

Precision predictions for Higgs productions at the LHC

贵州民族大学

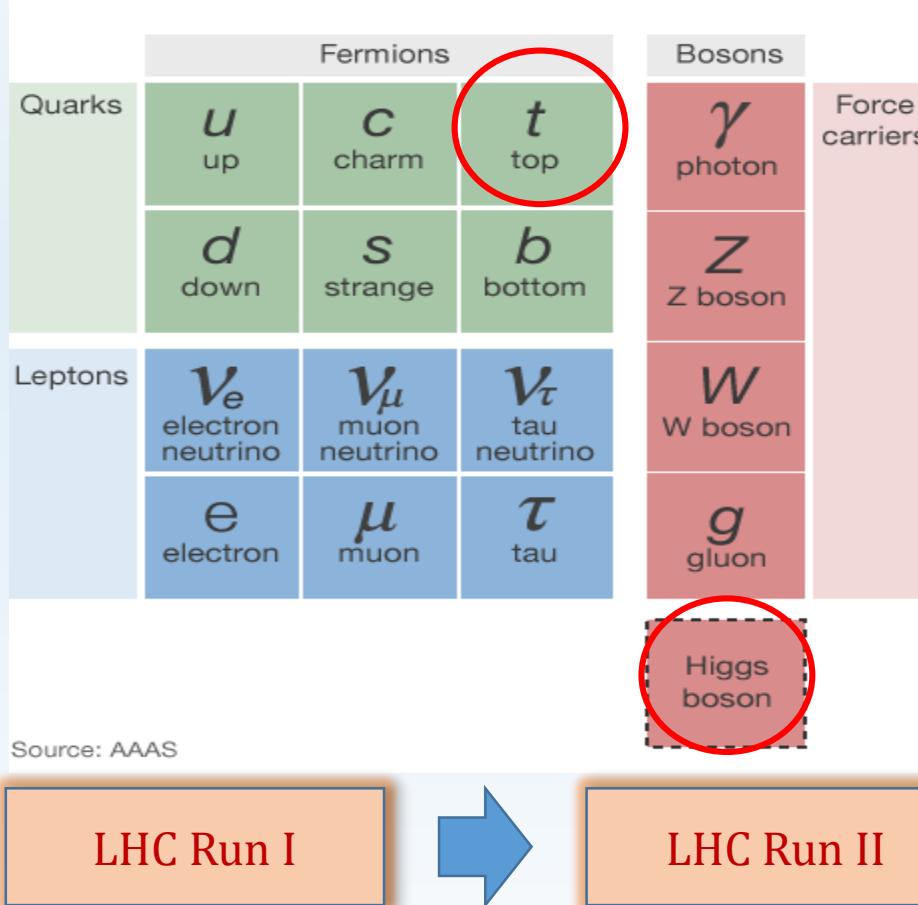
王声权

2016.12.18 北京

Outline

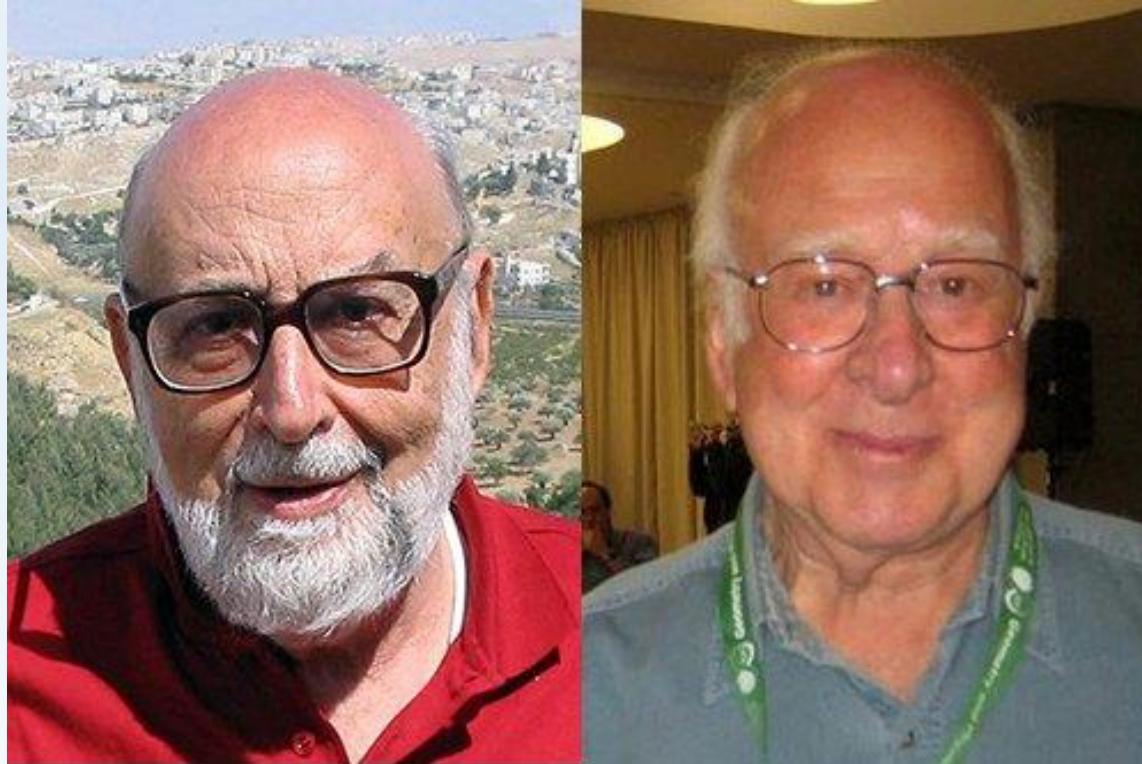
- Introduction
- Principle of Maximum Conformality(PMC)
- Higgs physics
 - Higgs production
 - $H \rightarrow \gamma\gamma$
 - $H \rightarrow b\bar{b} | bar$
 - $H \rightarrow gg$
- Summary

Introduction



A new era of precision studies of Higgs phenomenology

Introduction



Englert

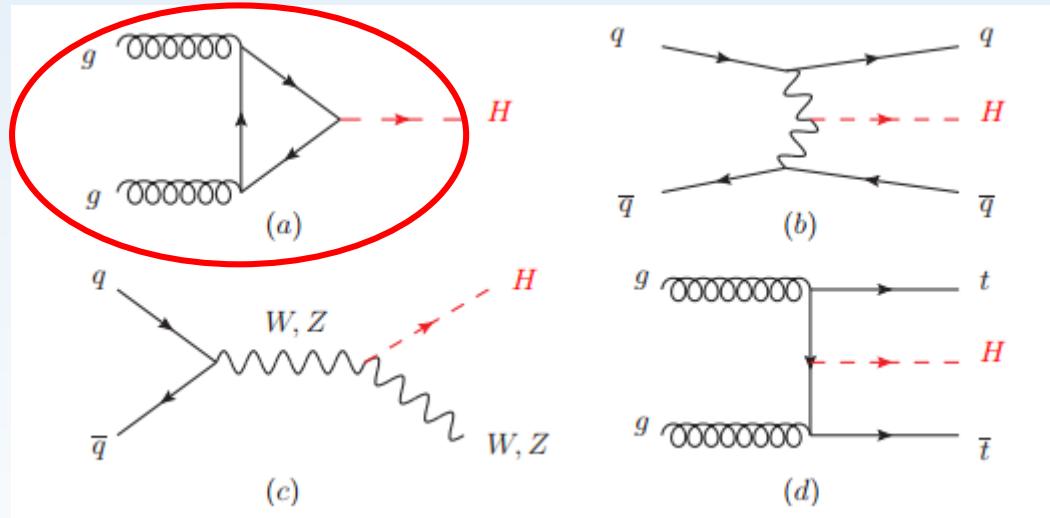
Nobel prize
2013

Higgs

Introduction

~87%

\sqrt{s} (TeV)	Production cross section (in pb) for $m_H = 125$ GeV					
	ggF	VBF	WH	ZH	$t\bar{t}H$	total
1.96	$0.95^{+17\%}_{-17\%}$	$0.065^{+8\%}_{-7\%}$	$0.13^{+8\%}_{-8\%}$	$0.079^{+8\%}_{-8\%}$	$0.004^{+10\%}_{-10\%}$	1.23
7	$15.1^{+15\%}_{-15\%}$	$1.22^{+3\%}_{-2\%}$	$0.58^{+4\%}_{-4\%}$	$0.33^{+6\%}_{-6\%}$	$0.09^{+12\%}_{-18\%}$	17.4
8	$19.3^{+15\%}_{-15\%}$	$1.58^{+3\%}_{-2\%}$	$0.70^{+4\%}_{-5\%}$	$0.41^{+6\%}_{-6\%}$	$0.13^{+12\%}_{-18\%}$	22.1
14	$49.8^{+20\%}_{-15\%}$	$4.18^{+3\%}_{-3\%}$	$1.50^{+4\%}_{-4\%}$	$0.88^{+6\%}_{-5\%}$	$0.61^{+15\%}_{-28\%}$	57.0

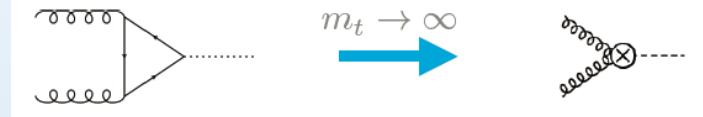


Chin.Phys.C38, 090001 (2014).

