

Soft QCD measurements with pp collisions in ATLAS

José Pretel

on behalf of the ATLAS Collaboration

QCD@LHC 2026

September 28 - October 2, 2026

Introduction

- Rich phenomenology in the non-perturbative regime of QCD, where α_s is strongly coupled
- This talk will focus on a recent ATLAS result on soft QCD

Observation of double parton scattering in same-sign W boson pair production in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector
[[Phys. Lett. B 870 \(2025\) 139892](#)]

Other talks from the ATLAS Collaboration:

Minibias measurements with pO collisions in ATLAS [[link](#)]

Lydia Audrey Beresford [DESY]

QCD jet measurements in ATLAS [[link](#)]

Hanfei Cui [University College London]

Drell-Yan precision in ATLAS [[link](#)]

James Ferrando [Lancaster University]

ATLAS measurements of α_s [[link](#)]

Laura Fabbri [INFN Bologna]

And more!

Double Parton Scattering (DPS)

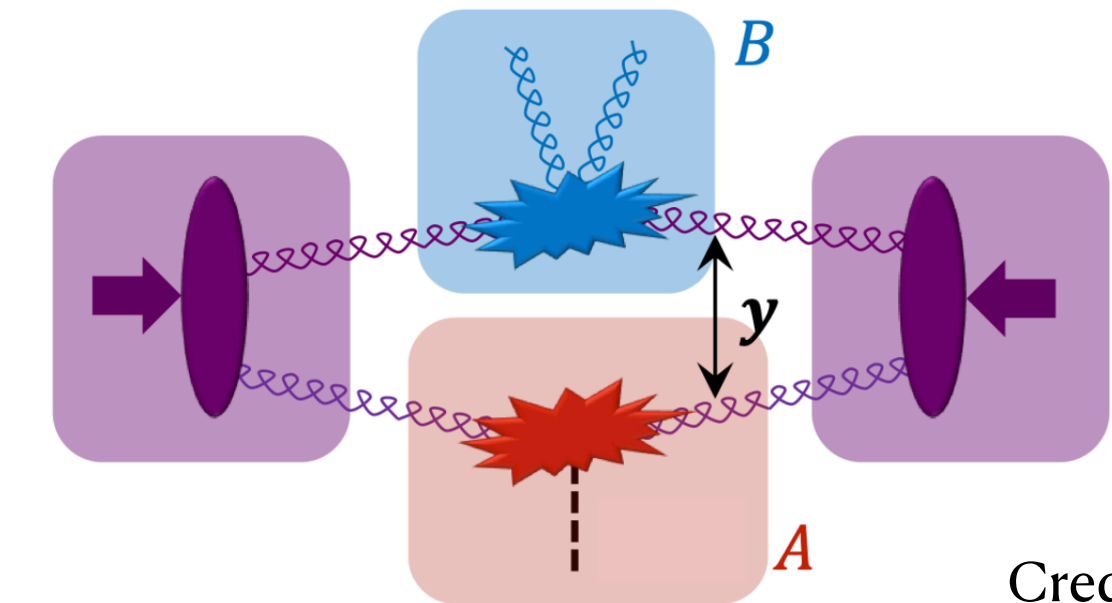
in a nutshell

Multiple hard interactions from two different partons in the same pp collision

DPS cross-sections can be estimated by simple factorized Ansatz (neglecting correlations between the two parton collisions)

- σ_{eff} effective cross-section spatial overlap of partons in plane perpendicular direction of motion.
→ Can be compared across experiments

Measurements of DPS in different processes provide a probe to inner hadron structure, as well as unexpected effects due to neglected correlations



Credit: J. Gaunt

$$\sigma_{DPS}^{(A,B)} = \int F_{ik}(x_1, x_2, \mathbf{y}) \otimes \hat{\sigma}_{ij}^A \hat{\sigma}_{kl}^B \otimes F_{jl}(x'_1, x'_2, \mathbf{y}) d^2\mathbf{y}$$

Double parton density (DPD)

$$\sigma_{AB}^{DPS} = \frac{1}{1 + \delta_{AB}} \frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

Double Parton Scattering

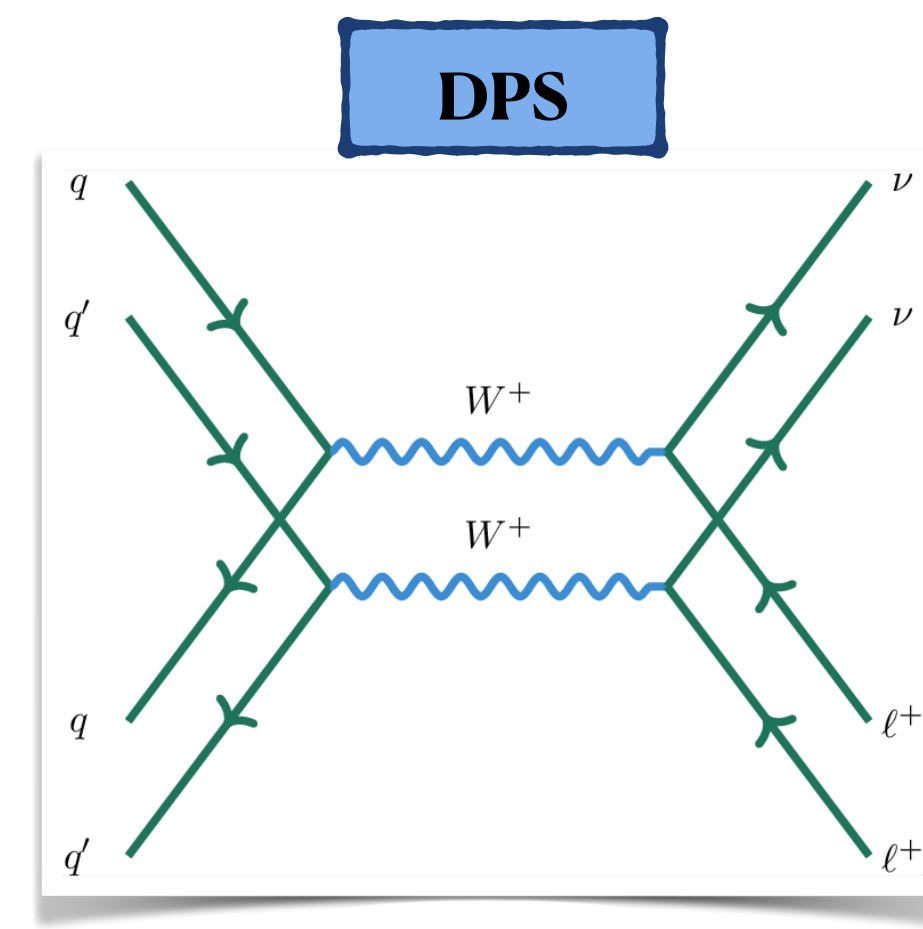
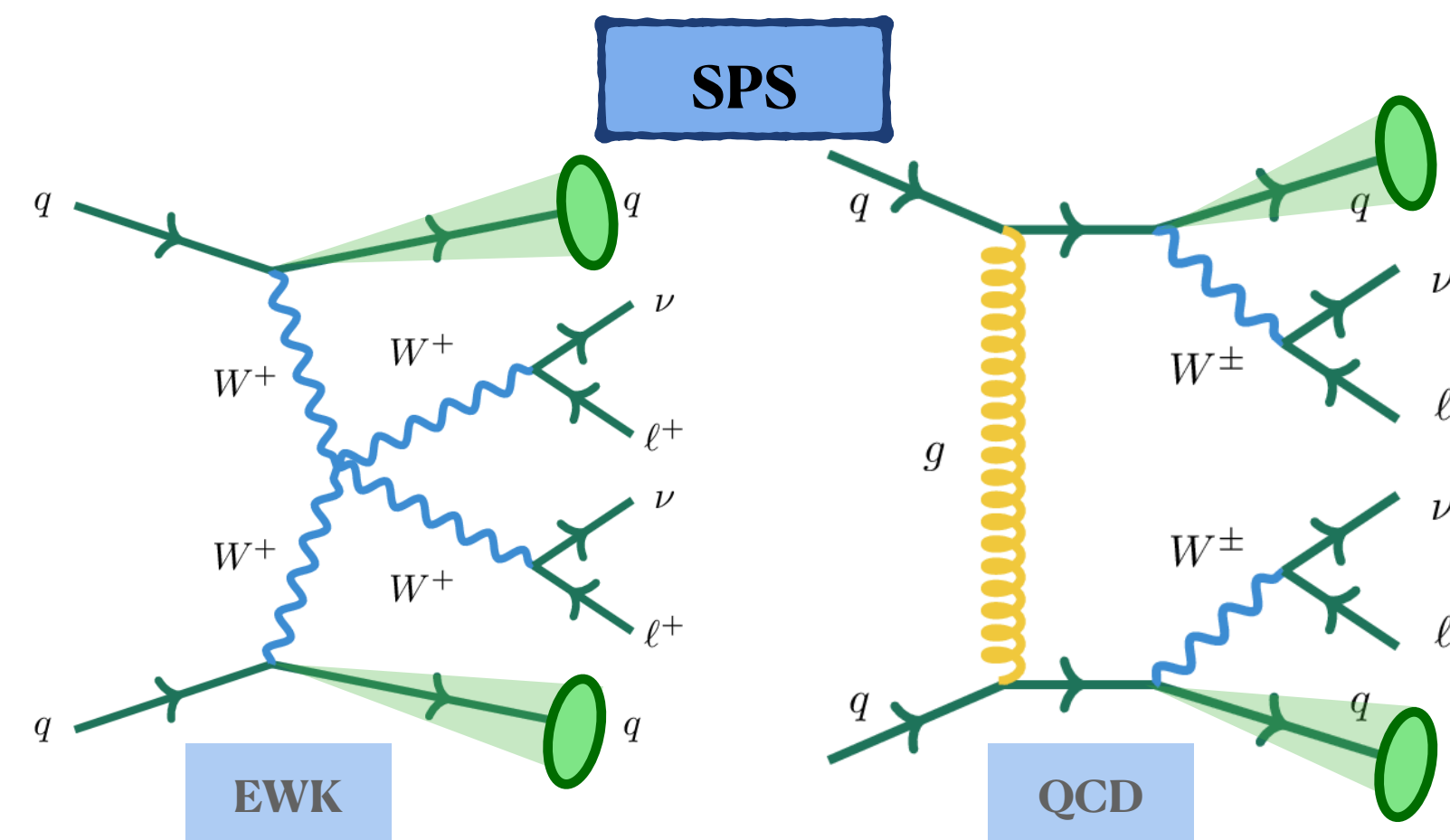
in $W^\pm W^\pm$ production

DPS extensively explored by experiments at the Tevatron and LHC hadron colliders.

