# double parton scattering at the LHC

## in the $W^{\pm}W^{\pm}$ channel

marc dünser (CERN)

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# outline

**1) introduction to double parton interactions**

- -> DPS vs. SPS
- -> factorization
- -> sigma effective
- -> problems of factorization

**2) non-factorization in DPS**

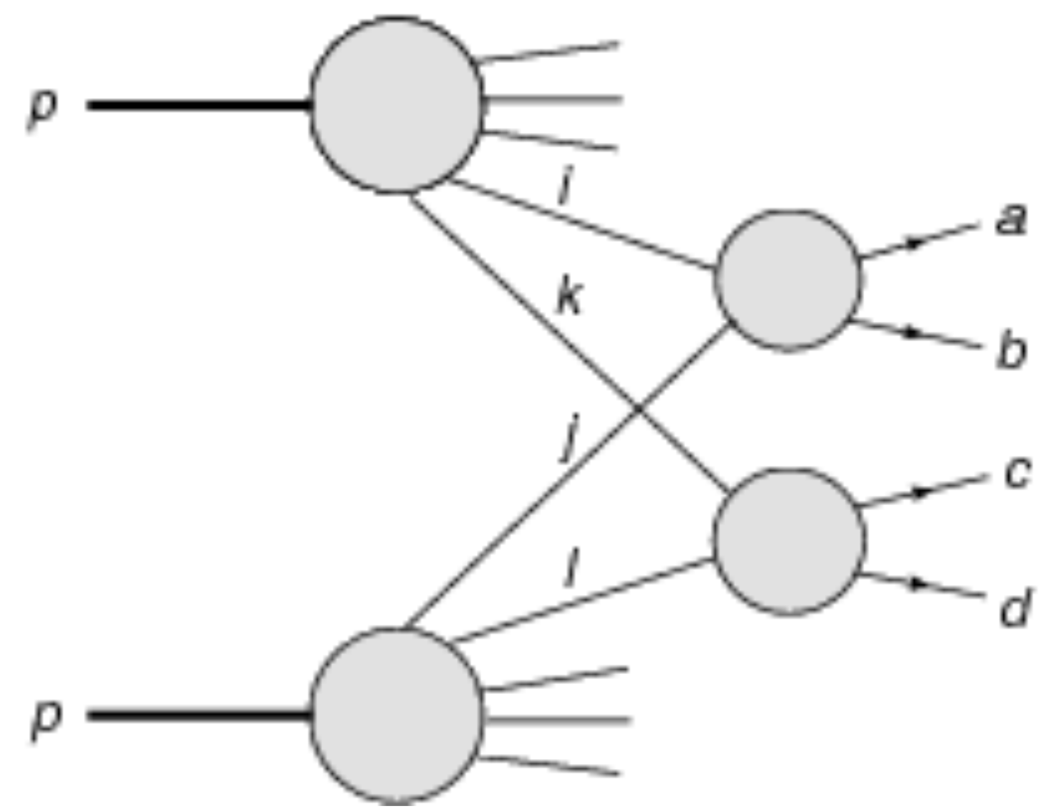
- -> observables in data

**3) two examples of DPS analyses**

- -> traditional analysis from 7 TeV
- -> newest analyses at 13 TeV

**4) outlook to the future**

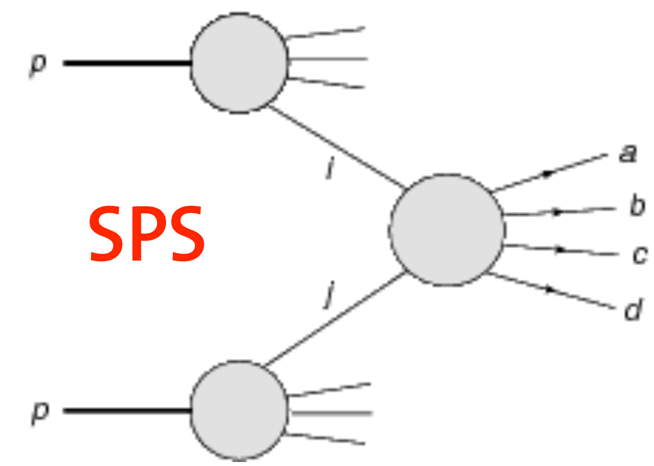
- -> Run2 and beyond



# introduction

**most analyses at the LHC focus on single parton-parton interactions (SPS)**

-> Higgs production
-> searches for new physics (SUSY, EXO)
-> precision SM measurements

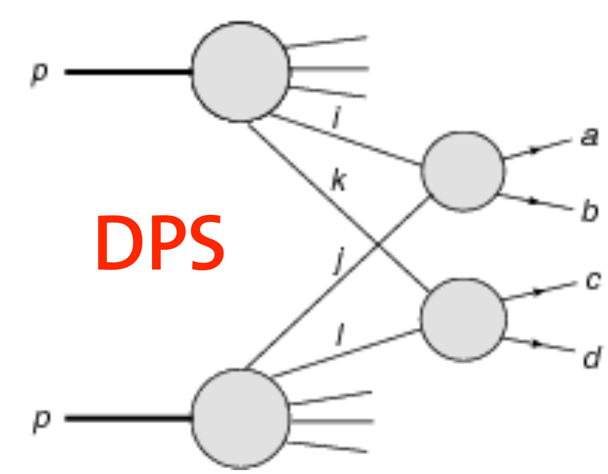



**most theoretical effort focuses on SPS as well**

-> first NNNLO calculations are appearing
-> at least (N)NLO is the standard for everything

**conversely, double parton scattering (DPS) is not very 'popular'**

-> only little experimental interest
-> also very little theoretical interest outside
a small group of theorists



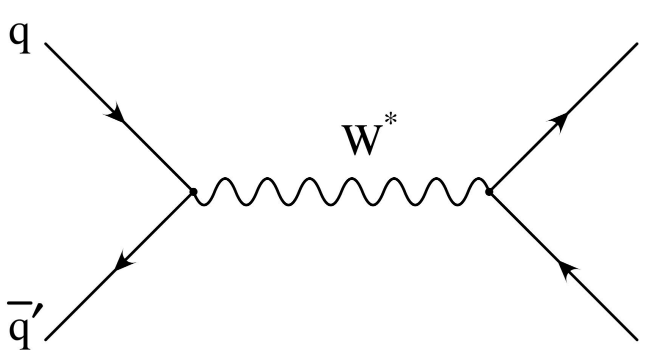

**there are good reasons to concentrate on SPS**

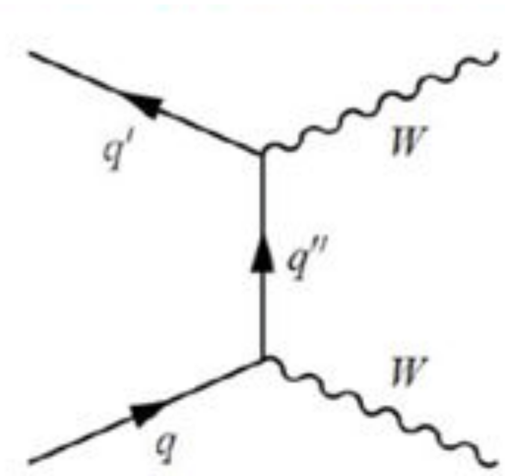
-> but i make a case for DPS anyway

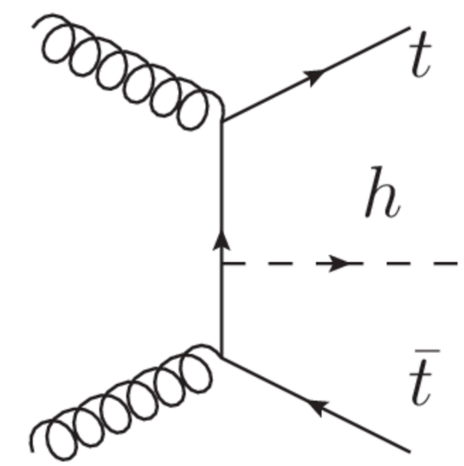
# what is DPS?