Introduction

◆ NLO is now standard, thanks to automated tools

◆ NNLO



R. V. Harlander and W. B. Kilgore, “Next-to-next-to-leading order Higgs production at hadron colliders,” Phys. Rev. Lett. **88**, 201801 (2002).

C. Anastasiou and K. Melnikov, “Higgs boson production at hadron colliders in NNLO QCD,” Nucl. Phys. B **646**, 220 (2002).

V. Ravindran, J. Smith and W. L. van Neerven, “NNLO corrections to the total cross-section for Higgs boson production in hadron hadron collisions,” Nucl. Phys. B **665**, 325 (2003).

D. de Florian and M. Grazzini, “Higgs production at the LHC: updated cross sections at $\sqrt{s} = 8$ TeV,” Phys. Lett. B **718**, 117 (2012).

◆ NNNLO

C. Anastasiou, C. Duhr, F. Dulat, F. Herzog and B. Mistlberger, “Higgs Boson Gluon-Fusion Production in QCD at Three Loops,” Phys. Rev. Lett. **114**, 212001 (2015).

Introduction

pQCD calculable quantity ρ can be expanded in perturbative series

$$\rho(\mu_R) = r_0 \alpha_s(\mu_R) \left[1 + \sum_{k=1}^{\infty} r_k \left(\frac{Q}{\mu_R} \right) \frac{\alpha_s^k(\mu_R)}{\pi^k} \right]$$

$$g_0 = Z_g \mu^{\varepsilon/2} g \quad (\varepsilon=4-d)$$

$$\frac{\partial \rho(\mu_R)}{\partial \mu_R} \equiv 0$$

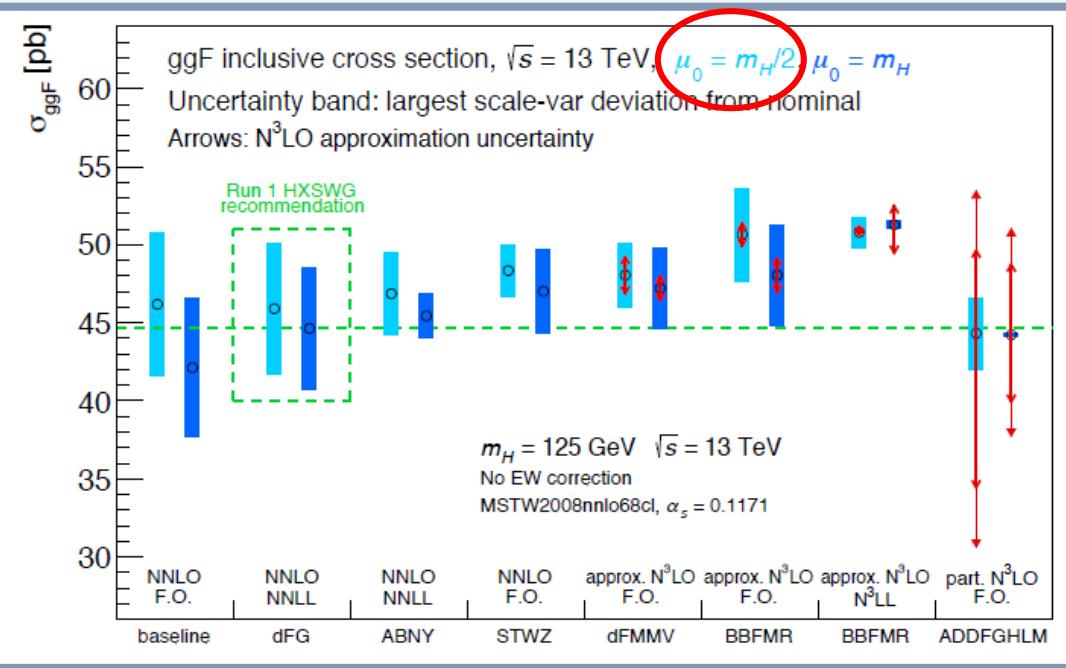
Conventional Scale Setting Method

- ◆ infinite order, no scheme- and scale-dependence
- ◆ fixed-order, the prediction, scheme- and scale-dependence
- ◆ Guessing a renormalization scale Q , only a guess work !

- ◆ Varying, e.g. $[Q/2, 2 Q]$ to discuss its uncertainty
- ◆ Convergence is usually problematic

$$[n! \beta_i^n \alpha_s^n]$$

Introduction

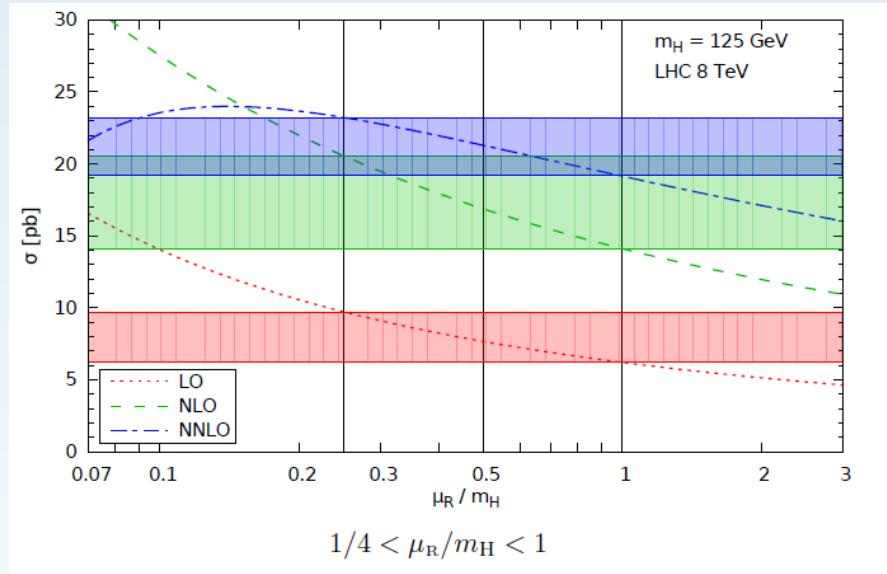
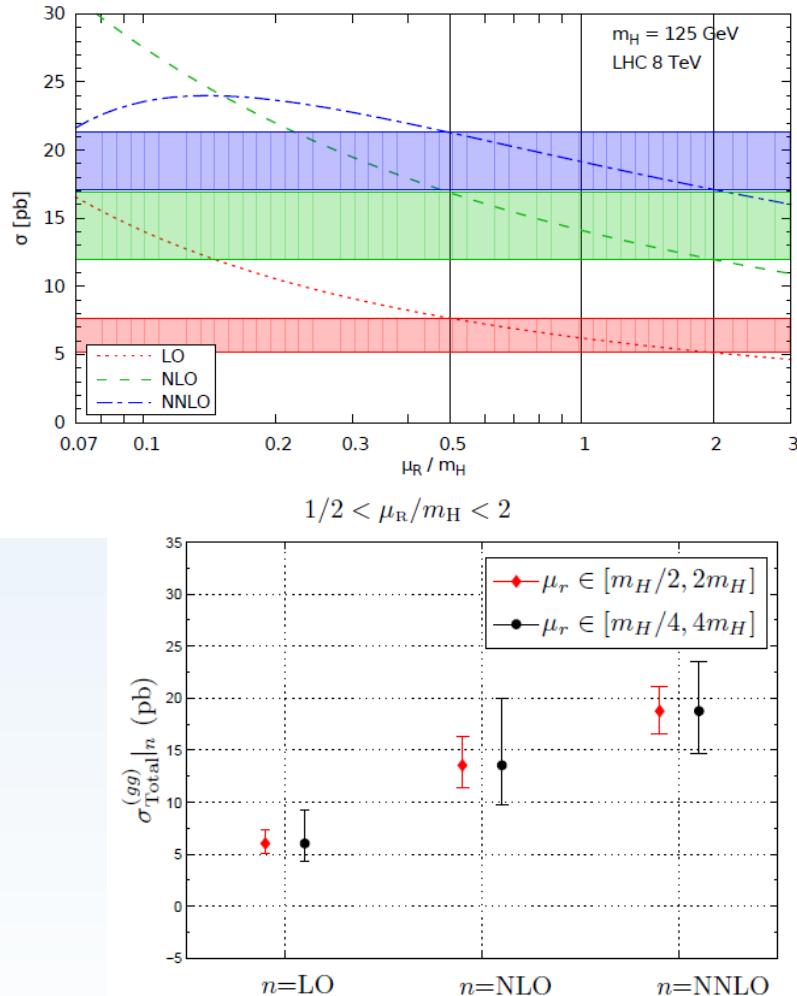


why?

