Higgs production @ NNLO

Up-to-date predictions for inclusive cross-sections and differential distributions in different decay channels

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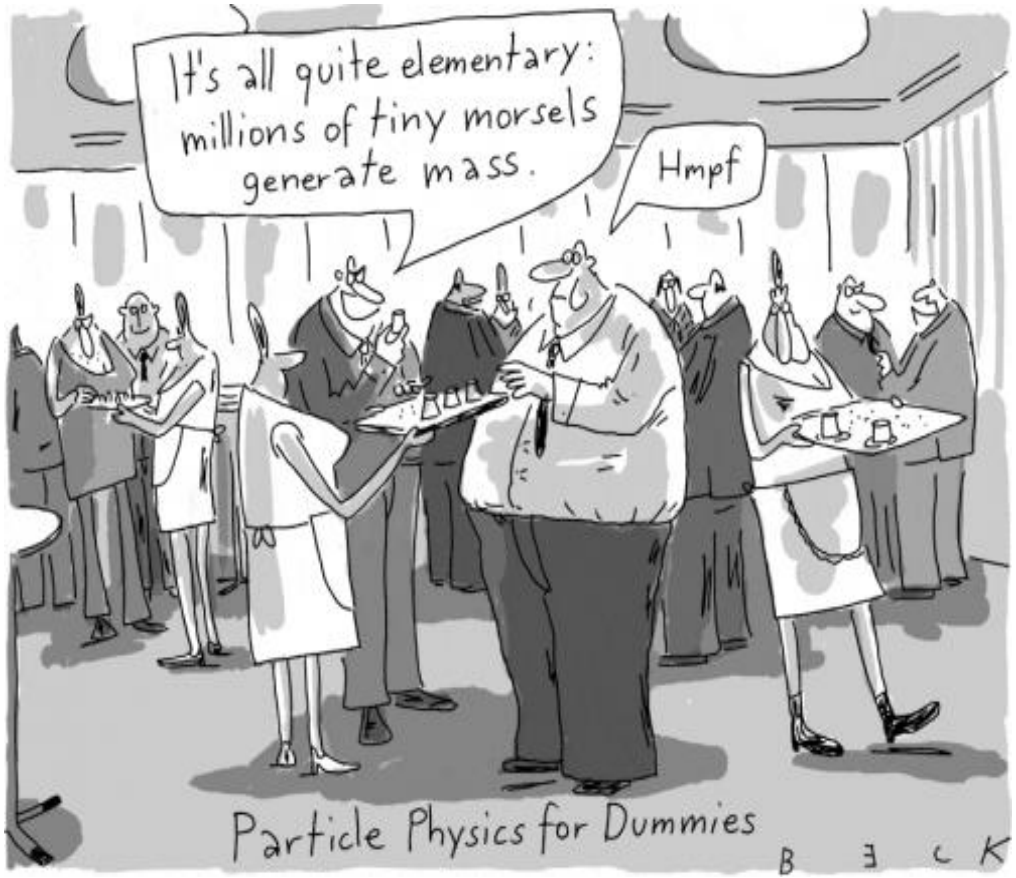
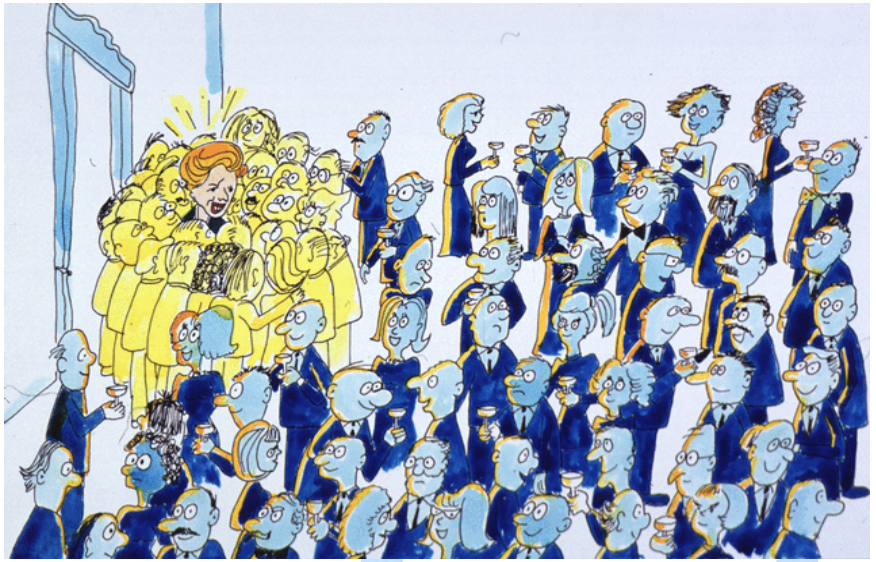
Higgs boson and particle masses





Motivation

- Assume you find a Higgs with $m_{\mathrm{h}} = 120$ and a cross-section $\sigma \sim 0.35\sigma_{\mathrm{SM}}$ ...
- ... do you claim to have found a BSM Higgs?
- What about $\sigma \sim 0.8\sigma_{\mathrm{SM}}$? $\sigma \sim 0.9\sigma_{\mathrm{SM}}$?

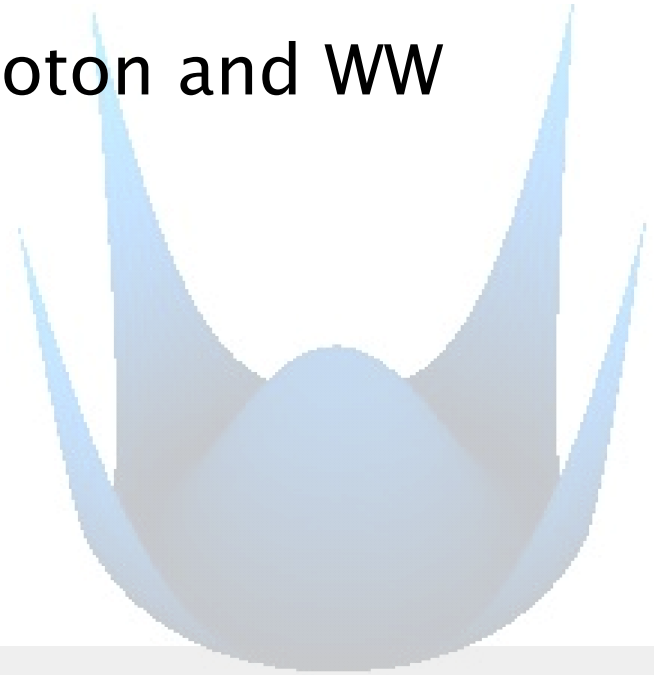
$\Rightarrow$ precise knowledge of σ_{SM} as well as σ_{BSM} is crucial!

... and a thorough estimation of uncertainties.

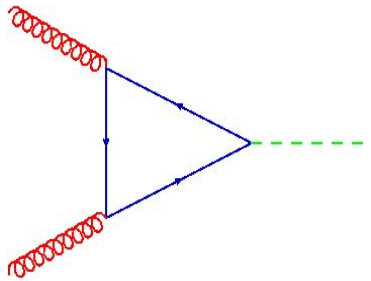
- All results presented here have been obtained with **FeHiPro** = **FEHiP** + **HPro** (to be published soon) and are preliminary

Outline

- Exact mass dependence through NLO
- Up-to-date inclusive cross-section
- Estimation of uncertainties
- Differential distributions in Di-photon and WW decay channel
- Conclusion and Outlook



Gluon fusion



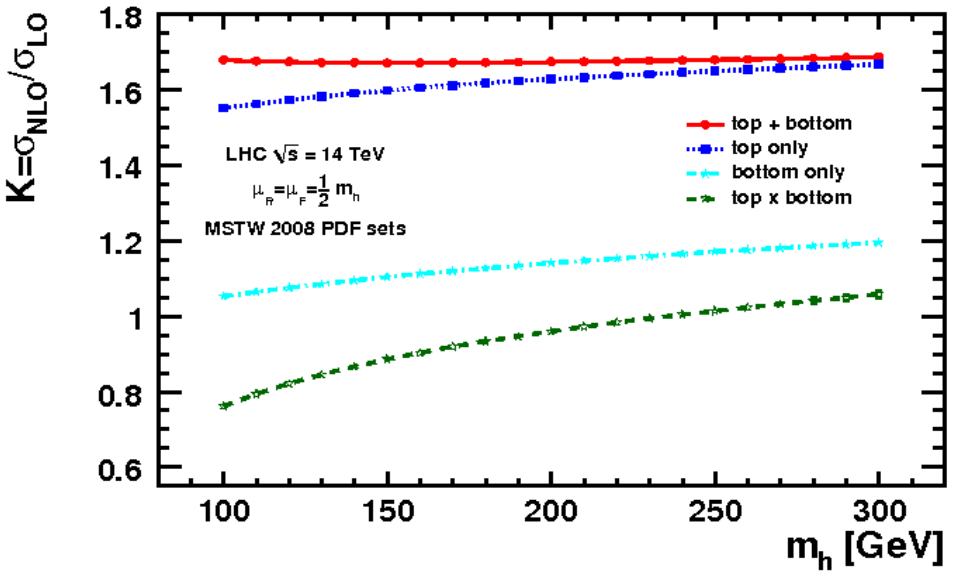
- $gg \to h$: main production channel in hadron colliders, one loop @ LO $\Rightarrow$ sensitive to new physics!
- Large higher order corrections:
  NLO: $> +70\%$ [Dawson; Graudenz, Spira, Zerwas; ...]
  NNLO: $> +20\%$ [Harlander, ...; Anastasiou, ...; Ravindran, ...]
- top & bottom in the loop
- $m_t \to \infty$ limit approximates top contribution within 2% for $m_h < 2\, m_t$
- bottom contribution $< 7\%$

