Precise theoretical predictions for Large Hadron Collider physics

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TIF LAB: particle physics phenomenology group

Members:

S. Forte (Head)
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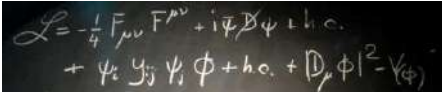
G. Ferrera
G. Sborlini (Postdoc)
Z. Kassabov (PhD)
C. Muselli (PhD)

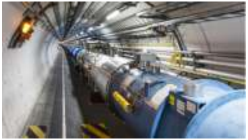
- Strong connections with scientific activities at CERN.
- Interactions with the local particle physics experimental groups (in particular ATLAS and LHCb).

High Energy Physics and the **LHC**

- Explore elementary **constituents of matter** and **energy**, their **interactions**.
- The **Standard Model (SM)** of elementary particles describes strong (QCD) and electroweak (EW) interactions.



$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$



- The **Large Hadron Collider (LHC)** at CERN is the world's largest particle accelerator (2009-2035). It **explores the unknown region of the TeV energy frontier (i.e. 10^{-18}m)**.
- The LHC is addressing many **fundamental questions** in High Energy Physics:
  - What is the **origin of the masses** of the elementary particles**?**
  - What is the nature of **"dark matter"?**
  - Why is there a **large matter and anti-matter asymmetry** in the Universe**?**
  - Do **extra spatial dimensions** exist**?**
  - What is the connection between **Higgs field** and **cosmological inflation?**

From Maxwell equations to Higgs boson

$\nabla\cdot\mathbf{E}=\rho$, $\nabla\cdot\mathbf{B}=0$, $\nabla\times\mathbf{E}=-\frac{\partial\mathbf{B}}{\partial t}$, $\nabla\times\mathbf{B}=\frac{\partial\mathbf{E}}{\partial t}+\mathbf{j}$ or $\partial_\mu F^{\mu\nu}=j^\nu$ $(F^{\mu\nu}=\partial^\mu A^\nu-\partial^\nu A^\mu,\ \ j^\nu=(\rho,\mathbf{j}))$

$\mathcal{L}_0=-\frac{1}{4}F^{\mu\nu}F_{\mu\nu}$ QED (massless photons) local gauge invariant $(A^\mu\to A^\mu+\partial^\mu\lambda(x))$

How to describe massive vector bosons (e.g. weak interactions)?

$\mathcal{L}_m=-\frac{1}{4}F^{\mu\nu}F_{\mu\nu}+\cancel{\frac{m^2}{2}A^\mu A_\mu}$ forbidden by gauge invariance (cannot quantize the theory!)

How to add a mass term preserving gauge invariance? The Higgs mechanism (1964):

$\mathcal{L}_H=-\frac{1}{4}F^{\mu\nu}F_{\mu\nu}+|(\partial_\mu+iqA_\mu)\phi|^2-V(\phi)$, ϕ complex scalar field ($\mathcal{L}_H$ gauge inv. $\phi\to e^{\theta(x)}\phi$)

$V(\phi)=\alpha|\phi|^2+\beta|\phi|^4$, $\alpha<0,\ \beta>0$, $\phi_0=\sqrt{\frac{-\alpha}{2\beta}}$, $\phi=\phi_0+h+i\pi$

$$\mathcal{L}_H=-\frac{1}{4}F^{\mu\nu}F_{\mu\nu}+(\partial_\mu h)^2-\frac{q^2\alpha}{4\beta}A^\mu A_\mu+2\alpha h^2+\cdots$$

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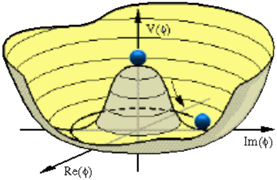

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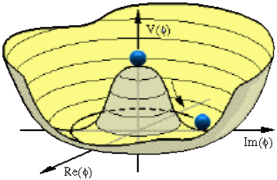

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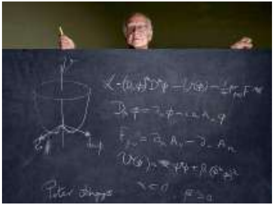
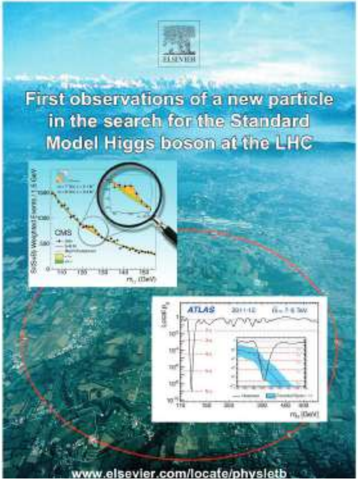


