QCD at the LHC
Recent progress and open problems

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QCD: The Toolbox for Discoveries at the LHC

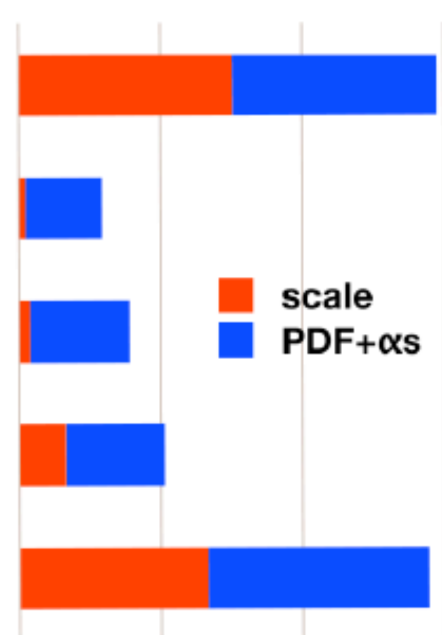
The days of "guaranteed" discoveries or of no-lose theorems in particle physics are over, at least for the time being ....

.... but the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU, ...)   **Mangano, Aspen14**

This simply implies that, more than for the past 30 years, future HEP's progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias

Improving our **quantitative understanding of the Standard Model** is essential in this new era for HEP, where we need to hunt, unbiased, **for answers to the big questions of our field**
Now, more than ever, **sharpening our QCD tools** could be the **key for new discoveries at the LHC**

		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
	VBF	1.56 pb	2.9%
NNLO QCD +NLO EW	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%



Campbell, ICHEP12

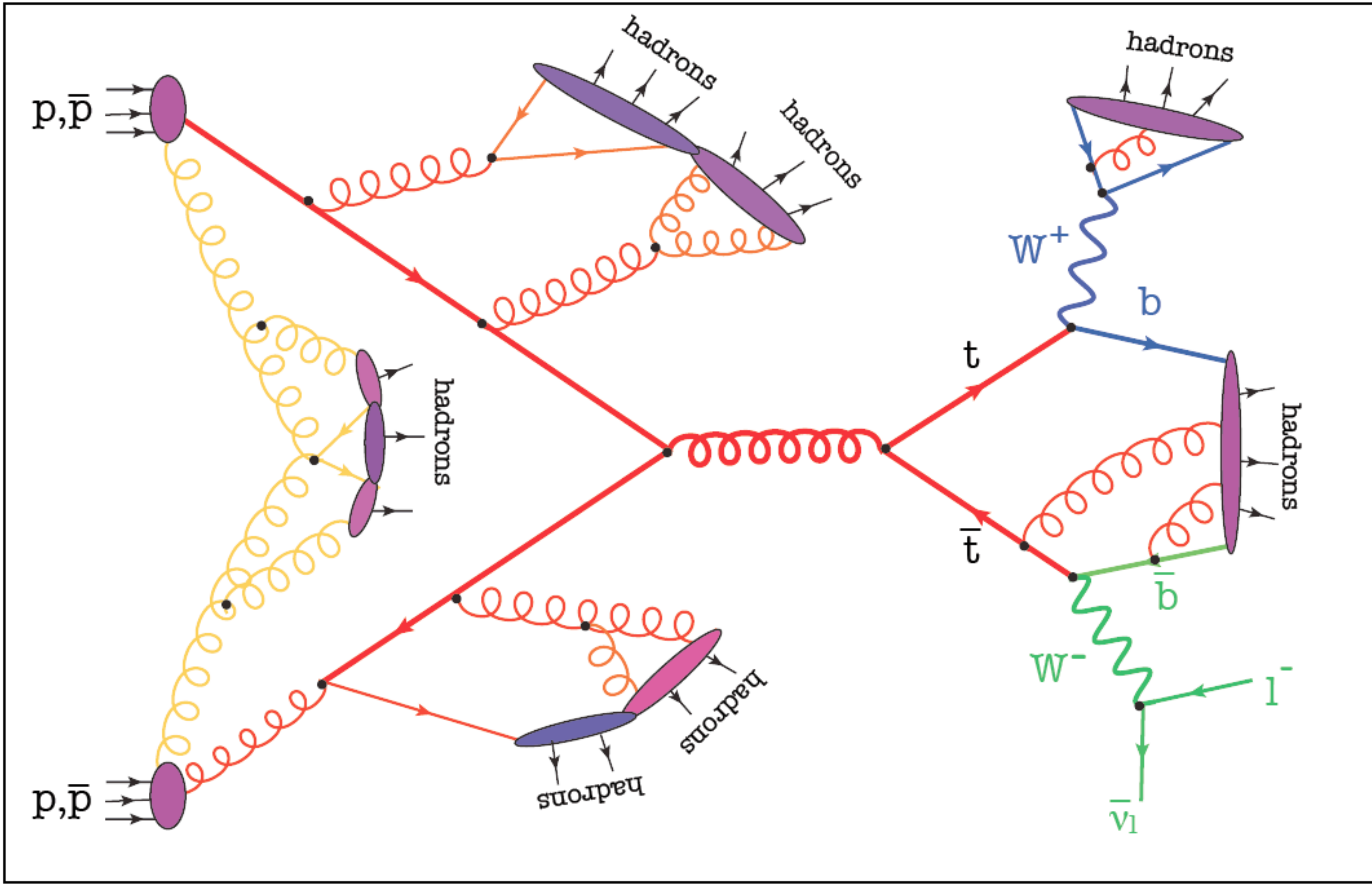
Prime example: **extraction of Higgs couplings** from LHC data soon to be **limited by QCD uncertainties**

Better **QCD predictions**

↓

Improved indirect **sensitivity to New Physics** via deviations of Higgs couplings from SM expectations

QCD at the LHC



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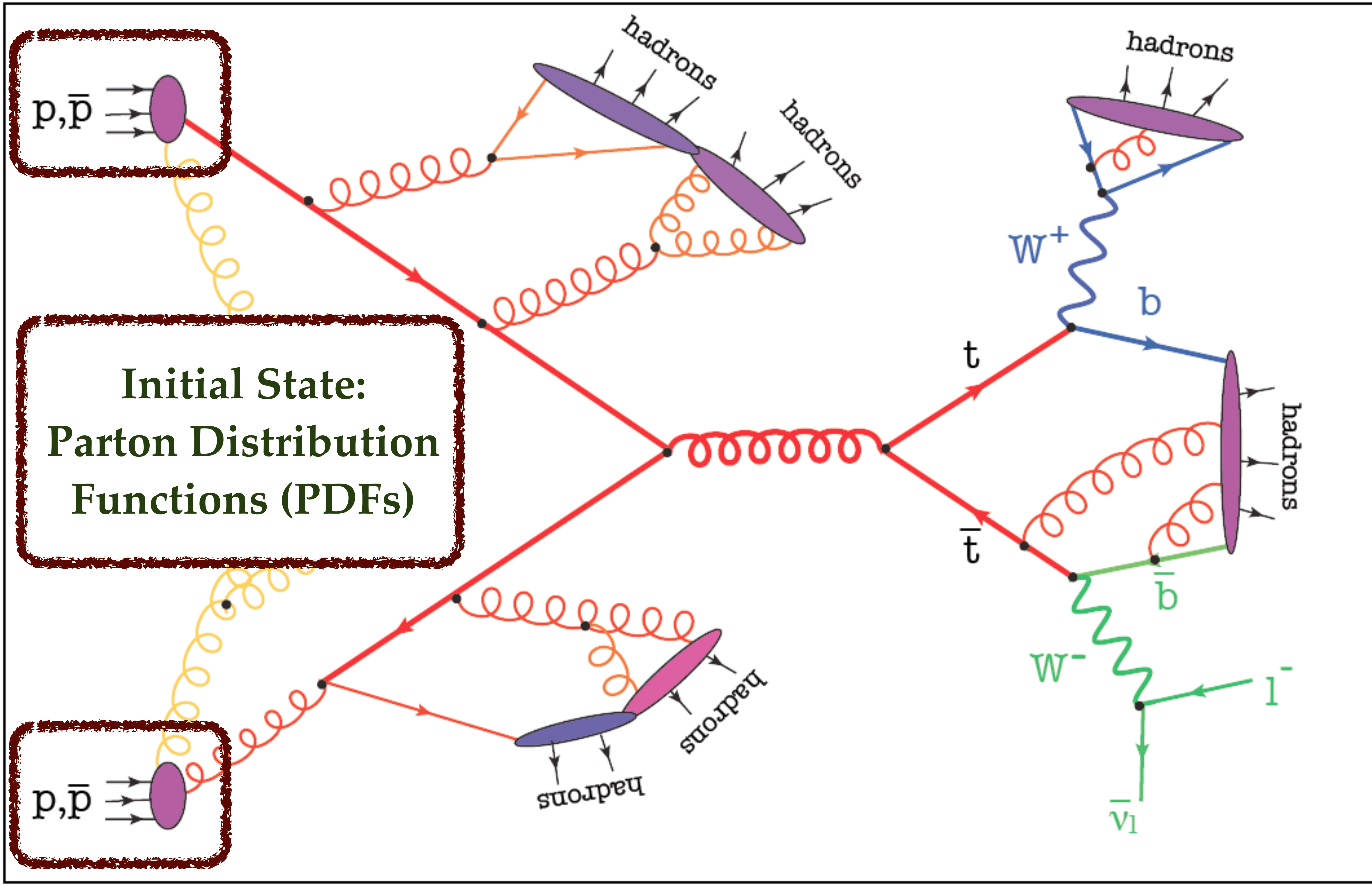
QCD at the LHC



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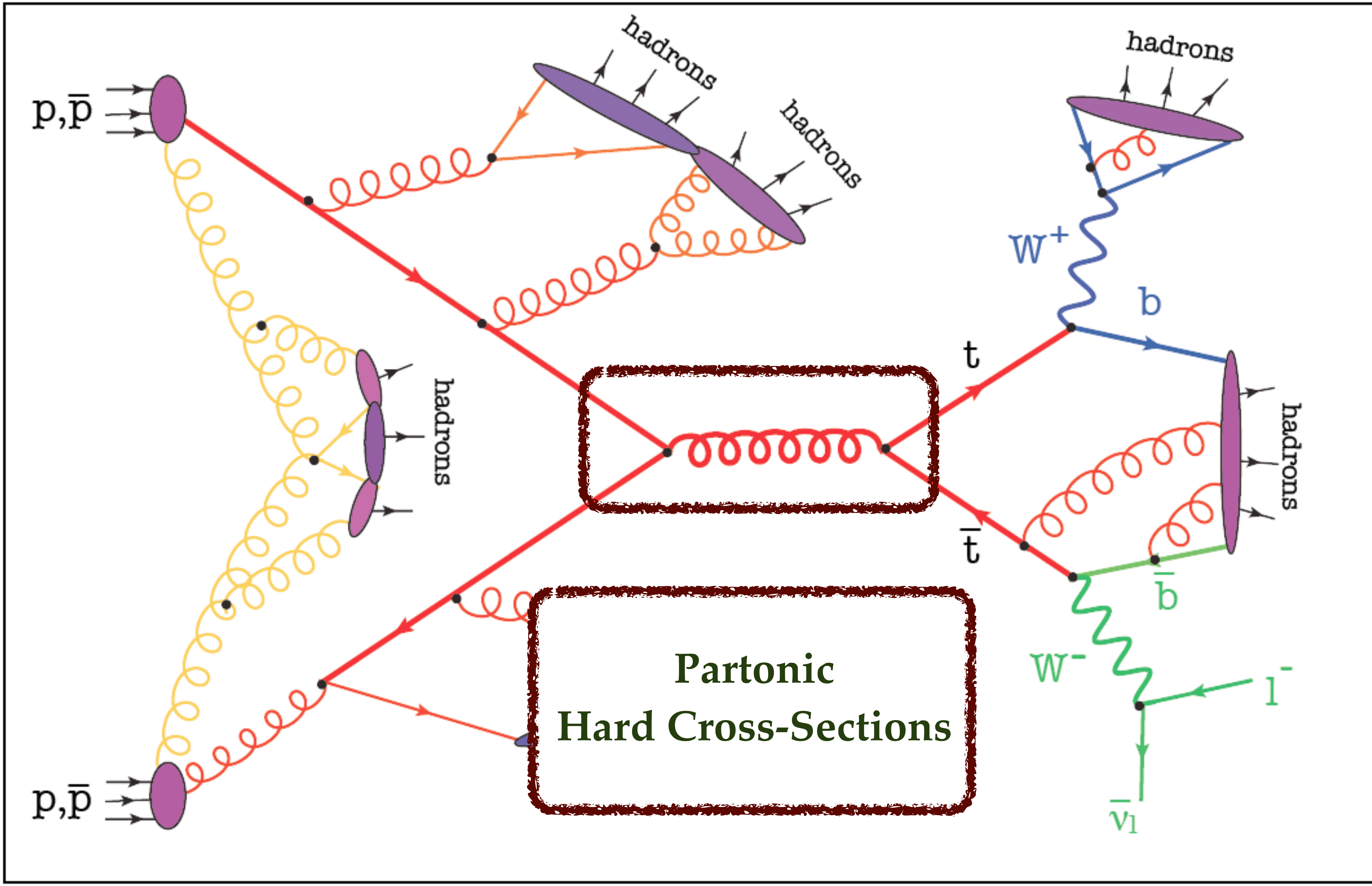
QCD at the LHC



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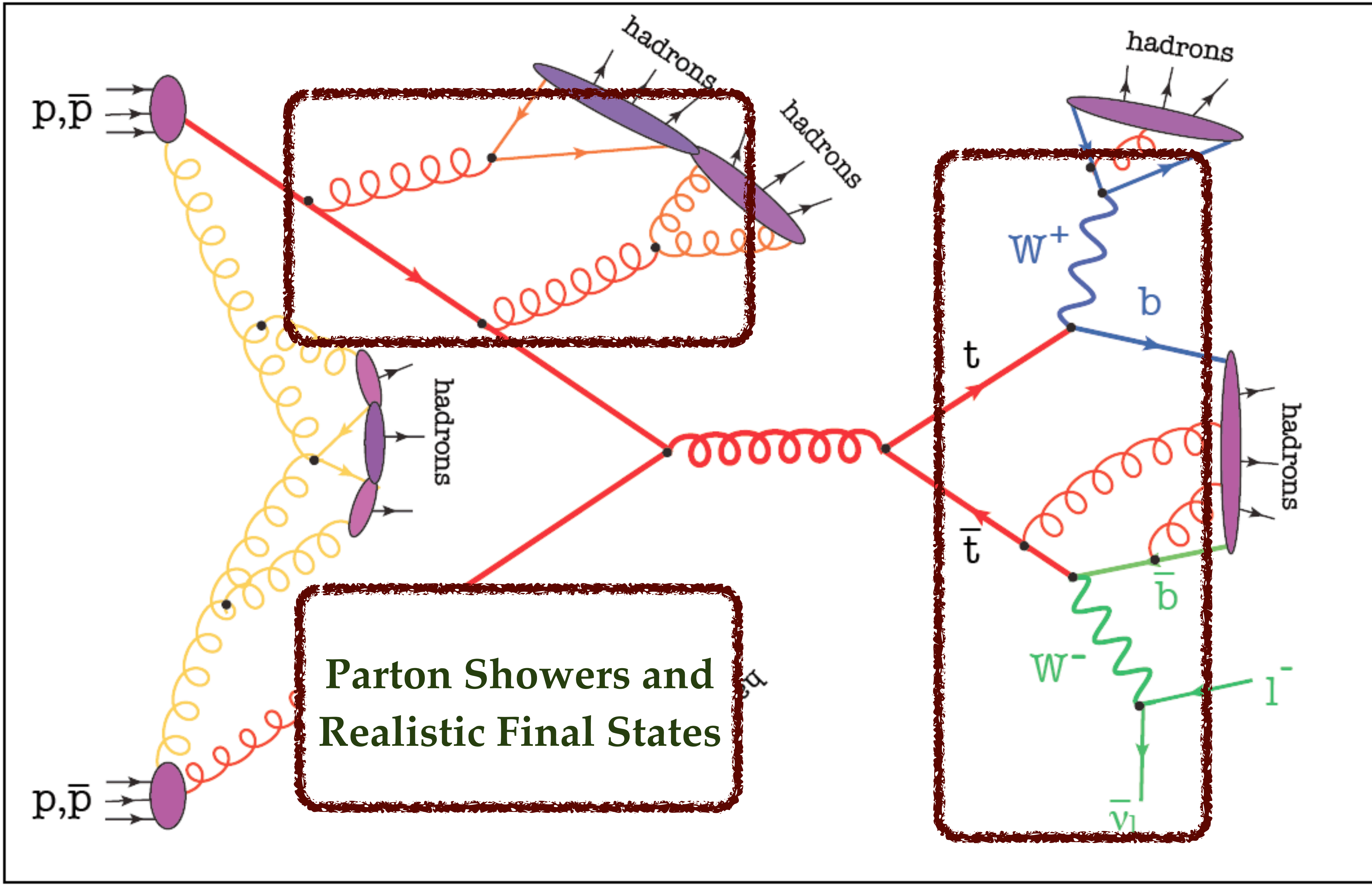
QCD at the LHC



