

# Standard Model Physics at the LHC

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2 Partonic Hard Cross Section

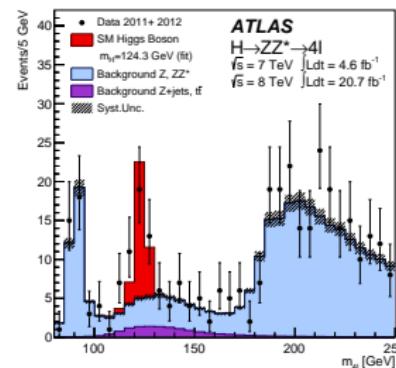
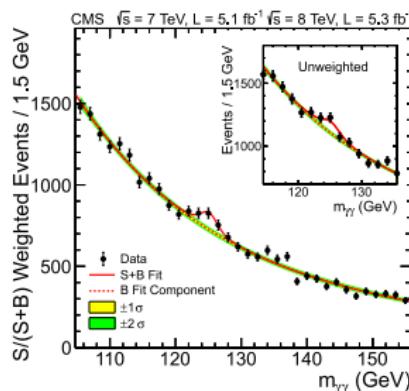
3 Shower Monte Carlo

4 Jets

5 Conclusions



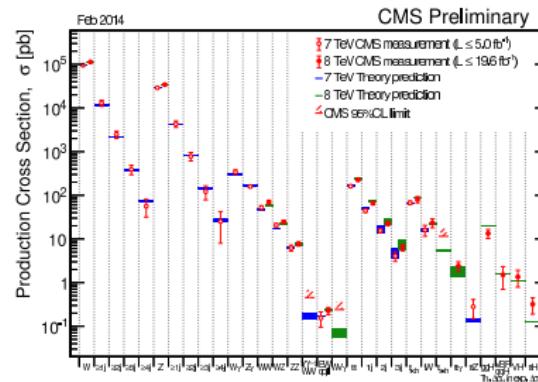
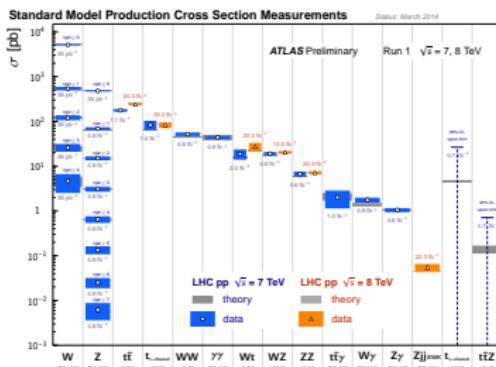
# LHC key results: Higgs signal



- Observation of the Higgs boson through sharp mass peak,  $m_H \simeq 136 \text{ GeV}$ , in various channels.
- Its properties are consistent with the Standard Model (SM) predictions at the  $\pm 20\%$  level: this accuracy can (must!) be further reduced with the help of more theoretical work.



# LHC key results: and much more

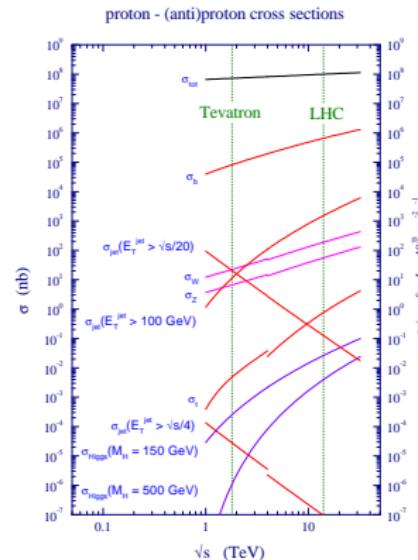


- Very good agreement between experimental results and SM theoretical predictions of the  $high-Q^2$  processes

# Motivations

The LHC is a (large) hadron collider machine: all the interesting high- $p_T$  reactions initiate by QCD hard scattering of partons.

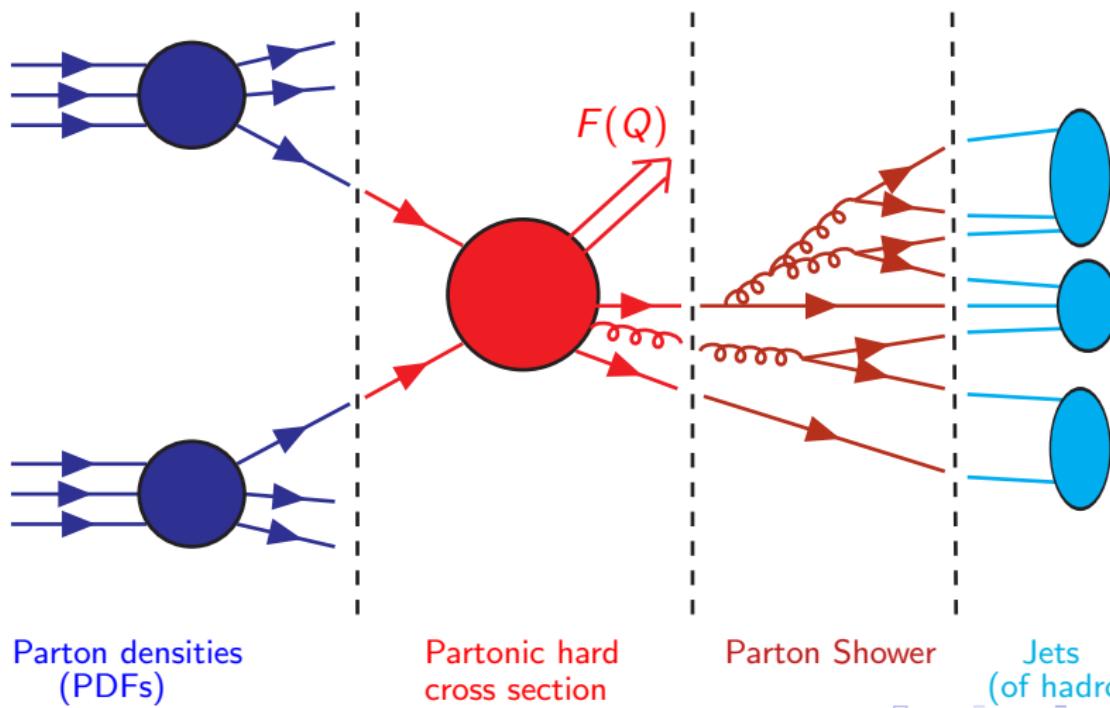
To claim for new-physics signals a good control of the SM processes is necessary.



To fully exploit the information contained in the LHC experimental data, precise theoretical predictions of the SM cross sections are needed, e.g. CMS limit on  $\Gamma_H$  [Caola,Melnikov('13)]

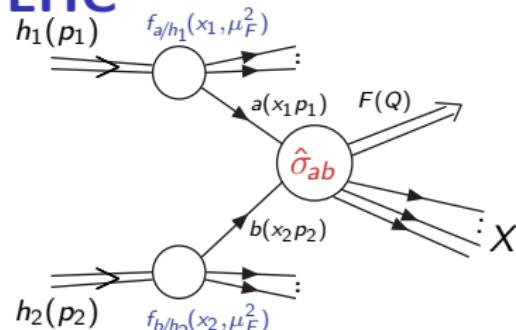


# Theoretical predictions at the LHC



# Theoretical predictions at the LHC

$$h_1(p_1) + h_2(p_2) \rightarrow F(Q) + X$$



The framework: **QCD factorization formula**

$$\sigma_{h_1 h_2}(p_1, p_2) = \sum_{a,b} \int_0^1 dx_1 \int_0^1 dx_2 f_{a/h_1}(x_1, \mu_F^2) f_{b/h_2}(x_2, \mu_F^2) \hat{\sigma}_{ab}(x_1 p_1, x_2 p_2; \mu_F^2) + \mathcal{O}\left(\frac{\Lambda_{QCD}}{Q}\right)^p$$

- $f_{a/h}(x, \mu_F^2)$ : Non perturbative **universal** parton densities (PDFs),  $\mu_F \sim Q$ . Measured from experiments at a given scale  $\mu_0$ , Evolution to  $\mu_F$  calculable in pQCD through DGLAP equation.
- $\hat{\sigma}_{ab}$ : Hard scattering cross section. **Process dependent**, calculable with a perturbative expansion in the strong coupling  $\alpha_S(Q) \sim 1/(\beta_0 \ln Q^2/\Lambda_{QCD}^2) \sim 0.1$  (for  $Q = m_H, m_W, m_Z, m_t, p_T^{jet}, \dots$ ).