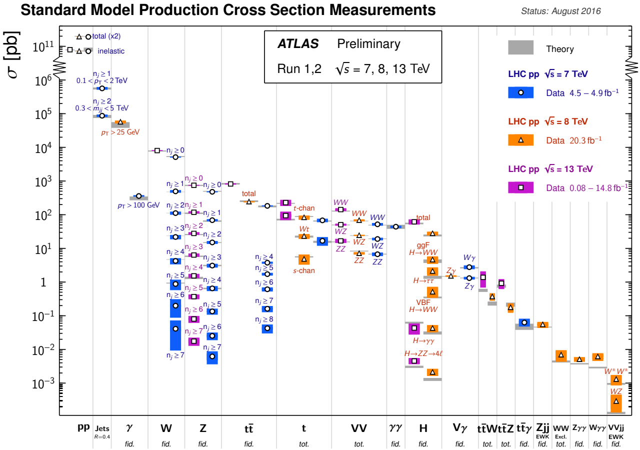
The **Higgs boson** discovery (→ see M. Fanti talk)



[ATLAS and CMS Coll. PLB716 ('12)]

- On July 2012 the **discovery of the Higgs boson** at CERN: most **important breakthrough in particle physics** of the last 30 years.
- Understanding the **electroweak symmetry breaking** and **the origin of the masses** of the elementary particles.
- Next LHC goal: **detailed measurement of the Higgs boson properties**. Key to **unravel deviation from Standard Model predictions**.
- Besides Higgs boson discovery **many outstanding results obtained by the LHC,** and **new discoveries are within the LHC reach in the next years.**

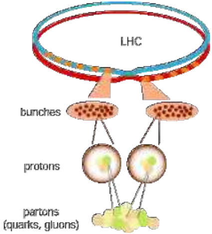
LHC key results: Higgs boson and much more



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

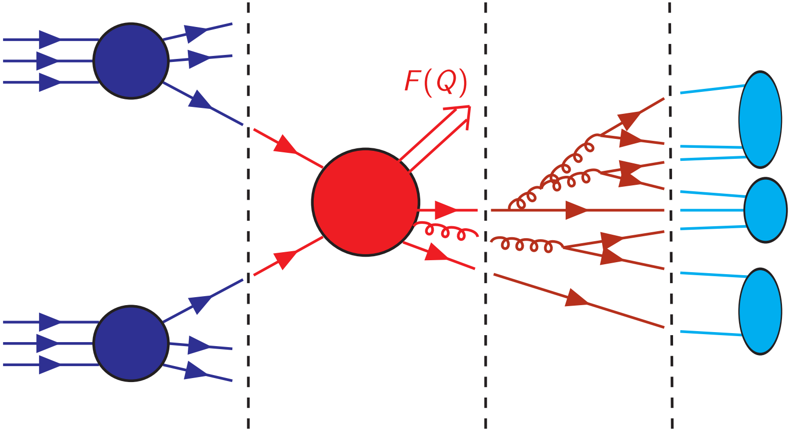
How to **increase the discovery power of the LHC?**

The LHC is a hadron collider machine: all the interesting reactions initiate by QCD hard scattering of partons: a good control of the QCD processes is necessary.



To fully exploit the information contained in the LHC experimental data, **precise theoretical predictions** of the Standard Model cross sections are needed.

Theoretical predictions at the LHC



$F(Q)$

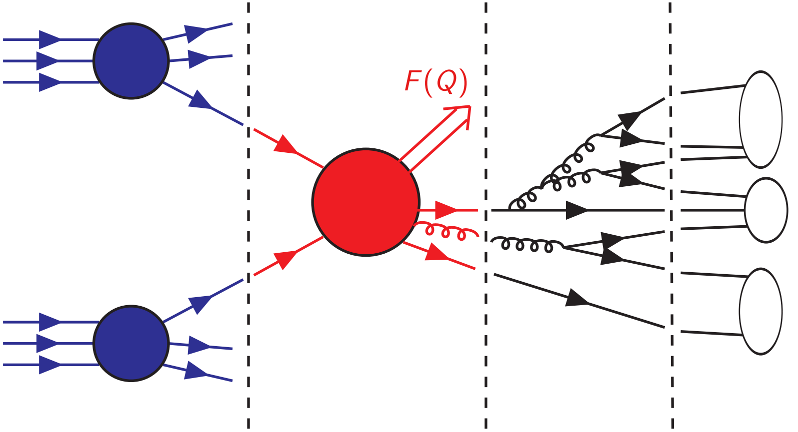
Parton densities
(PDFs)

