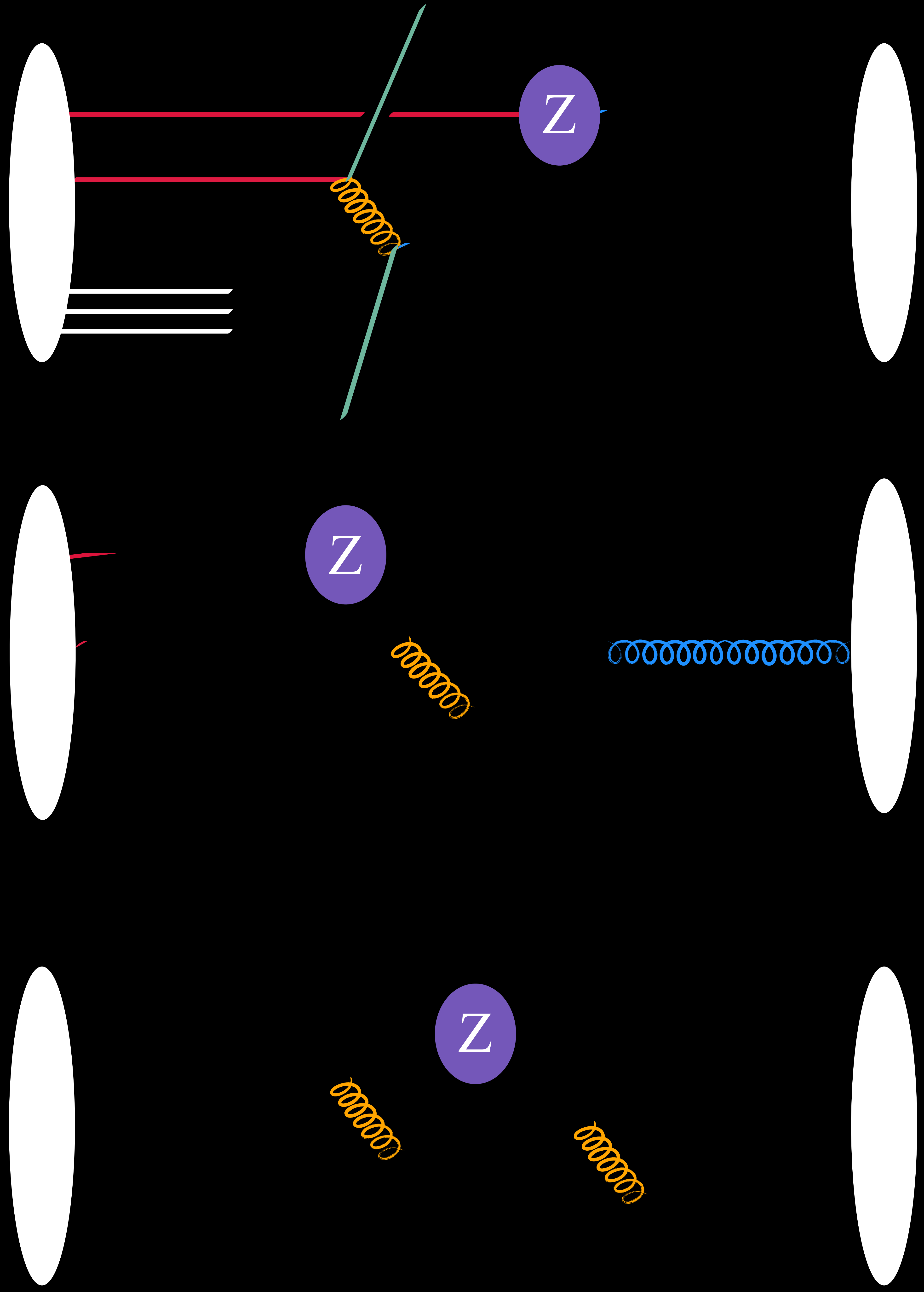
Exploring high-purity **multi-parton scattering** at the LHC

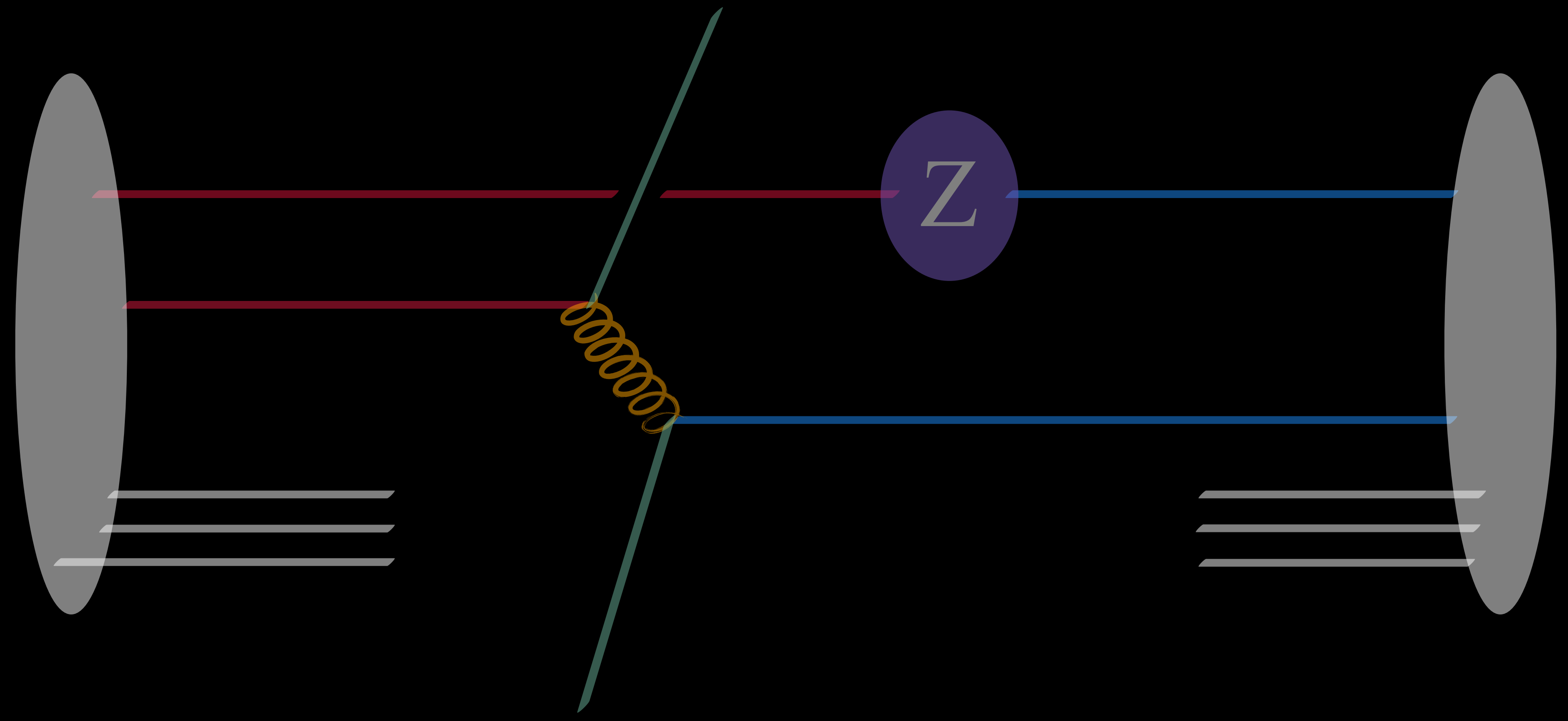


Alba Soto Ontoso

QCD seminar

CERN, 4th December, 2023

arXiv:2307.05693



Explo
multi-
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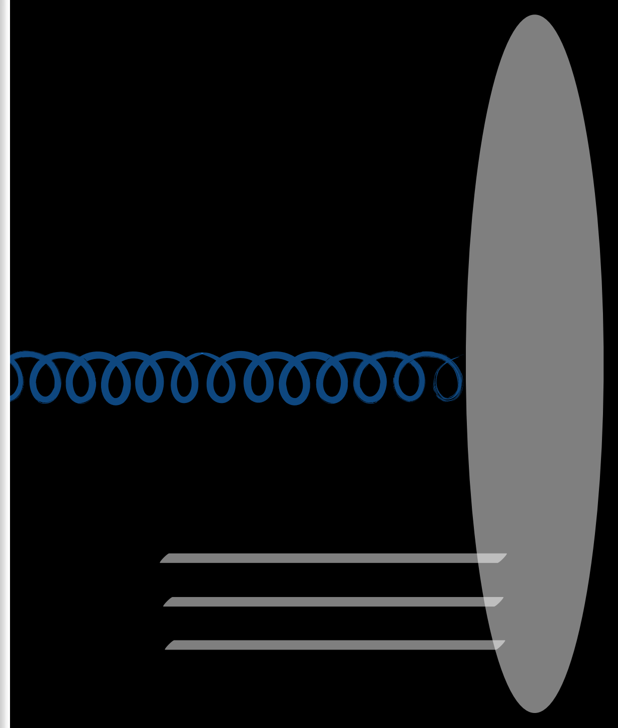

Exploring high-purity multi-parton scattering at hadron colliders

Jeppe R. Andersen,[1] Pier Francesco Monni,[2] Luca Rottoli,[3] Gavin P. Salam,[4,5] and Alba Soto-Ontoso[2]

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[2] *CERN, Theoretical Physics Department, CH-1211 Geneva 23, Switzerland*
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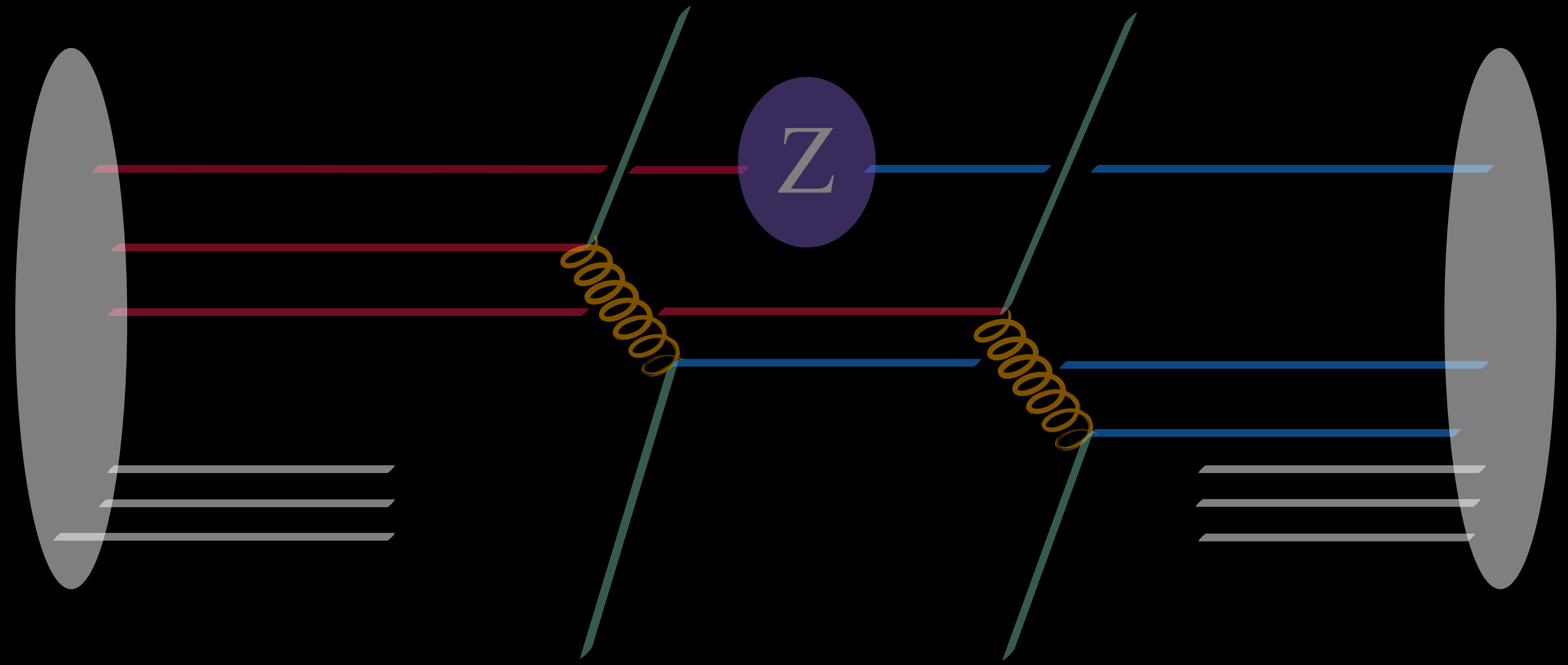
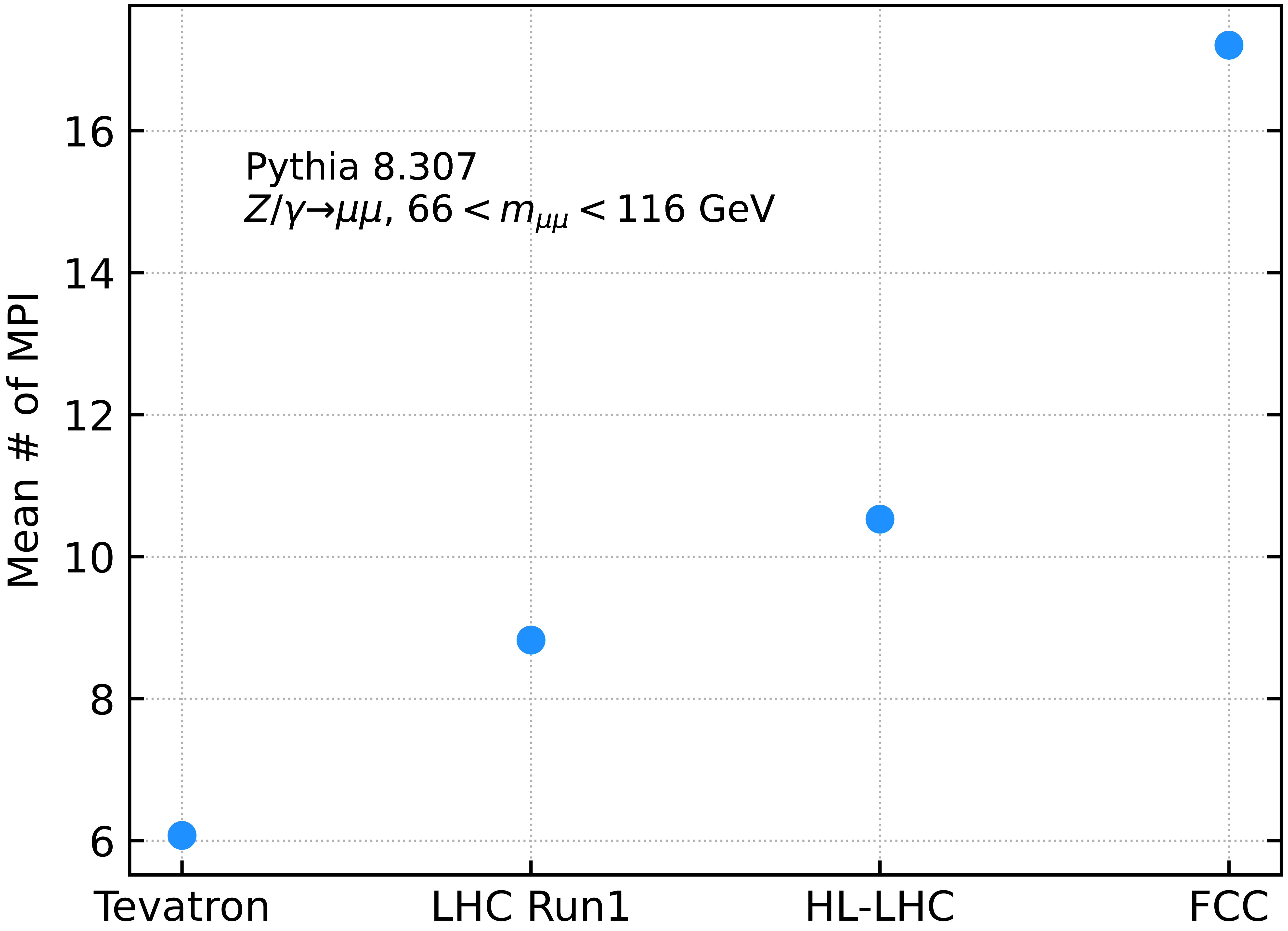


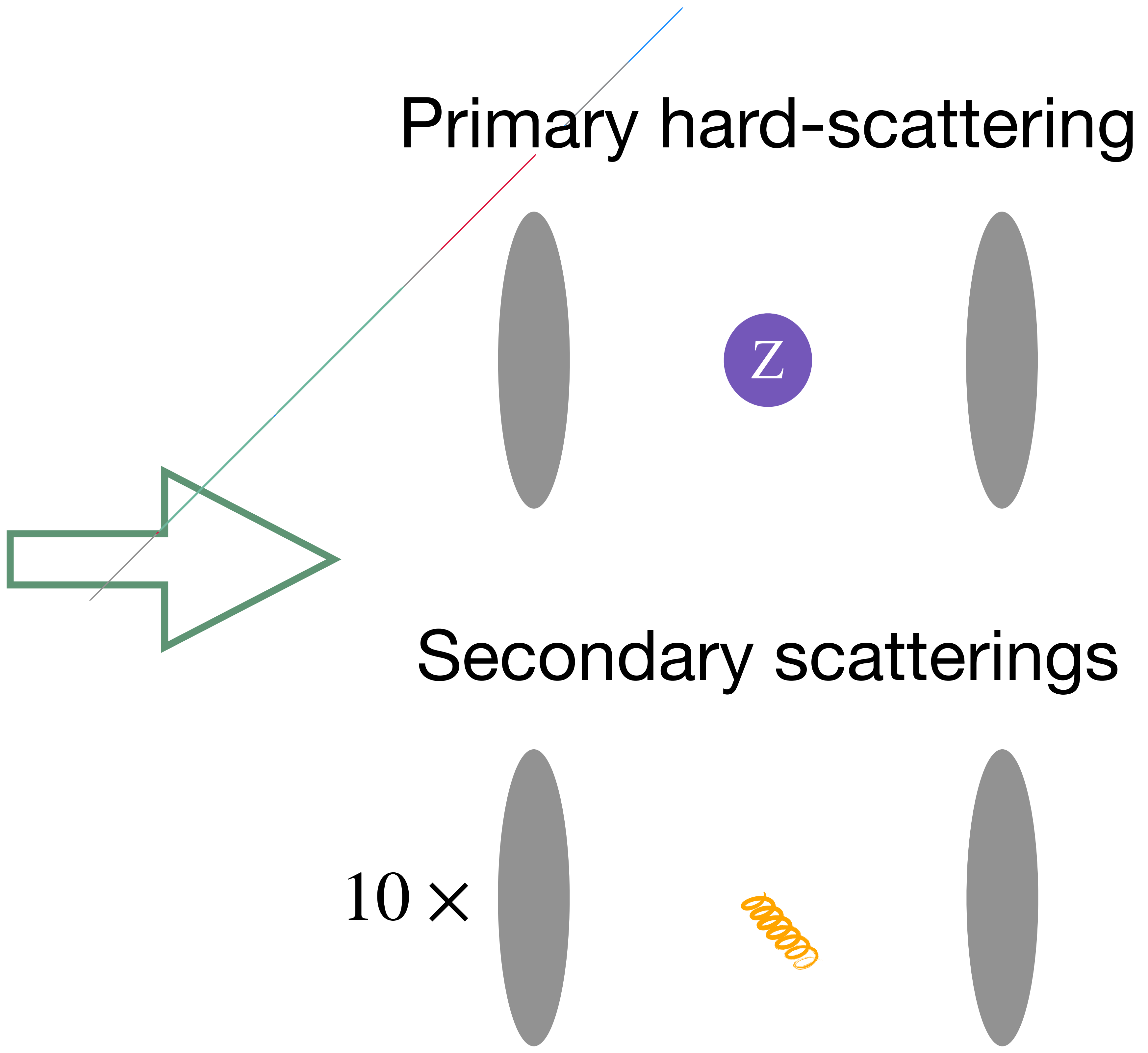
Alba Soto Ontoso

QCD seminar

CERN, 4th December, 2023

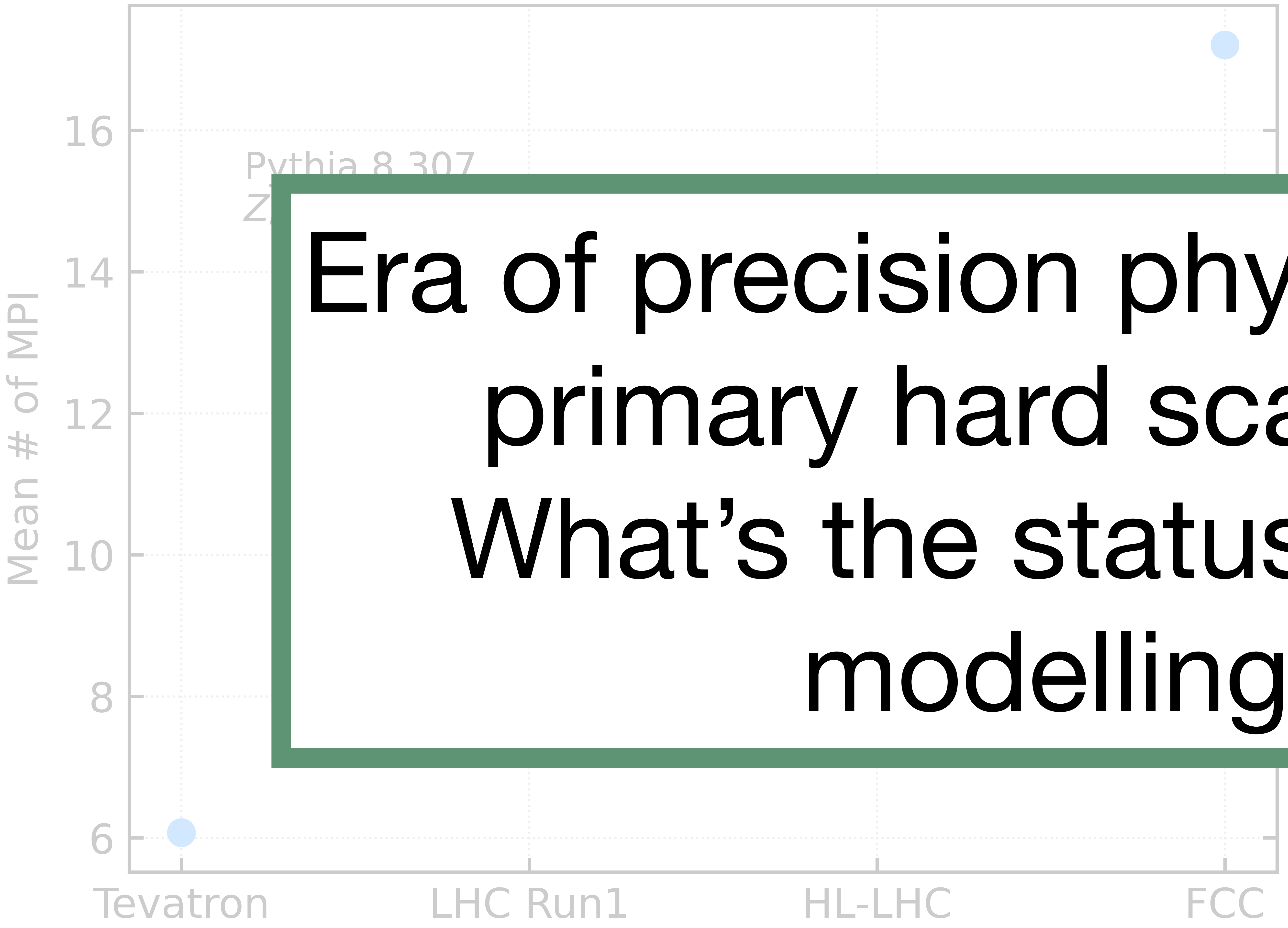
<# MPI> in Drell-Yan production at hadron colliders



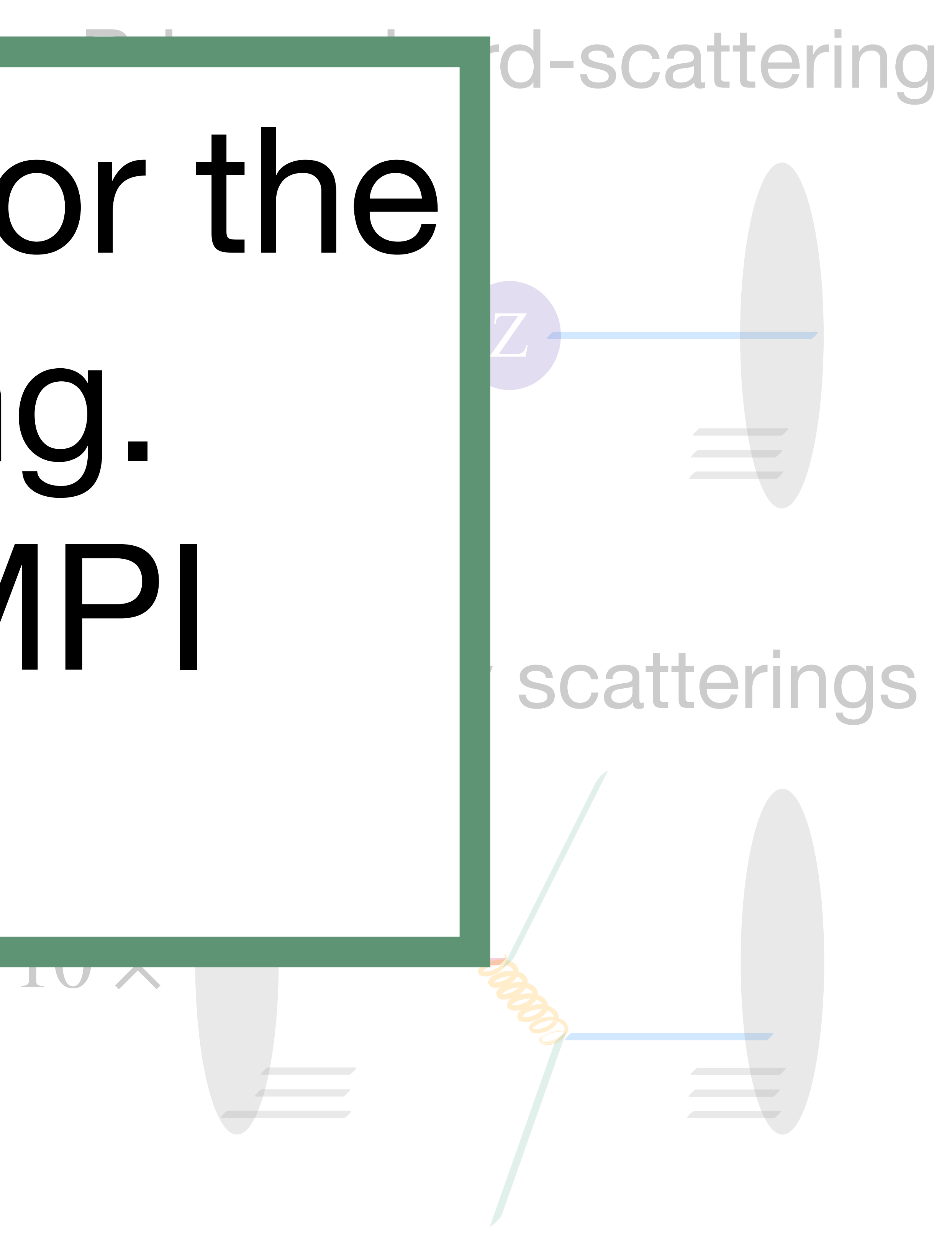


$\mathcal{O}(10)$ additional parton collisions per Drell-Yan event

<# MPI> in Drell-Yan production at hadron colliders

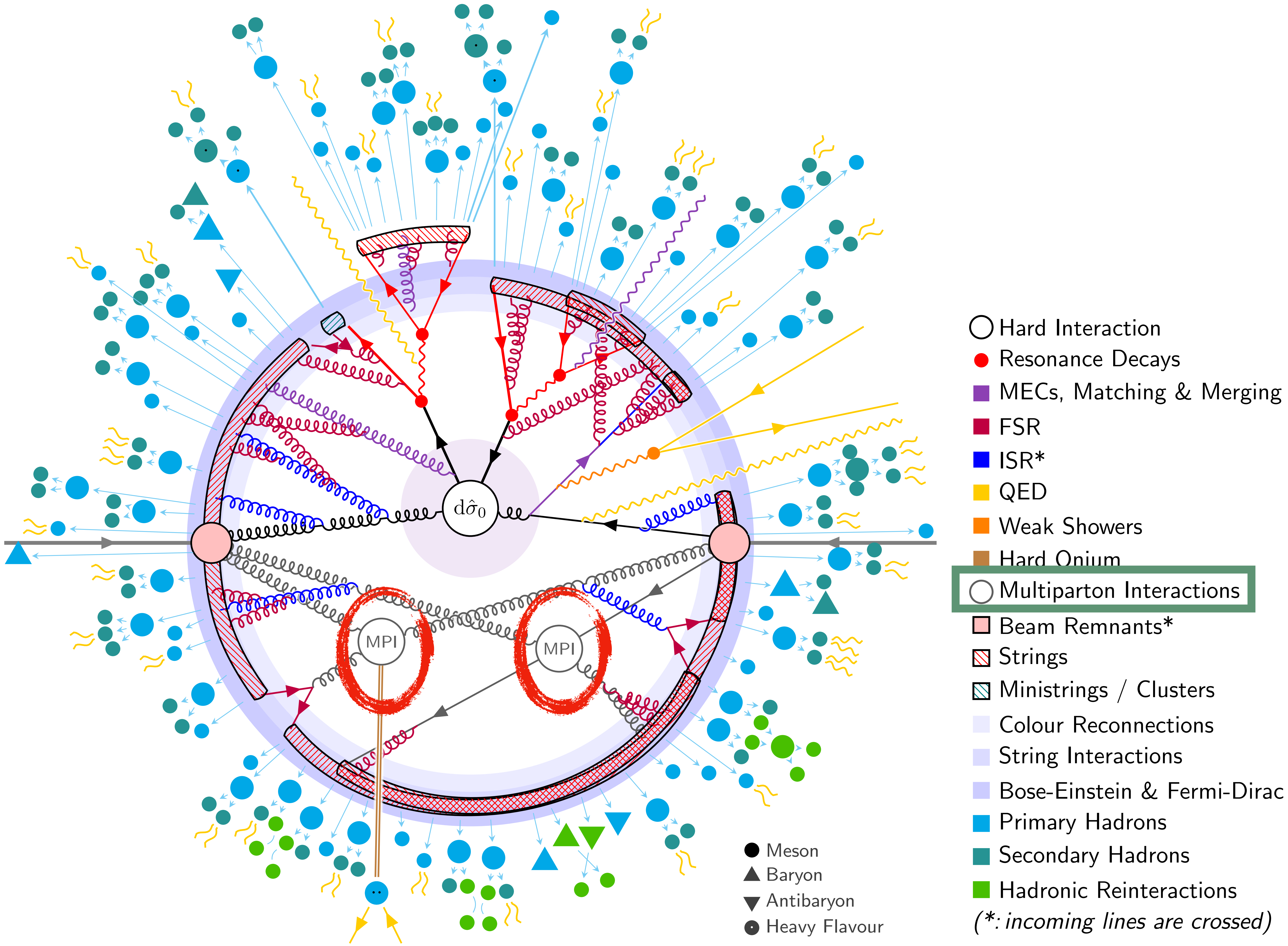


Era of precision physics for the primary hard scattering.
What’s the status on MPI modelling?



