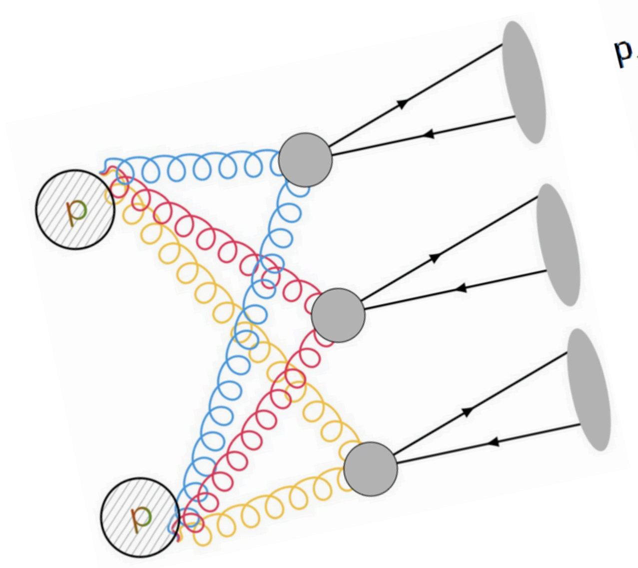
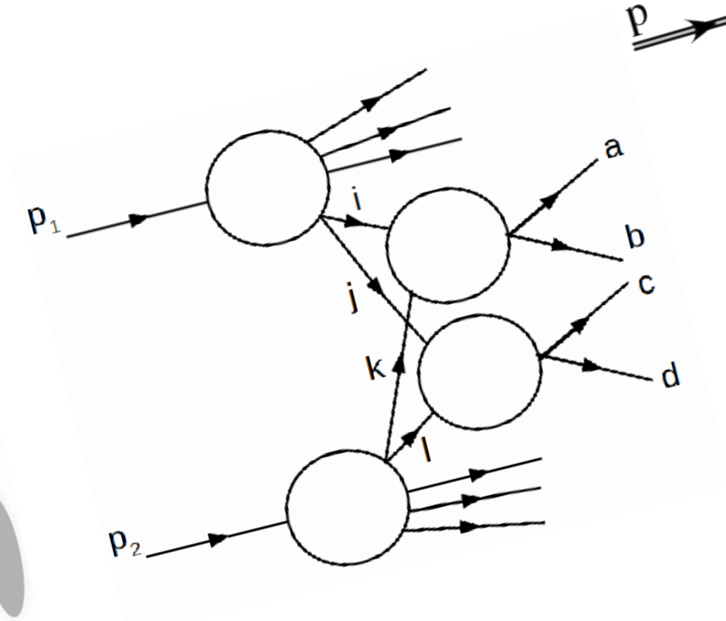
Latest measurements of double-parton scattering using hard objects

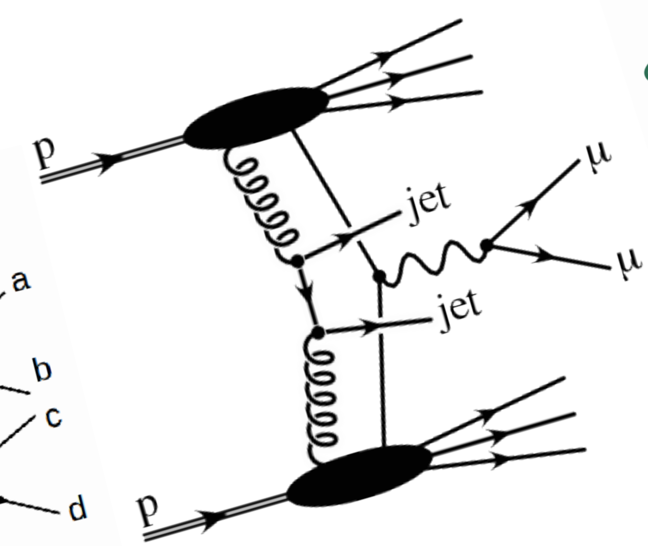
MPI@LHC2023, Manchester

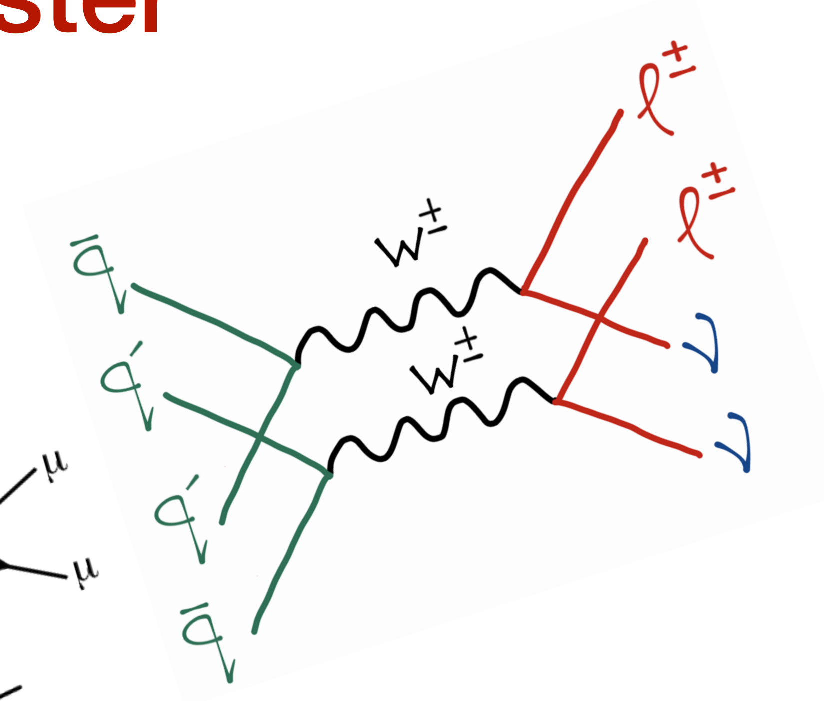
Ankita Mehta

(on behalf of the CMS Collaboration)



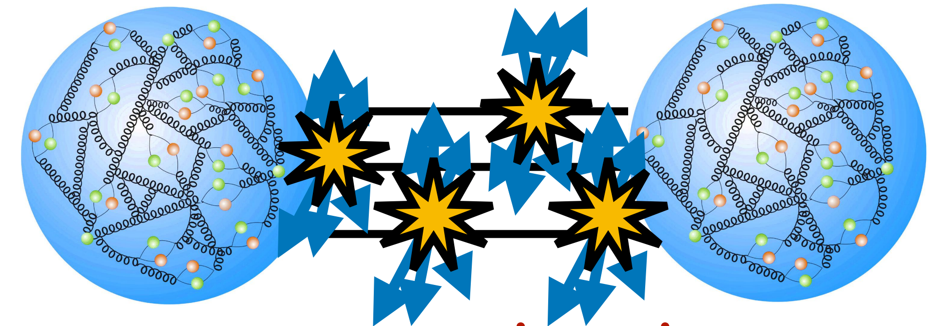






November 22, 2023

Double parton scattering



- Multi-parton interactions (MPI) ⇢"n" simultaneous parton-parton scatterings in a single pp collision
- First experimental evidence from CERN ISR
- Leading order in MPI: double parton scattering (DPS)
- Cross section for a "nPS" process is suppressed as compared to SPS

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

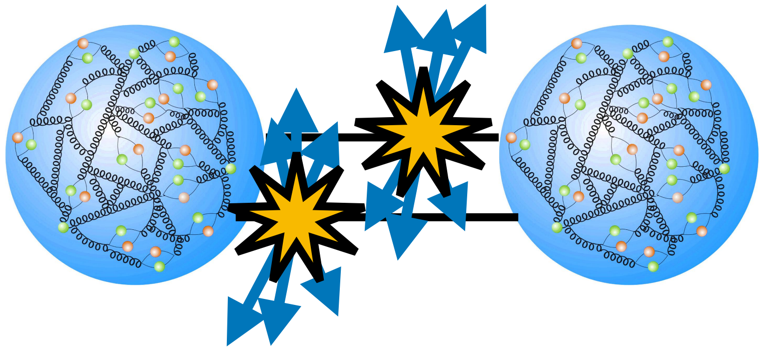
Λ^2 → hadronic scale ~1GeV

Q_h^2 → hard interaction scale

In certain phase space regions, contributions from DPS can't be neglected!!

