Scalar production to threshold N^3LO in QCD

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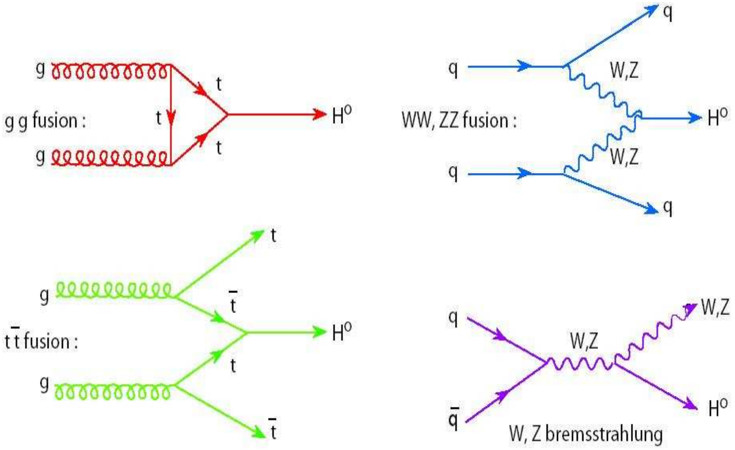
Outline

- Introduction
- Threshold corrections at N^3LO
- Higgs boson and pseudo scalar cross sections
  Higgs associated production
  Pseudo scalar production
- Summary

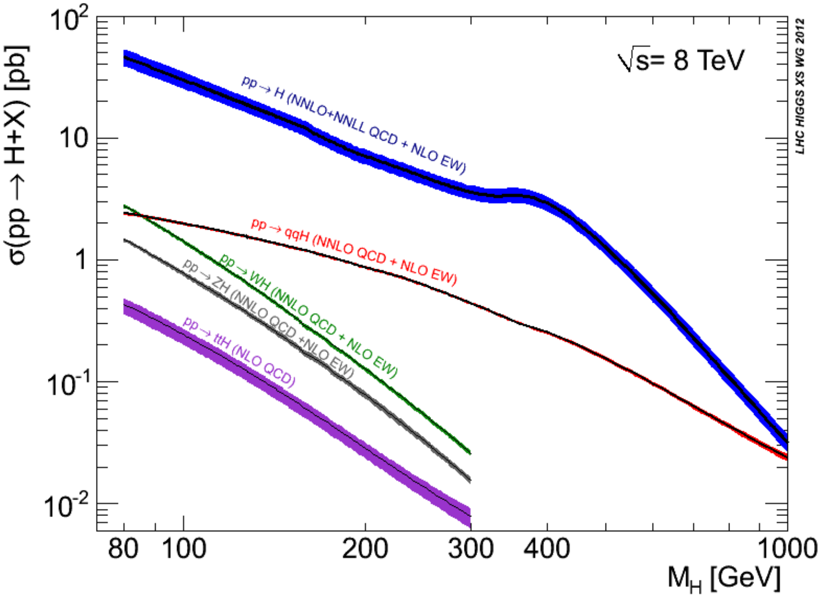
Higgs production at the LHC

- Inclusive production channels
  - Gluon fusion channel (dominant)
    $g + g \to H + X$
  - Vector boson fusion channel (VBF)
    $q + q \to VV \to H + X$
  - Bottom annihilation channel
    $b + \bar{b} \to H + X$
- Associated production channels
  - Higgs production associated with vector bosons
    $q + \bar{q} \to V + H$
  - Higgs production associated with top pairs
    $gg \to t\bar{t} + H$

Higgs production at the LHC
Dominant channels



Higgs production cross sections at the LHC
Dominant channels



State of the art for NNLO calculations ...

1. Higgs production
   C. Anastasiou and K. Melnikov, Nucl.Phys. B646 (2002) 220-256,
   M. Spira, A. Djouadi, D. Graudenz, P.M. Zerwas, NPB453 (1995) 17-82,
   Robert V. Harlander and William B. Kilgore, PRL 88 (2002) 201801,
   V. Ravindran, J. Smith, W. L. van Neerven, NPB665, 325 (2003)
2. Drell-Yan production
   R. Hamberg, W. L. van Neerven and T. Matsuura, NPB359, 343 (1991)
   R. V. Harlander and W. B. Kilgore, Phys. Rev. Lett. 88 (2002) 201801
3. Deep-Inelastic Scattering
   E.B. Zijlstra and W.L. van Neerven, Phys. Lett. B272 (1991) 12
   E.B. Zijlstra and W.L. van Neerven, Nucl. Phys. B383 (1992) 525
4. Diphoton production
   S. Catani, L. Cieri, Daniel de Florian, G. Ferrera, M. Grazzini,
   Phys.Rev.Lett. 108 (2012) 072001
5. Top pair production at hadron colliders
   Michal Czakon, Paul Fiedler, Alexander Mitov, Phys.Rev.Lett. 110 (2013) 252004

State of the art for N^3LO calculations ...