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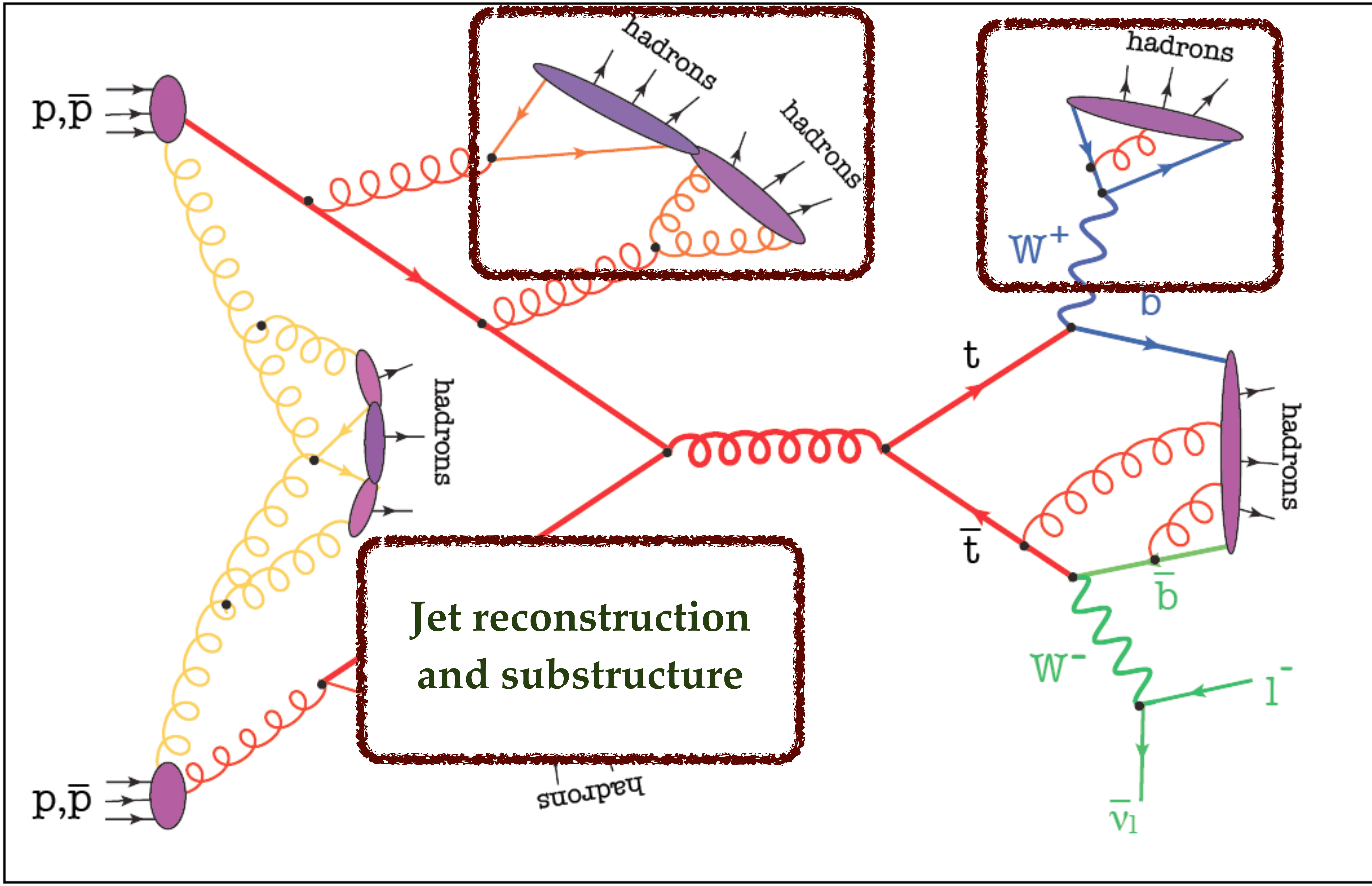

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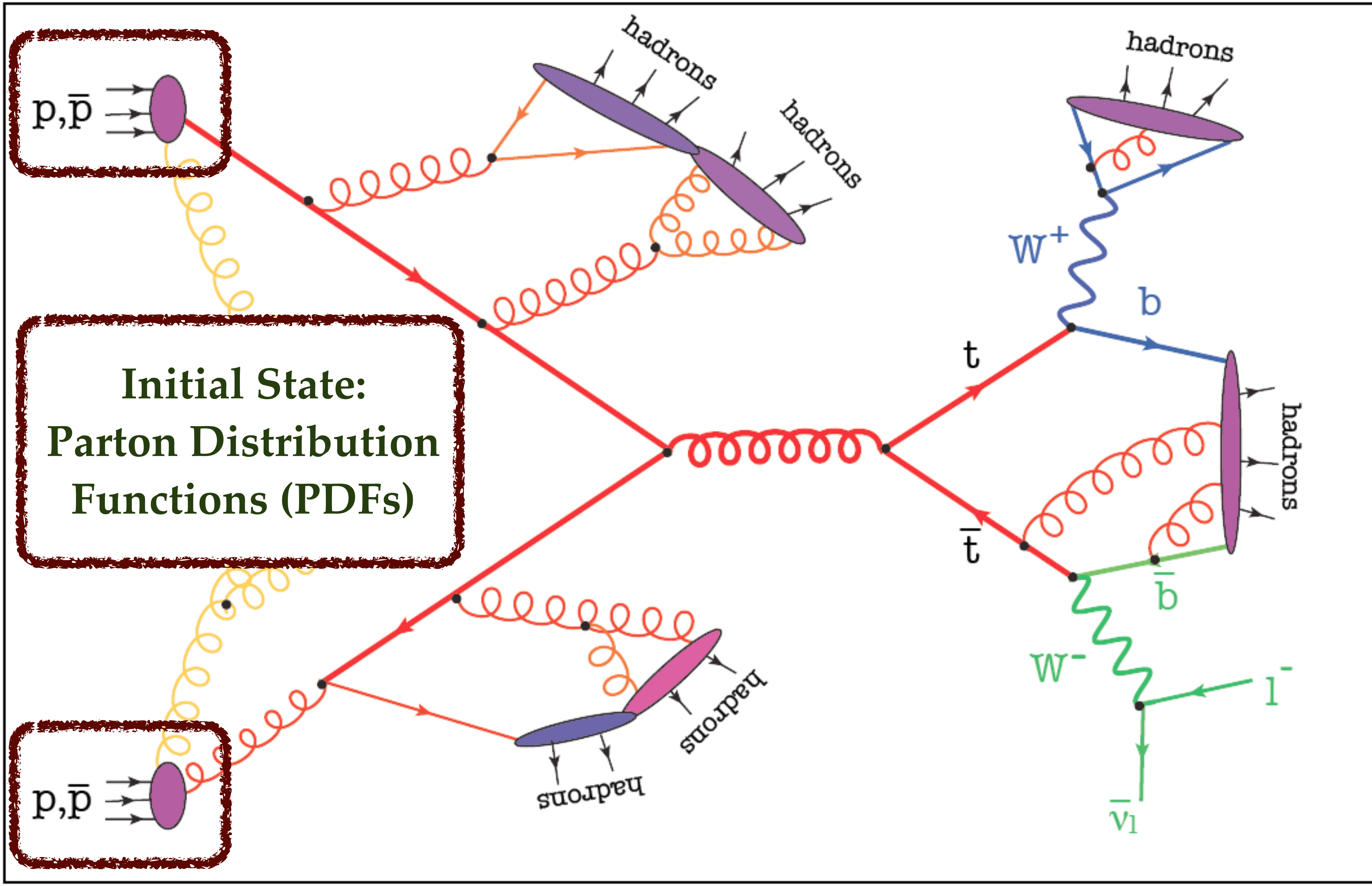
QCD at the LHC



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The inner life of the proton

The **Master Formula** for LHC cross-sections:

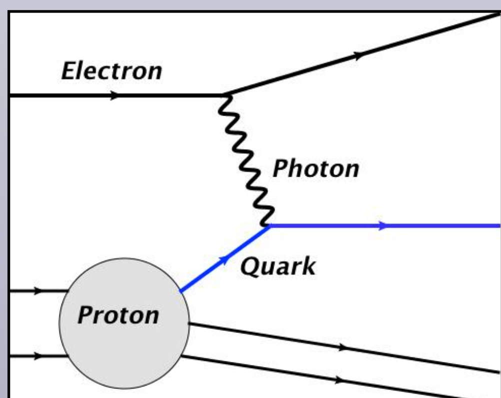
$$\sigma_X(s, M_X^2) = \sum_{a,b} \int_{x_{\min}}^{1} dx_1\, dx_2\, f_{a/h_1}(x_1, M_X^2)\, f_{b/h_2}(x_2, M_X^2)\, \hat{\sigma}_{ab\to X}\, (x_1 x_2 s, M_X^2)$$

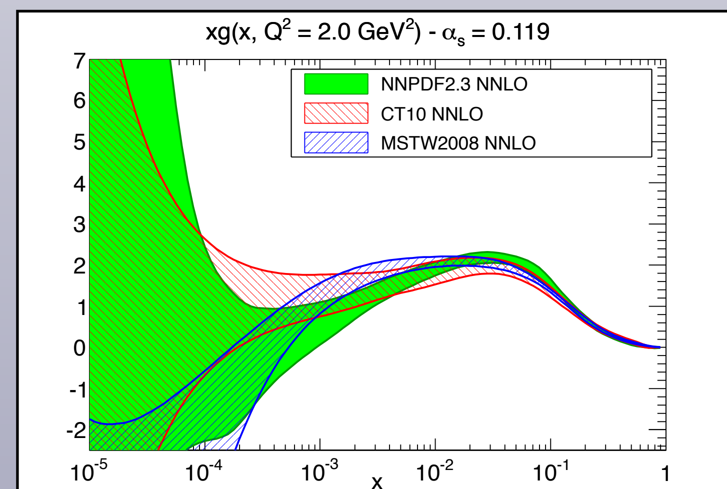
Parton Distributions:

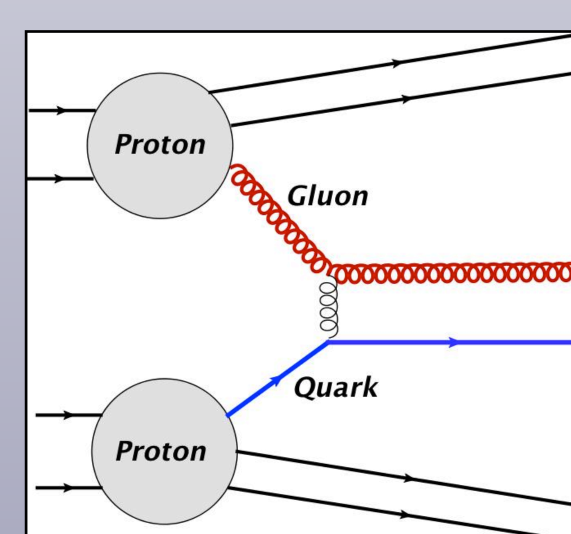
- *Energy distribution of quarks and gluons in proton*
- *Determined by non-perturbative dynamics*
- *Extract from **experimental data** + pQCD evolution*

Matrix Elements:

- *Hard-scattering between quarks, gluons, electroweak bosons, Higgs ....*
- *Compute in perturbation theory as series expansion in α_S, α_{QED}, α_{EW}*







Experimental data → **PDFs**

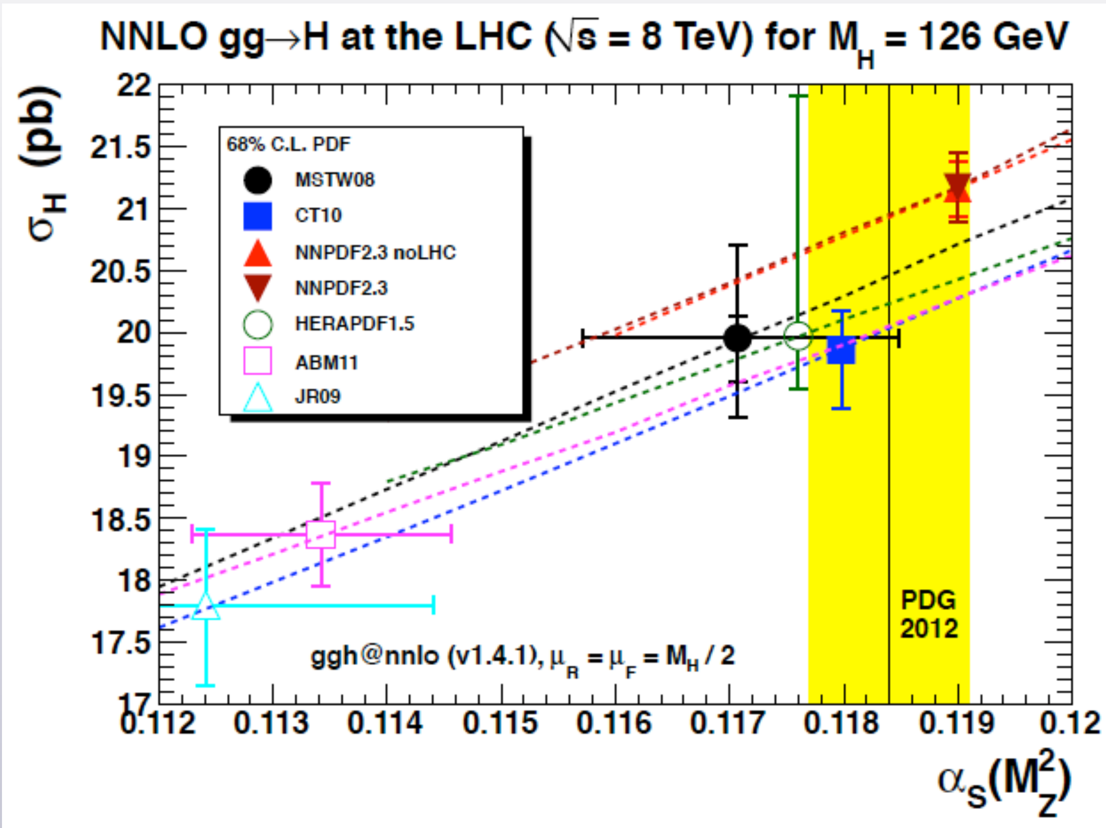
QCD Theory → **PDFs**

Statistical Methodology → **PDFs**

PDFs → **Predictions @ LHC**

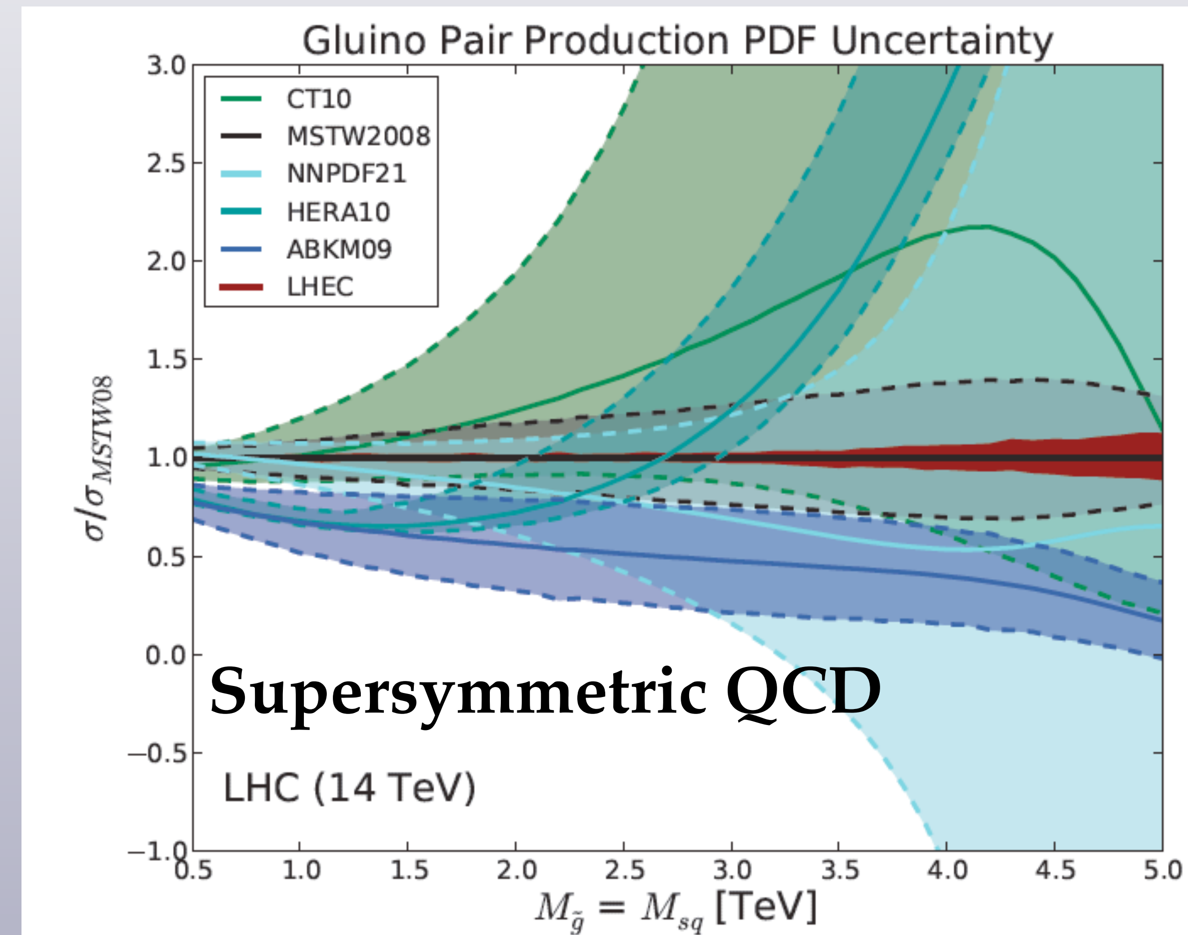
Parton Distributions: fundamental limit to theory predictions at LHC