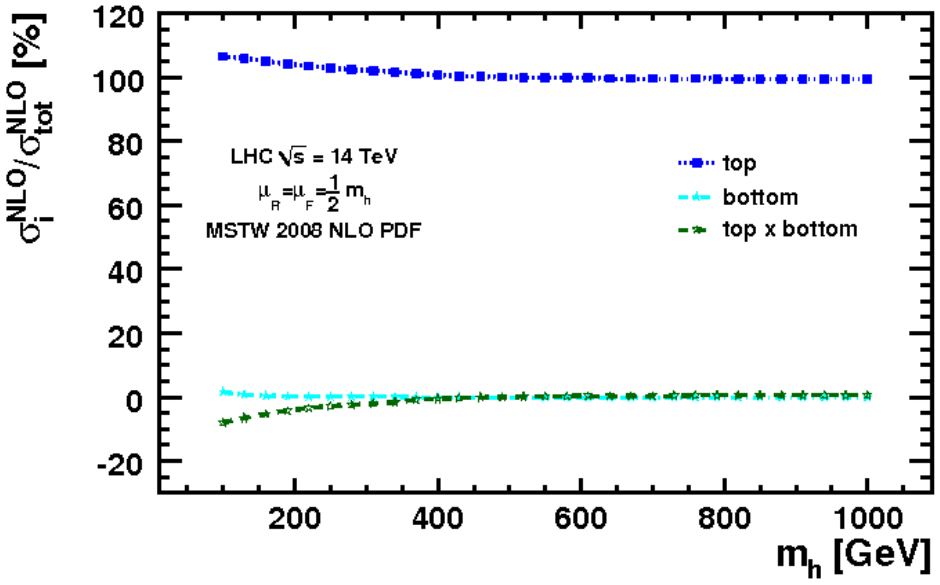
Exact mass dependence

- Well known at NLO:

$$\sigma^{\mathrm{NLO}} = K_{\mathrm{t}}^{\mathrm{NLO}}\sigma_{\mathrm{t}}^{\mathrm{LO}} + K_{\mathrm{t\times b}}^{\mathrm{NLO}}\sigma_{\mathrm{t\times b}}^{\mathrm{LO}} + K_{\mathrm{b}}^{\mathrm{NLO}}\sigma_{\mathrm{b}}^{\mathrm{LO}}$$
$$\neq K_{\mathrm{t}}^{\mathrm{NLO}}\left(\sigma_{\mathrm{t}}^{\mathrm{LO}} + \sigma_{\mathrm{t\times b}}^{\mathrm{LO}} + \sigma_{\mathrm{b}}^{\mathrm{LO}}\right)$$

- But: $K_{\mathrm{t}}^{\mathrm{NLO}} \sim K_{\infty}^{\mathrm{NLO}}$ within $< 1\%$
  NNLO: mass effects $< 0.5\%$ (talks by Harlander/Pak)



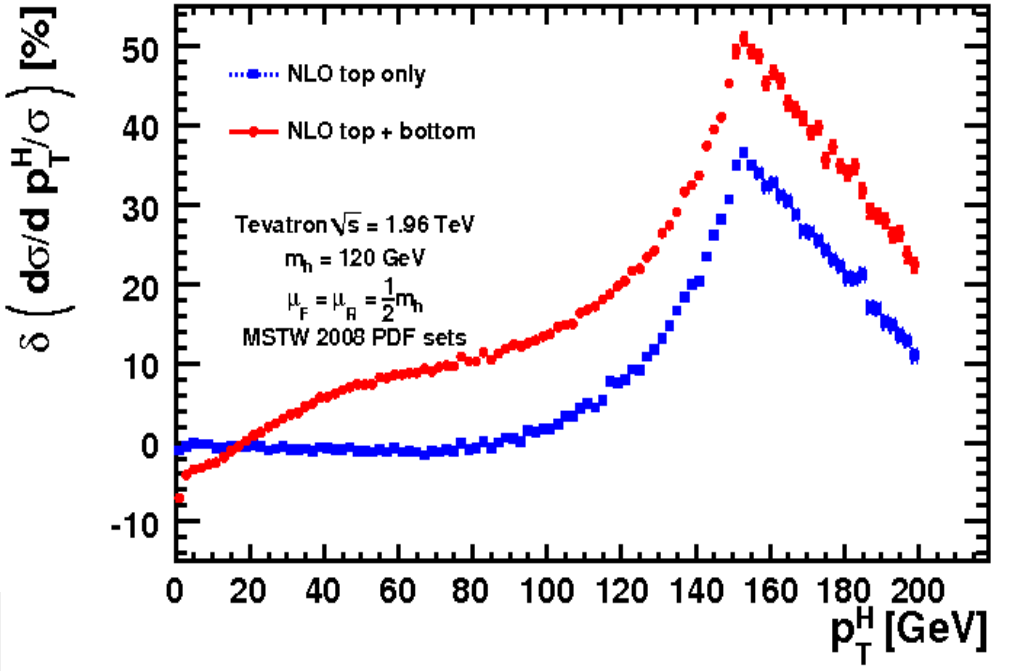


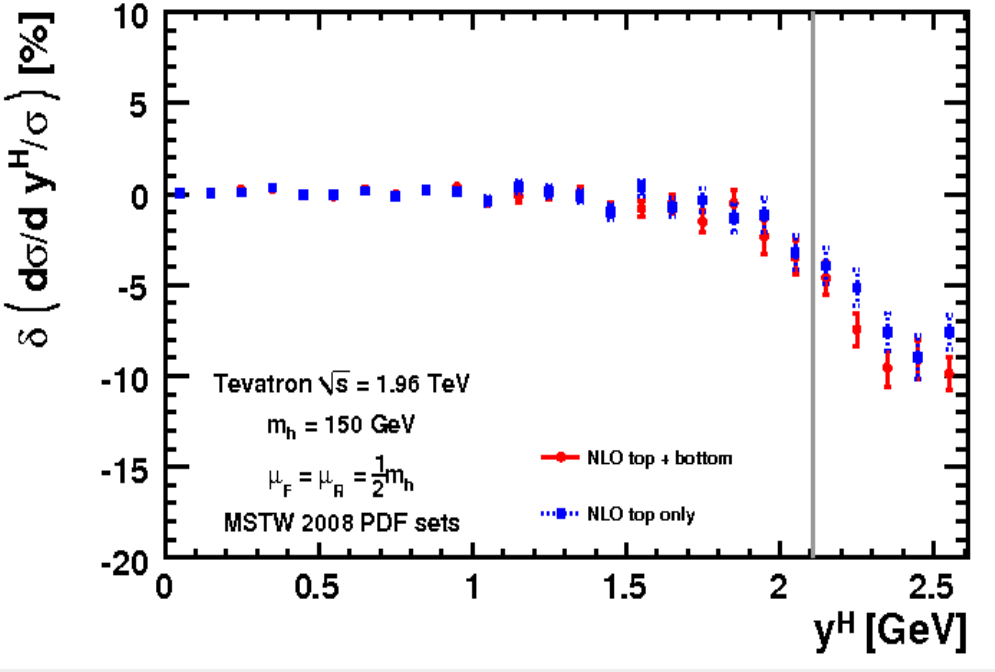
Results obtained with HPro

Exact mass dependence (2)

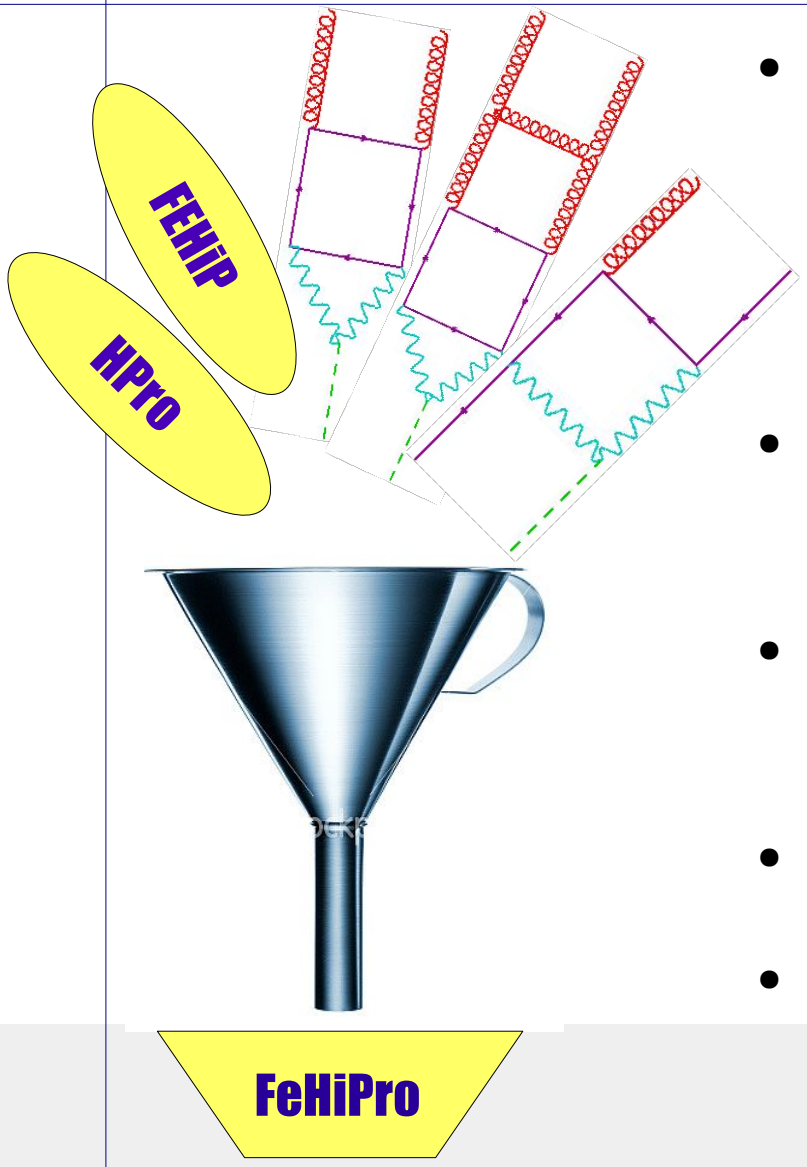
- What about mass effects in differential distributions? Shape changes only in low-rate region.
  [Anastasiou, SB, Kunszt]