$W^\pm W^\pm$ has become a promising channel for DPS measurements due to the strong background suppression

- Single-Parton Scattering (SPS) observed since early Run2 by CMS and ATLAS
- Cross-section measurements at $\sqrt{s} = 13$ TeV available for this process [CMS, ATLAS], also for polarized final states [CMS, ATLAS]

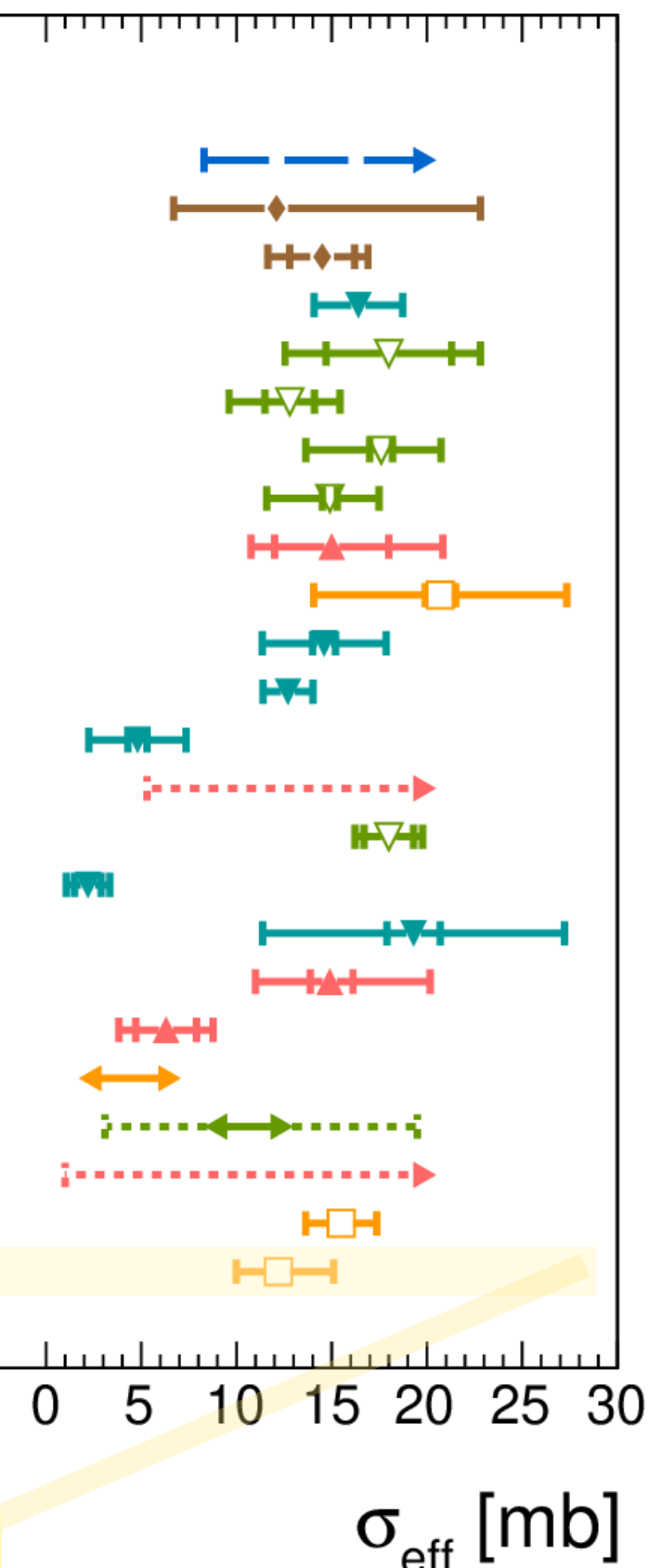
SPS dominates at $N_{jets} \geq 2$, where **tagging jets** are selected [Ref].



Experiment (energy, final state, year)

ATLAS $\sqrt{s} = 13$ TeV, 140 fb⁻¹

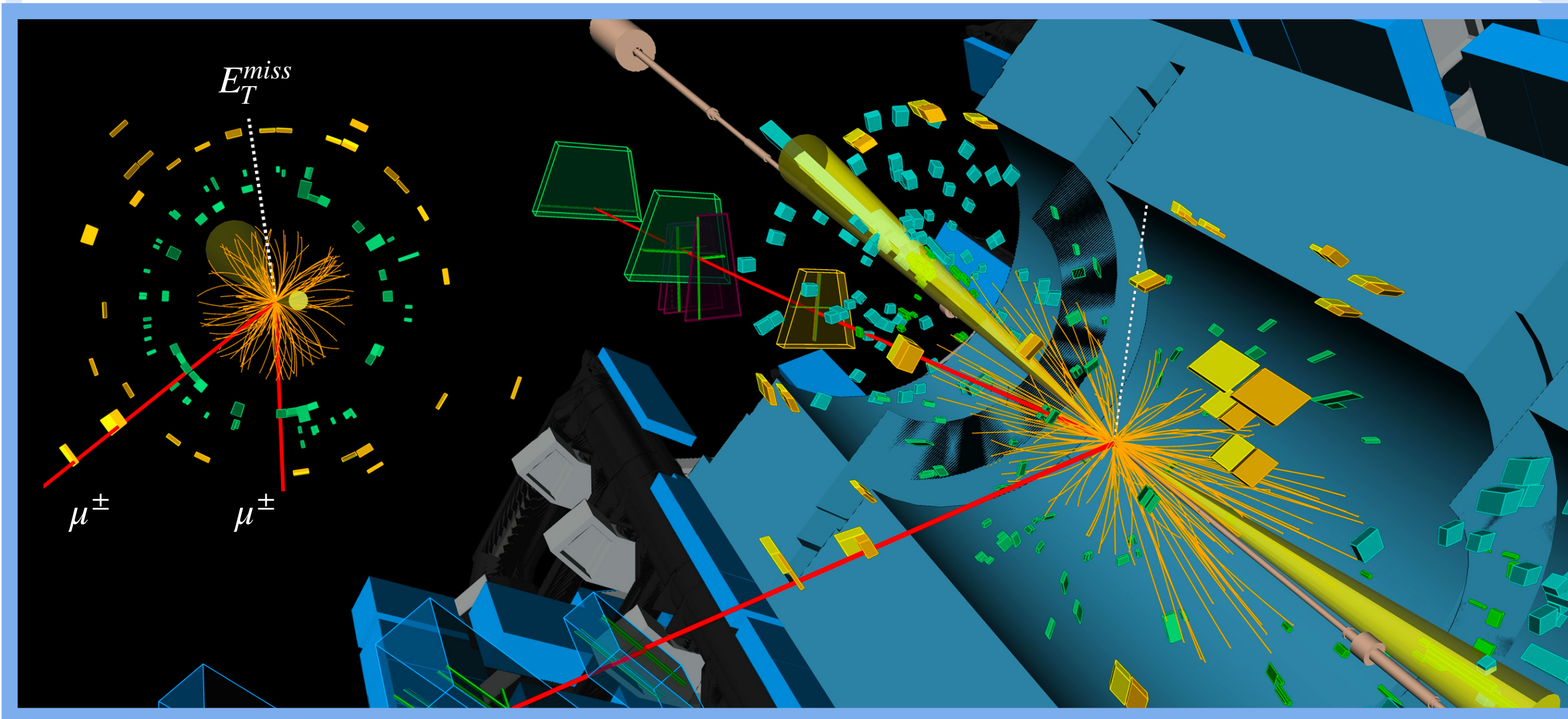
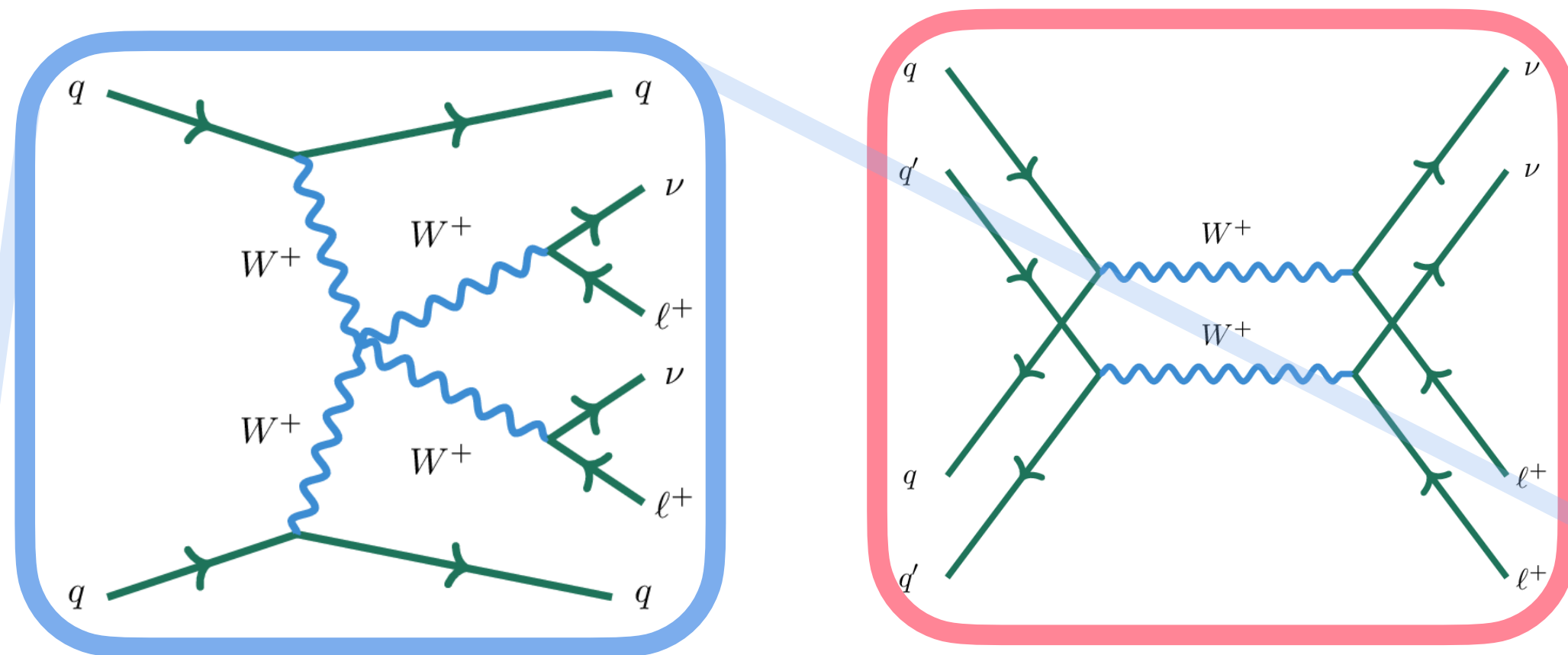
UA2 ($\sqrt{s} = 630$ GeV, 4 jets, 1991)
 CDF ($\sqrt{s} = 1.8$ TeV, 4 jets, 1993)
 CDF ($\sqrt{s} = 1.8$ TeV, $\gamma + 3$ jets, 1997)
 DØ ($\sqrt{s} = 1.96$ TeV, $\gamma + 3$ jets, 2010)
 LHCb ($\sqrt{s} = 7$ TeV, $J/\psi \Lambda_c^+$, 2012)
 LHCb ($\sqrt{s} = 7$ TeV, $J/\psi D_s^+$, 2012)
 LHCb ($\sqrt{s} = 7$ TeV, $J/\psi D^+$, 2012)
 LHCb ($\sqrt{s} = 7$ TeV, $J/\psi D^0$, 2012)
 ATLAS ($\sqrt{s} = 7$ TeV, $W + 2$ jets, 2013)
 CMS ($\sqrt{s} = 7$ TeV, $W + 2$ jets, 2014)
 DØ ($\sqrt{s} = 1.96$ TeV, $\gamma + b/c + 2$ jets, 2014)
 DØ ($\sqrt{s} = 1.96$ TeV, $\gamma + 3$ jets, 2014)
 DØ ($\sqrt{s} = 1.96$ TeV, $J/\psi + J/\psi$, 2014)
 ATLAS ($\sqrt{s} = 8$ TeV, $Z + J/\psi$, 2015)
 LHCb ($\sqrt{s} = 7$ & 8 TeV, $\Upsilon(1S) D^{0,+}$, 2015)
 DØ ($\sqrt{s} = 1.96$ TeV, $J/\psi + \Upsilon$, 2016)
 DØ ($\sqrt{s} = 1.96$ TeV, $2\gamma + 2$ jets, 2016)
 ATLAS ($\sqrt{s} = 7$ TeV, 4 jets, 2016)
 ATLAS ($\sqrt{s} = 8$ TeV, $J/\psi + J/\psi$, 2017)
 CMS ($\sqrt{s} = 8$ TeV, $\Upsilon + \Upsilon$, 2017)
 LHCb ($\sqrt{s} = 13$ TeV, $J/\psi + J/\psi$, 2017)
 ATLAS ($\sqrt{s} = 8$ TeV, 4 leptons, 2019)
 CMS ($\sqrt{s} = 13$ TeV, 4 jets, 2022)
 CMS ($\sqrt{s} = 13$ TeV, $W^\pm W^\pm$, 2023)