- Threshold N3LO corrections for Higgs in the gluon fusion channel
  T. Gehrmann et. al (2014)
- Threshold N3LO corrections to Deep-In-elastic Scattering (DIS)
  S. Moch et. al
- Threshold N3LO corrections to Drell-Yan production of di-lepton
  V. Ravindran, T. Ahmed, N.Rana et. al. (2014)
- Threshold N3LO corrections to Higgs-strauhlung process (VH)
  V. Ravindran, M.C. Kumar et. al. (2014)
- Threshold N3LO corrections to top pair production
  N. Kidonakis et. al. (2014)
- Full N3LO corrections for Higgs production in the gluon fusion channel
  C. Anastasiou et. al. (2015)

Higgs cross sections contd ...

- Higgs couples to SM fields via yukawa interactions i.e. $y_i \sim m_i/\nu$
- Higgs couples to gluons and photons via heavy quark loops $gg \to H \to \gamma\gamma +$ quark loops (top or bottom loops)
- Effective Thoery EFT $\Longrightarrow$ Quark loops are integrated out in the inifinite quark mass limit ($m_t \to \infty$)
- Exact Thoery $\Longrightarrow$ Quark loops are integrated out keeping finite quark mass (pole mass or running mass)
- DIFF = $\sigma_{\text{Exact}} - \sigma_{\text{EFT}}$

Effective theory

- Gluon fusion channel
  - Leading Order (LO)
  - Next-to-Leading Order (NLO) (DIFF $\sim$ 5%)
  - Next-to-Next-to-Leading Order (NNLO) (DIFF $\sim$ 1%)
  - Complete threshold corrections at N^3LO (EFT)
  - Full N^3LO result in the gluon fusion channel (EFT)
- Associated production channel W/ZH
  - Leading Order (LO)
  - Next-to-Leading Order (NLO)
  - Next-to-Next-to-Leading Order (NNLO)
  - Threshold corrections at N^3LO

A comment on the Higgs couplings to gluons

- In the gluon funsion channel via quark loops, bottom and other light quarks also will contribute.
- With only top quark ($m_t = 172.5$GeV) in the loop, the cross sections are
  LO = 13.75 pb
  NLO = 31.13 pb
  NNLO = 41.75
- With top ($m_t = 172.5$GeV) and bottom ($m_b = 4.75$ GeV)in the loop, the cross sections are
  LO = 12.24 pb
  NLO = 29.11 pb
  NNLO = 39.74 pb

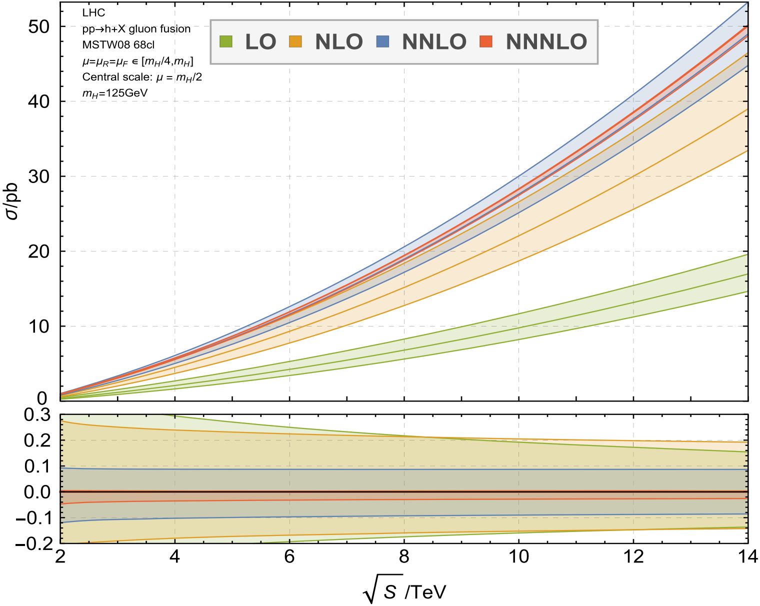
Hadronic cross sections ...