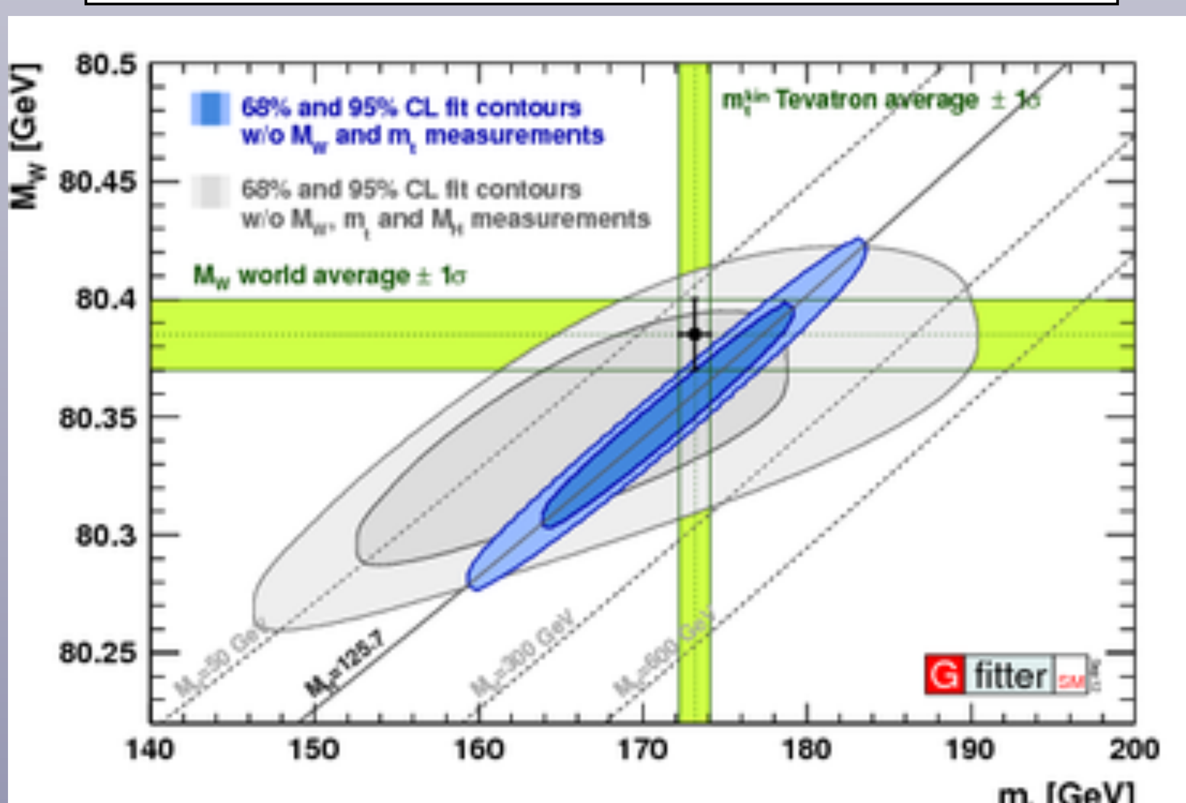
Parton Distributions and LHC phenomenology



1) PDFs fundamental limit for Higgs boson characterization in terms of couplings

2) Very large PDF uncertainties (>100%) for new heavy particle production





3) PDFs dominant systematic for precision measurements, like W boson mass, that test internal consistency of the Standard Model

PDFs and LHC data

- A major recent development in global PDF fits is the **inclusion of constraints from LHC data**
- The impact of **new data into PDFs** has been also studied by ATLAS and CMS themselves using the open-source QCD analyses framework **HERAfitter**

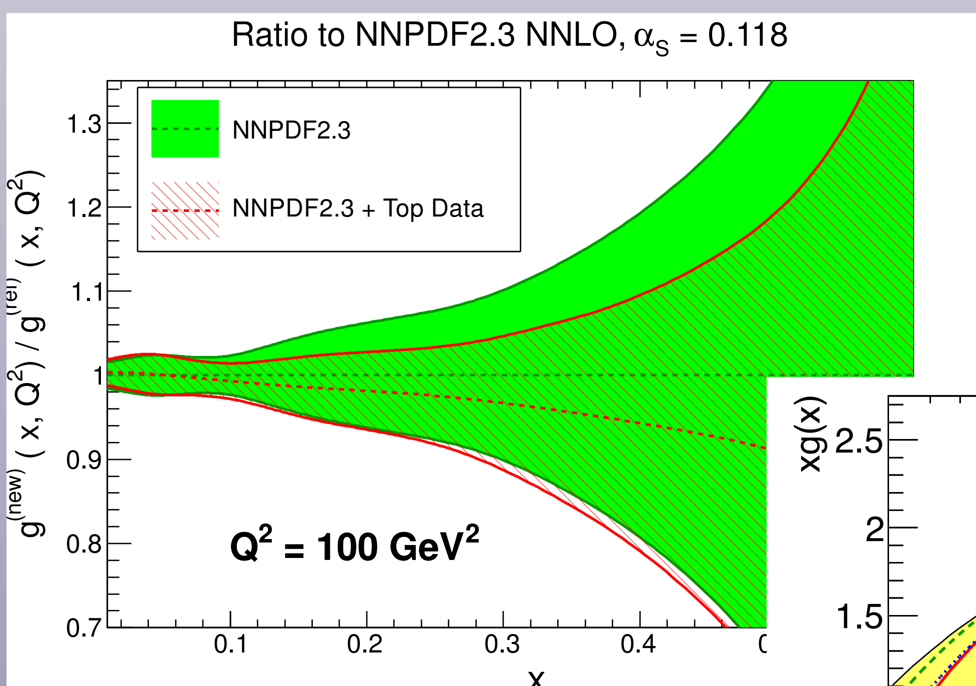
LHC data already **included in PDF fits:**

- *Inclusive W,Z production*
- *W production with charm quarks*
- *Isolated photon production*
- *Inclusive jet and dijet production*
- *Low and high-mass off-shell Drell-Yan*
- *Top quark pair cross-sections*
- *Ratios of cross-sections between different E_{cm}*

LHC data with potential PDF constraints

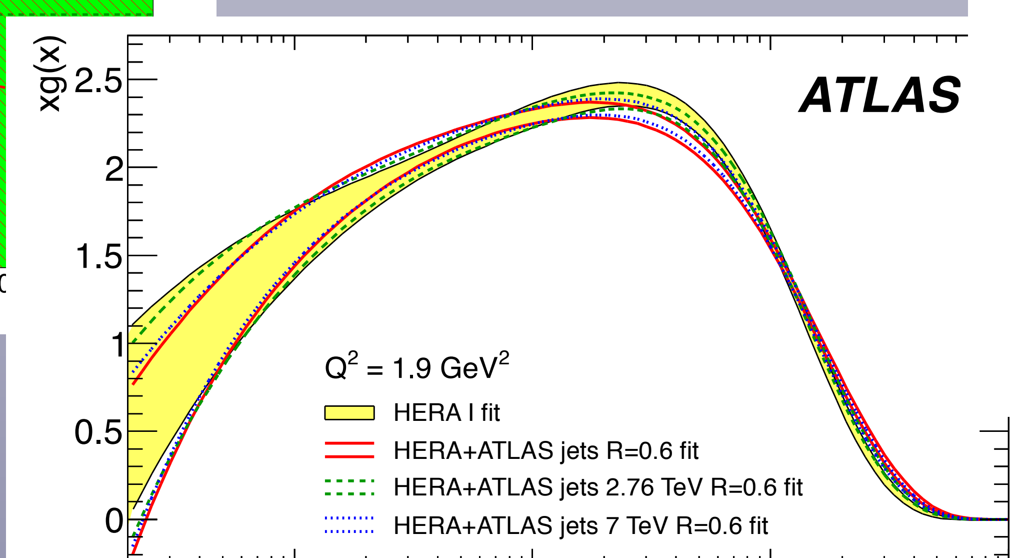
- *Z+jets, high-pT Z production*
- *Photon+jet production*
- *Photon+charm, Z+charm*
- *Single top production*
- *Top quark pair differential distributions*
- *Ratios between 13 and 8 TeV*

Pinning down large-x gluon with top quark data

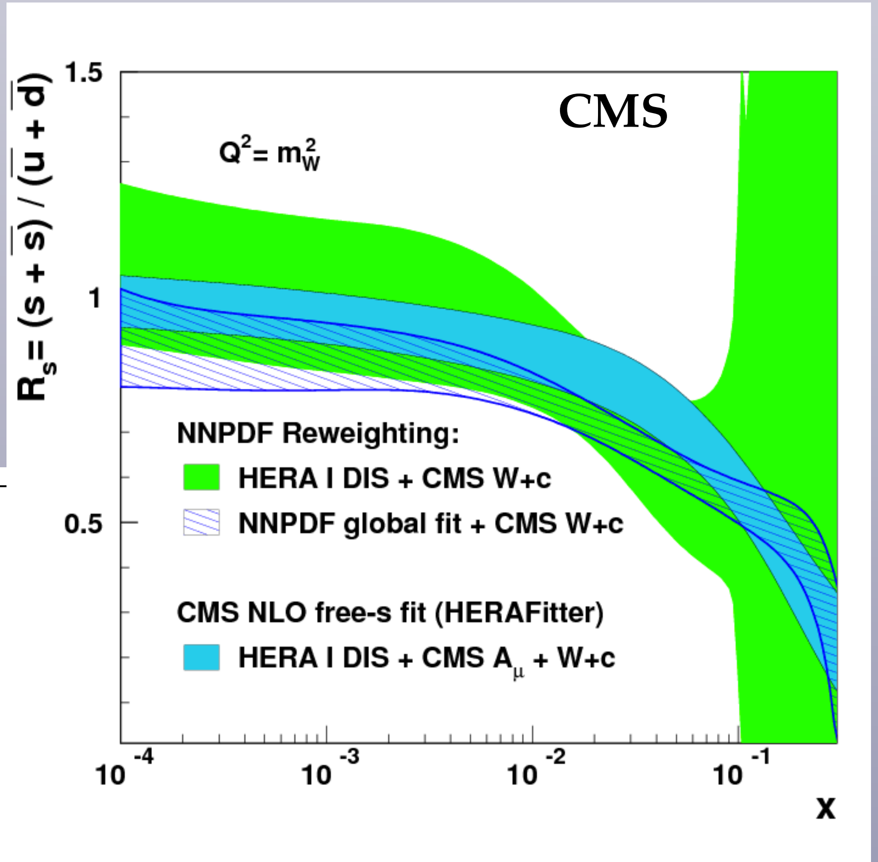


Czakon et at 13

Gluon PDF from ratio of 7 TeV and 2.76 TeV jet data

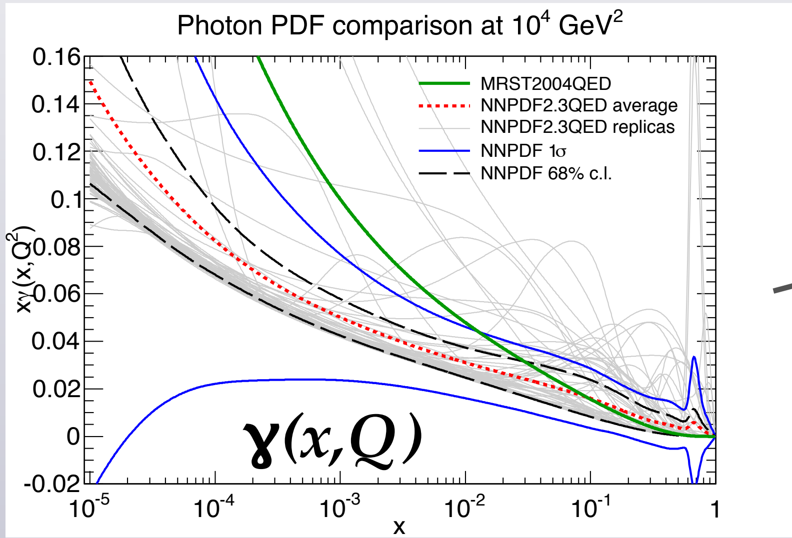


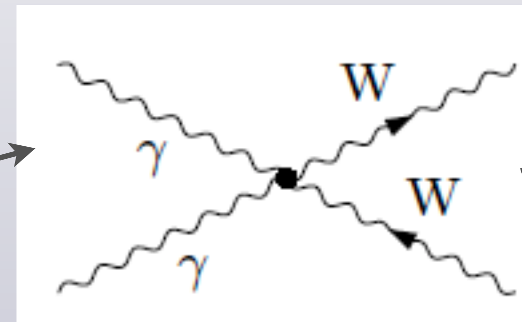
W+charm: accurate strangeness from LHC data

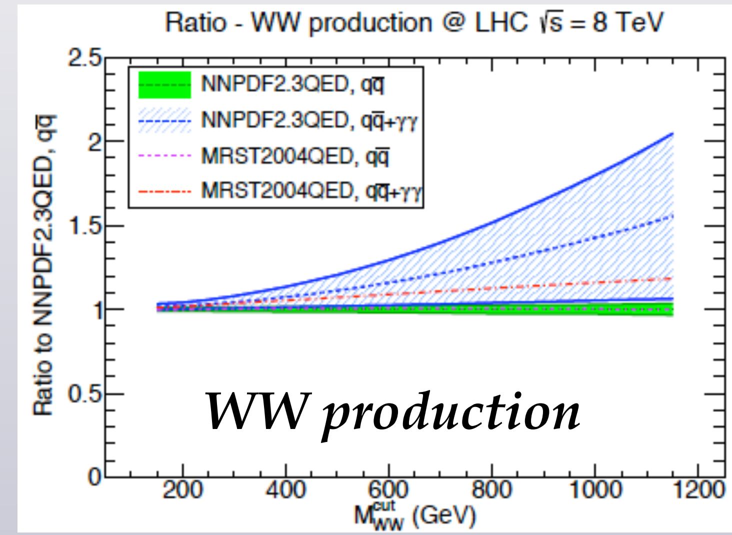


Theory Developments on PDFs

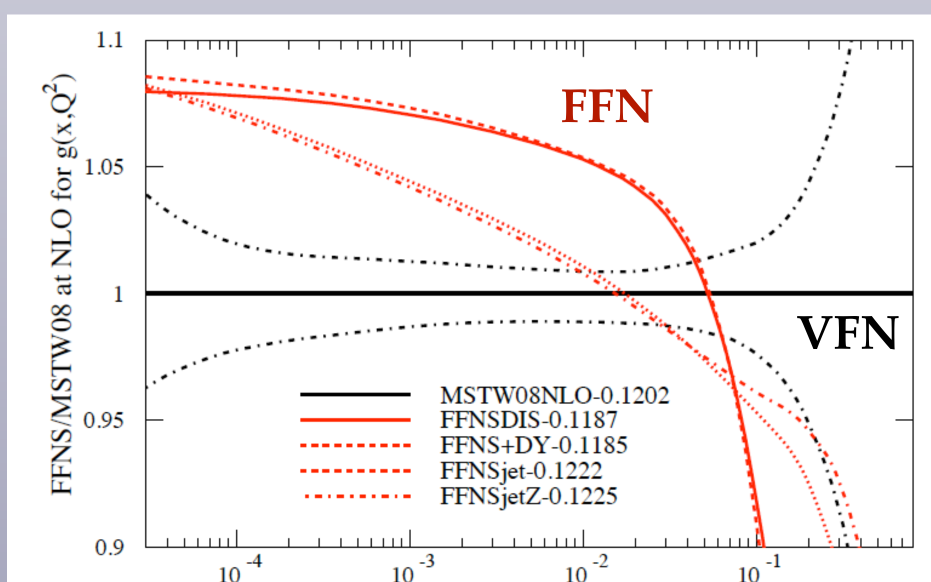
- Consistent inclusion of **QED effects in LHC calculations** require PDFs with **QED corrections**, and in particular a determination of the **photon PDF** from experimental data **(NNPDF 13, see S. Carrazza talk)**