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

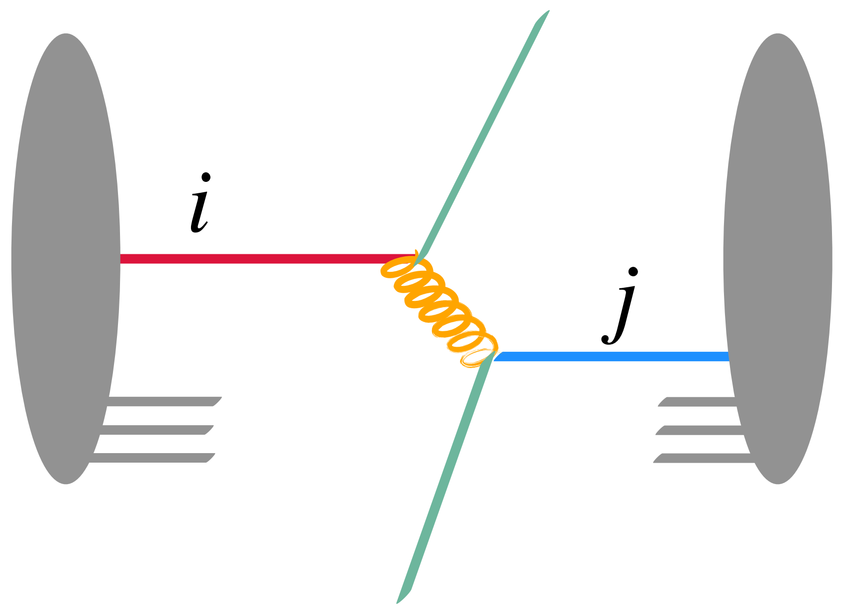
Option A: MPI as part of the MC toolkit



[Bierlich et al *SciPost Phys.* Codebases 8 (2022)]

MPI modelling in general purpose MCs in a nutshell

[Bierlich et al SciPost Phys. Codebases 8 (2022)] [Sjostrand and van Zijl PRD 36, 2019 (1987)] [Sjostrand and Skands JHEP 03 053 (2004)]



Standard $2 \to 2$ cross section

$$\frac{d\sigma}{dp_\perp^2} = \sum_{i,j,k} \iiint f_i(x_1, Q^2) f_j(x_2, Q^2) \frac{d\hat{\sigma}_{ij}^k}{d\hat{t}} \delta\left(p_\perp^2 - \frac{\hat{t}\hat{u}}{\hat{s}}\right) dx_1\, dx_2\, d\hat{t}$$

$$\frac{d\hat{\sigma}}{d\hat{t}} \propto \frac{\alpha_s^2(Q^2)}{\hat{t}^2} \Rightarrow \frac{d\hat{\sigma}}{dp_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4}$$

divergent when $p_\perp \to 0$

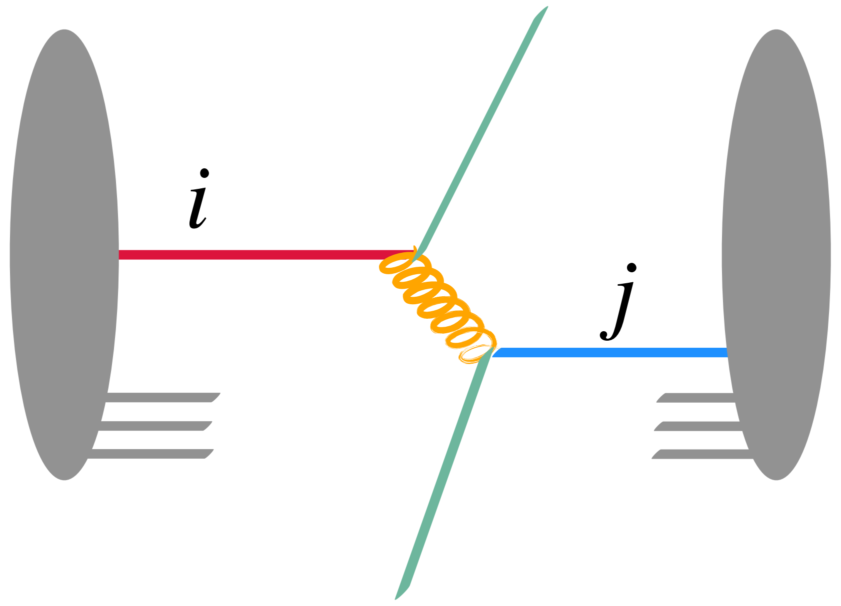
$$\frac{d\hat{\sigma}}{dp_\perp^2} \sim \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \longrightarrow \frac{\alpha_s^2(p_{\perp 0}^2 + p_\perp^2)}{(p_{\perp 0}^2 + p_\perp^2)^2}$$

with $p_{\perp 0}(\sqrt{s})$ a free parameter

MPI modelling in general purpose MCs in a nutshell

[Bierlich et al SciPost Phys. Codebases 8 (2022)] [Sjostrand, van Zijl PRD 36, 2019 (1987)] [Sjostrand, Skands JHEP 03 053 (2004)] [Corke, Sjostrand JHEP 1103 (2011)]

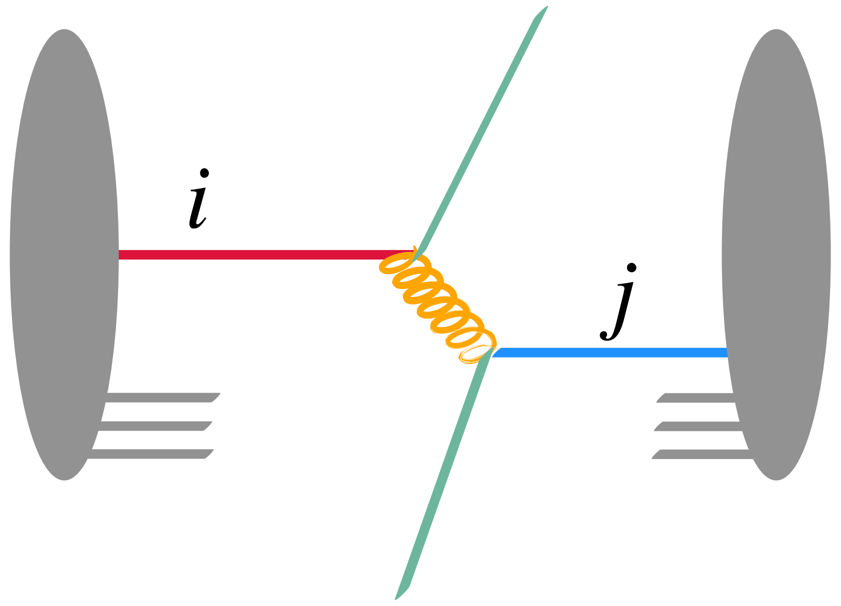
Standard $2 \to 2$ cross section



$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_\perp^2} = \sum_{i,j,k} \iiint f_i(x_1, Q^2)\, f_j(x_2, Q^2)\, \frac{\mathrm{d}\hat{\sigma}_{ij}^k}{\mathrm{d}\hat{t}}\, \delta\left(p_\perp^2 - \frac{\hat{t}\hat{u}}{\hat{s}}\right) \mathrm{d}x_1\, \mathrm{d}x_2\, \mathrm{d}\hat{t}$$

Interactions occur independently (w/ momentum, flavour sum rules): Poisson stat

ith



$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_{\perp i}} = \frac{1}{\sigma_{\mathrm{nd}}} \frac{\mathrm{d}\sigma}{\mathrm{d}p_{\perp i}} \exp\left(-\int_{p_{\perp i}}^{p_{\perp i-1}} \frac{1}{\sigma_{\mathrm{nd}}} \frac{\mathrm{d}\sigma}{\mathrm{d}p'_\perp} \mathrm{d}p'_\perp\right)$$

$\sigma_{\mathrm{nd}} = 50$ mb

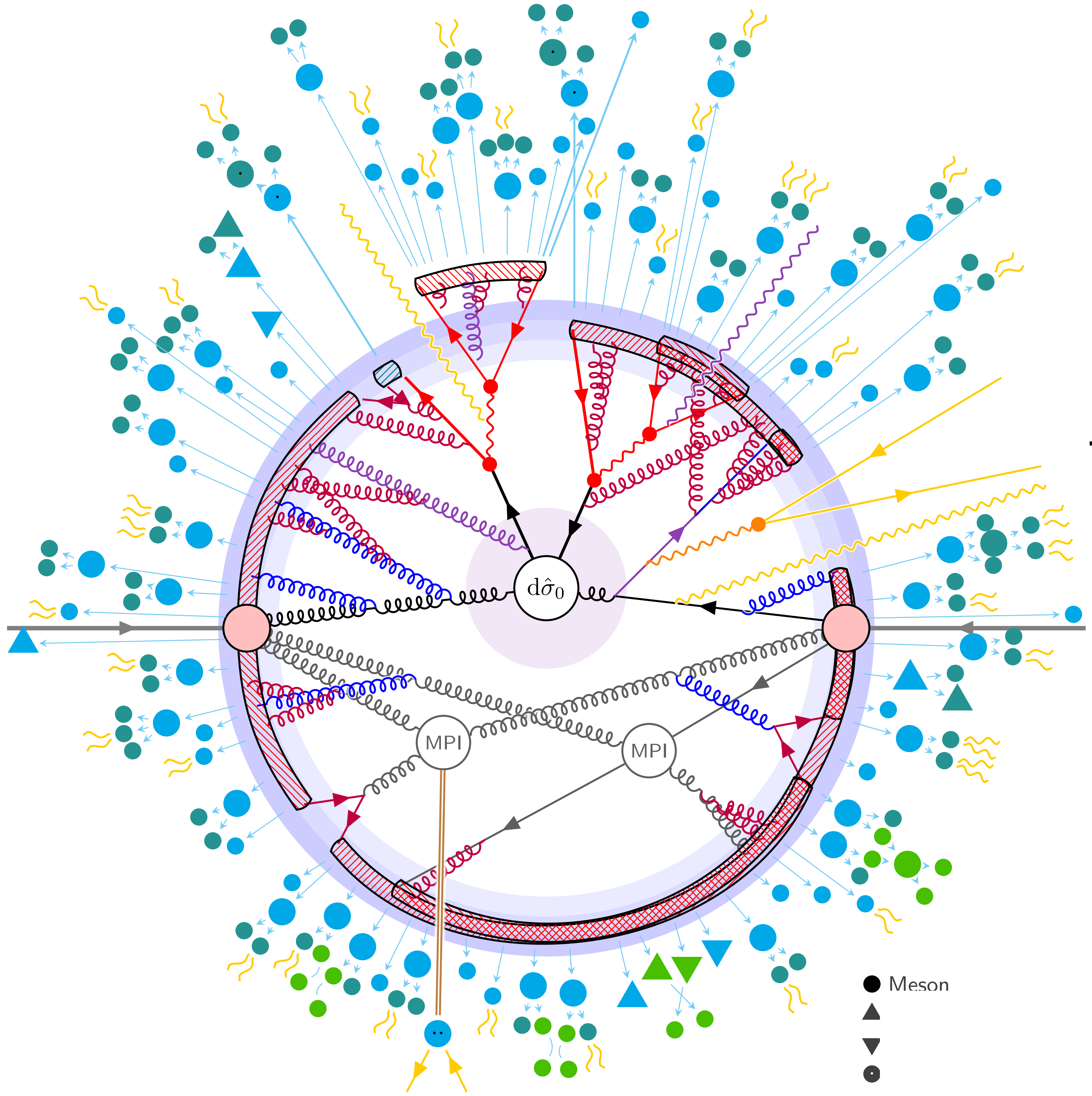
no-scattering probability

+ some impact-parameter distribution

MPI modelling in general purpose MCs in a nutshell

[Bierlich et al SciPost Phys. Codebases 8 (2022)] [Sjostrand and van Zijl PRD 36, 2019 (1987)] [Sjostrand and Skands JHEP 03 053 (2004)]

Multi-parton interactions are interleaved with the rest of the showering



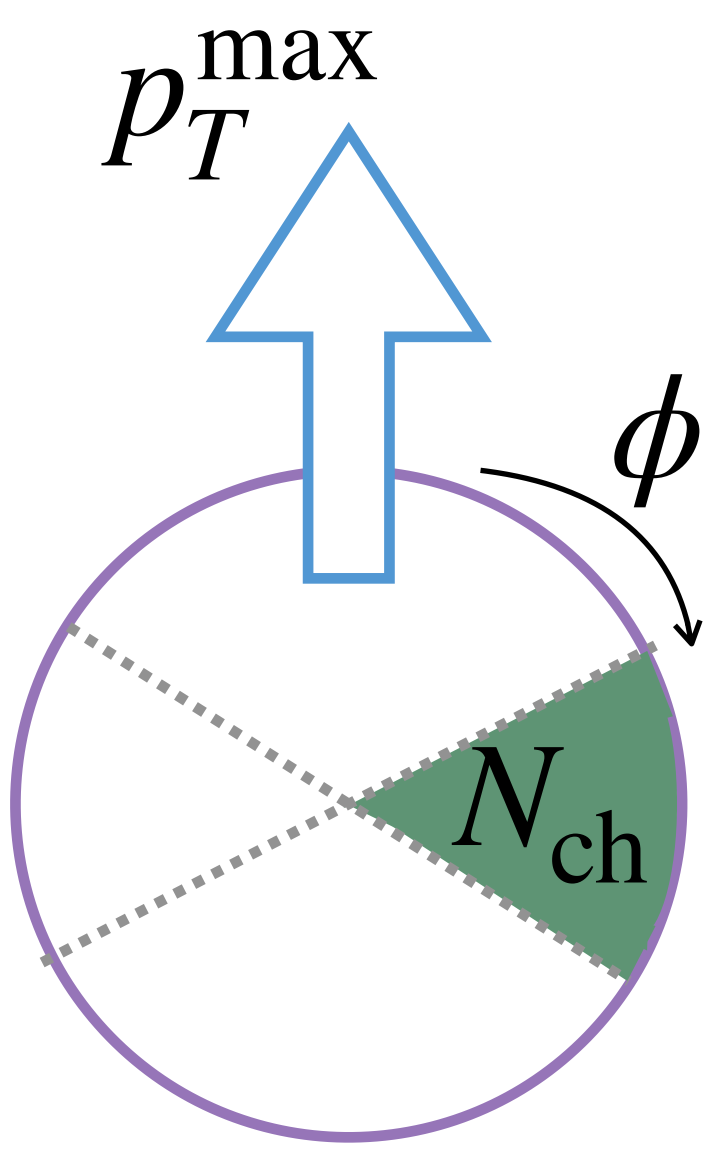
compete for x

$$\frac{d\mathcal{P}}{dp_\perp} = \left(\frac{d\mathcal{P}_{\rm MPI}}{dp_\perp} + \sum \frac{d\mathcal{P}_{\rm ISR}}{dp_\perp} + \sum \frac{d\mathcal{P}_{\rm FSR}}{dp_\perp}\right)$$
$$\times \exp\left(-\int_{p_\perp}^{p_{\perp\max}} \left(\frac{d\mathcal{P}_{\rm MPI}}{dp'_\perp} + \sum \frac{d\mathcal{P}_{\rm ISR}}{dp'_\perp} + \sum \frac{d\mathcal{P}_{\rm FSR}}{dp'_\perp}\right) dp'_\perp\right)$$

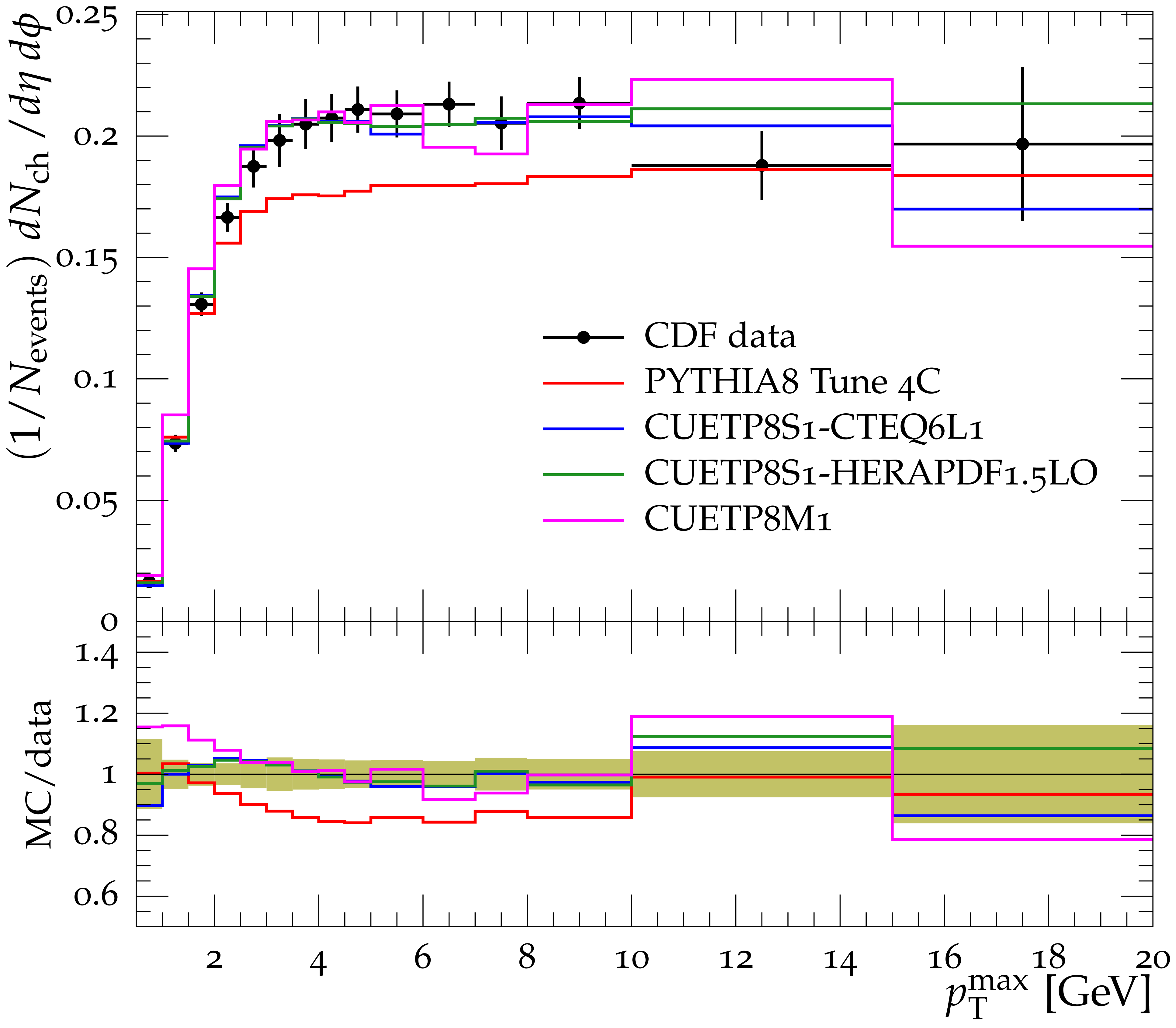
Tuning parameters: $p_{\perp 0}(\sqrt{s})$ and transverse geometry profile

MPI/underlying event tuning

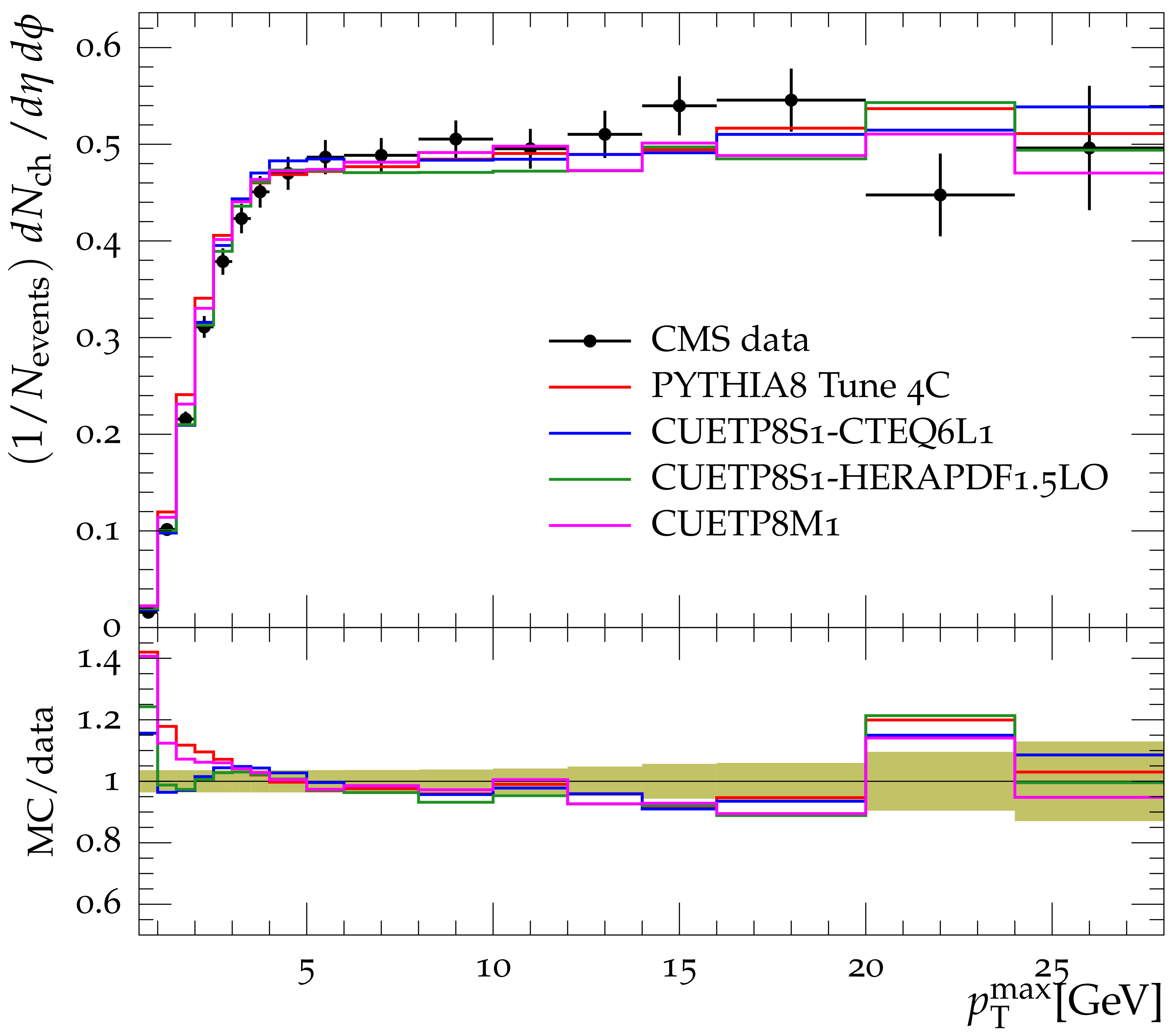
[CMS Collab. EPJC 76 (2016) 3, 155]



Tevatron



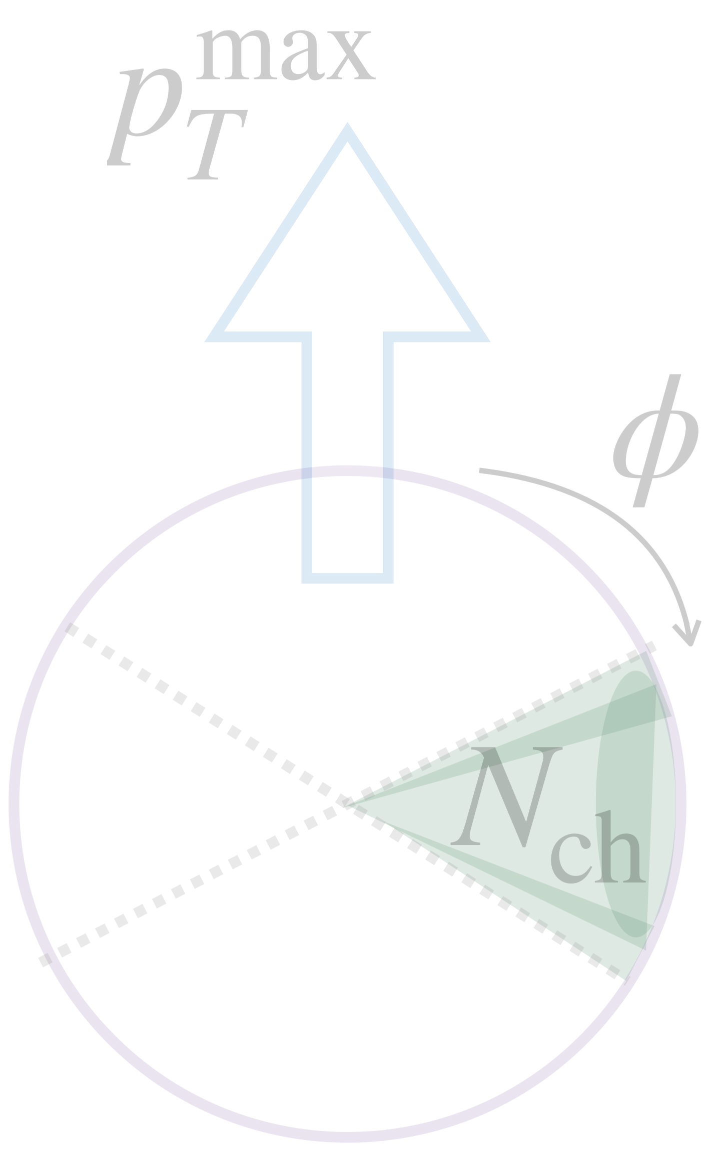
LHC-Run1



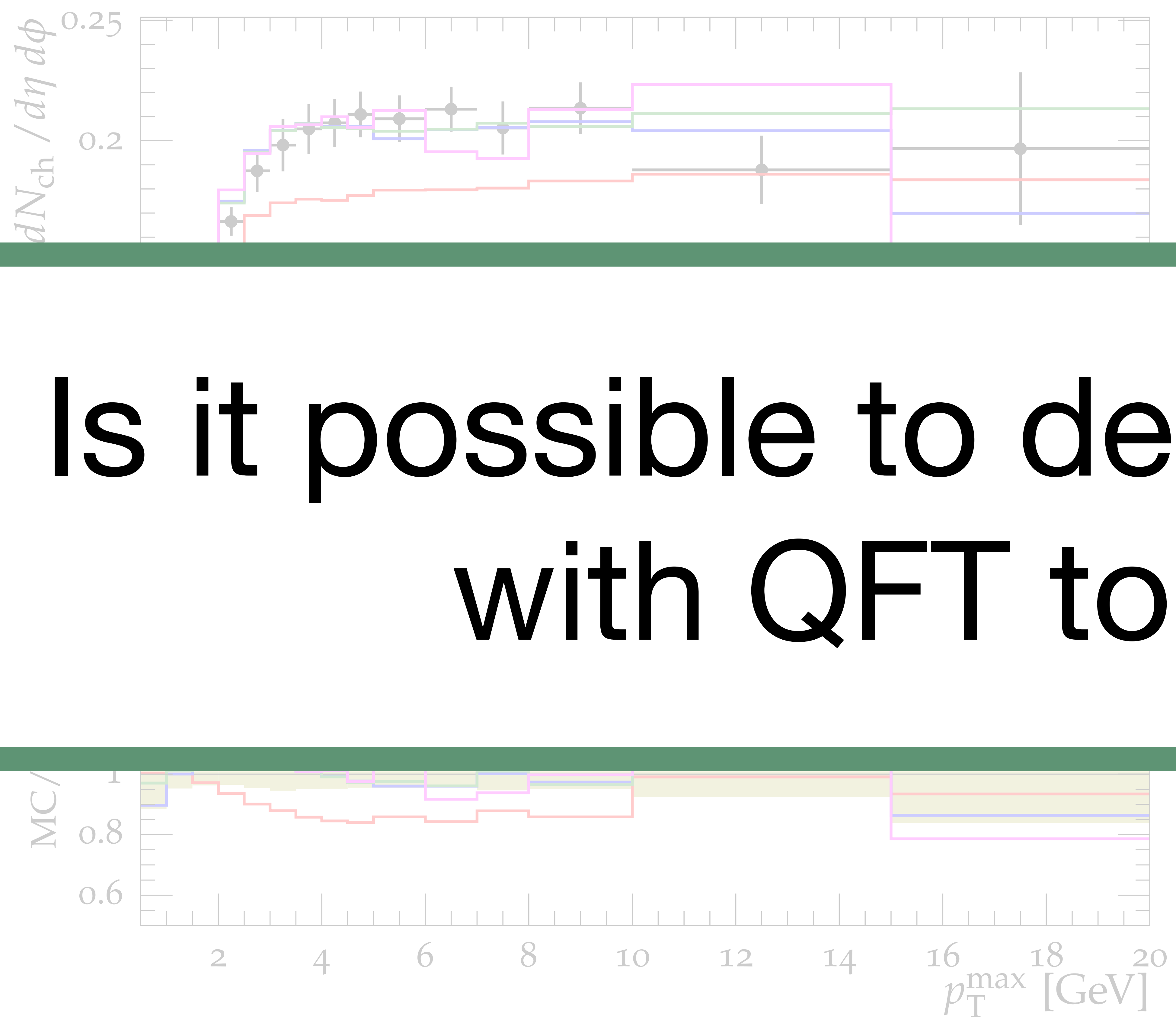
Tunes performed in events with at least one hard scatter

MPI/underlying event tuning

[CMS Collab. EPJC 76 (2016) 3, 155]



Tevatron



LHC-Run1

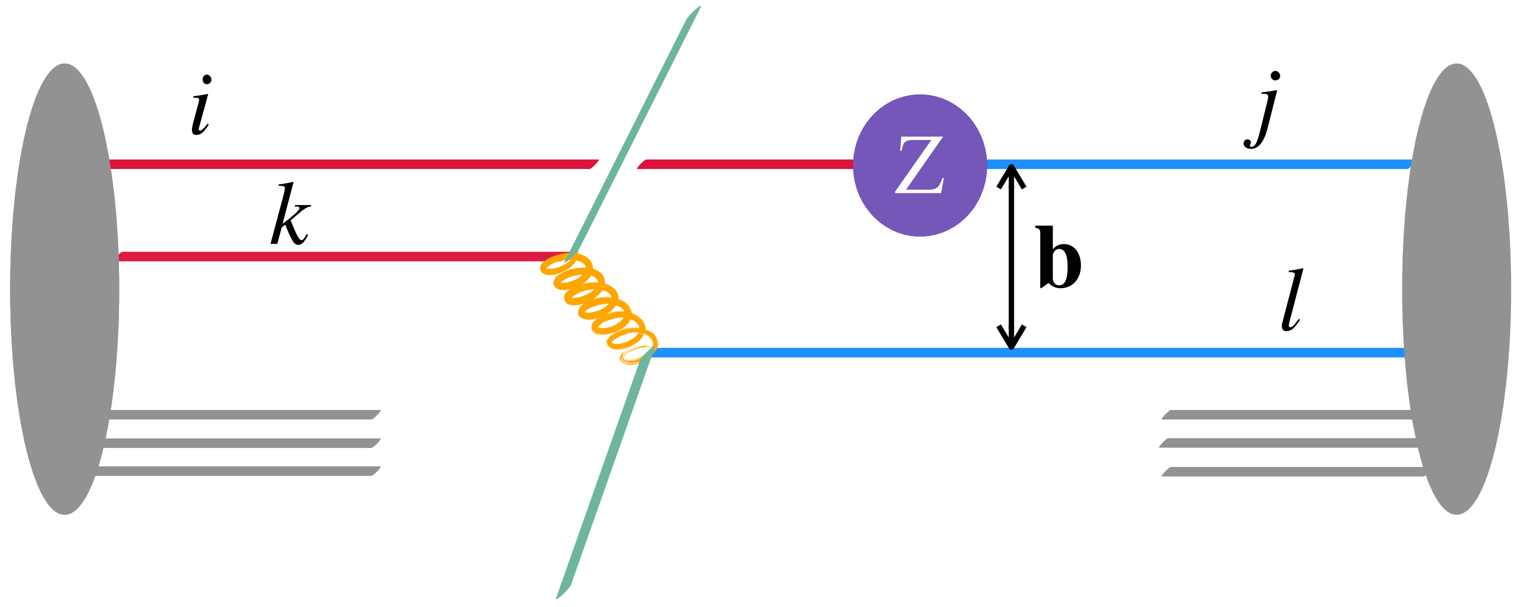
Is it possible to describe MPI with QFT tools?