$$\sigma^{P_1P_2} = \sum_{ab=q,\bar{q},g} \int_0^1 dx_1 \int_0^1 dx_2\ f_a^{P_1}(x_1,\mu_F)\ f_b^{P_2}(x_2,\mu_F) \quad d\hat{\sigma}^{ab}(x_1,x_2,\mu_F,\mu_R)$$

$$d\hat{\sigma}^{ab} = d\sigma^0 \left[1 + \alpha_s \Delta^{(1)} + \alpha_s^2 \Delta^{(2)} + \alpha_s^3 \Delta^{(3)} + \ldots \right]$$

- These are Leading Order (LO), Next-to-Leading Order (NLO), NNLO ...
- Truncation $\Longrightarrow$ scale uncertainties and missing higher order contributions
- QCD radiative corrections can be as big as 100%.

Higgs production at the LHC : Large uncertainties



C. Anastasiou et. al.; PRL (2015)

Fixed order vs. Threshold corrections

- The fixed order results in the perturbation theory :

$$\alpha_s^n \, \Delta^{(n)}(z) = \alpha_s^n \left[C_0 \delta(1-z) + \sum_{k=1}^{(2n-1)} C_k \left[\frac{\ln^k(1-z)}{(1-z)} \right]_+ + \mathrm{Reg}(z) \right]$$

- Plus distributions are defined as

$$f_+(z) g(z) = f(z)[g(z) - g(1)]$$

- Threshold corrections are:

$$\alpha_s^n \left[C_0 \delta(1-z) + \sum_{k=1}^{(2n-1)} C_k \left[\frac{\ln^k(1-z)}{(1-z)} \right]_+ \right]$$

- e.g. $z = Q^2/s, \quad Q^2 = m_H^2, m_A^2, m_{ZH}^2$
- The logarithmic contributions are significant in the threshold region : $z \longrightarrow 1$

Threshold corrections from the resummation

1. Resummation is based on the property of the factorization of the cross sections
2. Soft function
3. Form Factor
4. Collinear functions
5. parton level cross section
6. Hadronic cross section

V. Ravindran; Nucl. Phys. B 746 (2006) 58
V. Ravindran; Nucl. Phys. B 752 (2006) 173

Threshold corrections from the resummation

- Soft plus Virtual (SV) are obtained from

$$\Delta_g^{A,SV}(z, q^2, \mu_R^2, \mu_F^2) = \mathcal{C} \exp\left(\Psi_g^A\left(z, q^2, \mu_R^2, \mu_F^2, \epsilon\right)\right)\Big|_{\epsilon=0}$$

- The Mellin convolution

$$\mathcal{C}e^{f(z)} = \delta(1-z) + \frac{1}{1!}f(z) + \frac{1}{2!}f(z) \otimes f(z) + \cdots .$$

$$\Psi_g^A\left(z, q^2, \mu_R^2, \mu_F^2, \epsilon\right) = \left(\ln\left[Z_g^A(\hat{a}_s, \mu_R^2, \mu^2, \epsilon)\right]^2 + \ln\left|\mathcal{F}_g^A(\hat{a}_s, Q^2, \mu^2, \epsilon)\right|^2\right)\delta(1-z)$$
$$+ 2\Phi_g^A(\hat{a}_s, q^2, \mu^2, z, \epsilon) - 2\mathcal{C}\ln\Gamma_{gg}(\hat{a}_s, \mu^2, \mu_F^2, z, \epsilon) .$$

Research works

- Higgs plus Vector boson at threshold to N^3LO QCD
  MC Kumar, M. Mandal and V. Ravindran; JHEP 1503 (2015) 037
- Pseudo scalar to threshold N^3LO QCD
  T.Ahmed, M.C.Kumar, P.Mathews, N. Rana and V. Ravindran; arXiv:1510:02235

Higgs associated production (VH)

