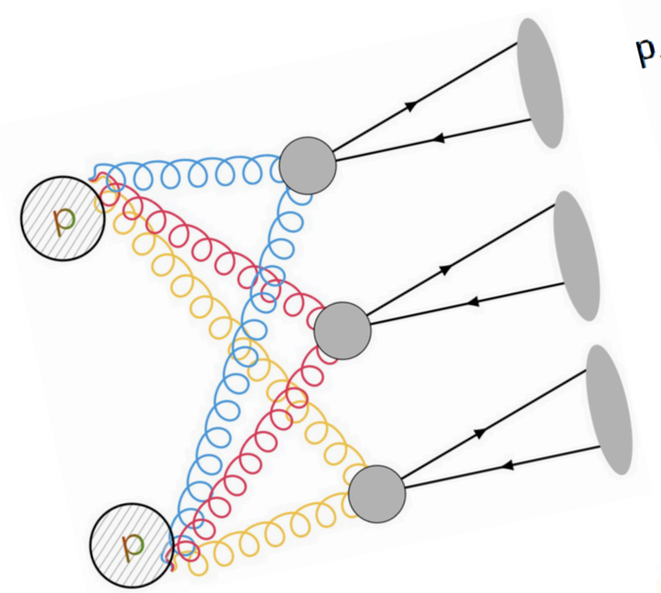
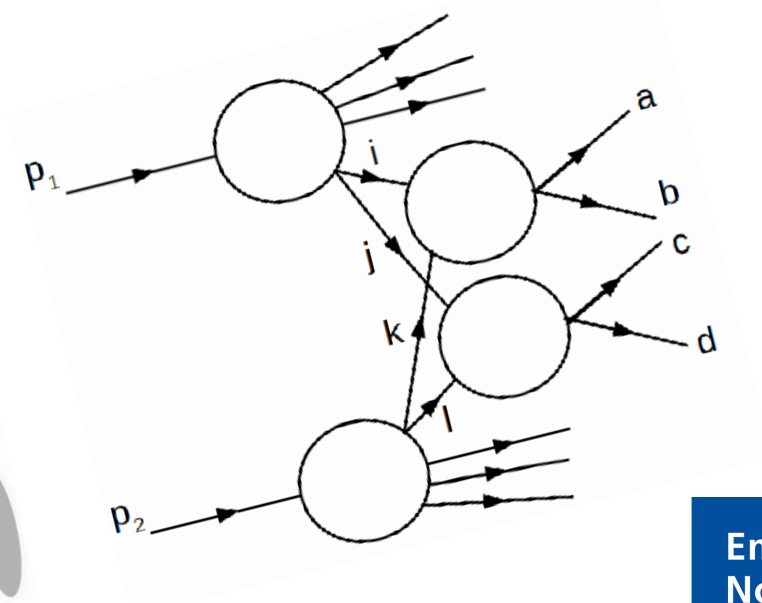
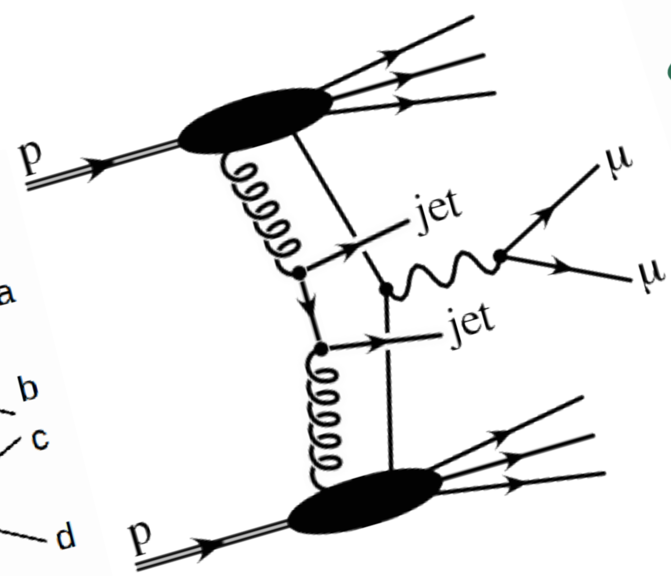
Double parton scattering production in CMS

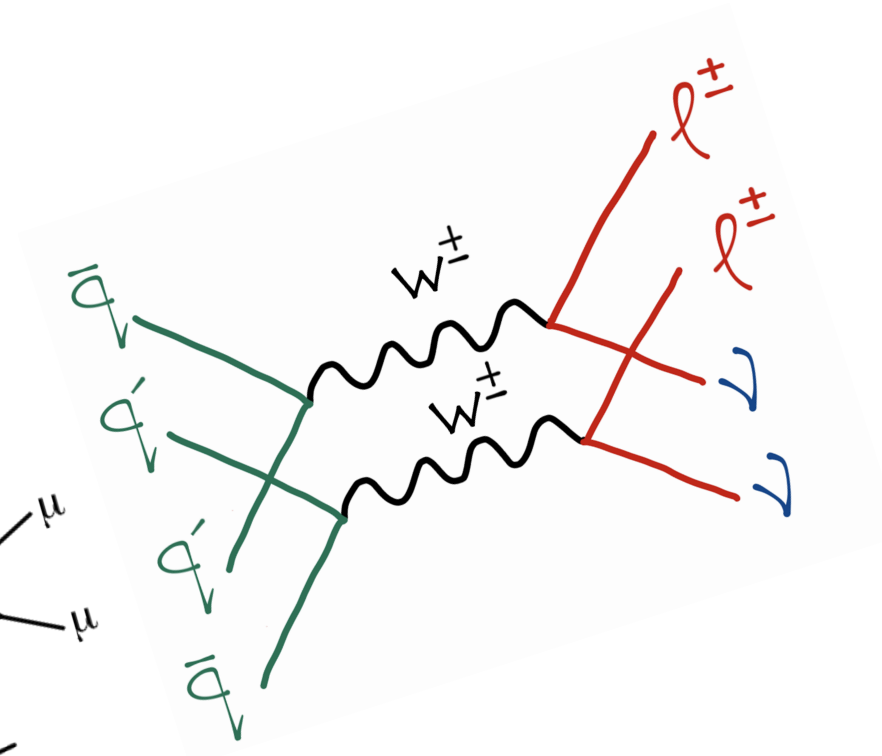
CERN LHC Seminar

Ankita Mehta
(on behalf of the CMS Collaboration)









June 28, 2022

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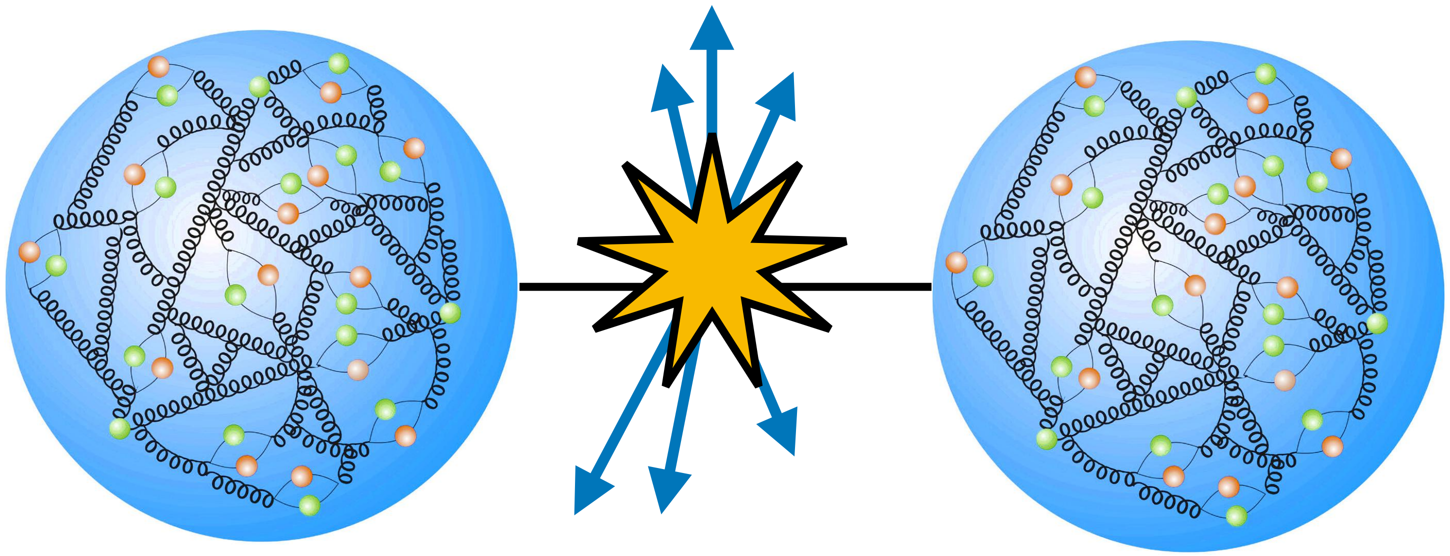
Outline



Single parton scattering

VS

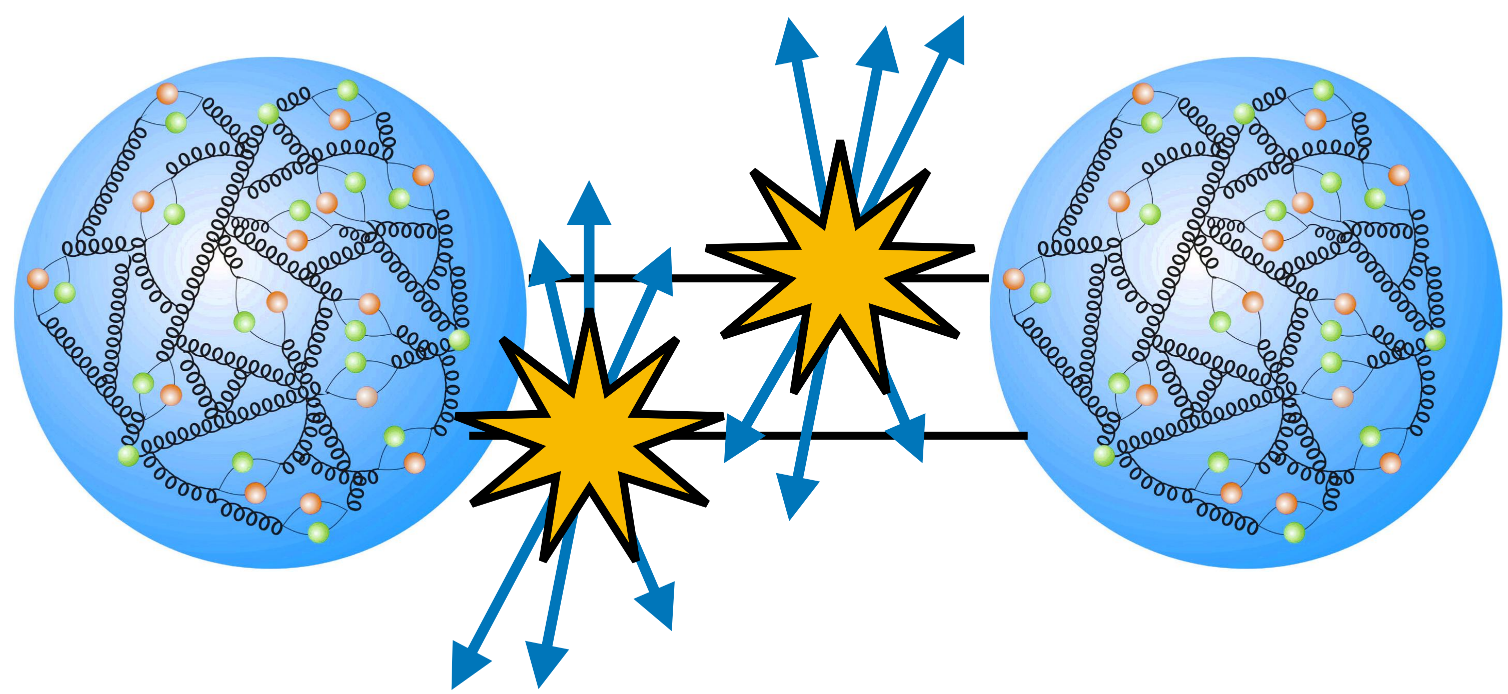
on today's agenda!

What?

Why?

How?

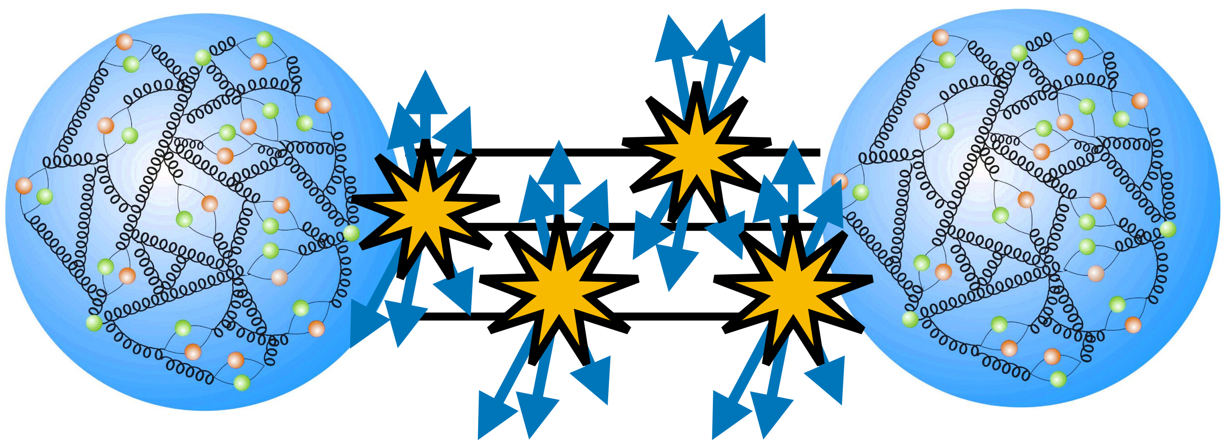
Which?

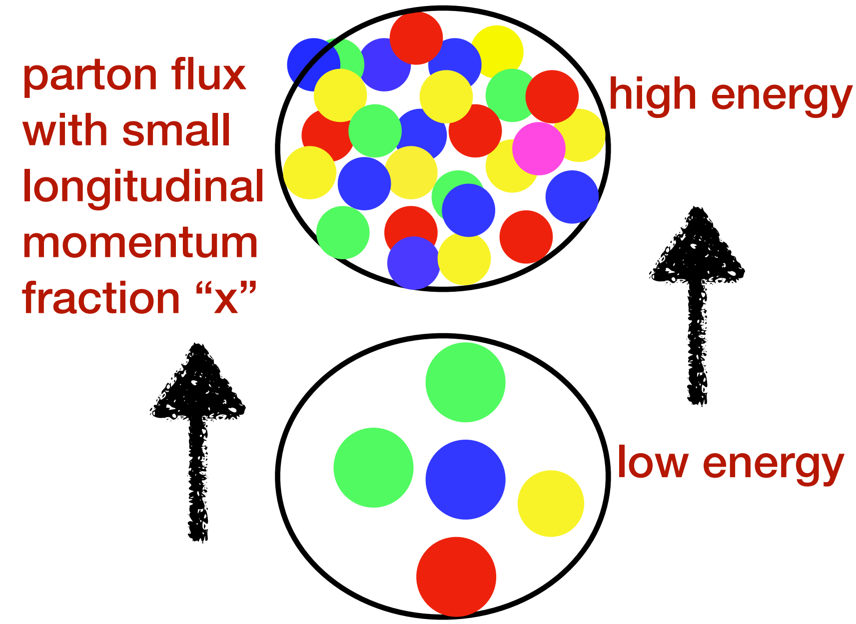


Double parton scattering

Introduction

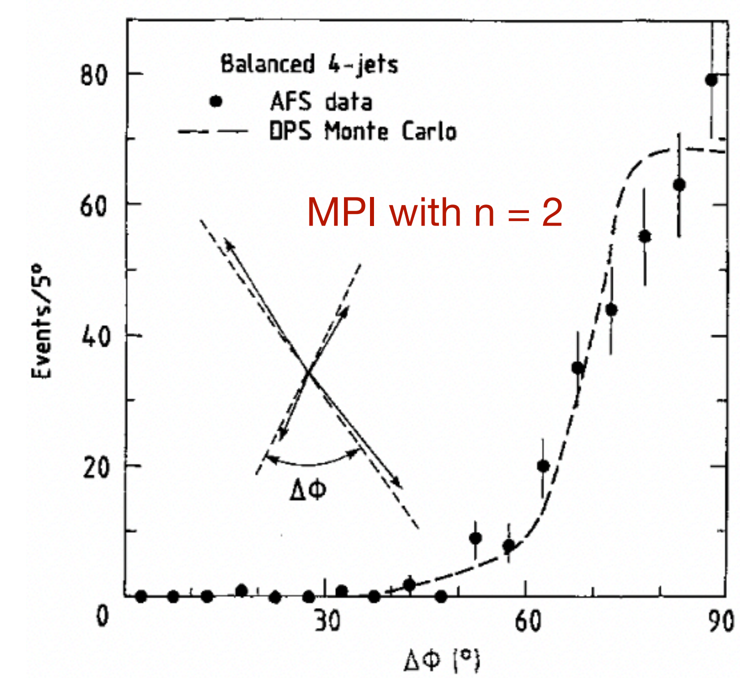
- Hadrons are “composite” ⇢ possibility to have “n” multiple hard parton-parton interactions (MPI) in a single hadron-hadron collision
- σ^{MPI} for a given interaction scale increases with $\sqrt{s}$





- First experimental evidence from CERN ISR
  - several measurements at Tevatron & LHC

Z. Phys.C- Particles and Fields 34,163(1987)



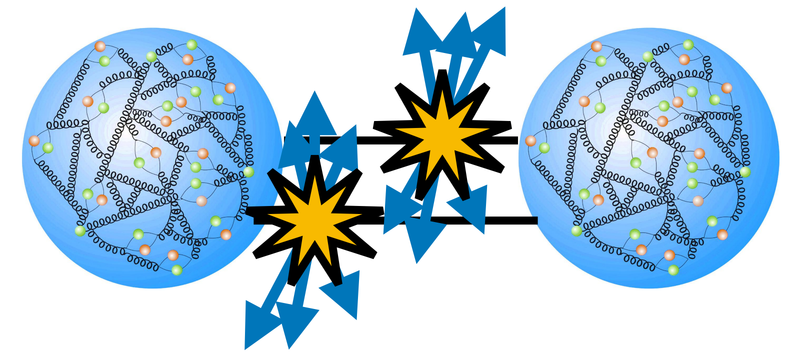
- MPI sensitive to interplay between non-perturbative & perturbative QCD effects ⇢ models need to be “tuned” using data

Hadron colliders such as LHC ideal to study MPI

Double & triple parton scatterings

Leading order in MPI: double parton scattering (DPS)

can also have triple parton scattering (TPS) ……..