μ_r	LO	NLO	$N^2\text{LO}$	Total	
$m_H/4$	9.42	10.64	3.50	23.56	scale error 24% for $[m_H/2, 2m_H]$
$m_H/2$	7.43	8.89	4.82	21.14	
m_H	6.02	7.53	5.21	18.76	scale error 47% for $[m_H/4, 4m_H]$
$2m_H$	4.98	6.45	5.19	16.62	
$4m_H$	4.19	5.58	4.95	14.72	slow convergence

Introduction

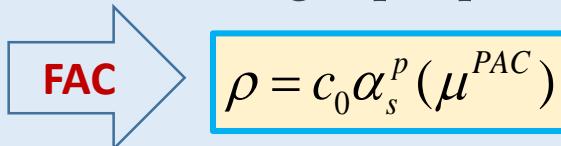
estimates the magnitude of unknown higher-order



Principle of Maximum Conformality(PMC)

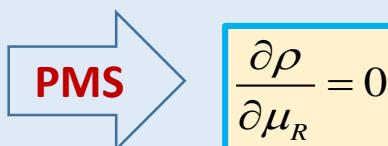
scale-setting methods

- ▶ the renormalization group improved effective coupling method(FAC).


$$\rho = c_0 \alpha_s^p(\mu^{PAC})$$

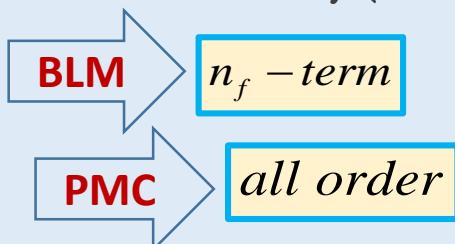
G. Grunberg, Phys. Lett. B 95, 70 (1980)

- ▶ the principle of minimum sensitivity (PMS).


$$\frac{\partial \rho}{\partial \mu_R} = 0$$

P.M. Stevenson, Phys. Lett. B 100, 61 (1981);

- ▶ the Brodsky-Lepage-Mackenzie method (BLM) and its underlying principle of maximum conformatity (PMC).



S.J. Brodsky, G.P. Lepage and P.B. Mackenzie, Phys. Rev. D 28, 228 (1983)



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Principle of Maximum Conformality(PMC)

PRL 110, 192001 (2013)

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PRL 109, 042002 (2012)

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Rep. Prog. Phys. 78 (2015) 126201 (15pp)

Reports on Progress in Physics

doi:10.1088/0034-4885/78/12/126201

Review

Renormalization group invariance and optimal QCD renormalization scale-setting: a key issues review

Xing-Gang Wu¹, Yang Ma¹, Sheng-Quan Wang¹, Hai-Bing Fu¹,
Hong-Hao Ma¹, Stanley J Brodsky² and Matin Mojaza³

- ▶ Stan and Wu, Phys.Rev.Lett.109,042002(2012)
- ▶ Stan and Wu, Phys.Rev.D85,034038(2012)
- ▶ Matin, Stan and Wu, Phys.Rev.Lett.110,192001(2013)
- ▶ Stan, Matin and Wu, Phys.Rev.D89, 014027 (2014)

- ▶ Wu, Stan and Matin, Prog.Part.Nucl.Phys. 72,44(2013)
- ▶ Wu, Ma, Wang, Fu, Ma, Stan and Matin, Rep.Prog.Phys. 78, 126201 (2015)

Principle of Maximum Conformality(PMC)

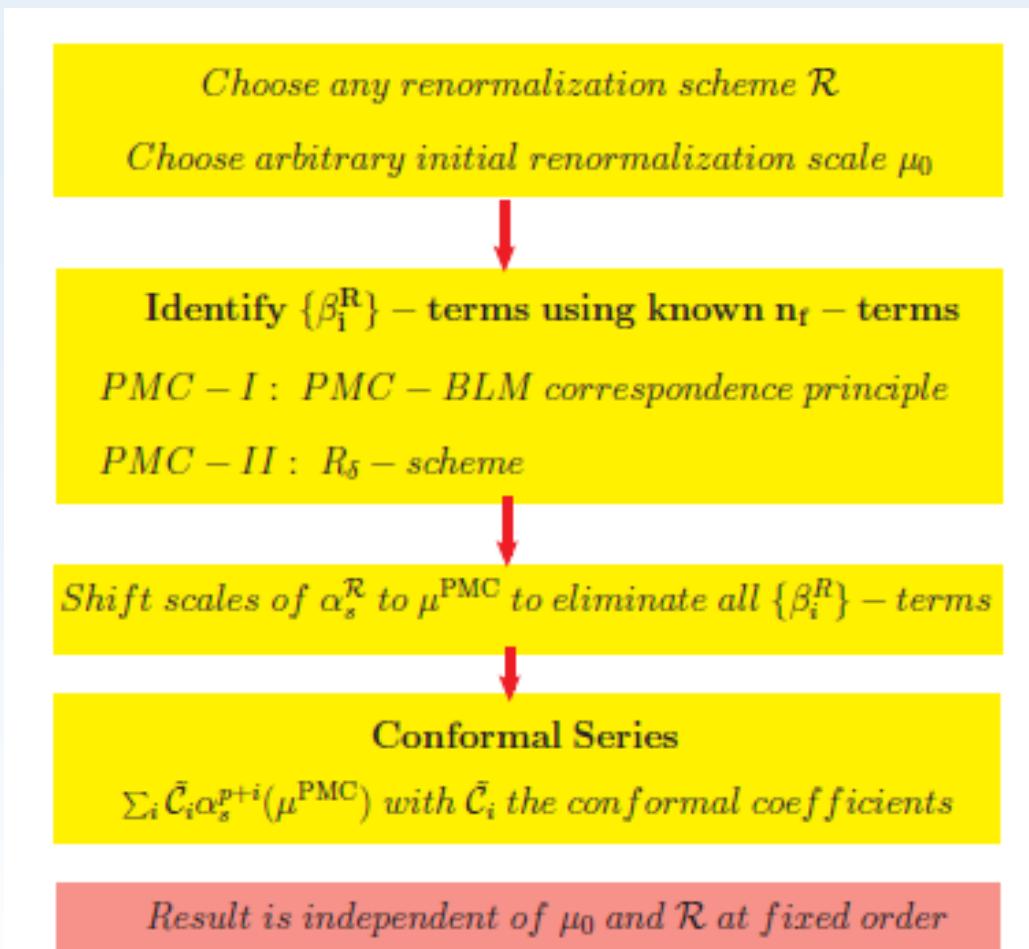
The scale dependence of the strong coupling constant is controlled by the renormalization group equation (RGE) via the β function:

$$\beta^{\mathcal{R}} = \mu_r^2 \frac{\partial}{\partial \mu_r^2} \left(\frac{\alpha_s^{\mathcal{R}}(\mu_r)}{4\pi} \right) = - \sum_{i=0}^{\infty} \beta_i^{\mathcal{R}} \left(\frac{\alpha_s^{\mathcal{R}}(\mu_r)}{4\pi} \right)^{i+2}.$$

If one can find a proper way to sum up all known-type of β_i -terms into the coupling constant, then one can determine the effective coupling for a specific process definitely at each perturbative order, and thus, the renormalization scale dependence can be greatly suppressed or even be eliminated.

Principle of Maximum Conformality(PMC)

flow chart



Principle of Maximum Conformality(PMC)

Introducing the R_δ -scheme by subtracting a constant $-\delta$ in addition to the standard subtraction, $\ln(4\pi) - \gamma_E$, the **degeneracy relation**:

Phys.Rev.Lett.110,192001(2013)

$$\begin{aligned}\varrho_n = & r_{0,0} + r_{1,0}a(\mu) + [r_{2,0} + \beta_0 r_{2,1}] a^2(\mu) + [r_{3,0} + \beta_1 r_{2,1} + 2\beta_0 r_{3,1} + \beta_0^2 r_{3,2}] a^3(\mu) \\ & + \left[r_{4,0} + \beta_2 r_{2,1} + 2\beta_1 r_{3,1} + \frac{5}{2}\beta_1\beta_0 r_{3,2} + 3\beta_0 r_{4,1} + 3\beta_0^2 r_{4,2} + \beta_0^3 r_{4,3} \right] a^4(\mu) + \dots\end{aligned}$$

$$\begin{aligned}\varrho_n = & r_{0,0} + r_{1,0}a(Q_1) + r_{2,0}a^2(Q_2) \\ & + r_{3,0}a^3(Q_3) + r_{4,0}a^4(Q_4) + \dots\end{aligned}$$

conformal series,
which is scale-and
scheme independent!