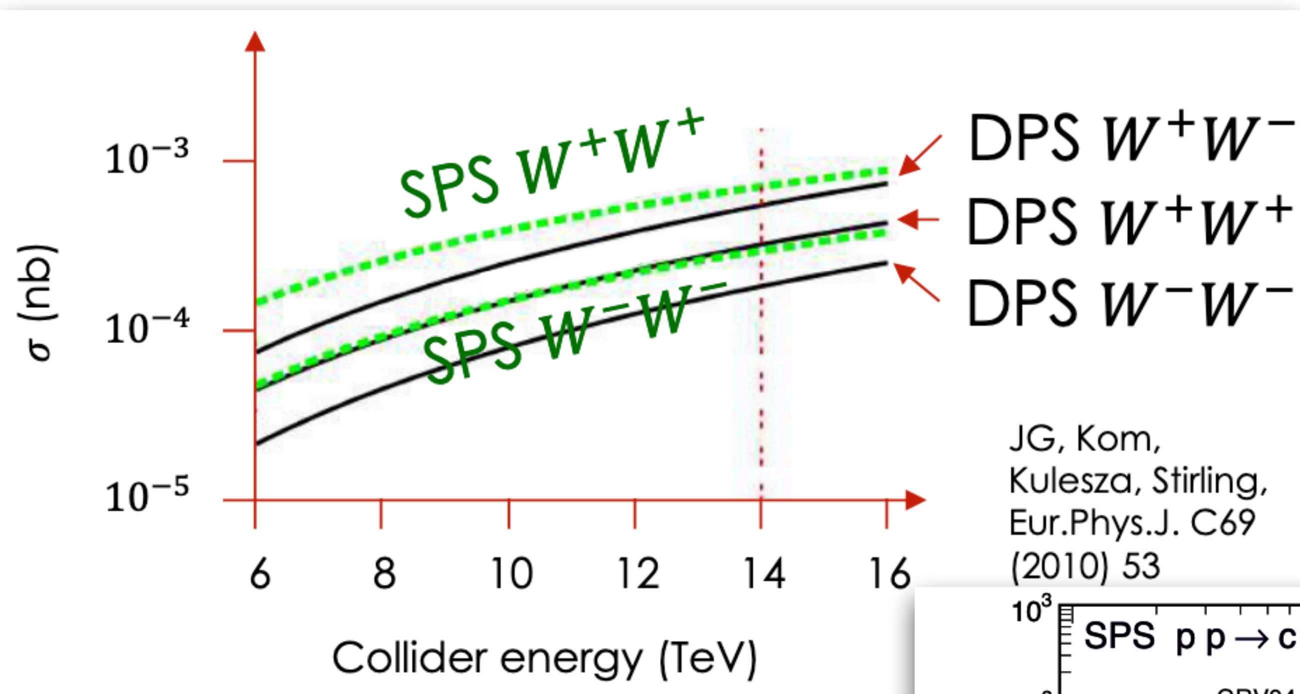
- Multiple studies using various final states with different energy scales (quark/gluon/quark-gluon mediated) at different √s
- DPS probed at LHC even with the hardest possible scale for DPS at 13TeV

Why study DPS?

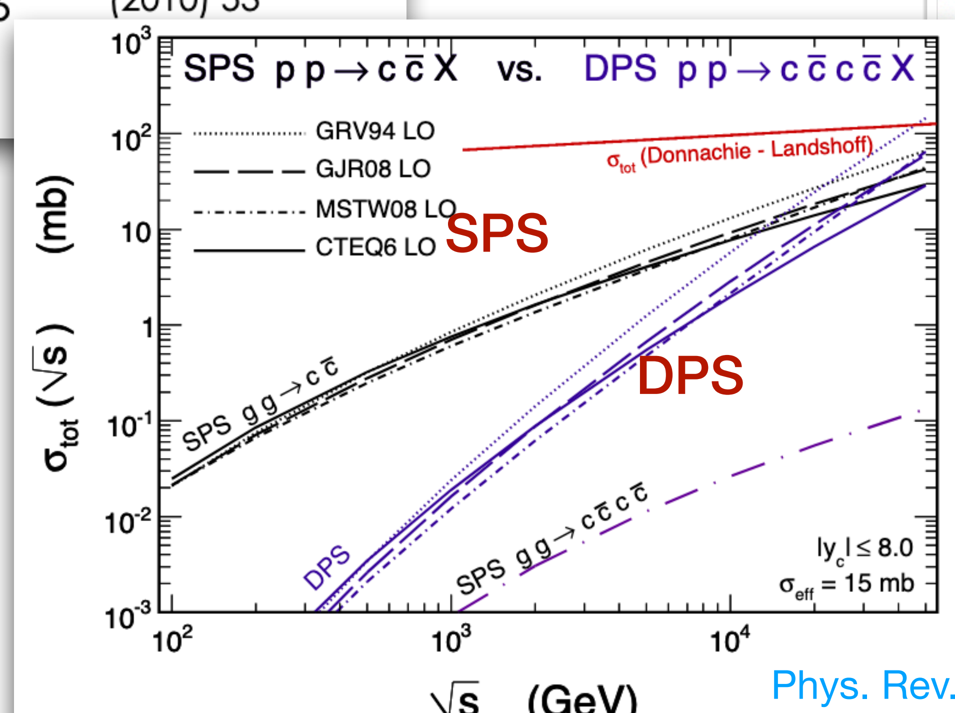


- Probes the internal structure of a proton
- Background for rare standard model and new physics processes
- Provides input for the tuning of Monte Carlo (MC) event generators

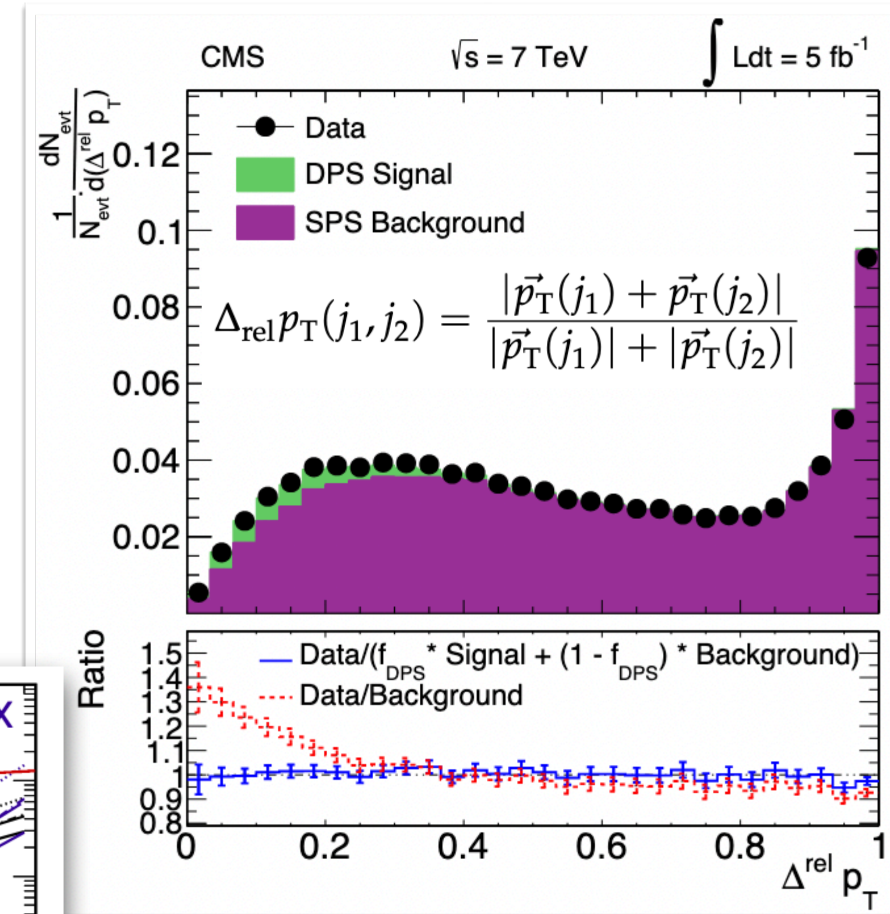
Cross section comparable with SPS



Grows faster than SPS with $\sqrt{s}$ (even more for low-scale processes (J/ψ,Y, etc.)



