# $W^+W^-$ pair production in $k_t$-factorisation in the SM and beyond

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MCnet meeting 2019 - CERN

# Outline

- $k_t$-factorization formalism and TMD PDFs
- $W^+W^-$ pair production
  - Production channels upto NNLO QCD level
  - Calculation framework
- Collinear approach: Herwig 7
- Results in the SM and beyond
- Summary & Conclusions

# $k_t$-factorization formalism and TMD PDFs

- Collinear factorization is based on DGLAP evolution equation: PDFs
- Great results → it is incomplete! $k_{t,0}^2 \ll k_{t,1}^2 \ll \cdots \ll k_{t,i}^2 \ll \cdots \ll k_{t,n}^2 \ll \mu^2$
- PDFs → systematically neglect the transverse momenta of the initial partons
- Improvement attempts:
  - BFKL: many improvement attempts → only valid at the small-x region!
  - CCFM: AOC for successive gluonic radiations → questionable quark solutions!
  - UDB: very good results → unnecessary complexity!
  - $k_t$-factorization formalism → introduction of UPDFs

[Kimber, Martin, Ryskin, '01; Martin, Ryskin, Watt, '10]

# $k_t$-factorization framework

- Main assumptions
  - Softening the strong-ordering assumption

$$k_{t,0}^2 \ll k_{t,1}^2 \ll \cdots \ll k_{t,i}^2 \ll \cdots \ll k_{t,n}^2 \sim \mu^2$$

  - Introducing the AOC to regulate the scale of the partonic evolution $\rightarrow$ suppressing the soft gluon singularities
- Defining identity

$$a(x,\mu^2) = \int^{\mu^2} \frac{dk_t^2}{k_t^2} f_a(x,k_t^2,\mu^2) \rightarrow f_a(x,k_t^2,\mu^2) \text{ are the Unintegrated PDF}$$

# KMR TMD PDFs

- Different visualizations of AOC → different UPDFs (KMR and MRW)
- The difference of these UPDF schemes can be cancelled out by an appropriate choice of factorization scale [Aminzadeh, Modarres, AM, '16]

$$f_a(x, k_t^2, \mu^2) = T_a(k_t^2, \mu^2) \sum_{b=q,g} \left[ \frac{\alpha_S(k_t^2)}{2\pi} \int_x^{1-\Delta} dz P_{ab}(z) b\left(\frac{x}{z}, k_t^2\right) \right], \qquad \Delta = \frac{k_t}{\mu + k_t}$$

$$T_a(k_t^2, \mu^2) = exp\left[ - \int_{k_t^2}^{\mu^2} \frac{dk^2}{k^2} \frac{\alpha_S(k^2)}{2\pi} \sum_{b=q,g} \int_0^{1-\Delta} dz\ z P_{ba}(z) \right], \qquad T_a(\mu^2, \mu^2) = 1$$

- We use the KMR UPDFs where the AOC is applied on both the diagonal and the non-diagonal splitting functions.

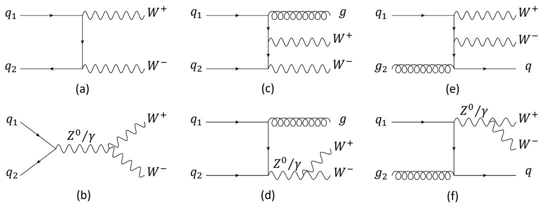
# $W^+W^-$ pair production channels

$$P_1 + P_2 \rightarrow a(k_1) + b(k_2) \rightarrow W^+(q_1) + W^-(q_2) + X \rightarrow l^+(p_1) + \nu_l(p_2) + l^-(p_3) + \bar{\nu}_l(p_4) + X$$

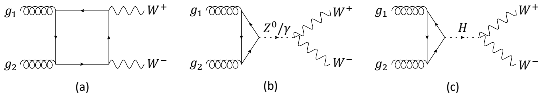
Partonic sub-processes

$$q_1 + q_2 \rightarrow W^+ + W^-$$
$$q_1 + q_2 \rightarrow Z^0/\gamma \rightarrow W^+ + W^-$$
$$q_1 + q_2 \rightarrow W^+ + W^- + J$$
$$q_1 + q_2 \rightarrow Z^0/\gamma + J \rightarrow W^+ + W^- + J$$
$$q_1 + g_2 \rightarrow W^+ + W^- + J$$
$$q_1 + g_2 \rightarrow Z^0/\gamma + J \rightarrow W^+ + W^- + J$$
$$g_1 + g_2 \rightarrow W^+ + W^-$$
$$g_1 + g_2 \rightarrow Z^0/\gamma \rightarrow W^+ + W^-$$
$$g_1 + g_2 \rightarrow H \rightarrow W^+ + W^-$$