First observation of DPS in $W^\pm W^\pm$ production by CMS!

$$\sigma_{eff}^{CMS} = 12.2_{-2.2}^{+2.9} \text{ [mb]}$$

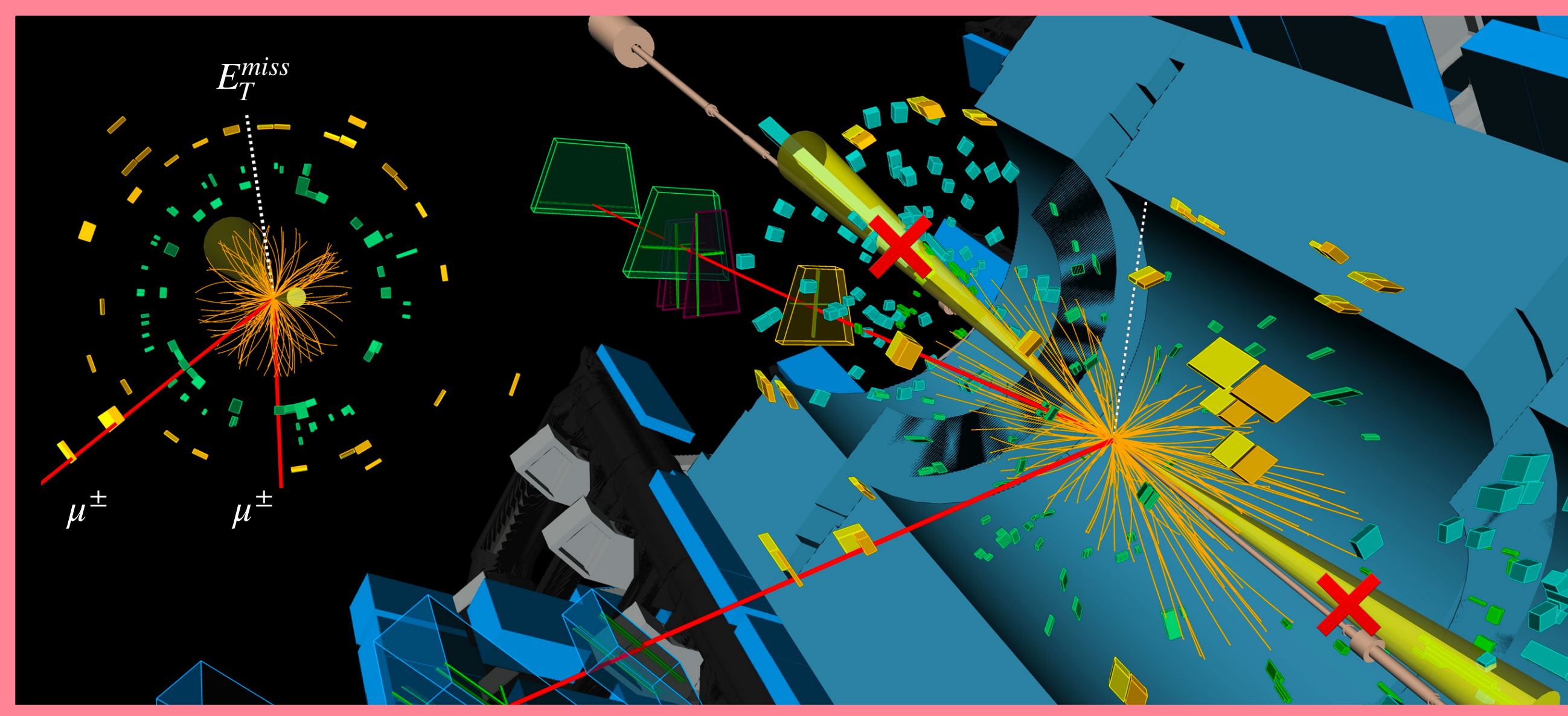
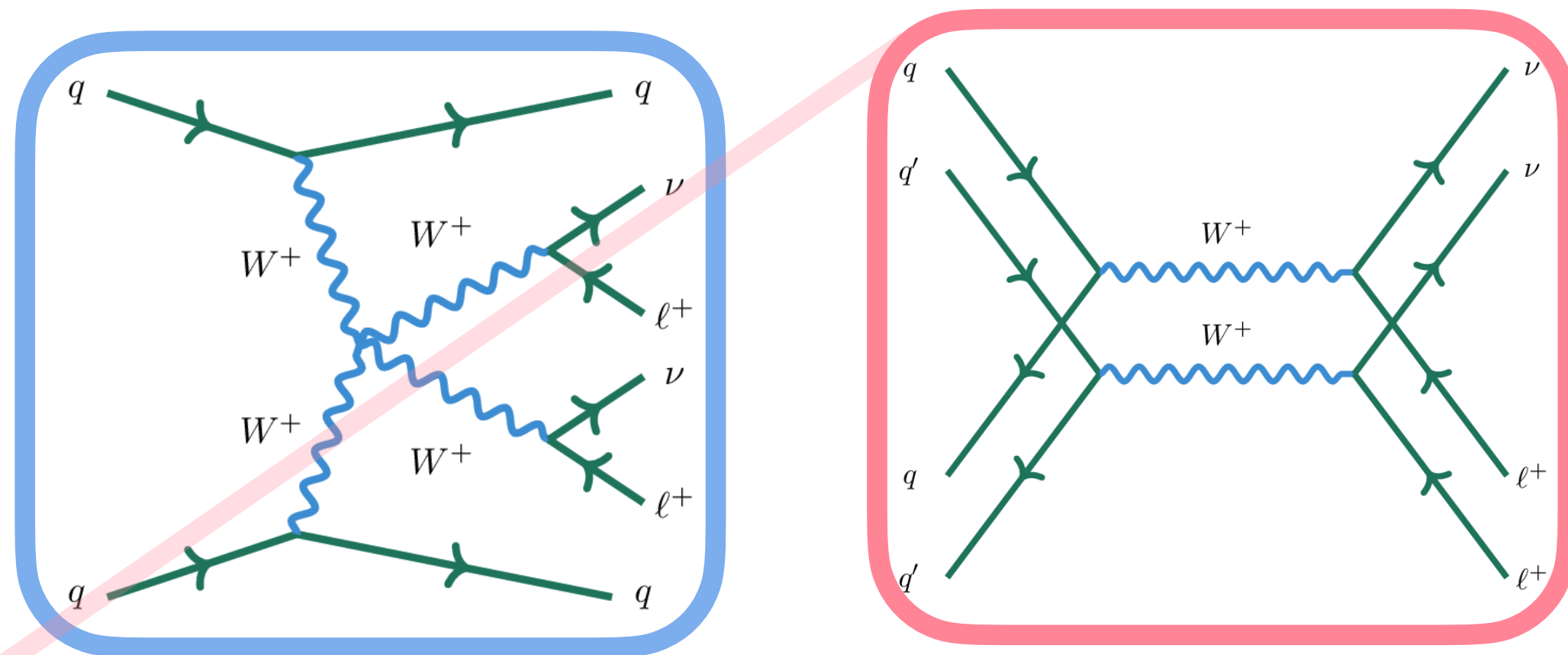
Expected signature



Selection requirements

- **Same-sign lepton pair** ($e^\pm, \mu^\pm$)
- Lepton $p_T > 27$ GeV
- Veto third lepton
- $m_{\ell\ell} > 20$ GeV && $|m_{\ell\ell} - m_Z^{\text{PDG}}| > 15$ GeV
- $N_{b\text{-jets}} = 0$ ($p_T > 20$ GeV, $|\eta| < 2.5$, DL1r 85%)
- $E_T^{\text{miss}} > 30$ GeV
- $N_{\text{jets}} \leq 1$ ($p_T > 30$ GeV, $|\eta| < 2.5$)

Expected signature



Selection requirements

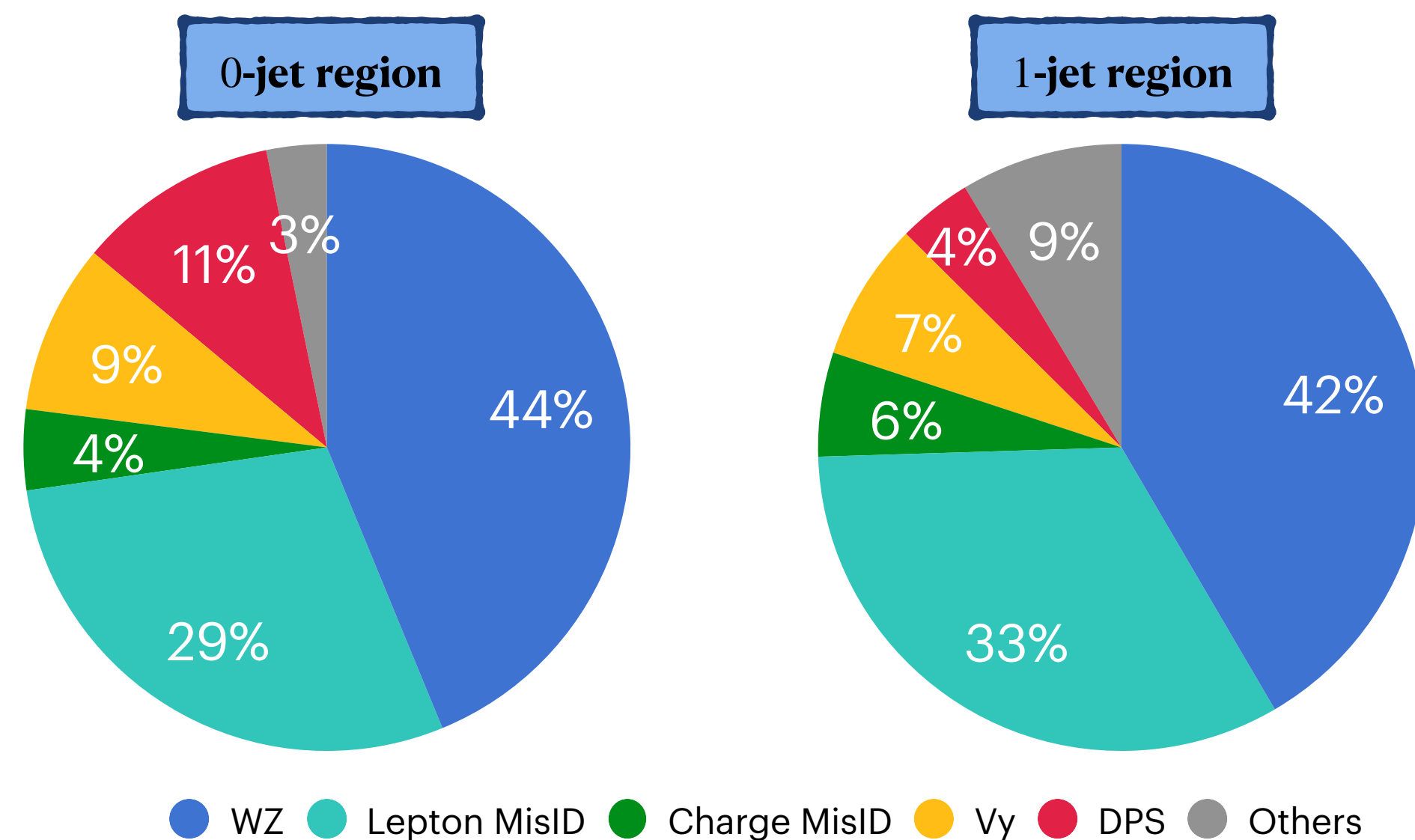
- **Same-sign lepton pair ($e^\pm, \mu^\pm$)**
- Lepton $p_T > 27$ GeV
- Veto third lepton
- $m_{\ell\ell} > 20$ GeV && $|m_{\ell\ell} - m_Z^{\text{PDG}}| > 15$ GeV
- $N_{b\text{-jets}} = 0$ ($p_T > 20$ GeV, $|\eta| < 2.5$, DL1r 85%)
- $E_T^{\text{miss}} > 30$ GeV
- $N_{\text{jets}} \leq 1$ ($p_T > 30$ GeV, $|\eta| < 2.5$)

