中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Precise Prediction on Higgs Production

Zhao Li
IHEP-CAS

First China LHC Physics workshop @USTC, Dec 18, 2015

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- Improved Numerical Approach
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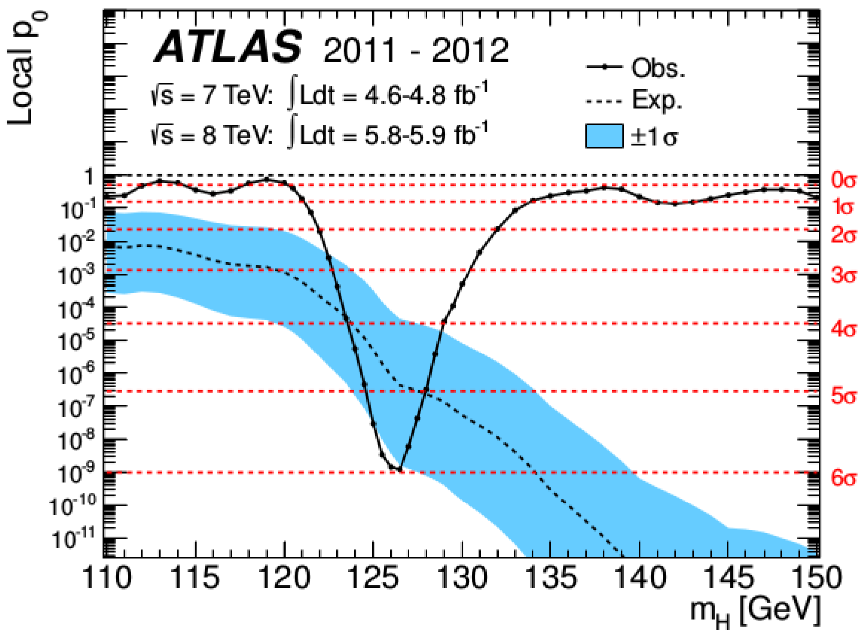
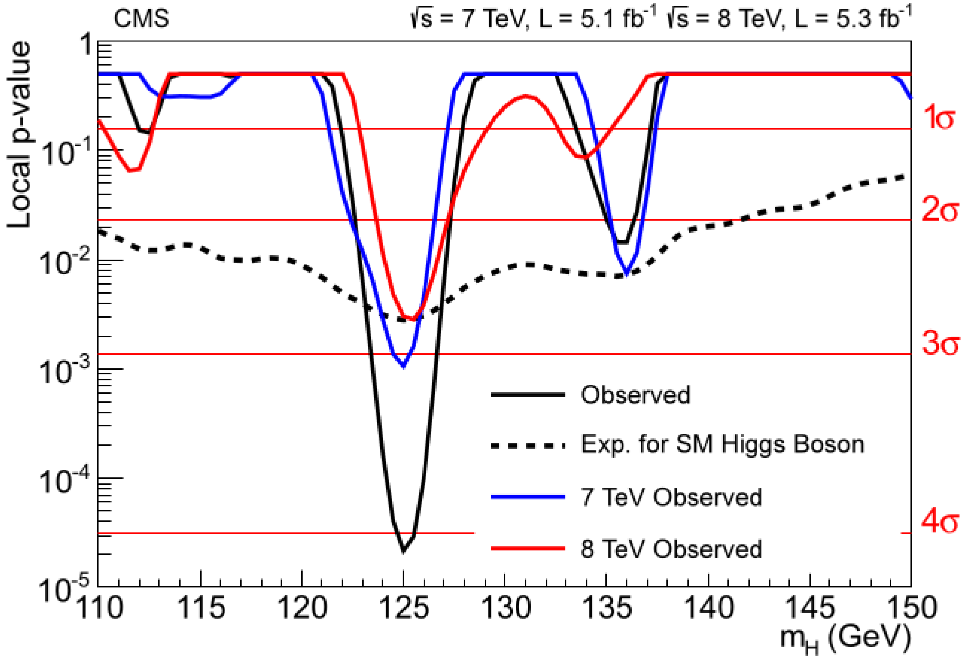
2012 July 4th Higgs observed