LO + NLO




NNLO



# Calculation framework

- Differential cross-section for the production of $W^+W^-$ pairs in $k_t$-factorization

$$d\sigma(PP \to l^+\nu_l l^-\bar{\nu}_l + [j]) = \sum_{a,b=q,g} \int \frac{dx_1}{x_1}\frac{dx_2}{x_2}\frac{dk_{1,t}^2}{k_{1,t}^2}\frac{dk_{2,t}^2}{k_{2,t}^2}\; f_a(x_1,k_{1,t}^2,\mu^2)\; f_b(x_2,k_{2,t}^2,\mu^2)$$
$$\times \frac{d\phi(ab \to l^+\nu_l l^-\bar{\nu}_l + [j])}{F_{PP\to ab}} |\mathcal{M}(ab \to W^+W^- \to l^+\nu_l l^-\bar{\nu}_l + [j])|^2$$

- To calculate the ME, we use
  - Feynman rules
  - Eikonal approximation for initial quarks [Baranov, Lipatov, Zoto ’08; Deak, ’09]
  - Nonsense Polarization approximations for initial gluons [Gribov, ’84; Catani, ’90; Levin, ’91; Collins, ’91]
  - ME are calculated by `FORM` and checked independently by `MATHEMATICA`

# Calculation framework

- The differential cross-section for $W^+W^-$ pair production of hadronic collisions:
  - For the LO sub-processes

$$d\sigma(PP \to l^+\nu_l l^-\bar{\nu}_l) = \sum_{a,b=q,g} \frac{dk_{1,t}^2}{k_{t,1}^2}\frac{dk_{2,t}^2}{k_{2,t}^2}\, dp_{1,t}^2\, dp_{2,t}^2\, dp_{3,t}^2\, dy_1\, dy_2\, dy_3\, dy_4\, \frac{d\psi_1}{2\pi}\frac{d\psi_2}{2\pi}\frac{d\phi_1}{2\pi}\frac{d\phi_2}{2\pi}\frac{d\phi_3}{2\pi}$$

$$\times\, f_a(x_1,k_{1,t}^2,\mu^2) f_b(x_2,k_{2,t}^2,\mu^2) \frac{|\mathcal{M}(ab \to W^+W^- \to l^+\nu_l l^-\bar{\nu}_l)|^2}{2024\pi^4(x_1x_2s)^2}$$

  - For the NLO sub-processes

$$d\sigma(PP \to l^+\nu_l l^-\bar{\nu}_l + j) = \sum_{a,b=q,g} \frac{dk_{1,t}^2}{k_{1,t}^2}\frac{dk_{2,t}^2}{k_{2,t}^2}\, dp_{1,t}^2\, dp_{2,t}^2\, dp_{3,t}^2\, dp_{4,t}^2\, dy_1\, dy_2\, dy_3\, dy_4\, dy_5$$

$$\times\, \frac{d\psi_1}{2\pi}\frac{d\psi_2}{2\pi}\frac{d\phi_1}{2\pi}\frac{d\phi_2}{2\pi}\frac{d\phi_3}{2\pi}\frac{d\phi_4}{2\pi} f_a(x_1,k_{1,t}^2,\mu^2) f_b(x_2,k_{2,t}^2,\mu^2)$$

$$\times\, \frac{|\mathcal{M}(ab \to W^+W^- \to l^+\nu_l l^-\bar{\nu}_l + j)|^2}{32768\pi^5(x_1x_2s)^2}$$

# Calculation framework

– For the NNLO sub-process that includes $H \to W^+W^-$ splitting

$$d\sigma(PP \to l^+\nu_l l^-\bar{\nu}_l) = exp\left(\frac{3\pi}{2}\alpha_S(\mu_c^2)\right)\frac{dk_{1,t}^2}{k_{1,t}^2}\frac{dk_{2,t}^2}{k_{2,t}^2}\,dp_{1,t}^2\,dp_{2,t}^2\,dp_{3,t}^2\,dy_1\,dy_2\,dy_3\,dy_4$$
$$\times\frac{d\psi_1}{2\pi}\frac{d\psi_2}{2\pi}\frac{d\phi_1}{2\pi}\frac{d\phi_2}{2\pi}\frac{d\phi_3}{2\pi}f_g(x_1,k_{1,t}^2,\mu^2)f_g(x_2,k_{2,t}^2,\mu^2)$$
$$\times\frac{|\mathcal{M}(gg \to H \to W^+W^- \to l^+\nu_l l^-\bar{\nu}_l)|^2}{2024\pi^4(x_1x_2s)^2}$$

$$x_{1,2} = \frac{1}{\sqrt{s}}\sum_{i\in\text{final-state}} m_{i,t}e^{\pm y_i}, \quad m_{i,t} = (m_i^2 + p_{i,t}^2)^{1/2}, \quad \mu_c = (m_H\sum_i p_{i,t}^2)^{1/2}$$

