### Associated Higgs+jets production at LHC and CCFM dynamics in proton

Maxim Malyshev<sup>1</sup>

*in collaboration with Artem Lipatov*<sup>1,2</sup>

<sup>1</sup>SINP, M.V. Lomonosov Moscow State University <sup>2</sup>JINR, Dubna

A.V. Lipatov, M.A. Malyshev, arXiv:2009.04908

## Outline

- 1. Motivation
- 2. Theoretical framework
- 3. Numerical results
- 4. Conclusion

## Motivation



Good test for pQCD predictions;

 Leading contribution from gluon fusion — allows to probe gluon distributions;

• Jet associated production allows to study special kinematical regions.

## Motivation

The goal of the present work is:

• to test applicability of the  $k_{\rm T}\mbox{-}factorization$  approach to a new process

• to test different parametrizations of CCFM TMD parton distribution functions.

• CASCADE3+PEGASUS:  $k_T$ -factorization with parton showers.

In this work we include for the first time parton showers for Higgs production in  $k_{\rm T}\text{-}$  factorization.

## $k_{\tau}$ -factorization

Main ingredients:

- Off-shell matrix elements
- TMD (unintegrated) parton densities.

The cross-section:

 $d\sigma(pp \to H + X) = d\sigma(g^*g^* \to H + X) \otimes$  $\otimes f_g(x_1, k_{T1}^2, \mu_{\text{fact}}^2) f_g(x_2, k_{T2}^2, \mu_{\text{fact}}^2)$ 

## $k_{\tau}$ -factorization: TMDs

#### **CCFM-based unintegrated distributions**

Numerical solutions of Catani-Ciafaloni-Fiorani-Marchesini evolution equation.

The starting distribution is chosen to satisfy data on proton structure functions  $F_2(x,\mu^2)$  only (A0) or both  $F_2(x,\mu^2)$  and  $F_2^{c}(x,\mu^2)$  (JH2013-set-2)

[H. Jung, hep-ph/0411287, F. Hautmann, H. Jung, Nucl. Phys. **B883** (2014) 1].

## **CCFM** distributions



## PEGASUS

- parton level Monte-Carlo event generator for pp and pp processes with simple user-friendly grafical interface;
- can work with TMDs;
- a lot of implemented processes (heavy quarks, quarkonia, etc.);
- can generate an event record according to the Les Houches Event (\*.lhe) format;
- an easy way to implement various kinematical restrictions;
- compatible with HEPData repository https://www.hepdata.net;
- built-in plotting tool PEGASUS Plotter

A.V. Lipatov, M.A. Malyshev, S.P. Baranov, Eur. Phys. J. C80, 4, 330 (2020); https://theory.sinp.msu.ru/doku.php/pegasus/overview

## Parameters

- Theoretical uncertainties are connected with the choice of the factorization and renormalization scales. We took  $\mu_R = m_H$ . We took  $\mu_{F^2} = (s+Q_T^2)$ , where s and  $Q_T^2$  are the energy of scattering subprocess and transverse momentum of the incoming off-shell gluon pair, respectively. Auxilliary "+" and "-" distributions were used to estimate theoretical uncertainties.
- We use 2-loop (1-loop) formula for the strong coupling constant  $\alpha_s(\mu^2)$  with  $n_f = 4$  active quark flavors at  $\Lambda_{QCD} = 200$  (250) MeV for JH2013 (A0) distributions.
- Parton showers are produced with CASCADE3.
- We use anti- $k_T$ -algorythm to construct jets with FastJet.
- Non-leading contributions (ttH, VBF, etc.) are taken from experimental papers

### Numerical results



Diphoton channel,  $\sqrt{S}$ =13 TeV

#### Numerical results



ZZ\* channel,  $\sqrt{S}$ =13 TeV



Diphoton channel,  $\sqrt{S}$ =13 TeV

#### Numerical results



ZZ\* channel,  $\sqrt{S}$ =13 TeV





15





### Numerical results



ZZ\* channel,  $\sqrt{S}$ =13 TeV

## Conclusion

Associated Higgs+jet(s) production at LHC ( $\sqrt{s}=8$ , 13 TeV) has been considered.