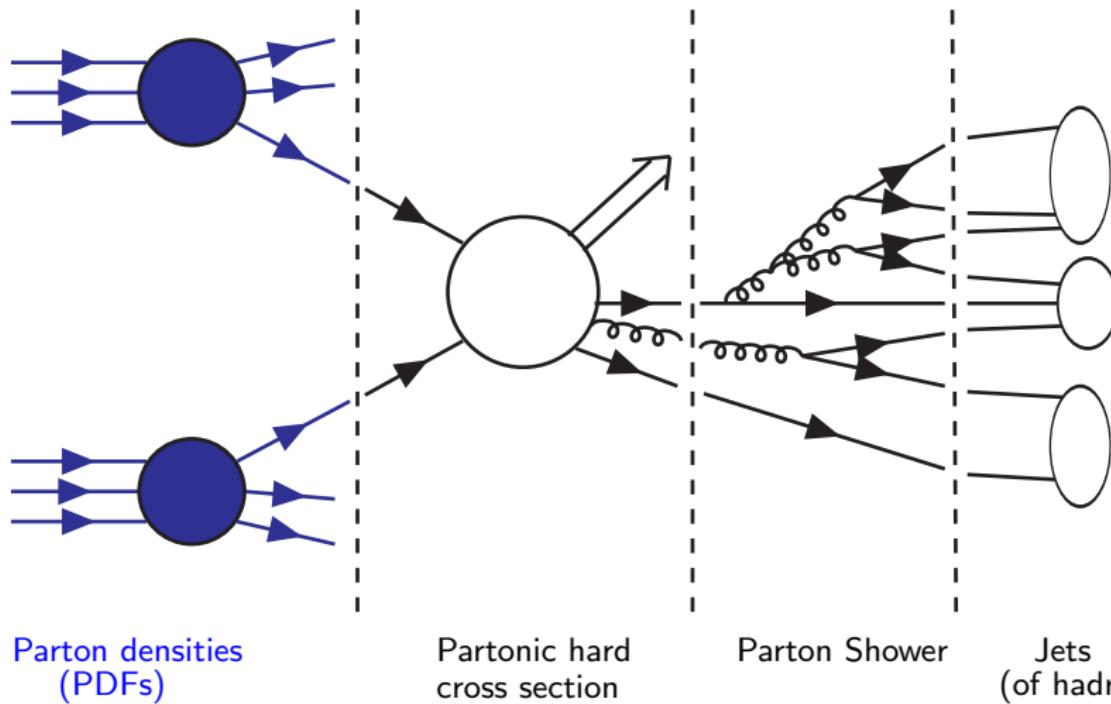
$$\hat{\sigma}_{ab} = \hat{\sigma}_{ab}^{(0)} + \alpha_S(\mu_R^2) \hat{\sigma}_{ab}^{(1)} + \alpha_S^2(\mu_R^2) \hat{\sigma}_{ab}^{(2)} + \mathcal{O}(\alpha_S^3).$$

- $\left(\frac{\Lambda_{QCD}}{Q}\right)^p$  (with  $p \geq 1$ ): Non perturbative power-corrections (higher-twist).

Precise predictions for  $\sigma$  depend on good knowledge of both  $\hat{\sigma}_{ab}$  and  $f_{a/h}(x, \mu_F^2)$



# PDFs



# Fit of PDFs

- Method: typical parametrization of parton densities at input scale  $\mu_0^2 \sim 1 \div 4 \text{ GeV}^2$ :

$$x f_a(x, \mu_0^2) = A_a x^{\lambda_a} (1-x)^{\eta_a} (1 + \epsilon_a \sqrt{x} + \gamma_a x + \dots).$$

Parameters constrained by imposing momentum sum rules:  $\sum_a \int_0^1 dx x f_a(x, \mu_0^2) = 1$ , then adjust parameters to fit data.

- Typical constraining process:

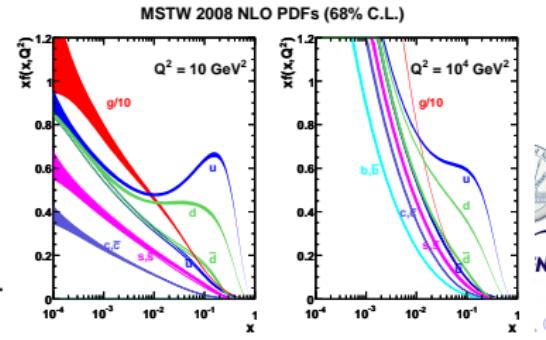
- DIS (fixed target exp. and HERA): sensitive to quark densities.
- Jet data (HERA and Tevatron): sensitive to high- $x$  gluon density.
- Drell-Yan (low energy and Tevatron data): sensitive to (anti-)quark densities.

- Evolution  $\mu_0 \rightarrow \mu$  using DGLAP equations:

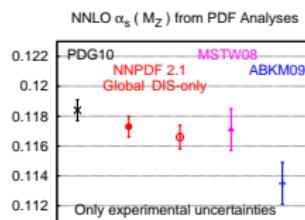
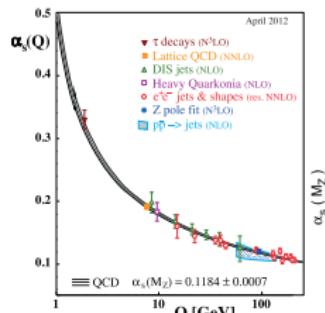
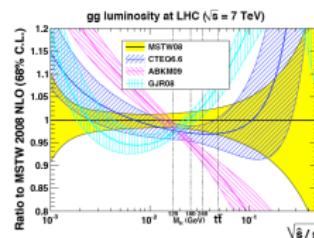
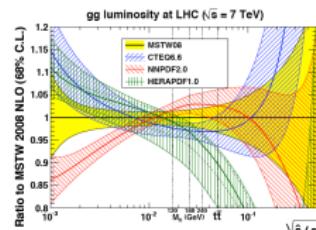
$$\frac{\partial f_a(x, \mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s(\mu^2)}{2\pi} \int_x^1 \frac{d\xi}{\xi} P_{ab}(x/\xi) f_b(\xi, \mu^2)$$

AP kernels calculable in pQCD

$$P_{ab}(z) = P_{ab}^{(0)}(z) + \frac{\alpha_s(\mu^2)}{2\pi} P_{ab}^{(1)}(z) + \left(\frac{\alpha_s(\mu^2)}{2\pi}\right)^2 P_{ab}^{(2)}(z) + \dots$$

