Review of DPS measurements at the LHC

XXV DAE-BRNS High Energy Physics Symposium 2022
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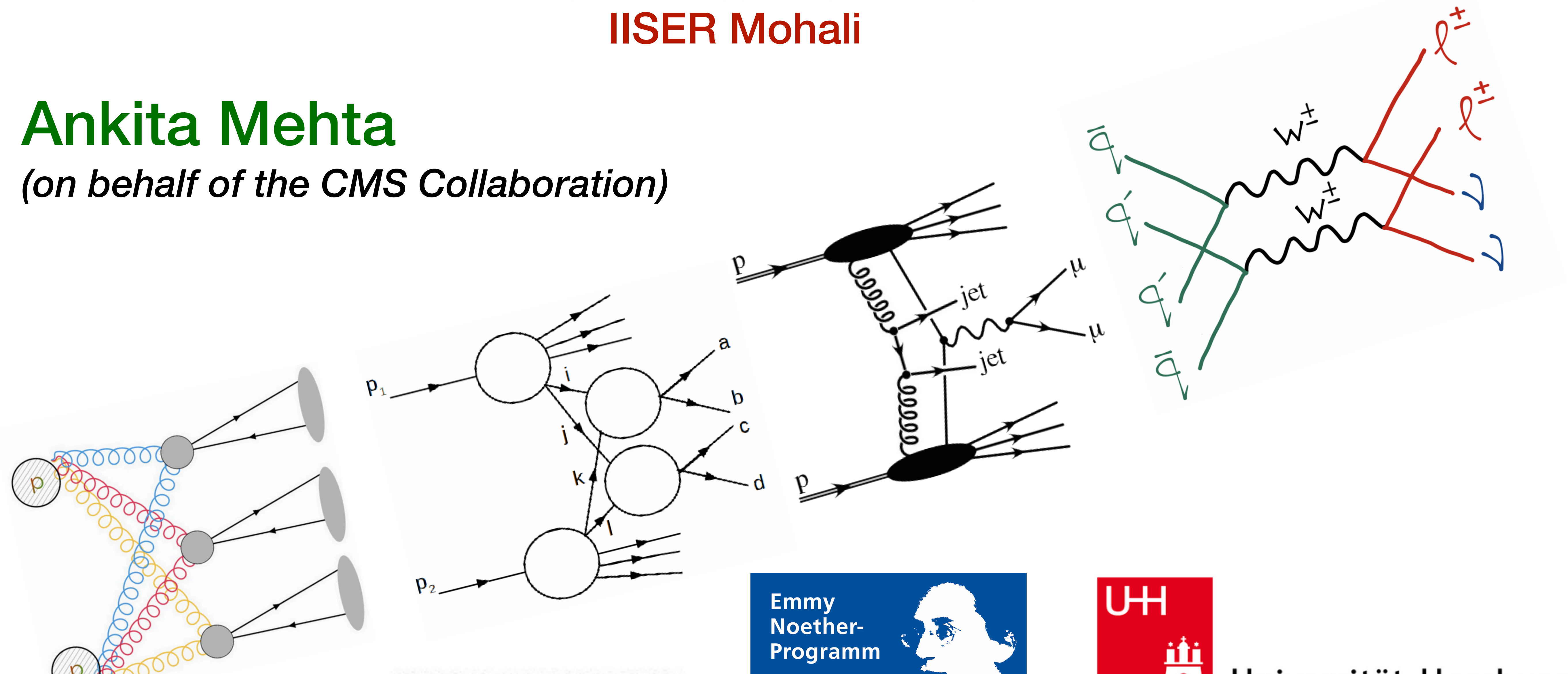
(on behalf of the CMS Collaboration)



Dec 12, 2022

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Double parton scattering (DPS)

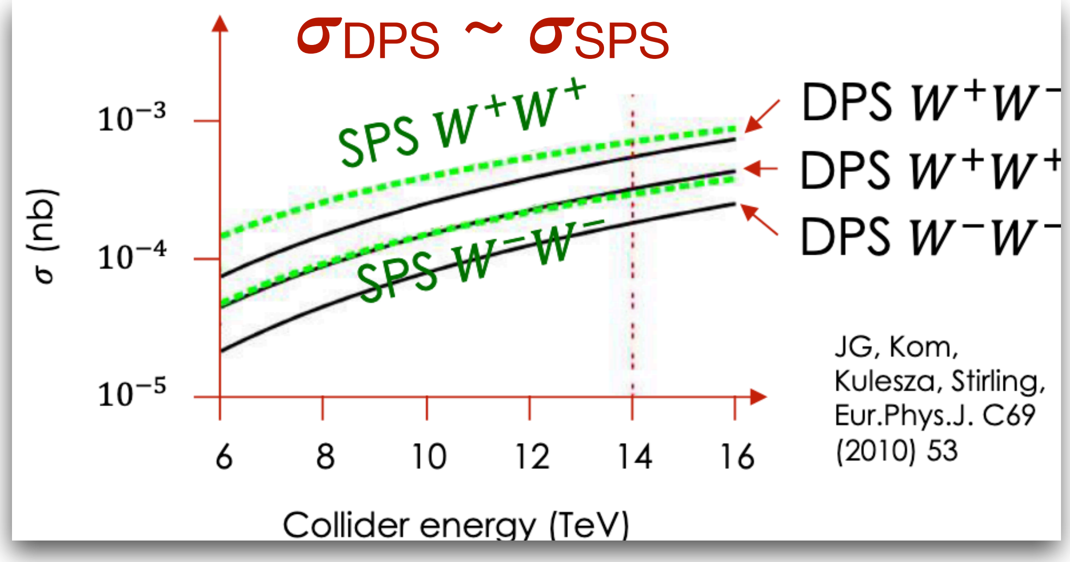
- Two distinct hard scatters in a single pp collision double parton scattering
- Cross section for a “nPS” process is suppressed as compared to SPS

$$\boxed{\frac{\sigma_{n\mathrm{PS}}}{\sigma_{\mathrm{SPS}}} \sim \left(\frac{\Lambda^2}{Q_h^2}\right)^{n-1}}$$

Λ → hadronic scale ~1GeV

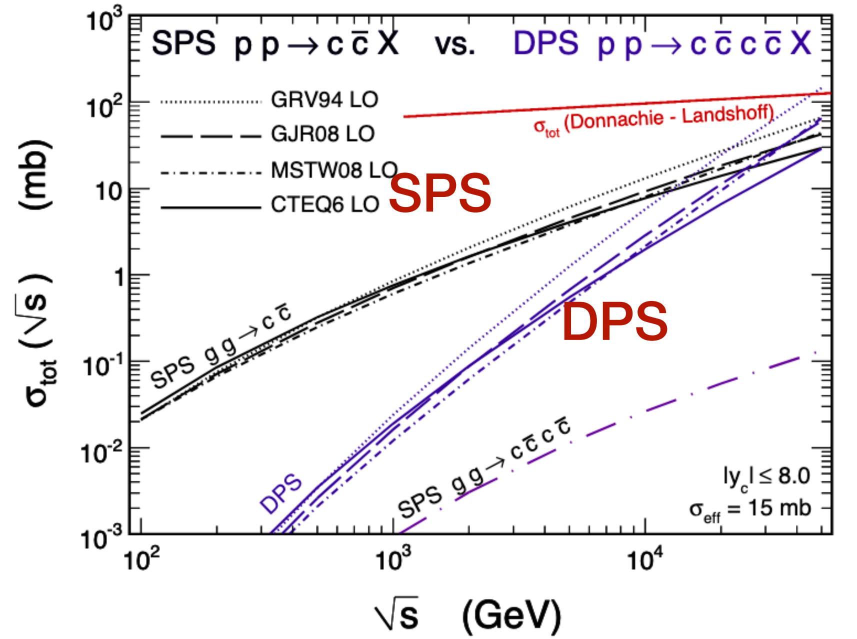
Q_h → hard interaction scale

In certain phase space regions contributions from DPS cannot be neglected

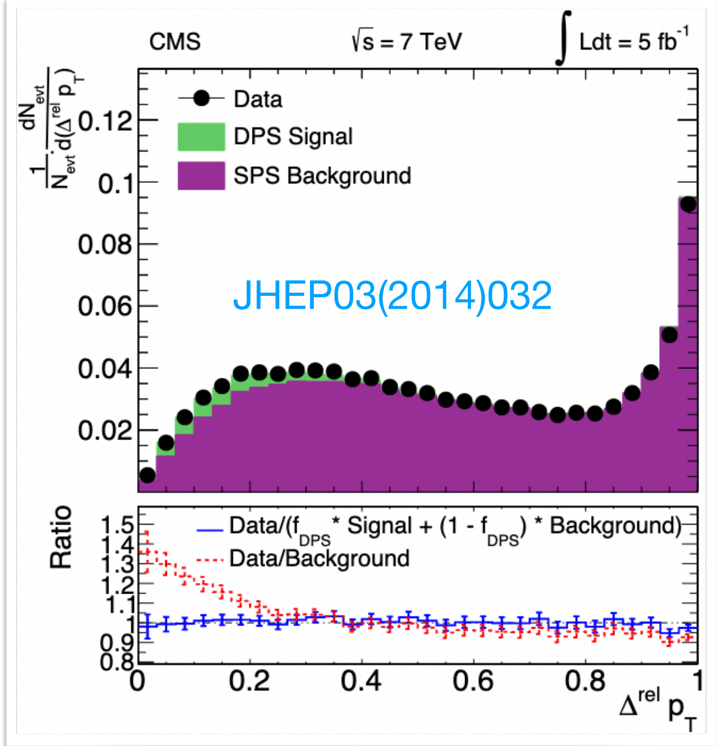


JG, Kom, Kulesza, Stirling, Eur.Phys.J. C69 (2010) 53

Phys. Rev. D79, 094034



Populates phase space in a different way from SPS

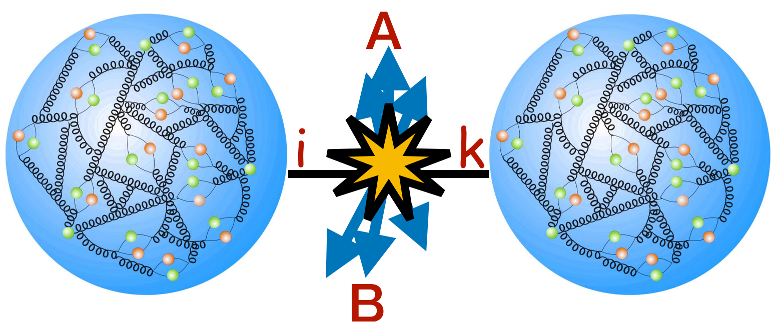


JHEP03(2014)032

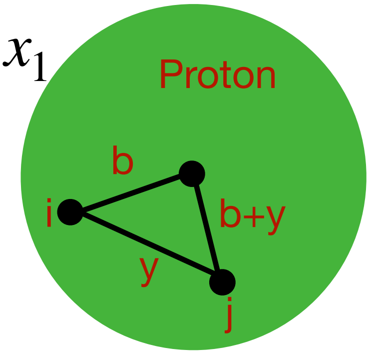
- Probes the internal structure of a proton
- Background for rare SM and new physics processes
- Provides input for the tuning of MC simulations

Cross section formula for DPS

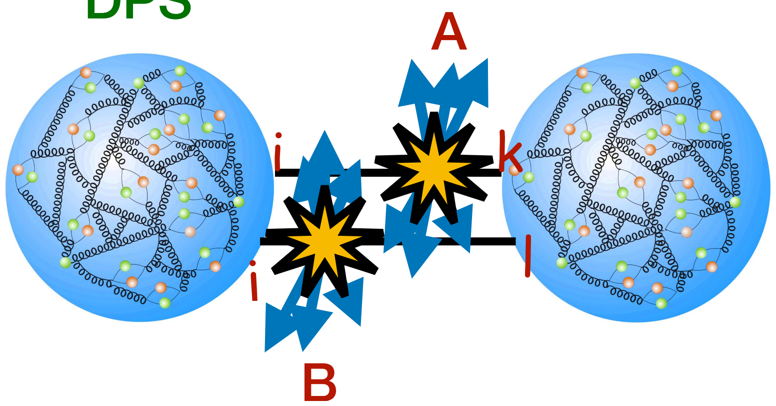
SPS



$$\sigma_{AB}^{\text{SPS}} = \sum_{i,k} \int \overset{\text{PDFs}}{\boxed{D^i(x_1;Q^2)D^k(x_1',Q^2)}} \times \overset{\text{partonic cross section}}{\boxed{\hat{\sigma}_{AB}^{ik}(x_1,x_1',Q^2)}} dx_1 d'x_1$$



DPS



$$\sigma_{AB}^{\text{DPS}} = \frac{m}{2} \sum_{i,j,k,l} \int \overset{\text{double PDFs}}{\boxed{\Gamma^{ij}(x_1,x_2;b_1,b_2;Q_A^2,Q_B^2)}} \times \overset{\text{partonic cross sections}}{\boxed{\hat{\sigma}_A^{ij}(x_1,x_1',Q_A^2)\hat{\sigma}_B^{ij}(x_2,x_2',Q_B^2)}} \times \boxed{\Gamma^{kl}(x_1',x_2';b_1-b,b_2-b;Q_A^2,Q_B^2)} dx_1 dx_2 dx_1' dx_2' d^2b_1 d^2b_2 d^2b$$

assuming longitudinal and transverse factorization of dPDFs

simplified expression for

σ_{DPS} ⇢ pocket formula

$$\boxed{\sigma_{AB}^{\text{DPS}} = \frac{m}{2}\frac{\sigma_A\sigma_B}{\sigma_{\text{eff}}} \quad \sigma_{\text{eff}} = \left[\int d^2b\, t(b)\right]^{-1}}$$

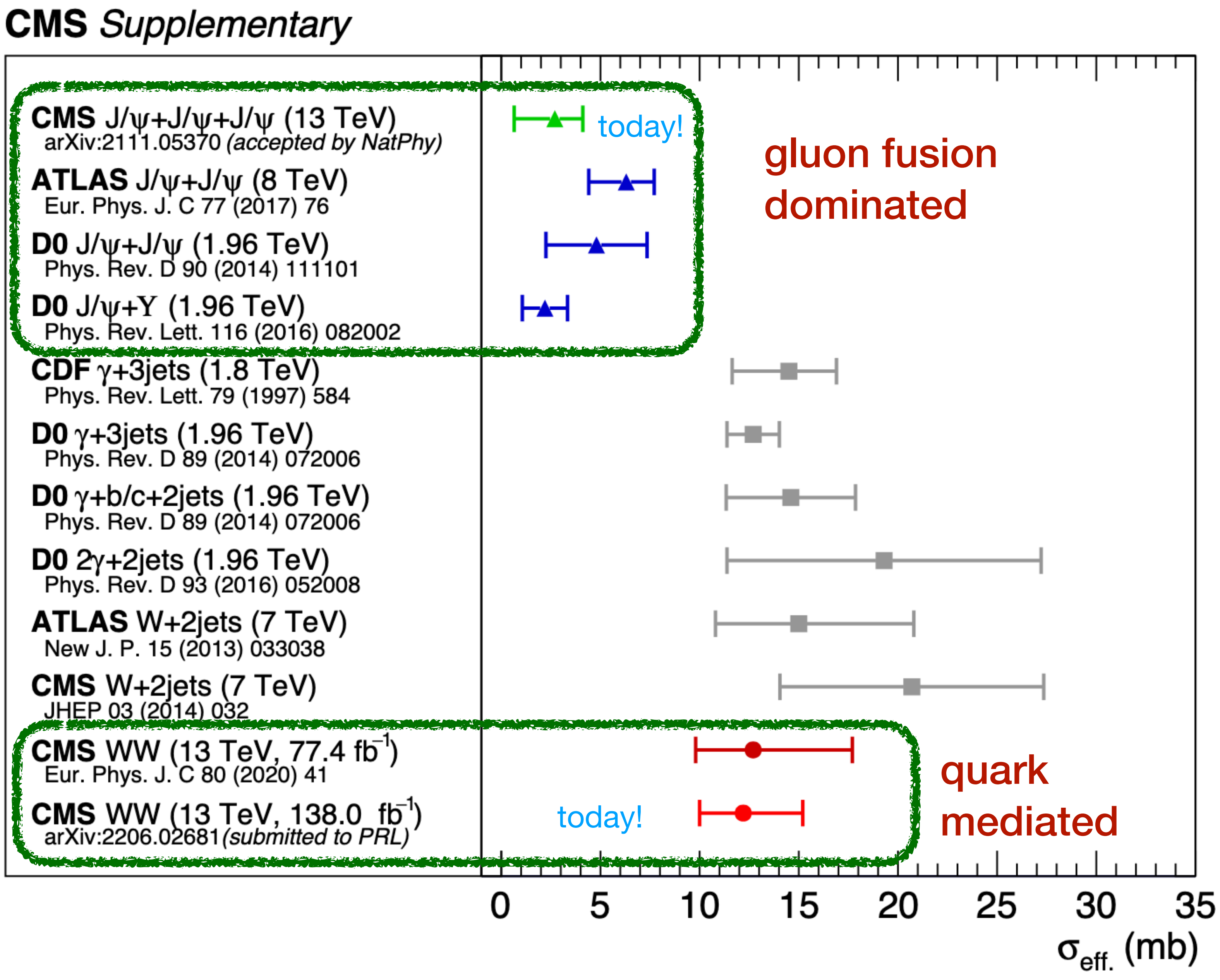
σ_A, σ_B : SPS cross sections for two interactions

m : 1 if A = B else 2

σ_{eff} : effective cross section for DPS

Effective cross section parameter

- Proxy to mean inter-parton transverse separation squared ⇢ sort of an impact parameter; smaller σ_{eff} implies a larger σ^{DPS} & vice-versa
- Expected to be process, scale & c.o.m. energy independent “in the assumed simplest model”



today!

