Aspects of QCD at the LHC

- Experiment and Theory
- QCD improved parton model
- Strong coupling constant
- Parton distribution function
- NLO, NNLO results
- Jet physics

Physics at the LHC

- Excellent discovery reach:
  - Higgs
  - Supersymmetry
  - Extra-Dimensional models
  - Anything else

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- Theories:
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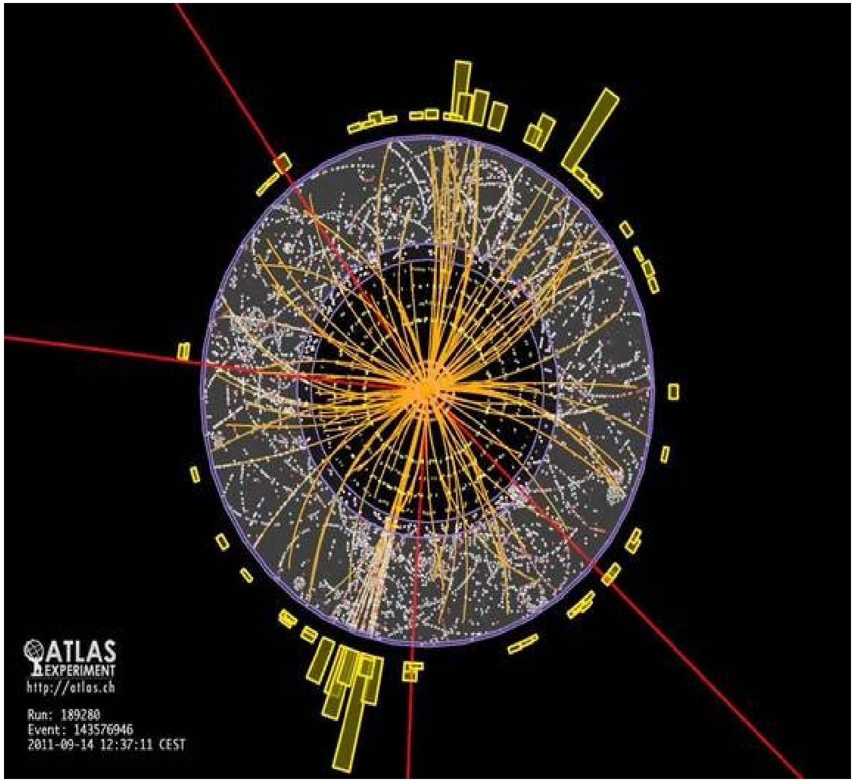
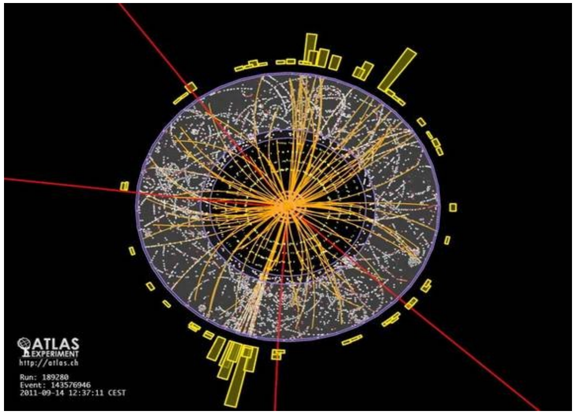
- Issues to be tackled:
  - Kinematics
  - Normalisation
  - Renormalisation and factorisation scale uncertainities
  - Parton Distribution Functions
  - Phase Space boundary effects and resummation of large logs

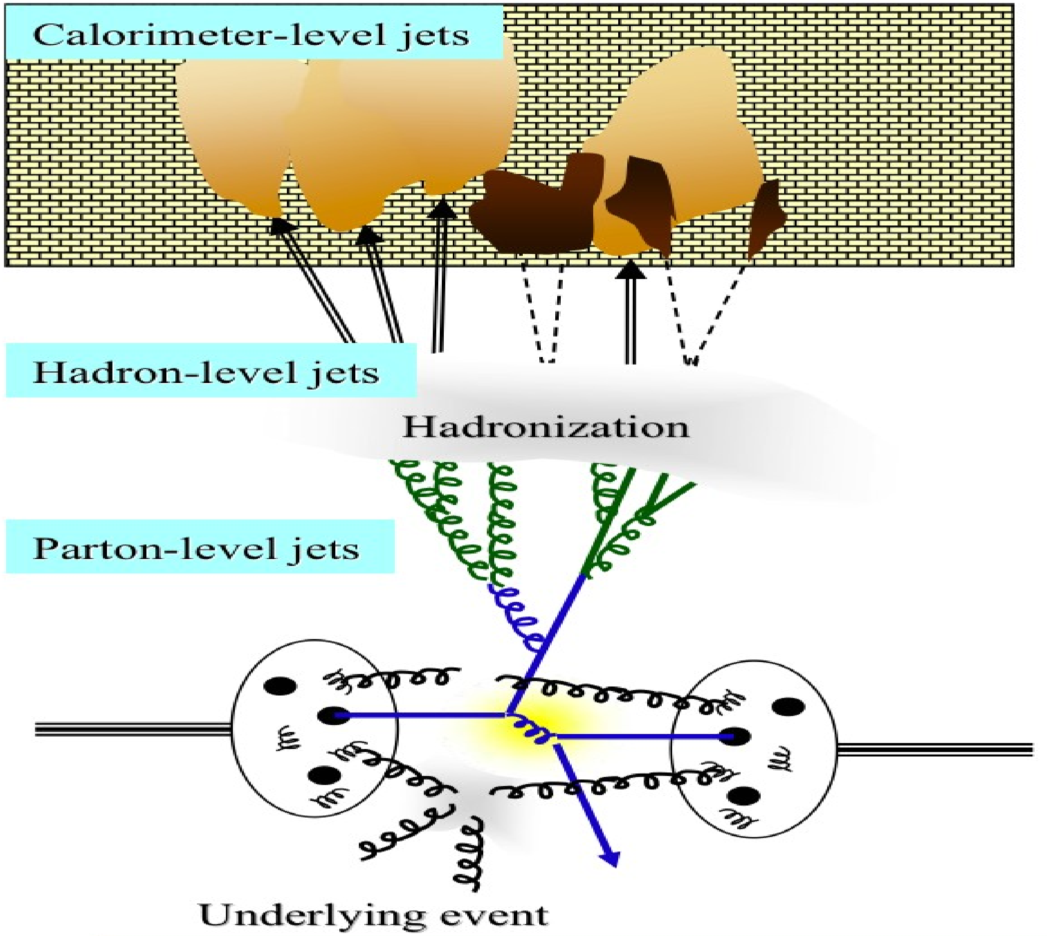
What we see in the experiment



- Large number of events of different kinds involving variety of particles at the detector level

What really happens





- Large number of events of different kinds involving variety of particles at the production and detector levels
- The underlying theory, Quantum Chromodynamics provides a physical picture.
- Exact computation of such an observable is unrealistic.

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- Parameter of QCD is strong coupling constant g_s or Λ_{QCD}.

QCD-a toolkit for discovering NEW PHYSICS at LHC

Infra-red safe observables in QCD

- We are interested processes involving hadrons

  1) Total cross sections: Higgs, slepton, gluino productions

  2) Differential cross sections: higt p_T jets, rapidity of leptons

  3) Decay of particles to hadrons: Jet physics, Fragmentation

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- In perturbation theory, large logs orginate from the infra-red sector of the theory:

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- We can compute them because they are "infra-red safe" due to their Factorisation properties

QCD improved Parton Model

$$P_1 + P_2 \to higgs + X$$

$$d\sigma^{P_1 P_2} = \sum_{ab} \int dx_1 \int dx_2 f_{\frac{a}{P_1}}\left(x_1, \mu_F^2\right) f_{\frac{b}{P_2}}\left(x_2, \mu_F^2\right) d\hat{\sigma}^{ab}\left(x_1, x_2, \{p_i\}, \mu_F^2\right),$$

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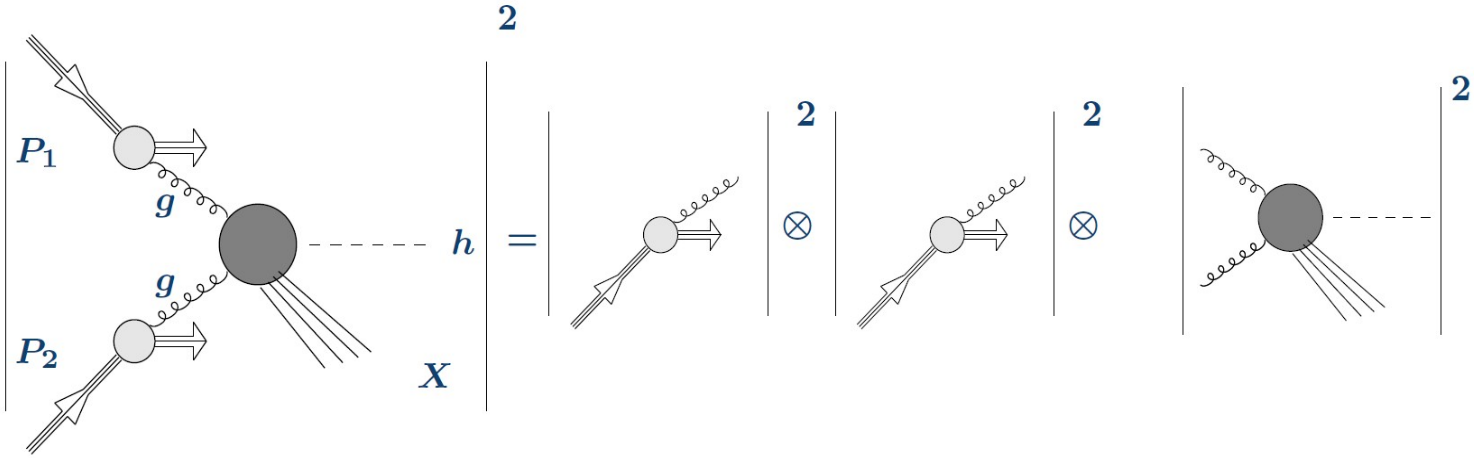