Tunes performed in events with at least one hard scatter

Option B: double-parton scattering as QFT playground

[Paver, Treleani, Nuovo Cim. A70 (1982) 215] [Blok, Dokshitzer, Frankfurt, Strikman, PRD 83 (2011) 071501] [Diehl, Ostermeier and Schäfer (JHEP 1203 (2012)]

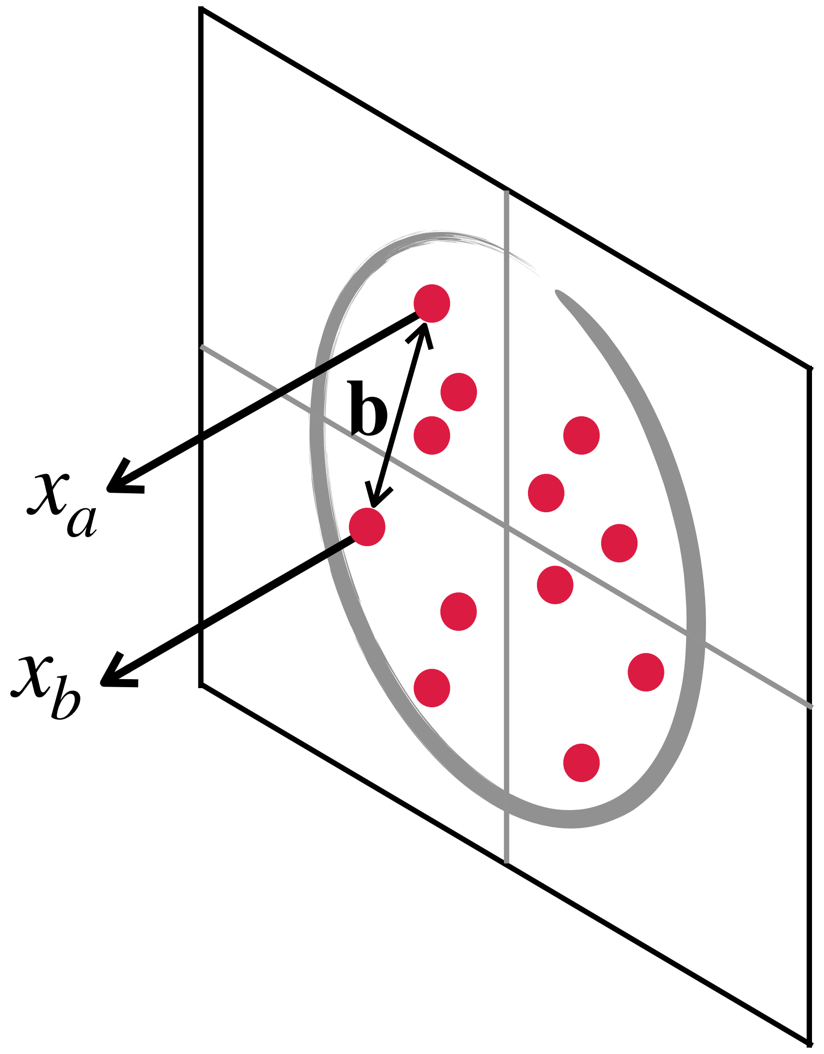
The double-parton scattering (DPS) cross section can be written as



$$= \int_{\mathbf{b}} F^{ik}(x_i, x_k, \mathbf{b}) \otimes \hat{\sigma}_{ij\to Z}\hat{\sigma}_{kl\to \mathrm{jets}} \otimes F^{jl}(x_j, x_l, \mathbf{b}) = \mathcal{O}\left(\frac{\lambda^2_{\mathrm{QCD}}}{Q^4}\right)$$

$1/\lambda^2_{\mathrm{QCD}}$ $\quad \lambda^2_{\mathrm{QCD}}$ $\quad 1/Q^2$ $\quad 1/Q^2$ $\quad \lambda^2_{\mathrm{QCD}}$

where we have introduced the double-parton density $F^{ab}(x_a, x_b, \mathbf{b})$



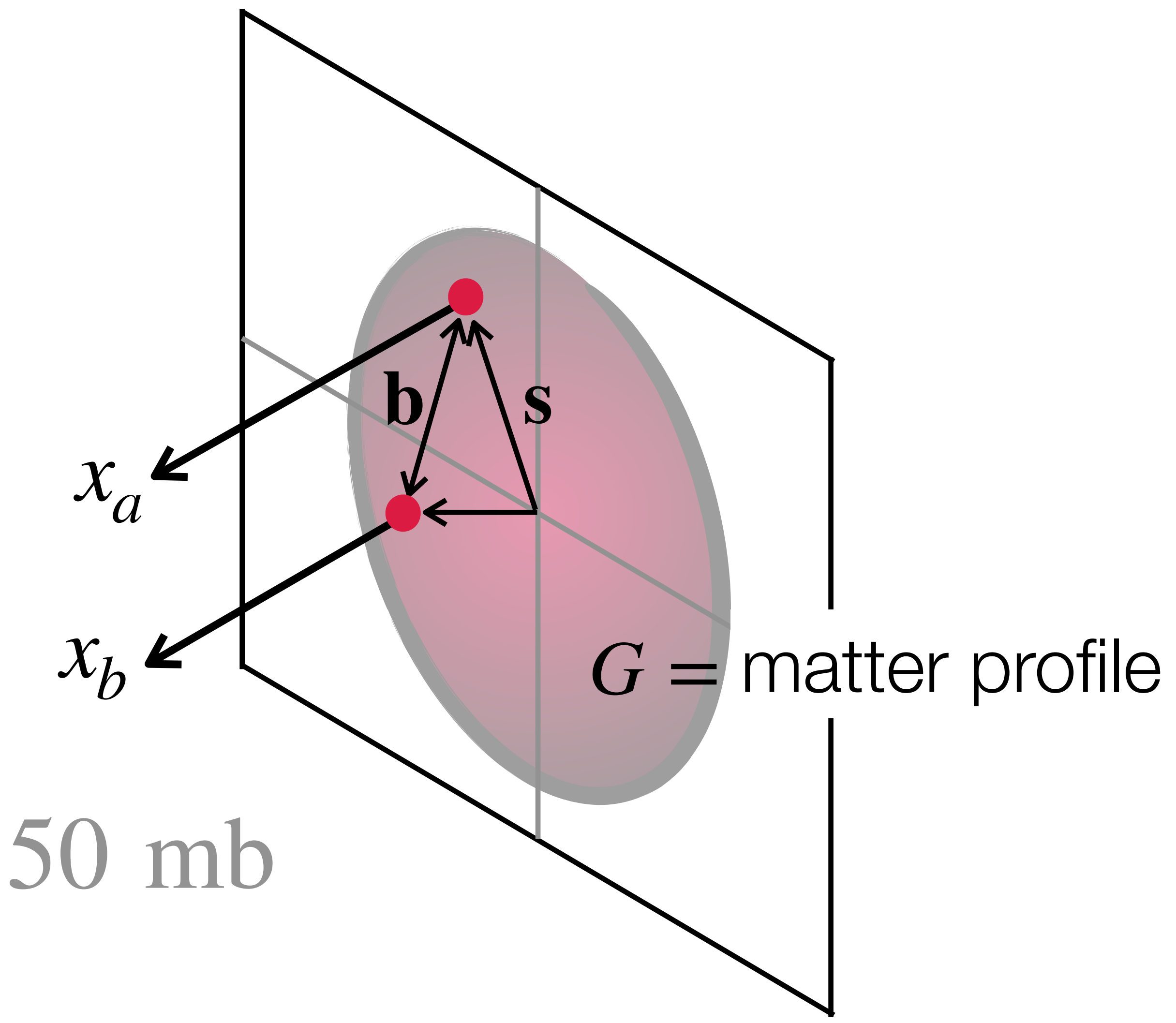
Double parton scattering can be used for proton tomography, i.e. extract partonic correlations

Option B: double-parton scattering as QFT playground

To **first approximation**, double-parton density is given by

$$F^{ab}(x_a, x_b, \mathbf{b}) \simeq f(x_a)f(x_b)\int_{\mathbf{s}} G(\mathbf{s})G(\mathbf{b}+\mathbf{s})$$

$\sim \pi R^2 \sim 50$ mb



This leads to the so-called **pocket-formula**

$$\sigma^{A,B}_{\mathrm{DPS}} = \frac{\sigma^{A}_{\mathrm{SPS}}\ \sigma^{B}_{\mathrm{SPS}}}{\sigma_{\mathrm{eff}}}$$

Option B: double-parton scattering as QFT playground

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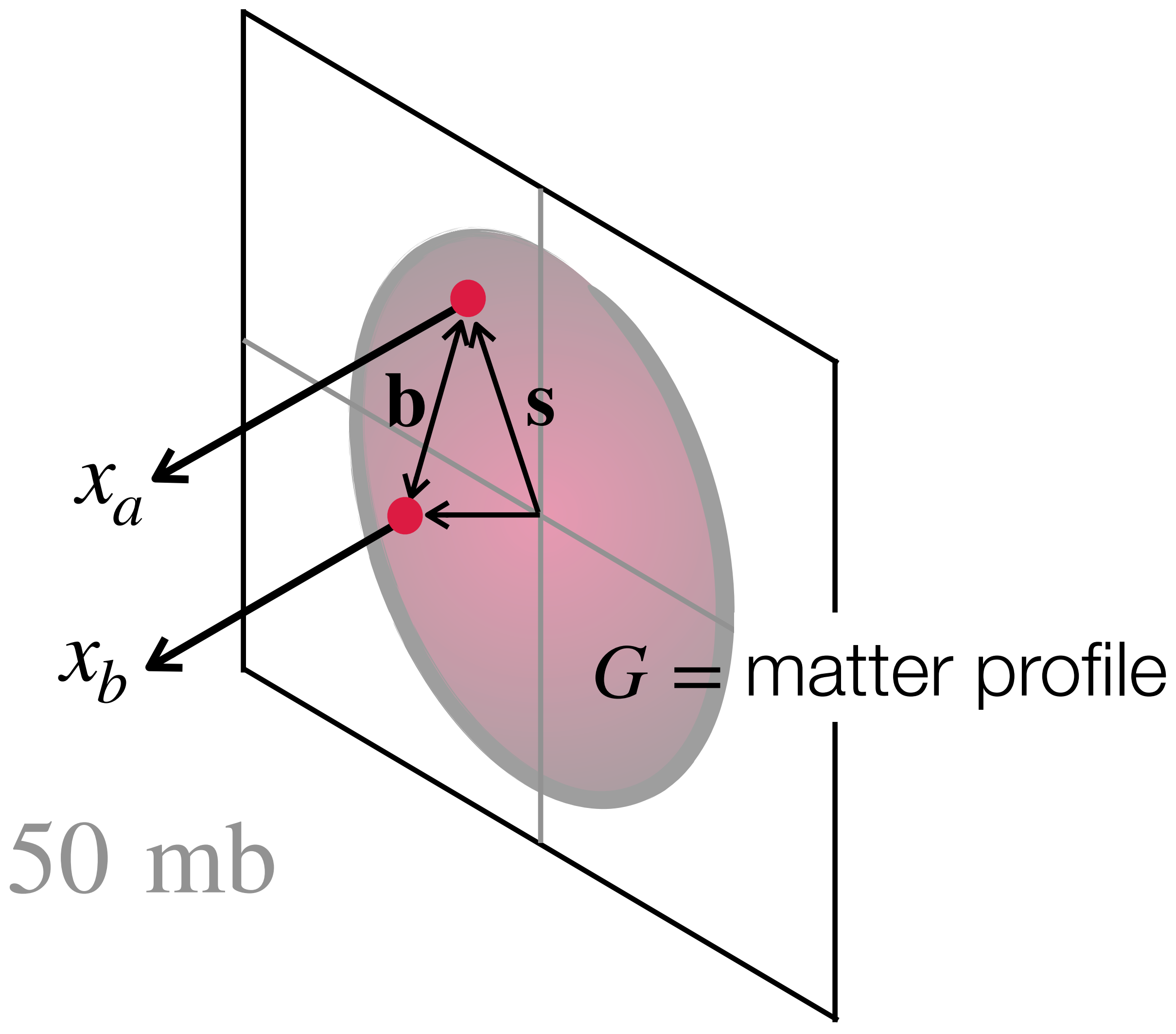

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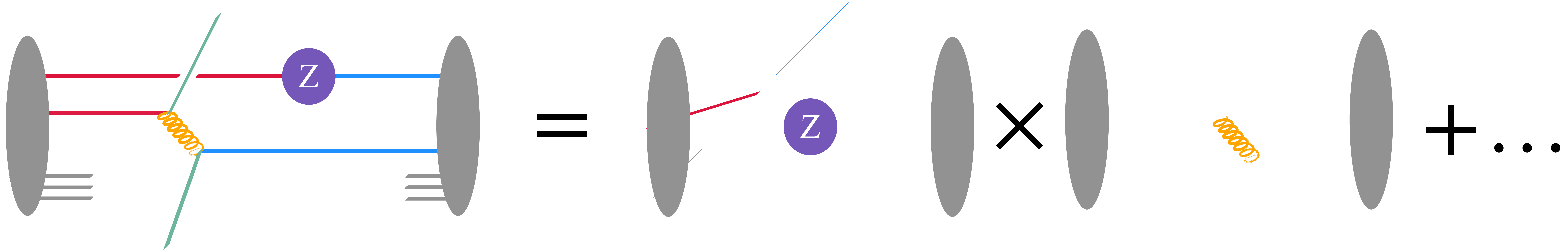
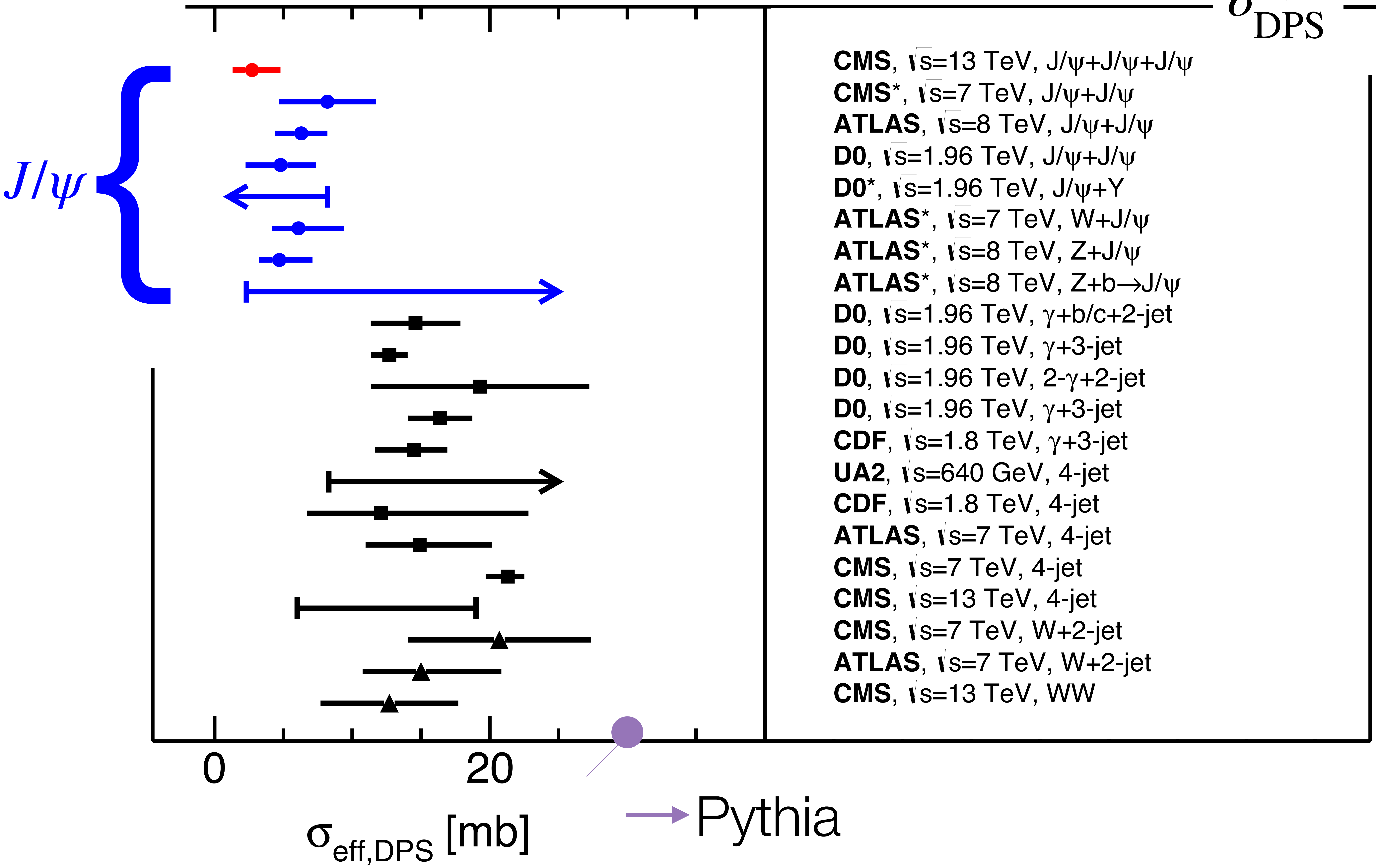
i.e.



Experimental extractions of $\sigma_{\rm eff}$

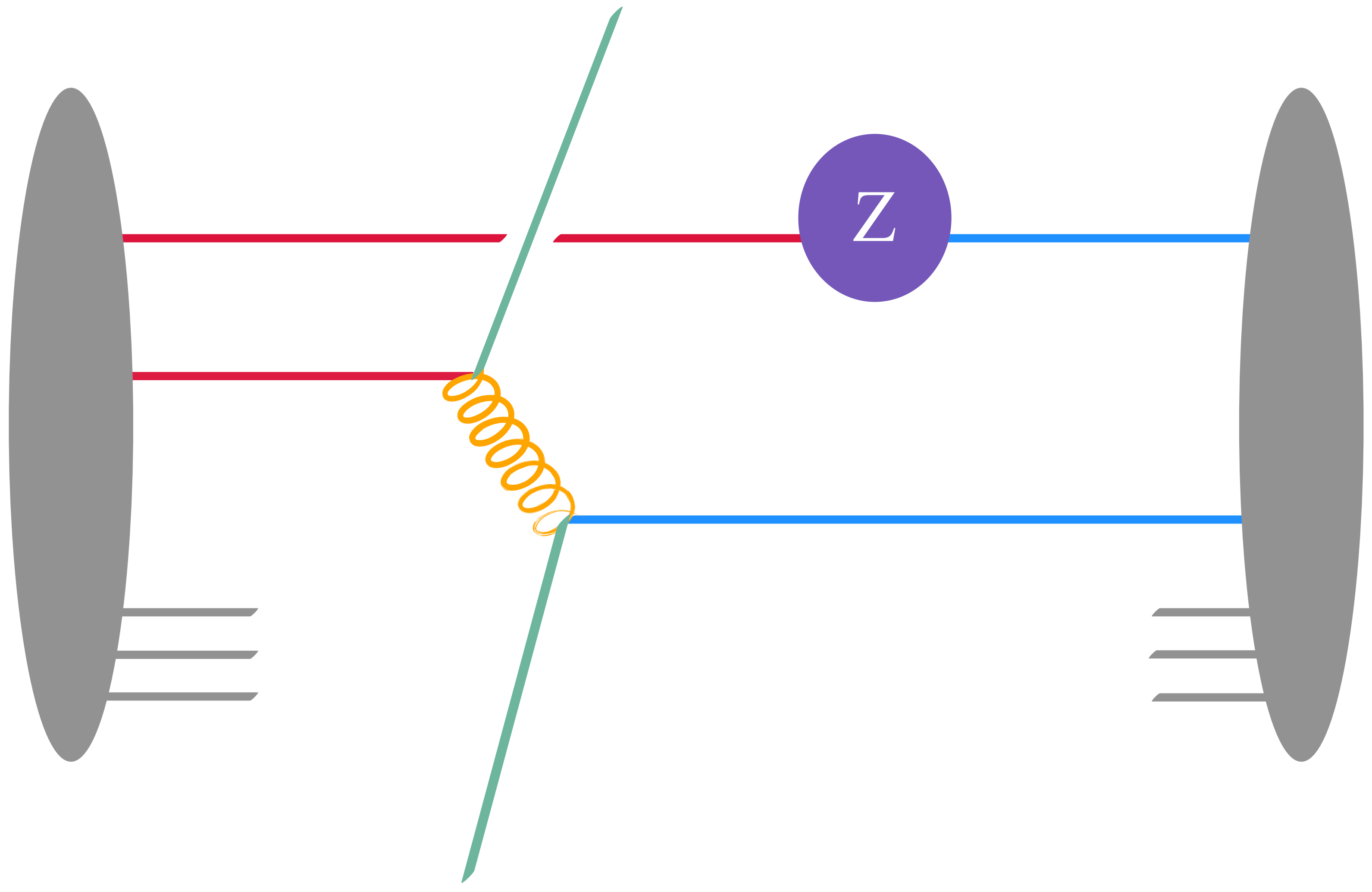
[CMS Collab. Nature Phys. 19 (2023) 3, 338-350]

$$\sigma^{A,B}_{\rm DPS} = \frac{\sigma^{A}_{\rm SPS}\ \sigma^{B}_{\rm SPS}}{\sigma_{\rm eff}}$$



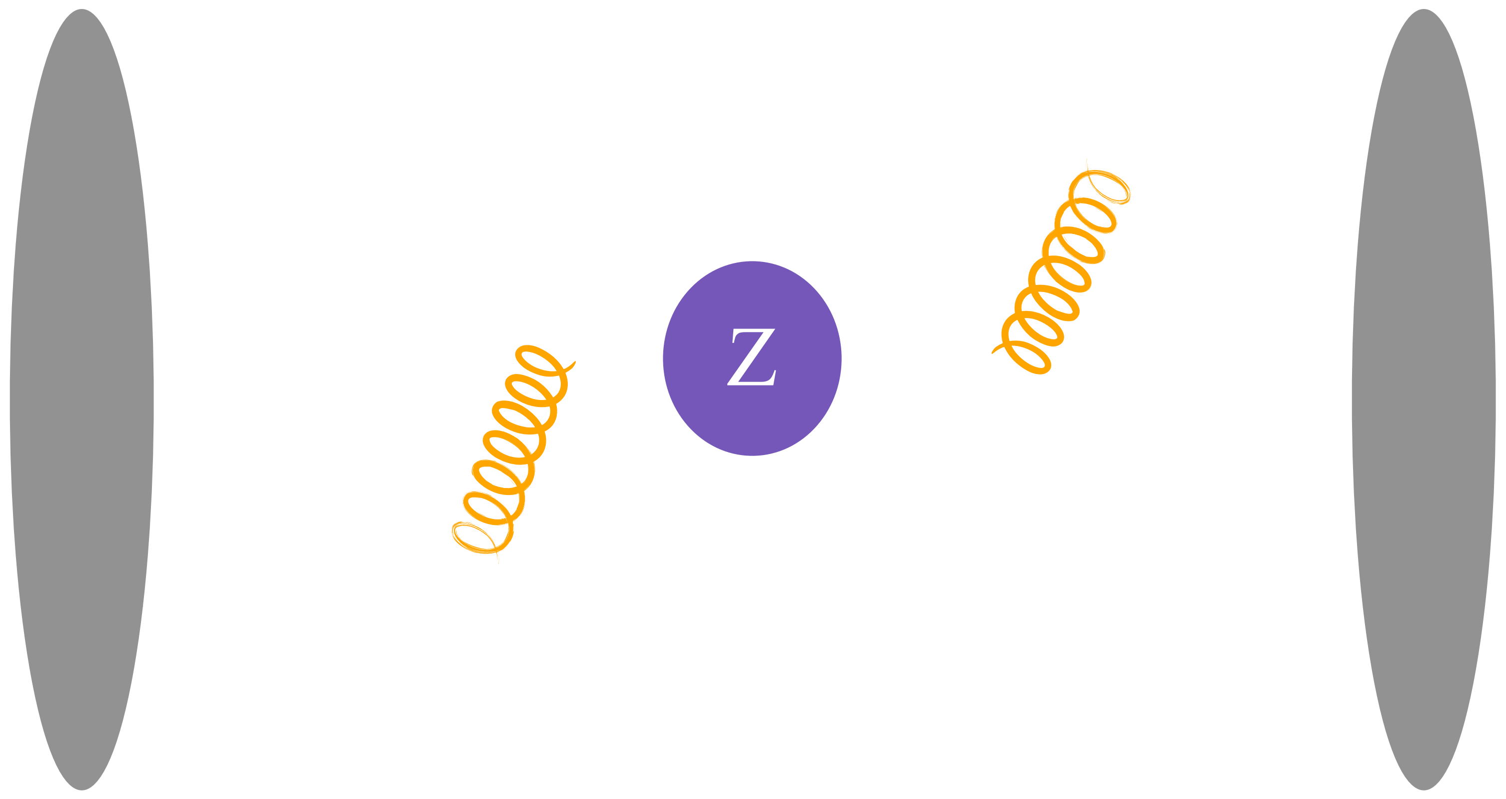
Classic experimental challenge in DPS

Signal (2HS)



vs

Background (1HS)



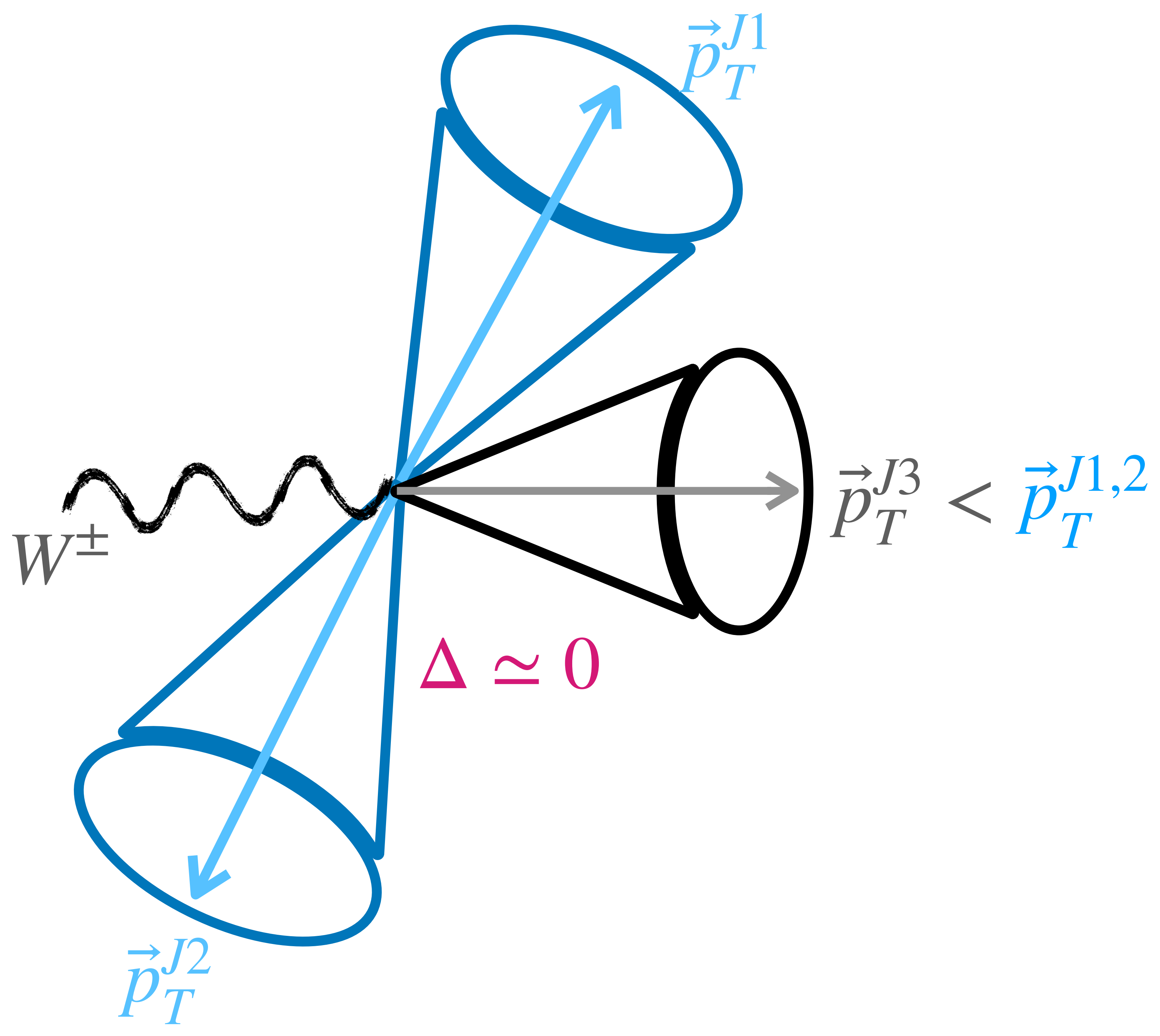
Same experimental signature: Z boson (2 leptons) + jets

