Review of DPS theory results from 2017

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MPI@LHC 2017, Shimla, India, 13th December 2017

DPS theoretical papers in 2017

Theoretical:

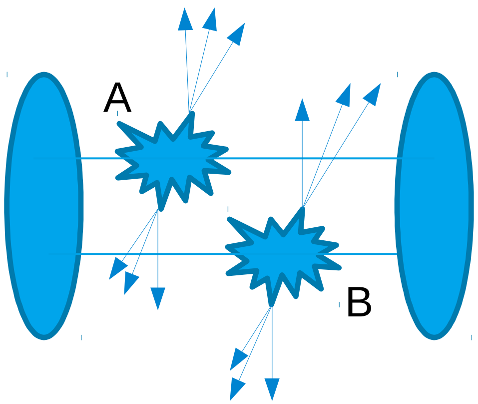
- Double parton scattering in the color glass condensate: Hanbury-Brown-Twiss correlations in double inclusive photon production, Kovner, Rezaeian, Phys.Rev. D95 (2017) 11, 114028
- Double hard scattering without double counting, Diehl, Gaunt, Schoenwald, JHEP 1706 (2017) 083
- Double parton scattering in the CGC: Double quark production and effects of quantum statistics, Kovner, Rezaeian, Phys.Rev. D96 (2017) no.7, 074018
- Transverse momentum in double parton scattering: factorisation, evolution and matching, Buffing, Diehl, Kasemets, arXiv:1708.03528
- Bose-Einstein enhancement in the evolution of the double parton densities at high energy, Gotsman, Levin, arXiv:1711.02647

Phenomenological:

- Parton correlations in same-sign W pair production via double parton scattering at the LHC, Ceccopieri, Rinaldi, Scopetta, Phys.Rev. D95 (2017) 11, 114030
- Evidence for Double Parton Scatterings in W + Prompt J/Psi Production at the LHC, Lansberg, Shao, Yamanaka, arXiv:1707.04350
- Double-parton scattering effects in associated production of charm mesons and dijets at the LHC, Maciula, Szczurek, Phys.Rev. D96 (2017) 7, 074013
- Double Parton Scattering of Weak Gauge Boson Productions at the 13 TeV and 100 TeV Proton-Proton Colliders, Cao, Liu, Xie, Yan, arXiv:1710.06315

Will summarise papers in red. Apologies if I missed any other papers!

Progress on formal side (factorisation proofs)



DPS power suppressed compared to SPS in terms of total cross section to produce AB:

$$\sigma_{DPS}/\sigma_{SPS} \sim \Lambda^2/Q^2$$

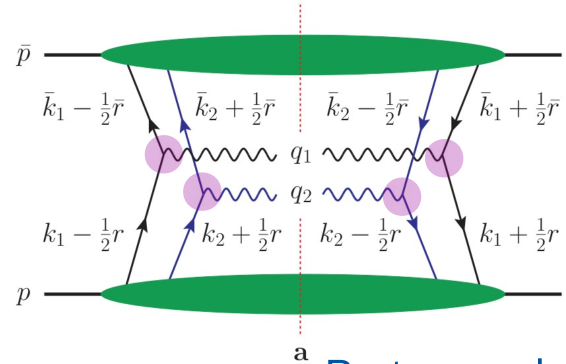
→ Experiments often have to use differential distributions to extract DPS signal

Key quantity from theory side: double differential cross section in p_T of A and B, for $p_T << Q$. For this quantity SPS and DPS are of the same power.

Does this quantity factorise? Desired end-goal:

$$\frac{d\sigma}{\prod_{i=1}^{2} dx_i\, d\bar{x}_i\, d^2\boldsymbol{q}_i} = \frac{1}{S} \times \sum_{\substack{a_1,a_2=q,\Delta q,\delta q \\ \bar{a}_1,\bar{a}_2=\bar{q},\Delta\bar{q},\delta\bar{q}}} \left[\prod_{i=1}^{2} \hat{\sigma}_{i,a_i\bar{a}_i}(q_i^2) \int \frac{d^2\boldsymbol{z}_i}{(2\pi)^2}\, e^{-i\boldsymbol{z}_i\boldsymbol{q}_i} \right] \times \int d^2\boldsymbol{y}\, F_{a_1,a_2}(x_i,\boldsymbol{z}_i,\boldsymbol{y})\, F_{\bar{a}_1,\bar{a}_2}(\bar{x}_i,\boldsymbol{z}_i,\boldsymbol{y})$$