- Two (three) distinct hard scatters in a single pp collision DPS (TPS)
- 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

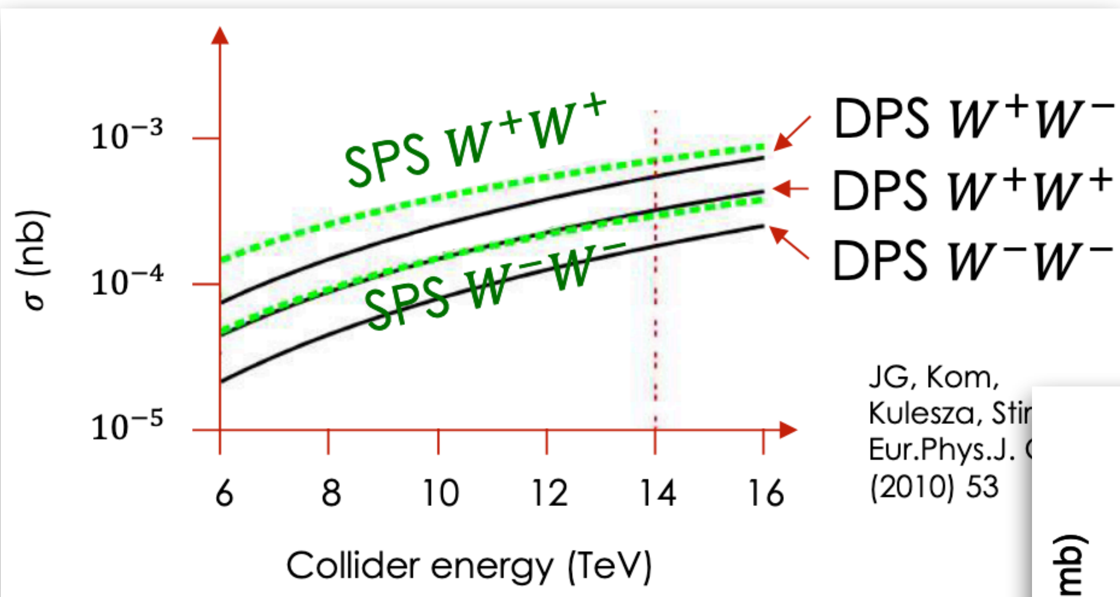
In certain phase space regions, contributions from DPS can’t be neglected!!

- 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
- TPS is relevant for final states with quarkonia production at LHC energies

Why study DPS (nPS)?

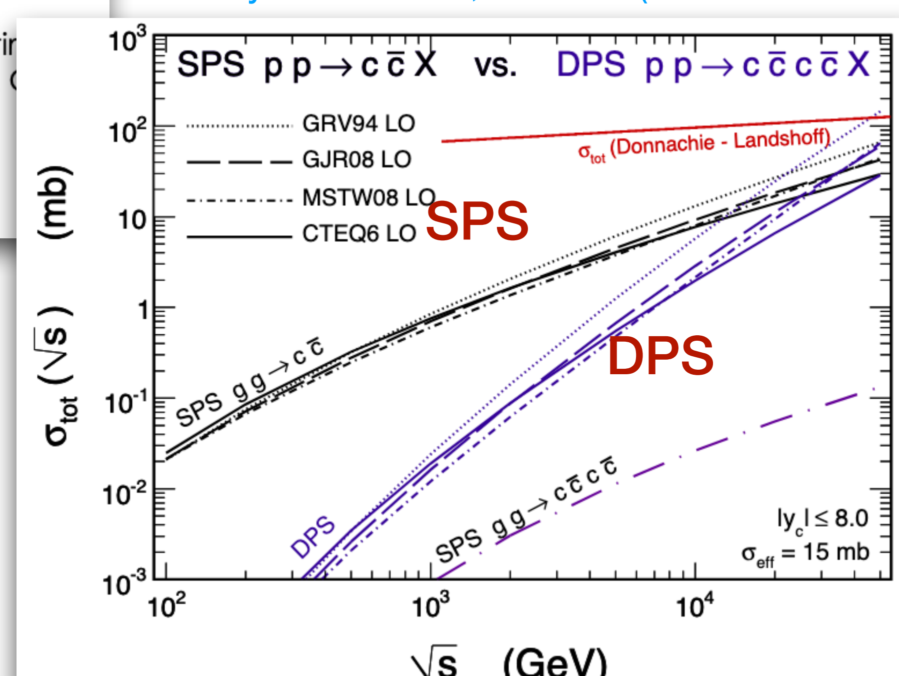
- Probes the internal structure of a proton ⇢role of partonic correlations (in space, momentum, flavour, colour, spin,...) in hadronic wave functions
- Background for rare standard model (SM) and new physics processes
- Provides input for the tuning of Monte Carlo (MC) event generators

Cross section comparable with SPS

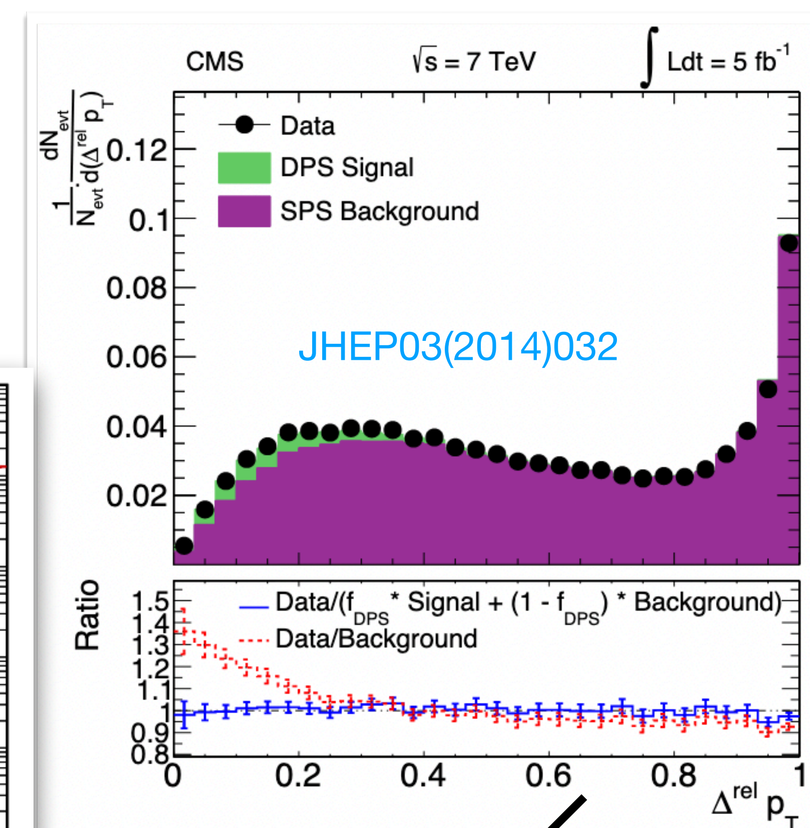


Grows faster than SPS with √s (even more for low-scale processes (J/ψ,Υ, etc.)

Phys. Rev. D79, 094034 (2012



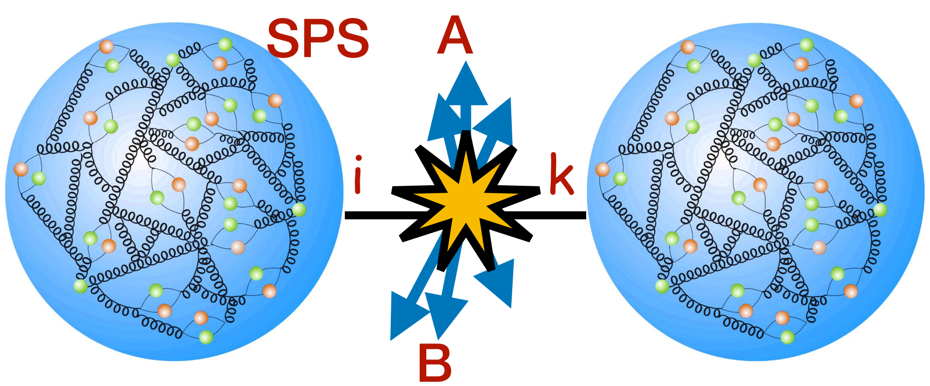
Populates phase space in a different way from SPS



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

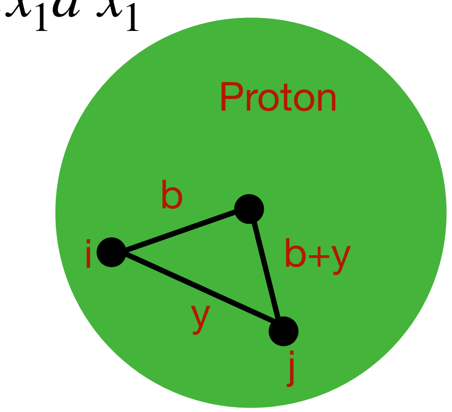
Cross section formula for DPS

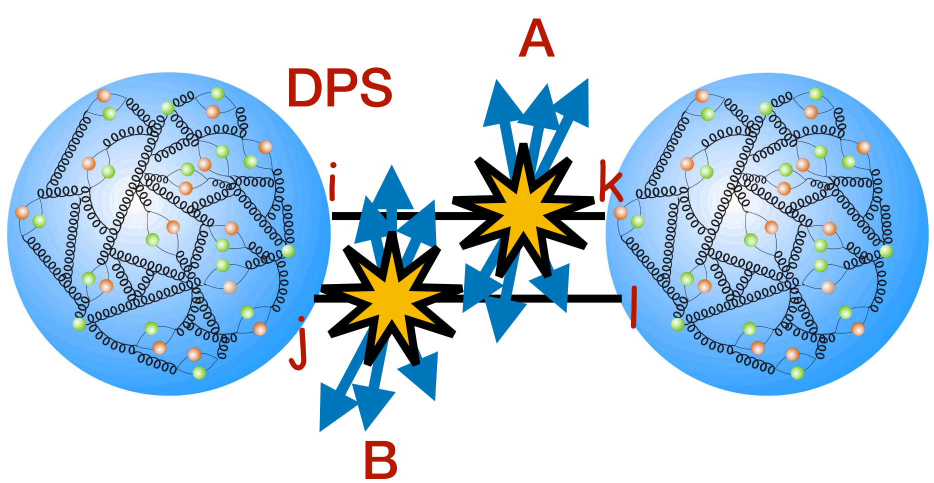
σ^{SPS} = partonic cross section $\otimes$ parton distribution functions



PDFs — partonic cross section

$$\sigma^{\mathrm{SPS}}_{AB} = \sum_{i,k} \int D^i(x_1; Q^2) D^k(x_1', Q^2) \times \hat{\sigma}^{ik}_{AB}(x_1, x_1', Q^2) dx_1 d'x_1$$





double PDFs — partonic cross sections

$$\sigma^{\mathrm{DPS}}_{AB} = \frac{m}{2} \sum_{i,j,k,l} \int \Gamma^{ij}(x_1, x_2; b; Q_A^2, Q_B^2) \times \hat{\sigma}^{ik}_{A}(x_1, x_1', Q_A^2) \hat{\sigma}^{jl}_{B}(x_2, x_2', Q_B^2) \times \Gamma^{kl}(x_1', x_2'; b; Q_A^2, Q_B^2) dx_1 dx_2 dx_1' dx_2' d^2b$$

- double PDFs (dPDFs) with an additional “b” dependence
- Unlike PDFs, dPDFs are missing experimental input; rather scarce theory developments ⇢ DPS cross section formula needs to be “simplified”

DPS pocket formula

Strategy: assume that the two hard interactions are independent

double PDFs — partonic cross sections

$$\sigma_{AB}^{\mathrm{DPS}} = \frac{m}{2} \sum_{i,j,k,l} \int \Gamma^{ij}(x_1, x_2; b; Q_A^2, Q_B^2) \times \hat{\sigma}_A^{ik}(x_1, x_1', Q_A^2) \hat{\sigma}_B^{jl}(x_2, x_2', Q_B^2) \times \Gamma^{kl}(x_1', x_2'; b; Q_A^2, Q_B^2) dx_1 dx_2 dx_1' dx_2' d^2b$$

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

Simplified expression for σ^{DPS} → pocket formula

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

m=1 if A=B else 2

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

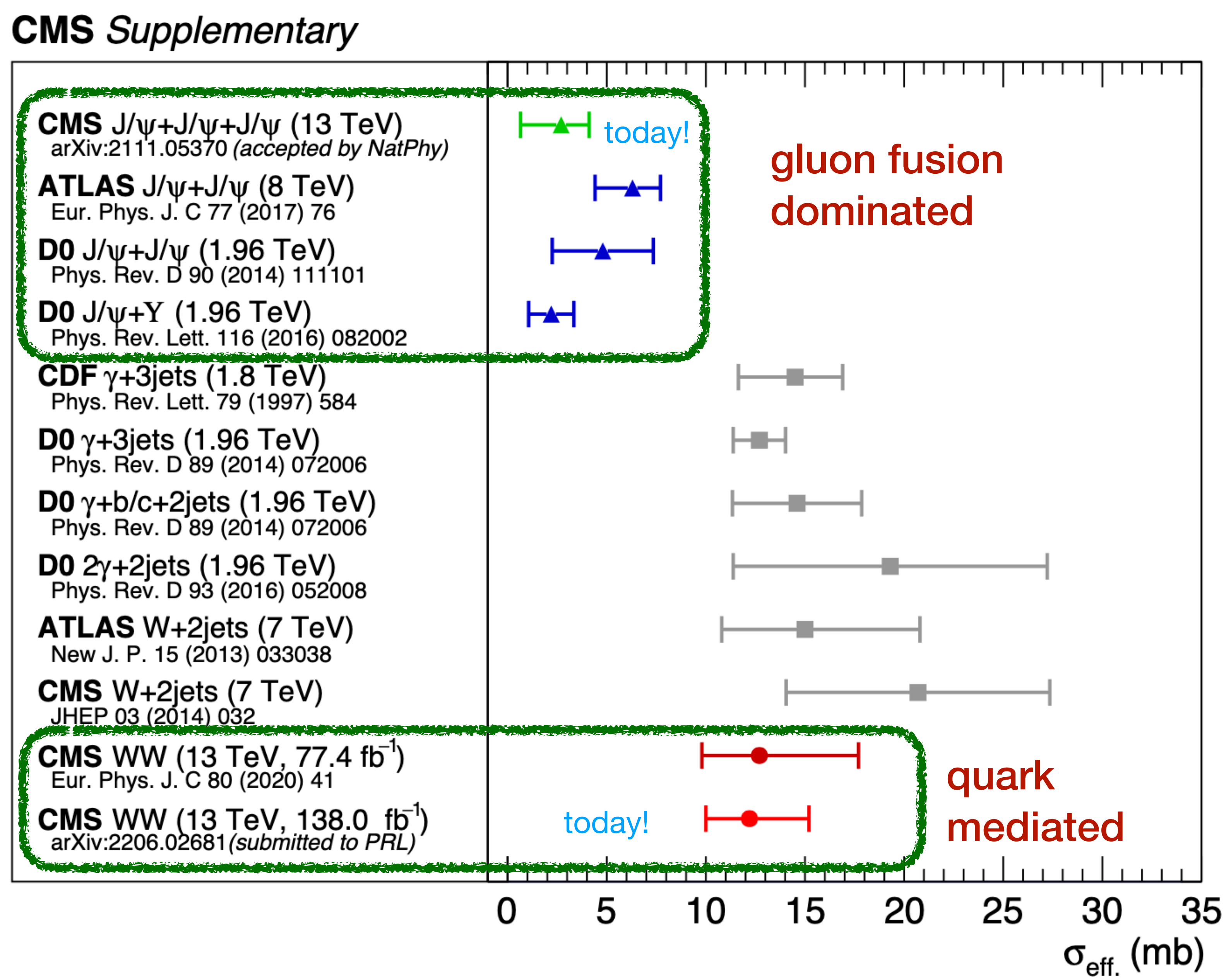
used in existing phenomenological models

σ_{eff} : effective cross section for DPS

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

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"



- Pythia8: 20-30 mb

(large tune dependence)

- Measurements: 5-20 mb

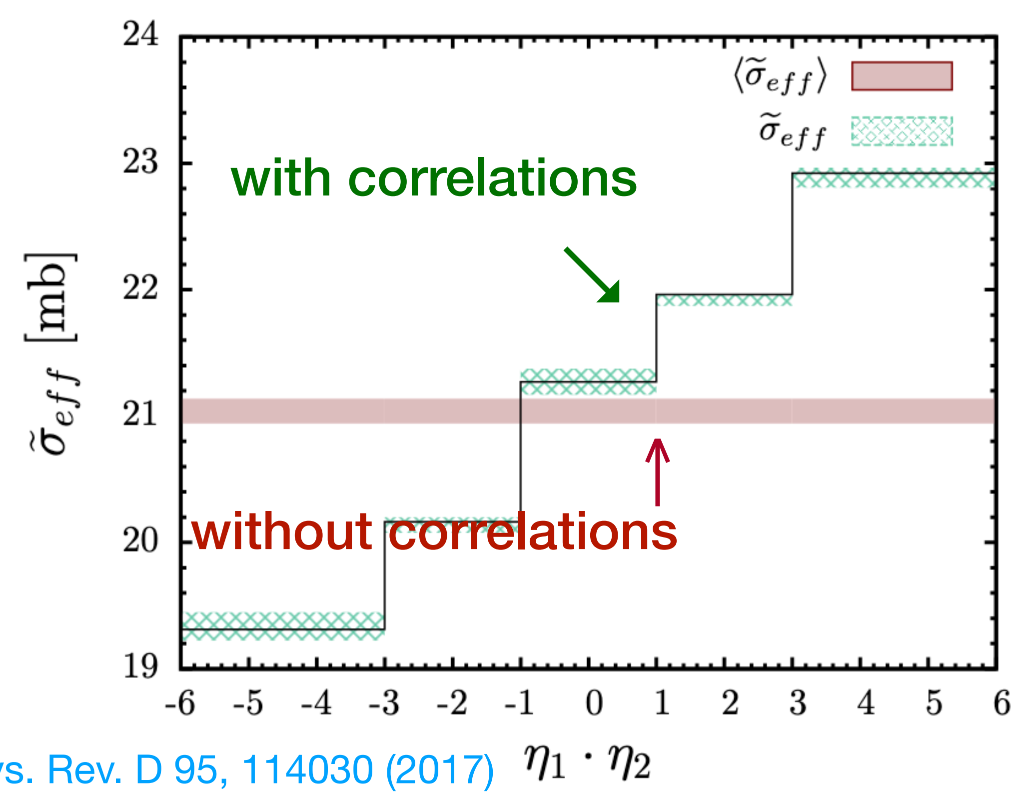
- Inter-parton correlations?
- Parton-flavor dependence (quark/gluon)?
- Flaws in DPS factorization?