gluon fusion dominated

today!

quark mediated

- Pythia8: 20-30 mb

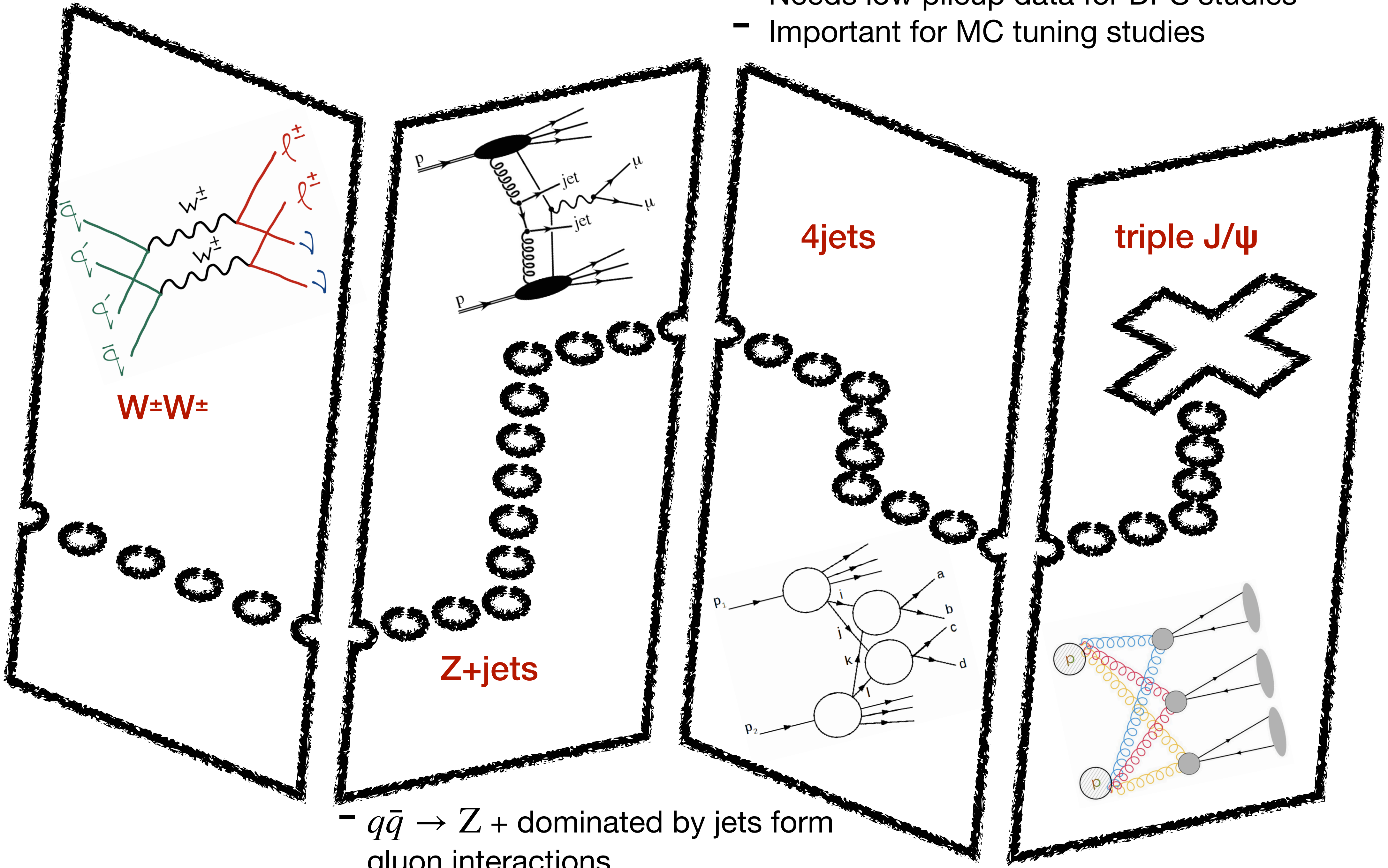
(large tune dependence)

- Measurements: 5-20 mb

- Inter-parton correlations?
- Parton-flavor dependence (quark/gluon)?
- Flaws in DPS factorization?

- At leading order $u\bar{d} \rightarrow \mathrm{W}^{+}$; $d\bar{u} \rightarrow \mathrm{W}^{-}$
- Tiny SPS contribution
- Sensitive to parton correlations

- Dominated by jets form gluon interactions
- Huge cross section
- Needs low pileup data for DPS studies
- Important for MC tuning studies



- $q\bar{q} \rightarrow \mathrm{Z}$ + dominated by jets form gluon interactions
- Large cross section
- Important for MC tuning studies

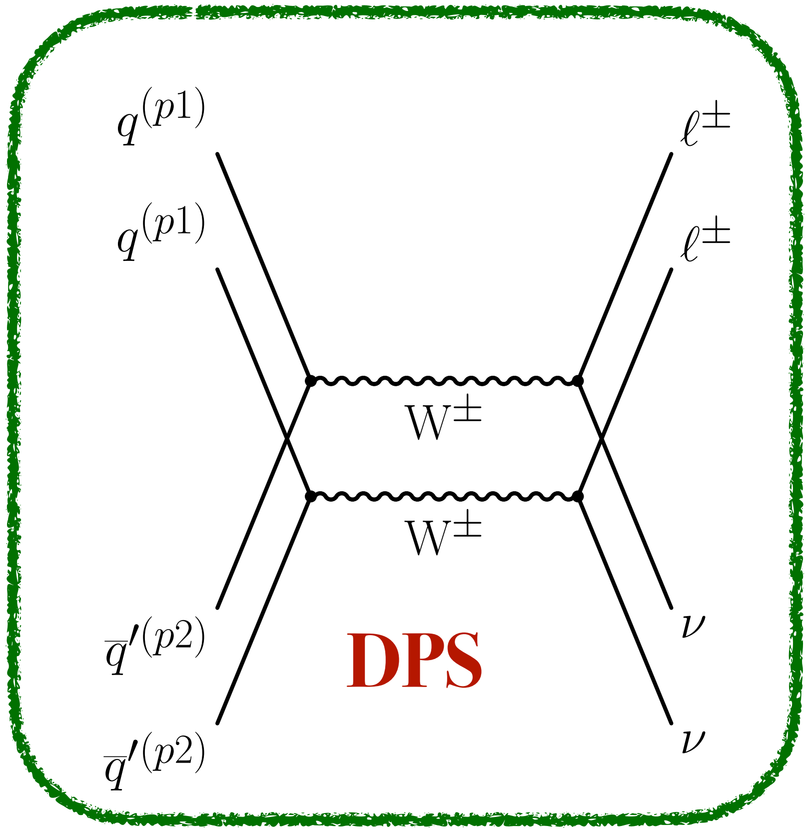
- Dominated by gluon interactions
- Experimentally clean
- Important for DPS &TPS

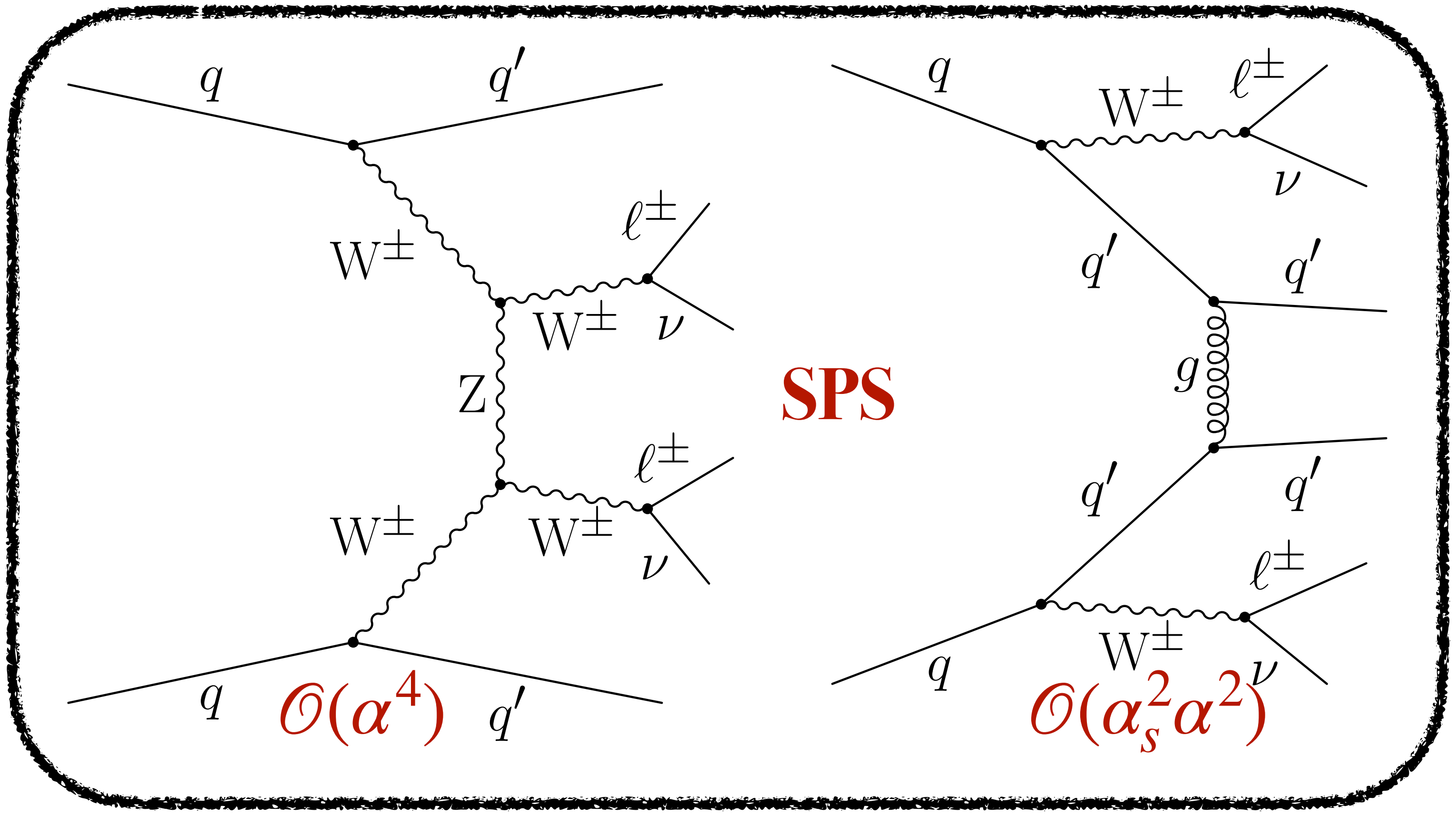
decreasing Q² →

arXiv:2206.02681

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

- Golden channel for DPS production since SPS $W^{\pm}W^{\pm}$ production suppressed at matrix element level due to presence of (two) extra jets
- Pythia8 predicts cross section for $W^{\pm}W^{\pm} \dashrightarrow 2l2\nu$ ~ 86 fb @13 TeV





- Sensitive to inter-parton correlations
- Experimentally clean final state with leptonic W decays
  - Negligible contributions from leptons from adjacent bunch crossings

Analysis strategy

- Analysis performed using pp collisions data at 13 TeV ⇢ 138 fb^{-1}
- Signal: $W^{\pm}W^{\pm}$ ⇢ eμ or μμ final states with moderate p_T^{miss} ⇢ modelled using Pythia8 & dShower with model uncertainties from Herwig

- Background contributions from prompt & nonprompt lepton productions
  - Prompt contributions ⇢ from MC simulations at NLO order in pQCD
  - Nonprompt contributions ⇢ estimated using data

- BDT-based signal & background discrimination

- Signal cross section extracted using binned maximum likelihood fit to the shape of the BDT classifier

event selection

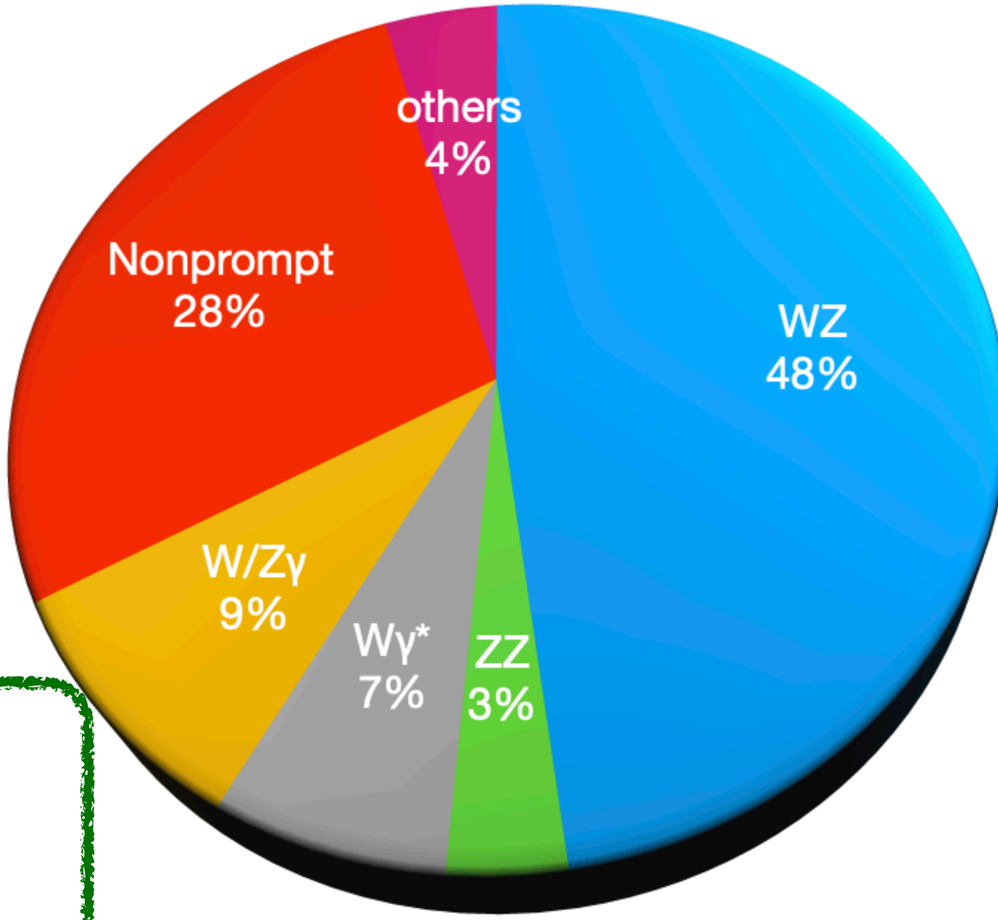
two leptons $e^{\pm}\mu^{\pm}$ or $\mu^{\pm}\mu^{\pm}$
$p_T^{\ell_1} > 25$ GeV, $p_T^{\ell_2} > 20$ GeV
$\lvert\eta_e\rvert < 2.5$, $\lvert\eta_\mu\rvert < 2.4$
$p_T^{\text{miss}} > 15$ GeV
$m_{\ell\ell} > 12$ GeV
$N_{\text{jets}} < 2$
$N_{\text{b-jets}} == 0$
veto on additional leptons
veto on hadronic τ leptons
$p_T^{\ell\ell} > 20$ GeV for $e^{\pm}\mu^{\pm}$ channel