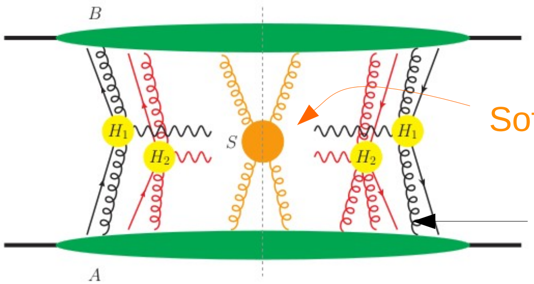
DTMD



Parton model picture

Obtaining this formula in QCD is not so simple!

Only consider colourless final states here – factorisation with colour in the final state is problematic

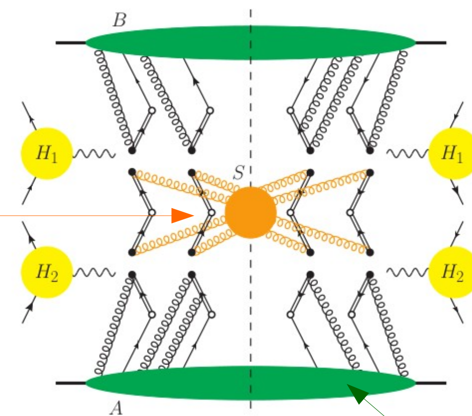


Soft and Glauber exchanges

Extra (unphysically polarised) gluon connections to hard

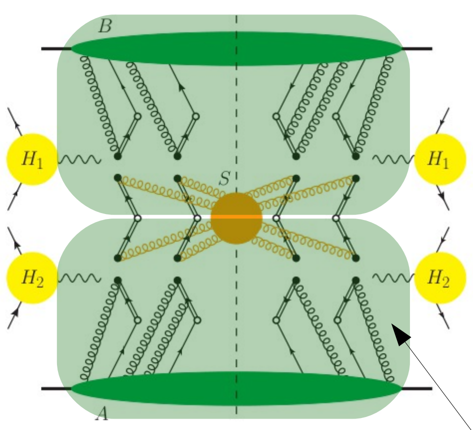
Initial picture

Cancel Glauber exchanges (Diehl, JG, Ostermeier, Ploessl, Schafer)
Use Ward identities to strip soft and collinear gluon attachments (Diehl, Ostermeier, Schafer)



Soft factor

Collinear factor



'Chop up soft factor and divide between DTMDs'

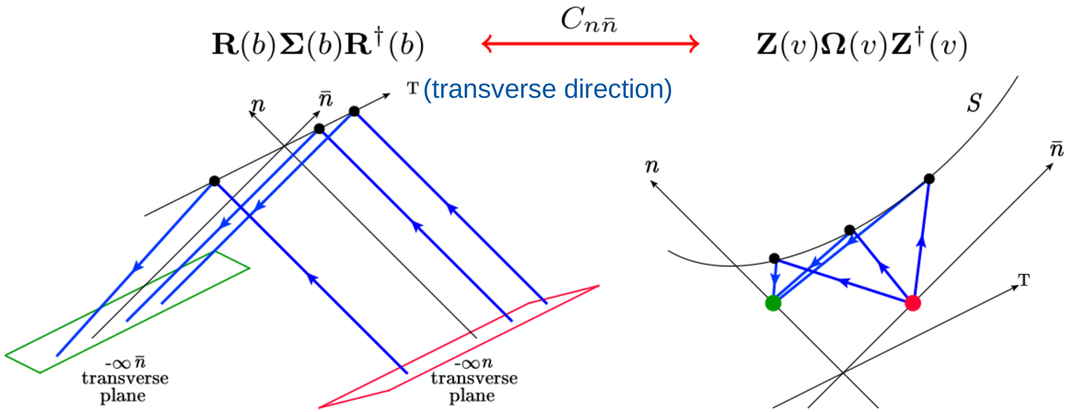
Both soft and collinear factors contain so-called rapidity divergences – have to be regulated using some appropriate regulator.