$$\delta X_i = \frac{X_i - X_\infty}{X_\infty}$$



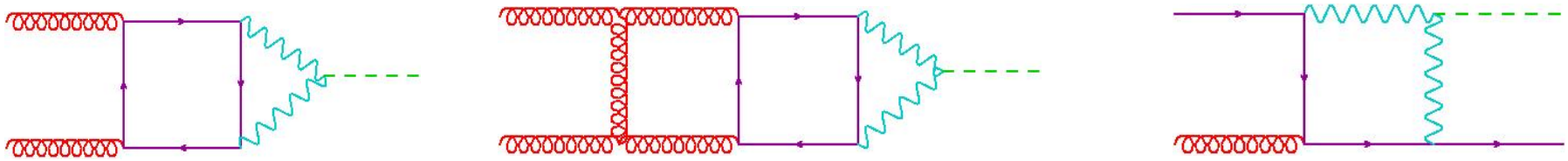


FeHiPro



- Include exact mass dependence into existing fully differential MC code @ NNLO
  FEHiP [Anastasiou, Melnikov, Petriello]
- Add mixed electroweak-QCD corrections [Anastasiou, Boughezal, Petriello]
- Add electroweak contributions to real radiation [Petriello, Keung]
- Improve histogramming
- Simplify computation of PDF error

Improved prediction



- Mixed virtual QCD corrections of the same order as in top quark case ⇒ up to 5 – 6% correction
  [Actis, Passarino, Sturm, Uccirati; Anastasiou, Boughezal, Petriello]

$$\mathcal{L}_{\text{eff}} = \alpha_S \frac{C}{12\pi v} G^a_{\mu\nu} G^{a,\mu\nu} H$$

$$C = 1 + \frac{\alpha_S}{\pi} C_{1q} + \left(\frac{\alpha_S}{\pi}\right)^2 C_{2q} + \lambda_{\text{EW}} \left[1 + \alpha_S \pi C_{1w} + \left(\frac{\alpha_S}{\pi}\right)^2 C_{2w}\right]$$

- Real radiation ⇒ –1% correction (treat it as mass correction)
  [Keung, Petriello]

$$\sigma_{\text{NNLO}} = \sigma^{\infty}_{\text{LO}} + \Delta\sigma^{\infty}_{\text{NLO}} + \Delta\sigma^{\infty}_{\text{NNLO}}$$

$$+\Delta\sigma^{\text{m}}_{\text{LO}} + \Delta\sigma^{\text{m}}_{\text{NLO}} + \Delta\sigma^{\text{ew}}_{\text{LO}} + \Delta\sigma^{\text{ew}}_{\text{NLO}} + \Delta\sigma^{\text{ew}}_{\text{NNLO}}$$

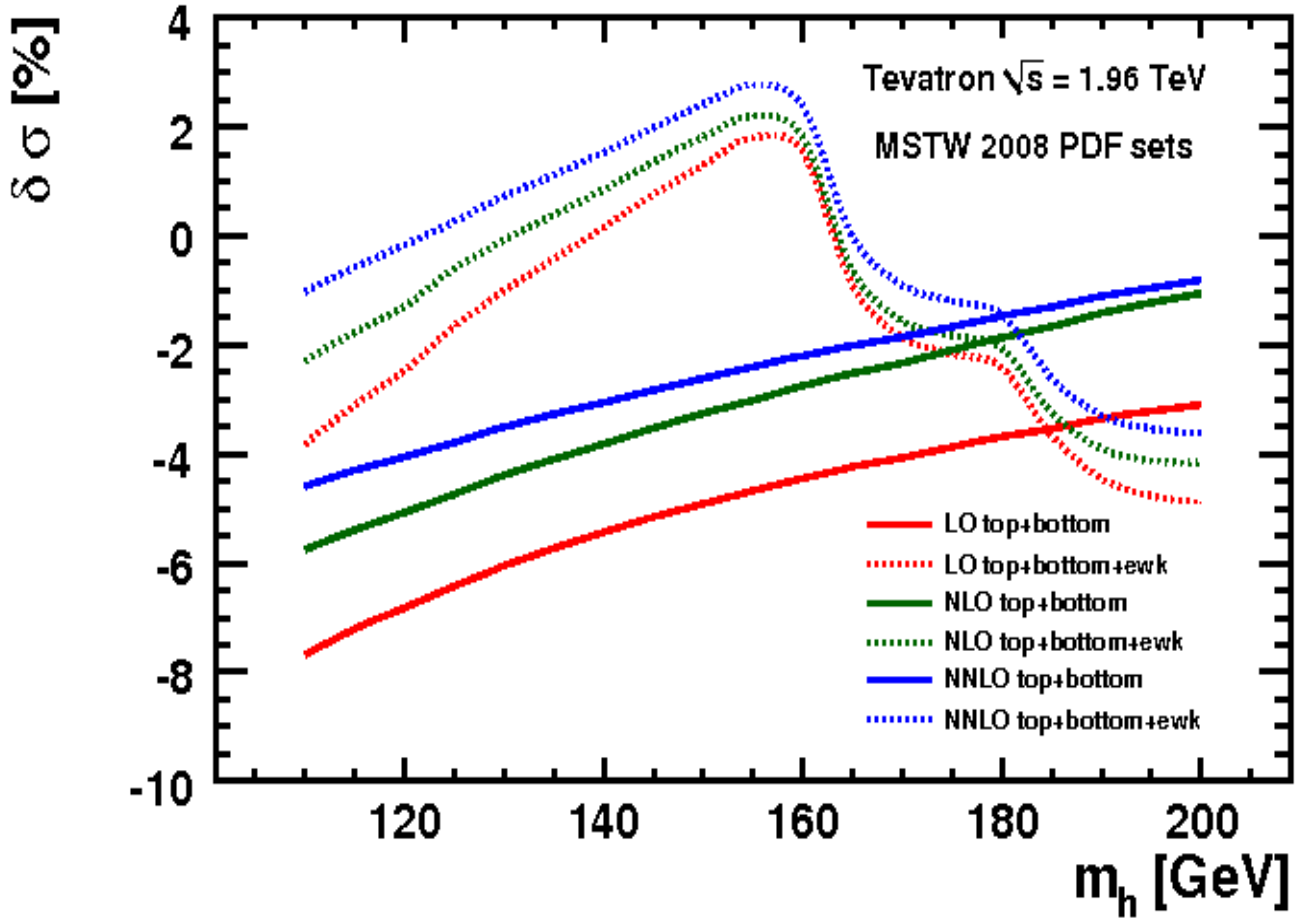
New features in FeHiPro (1)

- Fast option for inclusive cross-sections:
  Analytic integration of NNLO contribution.
- PDF error (using MSTW 2008 sets):

$$(\Delta\sigma)_{\pm} = \left\{ \sum_{k=1}^{n} \left[\max\left(\pm(\sigma(S_k^+) - \sigma(S_0)), \pm(\sigma(S_k^-) - \sigma(S_0)), 0 \right) \right]^2 \right\}^{1/2}$$

  $\Rightarrow$ 41 (n=40) evaluations of cross-section required for determining PDF error (times 5 for PDF+α_S error)
- FeHiPro: Compute all PDF error sets in one run!
- Performance: σ^{LO}, σ^{NLO} and σ^{NNLO} (improved prediction) including PDF error estimation:
  4'28" on INTEL processor @ 3 GHz (rel. error 0.08%)

