Proton Structure at the LHC via double parton scattering

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Outline

1- double parton distribution functions (dPDFs):

- dPDFs within Light-Front constituent quark models
- correlations induced by relativistic effects on dPDF evaluations

2- DPS cross section for same-sign W boson pairs production :

- longitudinal correlations

3- Hadronic structure : connection between the so-called effective cross section and the partonic mean transverse distance

M. Rinaldi, S. Scopetta, M. Traini and V. Vento, JHEP12, 028 (2014)
M. Rinaldi and F. A. Ceccopieri, Phys. Rev. D95, no. 3, 034040 (2017)
F. A. Ceccopieri, M. Rinaldi and S. Scopetta, Phys. Rev. D95(2017) no.11, 114030
M. Rinaldi and F. A. Ceccopieri, Phys. Rev. D97 (2018) no.7, 071501

dPDFs from model calculations

- dPDFs are essential ingredients in DPS cross sections calcuations
- Very poorly known objects: use model calculations
- They can be calculated starting form their light-cone correlator:

$$F(x_1, x_2, \vec{k}_\perp) = \int d\vec{k}_1 d\vec{k}_2 \, \Psi\left(\vec{k}_1 + \frac{\vec{k}_\perp}{2}, \vec{k}_2 - \frac{\vec{k}_\perp}{2}\right) \Psi^\dagger\left(\vec{k}_1 - \frac{\vec{k}_\perp}{2}, \vec{k}_2 + \frac{\vec{k}_\perp}{2}\right) \delta\left(x_1 - \frac{k_1^+}{M_0}\right) \delta\left(x_2 - \frac{k_2^+}{M_0}\right)$$
$$\times \langle SU(6)|D_1^\dagger D_1 D_2^\dagger D_2|SU(6)\rangle$$

- $k_\perp$ is transverse momentum unbalance
- Ψ is the proton wave function calculated via constituent quark model (CQM)
- Light Front proton wave function is related to the canonical one by Melosh operators D : $|k, \sigma\rangle_{LF} \propto \sum_\mu \langle \mu|\hat{D}|\sigma\rangle \; |k, \mu\rangle_C$
- dPDFs calculated this way have the good support, $x_1 + x_2 < 1$, and respect sum rules

Hadronic models

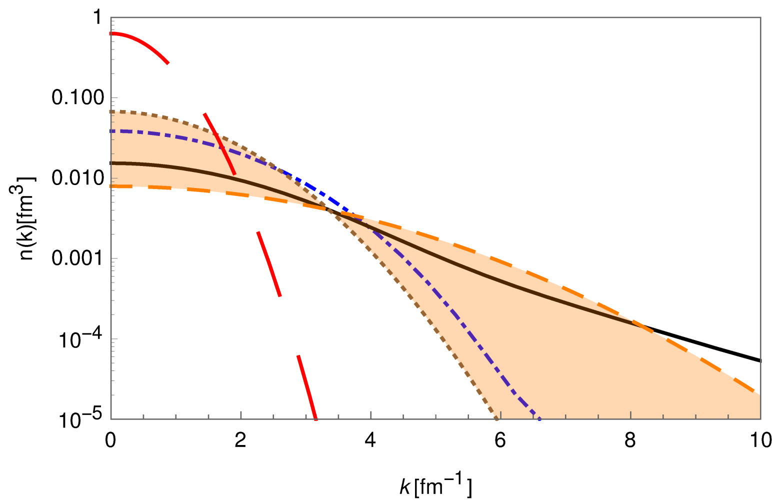
- Quark momentum distribution in term of the proton wave function:
  $n(k) = 3\int d\vec{k_1} d\vec{k_2} \delta(\vec{k} - \vec{k_1} - \vec{k_2} |\Psi(\vec{k_1}, \vec{k_2})|^2)$

- hypercentral quark model
  - relativistic RL (full black)
  - non relativistic NR (dot-dashed blue)

- harmonic oscillator model
  - original HO (dashed red)
    $\alpha^2 = 1.35 fm^{-2}$
  - modified relativistic version (orange)
    $6 < \alpha^2 < 25 fm^{-2}$

