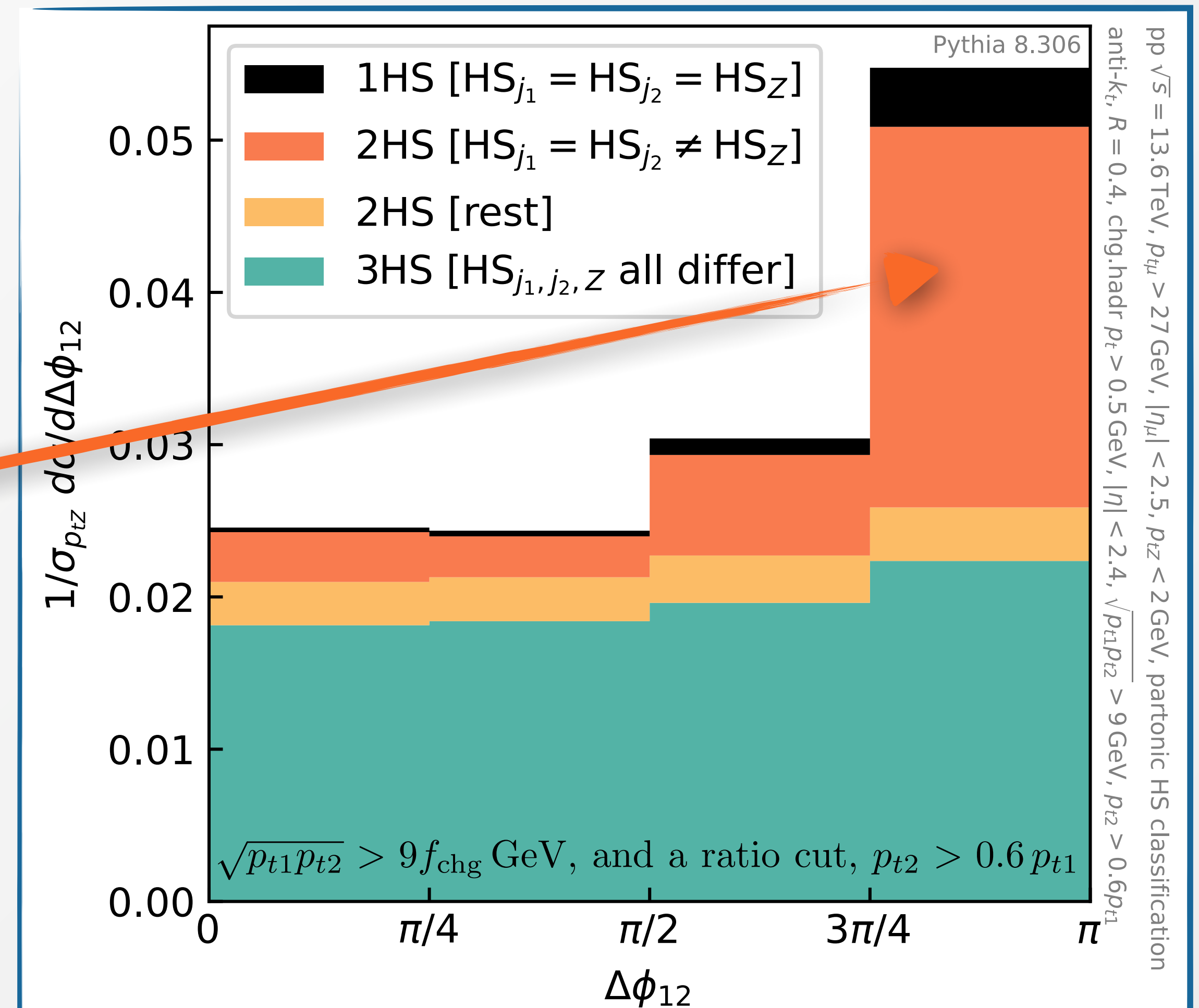
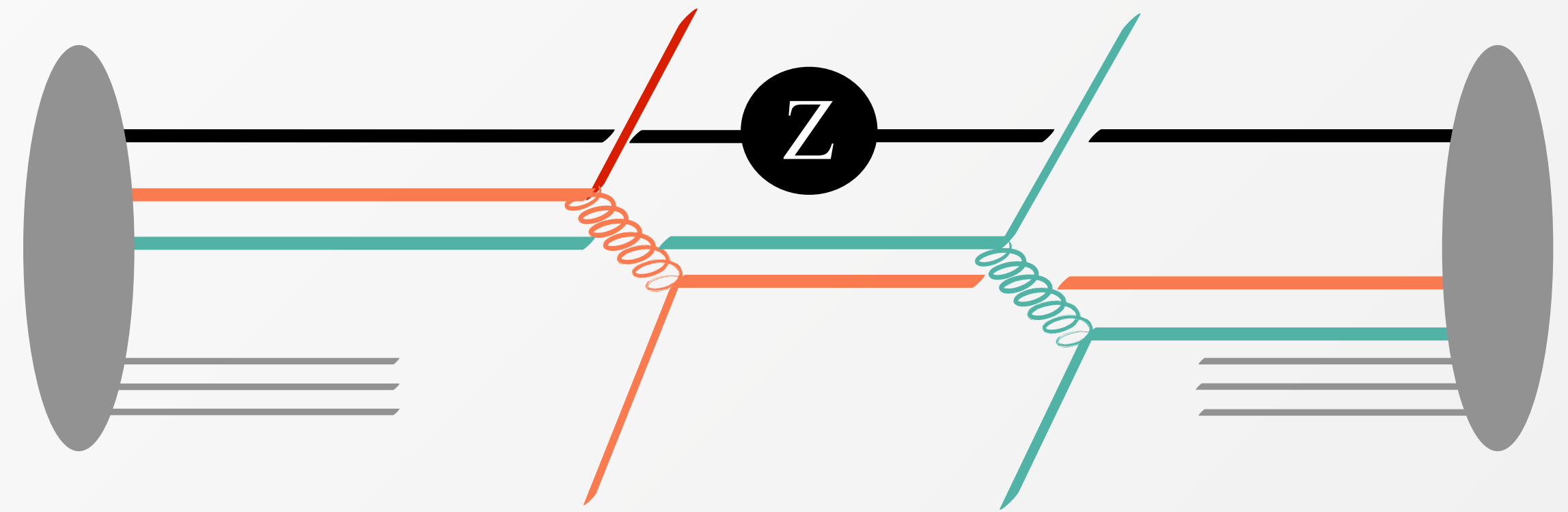
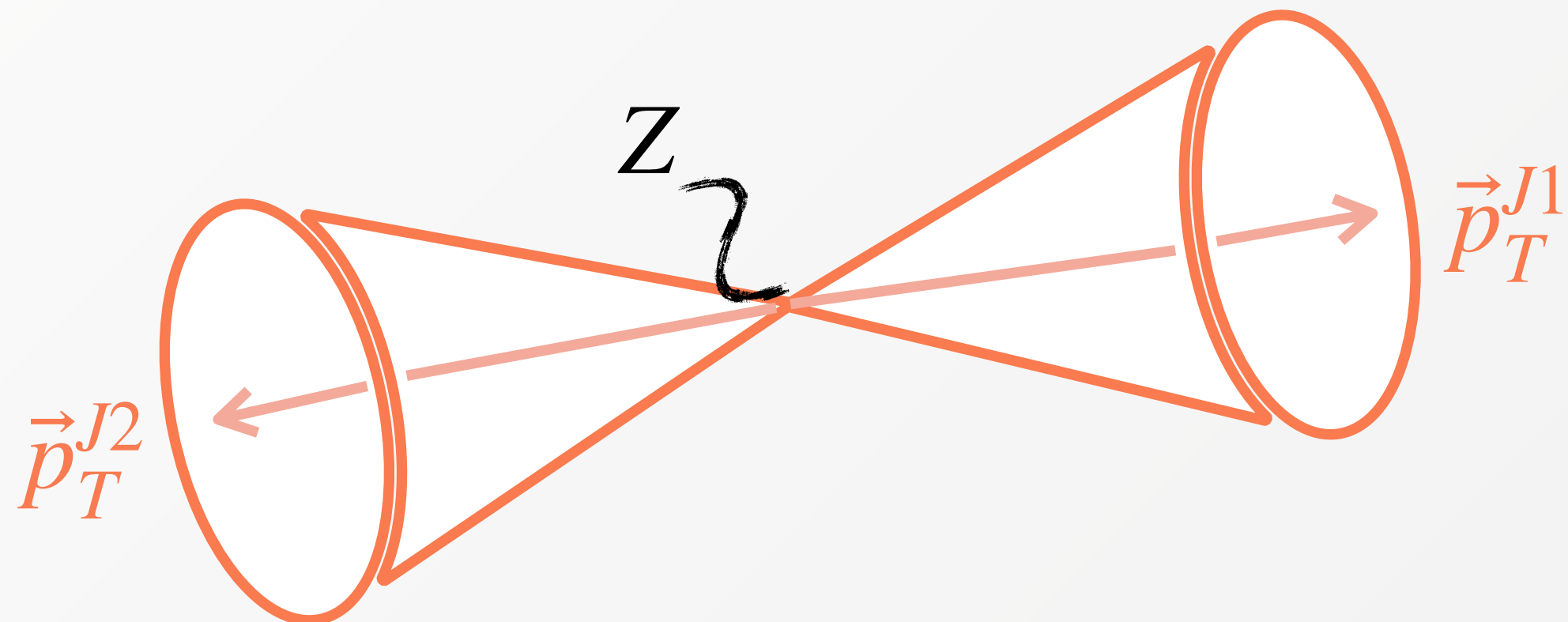
## Beyond 2HS

- Only measurements of 3HS are in  $J/\psi$  production, which is a difficult process to interpret even with just 1HS!
- Instead, put tight  $p_{tZ} < 2$  GeV cut and look at  $\Delta\phi$  between two leading charged-track jets, with low  $p_{tj}$  cuts ( $\sim 5$  GeV on charged-track sum)



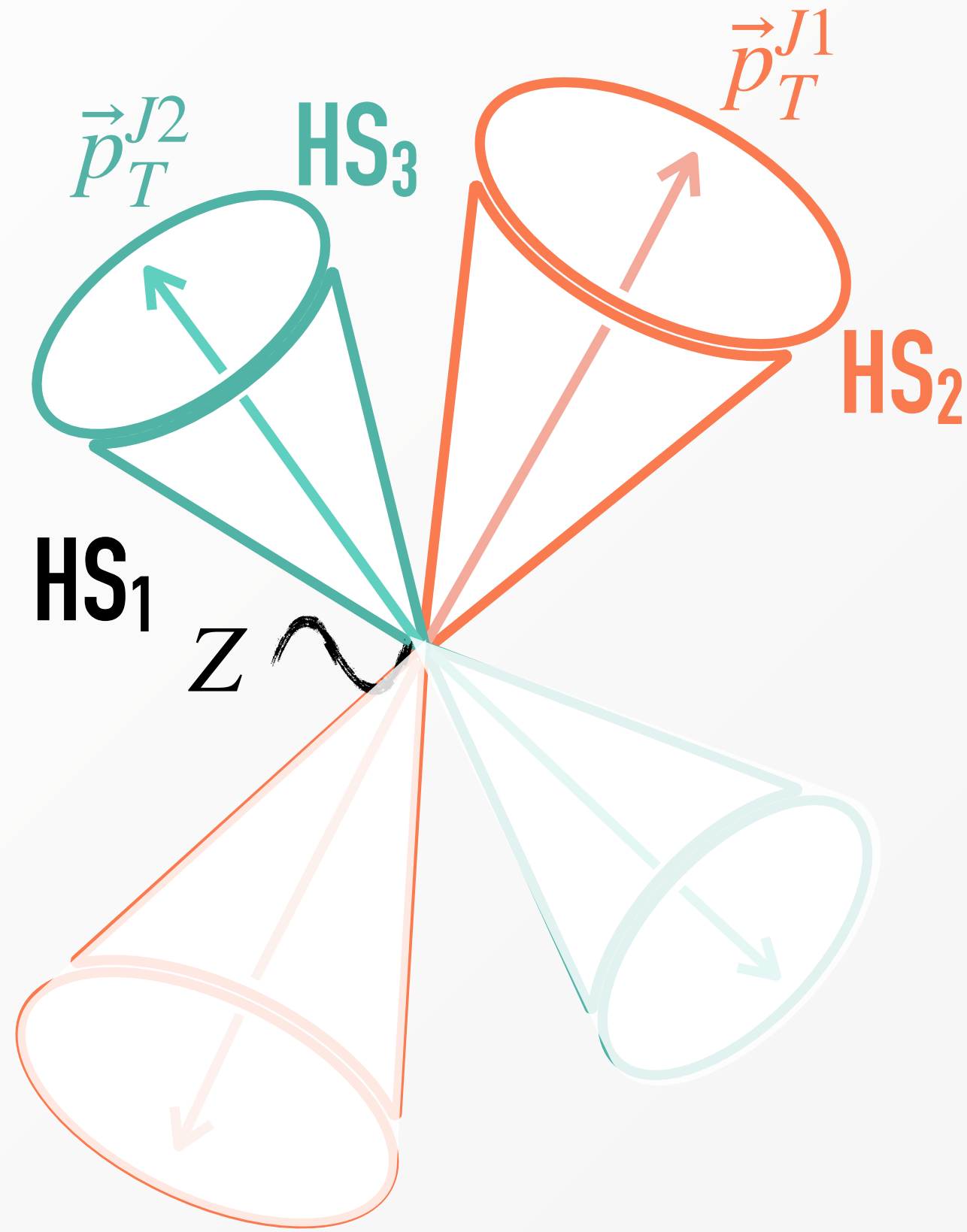
## Beyond 2HS

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- Instead, put tight  $p_{tZ} < 2$  GeV cut and look at  $\Delta\phi$  between two leading charged-track jets, with low  $p_{tj}$  cuts ( $\sim 5$  GeV on charged-track sum)
- gives clear **2HS** peak at  $|\Delta\phi| \simeq \pi$