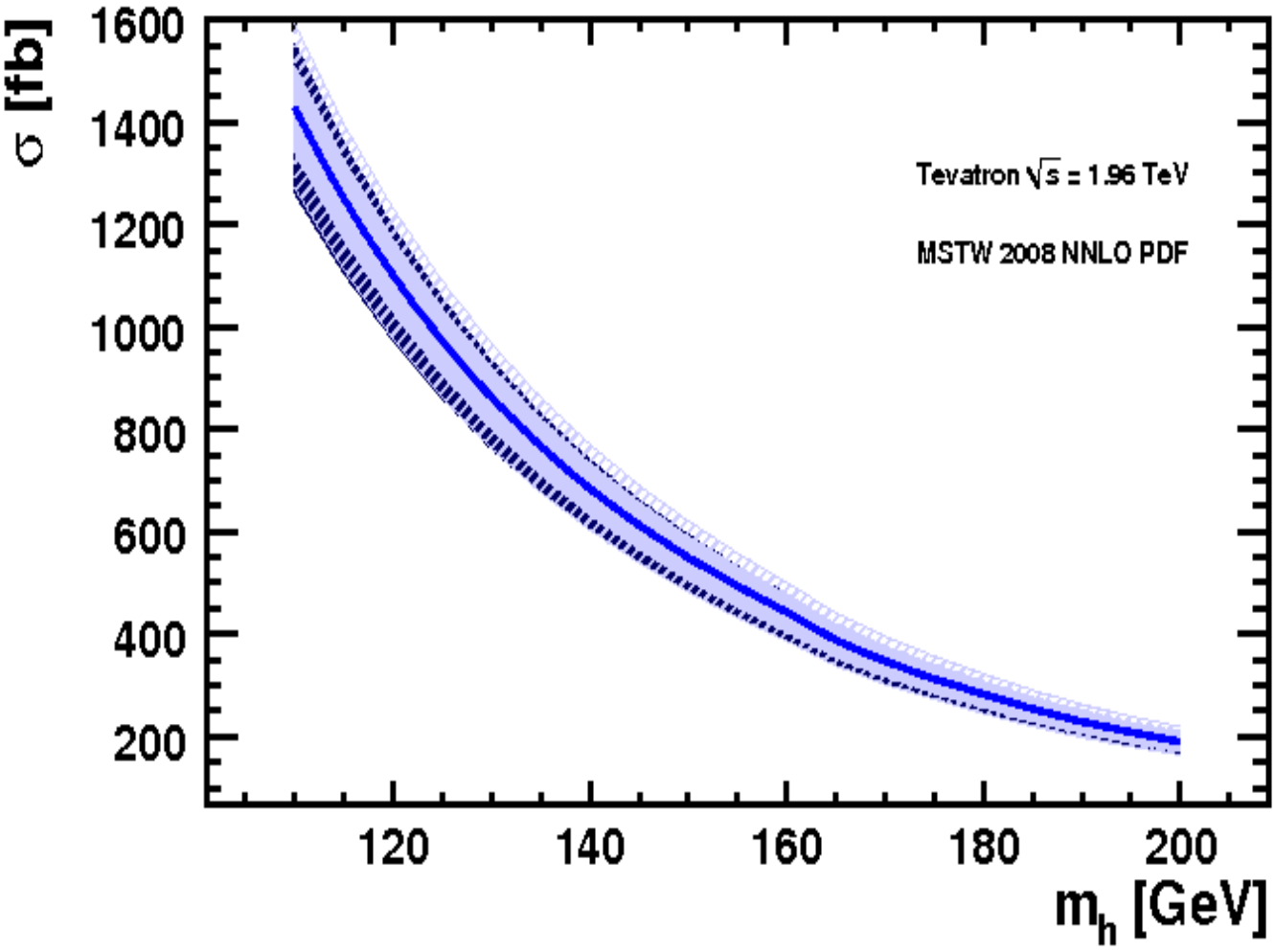
Updated cross-sections



Lesson:

Electroweak contributions are at least as important as finite mass effects!

PDF uncertainty



Tevatron:

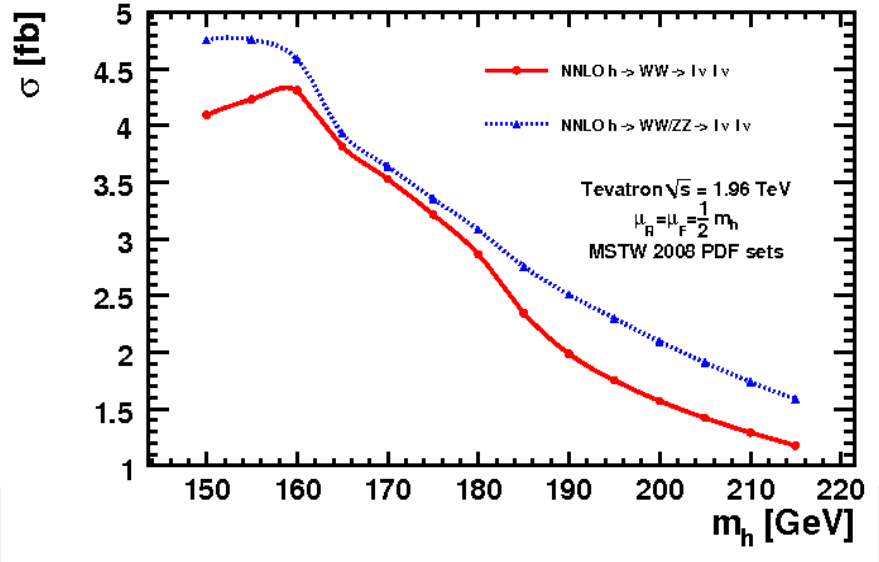
Combined PDF+α_S error: 8 – 12%
~ scale uncertainty

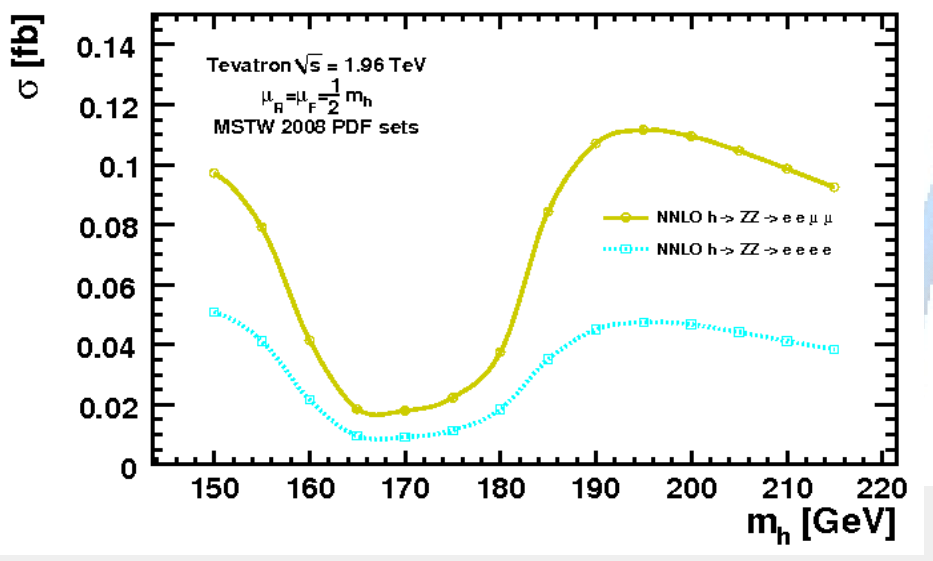
Remaining uncertainties

- Renormalization of bottom quark:
  Pole scheme vs. $\overline{\mathrm{MS}}$ scheme $\Rightarrow$ 1.5% deviation
- Resummation effects? Partly incorporated by scale choice $\mu = m_{\mathrm{h}}/2$.
  Good agreement with [de Florian, Grazzini], $<$ few %
- Unknown NNLO coefficient C_{2w} for mixed QCD–electroweak corrections $\Rightarrow$ $<$ 0.1% uncertainty
- PDF and α_{S} parameterization $\Rightarrow$ 8 – 12% uncertainty
- Scale variation $\Rightarrow$ approximately 10% uncertainty
- Finite mass effects at NNLO $\Rightarrow$ $<$ 0.5% uncertainty

Include decays

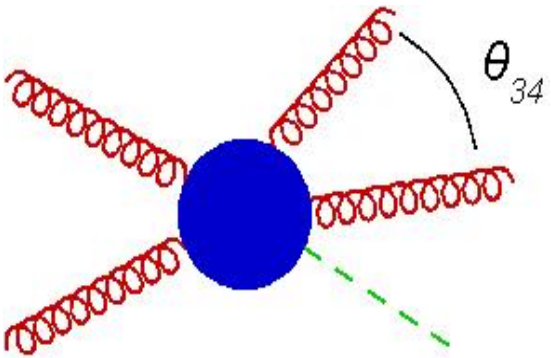
- Main decay channels:
  $h \to \gamma\gamma\,, \quad h \to WW \to \ell\nu\ell\nu\,, \quad h \to ZZ \to \ell\ell\ell'\ell'$
  (also implemented in **HNNLO** [Grazzini])
- New: consider interference $h \to WW/ZZ \to \ell\nu\ell\nu$
  Problem: Numerical stability (to be studied further)





New features in FeHiPro (2)

- **FeHiPro** applies sector decomposition.
  Adaptation for each sector separately required.
- **Problem**: Convergence for inclusive cross-section ≠ convergence for distributions when using histograms
- **Solution**: Introduce phase-space discriminant