Background processes

- Dominant contribution from WZ⇢3lν; one lepton from Z is lost
  - Kinematically very similar to the signal process

- Nonprompt lepton contributions (W+jets, QCD multijets, and semi-leptonic decays of $t\bar{t}$)

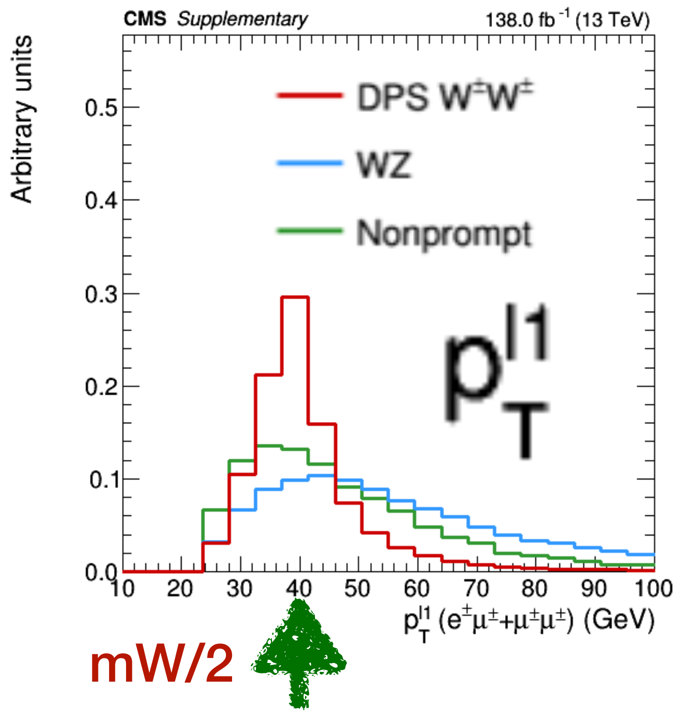
- Prompt lepton contributions also from:
  - Wγ*, ZZ, SPS $W^{\pm}W^{\pm}$, VVV, $t\bar{t}V$
  - Photon conversions (W/Zγ) Only in eμ channel
  - Lepton charge misidentification ($t\bar{t}$, DY, WW) (data-driven estimation)



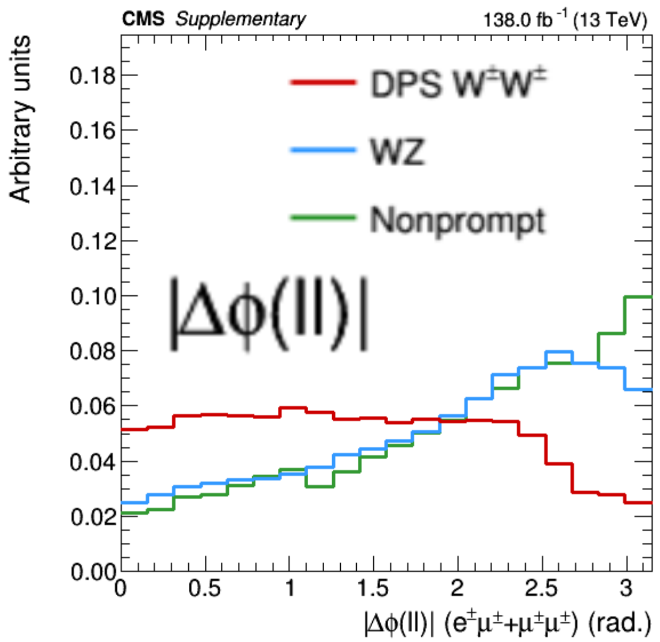
- Two separate BDT classifiers for WZ & nonprompt

BDT classifiers

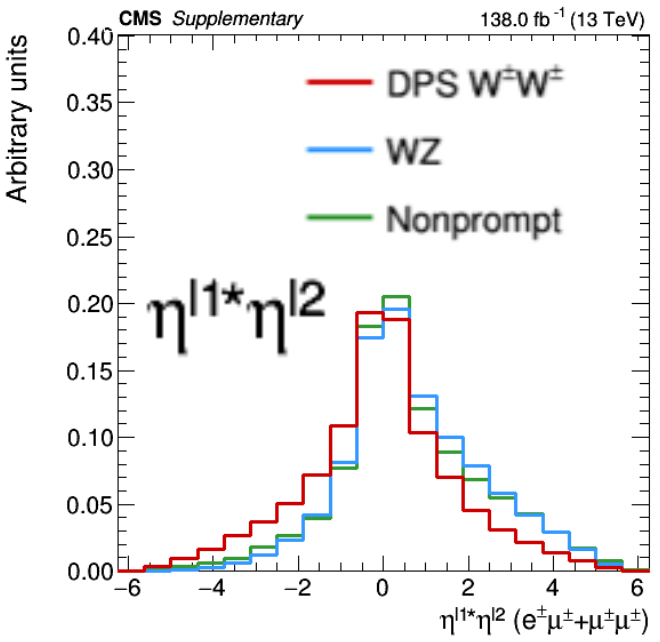
- Training variables ⇢ kinematic differences between (uncorrelated) signal & (correlated) backgrounds



mW/2



relatively flat signal



sensitive to correlations

training variables

$\mathrm{pT}_{l_{1,2}}$

$p_{\mathrm{T}}^{\mathrm{miss}}$

$\mathrm{M}_{\mathrm{T2}}^{\mathrm{ll}}$

$\eta_1 \times \eta_2$

$|\eta_1 + \eta_2|$

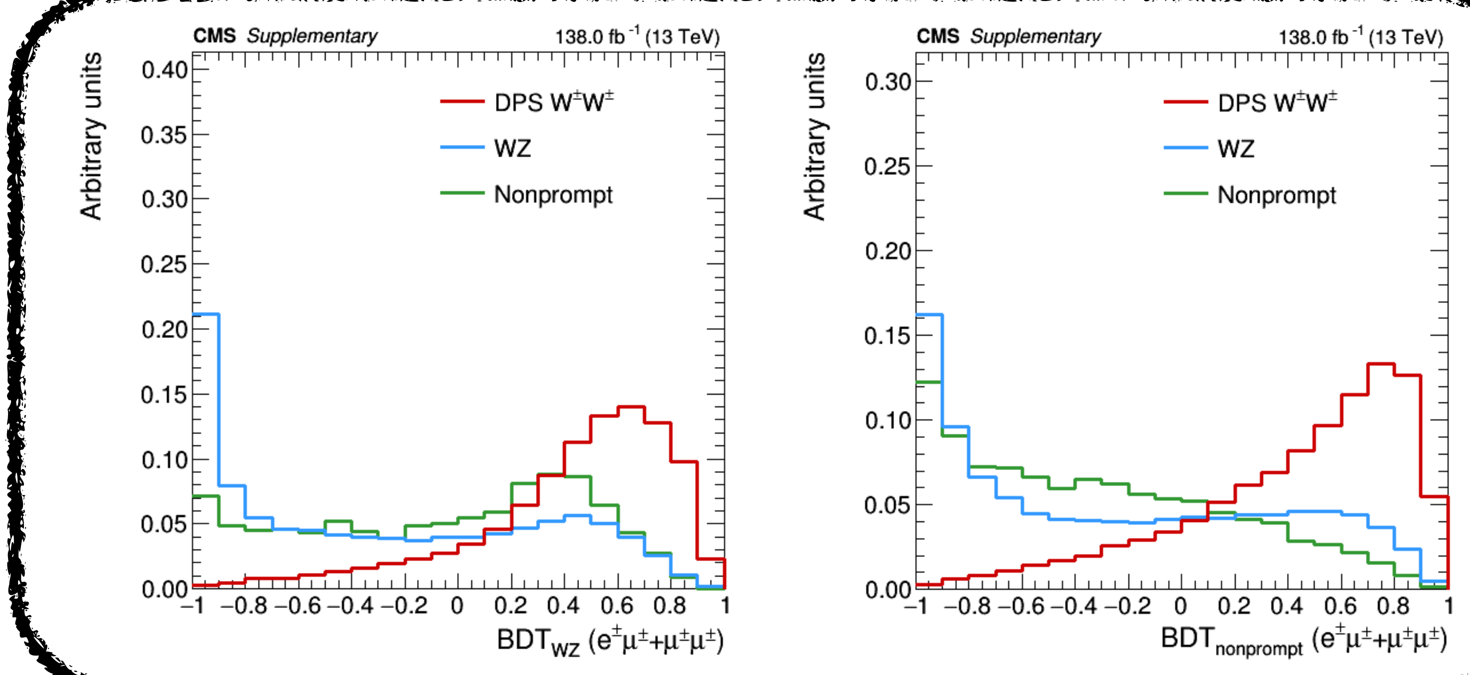
$\mathrm{m_T}(\mathrm{l}_1, p_{\mathrm{T}}^{\mathrm{miss}})$

$\mathrm{m_T}(\mathrm{l}_1, \mathrm{l}_2)$

$\Delta\phi(l_1, l_2)$

$\Delta\phi(l_2, p_{\mathrm{T}}^{\mathrm{miss}})$

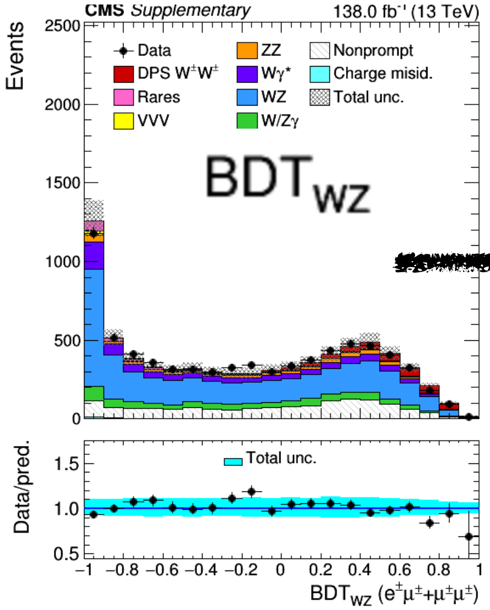
$\Delta\phi(l_1 l_2, l_2)$



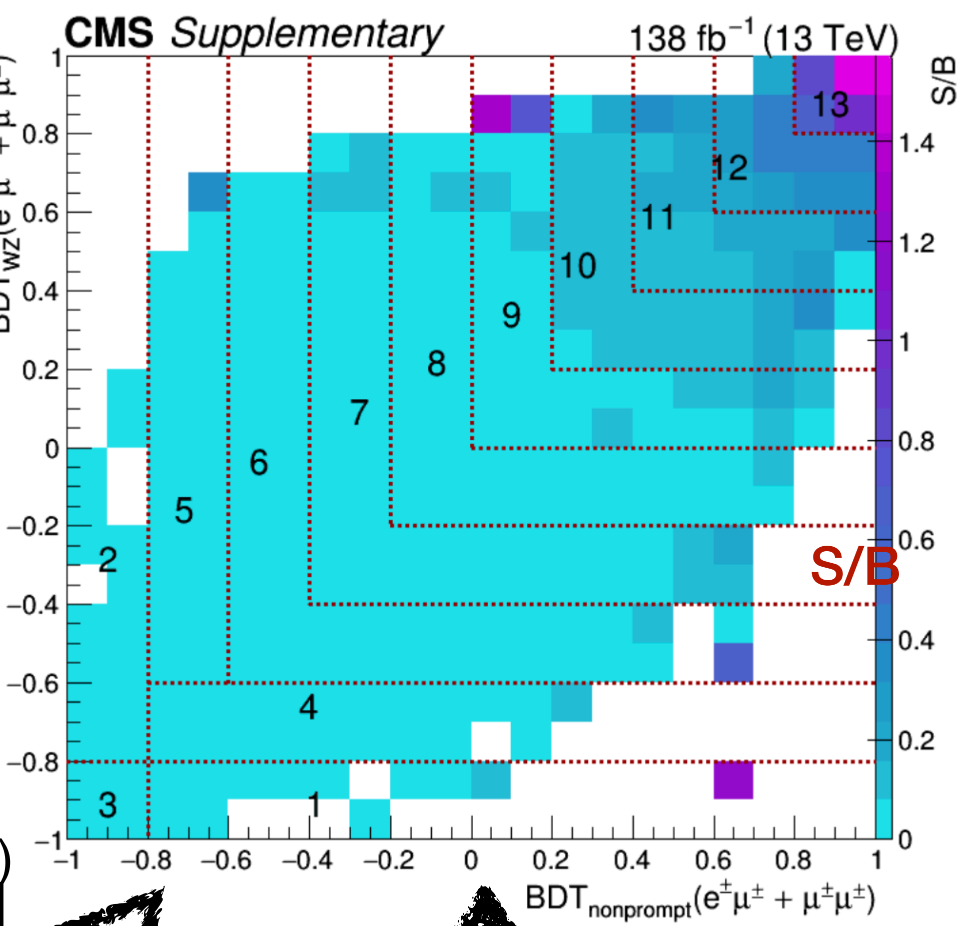
Statistical analysis

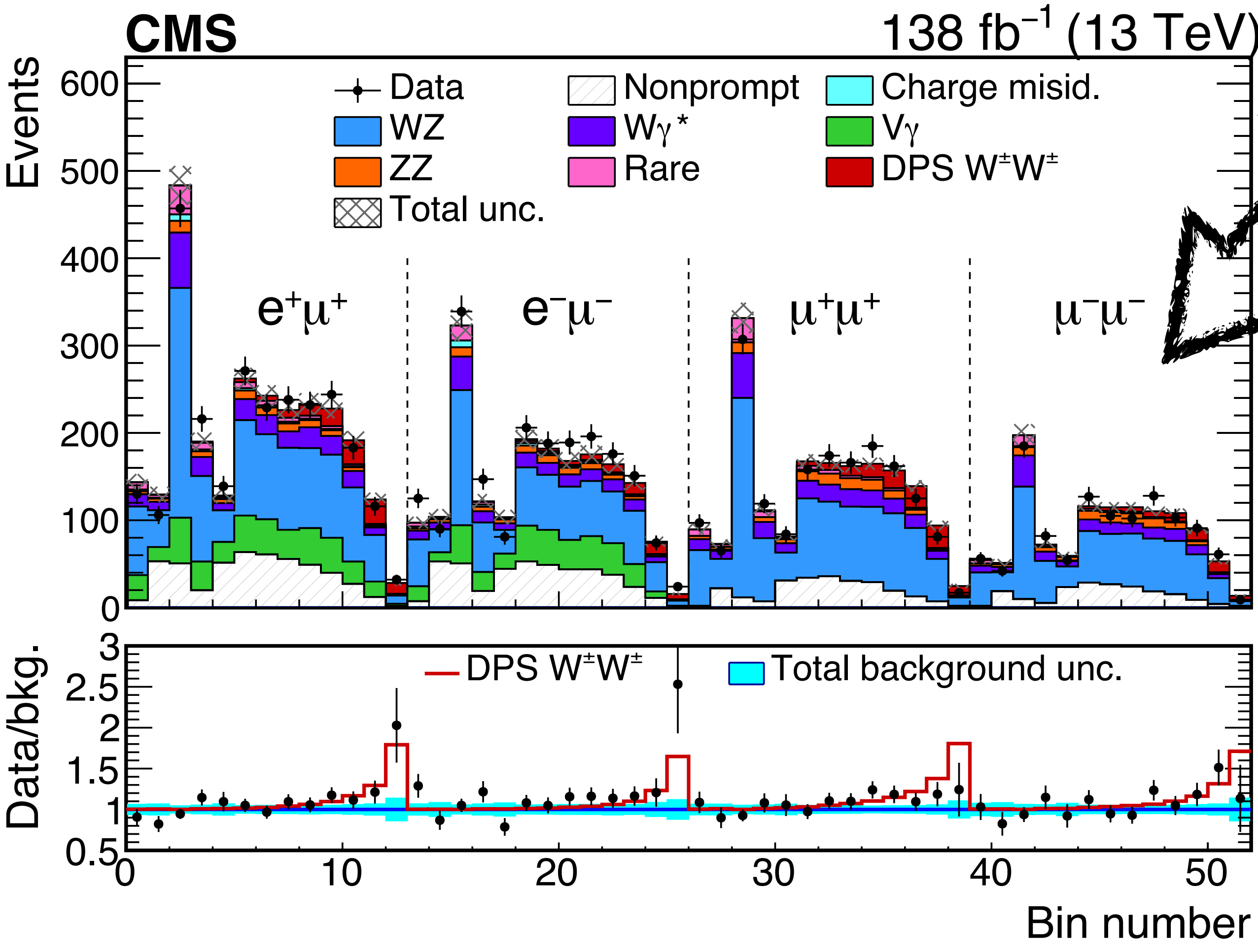
Two BDTs ⇢ 1D distribution

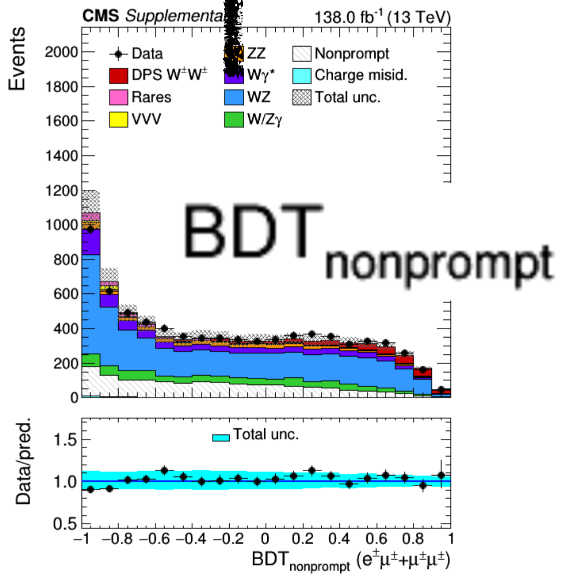
- Simultaneous fit to the shape of final BDT classifier in: **$e^+\mu^+$, $e^-\mu^-$, $\mu^+\mu^+$, $\mu^-\mu^-$**



high purity bins







signal visible in highest BDT bins

Results

First observation of W±W± via DPS with 6.2 s.d. (obs.)