Isolating DPS from background processes

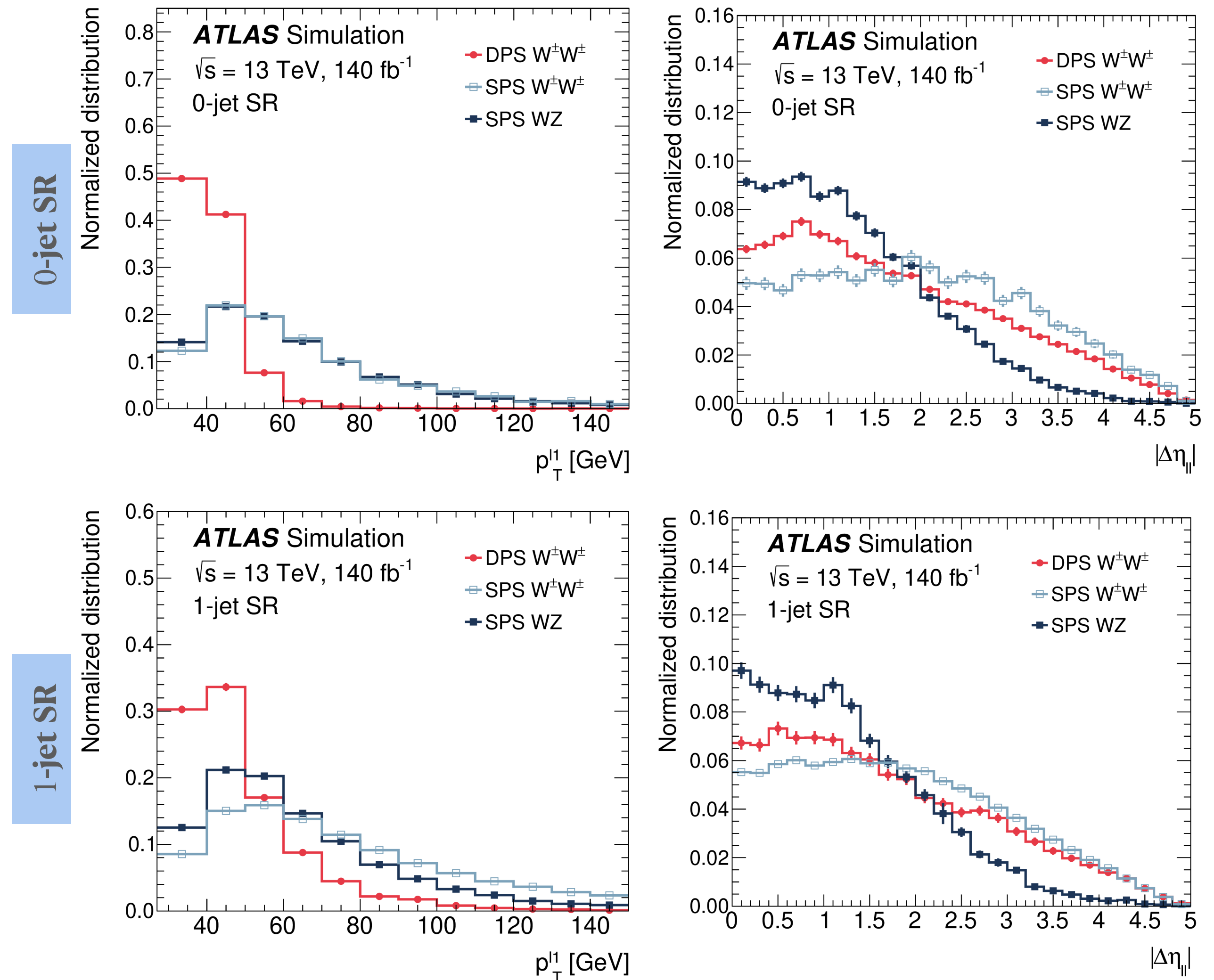
DPS signal modeled with Pythia8 (with A14 tune) at LO
(Herwig7 with default tune as alternative)

DPS signal expected to yield

- softer leptons,
- larger rapidity separation of lepton pair (non-correlated kinematics)



Most discriminating kinematic observables:



Signal extraction

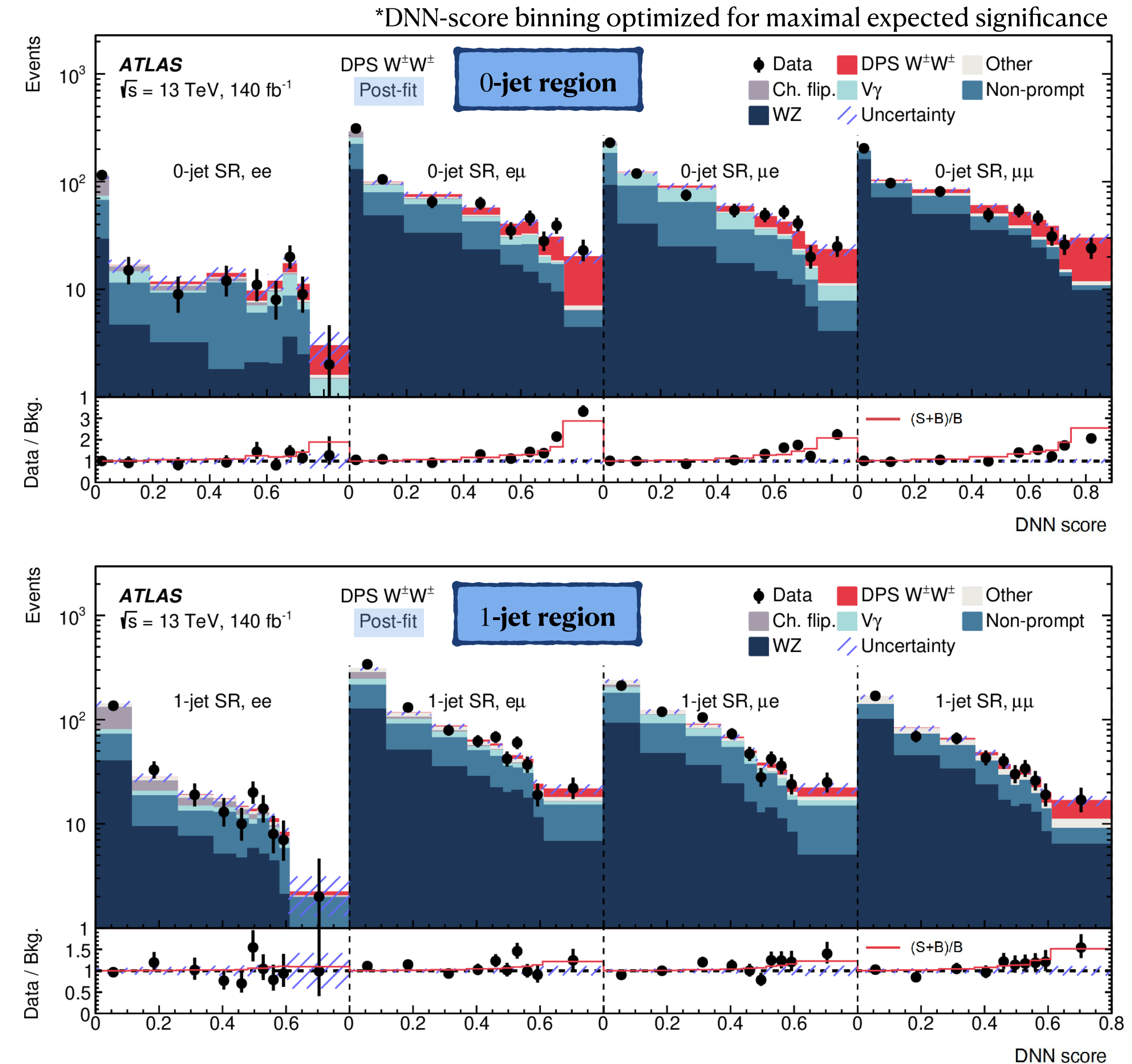
- Two dedicated DNNs in 0– and 1–jet SRs
- Binned maximum-likelihood fit using DNN scores in exclusive jet categories

$$\mu_{DPS\ W^{\pm}W^{\pm}}$$

$$\mu_{W^{\pm}Z, 0\text{--jet}}, \mu_{W^{\pm}Z, 1\text{--jet}}$$

- Other backgrounds based on data-driven estimation techniques (Non-prompt, ch. flip) and MC simulation.
- Good signal-background separation achieved
- Bkg-only hypothesis rejected with observed significance of 8.8σ .

Observation by CMS confirmed!



