Yukawa couplings and lifetime of Higgs boson: going beyond LHC

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based on arXiv: 1608.01746 and 1804.06858

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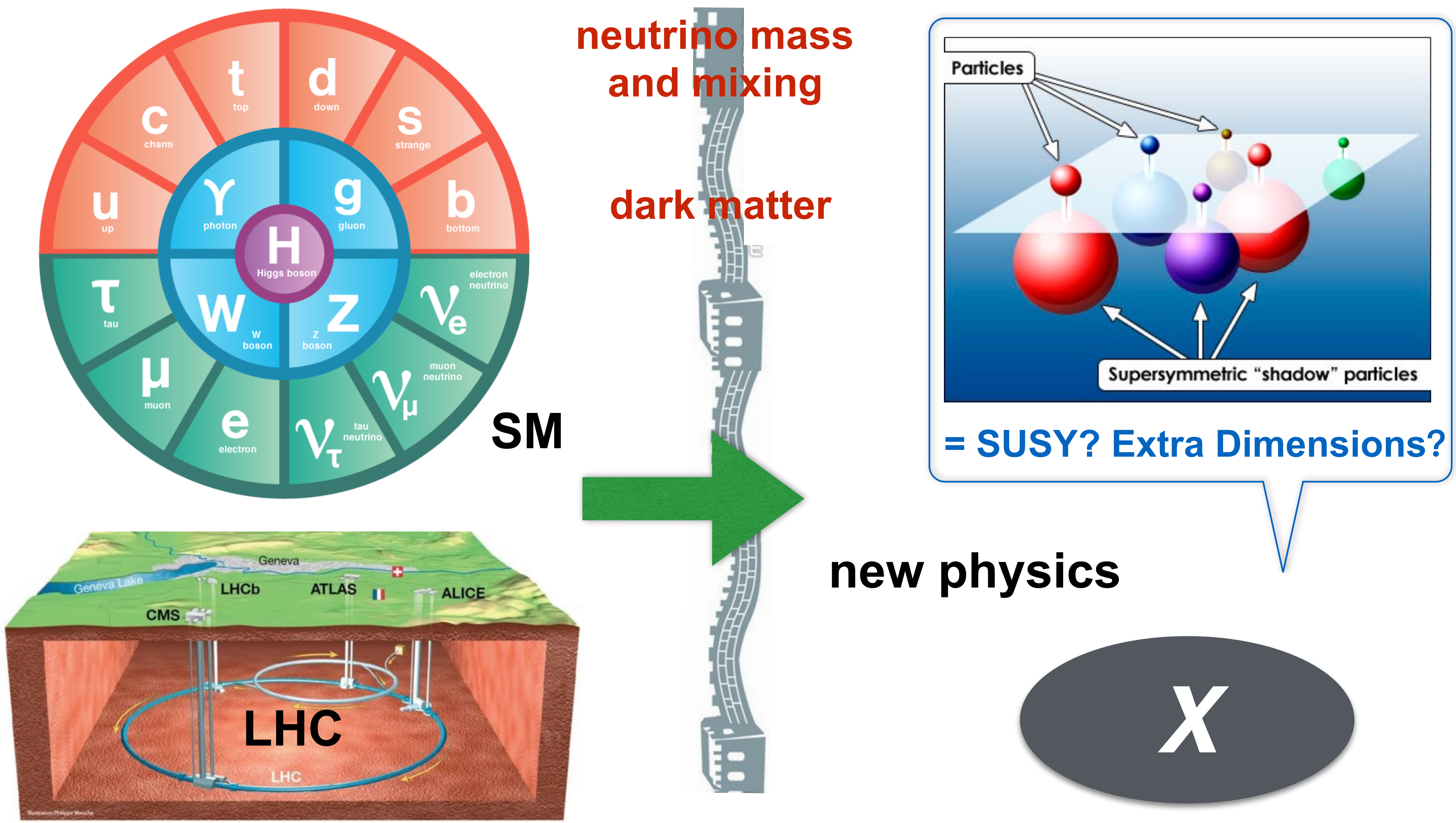
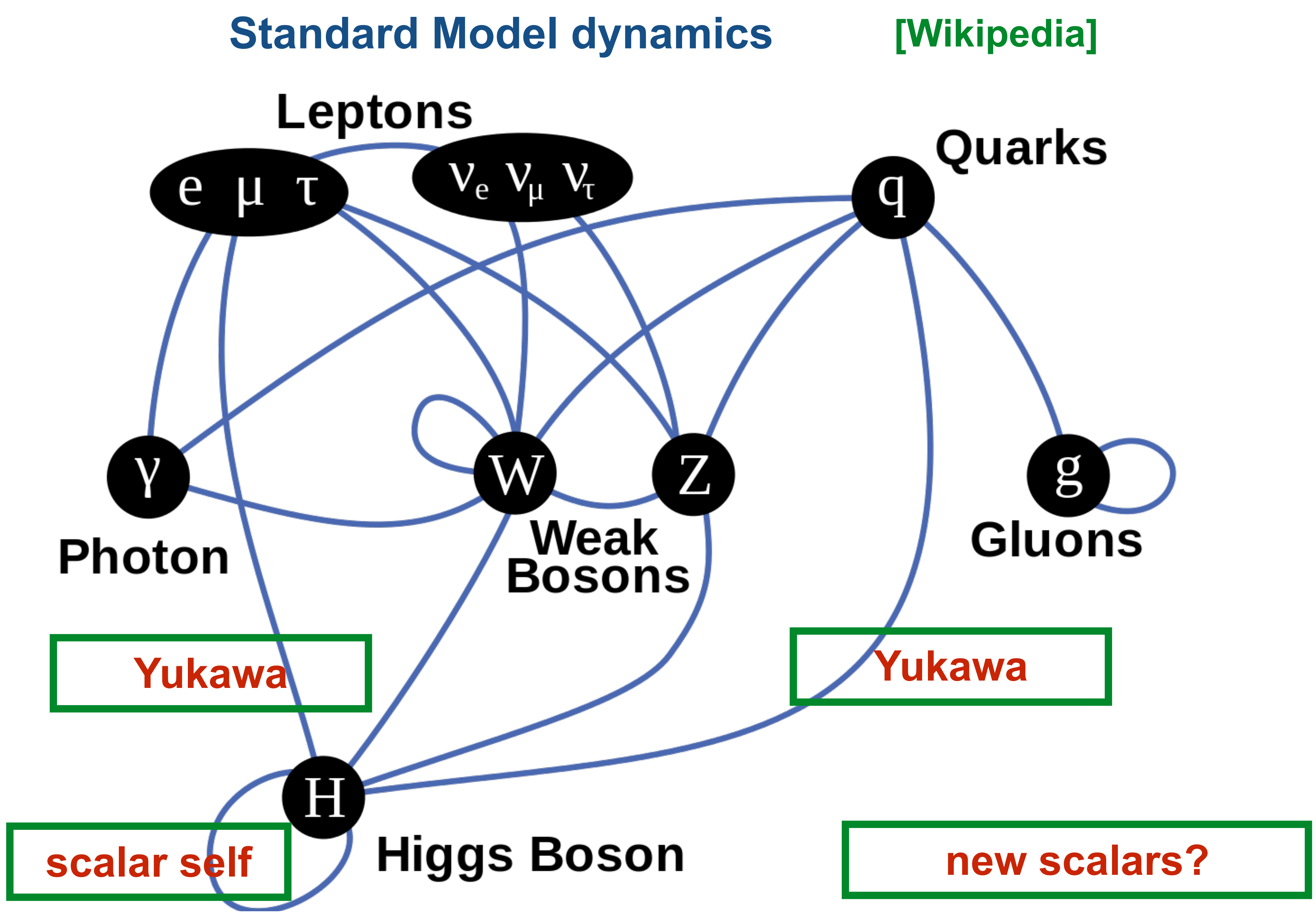
Standard Model of particle physics

- 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



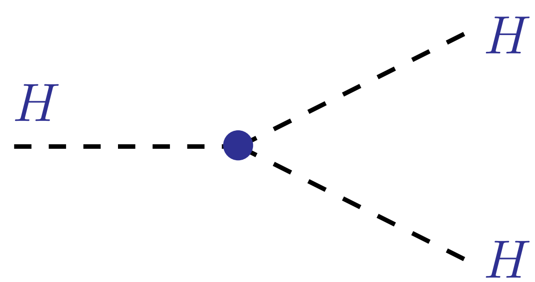
- Higgs boson introduces new phenomenas of study of elementary particles, spin-0 particle, scalar self interactions, Yukawa interactions

Higgs potential and self couplings

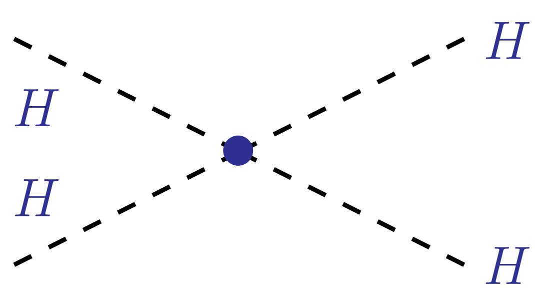
- Scalar potential are crucial for understanding EW symmetry breaking and for the fate of our EW vacuum **[Andreassen, Frost, Schwartz, 2017]**

Standard Model potential

$$\mathcal{L}_S = (D^\mu\Phi)^\dagger(D_\mu\Phi) - \mu^2\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2$$

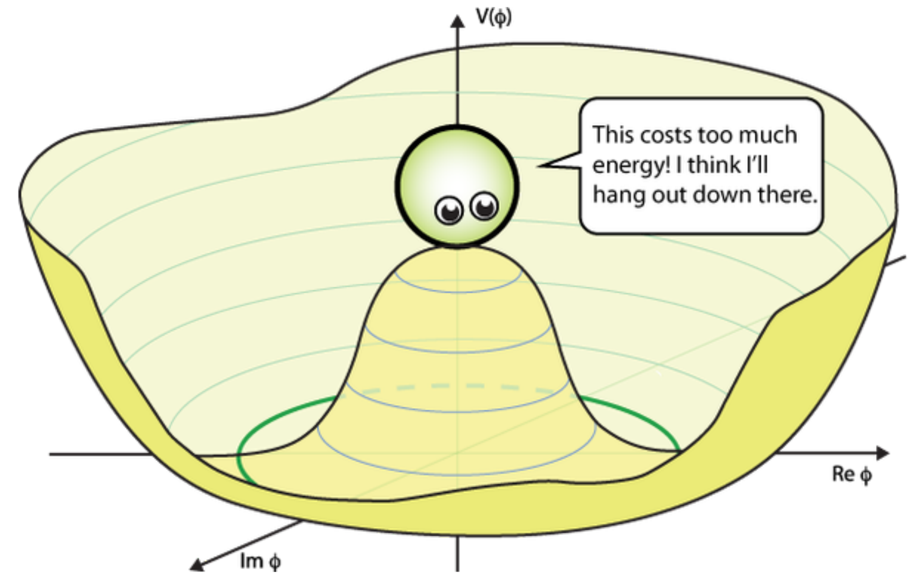


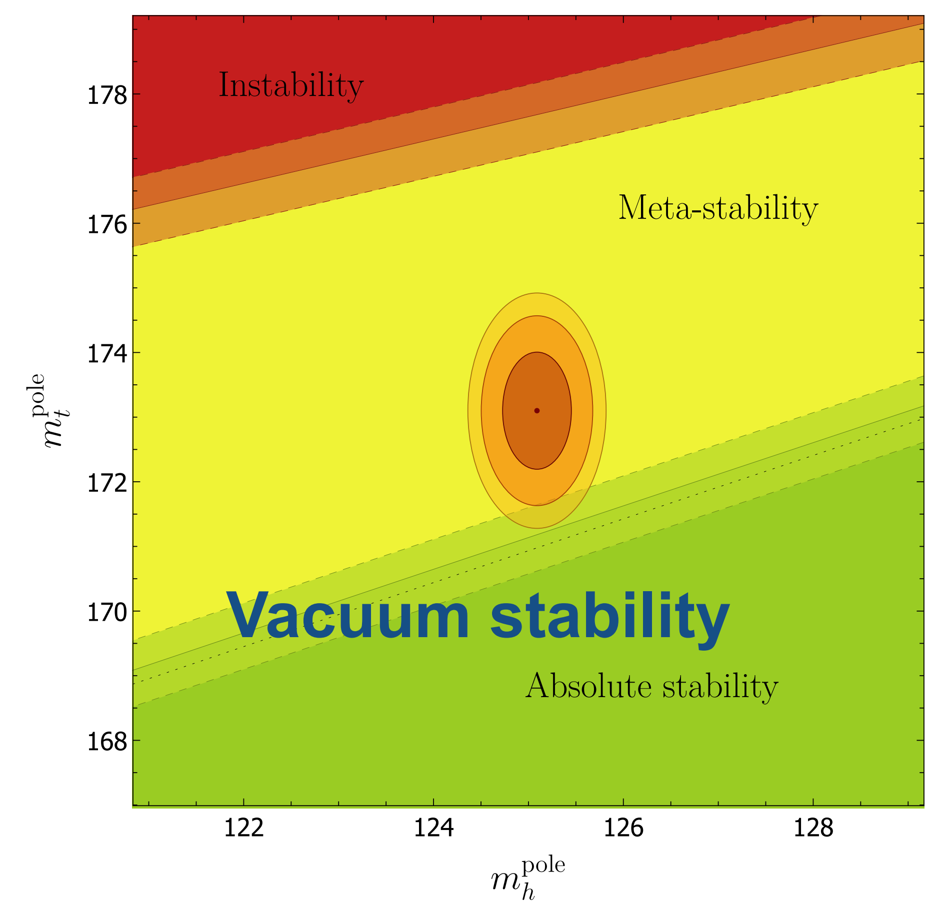
$$g_{HHH} = 3M_H^2/v$$



$$g_{HHHH} = 3M_H^2/v^2$$

- can be probed in pair production of the Higgs boson

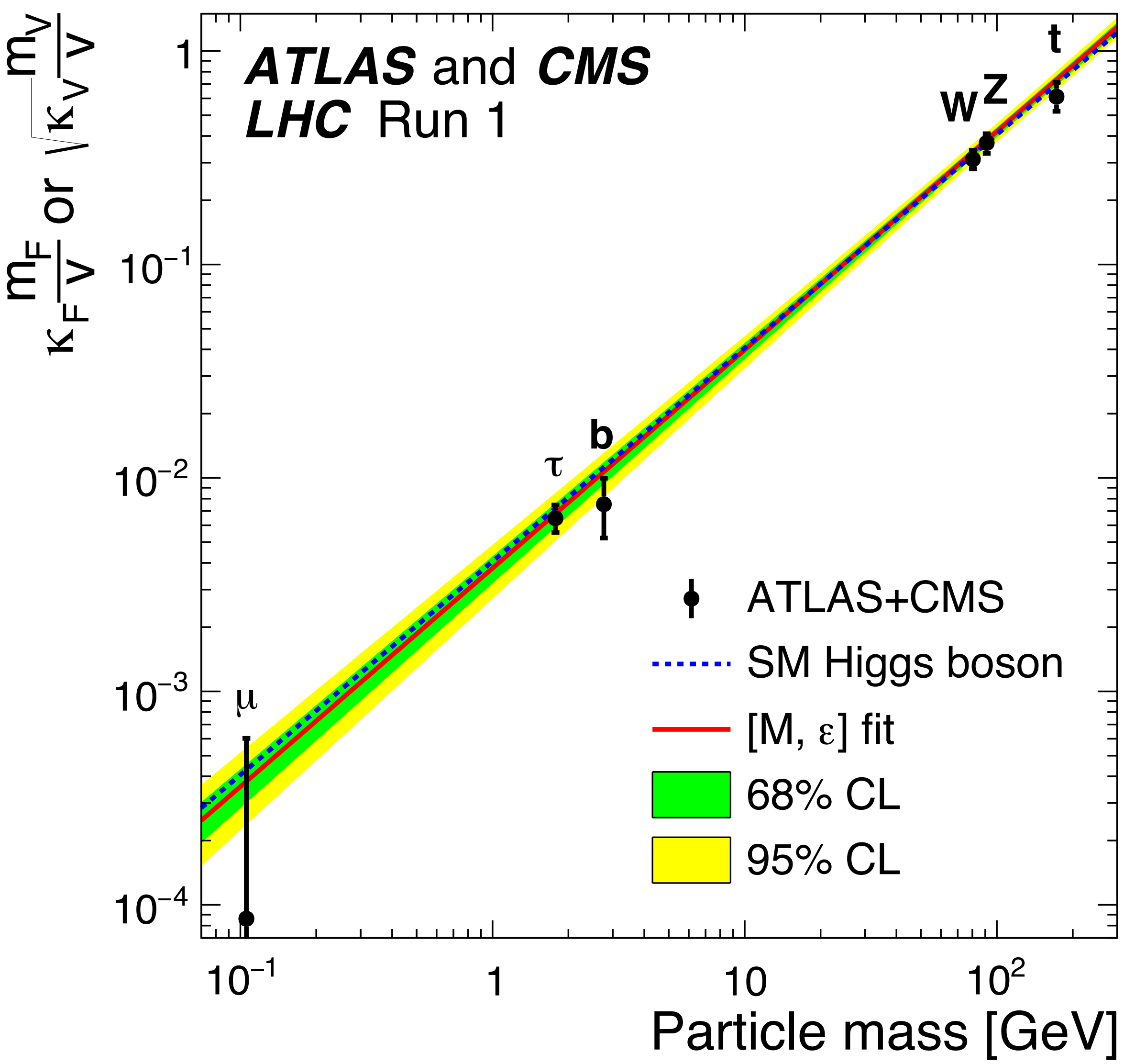




Yukawa couplings

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

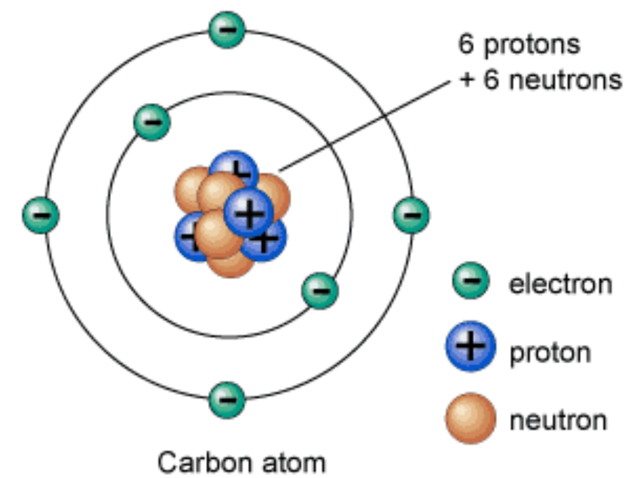
mass hierarchy



m_t=173.3 GeV, $y_t \simeq 1$

$$\beta_\lambda = \frac{1}{16\pi^2}\left(24\lambda^2 + 12y_t^2\lambda - 6y_t^4 + \ldots\right)$$

m_e=511 keV, $y_e \simeq 2\times10^{-6}$



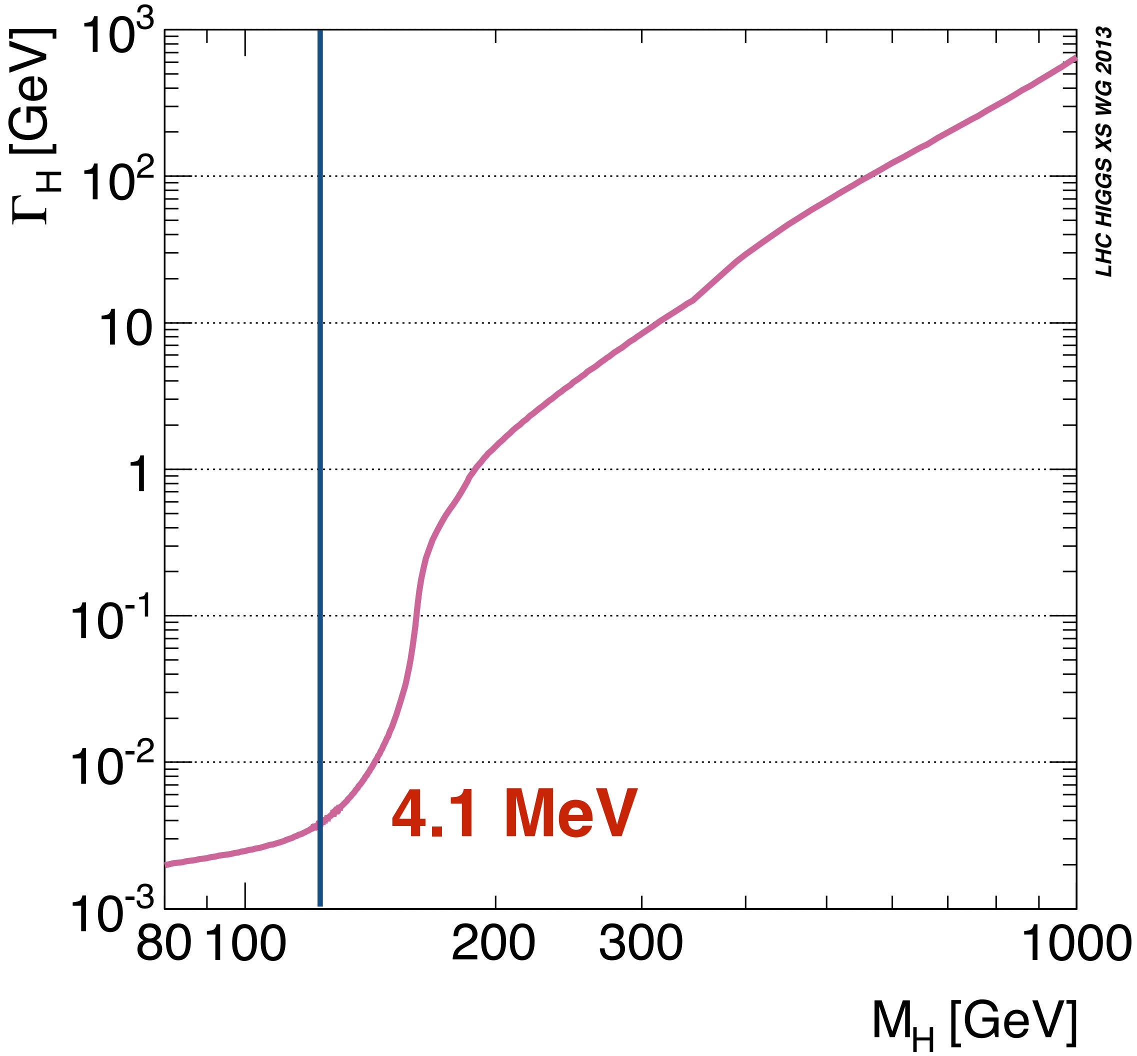
$$a_0 = \frac{\hbar}{m_e\, c\, \alpha}$$

- 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

Higgs width/lifetime

- Higgs boson with a mass of 125 GeV decays dominantly to bottom quark pair via Yukawa y_b~0.01 resulting in small width $\Gamma/m \sim 3\times10^{-5}$

width vs. mass



[LHCHXSWG]