Higgs production

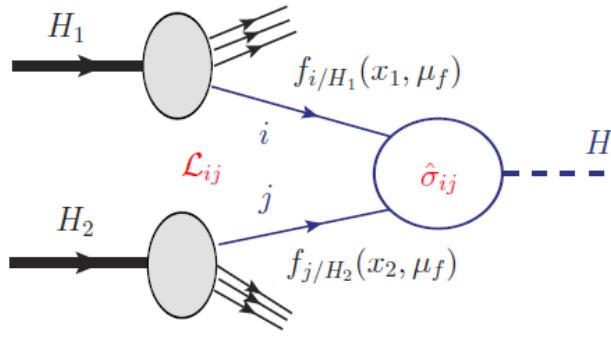


FIG. 1: Diagrammatic illustration of Higgs boson production at hadron colliders, computed from the convolution of partonic cross-sections $\hat{\sigma}_{ij}$ with the corresponding parton luminosities \mathcal{L}_{ij} .

$$\sigma_{H_1 H_2 \rightarrow H X} = \sum_{i,j} \int_{m_H^2}^S ds \mathcal{L}_{ij}(s, S, \mu_f) \hat{\sigma}_{ij}(s, M, R),$$

$$\mathcal{L}_{ij} = \frac{1}{S} \int_s^S \frac{d\hat{s}}{\hat{s}} f_{i/H_1}(x_1, \mu_f) f_{j/H_2}(x_2, \mu_f),$$

$$\hat{\sigma}_{ij}(s, M, R) = \frac{\pi}{576 v^2} \left[\eta_{ij}^{(0)}(s, M, R) a_s^2(\mu_r) + \eta_{ij}^{(1)}(s, M, R) a_s^3(\mu_r) + \eta_{ij}^{(2)}(s, M, R) a_s^4(\mu_r) + \mathcal{O}(a_s^5) \right],$$

$$\begin{aligned} \eta_{ij}^{(0)}(s, M, R) &= c_{1,0}^{ij}(s, M, R), \\ \eta_{ij}^{(1)}(s, M, R) &= c_{2,0}^{ij}(s, M, R) + c_{2,1}^{ij}(s, M, R) n_f, \\ \eta_{ij}^{(2)}(s, M, R) &= c_{3,0}^{ij}(s, M, R) + c_{3,1}^{ij}(s, M, R) n_f \\ &\quad + c_{3,2}^{ij}(s, M, R) n_f^2. \end{aligned}$$

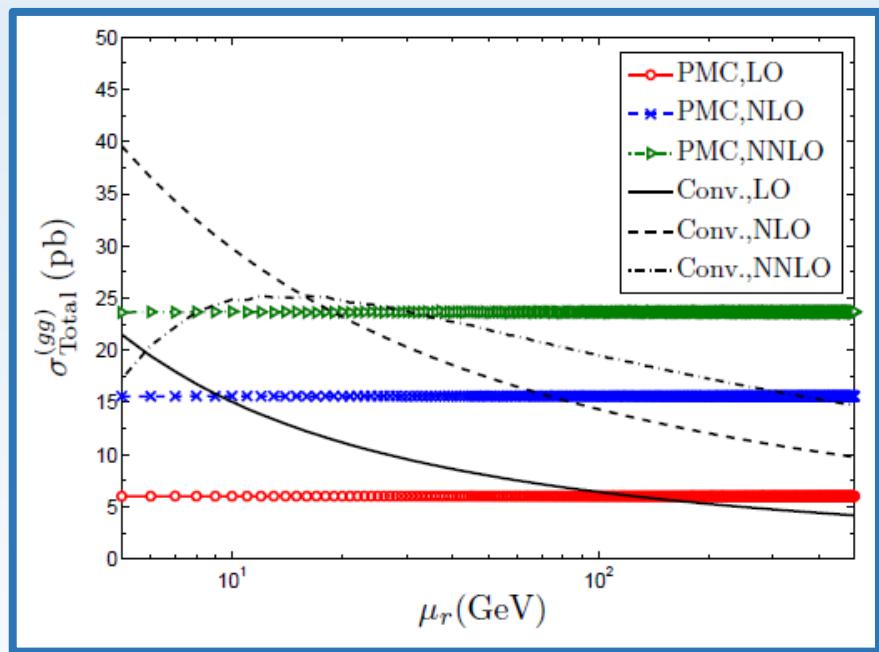
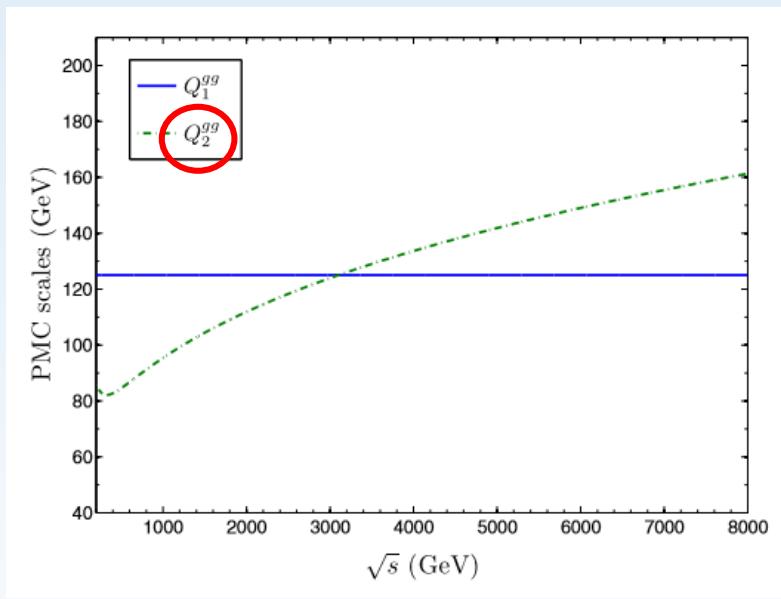
Higgs production

$$\hat{\sigma}_{ij}(s, M, R) = \frac{\pi}{576v^2} \left[r_{1,0}^{ij} a_s^2(\mu_r) + \left(r_{2,0}^{ij} + 2\beta_0 r_{2,1}^{ij} \right) a_s^3(\mu_r) + \left(r_{3,0}^{ij} + 2\beta_1 r_{2,1}^{ij} + 3\beta_0 r_{3,1}^{ij} + 3\beta_0^2 r_{3,2}^{ij} \right) a_s^4(\mu_r) + \mathcal{O}(a_s^5) \right]$$

$$\begin{aligned} r_{1,0}^{ij} &= c_{1,0}^{ij}, \\ r_{2,0}^{ij} &= \frac{1}{2}(2c_{2,0}^{ij} + 33c_{2,1}^{ij}), \quad r_{2,1}^{ij} = -\frac{3c_{2,1}^{ij}}{4}, \\ r_{3,0}^{ij} &= \frac{1}{4}(-642c_{2,1}^{ij} + 4c_{3,0}^{ij} + 66c_{3,1}^{ij} + 1089c_{3,2}^{ij}), \\ r_{3,1}^{ij} &= \frac{1}{2}(19c_{2,1}^{ij} - c_{3,1}^{ij} - 33c_{3,2}^{ij}), \quad r_{3,2}^{ij} = \frac{3c_{3,2}^{ij}}{4}. \end{aligned}$$

$$\begin{aligned} \hat{\sigma}_{ij}(s, M, R) &= \frac{\pi}{576v^2} \left[r_{1,0}^{ij} a_s^2(Q_1^{ij}) + r_{2,0}^{ij} a_s^3(Q_2^{ij}) \right. \\ &\quad \left. + r_{3,0}^{ij} a_s^4(Q_3^{ij}) + \mathcal{O}(a_s^5) \right], \end{aligned}$$