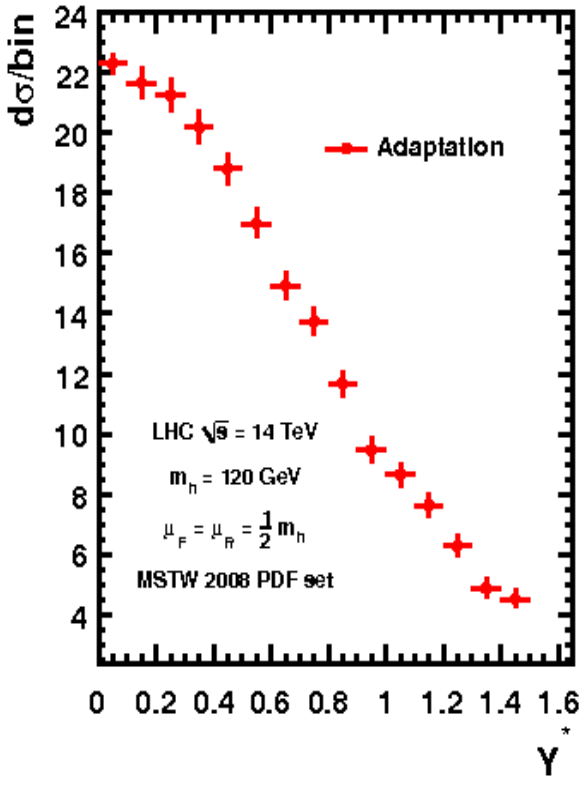


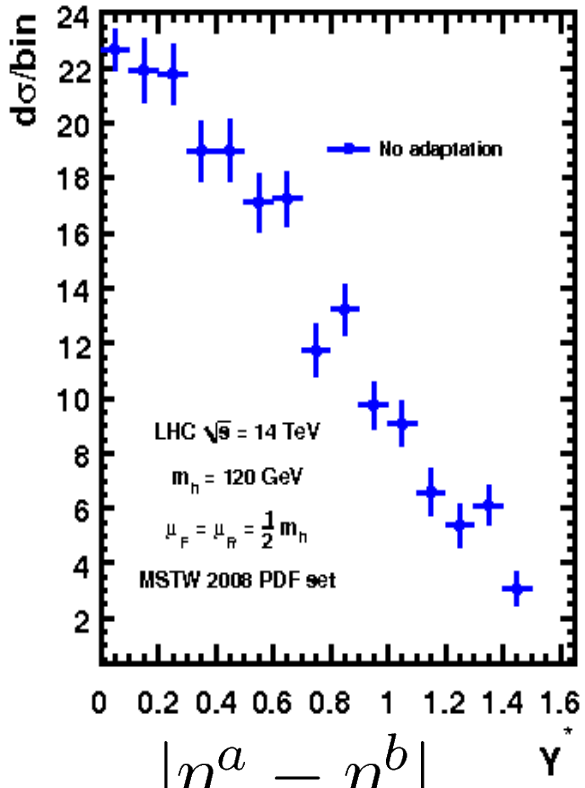
$$x_{\mathrm{discr}} = \frac{p_{\mathrm{T}}^{h}}{m_{\mathrm{h}}} \cos\theta_{34}$$

and use modified Vegas algorithm of Cuba library to adapt simultaneously to inclusive cross-section and a distribution in x_{discr}

Fighting bin-bin fluctuation

- **Example:** Require relative error 0.02% for accepted cross-section and maximal 500 Mio. evaluations





Additional adaptation:

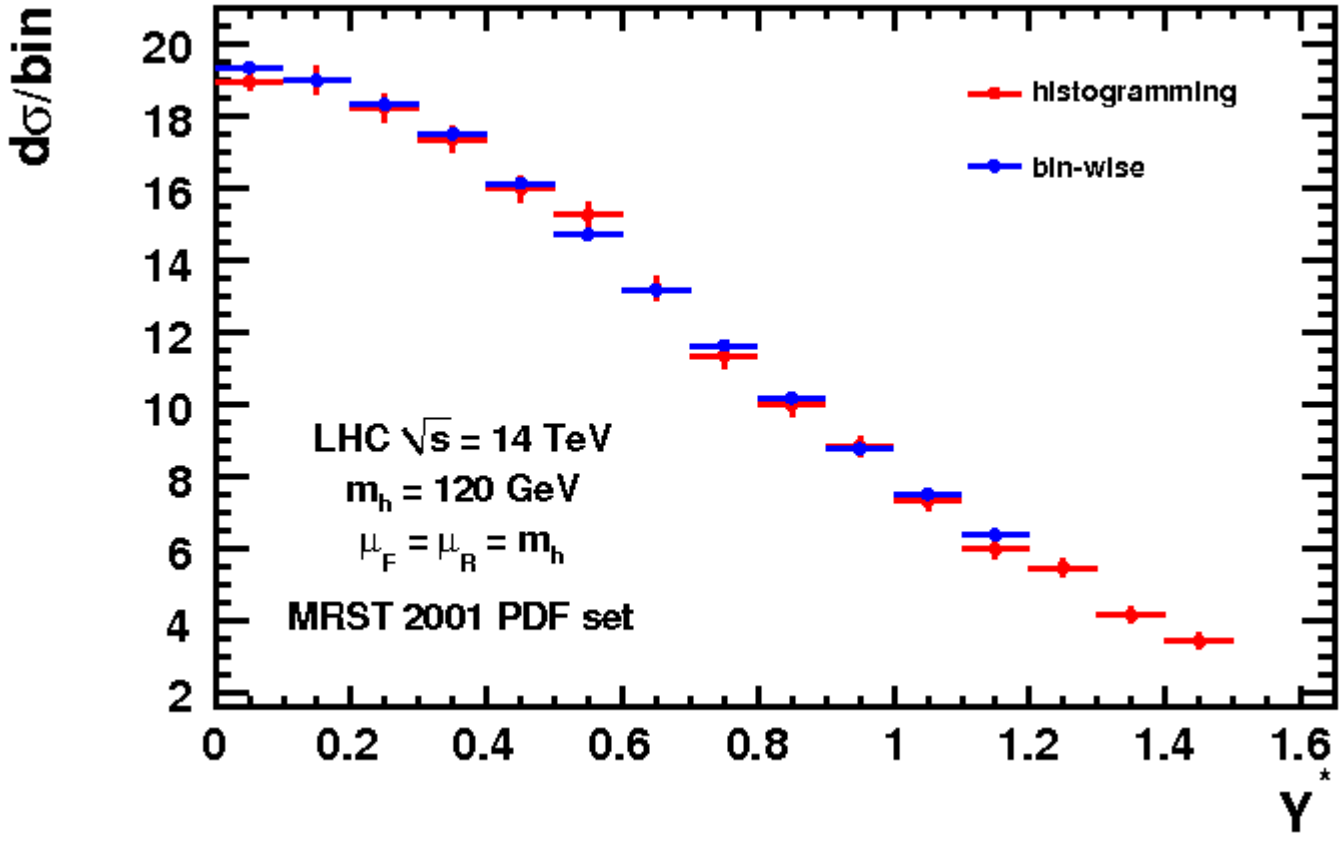
- reduces bin-bin fluctuation
- histogramming agrees with bin-wise integration within integration errors

Remark:
Use of quasi-random number sequence helps also

$$Y^* = \frac{|\eta^a - \eta^b|}{2}$$

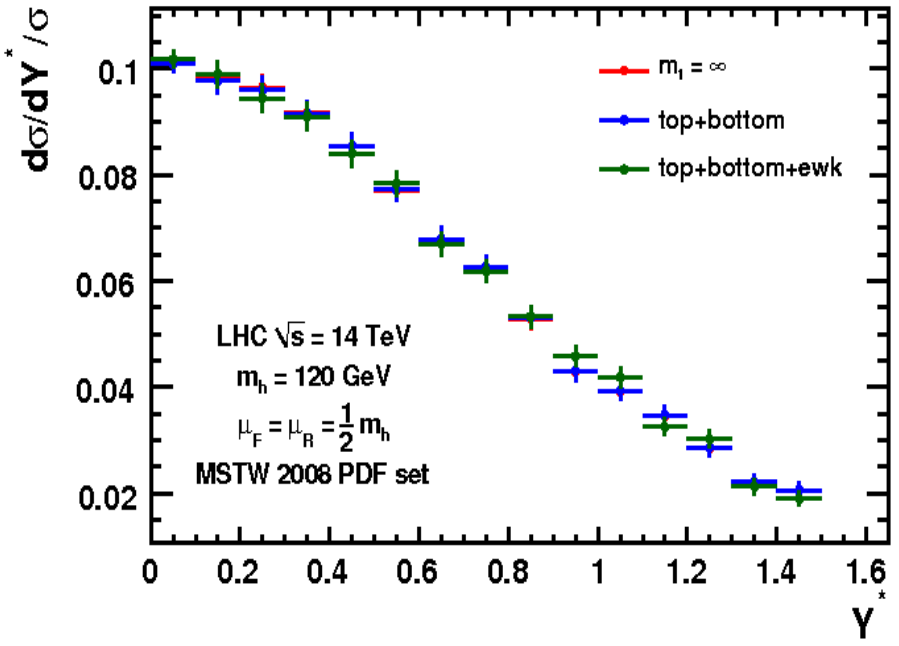
Fighting bin-bin fluctuation (2)