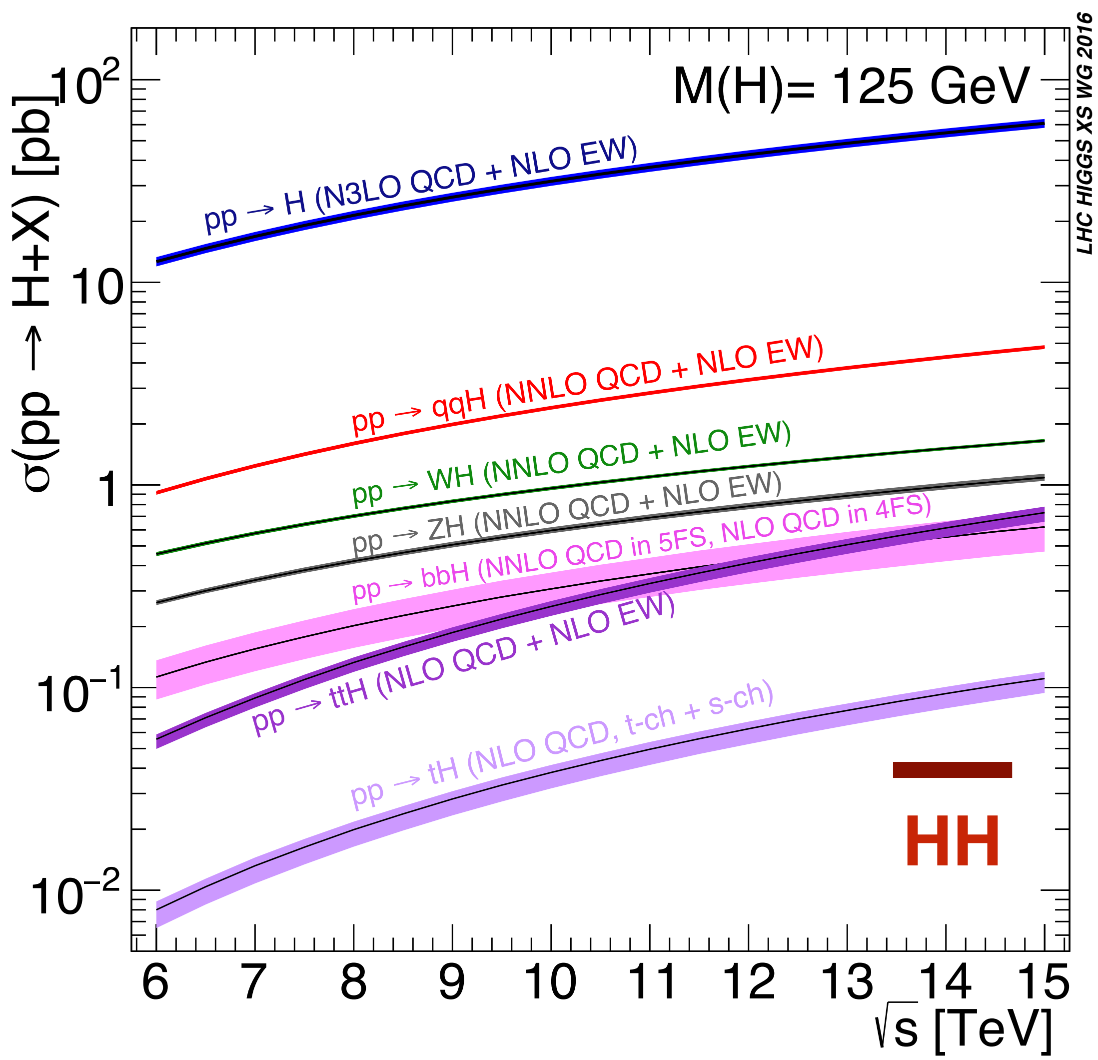
Particle	Width(GeV)	lifetime(fm/c)
top	1.3	0.15
Higgs	0.004	47
Z	2.5	0.08
W	2.1	0.09

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

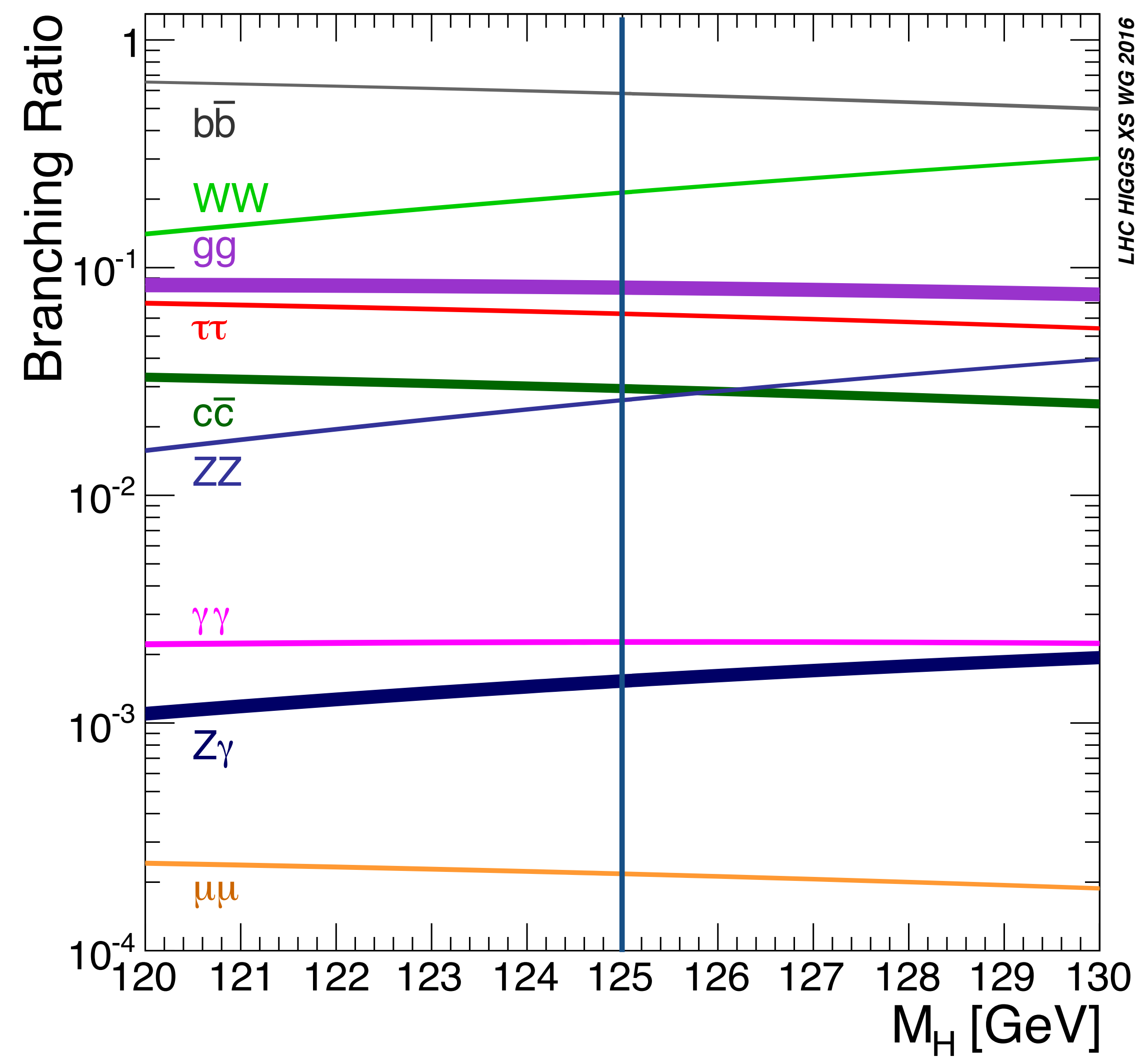
Higgs boson at the LHC

- ✦ Higgs boson can be produced abundantly at the LHC (HL-LHC), ~3(30)×10^7 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

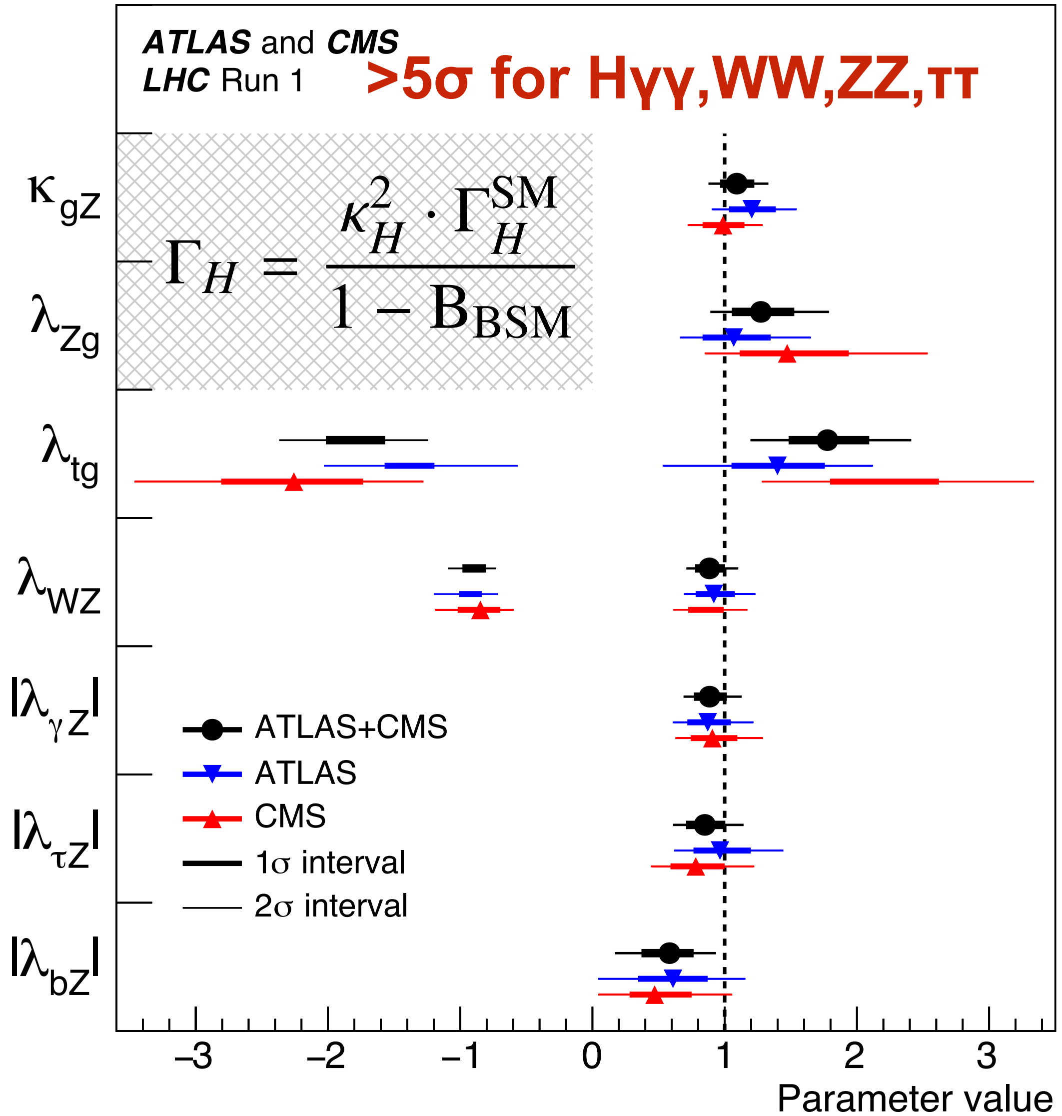
From LHC Higgs Cross Section Working Group, https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG

LHC measurements

- Current measurement agrees well with the standard model Higgs boson on various signal strength, **σ×BRs**, with a precision ~10-20%

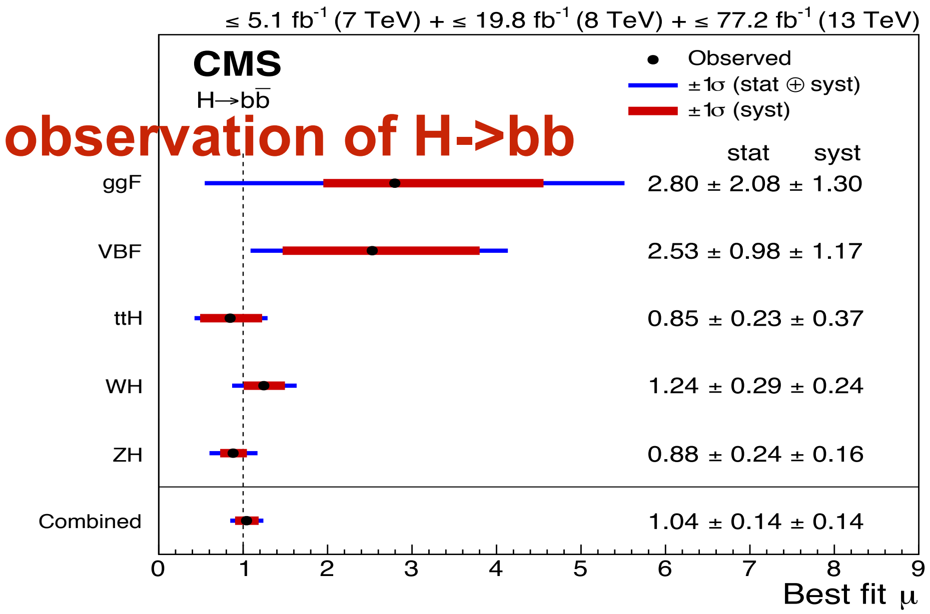
generic κ-framework

>5σ for Hγγ,WW,ZZ,ττ

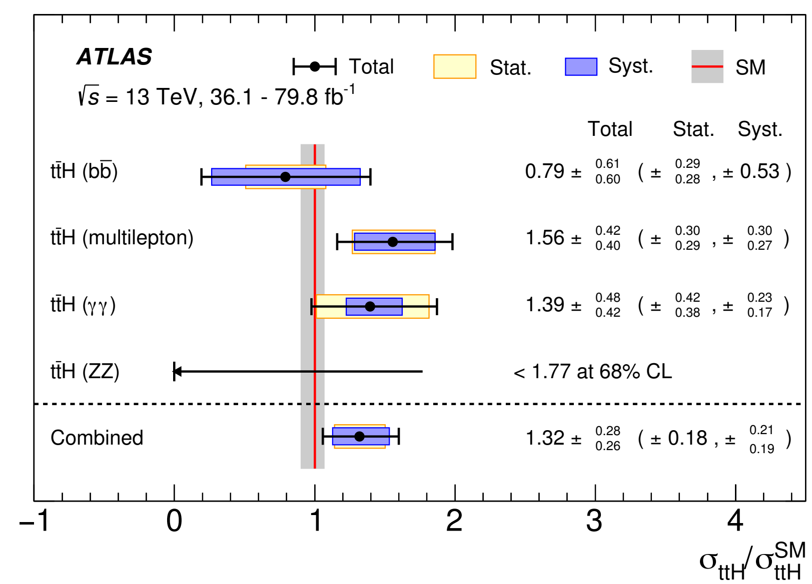


[Run I combined, 2016]

observation of H->bb



observation for Htt



[ATLAS, 2017, 2018]

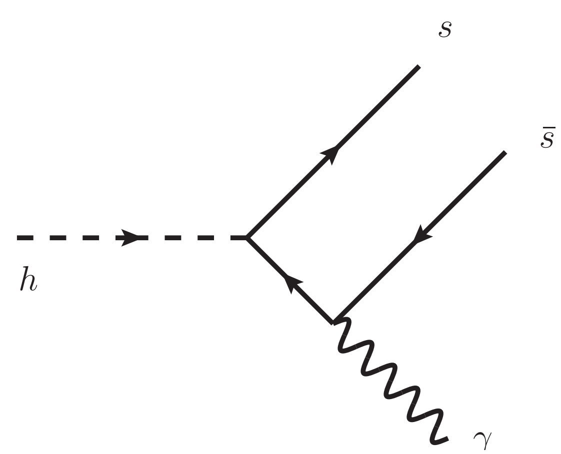
- Without model assumptions only ratios of Higgs couplings can be probed with sufficient precision at LHC due to unknown total width

Light-quark Yukawa couplings

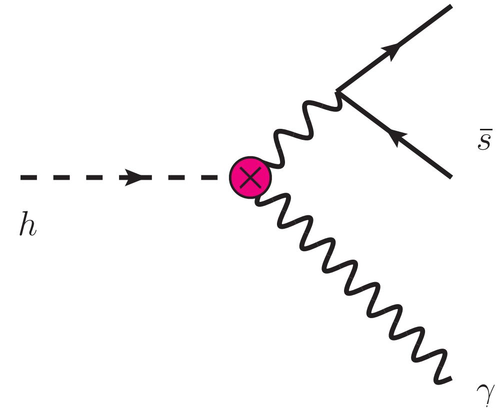
✦ Measuring Yukawa couplings of light-quarks at LHC are particularly challenging due to their smallness, **y_s/y_b~2%**, and huge QCD Bks

exotic decays (BR~10^{-6})

$$h \to \phi\gamma$$



Interference

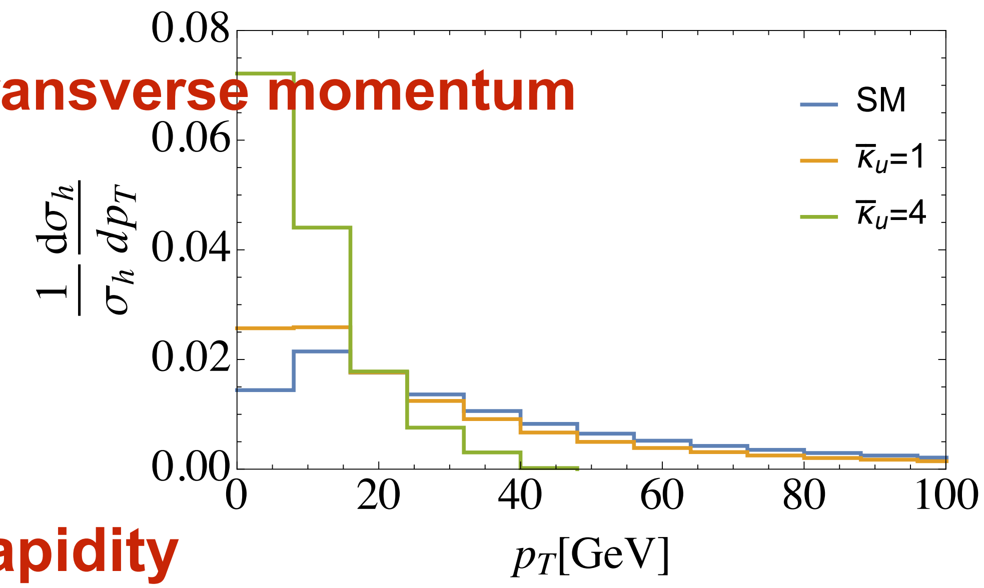


[Kagan +, 2014, 2016; D.N. Gao, 2014]

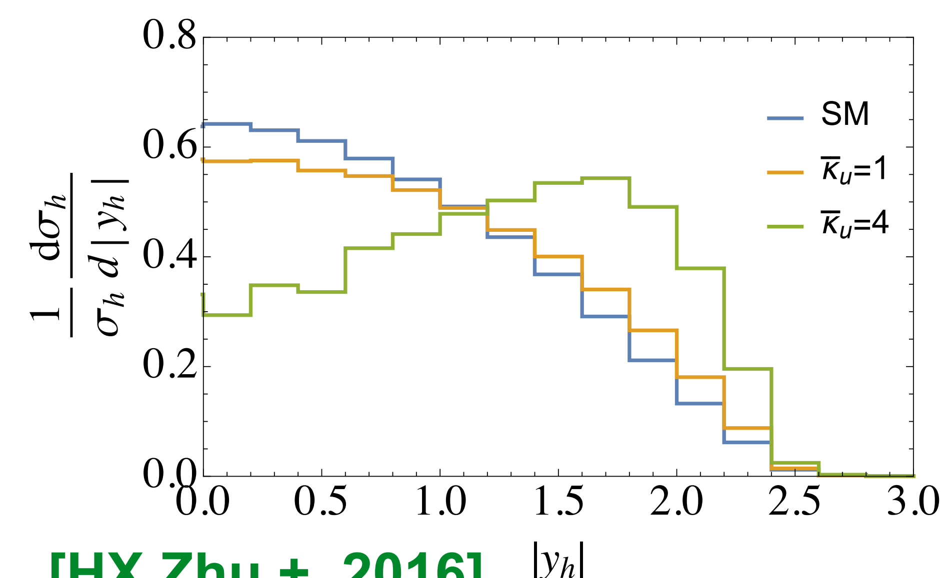
☆ conceptually good; in practice no sensitivity due to huge Bks

Higgs kinematics

transverse momentum



rapidity

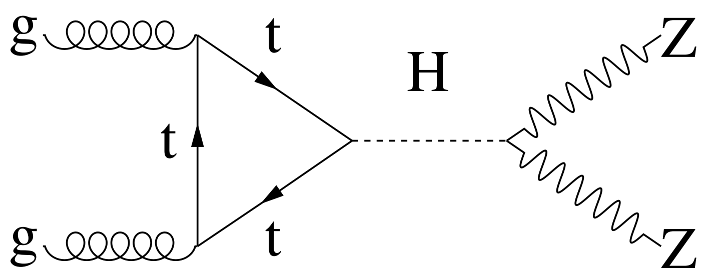


[HX Zhu +, 2016]

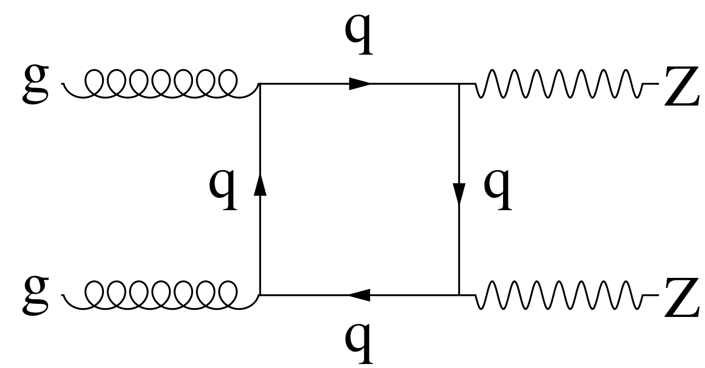
☆ LHC/HL-LHC can probe Yukawa of u/d quarks to ~0.3y_b

Limit on total width/lifetime

- Various limits on width/lifetime of the Higgs boson are set at the LHC either directly or indirectly, especially with **Higgs interferometry**