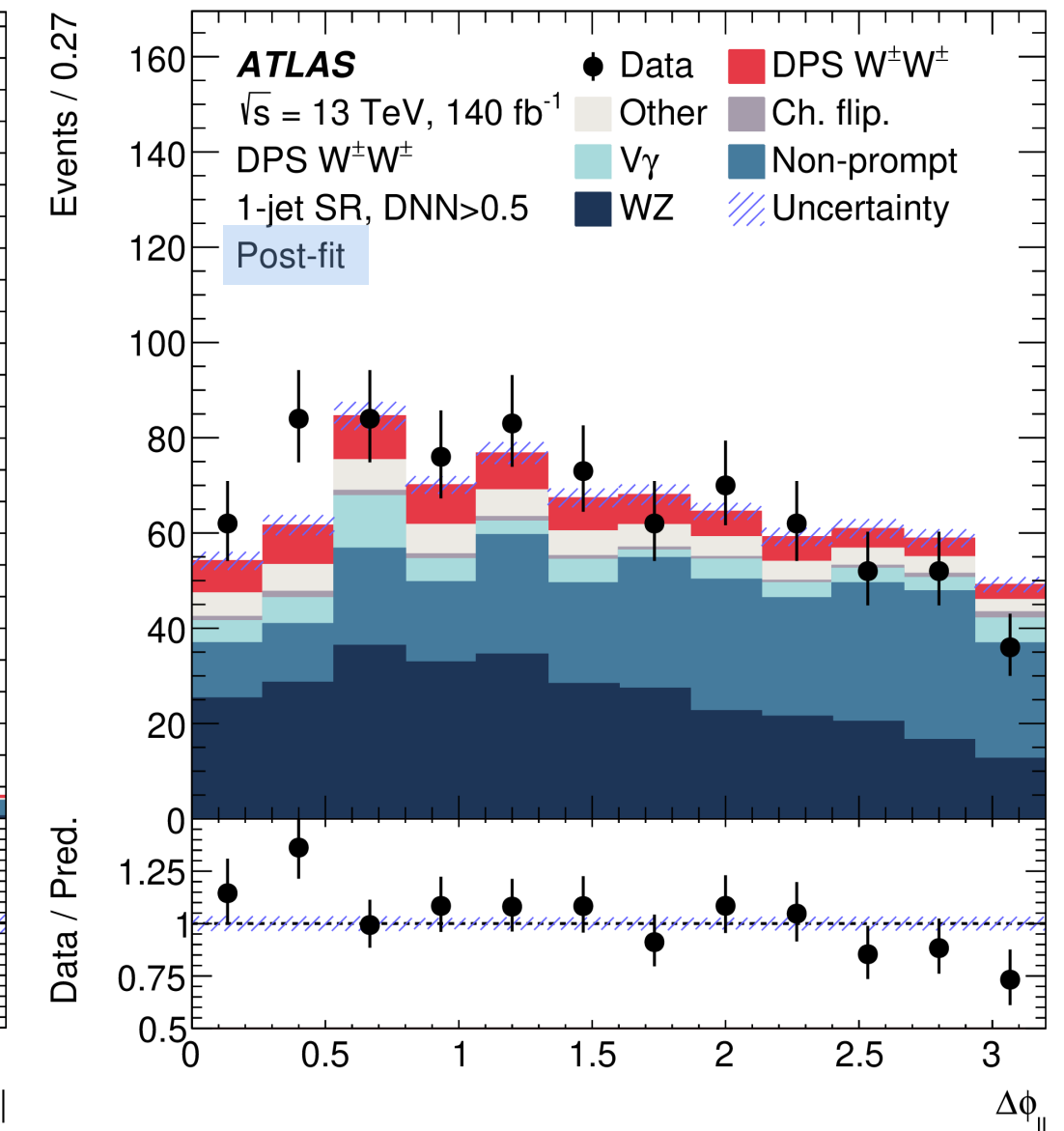
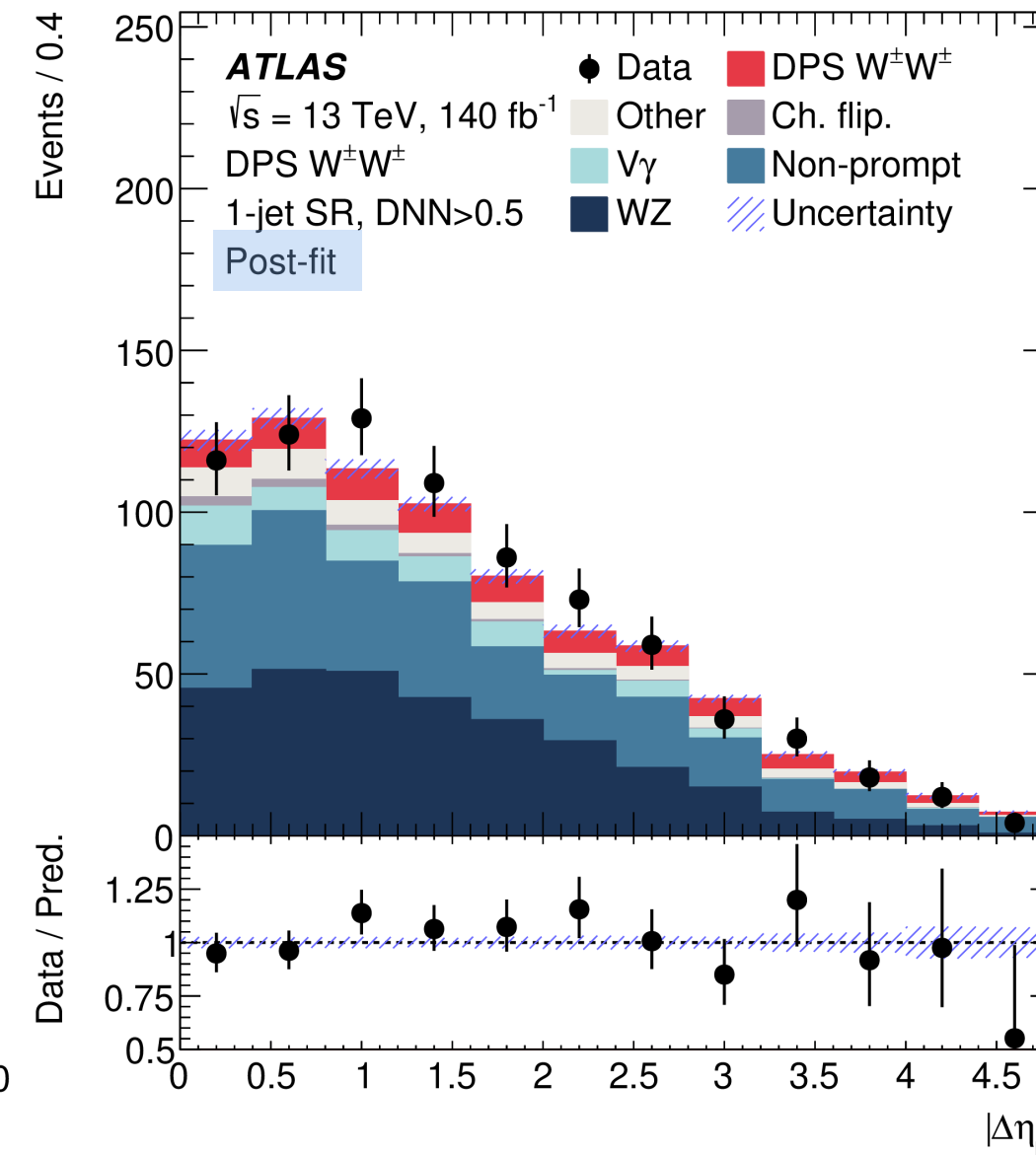
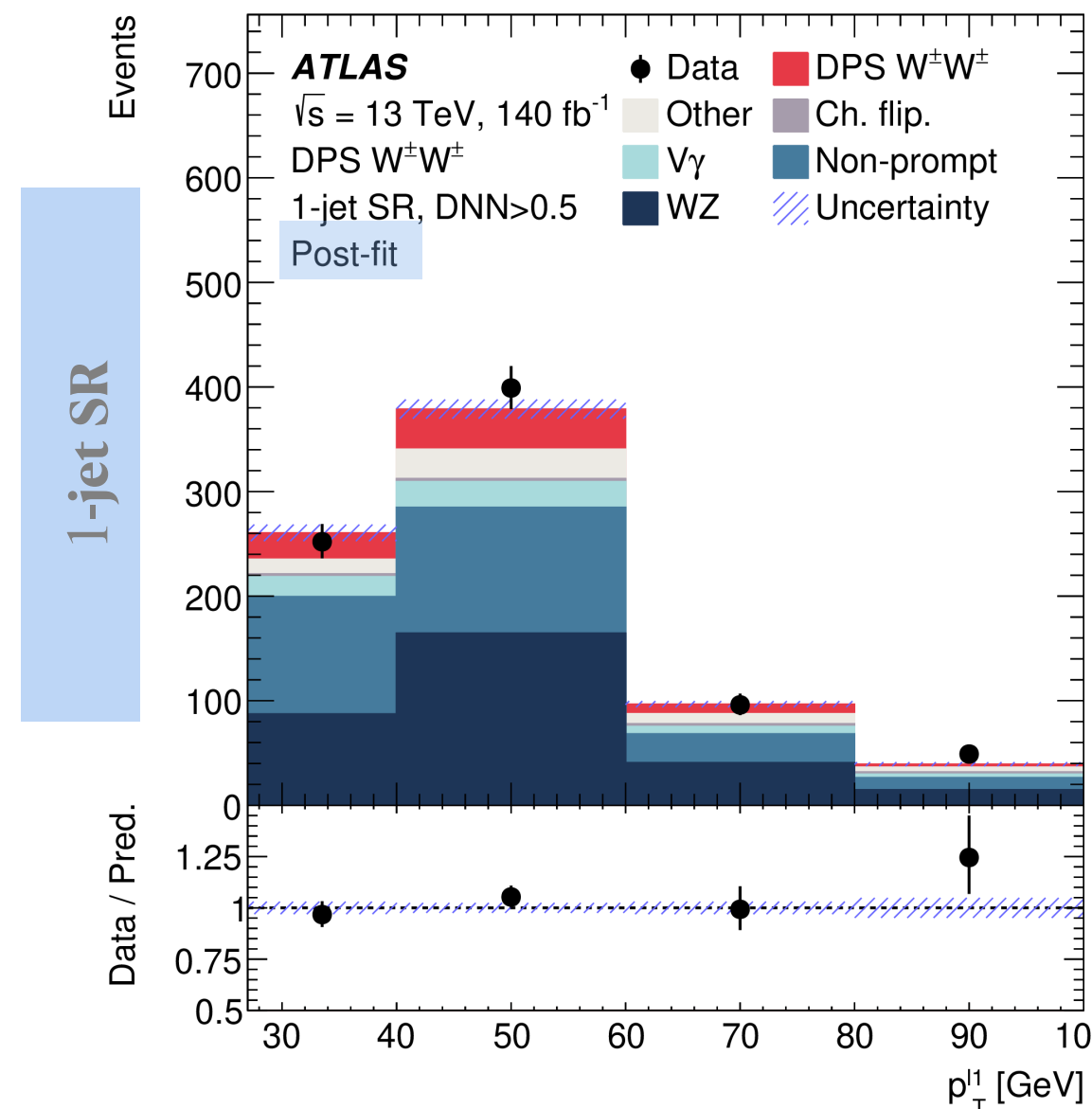