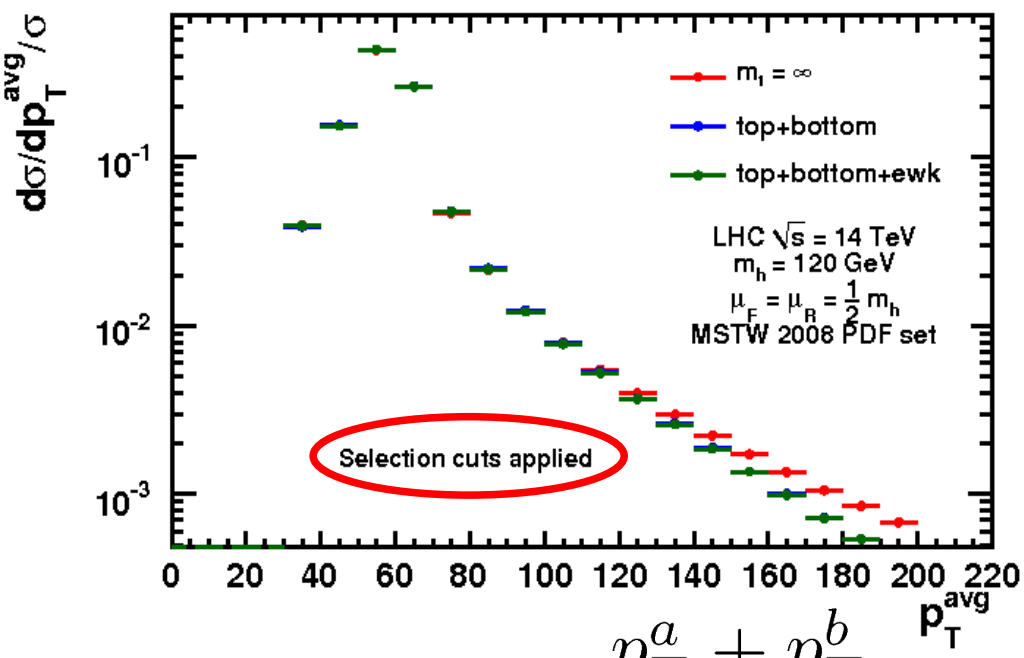
- Compare against bin-wise integration



Di-photon channel

- Mass and electroweak corrections only very mildly affect shape – if at all!





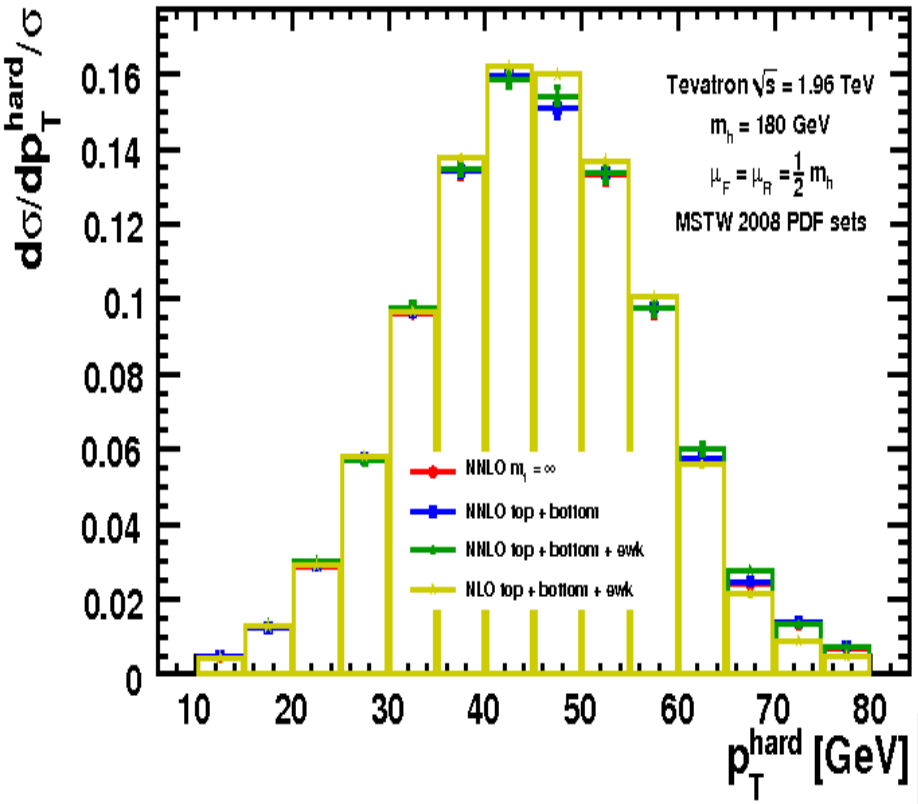
$$p_{\mathrm{T}}^{\mathrm{avg}} = \frac{p_{\mathrm{T}}^{a} + p_{\mathrm{T}}^{b}}{2}$$

WW channel

- Histogramming feature has already been successfully used in several publications
  [Anastasiou, Dissertori, Grazzini, Stockli, Webber]

- Redo studies including mass effects
- Study influence of phase-space discriminant

Work in progress - almost complete

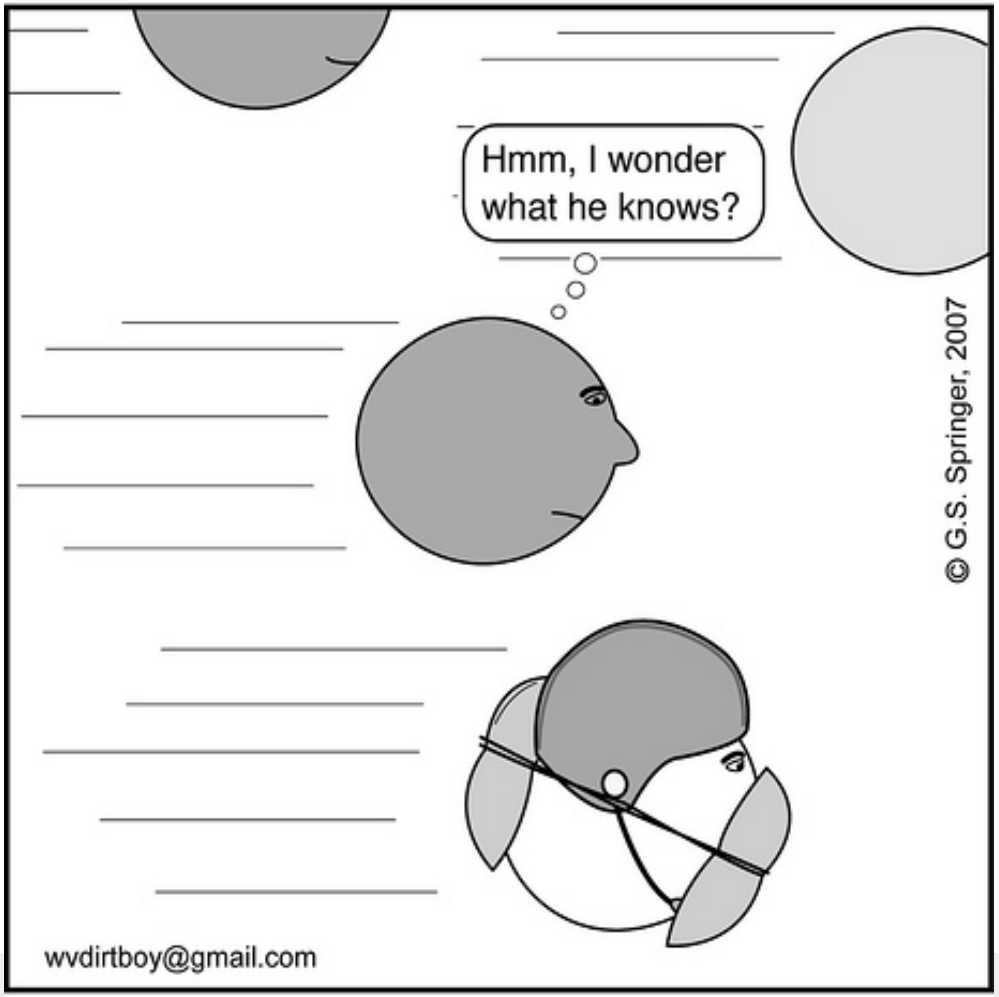


Conclusions & Outlook

- Gluon fusion cross-section for Higgs production is now under good control beyond the infinite top mass limit. Remaining uncertainty is due to PDF parameterization and contributions beyond NNLO.
- Histogramming can be improved by introducing phase-space discriminant.
- **FeHiPro**: Includes now all relevant finite mass effects and mixed QCD-electroweak effects for inclusive and exclusive cross-sections.
- Application to Drell-Yan? **FEWZ?**

Coming soon!

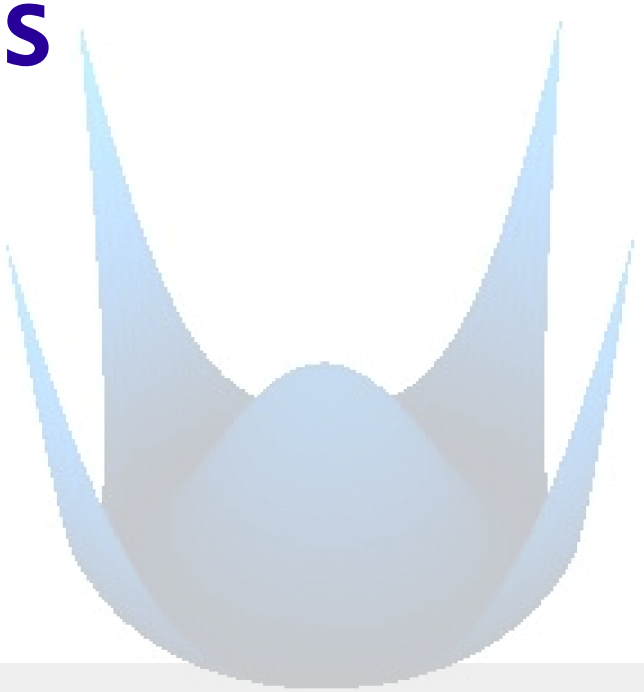
Let's be prepared...