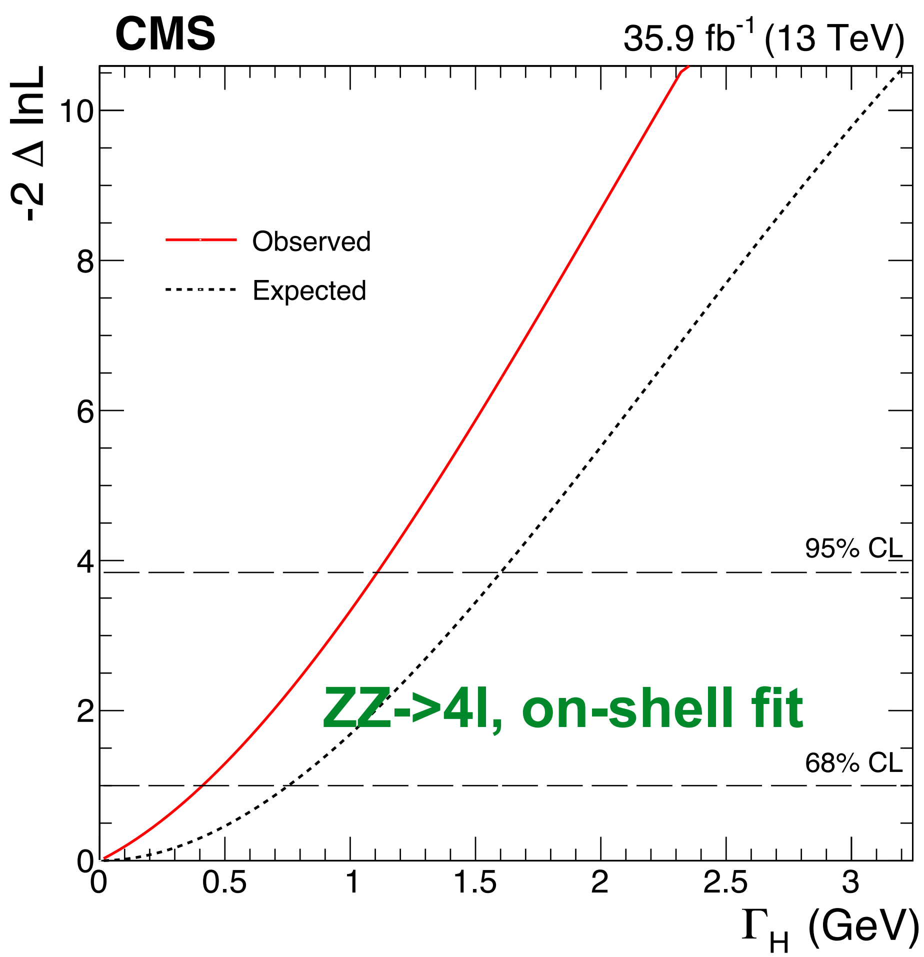


Interference

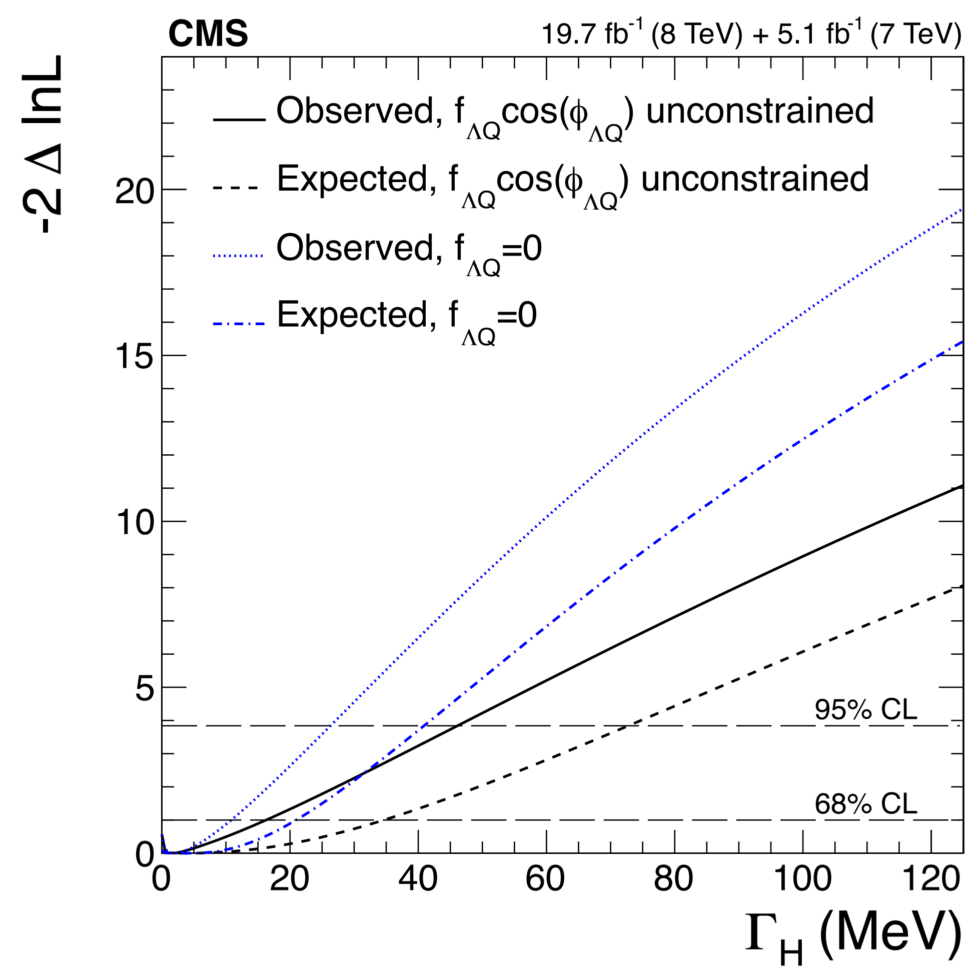


$$\sigma^{\text{on-shell}}_{\text{vv}\to\text{H}\to\text{ZZ}} \propto \mu_{\text{vvH}} \text{ and } \sigma^{\text{off-shell}}_{\text{vv}\to\text{H}\to\text{ZZ}} \propto \mu_{\text{vvH}}\,\Gamma_{\text{H}}$$

direct measurement

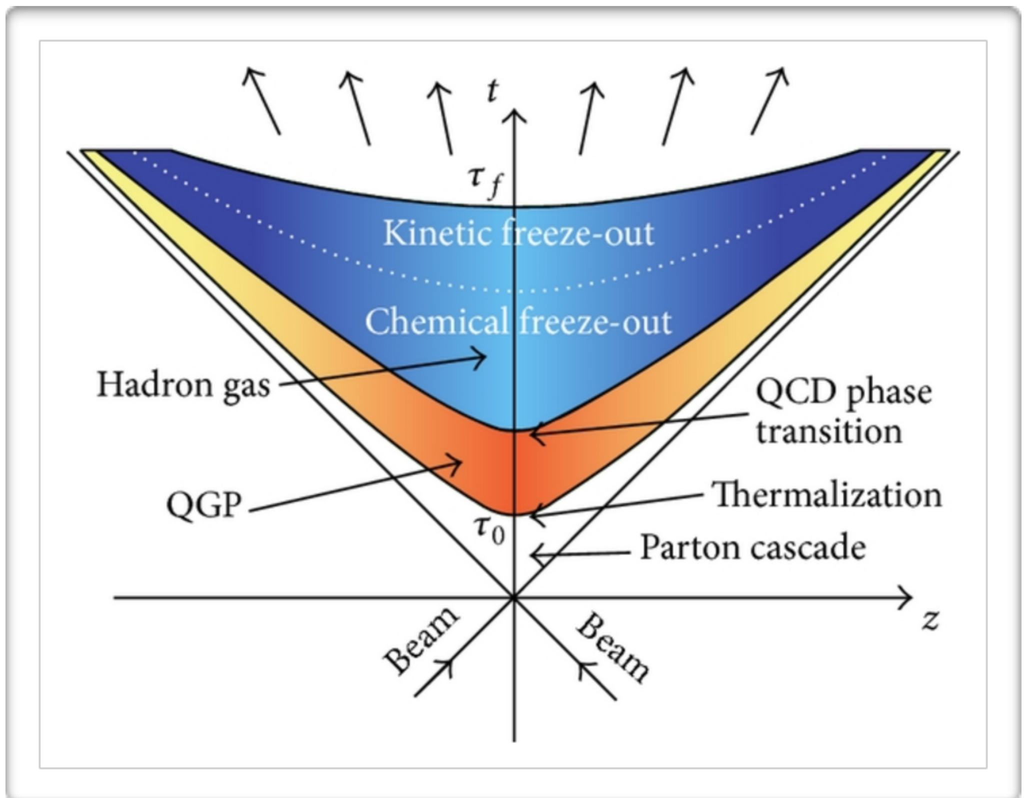


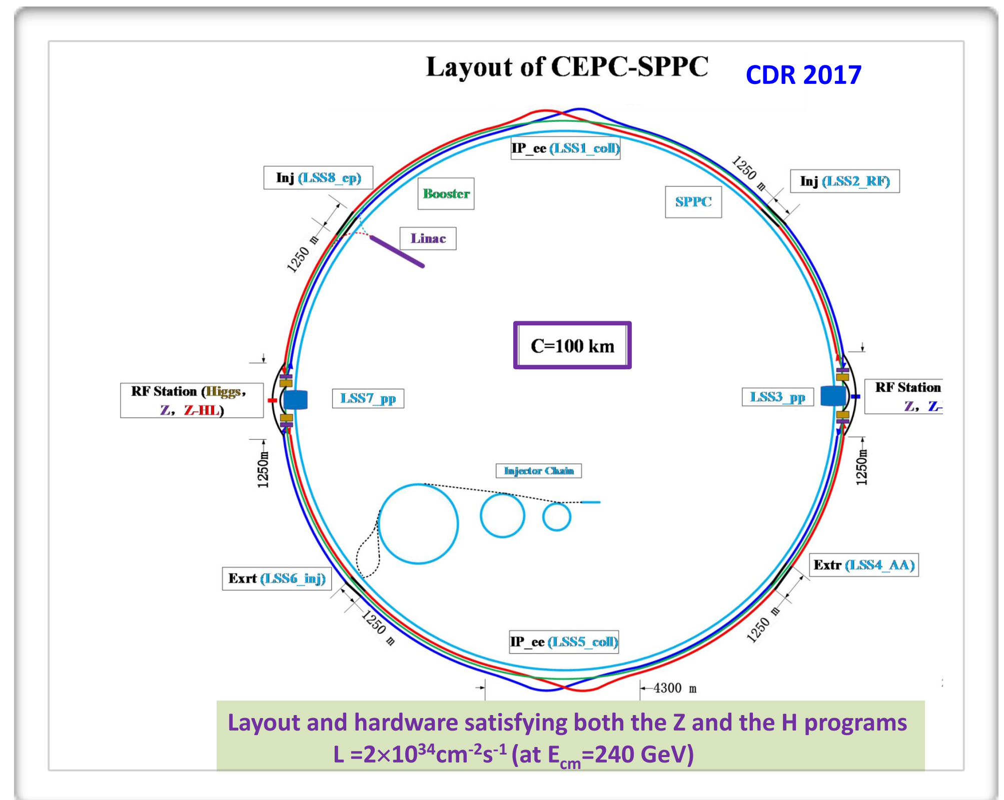
off-shell/on-shell



Going beyond LHC

- I. Higgs properties revealed in heavy-ion collisions
- II. Light-quark Yukawa couplings from CEPC

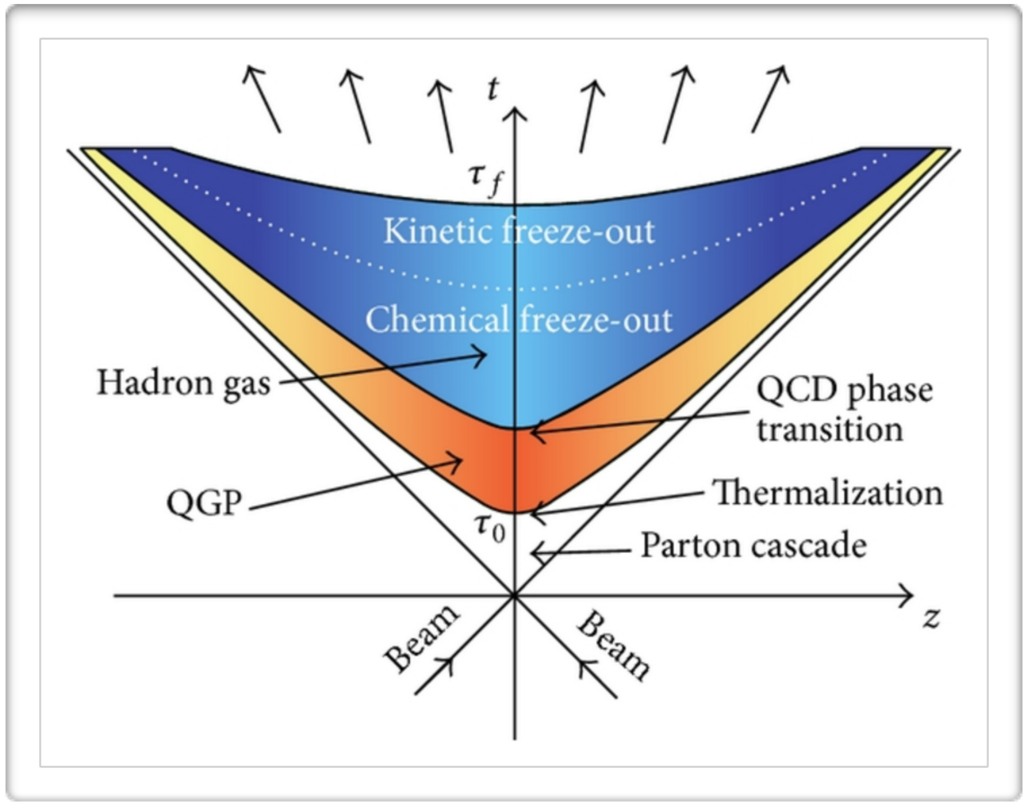




[Edmond Berger, Jun Gao, A. Jueid, Hao Zhang, arXiv:1804.06858]

[Jun Gao, arXiv:1608.01746]

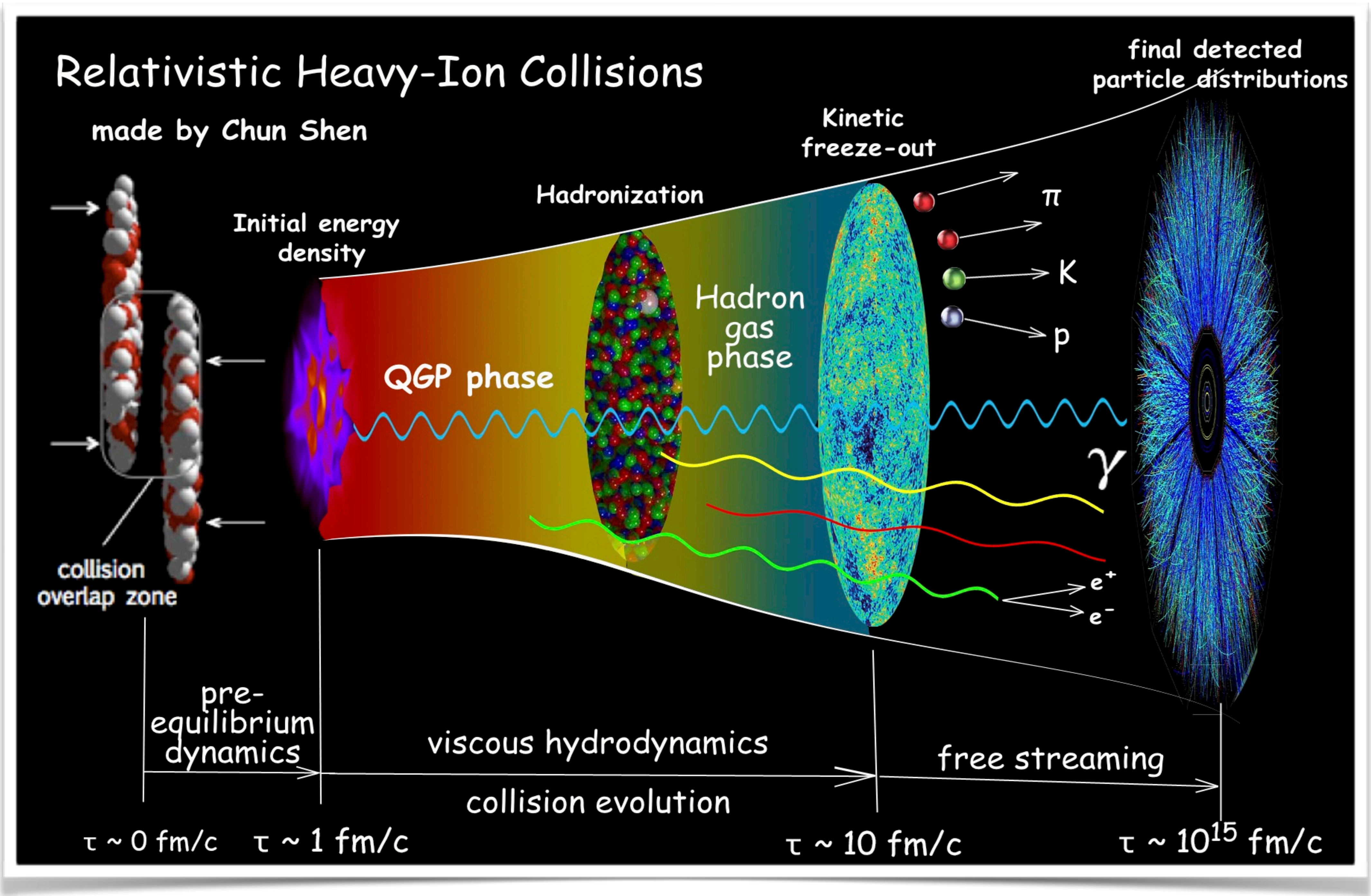
- I. Higgs properties revealed in heavy-ion collisions



[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

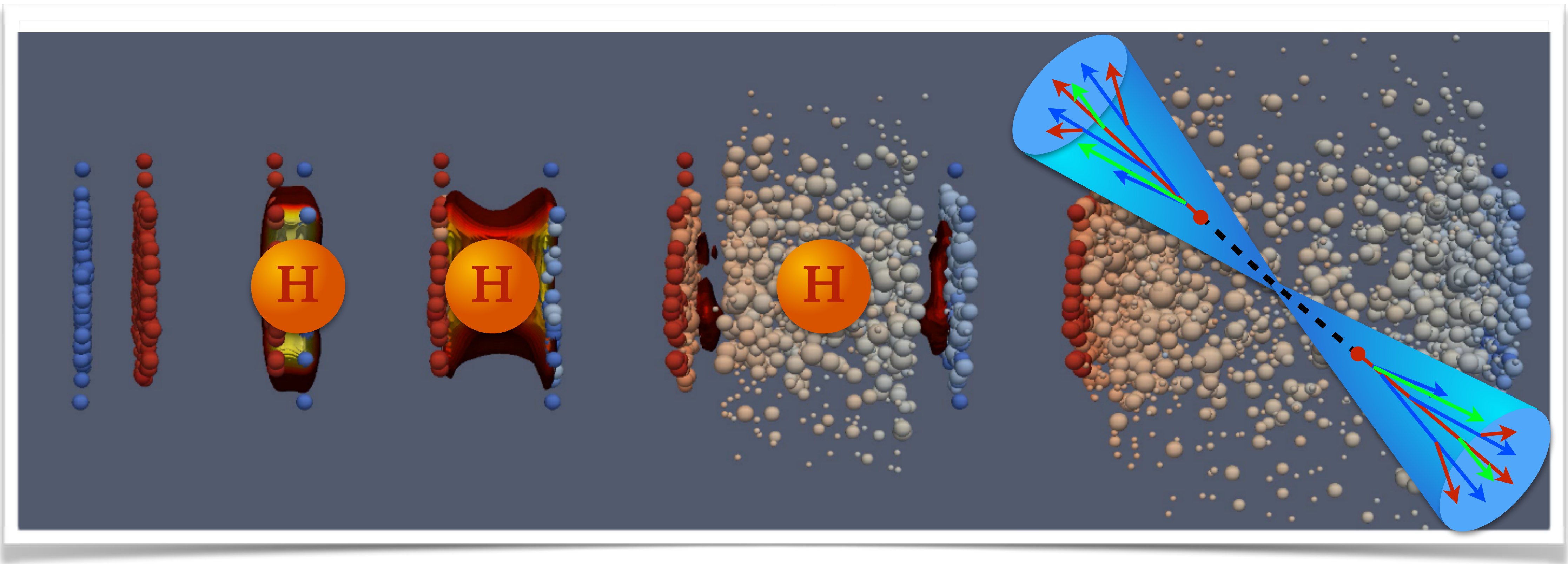


[Chun Shen]

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

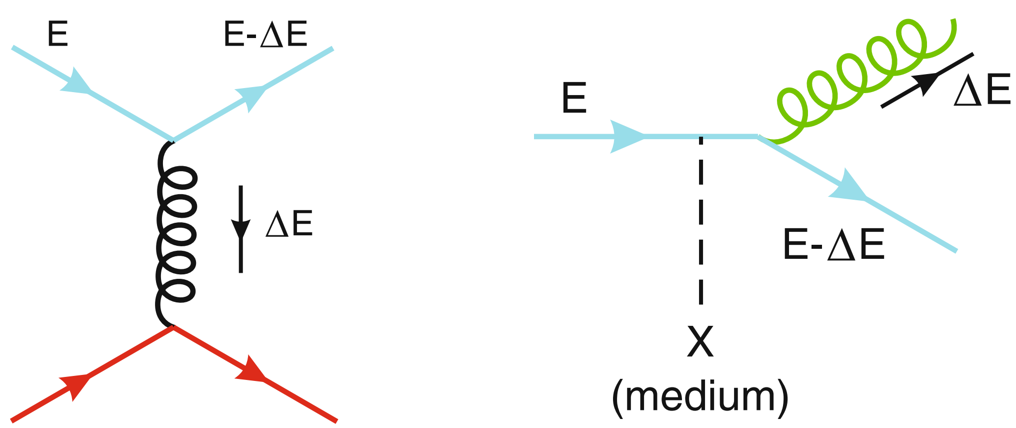


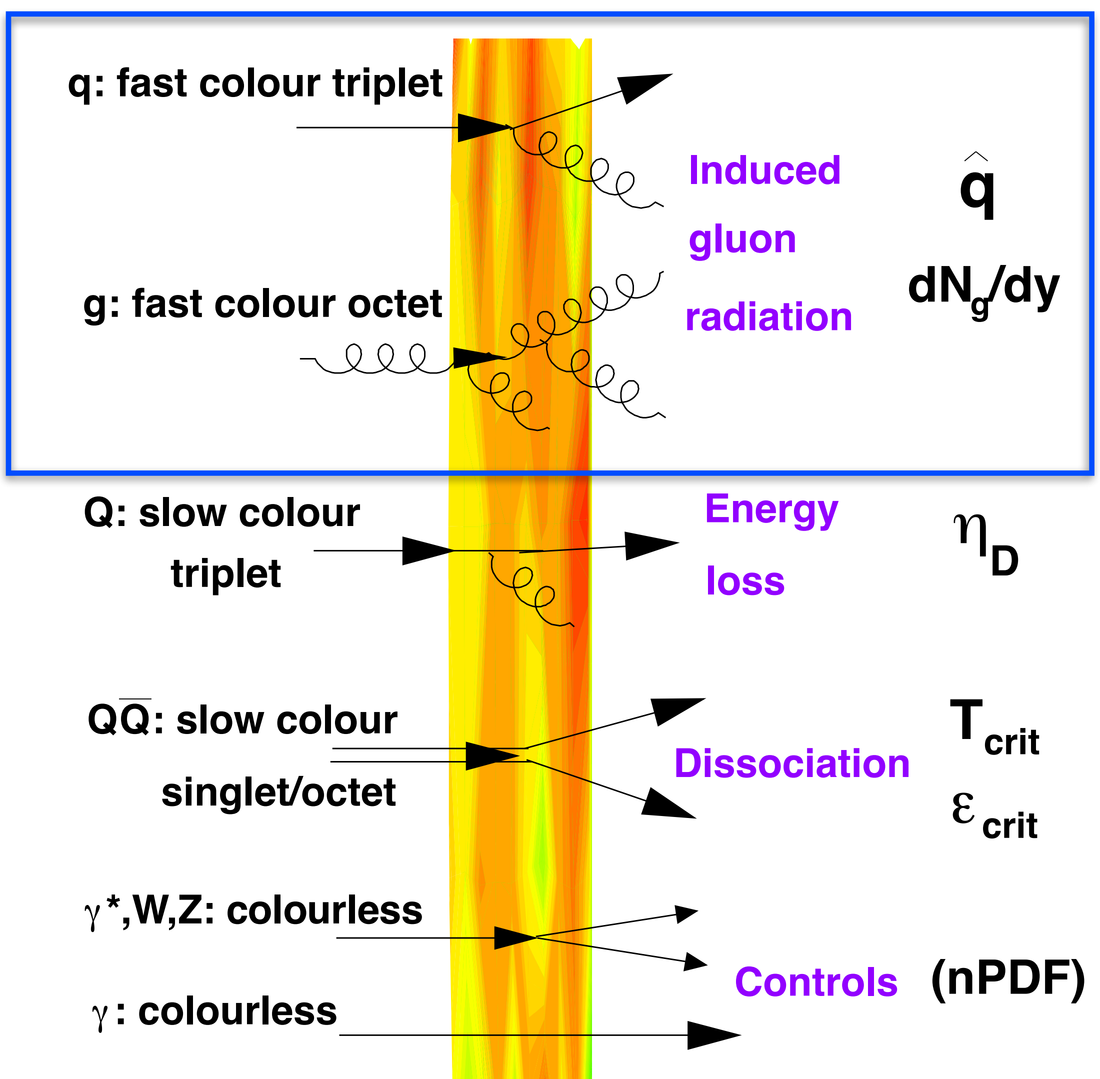
role of jet quenching **[Berger, JG, Jueid, Zhang, 2018]**