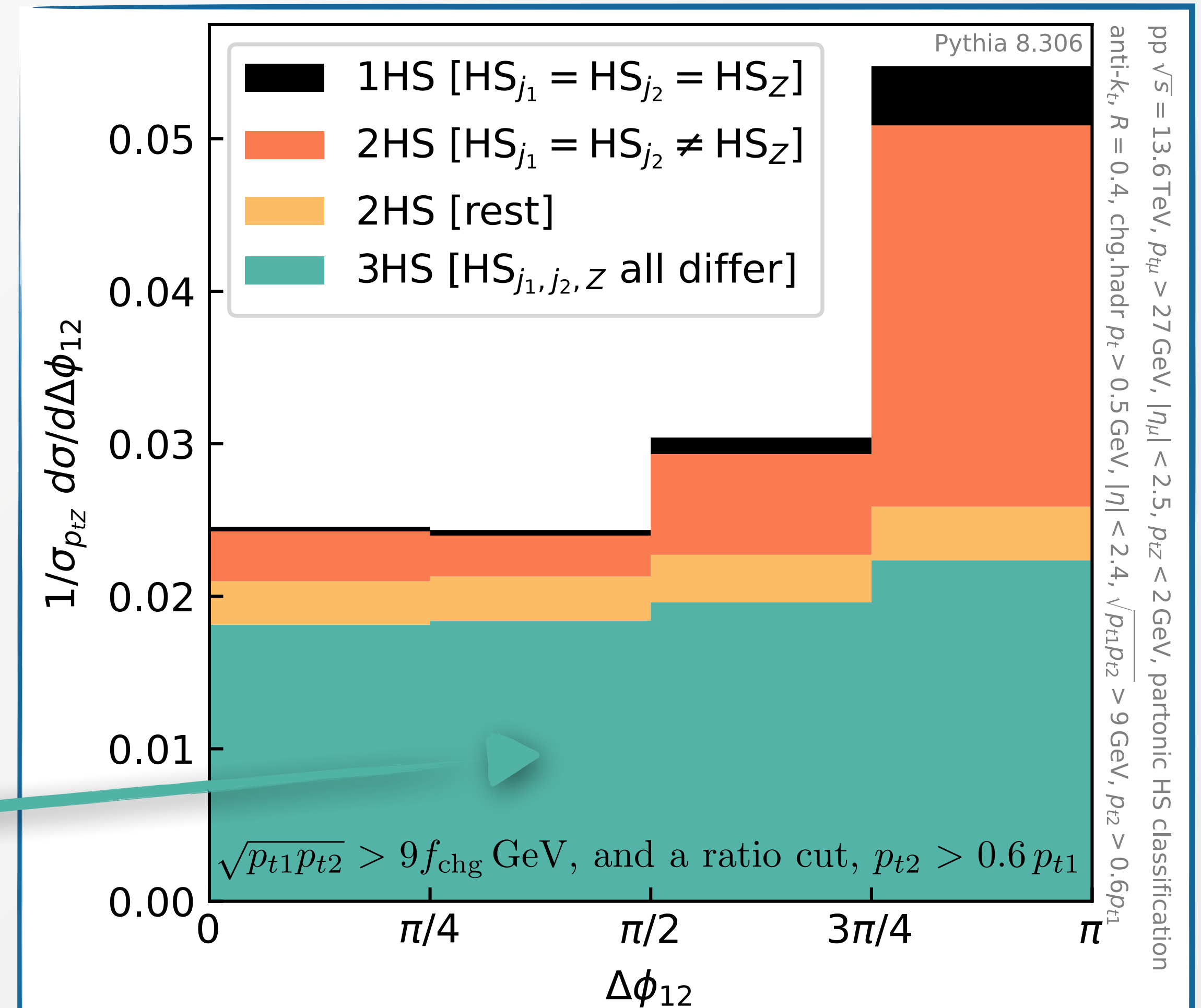
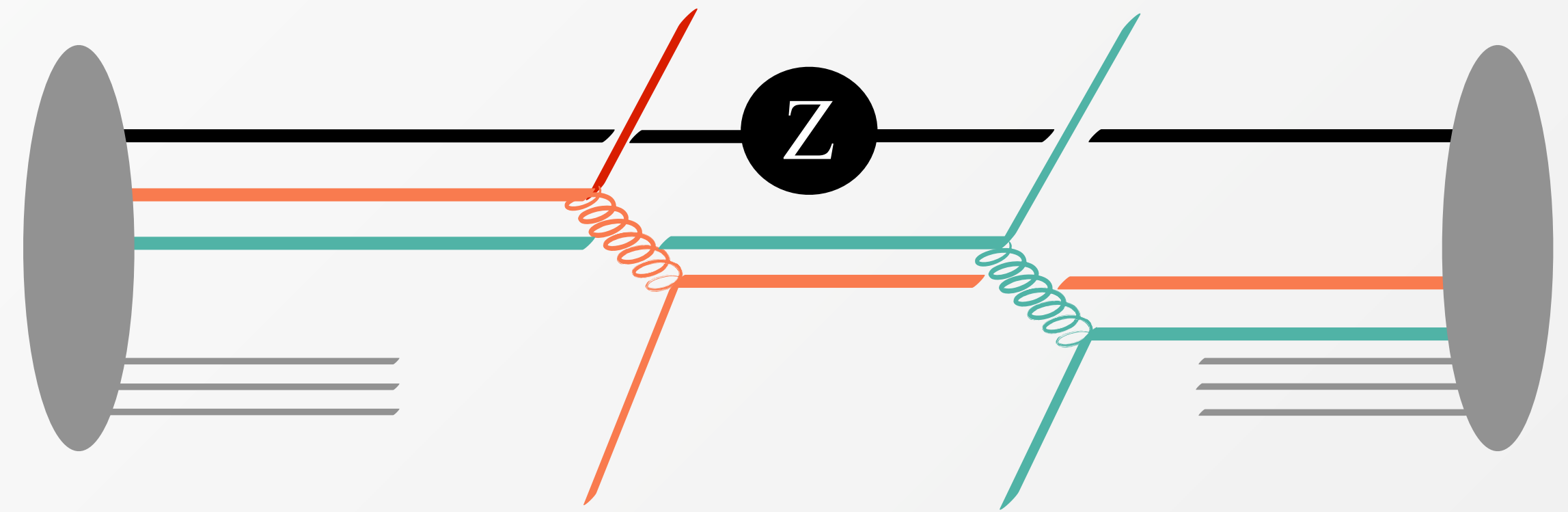


# Beyond 2HS

$$0 < \Delta\phi_{12} < \pi$$

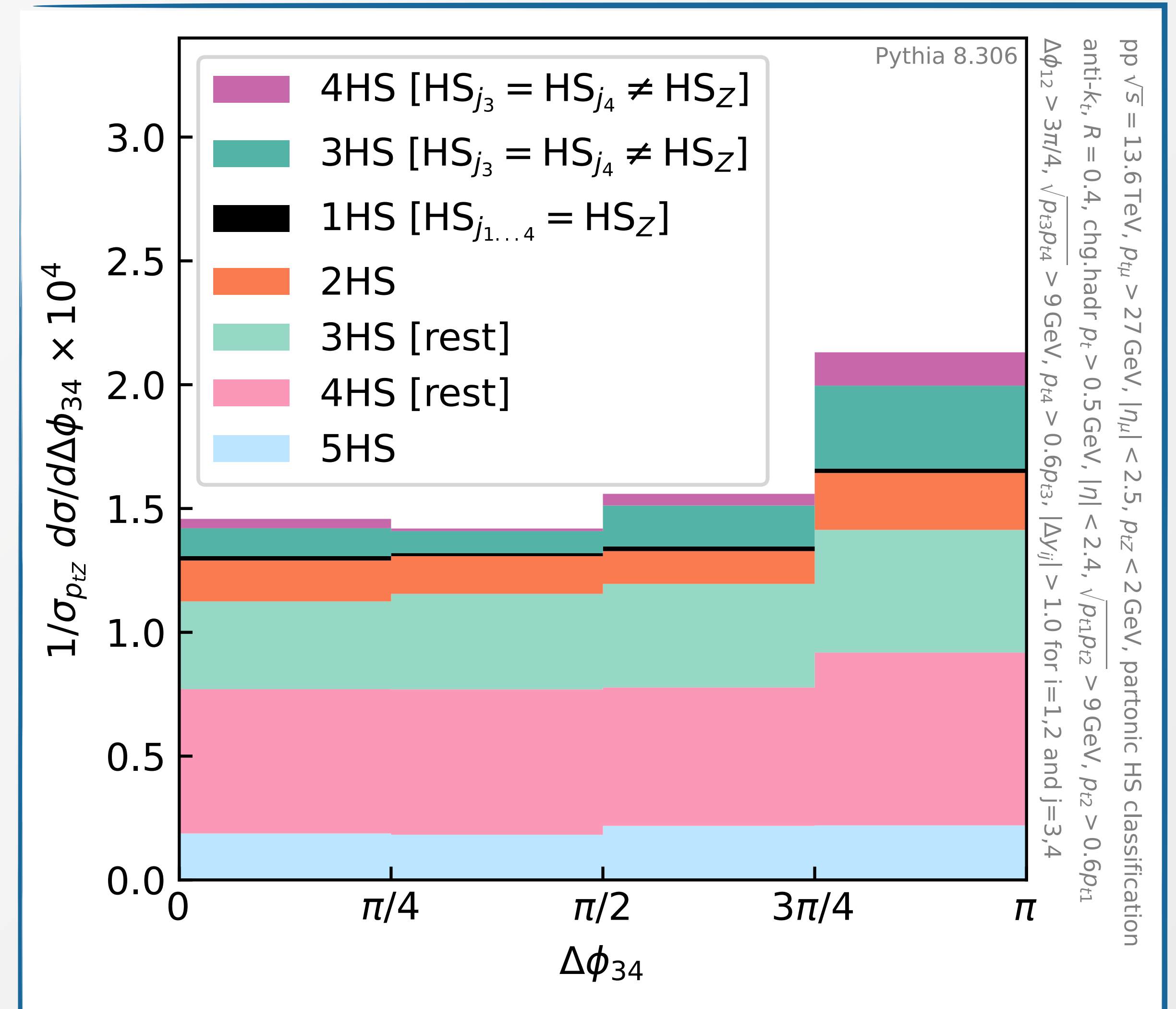


- gives distribution ~independent of  $|\Delta\phi|$ , when the Z and the 2 jets each come from different hard scatters (**total of 3HS**)



