

Exploring high-purity multi-parton scattering at the LHC

Alba Soto Ontoso CERN, 4th December, 2023 QCD seminar

Z

at the LHC

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 $M_{\rm H}$ are a fascinating phenomenon that occur in almost every high-energy in almost every high-energy high-ene

CERN-TH-2023-055, DCPT/23/54, IPPP/23/27, OUTP-23-04P, ZU-TH 17/23 **arXiv:2307.05693**

Exploring high-purity multi-parton scattering at hadron colliders
 Exploring high-purity multi-parton scattering at hadron colliders

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<# MPI> in Drell-Yan production at hadron colliders

<# MPI> in Drell-Yan production at hadron colliders

 $\mathcal{O}(10)$ additional parton collisions per Drell-Yan event

Z d-scattering scatterings $10 \wedge$ Era of precision physics for the primary hard scattering. What's the status on MPI modelling?

Option A: MPI as part of the MC toolkit

Figure 1: Schematic of the structure of a positive of the structure of the structure of the structure of ϵ_0 [Bierlich et al *SciPost Phys.* Codebases 8 (2022)]

$\alpha_s^2(p_\perp^2)$ ⊥) *p*4 ⊥ . (253)

n Zijl PRD 36, 2019
• **SciPost Physics Codebases Submission** [Bierlich et al SciPost Phys. Codebases 8 (2022)] [Sjostrand and van Zijl PRD 36, 2019 (1987)] [Sjostrand and Skands JHEP 03 053 (2004)]

MPI modelling in general purpose MCs in a nutshell ⊥ $\frac{1}{2}$ *i*,*j*,*k fi*(*x*1,*Q*2) *fj*(*x*2,*Q*2) **6.2.1 The perturbative cross section**

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Partonic cross section data do anticolation data do anticolation data do anticolation data do anticolation dat
P d*σ* dp_1^2 ⊥ = \sum *i*,*j*,*k*

 Ω (1987)] [Sjostrand and Skands JHEP 03 053 (2004)]
 Ω and Ω ranning massless, and *k* running massless, and Ω t andard $\angle \rightarrow \angle$ cross section The Standard 2 → 2 cross section can, to leading a standard 2 → 2 cross section

$$
\frac{d\sigma}{dp_{\perp}^2} = \sum_{i,j,k} \iiint f_i(x_1, Q^2) f_j(x_2, Q^2) \frac{d\hat{\sigma}_i^k}{d\hat{t}} \delta(p_{\perp}^2 - \frac{\hat{t}\hat{u}}{\hat{s}}) dx_1 dx_2 d\hat{t}
$$

$$
\frac{d\hat{\sigma}}{d\hat{t}} \propto \frac{a_s^2(Q^2)}{\hat{t}^2} \Rightarrow \frac{d\hat{\sigma}}{dp_{\perp}^2} \propto \frac{a_s^2(p_{\perp}^2)}{p_{\perp}^4}
$$

divergent when $p_{\perp} \to 0$

$$
\frac{d\hat{\sigma}}{dp_{\perp}^2} \sim \frac{a_s^2(p_{\perp}^2)}{p_{\perp}^4} \rightarrow \frac{a_s^2(p_{\perp 0}^2 + p_{\perp}^2)}{(p_{\perp 0}^2 + p_{\perp}^2)^2}
$$

with $p_{\perp 0}(\sqrt{s})$ a free parameter

Interactions occur independently (w/ momentum, flavour sum rules): Poisson stat over another independently (*w/ momentum* floweur quim rulee): Dejecon stat *parto dominated do ling (γγ*γγιστιστιστιστιστις πανοαι σαπιταισσ). Γοισσότι σται be any interaction in the range between !*s/*2 and *^p*⊥¹ for *^p*⊥¹ to be the hardest interaction. The procedure communication in the internal original terms of

MPI modelling in general purpose MCs in a nutshell **6.2.1 The perturbative cross section**

