

# Yukawa couplings and lifetime of Higgs boson: going beyond LHC

**Jun Gao** 

Institute of nuclear and particle physics, Shanghai Jiao Tong University

based on arXiv: 1608.01746 and 1804.06858

**ICTS, USTC Sep 29, 2018**







# Standard Model of particle physics

✦ Discovery of the Higgs boson completes the SM of particle physics, which is a model of great success though clear evidence exists for new physics beyond SM



# Post Higgs boson Era

✦ Study on properties of the Higgs boson including looking for further extensions has been the high priority in the next few decades



Higgs boson introduces new phenomenas of study of elementary particles,  $\sum$ spin-0 particle, scalar self interactions, Yukawa interactions

#### Higgs potential and self couplings  $\mathbf{z}$  $\mathbf{I}$  $\mathbf{r}$ ¯f  $\mathbf{y}_{\text{rel}}$   $\mathbf{y}_{\text{rel}}$ Higgs potential and self couplings

✦ Scalar potential are crucial for understanding EW symmetry breaking and for the fate of our EW vacuum [Andreassen, Frost, Sch  $\frac{1}{2}$   $\frac{1}{2}$  $\tilde{\epsilon}$ id for the fate rucial for understanding EVV sy **JUREAN METHIGHT (Andreassen, Frost, Schwartz, 2017)** 



# Yukawa couplings

✦ SM Yukawa couplings have a strong hierarchy structure, responsible for particle masses; essential for revealing nature of the Higgs boson Fatter of the Higgs liential for revealing nature of the Higgs liential



### **mass hierarchy**

 $\approx$  Top Yukawa plays a crucial role, e.g., in RG ru ☆ Top Yukawa plays a crucial role, e.g., in RG running; Yukawa couplings of light particles are also of great importance and challenging to access experimentally (red) line indicates the best fit result to the [*M*,✏] phenomenological model of Ref. [129] with the corresponding *<sup>V</sup>* (*V T*)light-cone = 10516<sup>409</sup> be exponentially small.  $\alpha$ <sup>*||g*</sup>/*g*<sub>2</sub>*,*  $\alpha$ *<sup><i>w*</sup>/*g*<sup>*l*</sup>/*m*<sup>*n*</sup>/*m*<sup>*n*</sup>/*m*<sup>*n*</sup>/*m*<sup>*n*</sup>/*m*<sup>*n*</sup>/*m*<sup>*n*</sup>/*m*<sup>*n*</sup>/*m*<sup>*n*</sup>/*m*<sup>*n*</sup>/*g*<sup>*n*</sup>/*m*<sup>*n*</sup>/*m*<sup>*n*</sup>/*m*<sup>*n*</sup>/*m*<sup>*n*</sup>/*m*<sup>*n*</sup>/*m*<sup>*n*</sup>/*m*<sup>*n*</sup>/*m*<sup>*n*</sup>/*m*<sup>*n*</sup>/*m*<sup>*n*</sup> *respectively (*left*). The Higgs quartic -function is shown in units of its top contribution, (top contribution)* = 3*y*<sup>4</sup> *<sup>t</sup> /*8⇡<sup>2</sup> *(*right*). The grey shadings cover values of the RG scale above the Also of great importance and challenging* 

# Higgs width/lifetime

✦ Higgs boson with a mass of 125 GeV decays dominantly to bottom quark pair via Yukawa yb~0.01 resulting in small width Γ/m~3×10-5



### **width vs. mass**



## **[LHCHXSWG]**

tiny width (long lifetime) leads to very different phenomenology as comparing  $\sum$ to other heavy resonances, e.g., top quark, W/Z bosons

# Higgs boson at the LHC

✦ Higgs boson can be produced abundantly at the LHC (HL-LHC),  $\sim$ 3(30) $\times$ 10<sup>7</sup> events though with huge QCD backgrounds

### **cross section vs. energy BRs vs. mass**



global analysis is required to maximize potential of experimental data and to probe Higgs couplings in a model-independent way

**From LHC Higgs Cross Section Working Group,<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG>**

## LHC measurements  $\mathbf{L}$

 $\rightarrow$  Current measurement agrees well with the standard model Higgs boson on various signal strength, **oxBRs**, with a precision ~10-20% significance is 5.6 (5.5)*s*, and the measured signal strength is *µ* = 1.04 *±* 0.20. In addition to s well with the standard model Higgs  $\overline{\phantom{a}}$  went when the standard inoder in  $\overline{\phantom{a}}$  $\pi$ th  $\pi$ v $\text{PD}_{\text{c}}$  with a procision 10.200/  $\mathbf S$ ui, Uxdrs,



