Perturbative QCD for collider physics: recent developments

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Outline

- Introduction
  - Challenges at the LHC
- All orders/leading order
  - Showers and matrix elements
  - CKKW: harder showers
- NLO:
  - examples and problems
  - Higgs production with $b\bar{b}$: choose the right scale
  - no sbottoms in $p\bar{p} \longrightarrow B + X$
  - MC@NLO
- NNLO
  - PDFs
  - Z, W production
  - Higgs production at the LHC
  - Higgs coupling extractions
- Conclusions

Introduction: challenges

- In about a year, LHC begins its first physics run offering unprecedented opportunities.
- Two distinct features: high luminosity and high energy.
- Enormous rates for SM processes; can be used to study SM; have to be understood since are backgrounds to New Physics.
- Factorization theorem

$$\sigma^{\mathcal{O}} = D_k^{\mathcal{O}} \otimes \sigma_{kj} \otimes F_{\mathrm{j}}.$$

  - F_{j} describes hadron-parton transition $\longrightarrow$ Data;
  - σ_{kj} describes parton-parton transition $\longrightarrow$ pQCD;
  - D_{k} describes "fragmentation" $\longrightarrow$ models, data, etc.
- pQCD is central for hadron collider phenomenology.

Introduction: challenges

- extraction of parton distribution functions
  - reliability
  - precision
- shower event generators
  - harder showers
  - combining with fixed order computations
  - hadronization models
- resummations
  - analytic resummations; numeric resummations
- NLO computations
  - higher multiplicity processes
- NNLO computations
  - general algorithms for NNLO calculations
  - NNLO phenomenology

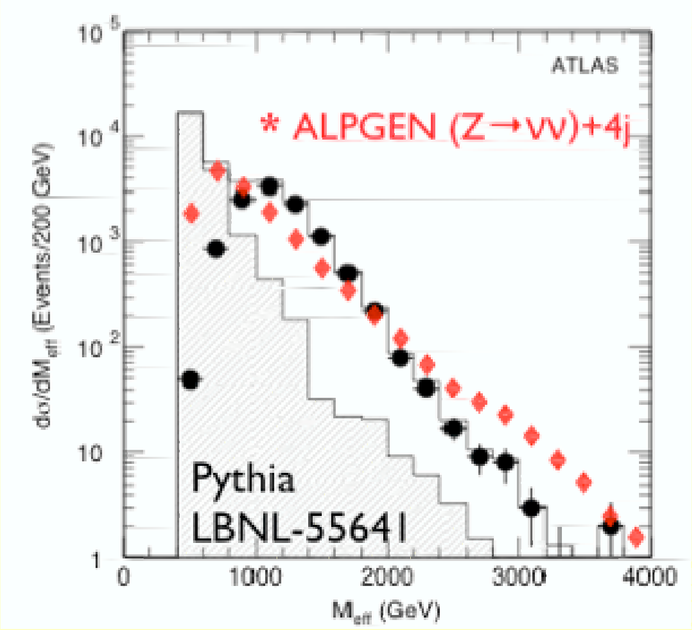
All orders/leading order

- $pp \to N$ jets $+ X$, $N \leq 10$ is a typical background process at the LHC.
- To deal with these multi-jet processes, we use all-purpose shower event generators, e.g. PYTHIA, HERWIG. Are these descriptions accurate?
- Showers are based on collinear emissions.
- Collinear emissions are independent $\Rightarrow$ probabilistic description.
- Showers are good for processes dominated by soft/collinear radiation.
- Showers generate large transverse momenta by emissions of many jets with moderate $p_\perp$ $\Rightarrow \alpha_s$ suppression of high $\boldsymbol{p}_\perp$ radiation.
- Shower do not change normalizations of total cross-sections

$$\int \mathrm{d}\sigma_{\mathrm{LO}} \times \mathrm{MC} = \sigma_{\mathrm{LO}}.$$

- An alternative: exact matrix elements for $ij \to N$ jets. How do these things compare?