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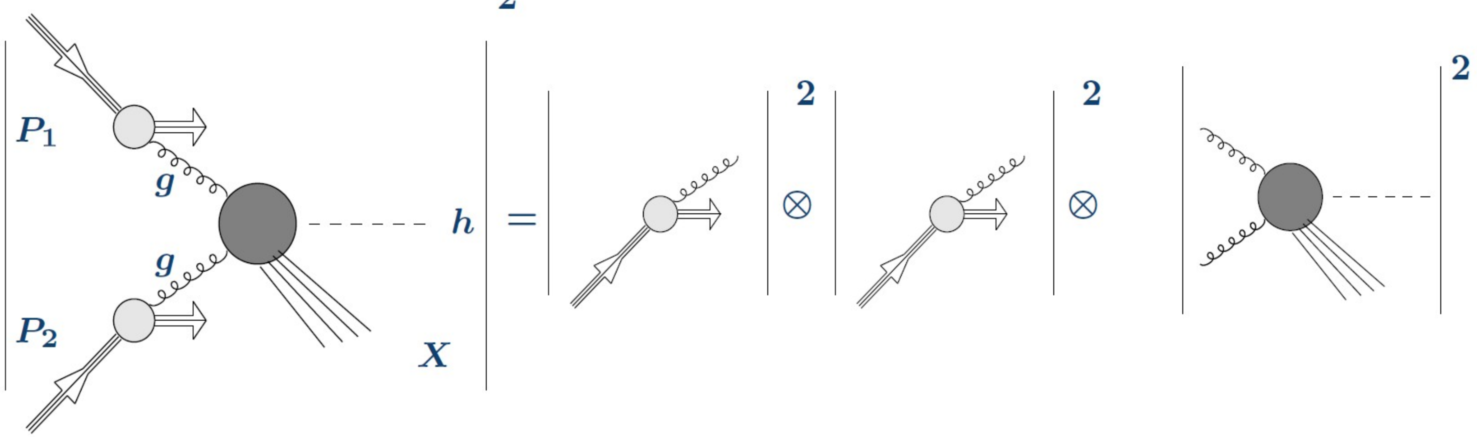

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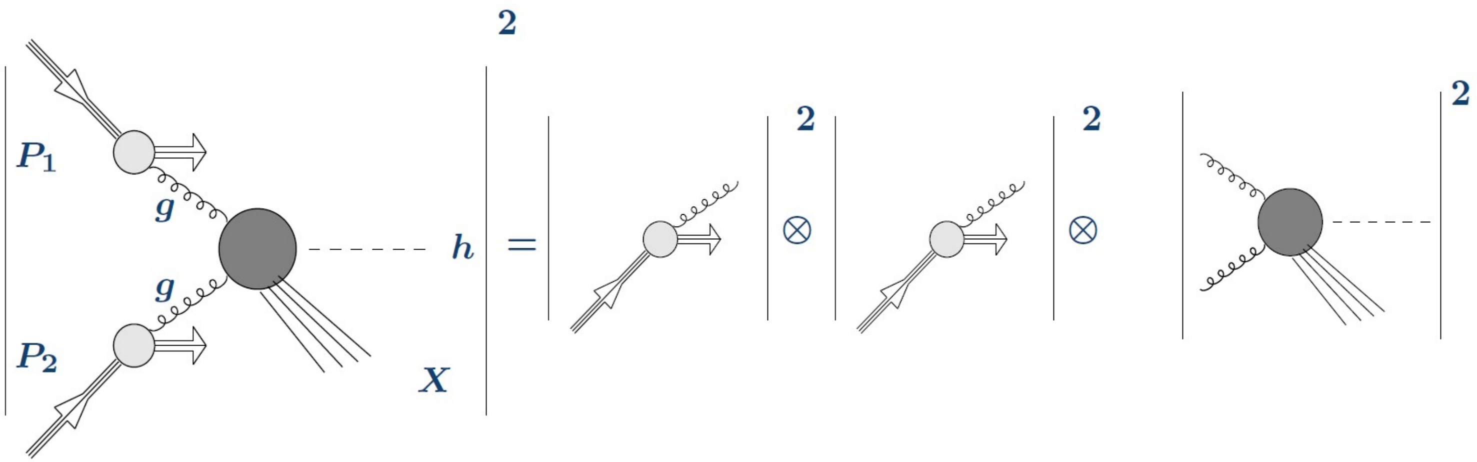

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- $\hat{\sigma}_{ab}(x_i, \{p_i\}, \mu_F^2)$ are the partonic cross sections.
- Perturbatively calculable.

Factorisation Theorem

Hadronic cross section in terms of partonic cross sections convoluted with appropriate PDF:

$$2S\, d\sigma^{P_1 P_2}\left(\tau, m_h^2\right) = \sum_{ab} \int_{\tau}^{1} \frac{dx}{x} \Phi_{ab}\left(x, \mu_F\right) 2\hat{s}\, d\hat{\sigma}^{ab}\left(\frac{\tau}{x}, m_h^2, \mu_F\right)$$

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- The Renormalisation group invariance:

$$\frac{d}{d\mu}\sigma^{P_1 P_2}(\tau, m_h^2) = 0, \qquad \mu = \mu_F, \mu_R$$

LO is a crude approximation!

Higgs Production through gluon fusion:

$$2S\, d\sigma^{PP}(x, m_H) = \int_x^1 \frac{dz}{z} \Phi_{gg}^{(0)}(z, \mu_F)\, 2\hat{s}\, d\hat{\sigma}_{gg}^{(0)}\left(\frac{x}{z}, m_H^2, \mu_R\right) + \cdots$$

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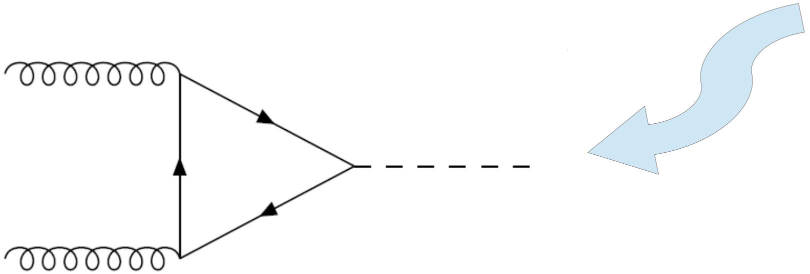

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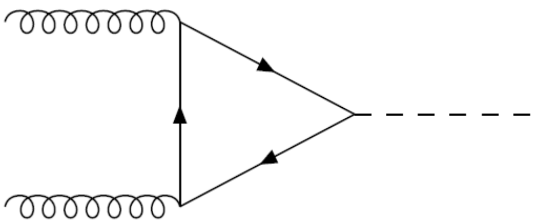

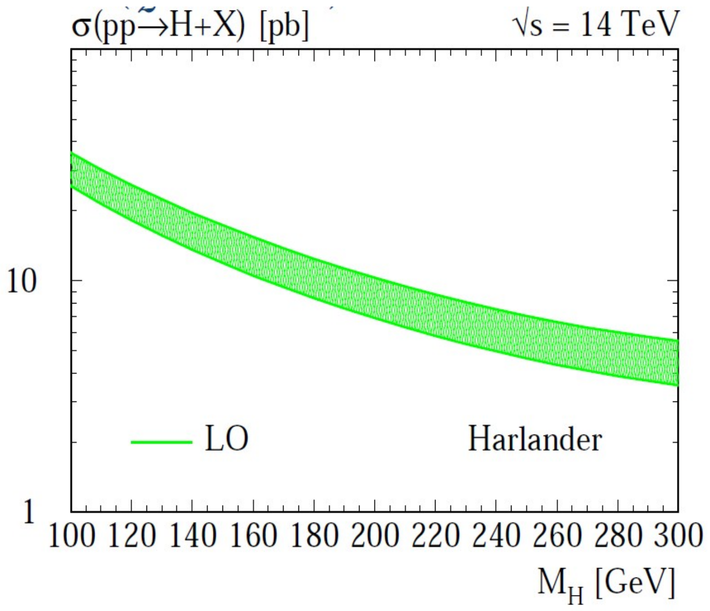

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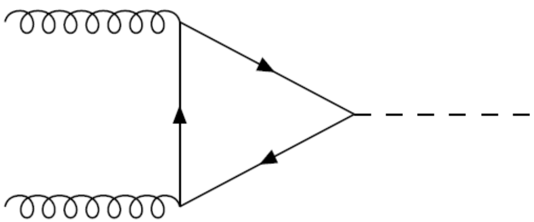

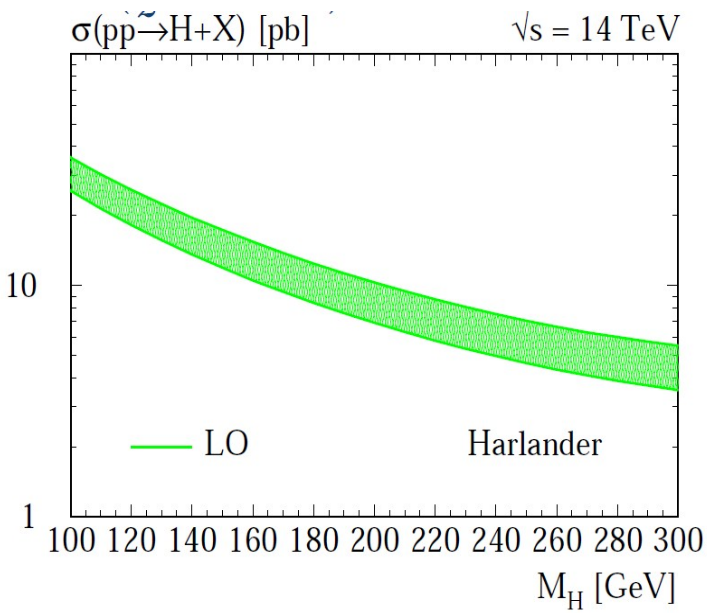

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$$2\hat{s}\, \hat{\sigma}_{gg}^{(0)}(\hat{s}, \mu_R) \sim \alpha_s^2(\mu_R)\, G_F \left[\frac{4m_t^2}{m_H^2} F\left(\frac{4m_t^2}{m_H^2}\right)\right], \qquad \frac{m_H}{2} < \mu_R = \mu_F < 2m_H$$