E_{CM}	LO	NLO	NNLO	N^3LO_{SV}
7	0.2292	0.3021	0.3230	0.3227
8	0.2826	0.3702	0.3984	0.3982
13	0.5797	0.7377	0.8146	0.8141
14	0.6440	0.8148	0.9037	0.9035

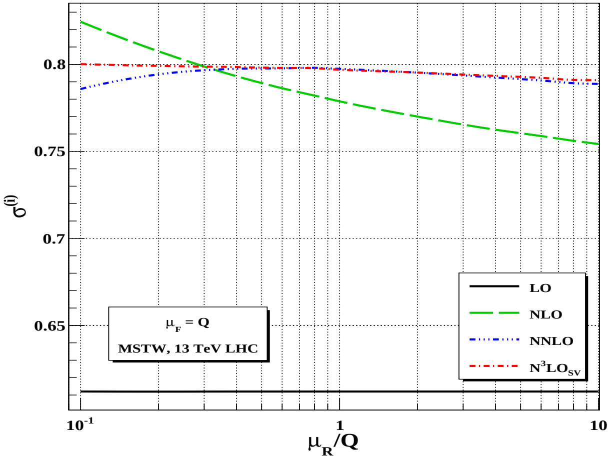
Table: Total cross sections (in pb) for *ZH* associated production

E_{CM}	LO	NLO	NNLO	N^3LO_{SV}
7	0.4254	0.5590	0.5785	0.5779
8	0.5208	0.6809	0.7043	0.7038
13	1.0474	1.3306	1.3803	1.3800
14	1.1607	1.4671	1.5220	1.5218

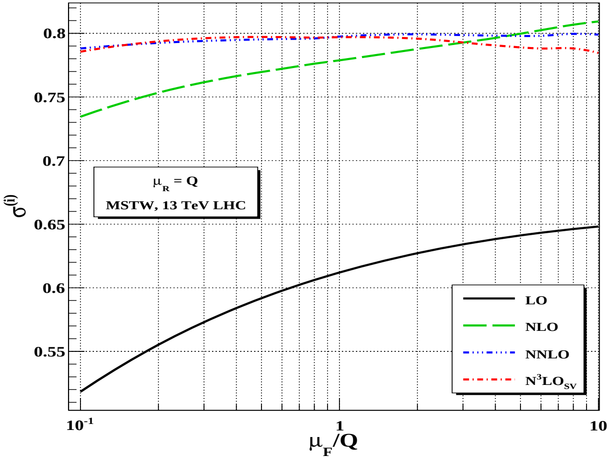
Table: Total cross sections (in pb) for *WH* associated production

MC Kumar, M.K. Mandal and V.Ravindran; JHEP 1503 (2015) 037

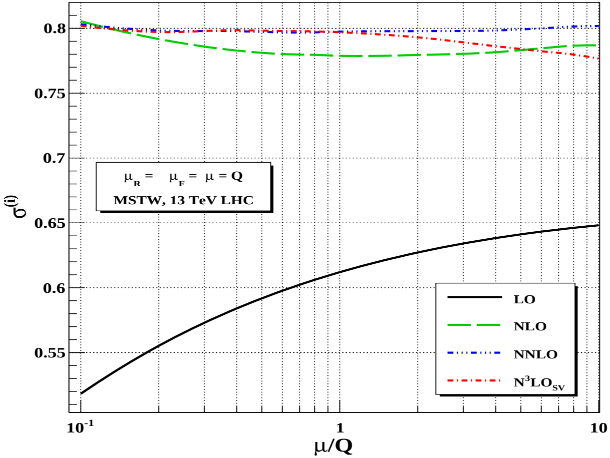
Higgs associated production at the LHC
Scale dependence



MC Kumar, M.K. Mandal and V.Ravindran; JHEP 1503 (2015) 037


0.8
0.75
0.7
0.65
0.6
0.55
$\sigma^{(i)}$
μ_R = Q
MSTW, 13 TeV LHC
LO
NLO
NNLO
N^3LO_{SV}
10^{-1}
1
10
μ_F/Q

Higgs associated production at the LHC
Scale dependence



- Two effective operators for pseudo scalar unlike Higgs boson

$$\mathcal{L}^A_{\rm eff} = \chi^A(x)\Big[-\frac{1}{8} C_G O_G(x) - \frac{1}{2} C_J O_J(x)\Big]$$

$$O_G(x) = G^{\mu\nu}_a \tilde{G}_{\mu\nu,a} \equiv \epsilon_{\mu\nu\rho\sigma} G^{\mu\nu}_a G^{\rho\sigma}_a \,, \qquad O_J(x) = \partial_\mu \left(\bar{\psi}\gamma^\mu \gamma_5 \psi\right) \,.$$