Beyond the factorization approach

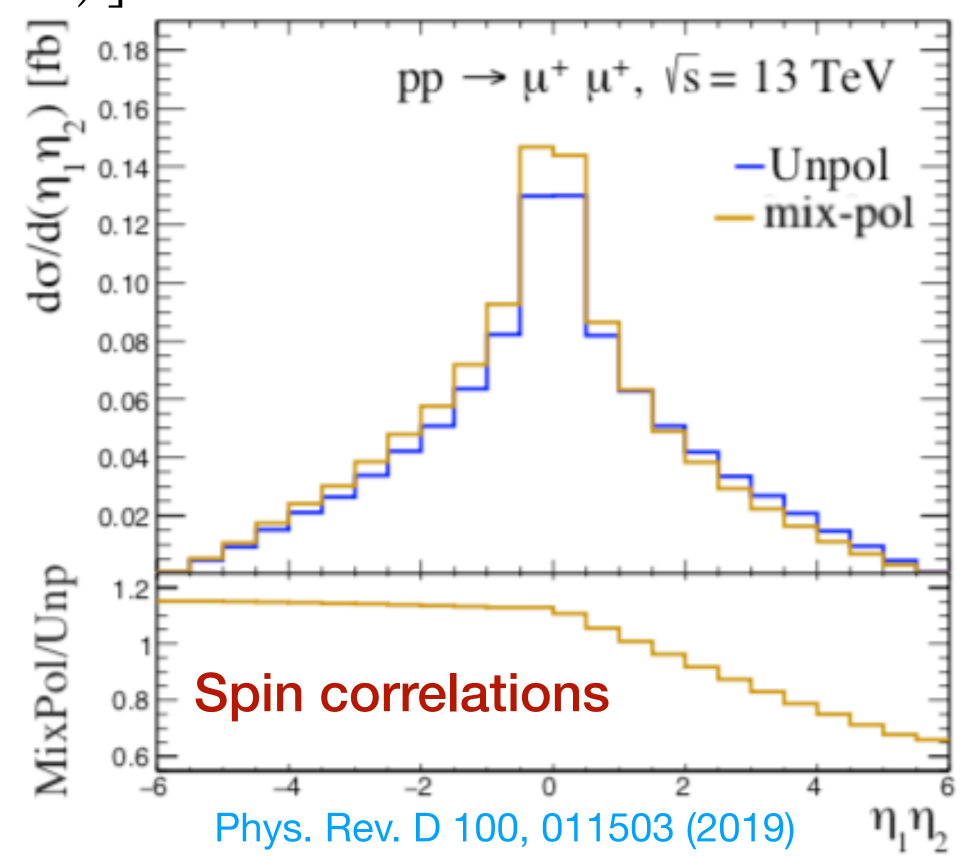
- Factorization can't be the complete picture; dPDFs ≠ pdf x pdf $\forall$ x
  - Subtle hints from measurements
  - dPDFs must obey "sum" rules $x_1+x_2 \leq 1$, $\int_0^1 f_{u_v}(x,\mu^2)\,dx = 2, \quad \int_0^1 f_{d_v}(x,\mu^2)\,dx = 1$
- Lots of progress towards a more complete description of DPS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



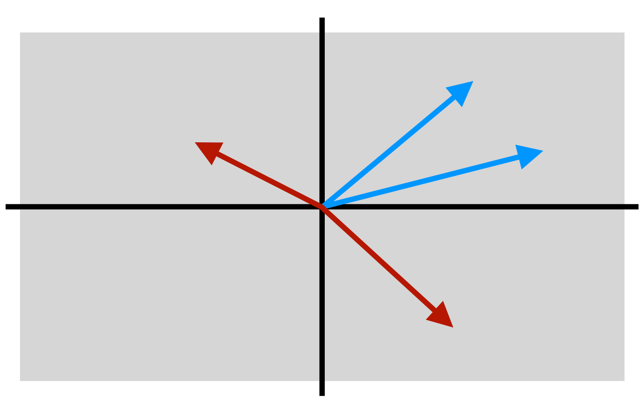
Phys. Rev. D 100, 011503 (2019)

DPS simulation models

- LO samples from Pythia/Herwig ⇢ 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

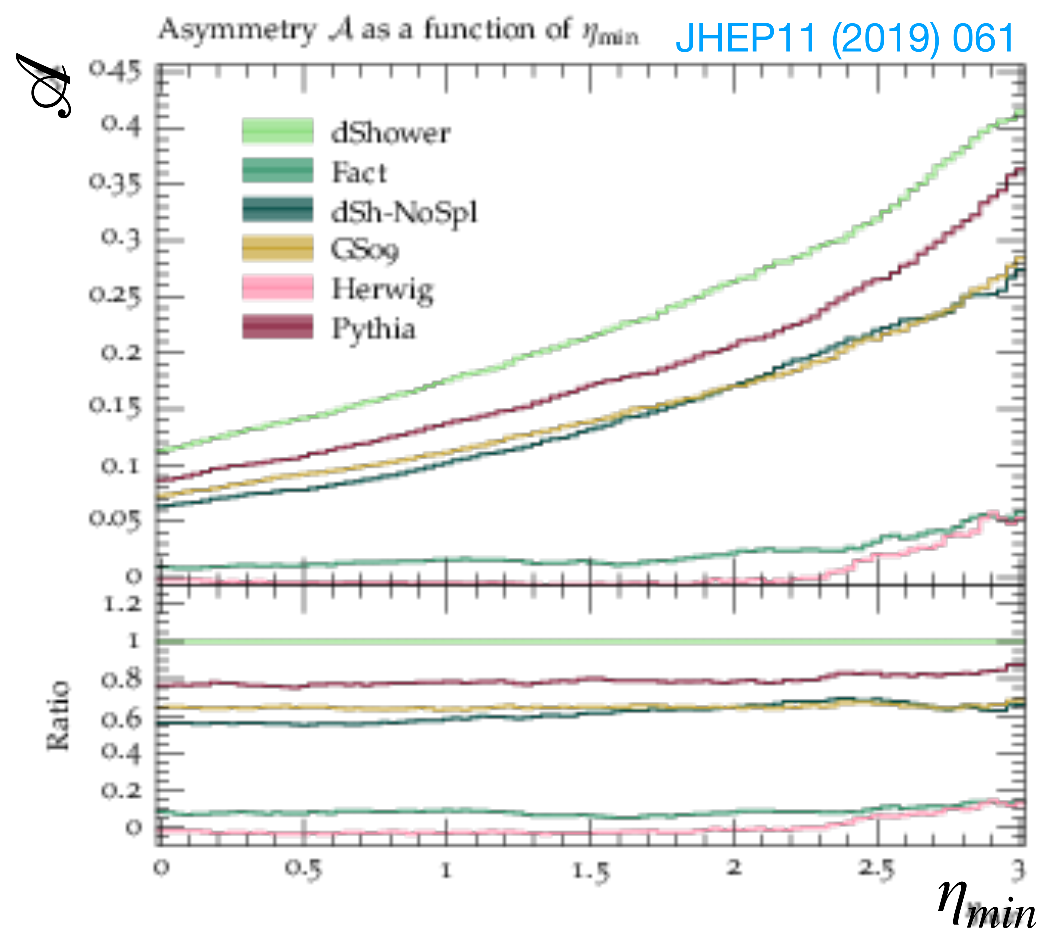
$\mathscr{A}$: leptons in different or same detector hemispheres

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



$\mathscr{A} = 0$ ⇢ uncorrelated

$\mathscr{A} > 0$ ⇢ correlated



JHEP11 (2019) 061

Anatomy of a DPS analysis

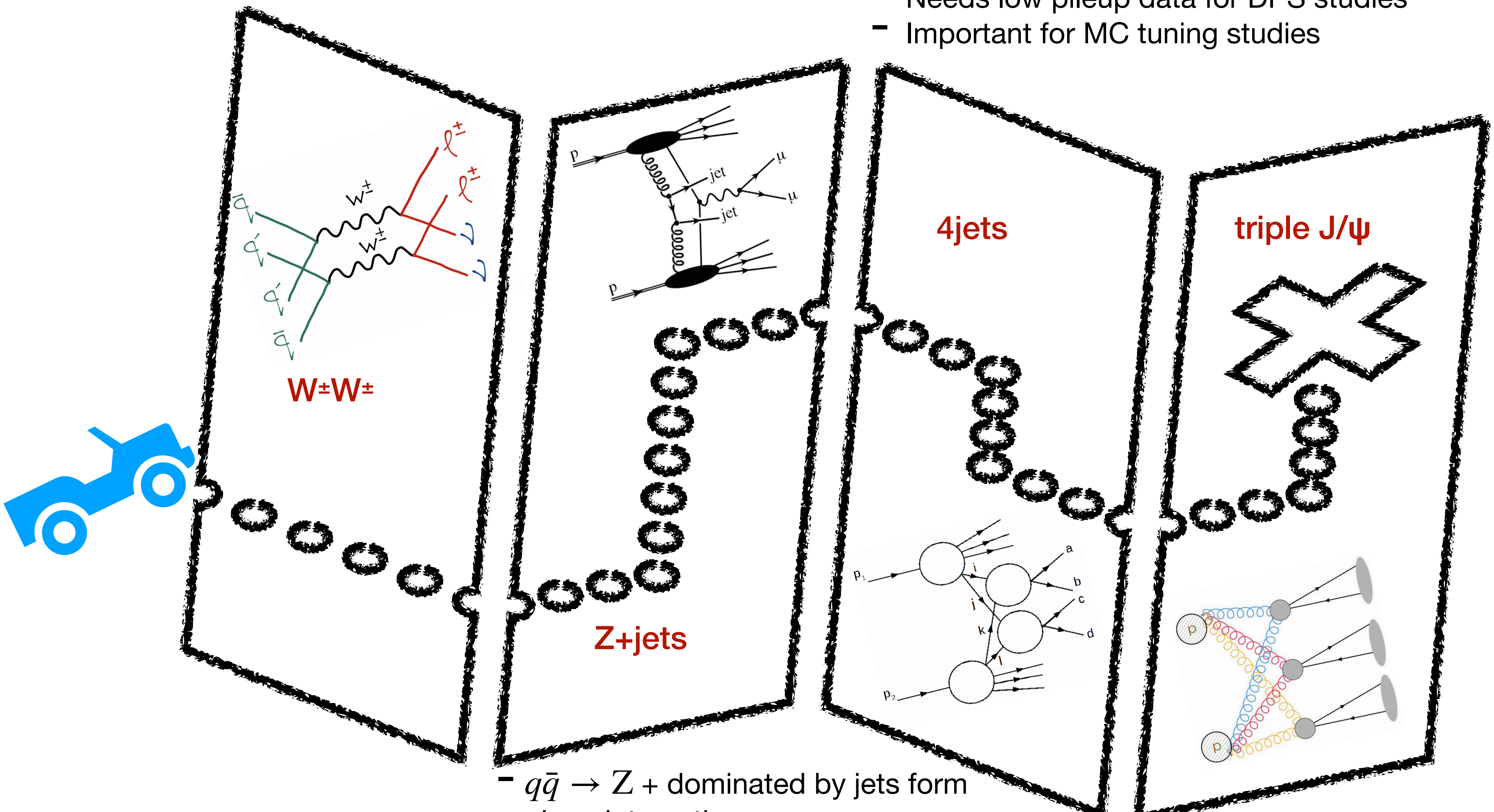
- Target a final state
  - depends on the physics objective
  - either a process with high production cross section (multijets) or one with experimentally clean final state (W/Z/J/ψ)

- 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

- 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

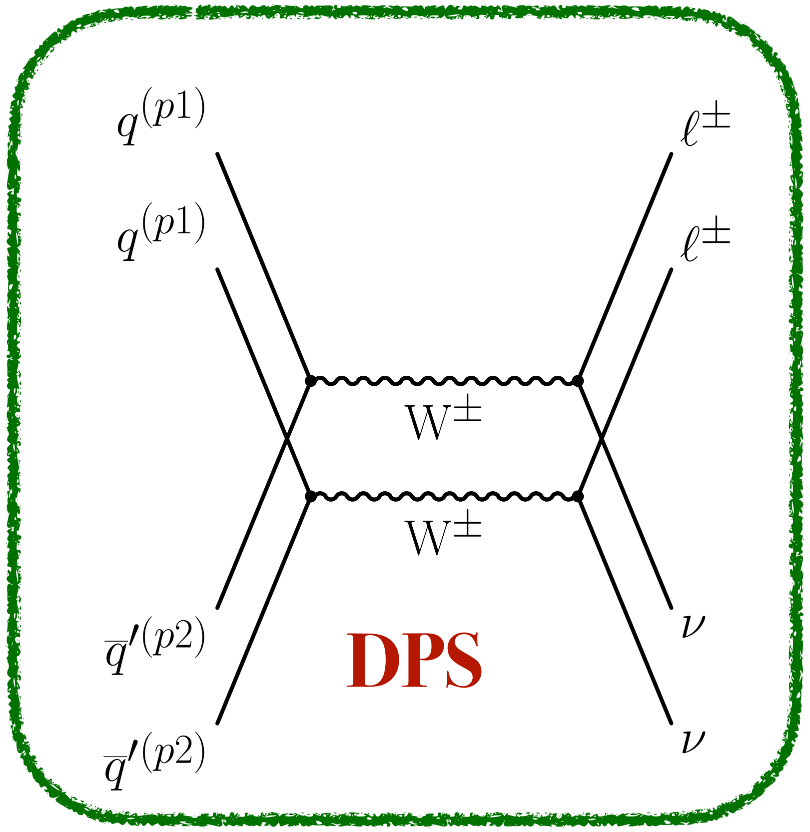
- Dominated by gluon interactions
- Experimentally clean
- Important for DPS &TPS

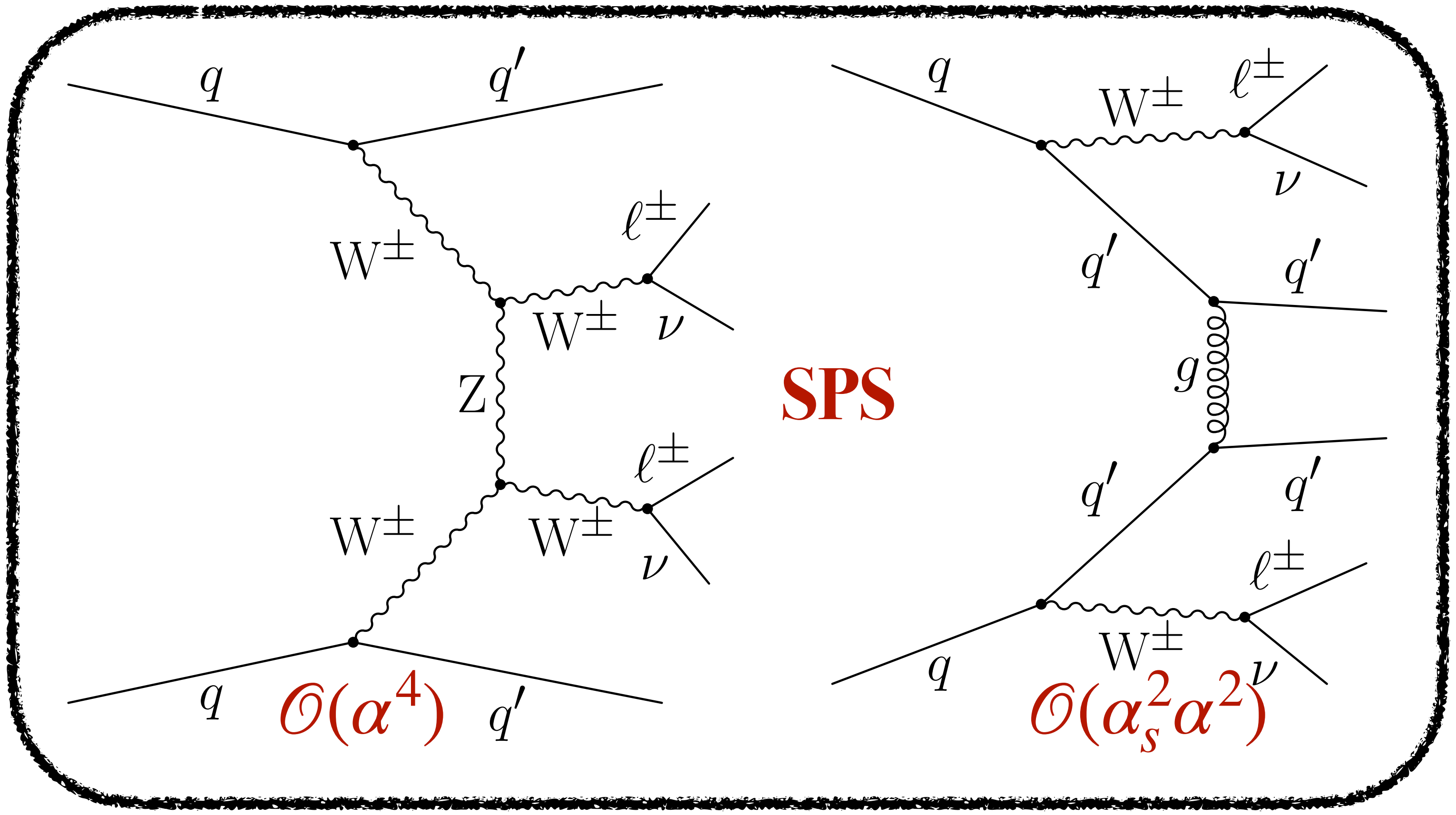
decreasing Q²

arXiv:2206.02681

DPS with W±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± ⇢ 2l2ν ~ 86 fb @13TeV