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

Jet quenching

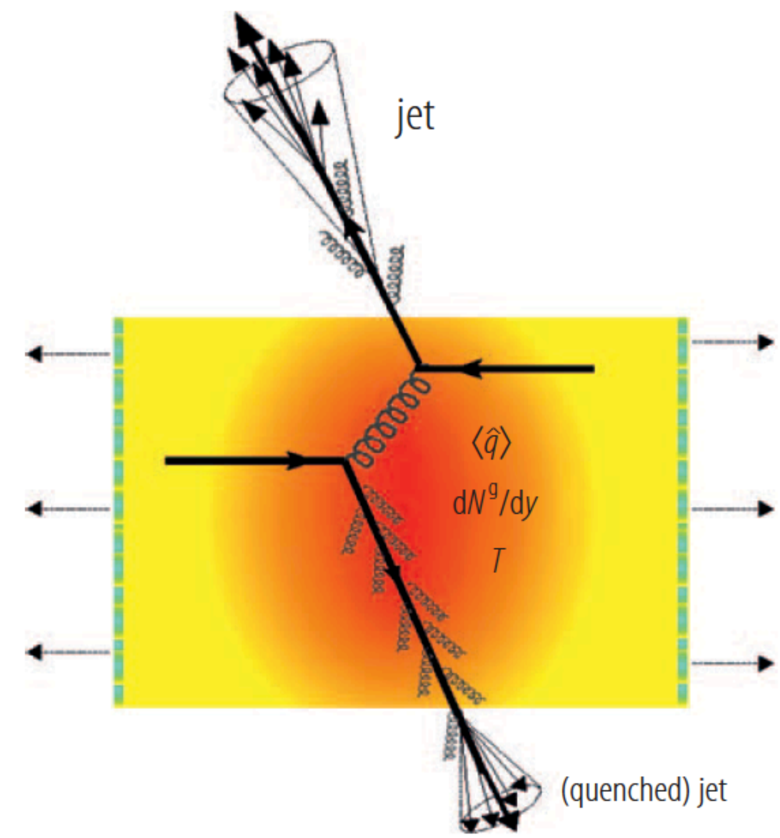
- Parton traversing QGP suffers energy lost due to both collisions (elastic) and medium induced radiations (inelastic)





[d'Enterria, 2012]

quenching of hard jets



- medium-induced enhanced radiations leads to more energy distributed outside the cone

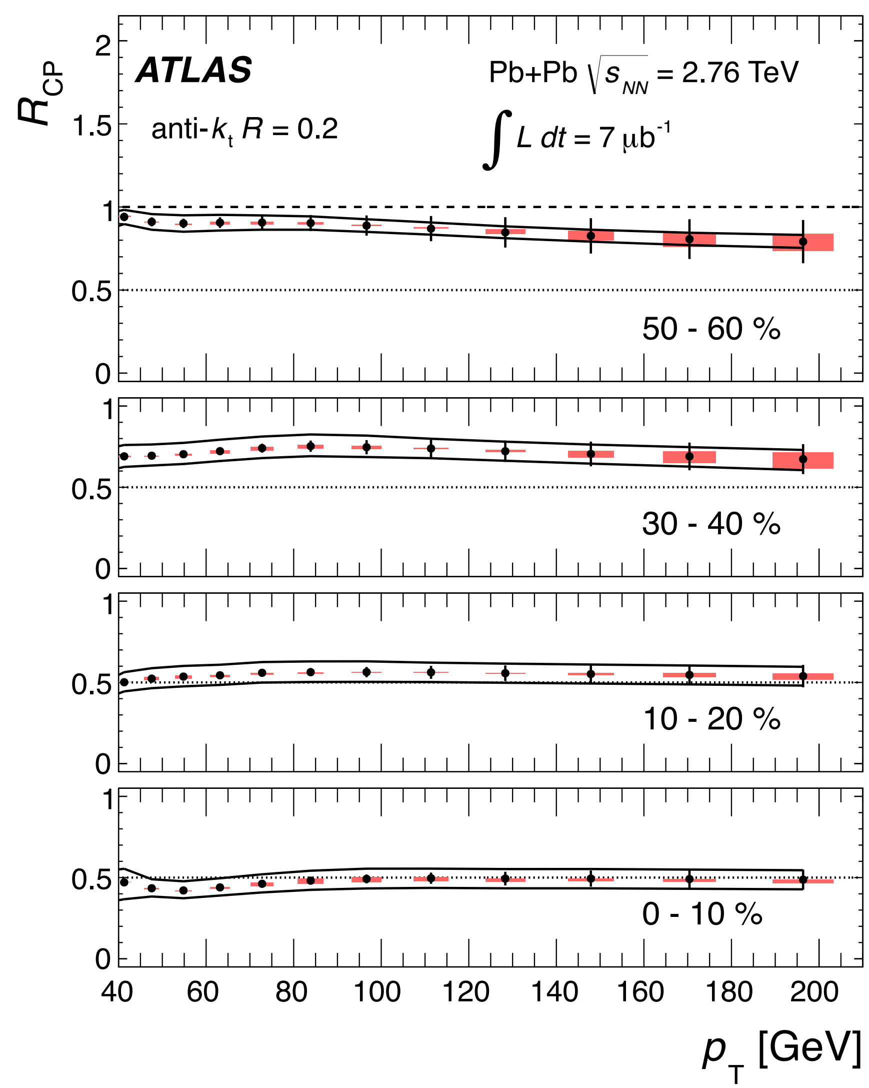
Hard probes: single inclusive jet

- Measurements on medium suppression of cross sections provide a strong evidence of jet quenching in AA collision

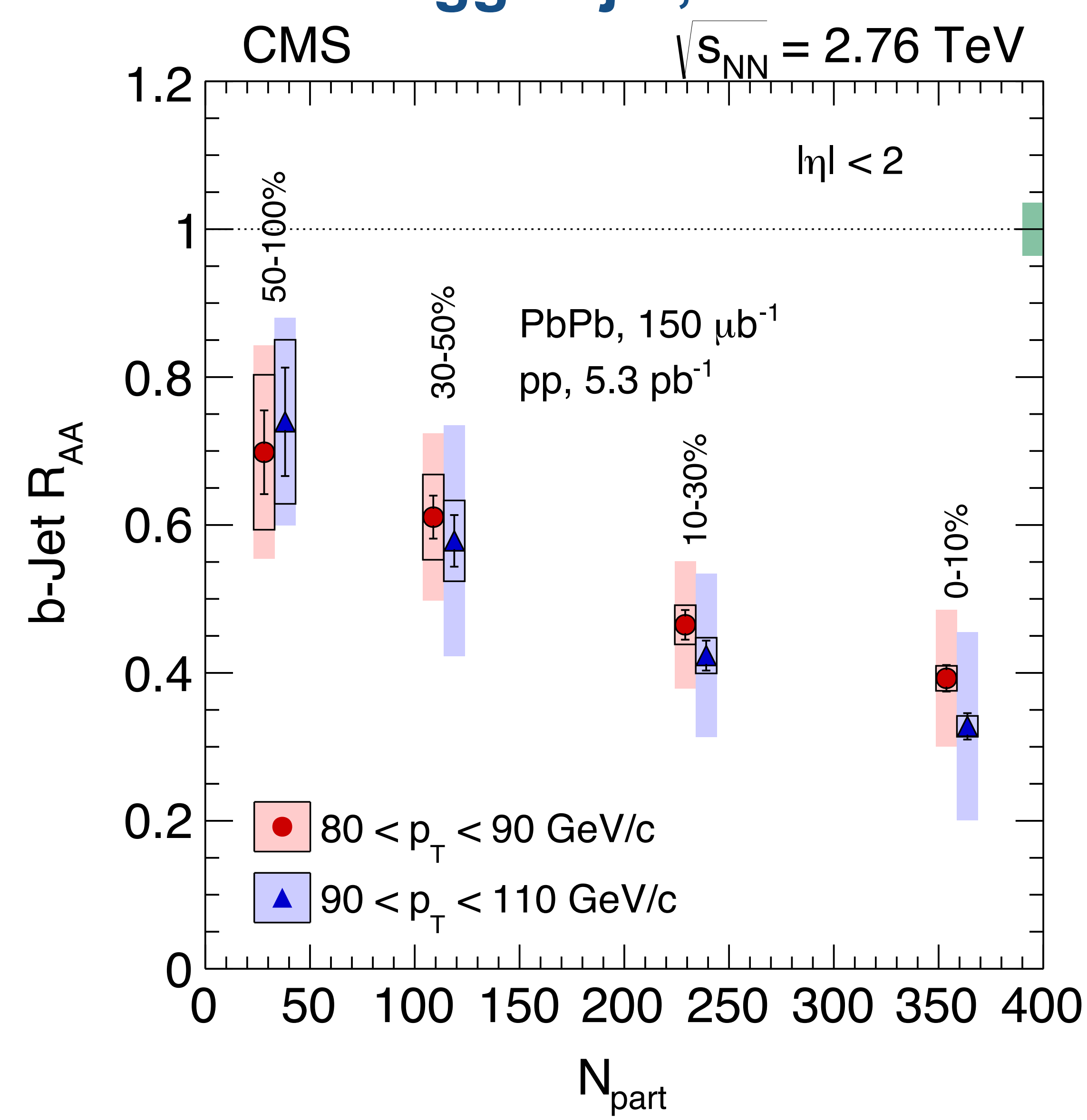
ratio of jet cross sections in PbPb to pp

$$R_{AA}(p_T, y; b) = \frac{d^2 N_{AA}/dy dp_T}{\langle T_{AA}(b) \rangle \times d^2 \sigma_{pp}/dy dp_T}$$

inclusive jet, 2012



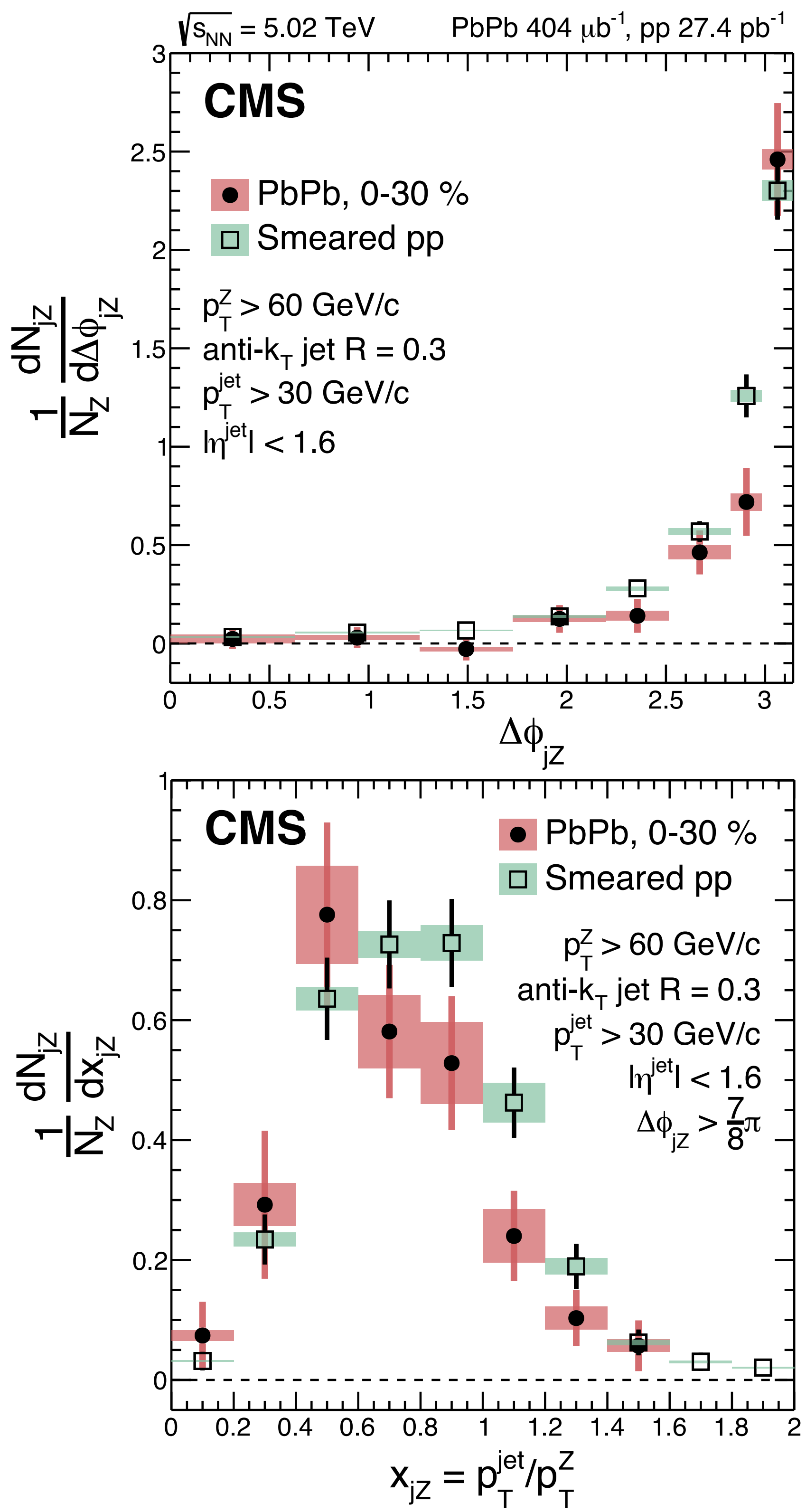
b-tagged jet, 2013



- Experimentally similar level of quenching for inclusive jet and b-jet

Hard probes: Z/photon+jet

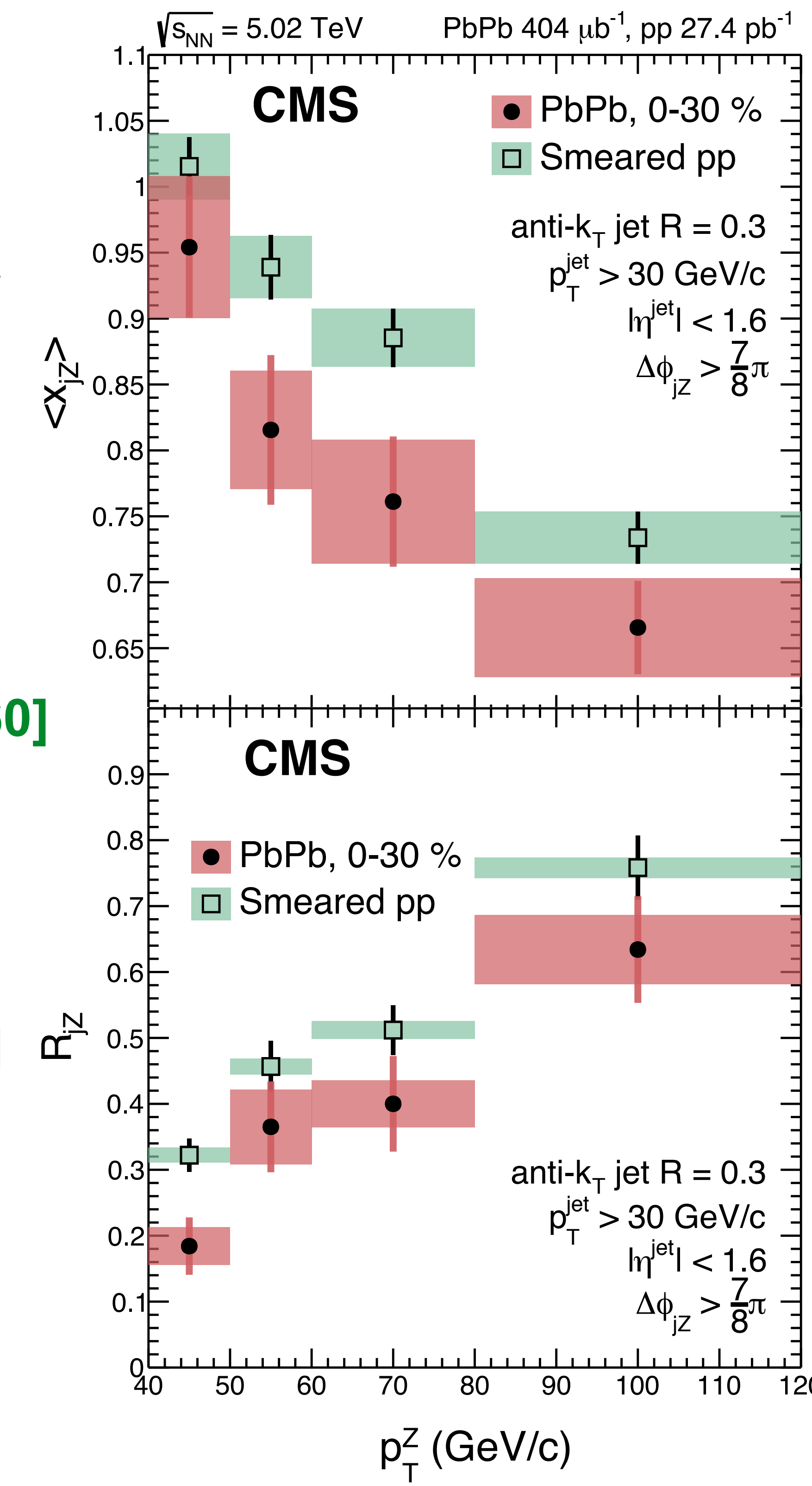
- Measurements on imbalance of the transverse momentum provide a direct probe of jet quenching in AA collision



Left: correlations of Z boson and recoiled jet

[arXiv:1702.01060]

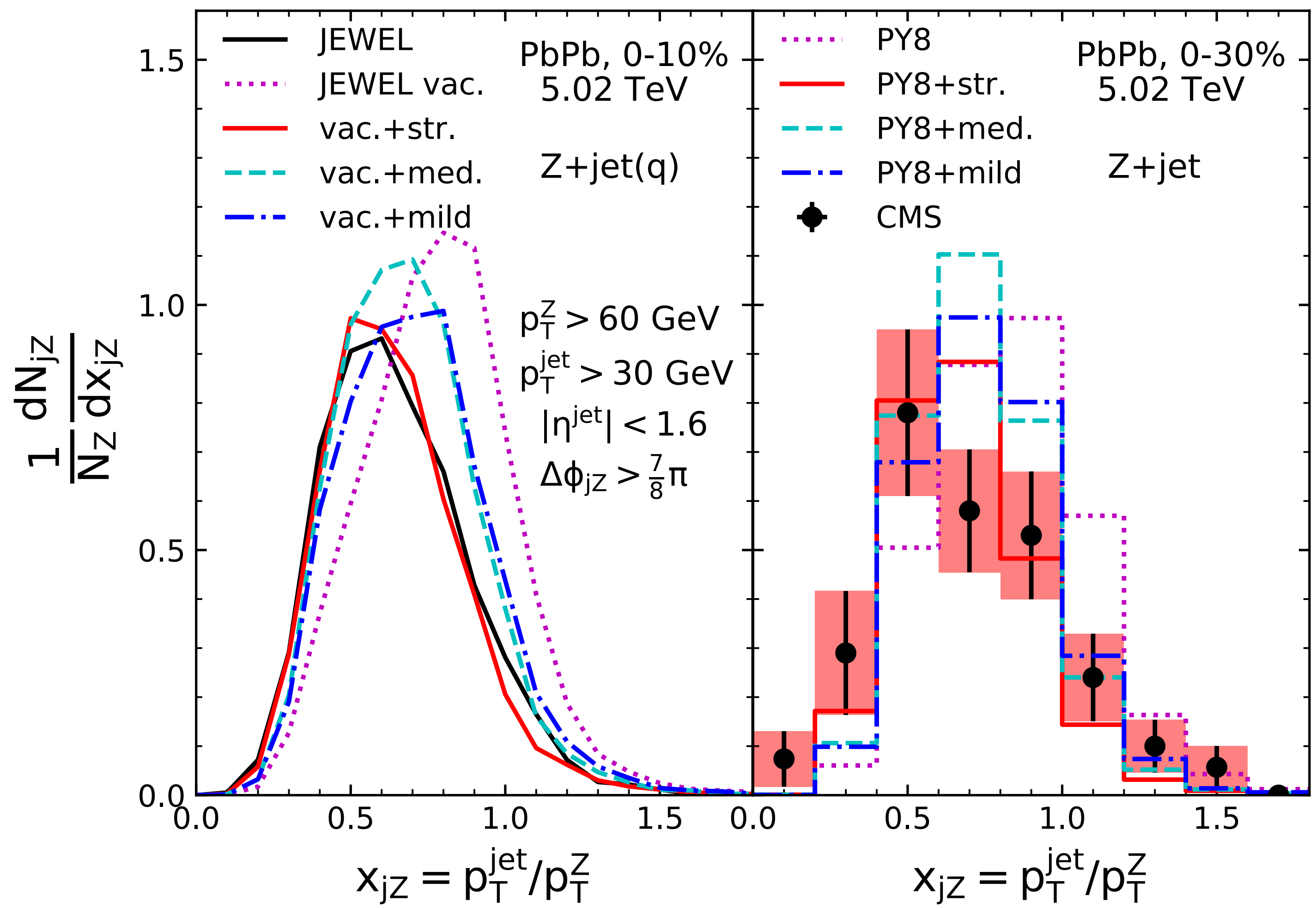
Right: imbalance and suppression vs. p_T



Simplified quenching models

- Simplified models on jet quenching are used for standard model backgrounds and tested against MC and CMS data

$$\langle \delta p_{\mathrm{T}} \rangle = a p_{\mathrm{T}} + b \ln(p_{\mathrm{T}}/\mathrm{GeV}) + c$$ **average p_T lost with Gaussian fluc.**



- **strong, a=0, b(c)=2(12) GeV**
- **medium, a=0.15, b(c)=0**
- **mild, a(b)=0, c=10 GeV**

for a p_T=100 GeV jet, corresponds to a lost of 21, 15, 10 GeV, respectively

- shown are distributions of momentum imbalance in Z + jet production; three models are considered for jet with anti-k_T (D=0.3) algorithm in 0-10% centrality

Signal and backgrounds

- We select the ZH associated production with Higgs decays to bottom pair, Z to leptons; major backgrounds are ZbB and top pair production