Figure 10: Best fit values of ratios of Higgs boson coupling modifiers, as obtained from the generic parameterisation



divided by the SM prediction. The and *Z Z*⇤ ! 4` analyses use 13 TeV data corresponding to an integrated s of Higgs couplings can be probed ☆ Without model assumptions only ratios of Higgs couplings can be probed uncertainties. The red vertical line indicates the SM cross-section prediction [37], and the grey band represents the a vitinout moder assumptions only ratios of riggs couplings can be probed<br>with sufficient precision at LHC due to unknown total width  $\mathbb{R}$  - VVIthout model assumptions only rai The hatched areas indicate the non-allowed regions for the parameters that are assumed to be positive without loss mance of the LHC and thank the technical and administrative staffs at CERN and at other CMS nly ratios of Higgs couplings can be probed L due to unknown total width infrastructure essential to our analyses. Finally,  $\sim$ 

# Light-quark Yukawa couplings

✦ Measuring Yukawa couplings of light-quarks at LHC are particularly challenging due to their smallness, **ys/yb~2%**, and huge QCD Bks

 $F = \frac{1}{2}$  and  $F = \frac{1}{2}$  a **exotic decays (BR~10-6)**



#### $f + 2044$ .  $2046$ ,  $\Box$  N,  $C_{0.9}$ ,  $2044$ ] [Kagan +, 2014, 2016; D.N. Gao, 2014] Figure 1: Direct-amplitude diagram (left) and indirect**agar**

If all of the Higgs couplings (including *h* ! *WW, ZZ, , gg,Z, b*¯*b* and ⌧ ⌧¯) are allowed to vary from two amplitudes which, however, only involves the real eptually good; in practice. Working in the limit of  $\mathbb{R}$ *<u>Ansitivity</u>* due to huge Bk amplitude diagram (right) contributing to *h* ! . no sensitivity due to hu ceptually good; in practi *d*ue to *m* conceptually good; in practice no sensitivity due to huge Bks

## **Higgs kinematics**



ceptually good; in practice and and LHC/HL-LHC can probe Yukawa channel in the systematic uncertainties cancel in the normalized shape distribution. The dominant of the domina of u/d quarks to ~0.3y<sub>b</sub>

#### Limit on total width/lifetime  $\lim_{\text{in}}$  instrumental precision. The technique summarized in Eq. (1) if  $\lim_{\text{in}}$ nonetheless allows the first direct experimental constraint on *t*H.  $T_{\text{t}}$  is a interference between the interference between the signal and background production  $T_{\text{t}}$

◆ Various limits on width/lifetime of the Higgs boson are set at the LHC either directly or indirectly, especially with Higgs interferometry fermion and vector boson induced couplings are induced couplings are induced in the coupling of the left unconstrained in the left unconstrained in the left unconstrained in the left unconstrained in the left unconstrained either directly or indirectly, esp



# Going beyond LHC

I. Higgs properties revealed in heavy-ion collisions





**[Edmond Berger, Jun Gao, A. Jueid, Hao Zhang, arXiv:1804.06858]**



### **[Jun Gao, arXiv:1608.01746]**

### I. Higgs properties revealed in  $\bigodot$ heavy-ion collisions



**[Edmond Berger, Jun Gao, A. Jueid, Hao Zhang, arXiv:1804.06858]**

# Heavy-ion collision and quark gluon plasma

✦ Relativistic heavy-ion collisions (RHIC, LHC) are utilized to reproduce conditions of very early second of our universe and study QGP phase



**[Chun Shen]**

# Higgs boson in heavy-ion collision

✦ Higgs boson in the standard model has an intrinsic lifetime **~47 fm/c**, comparing with ~**10 fm/c** of time scale of quark gluon plasma

## **Higgs production with hadronic decays**



**role of jet quenching** 

**[Berger, JG, Jueid, Zhang, 2018]**

- a natural probe of the lifetime of Higgs boson  $\sum$
- filter for various standard model backgrounds, e.g., QCD jets, top quarks, EW  $\sum$ gauge bosons
- distinct kinematics, enhanced S/B ratio for hadronic decay modes, e.g., Yukawa  $\sum$ coupling of bottom quark