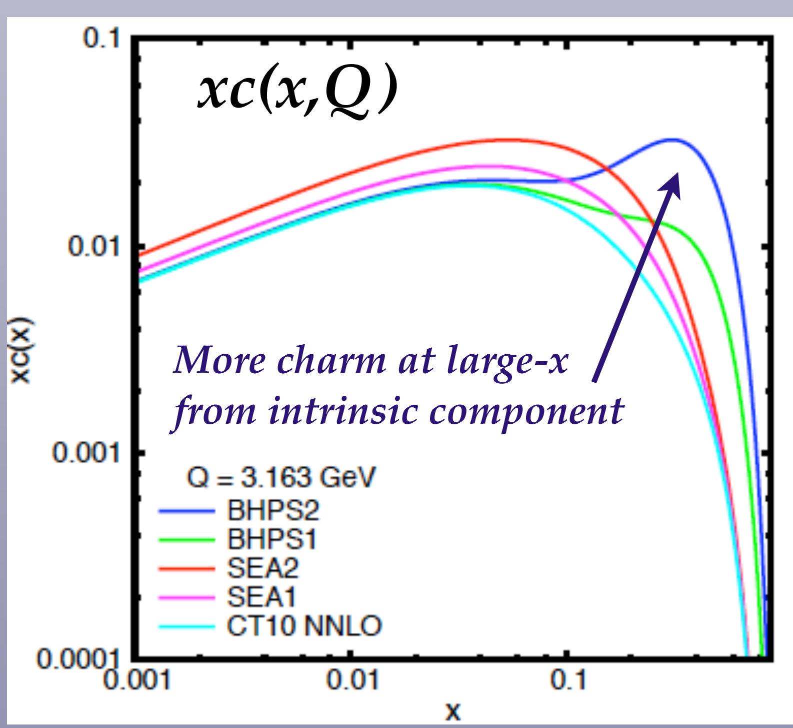




- Impact of **Fixed-Flavor** vs **Variable-Flavor-**Number **heavy quark schemes** on PDFs **(NNPDF13, Thorne 14)**



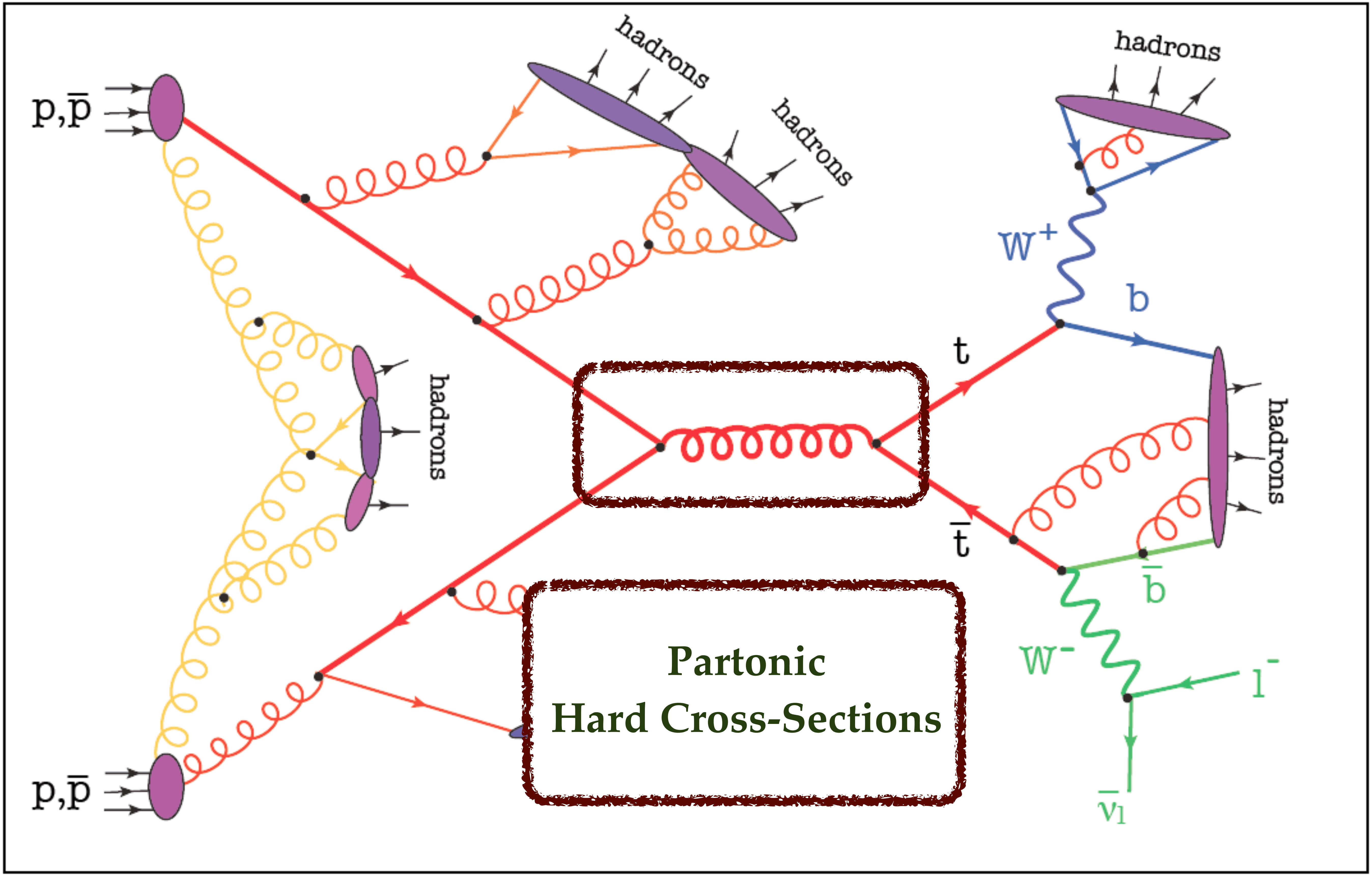
Use of different heavy flavor schemes responsible for part differences between some PDF sets
Fits in the FFN worse fit quality to DIS data than VFN fits



- Parton Distributions with **Intrinsic Charm** PDF **(CT 13)**

Intrinsic charm still allowed to carry up to 2% of the proton momentum
Accessible at LHC via photon+charm and Z+charm data

QCD at the LHC



Drawing by K. Hamilton

The NLO revolution

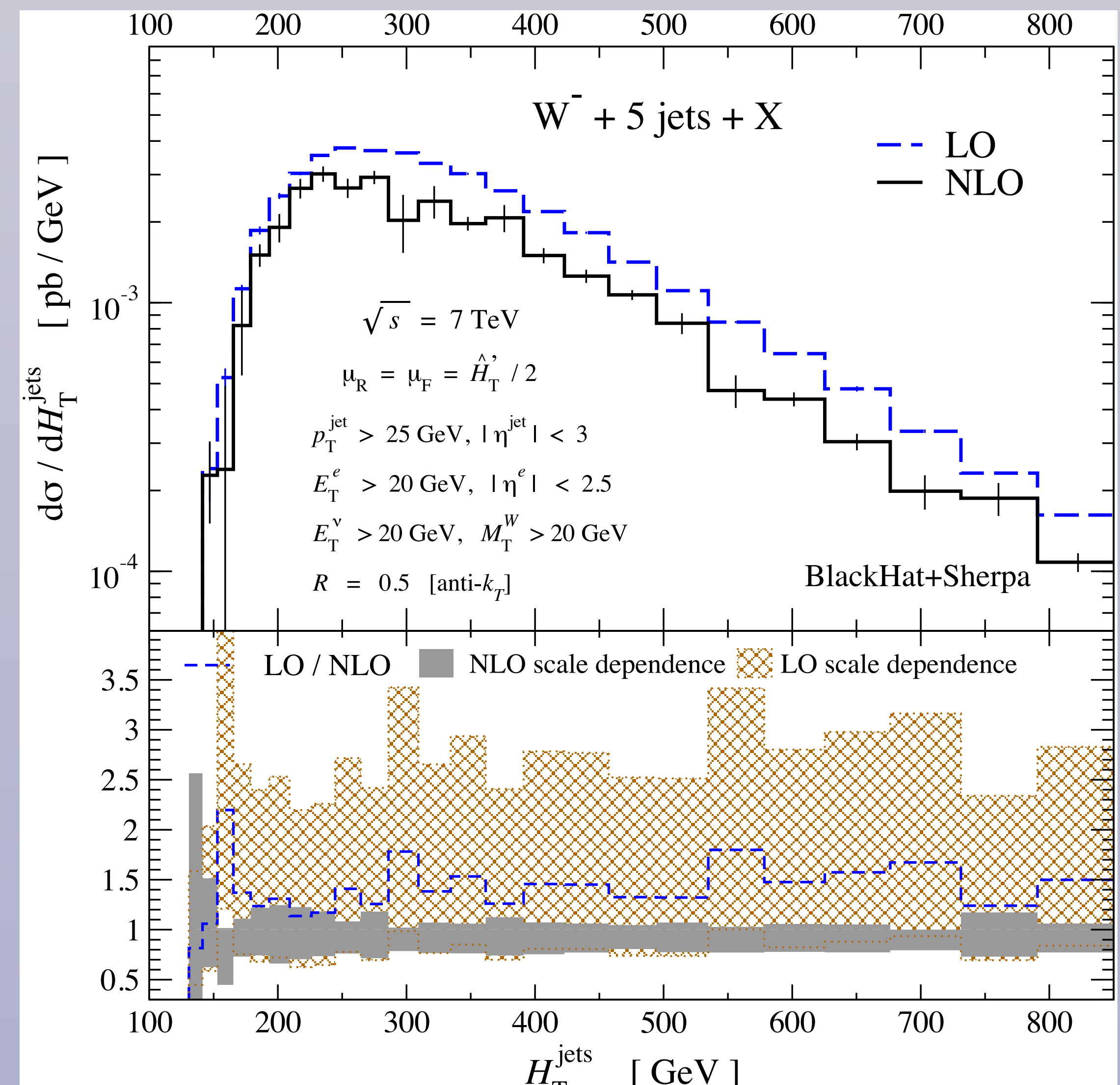
- During many years, the needs for **NLO calculations** were summarized in the **Les Houches wishlist**
- The **NLO revolution** in the last years makes **computations of NLO cross-sections a solved process**
- Key has been the automation of **NLO real emission and subtraction** and of **virtual corrections** **(MadFKS, MadLoop, GoSam, Sherpa, OpenLoops, HelacNLO, ...)**
- Despite automation, for **high final state multiplicities**, **tailored calculations** still required for efficiency (**BlackHat, NJet, Rocket**, ...)

Process ($V \in \{Z, W, \gamma\}$)	Comments
1. $pp \to VV$ jet	WW jet completed by Dittmaier/Kallweit/Uwer; Campbell/Ellis/Zanderighi ZZ jet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti WZ jet, $W\gamma$ jet completed by Campanario et al.
2. $pp \to$ Higgs+2 jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier Interference QCD-EW in VBF channel
3. $pp \to V\,V\,V$	ZZZ completed by Lazopoulos/Melnikov/Petriello and WWZ by Hankele/Zeppenfeld see also Binoth/Ossola/Papadopoulos/Pittau VBFNLOmeanwhile also contains $WWW, ZZW, ZZZ, WW\gamma, ZZ\gamma, WZ\gamma, W\gamma\gamma, Z\gamma\gamma, \gamma\gamma\gamma, W\gamma\gamma j$
4. $pp \to t\bar{t}\,b\bar{b}$	relevant for $t\bar{t}H$, computed by Bredenstein/Denner/Dittmaier/Pozzorini and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek
5. $pp \to V$+3 jets	W+3 jets calculated by the Blackhat/Sherpa and Rocket collaborations Z+3jets by Blackhat/Sherpa
6. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$, computed by Bevilacqua/Czakon/Papadopoulos/Worek
7. $pp \to VV\,b\bar{b}$,	Pozzorini et al.Bevilacqua et al.
8. $pp \to VV$+2jets	W^+W^++2jets, W^+W^-+2jets, relevant for VBF $H \to VV$ VBF contributions by (Bozzi/)Jäger/Oleari/Zeppenfeld
9. $pp \to b\bar{b}b\bar{b}$	Binoth et al.
10. $pp \to V+4$ jets	top pair production, various new physics signatures Blackhat/Sherpa: W+4jets, Z+4jets see also HEJfor W + $n$jets
11. $pp \to Wb\bar{b}j$	top, new physics signatures, Reina/Schutzmeier
12. $pp \to t\bar{t}t\bar{t}$	various new physics signatures, Bevilacqua/Worek

Closed

Current frontier of NLO calculations

pp -> W + 5 jets @ NLO, BlackHat 13



NLO crucial for reliable scale uncertainties

The NNLO revolution

- Until recently, few processes were known **differentially at NNLO**, in particular only processes with either **colorless initial state** or **colorless final state**

Process	Calculation	Relevance
pp -> H	**Anastasiou, Melnikov, Petriello Catani, Grazzini**	**Higgs production**
pp -> V	**Melnikov, Petriello Catani, Cieri, de Florian, Ferrera, Grazzini**	**Electroweak precision tests Quark flavor separation**
e+e- -> 3 jets	**Gerhman, Glover, Heinrich**	**Fits of α_s**
pp -> gamma gamma pp -> VH	**Catani, Ferrera, Grazzini, Tramontano**	**Background to Higgs production Higgs associated production**

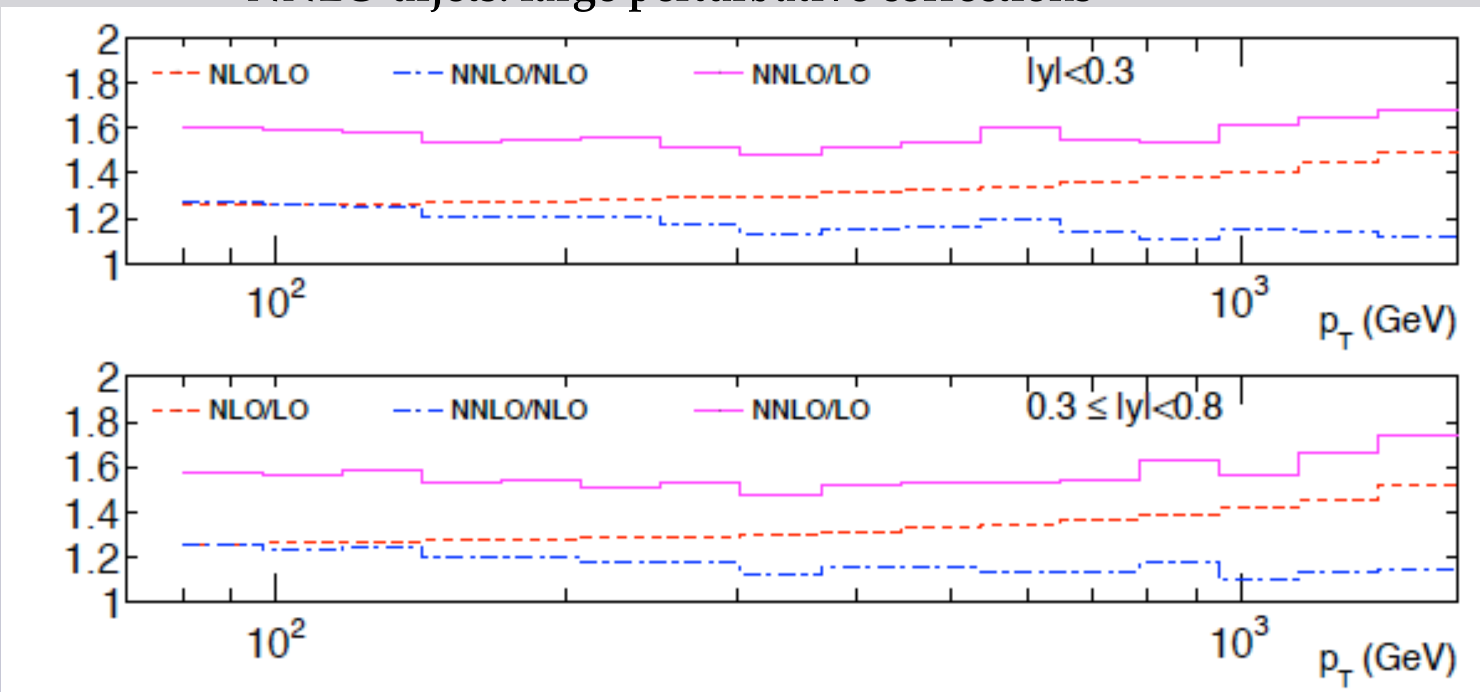
- The development of new calculational techniques, ***Antenna Subtraction*** and ***Sector-Improved subtraction***, lead to the **2013 NNLO breakthrough**: it is now possible to compute NNLO QCD corrections to processes with both **colored initial and final states**