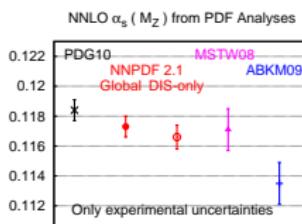
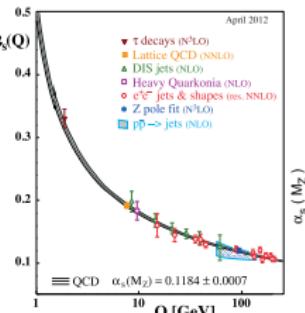
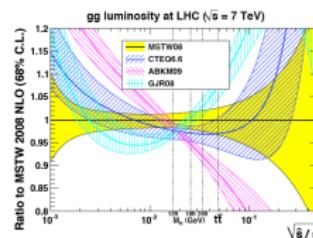
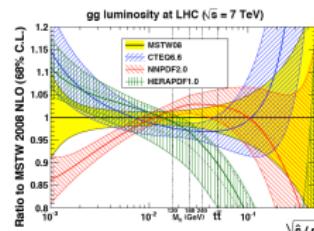


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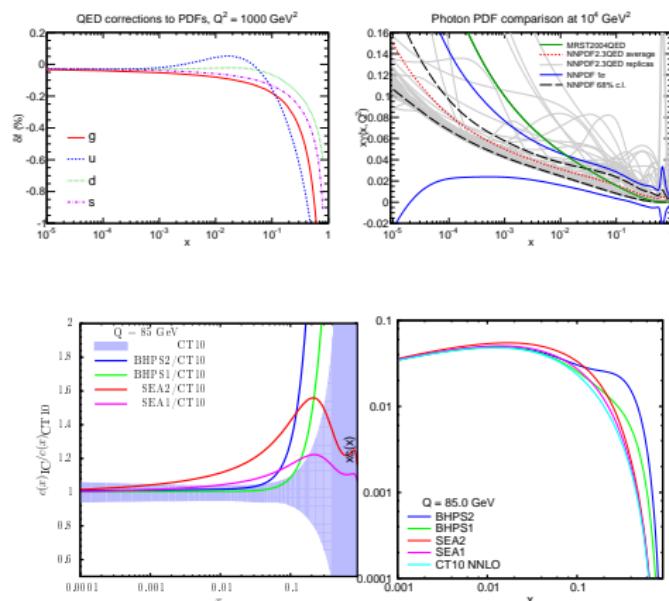
- Several PDFs sets available:  
MSTW, NNPDF, CTEQ/CT, GJR, ABKM, HERAPDF.  
**MSTW**:  $\sim 3000$  data pts.,  $\sim 50$  free param.  
**NNPDF**:  $\sim 3000$  data pts.,  $\sim 250$  free param.
- Differences among sets include:  
data set in the fit, parton parametrization, statistical treatment, perturbative accuracy (NLO,NNLO), value of  $\alpha_S$ .
- PDFs sets can be combined using the "PDF4LHC recommendation" to obtain a central value and an estimate of the uncertainty.
- Simultaneous extraction of  $\alpha_S(m_Z)$  from NNLO fits lead to some tension:  
World avg.'12  $\alpha_S(m_Z) = 0.1184 \pm 0.0007$   
ABKM11  $\alpha_S(m_Z) = 0.1135 \pm 0.0014$   
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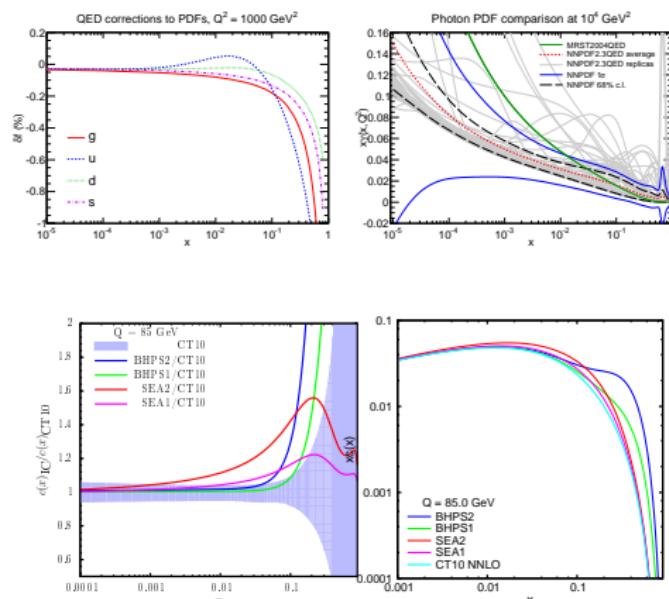


Recent developments in PDFs sets:

- **inclusion of LHC experimental data ( $W$ ,  $Z$ , isolated  $\gamma$ , jets,  $t\bar{t}$  production, low/high-mass Drell-Yan).**
- Parton distributions with QED corrections NNPDF2.3 QED ('13): **photon PDF** (with uncertainty) from data and QED parton evolution. Implications for dilepton and  $W$  pair production at the LHC. LHC data constrain the photon PDF for  $10^{-5} \lesssim x \lesssim 10^{-1}$  at  $Q^2 = 2 \text{ GeV}^2$
- Study the possibility of intrinsic (non-perturbative) charm (IC) in PDF CTEQ-CT10 ('13): IC allowed to carry around 2% of proton momentum. Implications for/constraints from  $Z/\gamma +$  jet at the LHC.



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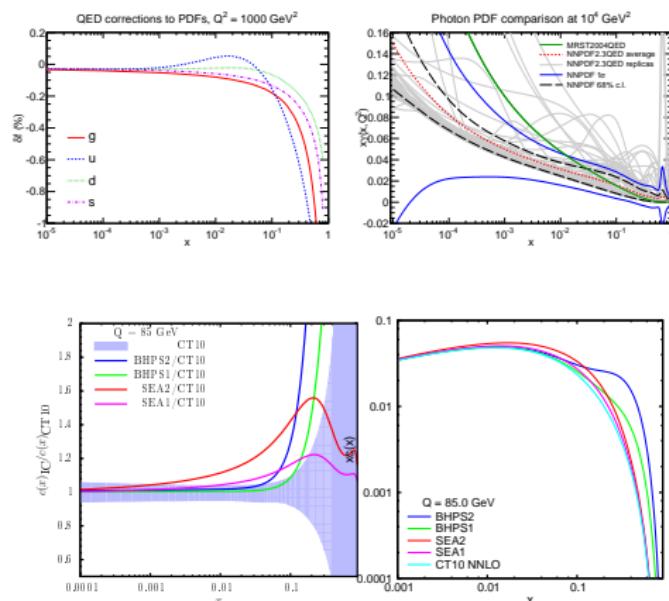


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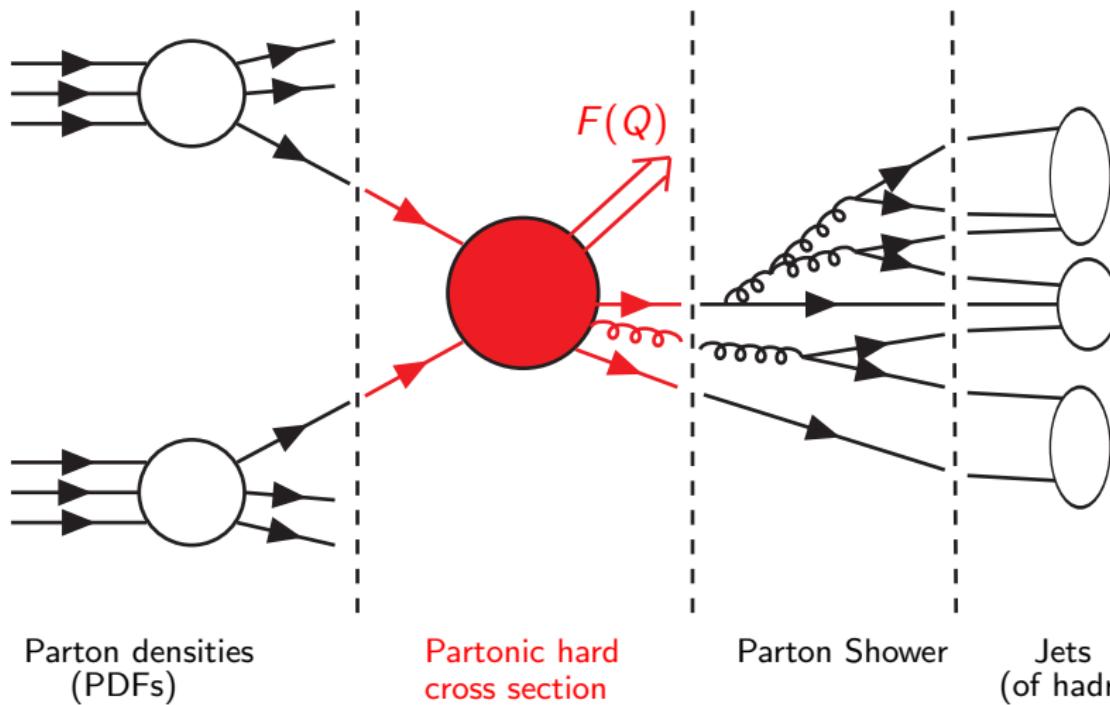