Finite DTMDs

Proof that soft factor can be divided up between the DTMDs was given this year by Vladimirov (under “exponential” rapidity regulator of Li, Neill, Zhu, 1604.00392) [arXiv:1707.07606]

Proof starts with a conformal theory, and uses a conformal transform to map rapidity divergences to UV divergences:

Conformal transformation



Rapidity divergences here

UV divergences here

Proof extended order-by-order to QCD (inductive proof)

This shows divergent parts of soft can be appropriately divided up between DTMDs, leaving finite DTMDs and finite soft. Finite soft can also be divided up between DTMDs: $F_{\{f\}\leftarrow h_1}(\{x\},\{b\},\zeta,\nu^2) \to \mathbf{S}\times F_{\{f\}\leftarrow h_1}(\{x\},\{b\},\zeta,\nu^2).$

$$\mathbf{\Sigma}_0^{-1}(\{b\},\mu,\nu^2) \to (\mathbf{S}^{-1})^T\mathbf{\Sigma}_0^{-1}(\{b\},\mu,\nu^2)\mathbf{S}^{-1}.$$

Pick $\mathbf{S}(b,\mu,\nu^2)\mathbf{\Sigma}_0(\{b\},\mu,\nu^2)\mathbf{S}^T(b,\mu,\nu^2) = \mathbf{I}.$

Buffing, Diehl, Kasemets, [arXiv:1708.03528]

This paper also contains various results on rapidity (and scale) evolution of DTMDs (and DPDFs)

DTMDs at perturbative transverse momenta

DTMDs are complex objects with many arguments – difficult to model!:

Colour representation

Two scales

Rapidity parameter

$$^{R}F(x_1, x_2, \boldsymbol{z}_1, \boldsymbol{z}_2, \boldsymbol{y}; \mu_1, \mu_2, \zeta)$$

Mtm fractions of two partons

Average transverse separation of two partons

Conjugate to average transverse mta of two partons

For $\Lambda << q_T << Q$ DTMDs can be expressed as convolutions of simpler collinear objects and perturbative kernels. Two regimes:

Buffing, Diehl, Kasemets, [arXiv:1708.03528]

Large y $|\boldsymbol{y}| \sim 1/\Lambda$

$$^{R}F_{a_1 a_2}(x_i, \boldsymbol{z}_i, \boldsymbol{y}; \mu_i, \zeta) = \sum_{b_1 b_2} {}^{R}C_{a_1 b_1}(x_1, \boldsymbol{z}_1, \mu_1, x_1\zeta/x_2) \underset{x_1}{\otimes} {}^{R}C_{a_2 b_2}(x_2, \boldsymbol{z}_2, \mu_2, x_2\zeta/x_1) \underset{x_2}{\otimes} {}^{R}F_{b_1 b_2}(x_i, \boldsymbol{y}; \mu_i, \zeta)$$

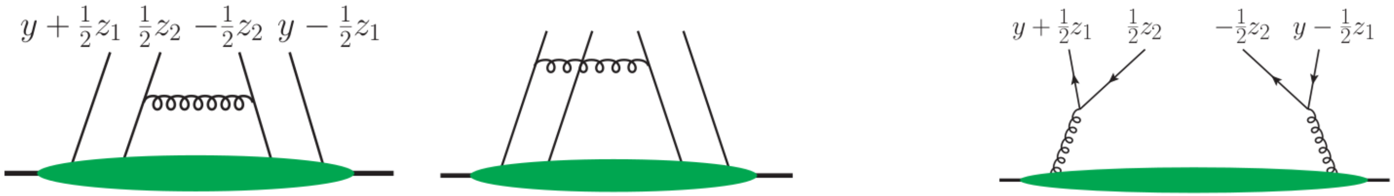
DPDFs

Analogous matching as for single parton TMDs (and kernels same for R=1)

Small y $|\boldsymbol{y}| \sim 1/q_T \sim |\boldsymbol{z}_i|$

Buffing, Diehl, Kasemets,
[arXiv:1708.03528]

$$F(x_i, \boldsymbol{z}_i, \boldsymbol{y}) = F_{\text{int}} + F_{\text{spl}}$$ + twist-three contribution, negligible for low x



$$F_{\text{int}} = G + C_{\text{tw4}}(\boldsymbol{z}_i, \boldsymbol{y}; \mu_i) \otimes G \sim \Lambda^2$$

$$F_{\text{spl}} \sim \frac{\boldsymbol{y}_+}{\boldsymbol{y}_+^2} \frac{\boldsymbol{y}_-}{\boldsymbol{y}_-^2} P_{\text{spl}} \cdot f(x_1 + x_2) \sim q_T^2$$