Process	Calculation	Relevance
pp -> tt	**Czakon, Fiedler, Mitov**	**Precision studies of top sector Large-x gluon PDF**
gg -> dijets	**Gehrmannn-De Ridder, Gehrmann, Glover, Pires**	**Background to New Physics Gluon PDF + alphas fits**
pp -> H + jets	**Boughezal, Caola, Melnikov, Petriello, Schulze**	**Higgs production in association with hard jets**

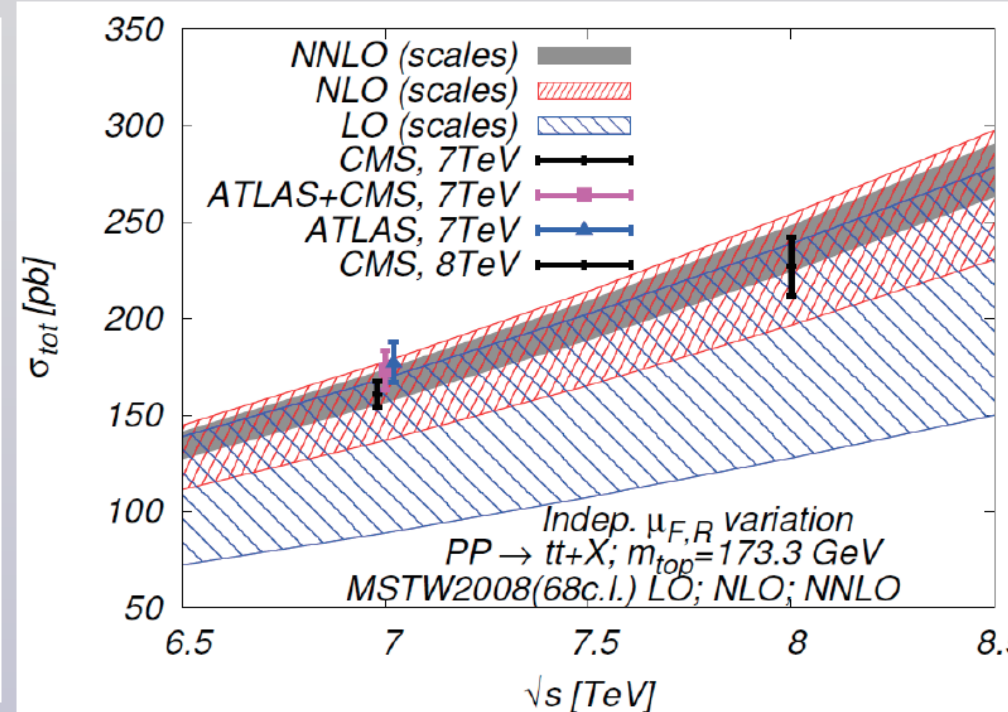
Other recent NNLO calculations include **pp -> HH in gluon fusion** (De Florian, Mazzitelli 13), and **pp -> HHjj VBF** (Liu-Sheng et al 14)

The NNLO revolution

NNLO dijets: large perturbative corrections



ttbar: scale uncertainties now at 2-3% level



- Whats in the pipeline? We have new **Les Houches whishlist**, now for **NNLO + EWK calculations**
- **NNLO is crucial for many precision measurements**, expect lots of rapid progress in the following years

Process	known	desired	details
$t\bar{t}$	σ_{tot} @ NNLO QCD $d\sigma$(top decays) @ NLO QCD $d\sigma$(stable tops) @ NLO EW	$d\sigma$(top decays) @ NNLO QCD + NLO EW	precision top/QCD, gluon PDF, effect of extra radiation at high rapidity, top asymmetries
$t\bar{t}+j$	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW	precision top/QCD top asymmetries
single-top	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD (t channel)	precision top/QCD, V_{tb}
dijet	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO weak	$d\sigma$ @ NNLO QCD + NLO EW	Obs.: incl. jets, dijet mass → PDF fits (gluon at high x) → α_s CMS http://arxiv.org/abs/1212.6660
3j	$d\sigma$ @ NLO QCD	$d\sigma$ @ NNLO QCD + NLO EW	Obs.: $R3/2$ or similar → α_s at high scales dom. uncertainty: scales CMS http://arxiv.org/abs/1304.7498
$\gamma+j$	$d\sigma$ @ NLO QCD $d\sigma$ @ NLO EW	$d\sigma$ @ NNLO QCD +NLO EW	gluon PDF $\gamma+b$ for bottom PDF

Differential NNLO calculations bring QCD to a new level of precision at LHC

QED and Electroweak corrections

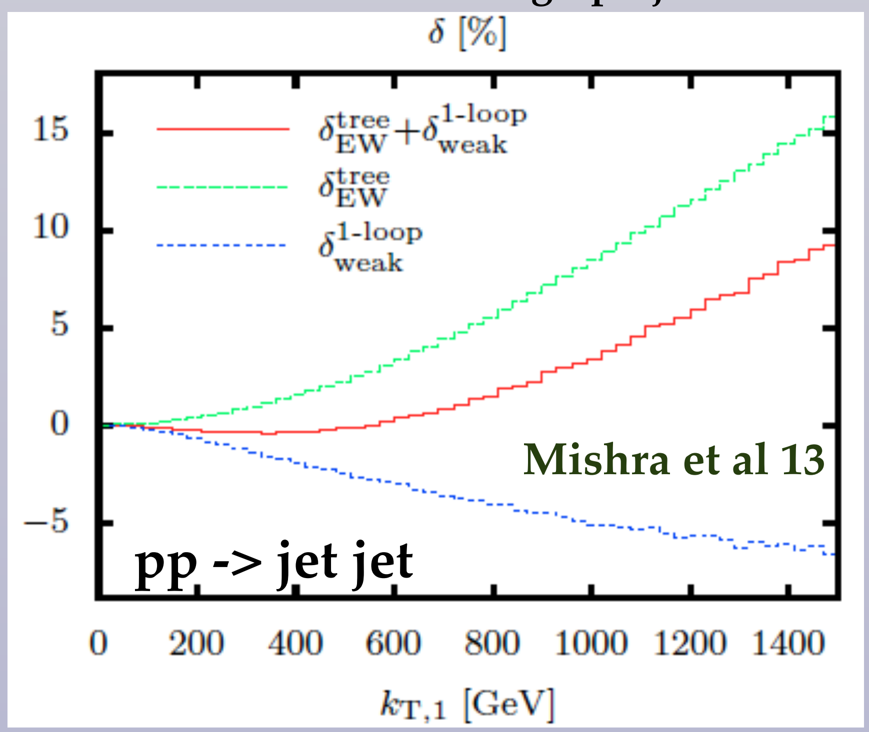
- At present level of precision in QCD calculations, **electroweak corrections** become **comparable if not larger**
- **Electroweak Sudakov logarithms** grow with energy, more important at **LHC 13 TeV**

Typical impact on $2 \rightarrow 2$ reactions at $\sqrt{s} \sim 1\ \text{TeV}$:

$$\delta^{1-\text{loop}}_{\text{LL}} \sim -\frac{\alpha}{\pi s^2_{\text{W}}} \ln^2\left(\frac{s}{M^2_{\text{W}}}\right) \simeq -26\%, \qquad \delta^{1-\text{loop}}_{\text{NLL}} \sim +\frac{3\alpha}{\pi s^2_{\text{W}}} \ln\left(\frac{s}{M^2_{\text{W}}}\right) \simeq 16\%$$

- Electroweak corrections affect the **TeV scale phenomenology**, both for **New Physics searches** in the high-mass tails, **Higgs characterization** and **precision SM measurements**, such as PDF fits

Electroweak corrections to high-pT jets @ LHC8



QED photon-induced and EW effects in high-mass Drell-Yan

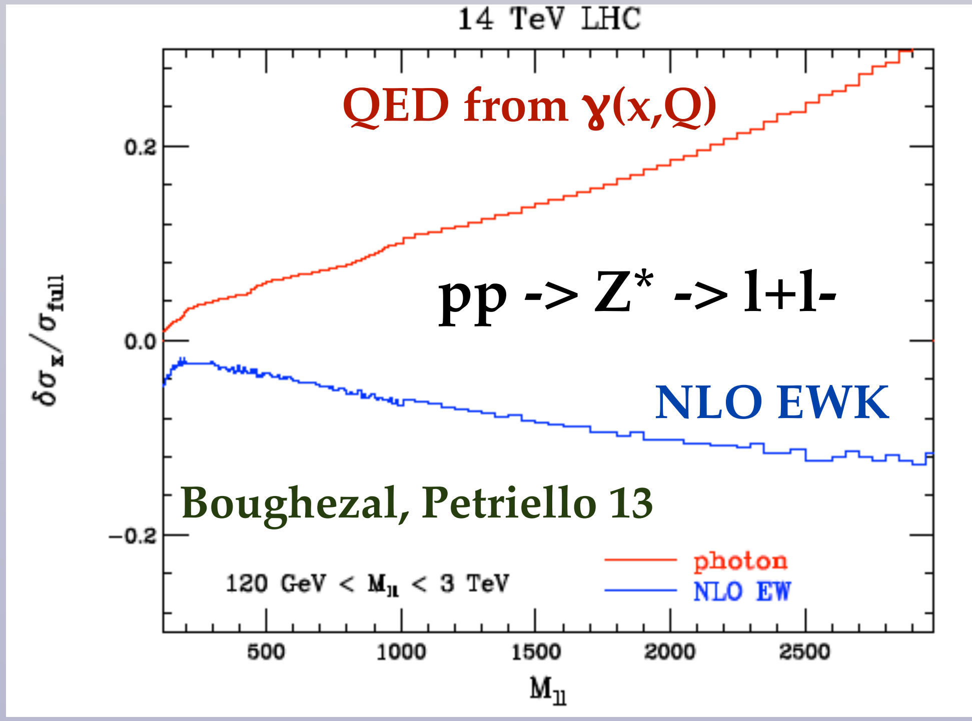
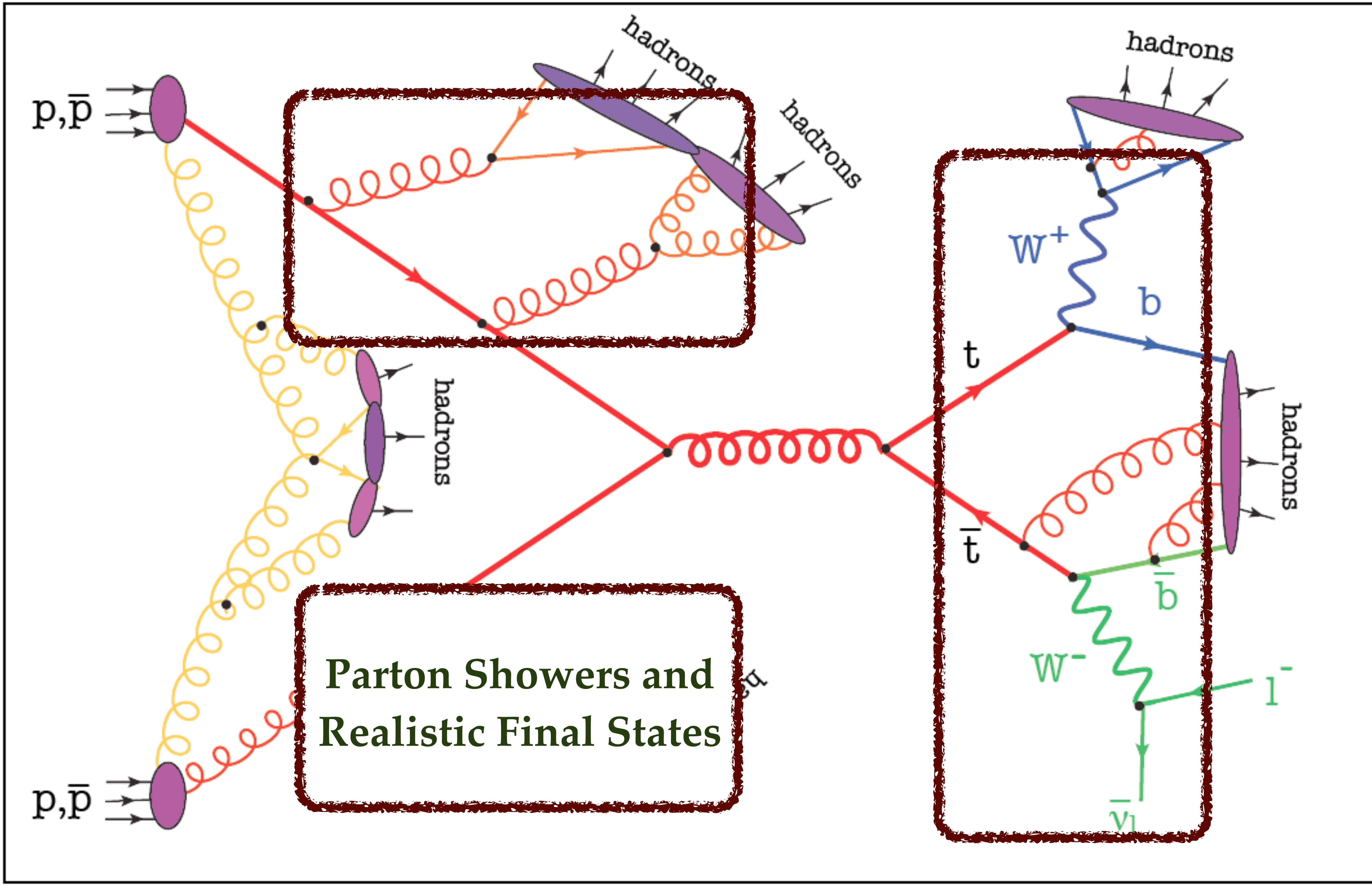


TABLE V: Are we in the Sudakov zone yet?

Process	$\sqrt{s} = 8\,\text{TeV}$	$\sqrt{s} = 14\,\text{TeV}$	$\sqrt{s} = 33, 100\,\text{TeV}$
Inclusive jet, dijet	Yes	Yes	Yes
Inclusive W/Z tail	∼ Yes	Yes	Yes
Wγ, Zγ tail ($\ell\nu\gamma, \ell\ell\gamma$)	No	∼ Yes	Yes
W/Z+jets tail	∼ Yes	Yes	Yes
WW leptonic	Close	∼ Yes	Yes
WZ, ZZ leptonic	No	No	Yes

- The region where EW corrections become relevant known as the **Sudakov zone**
- At LHC 13 TeV, many **crucial processes** will require these EW corrections (see review in arxiv:1308.1430)
- **PDF sets** which include **non only QED, but also electroweak corrections**, are required for consistent implementation of EW effects