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# Partonic Hard Cross Section



# Higher orders: NLO

- Calculations at LO give the order of magnitude of cross sections and distributions,  
NLO corrections provide reliable estimate
- Experiments have finite acceptance important to provide exclusive theoretical predictions.
- At NLO infrared singularities in *real* and *virtual* corrections prevent the straightforward implementation of Monte Carlo numerical techniques (especially for fully exclusive quantities).
- NLO subtraction method: introduction of auxiliary QCD cross section *in a general way* exploiting the universality of the soft and collinear emission [Frixione,Kunszt,Signer ('96) (FKS), Catani,Seymour ('97) (CS)]. It allows (relatively) straightforward calculations, once the QCD amplitudes are available

$$\begin{aligned}\sigma^{NLO} &= \int_{m+1} d\sigma^R(\epsilon) + \int_m d\sigma^V(\epsilon) \\ &= \int_{m+1} \left[ d\sigma^R(\epsilon) - d\sigma^A(\epsilon) \right]_{\epsilon=0} + \int_m \left[ d\sigma^V(\epsilon) + \int_1 d\sigma^A(\epsilon) \right]_{\epsilon=0}\end{aligned}$$



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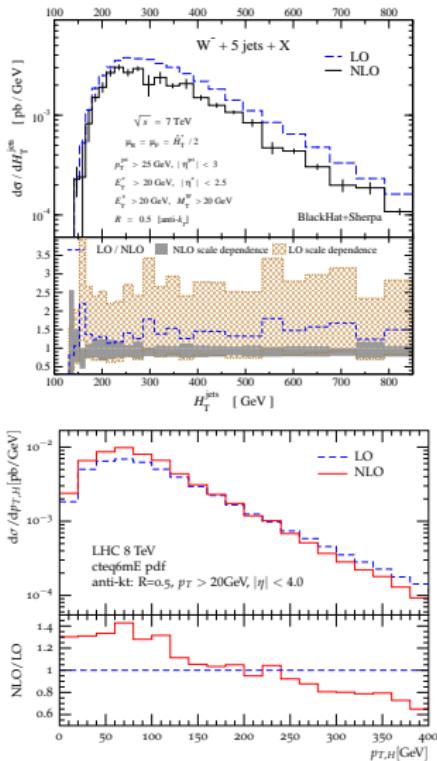
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# NLO: automation



- NLO calculations are now highly automated. Virtual corrections can be combined with real corrections (based on CS or FKS subtraction formalism).
- HELAC-NLO [Bevilacqua, Czakon, Garzelli, van Hameren, Kardos, Papadopoulos, Pittau, Worek].
- BlackHat+Sherpa [Berger, Bern, Dixon, Cordero, Forde, Gleisberg, Ita, Kosower, Maitre].
- MadLoop+MadFKS [Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau].
- Rocket [Ellis, Giele, Kunszt, Melnikov, Zanderighi].
- GoSam [Cullen, Greiner, Heinrich, Luisoni, Mastrolia, Ossola, Reiter, Tramontano].
- OpenLoops [Cascioli, Maierhöfer, Pozzorini].
- NLO dedicated calculations also available: MCFM, VBFNLO, NLOJet++, ...



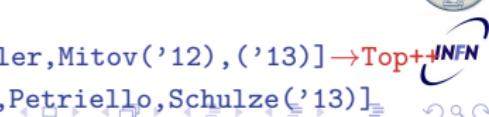
# Higher orders: fully-exclusive NNLO calculation

- NNLO corrections allow a good control of theoretical uncertainties: important to provide exclusive prediction to implement the experimental cuts.
- NNLO computations cumbersome, in hadronic collisions only few calculations exist:
  - **Sector decomposition:** [Binoth,Heinrich('00)]  
 $pp \rightarrow H$  (gg fusion) [Anastasiou,Melnikov,Petriello('04)] → FEHIP  
 Drell-Yan [Melnikov,Petriello('06)] → FEWZ
  - **$q_T$ -subtraction:** [Catani,Grazzini('07)]  
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 Diphoton production [Catani,Cieri,de Florian,G.F.,Grazzini('11)] →  $2\gamma$ NNLO  
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  - **Non-linear mapping:** [Anastasiou,Herzog,Lazopoulos('10)]  
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 $pp \rightarrow t\bar{t}$  (total cross sec.) [Baernreuther,Czakon,Fiedler,Mitov('12),('13)] → Top++  
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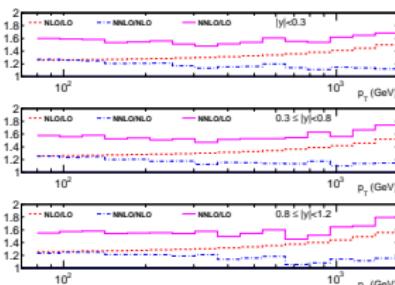


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# Recent results on NNLO calculations

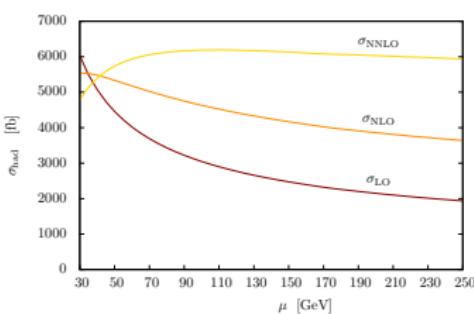


Dijet prod.: Double differential K-factors for  $p_T > 80$  GeV and various  $|y|$  slices.

- Dijet production [Gehrmann, G.-De Ridder, Glover, Pires ('13)]: Fully exclusive calculation implemented in (parton level) Monte Carlo code **NNLOJET** using Antenna Subtraction formalism (pure gluon at leading colour).
- Higgs+jet production [Boughezal, Caola, Melnikov, Petriello, Schulze ('13)]: NNLO using sector-improved subtraction scheme (total cross section for pure gluon contributions).
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- soft-virtual term at N3LO for  $gg \rightarrow H$  production (in large  $m_{top}$  app.) [Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Mistlberger ('14)].
- Higgs pair production (in large  $m_{top}$  app.) de Florian, Mazzitelli ('13). Important to measure Higgs trilinear coupling at high luminosity LHC. Large  $\mathcal{O}(20\%)$  NNLO corrections at  $\sqrt{s} = 14$  TeV



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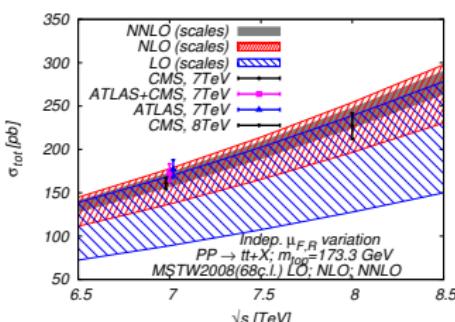


H+jet prod.: scale dependence of the hadronic cross section in perturbative QCD.