Inclusive W±W± ⇢ 2l2ν cross section

$$80.7 \pm 11.2\,(\mathrm{stat})^{+9.5}_{-8.6}\,(\mathrm{syst}) \pm 12.1\,(\mathrm{model})\ \mathrm{fb}$$

from Herwig: difference in reconstruction

Fiducial cross section

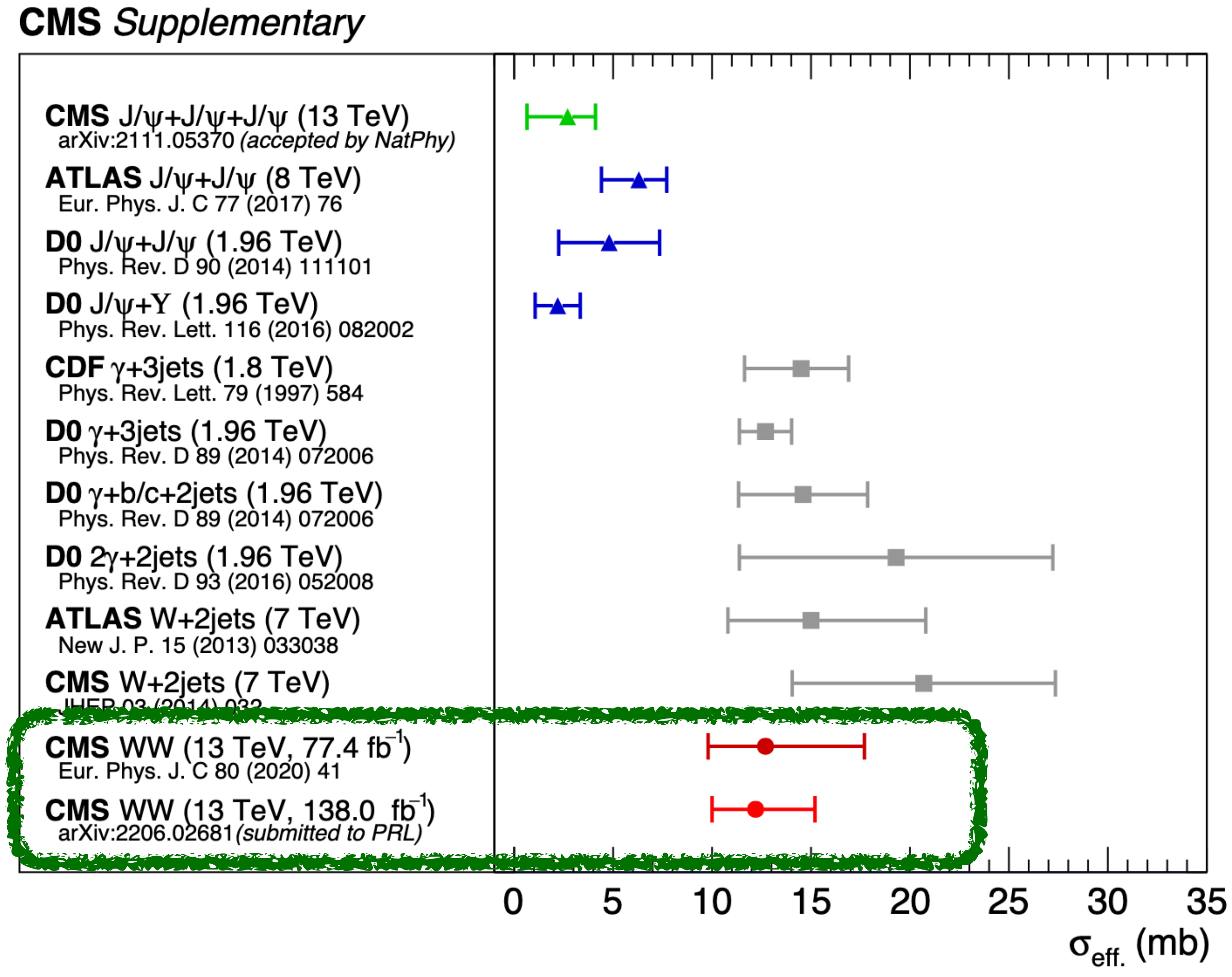
$$6.28 \pm 0.81\,(\mathrm{stat}) \pm 0.69\,(\mathrm{syst}) \pm 0.37\,(\mathrm{model})\ \mathrm{fb}$$

Efficiencies for leptons & generator acceptance

Using pocket formula

$$\sigma_{\mathrm{eff}} = 12.2^{+2.9}_{-2.2}\ \mathrm{mb}$$

- Consistent with previous measurement from the same channel and with the ones involving W bosons
- Improved precision



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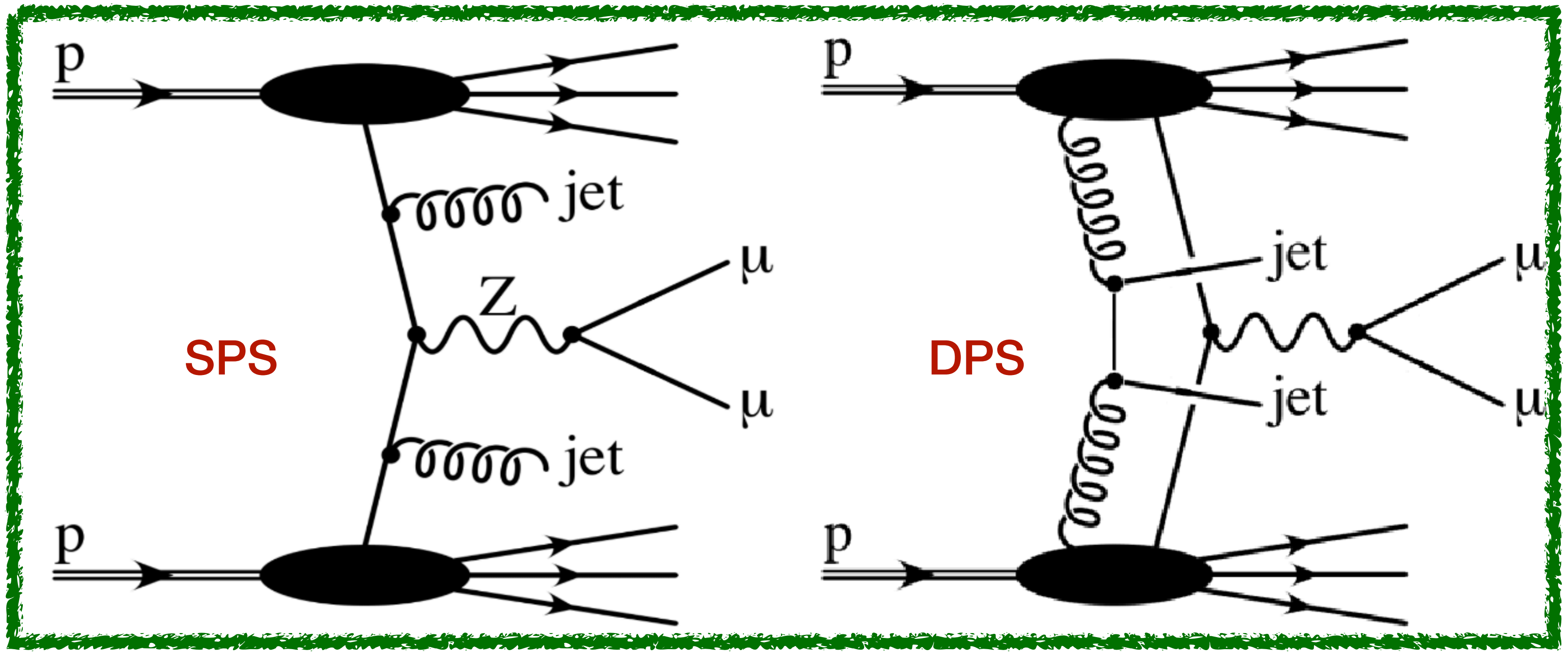
DPS with Z+jets

- Z+jets production excellent testing ground for theoretical predictions
  - Next-to-leading order matrix element generators interfaced to parton shower models ⇢ plenty of room for theoretical development, tuning etc
- Constitutes a non-negligible background for many SM measurements and new physics searches

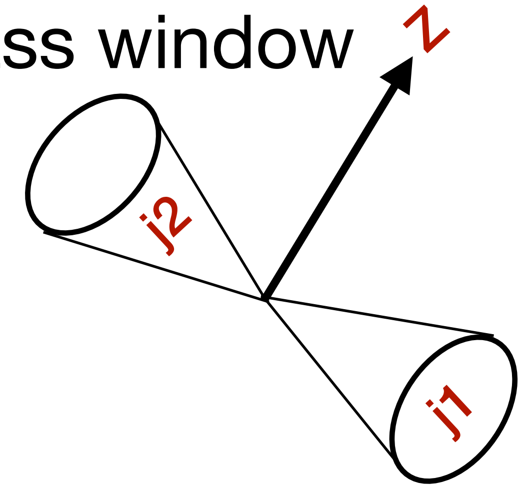
Z+jets events to explore observables sensitive to the presence of DPS

- Differential cross sections in Z+≥1 jet & Z+≥2 jets categories as function of DPS-sensitive observables



Analysis strategy

- 35.9 fb^{-1} of pp collisions data at 13 TeV
- Clean experimental signature with $Z \dashrightarrow \mu\mu$
- Events triggered using single muon triggers with pT > 24 GeV
  - Offline selection:
    - dimuon pair with pT > 27 GeV & |η| < 2.4 within a Z mass window
    - at least one jet with pT > 20 GeV and |η| < 2.4
- Signal modelled using LO & NLO simulation models
- Minor background contribution from $t\bar{t}$



DPS sensitive observables

Z+≥1jet

Δϕ(Z,j1) $$\Delta_{\mathrm{rel}} p_{\mathrm{T}}(\mathrm{Z}, j_1) = \frac{|\vec{p_{\mathrm{T}}}(\mathrm{Z}) + \vec{p_{\mathrm{T}}}(j_1)|}{|\vec{p_{\mathrm{T}}}(\mathrm{Z})| + |\vec{p_{\mathrm{T}}}(j_1)|}$$

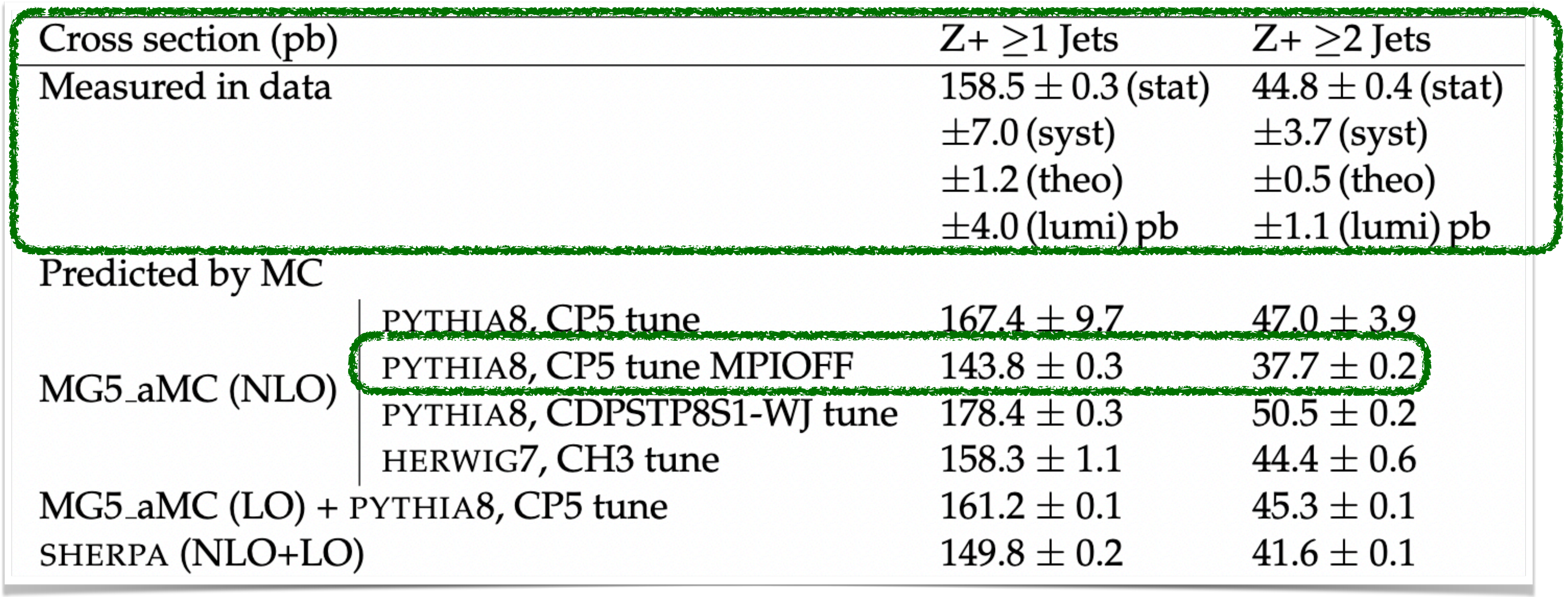
Δϕ(Z,dijet) Z+≥2jets

$$\Delta_{\mathrm{rel}} p_{\mathrm{T}}(j_1, j_2) = \frac{|\vec{p_{\mathrm{T}}}(j_1) + \vec{p_{\mathrm{T}}}(j_2)|}{|\vec{p_{\mathrm{T}}}(j_1)| + |\vec{p_{\mathrm{T}}}(j_2)|}$$

$$\Delta_{\mathrm{rel}} p_{\mathrm{T}}(\mathrm{Z}, \mathrm{dijet}) = \frac{|\vec{p_{\mathrm{T}}}(\mathrm{Z}) + \vec{p_{\mathrm{T}}}(\mathrm{dijet})|}{|\vec{p_{\mathrm{T}}}(\mathrm{Z})| + |\vec{p_{\mathrm{T}}}(\mathrm{dijet})|}$$