# Beyond 2HS

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



# Conclusion

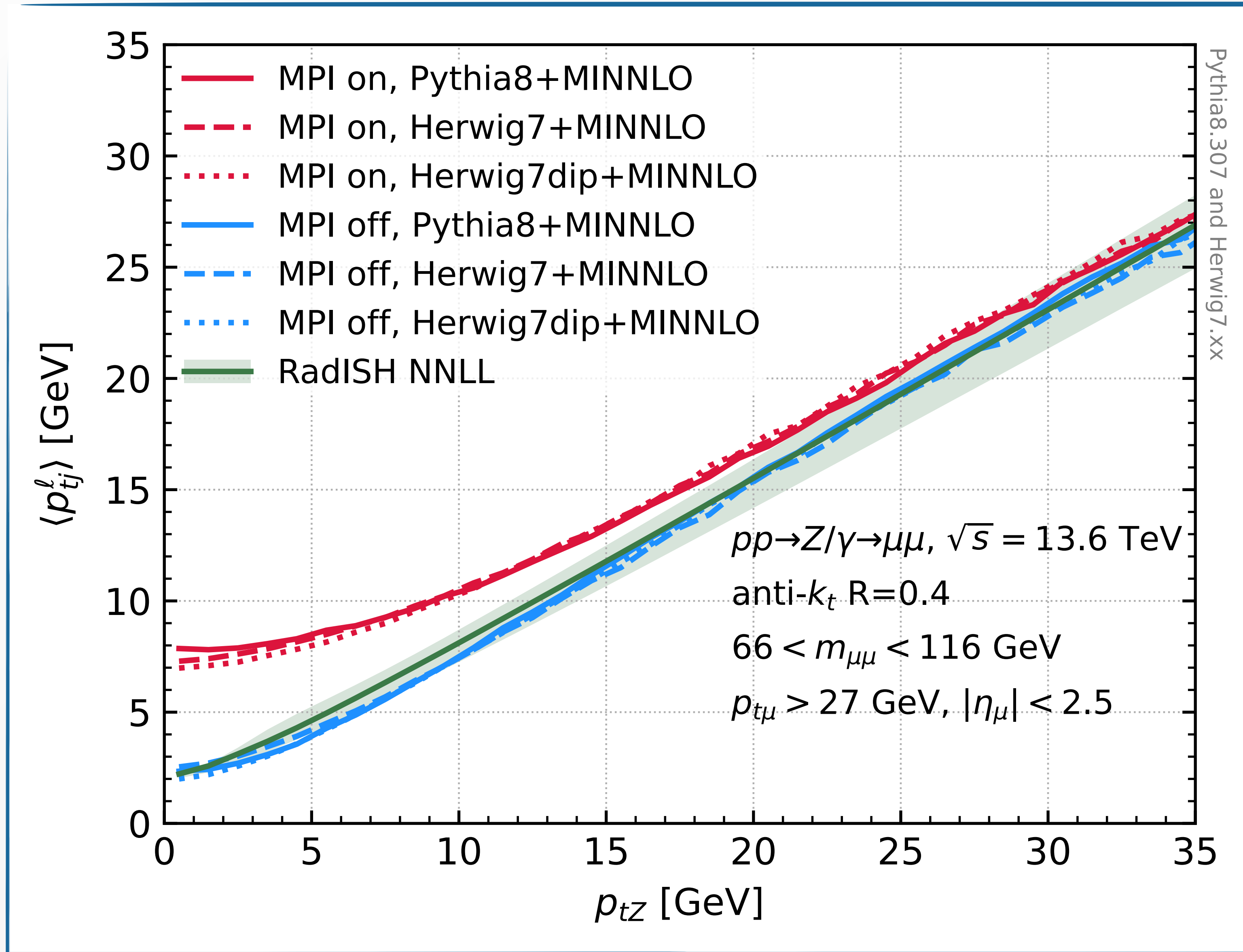
- Modelling of MPI is an essential component of all major simulation tools, but its quantitative study remains challenging
- Process with one (or more) hard extra interaction, 2HS/3HS etc, is interesting as a signal, and as a background to rare processes
- The insight gained by studying hard MPI may improve the modelling of soft MPI for MB/UE: soft MPI models are often conceived as extensions of the one used for harder MPI
- Study of Drell-Yan events with tight cut on  $p_{tZ}$  opens door to numerous new MPI studies (high-purity 2HS samples, interconnections, 3HS studies)

## Overall

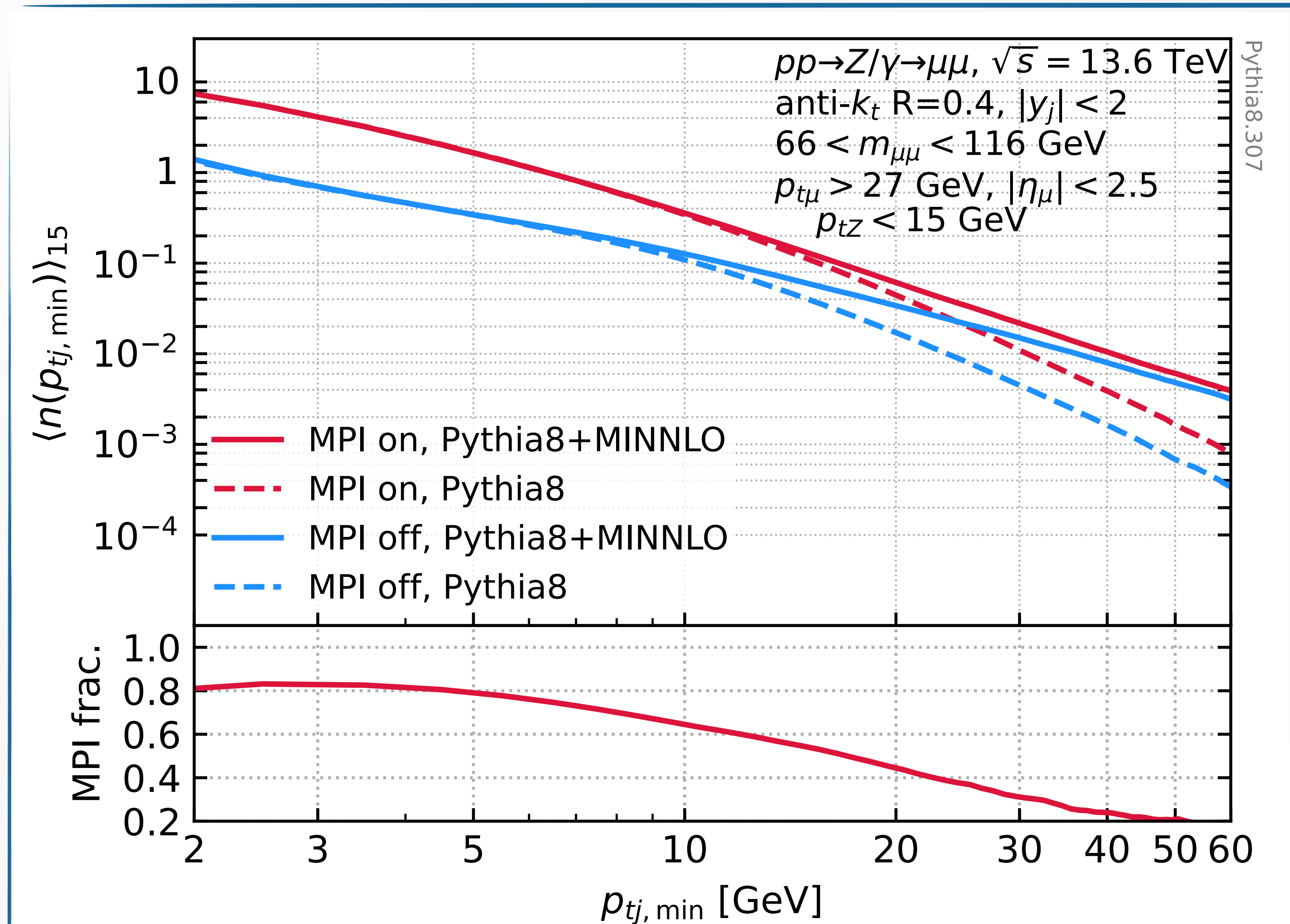
potential for significant impact on conceptual and quantitative understanding of MPI

# Backup

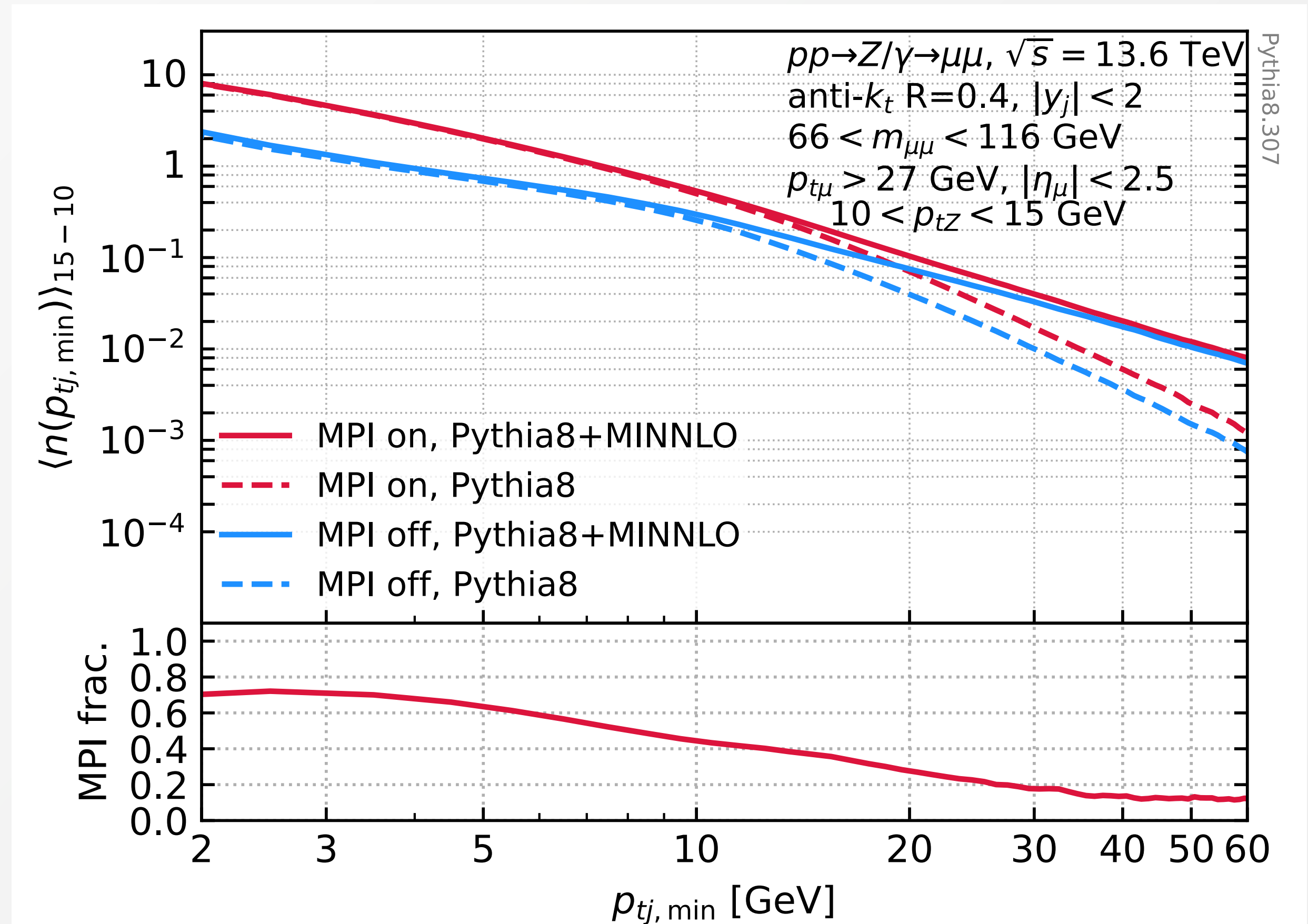
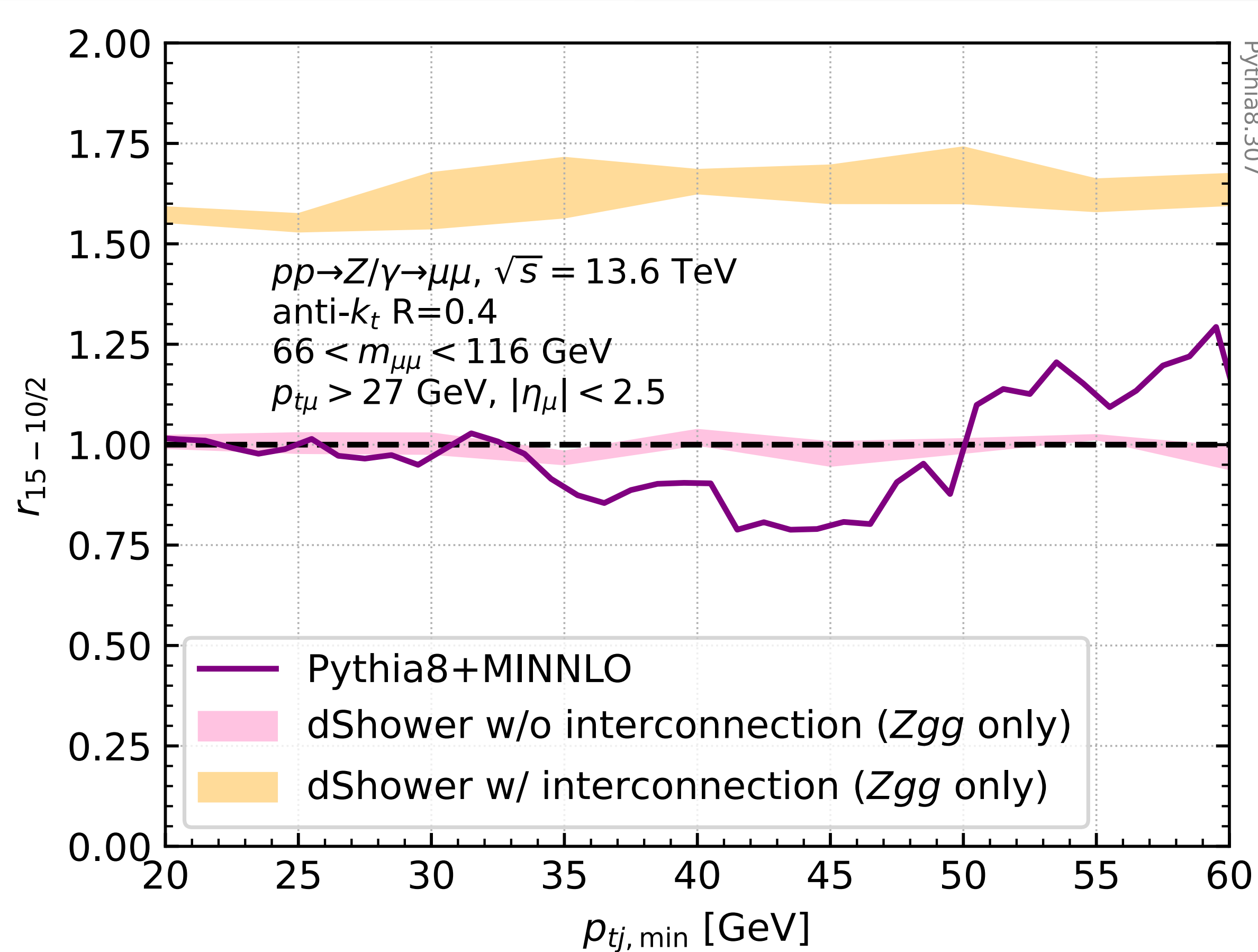
# HERWIG results