#### **1. Introduction** ∆*E*1scat rad = # *<sup>E</sup>*  $\mathbf{l}$  $1\Omega$ *d*ω *Jet quenching*  $\Delta$ <sup>1</sup> ω *d I*rad *d*ω Jet quenching

Nucleus-nucleus collisions (A-A) at ultrarelativistic energies provide the experimental means tastic) and medium mudeed faulations (melastic) ◆ Parton traversing QGP suffers energy lost due to both collisions *For incoherent scatterings one delargering one delargering one a R E*<sub>2</sub> *i*<sup>2</sup> *Z*<sub>*Z*</sub> the operation of the energy power of the energy power of the energy power of the stopping power of the stopping p<br>Stopping powerful and the stopping power of the stopping power of the stopping power of the stopping power o *For incoherent scatterings one diations one adjations one adjations one adjations one adjations one* the opacity. The energy loss per unit length or *stopping power*<sup>5</sup> is: (elastic) and medium induced radiations (inelastic)



# Hard probes: single inclusive jet

✦ Measurements on medium suppression of cross sections provide a strong evidence of jet quenching in AA collision collisions take a simple form15: ⟨*TAB*⟩ <sup>=</sup> *A B /*σgeo *AB* and ⟨*N*coll⟩ <sup>=</sup> *A B* · <sup>σ</sup>*N N /*σgeo Ippression of cross sections provide a probe in a *AA* reaction is thus given by the *nuclear modification factor*:

**ratio of jet cross sections in PbPb to pp**

 $\mathbf{S} \mathbf{E} \mathbf{C}$  **Constrains in PhPh to nn**  $R_{AA}(p_{T},y;h) = \frac{d^2 N_{AA}/dy dp_{T}}{d^2 N_{AA}/dy dp_{T}}$  $R_{AA}(p_T, y; b) =$  $d^2N_{AA}/dydp_T$  $\langle T_{AA}(b) \rangle \times d^2 \sigma_{pp} / dy dp_T$ 



mentally similar level of quenching for inclusive jet and b-jet  $\hspace{0.1cm}$  $\leftrightarrow$  Experimentally similar level of quenching for inclusive iet and b-ie  $\hat{\mathbf{x}}$  Experimentally similar level of quenching for inclusive jet and b-jet

# Hard probes: Z/photon+jet

✦ Measurements on imbalance of the transverse momentum provide a **6** direct probe of jet quenching in AA collision



# Simplified quenching models

✦ Simplified models on jet quenching are used for standard model backgrounds and tested against MC and CMS data v supplined inoucle on jet quenching are  $\rightarrow$  Simplified models on jet quenching are u the vackgrounds and test

 $t \in \mathbb{R}$  $\langle \delta p_T \rangle = a p_T + b \ln(p_T/{\rm GeV}) + c$  (average p **average p<sub>T</sub> lost with Gaussian fluc.** 



 $\hat{\mathbf{x}}$  shown are distributions of momentum imbalance in Z + jet production; three  $\Box$  models are considered for jet with anti-k<sub>T</sub> (D= models are considered for jet with anti-k<sub>T</sub> (D=0.3) algorithm in 0-10% centrality

#### Signal and backgrounds Representative values of the *C*, *S*, and *N* parameters  $\sigma$  is regarderent collinear in  $\sigma$  $\mathcal{L}_{\mathcal{C}}$

laboration in PbPb collisions at p*s*NN = 5*.*02 TeV as a

◆ We select the ZH associated production with Higgs decays to bottom pair, Z to leptons; major backgrounds are ZbB and top pair production The transverse momentum imbalance in *Z* boson plus pan, *L* to reptons, major backgrounds are ZDD and top pair production *•* A pair of same-flavor opposite-sign charged leptons  $\alpha$  tion with Higgs decays to botto  $\triangle M/e$  coloct the  $7H$  accociated production  $\blacktriangleright$  vve select the  $2H$  associated producti nair, 7 to leptons: maior backgrounds PbPb and *pp*-collisions, respectively.