- Sensitive to inter-parton correlations (theoretically very "famed")
- 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

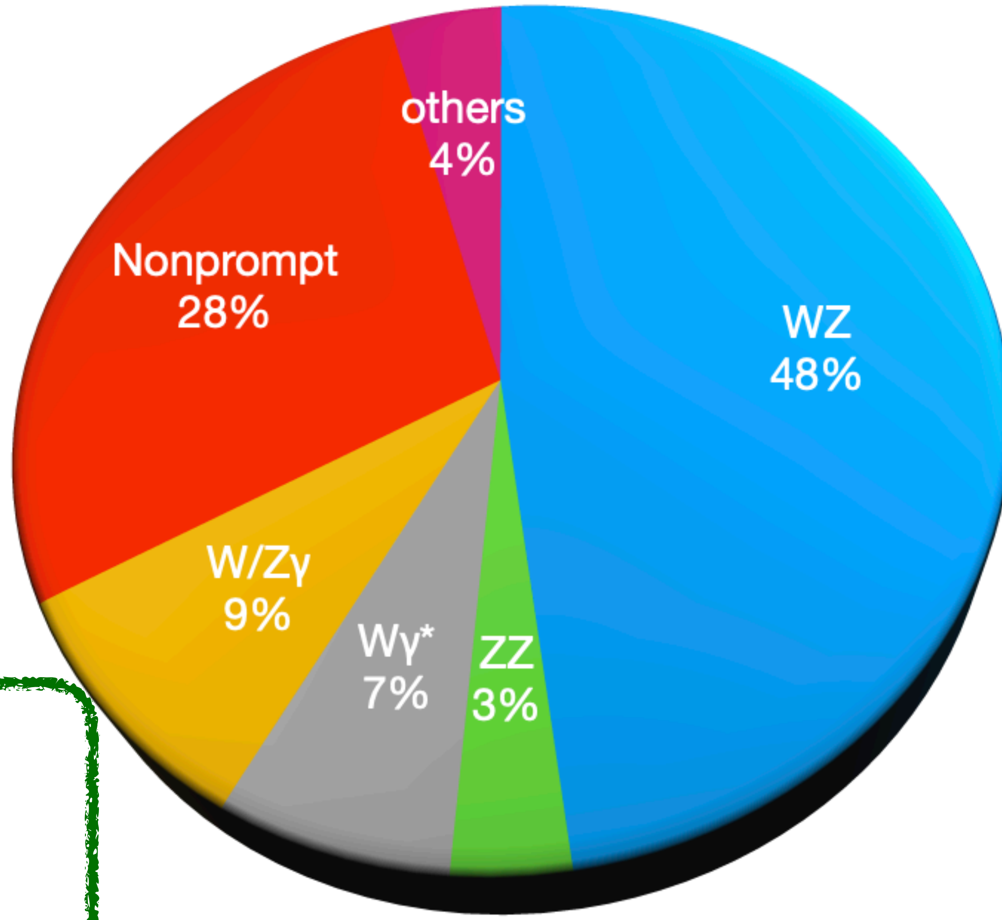
- Signal cross section extracted using binned maximum likelihood fit to the shape of the BDT classifier

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

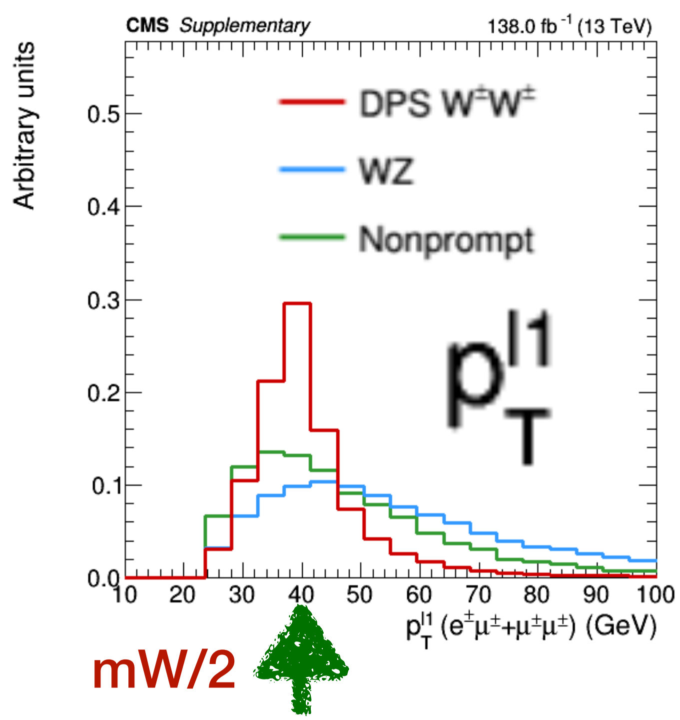
- Dominant contribution from WZ⇢3lν; one lepton from Z is lost
  - Kinematically very similar to the signal process
- Nonprompt lepton contributions (W+jets, QCD multijets, and semi-leptonic decays of $t\bar{t}$)
- Prompt lepton contributions also from:
  - Wγ*, ZZ, SPS $W^{\pm}W^{\pm}$, VVV, $t\bar{t}V$
  - Photon conversions (W/Zγ) Only in eμ channel
  - Lepton charge misidentification ($t\bar{t}$, DY, WW) (data-driven estimation)



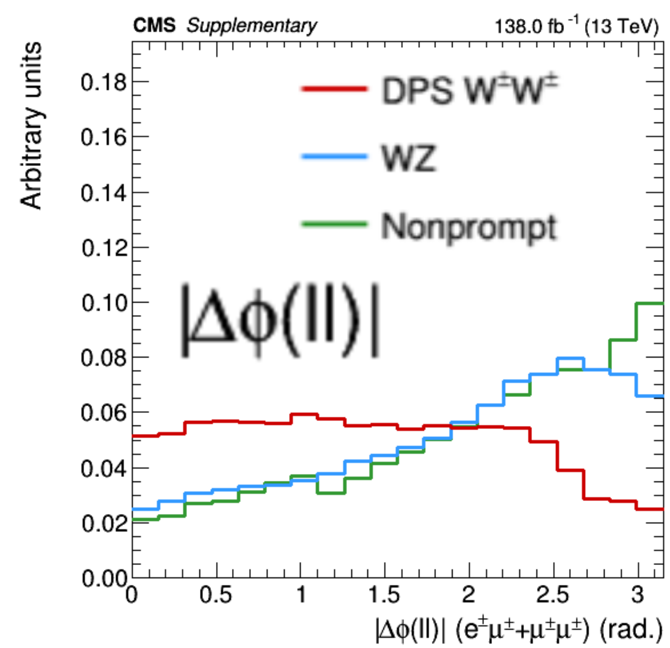
- Two separate BDT classifiers for WZ & nonprompt

BDT classifiers

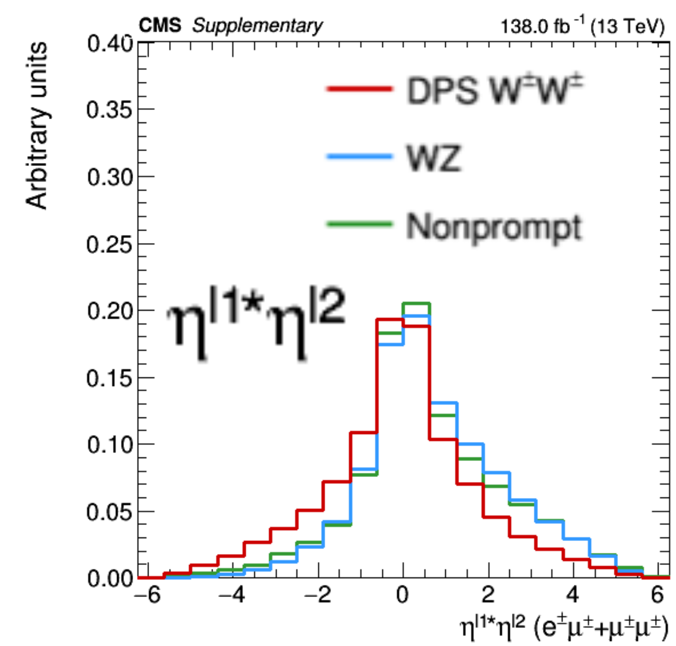
- Training variables ⇢ kinematic differences between (uncorrelated) signal & (correlated) backgrounds



mW/2



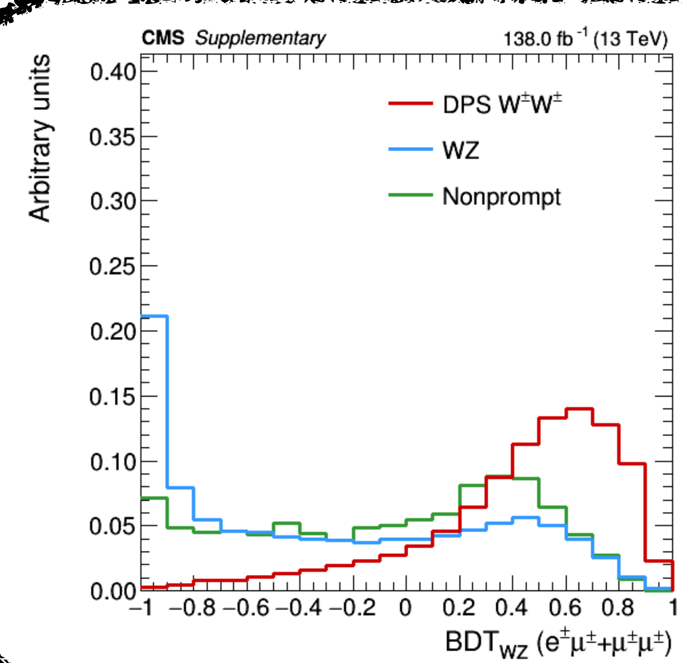
relatively flat signal

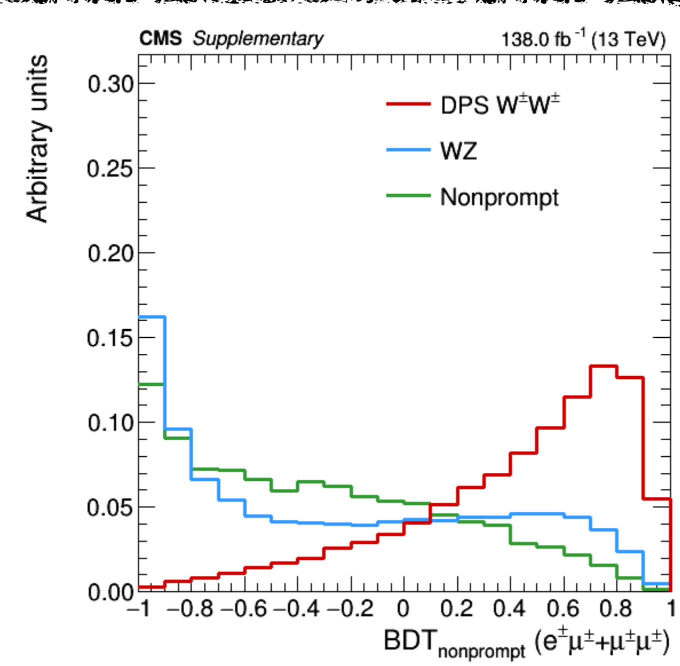


sensitive to correlations

training variables

$\mathrm{pT}_{l_{1,2}}$	$\mathrm{m_T}(\mathrm{l}_1, p_\mathrm{T}^\mathrm{miss})$
$p_\mathrm{T}^\mathrm{miss}$	$\mathrm{m_T}(\mathrm{l}_1, \mathrm{l}_2)$
$\mathrm{M}_\mathrm{T2}^\mathrm{ll}$	$\Delta\phi(l_1, l_2)$
$\eta_1 \times \eta_2$	$\Delta\phi(l_2, p_\mathrm{T}^\mathrm{miss})$
$\lvert\eta_1 + \eta_2\rvert$	$\Delta\phi(l_1 l_2, l_2)$