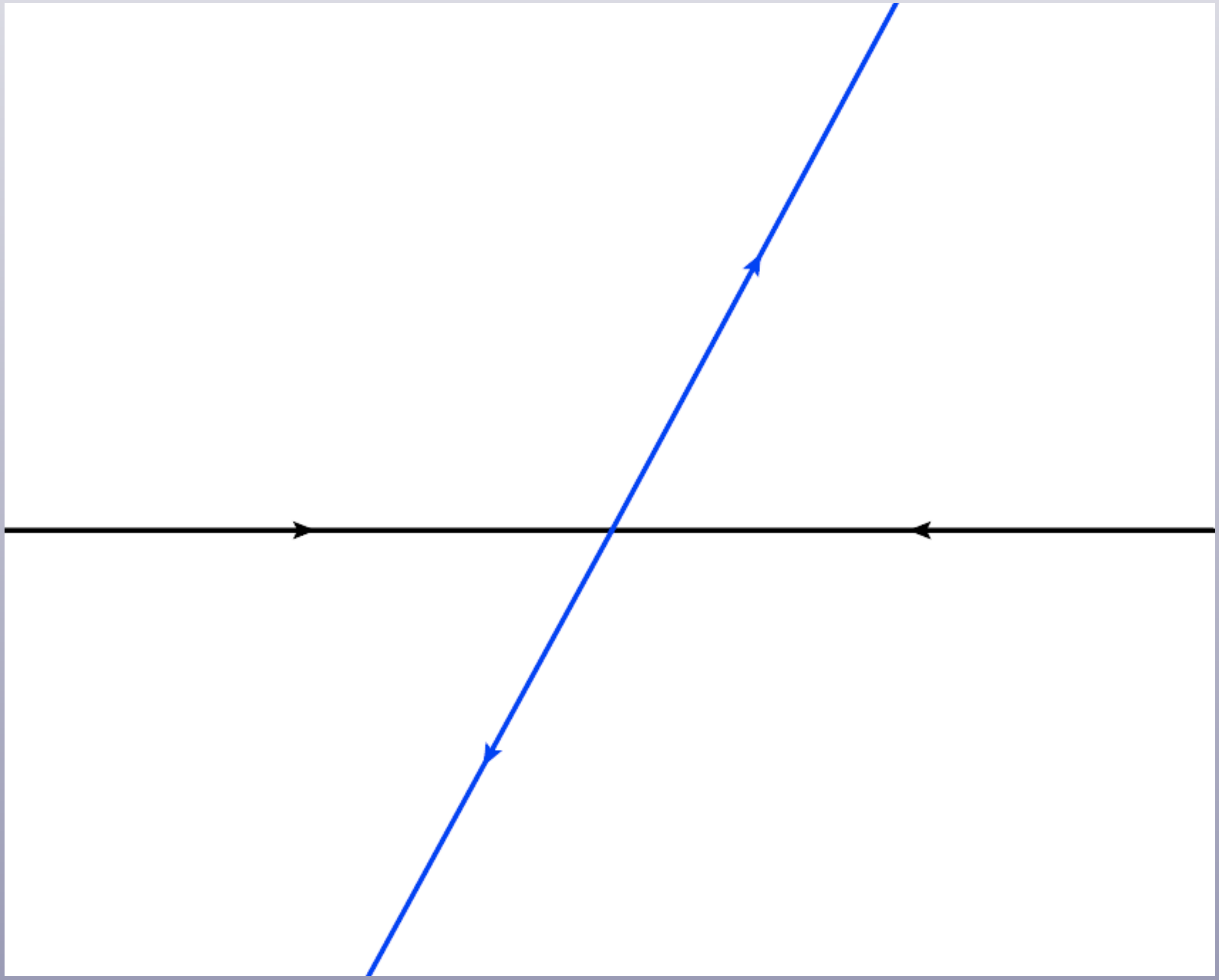
QCD at the LHC



Drawing by K. Hamilton

NLO parton showers

- **Fixed order calculation** do not provide a realistic description of final states in hadronic collisions
- They need to be supplemented with **parton showers, all-order resummations** of QCD soft and collinear radiation (**Pythia6/8, Herwig/++, Sherpa, Ariadne, ...**)
- In addition, **merging matrix elements** with high multiplicity improves final state description
- Matching to parton showers trivial at LO. LO merging requires **prescriptions to avoid double counting**



Leading Order
QCD jet production

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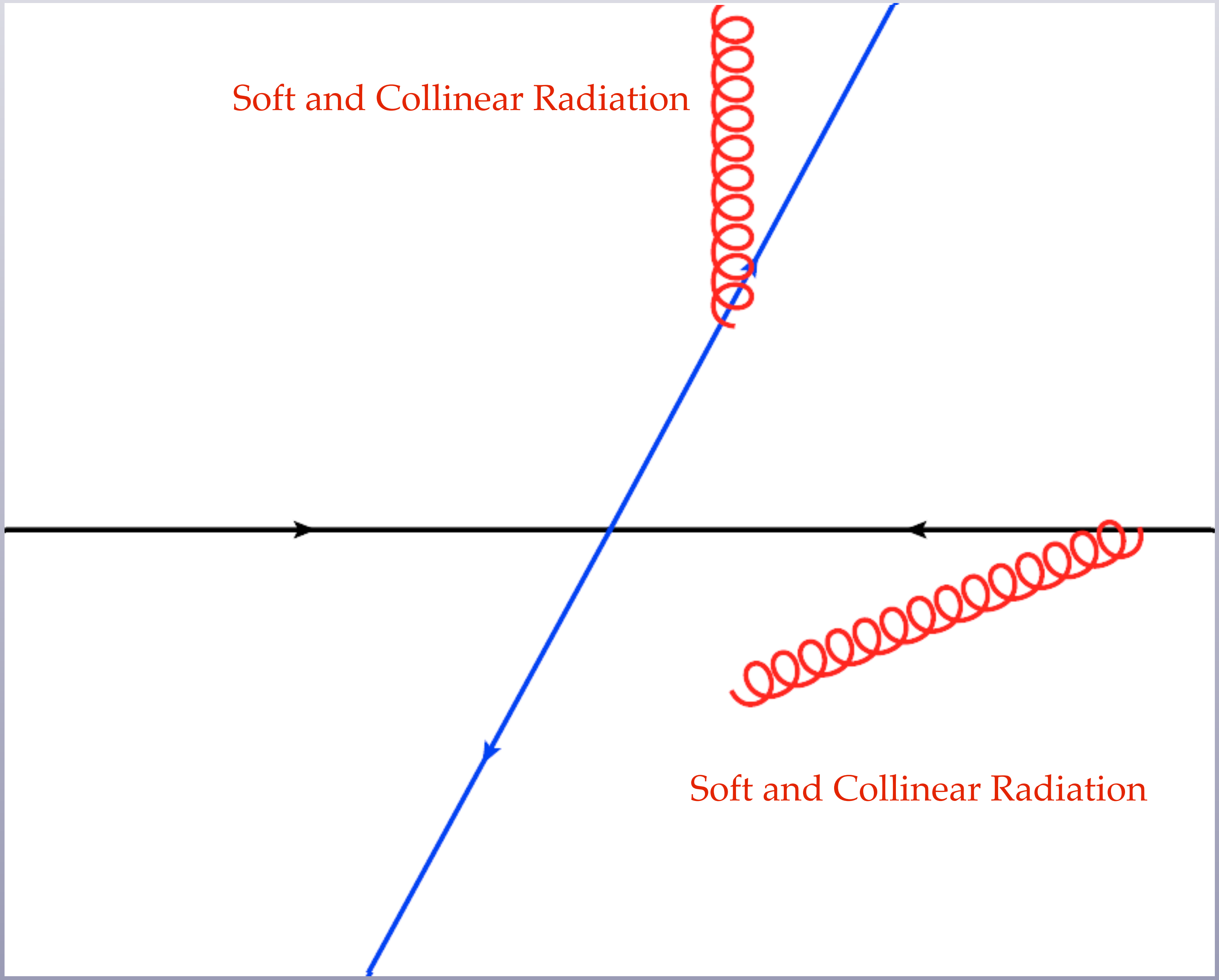

Leading Order +
Parton Shower
QCD jet production

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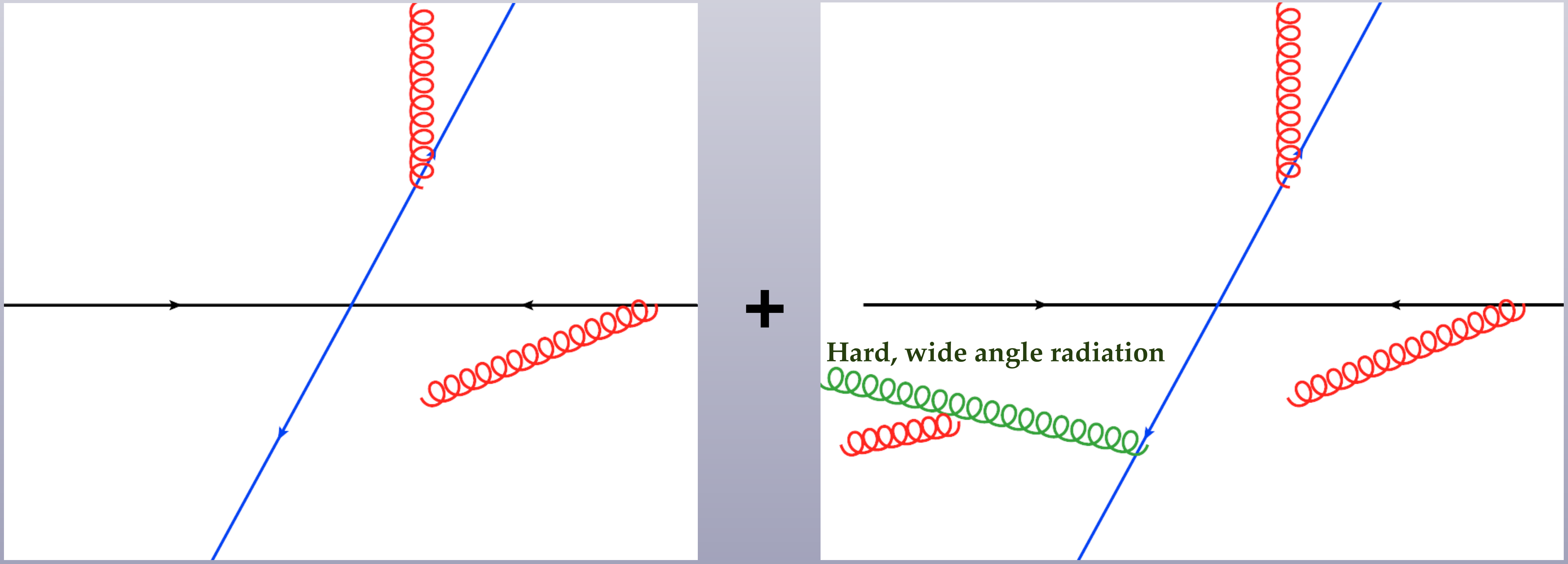
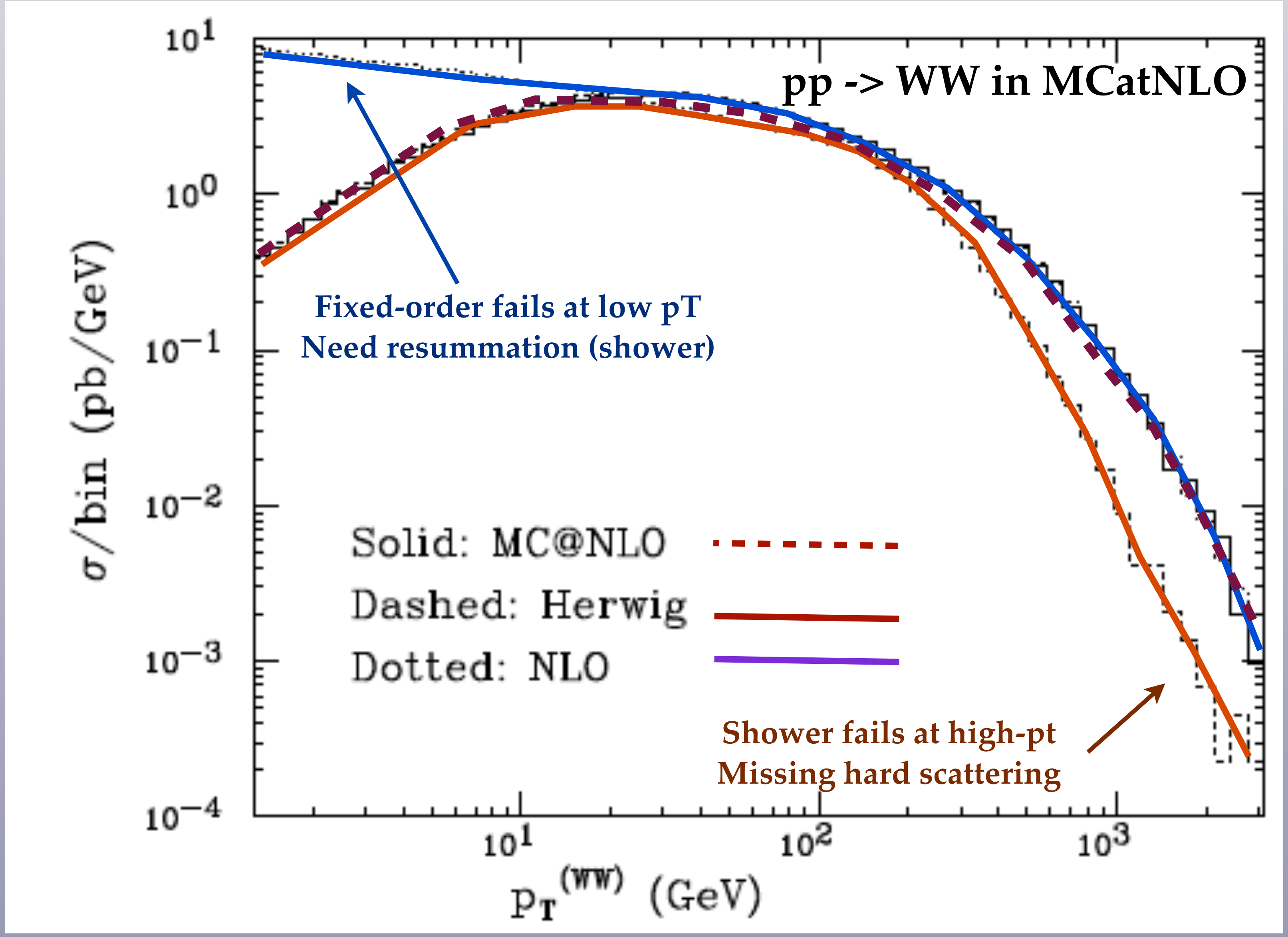
Leading Order + Parton Shower + Merging
QCD jet production



LO merging requires a prescription to avoid double counting
CKKW, Catani, Krauss, Kuhn, Webber 02
MLM, Mangano 02

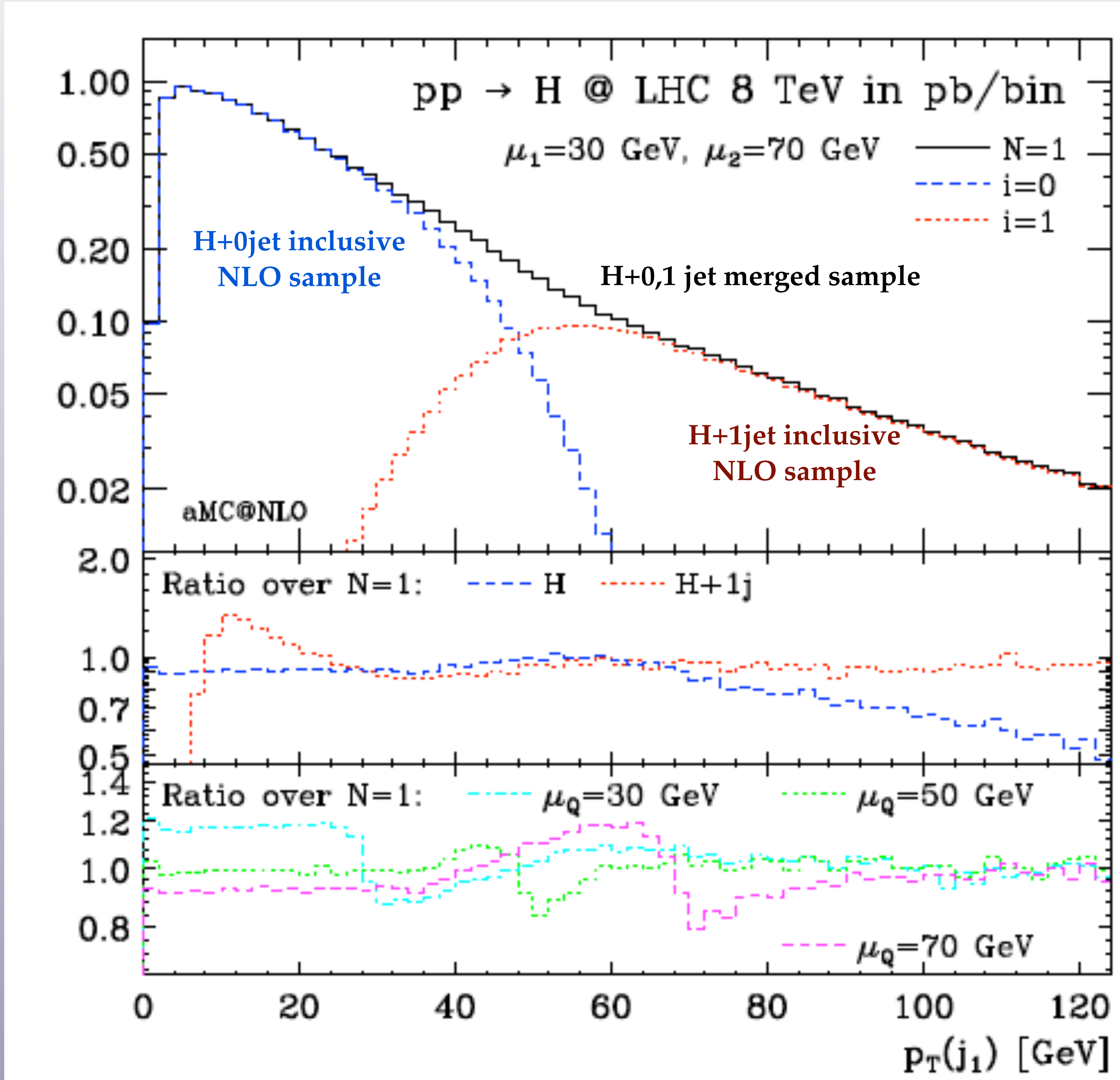
NLO parton showers

- At **NLO matching to parton showers** non-trivial, requires either i) modify/veto the shower first emission or ii) subtract from the NLO the first shower emission, to avoid **double counting**
- Two main methods: **MCatNLO (Frixione, Webber 02)** and **POWHEG (Nason 04, Alioli, Oleari, Nason, Re 10)** are of common use. These approaches are now largely automated: **aMCatNLO**, **POWHEG-Box**, also in **Sherpa**, **Herwig++**, ...
- **NLO+PS calculations** now available for virtually **all relevant LHC process**