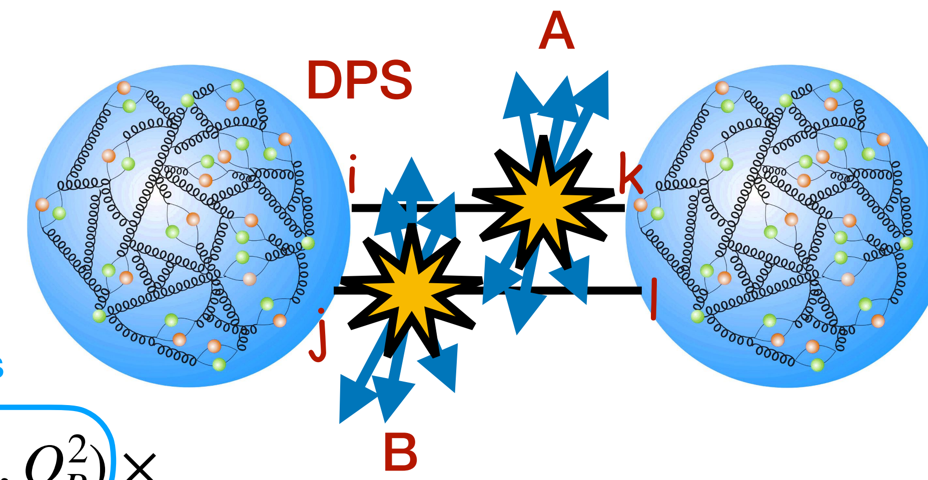
Phys. Rev. D79, 094034 (2012)



JHEP03(2014)032

Populates phase space in a different way from SPS

DPS cross section

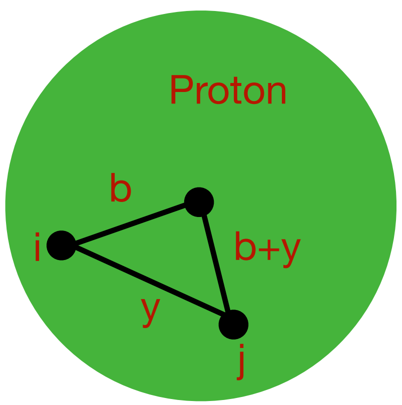


double PDFs — partonic cross sections

$$\sigma_{AB}^{\rm DPS} = \frac{m}{2}\sum_{i,j,k,l}\int \Gamma^{ij}(x_1,x_2;b;Q_A^2,Q_B^2)\times\hat{\sigma}_A^{ik}(x_1,x_1',Q_A^2)\hat{\sigma}_B^{jl}(x_2,x_2',Q_B^2)\times \Gamma^{kl}(x_1',x_2';b;Q_A^2,Q_B^2)dx_1dx_2dx_1'dx_2'd^2b$$

transverse distance Between partons

decompose dPDFs in longitudinal & transverse components



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

transverse parton density → considered same for all pair of partons

further assume longitudinal factorization

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

PDFs

"pocket formula" for σ_{DPS}

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

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

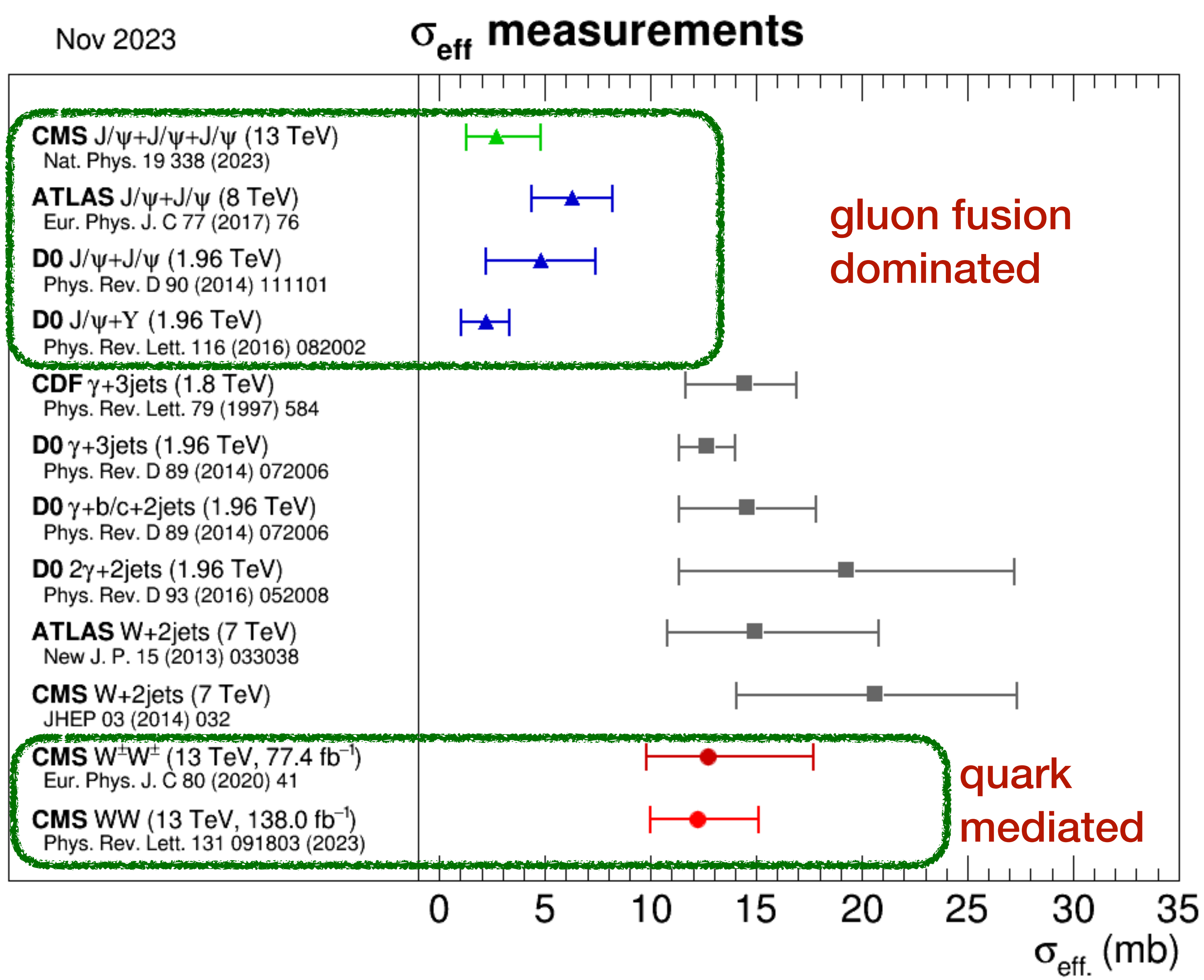
Eur.Phys.J.C 69(2010)53

Effective cross section parameter

- Proxy to mean inter-parton transverse separation squared ⇢ sort of an impact parameter
- Expected to be process, scale & c.o.m. energy independent "in the assumed simplest model"

- PYTHIA8: 20-30 mb (large tune dependence)
- Measurements: 5-20 mb

- Inter-parton correlations?
- Parton-flavor dependence?
- Flaws in DPS factorization?