Fiducial cross section

Fiducial cross section measurement compared with different predictions



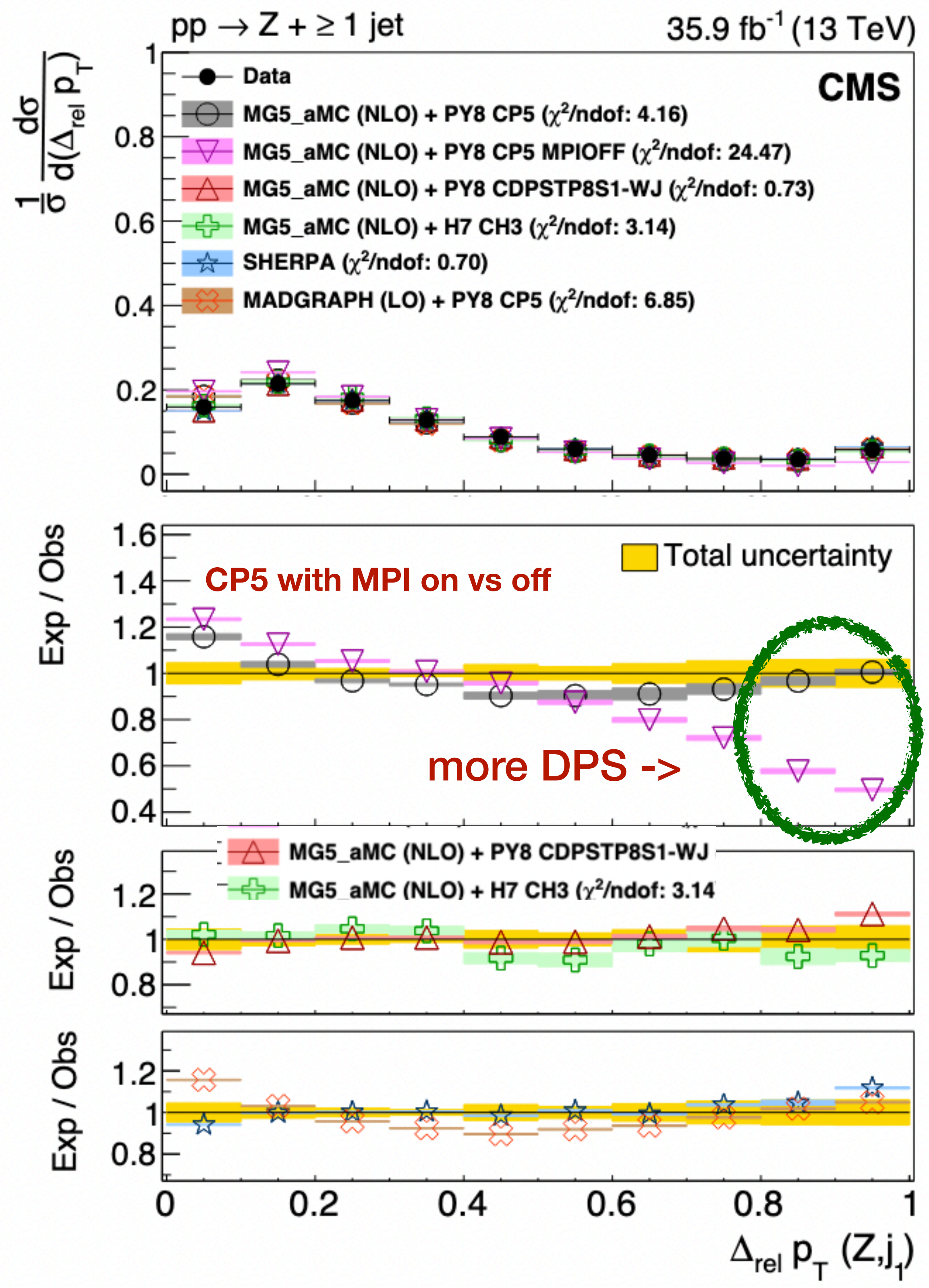
Cross section (pb)		$Z+\geq 1$ Jets	$Z+\geq 2$ Jets
Measured in data		158.5 ± 0.3 (stat) ± 7.0 (syst) ± 1.2 (theo) ± 4.0 (lumi) pb	44.8 ± 0.4 (stat) ± 3.7 (syst) ± 0.5 (theo) ± 1.1 (lumi) pb
Predicted by MC			
MG5_aMC (NLO)	PYTHIA8, CP5 tune	167.4 ± 9.7	47.0 ± 3.9
	PYTHIA8, CP5 tune MPIOFF	143.8 ± 0.3	37.7 ± 0.2
	PYTHIA8, CDPSTP8S1-WJ tune	178.4 ± 0.3	50.5 ± 0.2
	HERWIG7, CH3 tune	158.3 ± 1.1	44.4 ± 0.6
MG5_aMC (LO) + PYTHIA8, CP5 tune		161.2 ± 0.1	45.3 ± 0.1
SHERPA (NLO+LO)		149.8 ± 0.2	41.6 ± 0.1

- CP5 tune with MPI off underestimates the measurement by ~10 (16)% for $Z+\geq 1(2)$ jet events
- DPS-specific tune over predicts the cross section by 10%
- Well described by Sherpa, MG+Py8 (CP5) & MG+Hw7

Differential cross section

Normalized differential cross section

- MG+Py8 with MPI-off underestimates the measurement by ~ 50% in the MPI-dominated region
- MG+Py8 (CP5) overestimates (up to 20%) in the SPS-dominated region
- MG+Py8 with DPS-specific tune describes the measurement well
- MG+Hw7 and Sherpa describe the distribution well within uncertainties



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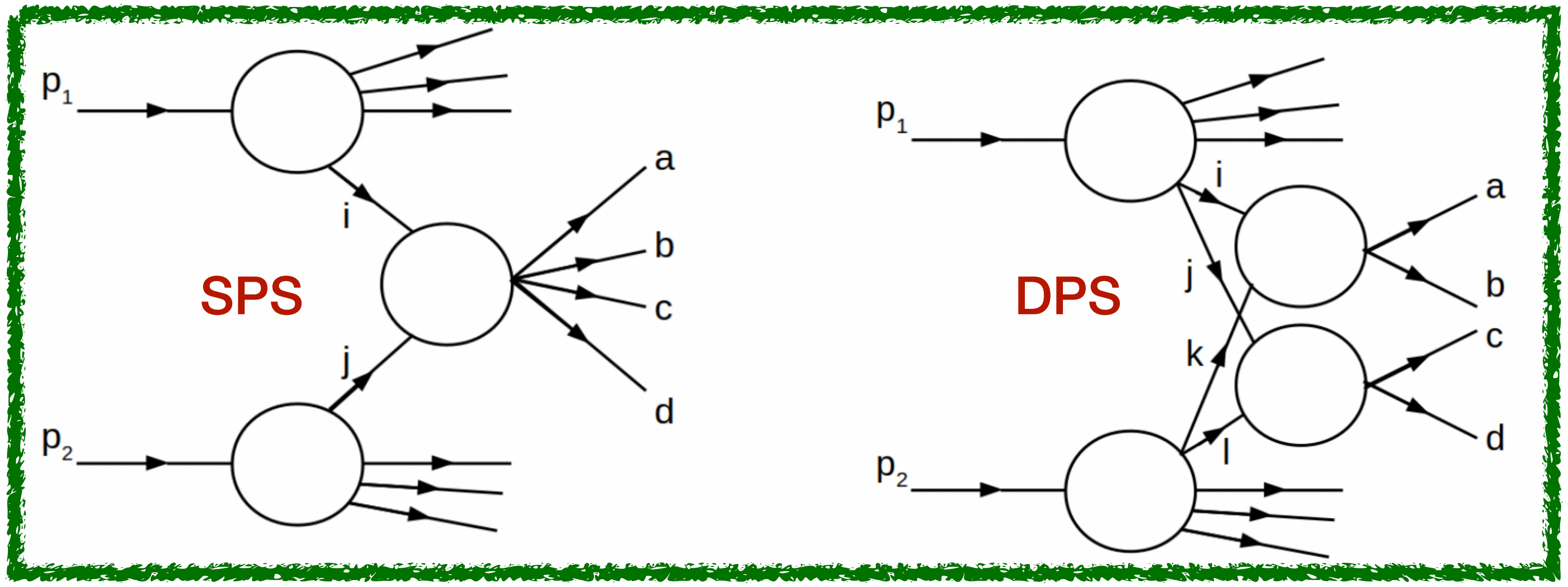
DPS with 4jets

- Jet production is one of the most abundant processes at LHC
- Low transverse momentum and forward/backward jets allow for the low-x region to be probed ⇢ important information for MC tuning

Four jets production via SPS vs two independent dijets via DPS

(simplest scenario)

- Multiple simulation setups compared with data using DPS-sensitive variables

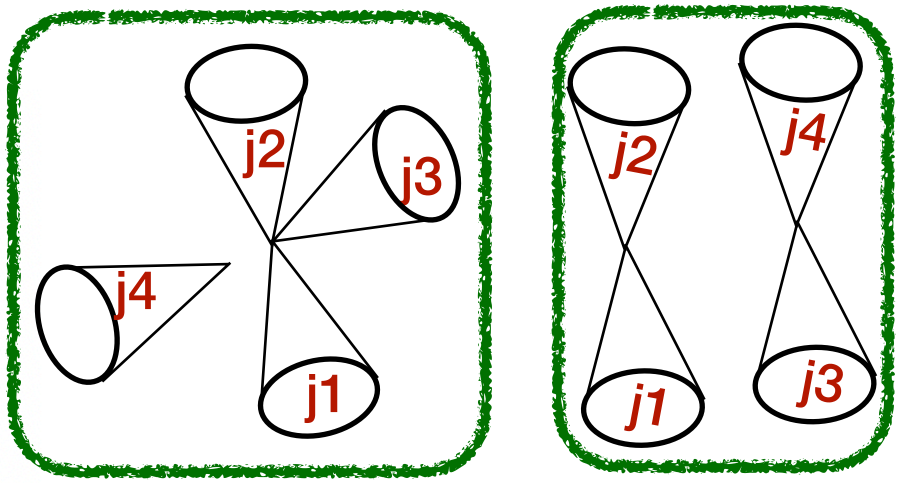


- DPS cross section is extracted using template fit method
- σ_{eff} extraction using pocket formula

Analysis strategy

- 42 nb^{-1} of low-pileup ($\langle\mu\rangle = 1.3$) pp collisions data at 13 TeV selected using single-jet triggers
- Offline selection:
  - Exactly one primary vertex
  - 4 jets with asymmetric pT cuts going down to 20 GeV
- SPS template from MC, DPS from random mixing of single jet data events

angular observables tested for DPS-sensitivity



Azimuthal angle of the soft jet pair: $\Delta\phi_{Soft} = |\phi_3 - \phi_4|$

Combined minimum angle of 3 jets: $\Delta\phi_{3j}^{min} = min_{ijk}\{|\phi_i - \phi_j| + |\phi_j - \phi_k|\}$

Transversal momentum balance of the soft jet pair: $\Delta p_{T,soft} = \frac{|\vec{p}_{T,3}| + |\vec{p}_{T,4}|}{|\vec{p}_{T,3} + \vec{p}_{T,4}|}$

Maximum difference in pseudorapidity: $\Delta Y = max_{ij}\{|\eta_i - \eta_j|\}$

Azimuthal angle of the most remote jets: $\phi_{ij} = |\phi_i - \phi_j|$ for $\Delta Y = max_{ij}\{|\eta_i - \eta_j|\}$

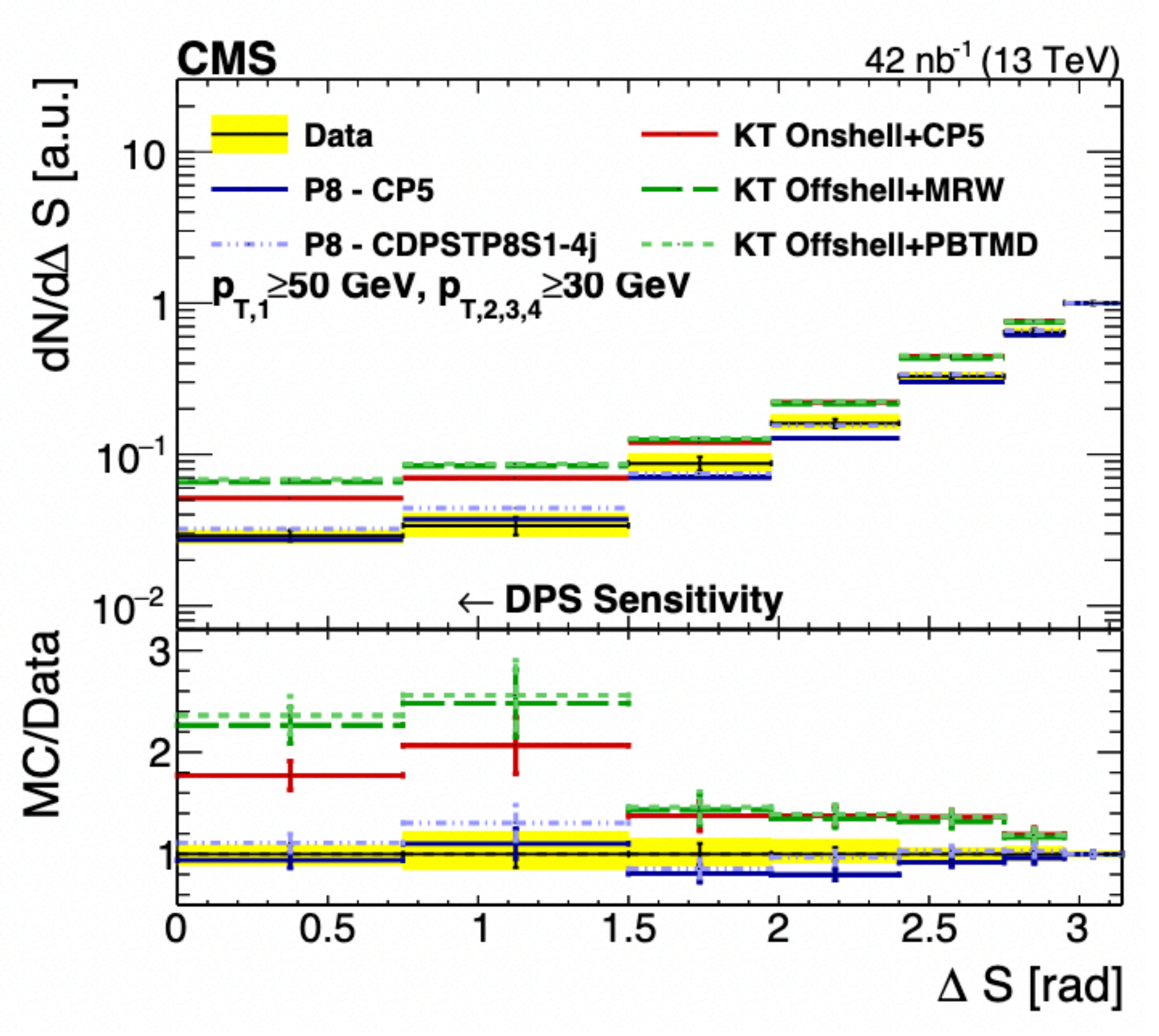
Azimuthal angle between the hardest and the softest jet pair $\Delta S = \arccos\left(\frac{(\vec{p}_{T,1} + \vec{p}_{T,2}) \cdot (\vec{p}_{T,3} + \vec{p}_{T,4})}{|\vec{p}_{T,1} + \vec{p}_{T,2}| \cdot |\vec{p}_{T,3} + \vec{p}_{T,4}|}\right)$

most sensitive to DPS

Results

- Distribution normalized to the last bin (having lowest DPS contribution)

- Py8 with CDPSTP8S1-4j tune describes the data well



$$\sigma^{\text{data}}(\Delta S) = f_{\text{DPS}}\sigma^{\text{data}}_{\text{DPS}}(\Delta S) + (1-f_{\text{DPS}})\sigma^{\text{MC}}_{\text{SPS}}(\Delta S)$$