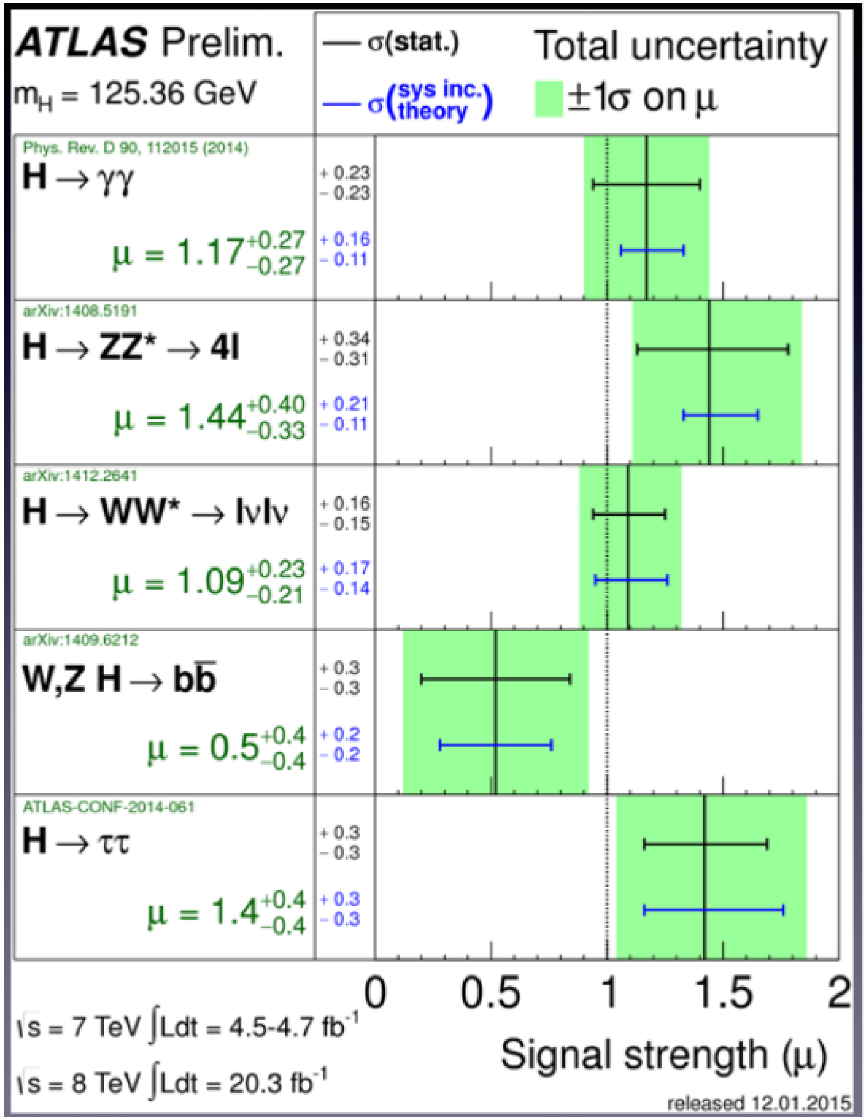




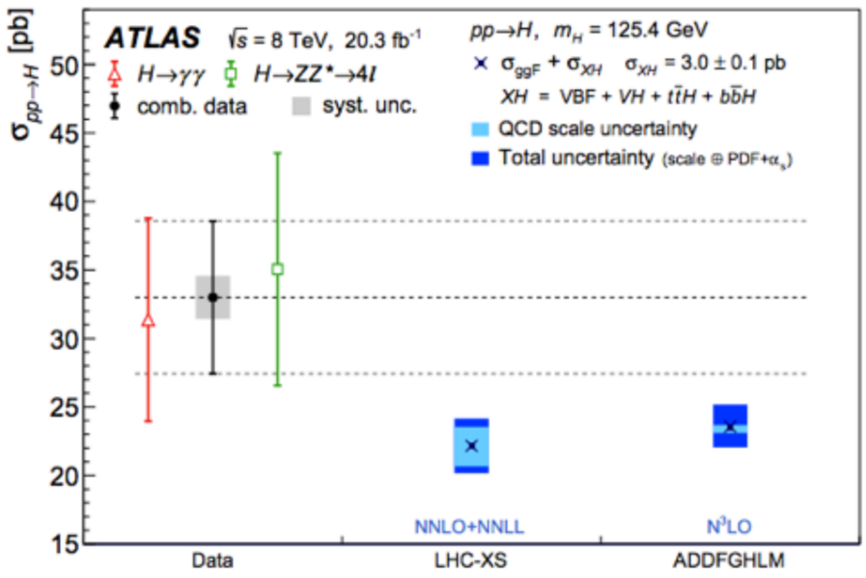
Properties of Higgs

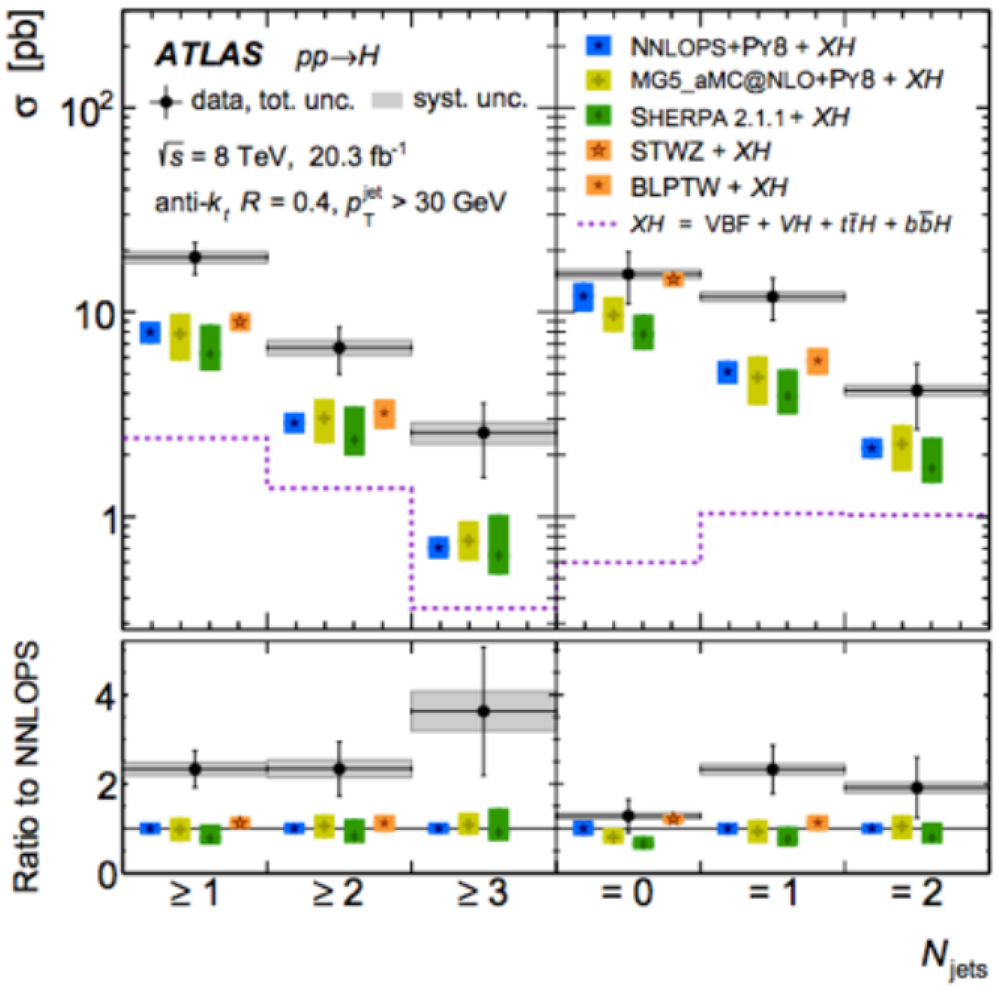
- Scalar
- Mass ~125GeV
- Br's ~ SM

100% satisfied?