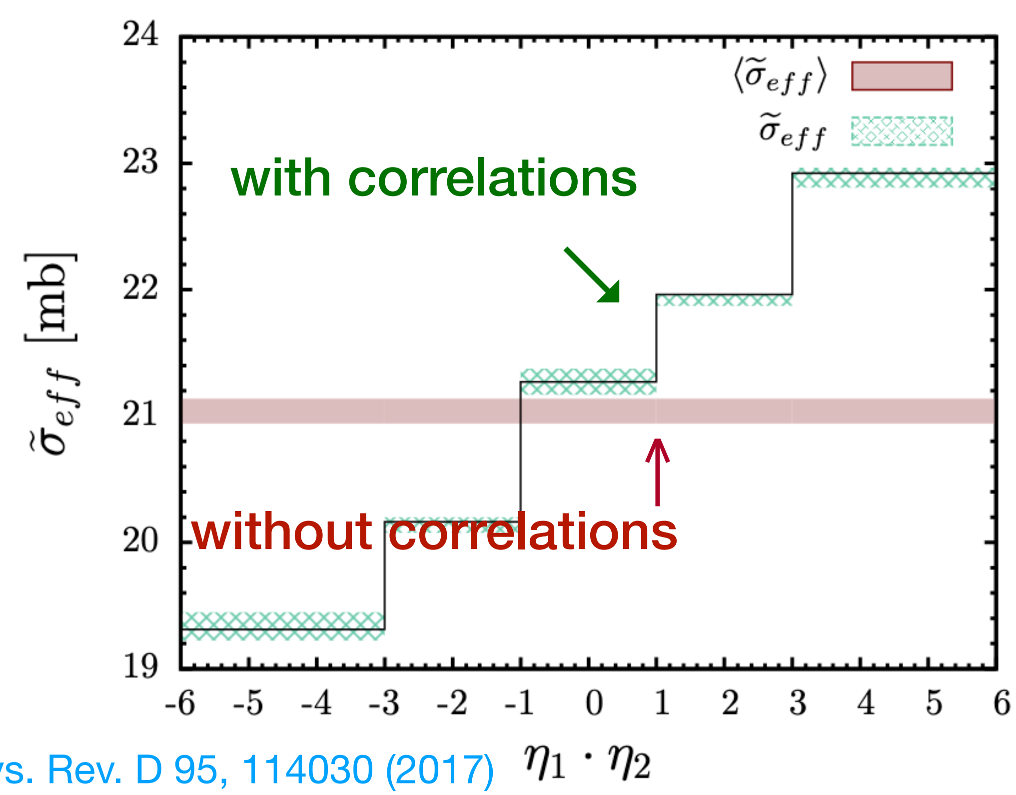
Beyond the factorization approach

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

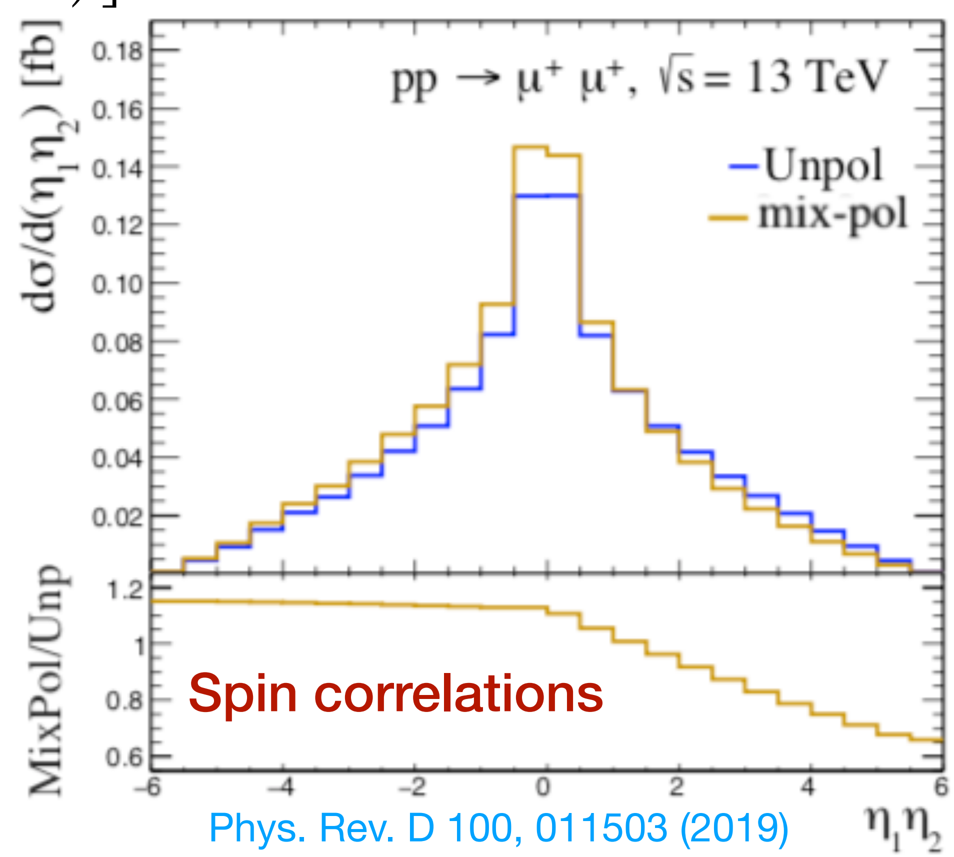
- Can we probe parton correlations using some kinematic variables?

η product of leptons in $W^{\pm}W^{\pm}$

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



Phys. Rev. D 95, 114030 (2017)



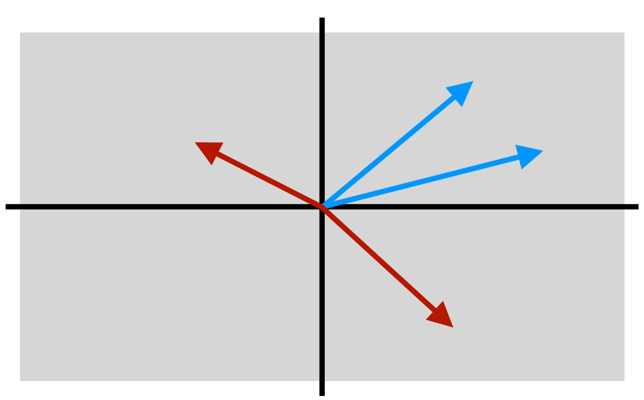
Phys. Rev. D 100, 011503 (2019)

DPS simulation models

- LO samples from PYTHIA/Herwig
  - SPS ⇢ nPS, where N per event follows a Poisson distribution
  - Some differences between the two 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

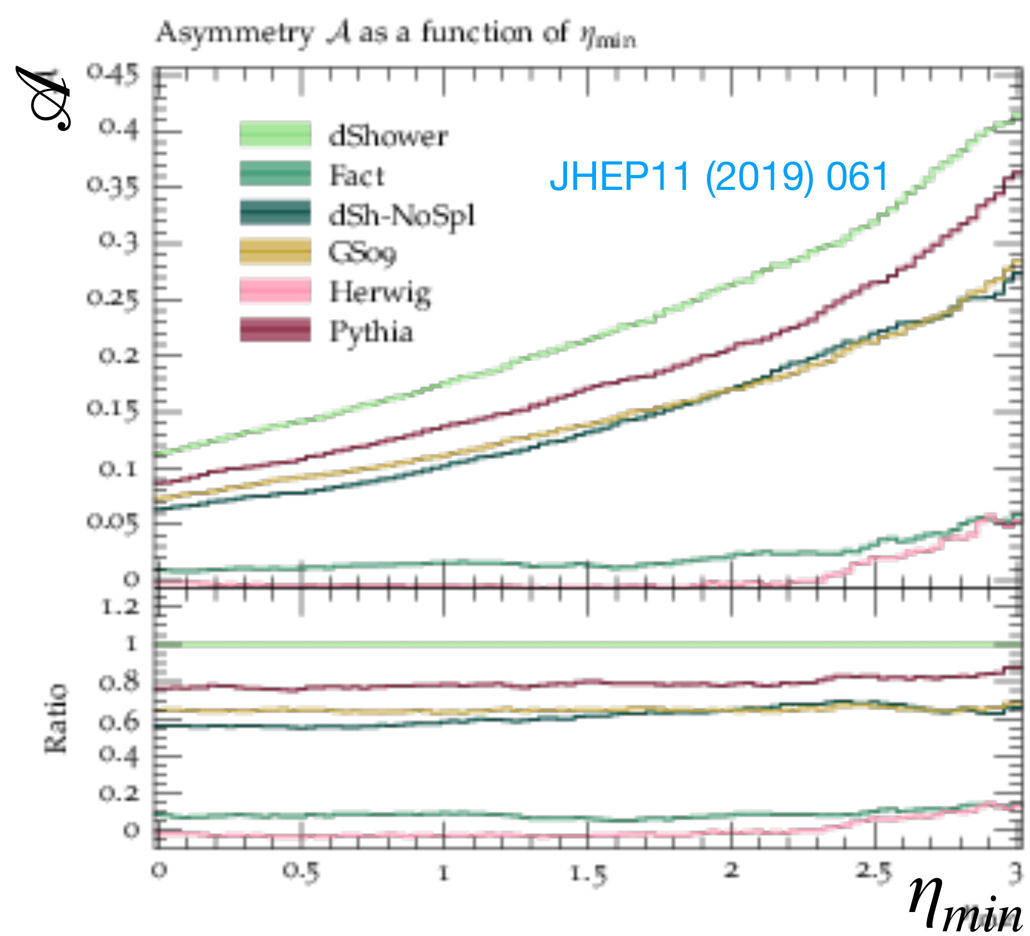
$\mathscr{A}$: leptons in different or same detector hemispheres