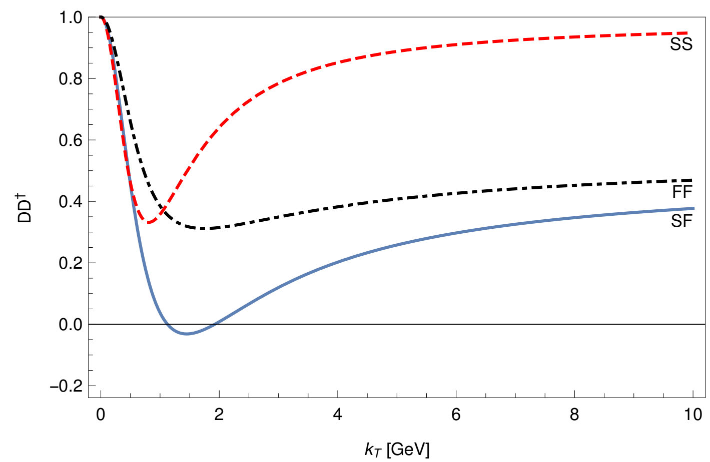
- These model contains different dynamics : address model dependence

- Broad tail = relativistic



Melosh operators

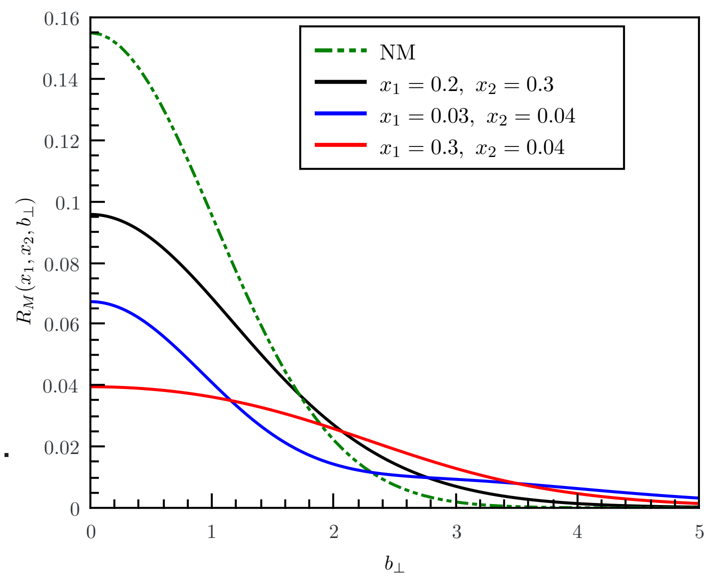
- Melosh operators are given by
$$\hat{D}_i = \frac{m + x_i M_0 + i(k_{ix}\sigma_y - k_{iy}\sigma_x)}{\sqrt{(m + x_i M_0)^2 + k_{ix}^2 + k_{iy}^2}}$$
- In order to better visualize them consider the special kinematical configuration:
  - $DD^\dagger(\vec{k}_\perp, x_1, x_2, \vec{k}_{1\perp} = 0, \vec{k}_{2\perp} = 0)$
  - 2 fast partons (FF), $x_1 = 0.2, x_2 = 0.3$
  - 1 slow and 1 fast (SF), $x_1 = 0.04, x_2 = 0.3$
  - 2 slow partons (SS), $x_1 = 0.04, x_2 = 0.03$



- Melosh reduce to unity at $k_\perp \to 0$
  - No effect for diagonal distributions, as PDFs
  - Present for off-diagonal distributions ($k_\perp \neq 0$) as dPDFs
- Melosh are weighted by the hadronic wave function