All orders/leading order

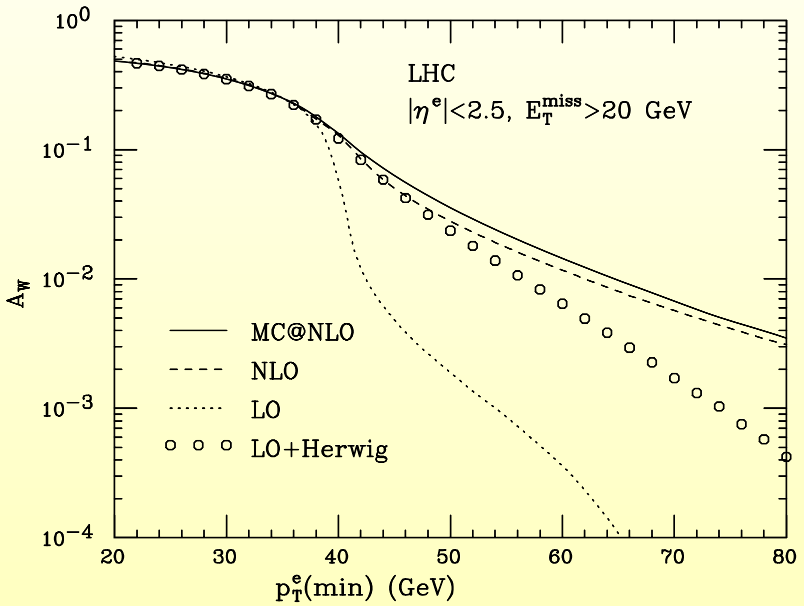


$$M_{\text{eff}} = \sum_{\text{jets}} p_\perp + E_\perp^{\text{miss}}$$

Mangano

- ALPGEN: exact matrix elements; correct hard emissions built in.
- PYTHIA: emulates hard emissions by producing large number of softer jets.
- PYTHIA underestimates the background significantly.

All orders/leading order



Mangano, Frixione

Acceptances for $pp \to W^- \to e\bar{\nu}$.

$$A_W = \frac{1}{\sigma_{\rm tot}} \int_{p_\perp^{e,\rm min}} {\rm d}p_\perp^e \, \frac{{\rm d}\sigma}{{\rm d}p_\perp^e}.$$

- NLO is just LO ($pp \to W + \text{jet} \to e\bar{\nu} + \text{jet}$) for $p_\perp^{e,\rm min} > m_W/2$.

$$\frac{A_W[\text{NLO}]}{A_W[\text{HERWIG}]} \sim 2 - 10, \quad \text{for } \; p_\perp^{e,\rm min} > 50 \text{ GeV}.$$

All orders/leading order: CKKW

- An $N+1$-jet event is obtained from an N-jet event either by

  large angle hard emission or shower.

- Event generators can do a better job for multi-jet processes if both mechanisms are taken into account.
- Catani-Krauss-Kuhn-Webber (CKKW) procedure:
  - calculate $pp \to m$ HARD jets, with $m < N$. Determine probability of an event with m hard jets using the cross-section values,

$$P_m = \frac{\sigma_m}{\sigma_0 + \sigma_1 + \sigma_2 + \ldots \sigma_N}, \qquad \sigma_m = \sigma_m(y_{\rm cut}).$$

  - Generate hard jet configuration according to the probability distribution; shower it.
  - Requires introduction of a measure to distinguish between hard jet and shower jet.
- This procedure is being currently implemented in major shower event generators, such as PYTHIA and HERWIG.

Mrenna, Richardson

Leading order: uncertainties

- Any leading order prediction has the renormalization and factorization scales uncertainty.
- $pp \to \nu\bar{\nu} + N$ jets; $p_\perp^{\rm j} > 80$ GeV; $|\eta| < 2.5$.
- $\mu = \sqrt{M_z^2 + \sum_{\rm jets} p_\perp^2}$; $\mu_r = \mu_f = \mu/2 ... 2\mu$.

N	$\sigma(2\mu)$pb	$\sigma(\mu/2)$pb	variation
1	182	216	17%
2	47.1	75.4	46%
3	6.47	13.52	70%
4	0.90	2.48	93%

Next-to-leading order computations are necessary.