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



$\mathscr{A} = 0$ ⇢ uncorrelated

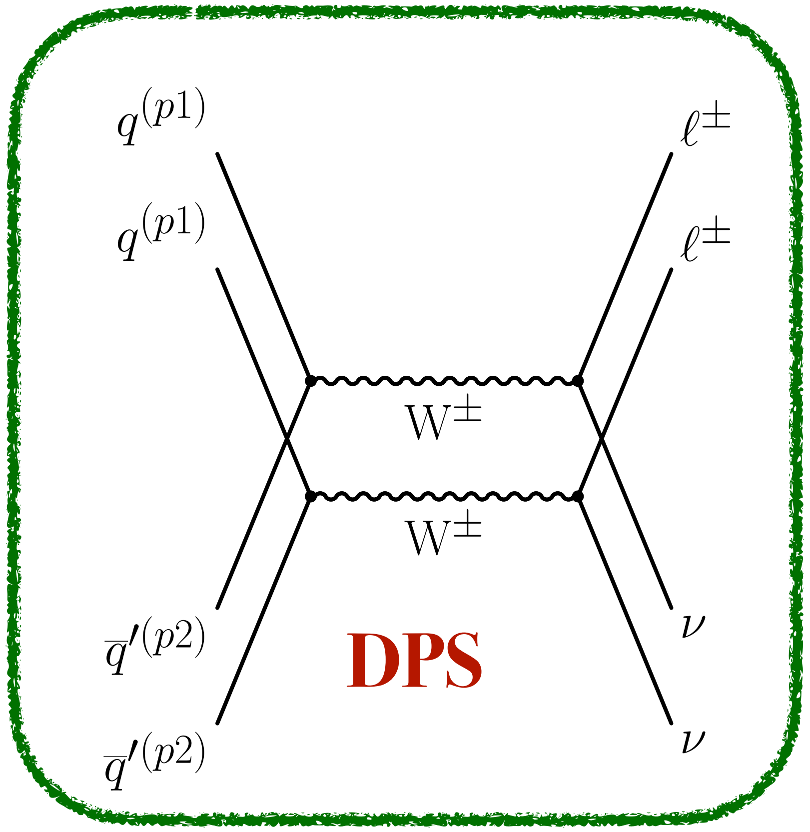
$\mathscr{A} > 0$ ⇢ correlated

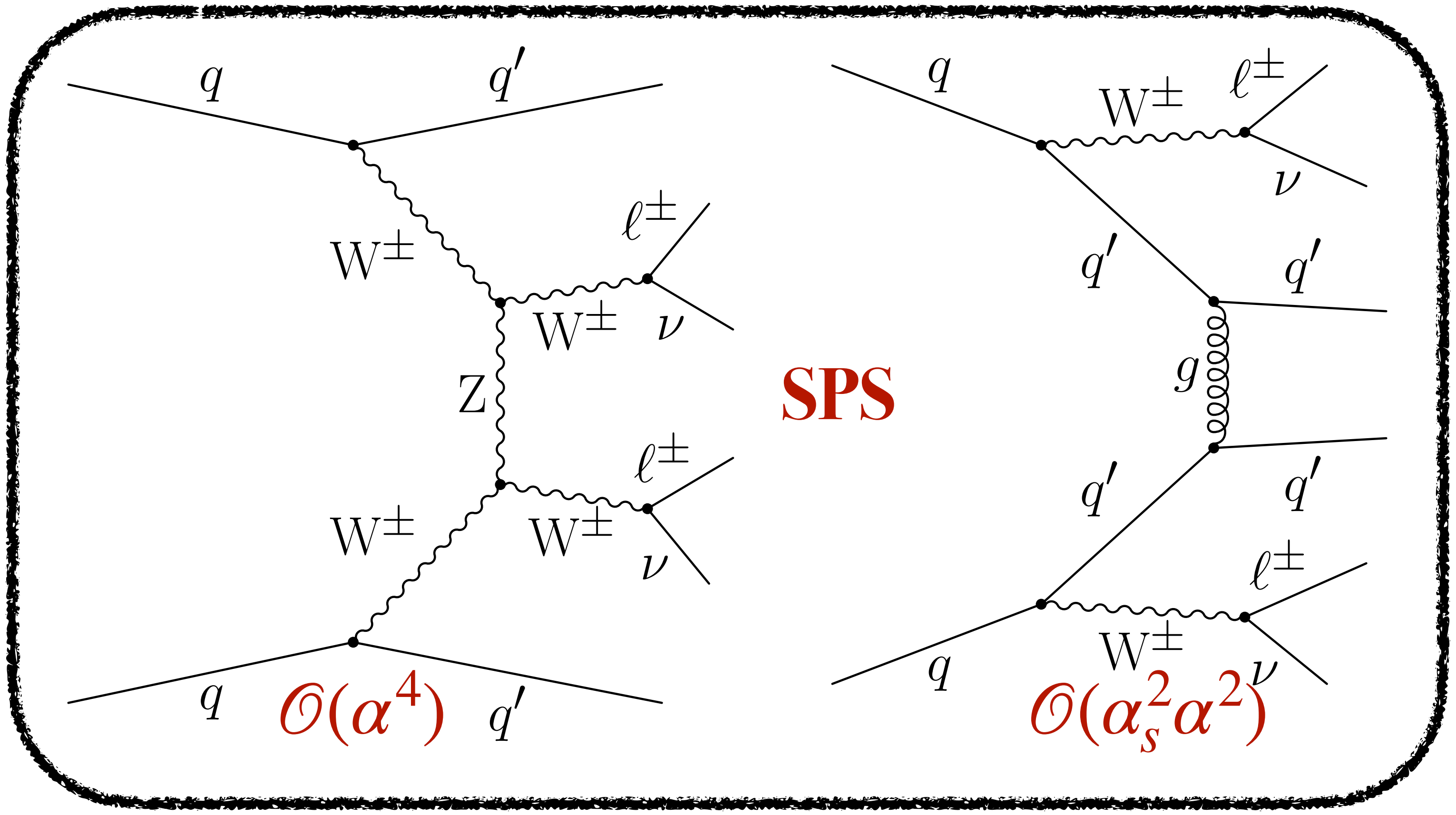


Phys. Rev. Lett. 131 (2023) 091803

DPS with W±W±

- Golden channel for DPS production since SPS W±W± production suppressed at matrix element level due to presence of (two) extra jets
- PYTHIA8 predicts cross section for W±W± ⇢ 2l2v ~ 86(±40%) fb @13TeV





- Experimentally clean final state with leptonic W decays
  - Negligible contributions from leptons from adjacent bunch crossings