Illustration: first LHC DPS measurement with $W(\to \ell\nu) + jj$

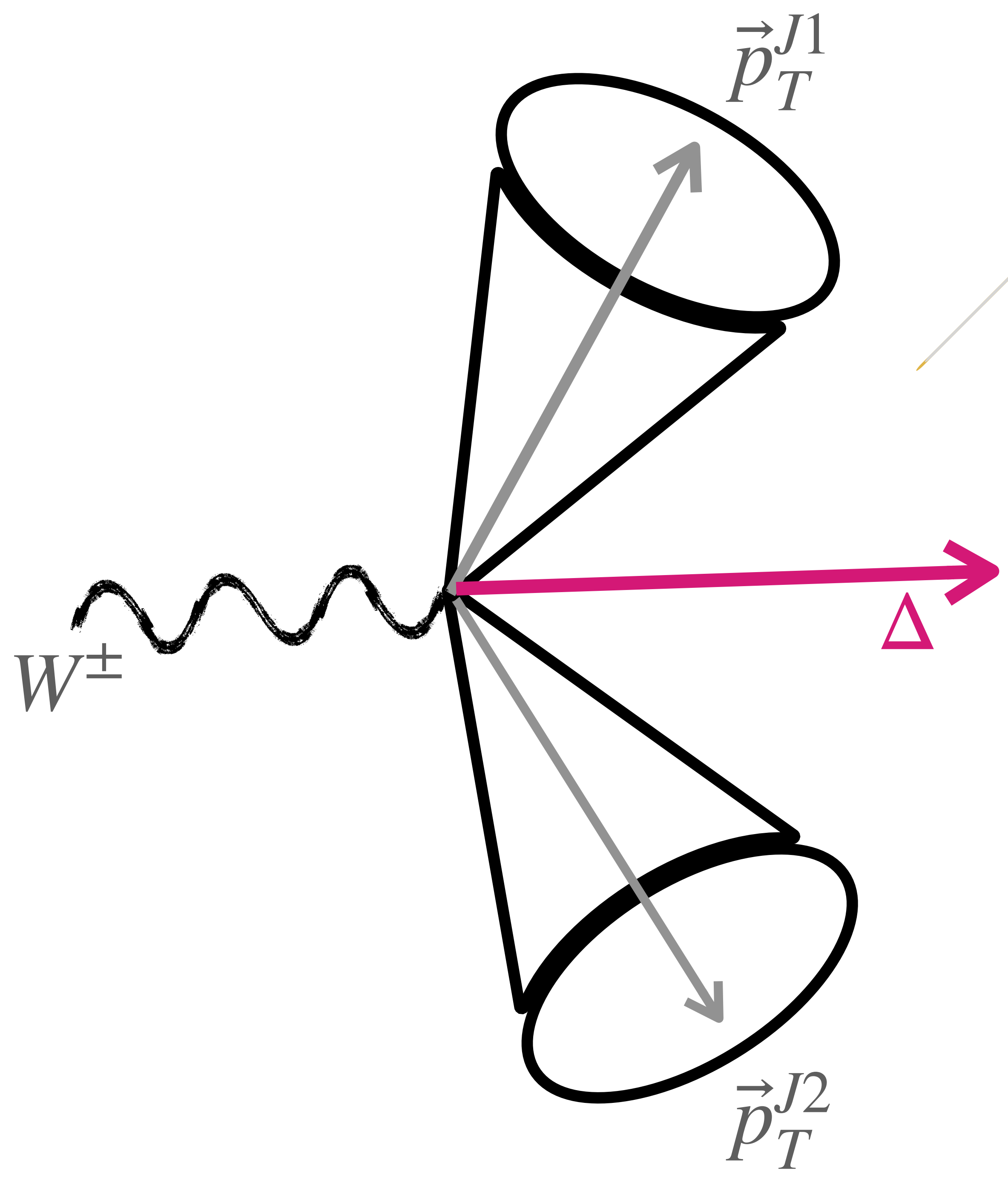
[ATLAS Collab. New J.Phys. 15 (2013) 033038]

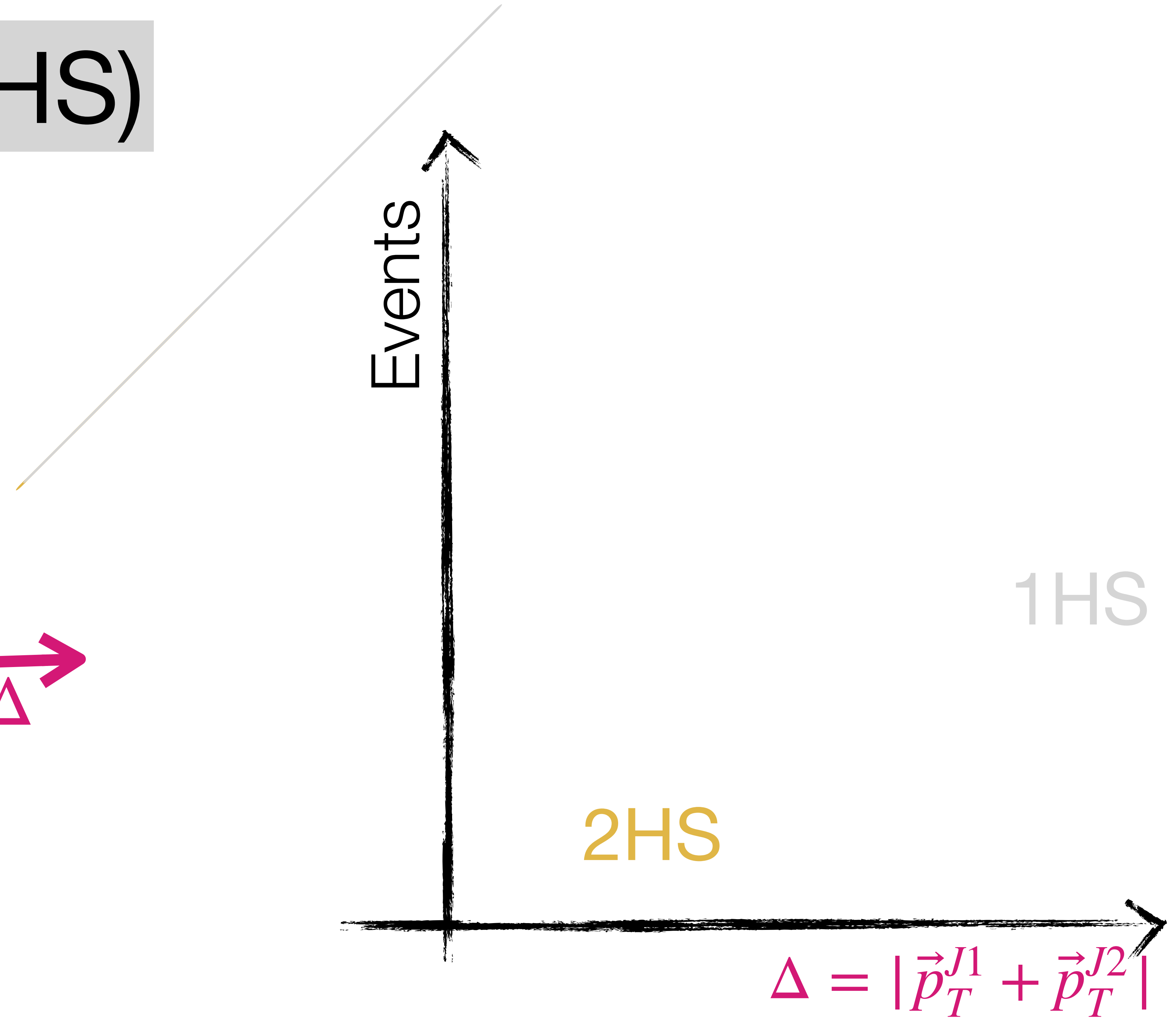
Introduce a metric to characterise MPI-likelihood: $\Delta = |\vec{p}_T^{J1} + \vec{p}_T^{J2}|$

Signal (2HS)



Background (1HS)





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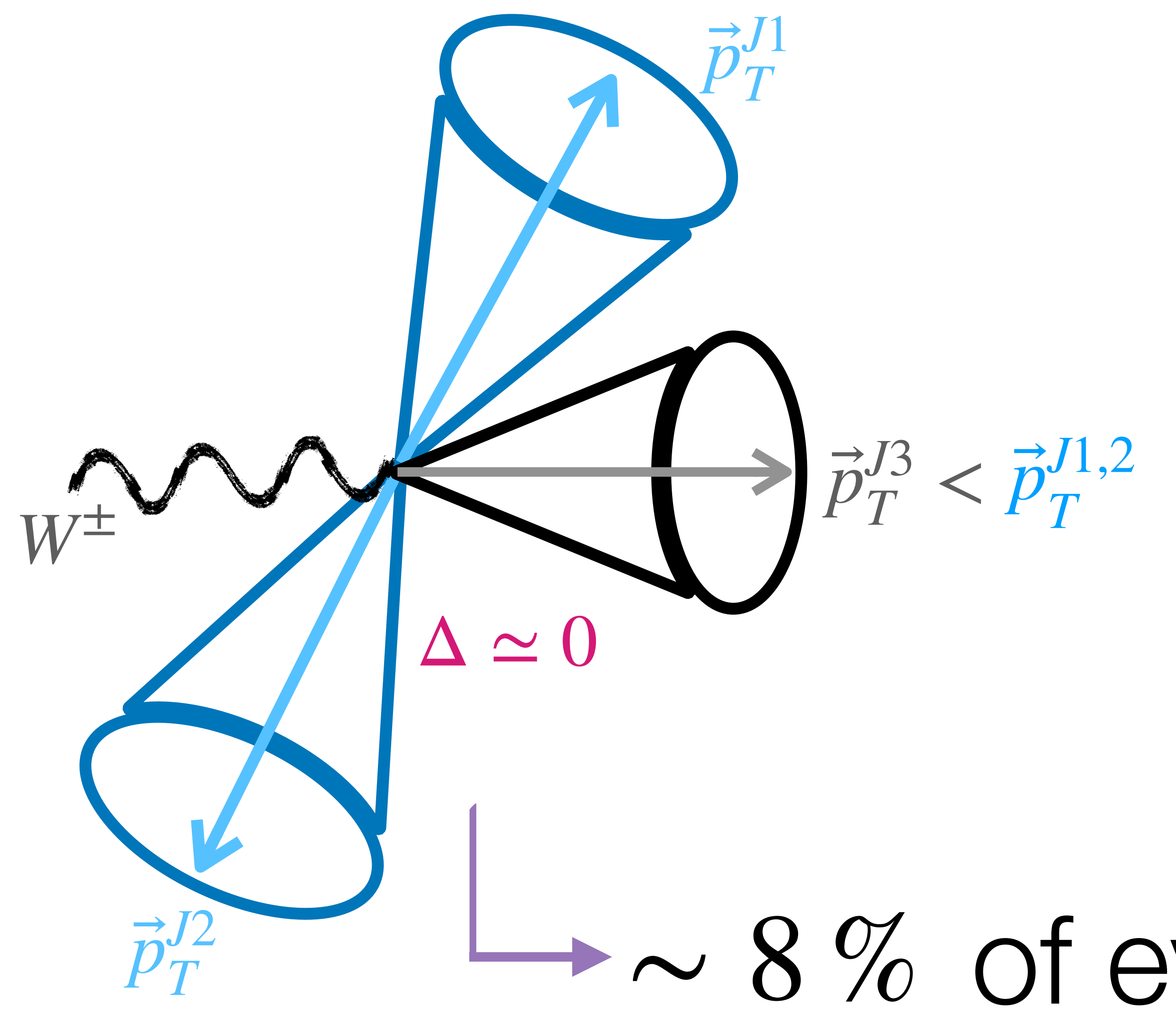
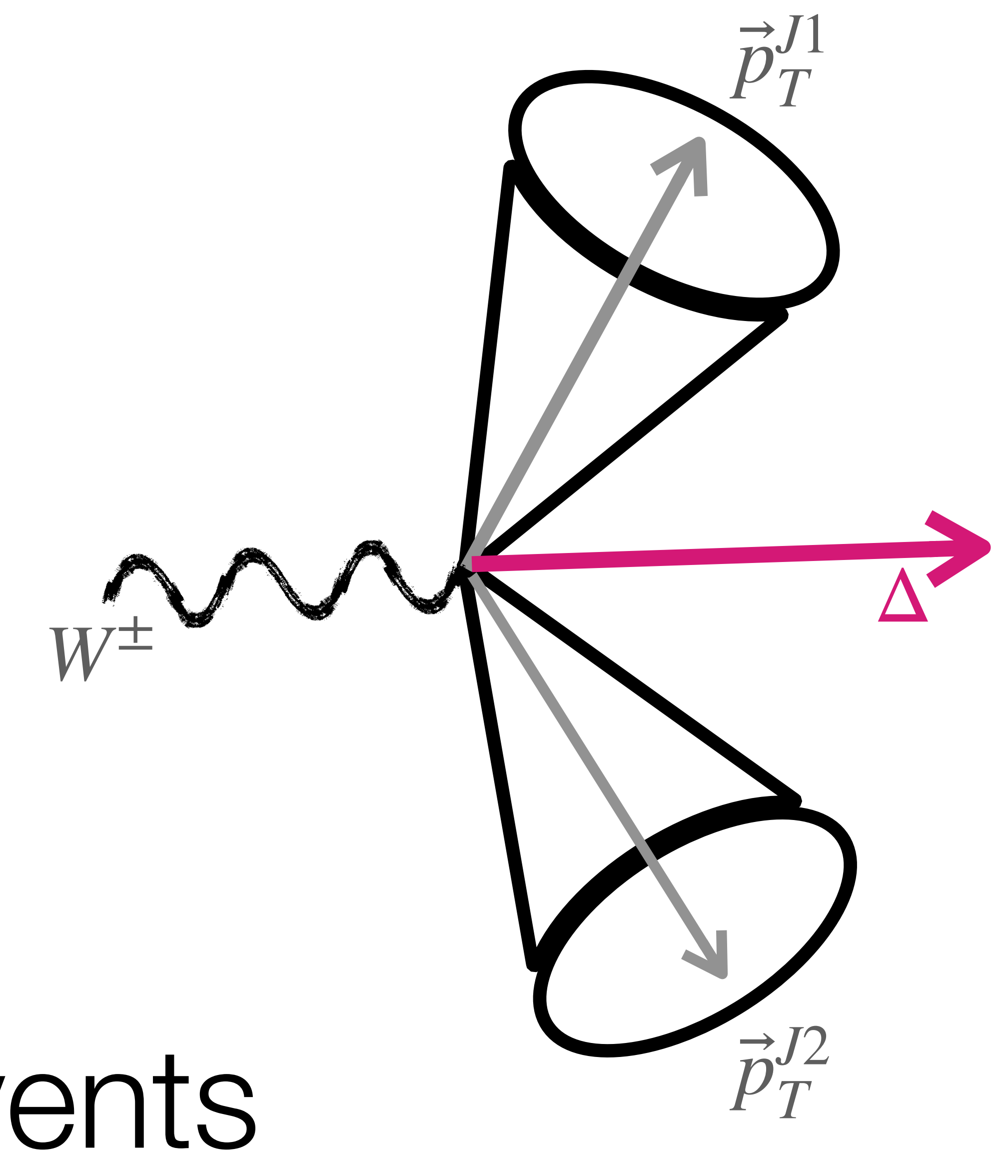
[ATLAS Collab. New J.Phys. 15 (2013) 033038]

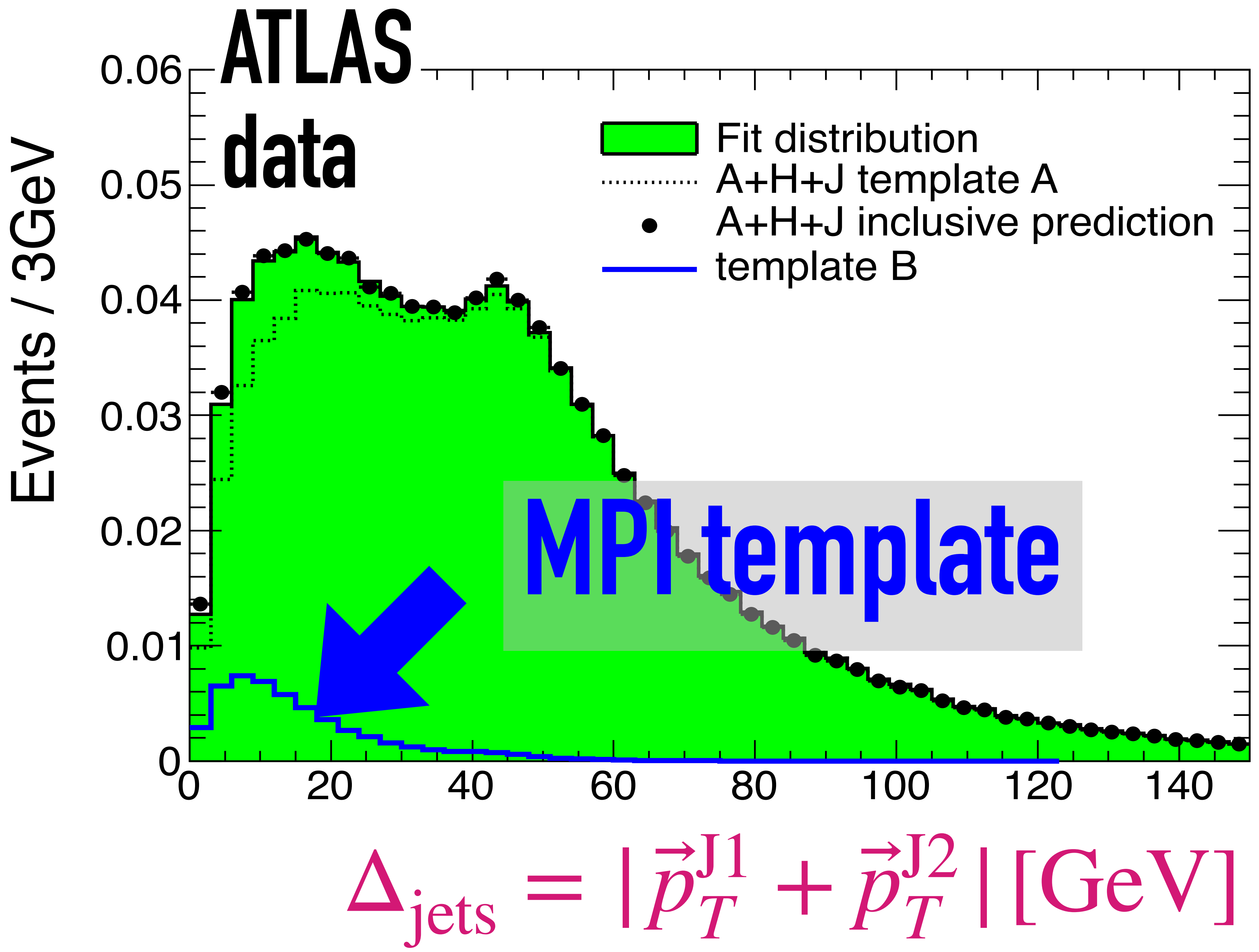
Signal (2HS)



$\sim 8\,\%$ of events

Background (1HS)





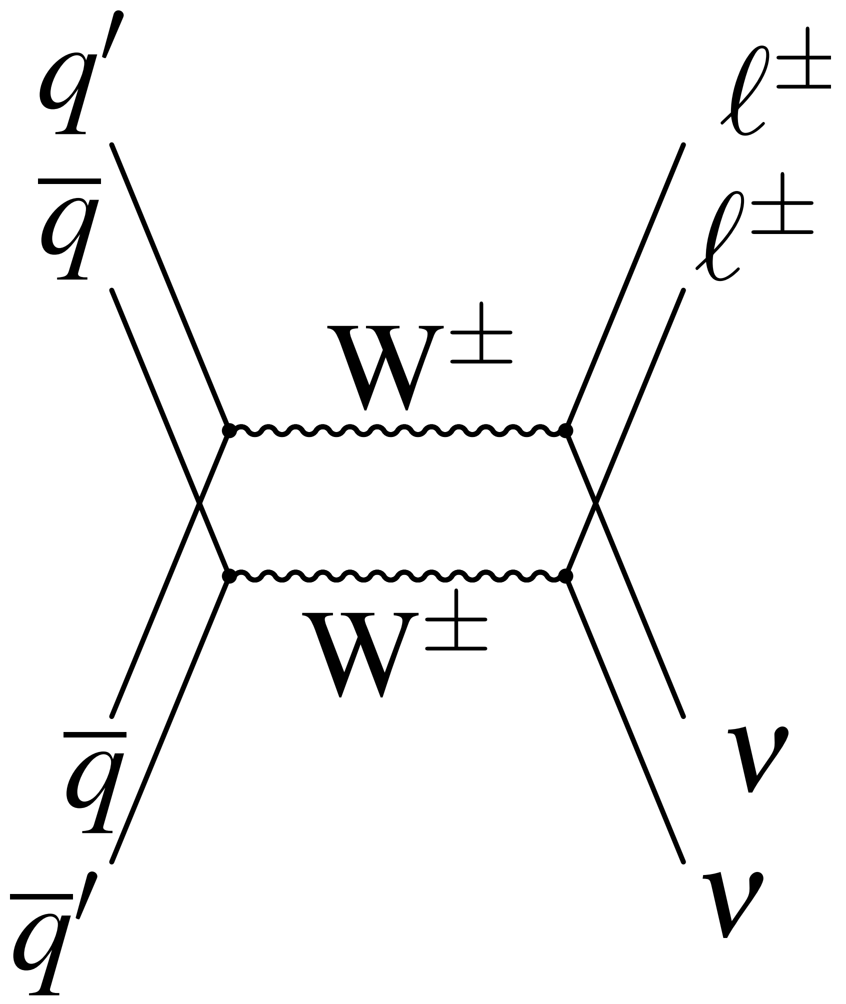
Low 2HS purities require very good understanding of 1HS

Avoid QCD radiation issue: same-sign $W^{\pm}W^{\pm}$

[CMS Collab. PRL 131 (2023) 091803]

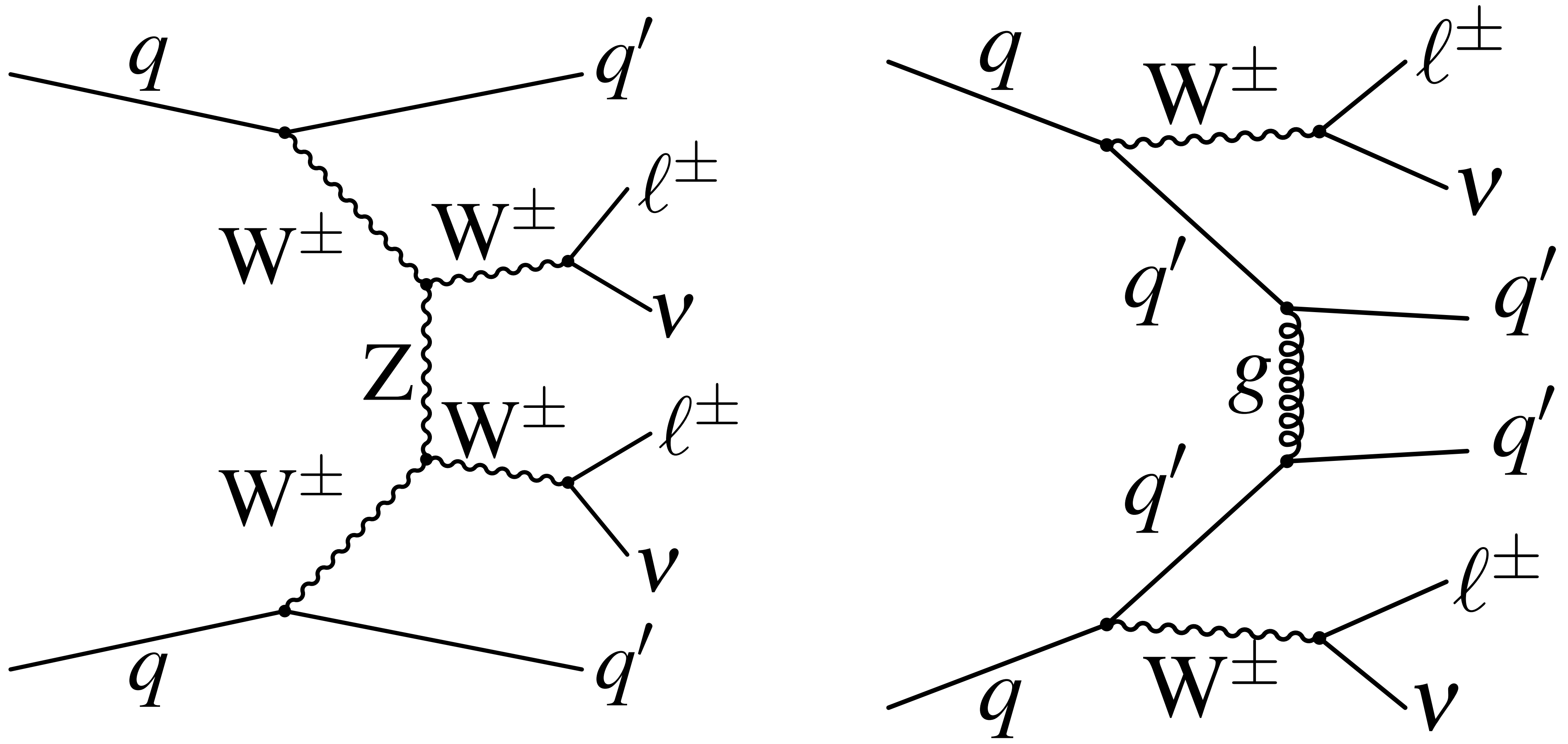
Traditional gold-plated observable for MPI:

Signal (2HS)



$\mathcal{O}(\alpha^2)$

Background (1HS)



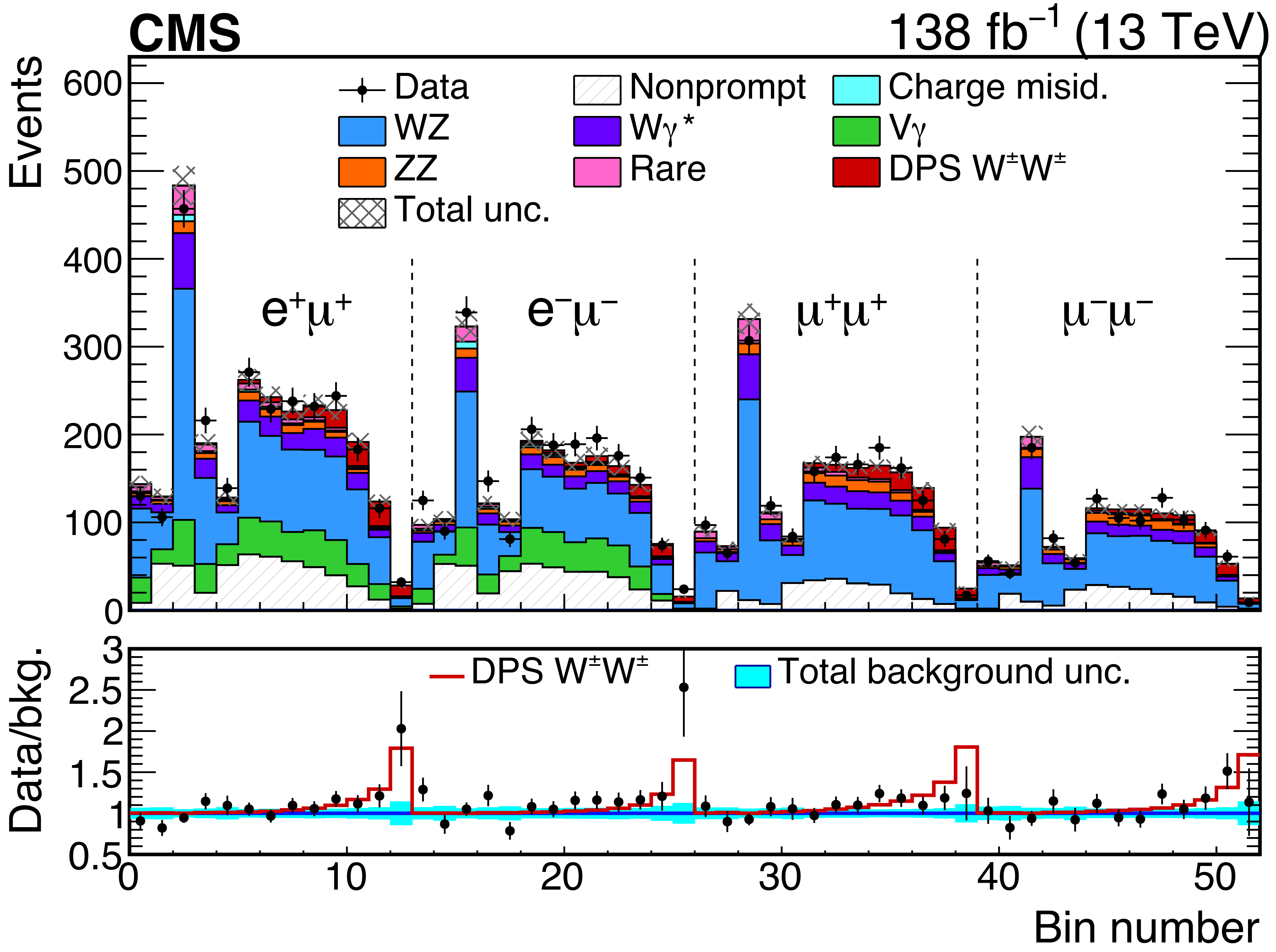
$\mathcal{O}\left(\alpha^4, \alpha_s^2\alpha^2\right)$

Experimental signature: $e^{\pm}\mu^{\pm}, \mu^{\pm}\mu^{\pm} + p_{T,\text{miss}}$

Avoid QCD radiation issue: same-sign $W^{\pm}W^{\pm}$

[CMS Collab. PRL 131 (2023) 091803]

Traditional gold-plated observable for MPI suffers from **background**:

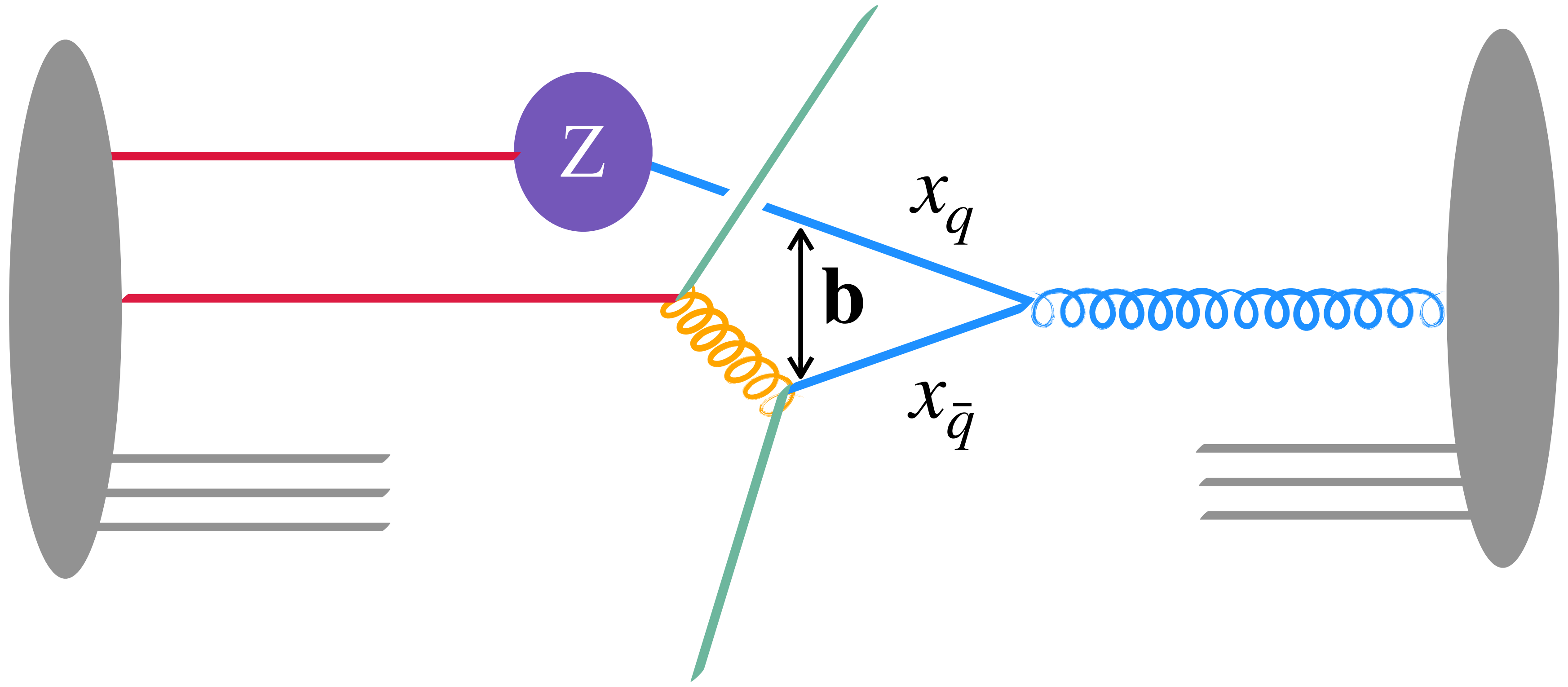


BDT discriminant

Just 6.2σ statistical significance with full Run 2 dataset

Theory challenges in DPS: beyond pocket-formula

[Diehl, Ostermeier, Schafer JHEP 1203 (2012)], [Diehl, Gaunt, Schönwald JHEP 1706 (2017) 083]



Perturbative interconnection, i.e. $1 \to 2$

$$\lim_{\mathbf{b}\to 0} F^{q\bar{q}}(x_q, x_{\bar{q}}, \mathbf{b}) \sim \alpha_s \frac{f(x_q + x_{\bar{q}})}{x_q + x_{\bar{q}}} P_{g\to q\bar{q}}\left(\frac{x_q}{x_q + x_{\bar{q}}}\right) \frac{1}{\mathbf{b}^2}$$

Delicate interplay with loop corrections to 1HS: need to avoid double counting

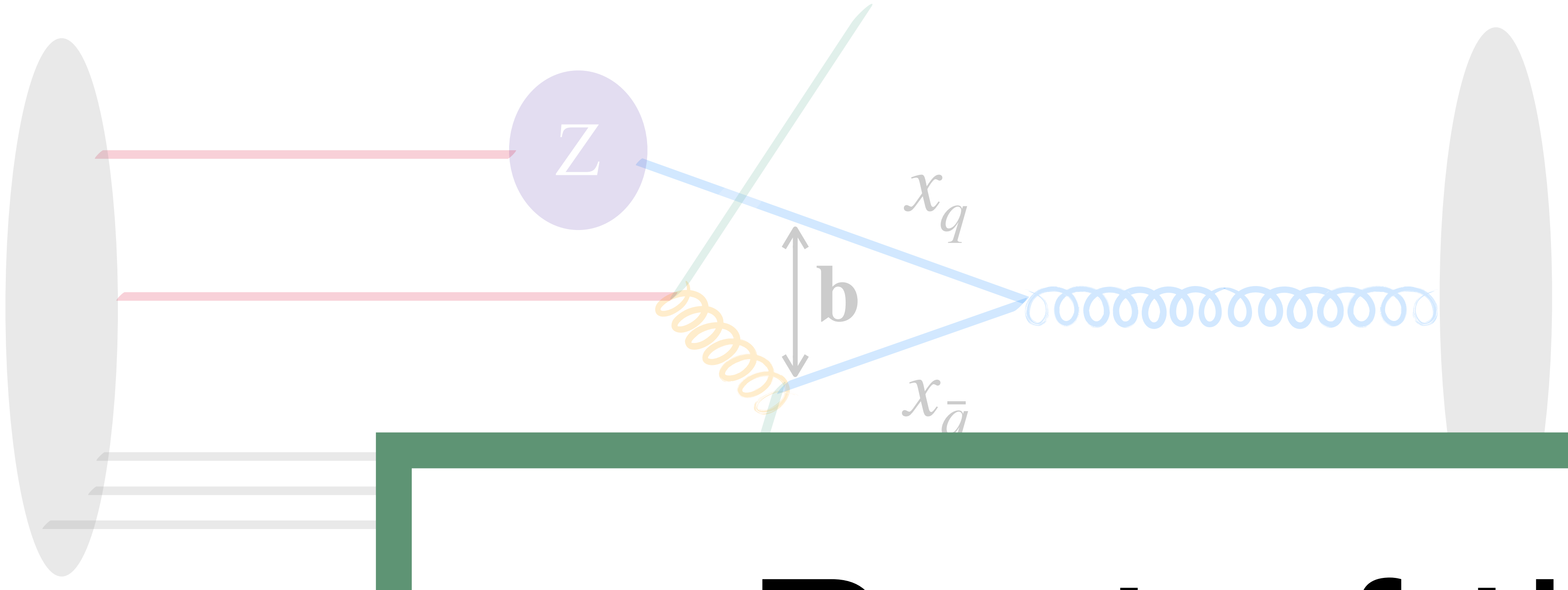
Extend 1HS theory to 2HS: double PDFs, colour flow, sum rules, DGLAP

Substantial progress in describing 2HS with MC tools: dShower

[Cabouat, Gaunt, Ostrolenk JHEP 11 (2019) 061], [Cabouat, Gaunt JHEP 10 (2020) 012]

Theory challenges in DPS: beyond pocket-formula

[Diehl, Ostermeier and Schafer JHEP 1203 (2012)], [Diehl, Gaunt, Schönwald JHEP 1706 (2017) 083]



Perturbative interconnection, i.e. $1 \to 2$

Delicate … counting

Rest of this talk: present an experimental strategy to optimally disentangle 1HS from MPI

Double parton densities, colour flow, sum rules, DGLAP evolution?

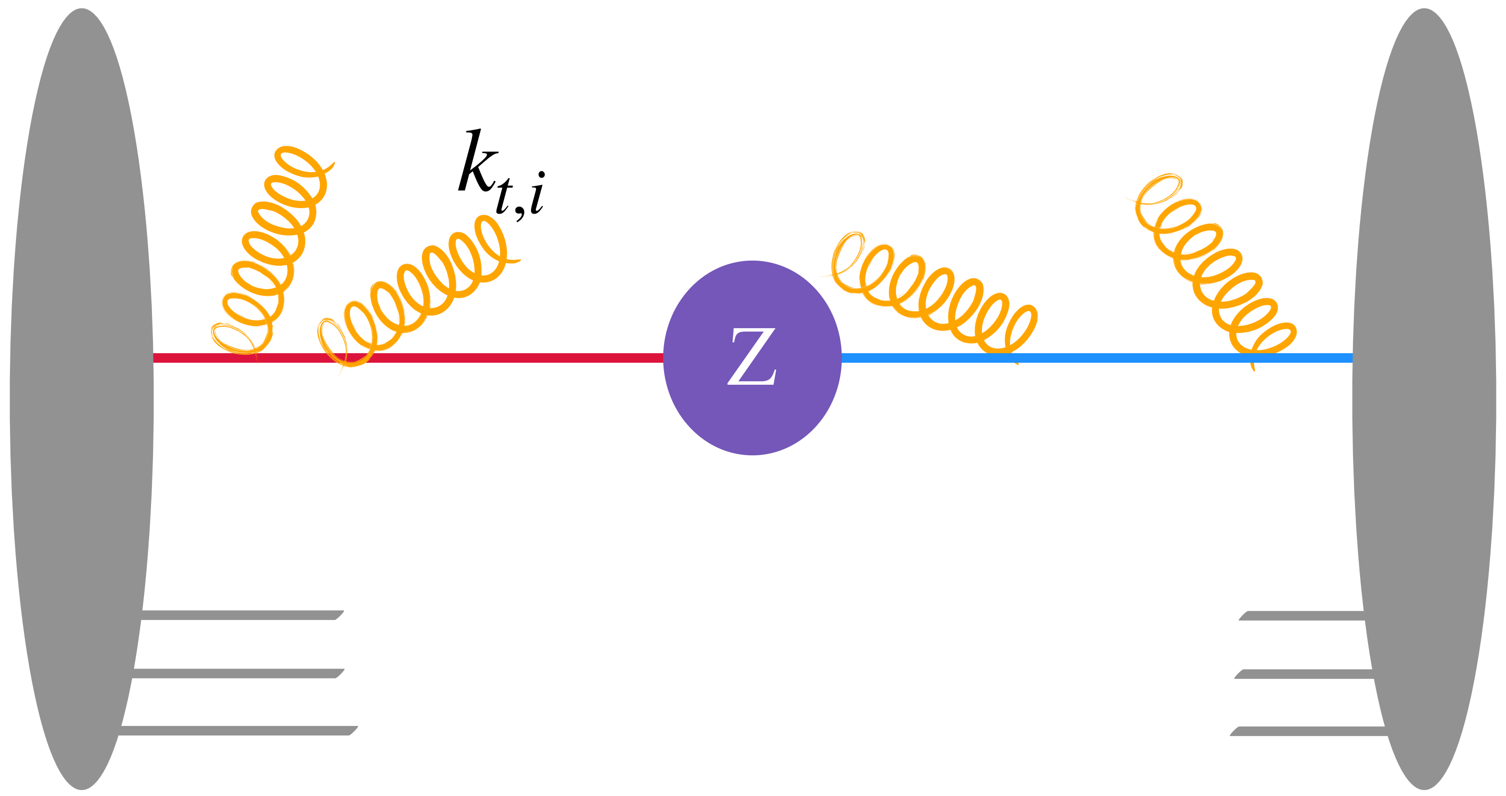
Substantial progress in describing 2HS with MC tools: dShower

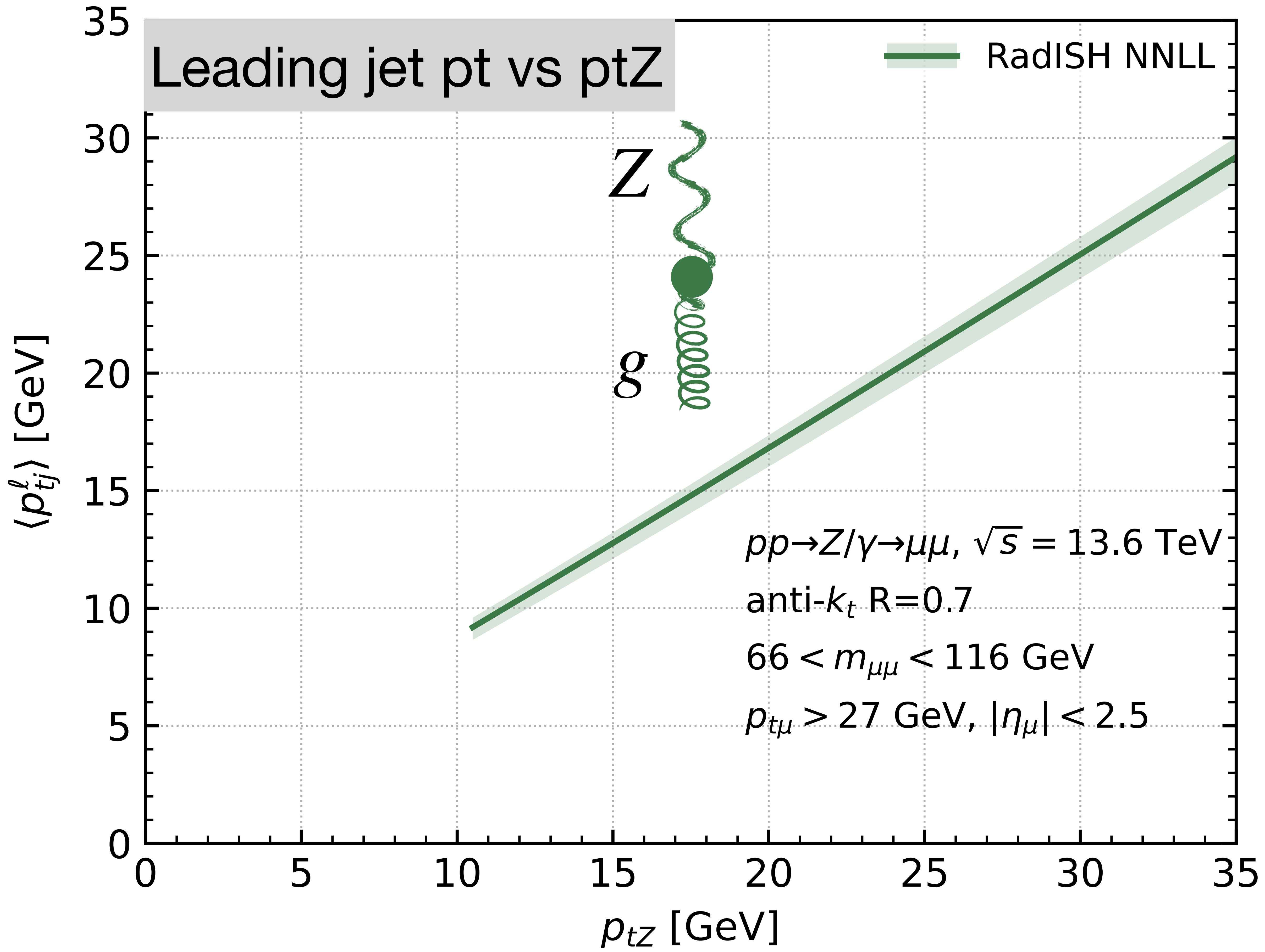
[Cabouat, Gaunt, Ostrolenk JHEP 11 (2019) 061], [Cabouat, Gaunt JHEP 10 (2020) 012]

Idea: exploit Parisi-Petronzio lesson from 1979

[Parisi, Petronzio, NPB 154 (1979) 427-440] [RadISH: Monni, Re, Torrielli PRL 116, 242001, Monni, Rottoli, Torrielli PRL 124 (2020) 25, 252001]

We explore Drell-Yan events and study the $p_{tZ} \to 0$ limit. Two concurring mechanisms:





1 Exponential suppression of the spectrum (Sudakov peak)

$$p_{tZ}^2 \sim k_{t,i}^2 \ll M_Z$$

Idea: exploit Parisi-Petronzio lesson from 1979

[Parisi, Petronzio, NPB 154 (1979) 427-440] [RadISH: Monni, Re, Torrielli PRL 116, 242001, Monni, Rottoli, Torrielli PRL 124 (2020) 25, 252001]

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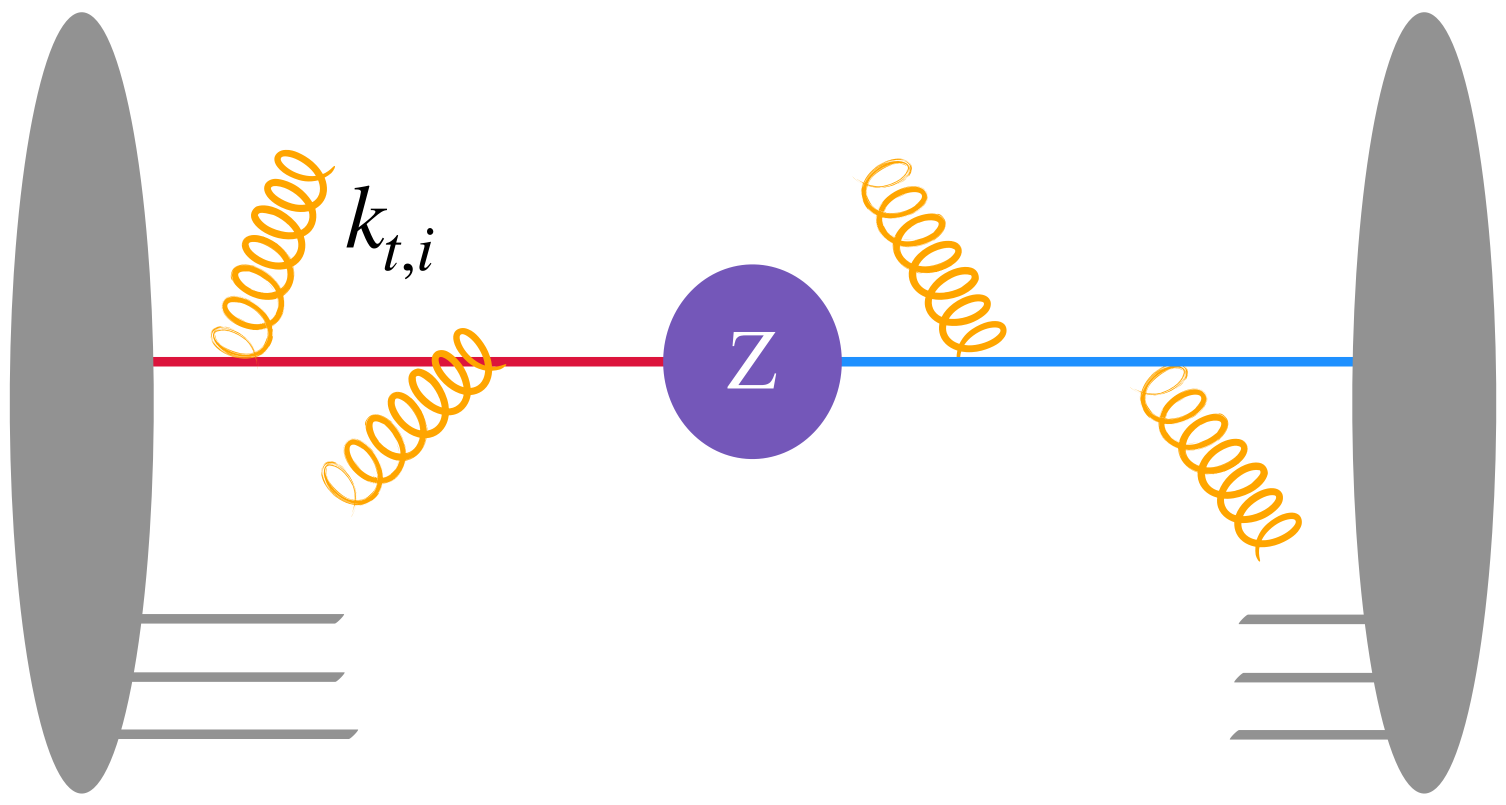
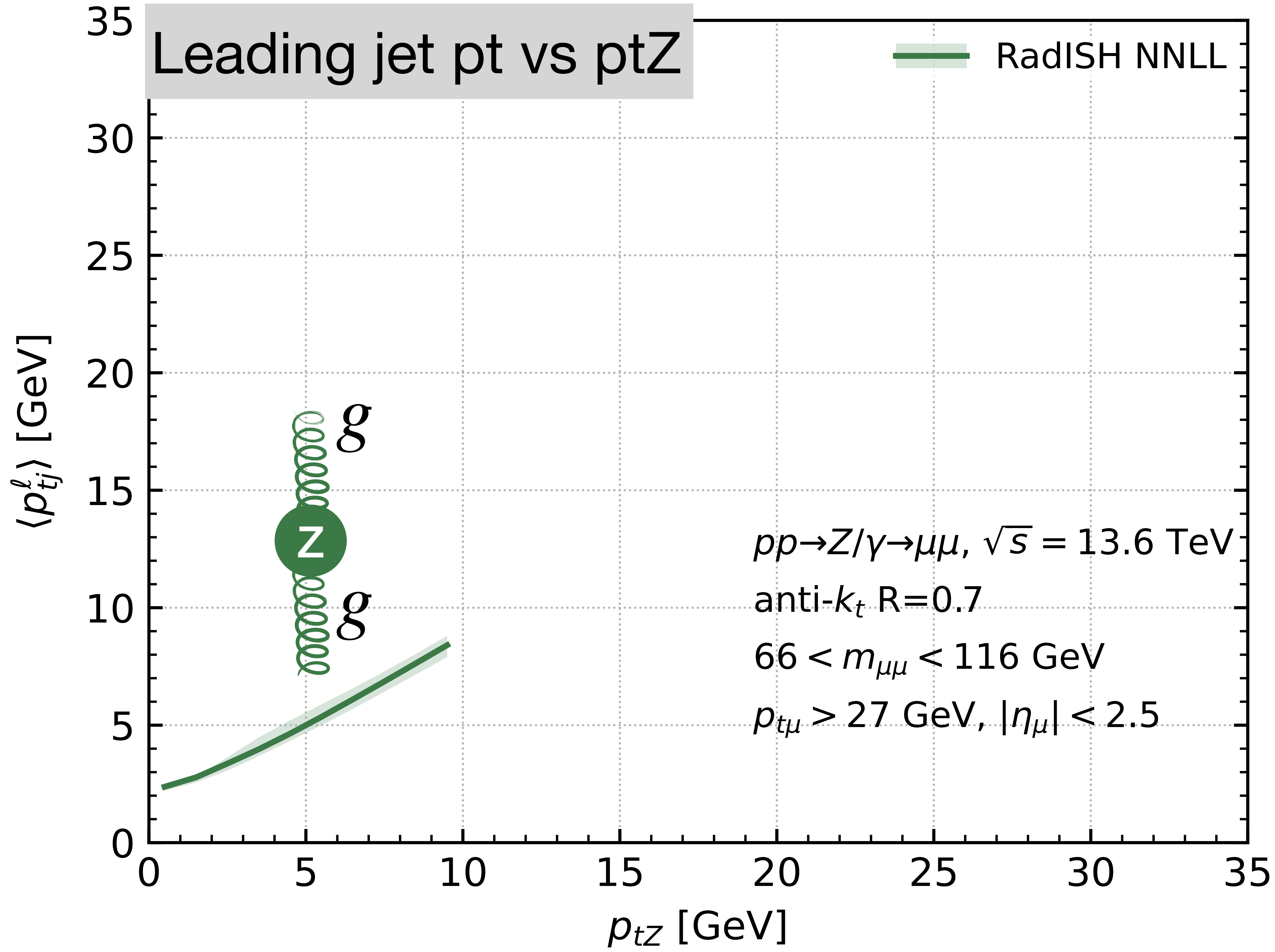


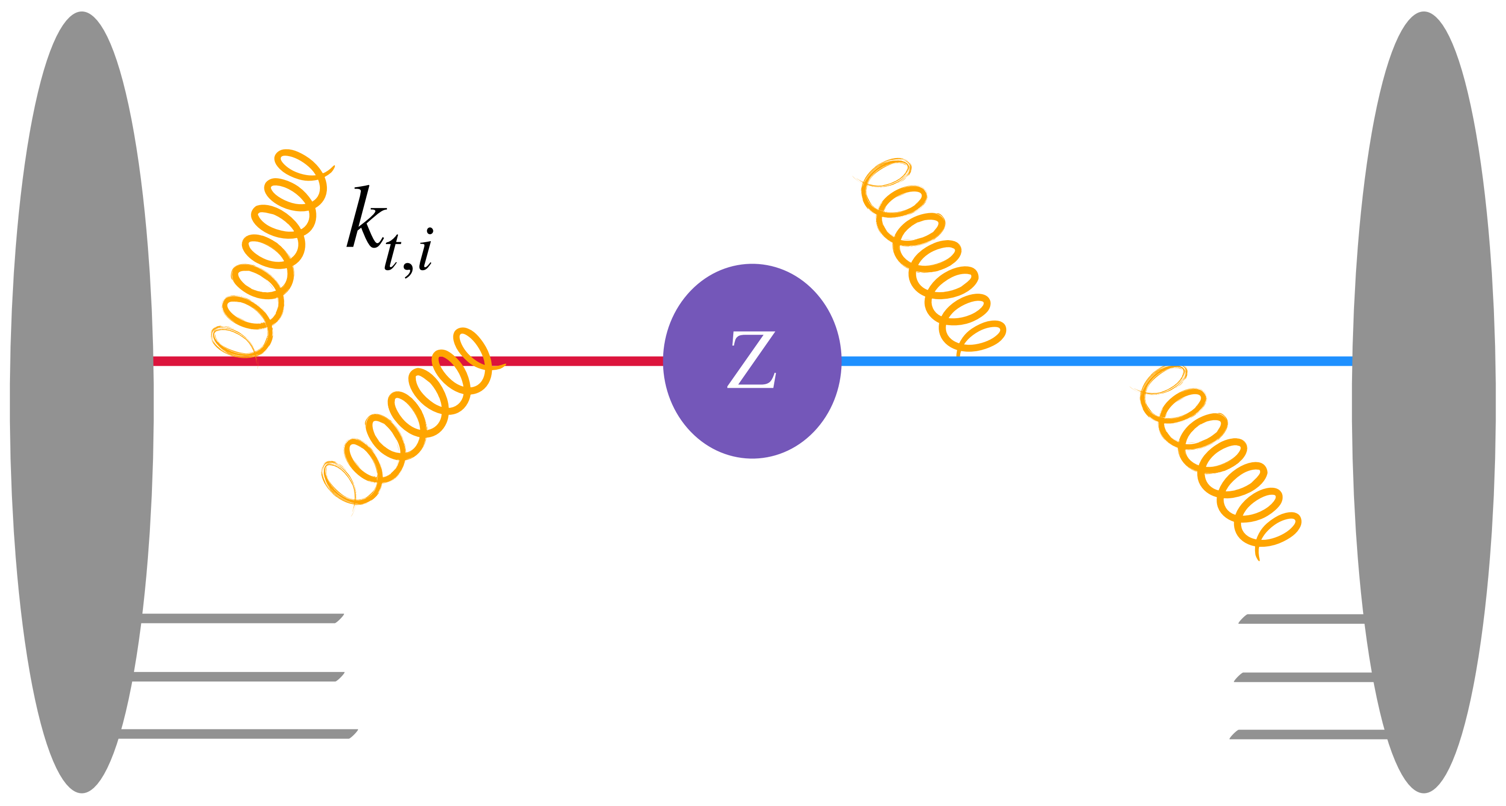


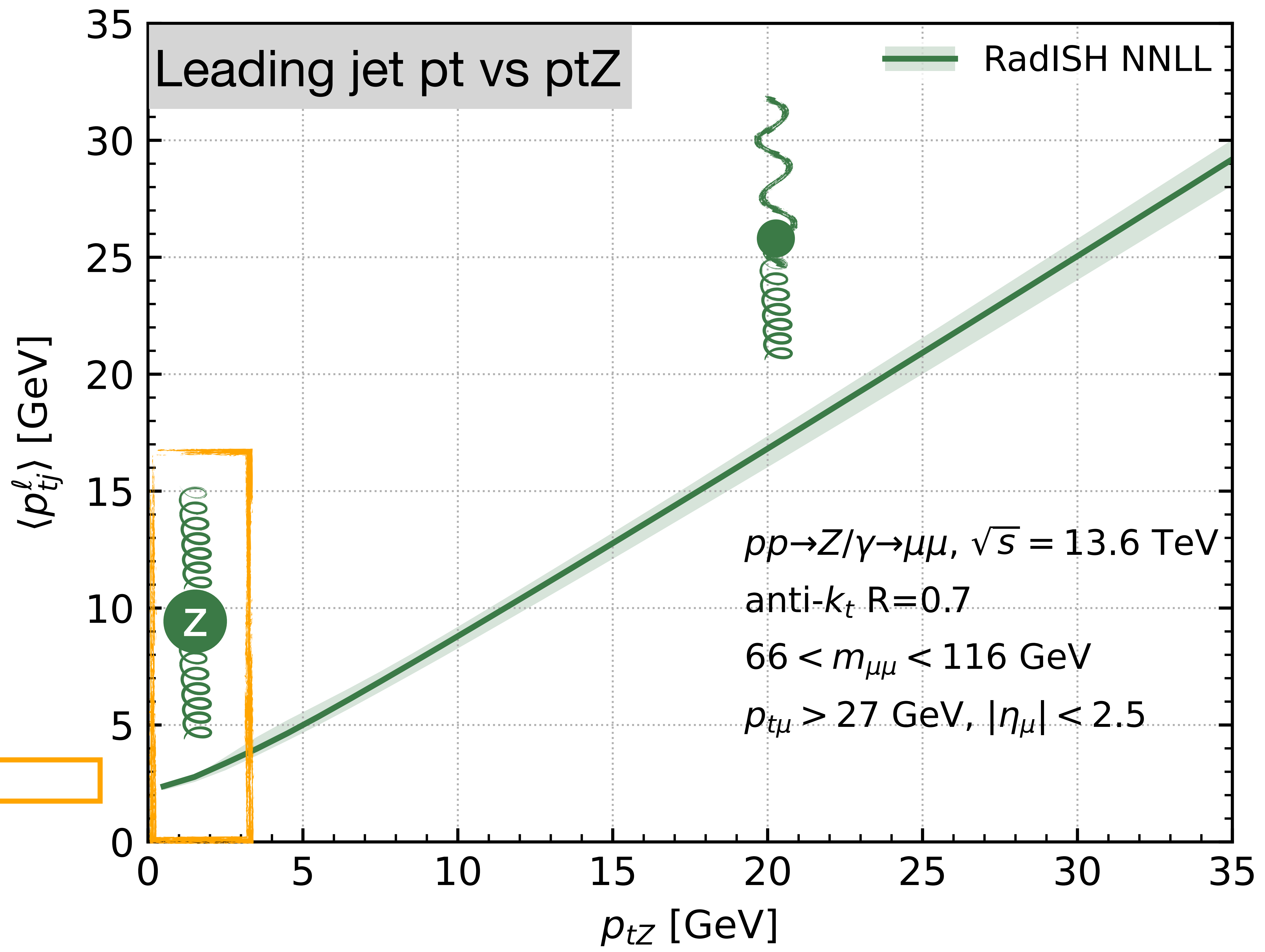
2 $\mathcal{O}(p_t)$ suppression of the spectrum (dominant for $p_{tZ} \to 0$)

$$\sum k_{t,i}^2 \simeq 0, p_{tZ}^2 \ll k_{t,i}^2 \ll M_Z$$

Idea: exploit Parisi-Petronzio lesson from 1979

[Parisi, Petronzio, NPB 154 (1979) 427-440] [RadISH: Monni, Re, Torrielli PRL 116, 242001, Monni, Rottoli, Torrielli PRL 124 (2020) 25, 252001]