↓

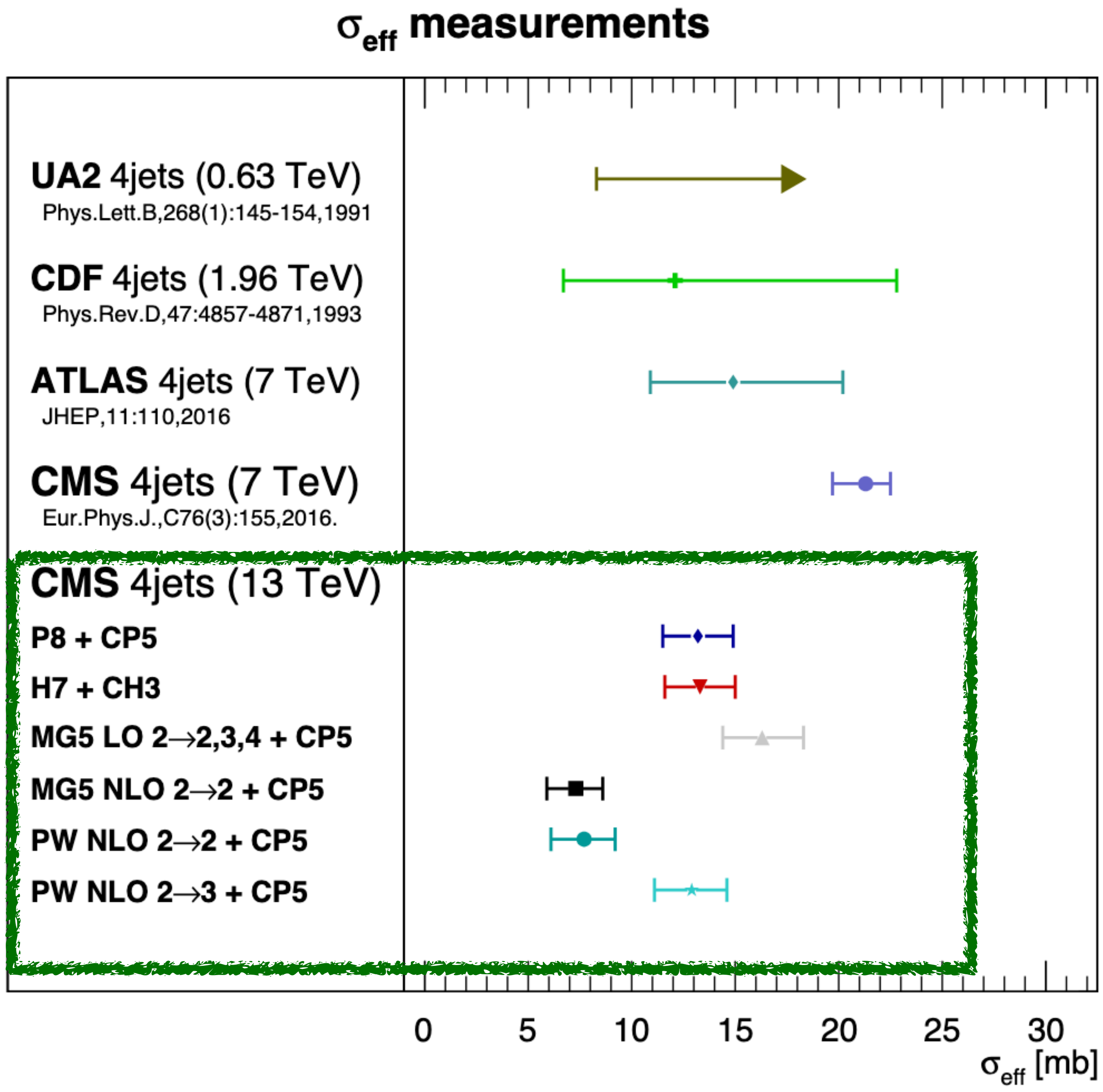
$$\sigma^{\text{DPS}}_{\text{A,B}} = f_{\text{DPS}}\int \sigma^{\text{data}}(\Delta S)\,\text{d}(\Delta S).$$

→ Pocket formula → σ_{eff}

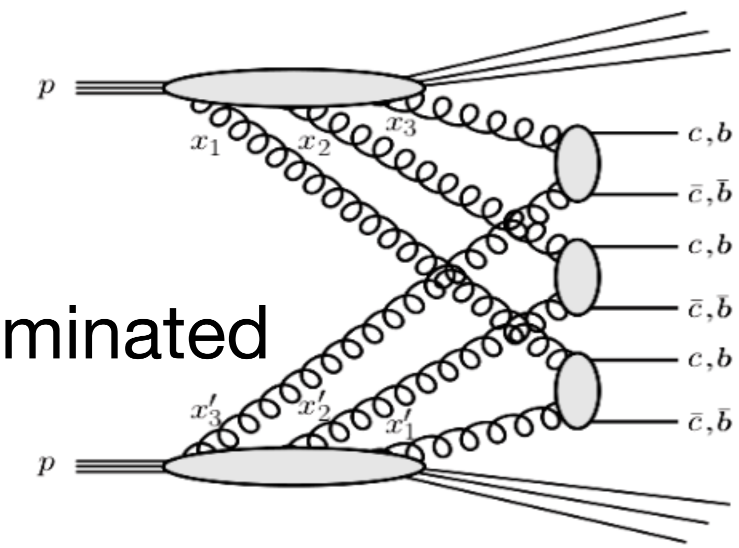
Effective cross section

Excellent sensitivity to different models used to model SPS

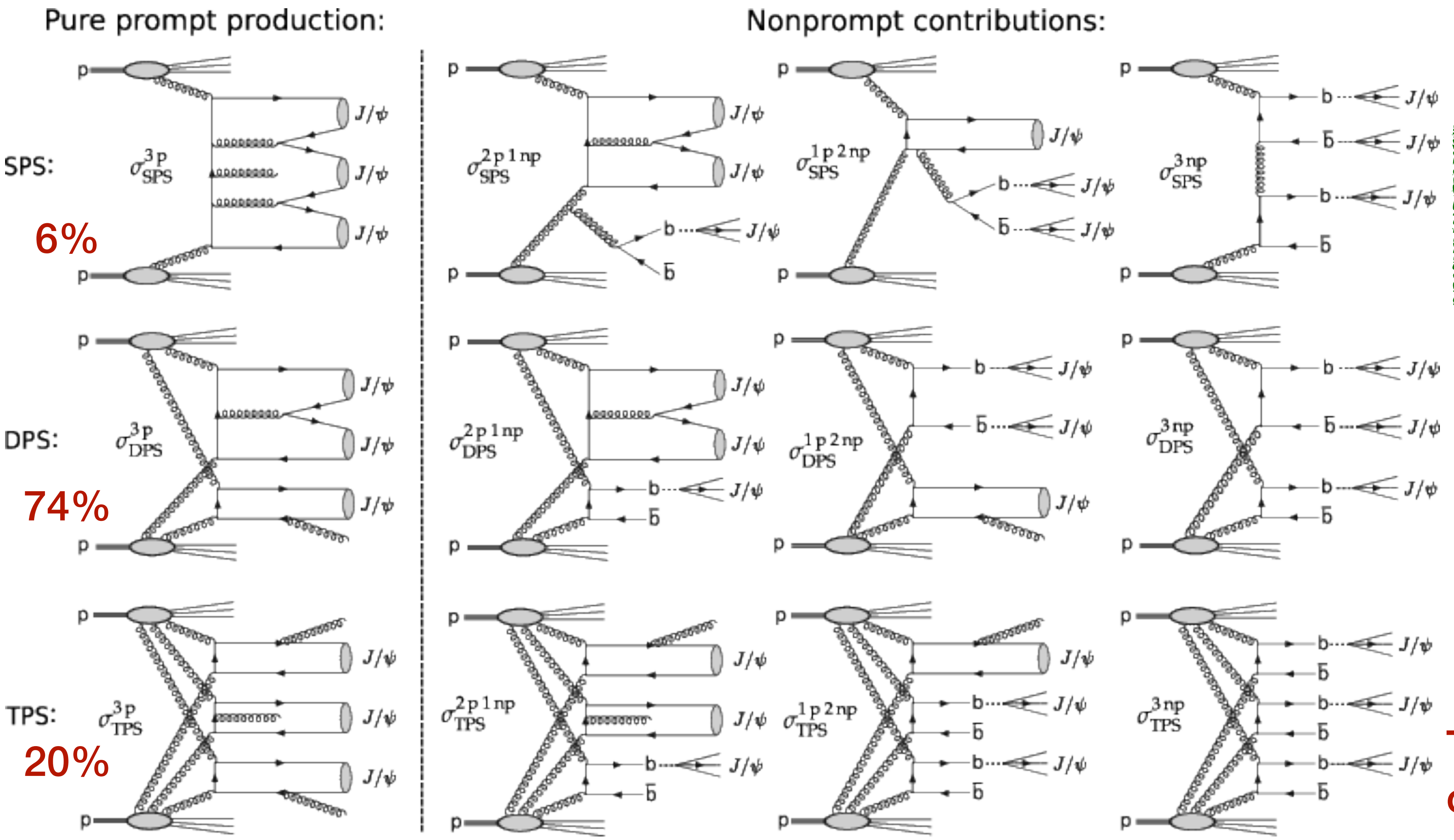
- Extracted σ_{eff} agrees with UA2, CDF, and ATLAS experiments
- Models using a 2→2 ME with older UE tunes ⇢ need the smallest DPS contribution
- NLO models yield lowest values of σ_{eff} ⇢ need even more DPS



Triple J/ψ production



- First study of inclusive triple J/ψ production & TPS
- Measured cross section ⇢ contributions from DPS (dominated contribution) + TPS + SPS (minor contribution)
- Novel approach to extract DPS effective cross section



$$\boxed{\sigma^{\rm NPS}_{f_1\cdots f_N} = \frac{m}{N!}\,\frac{\prod_{i=1}^{N}\sigma^{\rm SPS}_{f_i}}{(\sigma_{\rm eff,N})^{N-1}}}$$

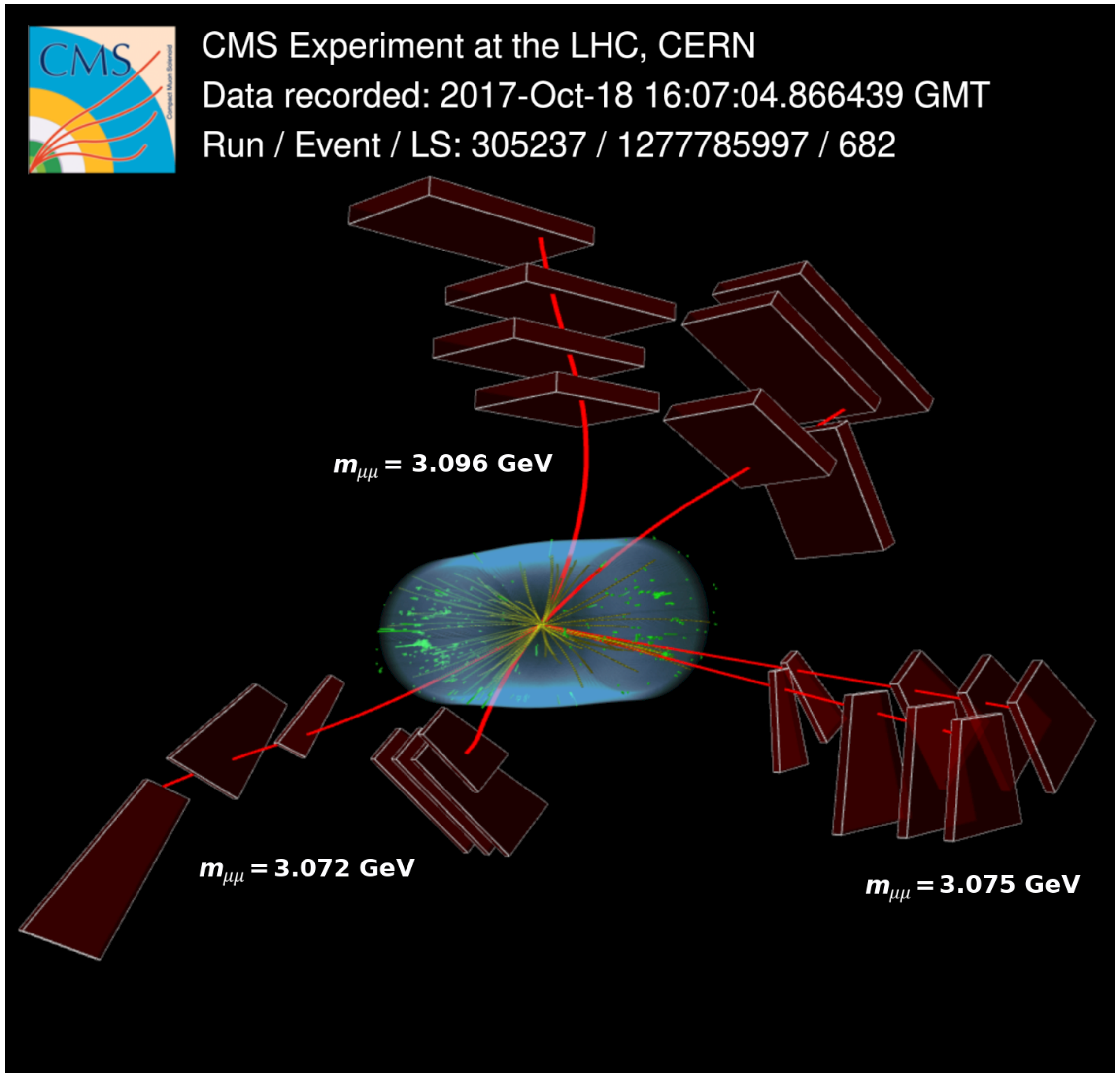
Pocket formula

$$\boxed{\sigma^2_{\rm eff,TPS} = \left[\int d^2b\, T^3(\mathbf{b})\right]^{-1}}$$

T(b): transverse hadron-hadron overlap function

Event selection

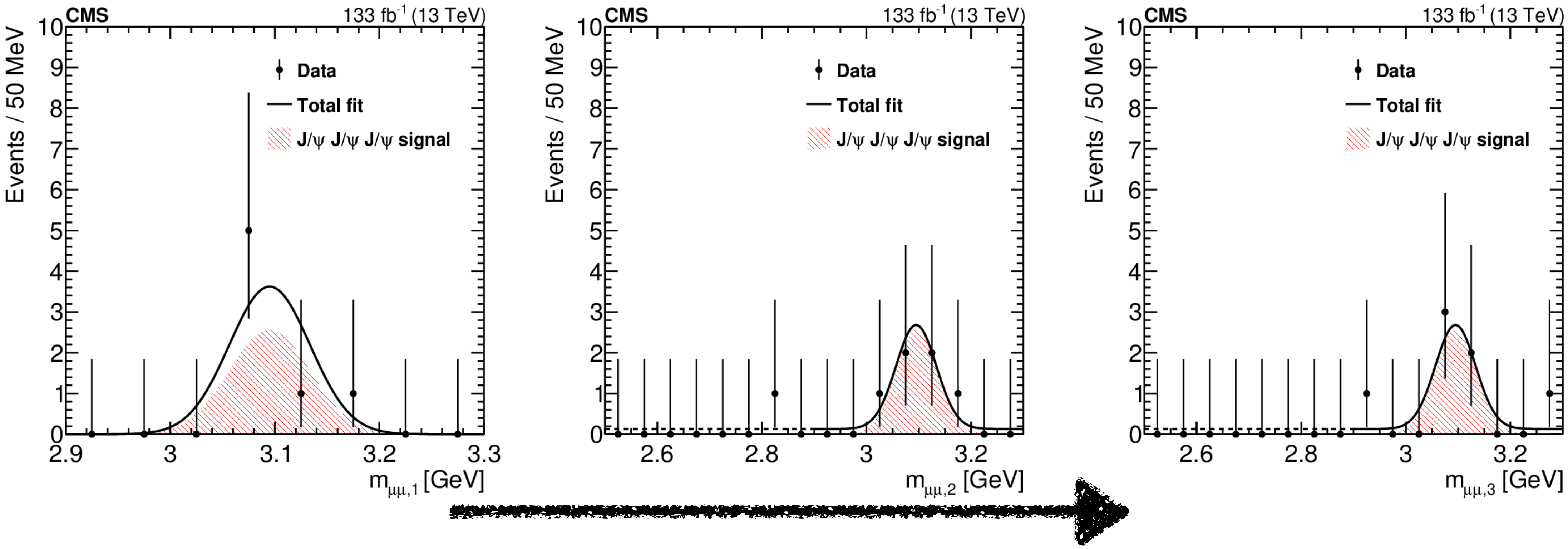
- pp collisions at 13 TeV with integrated luminosity 133 fb^{-1}
- Experimentally clean and pure final states with (six) muons
- Triple muon trigger (84% efficient):
  - $p_T > 3.5$ GeV (barrel), $p_T > 2.5$ GeV (endcaps)
  - at least one $\mu^\mp\mu^\pm$ with $2.8 < m_{\mu\mu} < 3.35$ GeV from same vertex
- Offline selection (efficiency = 78%):
  - $\mu^\mp\mu^\pm$ pairs from same primary vertex with $2.9 < m_{\mu\mu} < 3.3$ GeV
  - J/ψ candidates: $p_T > 6.5$ GeV & $|y| < 2.4$



- Background: semi-leptonic decays of heavy flavour & DY
- 6 events in data after selection

Signal extraction

- 3D un-binned extended maximum likelihood fit to $m_{\mu\mu}$ within 2.9-3.3 GeV
- Signal modelled using Gaussian with resolution fixed to MC & mean to PDG J/ψ mass
- Exponential background



decreasing pTμμ

- N(signal) = $5.0^{+2.6}_{-1.9}$, N(background) = $1.0^{+1.4}_{-0.8}$
- Extended mass region, down to 2.3 GeV to confirm background estimation

Results

$$\boxed{\sigma(\mathrm{pp} \to \mathrm{J}/\psi\mathrm{J}/\psi\mathrm{J}/\psi\,\mathrm{X}) = 272^{+141}_{-104}\,(\mathrm{stat}) \pm 17\,(\mathrm{syst})\,\mathrm{fb}}$$

Signal significance: 6.7 s.d. (obs.) 5.5 s.d. (exp.)