LO prediction is Unreliable due $100 - 200\%$ scale uncertainity

Inputs that can affect the predictions

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- Parton Distribution Functions PDF extracted from experiments

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- Any "Fixed order" perturbative result is bound to depend on μ_R and μ_F and type of PDF sets.
- Observables are "free" of μ_R and μ_F.

$$\mu \frac{d}{d\mu} \sigma^{P_1 P_2} \quad = \quad 0, \qquad \mu = \mu_F, \mu_R, PDF$$

Strong Coupling Constant

$$\alpha_s(\mu_R)$$

Renormalisation Group Equation α_s

Renormalisation group equation for α_s:

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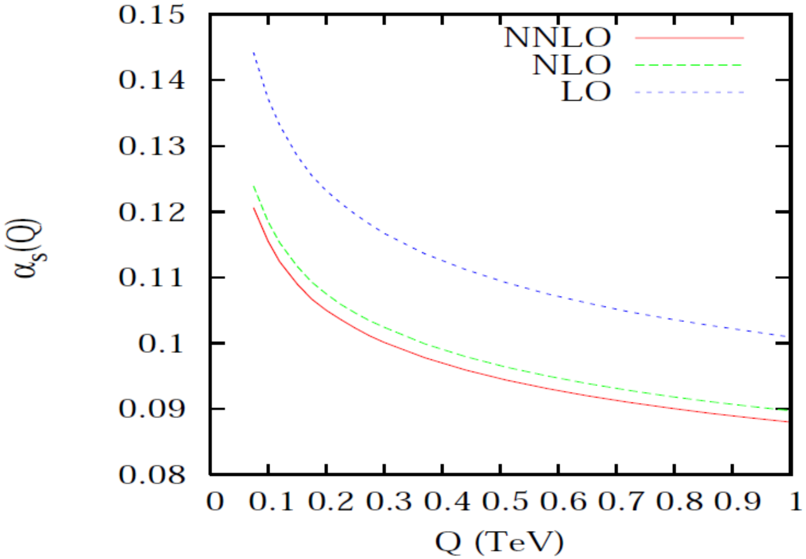

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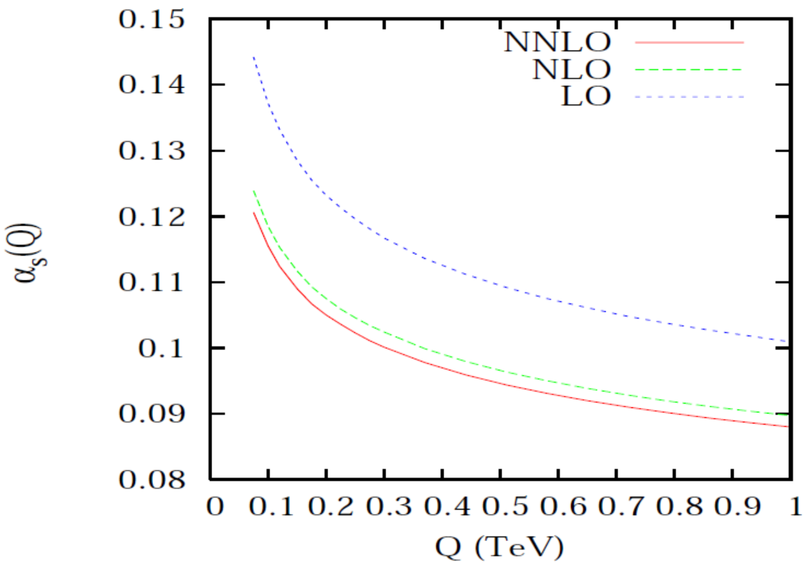


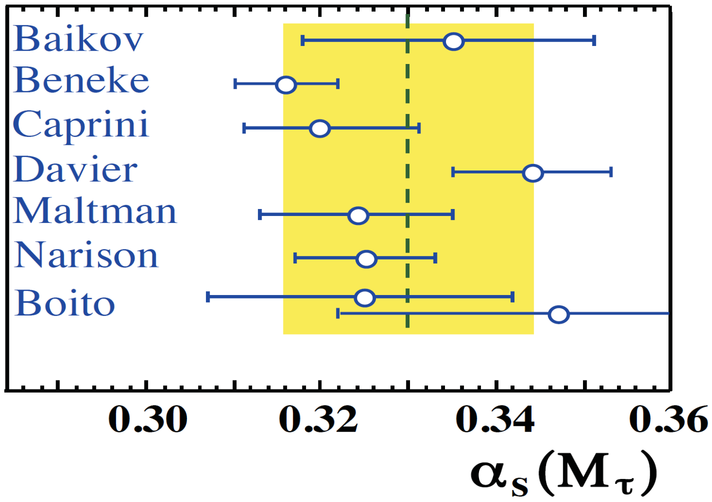
Measured from :

- Tau decays,
- lattice,
- heavy quarkonia decays,
- non-single structure functions,
- Jets from HERA,
- event shape variables from LEP

From various sources

S. Bethke

α_s from τ-decays



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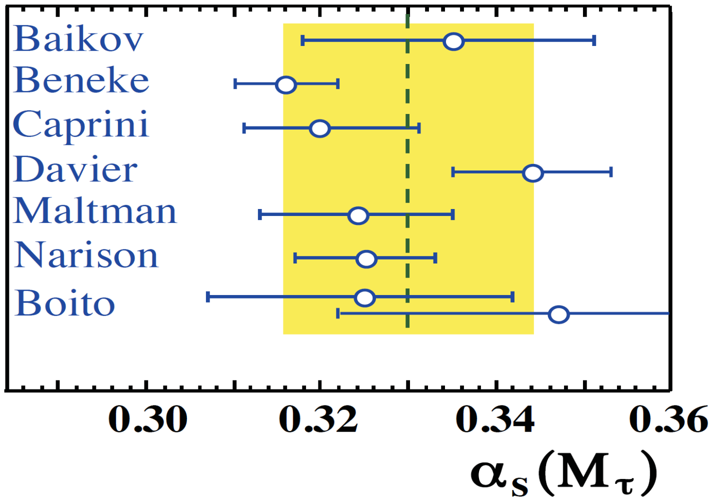
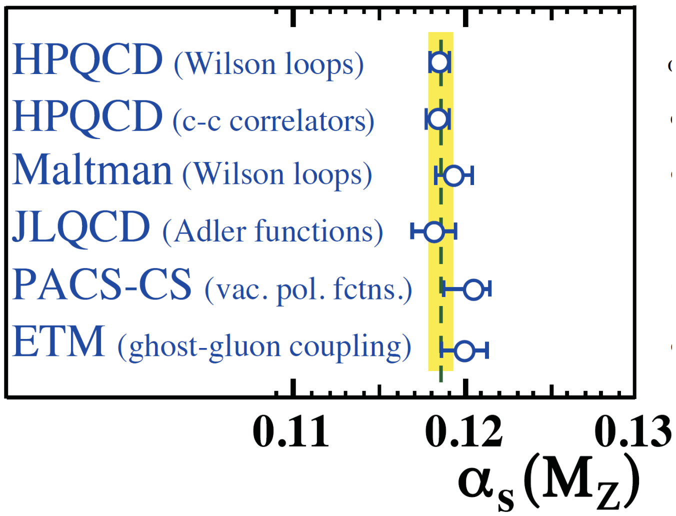