Next-to-leading order

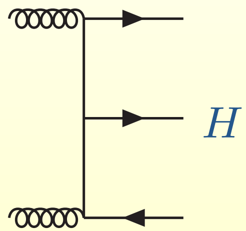
- The NLO prediction is often the first quantitative prediction.
- Typical background $(t\bar{t})^n\ (WZ)^m\ \mathrm{jets}^l,\ n,m,l > 0$.
- Current state of the art is $2 \longrightarrow 3$ processes:
  - NLOJET++ [Nagy] $pp \longrightarrow (2,3)j,\ \ ep \longrightarrow 3j,\ \ e^+e^- \longrightarrow 3,4j, \gamma^* p \longrightarrow (2,3)j$;
  - AYLEN/EMILIA [de Florian, Dixon, Kunszt, Signer] $pp \longrightarrow (W,Z) + (W,Z,\gamma)$;
  - MCFM [Campbell, Ellis] $pp \longrightarrow (W,Z) + (0,1,2)j, pp \longrightarrow (W,Z) + b\bar{b}$;
  - DIPHOX/EPHOX [Aurinche et. al] $pp \longrightarrow \gamma + 1j, pp \longrightarrow \gamma\gamma, \gamma^* p \longrightarrow \gamma + 1j$;
  - VBFNLO [Figy, Zeppenfeld, Oleari] $pp \longrightarrow (W,Z,H) + 2j$.
- Flexible programs: arbitrary restrictions on the final state can be applied.
- We want to extend the NLO computations to $2 \longrightarrow 4, 5, \mathrm{etc.}$ processes.
- Problem: one-loop $5, 6, 7 \ldots n$-point functions.
  - Direct numerical integration is not possible because those functions have soft and collinear divergences.
  - Simplifications of many-point functions produce fictitious singularities that are hard to handle.

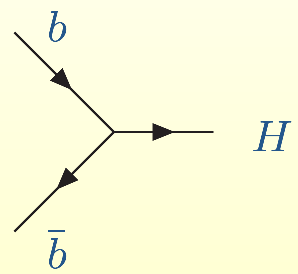
Next-to-leading order

- Recent progress (technical):
  - Mellin-Barnes transform — Anastasiou, Daleo;
  - IBP's, sector decompozition, numerics — Binoth, Heinrich;
  - Numerical solutions of IBP's — Glover, Giele;
  - Bernstein-Tkachov theorem — Passarino et al.;
  - Integration in momentum space — Soper, Krämer.
- Recent progress (calculations):
  - $pp \to H \to 2$ jets (virtual), — Zanderighi, Giele, Ellis;
  - $pp \to t \to Wb$, — Ellis, Campbell;
  - $pp \to Hb\bar{b}, Ht\bar{t}$, — Dawson, Jackson, Wackeroth, Reina, Spira, Krämer;
  - $pp \to W^+W^-(ZZ) + 2j$, [VBF] — Jäger, Oleari, Zeppenfeld.
- First complete $2 \to 4$ computation: $e^+e^- \to 4$ fermions, — Denner, Dittmaier et al.
- Flexible methods are needed; must be easily adaptable to New Physics models.

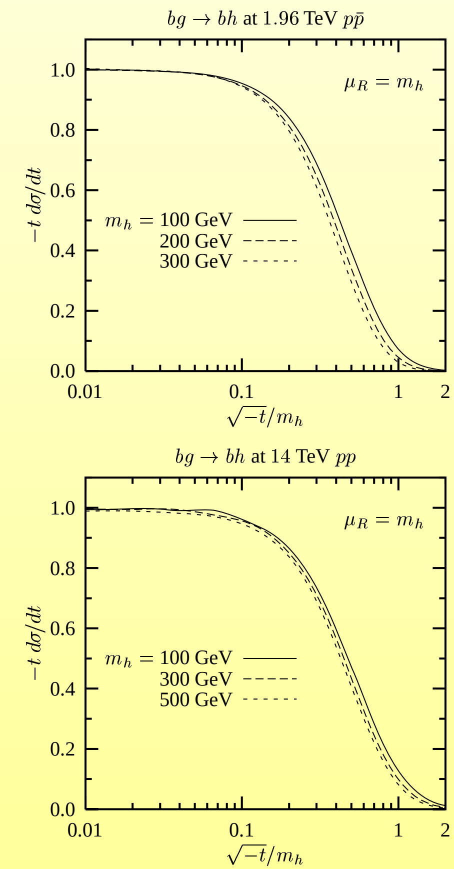
Next-to-leading order

- Consider Higgs production in association with b quarks. Two options:





$$\text{PT in } \frac{\alpha_s}{\pi}\ln(m_H^2/m_b^2) \qquad\qquad \text{PT in } \frac{\alpha_s}{\pi}$$



- Puzzle: $\sigma_{\rm LO}(gg \to b\bar{b}H) \sim 0.1\ \sigma_{\rm LO}(b\bar{b} \to H)$.
- Resolution: $\mu_F = m_H/4$ is an appropriate scale (kinematics).