First observation of triple J/ψ

Measured cross section = predicted cross section for SPS+DPS+TPS

$$\begin{aligned}
\sigma^{3\mathrm{J}/\psi}_{\mathrm{tot}} &= \sigma^{3\mathrm{J}/\psi}_{\mathrm{SPS}} + \sigma^{3\mathrm{J}/\psi}_{\mathrm{DPS}} + \sigma^{3\mathrm{J}/\psi}_{\mathrm{TPS}} = \\
&= \left(\sigma^{3\,\mathrm{p}}_{\mathrm{SPS}} + \sigma^{2\mathrm{p}1\mathrm{np}}_{\mathrm{SPS}} + \sigma^{1\mathrm{p}2\mathrm{np}}_{\mathrm{SPS}} + \sigma^{3\,\mathrm{np}}_{\mathrm{SPS}}\right) + \\
&+ \left(\sigma^{3\,\mathrm{p}}_{\mathrm{DPS}} + \sigma^{2\mathrm{p}1\mathrm{np}}_{\mathrm{DPS}} + \sigma^{1\mathrm{p}2\mathrm{np}}_{\mathrm{DPS}} + \sigma^{3\,\mathrm{np}}_{\mathrm{DPS}}\right) + \left(\sigma^{3\,\mathrm{p}}_{\mathrm{TPS}} + \sigma^{2\mathrm{p}1\mathrm{np}}_{\mathrm{TPS}} + \sigma^{1\mathrm{p}2\mathrm{np}}_{\mathrm{TPS}} + \sigma^{3\,\mathrm{np}}_{\mathrm{TPS}}\right)
\end{aligned}$$

factorize DPS & TPS cross sections

$$\sigma^{3\mathrm{J}/\psi}_{\mathrm{DPS}} = \frac{m_1\left(\sigma^{2\mathrm{p}}_{\mathrm{SPS}}\sigma^{1\mathrm{p}}_{\mathrm{SPS}} + \sigma^{2\mathrm{p}}_{\mathrm{SPS}}\sigma^{1\mathrm{np}}_{\mathrm{SPS}} + \sigma^{1\mathrm{p}}_{\mathrm{SPS}}\sigma^{1\mathrm{p}1\mathrm{np}}_{\mathrm{SPS}} + \sigma^{1\mathrm{p}1\mathrm{np}}_{\mathrm{SPS}}\sigma^{1\mathrm{np}}_{\mathrm{SPS}} + \sigma^{1\mathrm{p}}_{\mathrm{SPS}}\sigma^{2\mathrm{np}}_{\mathrm{SPS}} + \sigma^{2\mathrm{np}}_{\mathrm{SPS}}\sigma^{1\mathrm{np}}_{\mathrm{SPS}}\right)}{\sigma_{\mathrm{eff,DPS}}}$$

$$\sigma^{3\mathrm{J}/\psi}_{\mathrm{TPS}} = \frac{m_3\left(\left(\sigma^{1\mathrm{p}}_{\mathrm{SPS}}\right)^3 + \left(\sigma^{1\mathrm{np}}_{\mathrm{SPS}}\right)^3\right) + m_2\left(\left(\sigma^{1\mathrm{p}}_{\mathrm{SPS}}\right)^2\sigma^{1\mathrm{np}}_{\mathrm{SPS}} + \sigma^{1\mathrm{p}}_{\mathrm{SPS}}\left(\sigma^{1\mathrm{np}}_{\mathrm{SPS}}\right)^2\right)}{\sigma^2_{\mathrm{eff,TPS}}},$$

- Predictions for SPS cross sections from HELAC-ONIA & MG
- In absence of parton correlations: $\sigma_{\mathrm{eff,TPS}} = (0.82 \pm 0.11) \times \sigma_{\mathrm{eff,DPS}}$

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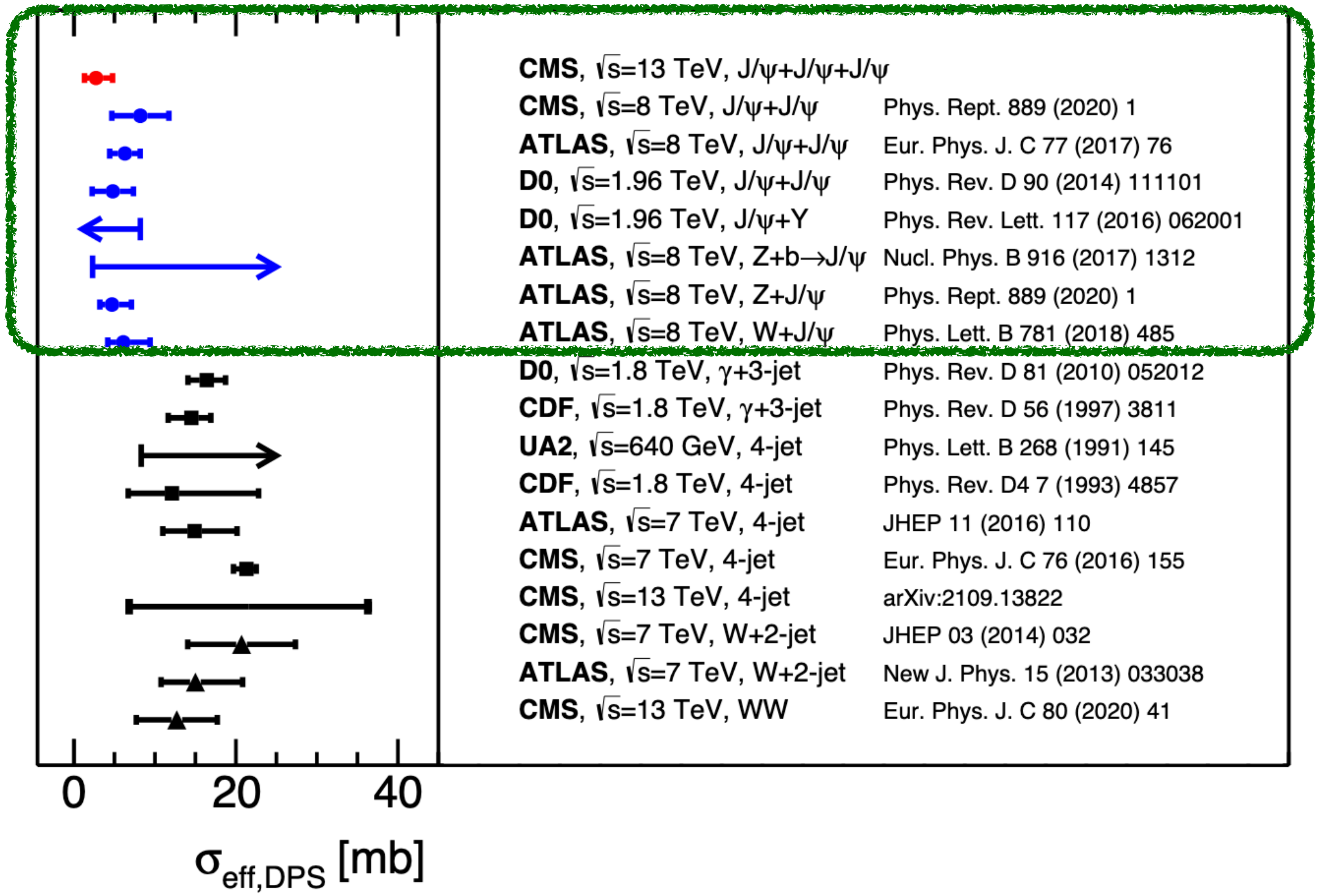
$$\boxed{\sigma_{\mathrm{eff,DPS}} = 2.7^{+1.4}_{-1.0}\,(\mathrm{exp})^{+1.5}_{-1.0}\,(\mathrm{theo})\,\mathrm{mb}}$$

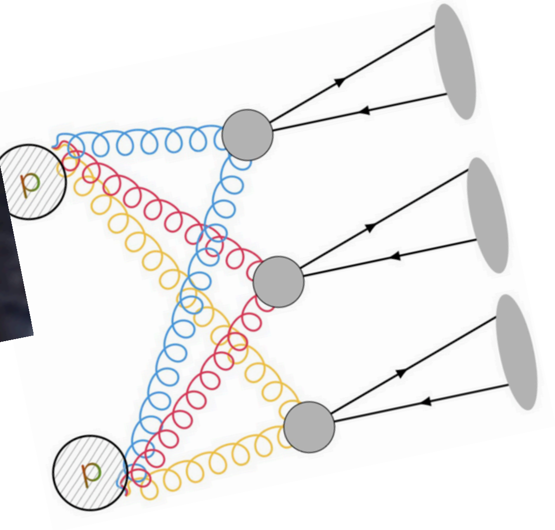
Summary

- σ_{eff} consistent with existing quarkonia measurements from DPS events
- σ_{eff} obtained from quarkonia measurements (x~ 0.005) favor a smaller value compared to the final states with W/Z (x~0.01)

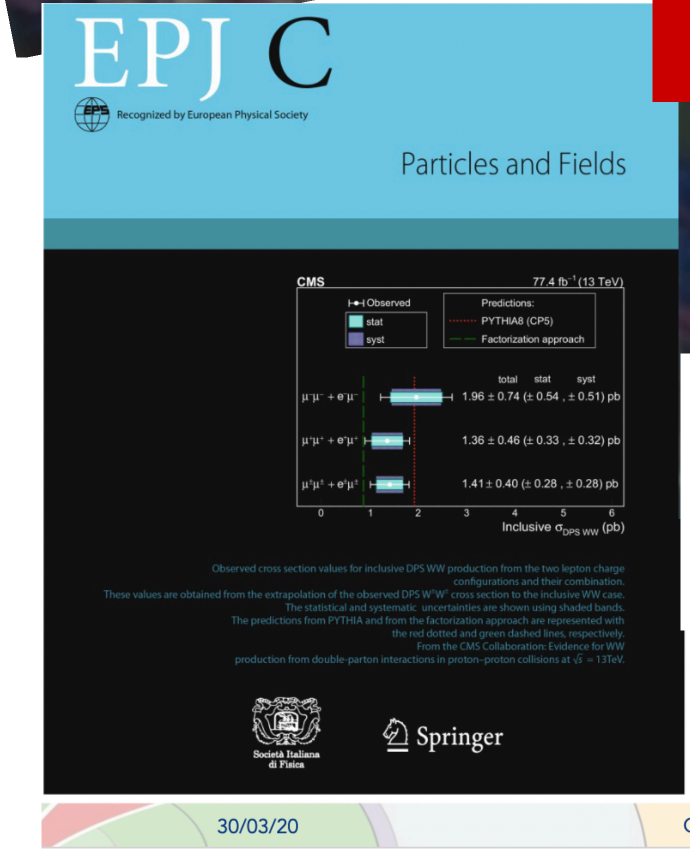


- For a given scale of process, different measurements from different experiments agree within uncertainties
- Differences in measured σ_{eff} for gluon & quarks induced processes ⇢ can we improve factorisation approach?
  - Inclusion of parton correlations in MC event generators
    - dShower is just the first step!
  - Many theoretical advancements but need experimental verification

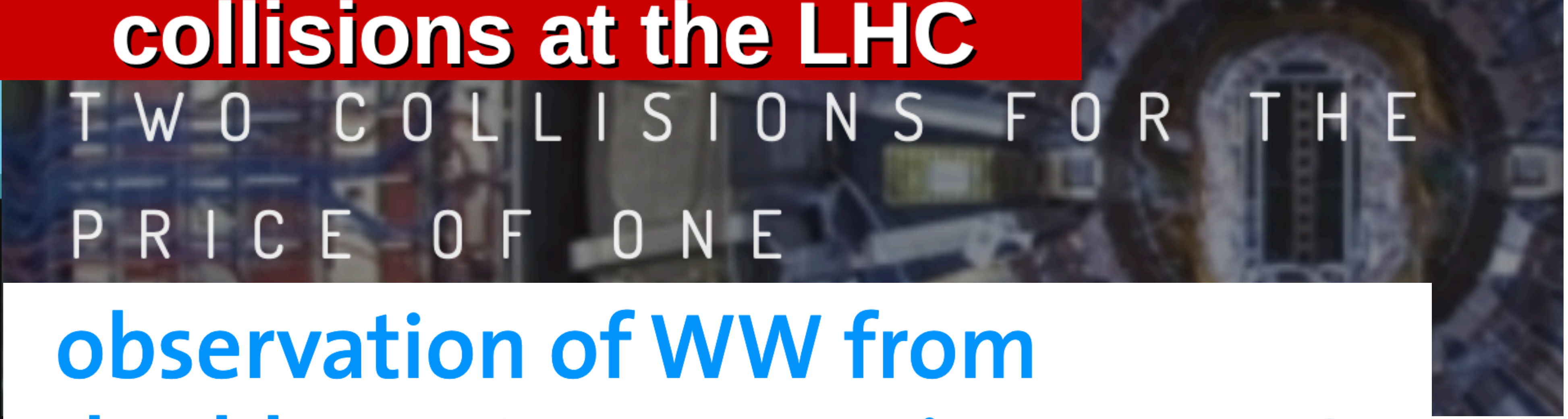
quick reads :)



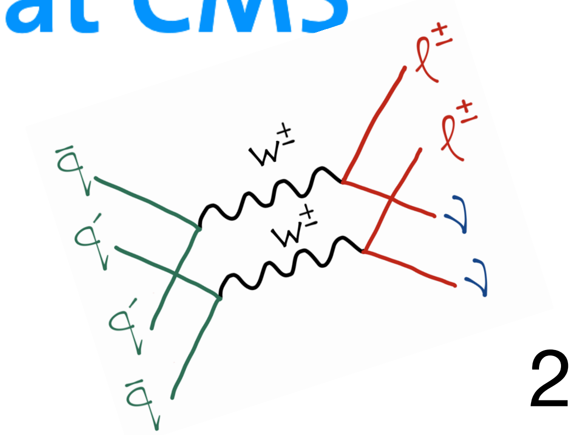
Observation of triple-J/Ψ production in p-p collisions at the LHC



Observed cross section values for inclusive DPS WW production from the two lepton charge configurations and their combination.
These values are obtained from the extrapolation of the observed DPS $W^\pm W^\pm$ cross section to the inclusive WW case.
The statistical and systematic uncertainties are shown using shaded bands.
The predictions from PYTHIA and from the factorization approach are represented with the red dotted and green dashed lines, respectively.
From the CMS Collaboration: Evidence for WW production from double-parton interactions in proton–proton collisions at $\sqrt{s} = 13$TeV.