*•* The transverse momentum of the reconstructed  $\hat{\mathbf{x}}$  total cross sections of typical  $\mu$ <sup>2</sup> b-tagging equation enargers, but b  $\frac{dy}{dx}$  vs. pp; centrality factors not  $\frac{f}{(p)}$  applied here  $s$  is distinguished to  $r$  of the ratio of the rati production channels, PbPb apprice riche applied here

#### in Jewel 2.0. We turn on one only the hard matrix end of the associated production with a *a z* boments for quark final states. The initial temperature of subsequent leptonic design and its subsequent leptonic decay gives the strongest of  $\mathcal{L}$ cuts similar to those in the CMS heavy-ion analysis  $[34]$ ,  $[$ **basic selections**

$$
p_T^{\ell} > 15 \,\text{GeV}, \quad |\eta^{\ell}| < 2.5, \quad \Delta R_{\ell\ell} > 0.2
$$
  
 $p_T^j > 30 \,\text{GeV}, \quad |\eta^j| < 1.6, \quad \Delta R_{j\ell} > 0.3$ 

- A pair of same-flavor opposite-sign charged leptons  $\mathbf{\times}$ with invariant mass  $|m_{\ell\ell} - m_Z| < 10 \text{ GeV};$ <br> **•**  $\frac{8}{9}$  10  $\bullet$  A pair of same-flavor opposite-sign charged lepter *•* A pair of same-flavor opposite-sign charged leptons with invariant mass  $|m_{\ell\ell} - m_Z| < 10 \text{ GeV};$
- **Exactly two jets, both b-tagged, with separation**  $\sigma$  10  $\Delta R_{bb} < 2.0;$  $\Delta R_{11} < 2.0$  $\mathcal{L}_{\mathcal{L}}$  in the dead-cone  $\mathcal{L}_{\mathcal{L}}$ • Exactly two jets, both  $b$ -tagged, with separation
- compare our folder results with the CMS data measured results with the CMS data me Find transverse momentum of the reconstruction  $\frac{1}{1}$   $\frac{1}{1}$  with both gluon and  $\frac{1}{2}$ • The transverse momentum of the reconstructed vector boson  $p_{\rm T}^Z \equiv p_{\rm T}^{\ell\ell} > 100$  GeV. *•* Exactly two jets, both *b*-tagged, with separation • The transverse momentum of the reconstructed



# Significance

◆ Cuts on pT imbalance and leading-jet pT can enhance signal to BK ratio; significance based on invariant mass distribution of two b-jets ialio, significance based on invalid  $t$  calculate the signal based signal based signal based signal based signal based  $\frac{1}{2}$ on the *Mb*¯*<sup>b</sup>* distribution, as a function of the integrated lu- $\therefore$  clear peak  $\therefore$   $\Gamma$  arge width  $\Gamma$  $\log$ -jet p1 can enhance signal to B  $\epsilon$  riant mass distribution of two b-iets and, significanted bacter chinimatic mass alternation of the log-like

minosity of the collision program. The results are shown moder or strong quenching p<sub>T</sub><sup>bb</sup>/p<sub>T</sub><sup>Z</sup>>0.75, p<sub>T</sub><sup>j1</sup>>60 GeV; with model of strong quenching on the *Mb*¯*<sup>b</sup>* distribution, as a function of the integrated lu-



 $t_{\text{NDP}}$  and  $t_{\text{NIP}}$  and collision  $t_{\text{NIP}}$ 





## **M<sub>bb</sub> after all cuts significance vs. ion lum.**

- **Example 8** ion luminosity needed for 5 ) and lifetime of the long lifetime of the Higgs boson relafunction of ion luminosity for  $\mathbf{F} = \mathbf{F} \mathbf{F} \mathbf{F}$  for  $\mathbf{F} = \mathbf{F} \mathbf{F} \mathbf{F} \mathbf{F}$ **Example 18 April 2** ion luminosity needed for 5  $\frac{\text{vacuum}}{\text{vacuum}}$  σ discovery or 3 σ evidence
	- tive to the typical time scale of the QGP makes it plausi- $\frac{1}{\lambda}$   $\approx$  improvement by a factor of 2  $\frac{1}{2}$  can be expected  $u_{\rm{max}}$ ected. On the other hand,  $\alpha$ CD backgrounds will be other hand,  $\alpha$

### II. Light-quark Yukawa couplings  $\bigcirc$ from CEPC



### **[Jun Gao, arXiv:1608.01746]**

# A Circular Electron Positron Collider

✦ Chinese HEP community is planning for a new collider facility aiming at a Higgs/Z factory with later upgradable to pp collision





### Higgs couplings at CEPC the small cross section of the *W fusion of the PRS* couplings at  $CLFC$ <sup>1993</sup> two methods, after taking into account the correlations, shows that CEPC is capable of measuring *<sup>H</sup>*

### ◆ CEPC Higgs factory can provide percent-level precision on modelindependent measurement of various Higgs couplings  $1995$  used in the much properties properties in a model independent way as discussed in a model in

Table 2.9 Estimated precisions of Higgs boson property measurements at the CEPC. All the numbers refer to relative precision except for  $M_H$  and  $BR(H \to inv)$  for which  $\Delta M_H$  and 95% CL upper limit are quoted respectively.