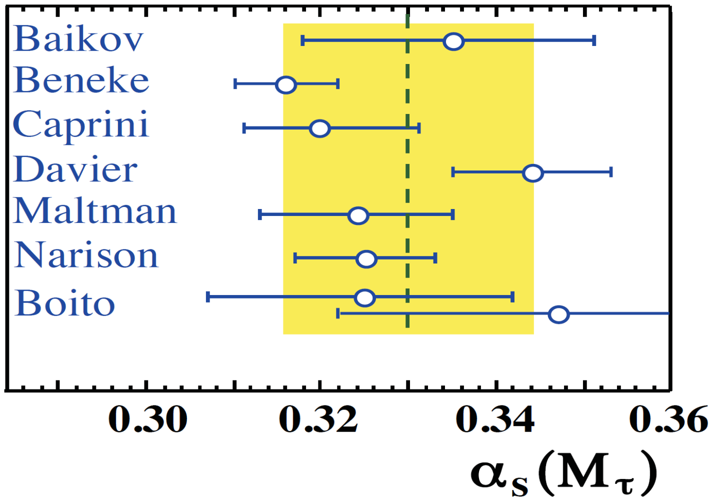
α_s from lattice QCD



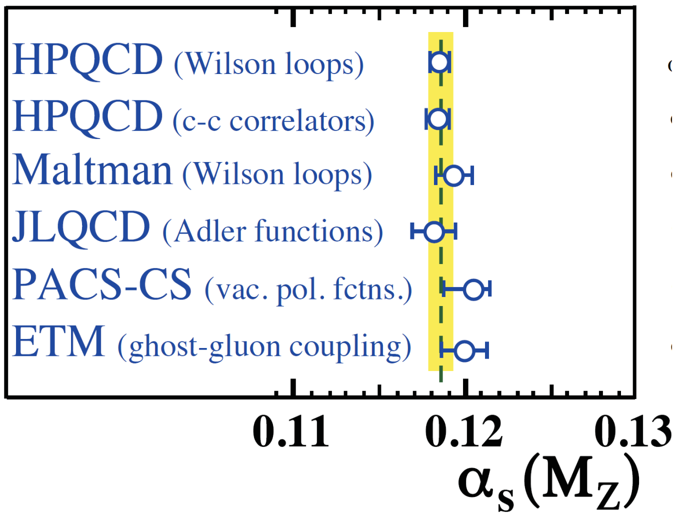
From various sources

S. Bethke

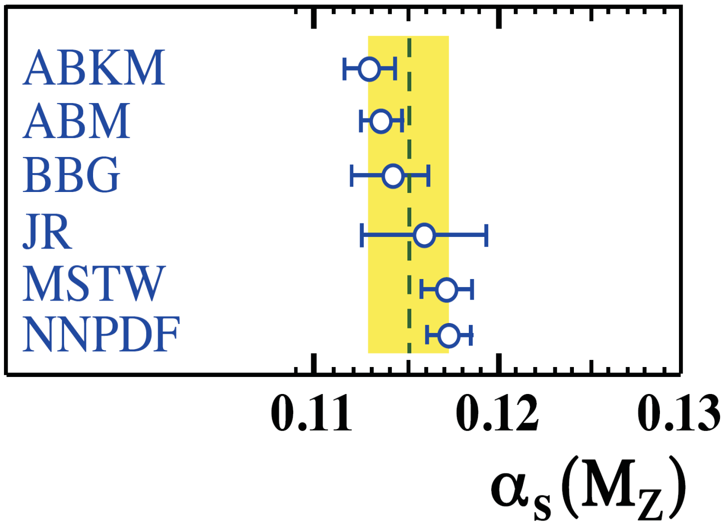
α_s from τ-decays



α_s from lattice QCD



α_s from DIS structure functions



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S. Bethke

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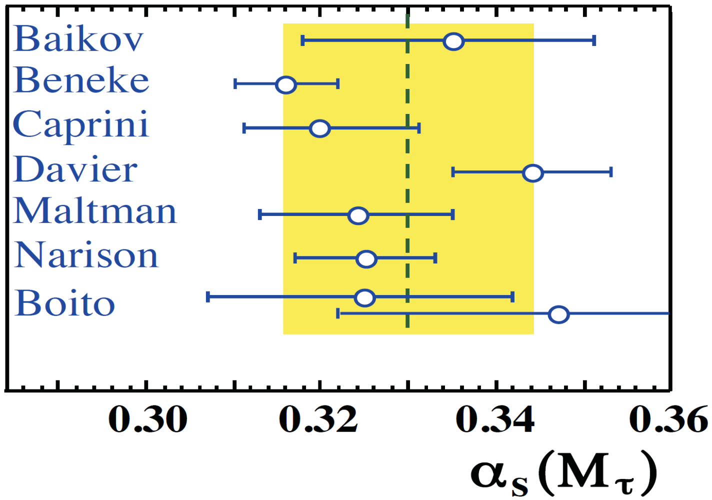

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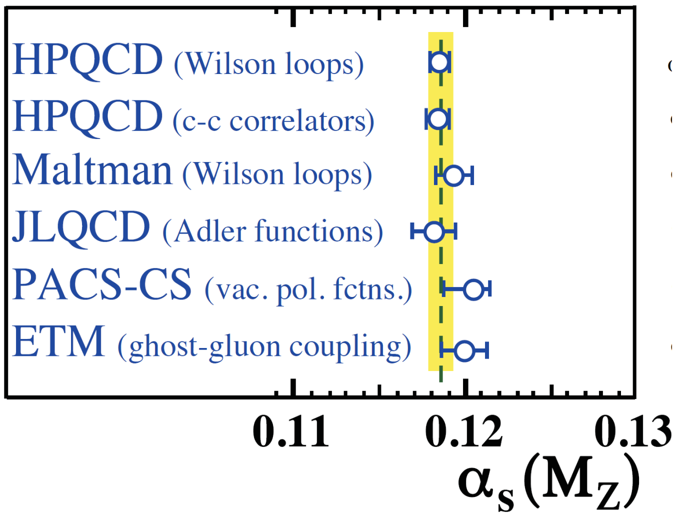

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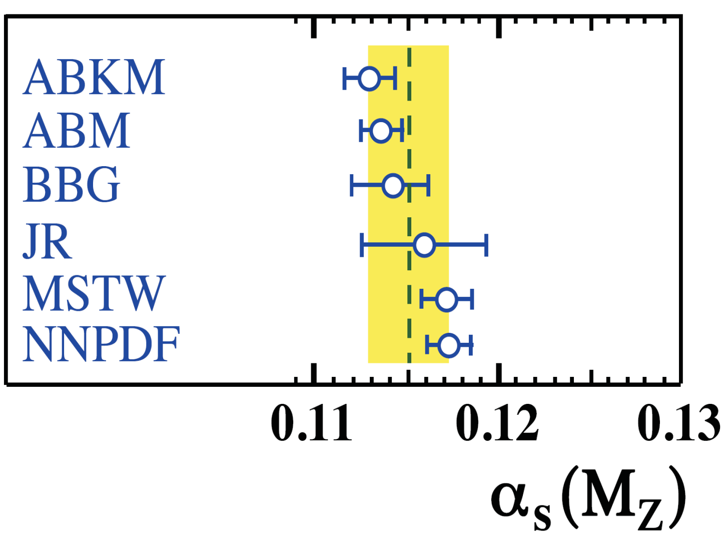
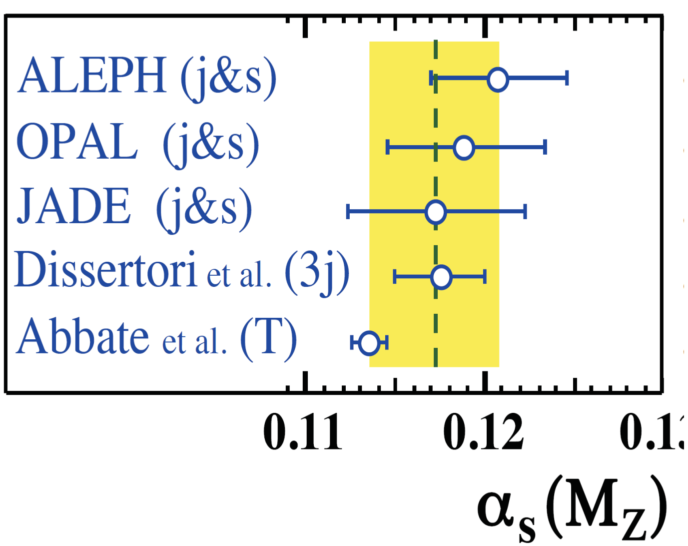
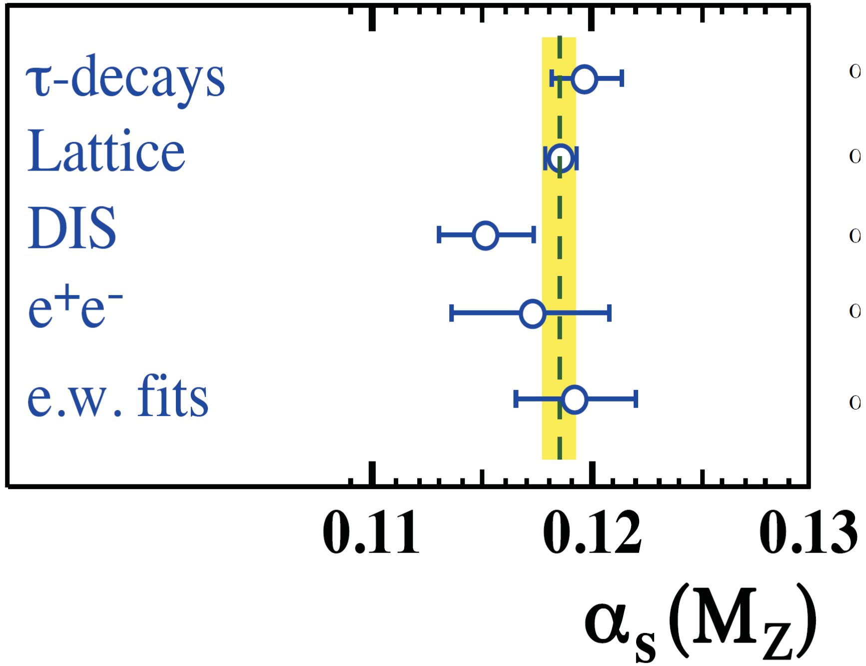


α_s from jets and event shapes in e^+e^- annihilation



World Summary of α_s 2012:

S. Bethke



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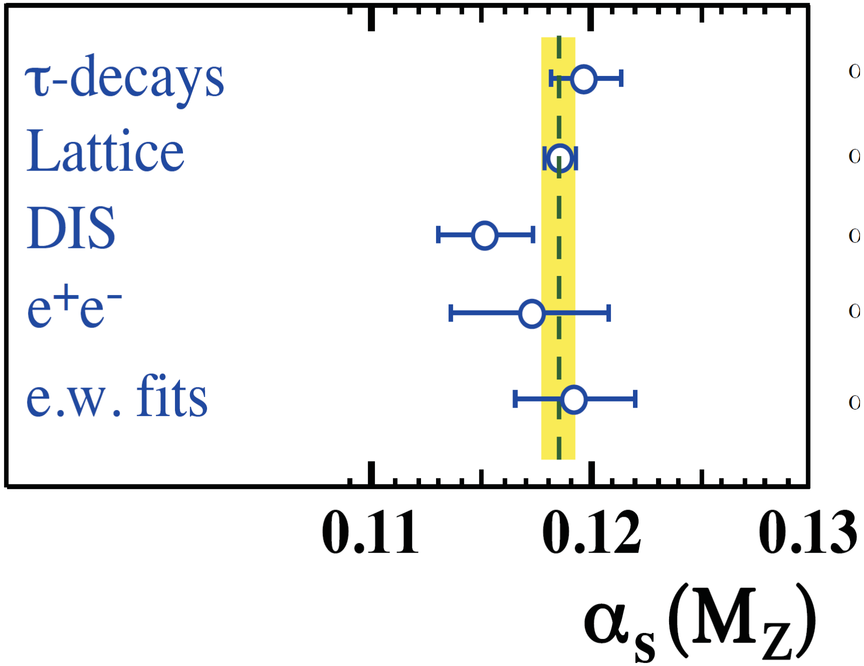