Higgs Xsection reconstruction



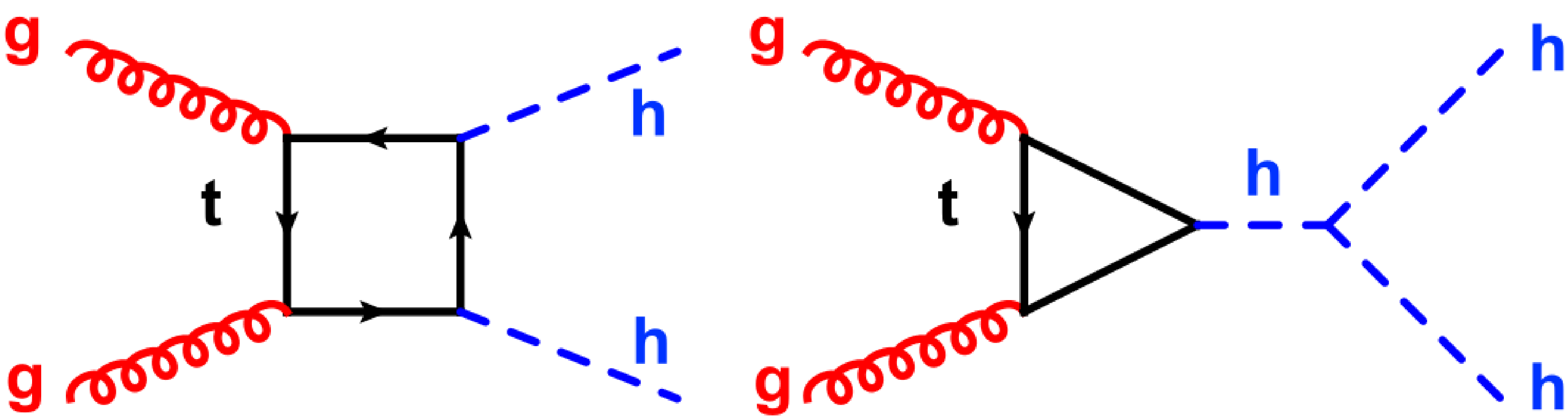


Les Houches wishlist

Process	known	desired	motivation
H	d\sigma @ NNLO QCD d\sigma @ NLO EW finite quark mass effects @ NLO	d\sigma @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H+j	d\sigma @ NNLO QCD (g only) d\sigma @ NLO EW	d\sigma @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H+2j	\sigma_tot(VBF) @ NNLO(DIS) QCD d\sigma(gg) @ NLO QCD d\sigma(VBF) @ NLO EW	d\sigma @ NNLO QCD + NLO EW	H couplings
H+V	d\sigma(V decays) @ NNLO QCD d\sigma @ NLO EW	with H→bb @ same accuracy	H couplings
t\bar tH	d\sigma(stable tops) @ NLO QCD	d\sigma(NWA top decays) @ NLO QCD + NLO EW	top Yukawa coupling
HH	d\sigma @ LO QCD finite quark mass effects d\sigma @ NLO QCD large m_t limit	d\sigma @ NLO QCD finite quark mass effects d\sigma @ NNLO QCD	Higgs self coupling

Higgs Pair Production

HH	d\sigma @ LO QCD finite quark mass effects d\sigma @ NLO QCD large m_t limit	d\sigma @ NLO QCD finite quark mass effects d\sigma @ NNLO QCD	Higgs self coupling



Higgs Self Coupling

SM

$$\lambda_{HHH} = 3M_H^2/M_Z^2$$

MSSM (2HDM)

$$\lambda_{hhh} \;=\; 3\cos 2\alpha \sin(\beta+\alpha) + 3\frac{\epsilon}{M_Z^2}\frac{\cos\alpha}{\sin\beta}\cos^2\alpha$$

$$\epsilon \;=\; 3G_F M_t^4/(\sqrt{2}\pi^2\sin^2\beta)$$

gg→HH @ NLO and beyond

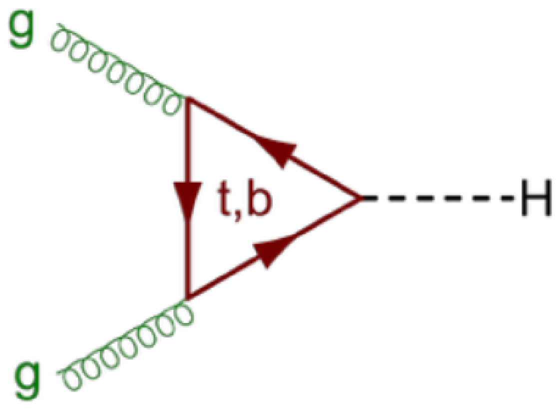
- First attempt PRD58(1998)115012,

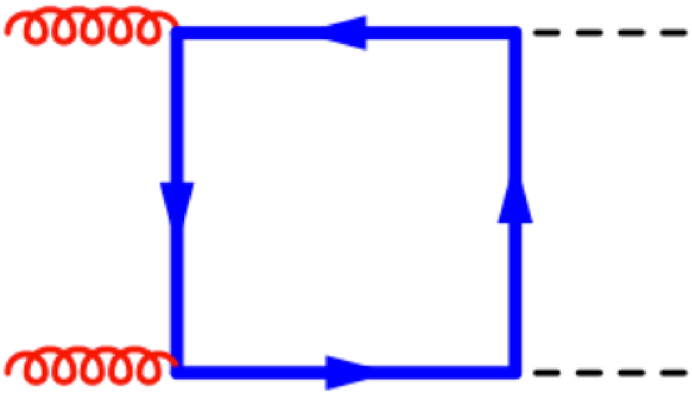
  S. Dawson, S. Dittmaier, M. Spira

- Further attempts: 1305.7340, 1311.7425, 1401.7340, 1408.6542, 1505.07122, 1508.00909, etc.

Large Mt Approx.