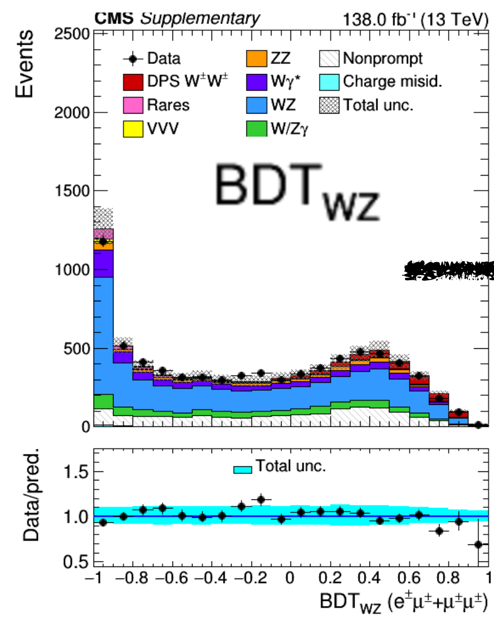




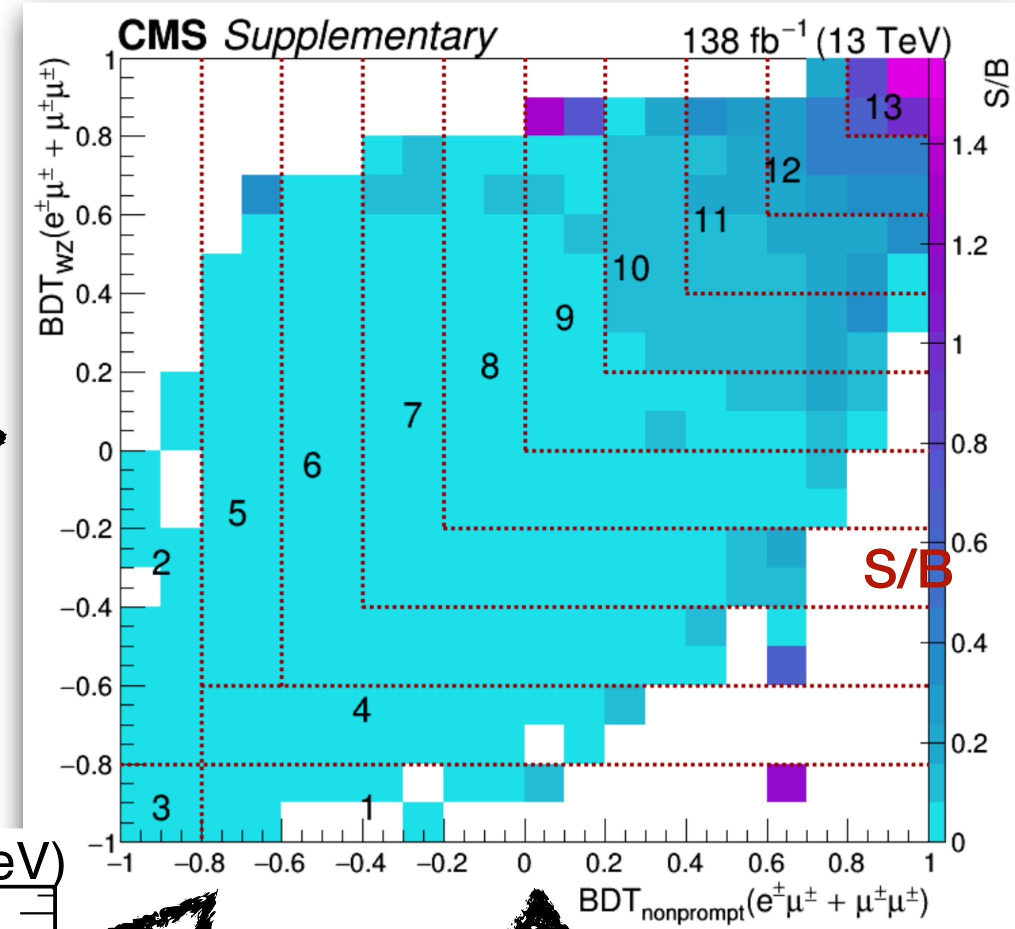
Statistical analysis

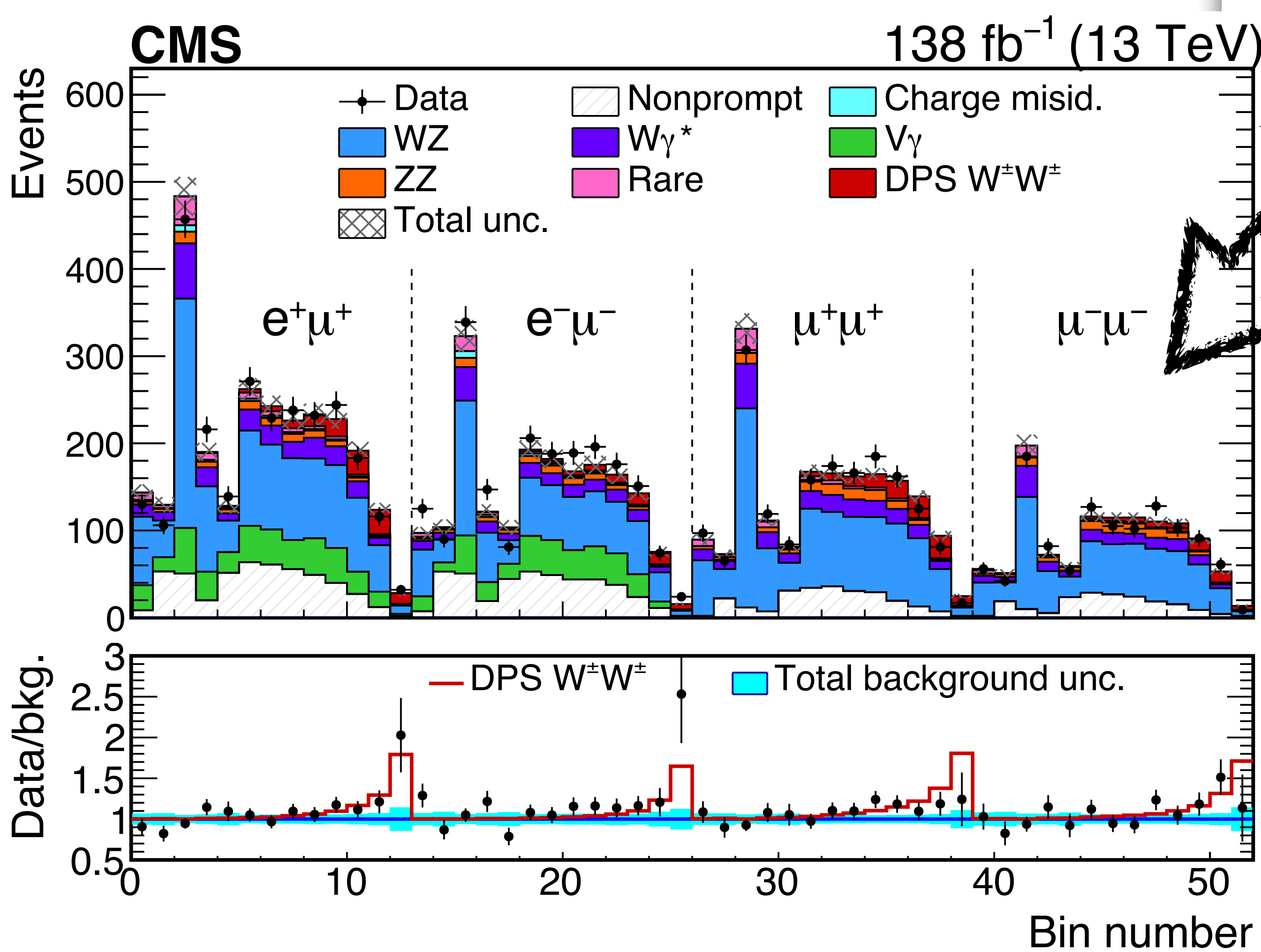
Two BDTs ⇢ 1D distribution

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

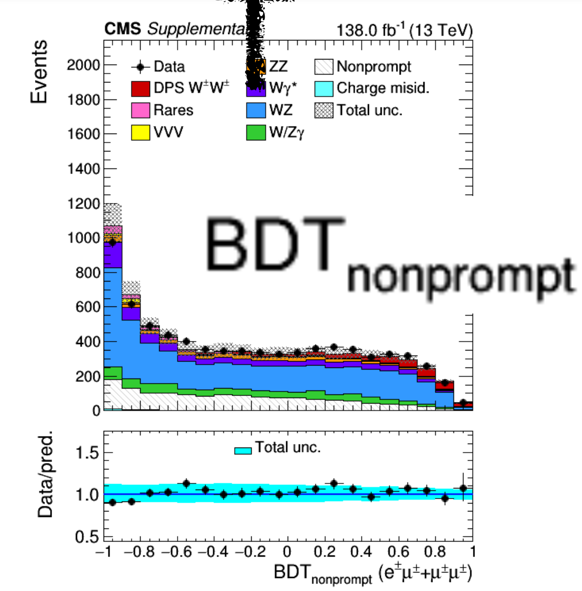


high purity bins





signal visible in highest BDT bins



Results

First observation of $W^{\pm}W^{\pm}$ via DPS with 6.2 s.d. (obs.)

Inclusive $W^{\pm}W^{\pm} \to 2l2\nu$ cross section

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

Fiducial cross section

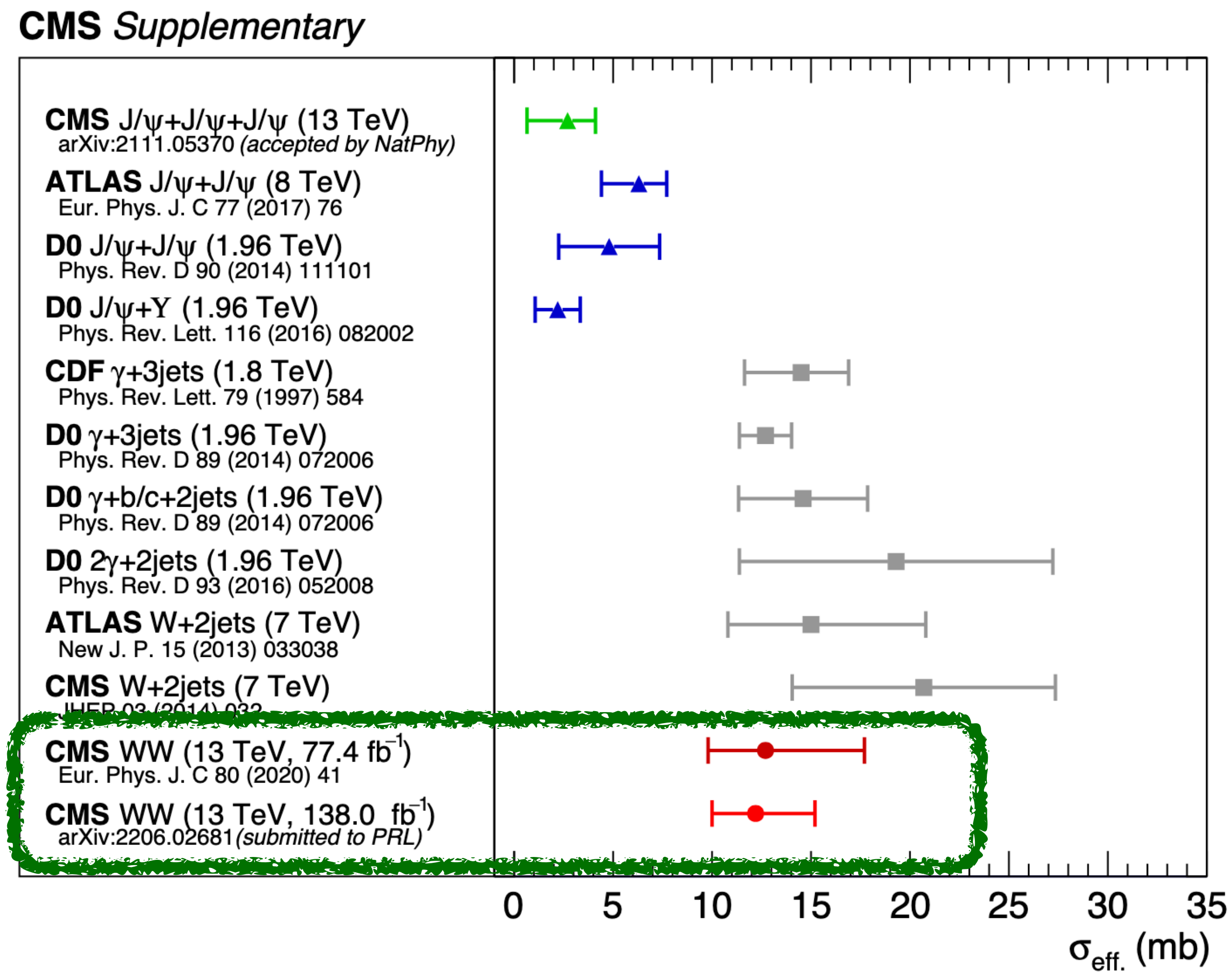
$$6.28 \pm 0.81\,(\mathrm{stat}) \pm 0.69\,(\mathrm{syst}) \pm 0.37\,(\mathrm{model})\,\mathrm{fb}$$

from Herwig: difference in reconstruction

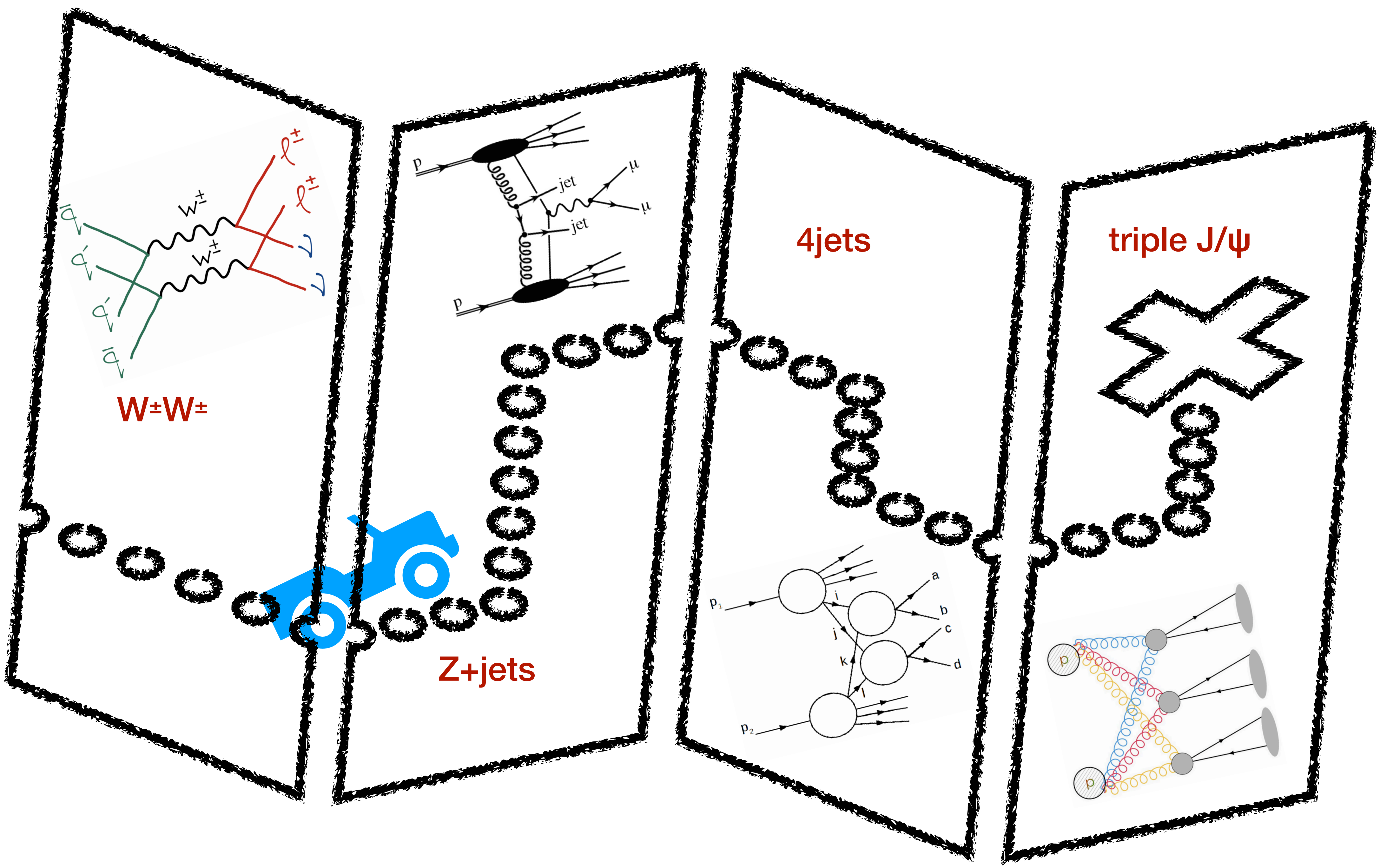
Efficiencies for leptons & generator acceptance

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



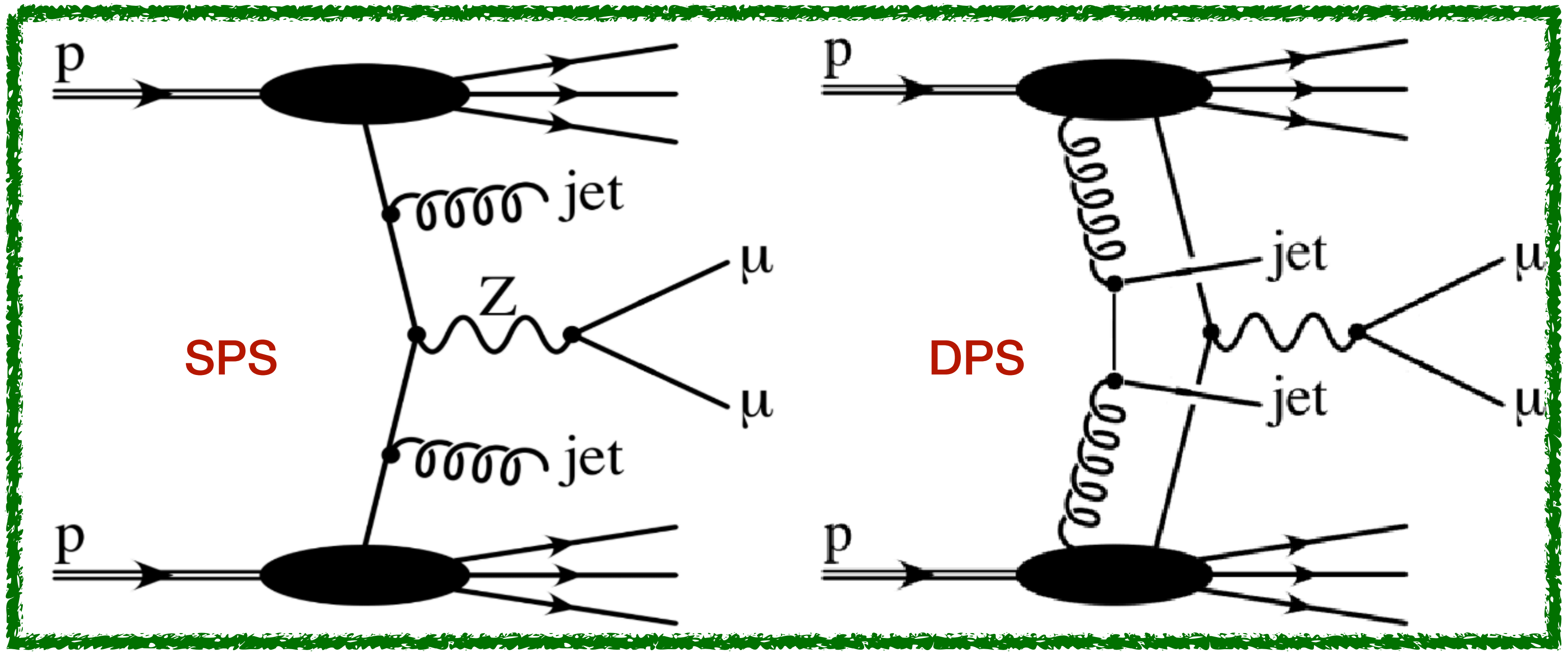
W±W±
Z+jets
4jets
triple J/ψ

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

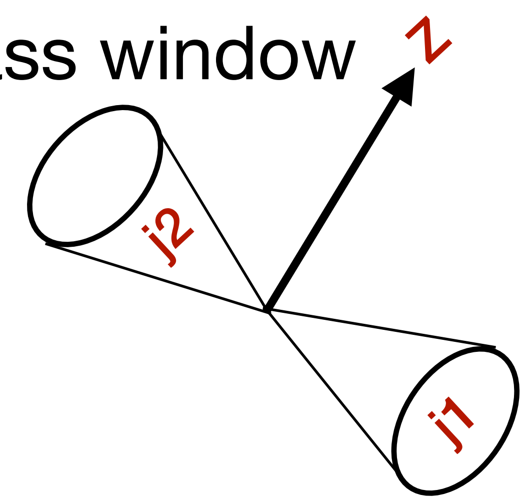
Z+jets events to explore observables sensitive to the presence of DPS

- 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 13TeV
- Clean experimental signature with Z→μμ
- 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