Process	$\alpha_s(M_{Z^0})$	excl. mean $\alpha_s(M_{Z^0})$	std. dev.
τ-decays	0.1197 ± 0.0016	0.1183 ± 0.0007	0.8
Lattice QCD	0.1186 ± 0.0007	0.1182 ± 0.0011	0.3
DIS [F_2]	0.1151 ± 0.0022	0.1188 ± 0.0010	1.5
e^+e^- [jets & shps]	0.1172 ± 0.0037	0.1185 ± 0.0006	0.3
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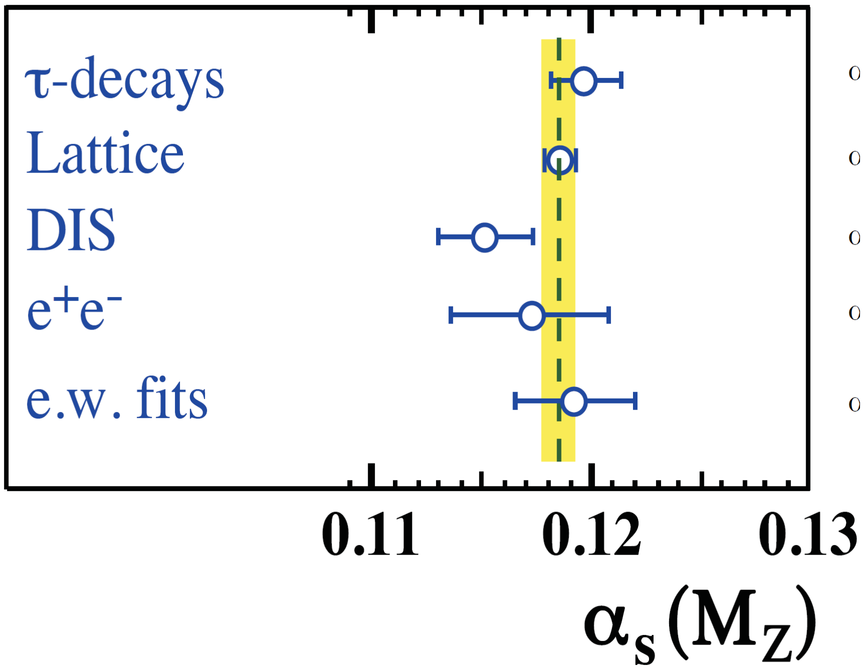

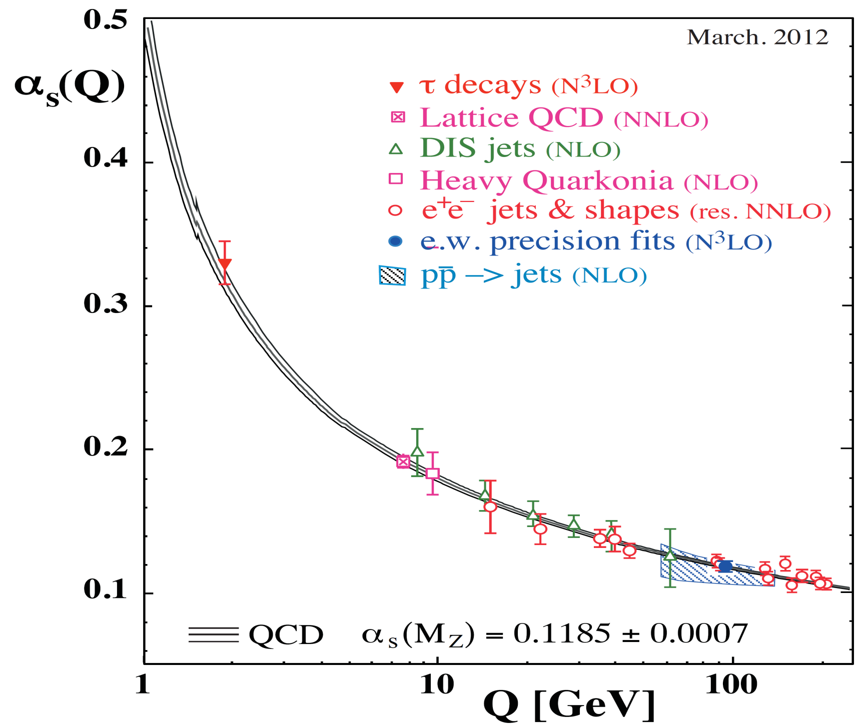

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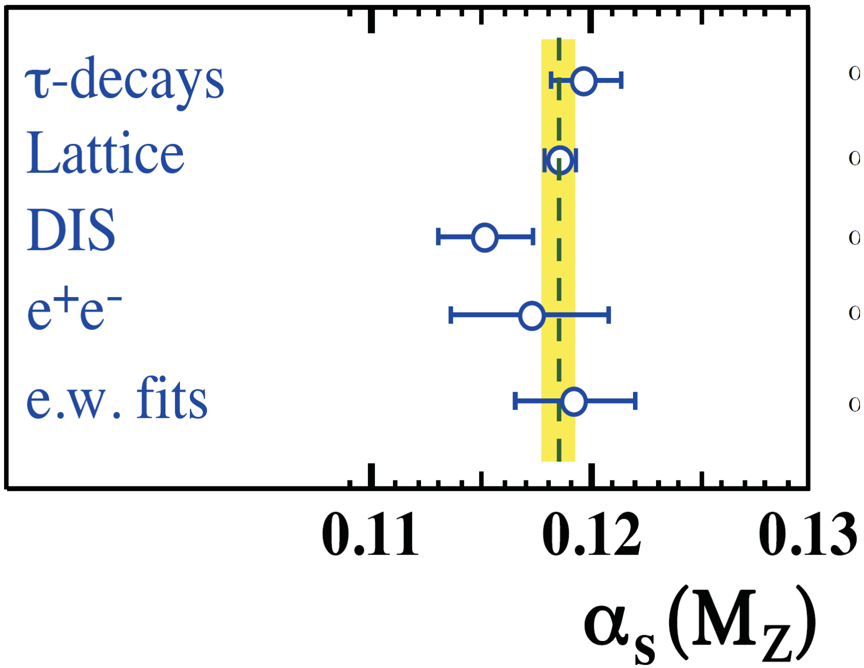

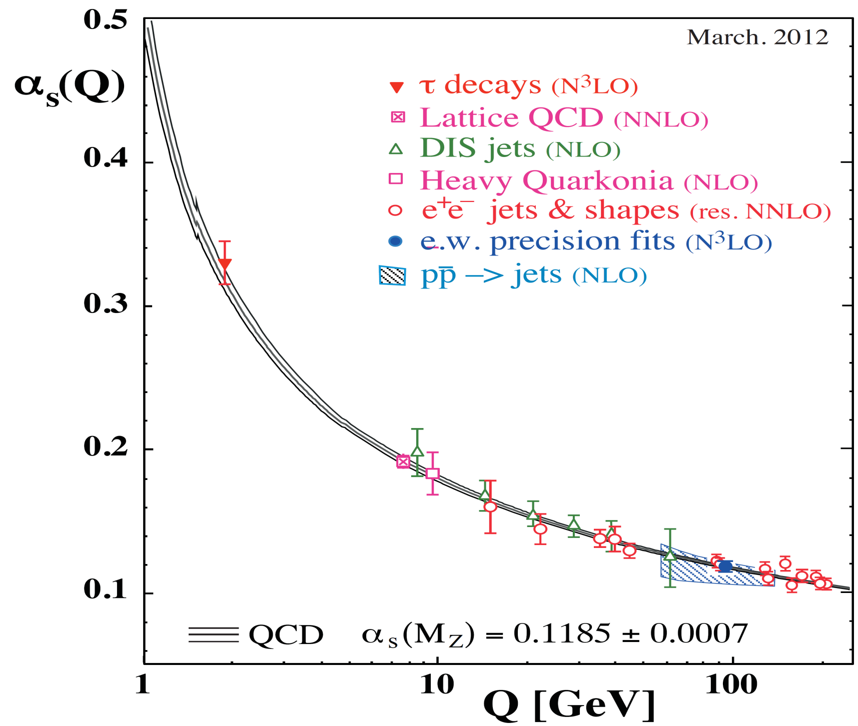

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$$\alpha_s(M_Z) = 0.1185 \pm 0.0007$$

$$\Lambda_{\overline{MS}}^{(5)} = (214 \pm 9)\ \text{MeV}$$
$$\Lambda_{\overline{MS}}^{(4)} = (297 \pm 11)\ \text{MeV}$$

Parton Distribution Function

$$f_a(z, \mu_F)$$

PDF and DGLAP evolution equation

Renormalised parton density:

$$f_a(z, \mu_F) = \Gamma_{ab}\left(z, \mu_F, \frac{1}{\varepsilon_{\mathrm{IR}}}\right) \otimes \; f_a^B(z)$$