$\Delta M_H$	$\Gamma_H$	$\sigma(ZH)$	$\sigma(\nu \nu H) \times BR(H \rightarrow bb)$
5.9 MeV	2.8%	0.51%	2.8%
Decay mode		$\sigma(ZH) \times \text{BR}$	<b>BR</b>
$H \rightarrow bb$		0.28%	$0.57\%$
$H\to cc$		$2.2\%$	2.3%
$H \rightarrow gg$		1.6%	$1.7\%$
$H\to \tau\tau$		1.2%	$1.3\%$
$H \to WW$		1.5%	1.6%
$H \to ZZ$		$4.3\%$	$4.3\%$
$H\to\gamma\gamma$		$9.0\%$	$9.0\%$
$H \to \mu\mu$		17%	$17\%$
$H \to inv$			0.28%

## **CEPC-SppC pre-CDR, 5 ab-1**

decay modes to light-quarks can be measured but with degeneracies to  $\sum$ gluon channels, H->jj

# Higgs couplings at CEPC

• One possibility is to apply quark/gluon jet discriminators on top of the jet algorithm with heavy-flavor tagging



### Hadronic event shapes such an enhanced-coupling scenario is observed, it will be a second-coupling scenario is observed, it will be a  $\partial_{\alpha}$

← A better way from theoretical point of view, utilizing global hadronic event shape observables; e.g., thrust (T) distribution  $\mathbf{f}$  , including throse of  $\mathbf{f}$ , including thrust T (or  $\mathbf{f}$  (or  $\mathbf{f}$  ), including thrust T (or  $\mathbf{f}$  ), including the  $\mathbf{f}$ 



**PAL Thrust definition:** 



 $\frac{197 \text{ GeV}}{2}$   $\approx$  0.5<T<1, described by resummed  $\begin{array}{r} \begin{array}{r} \hline \end{array}$  prediction matched with fixed-order, plus additional non-perturbative corrections

### **sensitive to α<sup>s</sup>**

### Hadronic event shapes such an enhanced-coupling scenario is observed, it will be a second-coupling scenario is observed, it will be a  $\sum_{n=1}^{\infty}$

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## **sensitive to the color factors**

#### Hadronic final state from Higgs decay Hadronic final state from  $I_{\partial \theta}$  accuy

 $\triangle$  Events of Higgs boson hadronic decay can be selected based on the recoil mass and be fully reconstructed perched of  $\frac{1}{2}$  radius. Using the same the same  $\frac{1}{2}$ lationship between the precision of *ZH* and TPC radius pression can be achieved by using Higgs decay informatay can be selected based on the  $\mathsf{h}$ 

#### SM event numbers assuming 250 GeV 5 ab<sup>-1</sup> and 7 to electron event selection in MD analysis also composed of a pre-SM event numbers assuming 250 GeV, 5 ab<sup>-1</sup> and Z to electron and muon





### Thrust distribution  $Thm1<sub>dist</sub>$  digtwibution the event shape distributions using the MC event generator Sherpa 2.2 and Sherpa 2.2 and Sherpa 2.3 and the effective state  $\frac{1}{2}$

← Color-singlet di-gluon and di-quark initiated distributions show an approximate Casimir scaling on the peak position,  $C_A/C_F=9/4$ next-to-leading-order and leading-order accuracy. The hadronization corrections are correction

### **normalized shapes of the thrust and dependent of the thrust and decays of the thrust conduction models and decays of the thrust conduction models and decays of the thrust conduction models and decays of the thrust conduct distribution (PS+3 j LO) hadronization corrections**





parton level + hadronization corrections; theoretical uncertainties [0.02, 0.03] −5 22 −3 −0*.*3 −0*.*4 −0*.*4 from both sides

# Extraction of Yukawa Couplings

✦ Projected sensitivity on light-quark Yukawa couplings is obtained using pseudo-data **[JG, 1608.01746]**