Standard 2
$$
\rightarrow
$$
 2 cross section
\n
$$
\frac{i}{dp_{\perp}^2} \left\{ \int_0^1 f_i(x_1, Q^2) f_j(x_2, Q^2) \frac{d\hat{\sigma}_{ij}^k}{d\hat{t}} \delta \left(p_{\perp}^2 - \frac{\hat{t}\hat{u}}{\hat{s}} \right) dx_1 dx_2 d\hat{t} \right\}
$$

$$
\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\perp i}}\exp\left(-\int_{p_{\perp i}}^{p_{\perp i-1}}\frac{1}{\sigma_{\mathrm{nd}}}\frac{\mathrm{d}\sigma}{\mathrm{d}p'_{\perp}}\mathrm{d}p'_{\perp}\right)
$$

 \overline{C} no-scattering probability The exponential factors resemble \sim no-scattering probability

 $t_{\text{non-}0}$ in the Region population of $\mathcal{L}_{\text{non-}0}$ fills the same function of ensuring $\mathcal{L}_{\text{non-}0}$ $\frac{1}{100}$ uniqued by unity. We will use the Sudakov terminology to stress the Sudak + some impact-parameter distribution

[Bierlich et al SciPost Phys. Codebases 8 (2022)] [Sjostrand, van Zijl PRD 36, 2019 (1987)] [Sjostrand, Skands JHEP 03 053 (2004)] [Corke, Sjostrand JHEP 1103 (2011)]

Multi-parton interactions are interleaved with the rest of the showering

MPI modelling in general purpose MCs in a nutshell collision moment, while ISR stretches backwards in time from it, and FSR forwards. But we have

-
[Bierlich et al SciPost Phys. Codebases 8 (2022)] [Sjostrand and van Zijl PRD 36, 2019 (1987)] [Sjostrand and Skands JHEP 03 053 (2004)]

Instead we choose the same guiding principle as we did when we originally decided to consider

lined previously, with a few straightforward extensions. For ISR, *e.g.* the *x* and flavour of the own

MPI/underlying event tuning

Tunes performed in events with at least one hard scatter

MPI/underlying event tuning

Option B: double-parton scattering as QFT playground

The double-parton scattering (DPS) cross section can be written as

[Paver, Treleani, Nuovo Cim. A70 (1982) 215] [Blok, Dokshitzer, Frankfurt, Strikman, PRD 83 (2011) 071501] [Diehl, Ostermeier and Schäfer (JHEP 1203 (2012)]

where we have introduced the double-parton density *Fab*

$$
= \int_{\mathbf{b}} F^{ik}(x_i, x_k, \mathbf{b}) \otimes \hat{\sigma}_{ij \to Z} \hat{\sigma}_{kl \to jets} \otimes F^{jl}(x_j, x_l, \mathbf{b}) = \mathcal{O}\left(\frac{\lambda_Q^2}{\zeta}\right)
$$

1/ λ_{QCD}^2 1/ Q^2 1/ Q^2 λ_{QCD}^2

 (x_a, x_b, \mathbf{b})

Double parton scattering can be used for proton tomography, i.e. extract partonic correlations

Option B: double-parton scattering as QFT playground

 $\sigma_{\rm{DPS}}^{A,B}$ DPS

Fab $(x_a, x_b, \mathbf{b}) \simeq f(x_a)f(x_b)$

To first approximation, double-parton density is given by

This leads to the so-called pocket-formula

Option B: double-parton scattering as QFT playground

i.e.