**as mentioned, we are usually interested in SPS processes**

-> have nice Feynman diagrams




**we can describe the cross section of an SPS process** (example: higgs)

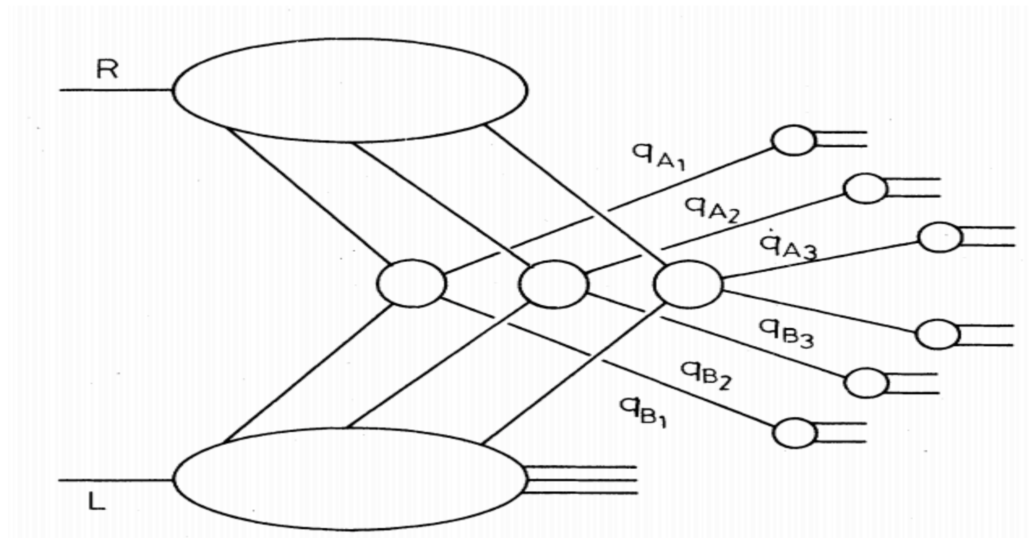
$$\sigma = \sum_{ij} \int dx_1\, dx_2\, \underbrace{f_i(x_1)\, f_j(x_2)}_{\text{pdf term}}\, \underbrace{\hat{\sigma}_{ij}(m_H^2, x_1\, x_2\, s)}_{\text{partonic cross section}}$$

-> one can do this differentially and at various orders

# what is DPS?

**even naively, once the parton model is introduced, DPS *must* exist**

-> Feynman diagrams become a bit more complicated




P.V. Landshoff, J.C. Polkinghorne, Phys. Rev. D, 18/9, 1978

**we can write the cross section of any DPS process similar to before**

$$\sigma^D_{(A,B)} = \frac{m}{2} \sum_{i,j,k,l} \int \Gamma_{ij}(x_1, x_2, b; t_1, t_2) \hat{\sigma}^A_{ik}(x_1, x'_1) \hat{\sigma}^B_{jl}(x_2, x'_2) \times \Gamma_{kl}(x'_1, x'_2, b; t_1, t_2) dx_1 dx_2 dx'_1 dx'_2 d^2 b$$

partonic cross sections

pdf terms

distance between partons

-> processes A and B are distinct perturbatively described processes

-> factor m is 1 if A=B, else 2

# what is DPS?

**this integral is clearly a bit more complicated than before**

-> the partonic cross sections are the same as before

$$\sigma^D_{(A,B)} = \frac{m}{2} \sum_{i,j,k,l} \int \Gamma_{ij}(x_1, x_2, b; t_1, t_2) \hat{\sigma}^A_{ik}(x_1, x'_1) \hat{\sigma}^B_{jl}(x_2, x'_2)$$

partonic cross sections

$$\times \Gamma_{kl}(x'_1, x'_2, b; t_1, t_2) dx_1 dx_2 dx'_1 dx'_2 d^2 b$$

pdf terms

distance between partons

**but none of the other things are quite the same**

-> there are two terms each

-> the pdf terms are now *generalized double pdfs* (x and b!) not the single pdfs from before!

-> there is a transverse distance parameter b

**how to deal with this complication?**

-> we can make assumptions regarding the correlations between partons

# factorization in DPS processes

**we can assume that the two parton-parton interactions are factorizable**

-> i.e. that there is no correlation at all between them

$$\sigma^D_{(A,B)} = \frac{m}{2} \sum_{i,j,k,l} \int \Gamma_{ij}(x_1, x_2, b; t_1, t_2) \hat{\sigma}^A_{ik}(x_1, x'_1) \hat{\sigma}^B_{jl}(x_2, x'_2)$$
$$\times \Gamma_{kl}(x'_1, x'_2, b; t_1, t_2) dx_1 dx_2 dx'_1 dx'_2 d^2 b$$

partonic cross sections

pdf terms

distance between partons

**decompose in longitudinal versus transverse components**

$$\Gamma_{ij}(x_1, x_2, b; t_1, t_2) = D^{ij}_h(x_1, x_2; t_1, t_2) F^i_j(b)$$

-> F(b) now related to the extend of the transverse parton flux

**can also assume longitudinal factorization**

$$D^{ij}_h(x_1, x_2; t_1, t_2) = D^i_h(x_1; t_1) D^j_h(x_2; t_2)$$

-> these pdf terms are now again the ones from the SPS process

# the 'pocket formula'

**if those factorizations are assumed, the cross sections simplifies**

-> a very simplified way of calculating DPS cross sections

**write down the transverse component as a cross section**

-> call this the 'effective cross section'

$$\sigma_{\text{eff}} = \left[ \int d^2b (F(b))^2 \right]^{-1}$$

**the rest are now exactly the SPS cross sections for processes A and B**

-> leading to the fully factorized cross section for DPS

$$\sigma^D_{(A,B)} = \frac{m}{2} \frac{\sigma^S_{(A)} \sigma^S_{(B)}}{\sigma_{\text{eff}}}$$

**really simple to calculate cross-sections on the back of an envelope**

# sigma effective

**derived from the transverse extend of the partons in the proton**

-> theoretically calculable to some degree

**in the factorization approach sigma effective is a constant**

-> independent of the CM energy

-> independent of the DPS process

**quite a number of experimental measurements**

-> some tension between different measurements

-> more on this later...

**in any case:**

$$\sigma_{\mathrm{eff}} = \left[\int d^2b (F(b))^2\right]^{-1}$$ **≃ 10-20 mb**

# example cross sections for DPS processes

**can make a quick estimate of some interesting cross sections**

- -> a randomly chosen list
- -> at CM energy of 13 TeV
- -> all assuming $\sigma_{eff}$ = 20 mb

| $\sigma^{SPS}_{13\ TeV}$ | 832 pb | 61 nb | 6 nb | 170 nb | 5.4 μb | 430 pb |
|---|---|---|---|---|---|---|
| | **tt** | **W->lν** | **Z->ll** | **J/ψ** | **2jets** | **2γ** |
| **tt** | << | **2.56 fb** | 0.23 fb | 7 fb | 2.2 pb | << |
| **W->lν** | - | **95 fb** | 17 fb | **523 fb** | 166 pb | 1.3 fb |
| **Z->ll** | - | - | 0.83 fb | **50 fb** | 15 pb | << |
| **J/ψ** | - | - | - | 720 fb | 460 pb | 3.7 fb |
| **2jets** | - | - | - | - | 73 nb | 1.1 pb |
| **2γ** | - | - | - | - | - | << |

**compare: $\sigma_{Higgs}$ = 50 pb, $\sigma_{WZ\to 3l}$ = 5 pb**

# problems with factorization

**clearly the factorization assumption must break down**

-> at least in extreme cases this is evident

**if both x1 and x2 are large, energy conservation can be violated**

-> unlikely, but it shows that factorization is fundamentally wrong

$$D_h^{ij}(x_1, x_2; t_1, t_2) = D_h^i(x_1; t_1) D_h^j(x_2; t_2)$$

-> less trivial: what is the pdf after taking out a large-x parton?

-> even more complex: what about color/b/q/spin correlations

**difficult to test is transverse factorization**

-> i.e. are partons correlated in the transverse plane?

**more correlations to consider:**

-> color correlations

-> spin-correlations

# solutions to the factorization issue

**there are theoretical calculations that do *not* assume factorization**

-> largely still very theoretical of nature
-> not implemented in any large-scale MC simulation (yet)

**summarizing here the works of many theorists:**

-> Gaunt, Stirling, arXiv:0910.4347v4, 2010
*Double Parton Distributions Incorporating Perturbative QCD Evolution and Momentum and Quark Number Sum Rules*
-> Ceccopieri, Rinaldi, Scopetta, arXiv:1702.05363v1, 2017
*Parton correlations in same-sign W pair production via double parton scattering at the LHC*

-> Bartalini, Gaunt
*Multiple parton interactions at the LHC, WorldScientific, 2019*

**these papers introduce complex theoretical calculations**

-> especially the last one is a state of the art summary
-> curiously doesn't spend much time on $W^{\pm}W^{\pm}$ production

# implications of these (theoretical) solutions

**any of the solutions presented imply *correlations***
-> especially longitudinal correlations of the partons

**some of these correlations have experimental implications**
-> those are subtle/small effects, difficult to test
-> we need a suitable probe (process)

**longitudinal effects affect especially the rapidity distributions**
-> e.g. relation between parton x and muon $p_T/\eta$ in W production

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

**any probe must satisfy a few criteria**
-> sensitivity to the correlations
-> large enough cross section (#events)
-> high purity to extract subtle correlations

# a probe for DPS: $W^\pm W^\pm$ production

**cross section for DPS WW -> lνlν: ~ 95 fb**

- -> inclusive in charge, but already di-leptonic!
- -> rough idea of #events in LHC data: 95*136 ≃ 13k events
  (this number is inclusive in flavors and charge etc.)