Higgs production

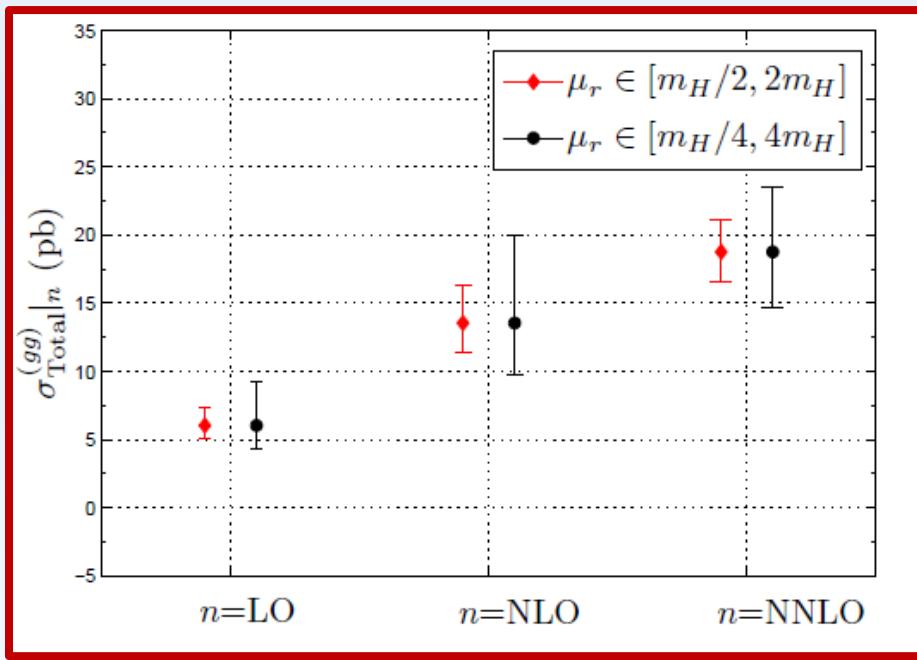


Higgs production

(ij)	Conventional				PMC			
	LO	NLO	N^2LO	Total	LO	NLO	N^2LO	Total
(gg)	6.02	7.53	5.21	18.76	6.02	9.58	8.01	23.61
(gq)	0.00	-0.11	-0.31	-0.42	0.00	-0.32	0.21	-0.11
$(g\bar{q})$	0.00	-0.08	-0.16	-0.24	0.00	-0.17	0.02	-0.15
$(q\bar{q})$	0.00	0.008	0.006	0.014	0.00	0.007	0.007	0.014
$(qq + qq')$	0.00	0.00	0.006	0.006	0.00	0.00	0.006	0.006
$(\bar{q}\bar{q} + \bar{q}\bar{q}')$	0.00	0.00	0.001	0.001	0.00	0.00	0.001	0.001

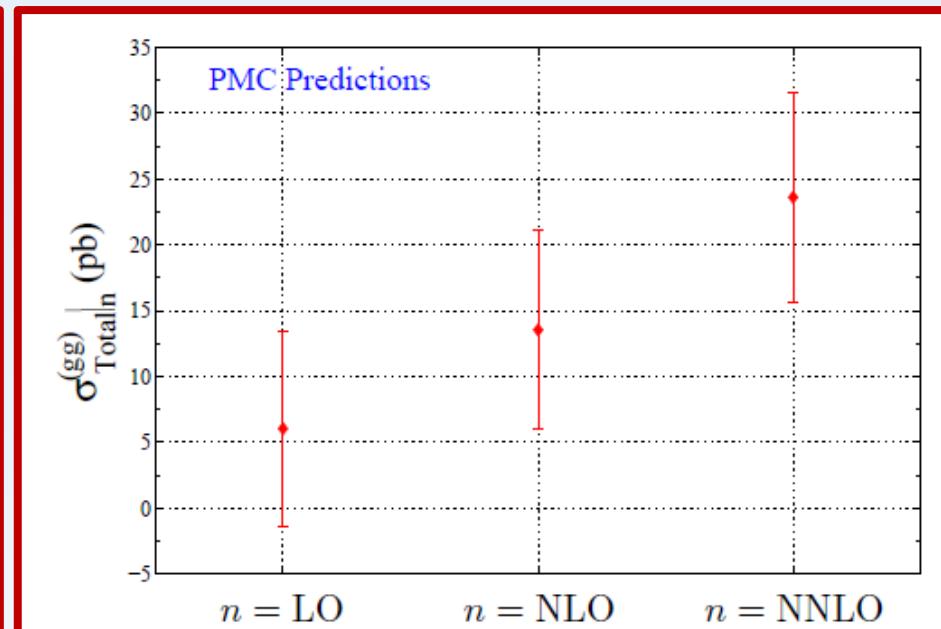
μ_r	Conventional				PMC			
	LO	NLO	N^2LO	Total	LO	NLO	N^2LO	Total
$m_H/4$	9.42	10.64	3.50	23.56	6.02	9.58	8.01	23.61
$m_H/2$	7.43	8.89	4.82	21.14	6.02	9.58	8.01	23.61
m_H	6.02	7.53	5.21	18.76	6.02	9.58	8.01	23.61
$2m_H$	4.98	6.45	5.19	16.62	6.02	9.58	8.01	23.61
$4m_H$	4.19	5.58	4.95	14.72	6.02	9.58	8.01	23.61

Higgs production



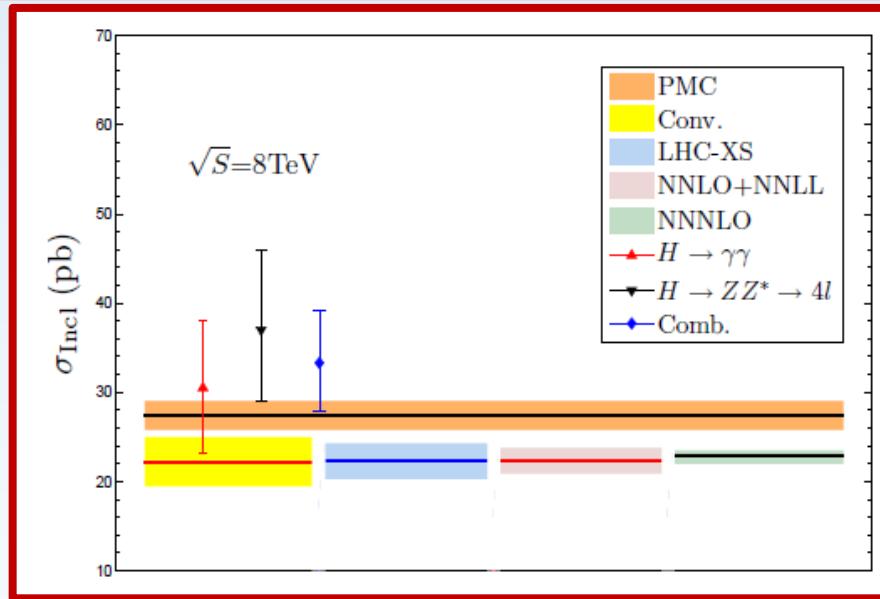
Non-conformal

conformal



Higgs production

σ_{Incl}	7 TeV	8 TeV	13 TeV
ATLAS($H \rightarrow \gamma\gamma$) [4, 5]	35^{+13}_{-12}	$30.5^{+7.5}_{-7.4}$	40^{+31}_{-28}
ATLAS($H \rightarrow ZZ^* \rightarrow 4l$) [4, 5]	33^{+21}_{-16}	37^{+9}_{-8}	12^{+25}_{-16}
LHC-XS [3]	17.5 ± 1.6	22.3 ± 2.0	$50.9^{+4.5}_{-4.4}$
PMC predictions	$21.21^{+1.36}_{-1.32}$	$27.37^{+1.65}_{-1.59}$	$65.72^{+3.46}_{-3.01}$



21%, 23% and 29%

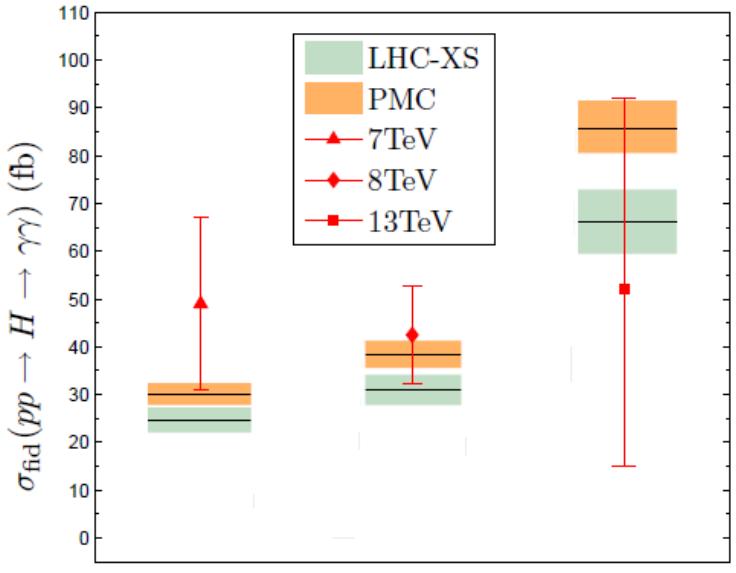
ATLAS-CONF-2016-081

$$\sigma_{\text{Incl}} = 59.0^{+9.7}_{-9.2}(\text{stat.})^{+4.4}_{-3.5}(\text{syst.}) \text{ pb}$$