Partonic hard
cross section

Parton Shower

Jets
(of hadrons)

Theoretical predictions at the LHC



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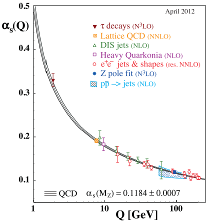
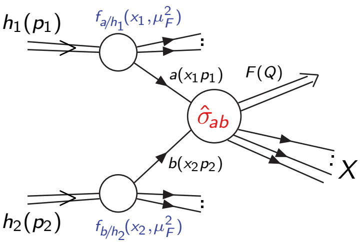


The asymptotically free QCD coupling $\alpha_S(Q)$

$$h_1 + h_2 \;\to\; F(Q) + X$$



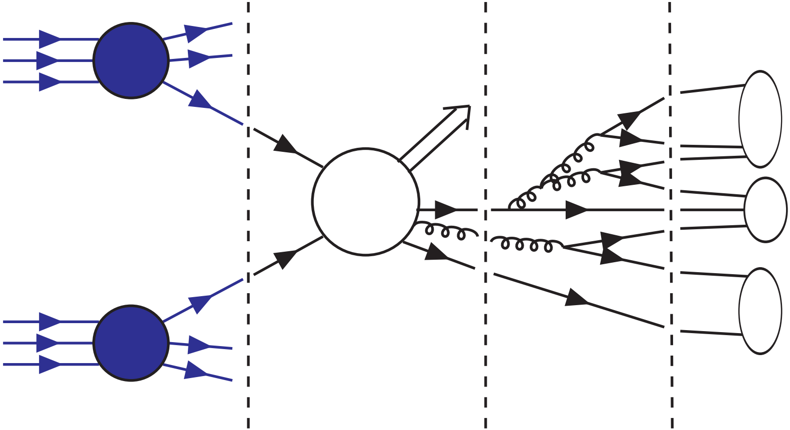
The framework: **QCD factorization formula**

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

- $f_{a/h}(x, \mu_F^2)$: Non perturbative universal parton densities (PDFs), $\mu_F \sim Q$.
- $\hat{\sigma}_{ab}$: Hard scattering cross section. Process dependent, calculable with a perturbative expansion i the strong coupling $\alpha_S(Q)$ ($Q \gg \Lambda_{QCD} \sim 1\,GeV$).
- $\left(\frac{\Lambda_{QCD}}{Q}\right)^p$ (with $p \geq 1$): Non perturbative power-corrections.

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

PDFs



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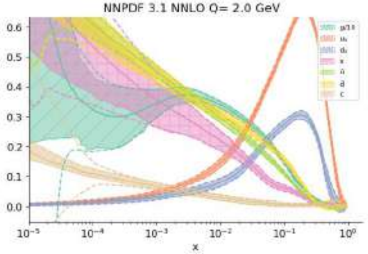
Fit of PDFs

- Method: typical parametrization of parton densities $f_a(x, \mu_0^2)$ at input scale $\mu_0^2 \sim 1 \div 4\ GeV^2$. 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 $\mu_0 \to \mu$ 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

$$P_{ab}(z) = P_{ab}^{(0)}(z) + \alpha_S P_{ab}^{(1)}(z) + \alpha_S^2 P_{ab}^{(2)}(z) + \cdots$$



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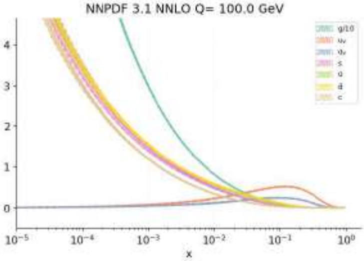
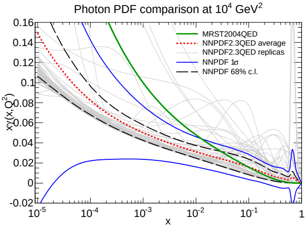


Recent results on PDFs



Some recent developments:

- inclusion of LHC experimental data (W, Z/γ^* (at low/high invariant mass), isolated γ, jets, $t\bar{t}$ production). and inclusion of QED corrections and extraction of photon PDF (with uncertainty) from data `NNPDF Coll. [Forte,Kassabov et al. ('13,'14,'17)]` (**N3PDF** ERC project).
- Photon PDF has to be consistently combined with the Altarelli-Parisi splitting functions with mixed QCD-QED corrections `[de Florian,Rodrigo, Sborlini('16)]`.