However…

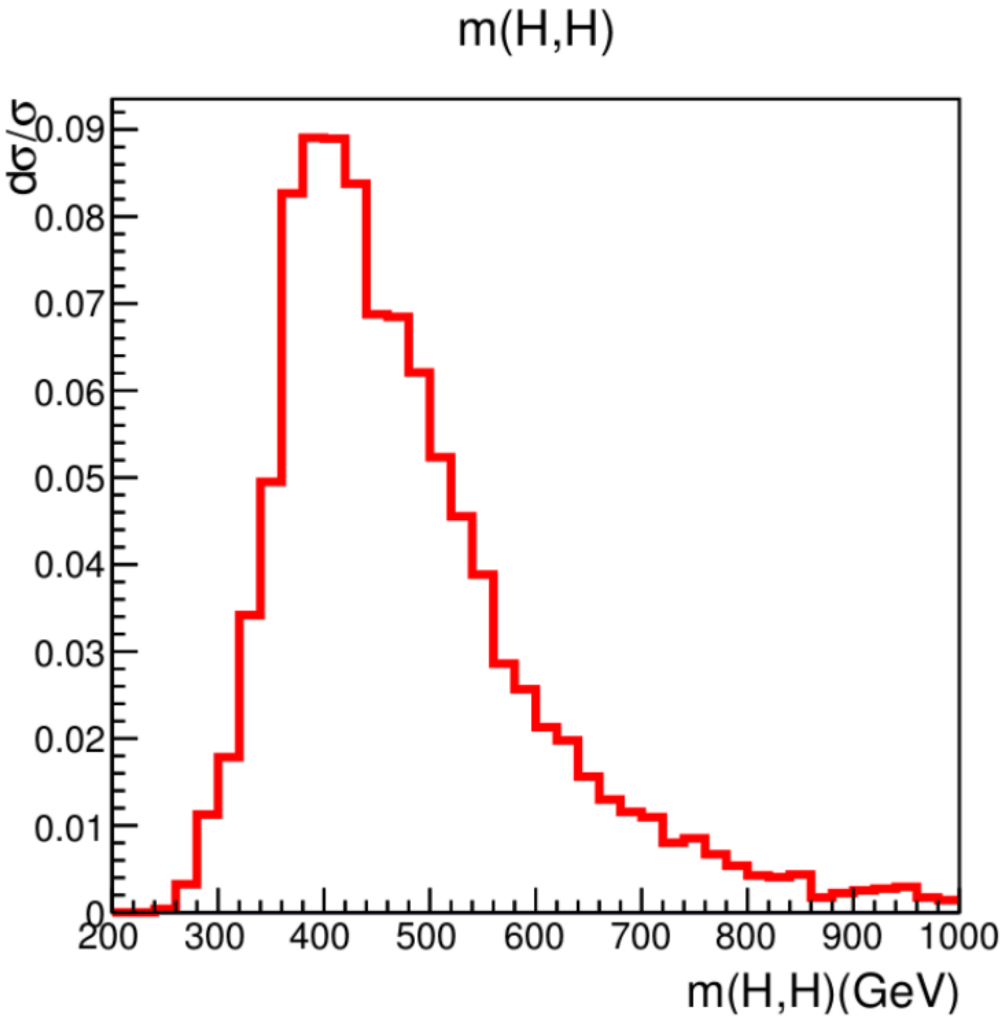




Large Mt Approx.

$$m_t^2 \gg s, t, m_H^2$$

Failed approximation



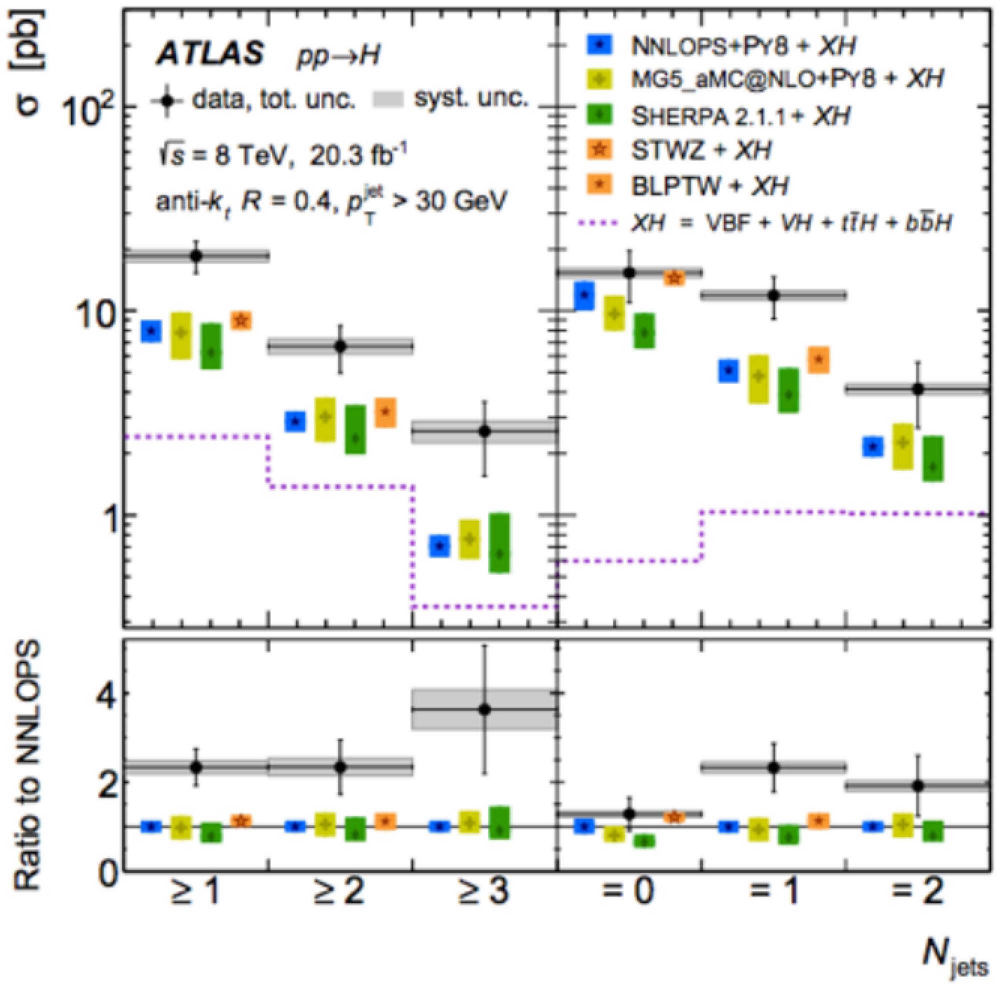
Large Mt Approx.

$$m_t^2 \gg s, t, m_H^2$$

Same problem in Higgs production

Mt >> M(H+j)

Pt(j) cannot be large



Large Mt approx. must be removed for Higgs investigations

Analytical Approach

- 1-loop: PV reduction, unitary cut or others => A, B, C and D functions
- Beyond 1-loop:

  Simple processes only, i.e. not too many scales. No breakthrough yet after more than ten years struggle.

Numerical approach

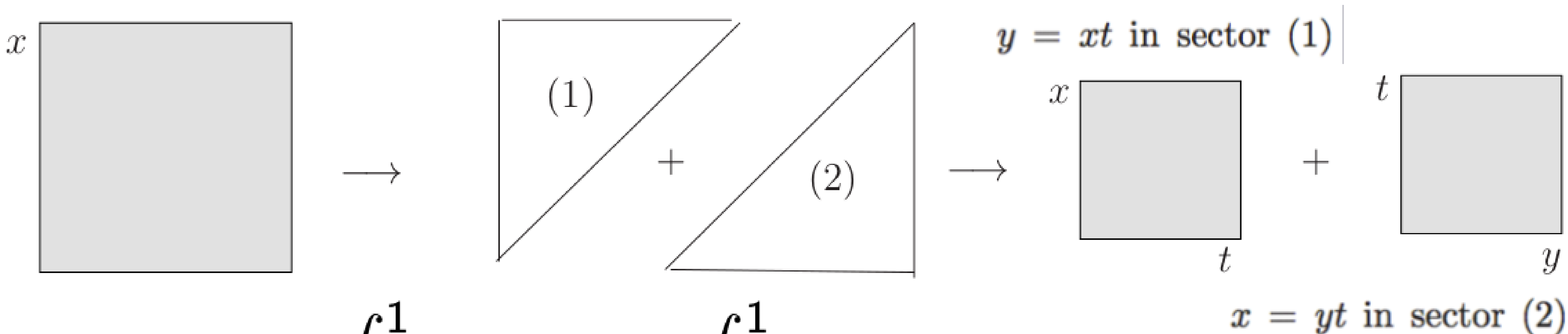
- **1-loop: OPP => aMC@NLO etc.**
- **Beyond 1-loop:**