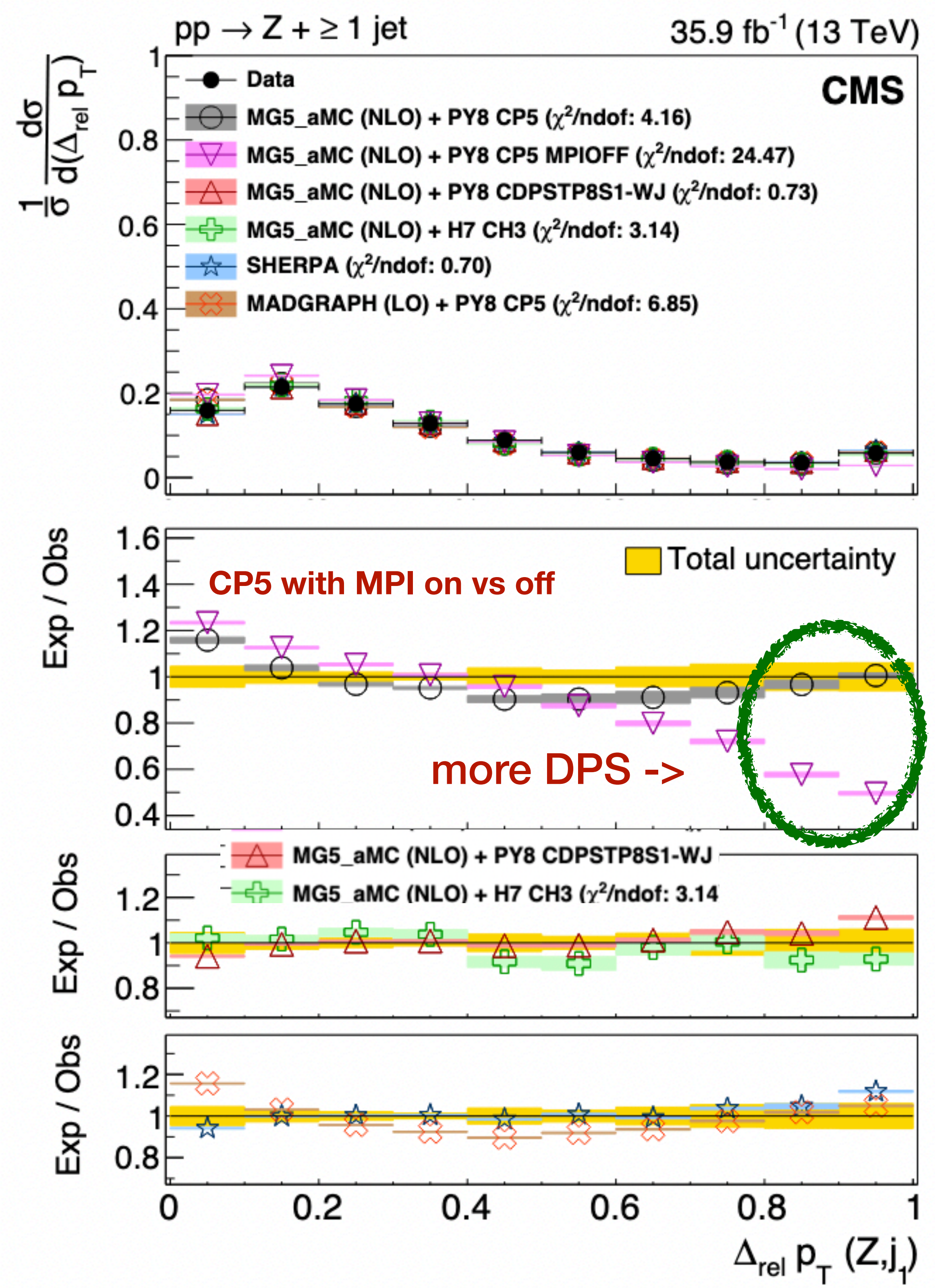
Cross section (pb)		Z+ $\geq$1 Jets	Z+ $\geq$2 Jets
Measured in data		158.5 ± 0.3 (stat) ± 7.0 (syst) ± 1.2 (theo) ± 4.0 (lumi) pb	44.8 ± 0.4 (stat) ± 3.7 (syst) ± 0.5 (theo) ± 1.1 (lumi) pb
Predicted by MC			
MG5_aMC (NLO)	PYTHIA8, CP5 tune	167.4 ± 9.7	47.0 ± 3.9
	PYTHIA8, CP5 tune MPIOFF	143.8 ± 0.3	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

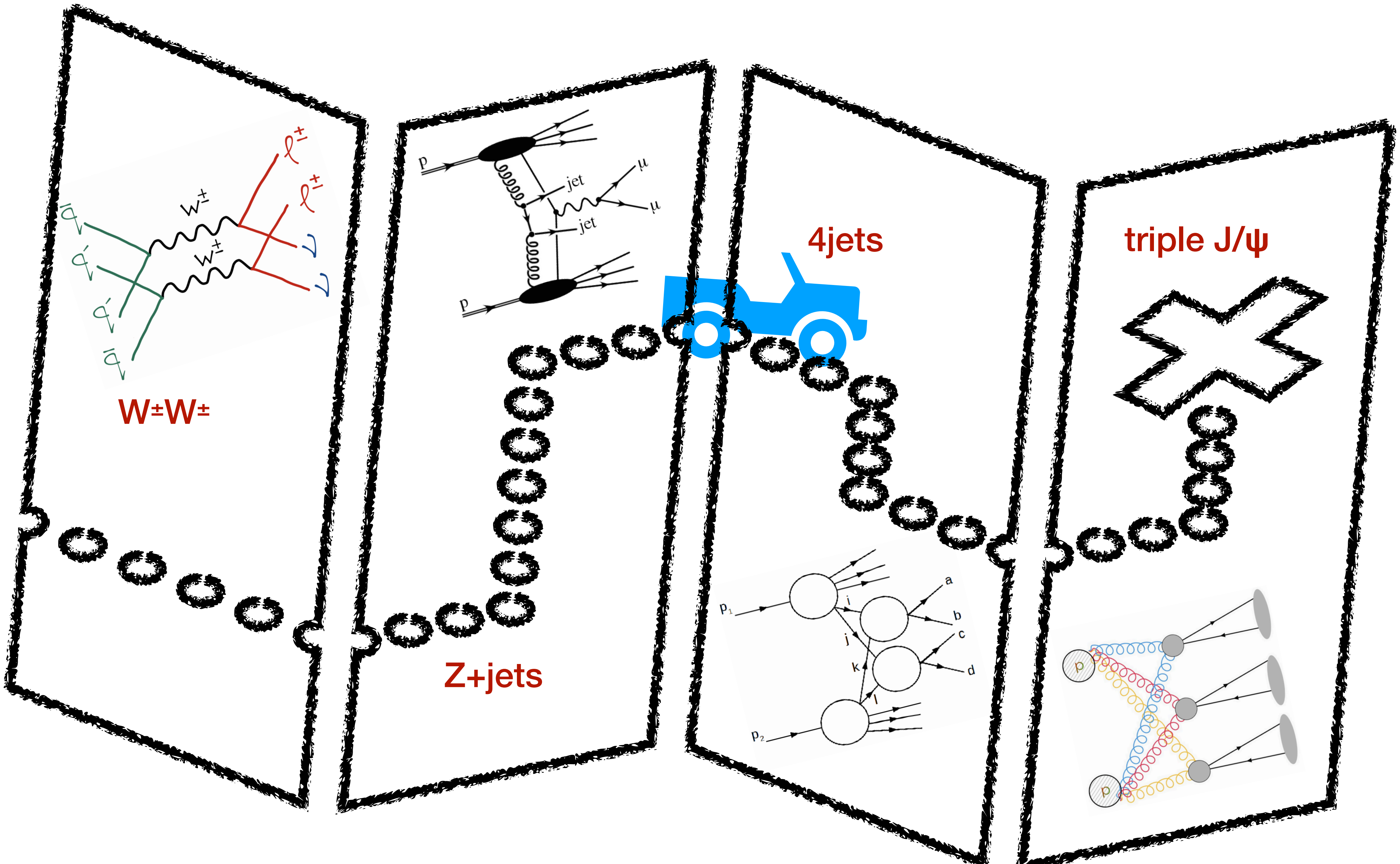
- CP5 tune with MPIoff underestimates the measurement ~10(16)% for Z+ ≥1(2) jet events
- DPS-specific tune over predicts the cross section by 10%
- Well described by Sherpa, MG+Py8 (CP5) & MG+Hw7

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




W±W±
Z+jets
4jets
triple J/ψ

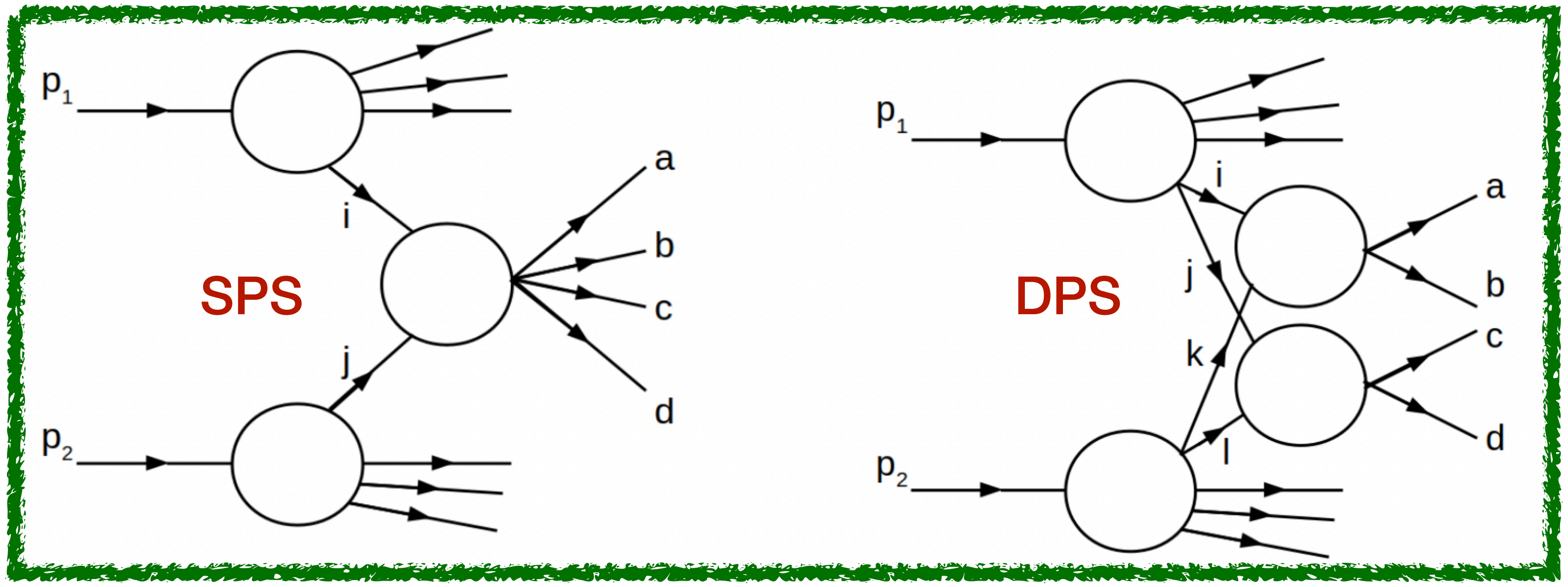
DPS with 4jets

- 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 (<μ> = 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: $\Delta\phi_{Soft} = |\phi_3 - \phi_4|$

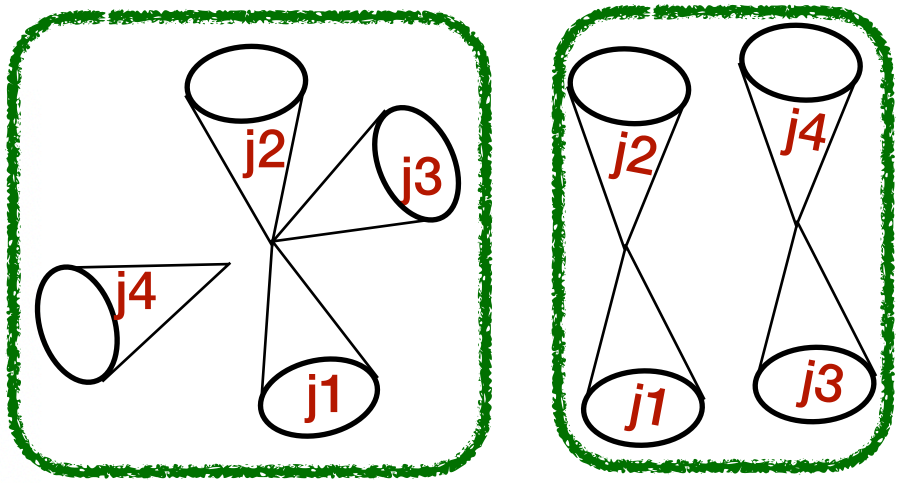
Combined minimum angle of 3 jets: $\Delta\phi_{3j}^{min} = min_{ijk}\{|\phi_i - \phi_j| + |\phi_j - \phi_k|\}$

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 $\Delta Y = max_{ij}\{|\eta_i - \eta_j|\}$

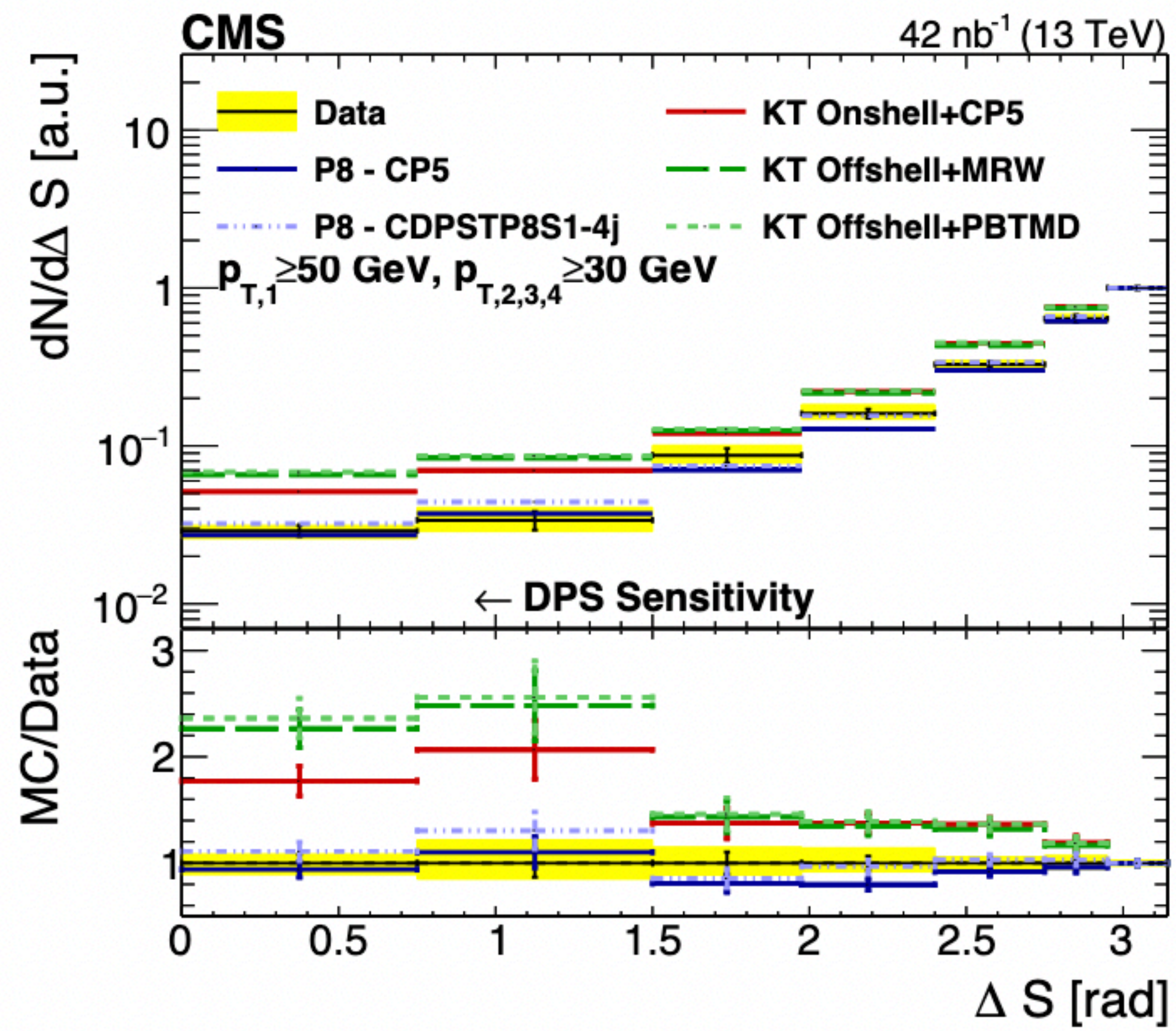
Azimuthal angle between the hardest and the softest jet pair $\Delta S = \arccos\left(\frac{(\vec{p}_{T,1} + \vec{p}_{T,2}) \cdot (\vec{p}_{T,3} + \vec{p}_{T,4})}{|\vec{p}_{T,1} + \vec{p}_{T,2}| \cdot |\vec{p}_{T,3} + \vec{p}_{T,4}|}\right)$



most sensitive to DPS

Results

- Distribution normalized to the last bin (having lowest DPS contribution)
- Py8 with CDPSTP8S1-4j tune describes the data well