$G =$ twist 4 distribution

$C_{\text{tw4}} \propto \alpha_s$ (unknown)

$f =$ PDF, $\boldsymbol{y}_\pm = \boldsymbol{y} \pm \frac{1}{2}(\boldsymbol{z}_1 + \boldsymbol{z}_2)$

$P_{\text{spl}} \propto \alpha_s$ (known)

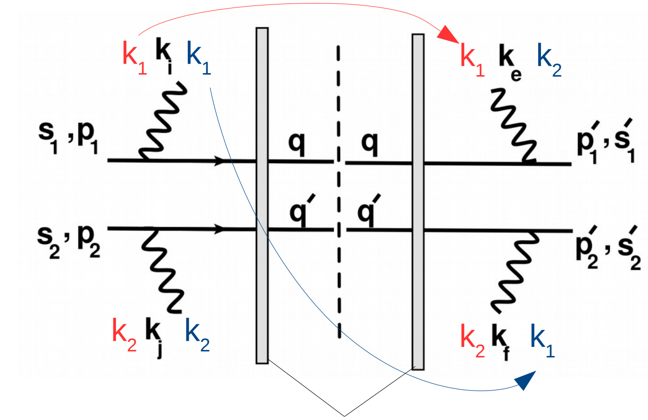
Large and small y expressions need to be appropriately combined, with a subtraction implemented to remove double counting (all worked out in arXiv:1708.03528).

DPS in the CGC

Hanbury Brown and Twiss correlations in double inclusive photon production

Kovner, Rezaeian Phys.Rev. D95 (2017) no.11, 114028

$$q(p_1) + q(p_2) + A \to \gamma(k_1) + \gamma(k_2) + \text{jet}(q) + \text{jet}(q') + X.$$



CGC of target nucleus

DTMD

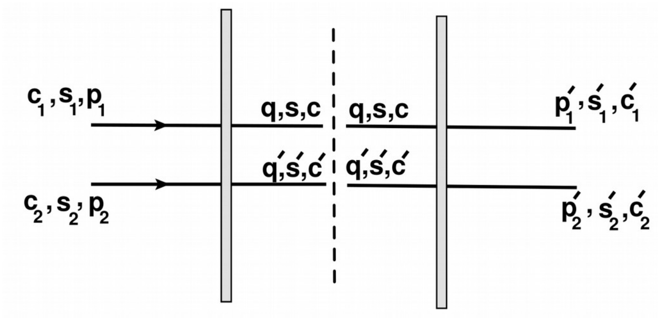
$$d\sigma^{qq+A\to\gamma\gamma+qq} = \int\int \frac{d^3p_1}{(2\pi)^3}\frac{d^3p_2}{(2\pi)^3}\Big[\mathcal{T}(x_1,x_2,\mathbf{p}_1,\mathbf{p}_2,0)\ d\sigma^{q(p_1)+A\to\gamma(k_1)+q(q)} \times d\sigma^{q(p_2)+A\to\gamma(k_2)+q(q')}$$
$$+\ \mathcal{T}(x_1,x_2,\mathbf{p}_1,\mathbf{p}_2,\Delta)\ d\sigma^{\text{Interference}}\Big], \quad \Delta = k_2 - k_1.$$

Enhanced double photon cross section for $|\mathbf{k}_1 - \mathbf{k}_2| < 1/R$

DPS in the CGC

Double Quark Production and Effects of Quantum Statistics

Kovner, Rezaeian Phys.Rev. D96 (2017) no.7, 074018



Production of identical quarks:

Uncorrelated term

$$\mathcal{I}_{uu} = 16\frac{(2\pi)^4}{4}\delta(p_1^- - q^-)\delta(p_1'^- - q^-)\delta(p_2^- - q'^-)\delta(p_2'^- - q'^-)q^- q'^-$$

$$\times 2N_c^2 \int_{p_1,p_2,\Delta}\Big[2\langle D(\mathbf{p}_1 - \mathbf{q} + \Delta/2, 2\Delta)D(\mathbf{p}_2 - \mathbf{q}' - \Delta/2, -2\Delta)\rangle \mathcal{T}_u(x_1, 0, \mathbf{p}_1, \Delta)\mathcal{T}_u^*(x_2, 0, \mathbf{p}_2, \Delta)$$

$$-\frac{1}{N_c}\langle Q(\mathbf{p}_1 - \mathbf{q} + \Delta/2, \mathbf{p}_2 - \mathbf{q}' - \Delta/2, \Delta)\rangle \mathcal{T}_u(x_1, x_2 - x_1, \mathbf{p}_1, \mathbf{p}_2 - \mathbf{p}_1 - \Delta)\mathcal{T}_u^*(x_1, x_2 - x_1, \mathbf{p}_1 + \Delta, \mathbf{p}_2 - \mathbf{p}_1 - \Delta)\Big].$$

GTMD

Correlated term (suppressed by $1/N_c$)

(Gaussian model)

$$S\delta^2(\Delta)G_T(\mathbf{p}_1 - \mathbf{q})G_T(\mathbf{p}_2 - \mathbf{q}') + S\delta^2(\mathbf{p}_1 - \mathbf{p}_2 + \Delta - \mathbf{q} + \mathbf{q}')G_T(\mathbf{p}_1 - \mathbf{q})G_T(\mathbf{p}_2 - \mathbf{q}').$$

Pauli blocking term

$$\mathcal{I}_{PB} \propto -\frac{2}{N_c}S\int_{\mathbf{p}_1,\mathbf{p}_2} G_T(\mathbf{p}_1 - \mathbf{q})G_T(\mathbf{p}_2 - \mathbf{q}')|\mathcal{T}_u(x_1, x_2 - x_1, \mathbf{p}_1, \mathbf{p}_2 - \mathbf{p}_1)|^2.$$

Suppression when mta of incoming quarks are close

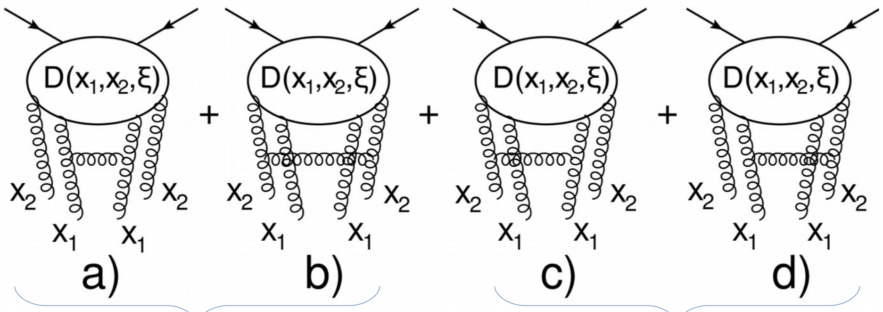
HBT correlation term

$$\mathcal{I}_{HBT} \propto -\frac{2}{N_c}S\int_{\mathbf{p}_1,\mathbf{p}_2} G_T(\mathbf{p}_1 - \mathbf{q})G_T(\mathbf{p}_2 - \mathbf{q}')\mathcal{T}_u(x_1, x_2 - x_1, \mathbf{p}_1, \mathbf{q}' - \mathbf{q})\mathcal{T}_u^*(x_1, x_2 - x_1, \mathbf{p}_2 + \mathbf{q} - \mathbf{q}', \mathbf{q}' - \mathbf{q}),$$

Effect when mta of outgoing quarks are close

Effects from non-diagonal cross-talk diagrams

Importance of interference graphs in which two parton ladders exchange partons with one another recently revisited in Gotsman, Levin [arXiv:1711.02647]



Effect of interference diagrams is incorporated into framework of Diehl, Gaunt Schoenwald via initial conditions at matching scale $\mu_y \sim 1/y$: JHEP 1706 (2017) 083

$$F_{y\to 0}(\boldsymbol{y}) = F_{\mathrm{spl,pt}}(\boldsymbol{y}) + F_{\mathrm{tw3,pt}}(\boldsymbol{y}) + F_{\mathrm{int,pt}}(\boldsymbol{y}),$$

$$F_{\mathrm{int,pt}}(x_1, x_2, \boldsymbol{y}; \mu) = G(x_1, x_2, x_2, x_1; \mu) + C(\cdots, \boldsymbol{y}; \mu) \otimes G(\cdots; \mu) + \ldots$$