New data 8th August

Higgs production

$$\sigma_{\text{fid}}(pp \rightarrow H \rightarrow \gamma\gamma) = \sigma_{\text{Incl}} \mathcal{B}_{H \rightarrow \gamma\gamma} \mathcal{A},$$



Application of the Principle of Maximum Conformality to the Hadroproduction of the Higgs Boson at the LHC

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²Department of Physics, Chongqing University, Chongqing 401331, P.R. China

³SLAC National Accelerator Laboratory, Stanford University, Stanford, California 94039, USA and

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Roslagstullsbacken 23, SE-10691 Stockholm, Sweden

(Dated: August 19, 2016)

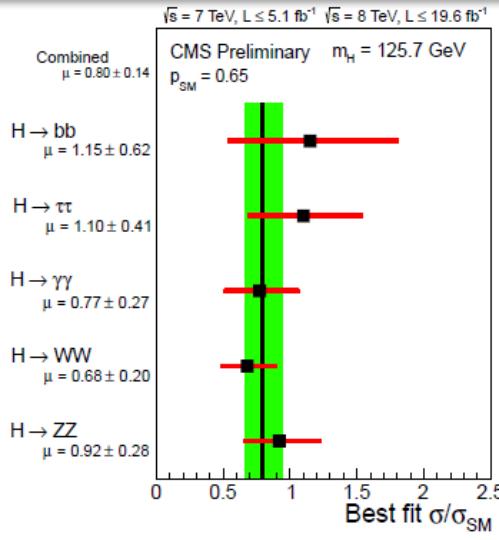
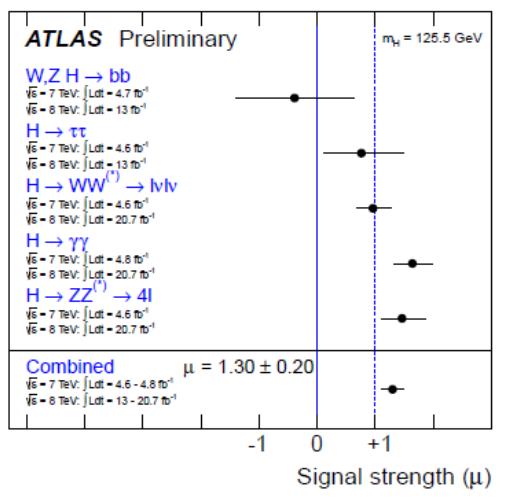
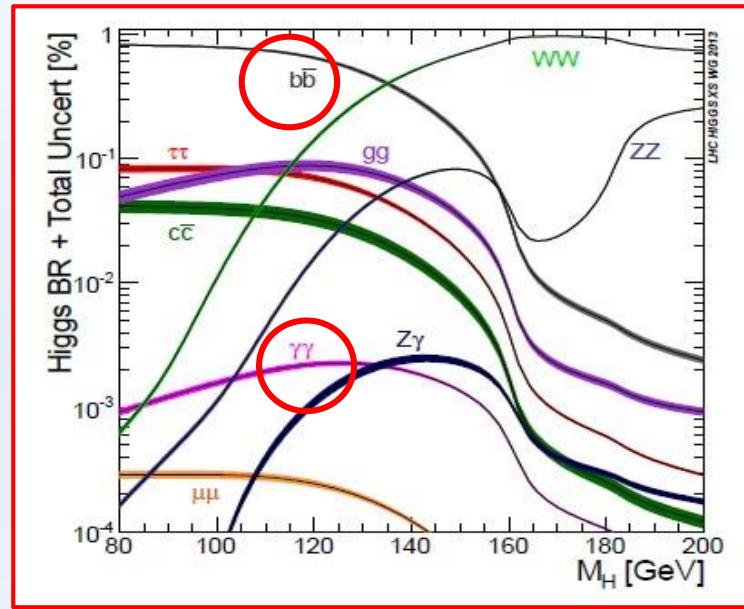
We present improved pQCD predictions for Higgs boson hadroproduction at the Large Hadronic Collider (LHC) by applying the Principle of Maximum Conformality (PMC), a procedure which resums the pQCD series using the renormalization group (RG), thereby eliminating the dependence of the predictions on the choice of the renormalization scheme while minimizing sensitivity to the initial choice of the renormalization scale. In previous pQCD predictions for Higgs boson hadroproduction, it has been conventional to assume that the renormalization scale μ_r of the QCD coupling $\alpha_s(\mu_r)$ is the Higgs mass, and then to vary this choice over the range $1/2m_H < \mu_r < 2m_H$ in order to estimate the theory uncertainty. However, this error estimate is only sensitive to the non-conformal β terms in the pQCD series, and thus it fails to correctly estimate the theory uncertainty in cases where

PRD 94, 053003 (2016)

$\sigma_{\text{fid}}(pp \rightarrow H \rightarrow \gamma\gamma)$	7 TeV	8 TeV	13 TeV
ATLAS data [50]	49 ± 18	$42.5^{+10.3}_{-10.2}$	52^{+40}_{-37}
LHC-XS [3]	24.7 ± 2.6	31.0 ± 3.2	$66.1^{+6.8}_{-6.6}$
PMC prediction	$30.1^{+2.3}_{-2.2}$	$38.3^{+2.9}_{-2.8}$	$85.8^{+5.7}_{-5.3}$

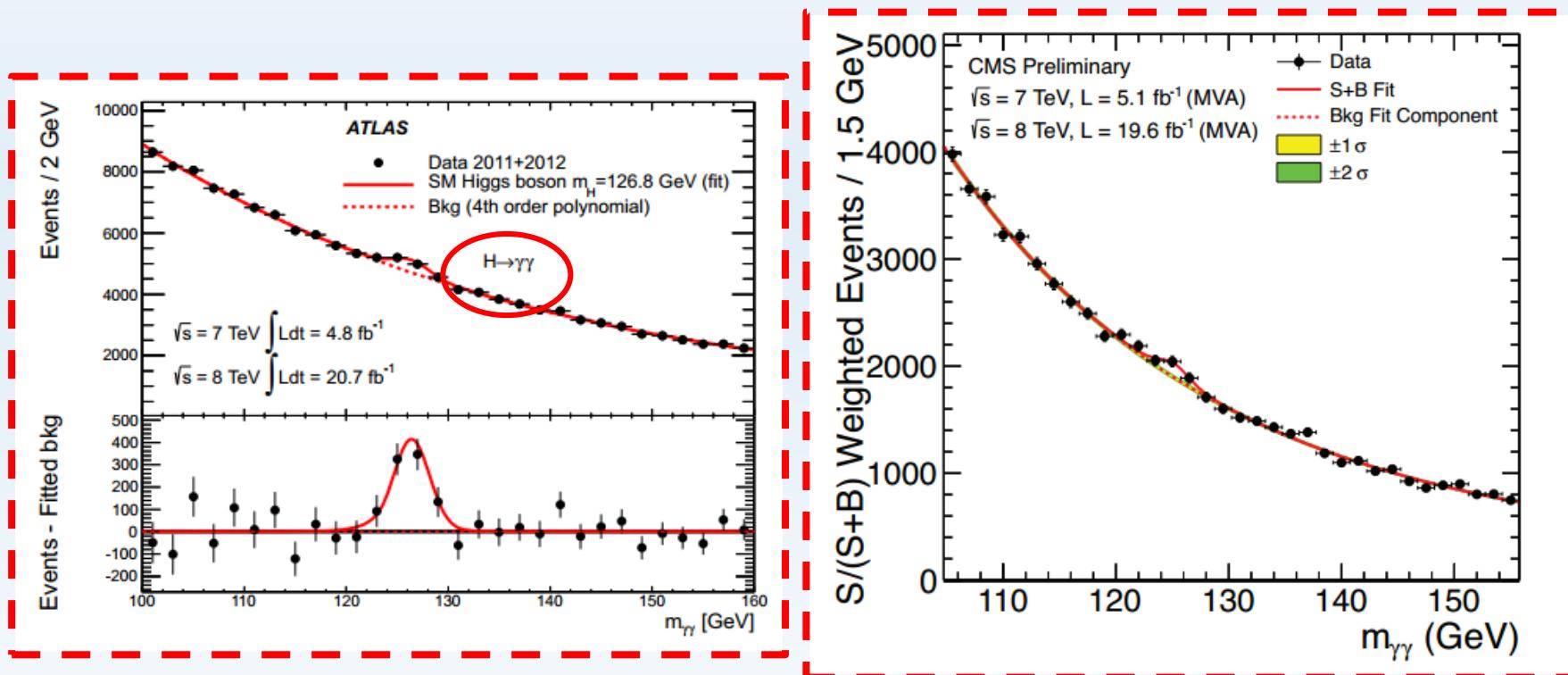
Higgs decays

- Higgs to $b\bar{b}$
- Higgs to gg
- Higgs to $\gamma\gamma$
- Higgs to $\tau\tau$
- Higgs to WW^*
- Higgs to ZZ^*