## **r=BR(qq)/(BR(qq)+BR(gg)) from thrust**



 $\lambda$  and a luminosity of  $0.06$ .  $\hat{\mathbf{x}}$  an exclusion limit on r of 0.06, to any of u/d/s, a Yukawa coupling of  $\begin{array}{c} \begin{array}{c} \begin{array}{c} \hline \end{array} \end{array}$ *g*% of SM y<sub>b</sub>, or 4 times of SM y<sub>s</sub> corresponds to a decay BR(qq) of 0.5%

## **comparison with LHC**

with any systematic errors, and adding various systematic errors in succession. We can adding various systematic errors in succession. We can adding various systematic errors in succession. We can adding various contract  $\approx$  best projected HL-LHC limit from  $_{0.00}$ exotic decay on s quark is 20 times of 1000 times of  $u/d$  is  $\sim$ 30% **Figure 4. Expected 95 a. Expected 35 fluctuation in and 20 fluctuation limit on and 20 fluctuation in and 20 fluctuation in and 20 fluctuation in and 20 fluctuation in and 20 fluctuations based on measure-**SM yb, from kinematic distribution on



## **from various event shapes**

### **expected exclusion limit**

# Summary

- ✦ Precision test of the Higgs couplings will be the most imperative task in the next few decades
- ✦ Measurement on Yukawa couplings and total width of the Higgs boson are of great importance but challenging at the LHC
- ✦ Heavy-ion collisions provide an unique environment for probing lifetime of the Higgs boson and also bottom Yukawa couplings
- ✦ CEPC Higgs factory has the potential of pinning down the Higgs to light-quark decay BRs to sub-percent, thus the strange quark Yukawa to a few times its SM value

# Thank you for your attention!

#### Heavy-ion collisions [backups] r the Anglerica boson. In this Letter we propose the Higgs boson we propose  $\mathbf{r}$  and the discovery of the Higgs boson, the final piece of the standard model (SM)  $\Gamma$  $\mathbf{r}$  the production and hadronic decays of the Higgs boson bo in heavy-ion collisions at the LHC. We point out the ma-

✦ Some basics: collision energy, Glauber model, centrality class, factorization on cross sections the complete production and the Claude in bonne basics. Complete chergy Gradue particle physics. Hence,  $\mathbf{p}$  and  $\mathbf{p}$  are contact in the contact of  $\mathbf{p}$ tions of the properties and couplings of the Higgs bosons of t joint differences of studying the Higgs production and definition and deenergy, Giauber model, centrality class, case. Jets produced in hadronic decays of the Higgs bo-

nucleon-nucleon center of mass energy S<sub>NN</sub><sup>1/2</sup>=Z/A\*S<sub>pp</sub><sup>1/2</sup> for PbPb, LHC 5.5 TeV, HE-LHC 11 TeV, FCC-hh 39.4 TeV  $G = \begin{bmatrix} G & G & G \\ G & G & G \end{bmatrix}$ case. Jets produced in the Higgs bo-set of the Higgs bo-set of the Higgs bo-set of the Higgs bo-set of the Higgs bo- $\frac{1}{2}$  so  $\frac{1}{2}$  is happens and  $\frac{1}{2}$  since it is not it happens at  $\frac{1}{2}$ sible new physics between the SM. That has been given between given between given between given between given <br>That has been given between given between given between given between given between given between given betwee  $\blacksquare$  with the highest priority at the set of  $\blacksquare$  $\frac{1}{2}$ V, NE-LNU TI TEV, FUU-NN 59.4 TEV



#### $-5$ of events that we can expect for an integrated luminosity *pp A*2*c*(*f*) where ¯ production and *A* is

#### $\Xi$ ard nrobos top-quark i ialu ploves. top qualn cay chain do not see the full do not see the full  $\alpha$  $\Box$  Hard probes: top quark p coherence times is contracted to the sum of times is correlated to the sum of times is correlated to the sum of Hard probes: top quark production **[backups]**