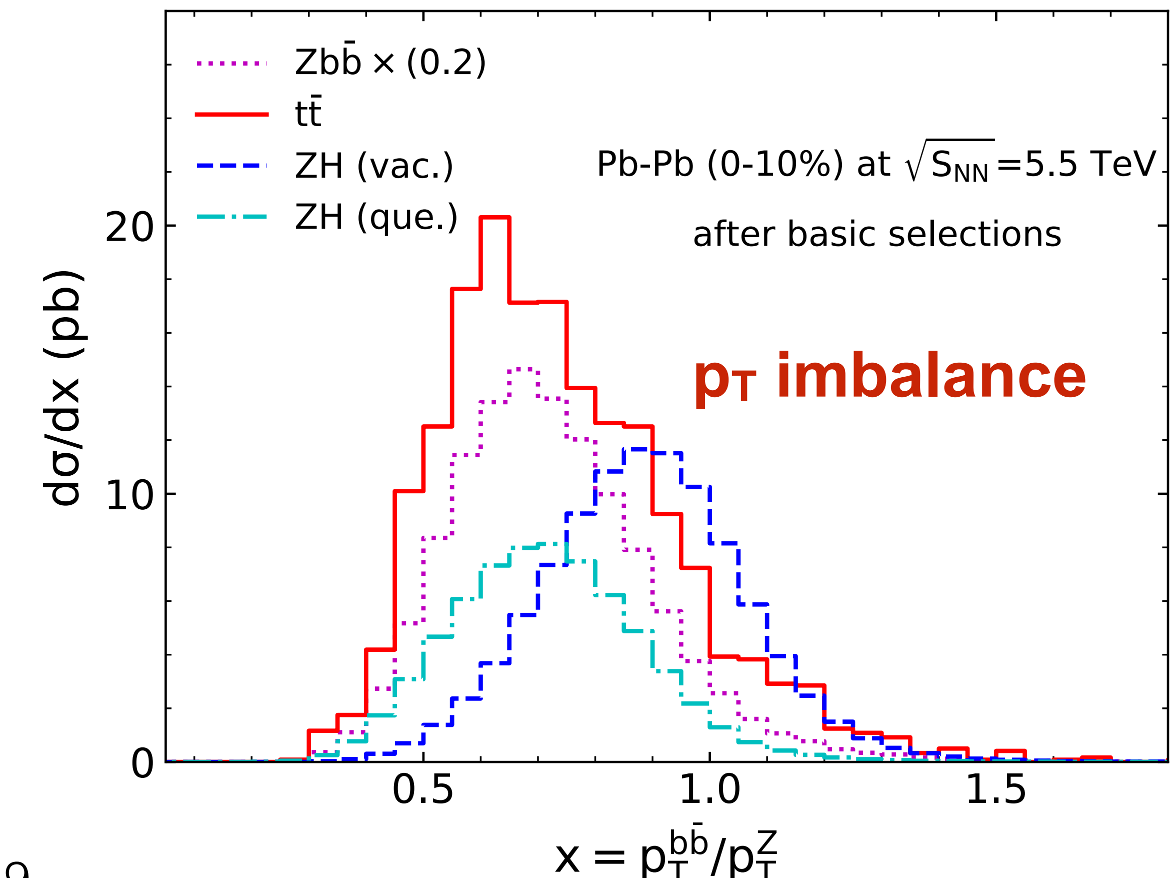
process	PbPb(pp) in nb(pb)		
	5.5 TeV	11 TeV	39.4 TeV
GF	480(10.2)	1556(35.2)	9580(235)
VBF	15.3(0.316)	65.6(1.40)	421(10.02)
ZH	10.2(0.230)	28.1(0.687)	147(3.97)
W^+H	8.38(0.162)	21.8(0.716)	94.2(3.19)
W^-H	9.22(0.143)	23.4(0.435)	99.5(2.34)

- total cross sections of typical production channels, PbPb vs. pp; centrality factors not applied here

basic selections

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

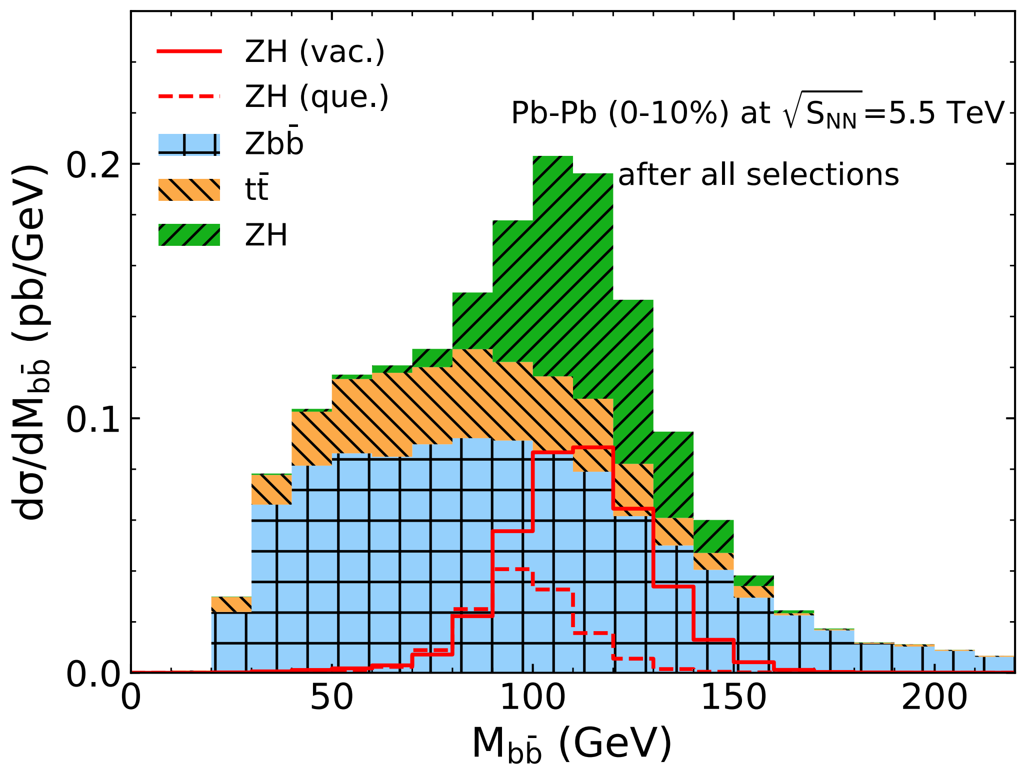
- A pair of same-flavor opposite-sign charged leptons with invariant mass $|m_{\ell\ell} - m_Z| < 10$ GeV;
- Exactly two jets, both b-tagged, with separation $\Delta R_{bb} < 2.0$;
- The transverse momentum of the reconstructed vector boson $p_T^Z \equiv p_T^{\ell\ell} > 100$ GeV.



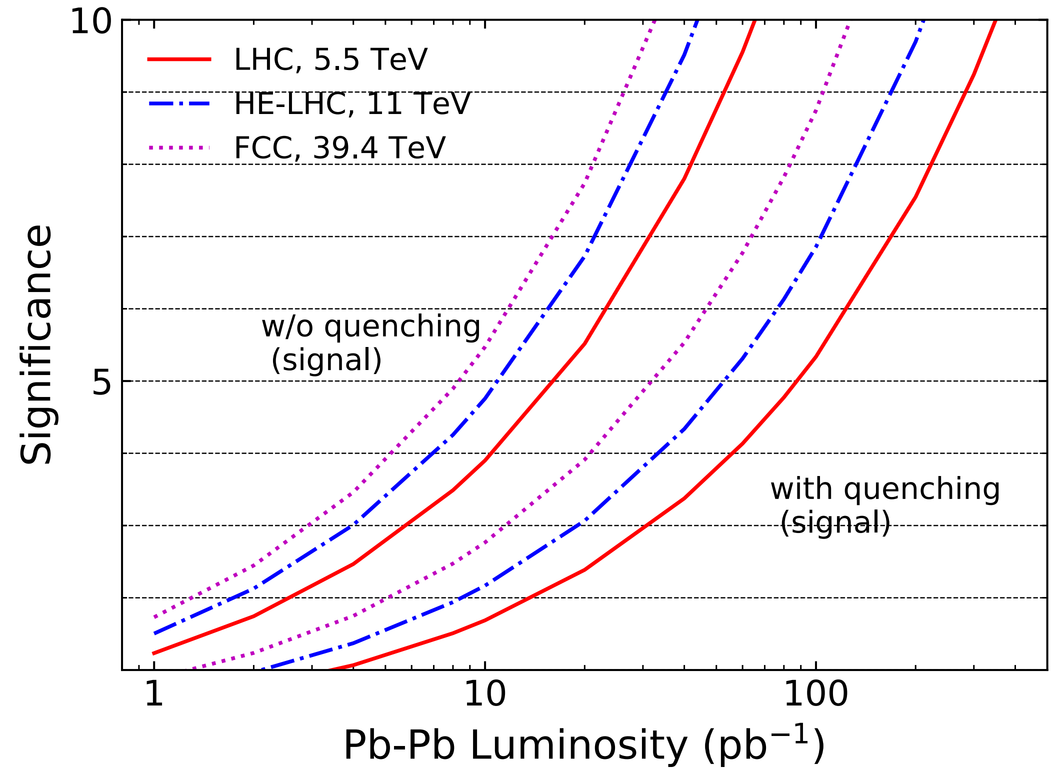
Significance

- Cuts on pT imbalance and leading-jet pT can enhance signal to BK ratio; significance based on invariant mass distribution of two b-jets

$p_T^{bb}/p_T^Z>0.75$, $p_T^{j1}>60$ GeV; with model of strong quenching



M_{bb} after all cuts

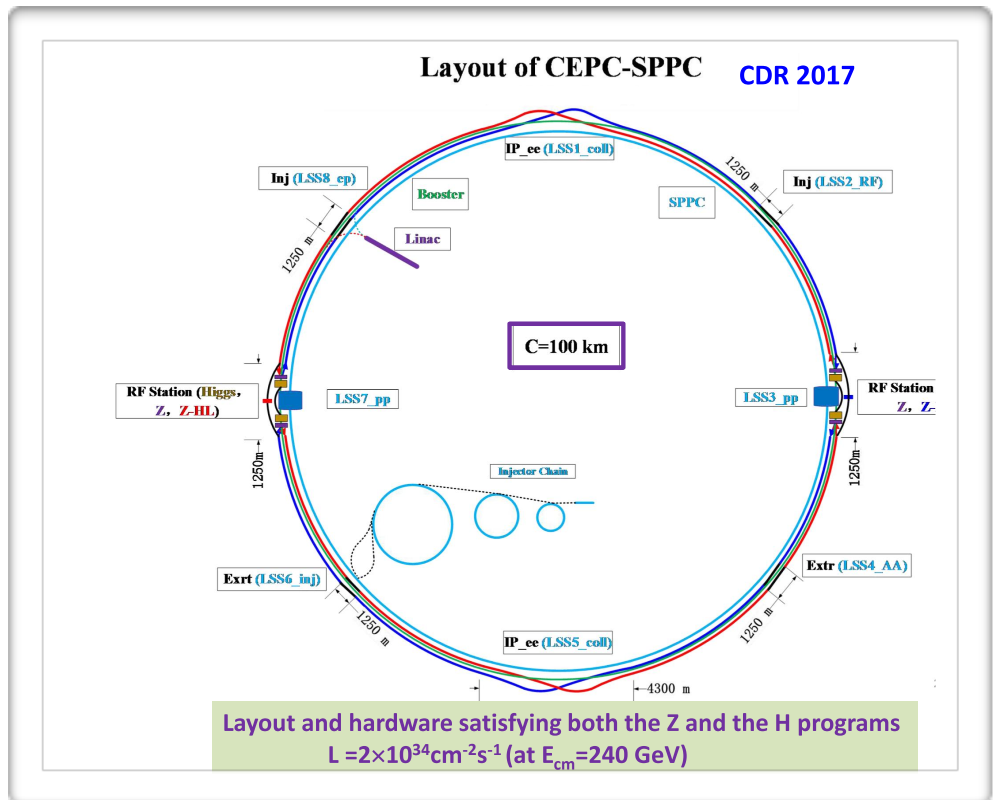


significance vs. ion lum.

lumi.(pb^{-1})	strong	medium	mild	vacuum
LHC	16(5.9)	27(9.8)	26(9.3)	48(17)
HE-LHC	11(4.0)	20(7.2)	20(7.2)	34(12)
FCC-*hh*	8.0(2.9)	14(5.0)	14(5.0)	23(8.2)

- ion luminosity needed for 5 σ discovery or 3 σ evidence
- improvement by a factor of 2 can be expected

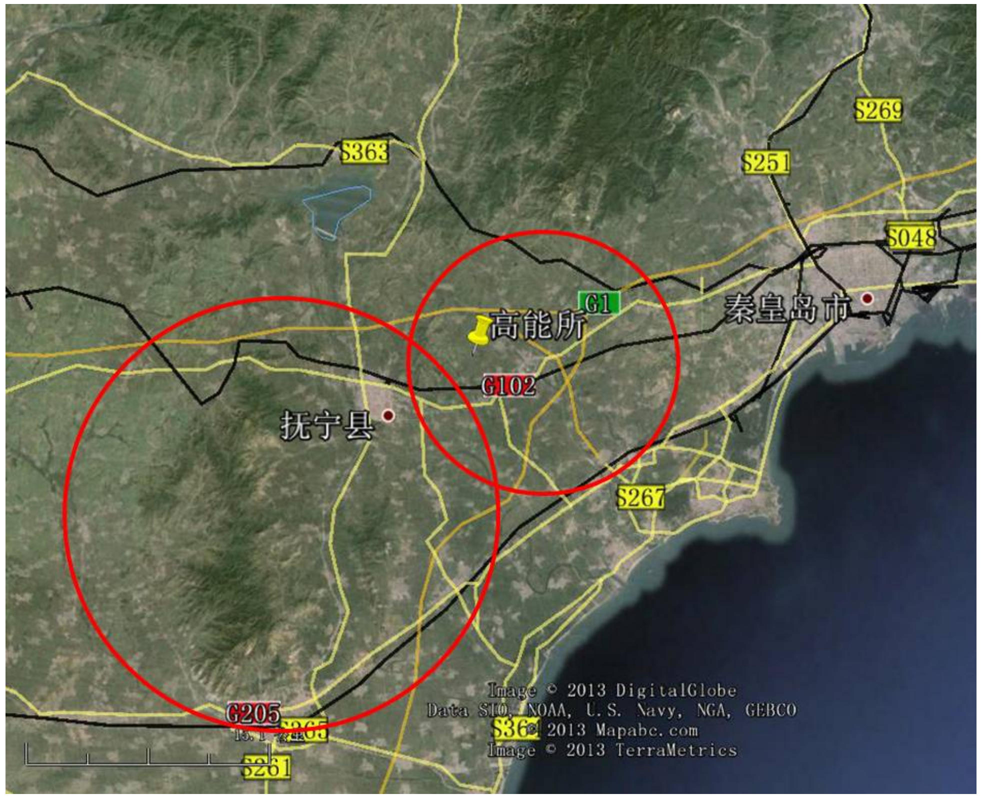
II. Light-quark Yukawa couplings from CEPC

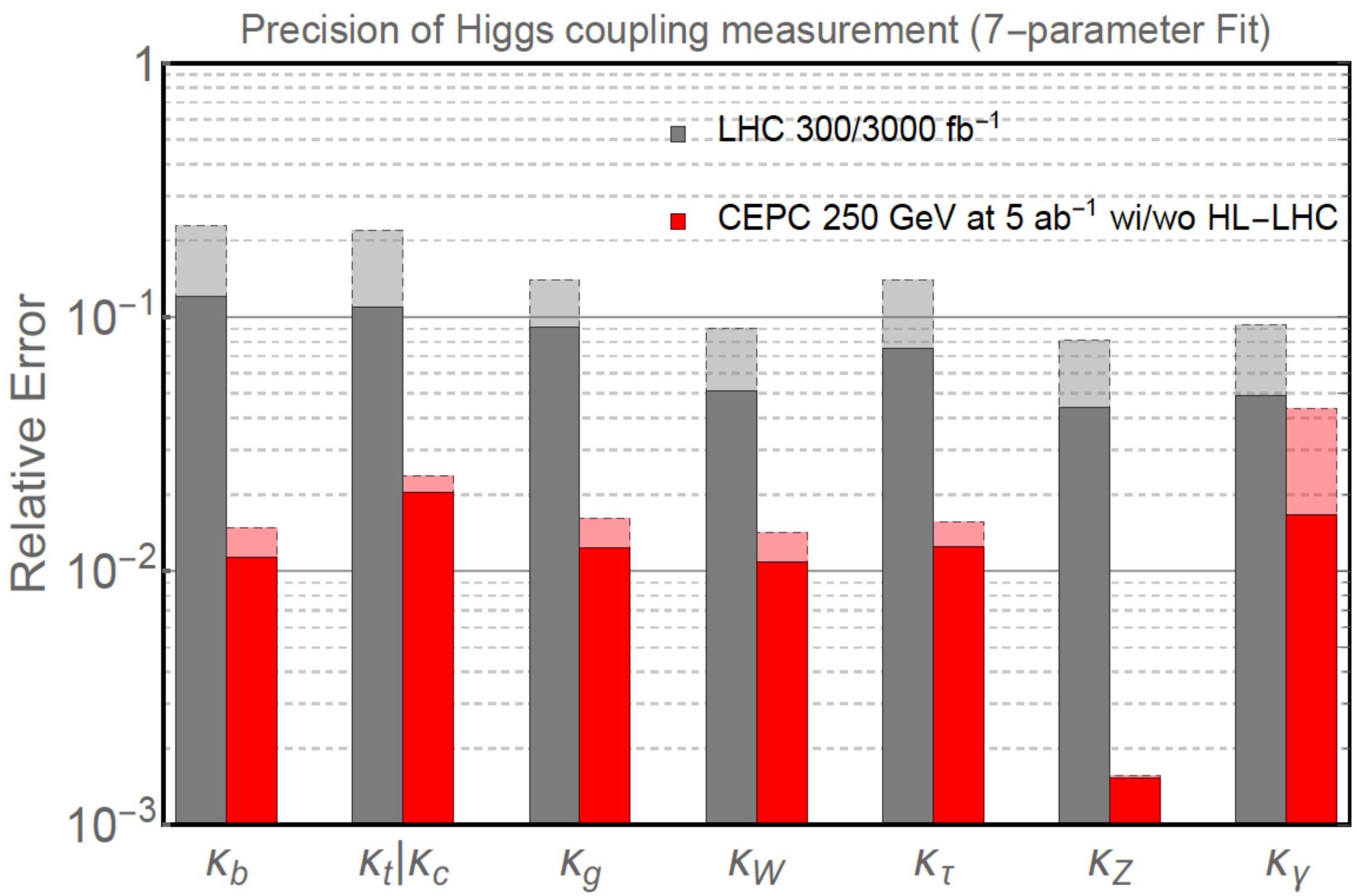


[Jun Gao, arXiv:1608.01746]

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





[Xin Chou Lou, 2017]

Higgs couplings at CEPC

- CEPC Higgs factory can provide percent-level precision on model-independent measurement of various Higgs couplings

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 $\mathrm{BR}(H \to \mathrm{inv})$ for which ΔM_H and 95% CL upper limit are quoted respectively.

ΔM_H	Γ_H	$\sigma(ZH)$	$\sigma(\nu\nu H) \times \mathrm{BR}(H \to bb)$
5.9 MeV	2.8%	0.51%	2.8%

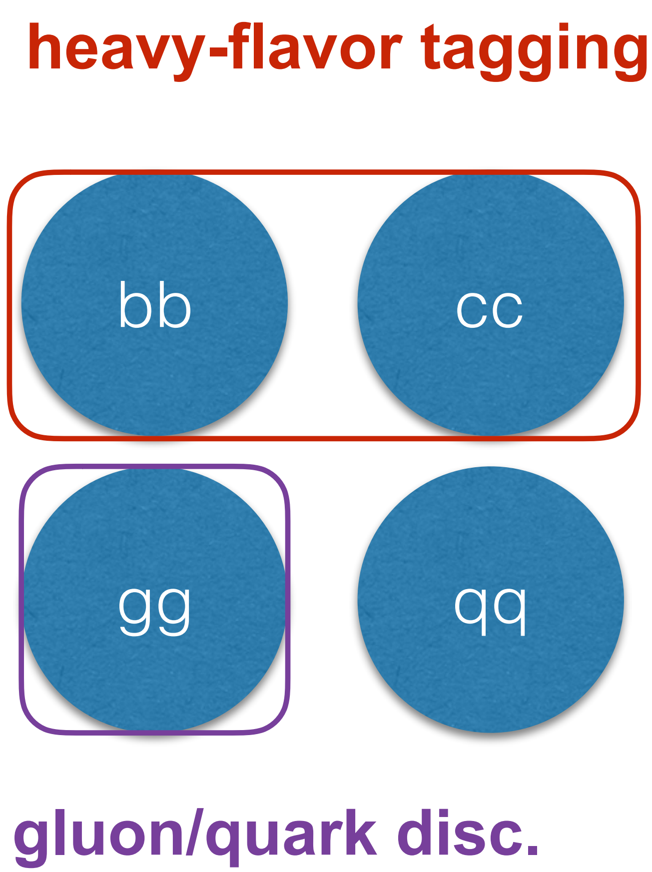
Decay mode	$\sigma(ZH) \times \mathrm{BR}$	BR
$H \to bb$	0.28%	0.57%
$H \to cc$	2.2%	2.3%
$H \to gg$	1.6%	1.7%
$H \to \tau\tau$	1.2%	1.3%
$H \to WW$	1.5%	1.6%
$H \to ZZ$	4.3%	4.3%
$H \to \gamma\gamma$	9.0%	9.0%
$H \to \mu\mu$	17%	17%
$H \to \mathrm{inv}$	–	0.28%

CEPC-SppC pre-CDR, 5 ab^{-1}

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

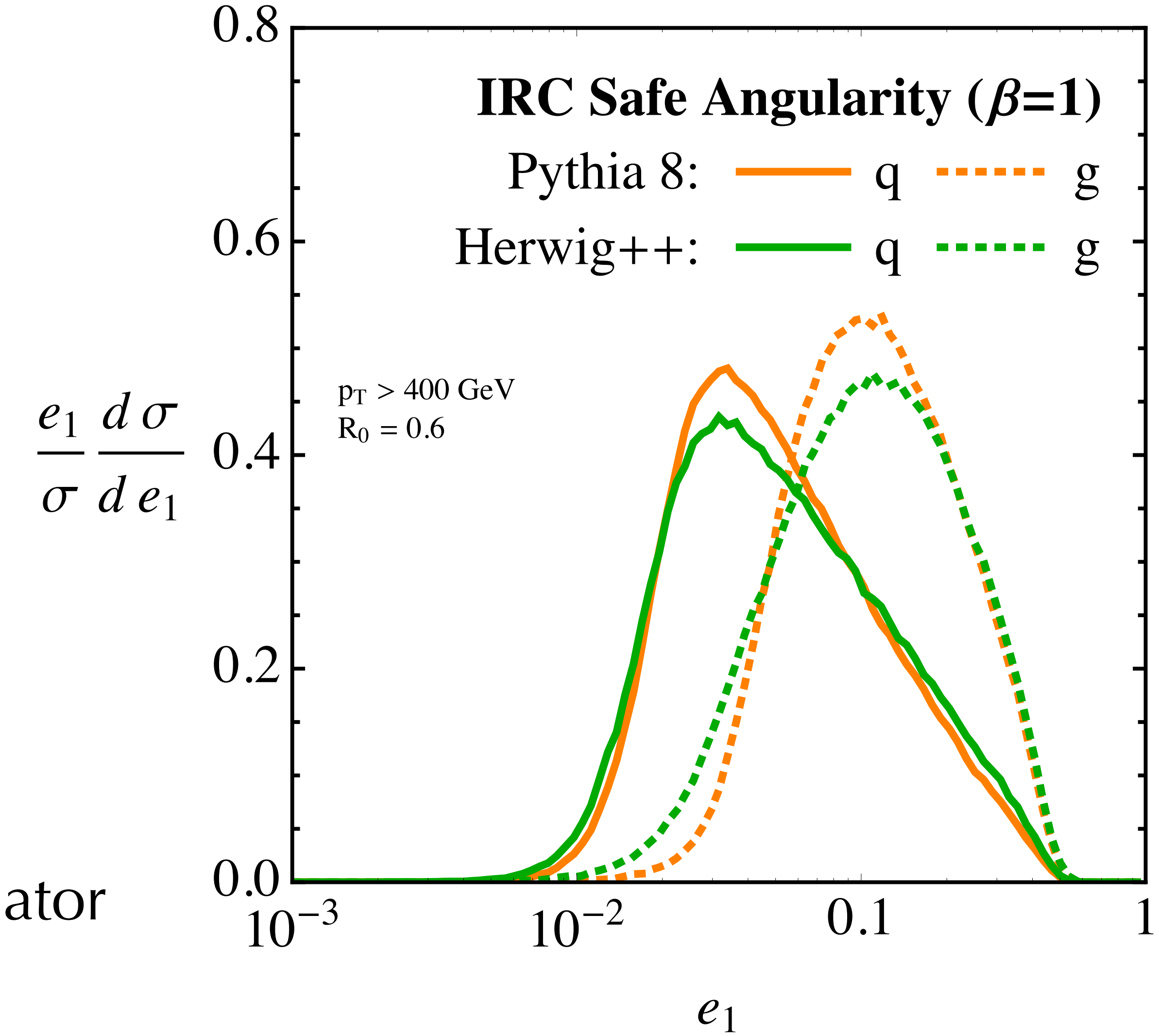
Higgs couplings at CEPC

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



- apply quark/gluon jet discriminator based on substructures, e.g., generalized angularities, net energy profile