**does this process fulfill the requirements?**

- -> sensitivity to the correlations -> **yes** (more in a minute)
- -> large enough cross section (#events) -> **sort of**
- -> high purity to extract subtle correlations -> **yes, in $l^\pm l^\pm$**

**correlations are not the only consequence**

- -> also the central cross section prediction changes
- -> small effect of 10-15% of total cross section

# observable correlations in $W^{\pm}W^{\pm}$

**non-factorized calculations lead to a number of observable effects**

-> largely related to the rapidities of the Ws and decay products

**gaunt&stirling define an asymmetry that maximizes sensitivity**

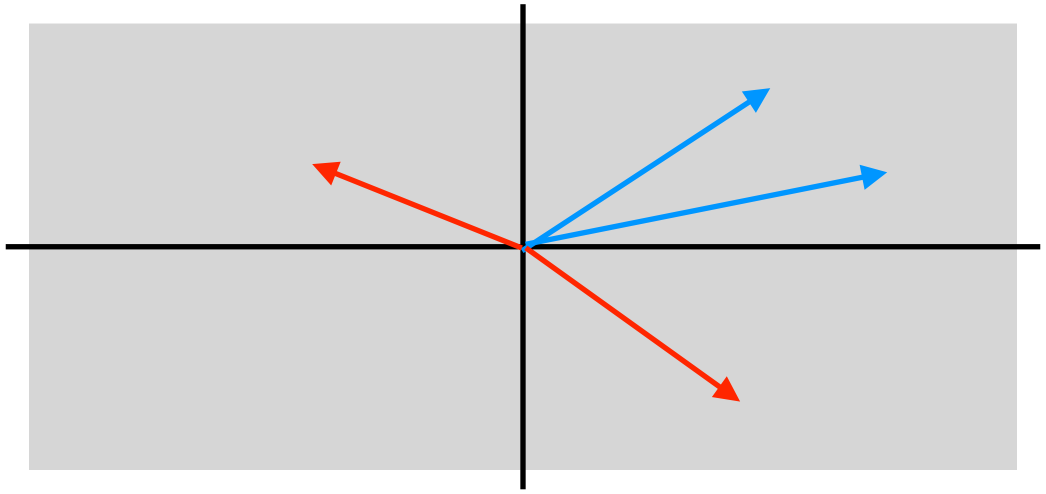
-> to longitudinal correlation effects

$$a_{\eta_l} = \frac{\sigma(\eta_{l_1} \times \eta_{l_2} < 0) - \sigma(\eta_{l_1} \times \eta_{l_2} > 0)}{\sigma(\eta_{l_1} \times \eta_{l_2} < 0) + \sigma(\eta_{l_1} \times \eta_{l_2} > 0)}$$

**looks more complicate than it is**

-> #events in opposite hemispheres minus #events in same

-> normalized to the total



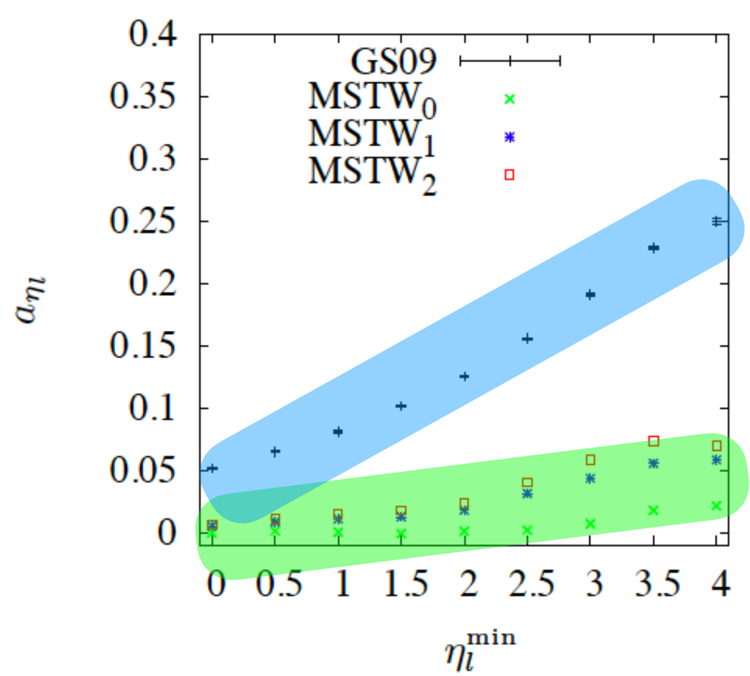
# asymmetry $a_\eta$

**is a measure of how a W at large rapidity affects the probability of a second W to be produced at high rapidity**

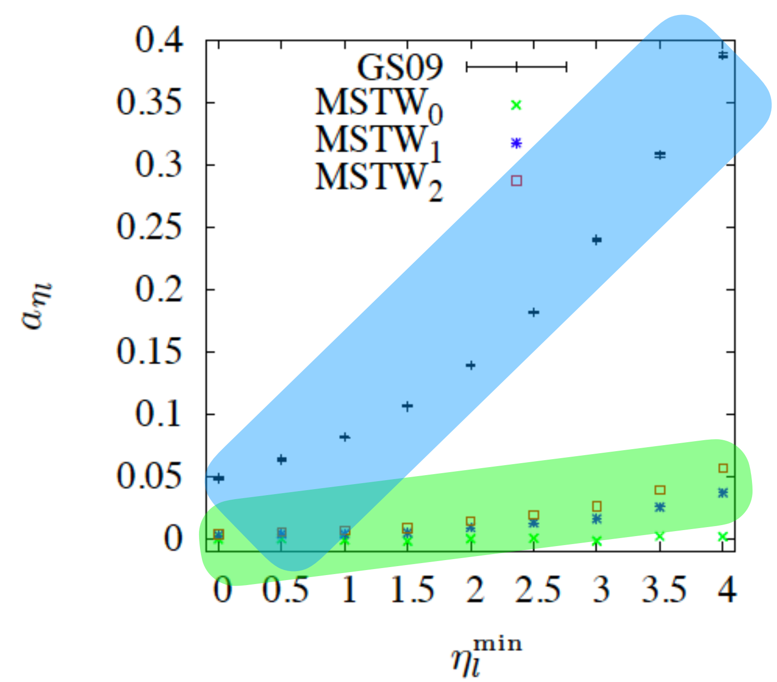
-> $a_\eta > 0$ if leptons prefer opposite hemispheres

**one can plot this asymmetry as a function of min(lepton-$\eta$)**

-> large sensitivity to the correlations is observed




(a) Positively charged leptons




(b) Negatively charged leptons

**black dots are with sophisticated dPDFs**

-> naively expected: if there are correlations, then especially if x is high!

# more observables

**Ceccopieri et al predict more observables related to correlations**

-> especially on the cross section

-> more easily accessible

| dPDFs | $\sigma^{++}$ [fb] | $\sigma^{--}$ [fb] | $\sigma^{++}/\sigma^{--}$ |
|---|---|---|---|
| GS09 | 0.54 | 0.28 | 1.9 |
| QM | 0.53 | 0.16 | 3.4 |
| GS09/QM | 1.01 | 1.78 | - |

**overall cross section ratios of ++/-- are sensitive to their model**

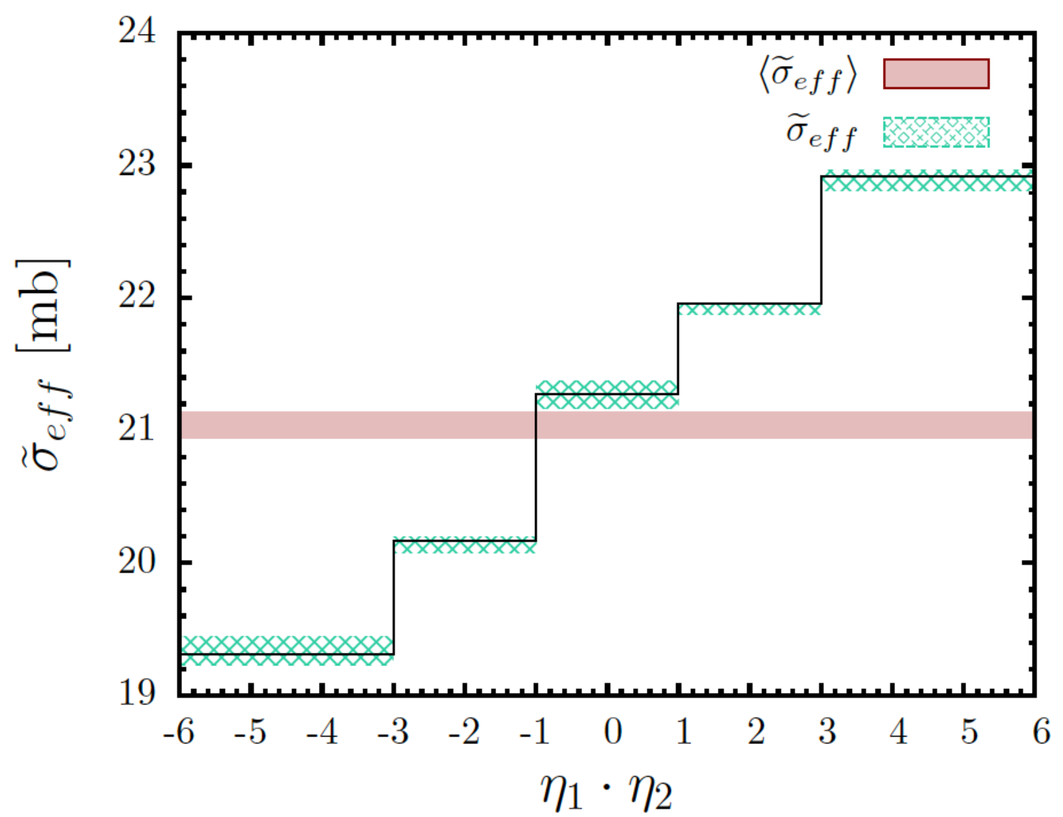
-> simple binning in charge will do!