observation of WW from double parton scattering at CMS



https://cms.cern/news/trio-jps-particles-one-go#

https://cms.cern/news/two-collisions-price-one

backup

DPS pocket formula

Strategy: assume that the two hard interactions are independent

$$\sigma^{\mathrm{DPS}}_{AB} = \frac{m}{2}\sum_{i,j,k,l}\int \overset{\text{double PDFs}}{\boxed{\Gamma^{ij}(x_1,x_2;b;Q_A^2,Q_B^2)}}\times\overset{\text{partonic cross sections}}{\boxed{\hat\sigma_A^{ik}(x_1,x_1',Q_A^2)\hat\sigma_B^{jl}(x_2,x_2',Q_B^2)}}\times$$

$$\boxed{\Gamma^{kl}(x_1',x_2';b;Q_A^2,Q_B^2)}\,dx_1dx_2dx_1'dx_2'\boxed{d^2b}$$

transverse distance
Between partons

decompose dPDFs in longitudinal & transverse components

$$\Gamma^{ij}(x_1,x_2;b;Q_A^2,Q_B^2) = D^{ij}(x_1,x_2;Q_A^2,Q_B^2)\boxed{F(b)}$$

transverse parton density → considered same
for all pair of partons

further assume longitudinal factorization

$$D^{ij}(x_1,x_2;Q_A^2,Q_B^2) = \boxed{D^i(x_1;Q_A^2)D^j(x_2;Q_B^2)}$$

PDFs

Simplified expression for σ^{DPS} ⇢ pocket formula

$$\boxed{\sigma^{\mathrm{DPS}}_{AB} = \frac{m}{2}\frac{\sigma_A\sigma_B}{\sigma_{\mathrm{eff}}}\ ; \quad \sigma_{\mathrm{eff}} = \left[\int d^2b(F(b))^2\right]^{-1}}$$

m=1 if A=B else 2

$\sigma_{A,B}$: SPS cross sections

Used in existing phenomenological models

σ_{eff}: effective cross section for DPS

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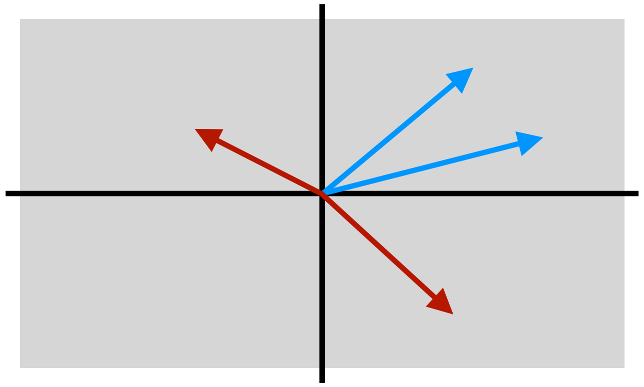
DPS simulation models

- LO samples from Pythia/Herwig ⇢ based on “Eikonal” model
  - SPS ⇢ nPS, where N per event follows a Poisson distribution
  - Some differences between Herwig & Pythia as how the two interactions are correlated and to what extent
- Latest dPDF-based simulations (dShower) for $W^{\pm}W^{\pm}$ production
  - Includes transverse parton correlations & parton splitting effects

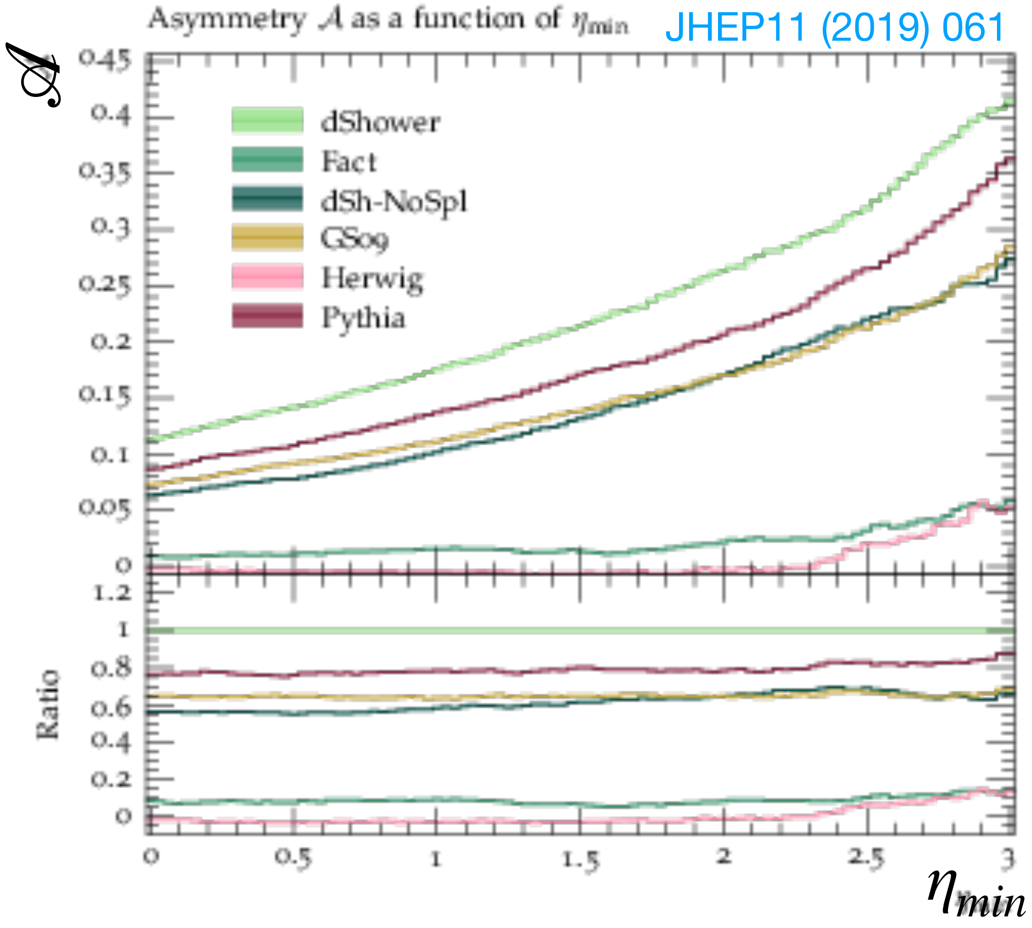
$\mathscr{A}$: leptons in different or same detector hemispheres

$$\mathscr{A} = \frac{\boxed{\sigma(\eta_{l1} \times \eta_{l1} < 0)} - \boxed{\sigma(\eta_{l1} \times \eta_{l1} > 0)}}{\sigma(\eta_{l1} \times \eta_{l1} < 0) + \sigma(\eta_{l1} \times \eta_{l1} > 0)}$$



$\mathscr{A} = 0$ ⇢ uncorrelated

$\mathscr{A} > 0$ ⇢ correlated



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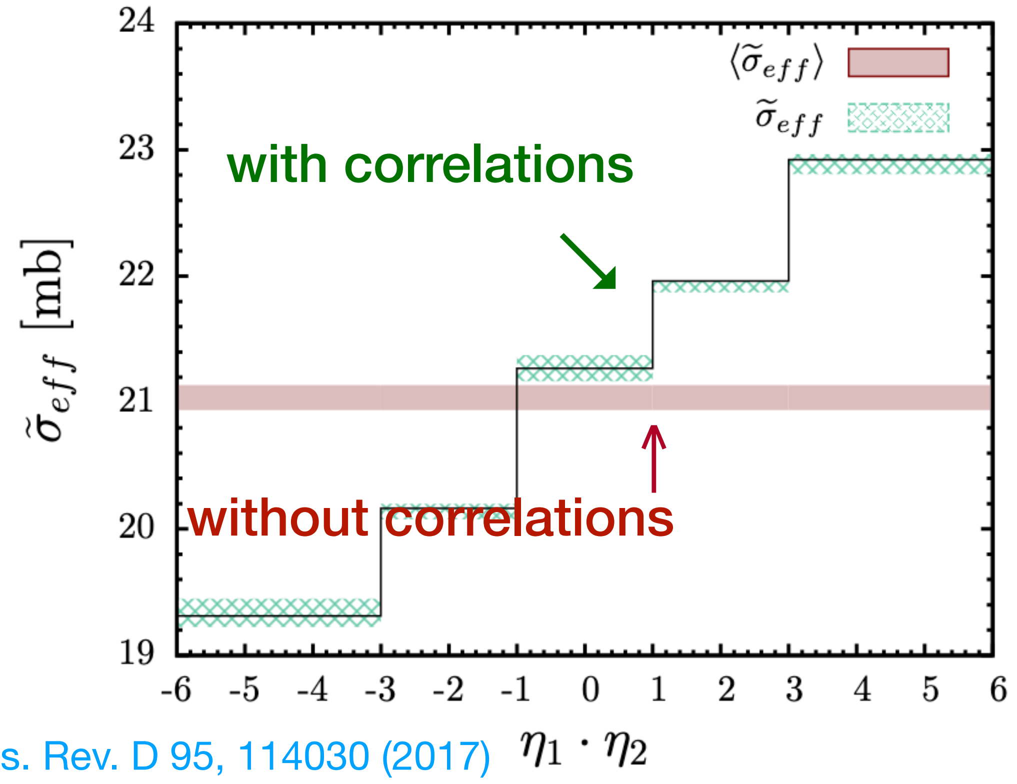
Beyond the factorization approach

- Factorization can't be the complete picture; dPDFs ≠ pdf x pdf ∀ x
  - Subtle hints from measurements
  - dPDFs must obey "sum" rules $x_1+x_2 \leq 1$, $\int_0^1 f_{u_v}(x,\mu^2)\,\mathrm{d}x = 2, \quad \int_0^1 f_{d_v}(x,\mu^2)\,\mathrm{d}x = 1.$
- Lots of progress towards a more complete description of DPS

- Can we probe parton correlations using some kinematic variables?

η product of leptons in $W^\pm W^\pm$

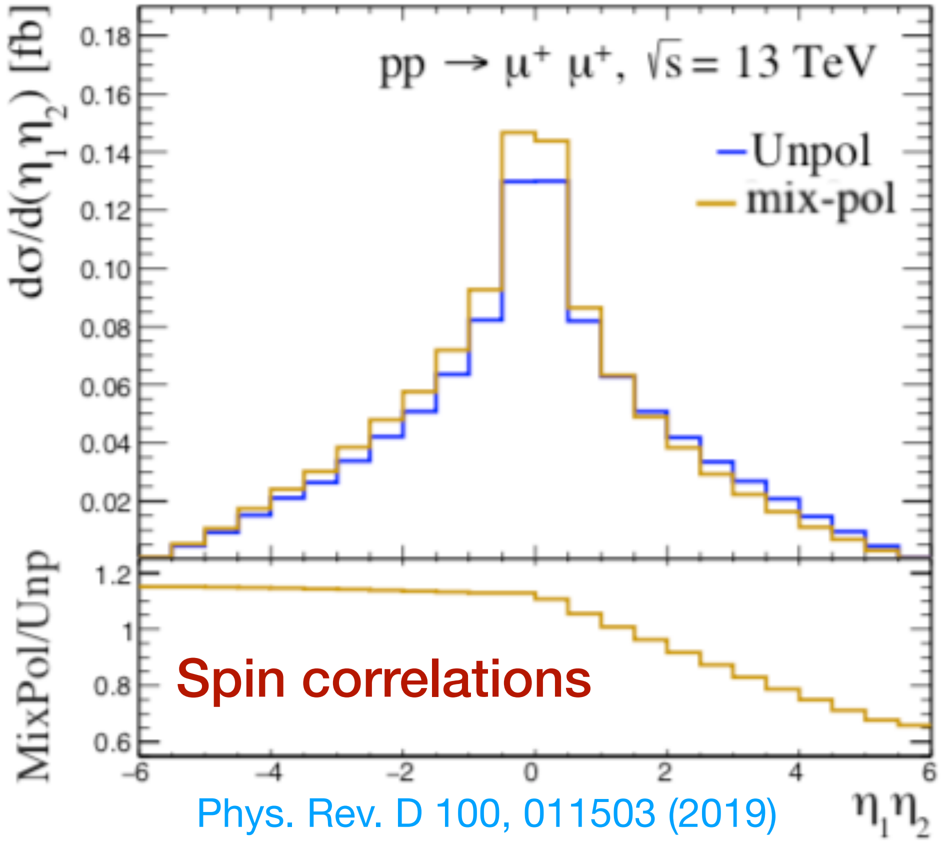
$$x_a = e^{\eta_\mu}\frac{M_W}{\sqrt{s}}\left[\frac{M_W}{2p_T} \pm \left(\sqrt{\left(\frac{M_W}{2p_T}\right)^2 - 1}\right)\right] \qquad x_b = e^{-\eta_\mu}\frac{M_W}{\sqrt{s}}\left[\frac{M_W}{2p_T} \mp \left(\sqrt{\left(\frac{M_W}{2p_T}\right)^2 - 1}\right)\right]$$



with correlations

without correlations

Phys. Rev. D 95, 114030 (2017)



Spin correlations

Phys. Rev. D 100, 011503 (2019)

Anatomy of a DPS analysis

- Target a final state
  - depends on the physics objective
  - either a process with high production cross section (multijets) or one with experimentally clean final state (W/Z/J/ψ)

- Signal modelling: data or simulation-based
- Background estimations: mostly similar to any SPS analysis
- Signal & background discrimination: single variables or MVA-based

- Extract production cross section for DPS by means of fit to data
- σ_{eff} computed using pocket formula
- Differential cross section measurements, if data sample is large enough

Systematic uncertainties: Z+jets

Table 3: Uncertainty sources and their effect on the differential cross section distributions.

Observable/Uncertainty	$\Delta\phi(\mathrm{Z}, j_1)$	$\Delta_{\mathrm{rel}} p_{\mathrm{T}}(\mathrm{Z}, j_1)$	$\Delta\phi(\mathrm{Z}, \mathrm{dijet})$	$\Delta_{\mathrm{rel}} p_{\mathrm{T}}(\mathrm{Z}, \mathrm{dijet})$	$\Delta_{\mathrm{rel}} p_{\mathrm{T}}(j_1, j_2)$
JES	2.7–7.5%	2.4–7.4%	4.9–7.9%	4.5–8.4%	4.4–7.3%
JER	0.9–6.6%	1.4–5.8%	1.2–7.2%	2.1–5.1%	1.1–4.2%
Pileup jet identification	1.3–1.7%	0.9–1.6%	1.7–2.1%	1.6–2.1%	1.7–2.3%
Integrated luminosity	2.5%	2.5%	2.5%	2.5%	2.5%
Pileup modelling	0.1–0.7%	0.2–1.0%	0.2–1.4%	0.4–1.4%	0.8–1.4%
Closure uncertainty	0.6–4.0%	0.8–5.1%	2.7–6.1%	2.2–8.7%	2.2–8.7%
Muon selection	<1.0%	<1.0%	<1.0%	<1.0%	<1.0%
Background modelling	<0.2%	<0.2%	<0.6%	<0.6%	<0.4%
Total	4–11%	4–10%	8–14%	8–14%	7–11%

Table 4: Uncertainty sources and their effect on the area-normalized distributions.

Observable/Uncertainty	$\Delta\phi(\mathrm{Z}, j_1)$	$\Delta_{\mathrm{rel}} p_{\mathrm{T}}(\mathrm{Z}, j_1)$	$\Delta\phi(\mathrm{Z}, \mathrm{dijet})$	$\Delta_{\mathrm{rel}} p_{\mathrm{T}}(\mathrm{Z}, \mathrm{dijet})$	$\Delta_{\mathrm{rel}} p_{\mathrm{T}}(j_1, j_2)$
JES	0.1–3.8%	0.7–3.7%	0.6–4.0%	0.3–2.6%	0.3–1.5%
JER	0.3–4.6%	0.4–4.4%	1.3–4.4%	0.2–4.8%	0.2–1.7%
Pileup jet identification	0.1–0.2%	0.1–0.2%	0.1–0.2%	0.1–0.2%	0.1–0.4%
Pileup modelling	0.1–0.5%	0.1–0.5%	0.1–1%	0.1–0.8%	0.2–0.4%
Closure uncertainty	0.8–2.5%	0.9–3.6%	0.3–5.0%	0.4–6.7%	0.5–3.7%
Muon selection	<1.0%	<1.0%	<1.0%	<1.0%	<1.0%
Background modelling	<0.1%	<0.1%	<0.2%	<0.2%	<0.2%
Total	1–6%	1–6%	2–7%	1–7%	1–4%