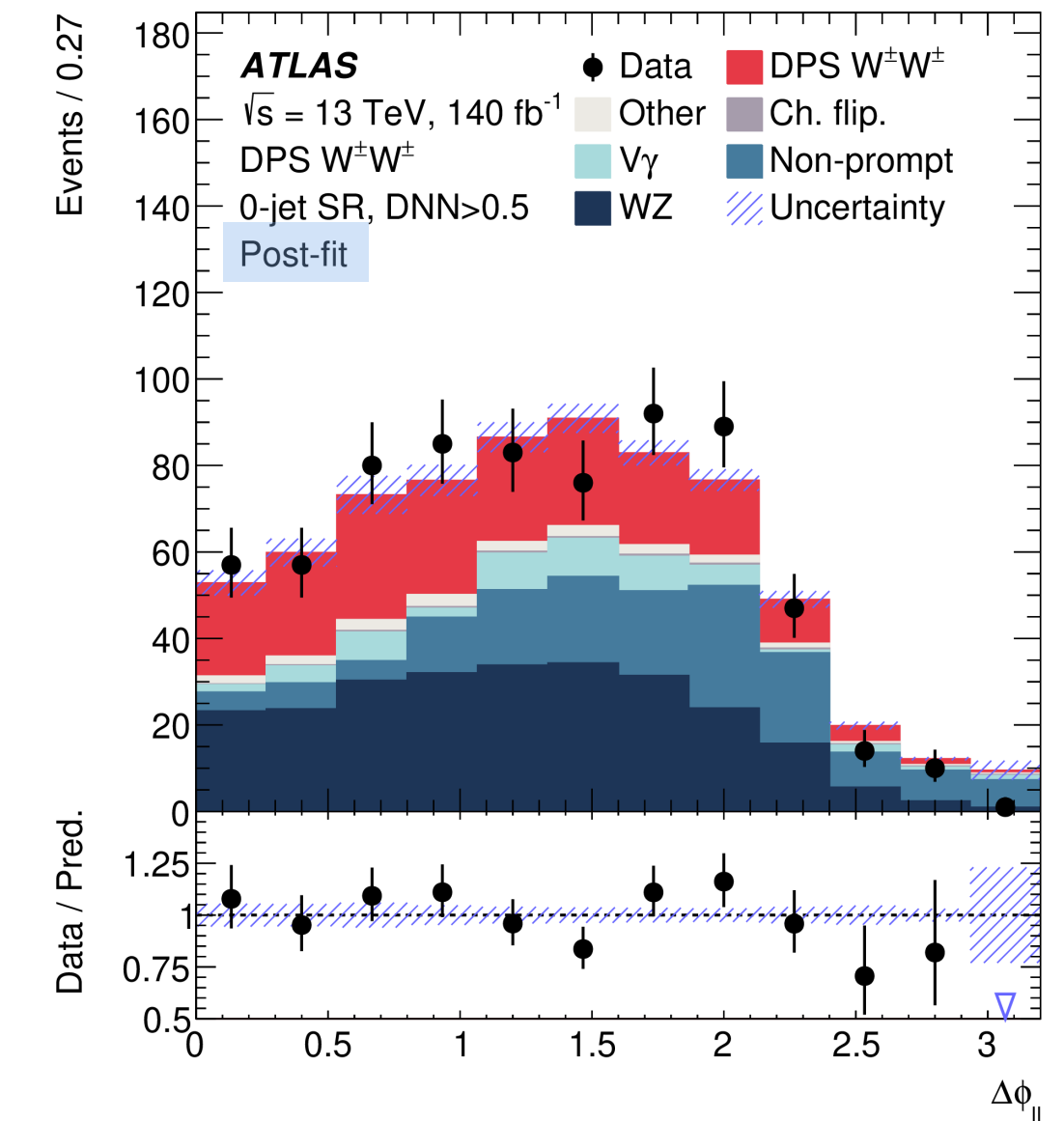
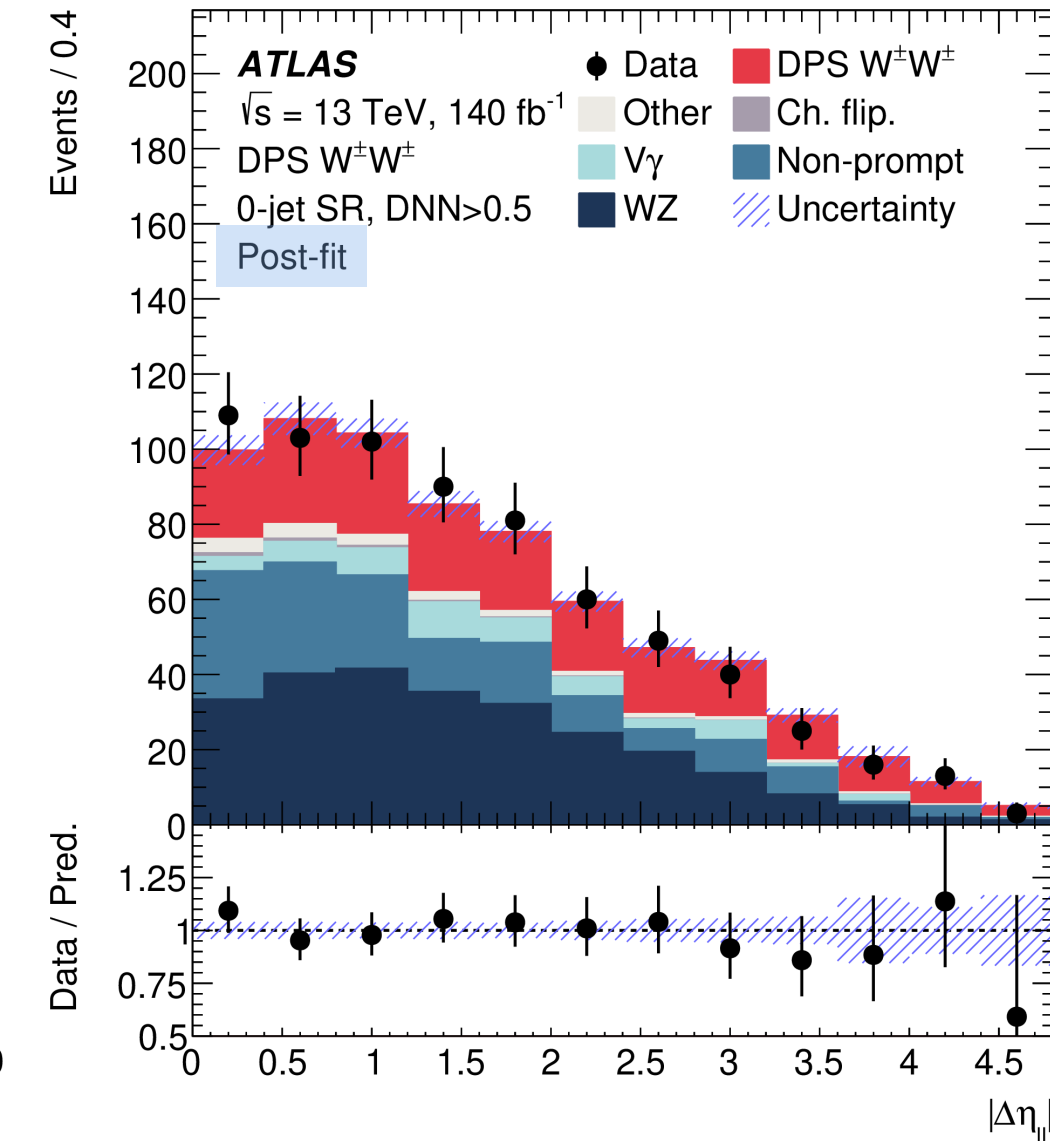
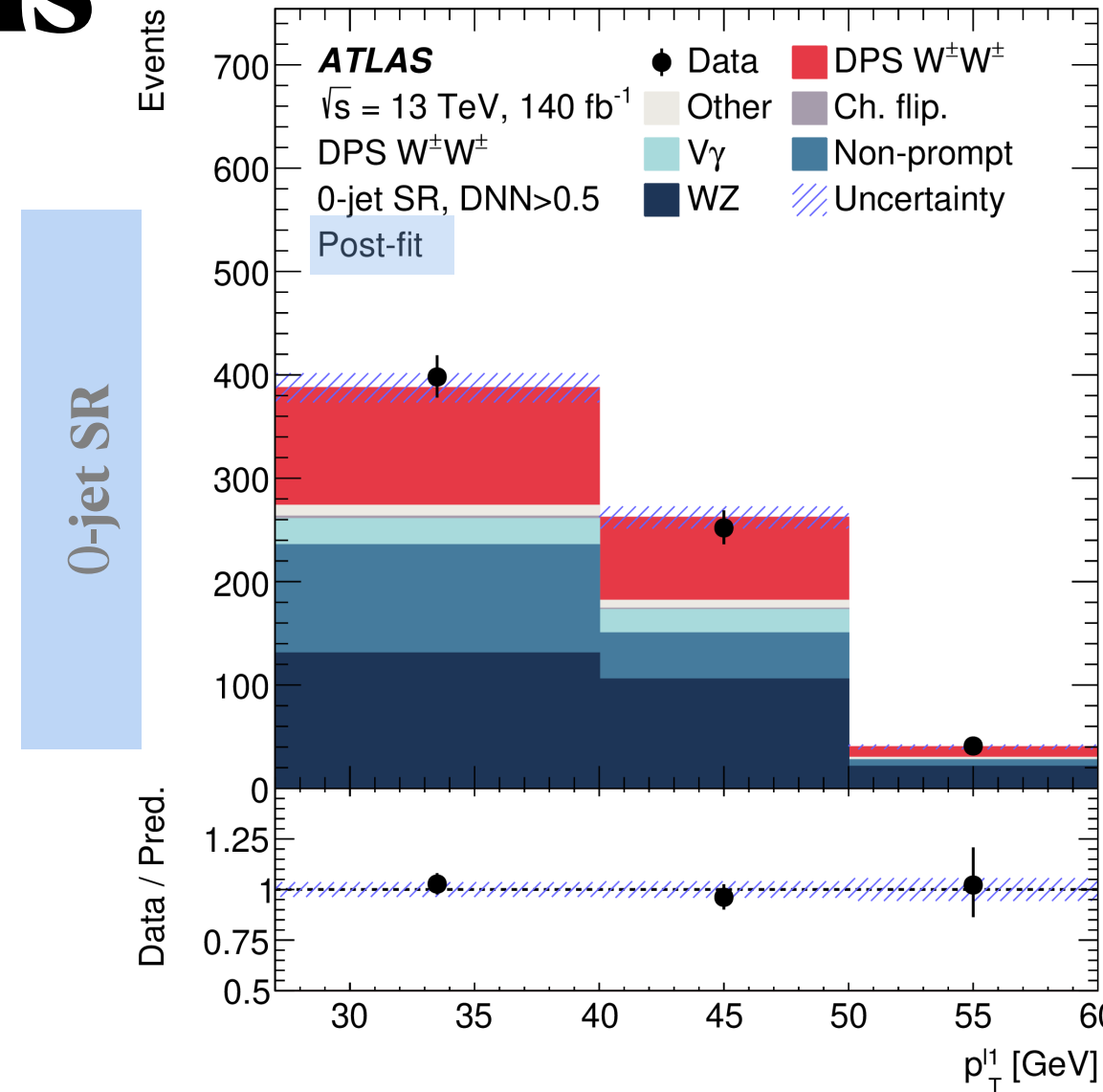
Kinematic distributions