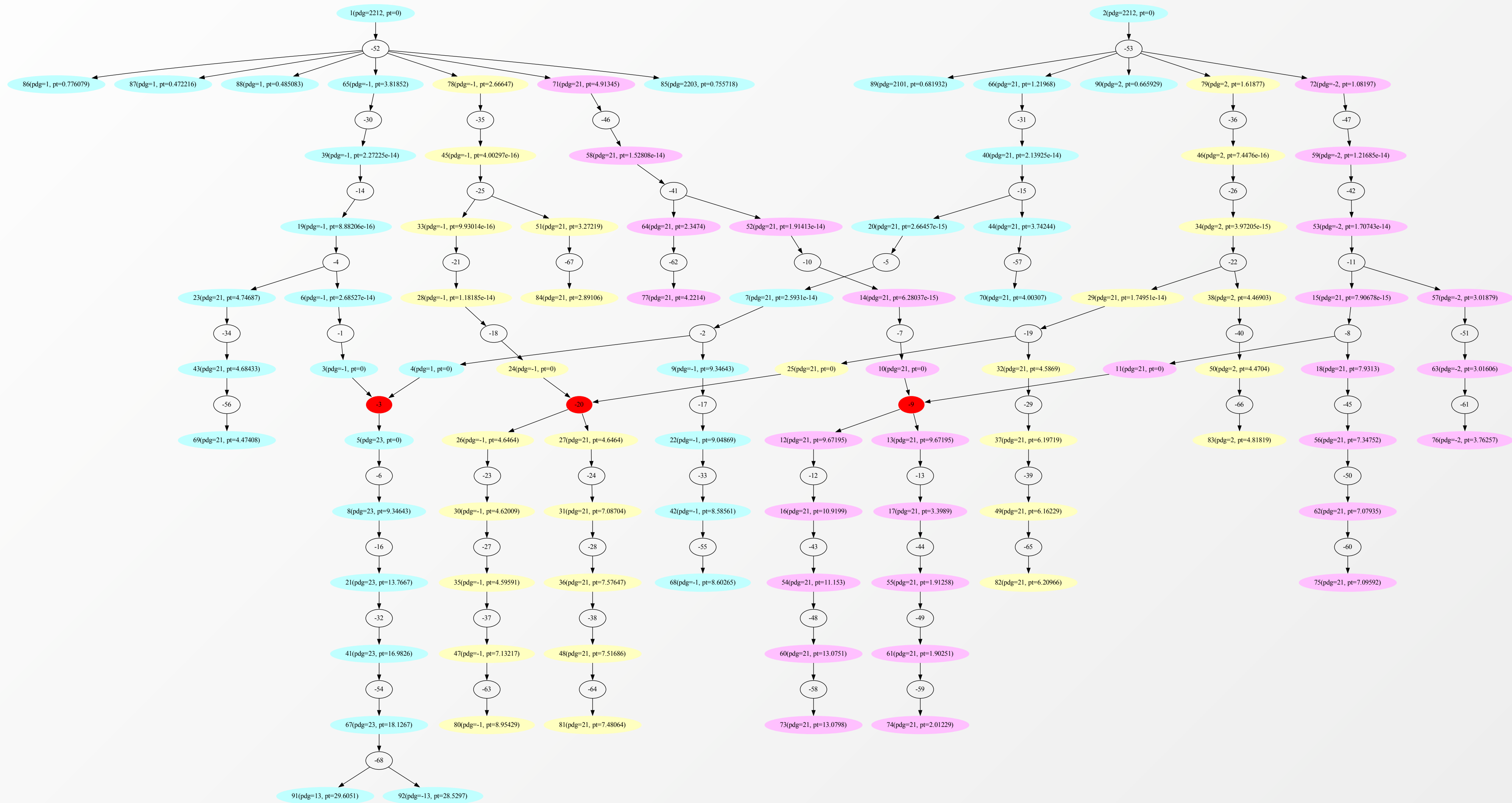
# MPI purity with 15 GeV cut on $p_{tZ}$



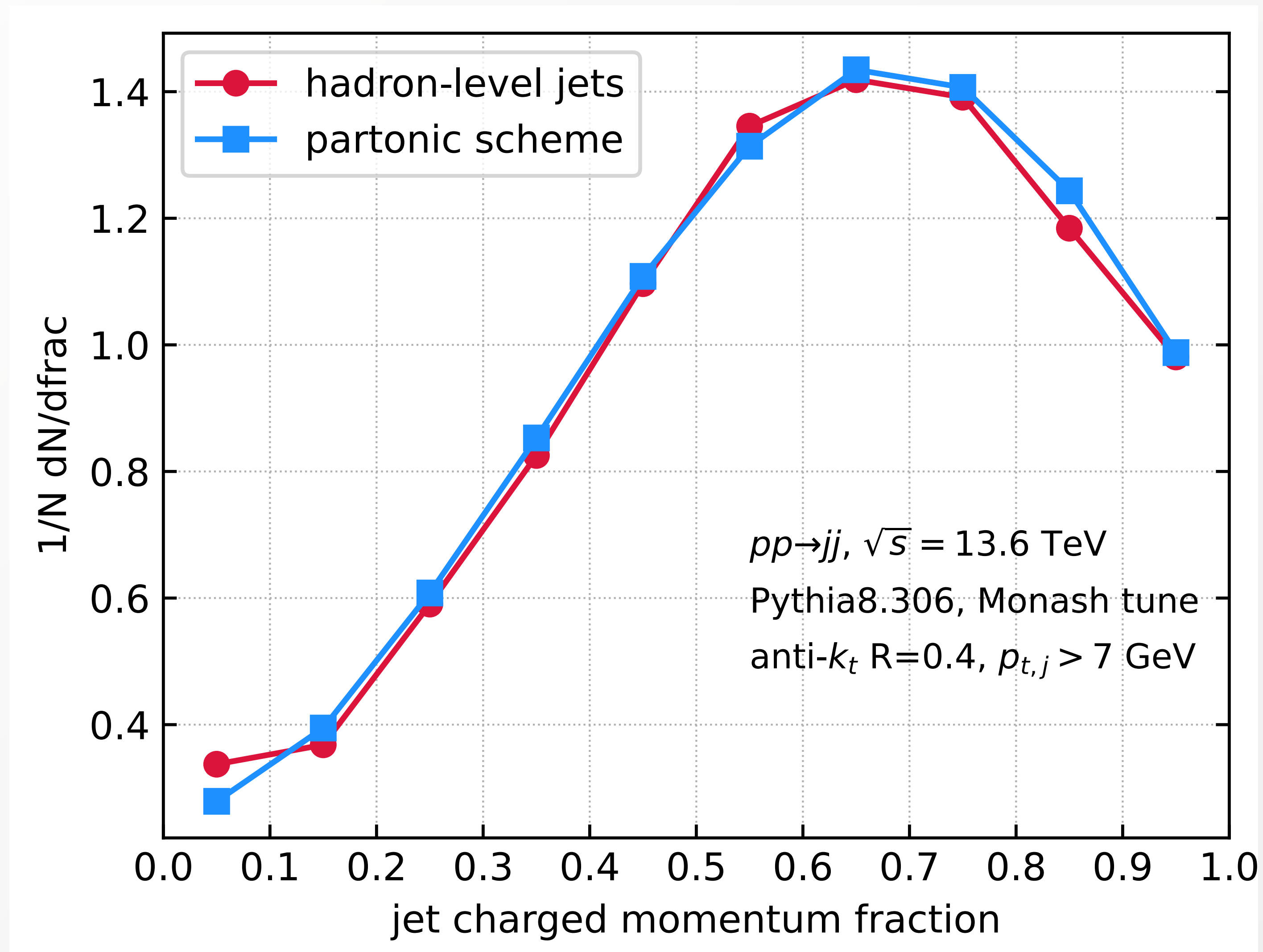
# $10 < p_{tZ} < 15$ GeV for the loose sample: increases interconnection, reduces purity