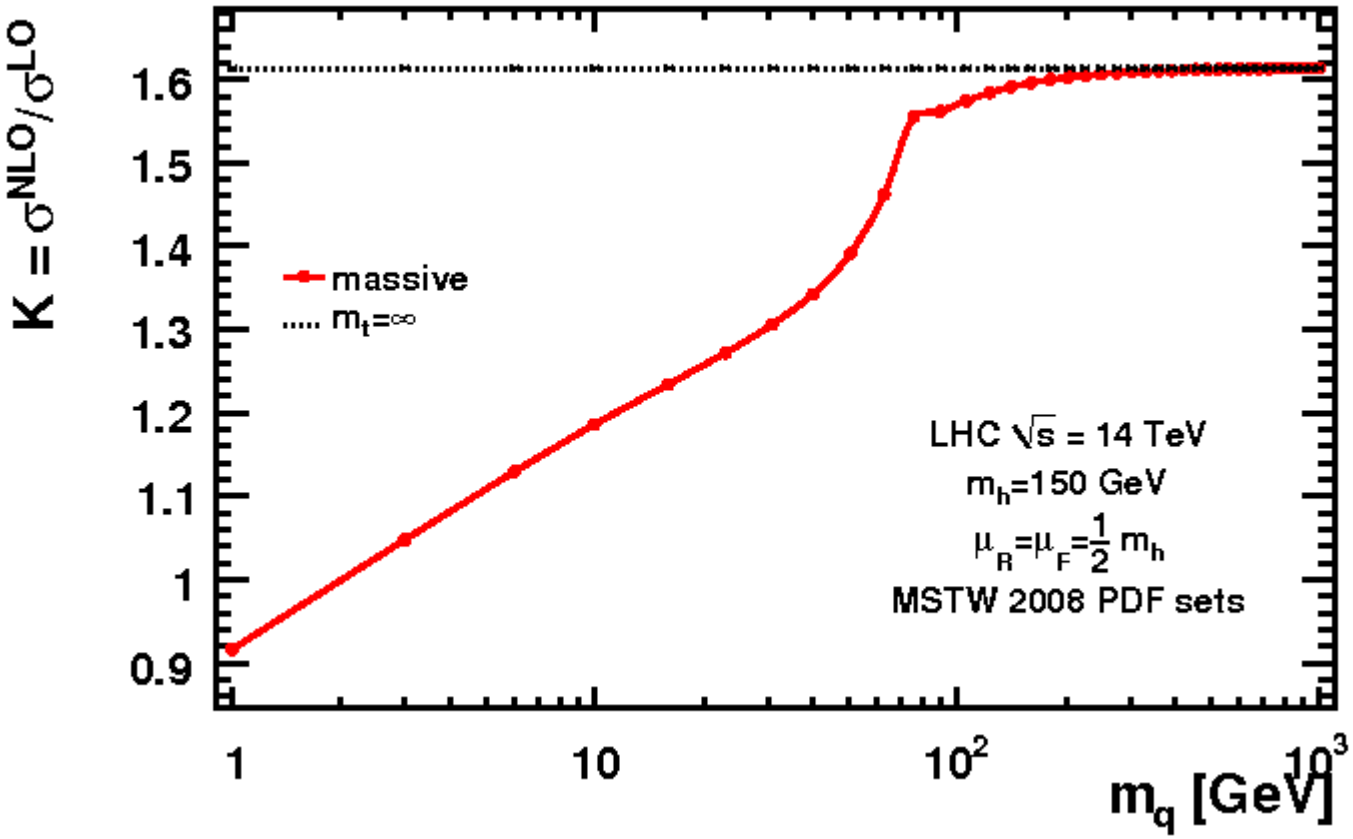
In a Particle Accelerator

... when LHC starts!