Higgs $\rightarrow \gamma\gamma$

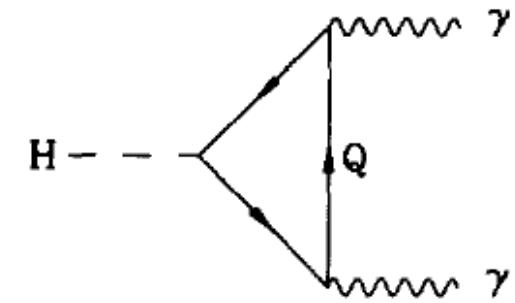
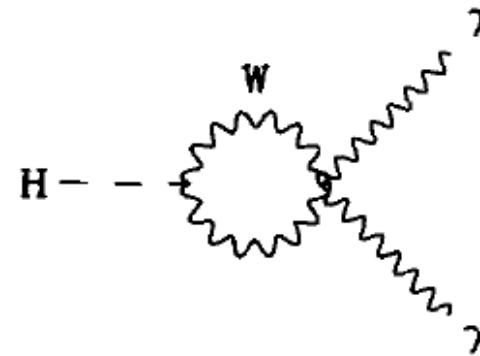
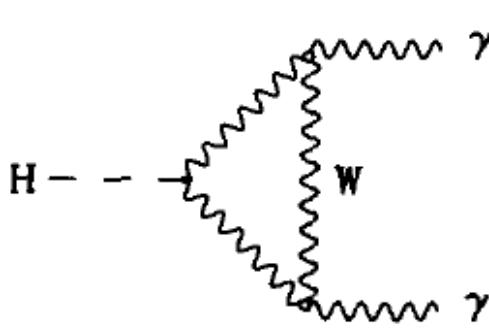
$H \rightarrow \gamma\gamma$



The ATLAS and CMS
Collaborations
arXiv:1503.07589

$$m_H^{\gamma\gamma} = 125.07 \pm 0.29 \text{ GeV}$$
$$= 125.07 \pm 0.25 \text{ (stat.)} \pm 0.14 \text{ (syst.)} \text{ GeV}$$

Higgs $\rightarrow \gamma\gamma$

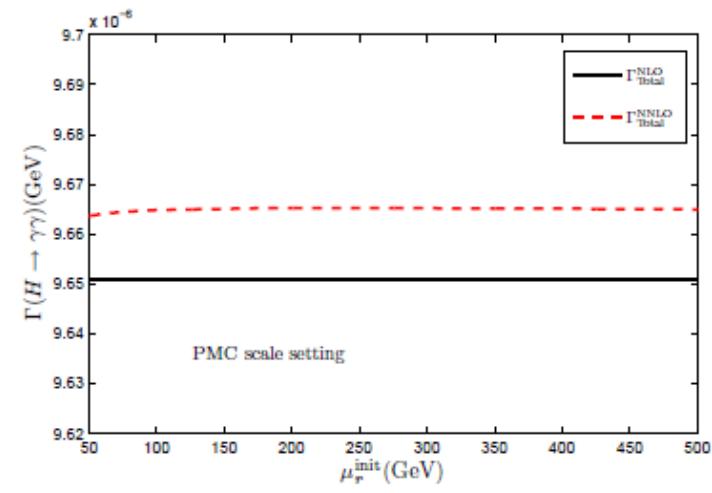
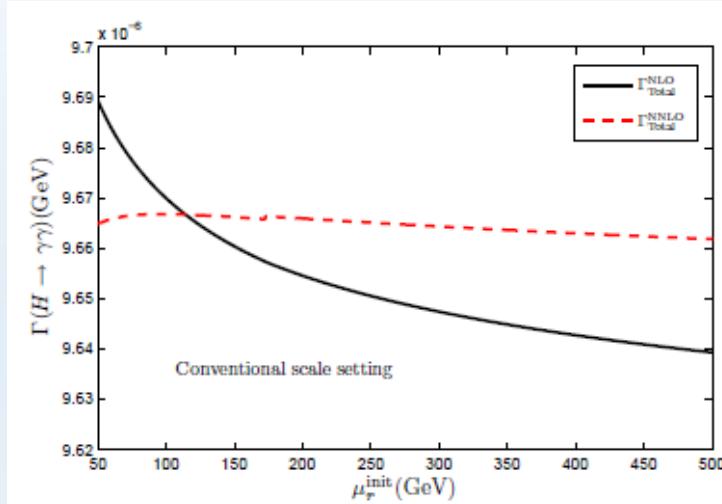


$Q = t, b, c, \tau$ heavy fermion, dominate by t quark

$$\begin{aligned} \Gamma(H \rightarrow \gamma\gamma) = & \frac{M_H^3}{64\pi} \left(A_{LO} + \frac{\alpha_s(\mu_r^{\text{init}})}{\pi} A_{NLO} \right. \\ & \left. + \left(\frac{\alpha_s(\mu_r^{\text{init}})}{\pi} \right)^2 A_{NNLO} + \frac{\alpha}{\pi} A_{EW} \right). \end{aligned} \quad (6)$$

Phys. Lett. B 721 131

Higgs $\rightarrow \gamma\gamma$



**Scale
error 18%**



	$\Gamma_{\text{NLO}} (10^{-3} \text{ keV})$		
μ_r^{init}	$M_H/2$	M_H	$2M_H$
Conventional scale setting	180.1	162.0	148.0
PMC scale setting	148.7	148.7	148.7

$$\Gamma(H \rightarrow \gamma\gamma)|_{\text{pole}} = [9.502 + (1.620^{+0.180}_{-0.140}) \times 10^{-1} + (2.200^{+18.585}_{-12.486}) \times 10^{-3}] \text{ keV},$$

$$\Gamma(H \rightarrow \gamma\gamma)|_{\text{PMC}} = [9.502 + 1.487 \times 10^{-1} + 1.415 \times 10^{-2}] \text{ keV},$$

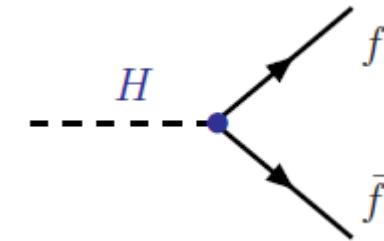
$$\Gamma(H \rightarrow \gamma\gamma)|_{\text{ATLAS}} = 9.502^{+0.229}_{-0.255} \text{ keV},$$

$$\Gamma(H \rightarrow \gamma\gamma)|_{\text{CMS}} = 9.567^{+0.197}_{-0.193} \text{ keV},$$

$\mu^{\text{PMC}} = 242.3 \text{ GeV}$

Higgs $\rightarrow b\bar{b}$

$H \rightarrow b\bar{b}$



The CMS Collaborations

arXiv:1303.0763

$$\begin{aligned} \Gamma(H \rightarrow b\bar{b}) = & \frac{3G_F M_H m_b^2(M_H)}{4\sqrt{2}\pi} [1 + c_{1,0} a_s(M_H) \\ & + (c_{2,0} + c_{2,1} n_f) a_s^2(M_H) + (c_{3,0} + c_{3,1} n_f \\ & + c_{3,2} n_f^2) a_s^3(M_H) + (c_{4,0} + c_{4,1} n_f \\ & + c_{4,2} n_f^2 + c_{4,3} n_f^3) a_s^4(M_H) + \mathcal{O}(a_s^5)] \quad (2) \end{aligned}$$