Twist 4 distribution – contains effects of interference graphs

For evolution between $\mu=\mu_y$ and $\mu=Q$, interference graphs do **not** contribute

Typically ignore contribution of interference graphs to G in pheno studies, but it is known that they cause G to be enhanced at low x

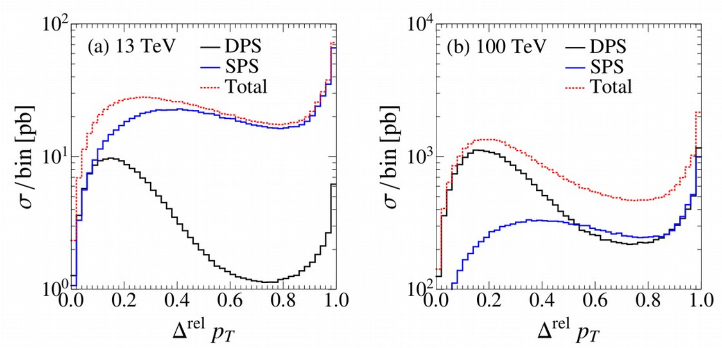
See e.g. Bartels, Ryskin, Z.Phys. C60 (1993) 751–756

Phenomenology for DPS

DPS involving vector bosons

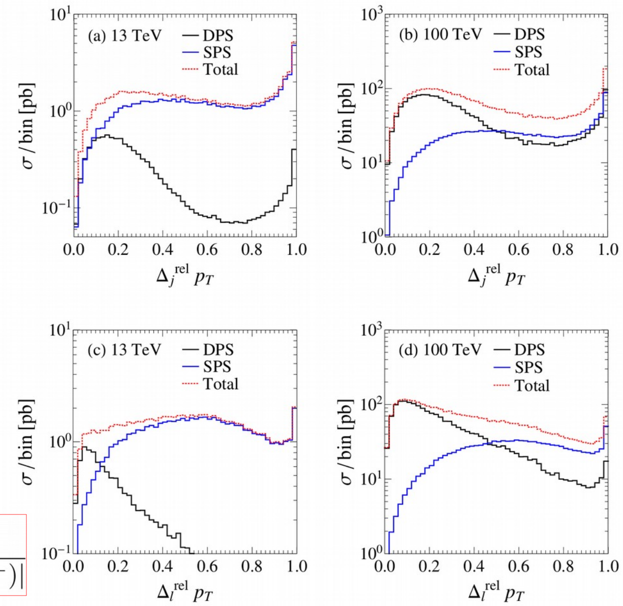
Cao, Liu, Xie, Yan arXiv:1710.06315

Wjj



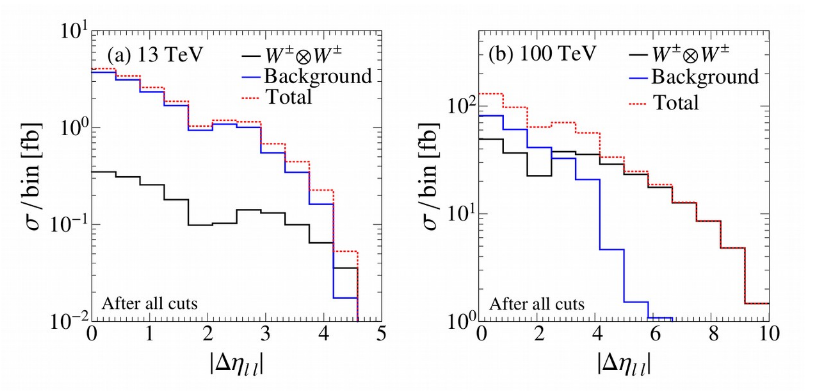
$$\Delta^{\rm rel} p_T = \frac{|p_T(j_1, j_2)|}{|p_T(j_1)| + |p_T(j_2)|},$$