◆ Top-quark as a hard probe in heavy-ion collisions (AA collision) for time-structure of quark gluon plasma (QGP) For each event that satisfies the reconstruction reconstruction requires that  $\mathbf{r}$ time-structure of quark gluon plasi ploited given a sucient number of events. time-structure of quark giuon plasifia



proton–proton (*pp*) and proton–nucleus (*pA*) collisions

 $\mathbf 0$ 

 $\lfloor$ 

 $\overline{\phantom{a}}$ 

 $\frac{1}{\sqrt{2}}$ 

 $\overline{\mathcal{S}}$ 



#### comi-lontonic channol of t<sup>T</sup> semi-leptonic channel of th  $\ddot{\text{c}}$  omilantanic channal of t<sup>T</sup> semi-leptonic channel of th **semi-leptonic channel of tT** before the *W* decay products start interacting with the

### **average initial time** once before studied for this purpose [33]). The latter

$$
\langle \tau_{\rm tot} \rangle = \gamma_{t,\rm top} \tau_{\rm top} + \gamma_{t,W} \tau_W + \tau_d
$$

products decohered a moment when the medium  $(0.97 \pm 0.0000, \text{FfC} \cdot (\text{C/T} \cdot \text{C} \cdot \text{C$  $\langle \tau_{\rm tot} \rangle (p_{t,\rm top}^{\rm reco}) \simeq (0.37 + 0.0022 p_{t,\rm top}^{\rm reco}/\text{GeV}) \text{ fm}/c$  $\frac{1}{\sqrt{2\pi}}$   $\frac{1}{\sqrt{2\pi}}$   $\frac{1}{\sqrt{2\pi}}$   $\frac{1}{\sqrt{2\pi}}$   $\frac{1}{\sqrt{2\pi}}$   $\frac{1}{\sqrt{2\pi}}$   $\frac{1}{\sqrt{2\pi}}$   $\frac{1}{\sqrt{2\pi}}$ 

## *m*  $\frac{1}{2}$  of particle **duenching-factor**

$$
\mathcal{Q}(\tau_{\text{tot}}) = 1 + (\mathcal{Q}_0 - 1) \frac{\tau_m - \tau_{\text{tot}}}{\tau_m} \Theta(\tau_m - \tau_{\text{tot}})
$$



reconstructed W boson mass from the two light jets shifted due to quenching, depending on lifetime of QGP



**FIG. 4. 2017 EXECUTE: Apolinario+, 2017 EXECUTE: 0.** 2017 reconstructed top *p<sup>t</sup>* for HE-LHC (left) and FCC (right) col-

#### Hard probes: top quark production **[backups]** σtt measured in two independent decay channels i.e., μ,e+jets μ,e+jets *doco.* cop quair proudent  $T_{\text{max}}$ orochlicar in hackulosissions section in hadronic collisions is a collisions in the pair production in gluon-g  $\mathbf{r}$ , which is the orientative today with great accuracy  $\mathbf{r}$  and  $\mathbf{r}$  via perturbative quantum characteristics  $\mathbf{r}$

◆ Top-quark as a hard probe in heavy-ion collisions (pA collision) for cold nuclear effects (CNM) *Minimally* relations for any  $\ln n$  ion collisions ( $\Delta$  collision) for available at NLO accuracy using the MCFM code [3]. The study of the *tt* cross section modifications in protonnucleus compared to pp collisions at the same nucleon-nucleon center-of-mass energy (p*s*NN ) provides a novel



———————————————————

EPPS16 (+CT14)

#### Hard probes: inclusive dijets [backups] probes: 1nc. **CMS 1. CMS 1. CMS** dijets | bacl **1.55**

✦ Measurements on imbalance of the transverse momentum provide a 0.2 direct probe of jet quenching in AA collision <mark>ur</mark><br>է <mark>r</mark>  $\overline{18}$  on imparance of the  $\mathsf A$   $\mathsf A$ 0.25 วf<br>า uansv<del>eise</del> monientum pro

 $\blacksquare$ 0.1 0.05 **ratio of pT of sub-leading to leading jet** 

**[arXiv:1802.00707]**



#### Experimentally similar level of quenching for inclusive iet and h the observable of the taken into consideration into consideration  $\mathcal{L}$ **Experimentally similar level of quenching for inclusive jet and b-jet**

#### Outlook [backups]  $\textbf{ups}$  is shape and the jet shape and the jet cross section in heavy ion collisions. The jet can be jet collisions. The jet can be jet collisions. The jet collisions in the jet can be jet collisions. The jet can be jet  $U$ utivun  $V$ utivung present inside the jet cone.  $U$