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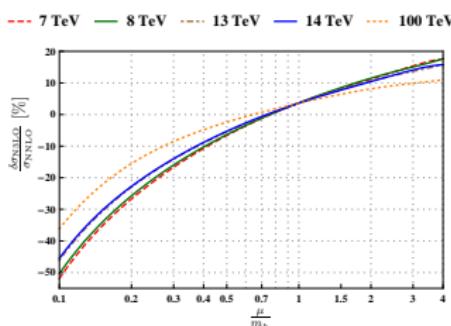
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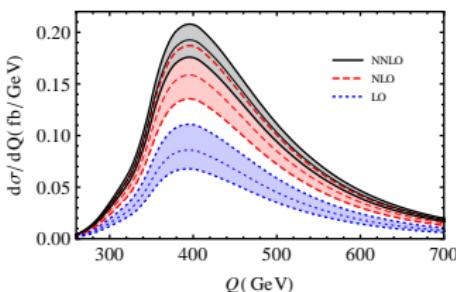


$gg \rightarrow H$  prod.: Percent difference from the NNLO to the  $N^3LO$  cross-section estimate at threshold for  
 $\sqrt{s} = 7, 8, 13, 14, 100$  TeV, as a function of  $\mu = \mu_R = \mu_F$ .

- Dijet production [Gehrmann, G.-De Ridder, Glover, Pires ('13)]: Fully exclusive calculation implemented in (parton level) Monte Carlo code **NNLOJET** using Antenna Subtraction formalism (pure gluon at leading colour).
- Higgs+jet production [Boughezal, Caola, Melnikov, Petriello, Schulze ('13)]: NNLO using sector-improved subtraction scheme (total cross section for pure gluon contributions).
- $t\bar{t}$  production [Baernreuther, Czakon, Fiedler, Mitov ('13)]: Total cross section computed for all partonic channels  $\rightarrow$  **Top++**.
- soft-virtual term at N3LO for  $gg \rightarrow H$  production (in large  $m_{top}$  app.) [Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Mistlberger ('14)].
- Higgs pair production (in large  $m_{top}$  app.) de Florian, Mazzitelli ('13). Important to measure Higgs trilinear coupling at high luminosity LHC. Large  $\mathcal{O}(20\%)$  NNLO corrections at  $\sqrt{s} = 14$  TeV



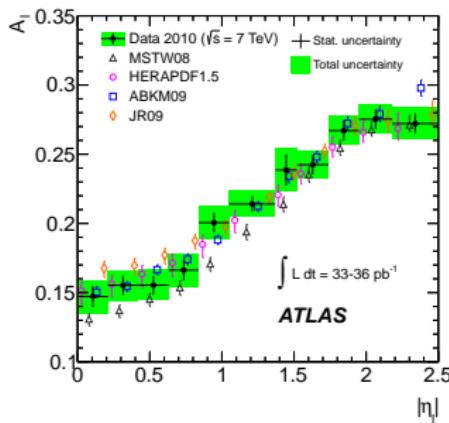
# Recent results on NNLO calculations



Higgs pair invariant mass distribution at LO, NLO and NNLO for  $E_{cm} = 14$  TeV. Bands are obtained by varying  $0.5 Q \leq \mu_F, \mu_R \leq 2 Q$  with  $0.5 \leq \mu_F/\mu_R \leq 2$ .

- Dijet production [Gehrmann, G.-De Ridder, Glover, Pires ('13)]: Fully exclusive calculation implemented in (parton level) Monte Carlo code **NNLOJET** using Antenna Subtraction formalism (pure gluon at leading colour).
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# NNLO: the $q_T$ -subtraction formalism

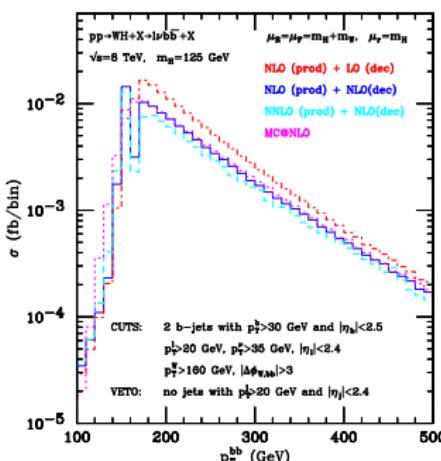


Lepton charge asymmetry from W decay measured by ATLAS and compared with NNLO QCD (from DYNNLO) with various PDFs.

NNLO extension of the subtraction formalism valid for hadroproduction of **colourless high-mass system** [Catani, Grazzini ('07)]: fully exclusive calculations implemented in (parton level) Monte Carlo numerical codes:

- Higgs prod. in gluon fusion: [Catani, Grazzini ('07)].  
Vector boson prod. (DY): [Catani, Cieri, de Florian, G.F., Grazzini ('09)].
- WH prod.: Direct information on Higgs-fermions coupling [G.F., Grazzini, Tramontano ('11) ('13)].
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# NNLO: the $q_T$ -subtraction formalism



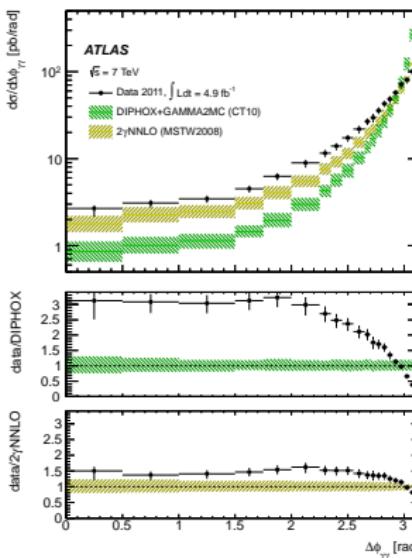
WH prod.:  $p_T$  spectra of the  $b\bar{b}$  pair from  $H$  decay at various perturbative orders and with MC@NLO.

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# NNLO: the $q_T$ -subtraction formalism



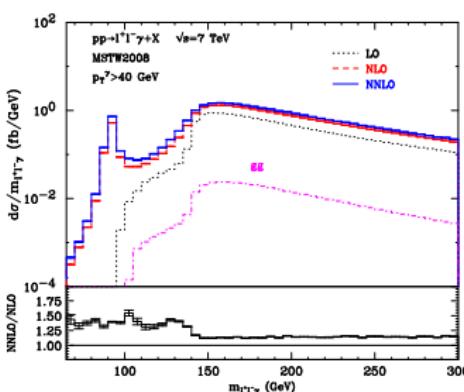
$\gamma\gamma$  prod.: Azimuthal angle  $\Delta\phi_{\gamma\gamma}$  spectrum measured by ATLAS and compared with NLO and NNLO QCD.

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# NNLO: the $q_T$ -subtraction formalism



$Z\gamma$  prod.: Invariant mass distribution of the  $l^{+/-}\gamma$  system at LO, NLO and NNLO QCD.