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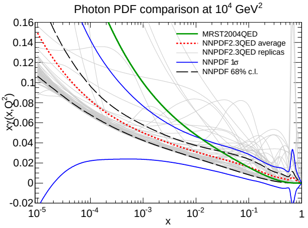

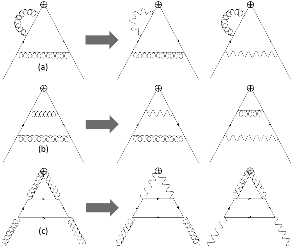

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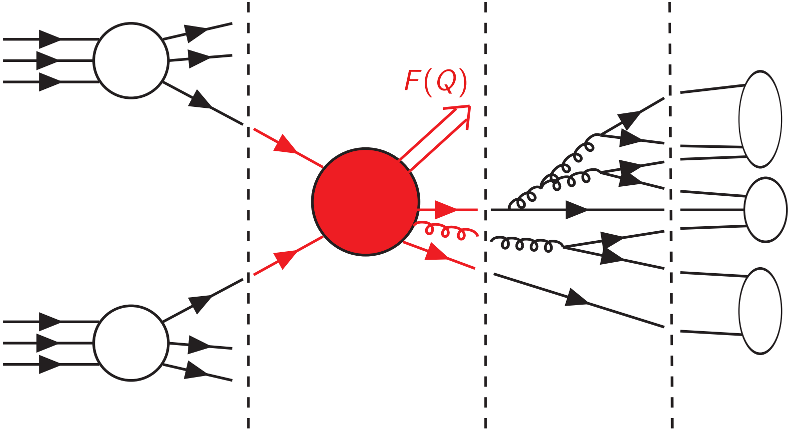
Partonic Hard Cross Section



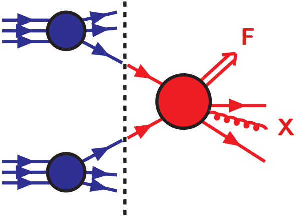
Parton densities
(PDFs)

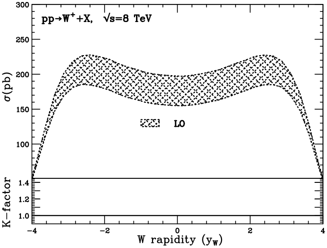
Partonic hard
cross section

Parton Shower

Jets
(of hadrons)

Higher-order calculations





- Factorization theorem

$$\sigma = \sum_{a,b} f_a(M^2) \otimes f_b(M^2) \otimes \hat{\sigma}_{ab}(\alpha_S) + \mathcal{O}\left(\frac{\Lambda}{M}\right)$$

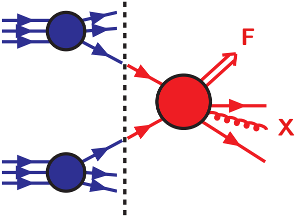
- Perturbation theory at **leading order (LO)**:

$$\hat{\sigma}(\alpha_S) = \hat{\sigma}^{(0)} + \alpha_S\,\hat{\sigma}^{(1)} + \alpha_S^2\,\hat{\sigma}^{(2)} + \mathcal{O}(\alpha_S^3)$$

- **LO result:** only **order of magnitude** estimate.
  NLO: first reliable estimate.
  NNLO: precise prediction & **robust uncertainty**.