A NLO+PS matched calculation provides improved description of a a **wider range of final state configurations** that NLO or PS alone

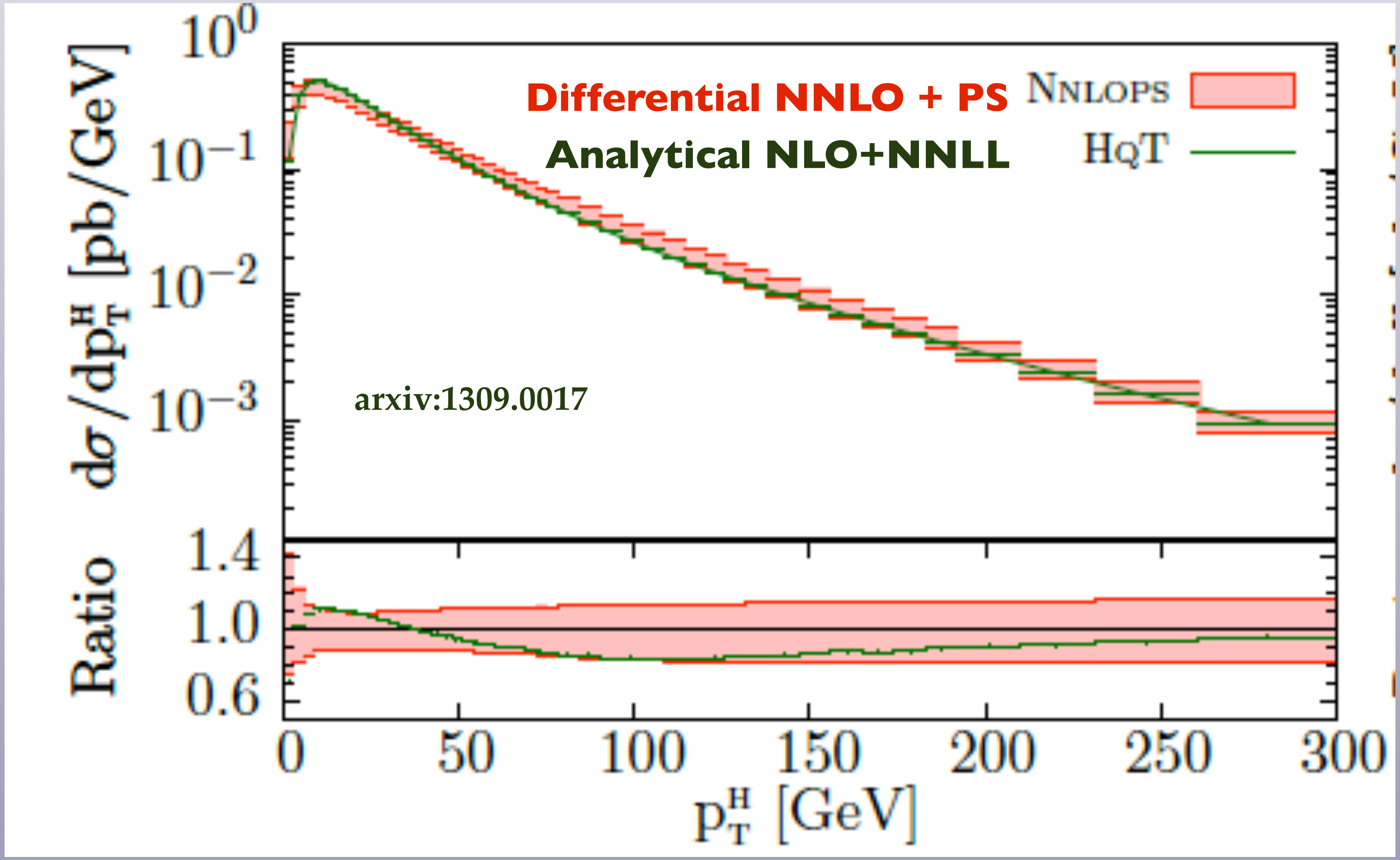
Multileg NLO+PS Merging



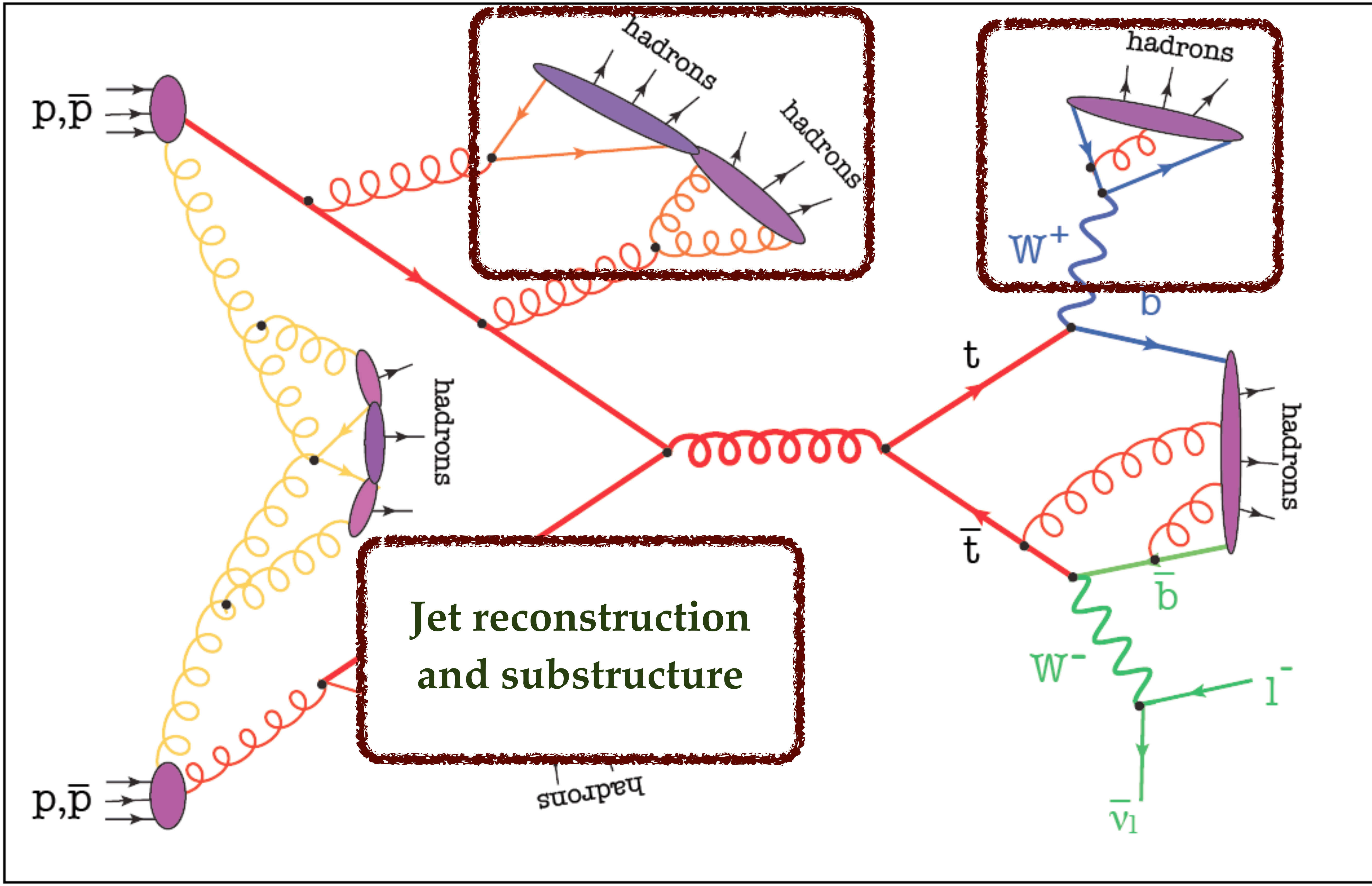
- The current frontier in NLO+PS is the **merging of matched NLO+PS samples with different multiplicities** into a common sample
- As illustration, consider **H+jet** in the **FxFx merging** approach (**Frederix, Frixione 12**)
  - **NLO+PS H+0jet** treats the extra jet at LO (fails at high jet pt)
  - **NLO+PS H+1jet** misses the **bulk of cross section**, which comes from events with no hard radiation
  - The **merged sample successfully interpolated between the two regimes** avoiding double counting
- Various different approaches have been proposed: **FxFx, MEPS@NLO (Sconherr, Hoeche, Krauss, Siegert 13), UNLOPS (Lonnblad and Prestel 12), ...**
- **Multileg NLO+PS merging** should become the standard for realistic NLO Monte Carlo simulations in the following years

Towards NNLO matched to parton showers

- Matching **fully differential NNLO calculations** to **parton showers** would provide the ultimate accuracy to QCD simulations at the LHC
- Many new conceptual issues need to be tackled, but already encouraging progress (**Hamilton, Nason, Re, Zanderighi 13, Alioli et al. (GENEVA) 13, ...**)



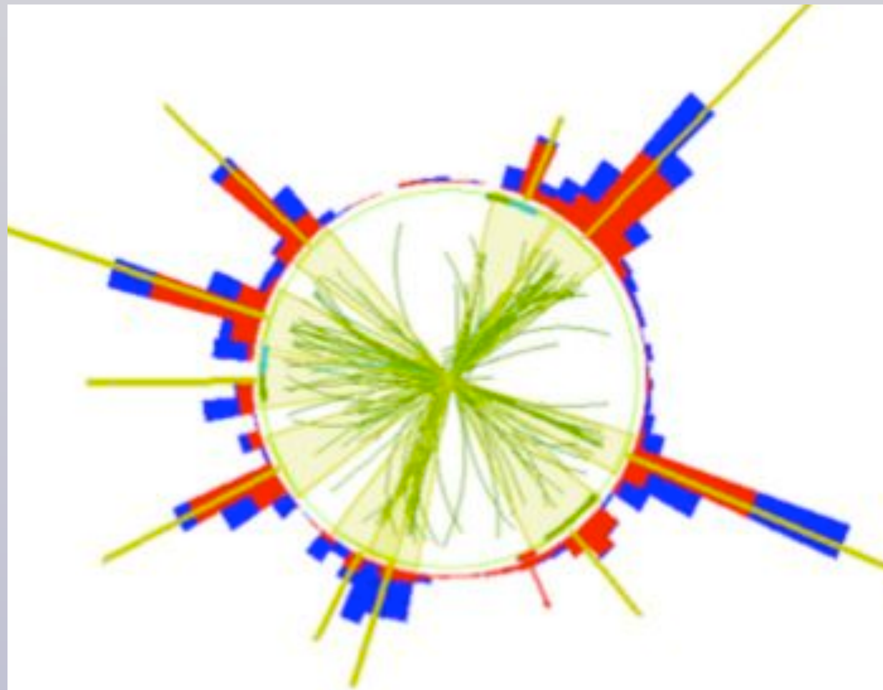
QCD at the LHC



Drawing by K. Hamilton

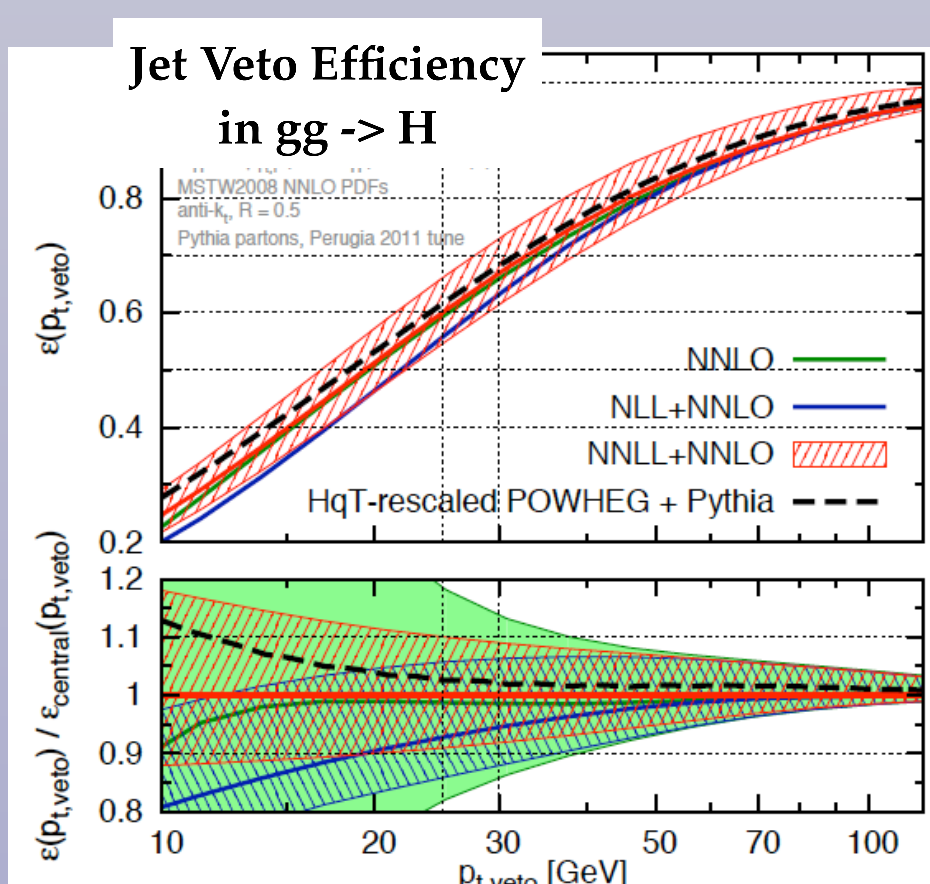
Jets at LHC

- *Jets are ubiquitous at LHC*, and required for almost all analysis **from SM measurements, Higgs physics** and **BSM searches**. Paradigm is **Anti-kt jets** (Cacciari, Salam, Soyez 08) with radius R in a range between **0.4 and 0.7.** Virtually all jet reconstruction tools available in the **FastJet framework** (Cacciari, Salam, Soyez)



Jets@LHC

- **Standard Model:** PDF determination, extraction of α_S, top quark reconstruction, hadronic V decays,
- **Higgs physics:** discrimination between production models, hadronic Higgs decays (bb, cc), associated production, ...
- **Beyond the Standard Model**: searches for compositeness, supersymmetry in the jets + missing ET, TeV scale gravity via quantum black holes, jet substructure .....