dPDFs : $b_\perp$ dependence

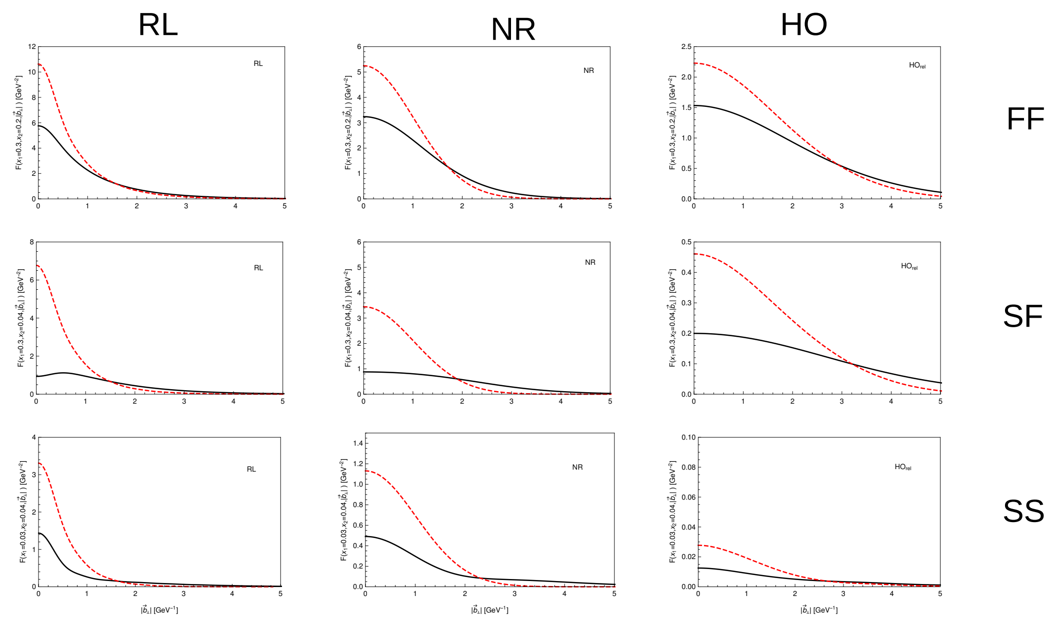
- Melosh operators and kinematic correlations on valence dPDFs at Q_0:
  $R_N(x_1, x_2, b_\perp) = \dfrac{F(x_1, x_2, b_\perp)}{\int d\vec{b}_\perp\; F(x_1, x_2, b_\perp)}$
- Denominator does not depend on Melosh, since they reduce to unity for $k_\perp \to 0$
- R_N evaluated with HO_{rel}: (x_1, x_2)-$k_\perp$ dependences are entirely factorized $\to$ correlation induced only by Melosh operators.
- dPDFs evalueated without Melosh give superimposed result (no x dependence)



- with Melosh included, significant reduction of dPDFs and progressive broadening of $b_\perp$ distribution depending on x.

dPDFs : $b_\perp$ shape

- valence-valence distribution at the hadronic scale Q_0
- with Melosh : black
- without Melosh : red
- sizeable hadronic model dependence
- substantial reduction of dPDFs
- taking ratio, Melosh effect are stable
  $\longrightarrow$ nearly model independent effect



- phenomenological extraction
  to supplement dPDFs asnsatz
  with relativistic effects (which are beyond factorized approach):

M. Rinaldi, F.A.C, arXiv 1812.04286

ssWW DPS cross section

- Same sign WW production golden channel for DPS studies
- SPS production is $\mathcal{O}(\alpha_s^2)$, controlled by jet veto
- DPS cross section can be written as:

$$\frac{d^4\sigma^{pp\to\mu^\pm\mu^\pm X}}{d\eta_1 dp_{T,1} d\eta_2 dp_{T,2}} = \sum_{i,k,j,l} \frac{1}{2} \int d^2\vec{b}_\perp F_{ij}(x_1, x_2, \vec{b}_\perp, M_W) F_{kl}(x_3, x_4, \vec{b}_\perp, M_W) \cdot$$

$$\cdot \frac{d^2\sigma_{ik}^{pp\to\mu^\pm X}}{d\eta_1 dp_{T,1}} \frac{d^2\sigma_{jl}^{pp\to\mu^\pm X}}{d\eta_2 dp_{T,2}} \mathcal{I}(\eta_i, p_{T,i})$$