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Dakshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) Evolution equation:

$$\mu_F \frac{d}{d\mu_F} f_a(x, \mu_F) = \int_x^1 \frac{dz}{z} P_{ab}(z, \mu_F) f_b\left(\frac{x}{z}, \mu_F\right), \qquad P \equiv \Gamma^{-1}\left(\mu_F \frac{d}{d\mu_F}\right)\Gamma$$

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Perturbatively Calculable:

$$\begin{aligned} P_{ab}(z, \mu_F) \quad &= \quad \left(\frac{\alpha_s(\mu_F)}{4\pi}\right) P^{(0)}(z) && \text{one loop} \quad (LO) \\ &+ \left(\frac{\alpha_s(\mu_F)}{4\pi}\right)^2 P^{(1)}(z) && \text{two loop} \quad (NLO) \\ &+ \left(\frac{\alpha_s(\mu_F)}{4\pi}\right)^3 P^{(2)}(z) && \text{three loop} \quad (NNLO) \end{aligned}$$

NNLO is already known (summer $\mathbf{2004}$)

Scale Variation of Flux at the LHC

$$\Phi^I_{ab}(x, \mu_F) = \int_x^1 \frac{dz}{z} \; f^I_a(z, \mu_F) \; f^I_b\left(\frac{x}{z}, \mu_F\right) \qquad I = LO, NLO, NNLO$$

DGLAP evolution:

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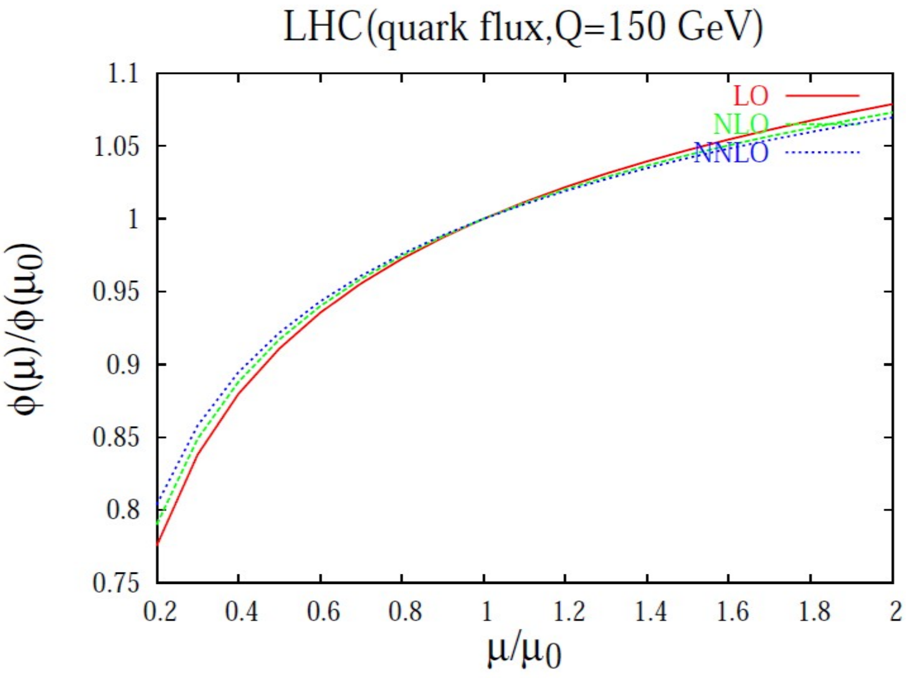
Scale Variation of Flux at the LHC

$$\Phi^I_{ab}(x,\mu_F) = \int_x^1 \frac{dz}{z} \; f_a^I(z,\mu_F) \; f_b^I\left(\frac{x}{z},\mu_F\right) \qquad I = LO, NLO, NNLO$$



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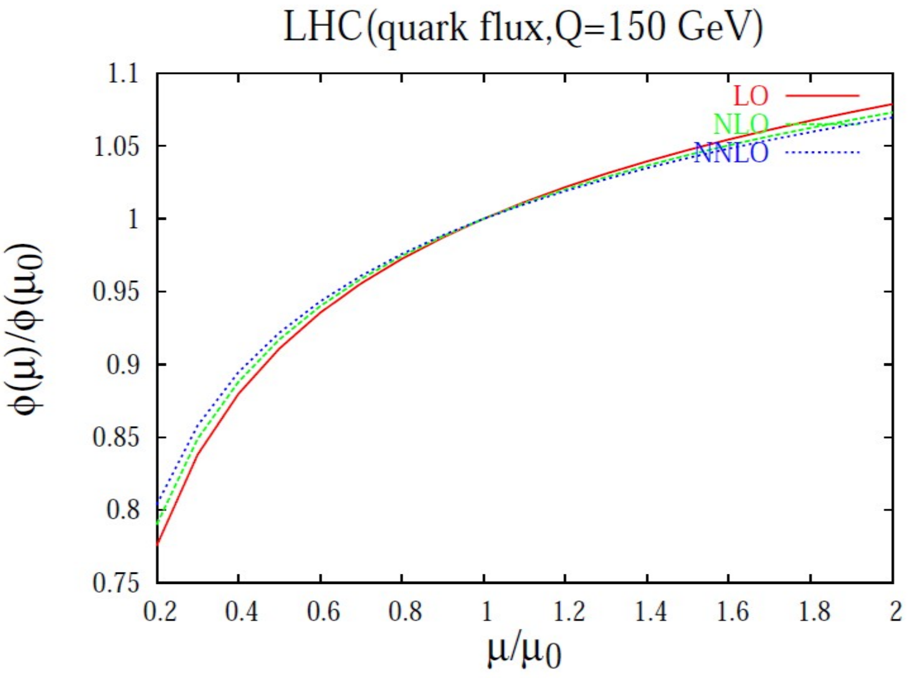

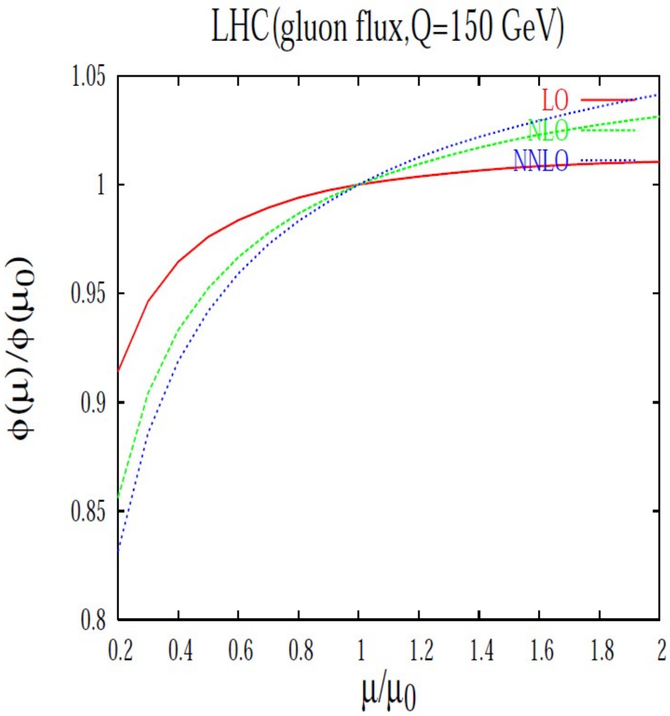

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PDF sets

Different Groups:

MSTW, CTEQ, ABKM, ABM, NNPD,HERAPDF, GJR, ...

PDF sets

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Exterimental inputs:

Deep Inelastic Scattering,
Drell-Yan,
Tevatron jets, Tevatron W,Z , ...

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PDF uncertainity:

Choice of data sets
Treatment of heavy quarks
Treatment of errors
Order of perturbation theory
Parametrisation of densities
Flavour symmetries
Asymptotic behavious of pdfs

PDF sets

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	MSTW08	CTEQ6.6[X]	NNPDF2.0	HERAPDF1.0	ABKM09	GJR08
HERA DIS	✓	✓	✓*	✓*	✓	✓
F-T DIS	✓	✓	✓	✗	✓	✓
F-T DY	✓	✓	✓	✗	✓	✓
TEV W,Z	✓	✓+	✓	✗	✗	✗
TEV jets	✓	✓+	✓	✗	✗	✓
GM-VFNS	✓	✓	✗	✓	✗	✗
NNLO	✓	✗	✗	✗	✓	✓

LHC-testing ground

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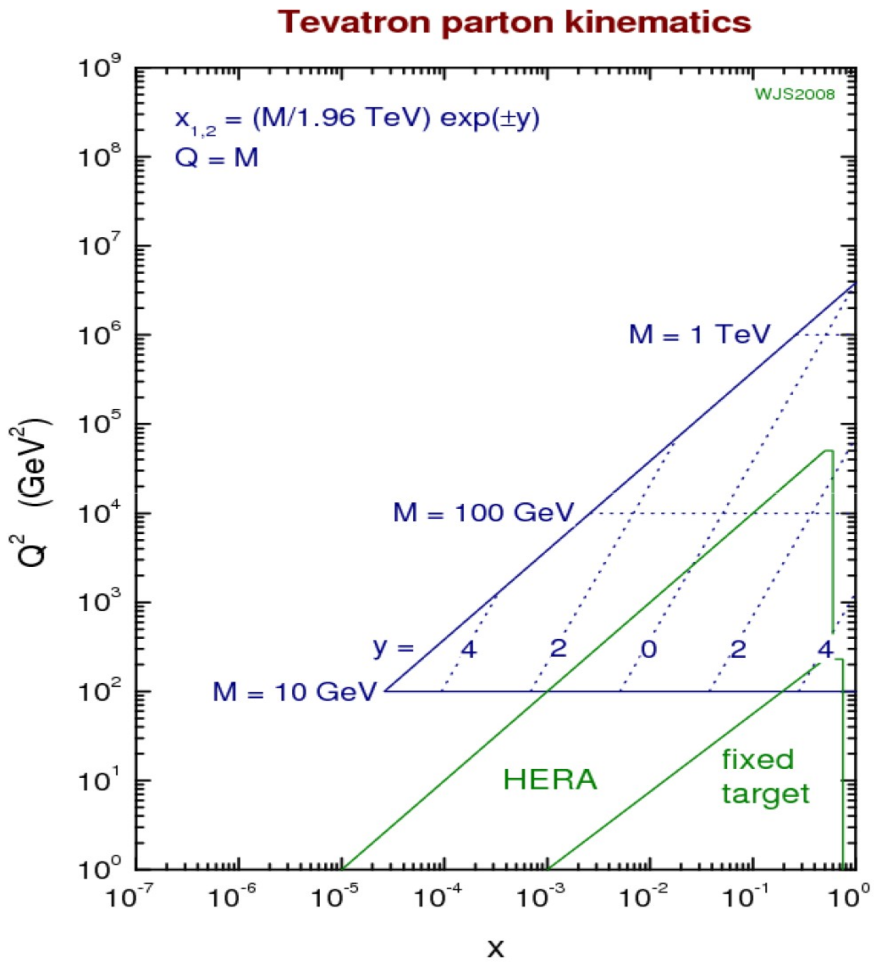