- Only first non-vansishing term in the Wilson coefficients

$$C_G = -a_s 2^{\frac{5}{4}} G_F^{\frac{1}{2}} \cot\beta \,,$$

$$C_J = -\left[a_s C_F \left(\frac{3}{2} - 3\ln\frac{\mu_R^2}{m_t^2}\right) + a_s^2 C_J^{(2)} + \cdots\right] C_G \,.$$

Pseudo scalar cross sections

$$\sigma^A(\tau, m_A^2) = \sigma^{A,(0)} \sum_{a,b=q,\bar{q},g} \int_\tau^1 dy\ \Phi_{ab}(y, \mu_F^2) \Delta_{ab}\left(\frac{\tau}{y}, m_A^2, m_t^2, \mu_F^2, \mu_R^2\right)$$

$$\sigma^{A,(0)} = \frac{\pi\sqrt{2}G_F}{16} a_s^2 \cot^2\beta \, \left|\tau_A f(\tau_A)\right|^2 .$$

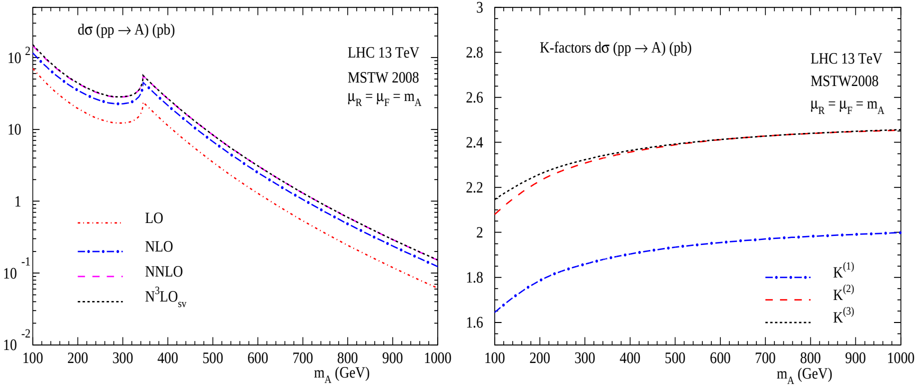
Here $\tau_A = 4m_t^2/m_A^2$

$$f(\tau_A) = \begin{cases} \arcsin^2 \frac{1}{\sqrt{\tau_A}} & \tau_A \geq 1\,, \\ -\frac{1}{4}\left(\ln \frac{1-\sqrt{1-\tau_A}}{1+\sqrt{1-\tau_A}} + i\pi\right)^2 & \tau_A < 1\,. \end{cases}$$

$$\Phi_{ab}(y, \mu_F^2) = \int_y^1 \frac{dx}{x} f_a(x, \mu_F^2) f_b\left(\frac{y}{x}, \mu_F^2\right) ,$$