2 Intercept calculable

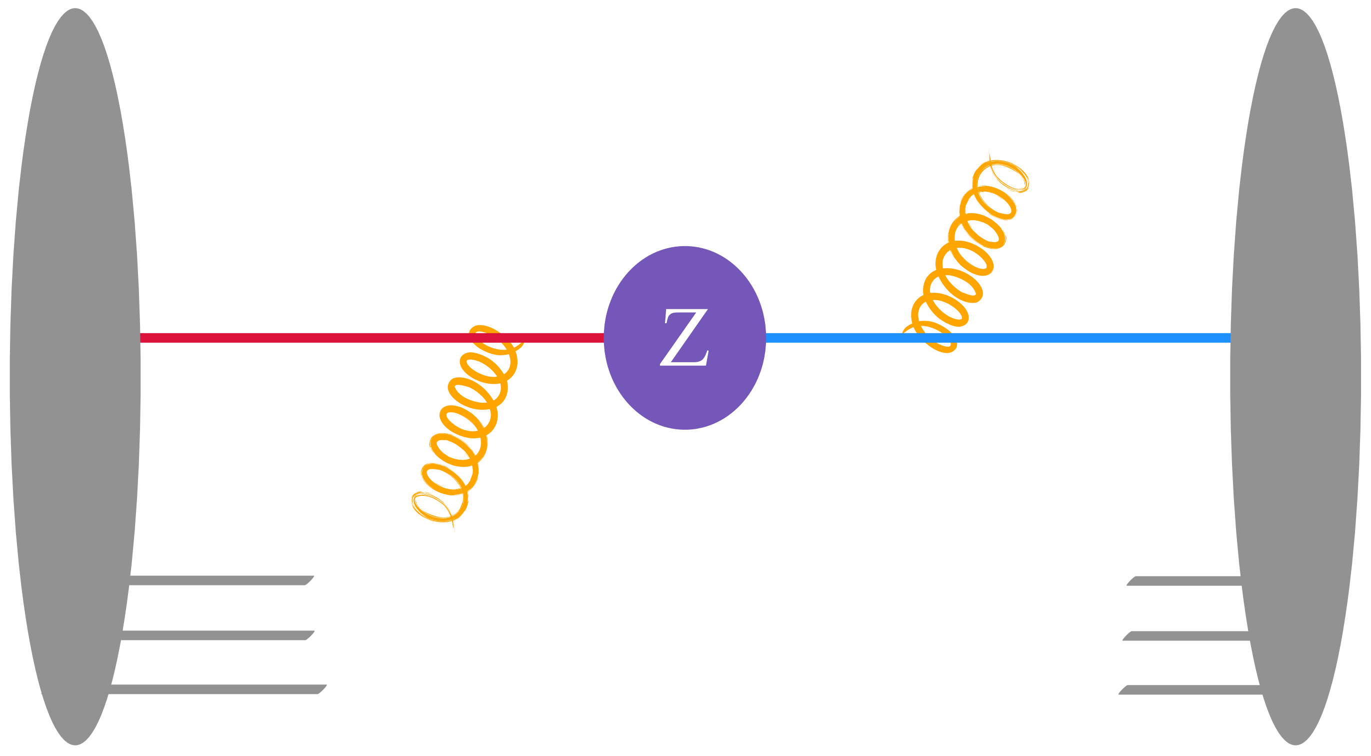
$$\langle p_{tj}^{\ell} \rangle_{p_{tZ}\to 0} \sim \Lambda \left(\frac{M}{\Lambda}\right)^{\kappa \ln \frac{2+\kappa}{1+\kappa}}$$

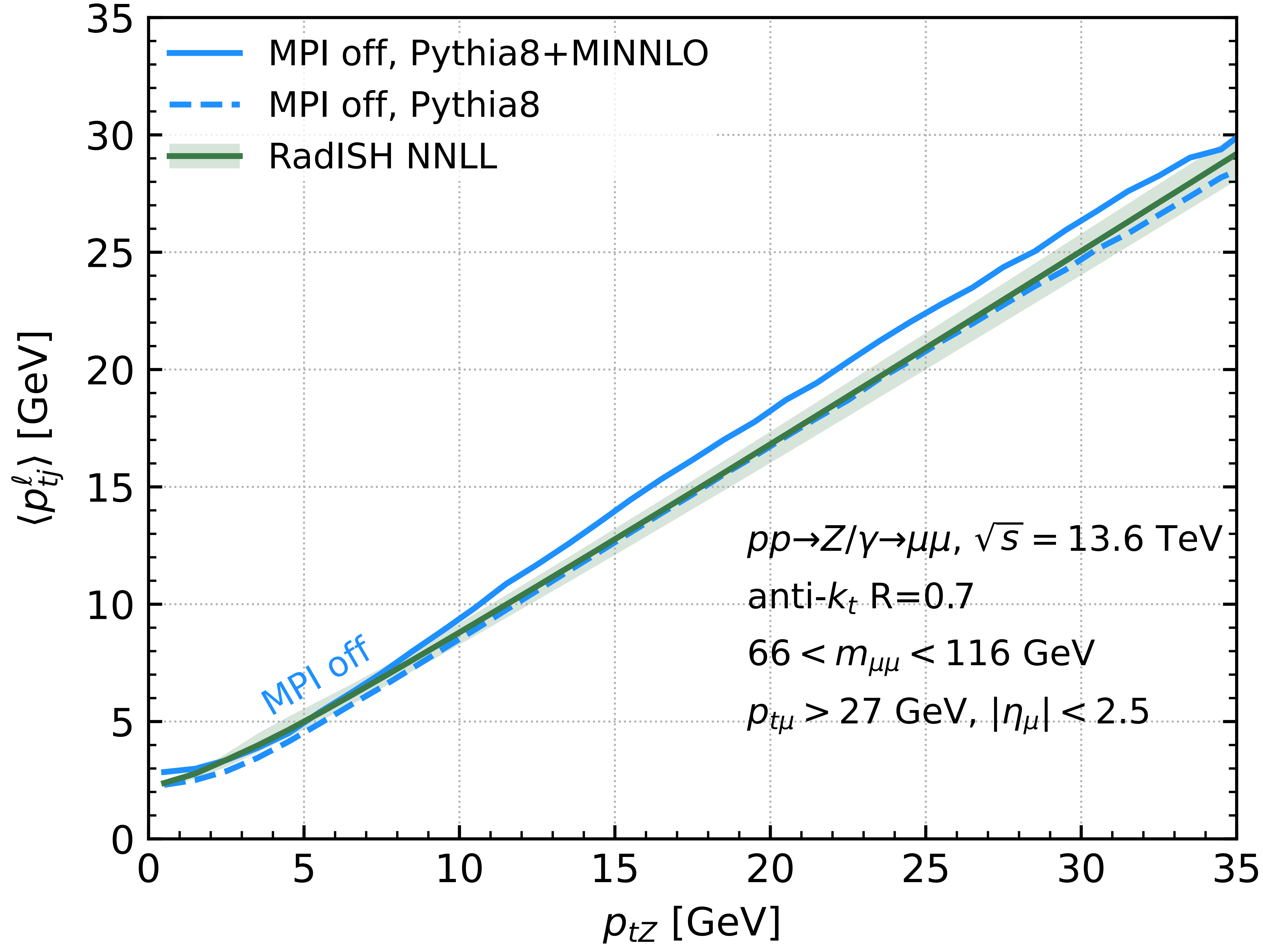
$\sim$ 2-3 GeV

$$\kappa = \frac{2C_F}{\pi\beta_0}$$

Key observation to suppress 1HS contribution

[RadISH: Monni, Re, Torrielli PRL 116, 242001, Monni, Rottoli, Torrielli PRL 124 (2020) 25, 252001] [MINNLO: Monni et al JHEP 05 (2020) 143]

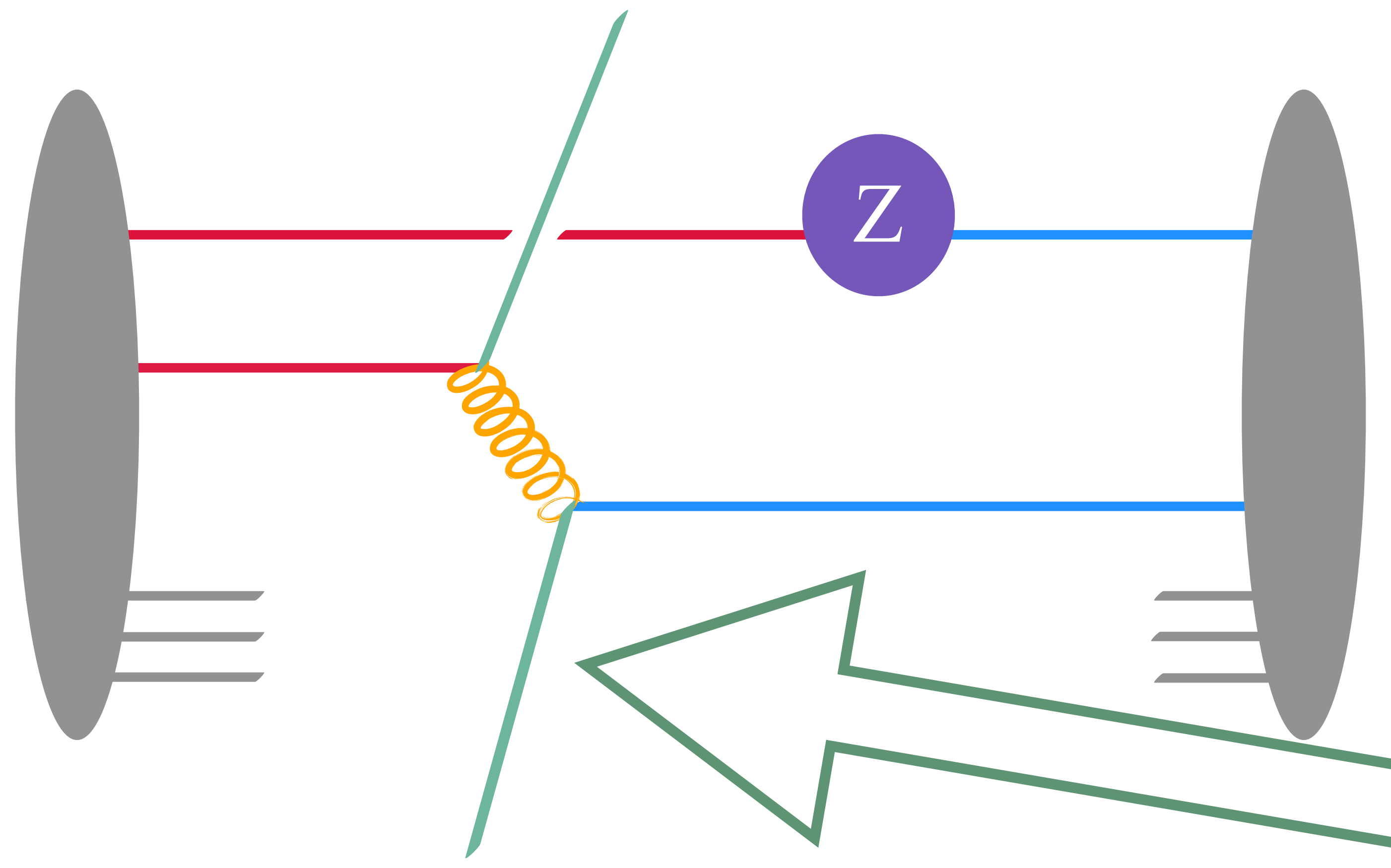


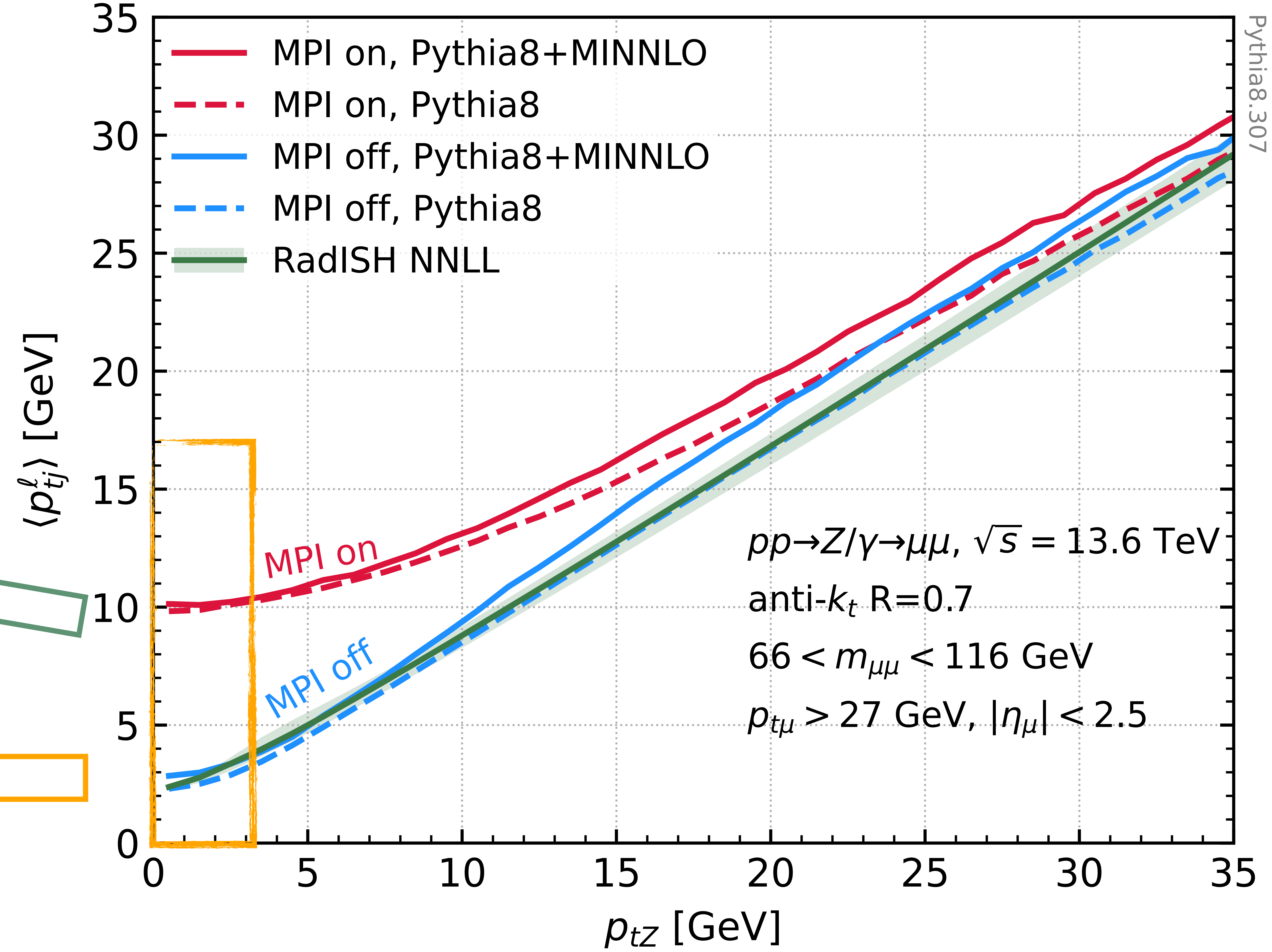


By constraining p_{tZ} we can forbid QCD radiation from 1HS above 2-3 GeV

What happens when switching on MPI?

[RadISH: Monni, Re, Torrielli PRL 116, 242001, Monni, Rottoli, Torrielli PRL 124 (2020) 25, 252001] [MINNLO: Monni et al JHEP 05 (2020) 143]





MPI off: $\langle p_{tj}^{\ell} \rangle_{p_{tZ} \to 0} \sim 2.5$ GeV

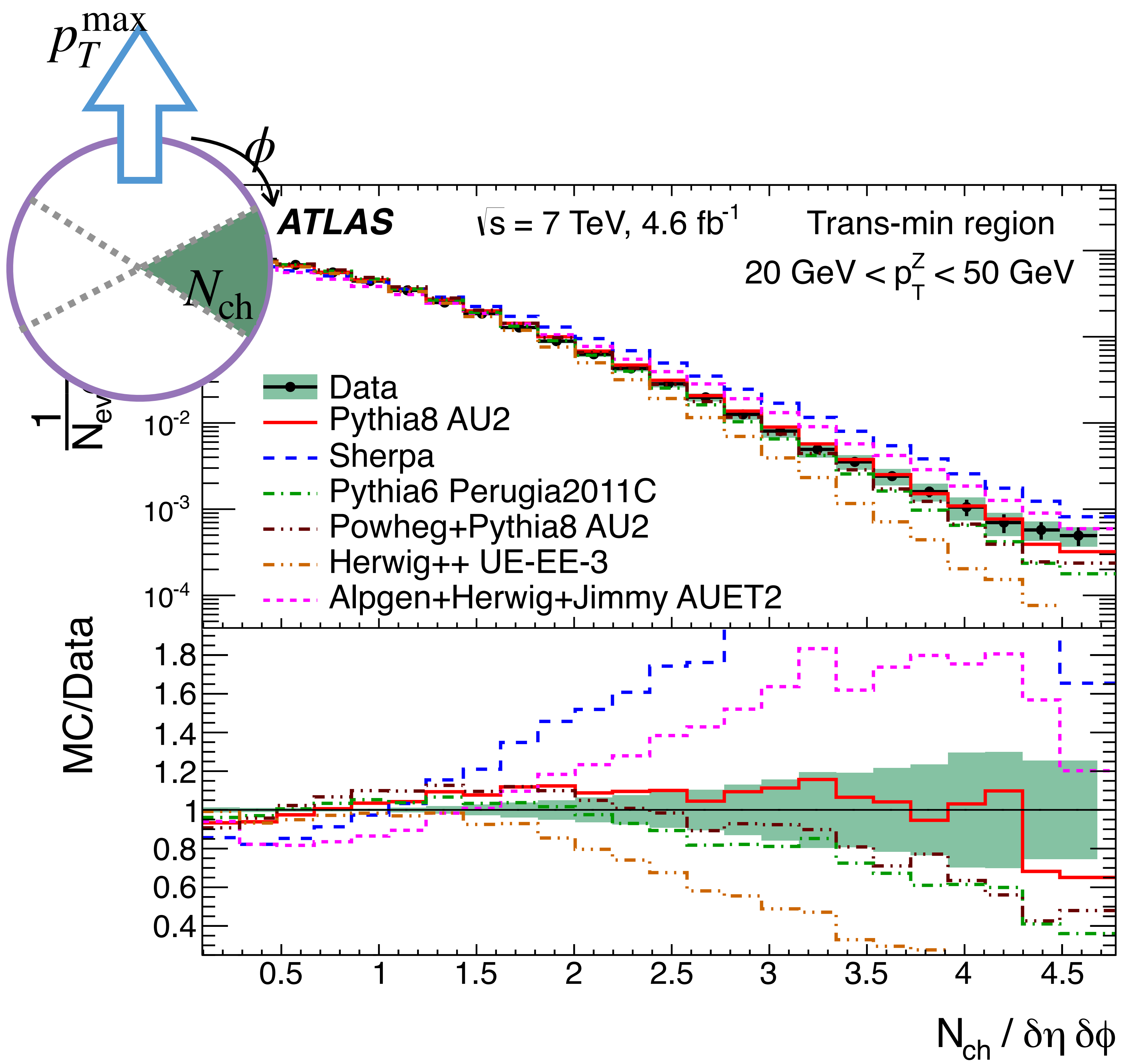
MPI on: $\langle p_{tj}^{\ell} \rangle_{p_{tZ} \to 0} \sim 10$ GeV

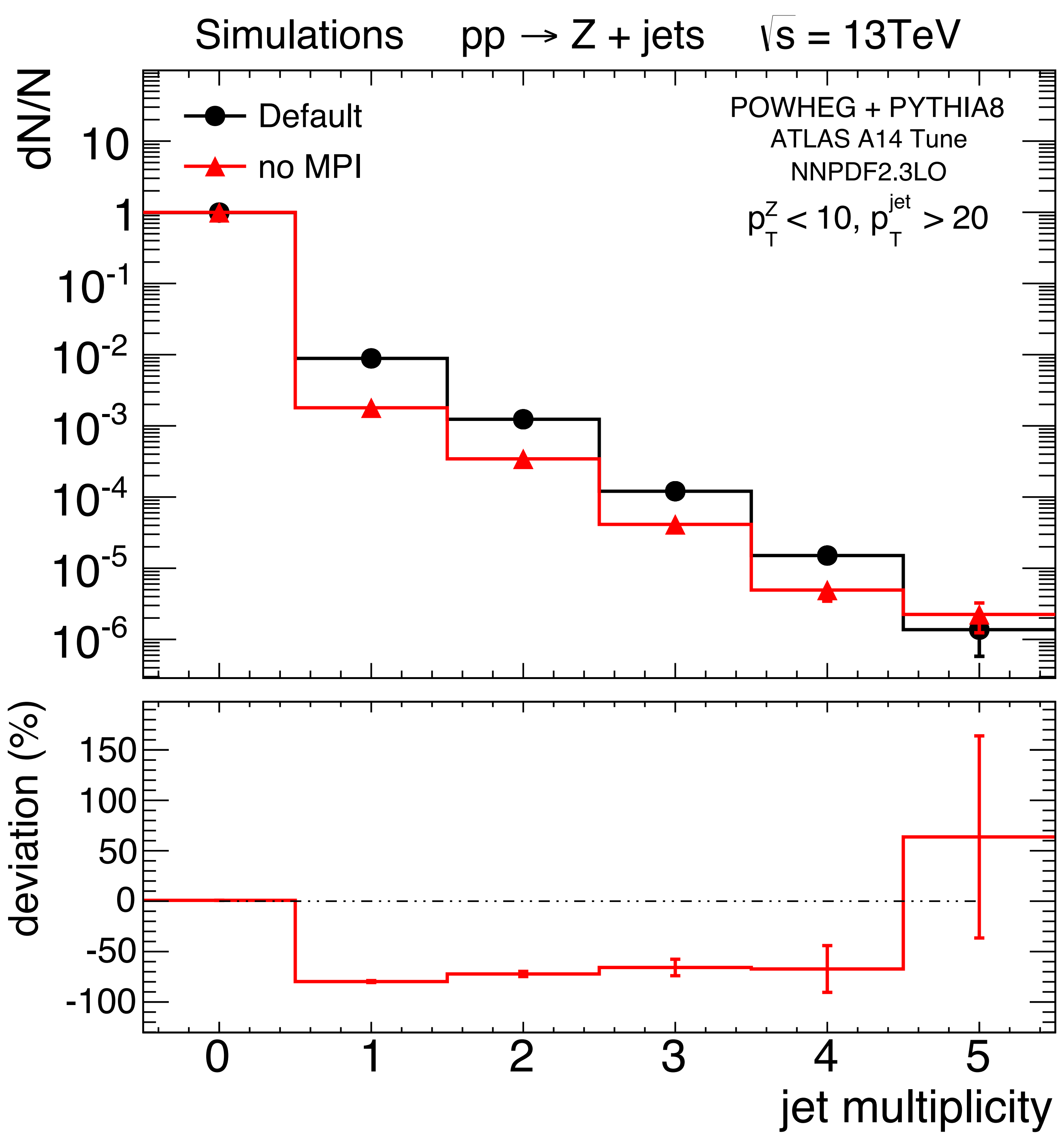
Suggests we should study MPI with help of a tight cut on p_{tZ}

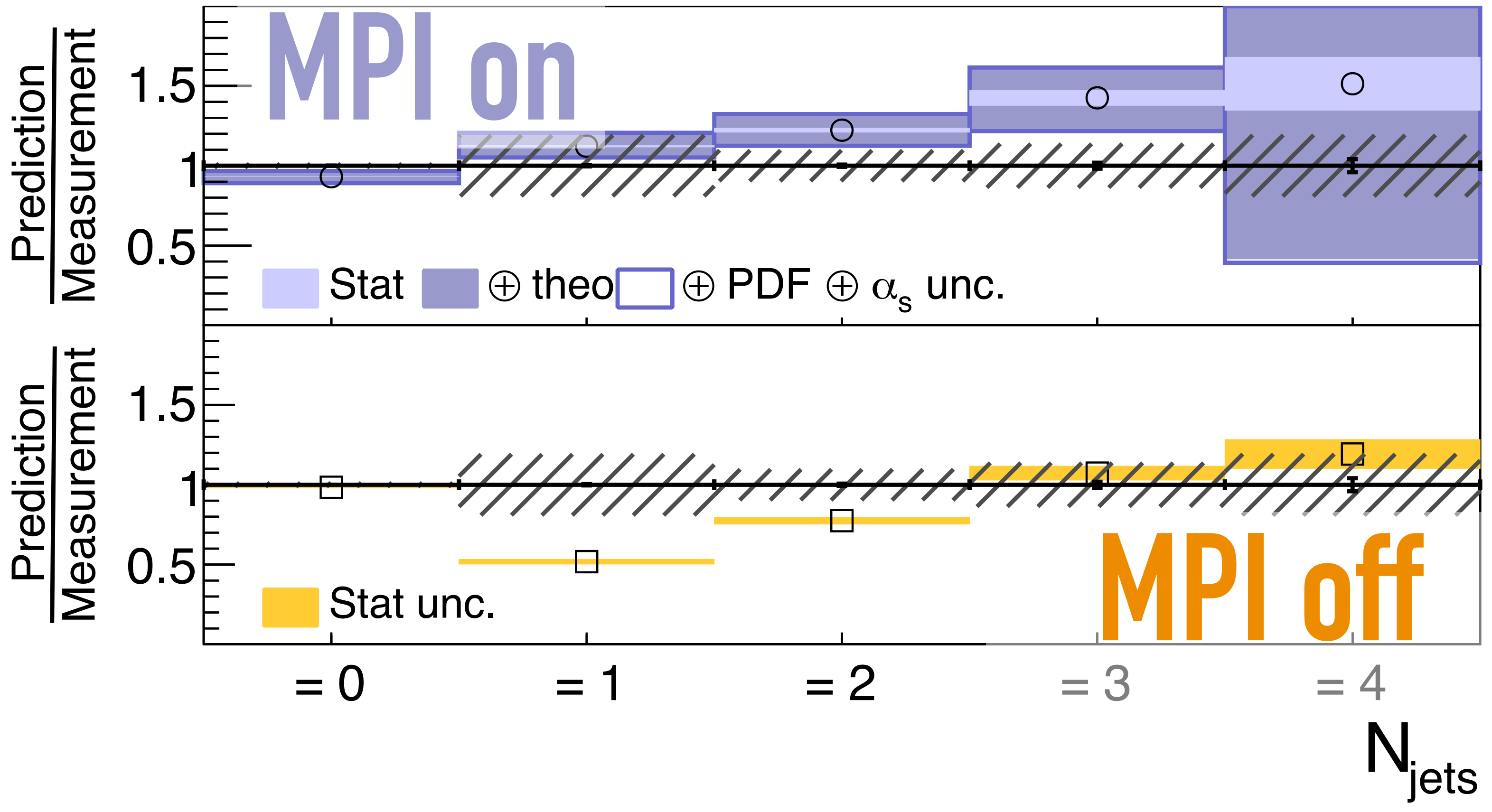
Did nobody think about this before?