  Willenbrock, Maltoni, Plehn, Boos

- This prediction is confirmed by explicit (later) higher order calculations.

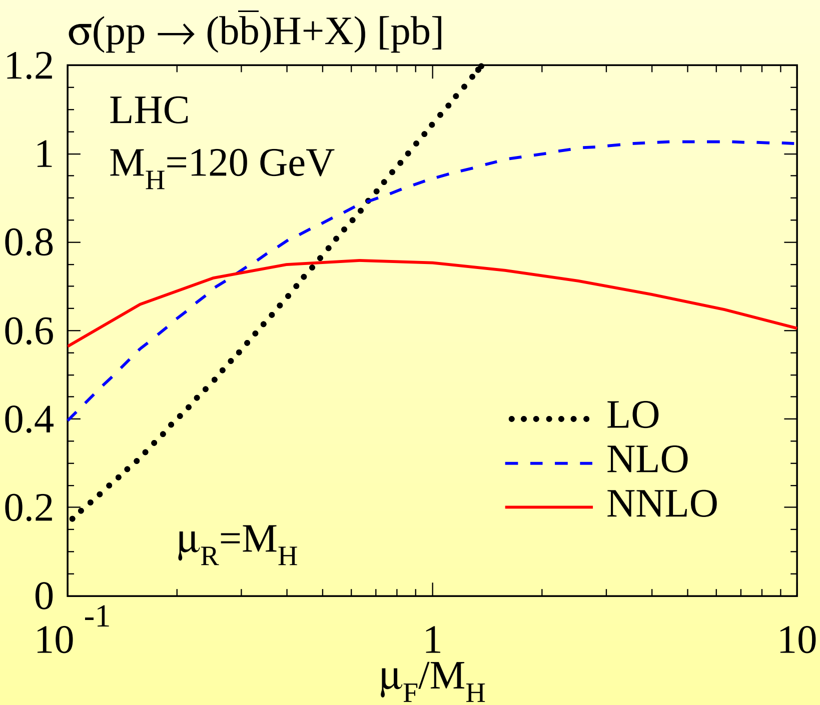
Next-to-leading order

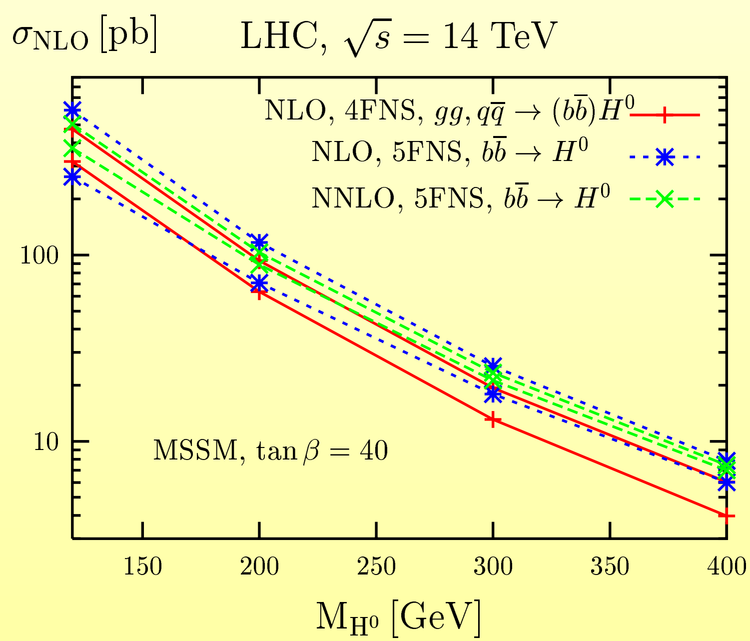
- $b\bar{b} \to H$ is currently known through NNLO; $\mu_F = m_H/4$ is the right scale!

  Harlander, Kilgore

- $gg \to b\bar{b}H$ is currently known through NLO; compares well with $b\bar{b} \to H$.