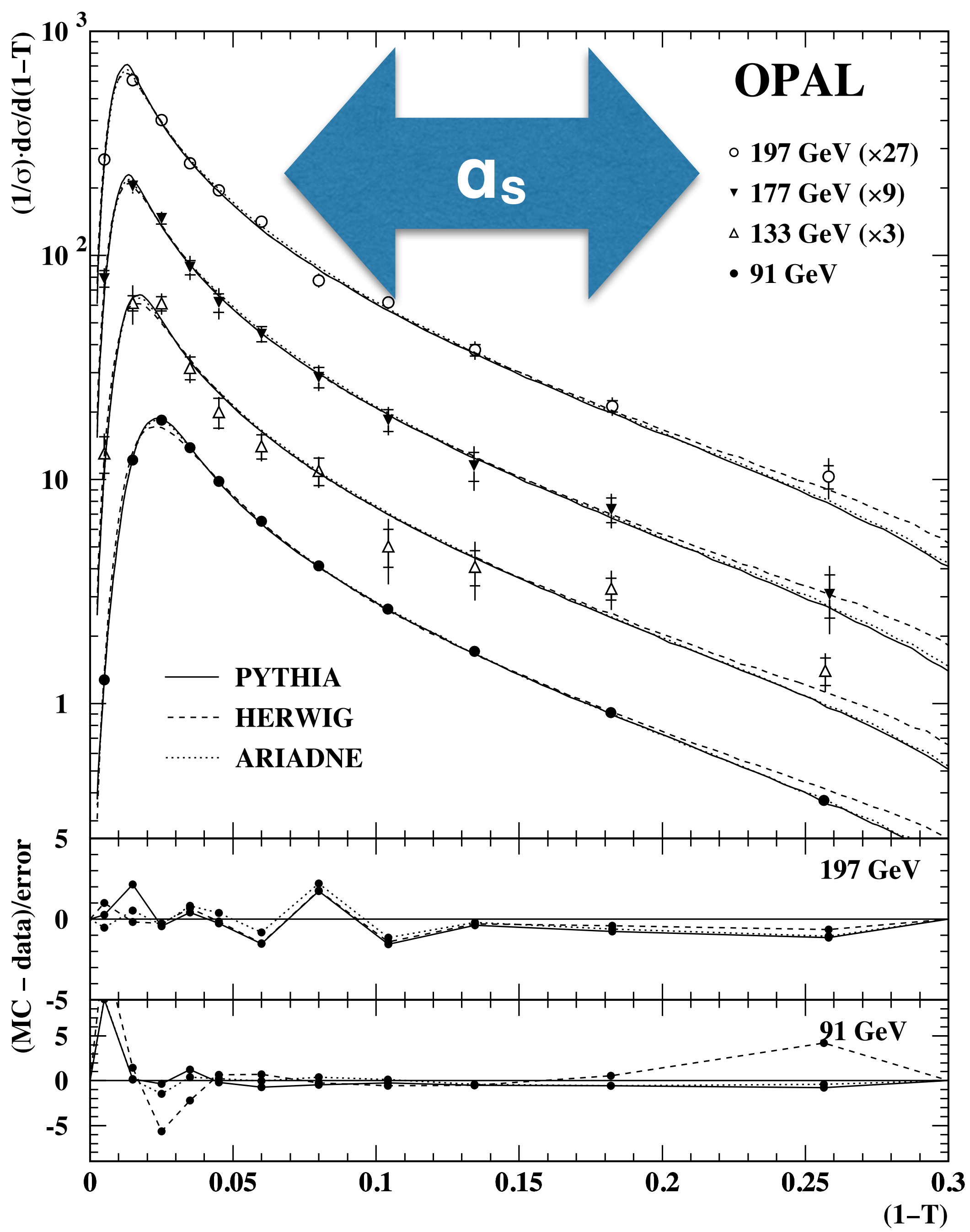
$$e_\beta \equiv \lambda_\beta^1 = \sum_{i \in \mathrm{jet}} z_i \theta_i^\beta$$



[Zhao Li +, 2011; Larkoski +, 2014]

Hadronic event shapes

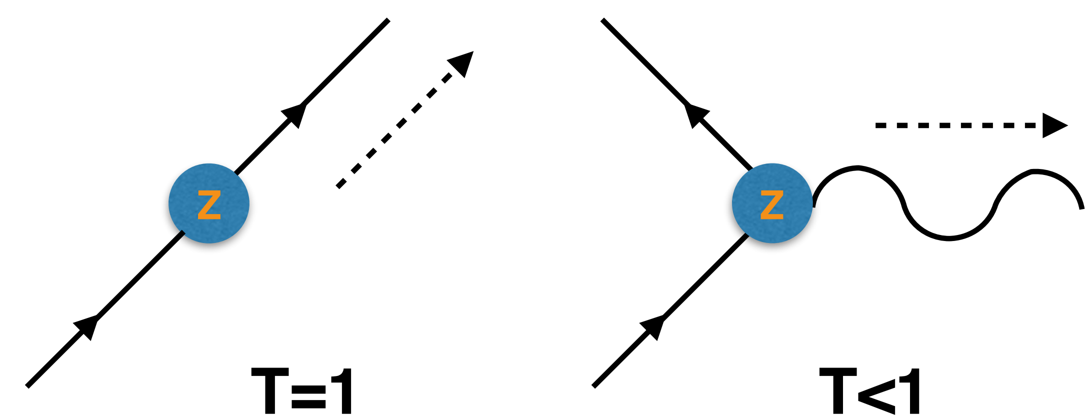
- A better way from theoretical point of view, utilizing global hadronic event shape observables; e.g., thrust (T) distribution



[OPAL, 2005]

Thrust definition:

$$T = \max_{\vec{n}} \left(\frac{\sum_i |p_i \cdot \vec{n}|}{\sum_i |p_i|} \right)$$



- 0.5<T<1, described by resummed prediction matched with fixed-order, plus additional non-perturbative corrections

sensitive to α_s

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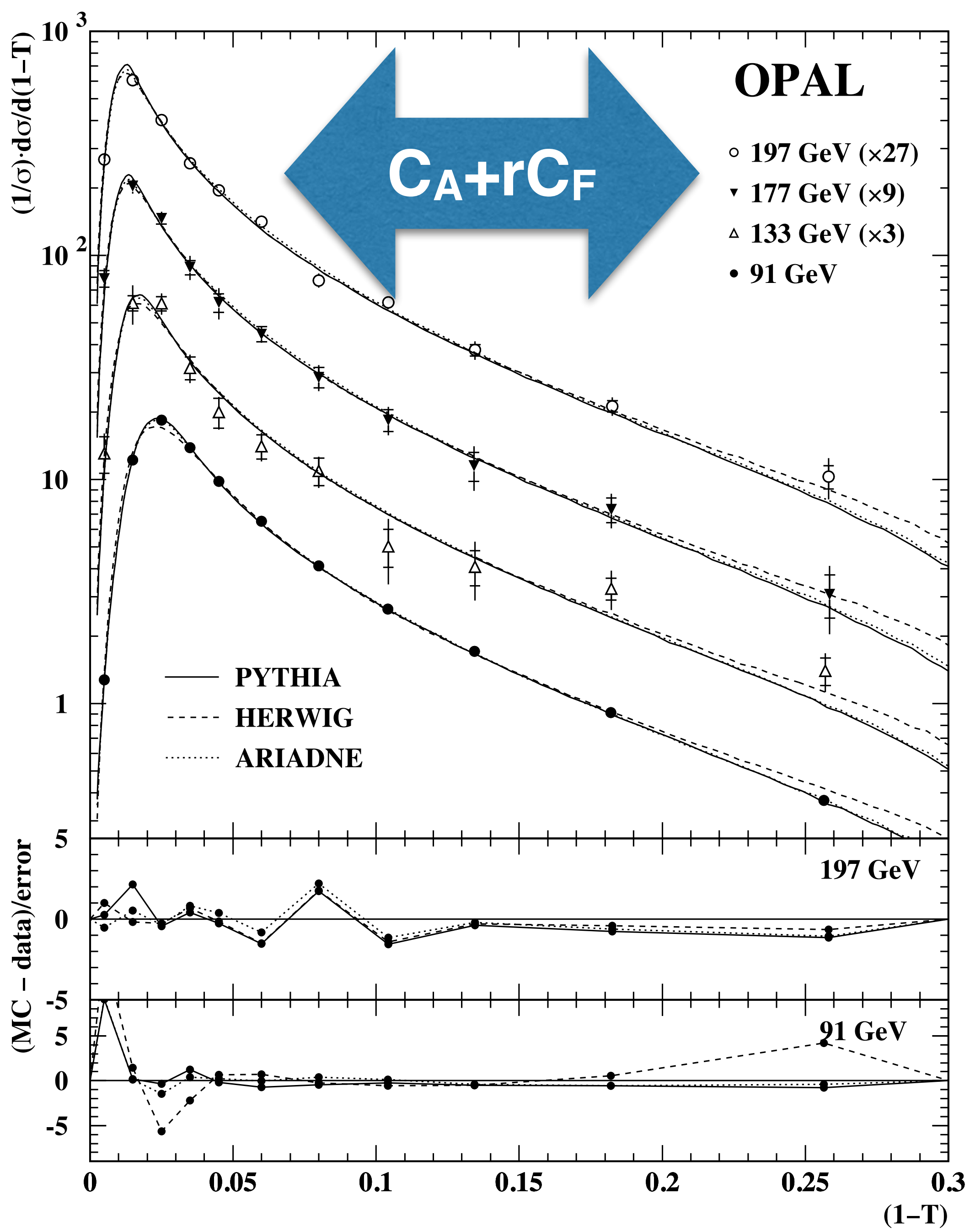
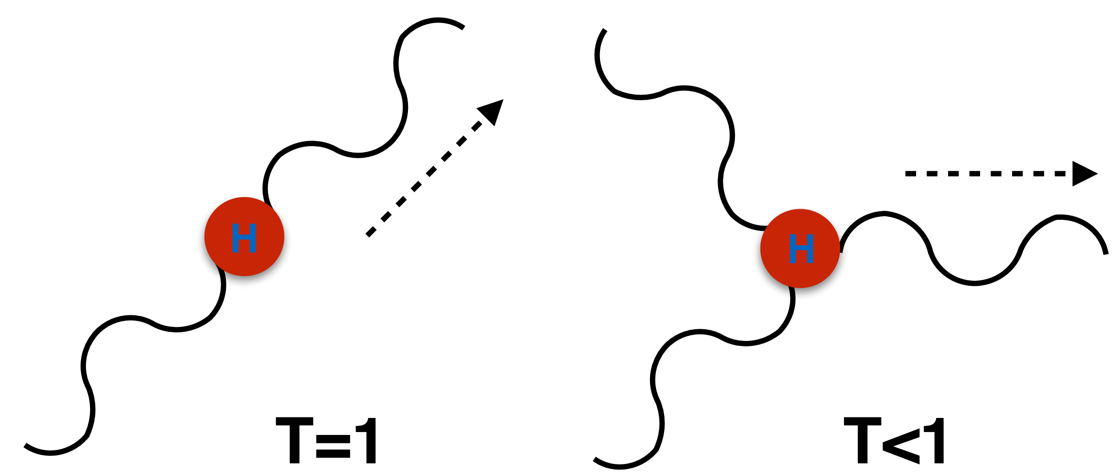
- A better way from theoretical point of view, utilizing global hadronic event shape observables; e.g., thrust (T) distribution



[OPAL, 2005]

Thrust definition:

$$T = \max_{\vec{n}} \left(\frac{\sum_i |p_i \cdot \vec{n}|}{\sum_i |p_i|} \right)$$



- 0.5<T<1, described by resummed prediction matched with fixed-order, plus additional non-perturbative corrections

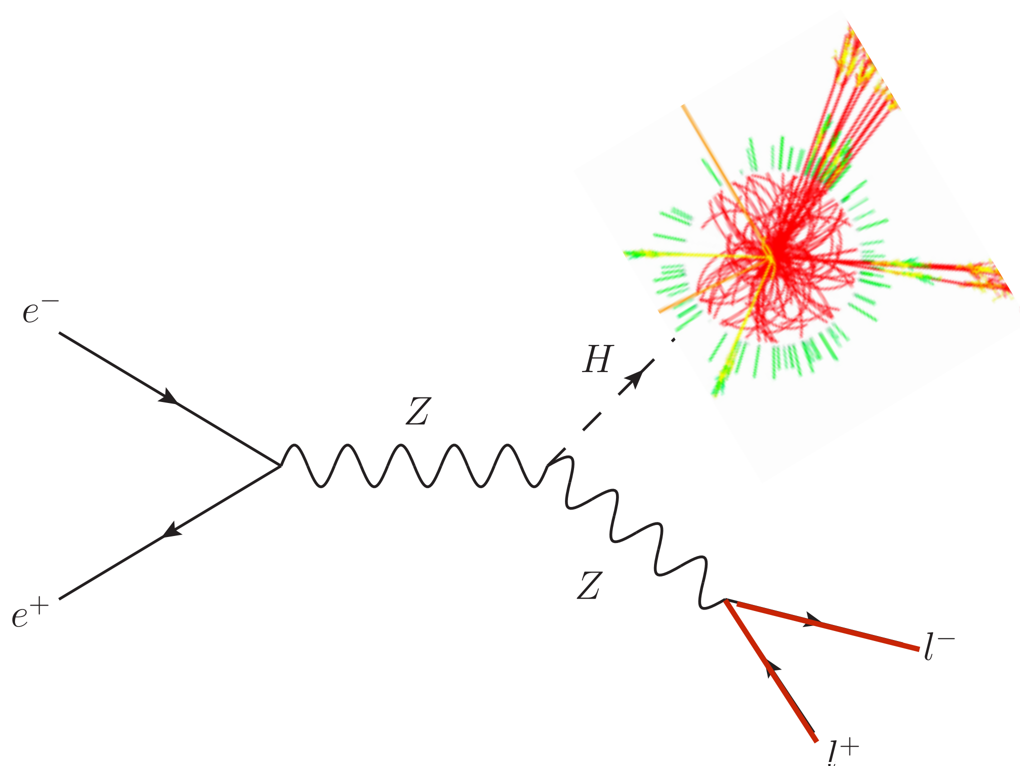
sensitive to the color factors

Hadronic final state from Higgs decay

- Events of Higgs boson hadronic decay can be selected based on the recoil mass and be fully reconstructed

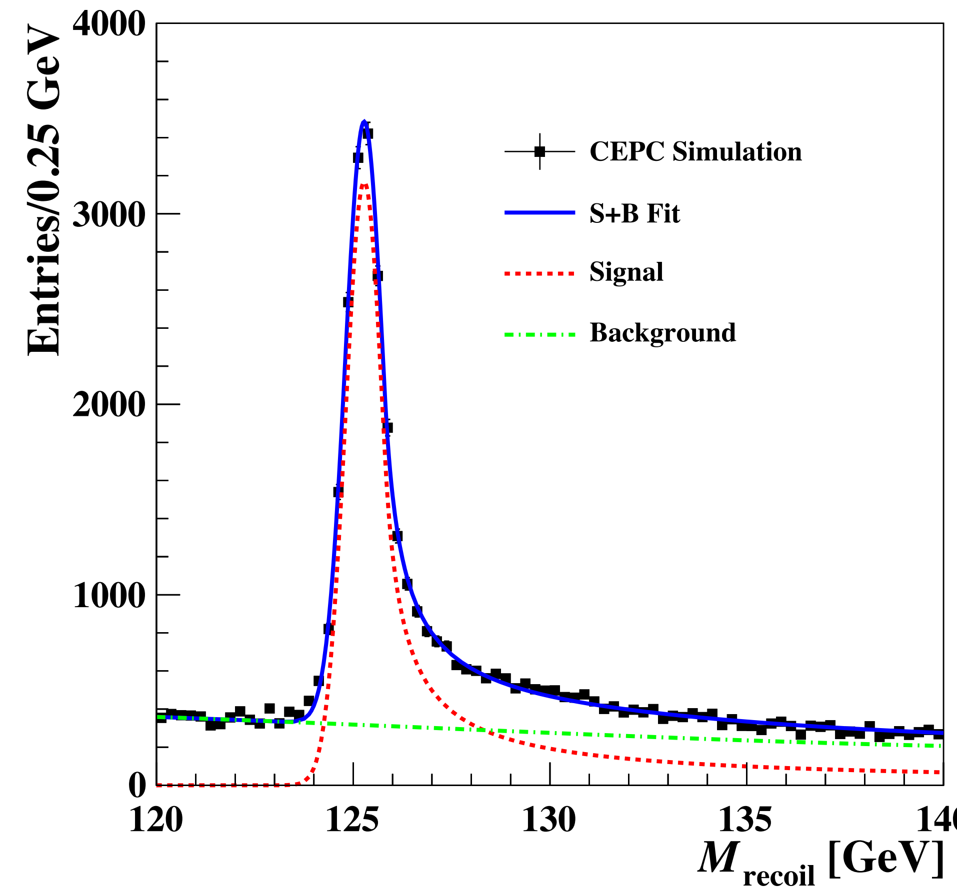
SM event numbers assuming 250 GeV, 5 ab^{-1} and Z to electron and muon

$Z(l^+l^-)H(X)$	gg	$b\bar{b}$	$c\bar{c}$	$WW^*(4h)$	$ZZ^*(4h)$	$q\bar{q}$
BR [%]	8.6	57.7	2.9	9.5	1.3	~ 0.02
N_{event}	6140	41170	2070	6780	930	14



- full kinematic information allowing measurement of event shapes in Higgs rest frame

$$m^2_{\rm recoil} = s - 2E_{f\bar{f}}\sqrt{s} + m^2_{f\bar{f}}$$

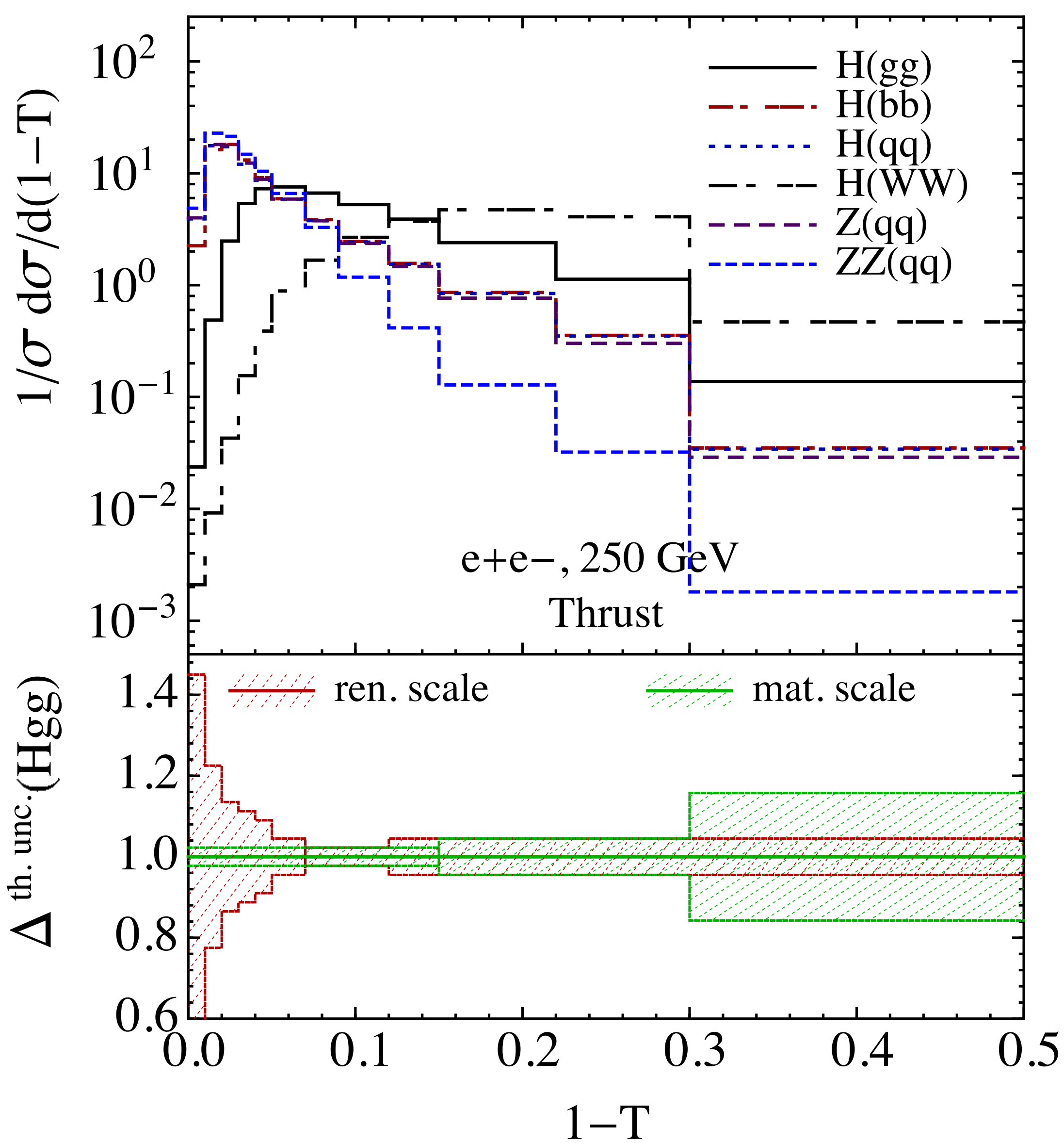


[Zhen-Xing Chen +, 2016]