✦ Further gains on S/B ratio can be achieved through e.g., multivariate analysis (MVA) or discriminations in jet shapes  $S/D$  is the cone of the cone of the cone of the substructure observables and it probes the transverse the transverse the transverse  $S/D$ energy profile inside a jet of size R reconstruction and the size R reconstruction of the size R reconstructio Further gains on  $S/R$  ratio can be achieved throwin the funture of the theoretical cuts the theoretical cuts that include all experimental cuts that the cuts t cess. This comparison will contribute the medium pot since



structed using the anti-*k*<sup>T</sup> algorithm with a distance parameter *R* = 0.3, and the jet shapes have

## Higgs as probe of QGP **[backups]**  $\mathbf{H} = \mathbf{A} \mathbf{A} \mathbf{A} \mathbf{B} \mathbf{B}$  ?  $\mathbf{H} = \mathbf{H} \mathbf{A} \mathbf{A} \mathbf{A} \mathbf{B}$

← There are also interesting studies from a different perspective, namely using Higgs boson as a probe of QGP instead  $\frac{6}{100}$  Higgs boson as a probo of OCP instead

## discovery in nominal channels **Higgs absorption in QGP**

![](_page_35_Figure_4.jpeg)

using precision Higgs cross section calculation and measurement to extract  $\sum$  $\mathbf{P}$ the possible suppression factor

### Extraction of Yukawa Couplings **[backups]** Only decays of the associated *Z* boson to electrons and muons are included. *h* represents any of the  $L$ xuaction of Tundwa Co

✦ Projected sensitivity on light-quark Yukawa couplings is obtained using pseudo-data Including both the signal and backgrounds to event shape distributions at the event shape distribution of the con be had

$$
\frac{dN}{dO} = N_S(r f_{H(q\bar{q})}(O) + (1 - r) f_{H(gg)}(O)) + N_{B,1} f_{H(b\bar{b})}(O) + N_{B,2} f_{ZZ(q\bar{q})}(O) + N_{B,3} f_{H(WW)}(O),
$$

- $★$  *r*, defined as BR(qq)/BR(jj), j=g+q
- $\star$  N<sub>S</sub>, total signal events of ZH(jj), assuming an efficiency of 50%
- $\star$  N<sub>B1</sub>, BKs from ZH(bb,cc), ~10% of N<sub>S</sub>(SM) using heavy-flavor tagging couplings from higher-orders in  $\mathcal{C}$  are suppressed by an additional factor of  $\mathcal{C}$  and  $\mathcal{C}$  are suppressed by an additional factor of  $\mathcal{C}$  and  $\mathcal{C}$ 
	- $\star$  N<sub>B2</sub>, BKs from ZZ(qq), ~20% of N<sub>S</sub>(SM) with selection using recoil mass
	- $N_{B3}$ , BKs from ZH(WW\*,ZZ\*), ~60% of  $N_S(SM)$ , (effects are small since far away from signal region)  $10/6$  of
	- various normalized shapes can be obtained either from theoretical calculation or using data-driven in a controlled region

#### Only decays of the associated *Z* boson to electrons and muons are included. *h* represents any of the  $L$ xuaction of Tundwa Co  $\bigcap$  1. II. 1.  $\mathbf{A}$  be set based on other event shape on other event shape observables which are event shape observables which are event shape of  $\mathbf{A}$ Extraction of Yukawa Couplings **[backups]**

✦ Projected sensitivity on light-quark Yukawa couplings is obtained using pseudo-data Including both the signal and backgrounds to event shape distributions at the event shape distribution of the con be had /ity on light-quark Yukawa couplings is obtained  $c$ 

$$
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$$

- ★ N<sub>S</sub> can be measured independently to **expected exclusion limit** ~3% via hadronic Z decays (pre-CDR) <sub>production</sub>, and the four-quarks  $\sim$  production, and the four-quarks  $\sim$  production, and the four-quarks  $\sim$  production, and the four-quarks  $\sim$  production. The four-quarks  $\sim$  pro Yukawa couplings.
- x systematics on N<sub>B1</sub>, N<sub>B2</sub>, N<sub>B3</sub> estimated to  $\frac{1}{\infty}$  0.25. be  $4\%$ 
	- $\overline{C}$  $\hat{\mathbf{x}}$  systematics due to scale variations of f(gg) and hadronizations of all shapes are included
	- $\star$  expected exclusion limit on r are obtained via pseudo-data and using profiled log-likelihood ratio with the CL<sub>S</sub> method

![](_page_37_Figure_7.jpeg)

### **expected exclusion limit**