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



# Validation of simple parton $\rightarrow$ charged hadron conversion for hard-scatter classification



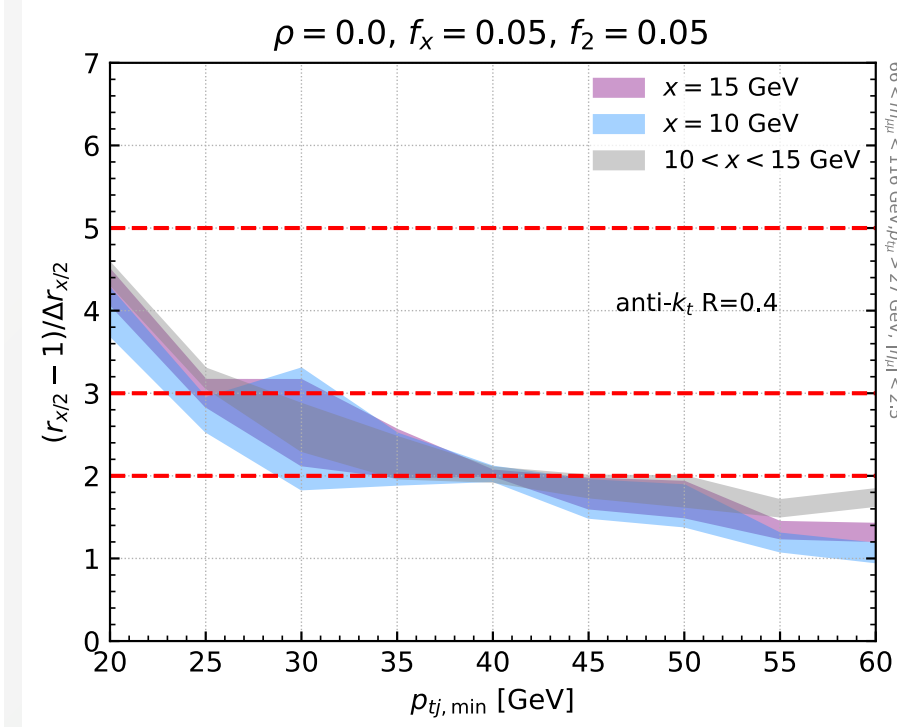
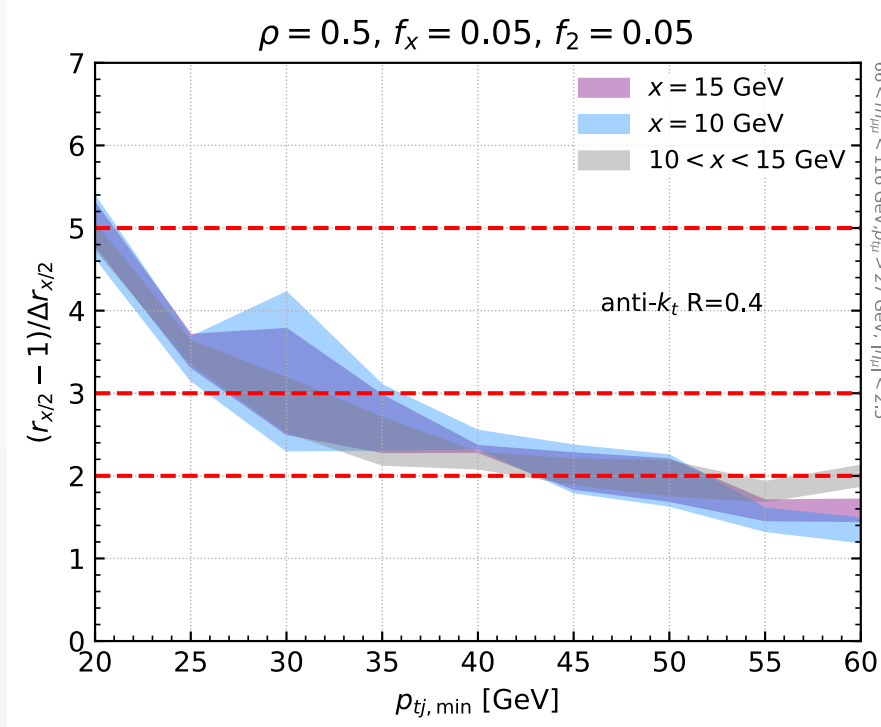
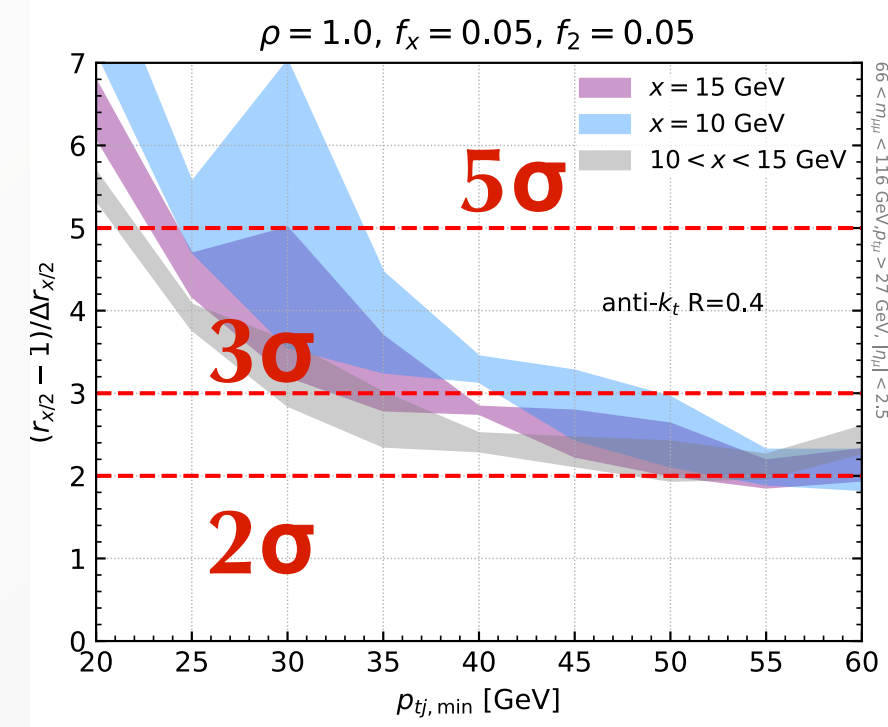
# Interplay of significance with MPI purity in different scenarios

1HS Th. uncert.  $\rightarrow$  100% correlated

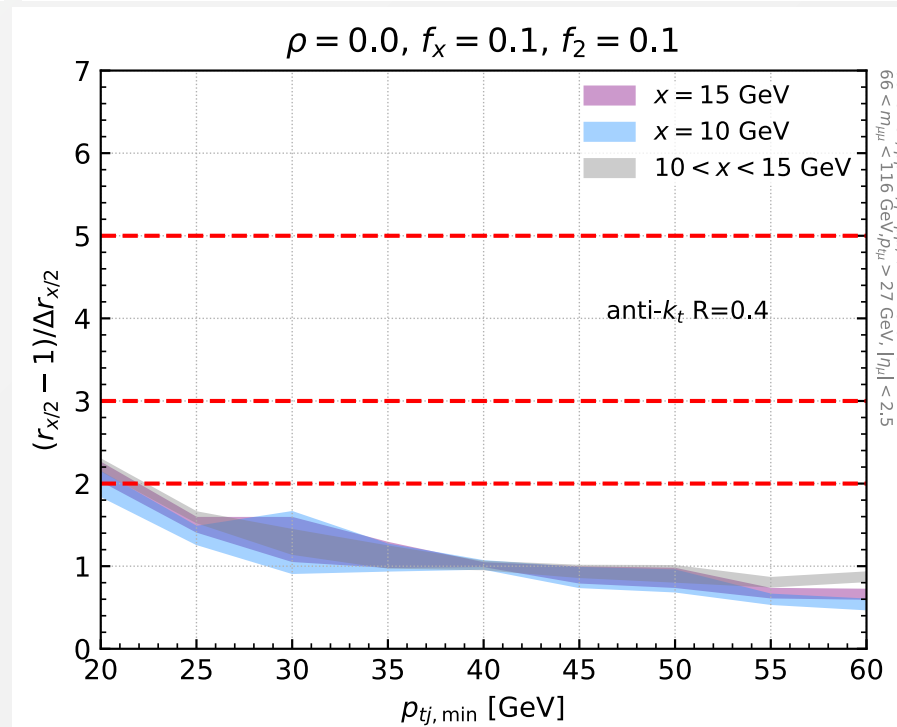
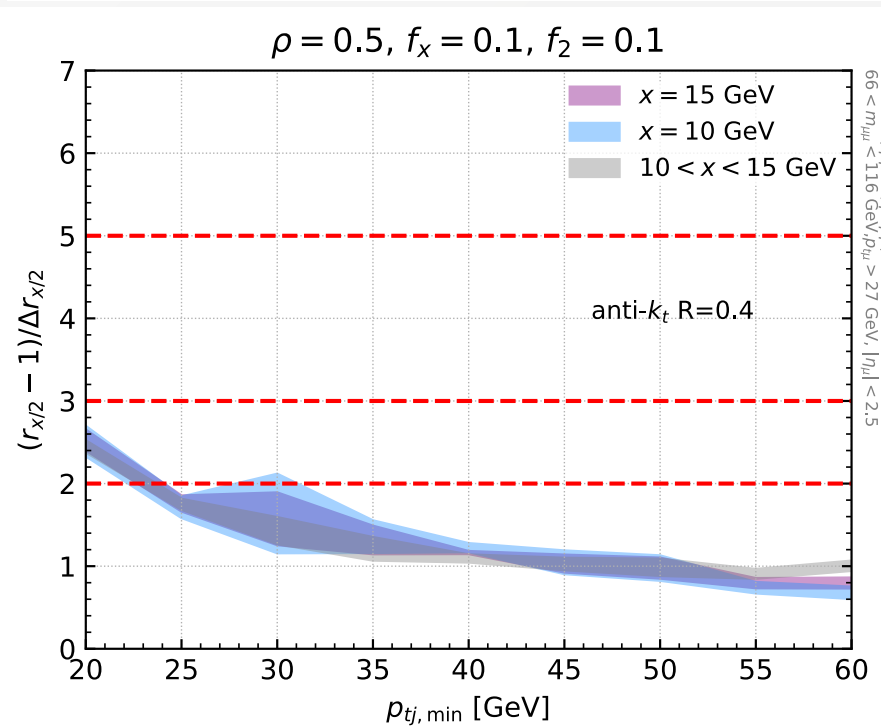
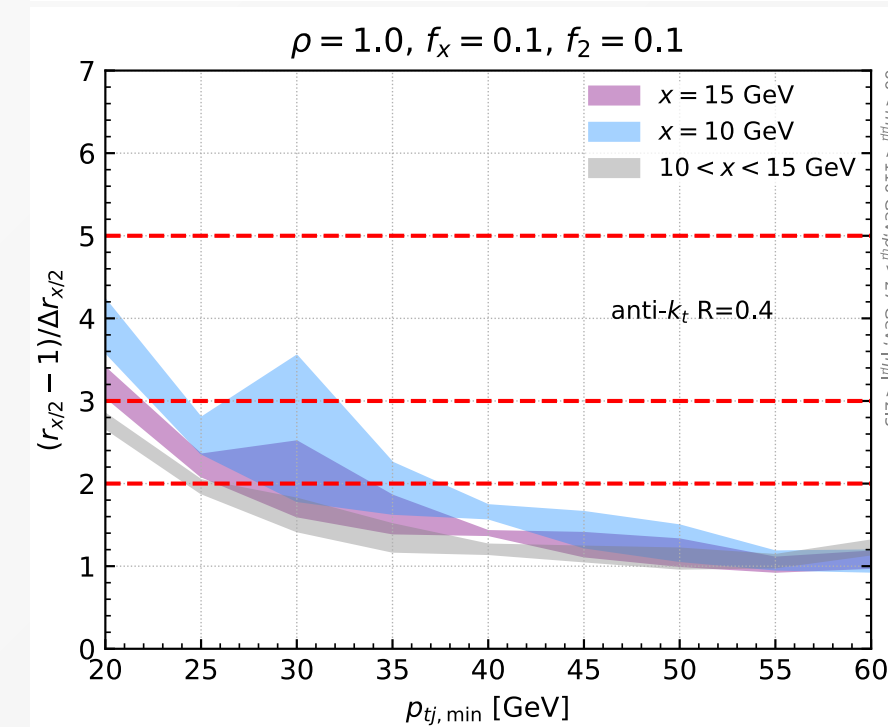
50% correlated

uncorrelated

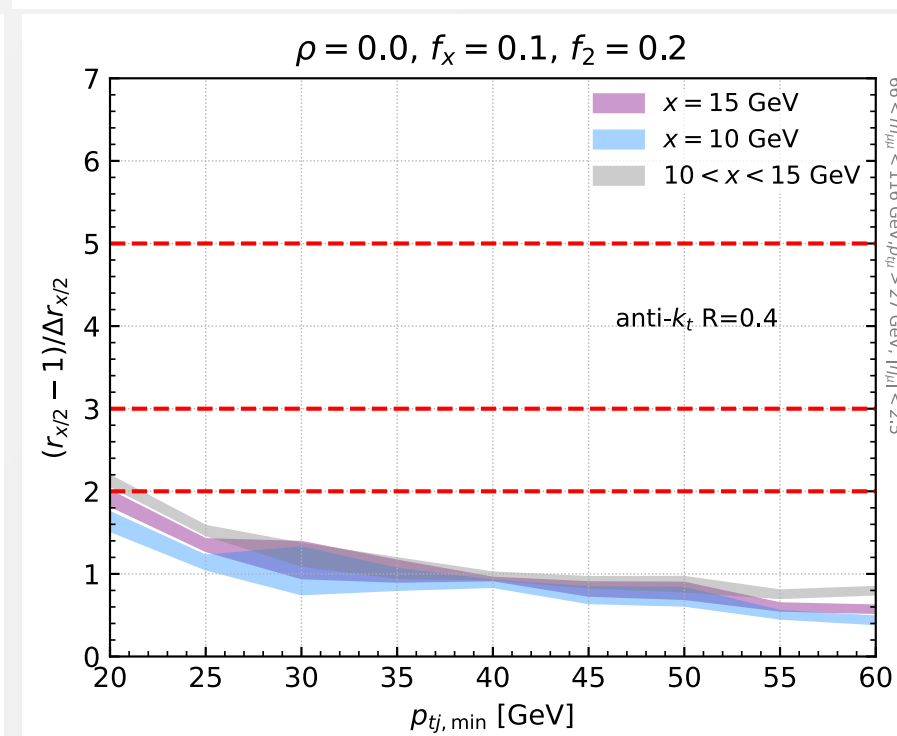
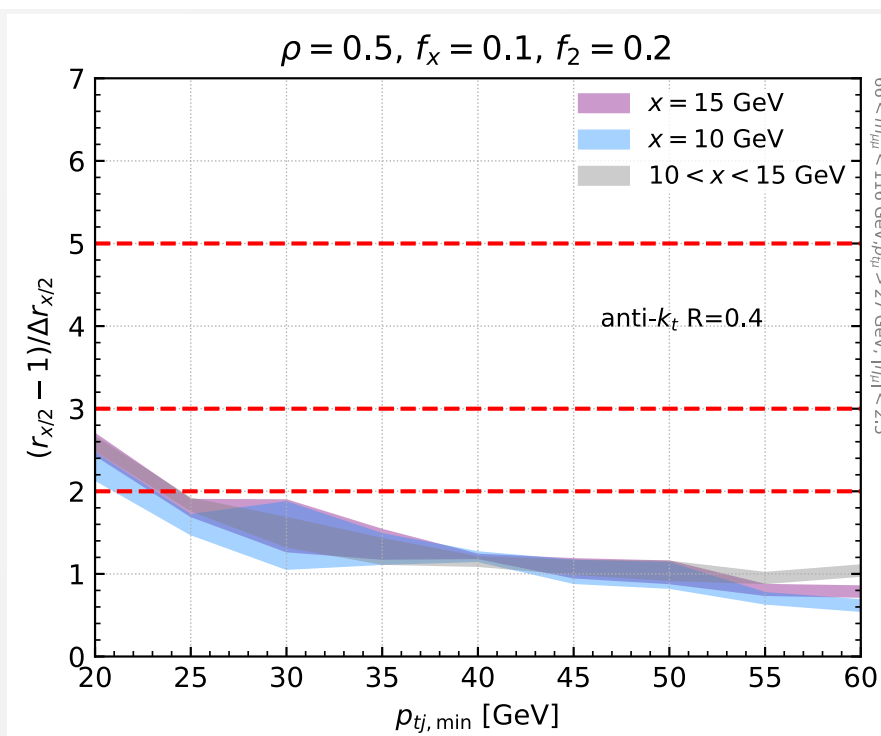
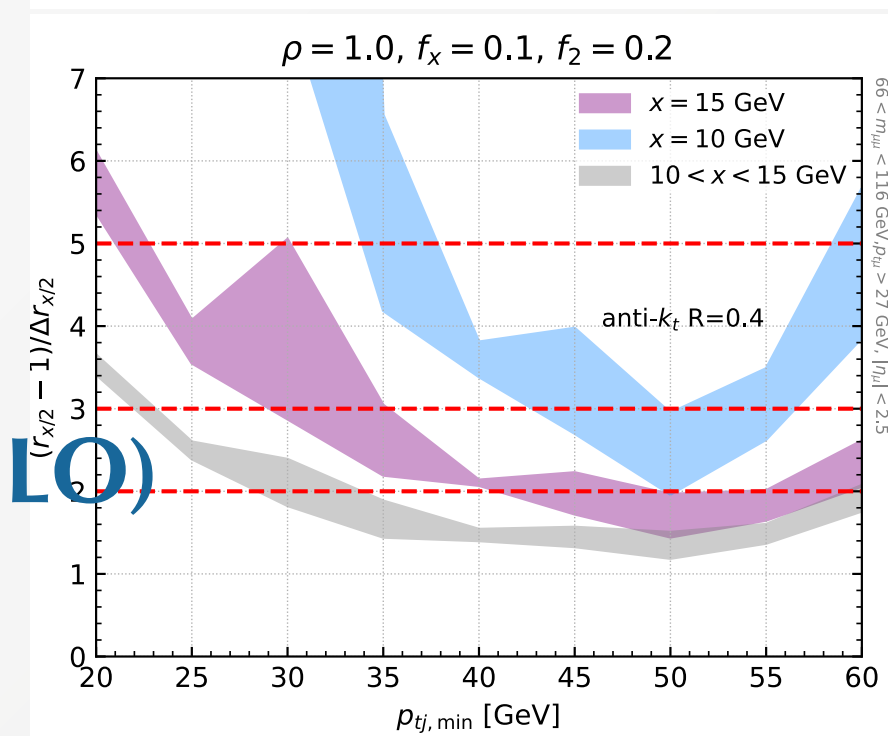
$\downarrow$   
5%