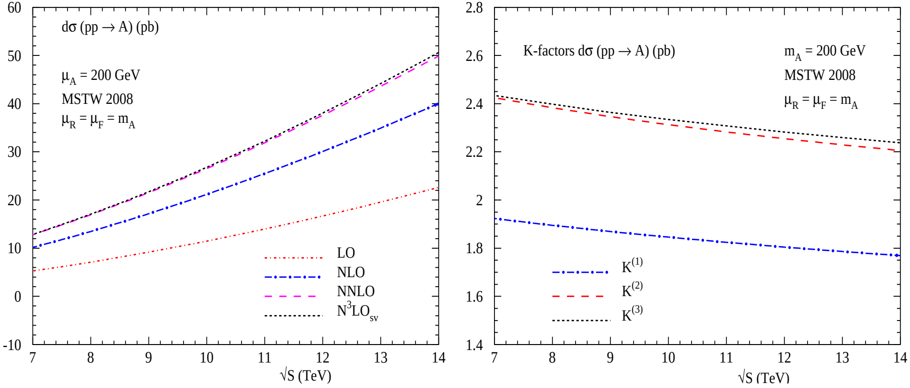
Pseudo scalar cross sections

Production cross sections to N^3LO



T.Ahmed, M.C. Kumar, P.Mathews, N.Rana and V.Ravindran; arXiv:1510:02235

Center of mass energy variation
Ecm variation



$\sqrt{s}$ TeV	SM Higgs			Pseudo-scalar		
	$K^{(1)}$	$K^{(2)}$	$K^{(3)}$	$K^{(1)}$	$K^{(2)}$	$K^{(3)}$
7	1.83	2.31	2.44	1.84	2.34	2.37
8	1.79	2.27	2.40	1.81	2.29	2.33
10	1.74	2.19	2.33	1.76	2.22	2.26
13	1.68	2.10	2.24	1.69	2.13	2.18
14	1.66	2.08	2.22	1.67	2.10	2.16

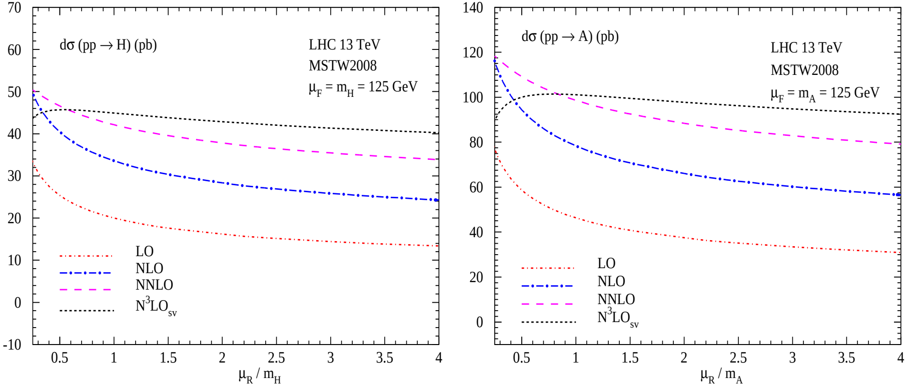
PDF uncertainties

PDF set	SM Higgs			Pseudo-scalar		
	NLO	NNLO	N^3LO_{SV}	NLO	NNLO	N^3LO_{SV}
ABM11	33.19	39.59	41.99	77.42	92.66	94.64
CT10	31.79	41.84	44.67	74.15	97.94	100.44
MSTW2008	33.59	42.13	44.92	78.35	98.61	101.06
NNPDF 23	33.55	43.01	45.87	78.26	100.70	103.19

- PDF uncertainties at NLO, NNLO and N3LO are : 5.7%, 8.6% and 9.2%
- Different groups differ at higher orders