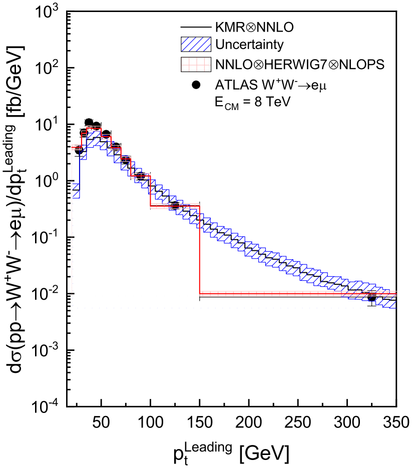
- Higher-order corrections to $H \to W^+W^-$ channel are non-negligible.
- The use of K-factor approximation can capture a good description of the event.

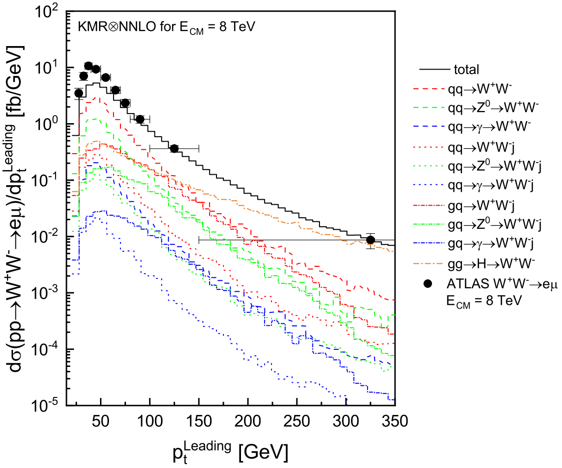
[Aminzadeh, Modarres, AM, '17]

# Collinear approach: Herwig 7

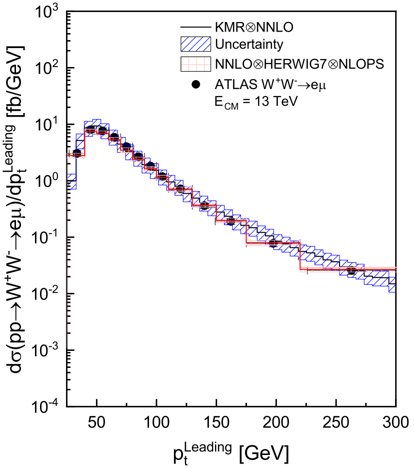
- The collinear factorization → `HERWIG` event generator [Bahr et al, '08; Bellm, '15]
- ME calculation:
  - LO and NLO tree-level channels → `MadGraph5` [Alwall et all, '14]
  - NNLO channels → `OpenLoops` [Cascioli, '11; Buccioni, '17; Kallweit, '14]
- Parton shower: [Bellm et al, arXiv:1602.05141]
  - Type: QCD+QED, angular ordered
  - Matching: MC@NLO
- Cluster hadronization model [Webber, '83]
- Data analysis → Rivet [Buckley et al, '10]

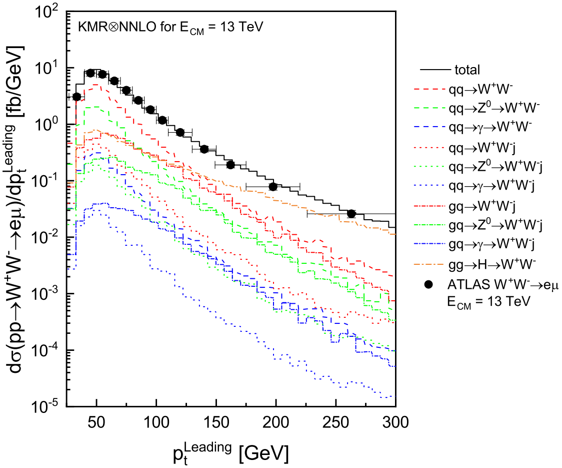
# Preliminary results of $W^+W^- \to e\mu$ at 8 TeV



# Preliminary results of $W^+W^- \to e\mu$ at 13 TeV



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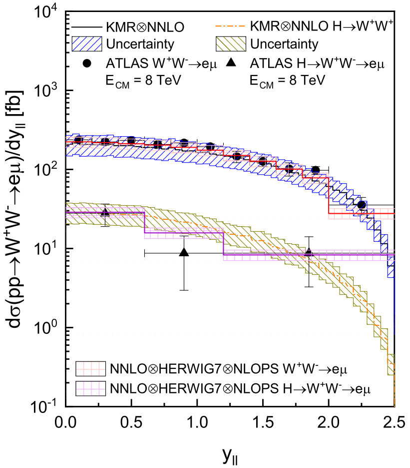