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# Sudakov resummation

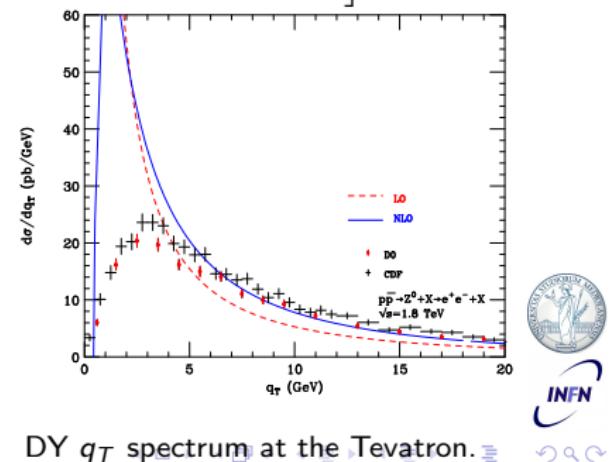
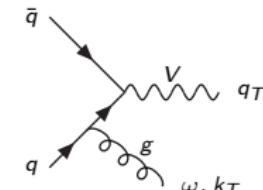
An example: Drell-Yan production at small  $q_T$  ( $q_T \ll M_V$ ).  
 The standard fixed-order QCD perturbative expansions gives:

$$\int_0^{Q_T^2} dq_T^2 \frac{d\hat{\sigma}_{q\bar{q}}}{dq_T^2} \sim 1 + \alpha_S \left[ c_{12} \log^2(M^2/Q_T^2) + c_{11} \log(M^2/Q_T^2) + c_{10}(Q_T) \right] \\ + \alpha_S^2 \left[ c_{24} \log^4(M^2/Q_T^2) + \dots + c_{21} \log(M^2/Q_T^2) + c_{20}(Q_T) \right] + \mathcal{O}(\alpha_S^3)$$

The logs are the residue of the cancellation of the real-virtual infrared singularities due to soft/collinear gluon emissions (recoiling radiation is forced to be soft/collinear).

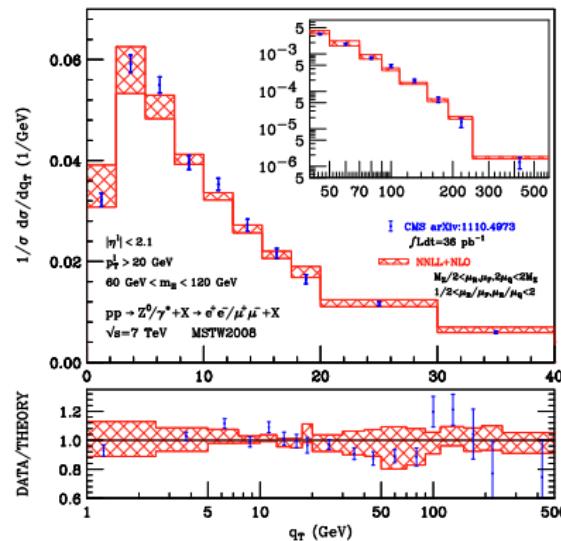
Fixed order calculation reliable only for  $q_T \sim M_V$

For  $q_T \rightarrow 0$ ,  $\alpha_S^n \log^m(M^2/q_T^2) \gg 1$ : need for resummation of logarithmic corrections.



DY  $q_T$  spectrum at the Tevatron.

# Resummed results

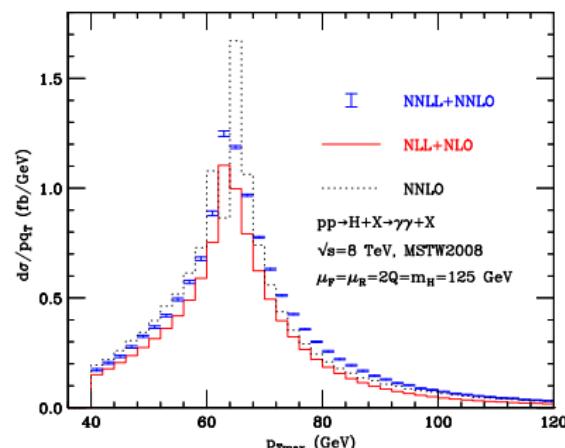


CMS data for the  $Z$   $q_T$  spectrum compared with DYRes NNLL+NLO result. (from [Catani, de Florian, G.F., Grazzini ('13)]).

- Transverse-momentum (small  $q_T$ ) resummation: resum to all order large logarithmic corrections of the form  $\log(q_T/M)$  when  $q_T \ll M$ .  
[Parisi,Petronzio('79)],  
[Collins,Soper,Sterman('85)] After resummation perturbative results became predictive also for small  $q_T$ .
- Threshold resummation: resum to all order large logarithmic corrections of the form  $\log(1 - M^2/\hat{s})$  when  $M^2/\hat{s} \rightarrow 1$  (large invariant mass limit).  
[Sterman('87)], [Catani,Trentadue('89)] Smaller quantitative effect of resummation, still reduction of perturbative uncertainty.



# Resummed results

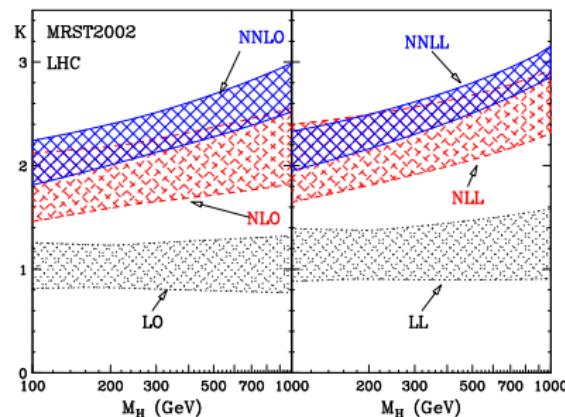


$p_T^{\gamma}$  from  $H \rightarrow \gamma\gamma$  at LHC (from **HRes** code [de Florian, G.F., Grazzini, Tommasini ('12), Grazzini, Sargsyan ('13)]).

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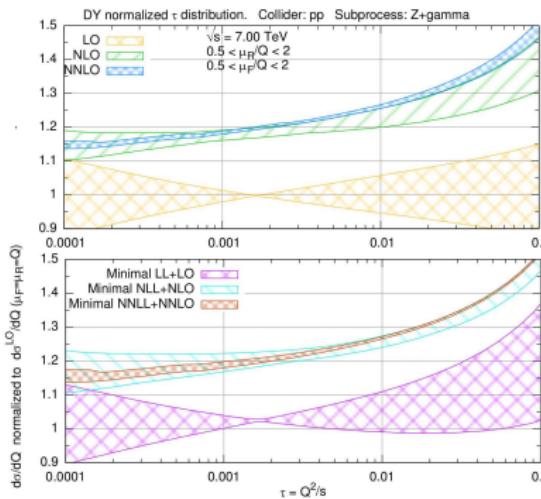


Higgs prod. at the LHC: Fixed-order and resummed  $K$ -factors. (from [Catani, de Florian, Grazzini, Nason ('03, '09, '12)]).

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# Resummed results



Neutral DY pairs at the LHC: Invariant mass distribution, perturbative uncertainty band for fixed order and resummed results (from [Bonvini,Forte,Ridolfi('10)]).