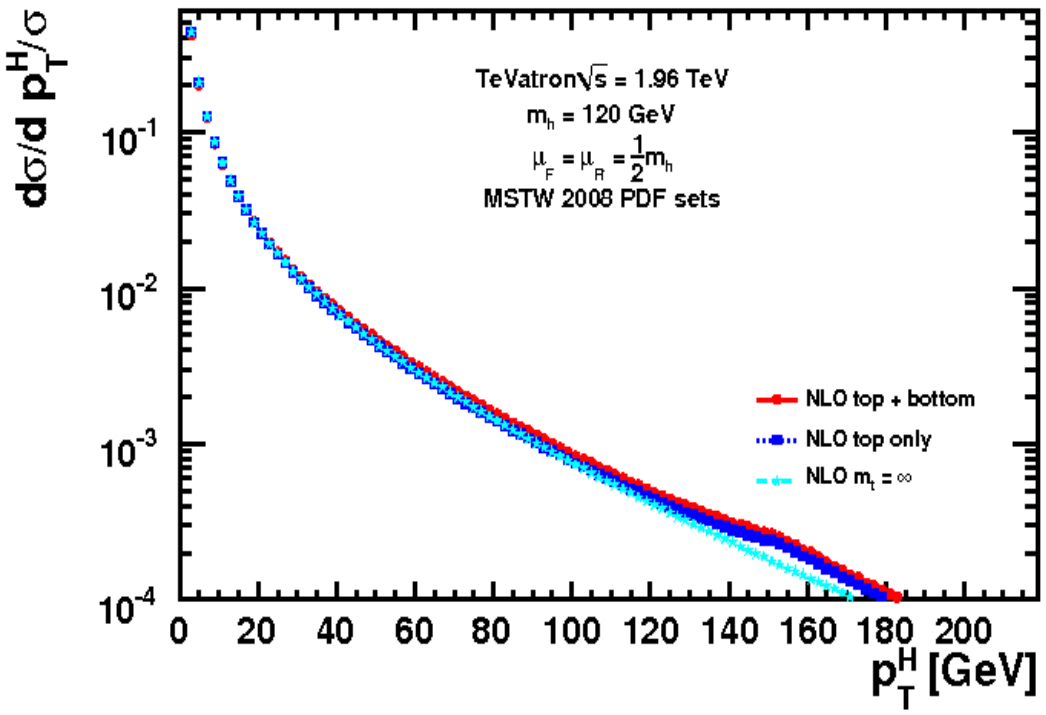
Backup slides

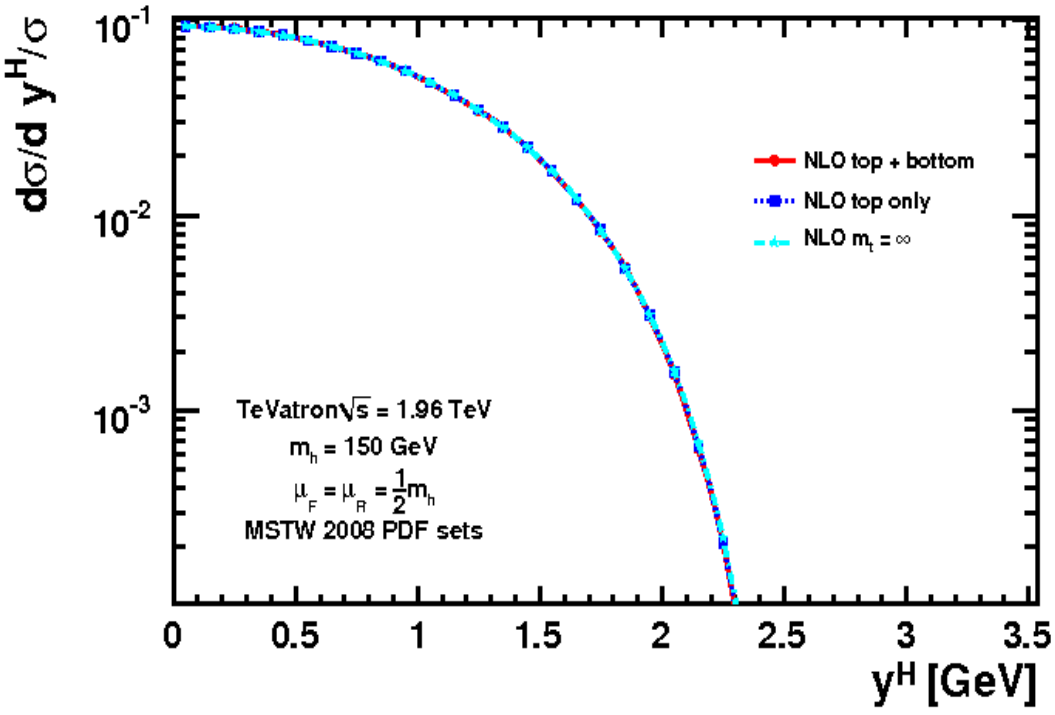


NLO K factor

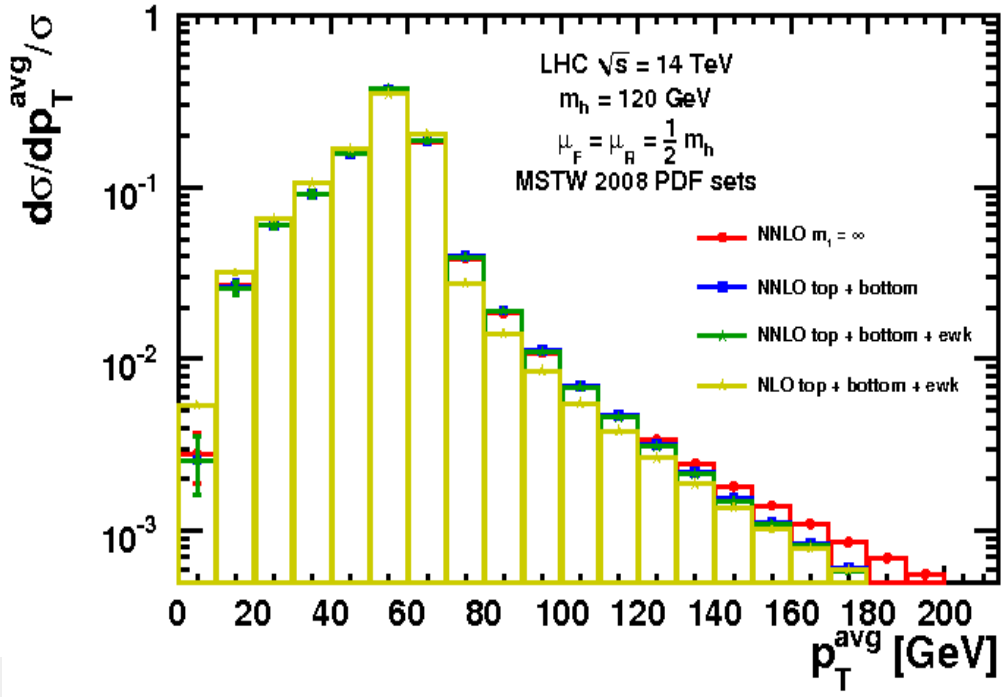

$K = \sigma^{NLO}/\sigma^{LO}$
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
massive
..... $m_t=\infty$
LHC $\sqrt{s}$ = 14 TeV
m_h=150 GeV
$\mu_R=\mu_F=\frac{1}{2}m_h$
MSTW 2008 PDF sets
1
10
10^2
10^3
m_q [GeV]

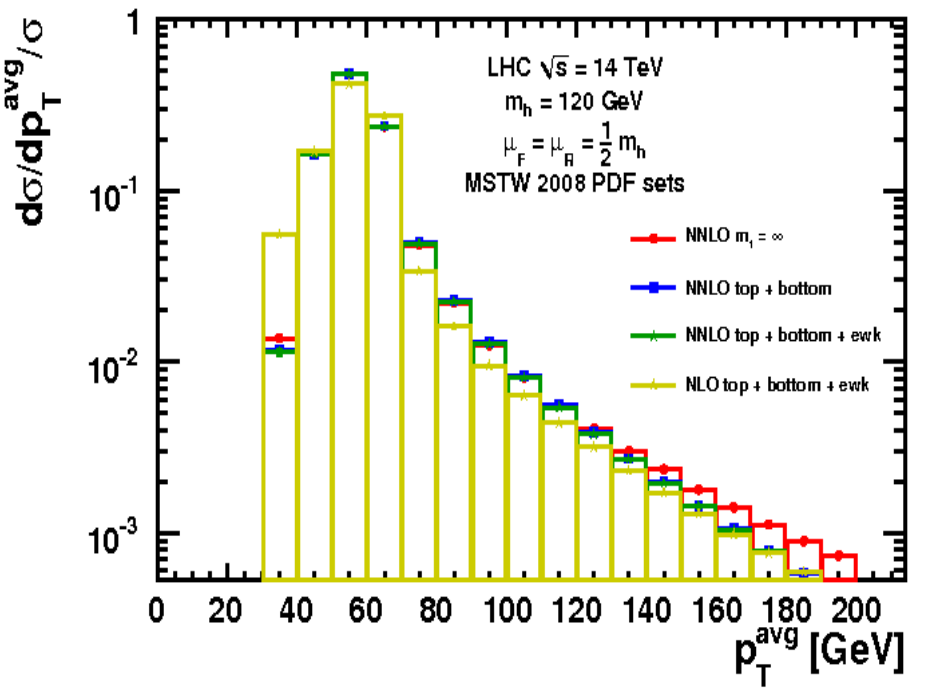
NLO distributions



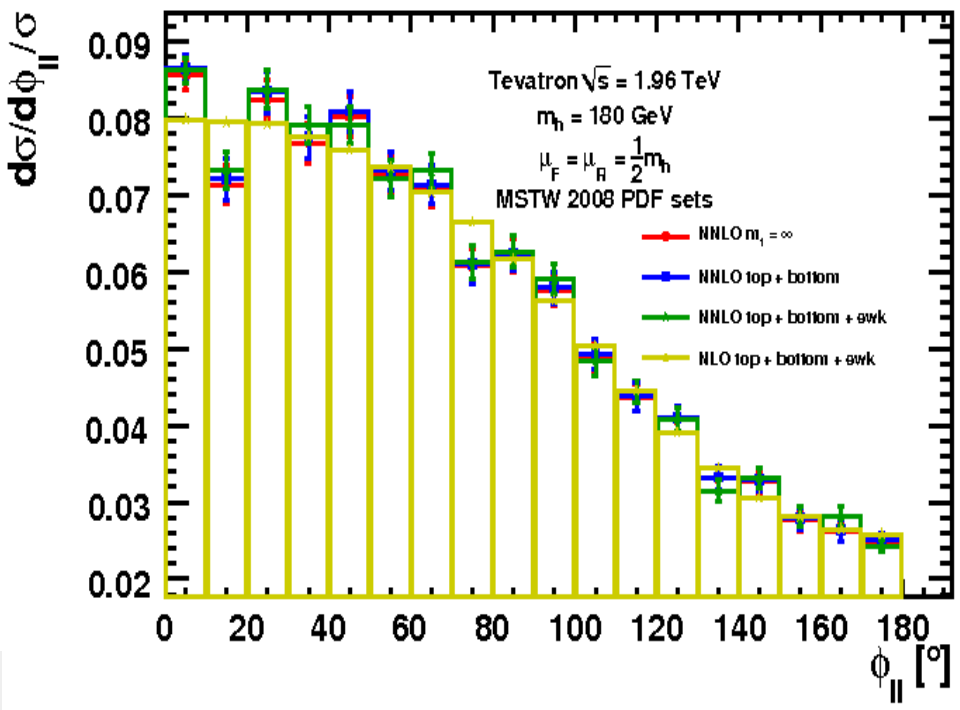


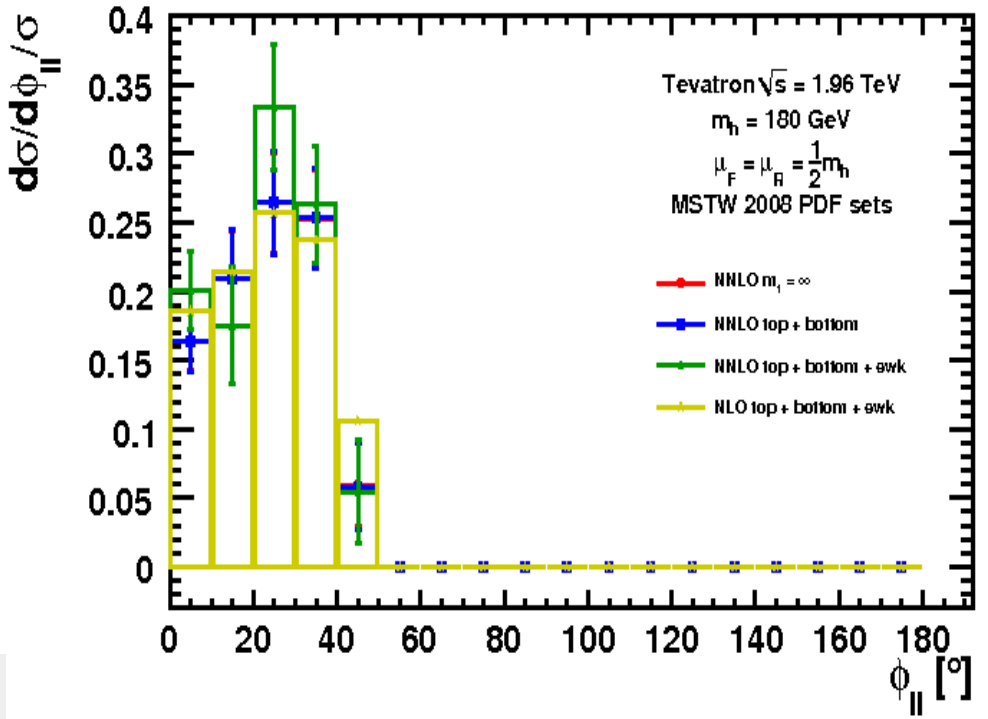
Di-photon channel





WW channel


$d\sigma/d\phi_{ll}/\sigma$
Tevatron $\sqrt{s}$ = 1.96 TeV
m_h = 180 GeV
$\mu_F = \mu_R = \frac{1}{2}m_h$
MSTW 2008 PDF sets
NNLO $m_t = \infty$
NNLO top + bottom
NNLO top + bottom + ewk
NLO top + bottom + ewk
ϕ_{ll} [°]


$d\sigma/d\phi_{ll}/\sigma$
Tevatron $\sqrt{s}$ = 1.96 TeV
m_h = 180 GeV
$\mu_F = \mu_R = \frac{1}{2}m_h$
MSTW 2008 PDF sets
NNLO $m_t = \infty$
NNLO top + bottom
NNLO top + bottom + ewk
NLO top + bottom + ewk
ϕ_{ll} [°]

WW/ZZ interference