  "Mellin-Barnes" Slow, and non-physical region

  "Sector Decomposition" Much slower (hours per MI per PS) but quite general (multiple scales)

Sector Decomposition

$$I = \int_0^1 dx \int_0^1 dy \; x^{-1-\epsilon} y^{-\epsilon} (x + (1-x)y)^{-1}$$



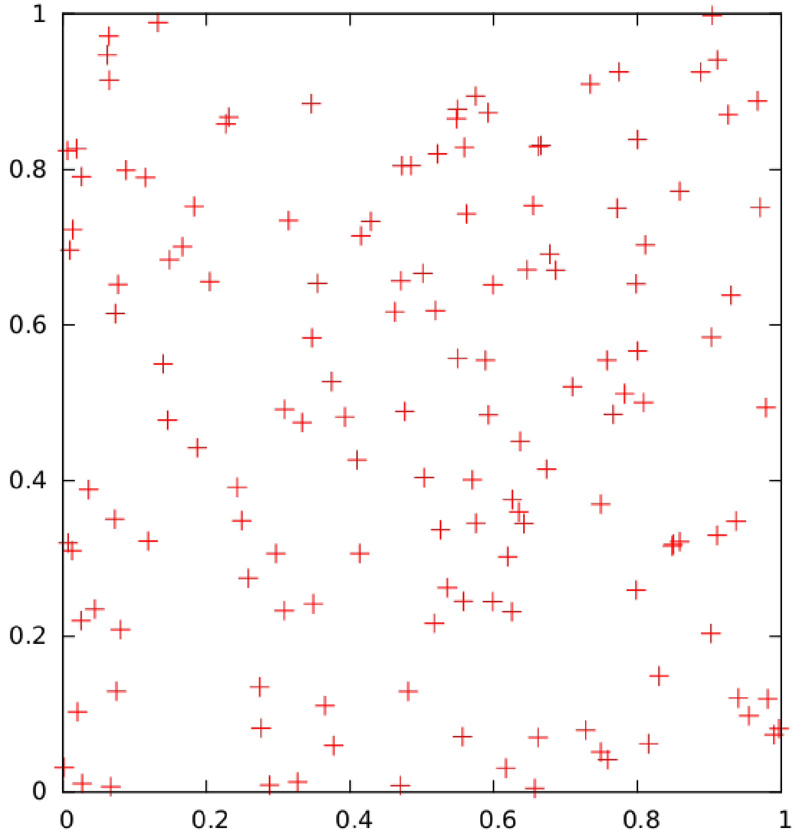
$$I = \int_0^1 dx \; x^{-1-\epsilon} \int_0^1 dt \; t^{-\epsilon} (1 + (1-x)t)^{-1}$$

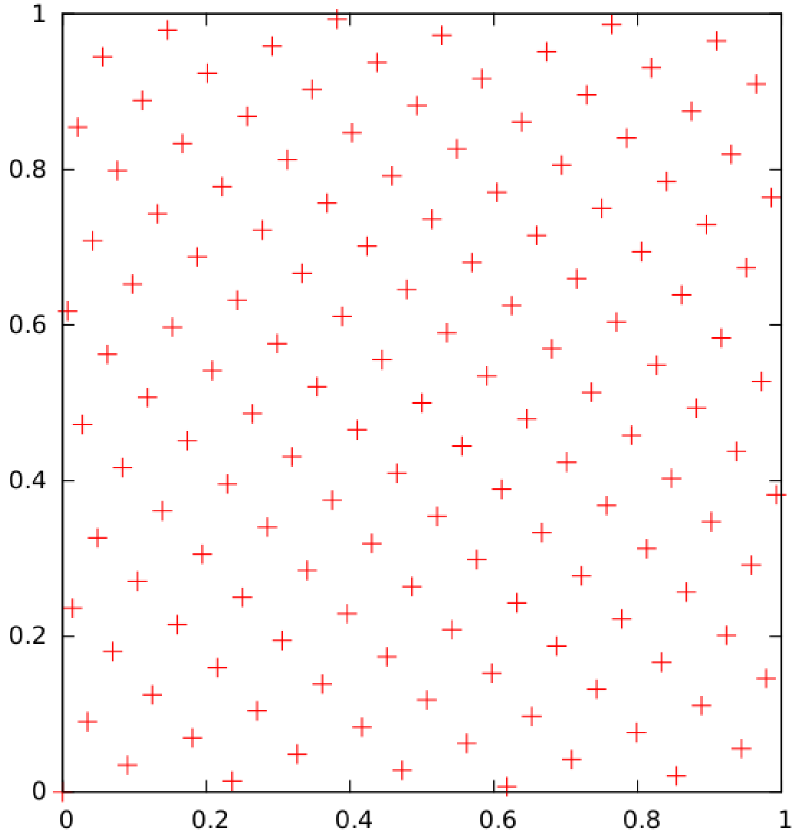
$$+ \int_0^1 dy \; y^{-1-2\epsilon} \int_0^1 dt \; t^{-1-\epsilon} (1 + (1-y)t)^{-1}$$