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

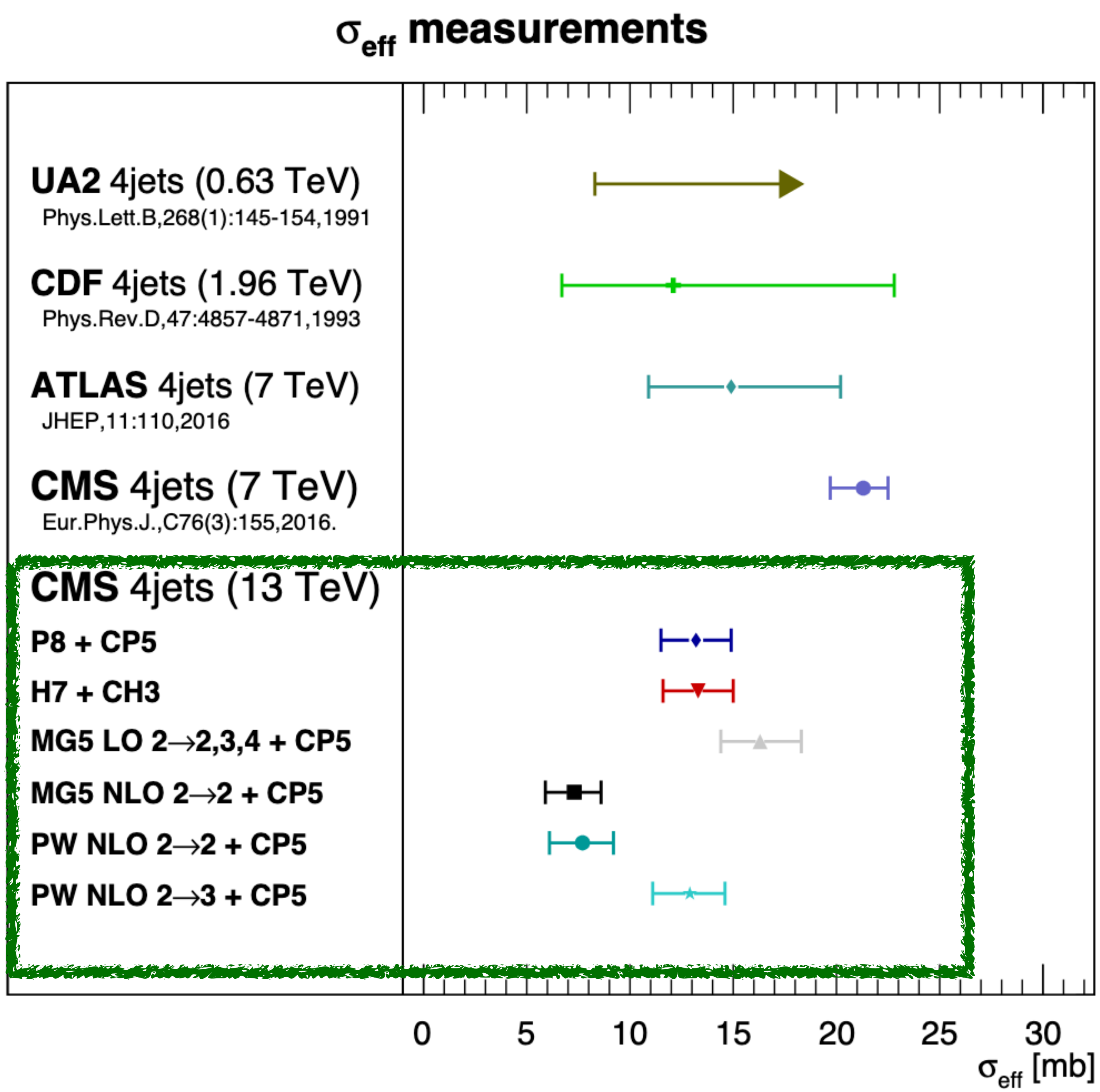
$$\sigma^{\text{DPS}}_{\text{A,B}} = f_{\text{DPS}} \int \sigma^{\text{data}}(\Delta S)\text{d}(\Delta S).$$

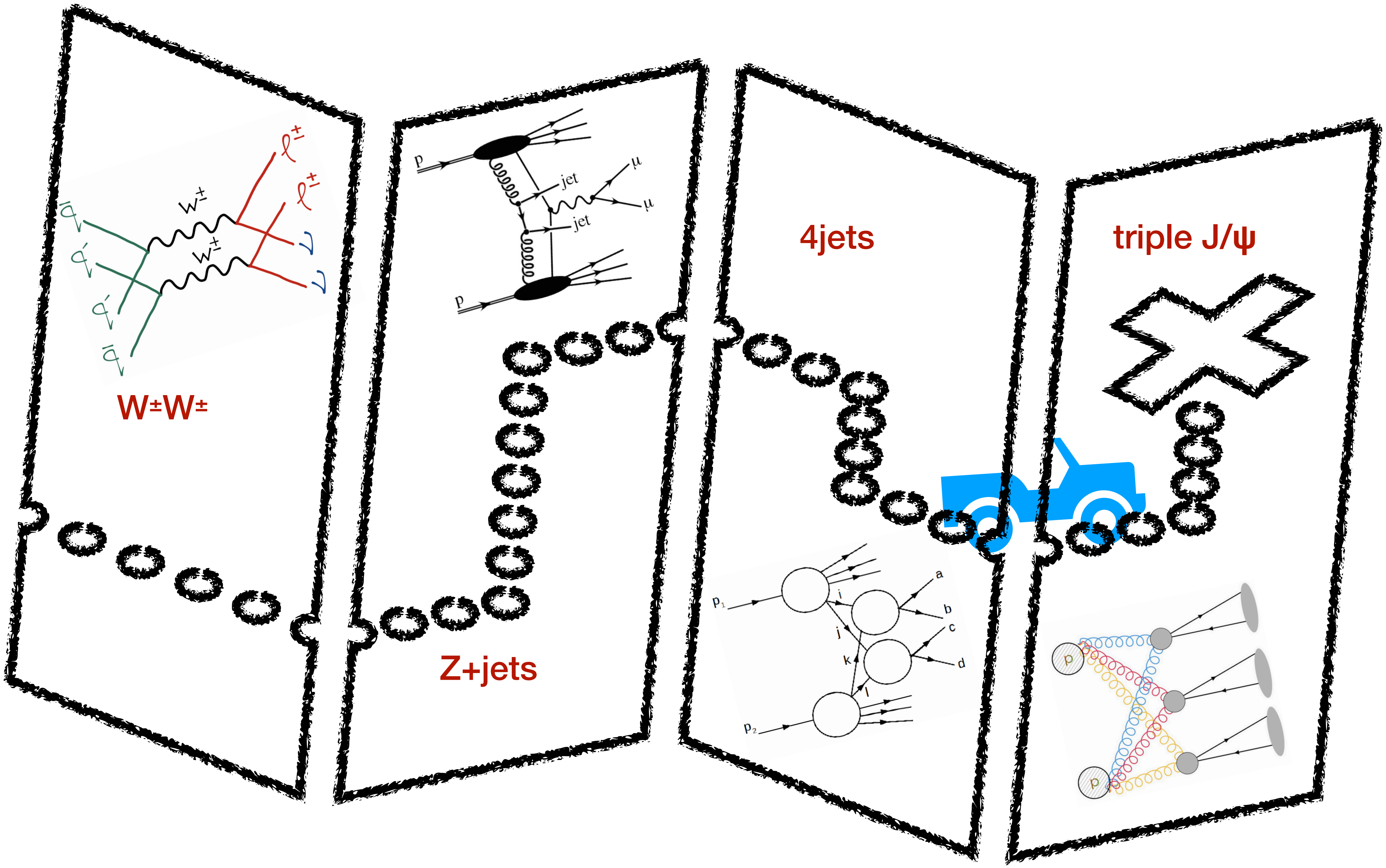
→ Pocket formula → σ_{eff}

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

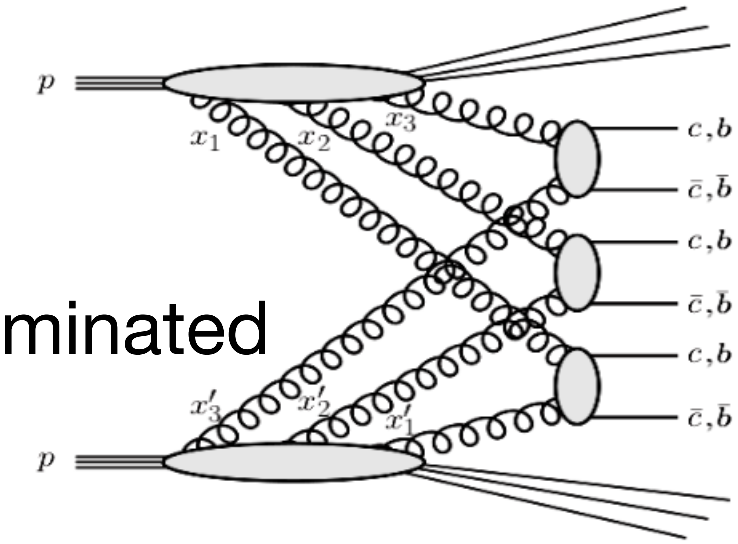




W±W±
Z+jets
4jets
triple J/ψ

arXiv:2111.05370

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

Generalised cross section and pocket formulae

triple parton distribution functions

transverse position of partons

$$\sigma^{\rm TPS}_{hh'\to abc} = \frac{m}{3!}\sum_{i,j,k,l,m,n}\int \Gamma^{ijk}_{h}(x_1,x_2,x_3;\mathbf{b_1},\mathbf{b_2},\mathbf{b_3};Q_1^2,Q_2^2,Q_3^2)$$
$$\times\hat{\sigma}^{il}_{a}(x_1,x_1',Q_1^2)\hat{\sigma}^{jm}_{b}(x_2,x_2',Q_2^2)\hat{\sigma}^{kn}_{c}(x_3,x_3',Q_3^2)$$
$$\times\Gamma^{lmn}_{h'}(x_1',x_2',x_3';\mathbf{b_1}-\mathbf{b},\mathbf{b_2}-\mathbf{b},\mathbf{b_3}-\mathbf{b};Q_1^2,Q_2^2,Q_3^2)$$
$$\times dx_1dx_2dx_3dx_1'dx_2'dx_3'd^2b_1d^2b_2d^2b_3d^2b.$$

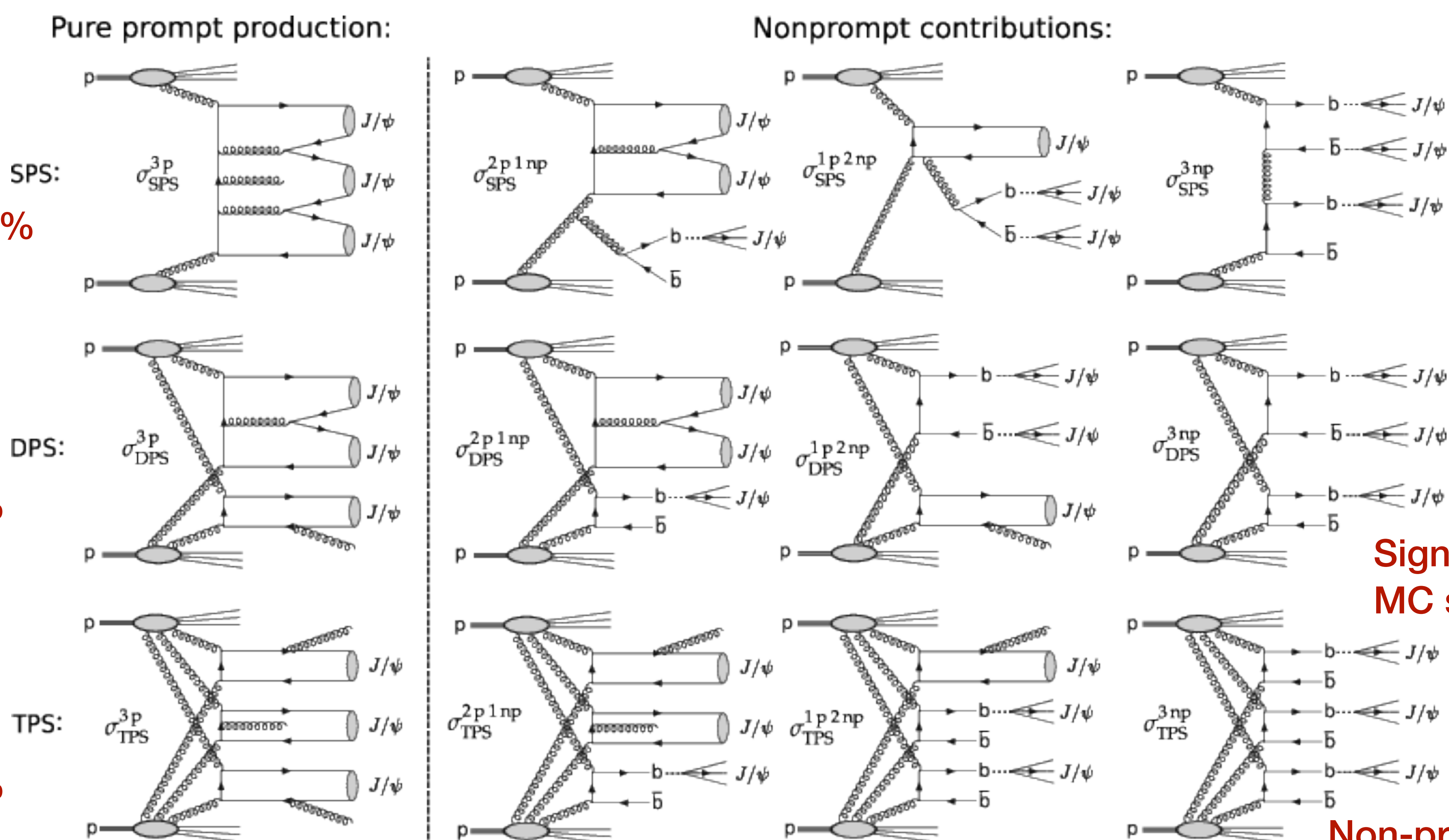
T(b): transverse hadron-hadron overlap function

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

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

Triple J/ψ production

- Prompt + non-prompt J/ψ production in pp collisions
- SPS negligible ⇢ Golden channel for DPS and TPS studies



6%

74%

20%

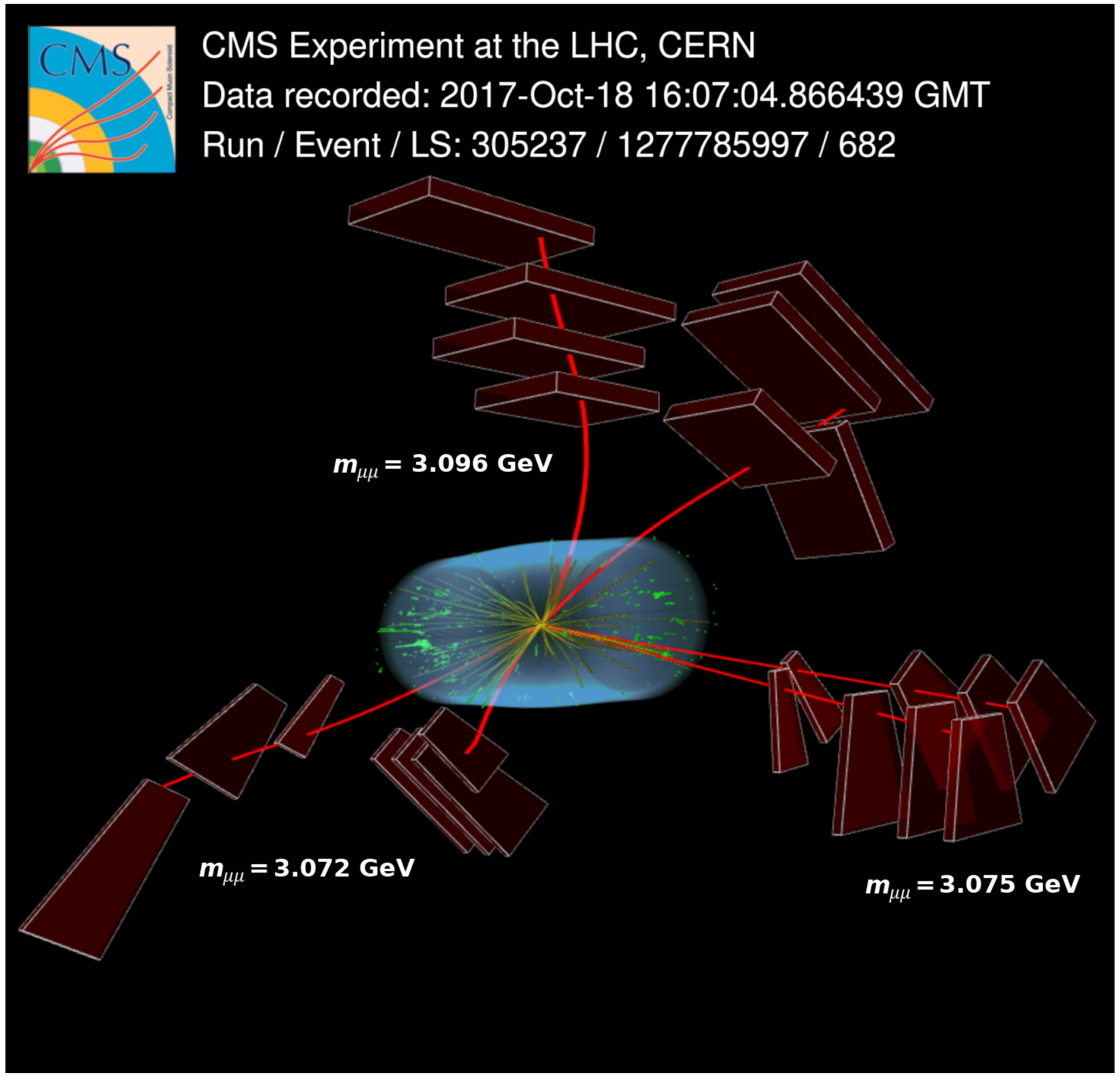
Signal modeling from MC simulation

Non-prompt contribution from MG while prompt using HELAC-ONIA

Event selection

- pp collisions at 13 TeV with integrated luminosity 133 fb^{-1}
- Experimentally clean and pure final states with (six) muons