**another effect again in the rapidities**

-> non-constant $\sigma_{\text{eff}}$ predicted

**subtle effect of ~10% in the cross section**

-> but easily done experimentally



# treatment in current MC generators

**just to understand what is implemented in current MC**

-> most of the sophisticated calculations are not

**i will be talking about pythia, because this is what i know best**

-> it is also what is mostly used in CMS for MPI

**things that are taken into account:**

-> sPDFs for second scatter get rescaled to 1-x
in other words: energy conservation

-> if quark from gluon splitting in first, anti-quark added
i.e. color conservation

**missing:**

-> longitudinal correlations, spin correlations, double PDFs

**pythia and herwig the only generators that allow *specific* second hard scatter!**

# measuring DPS experimentally

**why do it at all?**

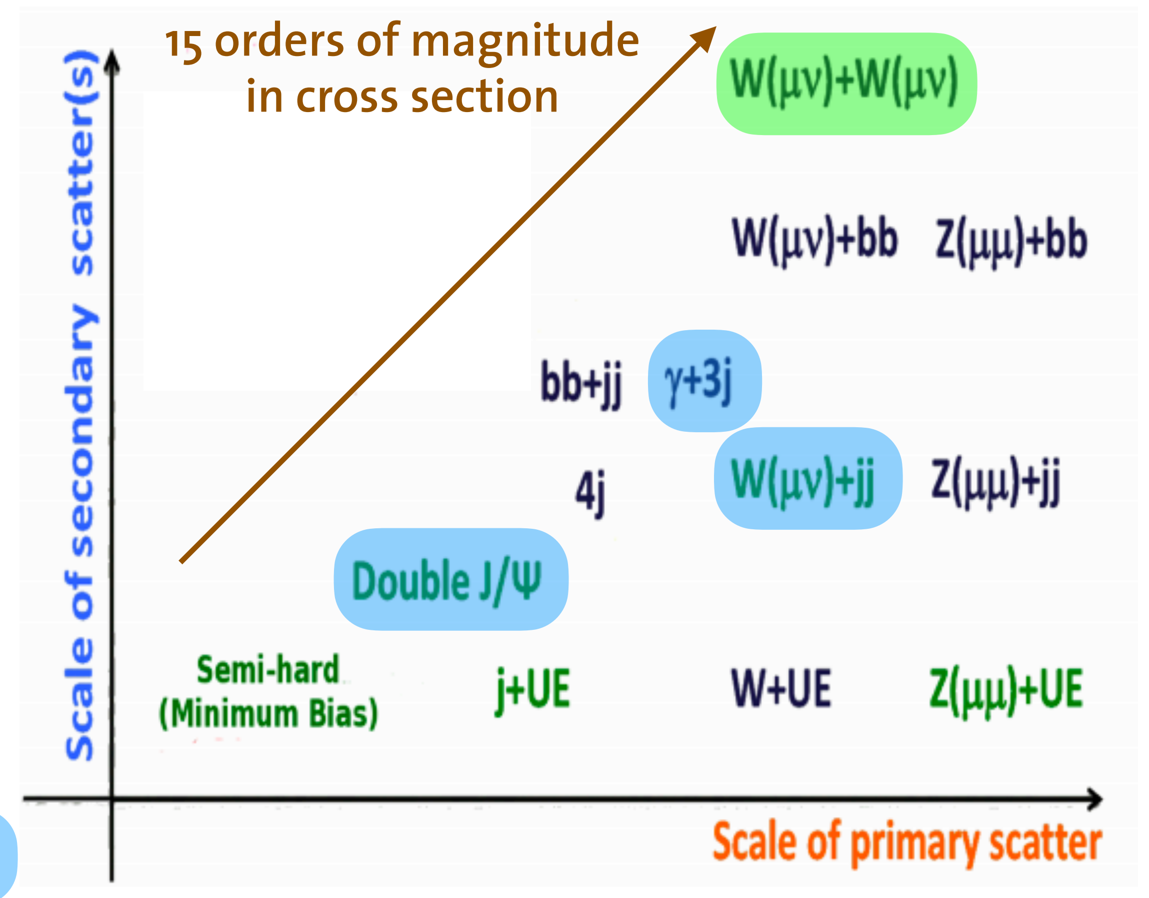
-> to understand the physics of DPS itself
-> to tune MC for *all* other analyses
-> some DPS processes are backgrounds for searches/Higgs/etc

**there are many ways of measuring DPS at the LHC**

-> all with upsides and downsides

**it very much depends on the goal**

-> study correlations -> WW
-> measure $\sigma_{eff}$ -> high statistics process



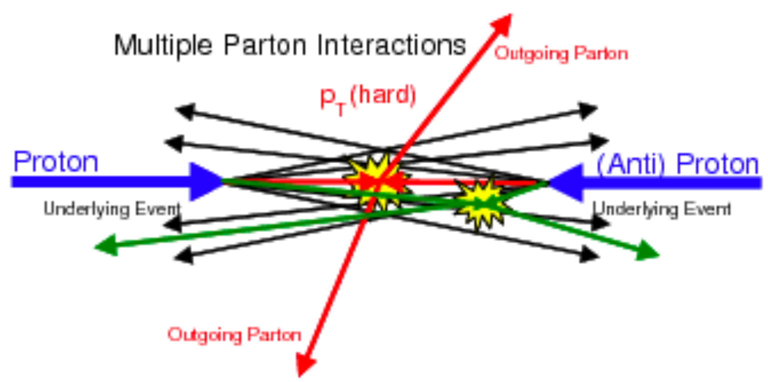

**important point: we *need* a hadron collider for this!**

-> when in rome...

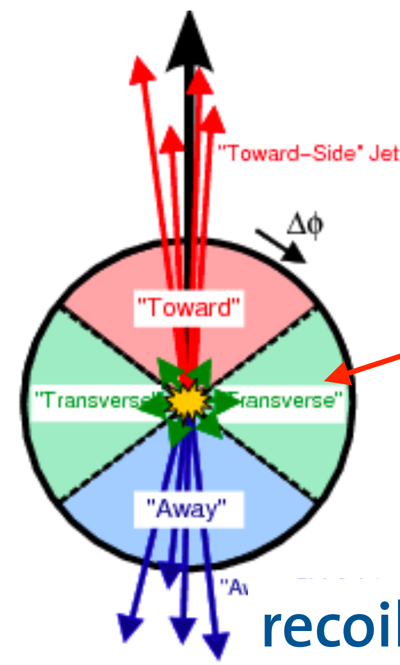
# underlying event versus DPS

**besides full-blown DPS, there is also the *"underlying event"***

-> usually treated as a nuisance
-> but also interesting in itself




hard object




most sensitive to UE

recoil

**very important for MC tuning**

-> e.g. in pythia the "shape" of the proton is derived from underlying event information
-> very important parameter for $\sigma_{eff}$!

**in general: DPS is "high enough" in scale to be treated perturbatively**

-> underlying event is whatever is "soft"

# measurement prerequisites

**a few things necessary**

- -> large enough cross section
- -> usually at least one *'good'* physics object (W, γ, J/ψ, ϒ, ...)
- -> an accelerator and a detector with good resolution