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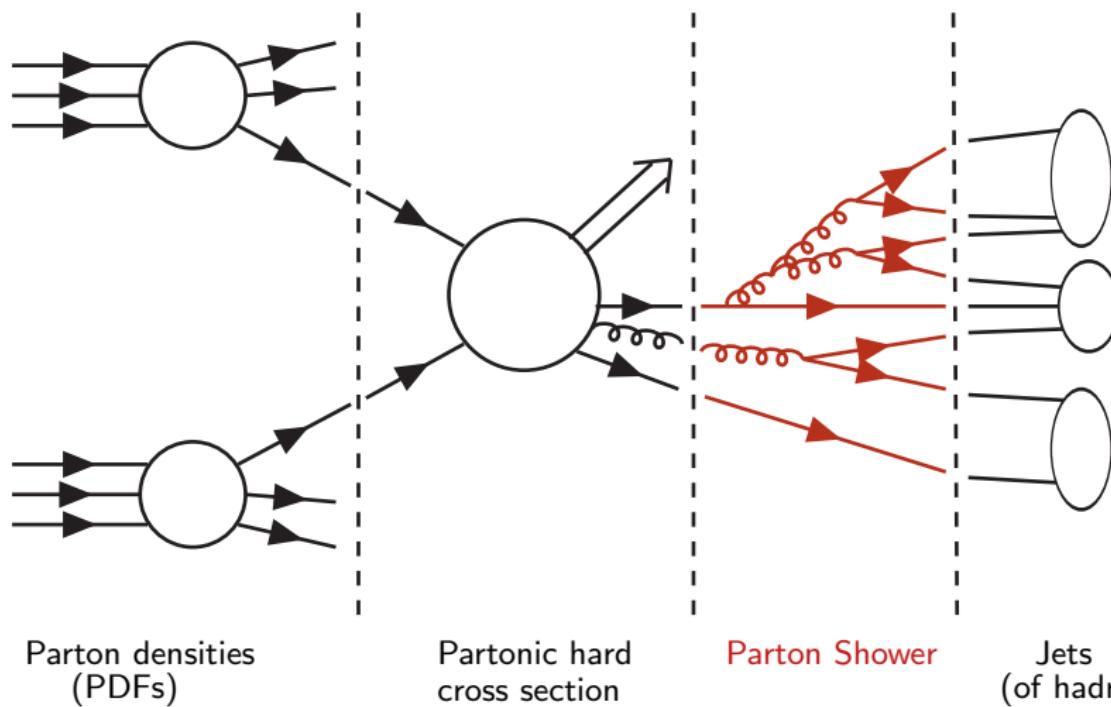


# Electro-Weak Corrections

- Size of NLO electro-weak (EW) corrections comparable with NNLO QCD:  $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_S^2)$
- Significant larger corrections from EW Sudakov logarithms:  $\alpha / \sin_W^2 \log^2(\hat{s}/M_W^2)$  (important at LHC 13 TeV, 30 TeV, ..., resummation needed).
- NLO EW corrections important for LHC phenomenology, known for important processes:  
 Drell-Yan HORACE, ZGRAD, SANC, RADY  
 V+jet [Kuhn et al. ('04) ('05) ('07), Hollik et al. ('07), Denner et al. ('09),  
 Maina et al. ('09), Denner et al. ('11), Actis et al. ('12)]  
 Diboson prod. [Accomando et al. ('01) ('04) ('05), Hollik, Meier ('04),  
 Bierweiler et al. ('12)]  
 Higgs prod.(H,H+V,VBF) [Aglietti et al. ('06), Actis et al. ('08)], HAWK  
 Higgs decay HDECAY, PROPHECY4F  
 jets/heavy-quarks:  $pp \rightarrow jj, pp \rightarrow t\bar{t}, pp \rightarrow b\bar{b}$  [Moretti et al. ('05) ('06),  
 Dittmaier et al. ('12), Bernreuther et al. ('08), Maina et al. ('03),  
 Kuhn et al. ('06) ('09) ('13)]
- Mixed NLO EW and QCD (NLO/NNLO) corrections also available in factorized form:  
 $1 + \delta_{QCD}^{NLO} + \delta_{EW}^{NLO}$  or  $(1 + \delta_{QCD}^{NLO}) \times (1 + \delta_{EW}^{NLO})$  [Ciccolini, Denner, Dittmaier ('07),  
 Barze et al. ('13), Anastasiou, Boughezal, Petriello ('09),  
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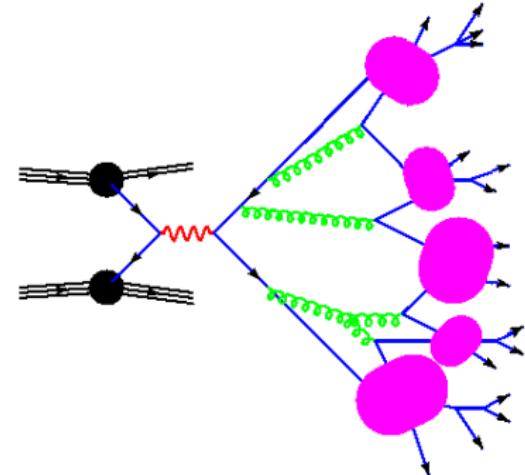
# Shower Monte Carlo



# Shower Monte Carlo

Complete description of a hadron scattering event.

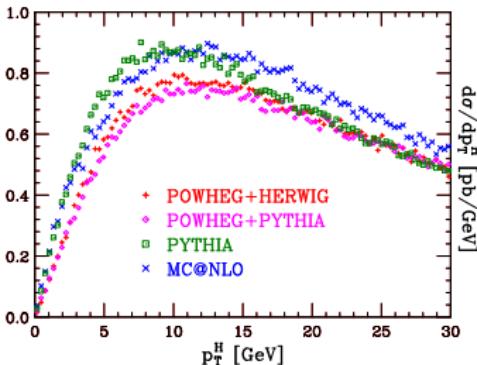
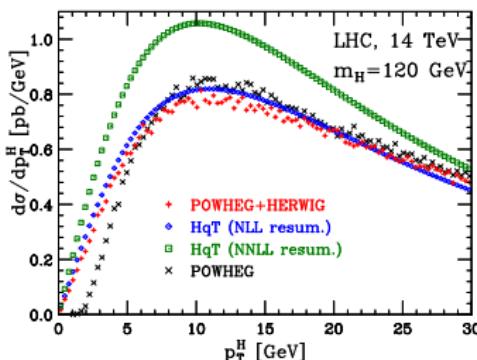
- **QCD parton shower (PS)**: Starting from LO QCD, inclusion of dominant collinear and soft-gluon emissions (by angular ordering thanks to color coherence) to all order in a approximate way as a Markov process (probabilistic picture).
- No analytic solution but simple iterative structure of **coherent parton branching**.
- QCD accuracy analogous to LL (plus part of NLL) Sudakov resummation.
- Implemented in **numerical Monte Carlo programs**.
- QCD parton cascade matched with **hadronization model** for conversion of partons into hadrons (and model for resonance decay)  $\Rightarrow$  **QCD event generators** (Herwig/PYTHIA/Sherpa).
- Possible to consistently combine Parton Shower with high multiplicity tree-level matrix elements: CKKW/MLM matching.



Scheme of QCD Parton Shower and hadronization from final states.



# Parton Shower+NLO

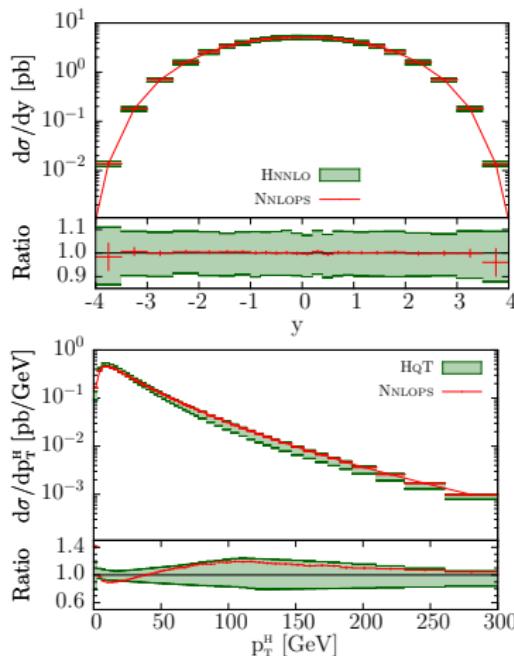


State of the art for QCD event generators: methods for combining Shower MC with perturbative calculation at NLO (avoiding double counting). Two general methods:

- MC@NLO [Frixione, Webber ('02)]: implements in a given Shower Monte Carlo the NLO accuracy for total cross section. Hard emission at NLO, all order soft/ collinear emissions included by the shower.
- POWHEG [Nason ('04)]: NLO+PS (with no negative weights) by a modification of existing shower.
- Present directions:
  - (i) NLO+PS towards automation for matrix elements and NLO matching: aMC@NLO [Frederix, Frixione, Hirschi, Maltoni, Pittau, Torrielli ('11)], POWHEG BOX [Alioli, Nason, Oleari, Re ('10)].
  - (ii) NNLO+PS accuracy: combining Multiscale Improved NLO MiNLO and POWHEG approaches possible to match NNLO accuracy for inclusive quantities with PS [Hamilton, Nason, Re, Zanderighi ('13)].