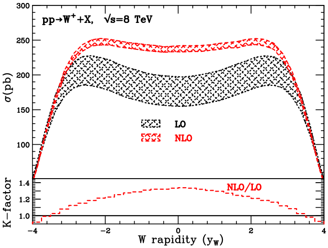
- Higher-order calculations **not an easy task** due to **infrared (IR) singularities**: impossible direct use of numerical techniques. (alternatives to standard techniques being explored [Rodrigo, Sborlini et al. ('15,'16,'17)])

Higher-order calculations



Parton densities (PDFs)

Partonic cross section $\hat{\sigma}$



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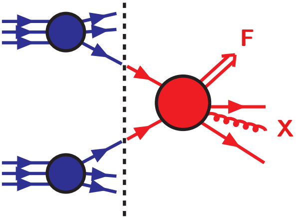

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(PDFs)

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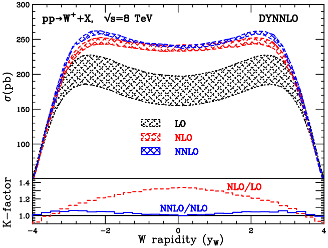

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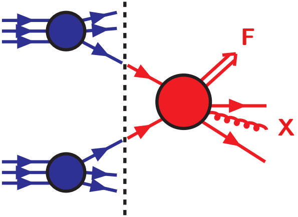
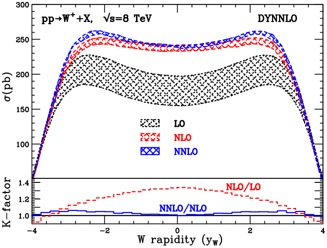


Parton densities (PDFs)

Partonic cross section $\hat{\sigma}$



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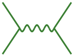
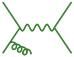
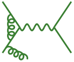
Drell-Yan process



LO
Drell,Yan
(1974)



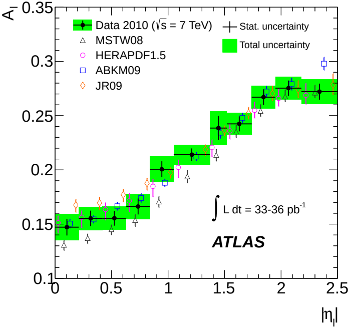
NLO
Altarelli,Ellis,Greco
Martinelli,(1980-84)



NNLO
Catani,Cieri,deFlorian,
G.F.,Grazzini (2009)

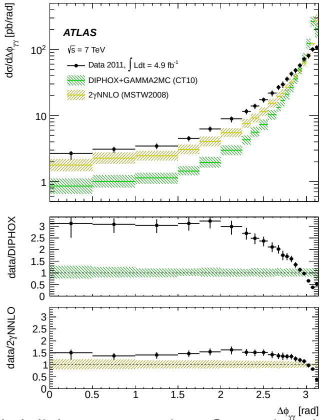
NNLO QCD predictions compared with LHC data

$\mathbf{pp \rightarrow W + X \rightarrow l\nu_l + X}$



Lepton charge asymmetry. Comparison between experimental data and NNLO predictions (DYNNLO [Catani, Cieri, de Florian, G.F., Grazzini ('09), ('10)]) using various PDFs (from [ATLAS Coll. ('12)]).

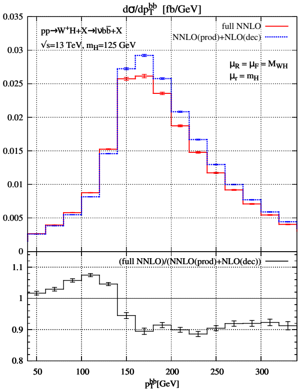
$\mathbf{pp \rightarrow \gamma\gamma + X}$



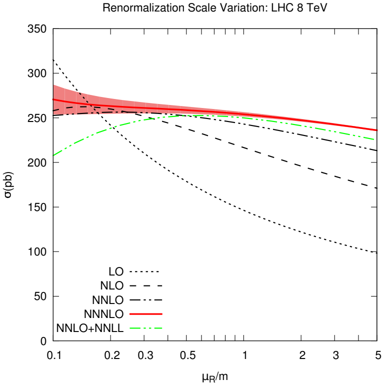
Azimuthal diphoton separation. Comparison between exp. data, NLO and NNLO predictions (2γNNLO [Catani, Cieri, de Florian, G.F., Grazzini ('12)]) (from [ATLAS Coll. ('13)]).