Quasi-Monte-Carlo

$$I(f) = \int_0^1 d^s x f(\vec{x})$$

$$I_{estimate}(f) = \sum_{i=0}^{n-1} f(\vec{x_i})$$





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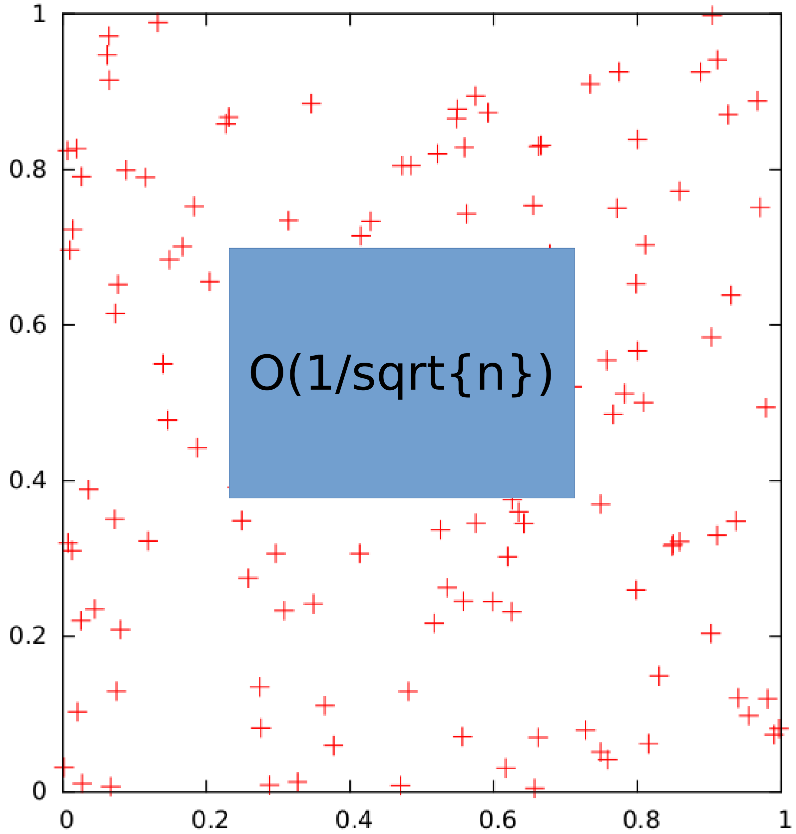
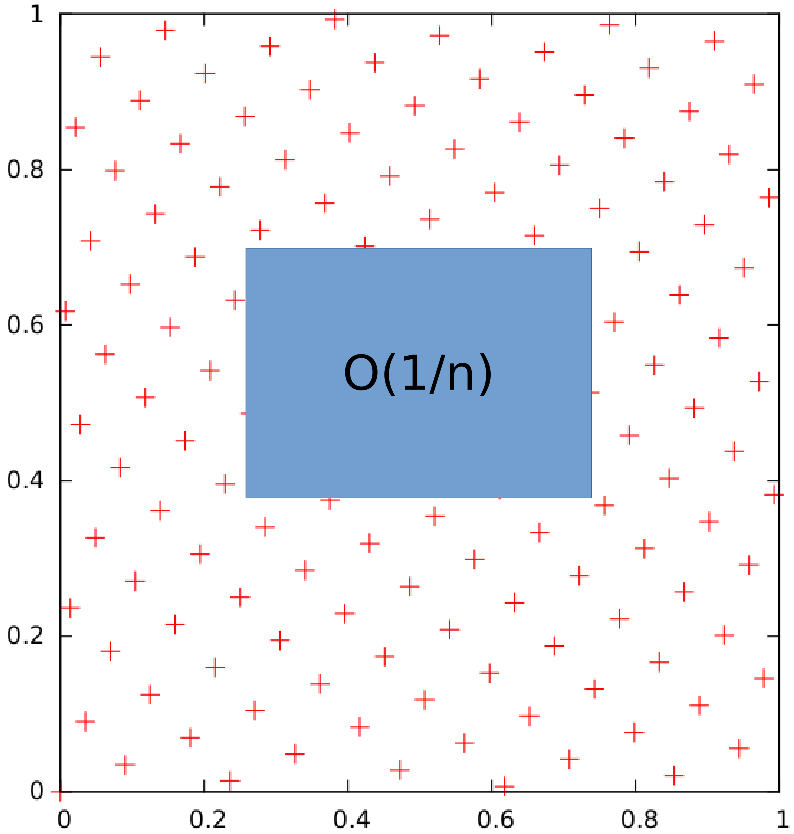
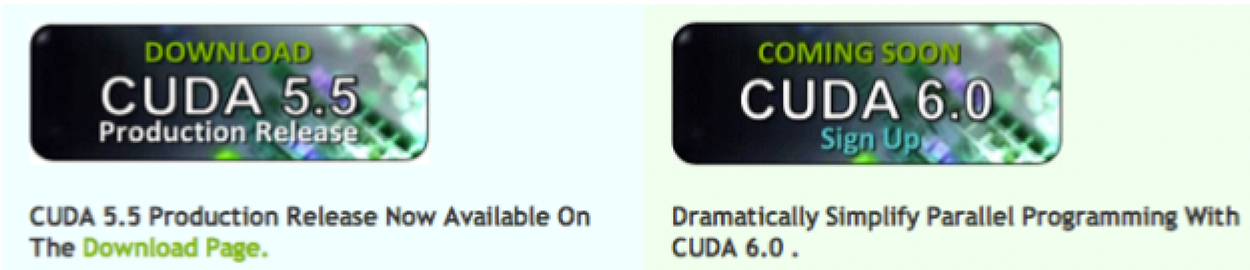
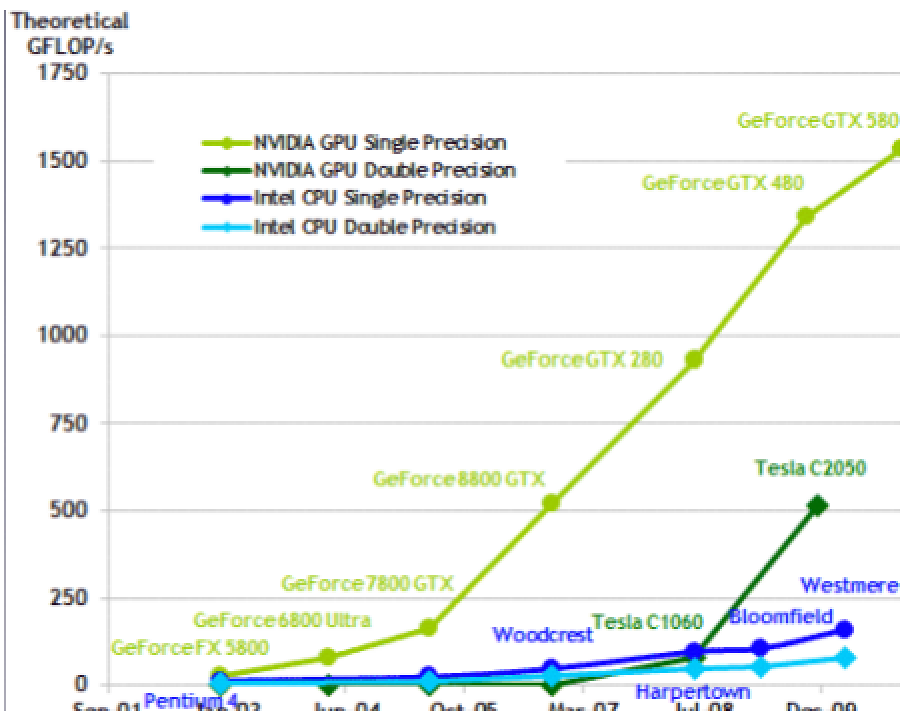
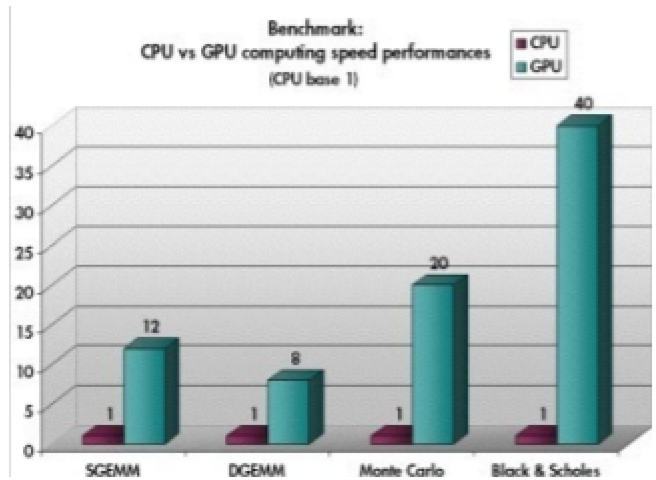