  Dawson, Jackson, Reina, Wackeroth, Krämer, Spira





- Gain confidence from looking at the same process in different ways.

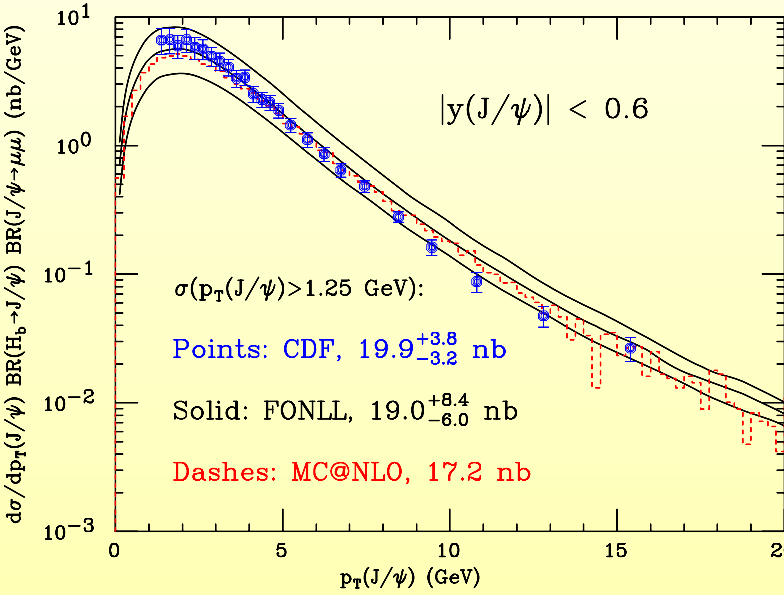
NLO: bottom production

- Bottom production in hadron collisions: $p\bar{p} \longrightarrow B + X$ was a long-standing problem for pQCD with discrepancy often quoted as a factor 2-4
- New Physics explanations, e.g. light gluinos, sbottoms

NLO QCD prediction for $p_\perp^B$ is non-trivial:

- $b \longrightarrow B$ fragmentation function;
- large uncertainties due to PDFs;
- large NLO QCD corrections;
- $\sigma_{\rm tot}$ is dominated by $p_\perp \sim m_b$.

Cacciari, Nason



- Excellent agreement of the total cross-sections

Cacciari et al.

$$\sigma^{\rm CDF}_{J/\psi} = 19.9^{+3.8}_{-3.2}\ {\rm nb}, \quad \sigma^{\rm pQCD}_{J/\psi} = 19.0^{+8.4}_{-6.0}\ {\rm nb}.$$

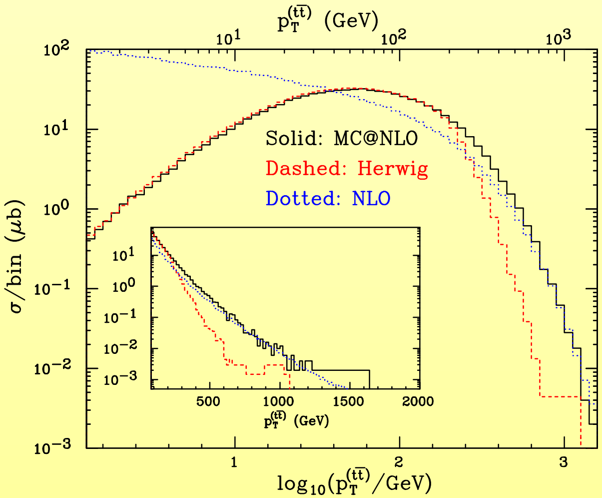
- Large $\pm 50\%$ theory uncertainty remains.

Event generators and higher orders

- Shower event generators and perturbative calculations are complimentary:
  - Showers: universal, realistic jets, automatic resummations, hadronization;
  - PT: correct rates, correct description of hard emissions, improvable errors.
- Combining MC's and perturbative computations is a good (old) idea — Dobbs
- The most advanced implementation is called MC@NLO (based on HERWIG shower):

  Frixione, Webber

$$\mathrm{MC@NLO} = \mathrm{MC}\left(1 + \alpha_s[\mathrm{NLO} - \mathrm{MC}_{\alpha_s}]\right).$$



Features:
outputs unweighted events;
no double counting;
total rates are accurate through NLO.
Processes included:
$H, W, Z, VV, HZ, t\bar{t}, b\bar{b}$ and single top.