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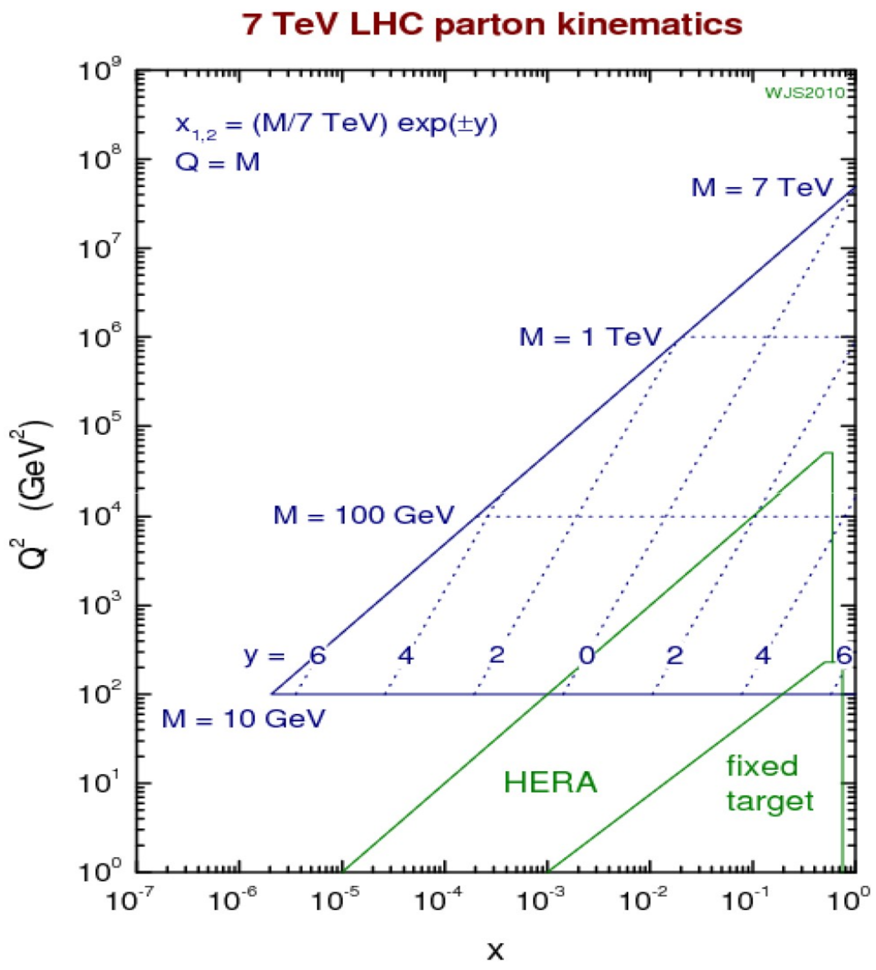
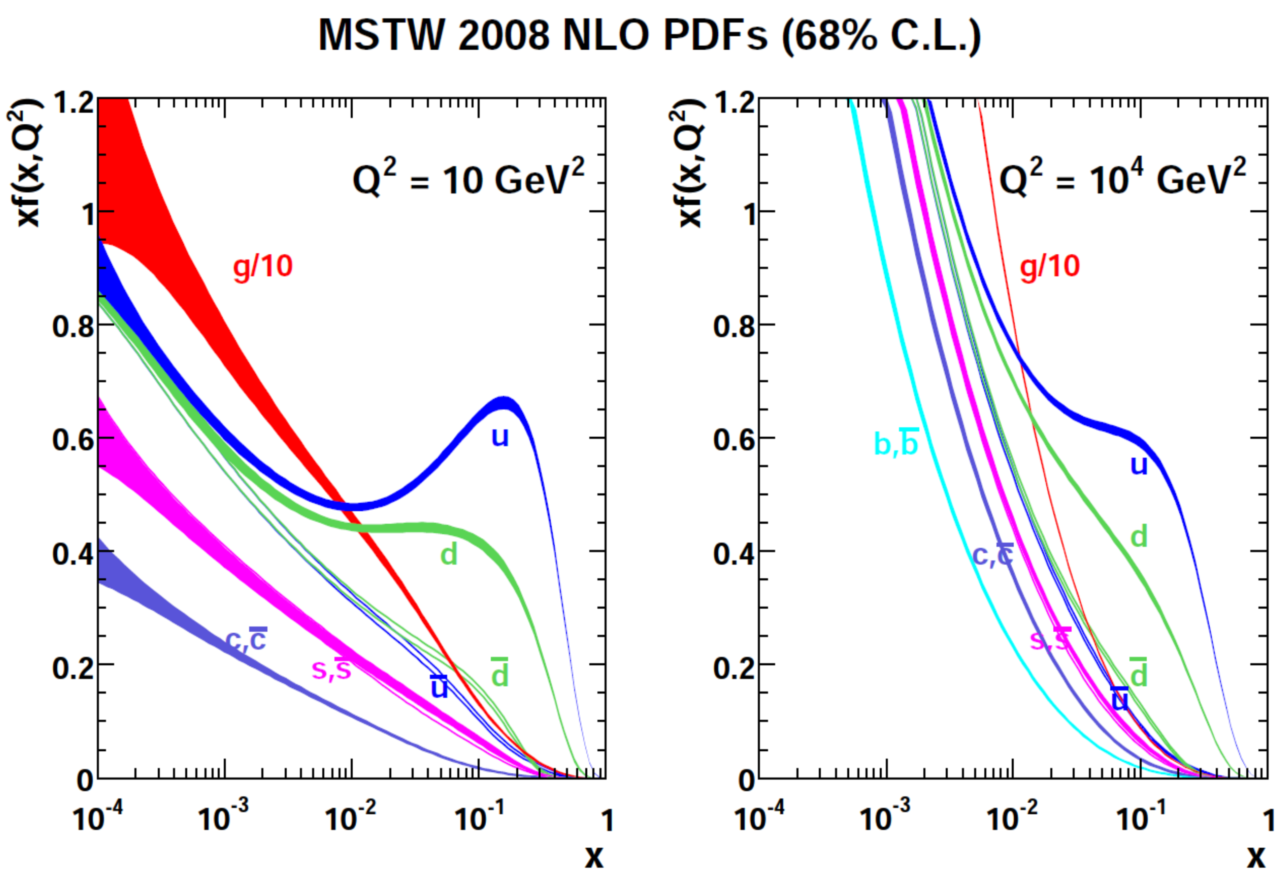


Uncertainty from Parton Distribution Functions



MSTW 2008 NLO PDFs at $Q^2 = 10$ GeV^2 and $Q^2 = 10^4$ GeV^2.

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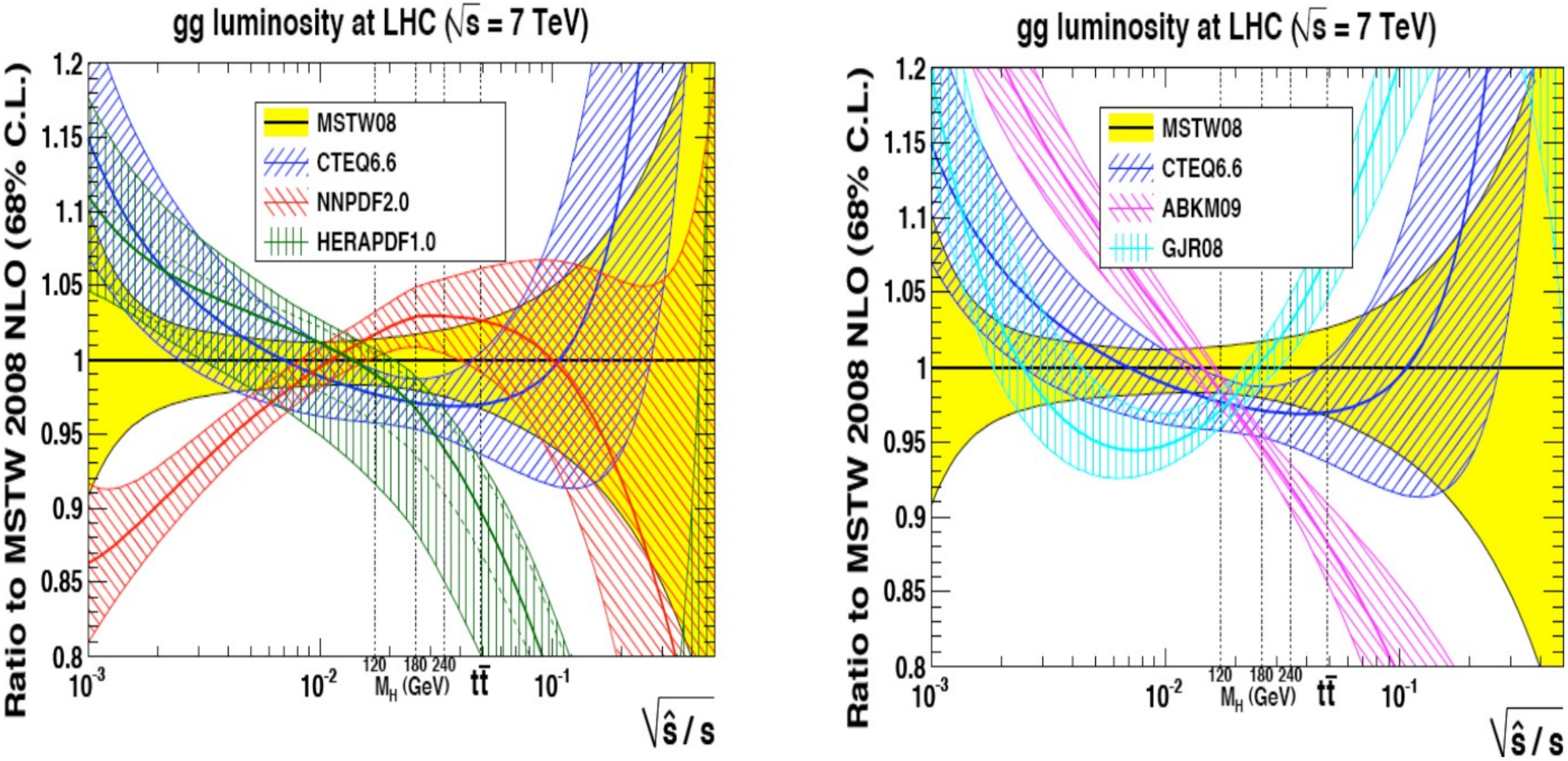
Gluon Luminosity