[ATLAS Collab EPJC 74 (2014) 12, 3195] [Bansal et al. PRD 93 (2016) 5, 054019] [CMS Collab EPJC 83 (2023) 8, 722]

There has been some past study of MPI with p_{tZ} cuts







Underlying event study

Enhanced MPI with $p_{tZ} < 10$ GeV

This study: establish what cut to use, explore new opportunities

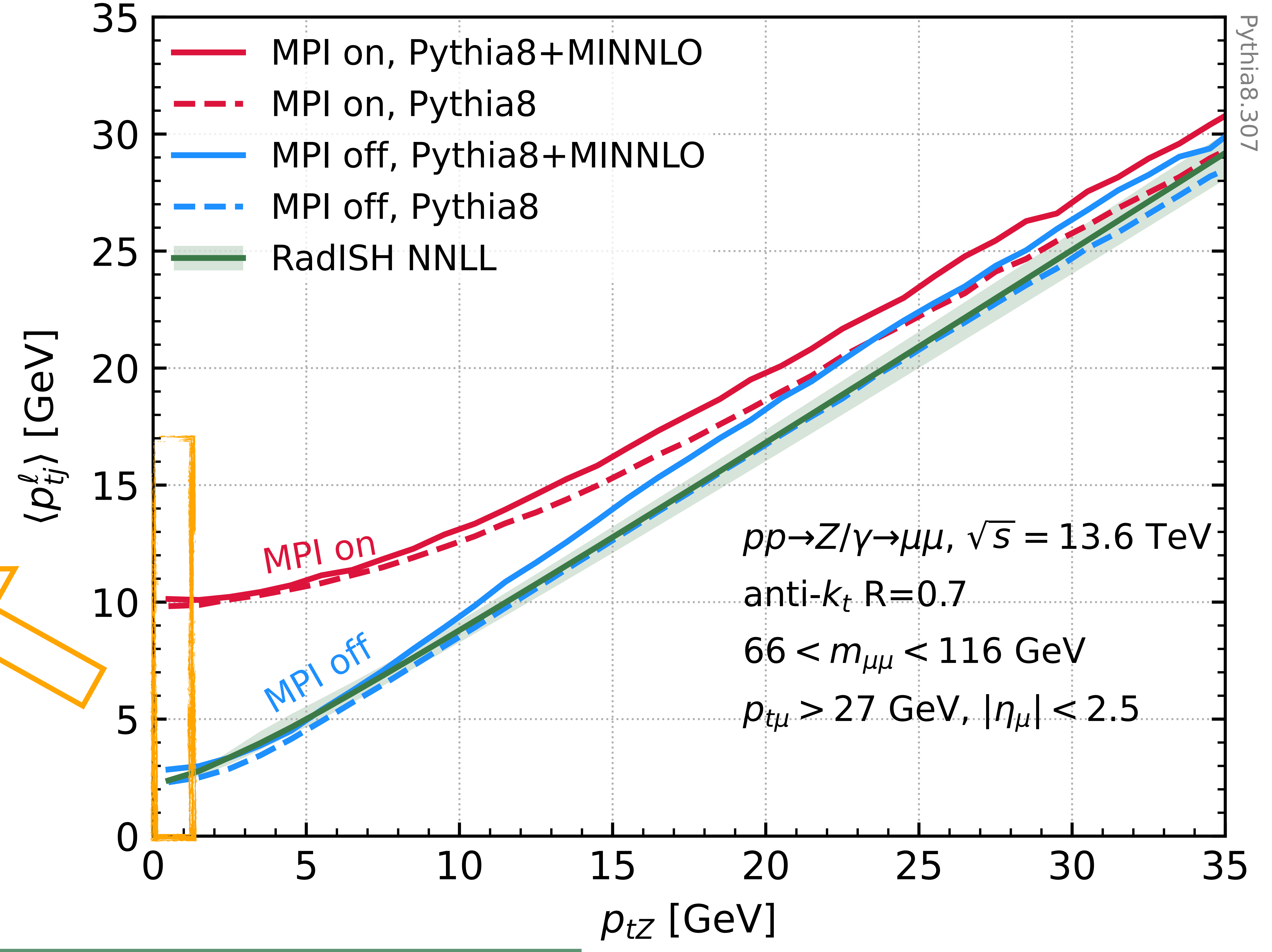
We want balance between :

- maximising stats (loose p_{tZ}^{cut})
- minimise 1HS (tight p_{tZ}^{cut})

Optimum at $p_{tZ}^{\text{cut}} = 2$ GeV

Experimental feasibility :

- p_{tZ}^{cut}= 2 GeV: 4-5% σ_{DY}



Corresponds to 12 million events in Run 3 at LHC

New observables: cumulative jet spectrum with $p_{tZ} < C_Z$

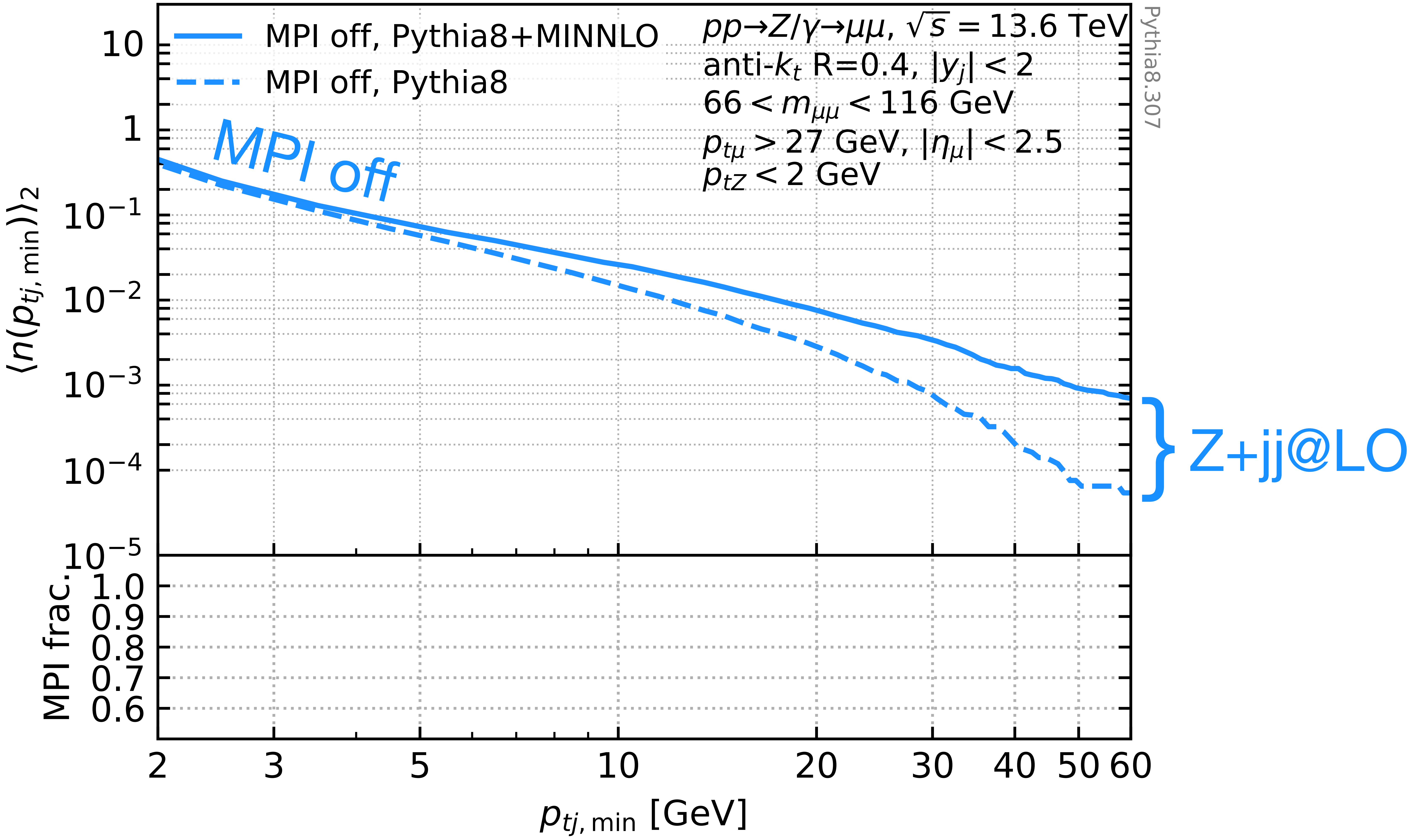
Average number of jets above $p_{tj,\min}$ for a given cut C_Z on p_{tZ} :

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

For small jet radii, R ,the total spectrum is a linear sum, i.e.:

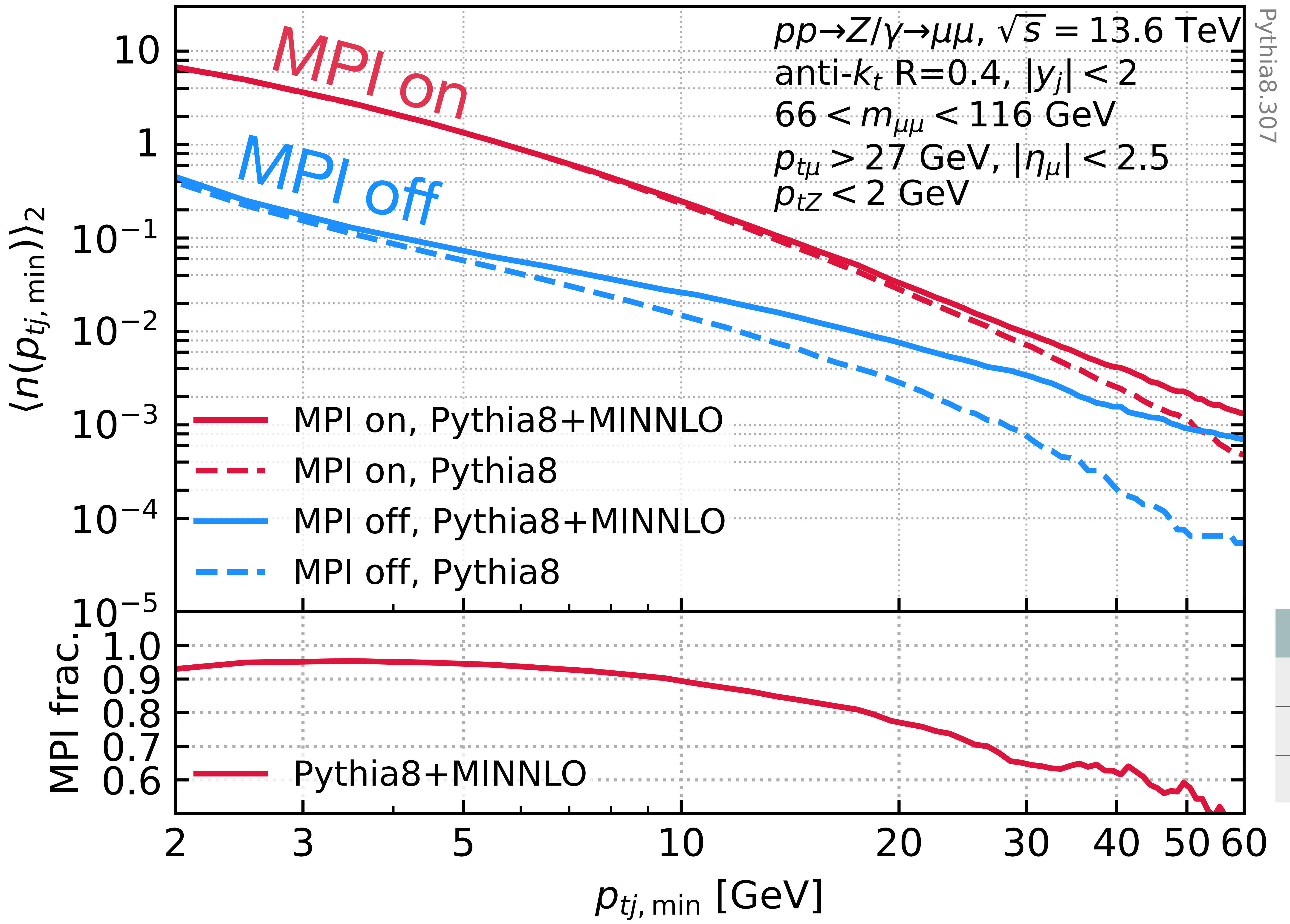
$$\langle n(p_{tj,\,\min})\rangle_{C_Z} \underset{R<1}{\simeq} \sum_{i}^{n-\mathrm{HS}} \langle n(p_{tj,\,\min})\rangle^{i}_{C_Z} = \langle n(p_{tj,\,\min})\rangle^{\mathrm{MPI-off}}_{C_Z} + \langle n(p_{tj,\,\min})\rangle^{\mathrm{MPI-on}}_{C_Z}$$

New observables: cumulative jet spectrum with $p_{tZ} < 2$ GeV



Less than 1 jet/event from the primary hard scattering

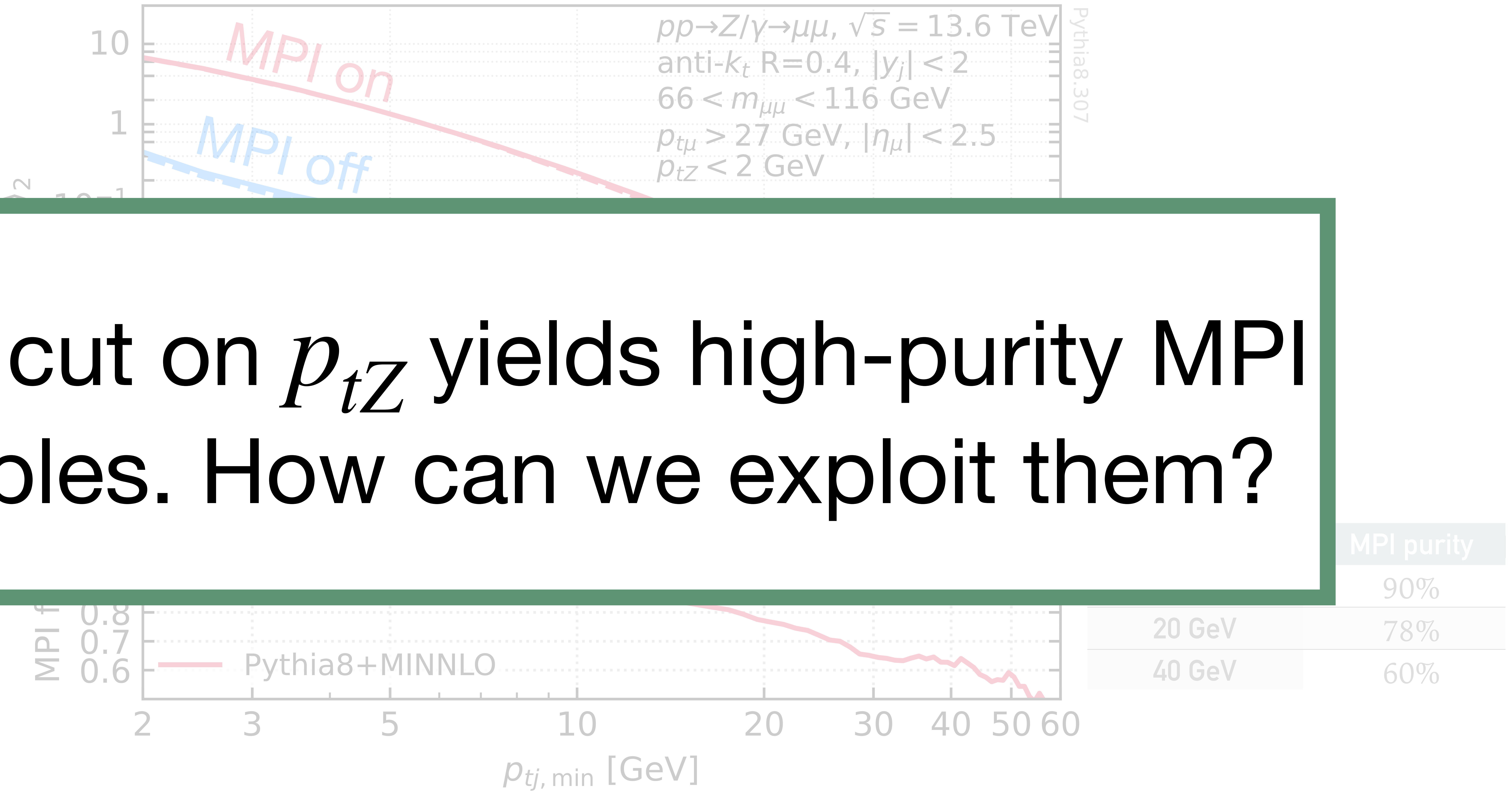
New observables: cumulative jet spectrum with $p_{tZ} < 2$ GeV



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

Around 10 jets/event from multi-parton interactions

New observables: cumulative jet spectrum with $p_{tZ} < 2$ GeV



Tight cut on p_{tZ} yields high-purity MPI samples. How can we exploit them?

Around 10 jets/event from multi-parton interactions

Pure MPI cumulative jet spectrum with $p_{tZ} < C_Z$

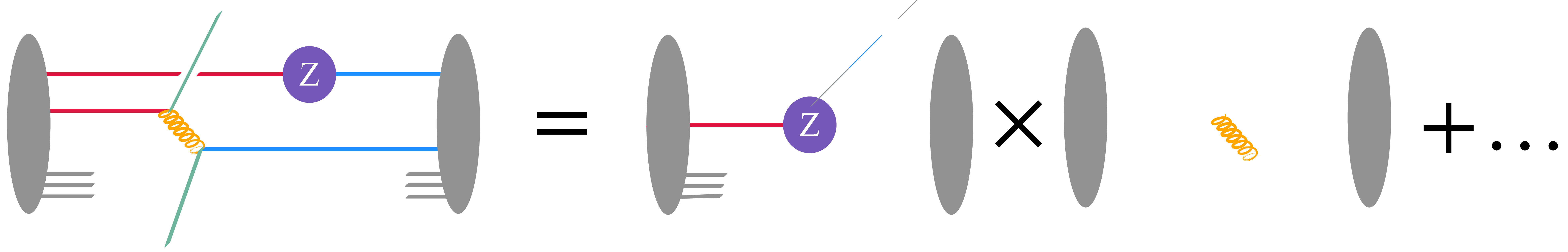
We introduce the pure MPI contribution to the inclusive jet spectrum

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

→ Z+jj@NLO theory prediction

In the pocket-formula approach this reduces to

$$\sigma_{\text{DPS}}^{A,B} = \frac{\sigma_{\text{SPS}}^{A}\ \sigma_{\text{SPS}}^{B}}{\sigma_{\text{eff}}}$$



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→ Z+jj@NLO theory prediction

In the pocket-formula approach this reduces to

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

→ Inclusive jet rate in min-bias (no Z)

Pocket formula predicts $\langle n(p_{tj,\min}) \rangle_{C_Z}^{\text{pure-MPI}}$ to be independent of C_Z

New observable: ratio of $\langle n(p_{tj,\min})\rangle^{\text{pure}-\text{MPI}}_{C_Z}$ with different $p_{tZ} < C_Z$

We propose to measure

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

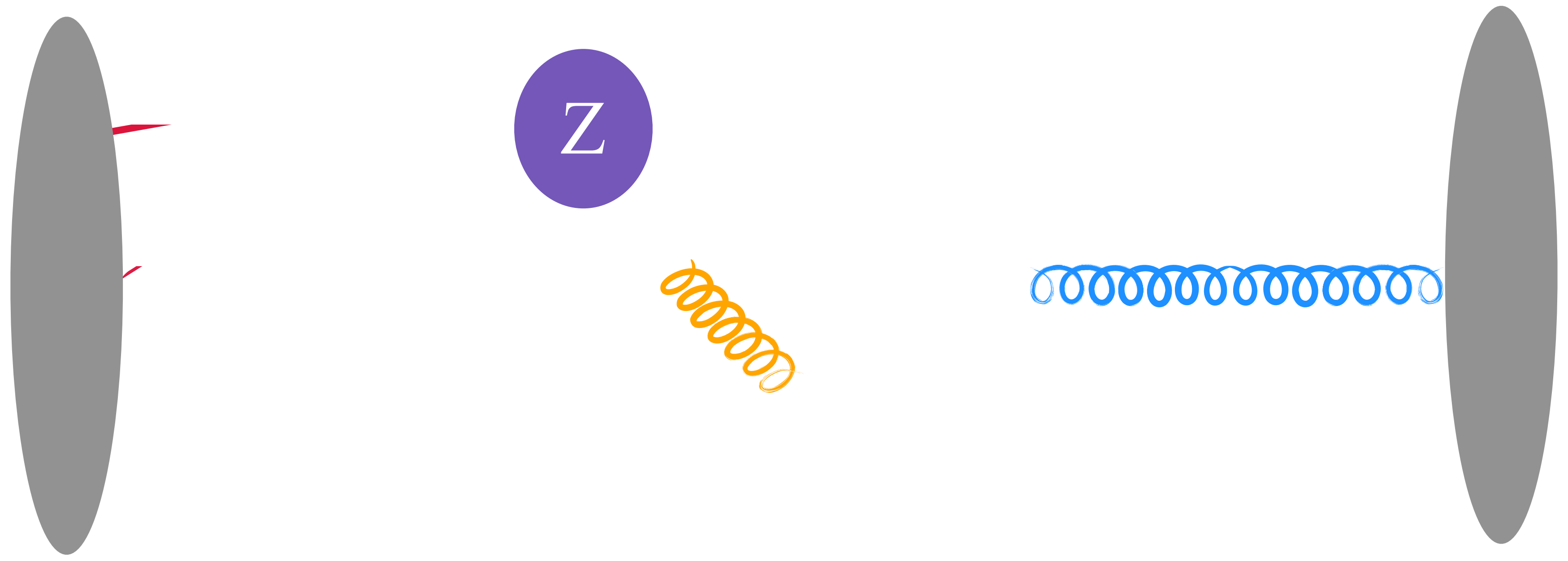
- Pocket formula: $r_{15/2} = 1$
- Pythia: $r_{15/2} \simeq 1$ (colour reconnection)

New observable: ratio of $\langle n(p_{tj,\min}) \rangle_{C_Z}^{\text{pure-MPI}}$ with different $p_{tZ} < C_Z$

We propose to measure

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

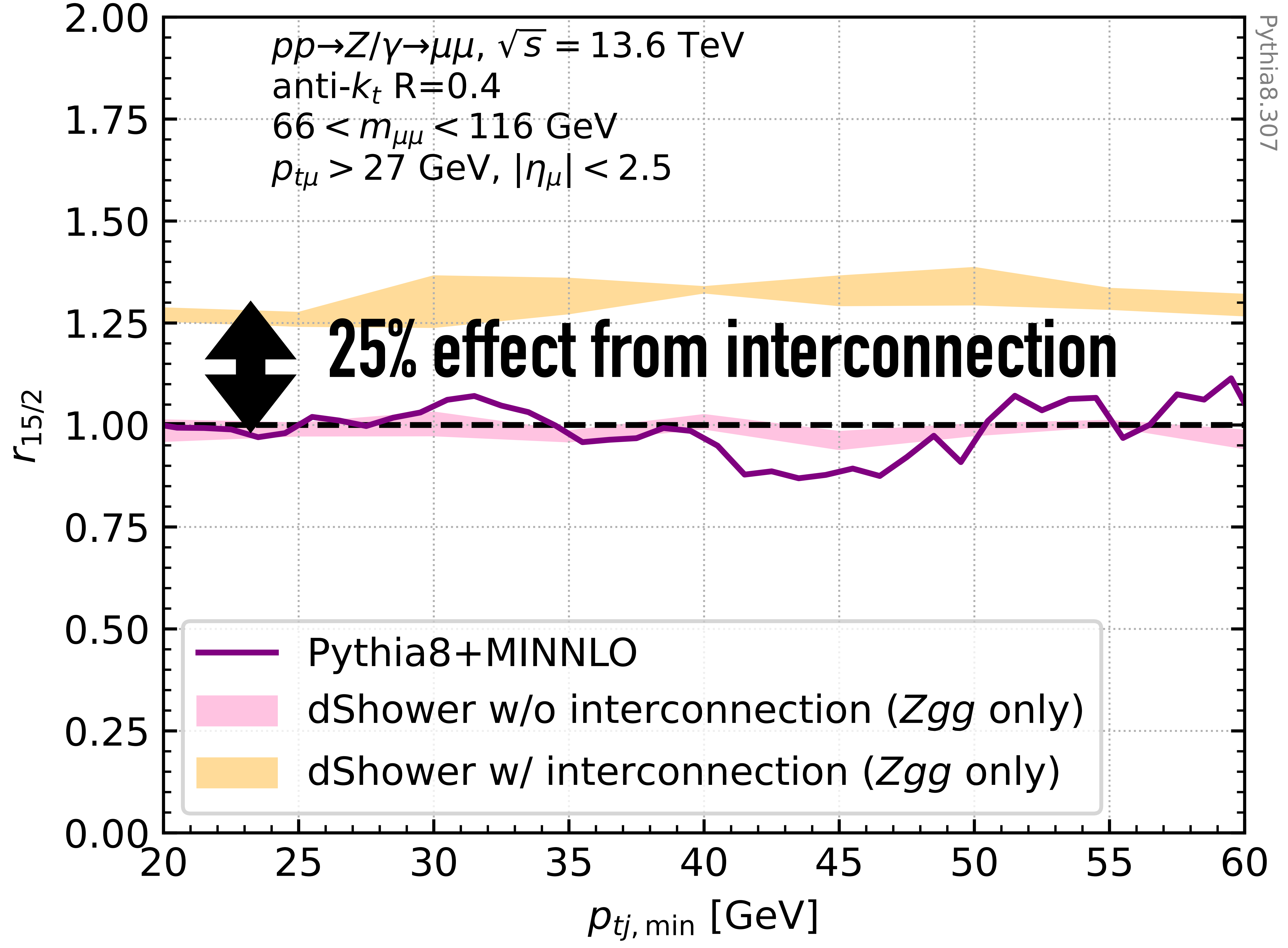
- Pocket formula: $r_{15/2} = 1$
- Pythia: $r_{15/2} \simeq 1$ (colour reconnection)
- Perturbative interconnection:



These splittings result in higher $p_{tZ} \Rightarrow r_{15/2} > 1$

Probing deviations from the pocket-formula

[dShower: Cabouat, Gaunt, Ostrolenk JHEP 11 (2019) 061, Cabouat, Gaunt JHEP 10 (2020) 012]



Can one see effect of perturbative interconnection in data?

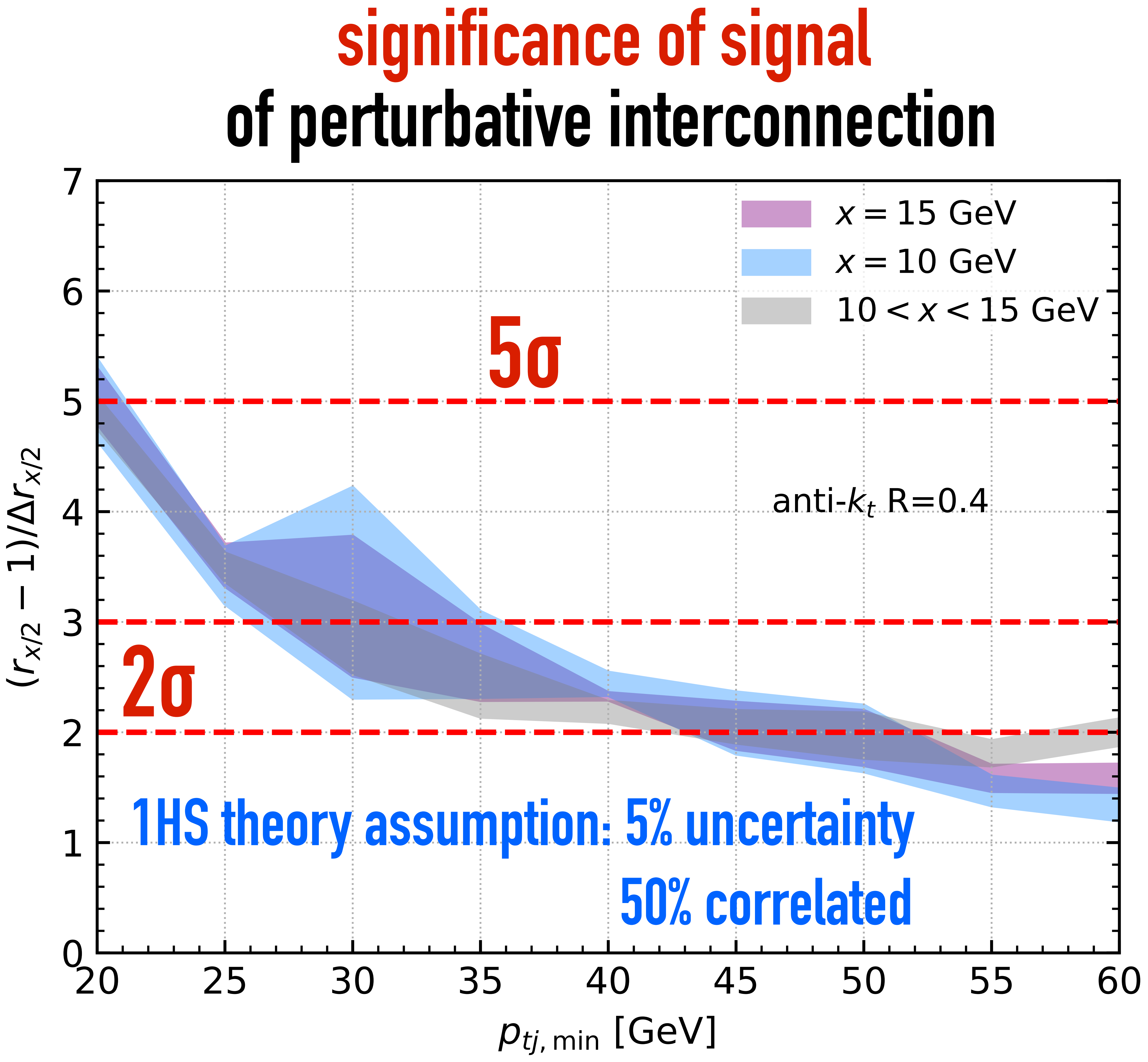
Assessing statistical significance of perturbative interconnection

Assume dShower size for signal.
Evaluate few assumptions for:

- theory uncertainty on 1HS subtraction

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

- + their correlation for different C_Z



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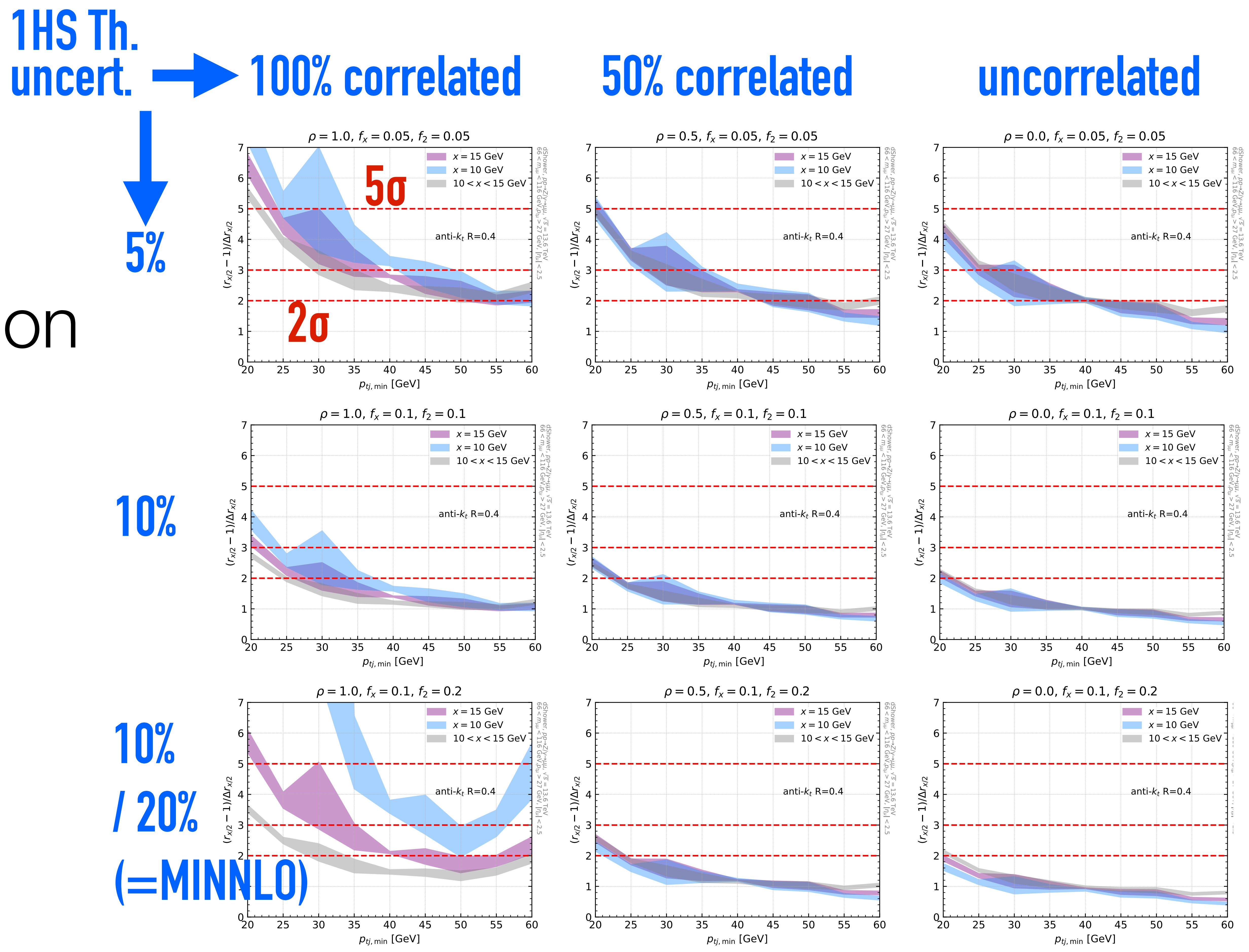
- + their correlation for different C_Z

Just barely feasible. Motivation for NNLO (matched) Z+2j calculations to reduce theory uncertainty



Assessing statistical significance of perturbative interconnection

Assume dShower size for signal.
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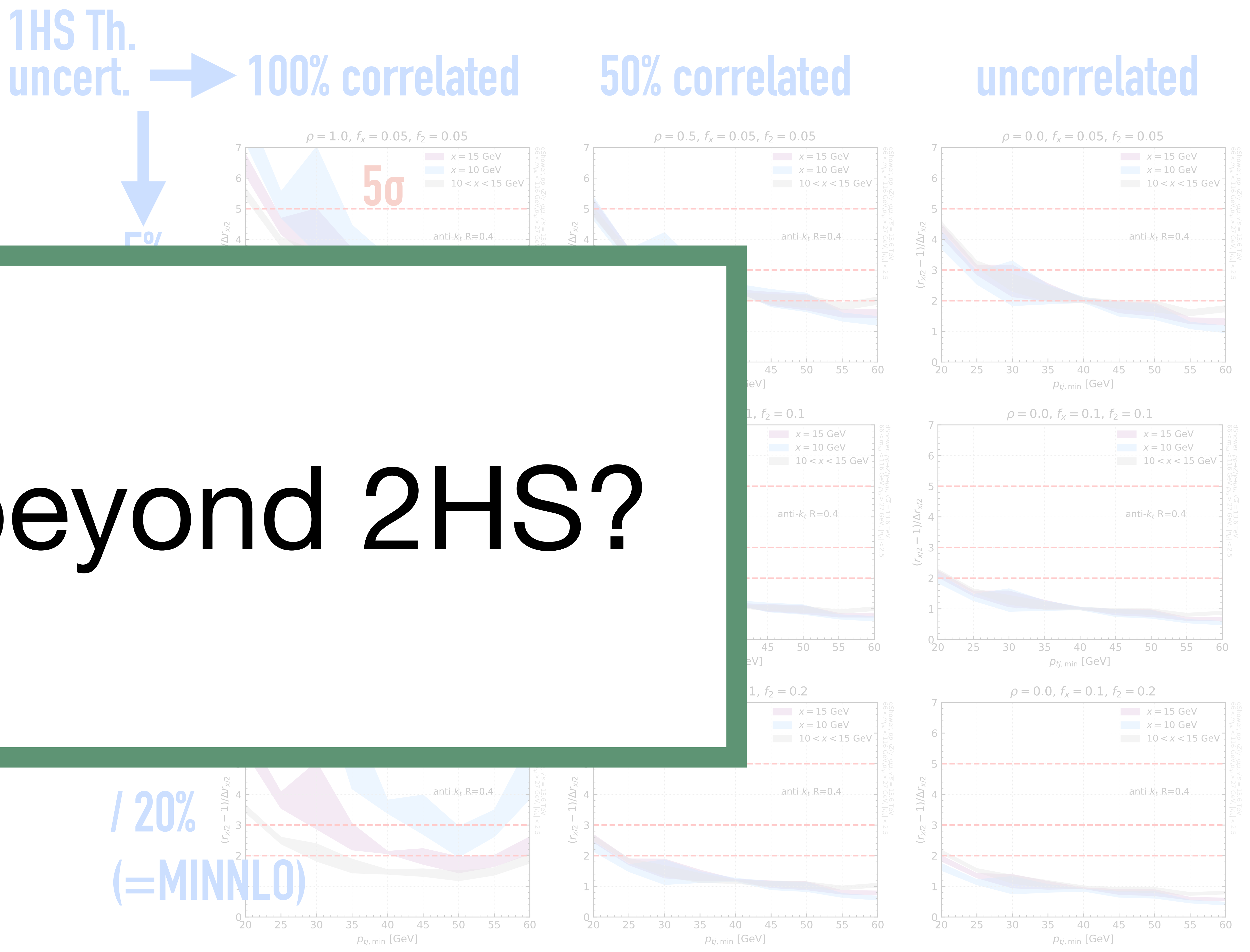
$\langle n(p_{tj,\min})\rangle^{\mathrm{pure-MPI}}_{C_Z} \equiv$

- + their corr



Can we go beyond 2HS?