Zjj

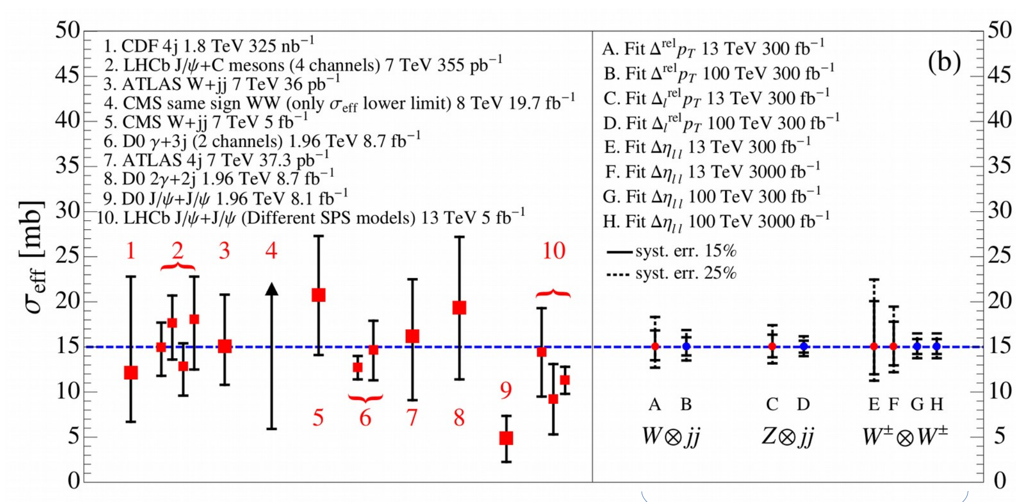


$$\Delta_\ell^{\rm rel} p_T = \frac{|p_T(\ell^+, \ell^-)|}{|p_T(\ell^+)| + |p_T(\ell^-)|}$$

Same-sign WW



$$\Delta\eta_{\ell\ell} = \eta_{\ell_1^\pm} - \eta_{\ell_2^\pm},$$

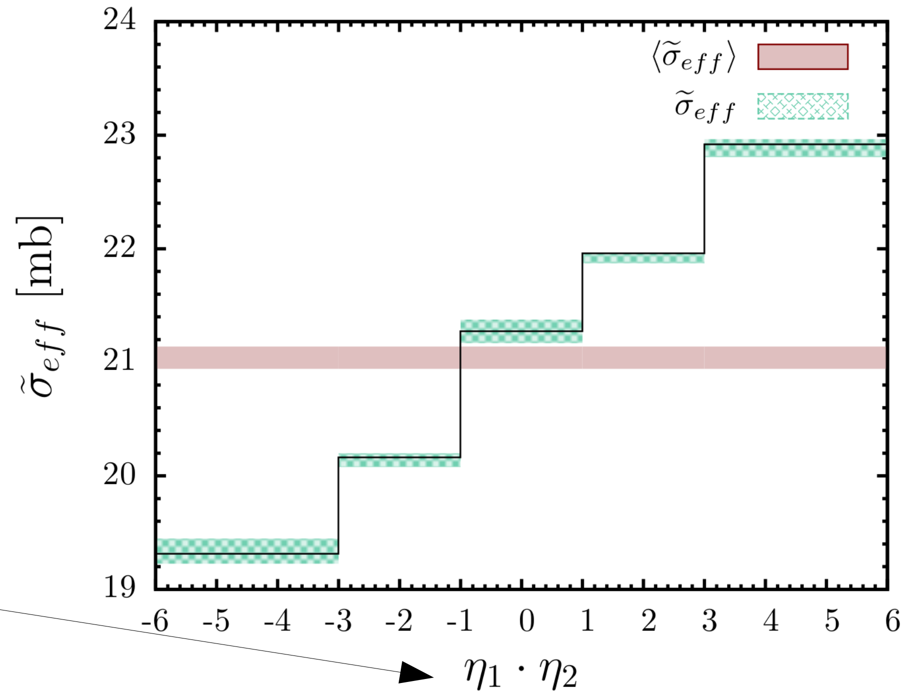


Projected accuracy in the 3 channels

Study of correlations in same-sign WW DPS

Ceccopieri, Rinaldi, Scopetta, Phys. Rev. D 95, 114030 (2017)

DPDs from their light-front quark model at low scale, evolved up to higher scale using independent ladder evolution



Product of pseudorapidities of leptons produced from W decays

Feasible to measure such departures from constant value at HL-LHC!

See talk by M. Dunser, Workshop on the physics of HL-LHC, and perspectives at HE-LHC, at CERN

For further discussion of DPS pheno, see talks by J.-P. Lansberg and A. Szczurek