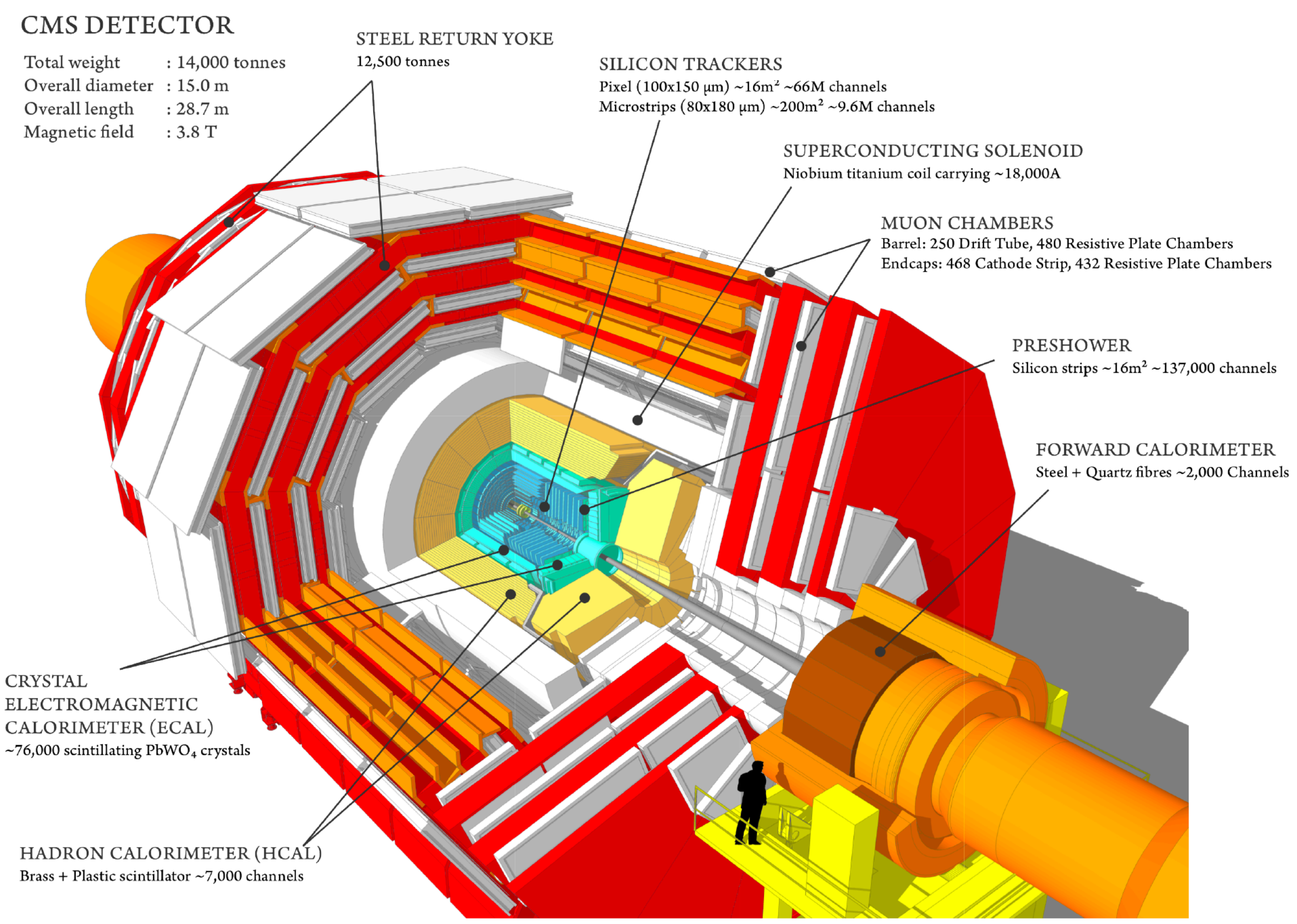
**CMS detector at the LHC**

- -> excellent resolution for leptons and γs
- -> good jet resolution
- -> good $ME_T$ resolution

**ATLAS detector**

- -> good resolution for leptons and γs
- -> very good jet and $ME_T$ resolution

**LHCb works too!**



# DPS in W+2jets in ATLAS New J. Phys. 15 (2013) 033038, arXiv:1301.6872

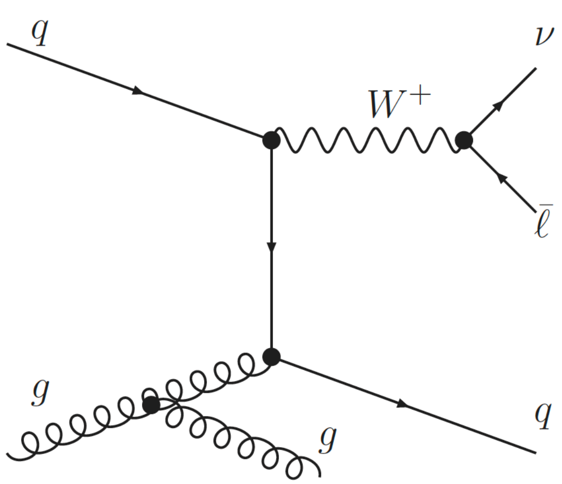
**a fairly old analysis out of ATLAS: 36 pb$^{-1}$ of 7 TeV data**

-> data taken in 2010!

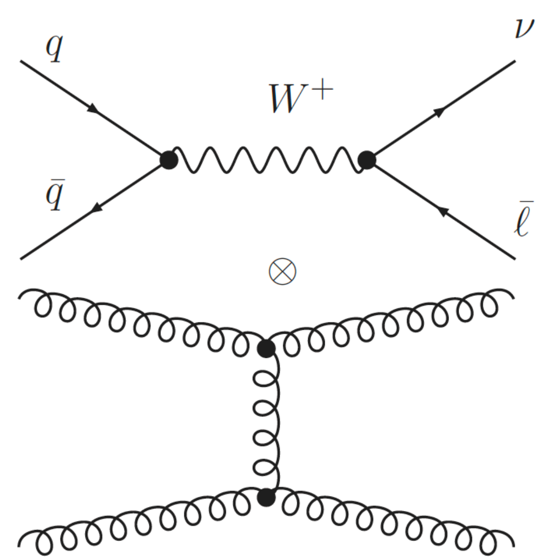
-> good illustration of a 'classic' DPS analysis

**the 'good' object is the leptonic W: isolated lepton, excellently measured**

-> want to distinguish




**versus**




**going back to the simplified factorization approach:**

$$d\hat{\sigma}^{(\mathrm{DPI})}_{Y+Z}(s) = \frac{d\hat{\sigma}_Y(s)\cdot d\hat{\sigma}_Z(s)}{\sigma_{\mathrm{eff}}(s)} \quad \text{and} \quad d\hat{\sigma}^{(\mathrm{tot})}_{Y+Z}(s) = d\hat{\sigma}^{(\mathrm{SPI})}_{Y+Z}(s) + d\hat{\sigma}^{(\mathrm{DPI})}_{Y+Z}(s)$$

**we can extract the fraction $f_{DPS}$ of DPS events over the total events**

# DPS in W+2jets in ATLAS

**definition of $f_{DPS}$ quite straightforward**

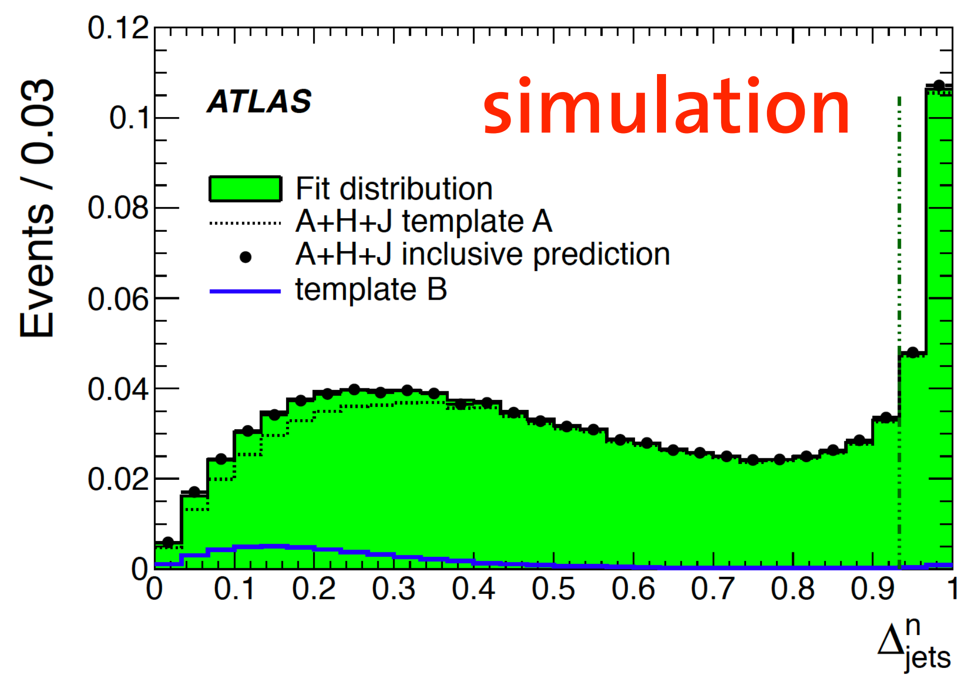
$$f_{DP} = \frac{N_{W_{0j}+2j_{DPI}}}{N_{W+2j}} = \frac{N_{W_{0j}+2j_{DPI}}}{N_{W_{2j}} + N_{W_{0j}+2j_{DPI}}}$$

**need to construct 2 templates: one for $W+2j_{SPS}$ (A), one for $W+2j_{DPS}$ (B)**

-> in some variable(s) that are sensitive to SPS vs. DPS

**the variable is the momentum of the normalized di-jet system**

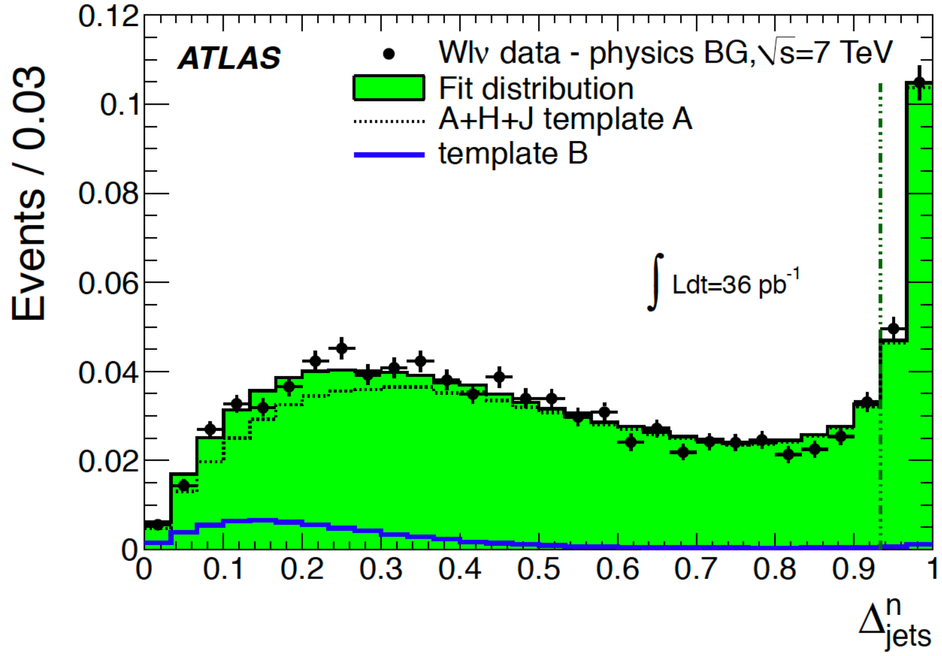
$$\Delta^{n}_{jets} = \frac{|\vec{p}_T^{\,J_1} + \vec{p}_T^{\,J_2}|}{|\vec{p}_T^{\,J_1}| + |\vec{p}_T^{\,J_2}|}$$