Good description of the Data in the DPS-enriched region ($DNN > 0.5$)

Confirms non-correlated kinematics of two hard-scattering parton collisions in the event

Complex correlations between hard interactions, neglected in simplified Ansatz, are subleading given the stat. uncertainties of the Data

DPS-enriched region, $DNN > 0.5$



Systematic uncertainties

Extract fiducial cross-section $\times$ branching ratio in phase-space close to reconstructed event selection

$$\sigma(W^\pm W^\pm) \cdot \mathcal{B} = 4.59 \pm 0.64 \text{ [fb]}$$

Leading uncertainties

Statistical uncertainties of the Data (13%)

Jet Energy Scale and Resolution (3%)

Non-prompt background estimate (2.6%)

Source	$\sigma(W^\pm W^\pm) \cdot \mathcal{B}$	Uncertainty [%]
Experimental		4.7
Electrons		0.4
Muons		0.8
Jets		3.1
E_T^{miss}		1.5
Flavor tagging		0.3
Non-prompt leptons		2.6
Charge flip		0.6
Pileup modeling		1.3
Luminosity		0.8
Modeling		1.5
DPS $W^\pm W^\pm$ scale		0.2
DPS $W^\pm W^\pm$ model		0.3
SPS $W^\pm W^\pm$ scale, PDF & α_S		0.2
WZ scale, PDF & α_S		0.8
WZ normalization		0.1
Other background normalizations		1.1
Model statistical		0.6
Experimental and modeling		5.0
Data statistical		13
Total		14

Cross-section measurements

$$\sigma(W^\pm W^\pm) \cdot \mathcal{B} = 4.59 \pm 0.64 \text{ [fb]}$$

$$\sigma_{AB}^{DPS} = \frac{1}{1 + \delta_{AB}} \frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

Extrapolate to full phase-space, given computed σ_{W^+} and σ_{W^-}

$\Rightarrow$ **Extract σ_{eff}**

$$\sigma_{eff}^{ATLAS} = 10.6 \pm 1.8 \text{ [mb]}$$

Experiment (energy, final state, year)

ATLAS $\sqrt{s} = 13 \text{ TeV}, 140 \text{ fb}^{-1}$

UA2 ($\sqrt{s} = 630 \text{ GeV}$, 4 jets, 1991)

CDF ($\sqrt{s} = 1.8 \text{ TeV}$, 4 jets, 1993)

CDF ($\sqrt{s} = 1.8 \text{ TeV}$, $\gamma + 3 \text{ jets}$, 1997)

DØ ($\sqrt{s} = 1.96 \text{ TeV}$, $\gamma + 3 \text{ jets}$, 2010)

LHCb ($\sqrt{s} = 7 \text{ TeV}$, $J/\psi \Lambda_c^+$, 2012)

LHCb ($\sqrt{s} = 7 \text{ TeV}$, $J/\psi D_s^+$, 2012)

LHCb ($\sqrt{s} = 7 \text{ TeV}$, $J/\psi D^+$, 2012)

LHCb ($\sqrt{s} = 7 \text{ TeV}$, $J/\psi D^0$, 2012)

ATLAS ($\sqrt{s} = 7 \text{ TeV}$, $W + 2 \text{ jets}$, 2013)

CMS ($\sqrt{s} = 7 \text{ TeV}$, $W + 2 \text{ jets}$, 2014)

DØ ($\sqrt{s} = 1.96 \text{ TeV}$, $\gamma + b/c + 2 \text{ jets}$, 2014)

DØ ($\sqrt{s} = 1.96 \text{ TeV}$, $\gamma + 3 \text{ jets}$, 2014)

DØ ($\sqrt{s} = 1.96 \text{ TeV}$, $J/\psi + J/\psi$, 2014)

ATLAS ($\sqrt{s} = 8 \text{ TeV}$, $Z + J/\psi$, 2015)

LHCb ($\sqrt{s} = 7 \text{ \& } 8 \text{ TeV}$, $\Upsilon(1S) D^{0,+}$, 2015)

DØ ($\sqrt{s} = 1.96 \text{ TeV}$, $J/\psi + \Upsilon$, 2016)

DØ ($\sqrt{s} = 1.96 \text{ TeV}$, $2\gamma + 2 \text{ jets}$, 2016)

ATLAS ($\sqrt{s} = 7 \text{ TeV}$, 4 jets, 2016)

ATLAS ($\sqrt{s} = 8 \text{ TeV}$, $J/\psi + J/\psi$, 2017)

CMS ($\sqrt{s} = 8 \text{ TeV}$, $\Upsilon + \Upsilon$, 2017)

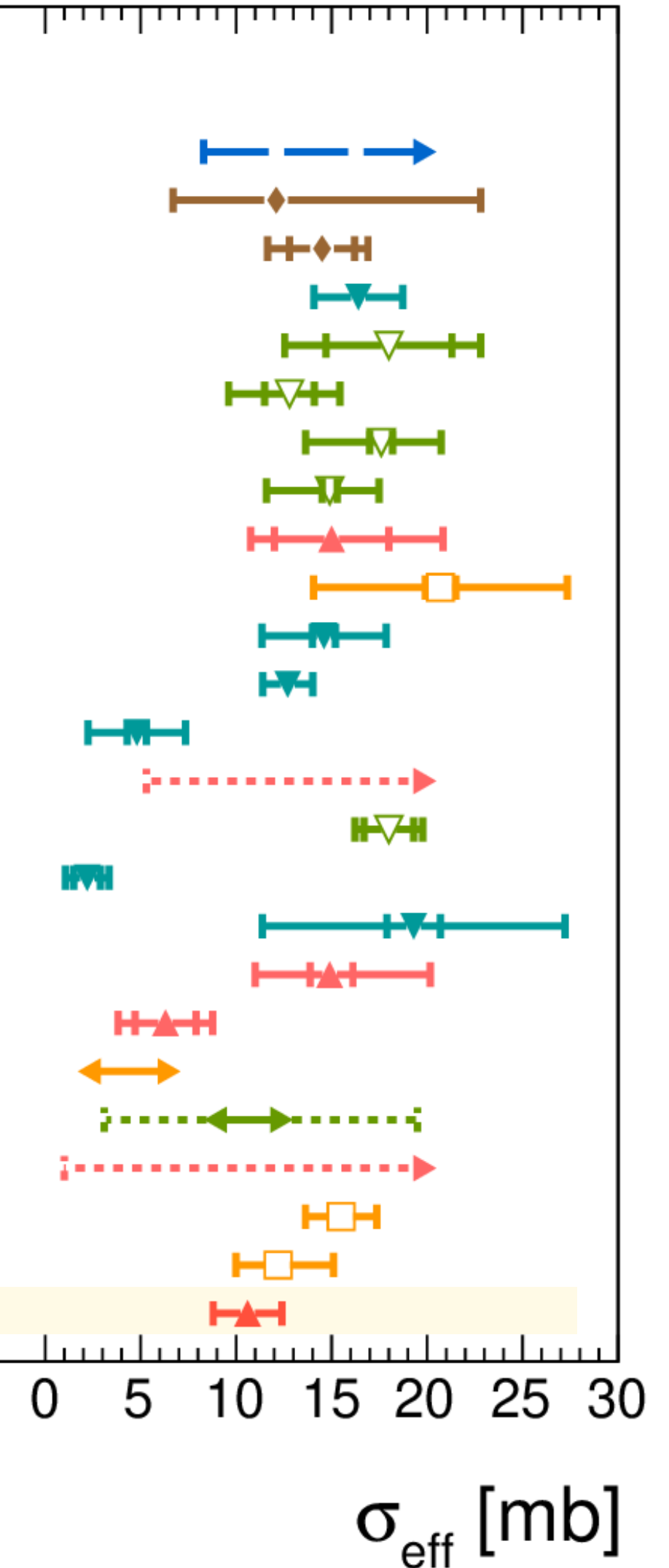
LHCb ($\sqrt{s} = 13 \text{ TeV}$, $J/\psi + J/\psi$, 2017)

ATLAS ($\sqrt{s} = 8 \text{ TeV}$, 4 leptons, 2019)

CMS ($\sqrt{s} = 13 \text{ TeV}$, 4 jets, 2022)

CMS ($\sqrt{s} = 13 \text{ TeV}$, $W^\pm W^\pm$, 2023)

ATLAS ($\sqrt{s} = 13 \text{ TeV}, W^\pm W^\pm$, 2025)



Summary

This talk focused on a recent ATLAS result on soft and non-perturbative QCD:

- First observation of DPS in same-sign WW by ATLAS using 140 fb^{-1} of recorded pp collision data at $\sqrt{s} = 13 \text{ TeV}$

Observed significance: 8.8σ

- Fiducial cross-section

$$\sigma(W^{\pm}W^{\pm}) \cdot \mathcal{B} = 4.59 \pm 0.64 \text{ [fb]}$$

- Effective cross-section

$$\sigma_{eff} = 10.6 \pm 1.8 \text{ [mb]}$$

- Total uncertainty (14%) dominated by statistical uncertainties of the Data (13%)

Observation of double parton scattering in same-sign W boson pair production in pp collisions at $\sqrt{s} = 13 \text{ TeV}$ with the ATLAS detector

[Phys. Lett. B 870 (2025) 139892]

Backup slides

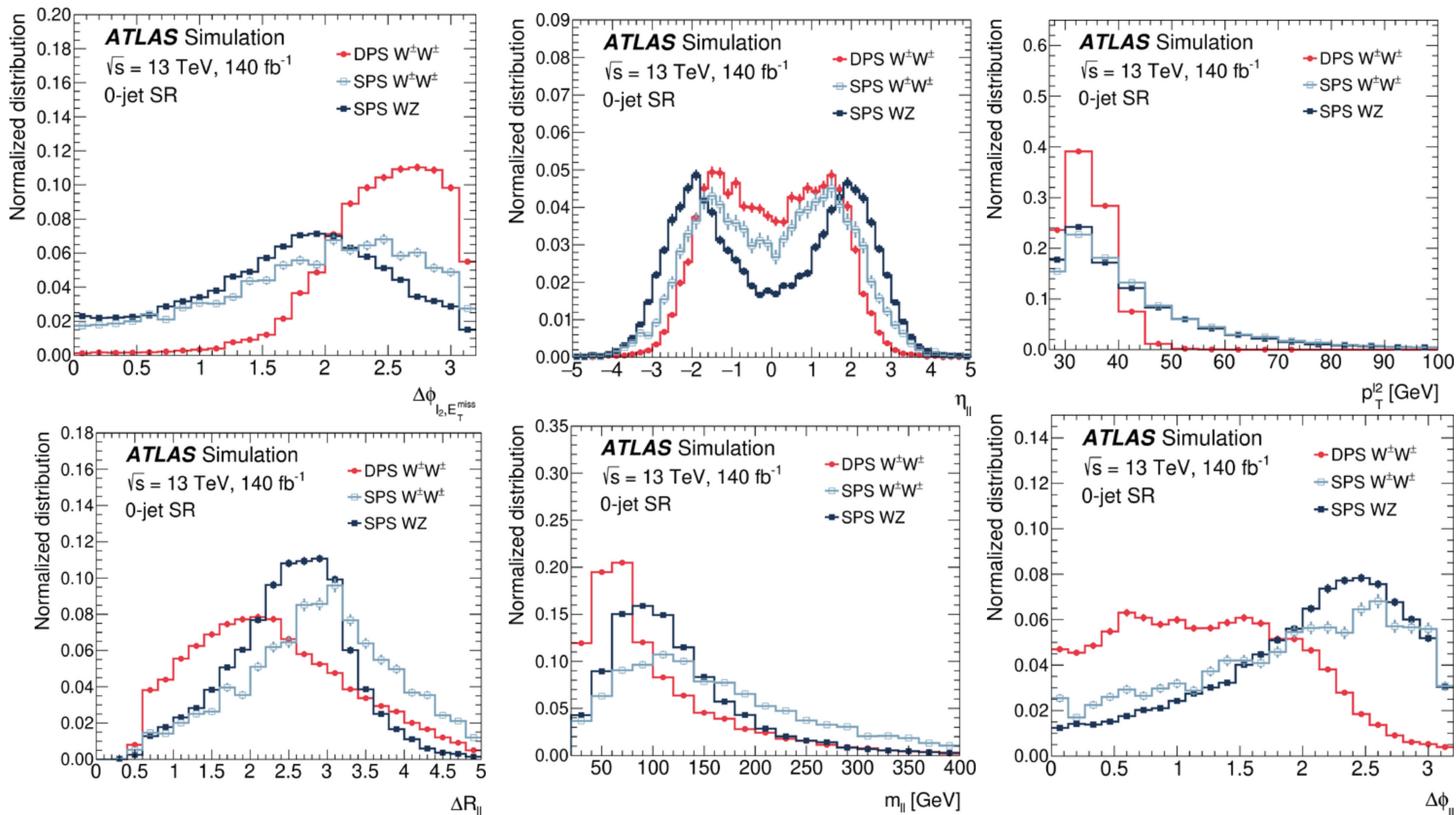
Lepton kinematic variables for DNN training