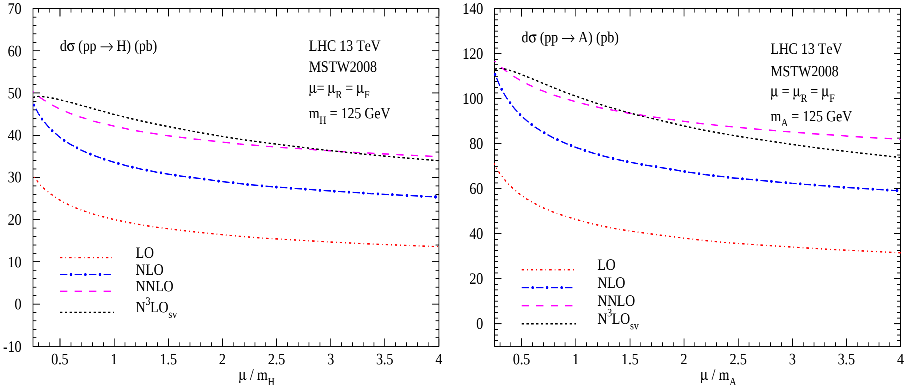
Higgs vs Pseudo scalar

QCD corrections are similar

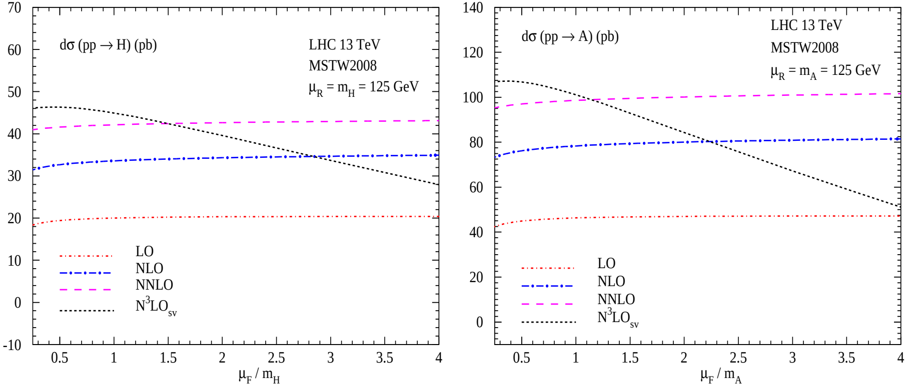


T.Ahmed, M.C. Kumar, P.Mathews, N.Rana and V.Ravindran; arXiv:1510:02235

Higgs vs Pseudo scalar
Scale uncertainties



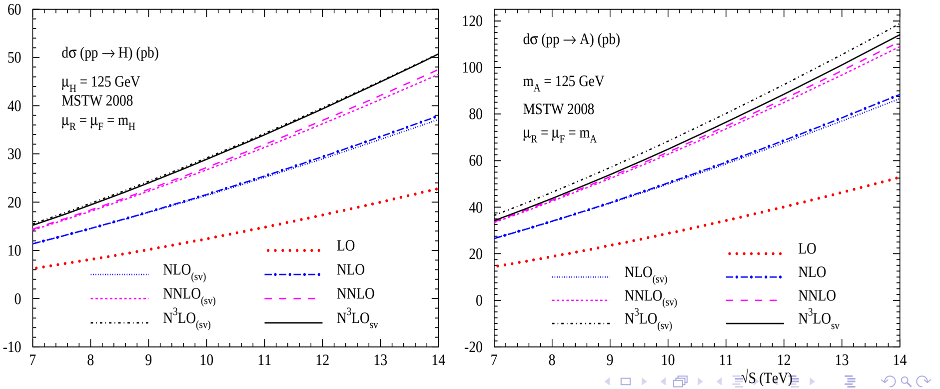
Higgs vs Pseudo scalar
Scale uncertainties



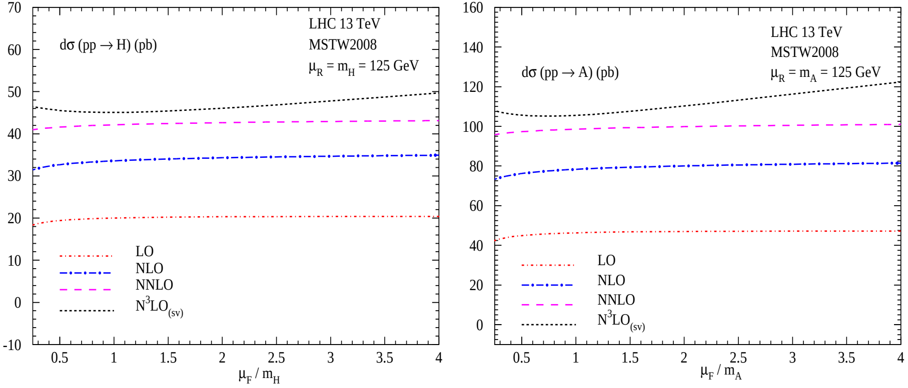
Enhanced threshold corrections

$$\sigma^A(\tau) = \sigma^{A,(0)} \sum_{a,b=q,\bar{q},g} \int_\tau^1 dy\; G\left(\frac{\tau}{y}\right) \Phi_{ab}(y) \left(\frac{\Delta_{ab}^A\left(\frac{\tau}{y}\right)}{G\left(\frac{\tau}{y}\right)} \right)$$

$$\Delta(z)/G(z) = \Delta^{\rm SV}(z) + \tilde{\Delta}^{\rm hard}(z)$$



Higgs vs Pseudo scalar
Scale uncertainties



Summary

- QCD corrections at threshold N3LO have been computed for VH and pseudo-scalar production processes at the LHC.
- The QCD corrections are identical for both Higgs and Pseudo scalar production in the gluon fusion channel
- They also minimize the uncertainties due to the unphysical scales μ_R and μ_F.
- QCD corrections besides offering precise theory predictions, also explore the rich quantum theory structures.


Thanks!

Threshold corrections for jet production

Cone size dependence