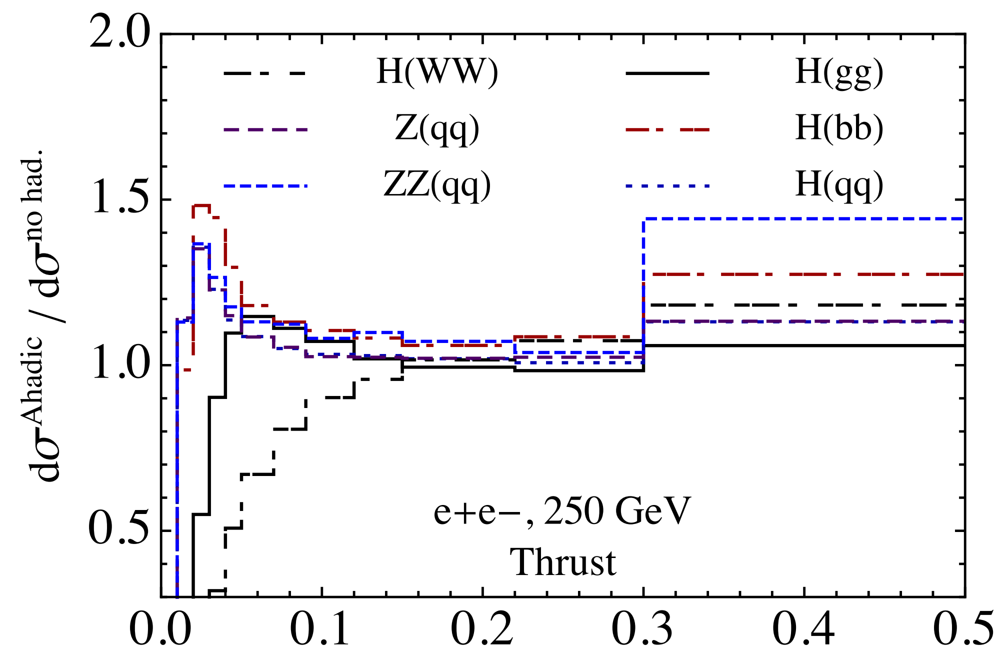
Thrust distribution

- Color-singlet di-gluon and di-quark initiated distributions show an approximate Casimir scaling on the peak position, $C_A/C_F=9/4$

normalized shapes of the thrust distribution (PS+3 j LO)



hadronization corrections



[JG, 1608.01746]

- parton level + hadronization corrections; theoretical uncertainties from both sides

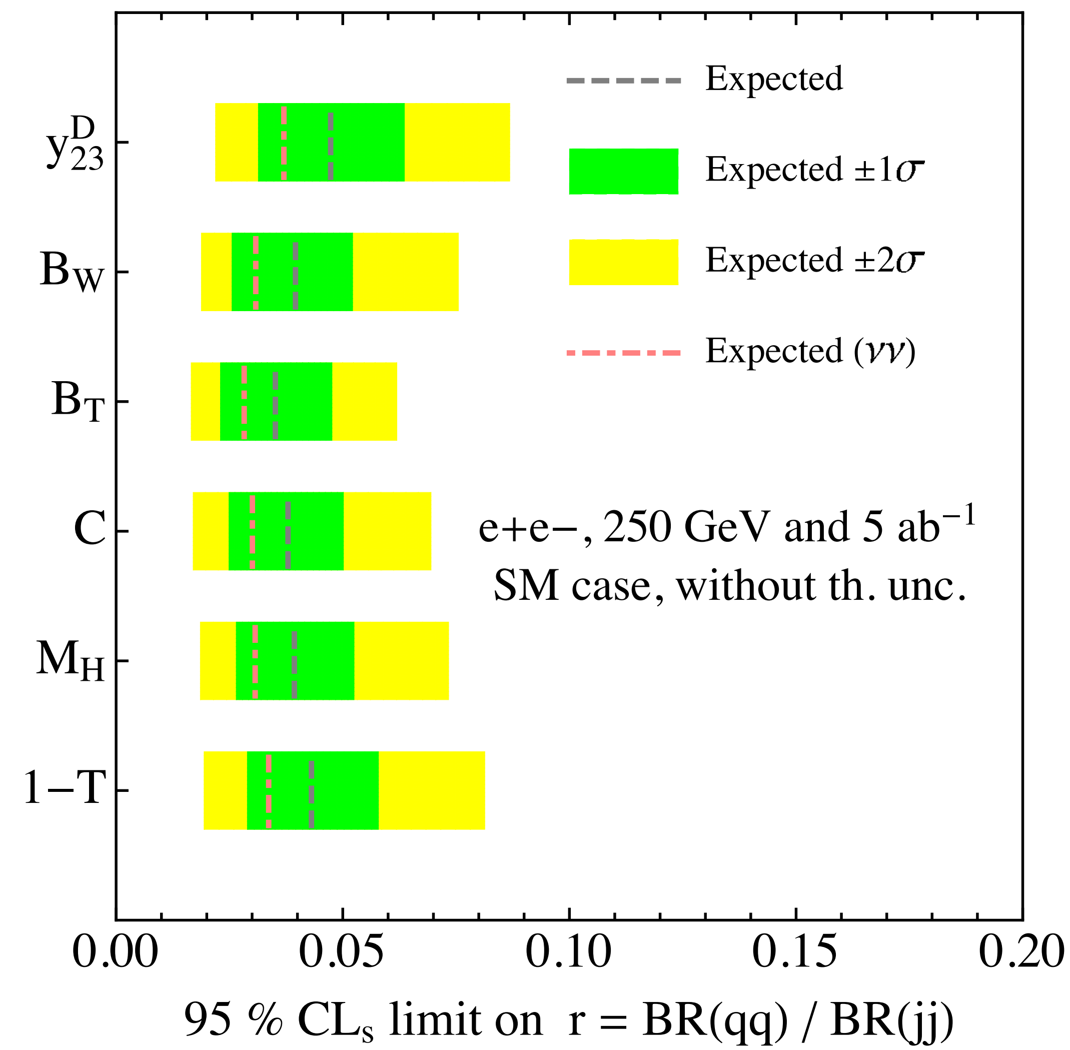
Extraction of Yukawa Couplings

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

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

expected exclusion limit

	no sys.	+pert.	+nor.	+had.
limit on r	0.036	0.040	0.045	0.056
limit on r (lumi.$\times 10^3$)	0.0012	0.0014	0.018	0.019



from various event shapes

- ☆ an exclusion limit on r of 0.06, corresponds to a decay BR(qq) of 0.5% to any of u/d/s, a Yukawa coupling of 9% of SM y_b, or 4 times of SM y_s

comparison with LHC

- ☆ best projected HL-LHC limit from exotic decay on s quark is 20 times of SM y_b, from kinematic distribution on u/d is ~30%

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

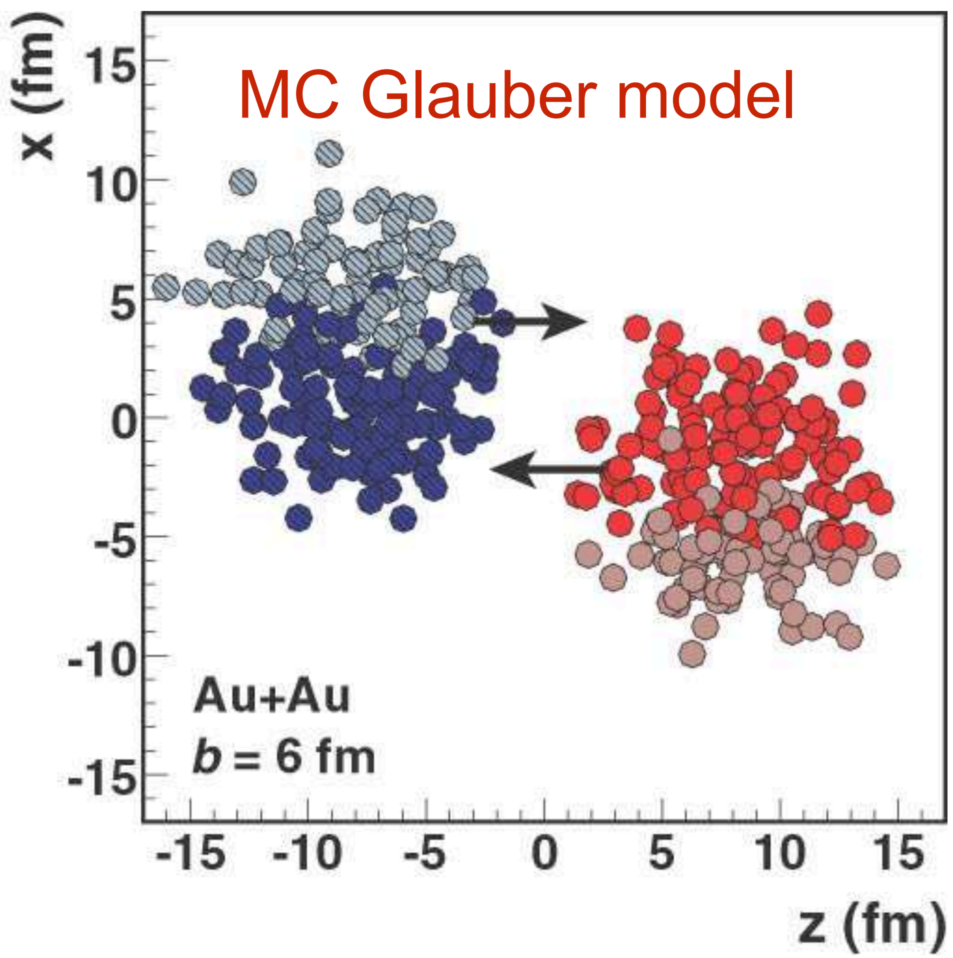
Thank you for your attention!

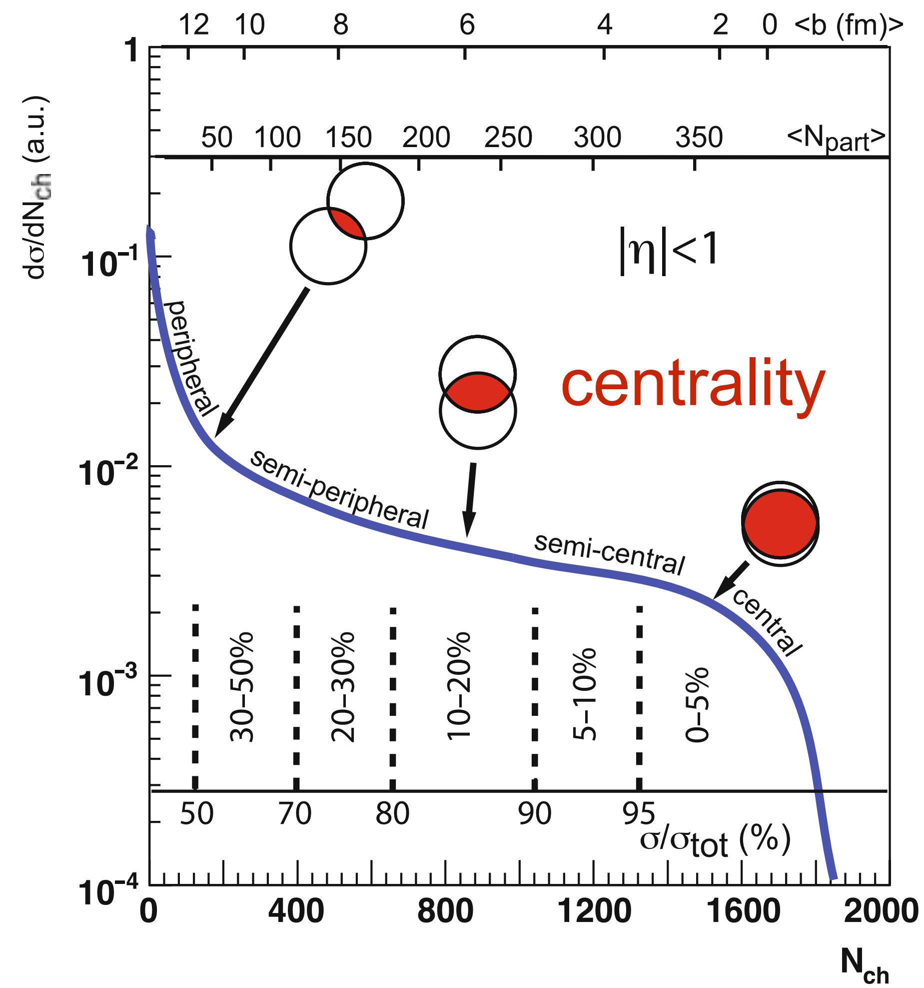
Heavy-ion collisions [backups]

- Some basics: collision energy, Glauber model, centrality class, factorization on cross sections

nucleon-nucleon center of mass energy $S_{NN}^{1/2}$=Z/A*$S_{pp}^{1/2}$

for PbPb, LHC 5.5 TeV, HE-LHC 11 TeV, FCC-hh 39.4 TeV





factorization **[Connors+, 2017]**

$$\sigma_{AA\to X} = \boxed{A^2 c(f)} \sum_{a,b} \int \mathrm{d}x_a \mathrm{d}x_b\, f_{a/A}(x_a, \mu_F^2) f_{b/A}(x_b, \mu_F^2) \hat{\sigma}_{ab\to X}(x_a x_b S_{NN})$$

centrality factor ~0.42 for PbPb at 0-10%

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)

semi-leptonic channel of tT

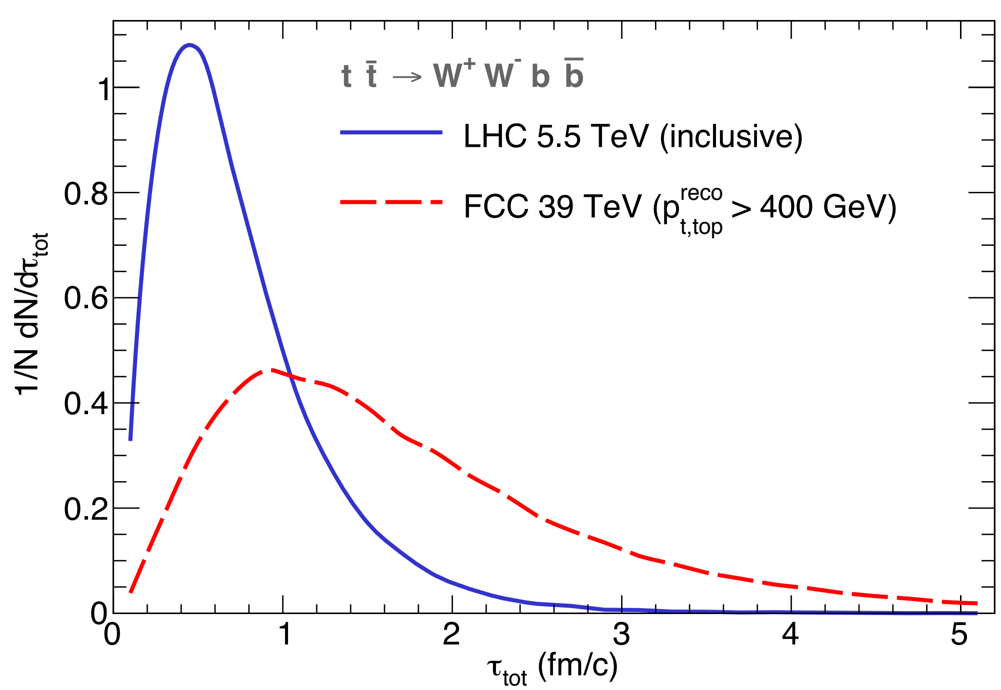
average initial time

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

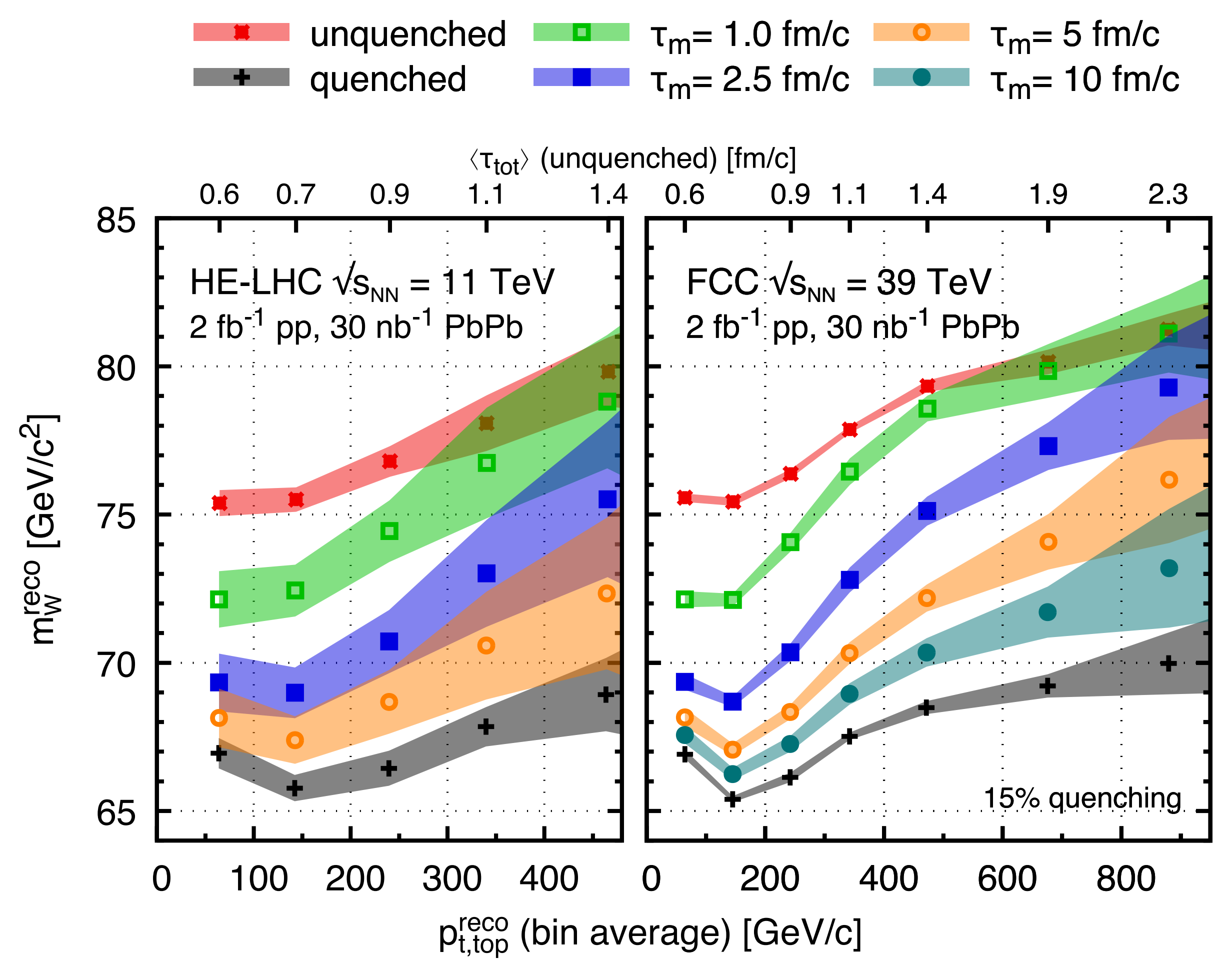
$$\langle \tau_{\rm tot} \rangle (p_{t,{\rm top}}^{\rm reco}) \simeq (0.37 + 0.0022\, p_{t,{\rm top}}^{\rm reco}/{\rm GeV})\ {\rm fm}/c$$

quenching-factor

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



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

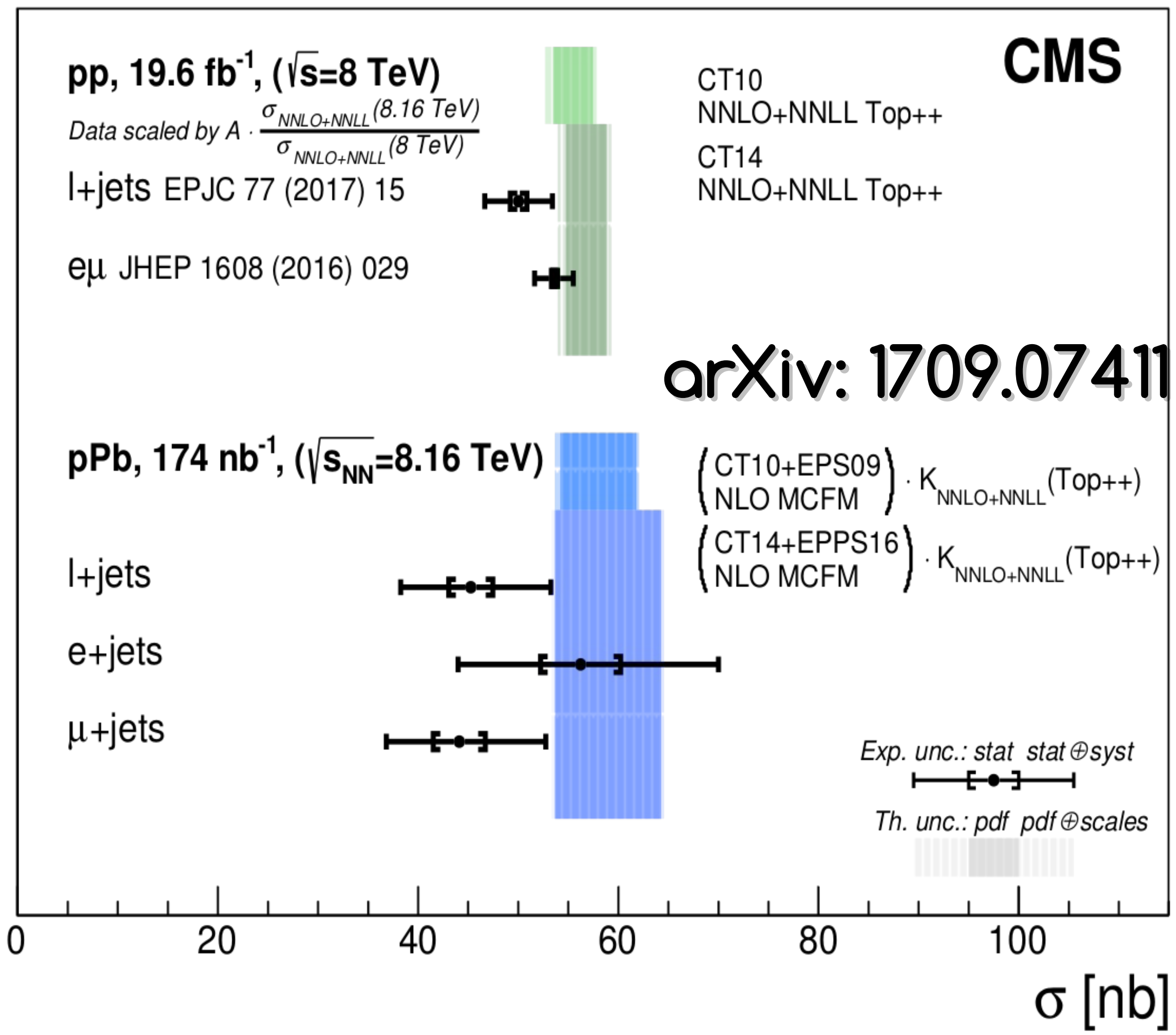


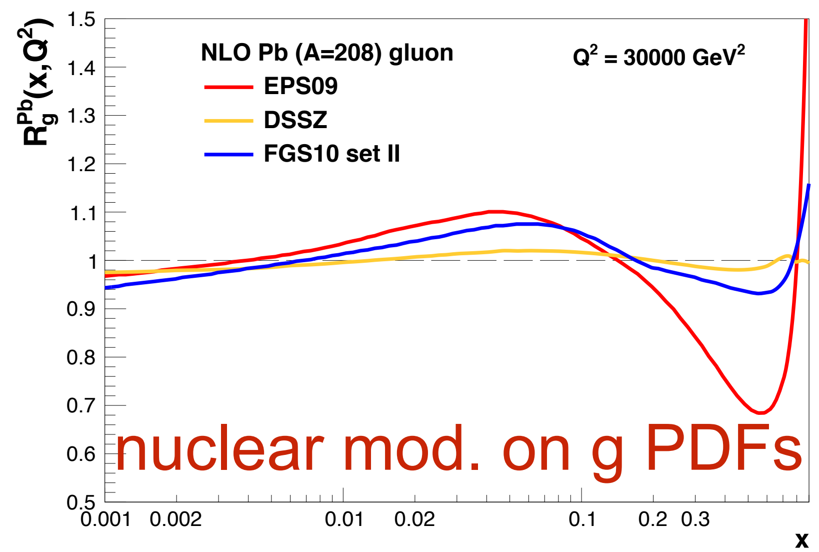
[Apolinario+, 2017]