Alternative implementations would be most useful — Krämer, Nagy, Soper

NNLO

- NNLO calculations are desirable for:
  - processes where good estimate of the uncertainty is required;
  - processes with large NLO corrections.
- This leaves us with $H, W, Z, 2\ \mathrm{jets}$, heavy quarks.
- What is known through NNLO for hadron colliders:
  - $W, Z, gg \to H, gg \to A, b\bar{b} \to H$ production; total cross-sections;

    van Neerven, Matsuura, Kilgore, Harlander, Anastasiou, K.M., Ravindran, Smith
  - W, Z, γ^* rapidity distribution;

    Anastasiou, Dixon, K.M., Petriello
  - $gg \to H, Z, W$ production, fully differential with spin correlations;

    Anastasiou, K.M., Petriello
- Generalization to $2 \to 2$ processes (jets, heavy quarks) is highly non-trivial.

NNLO: PDFs

- A consistent implementation of NNLO calculations requires NNLO PDFs and NNLO evolution kernels.
- NNLO Altarelli-Parisi splitting kernels known. Vermaseren,Moch,Vogt
- NNLO PDFs extractions exist. MRST, Alekhin.
- Broad measure of PDFs fits reliability:

$$\alpha_s^{\rm Alekhin}(M_Z) = 0.114(1), \quad \alpha_s^{\tau}(M_Z) = 0.121(1).$$

  NNLO effects increase the disagreement.
- For hard processes at the LHC, PDF uncertainty is

$$\frac{\delta\sigma}{\sigma} \approx 5\%, \quad M \sim 100 \text{ GeV}, \ \ |Y| < 2.$$

- For larger $|Y|$, $\ln(1/x)$ terms may require resummations (BFKL, saturation)

NNLO: Z and W production

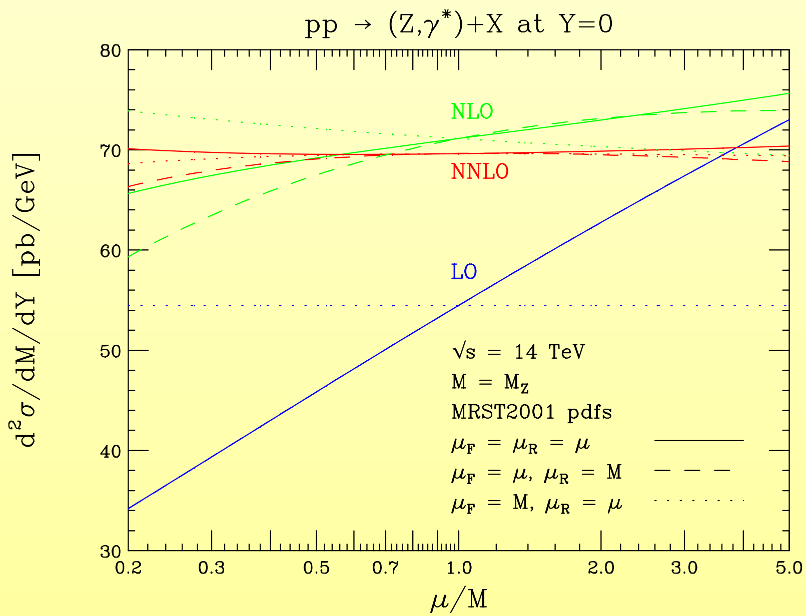
- Use the Z, W production to measure L.