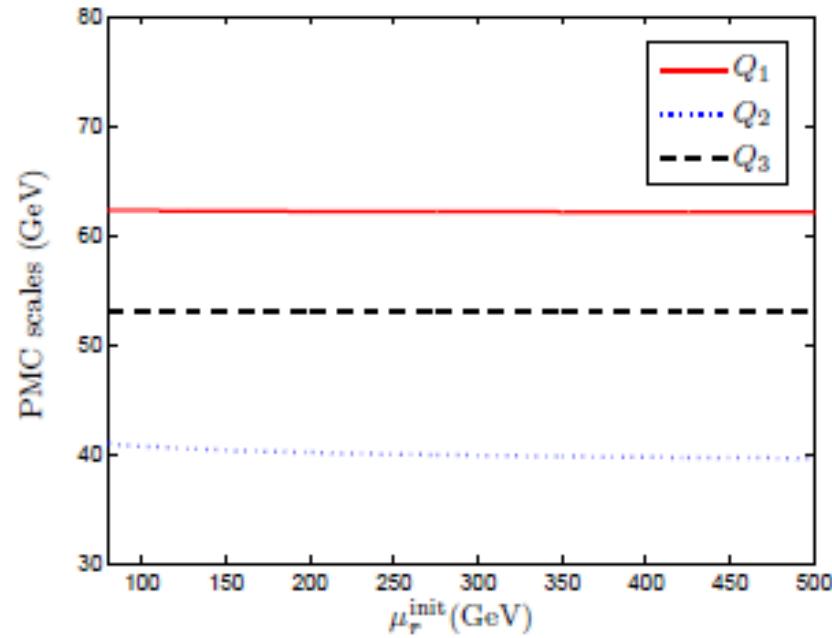
4 loop

PRL. 96,
012003

$$\Gamma(H \rightarrow b\bar{b}) = \frac{3G_F M_H m_b^2(M_H)}{4\sqrt{2}\pi} [1 + r_{1,0}(\mu_r^{\text{init}}) a_s(Q_1) + r_{2,0}(\mu_r^{\text{init}}) a_s^2(Q_2) + r_{3,0}(\mu_r^{\text{init}}) a_s^3(Q_3) + r_{4,0}(\mu_r^{\text{init}}) a_s^4(Q_4)] 15)$$

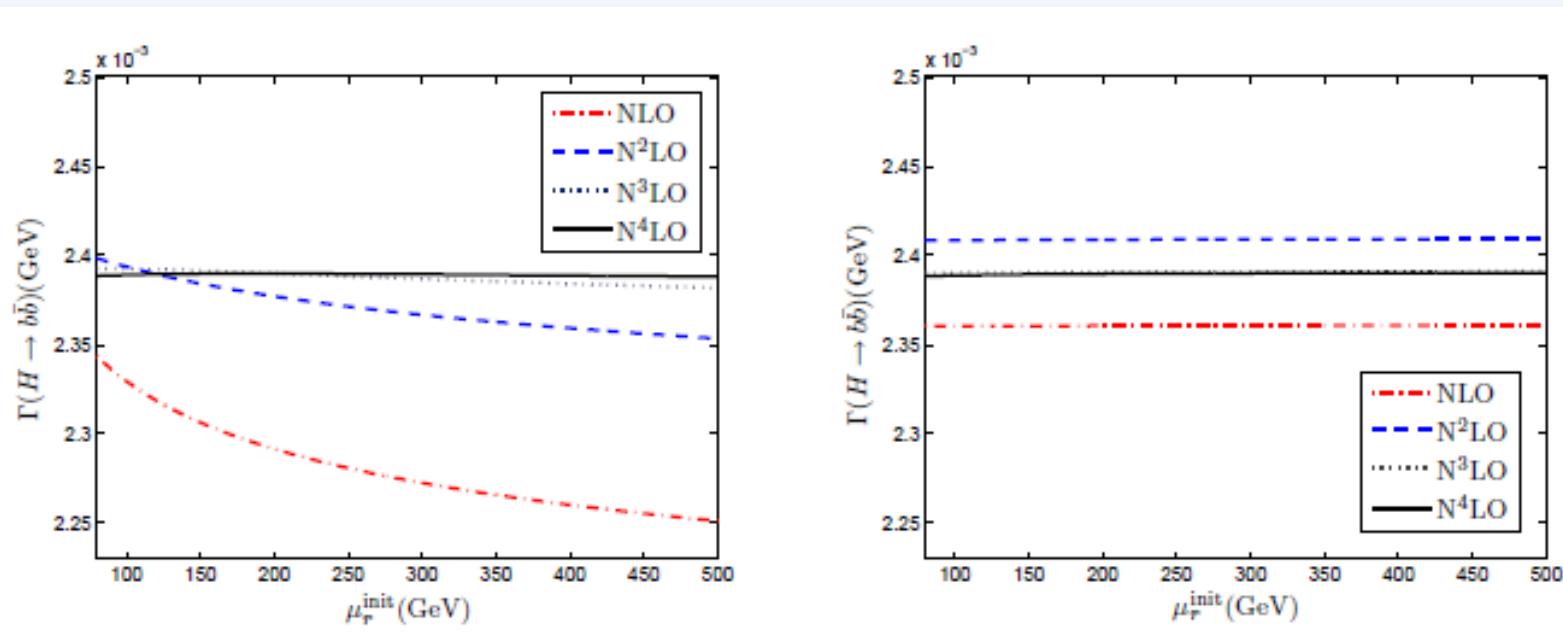
Higgs $\rightarrow b\bar{b}$

	Conventional scale setting						PMC scale setting					
	LO	NLO	N ² LO	N ³ LO	N ⁴ LO	Total	LO	NLO	N ² LO	N ³ LO	N ⁴ LO	Total
Γ_1 (KeV)	1924.28	391.74	72.38	3.73	-2.65	2389.48	1924.28	436.23	48.12	-18.12	-1.38	2389.13
$\Gamma_1/\Gamma_{\text{tot}}$	80.53%	16.39%	3.03%	0.16%	-0.11%		80.54%	18.26%	2.01%	-0.76%	-0.06%	



$$Q_1 = 62.3 \text{ GeV}, \quad Q_2 = 40.5 \text{ GeV}, \quad Q_3 = 53.1 \text{ GeV}.$$

Higgs $\rightarrow b\bar{b}$

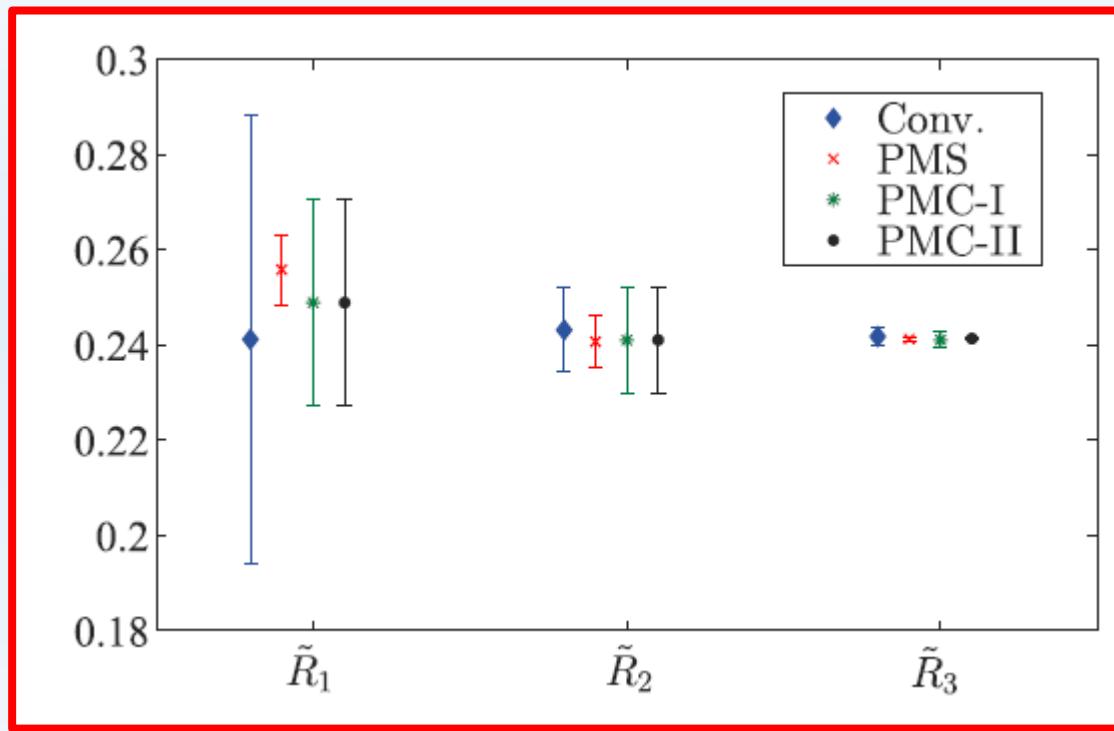


cited
by Peskin

$$\Gamma(H \rightarrow b\bar{b}) = 2.389 \pm 0.073 \pm 0.041 \text{ MeV},$$

S.Q. Wang, X.G. Wu, X.C. Zheng, J.M. Shen, and Q.L. Zhang, Eur.Phys.J. C74, 2825 (2014).

Higgs $\rightarrow b\bar{b}$



**Wu, Ma, Wang, Fu, Ma, Stan and Matin,
Rep.Prog.Phys. 78, 126201 (2015)**

Summary

- ✓ b and c physics、 differential calculation……
- ✓ The main uncertainties are removed
- ✓ the conformal series、 the convergence can be greatly improved in principle
- ✓ the precision of QCD tests
- ✓ the sensitivity of the collider experiments to new physics beyond the standard model

Summary

thanks

爽爽的贵阳
绿绿的贵阳