**trivially we want to fit:** $(1 - f_{DP}) \cdot A + f_{DP} \cdot B$

# DPS in W+2jets in ATLAS

**throw the model at the data, or the data at the model**




$$f_{\rm DP}\ (\Delta^{\rm n}_{\rm jets}) = 0.076 \pm 0.013\ ({\rm stat.})$$

**fairly large statistical uncertainties with that little data**

-> but good chi2/ndof from the fit

**can interpret $f_{DPS}$ in terms of a measurement of $\sigma_{eff}$**

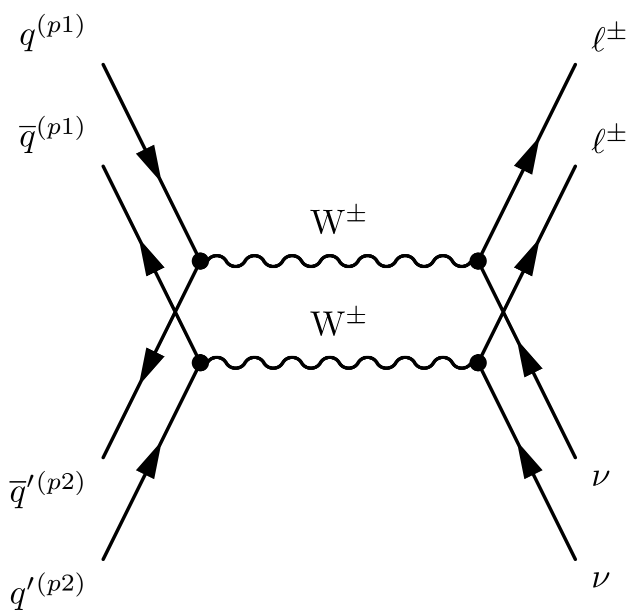
$$\sigma_{\rm eff} = \frac{N_{W_{0j}}\, N_{2j}}{f^{(D)}_{\rm DP} \cdot N_{W+2j}} = 15 \pm 3\ ({\rm stat.})\ {}^{+5}_{-3}\ ({\rm syst.})\ {\rm mb}$$

-> perfectly in line with other measurements

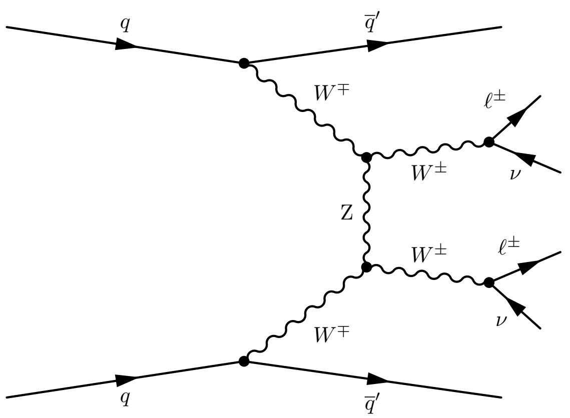
# DPS in W±W± in CMS

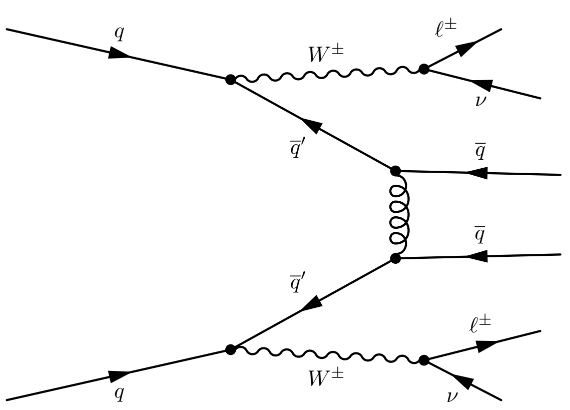
**newest DPS analysis from the LHC with 77 fb$^{-1}$ at 13 TeV**

-> highly sensitive channel to correlations




**versus**




**pro: SPS process is highly suppressed!**

-> need two jets to carry away some charge

-> can veto these jets in the analysis

**con: pretty low cross section, very crowded phase space**

-> few hundred events after all selections

-> not yet sensitive to the subtle correlation effects

# the story of the DPS WW cross section

**this analysis does not have a single, accurate estimation of the total cross section**

-> vastly different from Higgs, W/Z, top, even SUSY cross sections
-> no (N)NLO calculations with a MC generator exist

**two options to get an estimate of the inclusive cross section:**

**1) calculate the DPS WW cross section via the pocket formula**

-> take highest order theoretical W cross section (187 ± 7 nb)
-> choose a value for $\sigma_{eff}$ (say, 20.7 mb from CMS W+2jets)
-> plug it in the formula, and get: **0.87 pb**

**2) ask generators what the cross section is**

-> pythia is the only one with sensible results (herwig++ doesn't)
-> the pythia cross section is *very* tune dependent
-> for the sample we use we get: **1.92 pb**

**these numbers are very different, but reflect the uncertainty though**

# DPS in $W^{\pm}W^{\pm}$ in CMS

**this process was never measured before at a hadron collider**

-> until this week, that is

**goals different w/r/t W+2jets:**

-> prove that it's there first!

-> once established, investigate angular distributions

-> $f_{DPS}$ has no real meaning, because SPS negligible

-> can still extract $\sigma_{eff}$ of course

**phase space rather crowded, no strong handle to suppress backgrounds**

-> basically two W's at LO

-> no high-$p_T$ objects

-> no (b)-jets

| |
|---|
| two leptons: $e^{\pm}\mu^{\pm}$ or $\mu^{\pm}\mu^{\pm}$ |
| $p_T^{\ell_1} > 25\,\mathrm{GeV}$ , $p_T^{\ell_2} > 20\,\mathrm{GeV}$ |
| $\lvert\eta_e\rvert < 2.5$, $\lvert\eta_\mu\rvert < 2.4$ |
| $p_T^{miss} > 15\,\mathrm{GeV}$ |
| $N_{jets} < 2$ ($p_T > 30\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.5$) |
| $N_{b\text{-tagged jets}} = 0$ ($p_T > 25\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.4$) |
| veto on additional e, $\mu$, and $\tau_h$ |

# the backgrounds very briefly

**backgrounds are plentiful in this region of phase-space**

-> reducible and irreducible backgrounds

**two most important backgrounds:**

-> irreducible **WZ->3lnu** around 40% of total backgrounds
   if the right Z-lepton is lost, it's *very* similar

-> reducible **nonprompt leptons** around 30% of total backgrounds
   estimated with standard fakerate (tight-to-loose) method

**other backgrounds estimated from MC, most pretty standard**

-> $W\gamma^*$, WWW, SPS $W^\pm W^\pm$, ZZ, $W/Z\gamma$

-> charge flips for electrons
   very small contribution

# improving signal over background

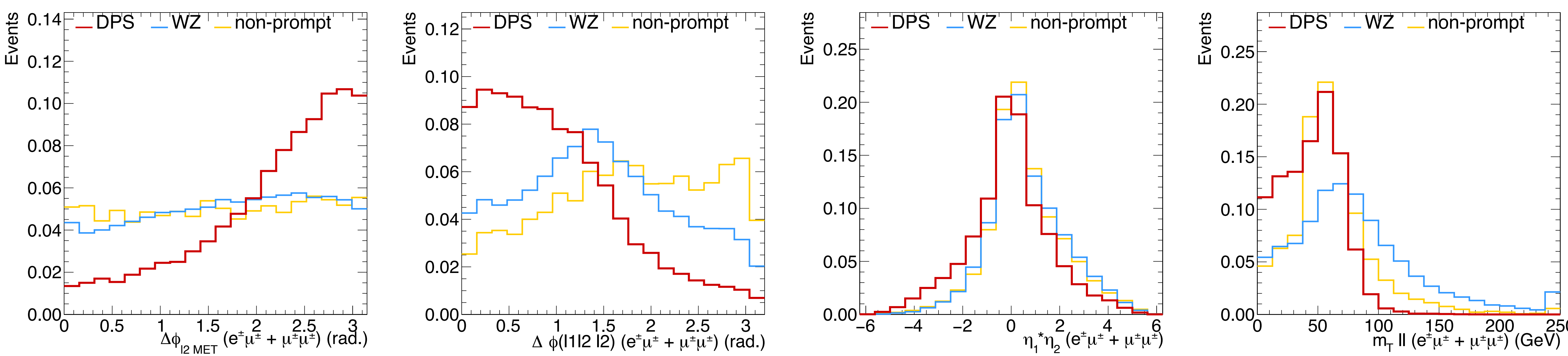
**train two BDTs in signal versus WZ and signal versus fakes**