- Reasonable description of ATLAS and CMS data is obtained.
- The process is sensitive to the choice of TMDs.
- Some observables ( $\Delta y$ ,  $\Delta \phi$ , m) can be used to distinguish very clearly between CCFM A0 and JH2013 TMD distributions.

# Back up



## Off-shell gluon polarization sum

$$\epsilon_{\mu}\epsilon_{\nu}^{*} = \frac{k_{T}^{\mu}k_{T}^{\nu}}{\mathbf{k}_{T}^{2}}$$

## **CCFM** equation

$$\mathcal{A}(x, k_t, p) = \mathcal{A}_0(x, k_t, p) + \int \frac{dz}{z} \int \frac{dq^2}{q^2} \Theta(p - zq)$$
$$\times \Delta(p, zq) \mathcal{P}(z, q, k_t) \mathcal{A}\left(\frac{x}{z}, k_t + (1 - z)q, q\right)$$

$$P_g(z,q,k_t) = \bar{\alpha}_s(q^2(1-z)^2) \left(\frac{1}{1-z} - 1 + \frac{z(1-z)}{2}\right) + \bar{\alpha}_s(k_t^2) \left(\frac{1}{z} - 1 + \frac{z(1-z)}{2}\right) \Delta_{ns}(z,q^2,k_t^2)$$

#### **PEGASUS Particle Event Generator: A Simple-in-Use System**

	ficer beam production			( *		HE -2*
QCD factorization	Inclusive 8 meson production Inclusive 8c meson production Inclusive 8c meson production				C6 Bc	
TMD factorization				1st parton PDF		
2nd parton	Inclusive Y(25) production Inclusive prompt ψ(25) production			B0 (CCFM)	B0 (CCFM)	
TMD factorization	Inclusive non-prompt j/ψ production			JH/2013 set 1 (CCFM) JH/2013 set 2 (CCFM)	JH 2013 set 1 (CCFM) JH 2013 set 2 (CCFM)	B: 2* B: 3*
	Inclusive Higgs boson production (diphoton	decay mode)		PB-NLO-HERAI-IF2018 set 1 PD-NLO-HERAI-IF2018 set 2	PS-NLO-HERAU-IT2018 set 1 PS-NLO-HERAU/T2018 set 2	
Colliding particles	Inclusive Higgs boson production (WW decay	(mode)		MD/2018 (CCFM)	MD'2018 (CCFM)	
prozon + prozon (Der.)						Процисс
Total energy (GeV): 7000.00				Hard scales		
	En a			Renormalization scale	Advanced settle	and
Monte-Carlo parameters:	Annanceo senago — A			produced particle transverse mass	* HPA SM param	eters
Number of iterations 10	Common Observables			Factorization scale		
Events per iteration	Kinematical range			CCTM scale		
		from	10	Scale variation		
	First b-quark range			[00MK		
	transverse momentum [GeV]	0	500	Generate Les Houches Event file (*.1he	d	
	rapidity	-7	7			
	pseudo-rapidity	-7	7		X Cancel	N OK
	Second b-quark range					and the second sec
	transverse momentum [GeV]	0	500		Transaction of the second s	
	rapidity	-7	7			
	Increase statistics at large trans	verse momenta				
Save log output		×¢	Cancel K			
	and the same of the life of the life of the same					
	are favors: 4 QCD scale [Lew]: 0.25 strong	coupling constant	: 010-100p		1	
PDV: AD TELE CIT. HNN BY [HN]: 7 ACTIVE QU						
C Save log output	Increase statistics at large trans	verse momenta	(ancel 🖌 🖉 QK			

A.V. Lipatov, S.P. Baranov, M.A. Malyshev, in preparation (2019)

#### **PEGASUS Particle Event Generator: A Simple-in-Use System**



A.V. Lipatov, S.P. Baranov, M.A. Malyshev, in preparation (2019)

#### **PEGASUS Particle Event Generator: A Simple-in-Use System**



A.V. Lipatov, S.P. Baranov, M.A. Malyshev, in preparation (2019)