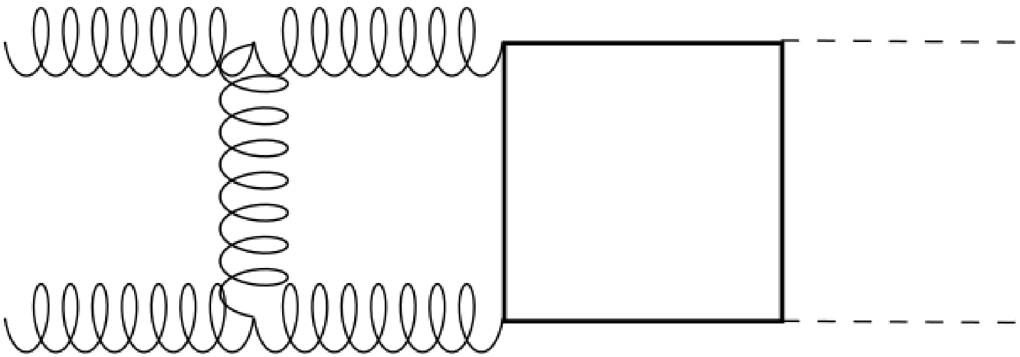
Parallel (GPU) technique







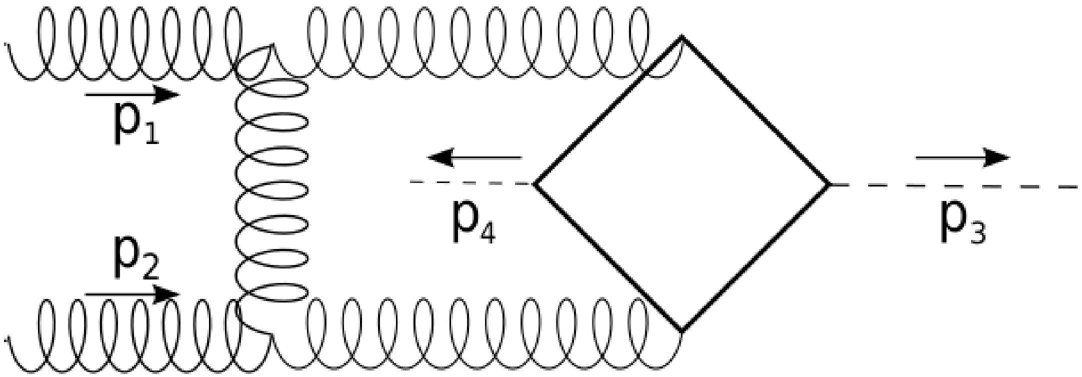
Planar Two-Loop Master Integral



$$I_C = e^{-2\epsilon\gamma_E} s^{-3-2\epsilon} \sum_{i=0}^{i=2} \frac{P_i}{\epsilon^i}.$$

	Vegas/CPU	QMC/GPU
P_2	$-7.959 \pm 0.009 - 10.586i \pm 0.009i$	$-7.949 \pm 0.003 - 10.585i \pm 0.005i$
P_1	$3.9 \pm 0.1 - 28.1i \pm 0.1i$	$3.831 \pm 0.005 - 28.022i \pm 0.005i$
P_0	$-3.9 \pm 0.8 + 92.3i \pm 0.8i$	$-4.63 \pm 0.07 + 92.13i \pm 0.07i$
Integration Time	45540s	19s