- factorization scale: $\mu_A = \mu_B = M_W$
- $\mathcal{I}(\eta_i, p_{T,i})$ implements experimental cuts on muons
- $1/2$ stems for identical particles in the final state
- We considered 3 dPDF models:

dPDFs models

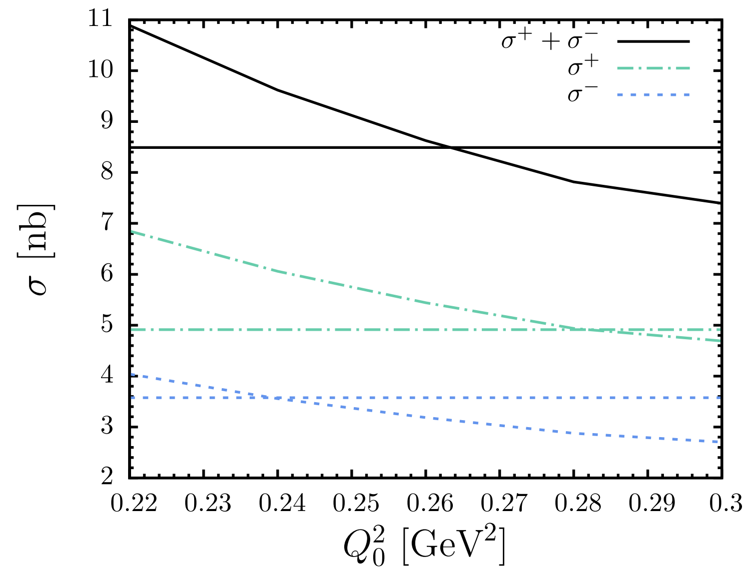
- MSTW08: $F_{ij}(x_1, x_2, \mu_A, \mu_B) \sim f_i^{\texttt{MSTW08}}(x_1, \mu_A) f_j^{\texttt{MSTW08}}(x_2, \mu_B)$
- GS09 : factorised ansatz based on MSTW08 plus additional factors to accomodate sum rule + dPDFs evo + inh term
- IMPORTANT: σ_{eff} MUST BE assumed to obtain σ^{DPS} via pocket formula
- QM : dPDFs from Light-Front Poincaré covariant constituent quark model:

$$F_{du} = F_{ud} = F_{uu}(x_1, x_2, Q_0^2, \vec{b}_\perp) \, .$$

  - Fulfills exactly sum rules when integrated over $\vec{b}_\perp$: e.g. $N_{uu} = 2$ at Q_0
  - homogenous double DGLAP evolution (valid at fixed $\vec{b}_\perp$) with same QCD parameters and evolution scheme used for single PDFs.
  - Same Q_0 as for single PDFs from CQM (see next slide)
  - IMPORTANT : $\vec{b}_\perp$-dep is embedded, avoid the use of external σ_{eff} !!

Q_0 fixing

- DGLAP evolution of $f_{u,d}(x, Q_0^2)$ from CQM
- Same evo scheme as `MSTW08`
  - $\alpha_s(M_Z) = 0.139$, VFNS
  - $m_c = 1.4$, $m_b = 4.76$ GeV
- infrared sensitivity: at Q_0, valence quarks carry all proton momentum
- Tune Q_0 to reproduce $\sigma^{W^\pm}$ from `DYNNLO` obtained with `MSTW08` at LO,
  muon PS $\equiv p_T^\mu > 20$ GeV and $|\eta^\mu| < 2.4$ at 13 TeV



- No simultaneous good description of σ^+ and σ^-. Isospin assumption in CQM: $f_d(x, Q_0^2) = 1/2 f_u(x, Q_0^2)$
- $Q_0^2 = 0.26$GeV^2. Associated theoretical syst error : $0.24 < Q_0^2 < 0.28$ GeV^2 (δQ_0)

ssWW fiducial cross section: results

- Cuts mutuated from CMS Collaboration: CMS-PAS-FSQ-13-001
- CQM : $\mu_F = M_W$ and $Q_0^2 = 0.260$ GeV^2
- GS09 and MSTW : $\mu_F = M_W$, $\bar{\sigma}_{eff} = 17.8 \pm 4.2$ mb $(\delta\bar{\sigma}_{eff})$ from $W + $ 2jet analysis (ATLAS and CMS)
- $\delta\mu_F \equiv 0.5 M_W < \mu_F < 2.0 M_W$: higher order corrections in hard scattering
- CQM scale fixing : $\delta Q_0 \equiv 0.24 < Q_0^2 < 0.28$ GeV^2
- Compatible within errors