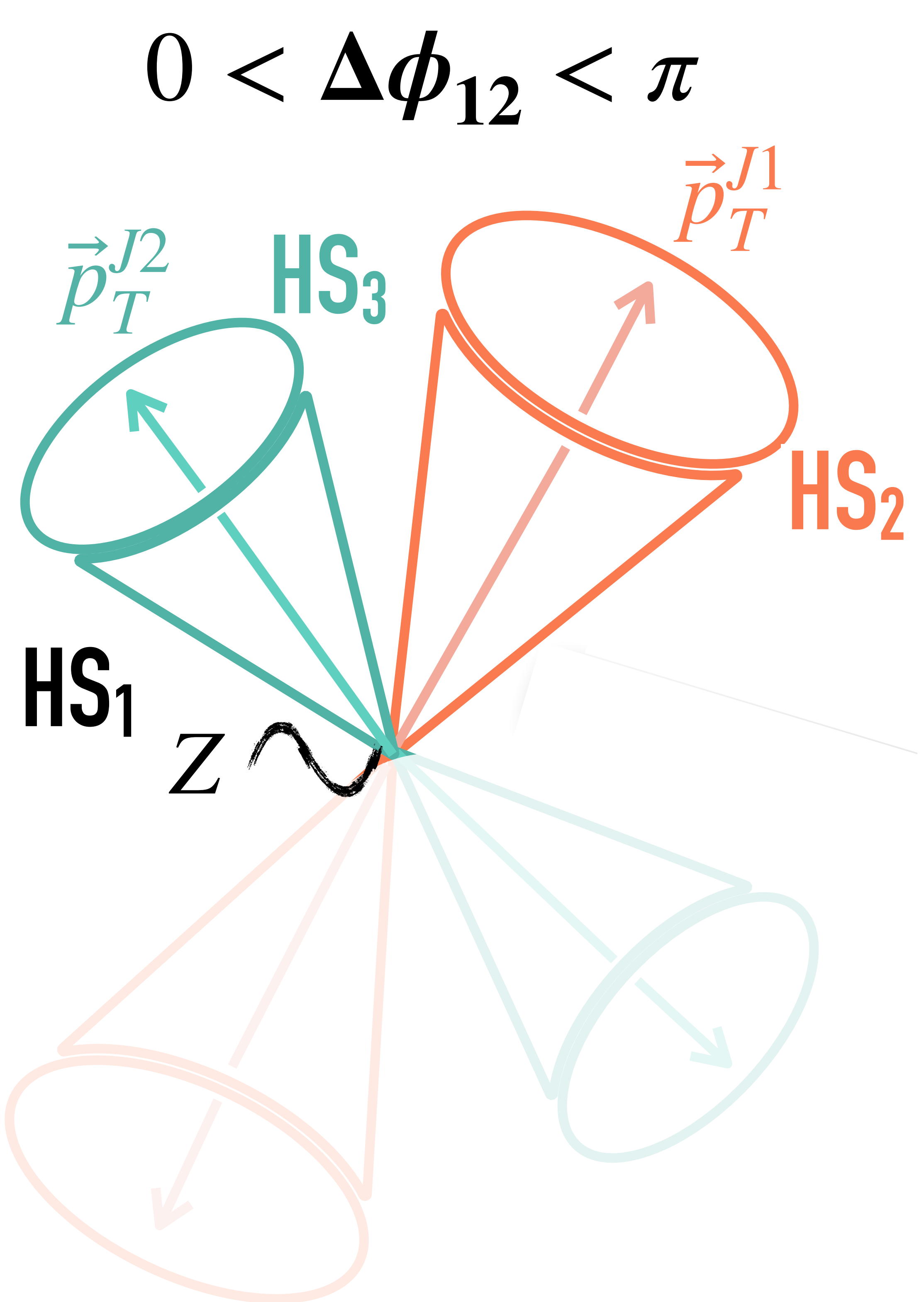
Just barely feasible. Motivation for NNLO (matched) Z+2j calculations

Final topic: seeing 3HS via azimuthal correlations

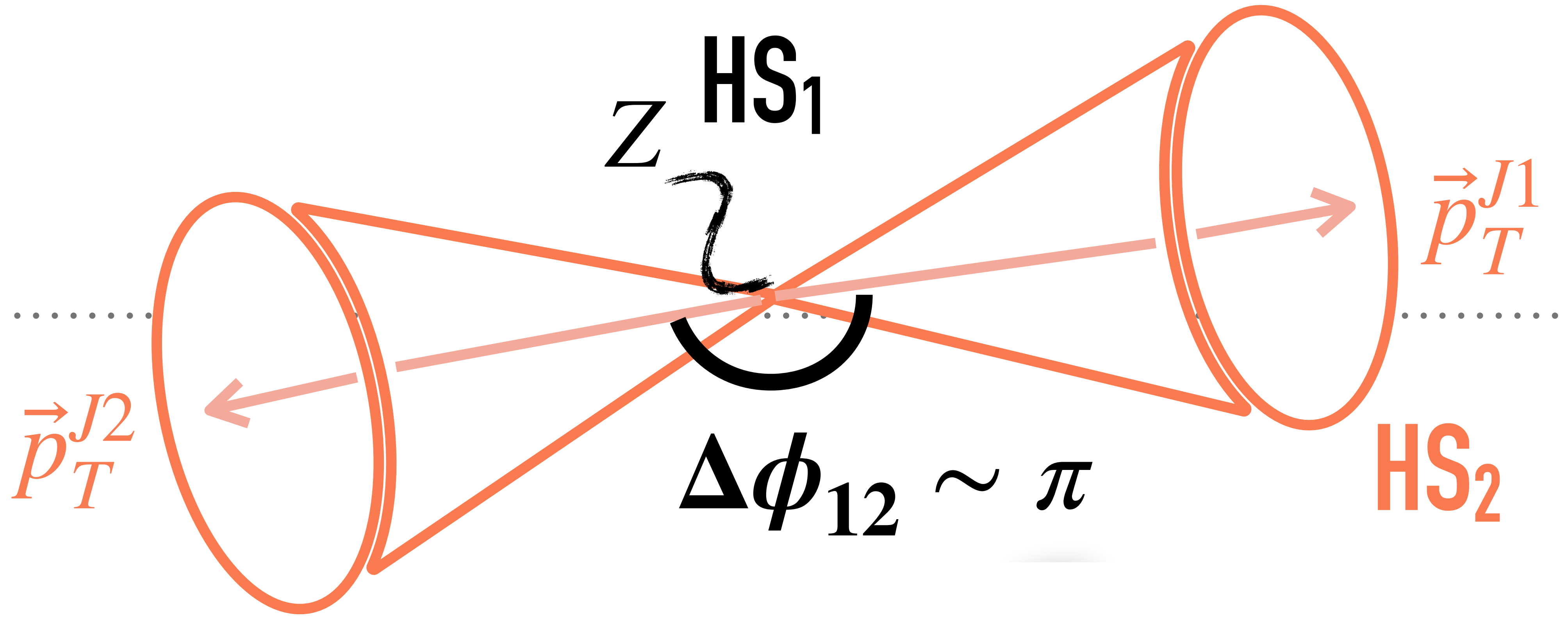
[Previous studies of 3HS: CMS Collab. Nature Phys. 19 (2023) 3, 338-350, D'Enterria, Snigirev PRL 118 (2017) 12, 122001]

Measure $\Delta\phi$ between leading jets using a tight cut on p_{tZ}

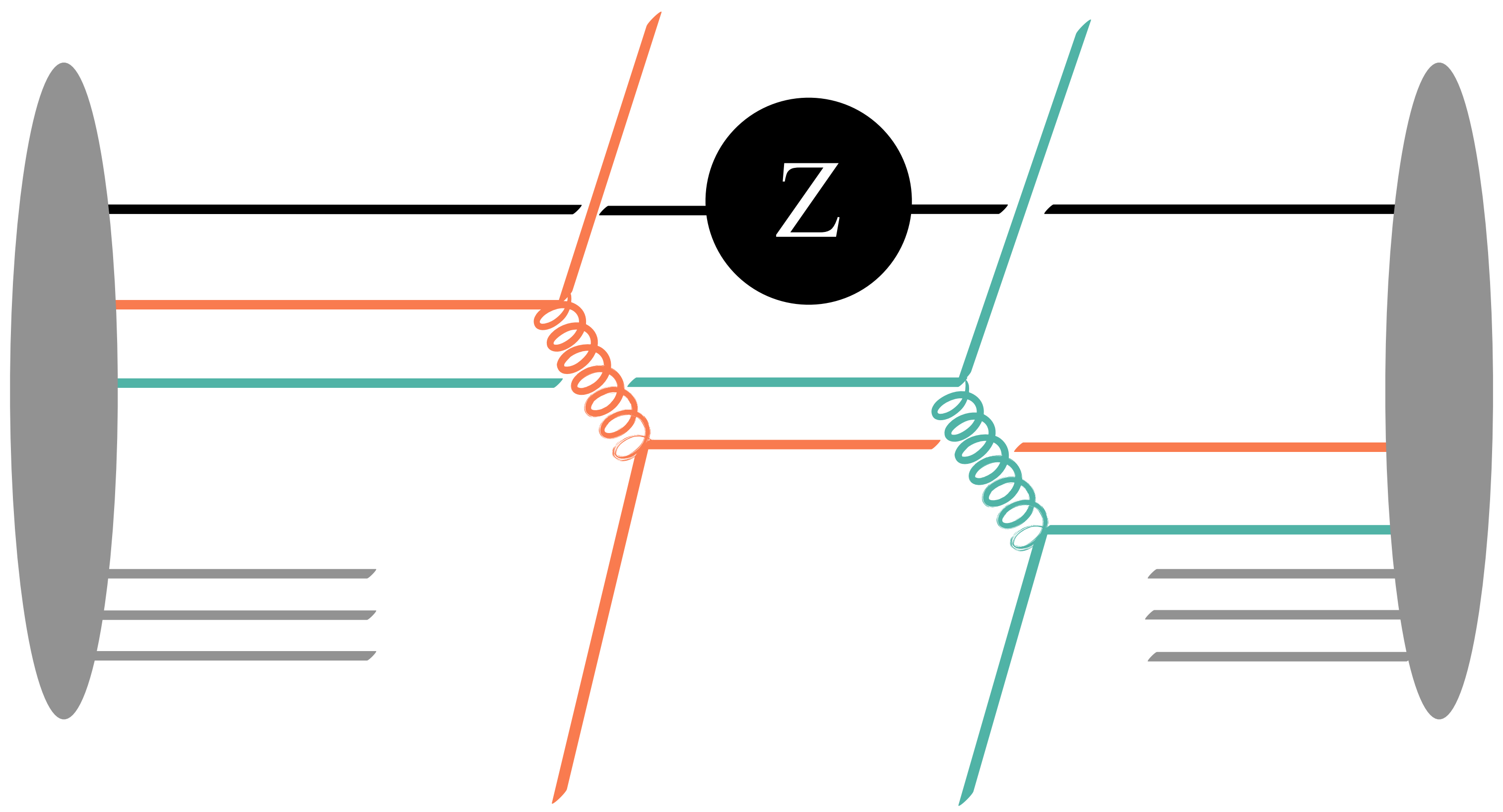
Signal (3HS)

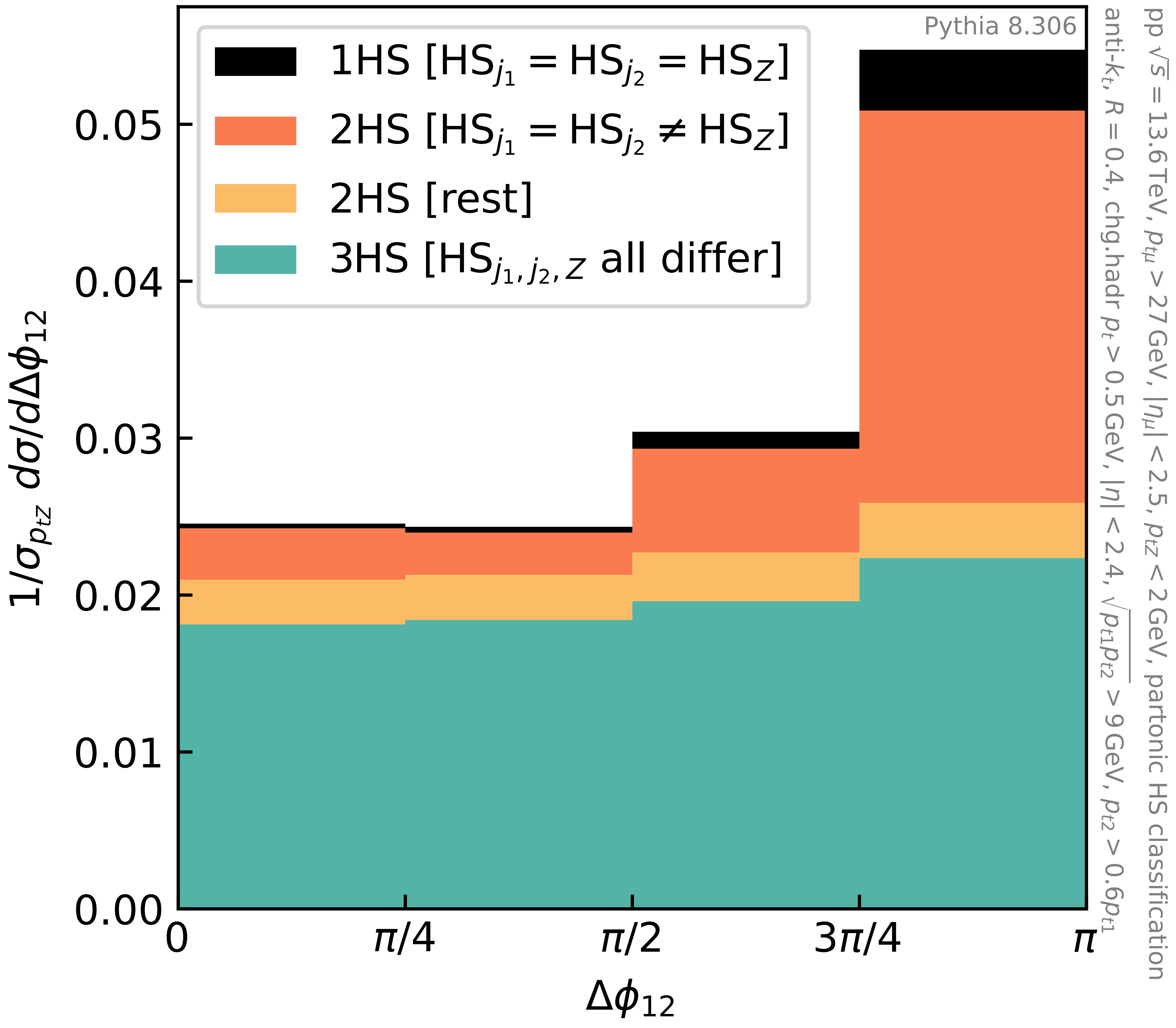


Background (2HS)



Final topic: seeing 3HS via azimuthal correlations



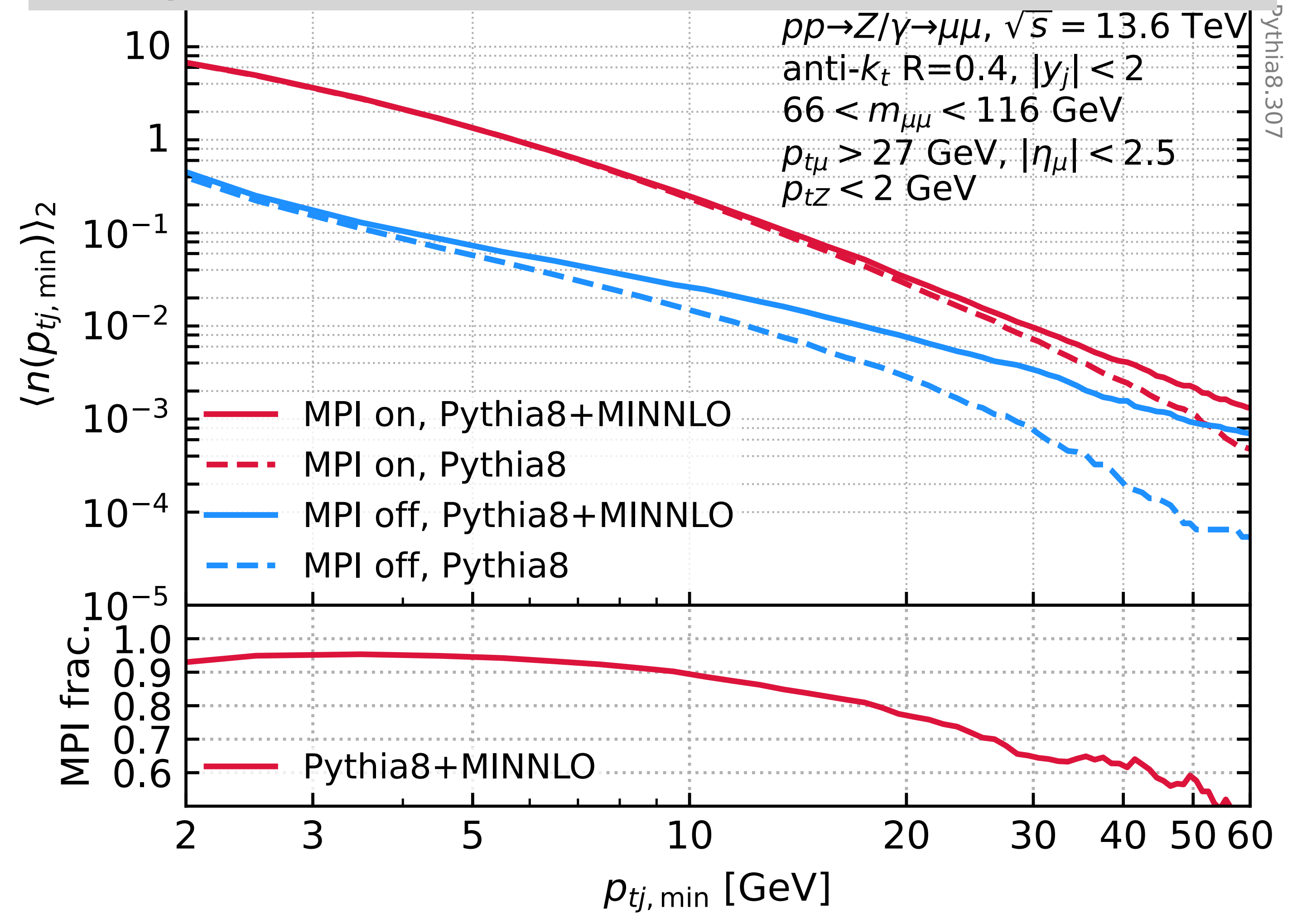


Clear signal of 3HS in terms of a plateau for all values of $\Delta\phi$

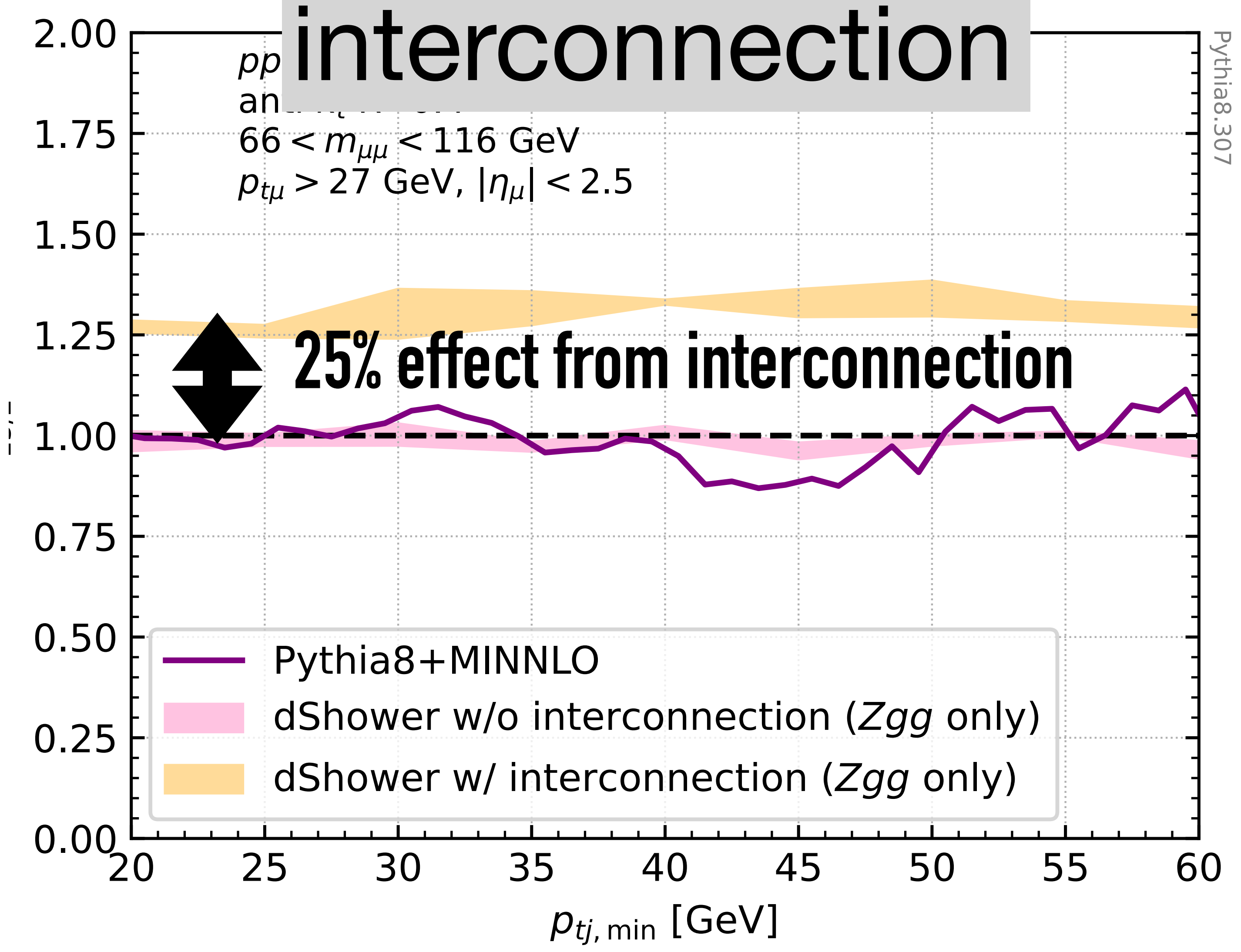
Conclusions

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

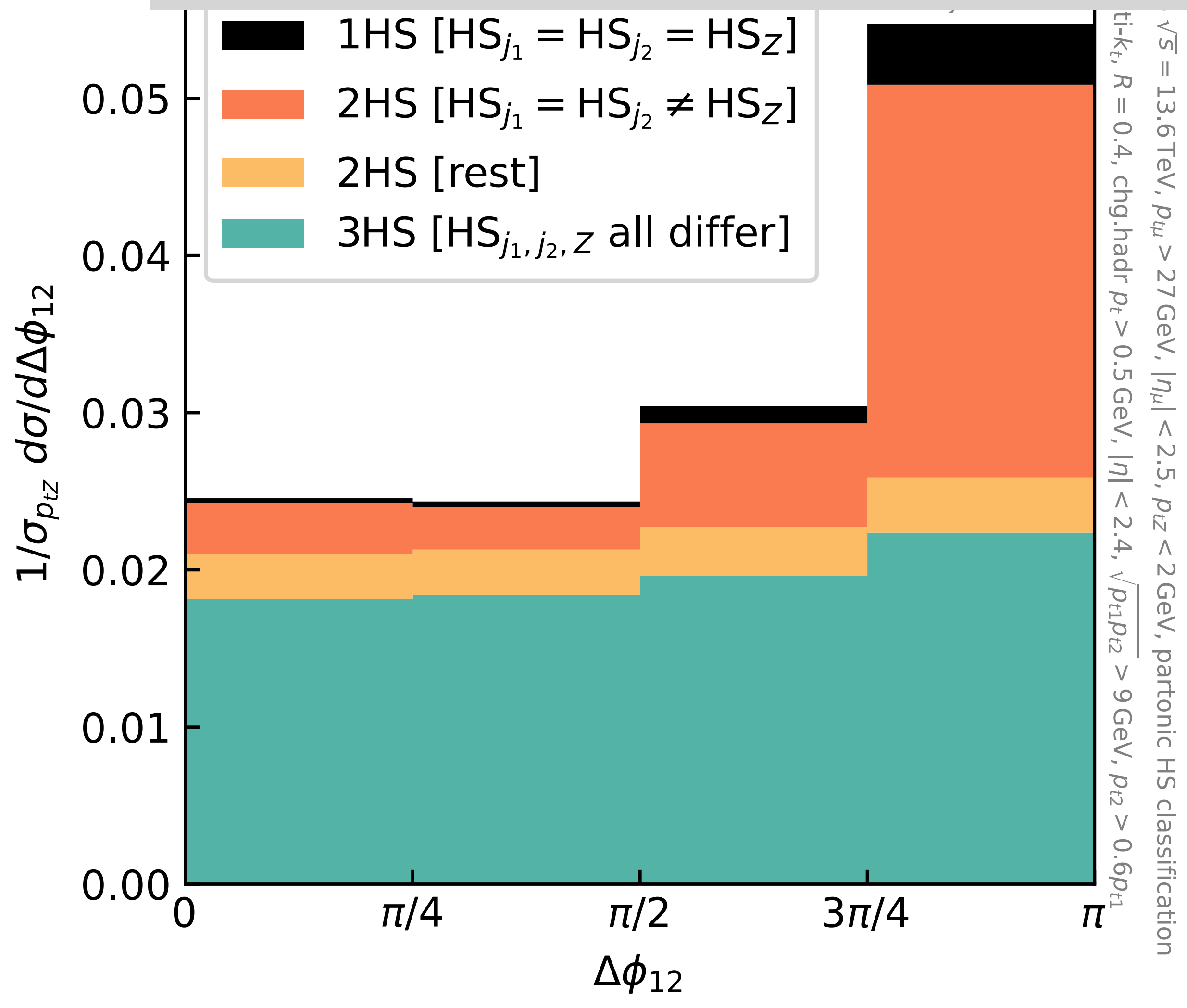
High-purity 2HS samples



Perturbative interconnection



3HS (and potentially 4HS)



Potential for significant impact on conceptual and quantitative understanding of multi-parton interactions