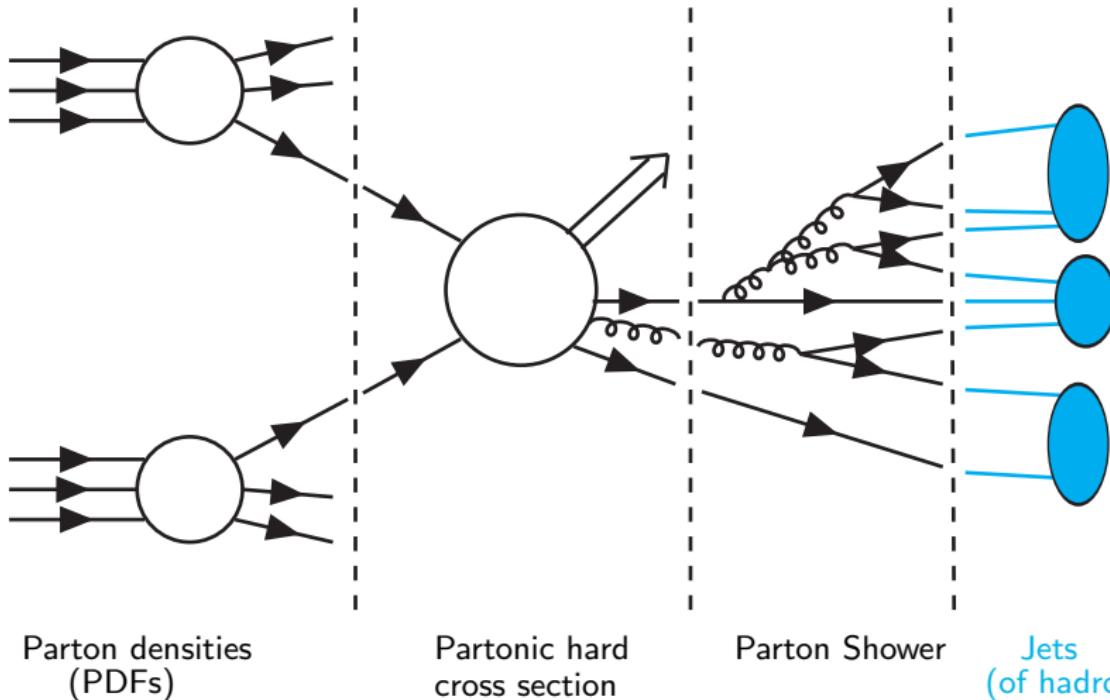
# Parton Shower+NLO



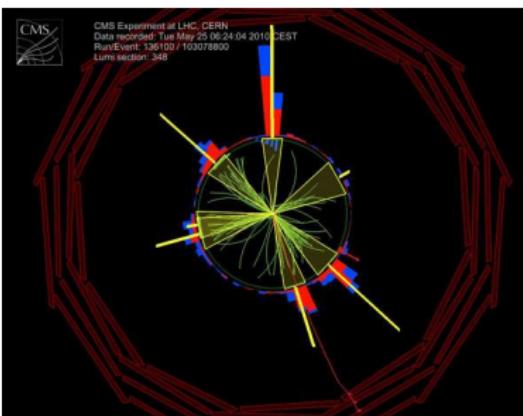
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# Jets



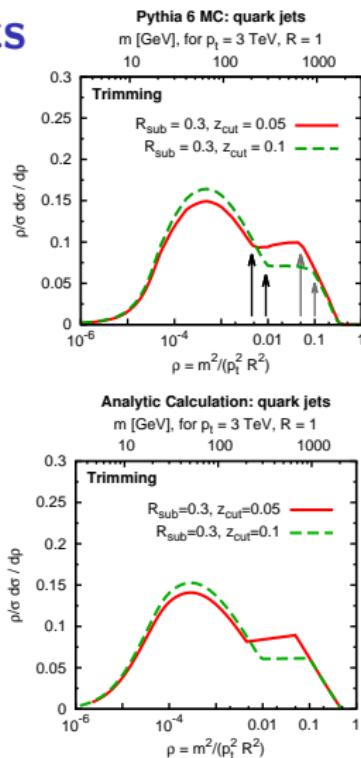
# Jets



- QCD matrix elements enhanced in the collinear regions, this give rise to **Jets**: **collimated spray of high-energy hadrons** (ubiquitous at the LHC).
- **Jet clustering algorithms** ( $k_T$ , anti- $k_T$ , C/A): iterative procedure to cluster particles in **experimental** analysis and in **theoretical** calculations (infrared/coll. safe).
  - (i) Define a “distance”  $d_{ij}$  between particles.
  - (ii) Merge particles with minimum  $d_{ij}$  until a fixed resolution  $d_{cut}$  is reached.
- **Jet substructure**: helps to discriminate “signals” from “background” jets (“grooming” and “tagging” techniques). Analytic results to understand these techniques start to appear [Dasgupta, Fregoso, Marzani, Powling, Salam ('13)].
- **Jet-veto efficiency resummation** at NNLL+NNLO: for Higgs prod. reduces uncertainties by about a factor 1.5-2. [Banfi, Monni, Salam, Zanderighi]



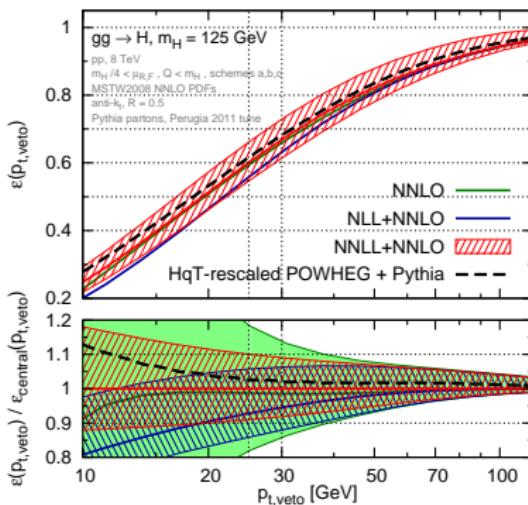
# Jets



Analytic resummed calculations and parton shower for the jet-mass distribution.

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# Jets



NNLO, NLL+NNLO and NNLL+NNLO results for jet-veto efficiencies for Higgs production at the LHC.

- QCD matrix elements enhanced in the collinear regions, this give rise to **Jets**: **collimated spray of high-energy hadrons** (ubiquitous at the LHC).
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# Conclusions

- This talk is an overview on some selected topic of Standard Model Physics at the LHC: PDFs, higher orders (NLO, NNLO and resummed) QCD and EW calculations, Shower Monte Carlo and Jets.
- Main message:  
**To fully exploit the information contained in the experimental data, and to increase the LHC discovery power, precise theoretical predictions of the SM cross sections are necessary.**