-> signal and background kinematics well defined

**we train on 11 kinematic input variables**

-> originally chosen between signal and WZ in 2016

-> they work very well against fakes too




-> full list: **$p_T^{1,2}$, $ME_T$, $eta_1{}^*eta_2$, $|eta_1+eta_2|$, $M_{T2}^{ll}$, $m_{T(l1,met)}$, $m_{T(l1,l2)}$, $dphi_{(l1,l2)}$, $dphi_{(l2,met)}$, $dphi_{(l1l2,l2)}$**

# analysis strategy

**want to be able to fit a 1D distribution out of these two BDTs**

-> also for plotting/presentation this is better

**combine the two BDT classifier into one discriminant variable with some underlying principles**

-> combine contiguous regions in the 2D plane

-> need/want some regions with:

large signal, low background

large WZ & low fakes

large fakes & low WZ

-> optimized on the expected significance

**profit further from two facts:**

-> larger ++ signal than - -

-> μμ much superior experimentally than eμ

**perform a binned ML fit in four flavor and charge channels**

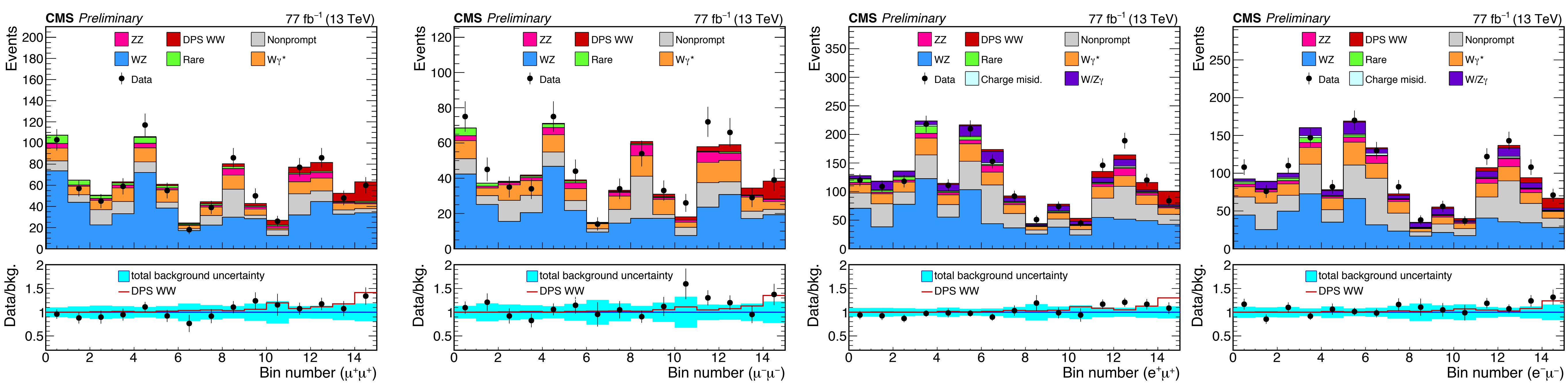
# results

**showing postfit plots of the final 1D classifier**

-> somewhat of an under fluctuation observed already in 2016

**found a total of 4921 events in data**

-> most of them to constrain backgrounds




$\mu^+\mu^+$ $\mu^-\mu^-$ $e^+\mu^+$ $e^-\mu^-$

decreasing sensitivity

# first evidence of DPS WW

**sensitivity large enough to claim first evidence**

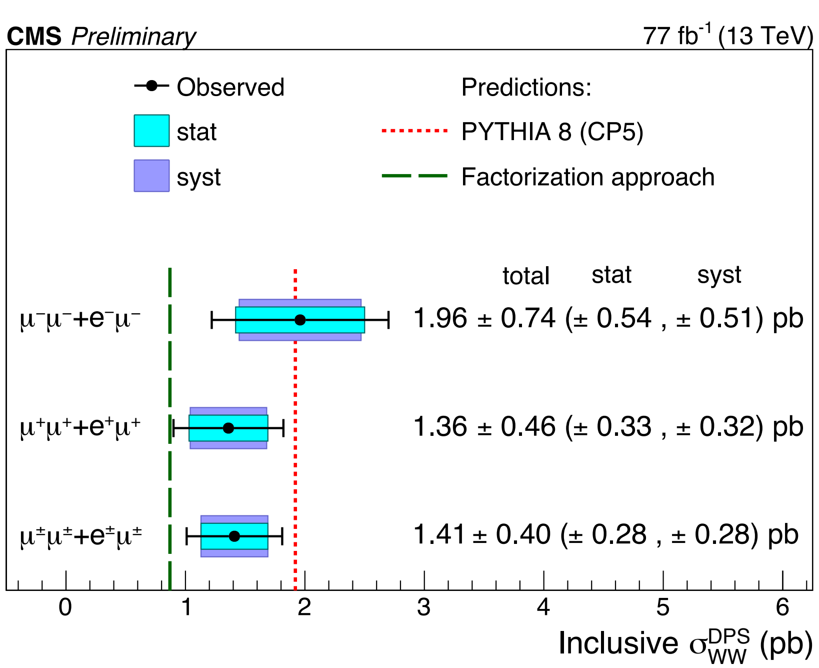
-> including 2018 should be enough to get to observation

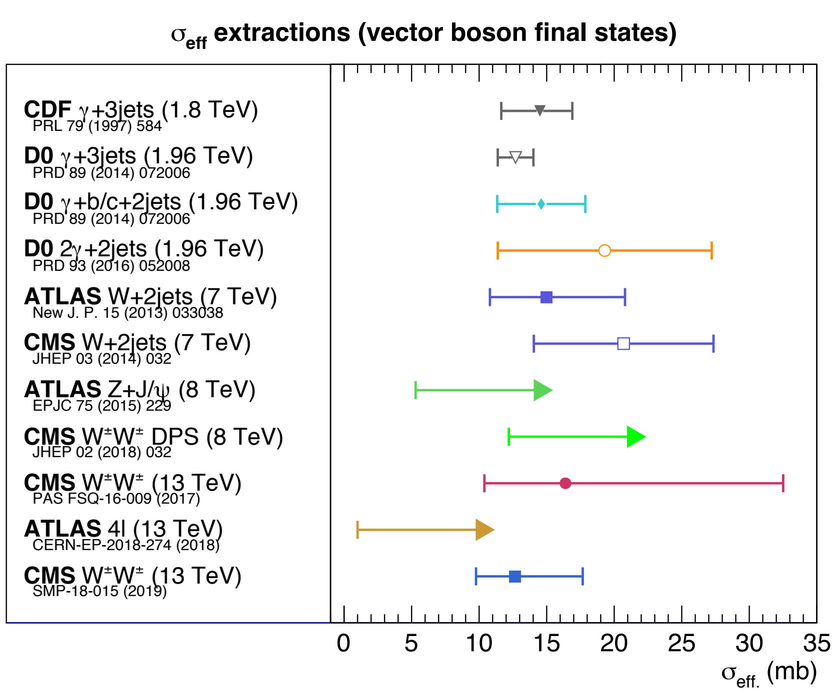
| | obtained value | significance (standard deviations) |
|---|---|---|
| $\sigma^{\mathrm{PYTHIA8}}_{\mathrm{DPS\,WW,\,exp}}$ | 1.92 pb | 5.4 |
| $\sigma^{\mathrm{factorized}}_{\mathrm{DPS\,WW,\,exp}}$ | 0.87 pb | 2.5 |
| $\sigma_{\mathrm{DPS\,WW,\,obs}}$ | $1.41 \pm 0.28$ (stat) $\pm$ 0.28 (syst) pb | 3.9 |
| $\sigma_{\mathrm{eff}}$ | $12.7^{+5.0}_{-2.9}$ mb | – |