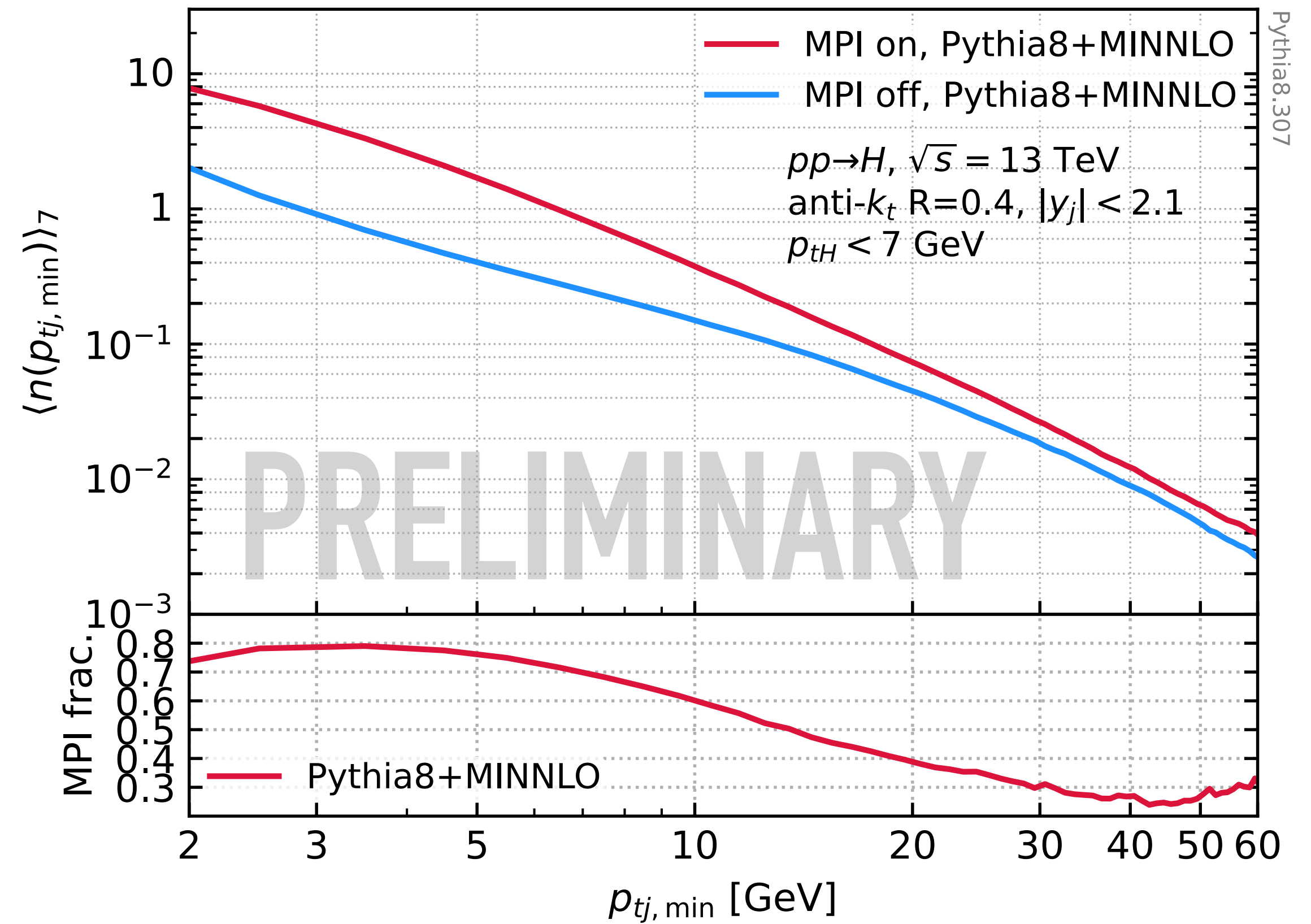
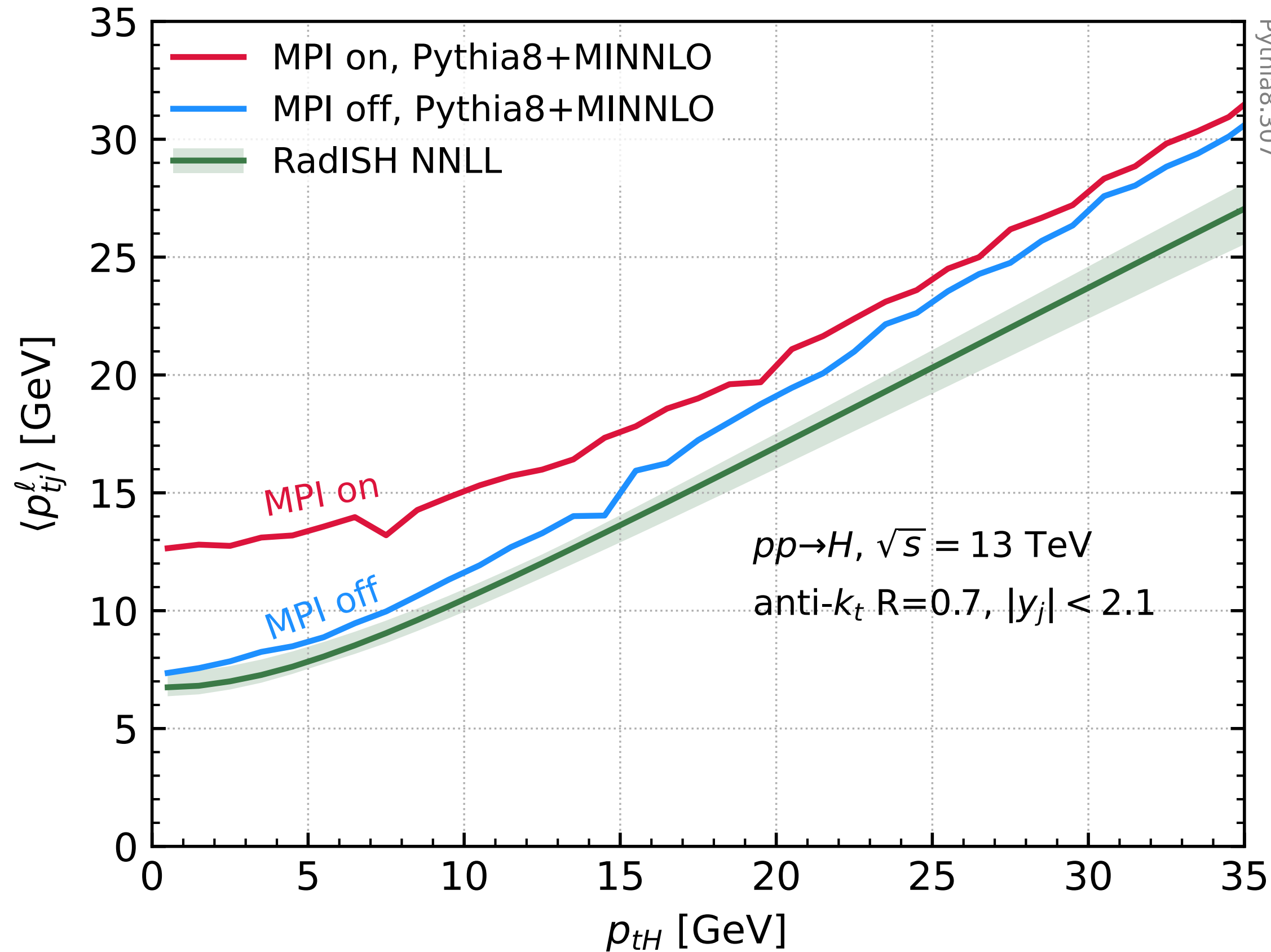
10%



10%  
/ 20%  
(=MINNLO)