NNLO QCD predictions at the LHC

$$pp \to W^+H + X \to l^+\nu b\bar{b} + X$$



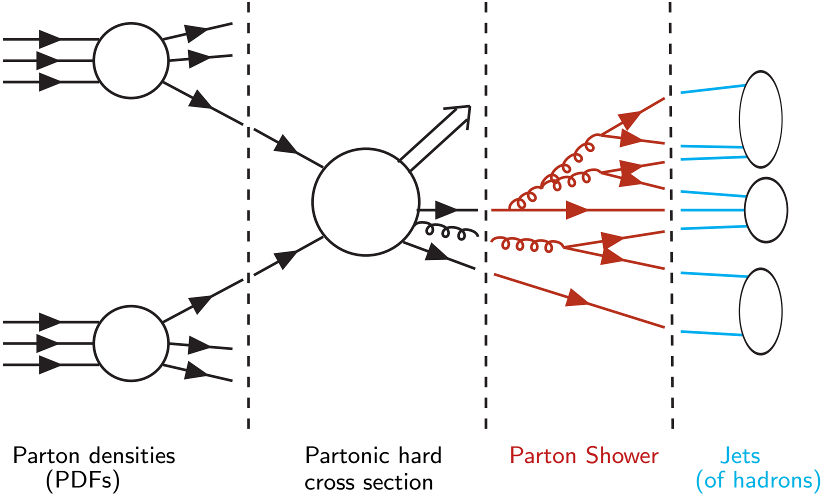
$$pp \to t\bar{t} + X$$



Left panel: transverse momentum of the Higgs boson in production in NNLO (`HVNNLO [G.F., Grazzini,Tramontano ('11),('14),('15),('17)]`*).*

Right panel: Total cross section for (dependence on unphysical renormalization scale) `[Muselli,Bonvini,Forte,Marzani,Ridolfi ('15)].`

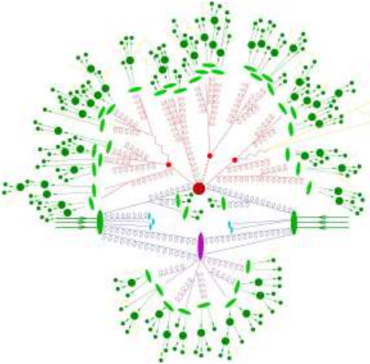
Parton Shower and Hadronization



Parton Shower and Hadronization

Complete description of a hadron scattering event.

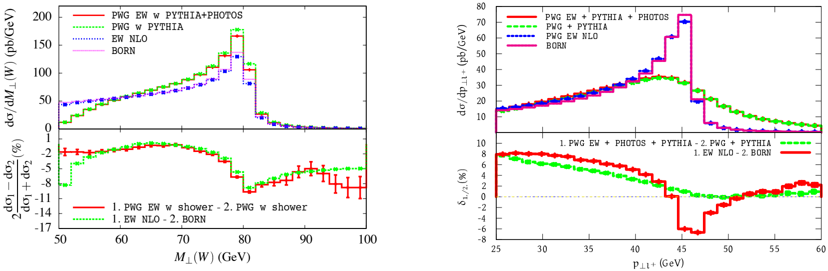
- QCD parton shower (PS): Starting from LO QCD, inclusion of dominant collinear and soft-gluon emissions to all order in a approximate way as a Markov process (probabilistic picture).
- No analytic solution but simple iterative structure of coherent parton branching.
- Implemented in numerical Monte Carlo programs.
- QCD parton cascade matched with hadronization model for conversion of partons into hadrons (and model for resonance decay) ⇒ QCD event generators.



Scheme of QCD Parton Shower and hadronization in hadron collisions.

Parton shower at NLO

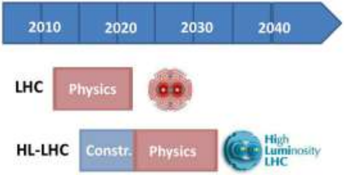
$\mathbf{pp \to W + X \to l\nu + X}$ $\mathbf{pp \to Z/\gamma^* + X \to l^+l^- + X}$



Transverse mass (left panel) and lepton transverse momentum (right panel) distribution in vector boson production. Parton shower predictions at NLO QCD×EW accuracy. Relative size of EW and QCD×EW corrections (lower panels) [Vicini et al. ('12,'13,'17)].

Conclusions

- The LHC is exploring the unknown region of the TeV energy frontier, trying to address many **fundamental questions** in High Energy Physics.



  - Main message: **to increase the LHC discovery power**, accurate theoretical predictions are necessary ⇒ **precise parton density (PDFs) determinations** and **higher-order perturbative calculations in QCD (and EW theory)**.
  - The members (including the younger ones) of TIF Lab obtained significant results relevant to the physics program of the LHC.