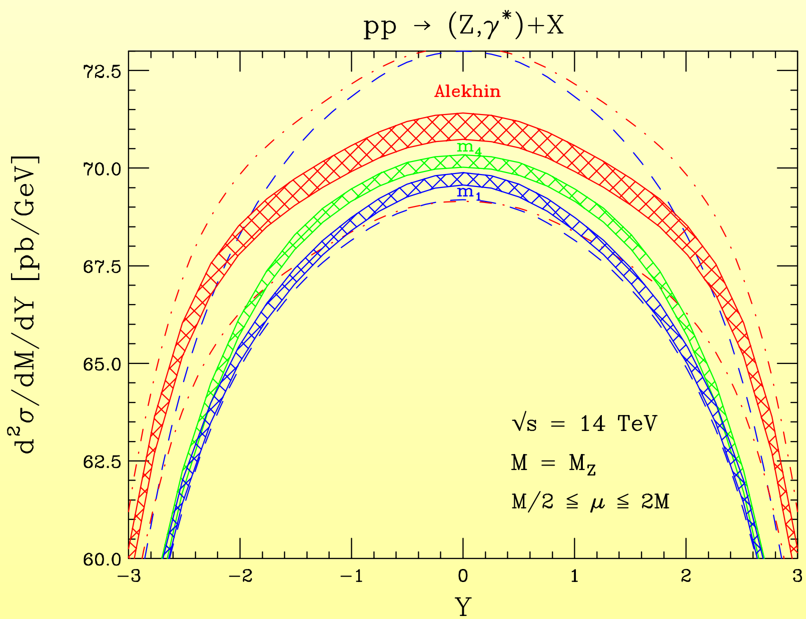
Dittmar et al.

- Partonic luminosities $\leftrightarrow$ rapidity of gauge bosons

$$\frac{d\sigma}{dMdY} \sim q_1(x_1)q_2(x_2), \quad x_{1,2} = \frac{M}{\sqrt{S}}e^{\pm Y}.$$

- NNLO results: scale stability and PDF sensitivity





Anastasiou, Dixon, Petriello, K.M.

NNLO: W^- production

- The knowledge of rapidity distributions of Z, W bosons is insufficient for deriving lepton distributions because of spin correlations.
- The fully differential NNLO QCD calculation for $pp \to e + \bar{\nu} + X$ is now available. Cuts of the form (ATLAS, CMS)

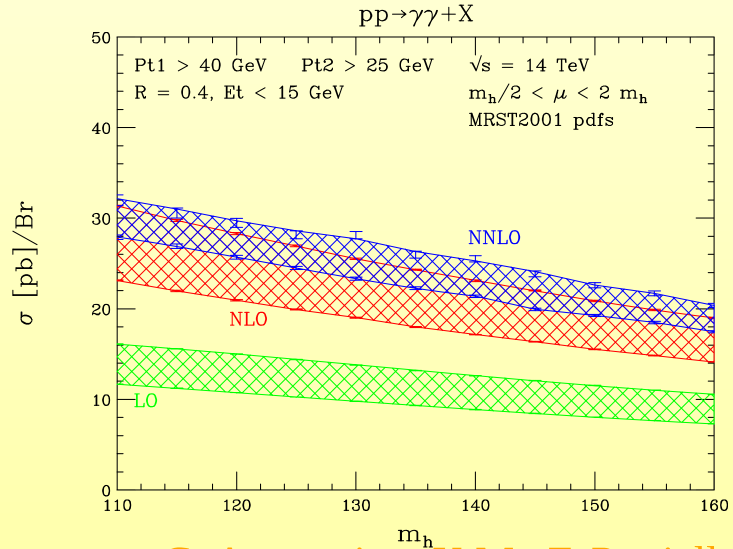
$$\text{Cut1} \quad p_\perp^e > 20 \text{ GeV}, \quad |\eta_e| < 2.5, \quad E_{\text{miss}} > 20 \text{ GeV}$$
$$\text{Cut2} \quad p_\perp^e > 40 \text{ GeV}, \quad |\eta_e| < 2.5, \quad E_{\text{miss}} > 40 \text{ GeV}$$

LHC	A(MC@NLO)	$\frac{\sigma_{\text{MC@NLO}}}{\sigma_{\text{NLO}}}$	A(NNLO)	$\frac{\sigma_{\text{NNLO}}}{\sigma_{\text{NLO}}}$
Cut1	0.485	1.02	0.492	0.983
Cut2	0.133	1.03	0.155	1.21