Experimental extractions of $\sigma_{\rm eff}$

[CMS Collab. Nature Phys. 19 (2023) 3, 338-350]

Classic experimental challenge in DPS

Same experimental signature: Z boson (2 leptons) + jets

Illustration: first LHC DPS measurement with $W(\rightarrow \ell \nu) + jj$

[ATLAS Collab. New J.Phys. 15 (2013) 033038]

Illustration: first LHC DPS measurement with W+2-jets 1301.
1301. – Jan Jawa Barat, politik politik († 1301.)
1301. – James Barat, politik († 1302.) $\mathcal{L} = \mathcal{L} = \mathcal$ W^{\pm} *p* $\Delta \simeq 0$

 W^{\pm}

[ATLAS Collab. New J.Phys. 15 (2013) 033038]

Δ

Low 2HS purities require very good understanding of 1HS | jets by a linear combination of Template *A* (dashed line) The result is shown as the green histogram. The bins to the vertical dash-dotted vertical dash-dotted vertical dash-

compared to the results of fitting ∆name and the results of fitting ∆name and the results of fitting ∆name and

⃗

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[CMS Collab. PRL 131 (2023) 091803]

Traditional gold-plated observable for *MRI*:

Avoid QCD radiation issue: same-sign $W^\pm W^\pm$ a function for the ML fit $f(x)$ for the four lepton $f(x)$ for $f(x)$ from $f(x)$ Avoid QUD radiation issue: same-sign $W - W$

[CMS Collab. PRL 131 (2023) 091803]
[CMS Collab. PRL 131 (2023) 091803]

Traditional gold-plated observable for MPI suffers from **background**: T_{tot} ditional oral dislated along up to be found the two Books are shown in A.

Just 6.2*σ* statistical significance with full Run 2 dataset and sign categories. The SPS Weight Contribution of the SPS With The SPS Water and Tennes are grouped as the "R
Experimental and "Rate" and "Rate" and "Rate" and "Rate "Rate" and "Rate "Rate "Rate" and "Rate "Rate "Rate" a

Theory challenges in DPS: beyond pocket-formula

[Diehl, Ostermeier, Schafer JHEP 1203 (2012)], [Diehl, Gaunt, Schönwald JHEP 1706 (2017) 083]

Delicate interplay with loop corrections to 1HS: need to avoid double counting Extend 1HS theory to 2HS: double PDFs, colour flow, sum rules, DGLAP

Substantial progress in describing 2HS with MC tools: dShower

$$
\frac{f(x_q + x_{\bar{q}})}{x_q + x_{\bar{q}}} P_{g \to q\bar{q}} \left(\frac{x_q}{x_q + x_{\bar{q}}} \right) \frac{1}{b^2}
$$

[Cabouat, Gaunt, Ostrolenk JHEP 11 (2019) 061], [Cabouat, Gaunt JHEP 10 (2020) 012]

Perturbative interconnection, i.e. $1 \rightarrow 2$

Theory challenges in DPS: beyond pocket-formula

[Diehl, Ostermeier and Schafer JHEP 1203 (2012)], [Diehl, Gaunt, Schönwald JHEP 1706 (2017) 083]

fain. present al xq + *xq*¯ $\frac{1}{2}$ opt i
I Y **b2** Rest of this talk: present an experimental strategy to optimally disentangle 1HS from MPI

Substantial progress in describing 2HS with MC tools: dShower

Double parton densities, colour flow, sum rules, DGLAP evolution?

[Cabouat, Gaunt, Ostrolenk JHEP 11 (2019) 061], [Cabouat, Gaunt JHEP 10 (2020) 012]

Perturbative interconnection, i.e. $1 \rightarrow 2$

Idea: exploit Parisi-Petronzio lesson from 1979

mechanisms:

[Parisi, Petronzio, [NPB 154 \(1979\) 427-440](https://doi.org/10.1016/0550-3213(79)90040-3)] [RadISH: Monni, Re, Torrielli PRL 116, 242001, Monni, Rottoli, Torrielli PRL 124 (2020) 25, 252001]

Exponential suppression of the spectrum (Sudakov peak)

 p_{tZ}^2 ∼ $k_{t,i}^2$ ≪ M_Z

Idea: exploit Parisi-Petronzio lesson from 1979

[Parisi, Petronzio, [NPB 154 \(1979\) 427-440](https://doi.org/10.1016/0550-3213(79)90040-3)] [RadISH: Monni, Re, Torrielli PRL 116, 242001, Monni, Rottoli, Torrielli PRL 124 (2020) 25, 252001]