**also extract**

-> signal strength as function of charge

-> a value for $\sigma_{\mathrm{eff}}$



# quo vadis, DPS?

**the LHC is only at the beginning of data-taking**

-> roughly 150 fb$^{-1}$ taken out of 3000+

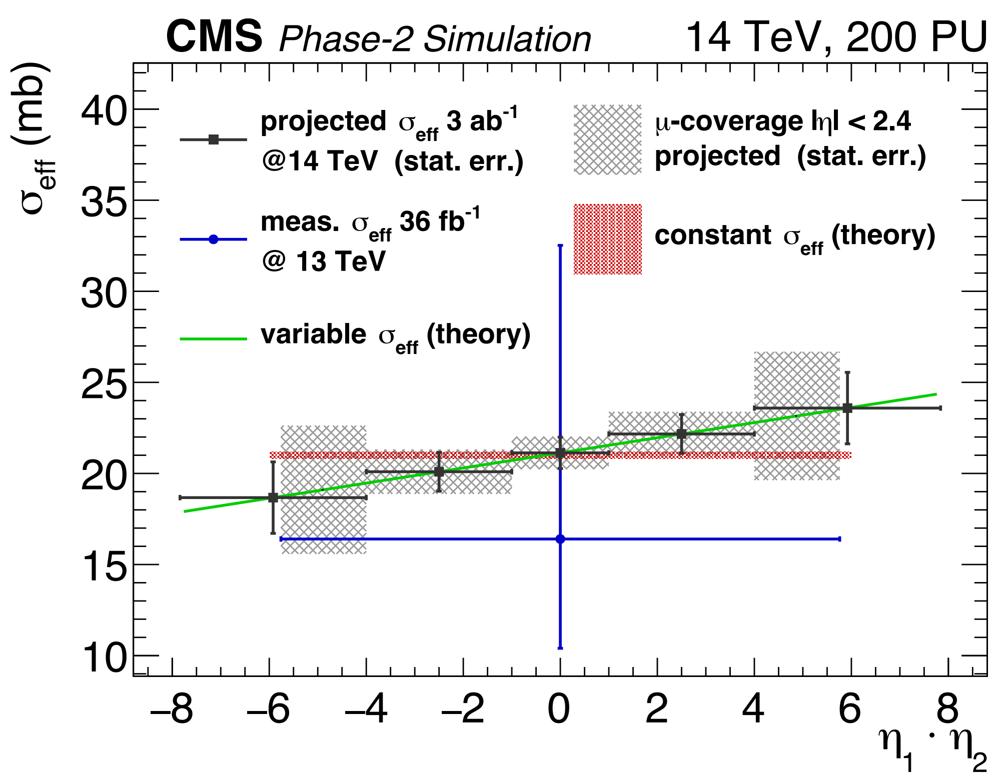
**focus here on DPS W±W± process**

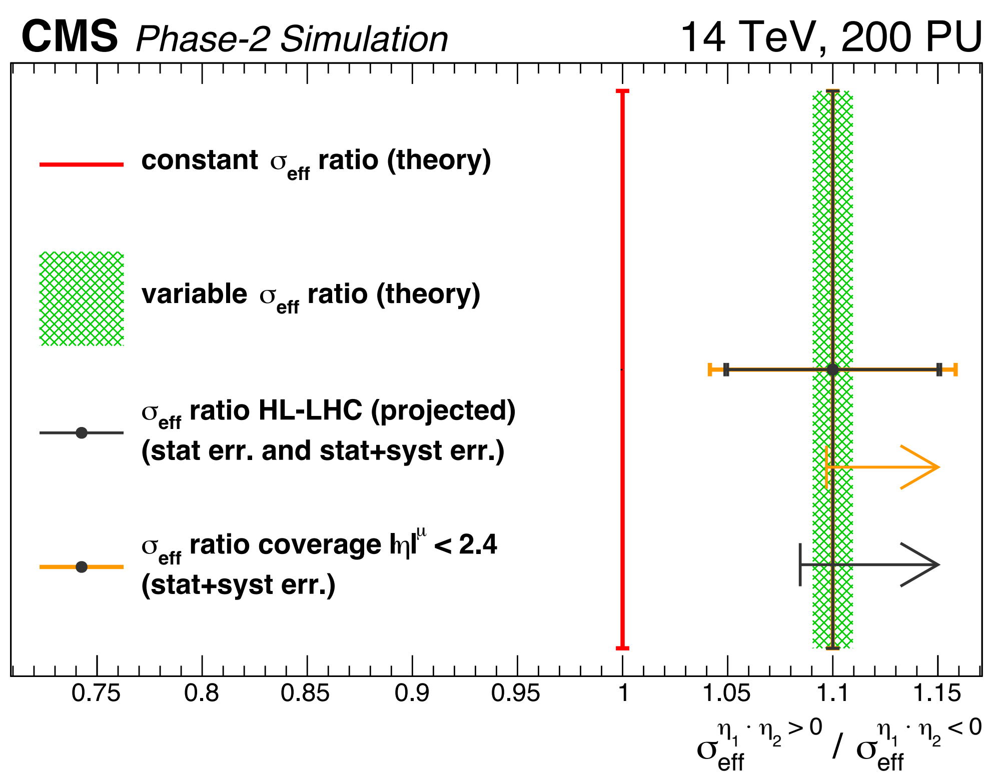
-> only process studies so far for HL-LHC

-> studied in the context of extended μ-coverage in CMS

**reminder: if parton correlated $\sigma_{eff}$ will vary with $\eta_1\eta_2$**

-> we will be sensitive to this at the latest with HL-LHC!



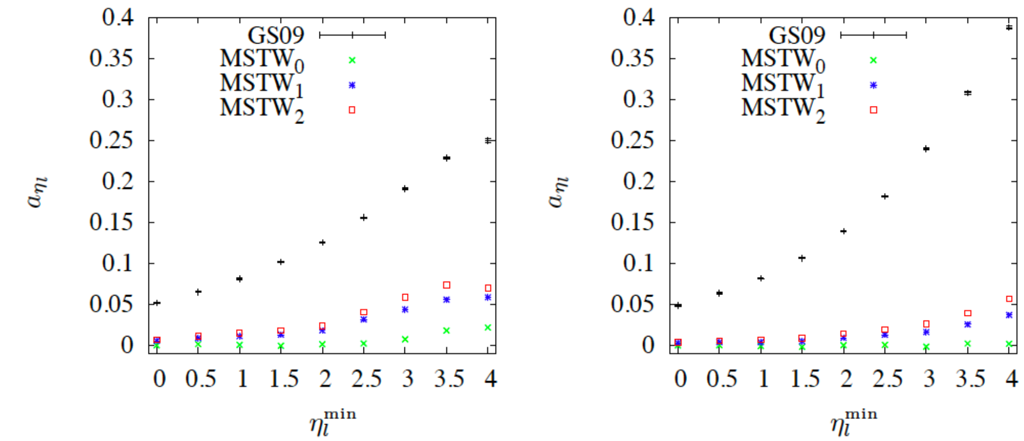



# quo vadis, DPS?

## more questions to answer down the road:

**how well can we measure $a_\eta$**

-> generally: can we probe correlations with less than 3000 fb$^{-1}$?

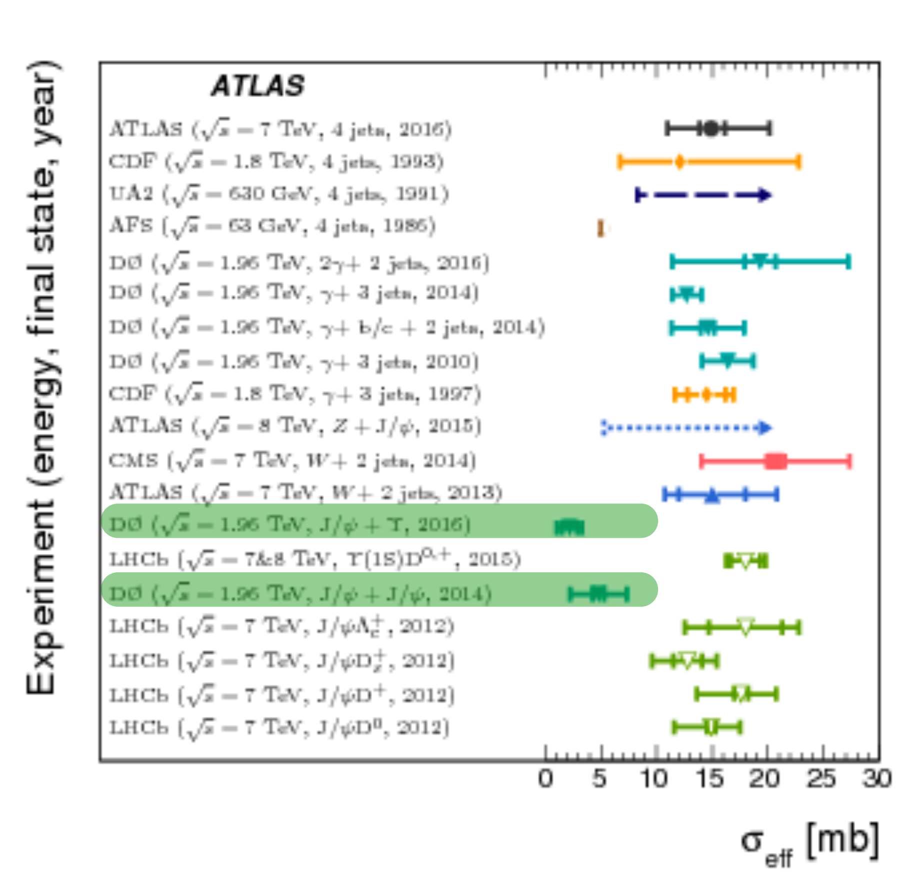



**does $\sigma_{\mathrm{eff}}$ depend on the production mode?**

-> some analyses indicate very small values

-> mostly in gluon-initiated processes

-> Do the extreme case, but also ATLAS and LHCb see $\sigma_{\mathrm{eff}}$ < 10 mb




**how high can we push the mass scale?**

-> can we go higher than WW?

**produce better MC, including correlations**

-> theorists & experimentalists needed!

# the end

marc dünser (CERN)

# extras