# Higgs production (gg channel said to have smaller $\sigma_{\text{eff}}$ , mainly from $J/\psi$ )



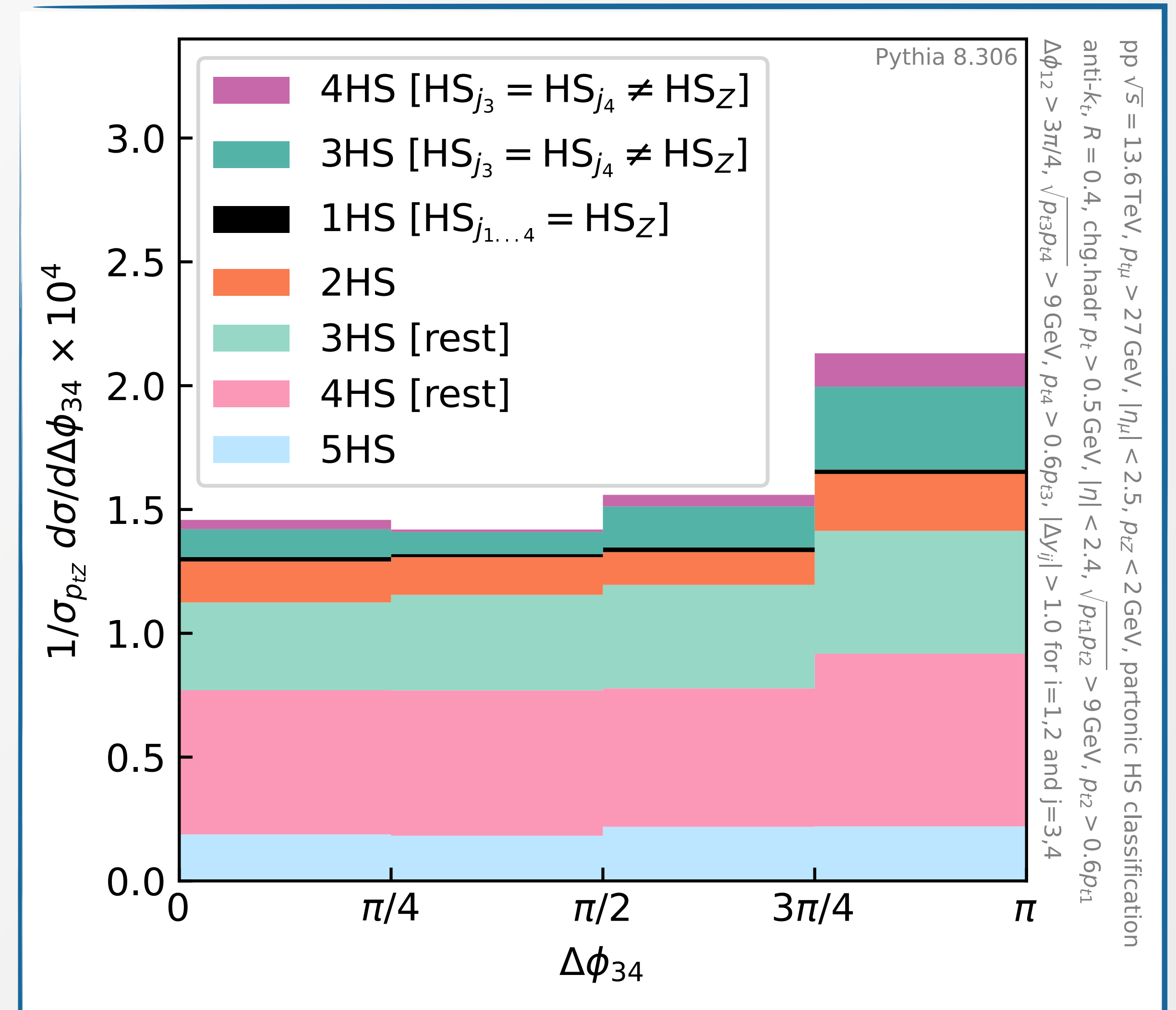
Optimal cut is  $p_{tH} \lesssim 7$  [GeV]

~10% of events H events pass this cut

(with  $p_{tH}$  cut, full run 2+3 stats in  $H \rightarrow ZZ^* \rightarrow 4\ell$  c. 50–100 events)

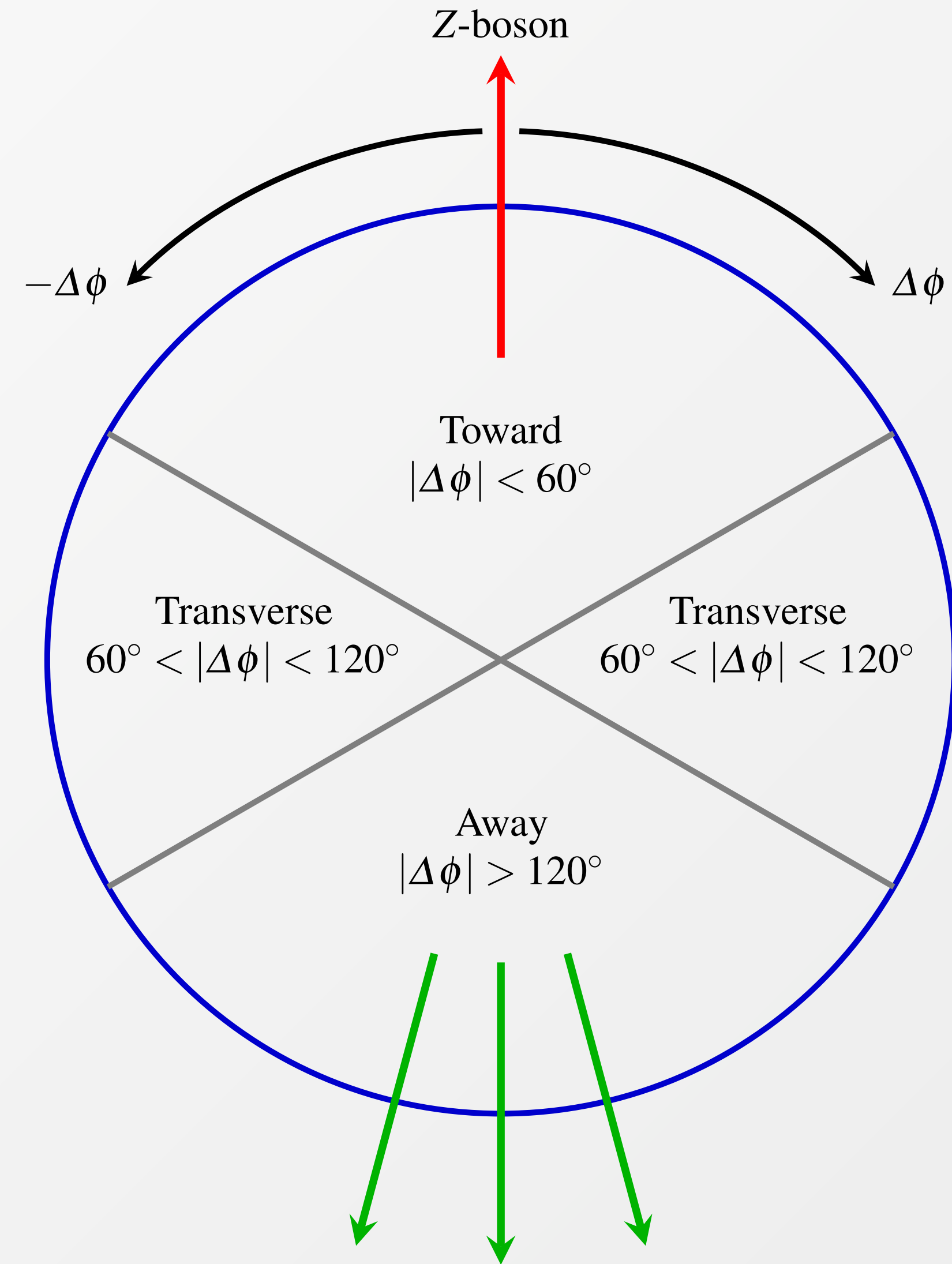
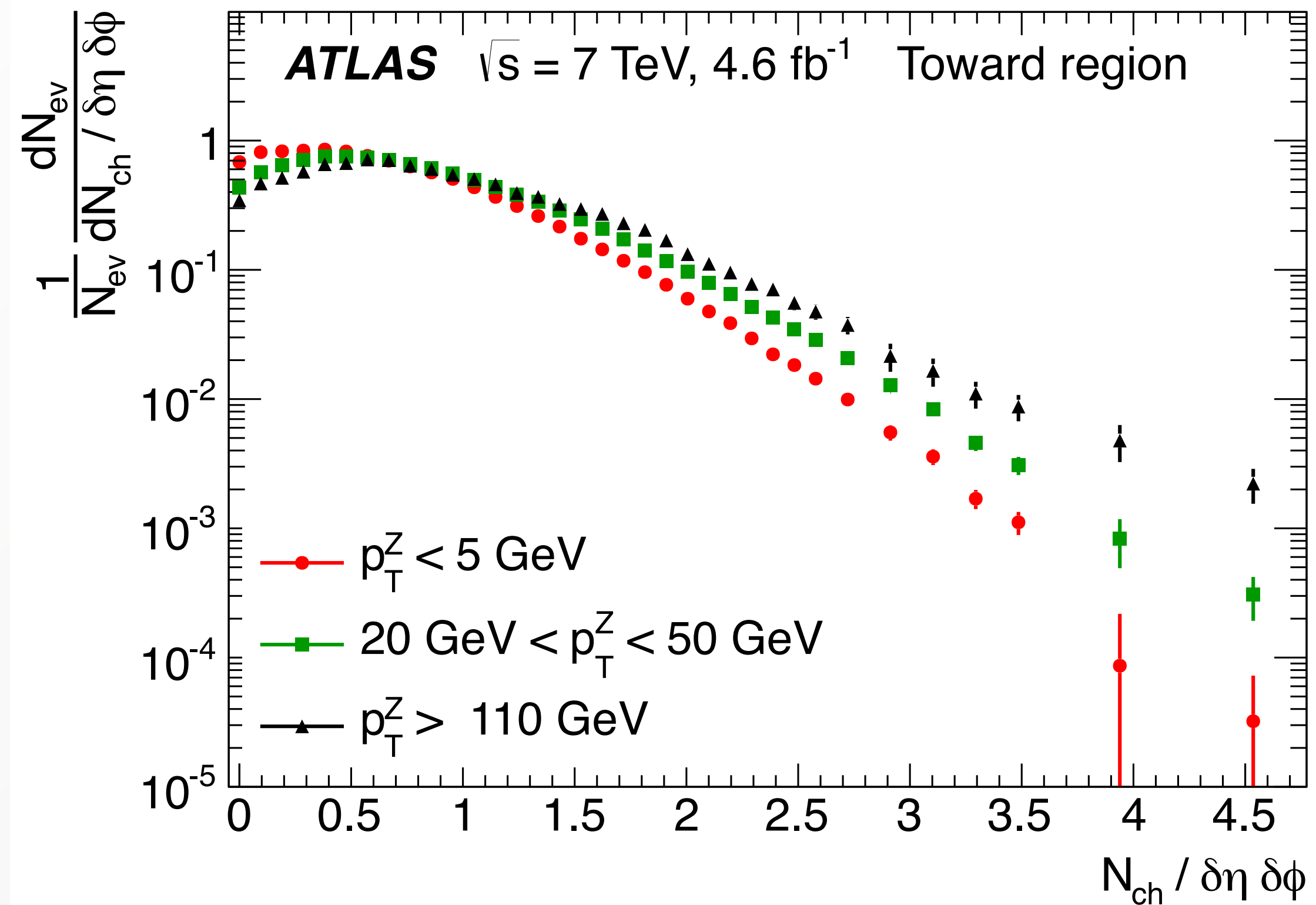
# Beyond 3HS?

- 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

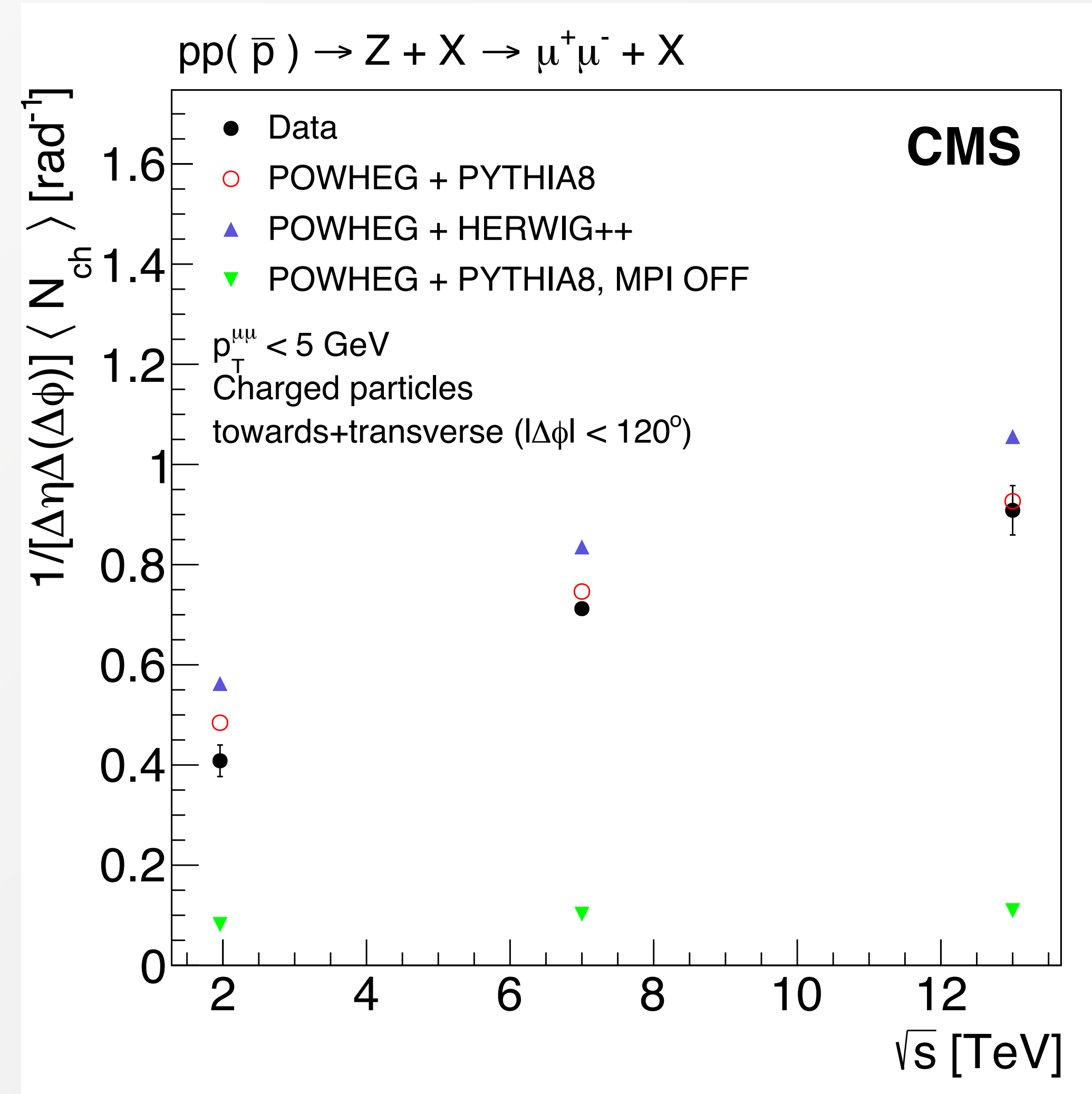
- mostly a UE study
- uses  $p_T^Z < 5 \text{ GeV}$