We explore Drell-Yan events and study the $p_{tZ} \rightarrow 0$ limit. Two concurring mechanisms: 35

Idea: exploit Parisi-Petronzio lesson from 1979

[Parisi, Petronzio, [NPB 154 \(1979\) 427-440](https://doi.org/10.1016/0550-3213(79)90040-3)] [RadISH: Monni, Re, Torrielli PRL 116, 242001, Monni, Rottoli, Torrielli PRL 124 (2020) 25, 252001]

Key observation to suppress 1HS contribution

[RadISH: Monni, Re, Torrielli PRL 116, 242001, Monni, Rottoli, Torrielli PRL 124 (2020) 25, 252001] [MINNLO: Monni et al JHEP 05 (2020) 143]

By constraining p_{tZ} we can forbid QCD radiation from 1HS above 2-3 GeV

[RadISH: Monni, Re, Torrielli PRL 116, 242001, Monni, Rottoli, Torrielli PRL 124 (2020) 25, 252001] [MINNLO: Monni et al JHEP 05 (2020) 143] 35 30 25 Z $\sqrt{p_{ij}^2}$ [GeV] 10 MPI off: $\langle p_{tj}^{\ell} \rangle_{p_{tZ} \to 0}$ ∼ 2.5 GeV 5 $\overline{0}$ MPI on: $\langle p_{tj}^{\ell} \rangle_{p_{tZ} \to 0} \sim 10 \text{ GeV}$

Suggests we should study MPI with help of a tight cut on p_{tZ}

What happens when switching on MPI?

This study: establish what cut to use, explore new opportunities

We want balance between :

- maximising stats (loose p_{tZ}^{cut}) *tZ*
- minimise 1HS (tight p_{tZ}^{cut}) *tZ*

Optimum at
$$
p_{tZ}^{\text{cut}} = 2 \text{ GeV}
$$

Corresponds to 12 million events in Run 3 at LHC

Experimental feasibility :

$$
\bullet p_{tZ}^{\text{cut}} = 2 \text{ GeV: } 4\text{-}5\% \text{ }\sigma_{\text{DY}}
$$

New observables: cumulative jet spectrum with p_{tZ} < C_Z

Average number of jets above $p_{t_i,min}$ for a given cut C_Z on p_{tZ} :

$$
\langle n(p_{ij,\min}) \rangle_{C_Z} = \frac{1}{\sigma(p_{tZ} < C_Z)} \int_{p_{ij,\min}} dp_{ij} \frac{d\sigma_{\text{jet}}(p_{tZ} < C_Z)}{dp_{ij}}
$$

For small jet radii, *R* ,the total spectrum is a linear sum, i.e.:

$$
\langle n(p_{tj, \min}) \rangle_{C_Z} \simeq \sum_{R < 1}^{n \text{--HS}} \langle n(p_{tj, \min}) \rangle_i^i
$$

 $i_{C_Z} = \langle n(p_{tj, min}) \rangle_{C_Z}^{\text{MPI-off}}$ $+ \langle n(p_{tj, min}) \rangle_{C_Z}^{\text{MPI-on}}$

New observables: cumulative jet spectrum with p_{tZ} < 2 GeV

Less than 1 jet/event from the primary hard scattering

Around 10 jets/event from multi-parton interactions

New observables: cumulative jet spectrum with p_{tZ} < 2 GeV

10 GeV 90% **20 GeV** 78% **40 GeV** 60%

Around 10 jets/event from multi-parton interactions

Ptj, min [GeV]

Tight cut on p_{tZ} yields high-purity MPI samples. How can we exploit them?