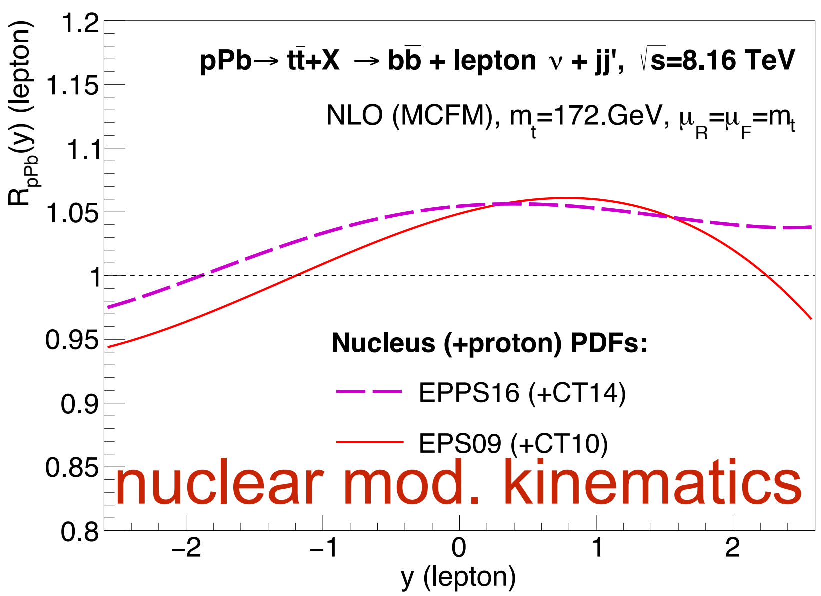
Hard probes: top quark production [backups]

- Top-quark as a hard probe in heavy-ion collisions (pA collision) for cold nuclear effects (CNM)

total inclusive corse sections





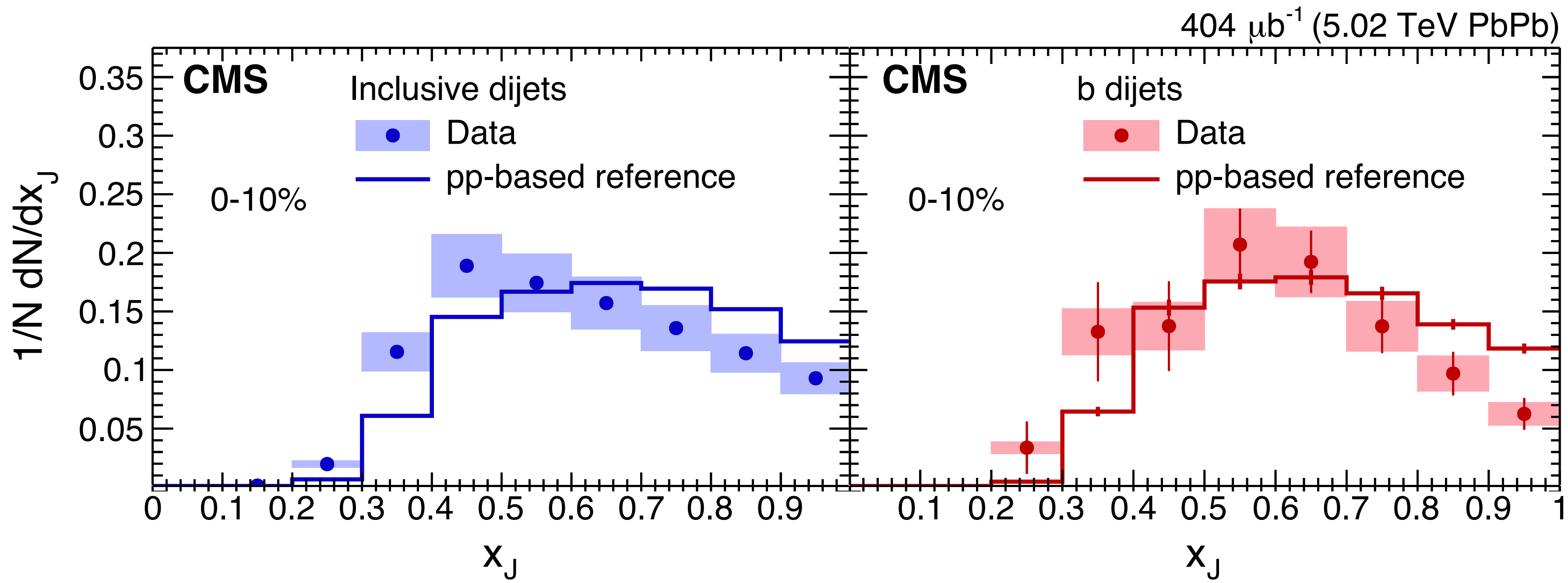


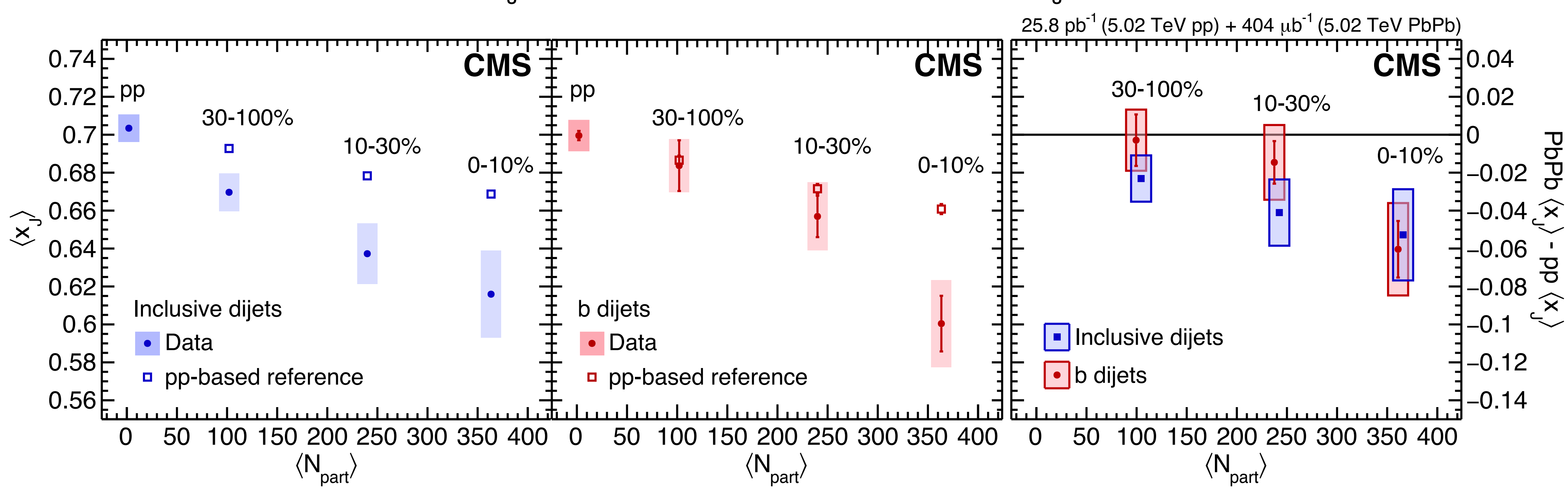
- ☆ unique probe of nuclear modifications to gluon parton distributions

Hard probes: inclusive dijets [backups]

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

ratio of p_T of sub-leading to leading jet **[arXiv:1802.00707]**

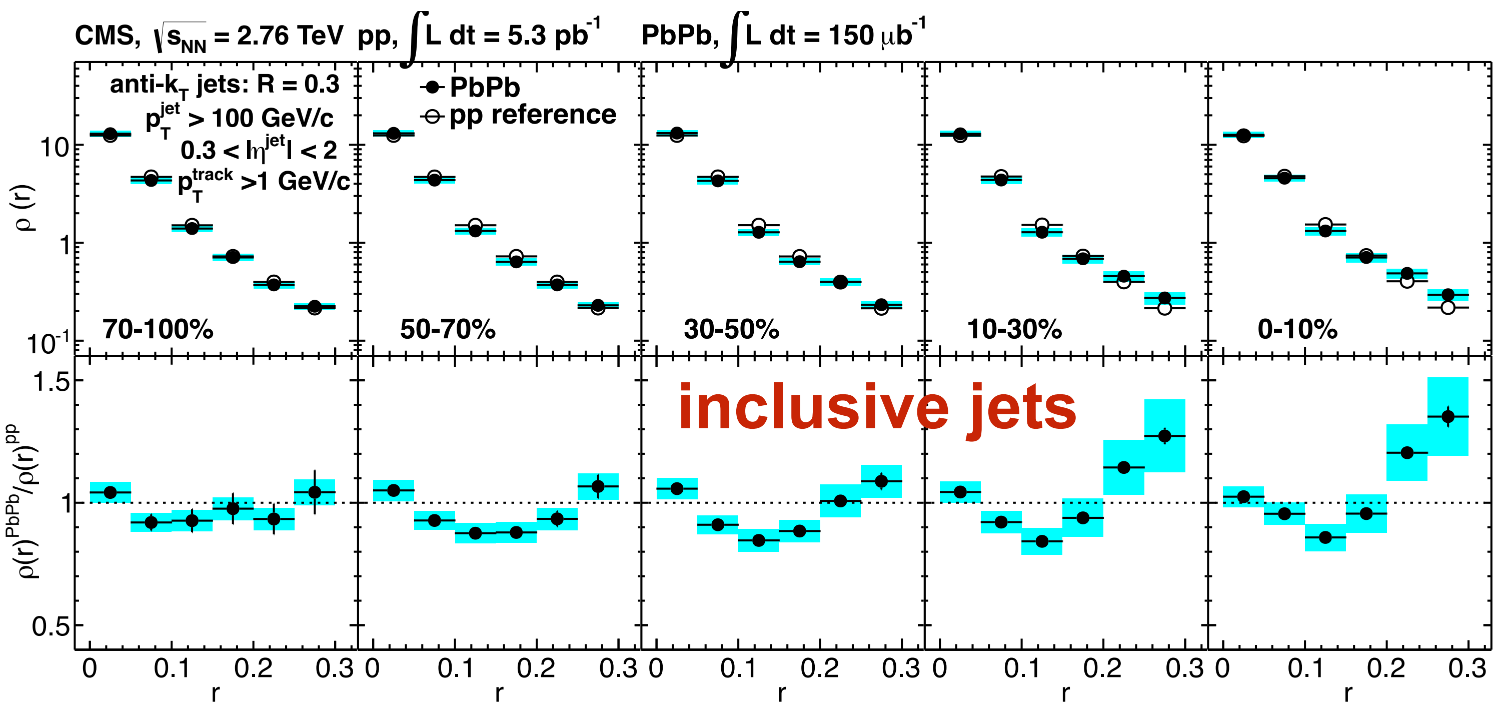




Experimentally similar level of quenching for inclusive jet and b-jet

Outlook [backups]

- Further gains on S/B ratio can be achieved through e.g., multivariate analysis (MVA) or discriminations in jet shapes

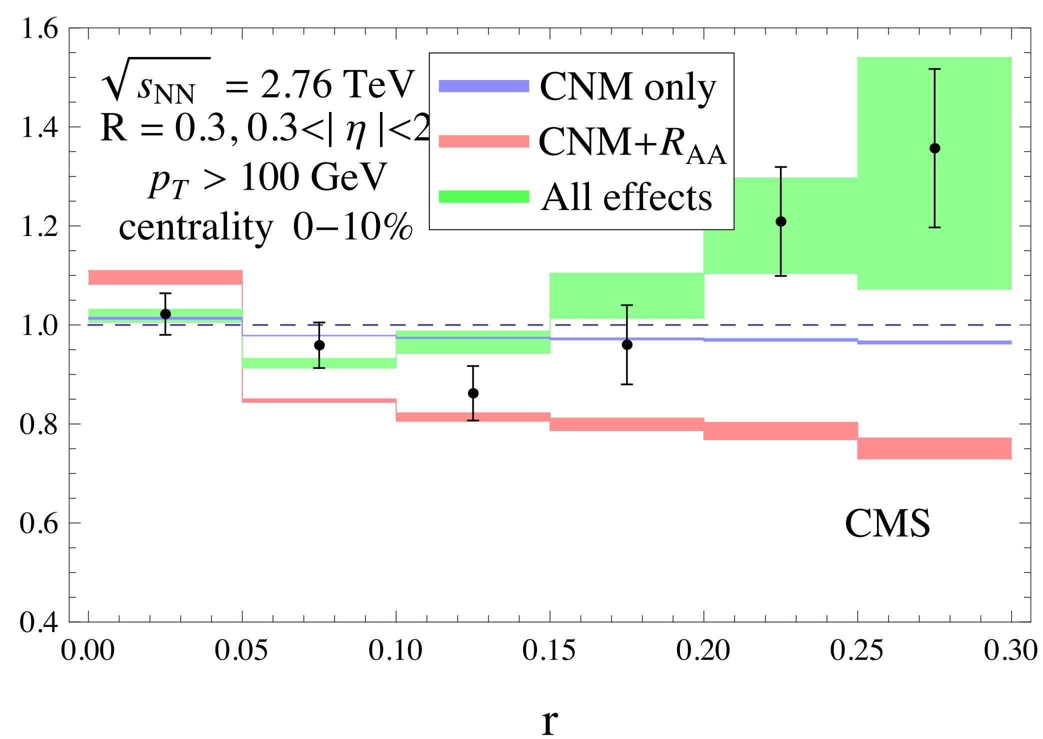


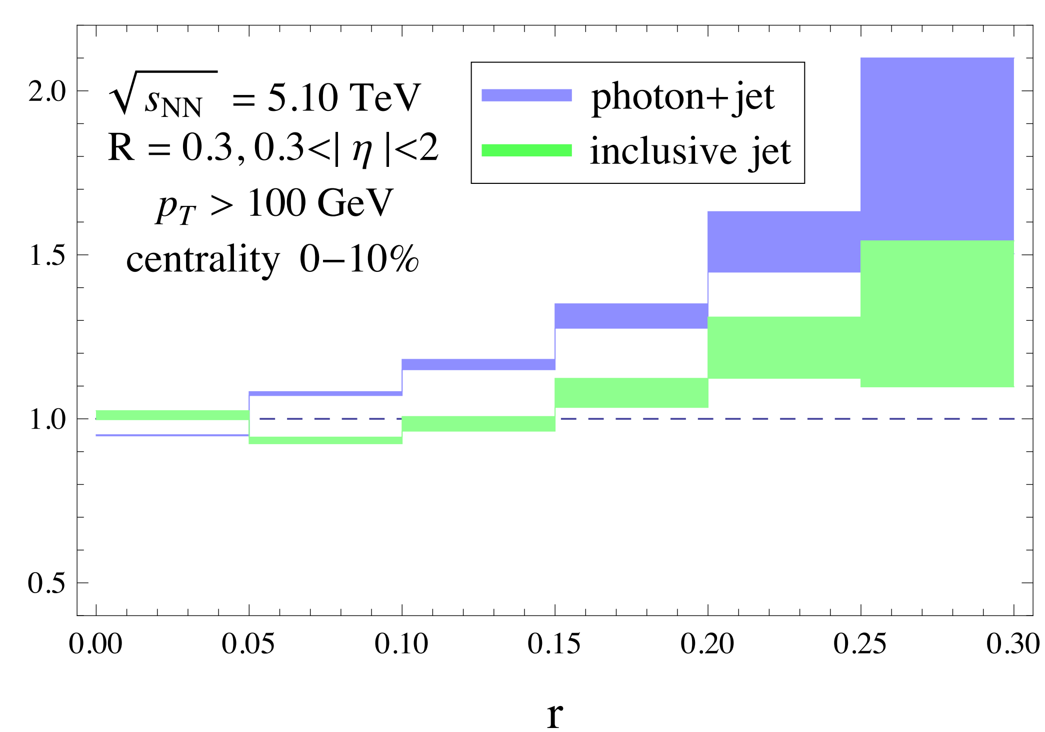
differential jet shape

$$\Psi_J(r) = \frac{\sum_{i,\ d_{i\hat{n}}<r} E_T^i}{\sum_{i,\ d_{i\hat{n}}<R} E_T^i}$$

$$\rho(r) = \frac{d}{dr}\Psi(r)$$

[Chien, Vitev, 2016]

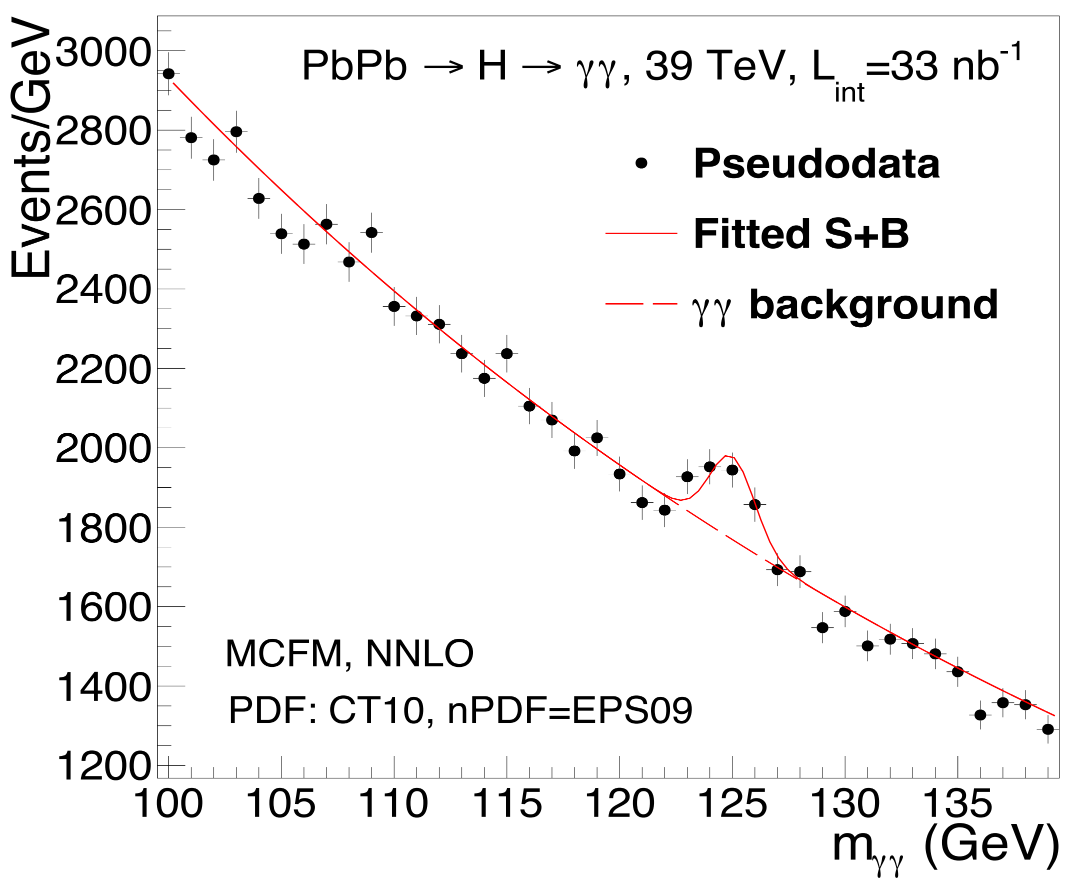




Higgs as probe of QGP [backups]

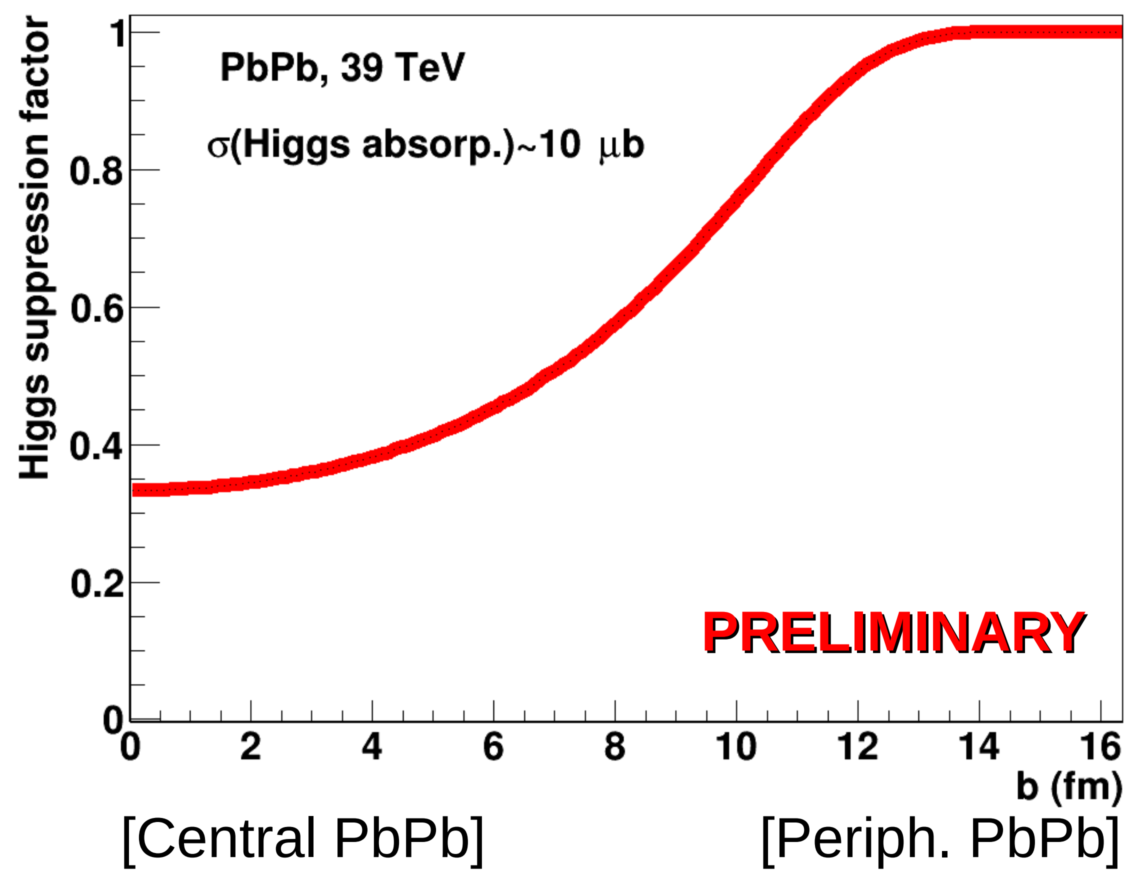
- There are also interesting studies from a different perspective, namely using Higgs boson as a probe of QGP instead

discovery in nominal channels



[d'Enterria, 2017]

Higgs absorption in QGP



[d'Enterria, Loizides, in preparation]

- using precision Higgs cross section calculation and measurement to extract the possible suppression factor

Extraction of Yukawa Couplings [backups]

- Projected sensitivity on light-quark Yukawa couplings is obtained using pseudo-data

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

  - r, defined as BR(qq)/BR(jj), j=g+q
  - N_S, total signal events of ZH(jj), assuming an efficiency of 50%
  - N_{B1}, BKs from ZH(bb,cc), ~10% of N_S(SM) using heavy-flavor tagging
  - N_{B2}, BKs from ZZ(qq), ~20% of N_S(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)
  - various normalized shapes can be obtained either from theoretical calculation or using data-driven in a controlled region

Extraction of Yukawa Couplings **[backups]**

- Projected sensitivity on light-quark Yukawa couplings is obtained using pseudo-data

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

- N_S can be measured independently to ~3% via hadronic Z decays (pre-CDR)
- systematics on N_{B1},N_{B2},N_{B3} estimated to be 4%
- systematics due to scale variations of f(gg) and hadronizations of all shapes are included
- expected exclusion limit on r are obtained via pseudo-data and using profiled log-likelihood ratio with the CL_S method

expected exclusion limit