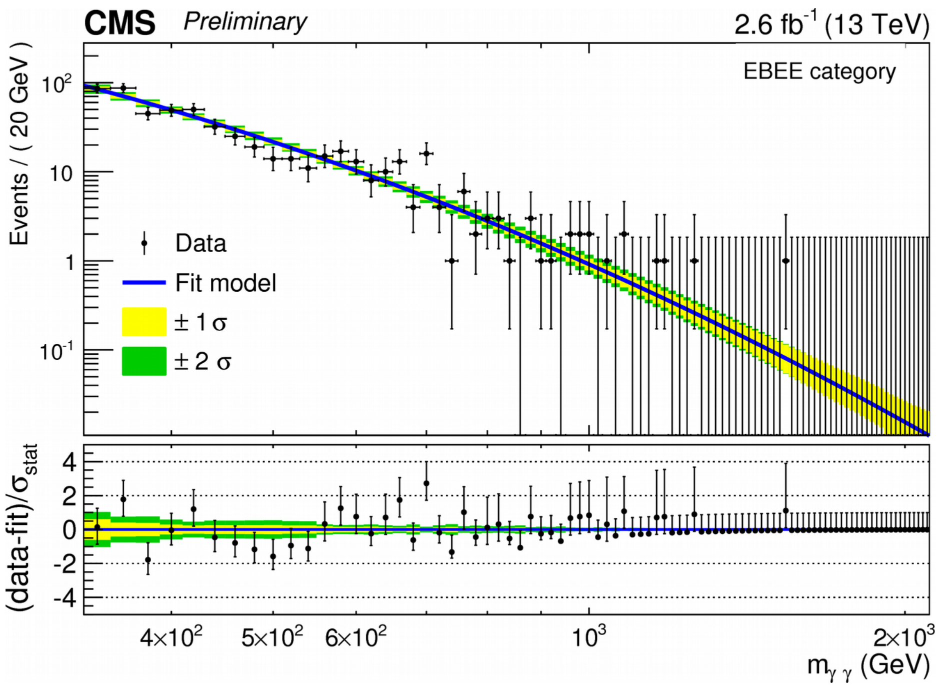
Non-Planar Two-Loop Master Integral

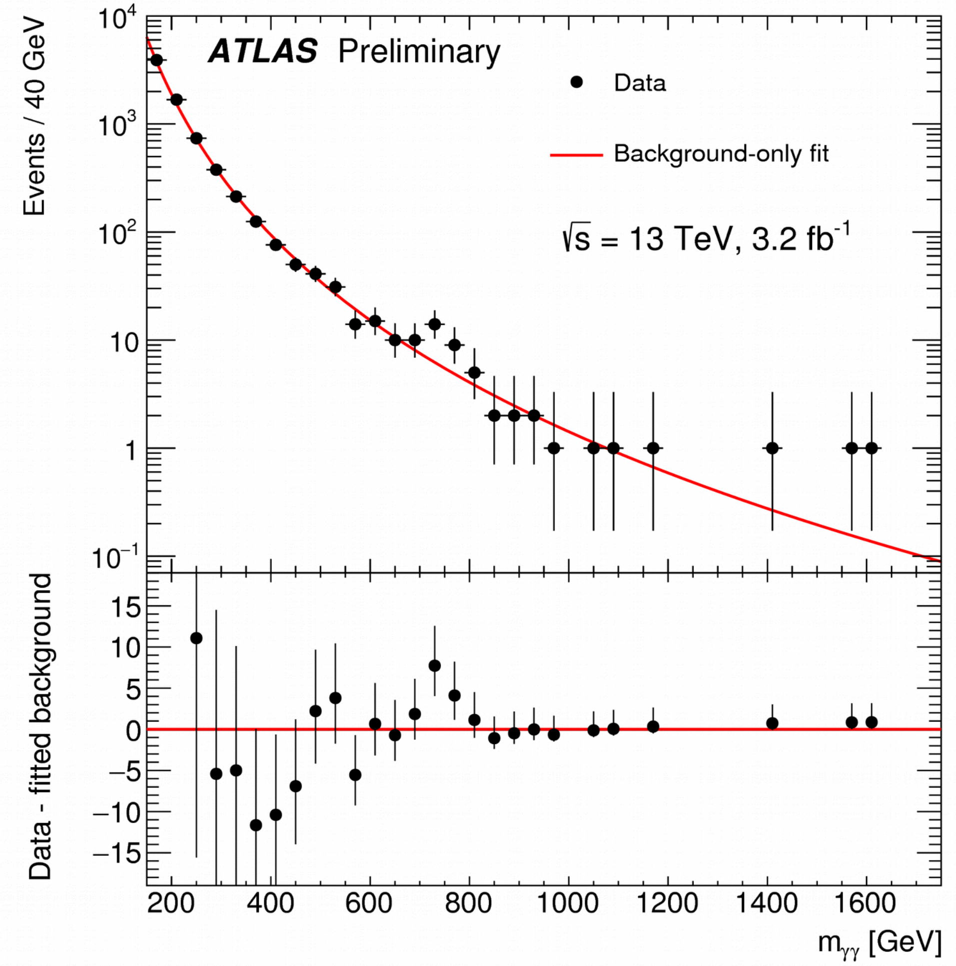


$$I_D = e^{-2\epsilon\gamma_E} s^{-3-2\epsilon} \sum_{i=0}^{i=2} \frac{P_i}{\epsilon^i}.$$

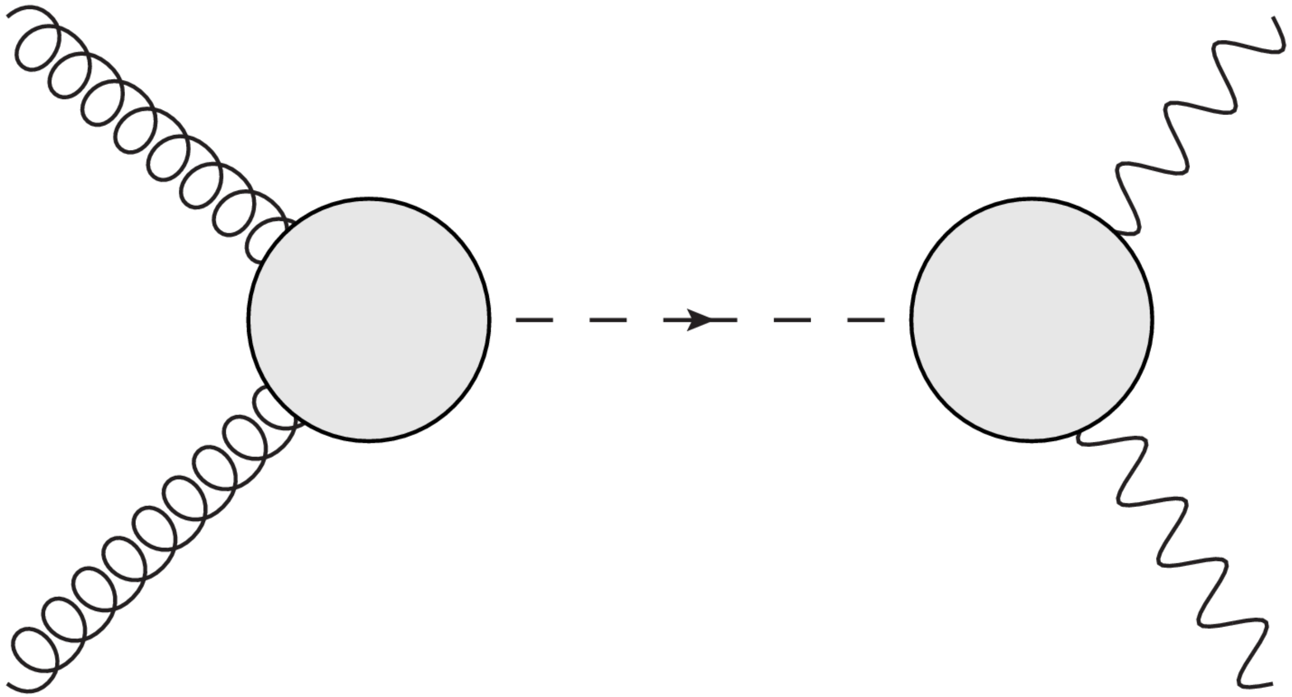
	Vegas/CPU	QMC/GPU
P_2	$-3.848 \pm 0.004 + 0.0005i \pm 0.003i$	$-3.8482 \pm 0.0007 + 0.0004i \pm 0.0003i$
P_1	$3.81 \pm 0.03 - 6.41i \pm 0.03i$	$3.83 \pm 0.02 - 6.40i \pm 0.02i$
P_0	$77.2 \pm 0.2 + 20.1i \pm 0.2i$	$77.2 \pm 0.1 + 19.9i \pm 0.1i$
Integration Time	54290s	20s

750GeV resonance @ 13TeV LHC





750GeV production via gluon fusion



Conclusion & Prospect

- **Large Mt approximation is not suitable for Higgs associated production investigation.**
- **For the first time, we present the results of two-loop master integrals for gg→HH with finite top quark mass.**
- **Our improved numerical algorithm can obtain results with reasonable accuracy in acceptible time for complete gg->HH@NLO (two-loop) with finite top mass.**

Conclusion & Prospect

- **750GeV (pseudo)scalar production via gluon fusion will rely on loop effect.**
- **H+j@NLO, ttH@NNLO, etc. may be important for HL-LHC**
- **Money, Money, Money**

Thank You