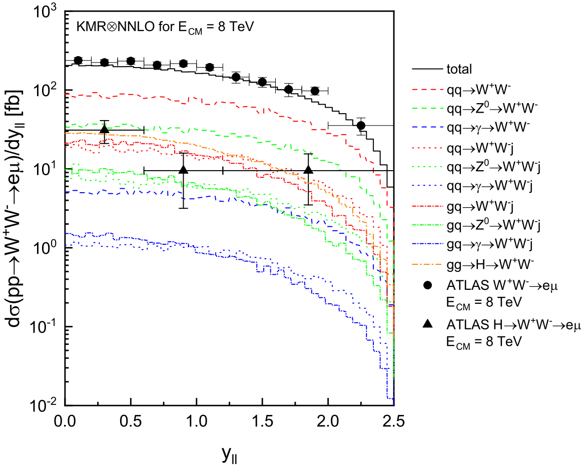

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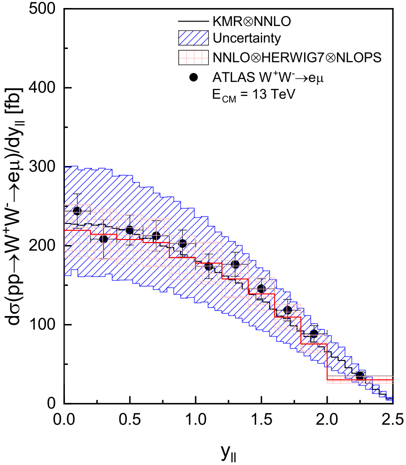
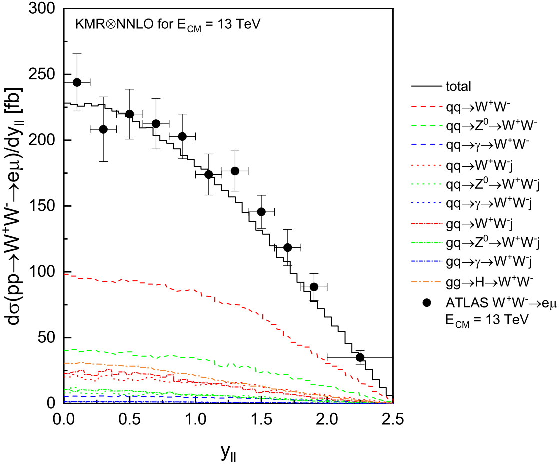


# Preliminary BSM results of $H \to W^+W^- \to e\mu$

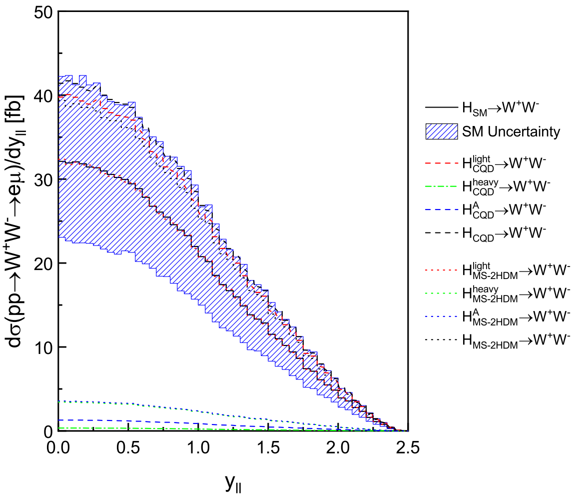
We have considered two BSM models with extended Higgs sectors:

**CQD-2HDM**

[Darvishi, Krawczyk, arXiv:1709.07219]

**MS-2HDM**

[Darvishi, Pilaftsis, arXiv:1904.06723]



# Summary & Conclusions

- We calculated the rate of $W^+W^-$ pair production in $k_t$-factorization.
- Similar calulations has been done using `HERWIG` event generator.
- Results are compared against the existing experimental measurements from ATLAS and CMS.
- The results of $k_t$-factorization framework are comparable with `HERWIG` predictions and the data.
- The large uncertainty is a consequence of putting the last-step evolution approximation on top of the intrinsic collinear uncertainties and forcing an additional controlling evolution scale ($k_t$) into the calculation.
- Our goal is to provide a SM base-line for our on-going search for BSM signal in the LHC run 2 data.

[Darvishi, Ostrolenk, AM, in preparation]

# Thank You!