pp, $\sqrt{s} = 13$ TeV
$p_{T,\mu}^{leading} > 20$ GeV, $p_{T,\mu}^{subleading} > 10$ GeV
$\lvert p_{T,\mu}^{leading}\rvert + \lvert p_{T,\mu}^{subleading}\rvert > 45$ GeV
$\lvert\eta_\mu\rvert < 2.4$
20 GeV $< M_{inv} <$ 75 GeV or $M_{inv} >$ 105 GeV

dPDFs	$\sigma^{++} + \sigma^{--}$ [fb]
MSTW	$0.77\,^{+0.23}_{-0.21}\,(\delta\mu_F)\,^{+0.18}_{-0.18}\,(\delta\bar{\sigma}_{eff})$
GS09	$0.82\,^{+0.24}_{-0.26}\,(\delta\mu_F)\,^{+0.19}_{-0.19}\,(\delta\bar{\sigma}_{eff})$
QM	$0.69\,^{+0.18}_{-0.18}\,(\delta\mu_F)\,^{+0.12}_{-0.16}\,(\delta Q_0)$

ssWW fiducial cross section: ratios

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

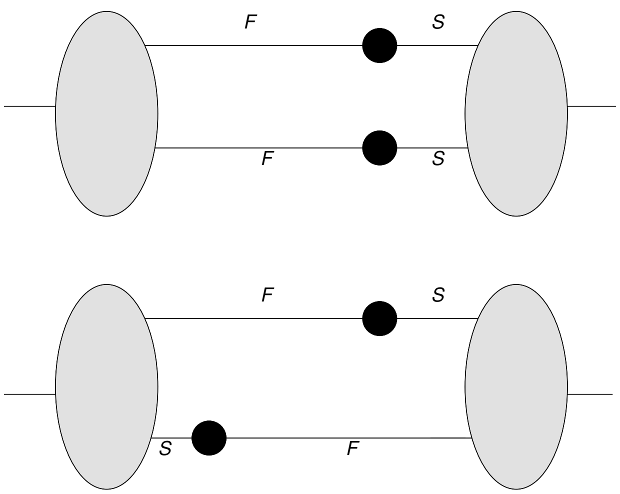
- σ^{++} OK
- σ^{--} significantly smaller :
  - isospin assumptions in CQM
  - F_{dd} and $F_{\bar{u}\bar{u}}$ are radiatively generated in QM
- Different predictions for σ^{++}/σ^{--}:
  - Good observable sensible to dPDFs flavour structure.

Observable sensitive to dPDFs longitudinal correlations

- Neglecting the boost from W decay to lepton:

$$\eta_1 \cdot \eta_2 \simeq \frac{1}{4} \ln \frac{x_1}{x_3} \ln \frac{x_2}{x_4}$$

- $x_1 x_3 = x_2 x_4 = M_W^2/s$
- $\eta_1 \cdot \eta_2 \gg 0$:
  muons in same emiphere FF vs SS
- $\eta_1 \cdot \eta_2 \ll 0$:
  muons in opposite emiphere FS vs SF