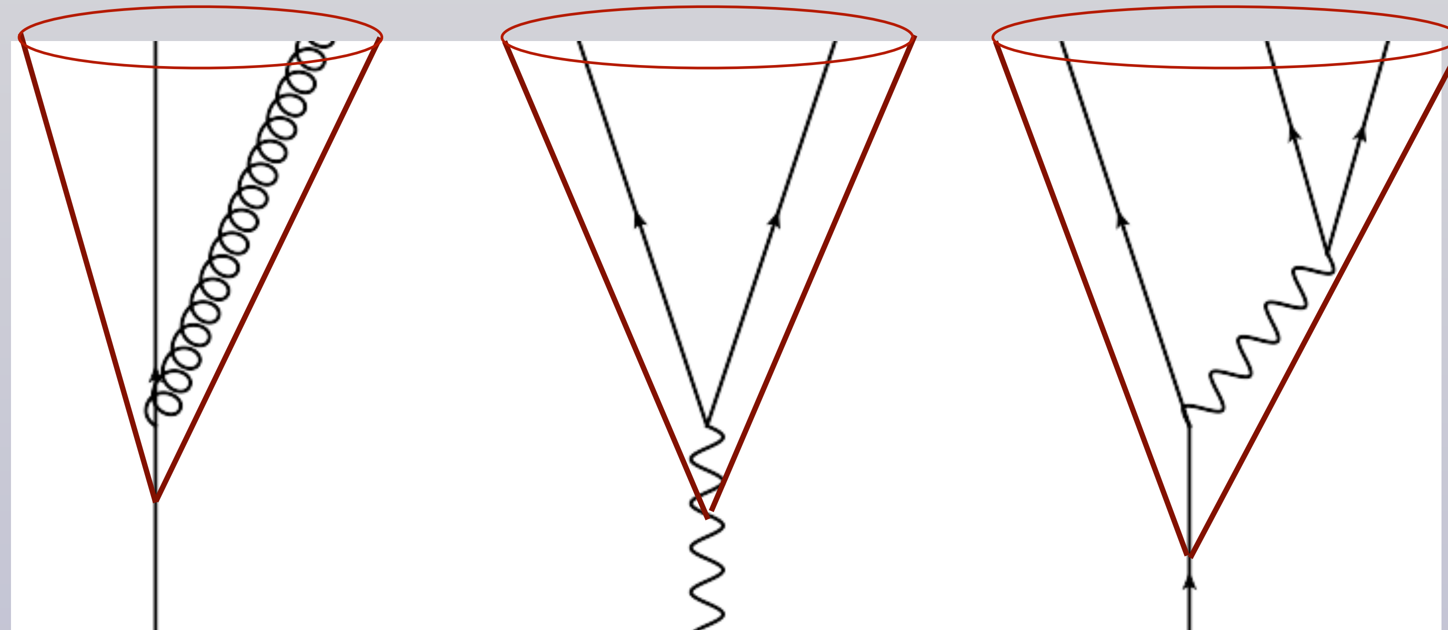


- Recently a lot of effort has ben done in **understanding the (large) theoretical uncertainties** associated to **vetoing jets**, as done for instance in **Higgs analysis** to separate gluon fusion from VBF
- **Resummed NNLO+NNLL calculations** allow to reduce higher-order uncertainties in the jet veto efficiency as function of the jet transverse momentum

Banfi, Monni, Salam, Zanderighi 12-13
Becher, Neubert 12-13
Tackmann, Walsh, Zuberi 13
Liu, Petriello 12

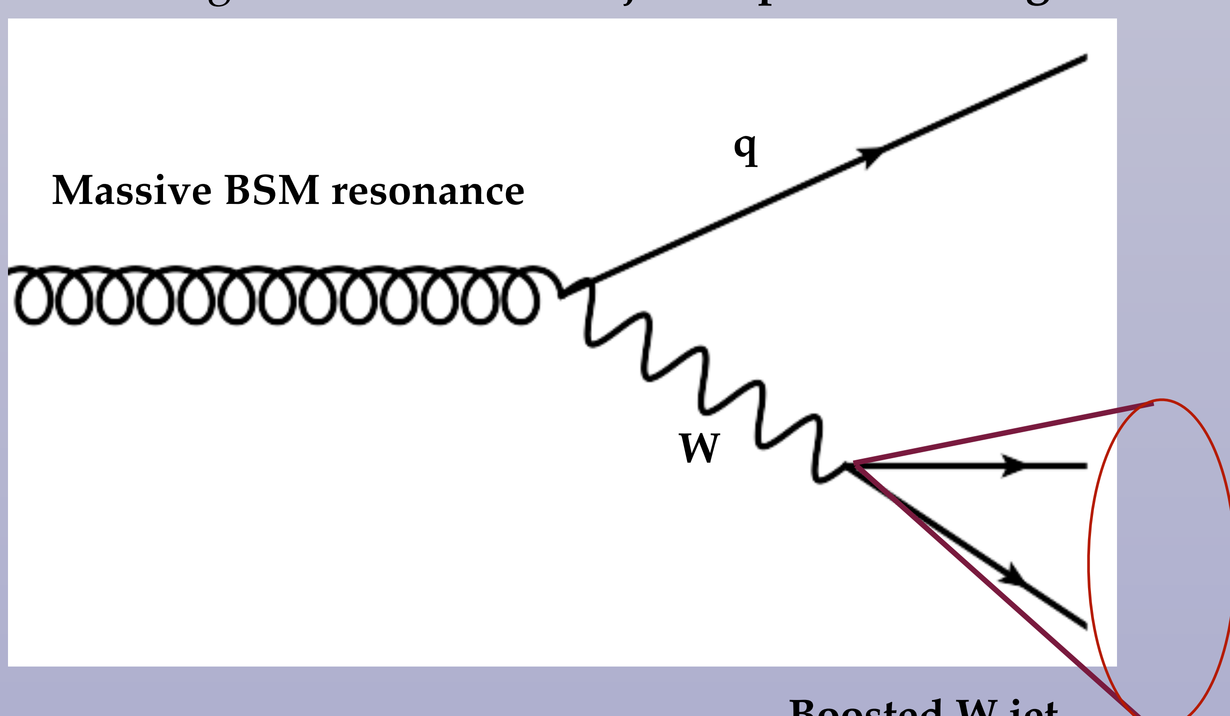
Jet substructure

- In the decays of a **massive enough resonances, boosted prongs** can often be collimated into a **single jet**
- Different **jet substructure** in these jets and QCD jets provide strong background suppression in **BSM searches**

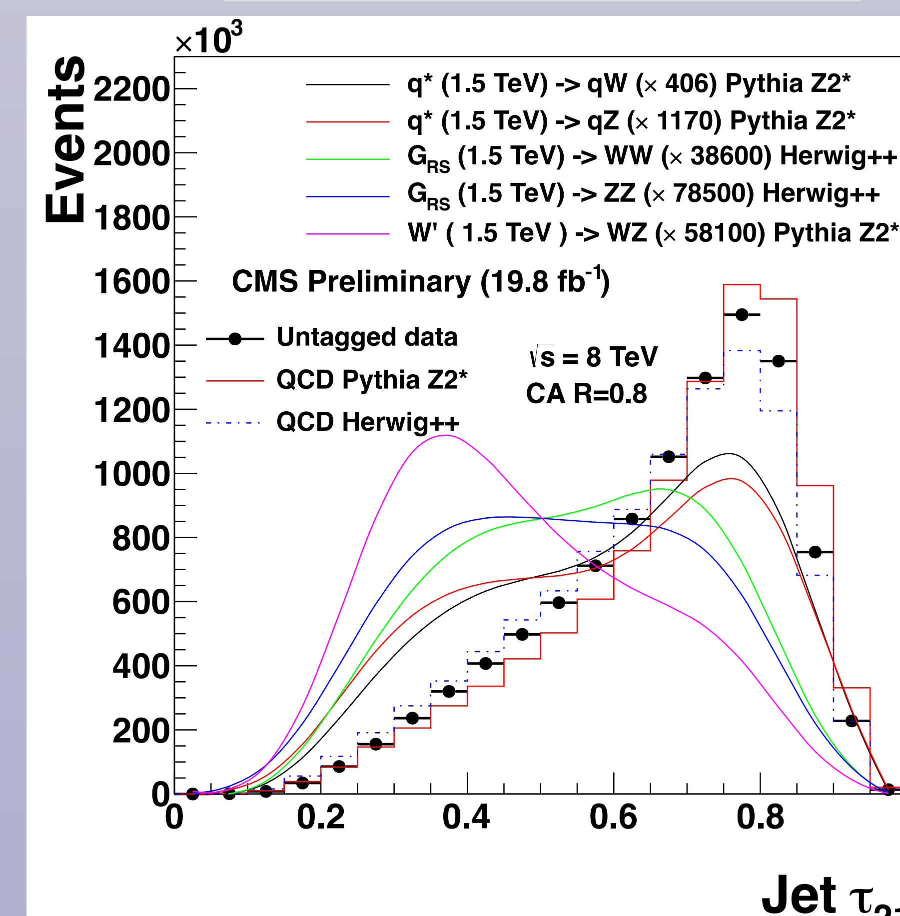


QCD jet — Boosted W jet — Boosted top quark jet

- LHC analysis are using more and more jet substructure techniques (also for Higgs)
- As illustration, recent CMS search for **q* -> qV in the tagged dijet final state**
- Discriminating variable: **different jet shape/mass in signal and in QCD background**

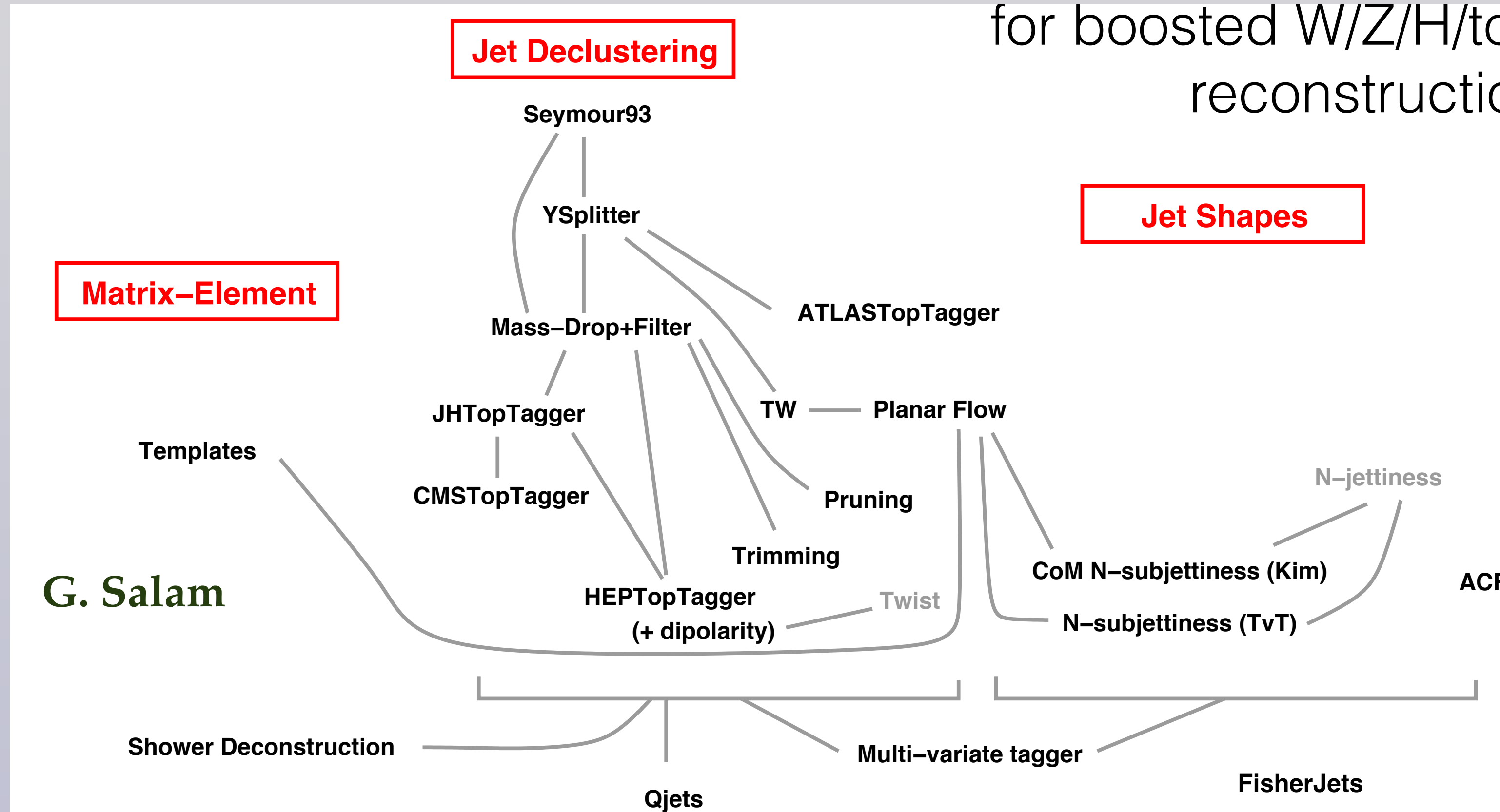


CMS PAS-EXO-12-024



Jet substructure

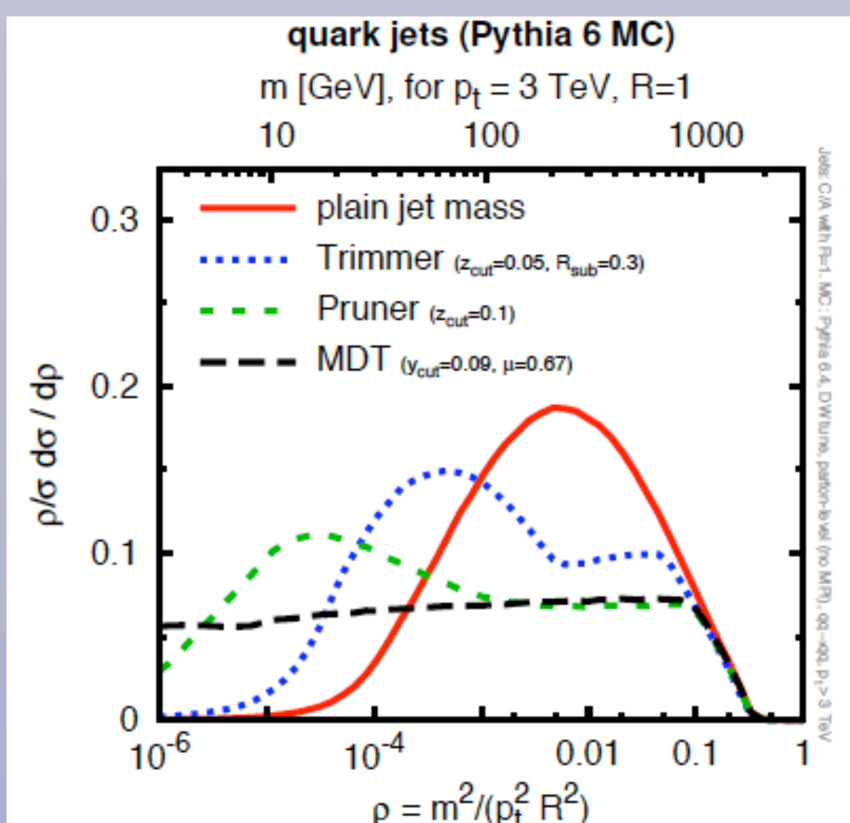
- Wide variety to **jet substructure tools**, useful to **sharpen interesting signals** and to **reduce QCD backgrounds**

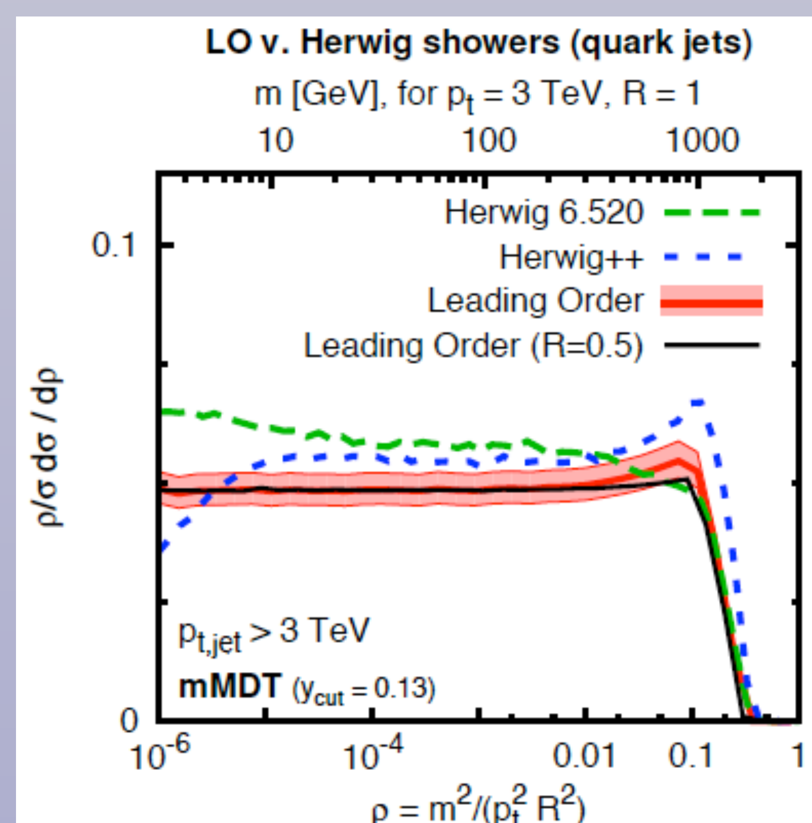


See the **proceedings of the BOOST workshops** for a complete set of references

arxiv:1311.2708

arxiv:1012.5412





- However, it should be avoided to **use blindly** these tools.
- It is essential to back then not only with **Monte Carlo studies** but also with **analytical calculations** (Dasgupta, Fregoso, Marzani, Salam 13)
- These calculations in turn show to to **further improve jet taggers**
- Note that even for something as fundamental as **jet mass, different taggers** lead to quite different results, and also a dependence with the scale $\mathbf{m^2/pt^2\ R^2}$

Summary

- **Quantum Chromodynamics** is an **essential ingredient** of the **LHC physics program**
- **Precision QCD calculations** are required for most LHC analysis, from **Higgs boson characterization**, **searches for new massive particles** to the **precision determination of Standard Model parameters**
- Huge progress in QCD in the last years including:
  - ☑ *Robust, statistically meaningful PDFs with LHC data and QED corrections*
  - ☑ *NNLO calculations for many LHC process including partons in both initial and final state*
  - ☑ *Automation of NLO matched to parton shower calculations and multileg NLO+PS merging*
  - ☑ *Precision jet reconstruction including resummed calculations, and standardization of jet tools in the FastJet framework*
  - ☑ *New taggers for jet substructure, and improved analytical understanding of these*
- And much more to come, to match the requirements of LHC data, so stay tuned!

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Thanks for your attention!

and apologies for the missing references....