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

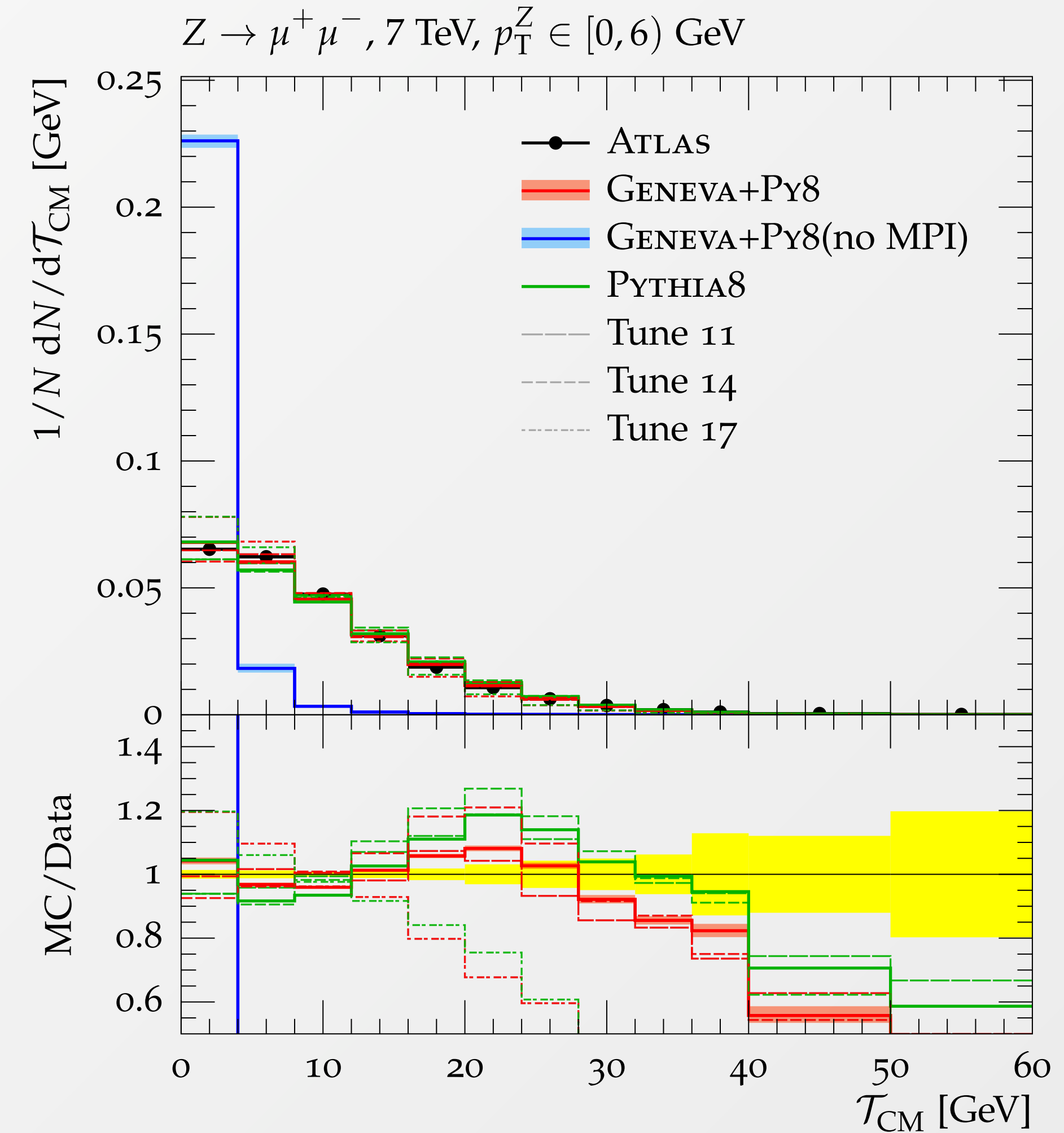
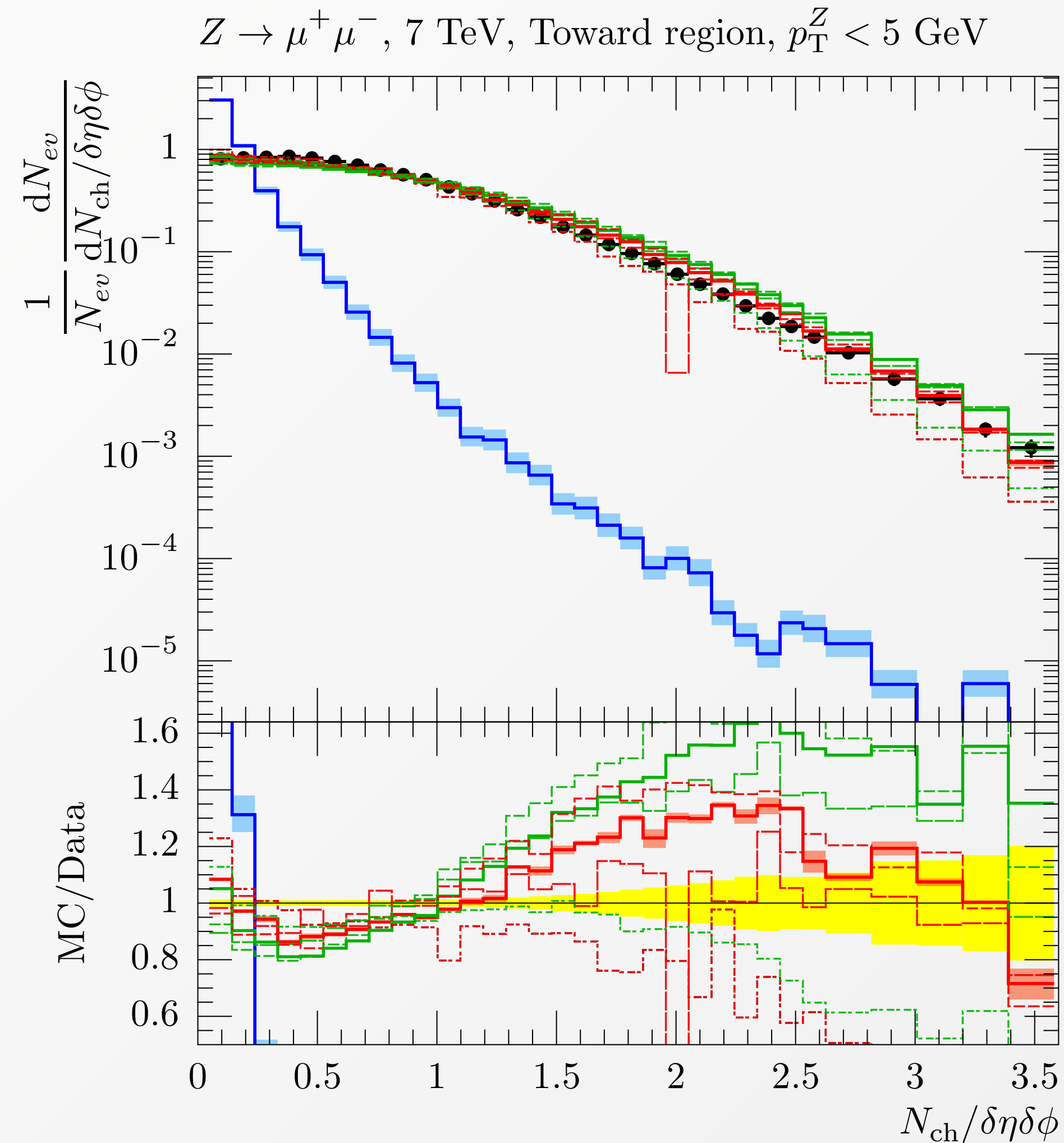
# CMS 1711.04299

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



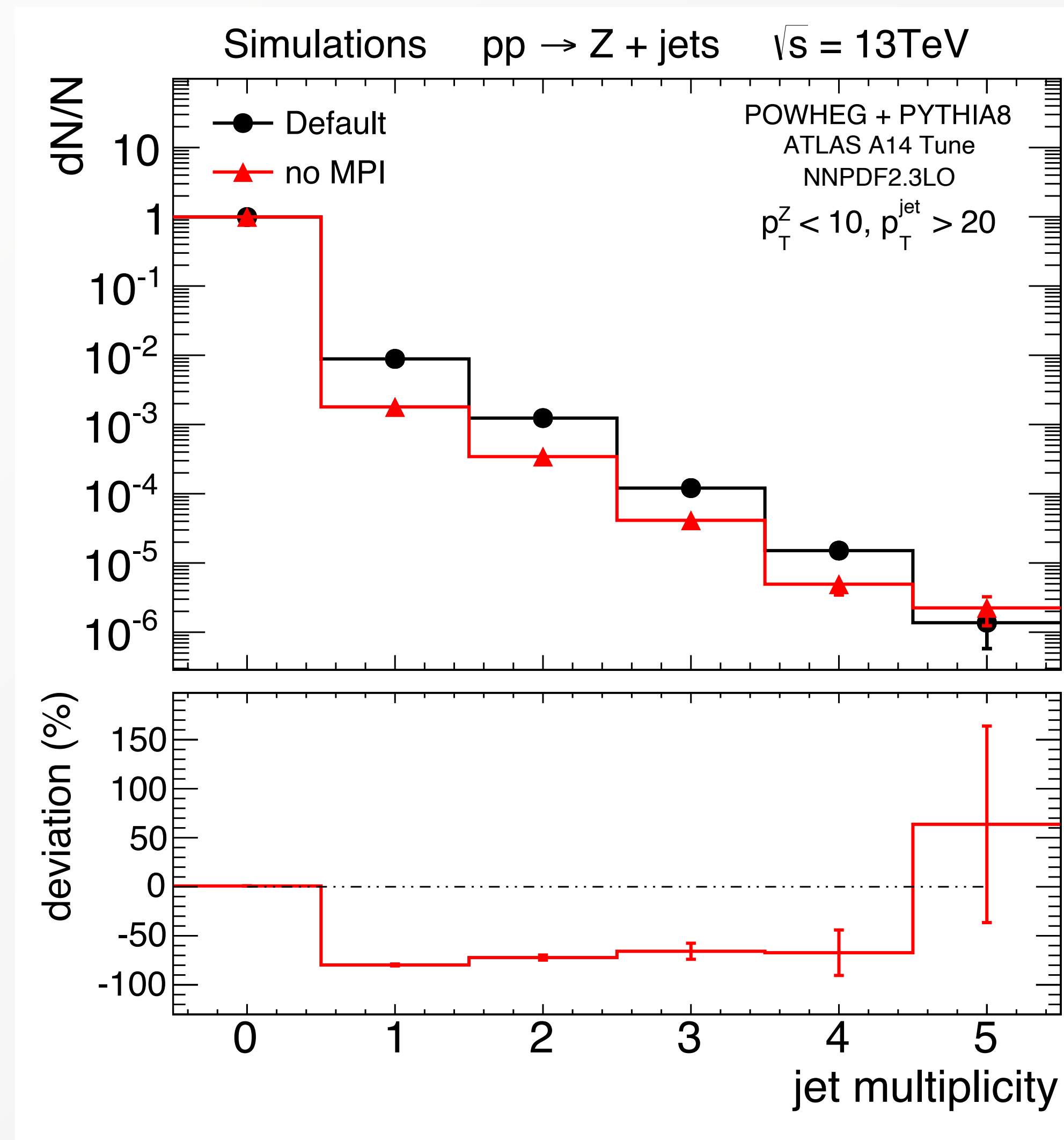
# Alioli, Bauer, Guns, Tackmann, 1605.07192

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



# Bansal, Bansal, Kumar, Singh 1602.05392

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



# 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  $\Delta\phi_{j_1 j_2}$ , though high  $p_T^J$  cut means only 2HS