ssWW σ^{DPS} : differential distribution

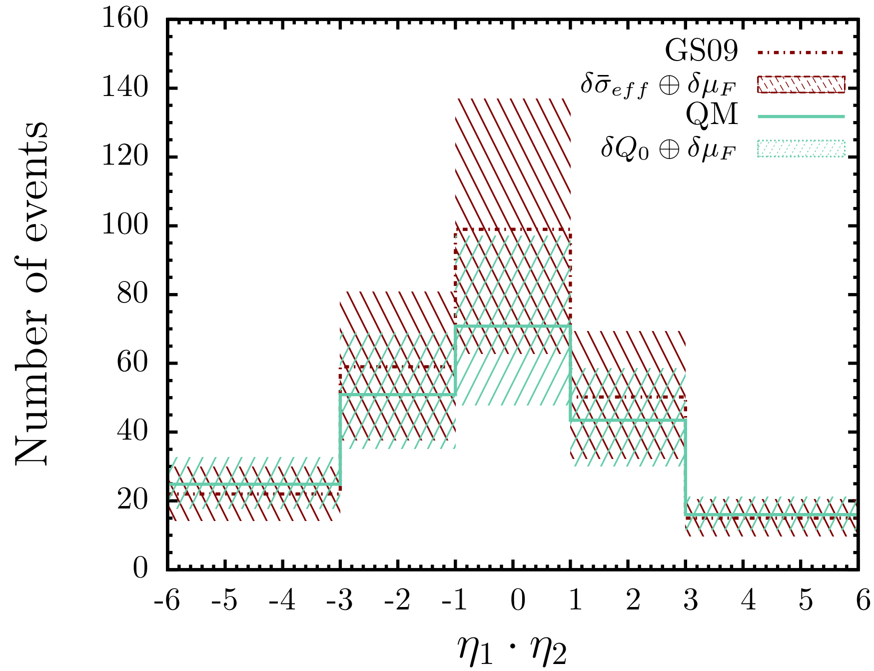
- Distribution converted to per-bin number of events assuming:

  $\mathcal{L} = 300\text{fb}^{-1}$

- Similar shapes for GS09 and CQM

- Compatible within (sizeable) errors

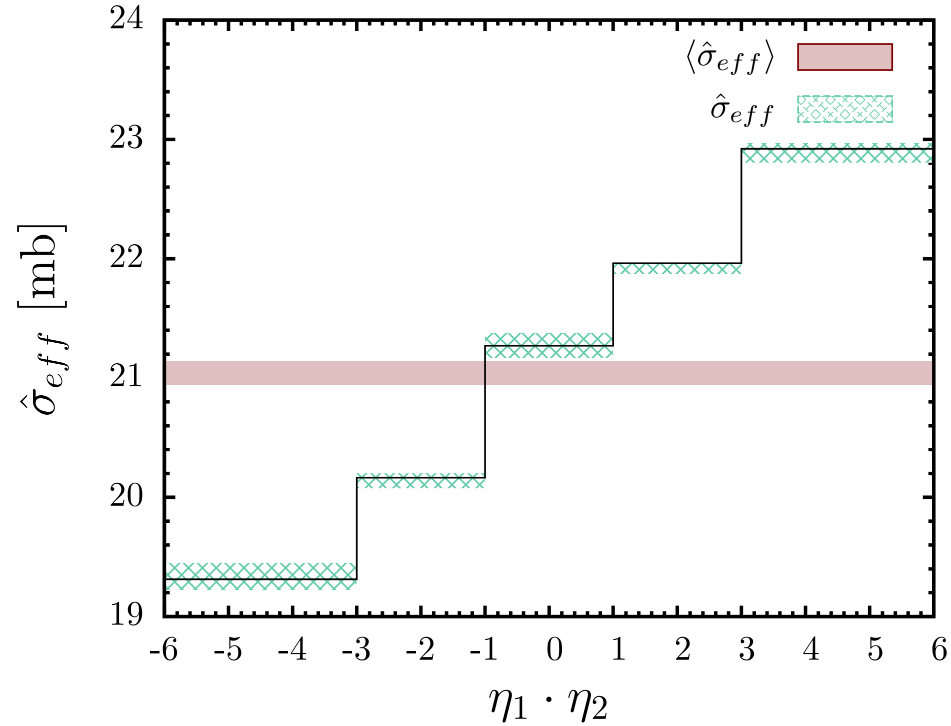
- maximun is located at $\eta_1 \cdot \eta_2 \sim 0$, all partons have $x \sim M_W/\sqrt{s}$



- skewed distribution: $F(x_1 \to 1, x_2 \to 1) < F(x_1 \to 1, x_2 \to 0)$

Correlations in $\widehat{\sigma}_{eff}$

- $\hat{\sigma}_{eff} \simeq \frac{1}{2} \frac{d\sigma_{SPS}^{CQM} d\sigma_{SPS}^{CQM}}{d\sigma_{DPS}^{CQM}}$
- $\hat{\sigma}_{eff}$ stable against scale variations (Q_0 and μ_F)
- Within this particular model, non-constant $\hat{\sigma}_{eff}$ could be appreciated IFF: $\mathcal{L} > 1000\,\text{fb}^{-1}$ at 68% C.L.