Analysis strategy

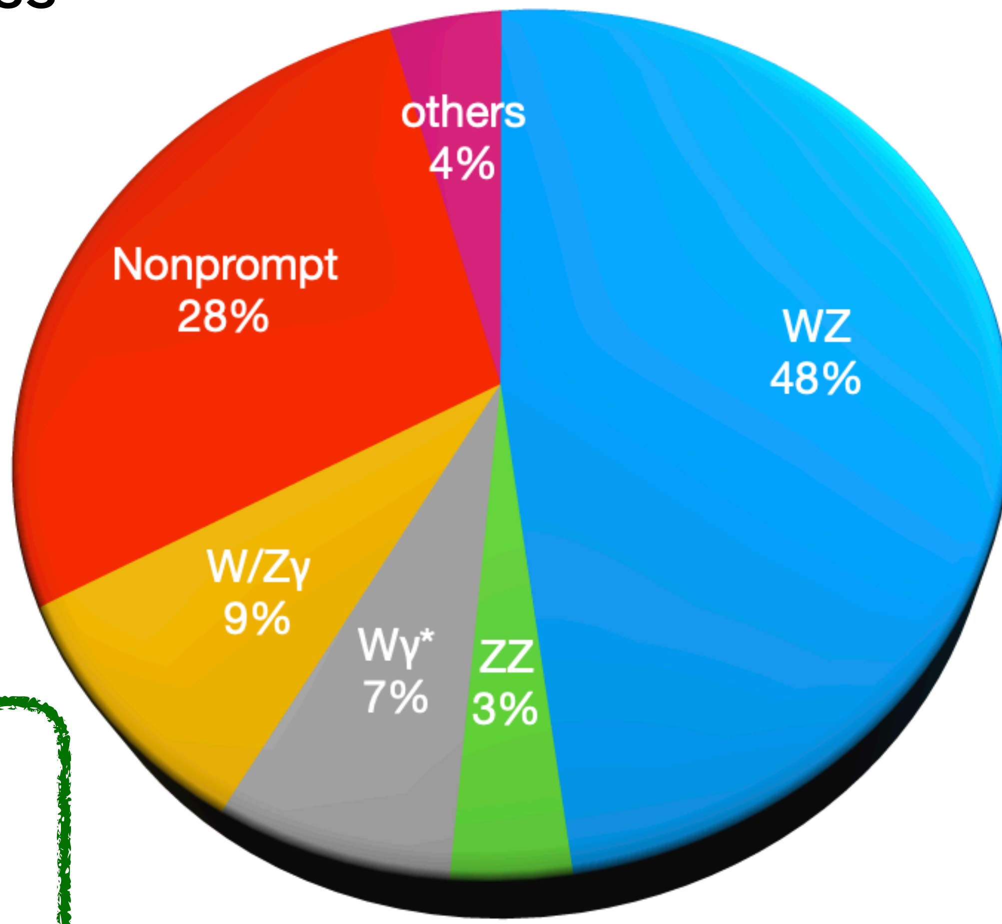
- Analysis performed using pp collisions data at 13TeV⇢ 138 fb^{-1}
- Signal: $W^{\pm}W^{\pm}$ ⇢ eμ or μμ final states with moderate p_T^{miss} ⇢ modelled using PYTHIA8 & dShower with model uncertainties from Herwig
- Background contributions from prompt & nonprompt lepton productions
  - Prompt contributions ⇢ 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
$\lvert\eta_e\rvert < 2.5$, $\lvert\eta_\mu\rvert < 2.4$
$p_T^{miss} > 15$ GeV
$m_{\ell\ell} > 12$ GeV
$N_{jets} < 2$
$N_{b\text{-}jets} == 0$
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



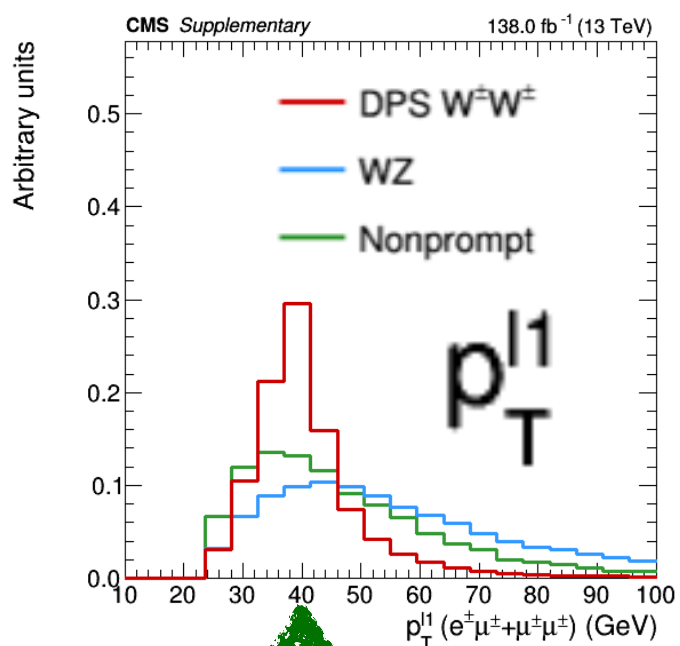
- Nonprompt lepton contributions (W+jets, QCD multijets, and semi-leptonic decays of $t\bar{t}$)

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

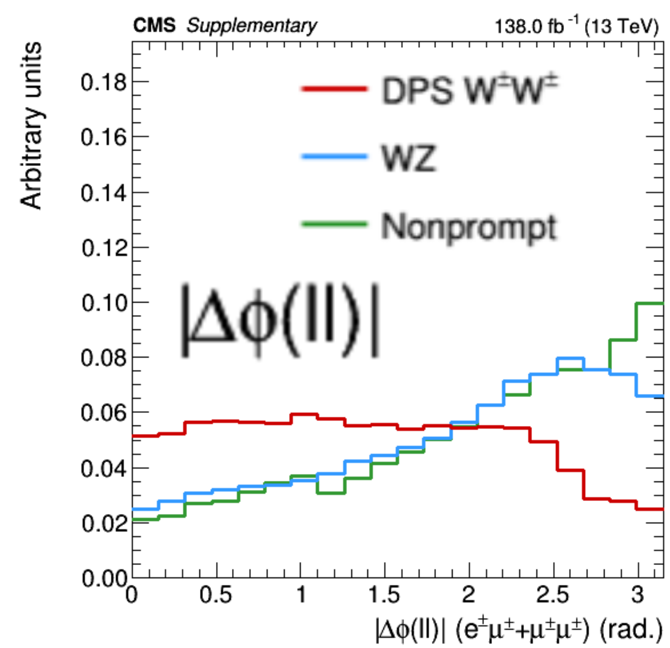
- Two separate BDT classifiers for WZ & nonprompt

BDT classifiers

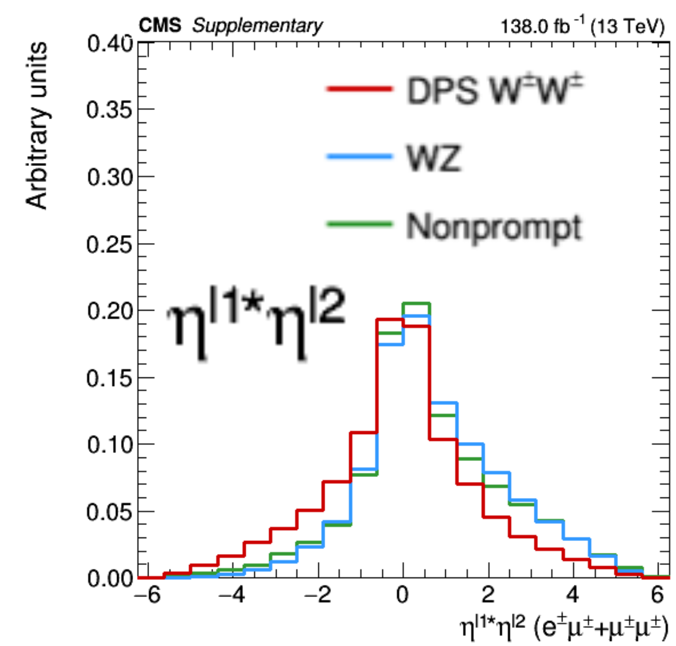
- Training variables ⇢ kinematic differences between (uncorrelated) signal and (correlated) backgrounds