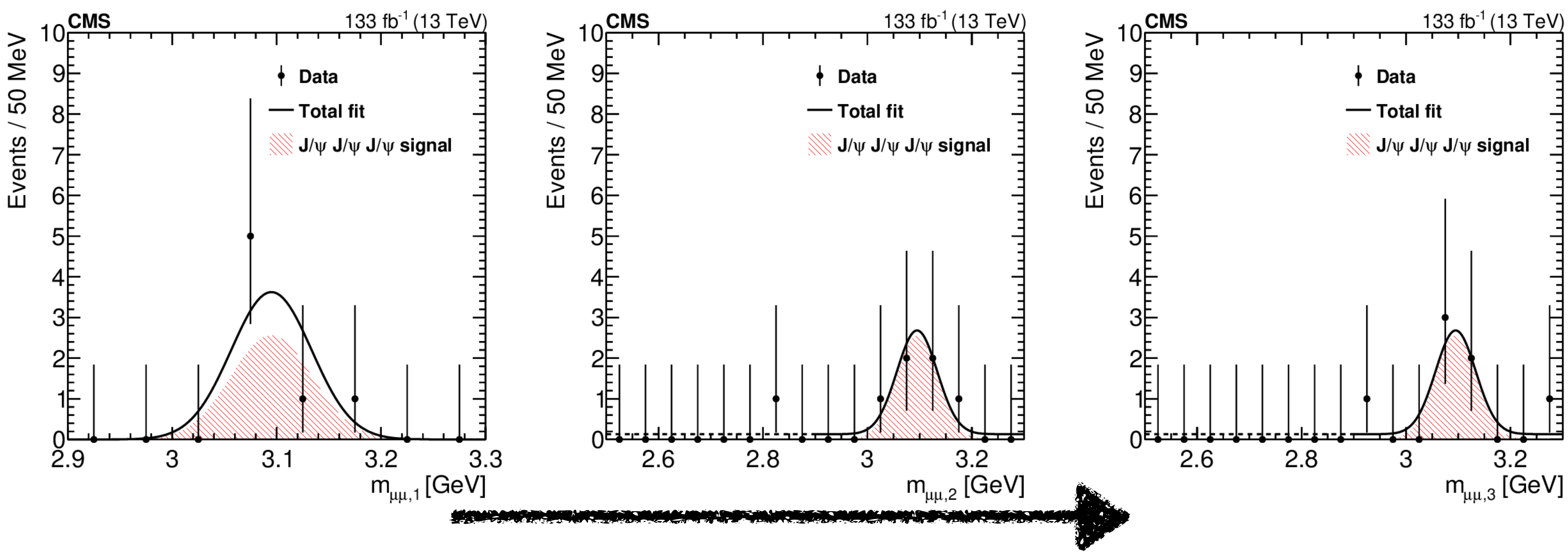
- Triple muon trigger (84% efficient):
  - $p_T > 3.5$ GeV (barrel), $p_T > 2.5$ GeV (endcaps)
  - at least one $\mu^{\mp}\mu^{\pm}$ with $2.8 < m_{\mu\mu} < 3.35$ GeV from same vertex
- Offline selection (efficiency = 78%):
  - $\mu^{\mp}\mu^{\pm}$ pairs from same primary vertex with $2.9 < m_{\mu\mu} < 3.3$ 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

Fiducial cross section

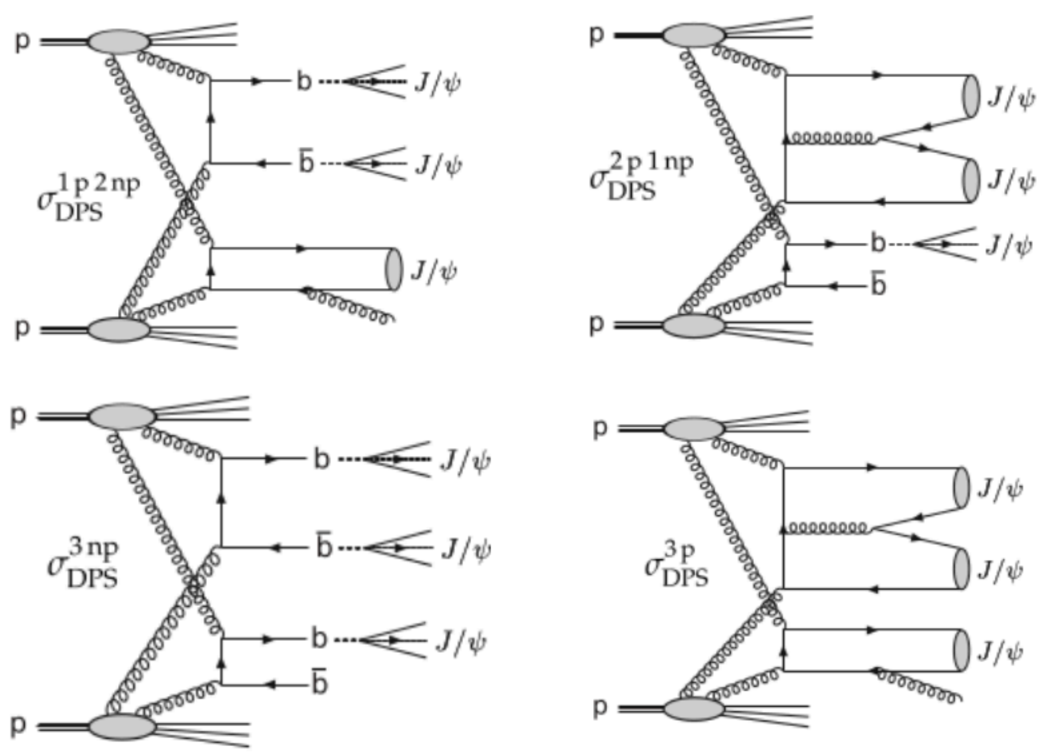
$$\sigma(\mathrm{pp} \rightarrow \mathrm{J}/\psi\, \mathrm{J}/\psi\, \mathrm{J}/\psi\, \mathrm{X}) = N_{\mathrm{sig}}^{3\mathrm{J}/\psi} / (\epsilon\, \mathcal{L}_{\mathrm{int}}\, \mathcal{B}^{3}_{\mathrm{J}/\psi\rightarrow\mu^{+}\mu^{-}})$$

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

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

First observation of triple J/ψ

- Identify prompt & nonprompt components in a narrower mass window
  - Using proper decay length of J/ψ candidate (60μm)



- 5 signal events:
  - 2 events: 2 nonprompt + 1 prompt
  - 1 event: 1 nonprompt + 2 prompt
  - 1 event: 3 nonprompt
  - 1 event: 3 prompt

SPS, DPS, & TPS contributions

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

$$\sigma_{\rm tot}^{3J/\psi} = \sigma_{\rm SPS}^{3J/\psi} + \sigma_{\rm DPS}^{3J/\psi} + \sigma_{\rm TPS}^{3J/\psi} =$$
$$= \left(\sigma_{\rm SPS}^{3\,\rm p} + \sigma_{\rm SPS}^{2\rm p1np} + \sigma_{\rm SPS}^{1\rm p2np} + \sigma_{\rm SPS}^{3\,\rm np}\right) +$$
$$+ \left(\sigma_{\rm DPS}^{3\,\rm p} + \sigma_{\rm DPS}^{2\rm p1np} + \sigma_{\rm DPS}^{1\rm p2np} + \sigma_{\rm DPS}^{3\,\rm np}\right) + \left(\sigma_{\rm TPS}^{3\,\rm p} + \sigma_{\rm TPS}^{2\rm p1np} + \sigma_{\rm TPS}^{1\rm p2np} + \sigma_{\rm TPS}^{3\,\rm np}\right)$$

factorize DPS & TPS cross sections

$$\sigma_{\rm DPS}^{3J/\psi} = \frac{m_1\left(\sigma_{\rm SPS}^{2\rm p}\sigma_{\rm SPS}^{1\rm p} + \sigma_{\rm SPS}^{2\rm p}\sigma_{\rm SPS}^{1\rm np} + \sigma_{\rm SPS}^{1\rm p}\sigma_{\rm SPS}^{1\rm p1np} + \sigma_{\rm SPS}^{1\rm p1np}\sigma_{\rm SPS}^{1\rm np} + \sigma_{\rm SPS}^{1\rm p}\sigma_{\rm SPS}^{2\rm np} + \sigma_{\rm SPS}^{2\rm np}\sigma_{\rm SPS}^{1\rm np}\right)}{\sigma_{\rm eff,DPS}}$$

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

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

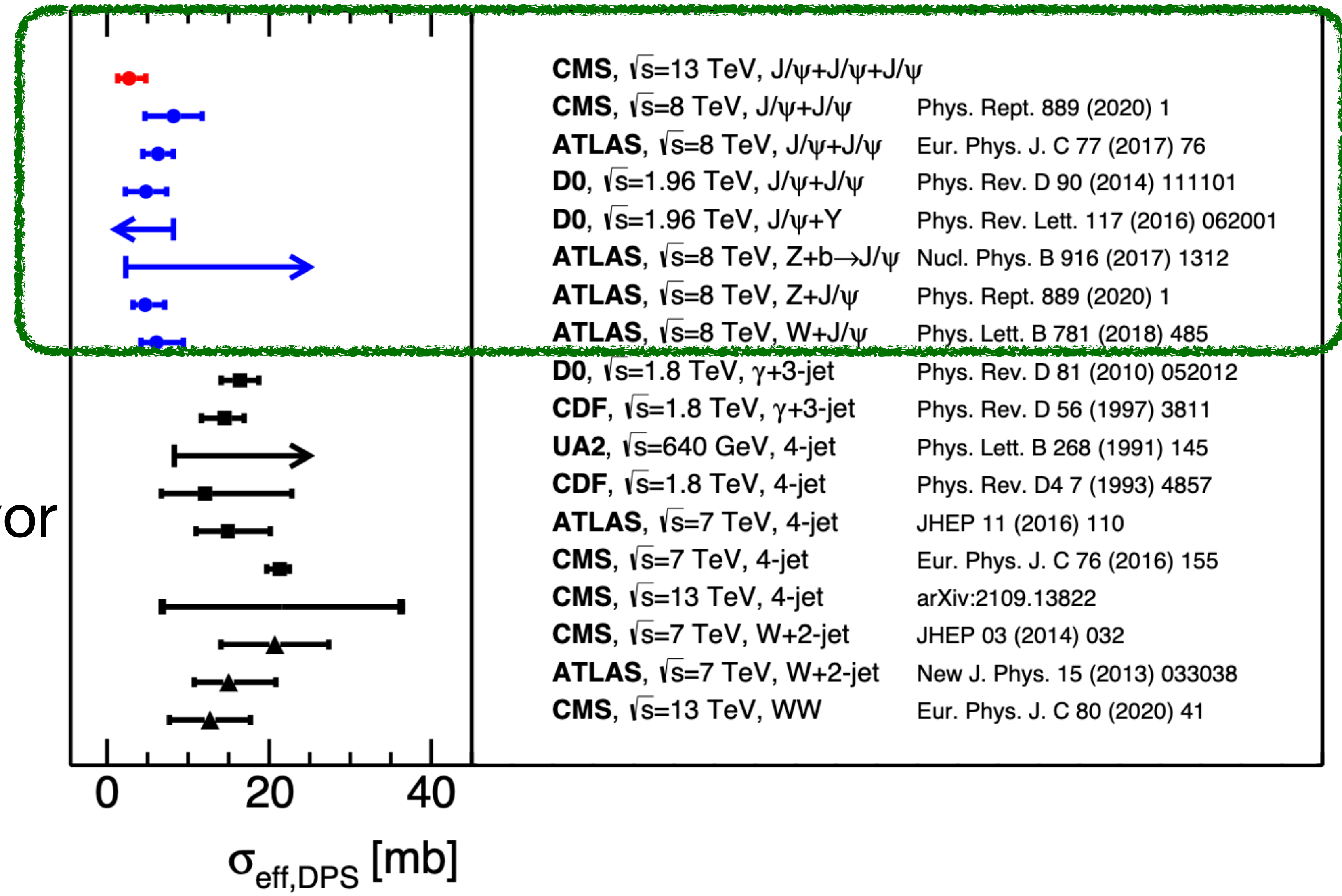
Phys. Rev. Lett. 118, 122001 (2017)

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

Effective cross section

- 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)



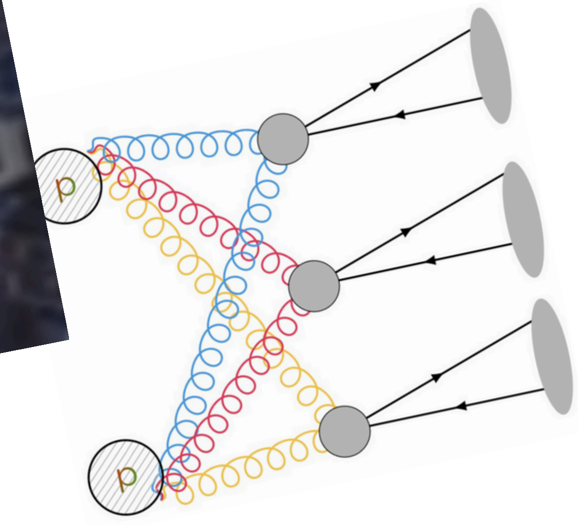
x-dependence of parton profiles?

Conclusions

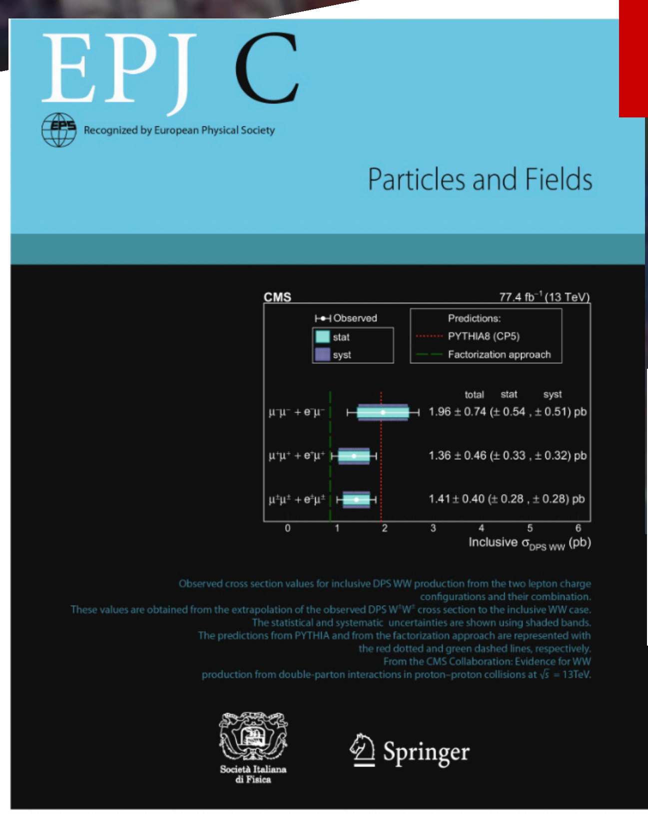
- Presented a selection of DPS studies based on 13TeV collision data
  - First ever study of triple J/ψ production, TPS and it's observation
  - First observation of $W^{\pm}W^{\pm}$
  - Important information for tuning of MC event generators from jets-based analyses
- For a given scale of process, different 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

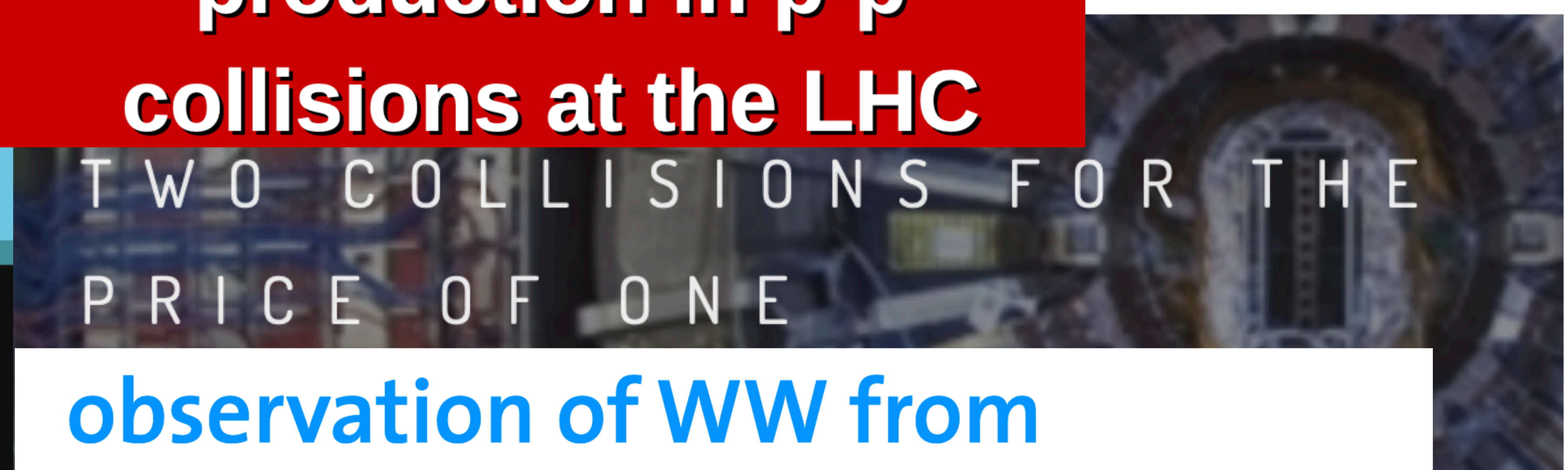
thanks for your attention!!

We made it to the headlines ;)

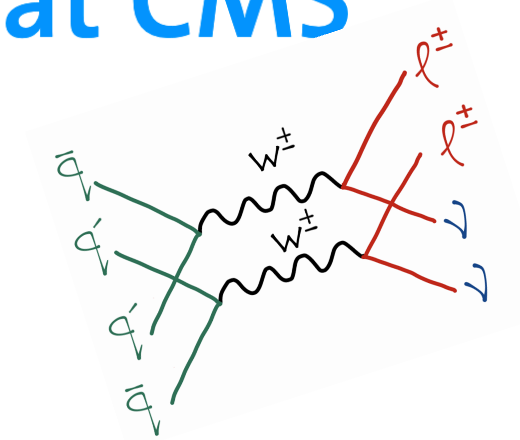


Observation of triple-J/Ψ production in p-p collisions at the LHC





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

Systematic uncertainties: Z+jets

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

Observable/Uncertainty	$\Delta\phi(Z, j_1)$	$\Delta_{rel} p_T(Z, j_1)$	$\Delta\phi(Z, \text{dijet})$	$\Delta_{rel} p_T(Z, \text{dijet})$	$\Delta_{rel} p_T(j_1, j_2)$
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	$\Delta\phi(Z, j_1)$	$\Delta_{rel} p_T(Z, j_1)$	$\Delta\phi(Z, \text{dijet})$	$\Delta_{rel} p_T(Z, \text{dijet})$	$\Delta_{rel} p_T(j_1, j_2)$
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%