New observables: cumulative jet spectrum with p_{tZ} < 2 GeV

Pure MPI cumulative jet spectrum with $p_{tZ} < C_Z$

We introduce the pure MPI contribution to the inclusive jet spectrum

 $\langle n(p_{tj, min}) \rangle$ pure−MPI

 $\sigma_{\rm{DPS}}^{A,B}$

Pure MPI cumulative jet spectrum with p_{tZ} < C_Z

We introduce the pure MPI contribution to the inclusive jet spectrum

$$
\langle n(p_{tj, \min}) \rangle_{C_Z}^{\text{pure-MPI}} \simeq \frac{1}{\sigma_{\text{eff}}} \int_{p_{tj, \min}} dp_{tj} \frac{d\sigma_{\text{jet}}}{dp_{tj}}
$$

Pocket formula predicts $\langle n(p_{tj, \text{min}})\rangle^{\text{pure-WIP1}}_{C_{7}}$ to be independent of pure−MPI *CZ CZ*

 $\langle n(p_{tj, min}) \rangle$ pure−MPI

pure-MPI
$$
\equiv \langle n(p_{tj,min}) \rangle_{C_Z} - \langle n(p_{tj,min}) \rangle_{C_Z}^{\text{no-MPI}}
$$

 \longrightarrow Z+j@NLO theory prediction

 \rightarrow Inclusive jet rate in min-bias (no Z)

In the pocket-formula approach this reduces to

New observable: ratio of $\langle n(p_{tj,\, \mathrm{min}})\rangle^{\mathrm{pure-NIP1}}_{C_7}$ with different *t* pure−MPI *CZ* p_{tZ} < C_Z

We propose to measure

$$
r_{15/2} = \frac{\langle n(p_{tj, \text{min}}) \rangle_{15}^{\text{pure-MPI}}}{\langle n(p_{tj, \text{min}}) \rangle_{2}^{\text{pure-MPI}}}
$$

• Pocket formula: $r_{15/2} = 1$ • Pythia: $r_{15/2} \approx 1$ (colour reconnection)

New observable: ratio of $\langle n(p_{tj,\, \mathrm{min}})\rangle^{\mathrm{pure-NIP1}}_{C_7}$ with different *t* pure−MPI *CZ* p_{tZ} < C_Z

We propose to measure

 $r_{15/2} =$

• Pocket formula: $r_{15/2} = 1$ • Pythia: $r_{15/2} \approx 1$ (colour reconnection)

• Perturbative interconnection:

$$
\langle n(p_{tj, min}) \rangle_{15}^{\text{pure-MPI}}
$$

$$
\langle n(p_{tj, min}) \rangle_{2}^{\text{pure-MPI}}
$$

$\left(\begin{array}{c} \nu \mathcal{L} \end{array} \right)$ adiation from the partons

mult**antial deviations** The **Brobing deviations from the pocket-formula** $\mathrm{scatter.}\ \text{in} \ \text{equation} \ \text{equation} \ \text{thereation} \ \text{equation} \ \text{equ$ SCAU UEF, I.C. IIICECASILLS
 AIIC DECEPT 11 o $2HS$, Fig. 1b. 2.00 $pp\rightarrow Z/\gamma\rightarrow \mu\mu$, $\sqrt{s} = 13.6$ TeV ivity to this effect, we $\frac{1}{100}$ 1.75 anti- k_t R=0.4 $66 < m_{\mu\mu} < 116 \,\, \mathrm{GeV}$ 2 HS rate with loose $(C_{Z}$ $p_{t\mu}$ > 27 GeV, $|\eta_{\mu}|$ < 2.5 $\left(P_{t}\right)$ constraints on $p_{tZ},$ 1.50 \mathcal{F} , obthout 1.25 **25% effect from interconnection** pure-MPI $\ket{\text{in}}\rangle$ 15 \overrightarrow{h} 1.0 pure-MPI $\ket{\text{in}}\rangle$ 2 0.75 normalised to the num 0.50 Pythia8+MINNLO ction cut. With the poc_{o-} dShower w/o interconnection (Zgg only) r^{\cup} \equiv ⁰ $\frac{1}{r}$ \sum_{ν} Protection (expectively) interesting \sum_{ν} dShower w/ interconnection (Zgg only) μ , and so an experimental to provide p μ , μ potential to provide p^{o.(} 25 50 55 60 30 35 40 45 $frac$ from the ne $p_{tj, min}$ [GeV] s from the pocket form $\begin{array}{c} \n\hline\n\end{array}$ the pure-M NLO to be Can one see effect of perturbative interconnection in data? **NLO** to be \sim \sim (26) $r_{\rm max}$