mW/2



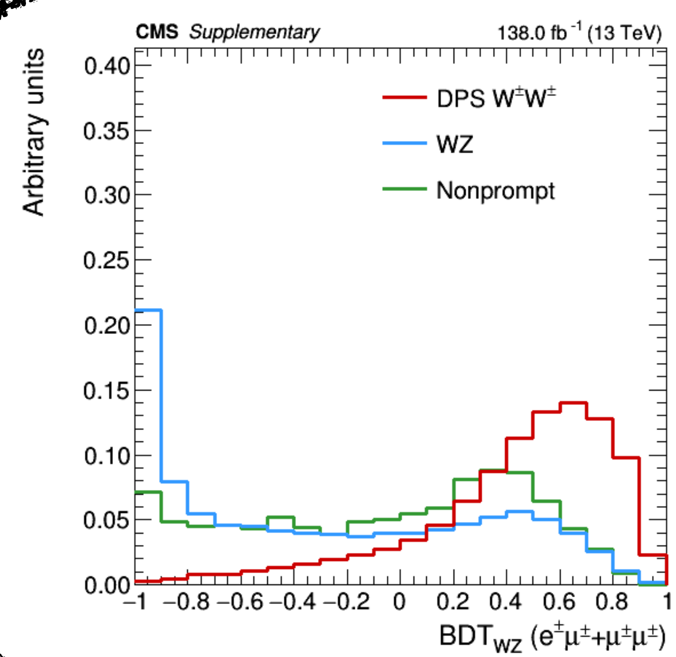
relatively flat signal

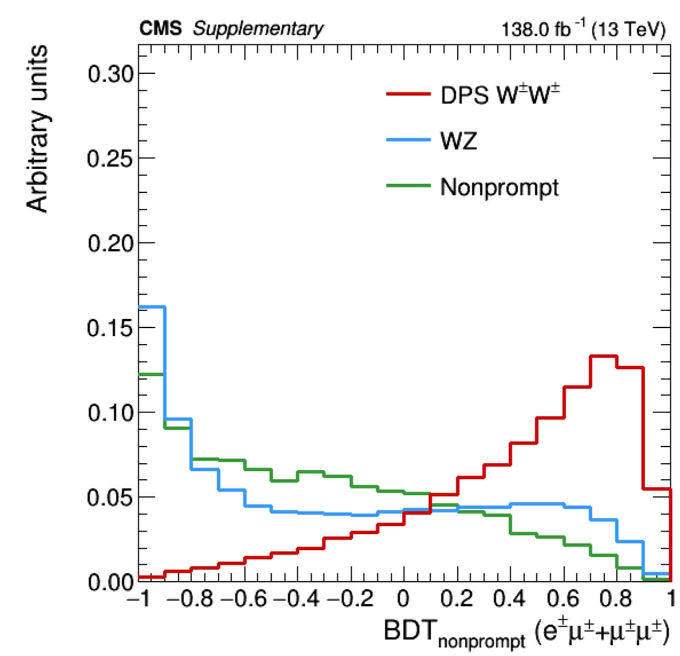


sensitive to correlations

training variables

$pT_{l_{1,2}}$	$m_T(l_1, p_T^{miss})$
p_T^{miss}	$m_T(l_1, l_2)$
M_{T2}^{ll}	$\Delta\phi(l_1, l_2)$
$\eta_1 \times \eta_2$	$\Delta\phi(l_2, p_T^{miss})$
$\lvert\eta_1 + \eta_2\rvert$	$\Delta\phi(l_1 l_2, l_2)$