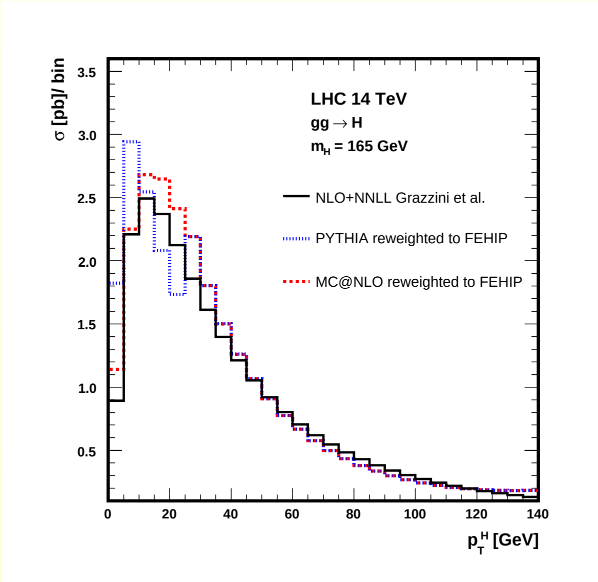
- $1-2$ percent NNLO effects for $p_\perp^{e,\min} > 20 - 30$ GeV;
  $10-20$ percent NNLO effects for $p_\perp^{e,\min} > 40 - 50$ GeV. Petriello, K.M.
- For Cut2, MC@NLO gets the acceptance wrong since second hard emission is important.

NNLO: Higgs boson signal at the LHC

- QCD effects increase the inclusive $gg \to H$ production cross-section by a factor two.
- For $H \to \gamma\gamma$, the following cuts on the final photons are imposed (ATLAS,CMS):
  - $p_\perp^{(1)} \geq 25$ GeV, $p_\perp^{(2)} \geq 40$ GeV, $|\eta_{1,2}| \leq 2.5$.
  - Isolation cuts, e.g. $E_{\mathrm{T,hadr}} \leq 15$ GeV, $\delta R = \sqrt{\delta\eta^2 + \delta\phi^2} < 0.4$.
- Do the conclusions based on inclusive calculations change when those cuts are imposed?



C. Anastasiou, K.M., F. Petriello



Re-weighting MC@NLO and PYTHIA to double differential distribution in Higgs $p_\perp$ and rapidity. [Davatz et al.]

Higgs coupling extractions

- Analyses of Higgs coupling use relation

$$\sigma(H) \times \mathrm{Br}(H \to X) = \frac{\sigma_{gg}^{\mathrm{SM}}}{\Gamma_{gg}^{\mathrm{SM}}} \times \frac{\Gamma_{gg}\Gamma_X}{\Gamma_{\mathrm{tot}}}.$$

- Calculate and assign theoretical uncertainty to $\sigma_{gg}^{\mathrm{SM}}/\Gamma_{gg}^{\mathrm{SM}}$, extract $\Gamma_{gg}\Gamma_X/\Gamma_{\mathrm{tot}}$; new states in loops drop out.
- Studies assign $\pm 20\%$ uncertainty to σ/Γ for $gg \to H$ production mode. Dührssen et al.

$$\Gamma^{\mathrm{SM}} = \alpha_s(\mu_r)^2 C_1(\mu_r)^2 \left[1 + \alpha_s(\mu_r) X_1 + ...\right];$$
$$\sigma^{\mathrm{SM}} = \alpha_s(\mu_r)^2 C_1(\mu_r)^2 \left[1 + \alpha_s(\mu_r) Y_1 + ...\right].$$

- Scale variation correlated; large μ_r variations cancel; $\Delta(\sigma/\Gamma) = \pm 5\%$.
- Recent developments:
  - N^3LO soft+virtual corrections to $\sigma_{gg\to H}$ Moch, Vermaseren, Vogt
  - N^3LO corrections to Γ_{gg} Baikov, Chetyrkin
  - $\Delta\sigma : \pm 10\% \to \pm 4\%; \quad \Delta\Gamma : \pm 5\% \to \pm 2\%.$

Conclusions

- Good understanding of pQCD is an important pre-requisite for the successful LHC physics program.
- Recent developments include
  - making showers more realistic (harder);
  - large-scale NLO computations;
  - merging shower event generators and NLO computations;
  - emerging NNLO phenomenology.
- From existing computations and comparison with data we should learn
  - to appreciate uncertainties;
  - to understand when popular techniques are applicable;
  - to choose “right” scales in perturbative predictions;
  - to avoid rushy conclusions if something does not add up.
- There are plenty of challenges, room for new ideas and unorthodox approaches even in Old Physics. A significant progress that occurred in pQCD in the last few years will be very useful once the LHC turns on.