which should be adequate tive interconnection is turned on between the primary and primary

between the two leading charged-track jets in events with

Assessing statistical significance of perturbative interconnection **Necorcing statistical significance of porturbative interconne**

FIG. 10. Statistical significance of the detection of the breaking of the pocket-formula with the *rx/*² observable for three **D@LHC, Durham, September 2023**

ng statistical significance of perturbative interconned Assessing statistical significance of perturbative interconnection

 $\bigcap_{n \geq 0} \mathcal{L}_{n} = \bigcup_{n=0}^{\infty} \mathcal{L}_{n} = \bigcup_{n=0}^{\infty} \mathcal{L}_{n}$ perturbative internet in the set of the set o
External intervals of the set of zw dosul *ptj*,min Assume dShower size for signal. Evaluate few assumptions for:

 \mathbf{r} for distribution \mathbf{r} ➤ with various possible assumptions • theory uncertainty on 1HS subtraction

 $f = \langle n(n, \cdot) \rangle_{\alpha} - \langle n(n, \cdot) \rangle_{\alpha}^{\text{no-MPI}}$ $\frac{1}{\sqrt{2}}$ **there** $\frac{1}{\sqrt{2}}$ **there** $\frac{1}{\sqrt{2}}$ $\langle n(p_{tj, min}) \rangle$ pure−MPI $\langle n(p_{tj, \text{min}}) \rangle_{C_Z} - \langle n(p_{tj, \text{min}}) \rangle_{C_Z}^{\text{no-MPI}}$

correlation for different C ulic
C *ptZ* \bullet + their correlation for different $\mathcal{C}_Z^{t_Z}$

to reduce theory uncertainty and the september 2023 $\mathbf{r} = \mathbf{r} \cdot \mathbf{r}$ $\frac{1}{2}$ $\text{cov}(G)$ Just barely feasible. Motivation for NNLO (matched) Z+2j calculations

 $\langle n(p_{tj, min}) \rangle$ pure−MPI *CZ*

• + their corr

Assessing statistical significance of perturbative interconnection

uncertainties on ≡ ⟨*n*(*ptj*, min)⟩*CZ* − ⟨*n*(*ptj*, min)⟩no−MPI *CZ*

Just barely feasible. Motivation for $(matched)$ $Z+2j$ calculations

Assume dShower size for signal. Evaluate few assumptions for:

• theory unc

Final topic: seeing 3HS via azimuthal correlations

[Previous studies of 3HS: CMS Collab. Nature Phys. 19 (2023) 3, 338-350, D'Enterria, Snigirev PRL 118 (2017) 12, 122001]

Measure $\Delta \phi$ between leading jets using a tight cut $\partial \Gamma_{1Z}^{\text{reg}}$

Final topic: seeing 3HS via azimuthal correlations

interconnection is turned on between the primary and second-sec-entropy and sec-entropy and sec-entropy and se
In the primary and second-sec-entropy and sec-entropy and sec-entropy and sec-entropy and sec-entropy and sec-

 $\sqrt{2}$ between the two leading charged-track jets in events with two leading charged-track jets in events with two le
The two leading charged-track jets in events with two leading charged-track jets in events with two leading ch

Clear signal of 3HS in terms of a plateau for all values of $\Delta\phi$ $\mathsf I$ Grade Signal of 3HS in terms of a plateau for all values of $\Delta\varphi\parallel$

 Ω ratio evaluated in the *r*¹⁵/₂ ratio e $minimum-biac$ are 200° to generate the