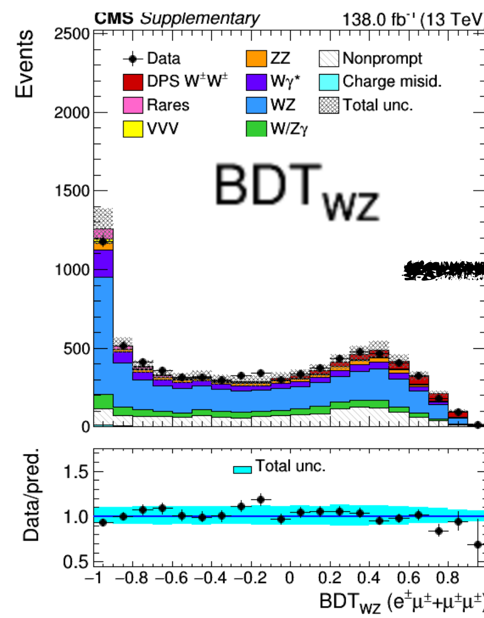




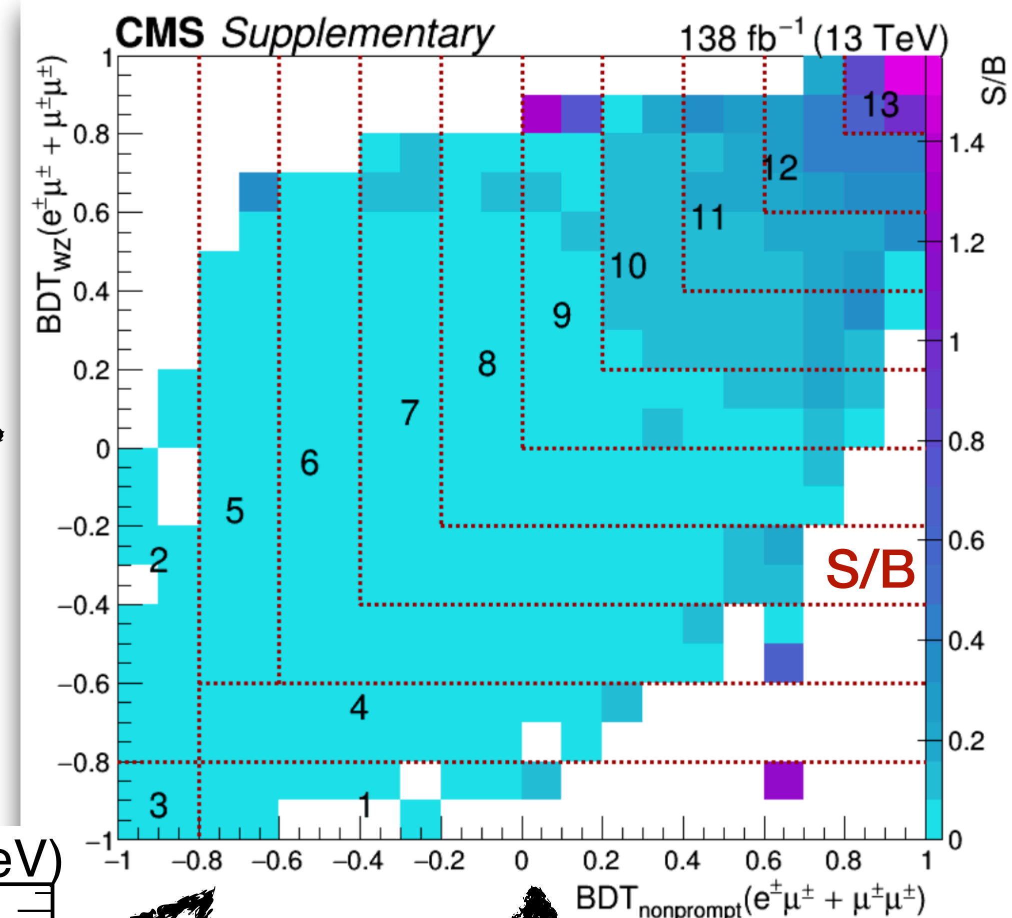
Statistical analysis

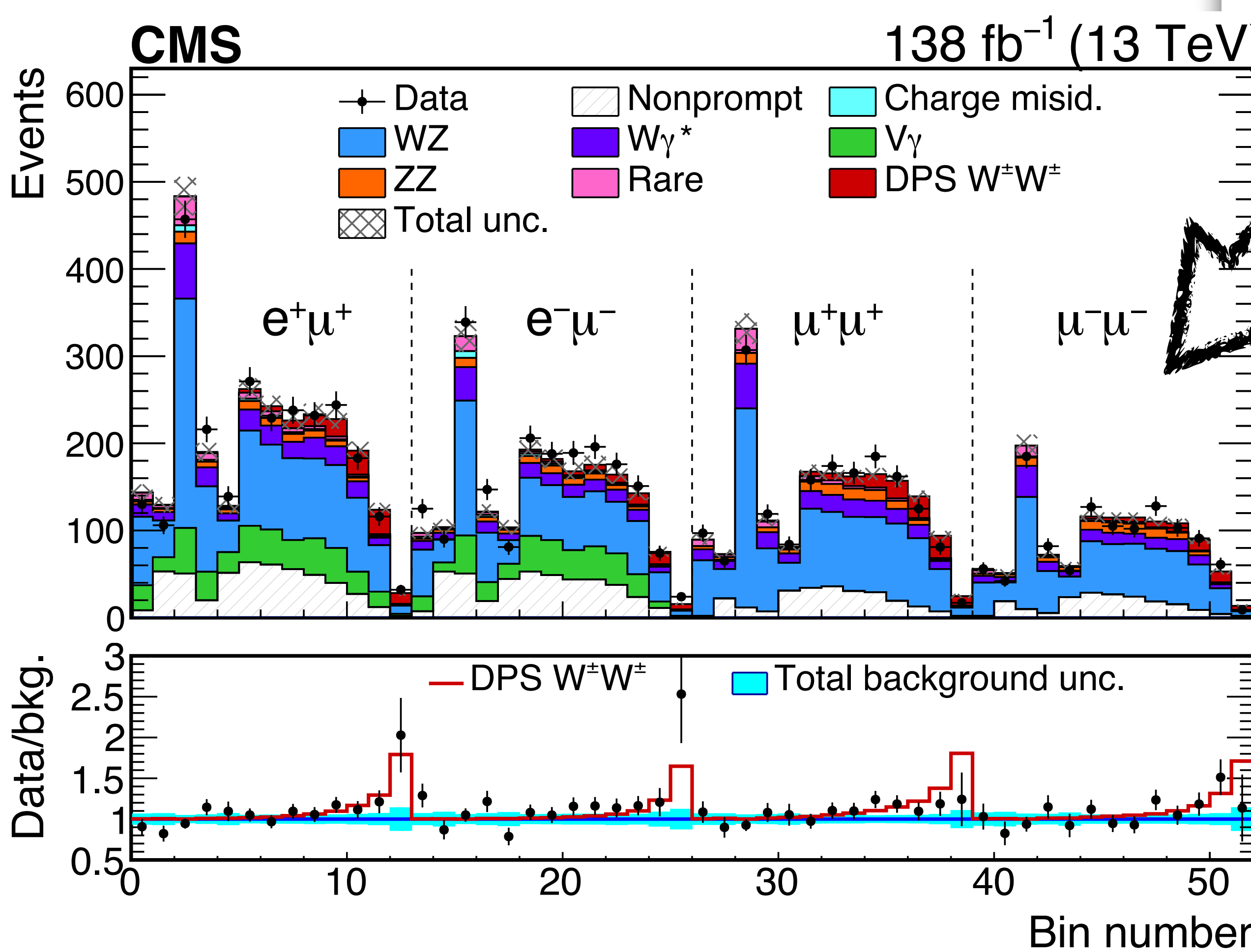
Two BDTs ⇢ 1D distribution

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

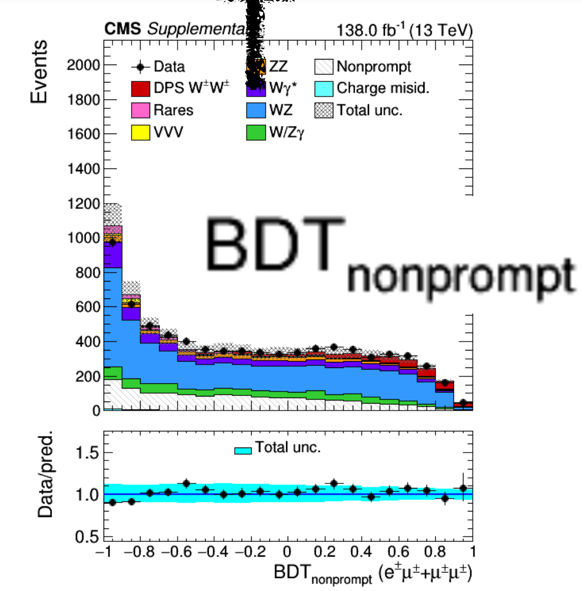


high purity bins





signal visible in highest BDT bins



Results

Observation of DPSW±W± with 6.2 s.d.

Inclusive W±W± ⇢ 2l2v cross section

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

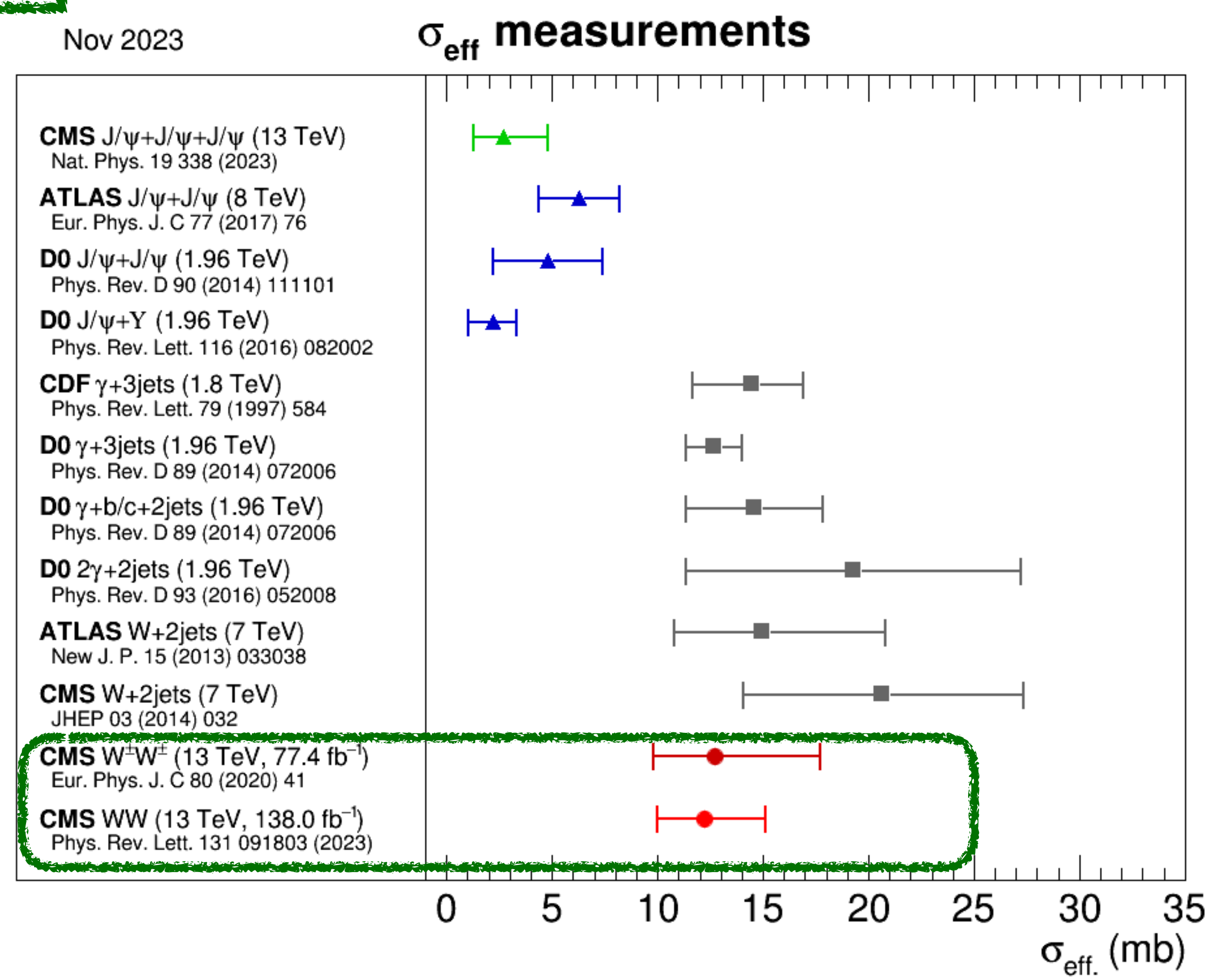
Fiducial cross section

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

from Herwig: difference in reconstruction efficiencies for leptons & generator acceptance

Using pocket formula

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



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

Conclusions

- Presented DPSWW studies based on 13TeV collision data from CMS
  - Observation of $W^{\pm}W^{\pm}$
  - Inclusive and fiducial cross section measurements
  - Effective cross section measurement
- 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, improve experimental precision,..?
  - Inclusion of parton correlations in MC event generators (dShower)
  - (More) angular observables to enhance sensitivity towards parton correlations ⇢ going differential with Run2+Run3 ⇢Run4
  - Machine learning to enhance SPS vs DPS discrimination for low pT objects
  - Reduction in model uncertainties
    - Combinations⇢ final states/experiments

thanks for your attention!!