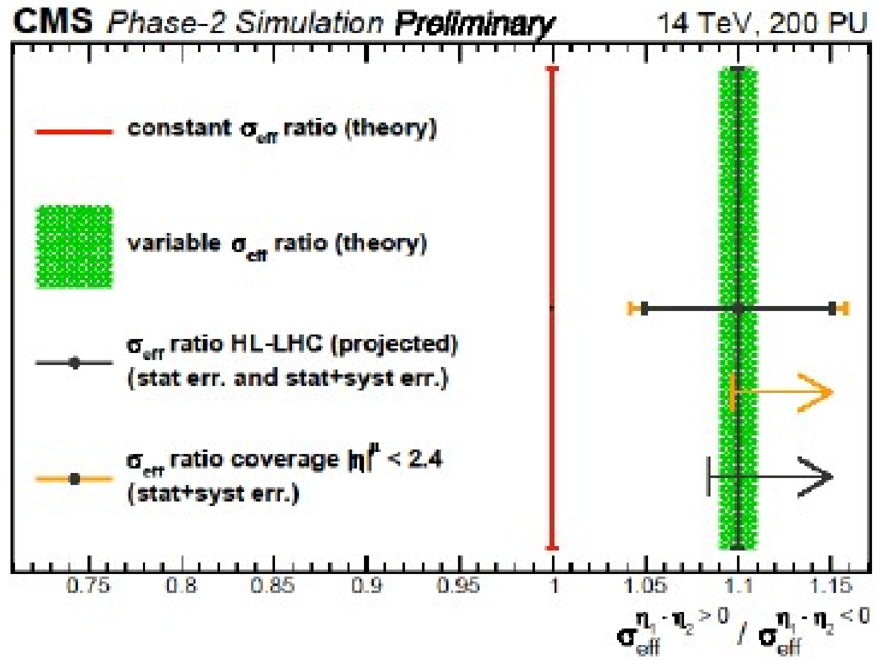


$$\langle\widehat{\sigma}_{eff}\rangle = 21.04\,^{+0.07}_{-0.07}\,(\delta Q_0)\,^{+0.06}_{-0.07}(\delta\mu_F)\ \text{mb}\ .$$

Hint for correlations in ssWW

	$\sigma_{eff}^{\eta_1 \cdot \eta_2 > 0} / \sigma_{eff}^{\eta_1 \cdot \eta_2 < 0}$
GS09	1.14
CQM	1.17
MSTW08	1.09

Interpretation requires care:



CMS-TDR-017-003

σ_{eff} vs $\langle b^2 \rangle$: derivation of a minimum

- Use "experimental" approximation to dPDFs:
  $F_{ij}(x_1, x_2, k_\perp, Q^2) \sim q_i(x_1, Q^2) q_j(x_2, Q^2) f(k_\perp)$
- The mean interpartonic distance between two partons, $\langle b^2 \rangle$, is given by
  $\langle b^2 \rangle = -4 \frac{d\ f(k_\perp)}{d\ k_\perp^2}\Big|_{k_\perp=0}$
- With the same approximation: $\sigma_{eff}^{-1} = \int \frac{d^2 k_\perp}{(2\pi)^2} f(k_\perp)^2$
- By exploiting very general properties of the hadronic wave function:
  $f(k_\perp = 0) = 1$ and $f(k_\perp \to \infty) = 0$
  we get a set of identities with which we analytically obtain a minimum to $\langle b^2 \rangle$:

$$\langle b^2 \rangle \geq \sigma_{eff}/(3\pi)$$

σ_{eff} vs $\langle b^2 \rangle$: derivation of a maximum

- A maximum for $\langle b^2 \rangle$ can not be analytically found unless an additional assumption on the behaviour of $f(k_\perp)$ at large $k_\perp$ is made
- Use a tunable dipole test function of the type: $f(k_\perp) = \left(1 + \frac{k_\perp^2}{m^2}\right)^{-r}$
- For $r > 1$ the problem allows a solution (argument technical, see paper)
- NB1: All form factors (e.m., two gluon etc.) in the literature satisfie this requirement
- NB2: $f(k_\perp)$ should fall at least as fast as other form factors, since $k_\perp$ is a transverse momentum imbalance.
- then we are able to derive a maximum to $\langle b^2 \rangle$:

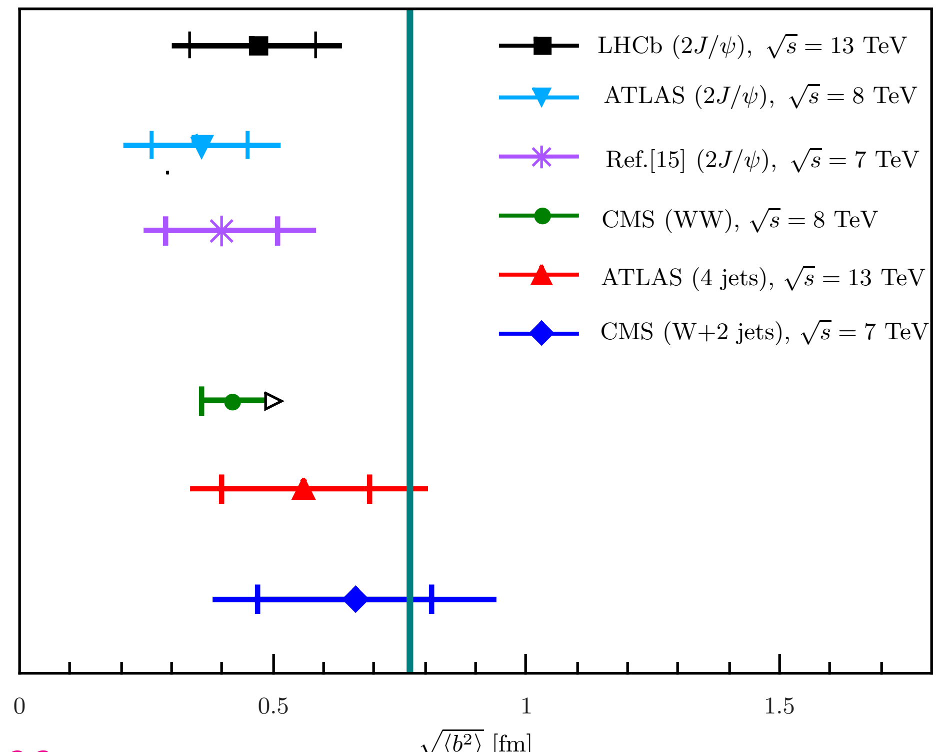
$$\langle b^2 \rangle \leq \sigma_{eff}/(\pi)$$

σ_{eff} vs $\langle b^2 \rangle$: results

- Minimum:
  fully analytical
- Maximum:
  analytical + assumption on $f(k_\perp)$ for $k_\perp \to \infty$

$$\frac{\sigma_{eff}}{3\pi} \leq \langle b^2 \rangle \leq \frac{\sigma_{eff}}{\pi}$$

- The inequality has been generalized to include:
  - 2v1 effects
  - (x_1, x_2) unfactorized dPDFs



M. Rinaldi and F.A.C. arXiv 1812.04286

Summary

- dPDFs from hadronic model calculations are important in this phase to "drive" dPDFs phenomenological analyses:
  - models have a built-in $b_\perp$-dependence*
  - impact of relativistic effects on dPDFs is sizeable: if properly parametrized, could be taken into account in dPDFs parametrization
- We presented results for ssWW cross sections built upon these dPDFs
  - model dependent but σ_{eff}-free estimate* of $ssWW$ cross section
  - Departure from constant $\sigma_{eff} \to$ correlations. Look for $\sigma_{eff}(\eta_1 \cdot \eta_2)$
  - Required luminosities to identify clear correlations have been provided
- we have derived a easy-to-use relation between the averaged mean interparton distance $\langle b^2 \rangle$ and σ_{eff} : insight in hadronic structure from DPS studies