Description	Variable
p_T of the leading lepton	$p_T^{\ell 1}$
p_T of the subleading lepton	$p_T^{\ell 2}$
Invariant mass of the dilepton system	$m_{\ell\ell}$
Pseudorapidity of the dilepton system	$\eta_{\ell\ell}$
Difference in azimuthal angle between the leading and subleading leptons	$\Delta\phi_{\ell\ell}$
Difference in pseudorapidity between the leading and subleading leptons	$ \Delta\eta_{\ell\ell} $
Distance ΔR between the leading and subleading leptons	$\Delta R_{\ell\ell}$
Difference in azimuthal angle between the missing transverse momentum and subleading lepton	$\Delta\phi_{\ell_2, E_T^{\text{miss}}}$

Lepton kinematic variables for DNN training

[Phys. Lett. B 870 (2025) 139892]

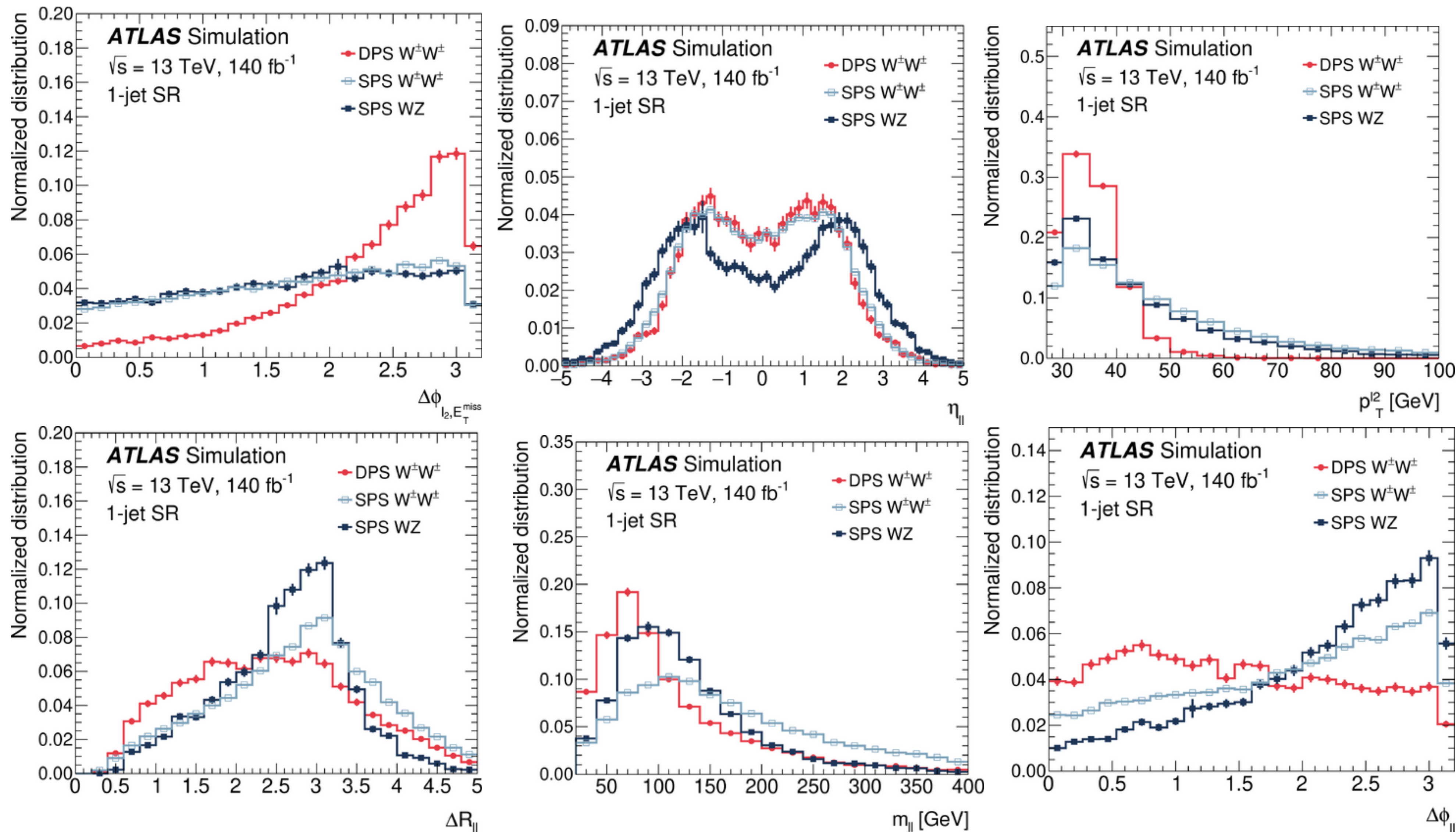
0-jet region



Lepton kinematic variables for DNN training

[Phys. Lett. B 870 (2025) 139892]

1-jet region



Post-fit selected events

0-jet SR

Process	ee	$e\mu$	μe	$\mu\mu$	Combined
DPS $W^{\pm}W^{\pm}$	13.7 ± 2.0	68 ± 9	66 ± 9	90 ± 12	237 ± 32
WZ	48.9 ± 2.9	288 ± 12	221 ± 9	409 ± 13	968 ± 31
Non-prompt	78 ± 10	204 ± 15	248 ± 18	108 ± 14	640 ± 50
Charge flip	43 ± 10	39 ± 6	13.0 ± 1.9	—	95 ± 17
$V\gamma$	20 ± 5	70 ± 15	107 ± 23	—	200 ± 40
Other	5.6 ± 0.8	18.7 ± 2.5	14.8 ± 1.8	31 ± 5	71 ± 9
Total	209 ± 10	688 ± 17	670 ± 19	639 ± 17	2210 ± 40
Data	201	716	665	612	2194

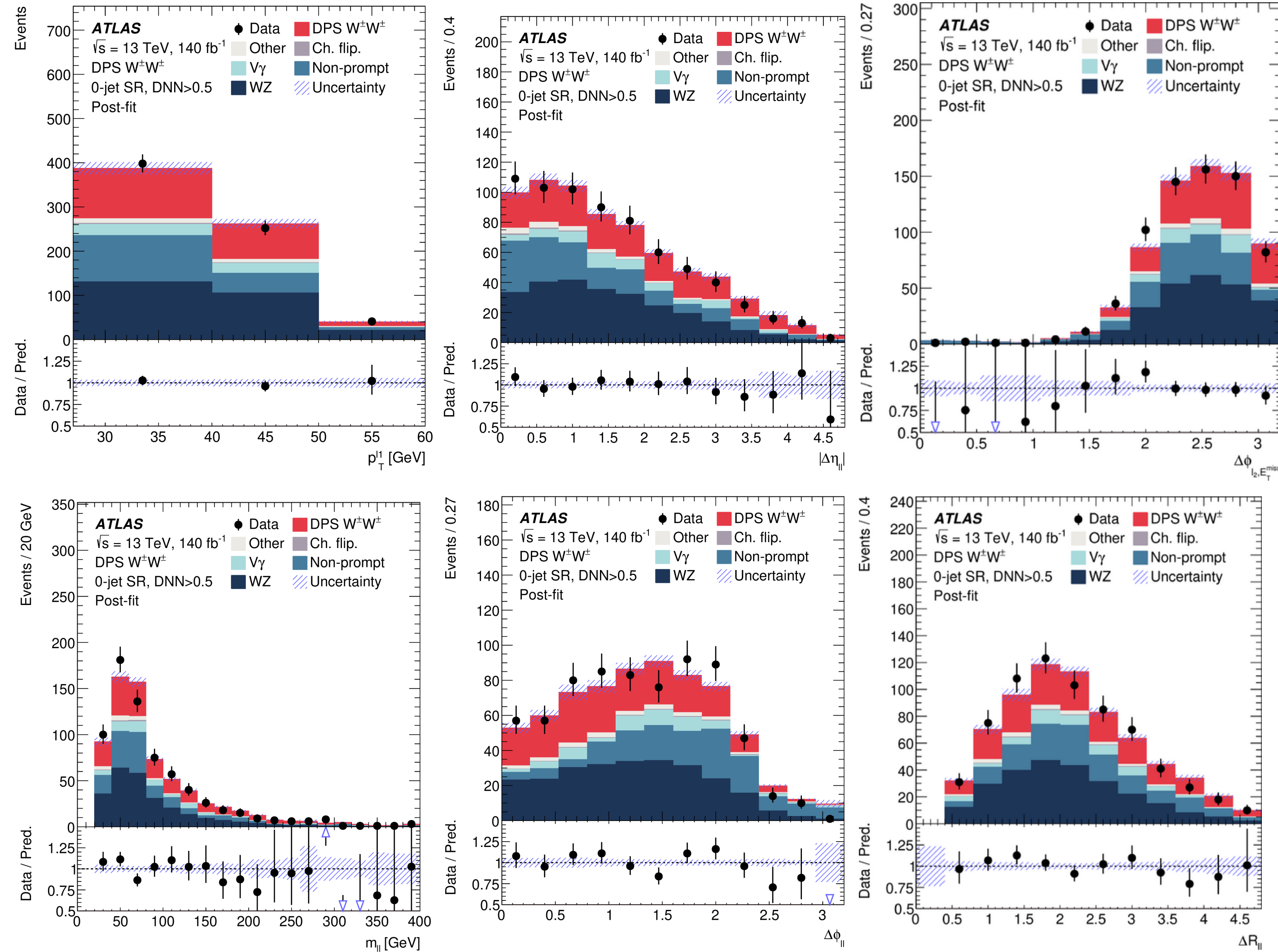
1-jet SR

Process	ee	$e\mu$	μe	$\mu\mu$	Combined
DPS $W^{\pm}W^{\pm}$	4.8 ± 0.8	26 ± 4	25 ± 4	35 ± 5	91 ± 14
WZ	84 ± 4	337 ± 12	265 ± 10	275 ± 11	959 ± 33
Non-prompt	79 ± 10	257 ± 19	271 ± 19	152 ± 19	760 ± 60
Charge flip	65 ± 15	49 ± 7	14.5 ± 2.1	—	128 ± 24
$V\gamma$	18 ± 4	73 ± 17	84 ± 18	—	170 ± 40
Other	17.8 ± 1.4	63 ± 5	54 ± 4	64 ± 4	199 ± 14
Total	269 ± 13	806 ± 18	714 ± 18	525 ± 17	2310 ± 40
Data	262	860	711	513	2346

(All) Kinematic distributions

[Phys. Lett. B 870 (2025) 139892]

0-jet SR, DNN > 0.5



(All) Kinematic distributions

[Phys. Lett. B 870 (2025) 139892]

1-jet SR, DNN > 0.5