- Data sets: Electroproduction, hadron production (fixed target and collider)
- Fits procedure: Hessian and Monte Carlo
- Treatment: α_s, m_b and m_c

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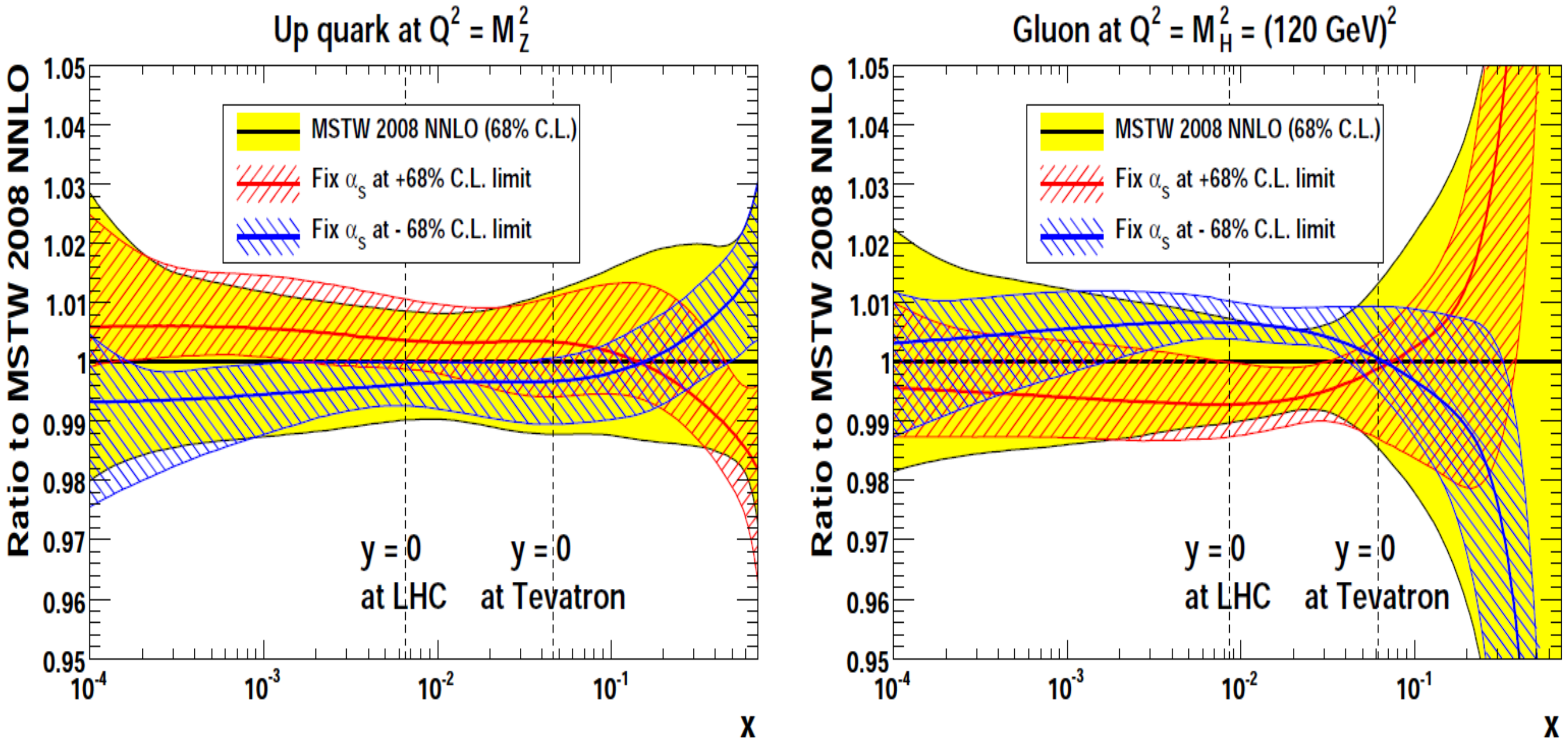
PDF Uncertainty



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Gluon PDF

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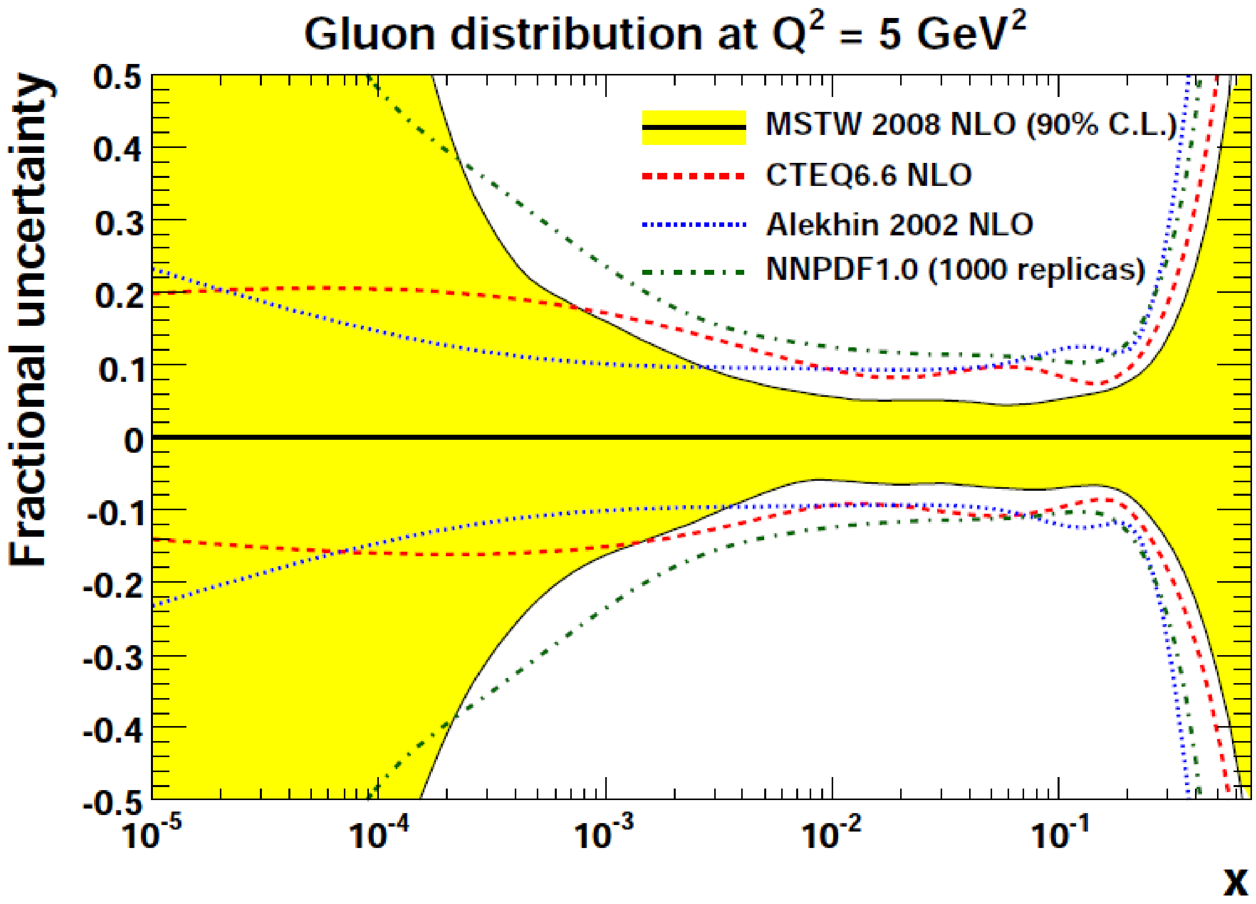

A comparison of the fractional uncertainty for the present MSTW, CTEQ6.6 , Alekhin and NNPDF1.0 NLO gluon distributions at $Q^2 = 5$ GeV^2. All uncertainty bands represent a 90% C.L. limit.

PDF and Higgs cross section

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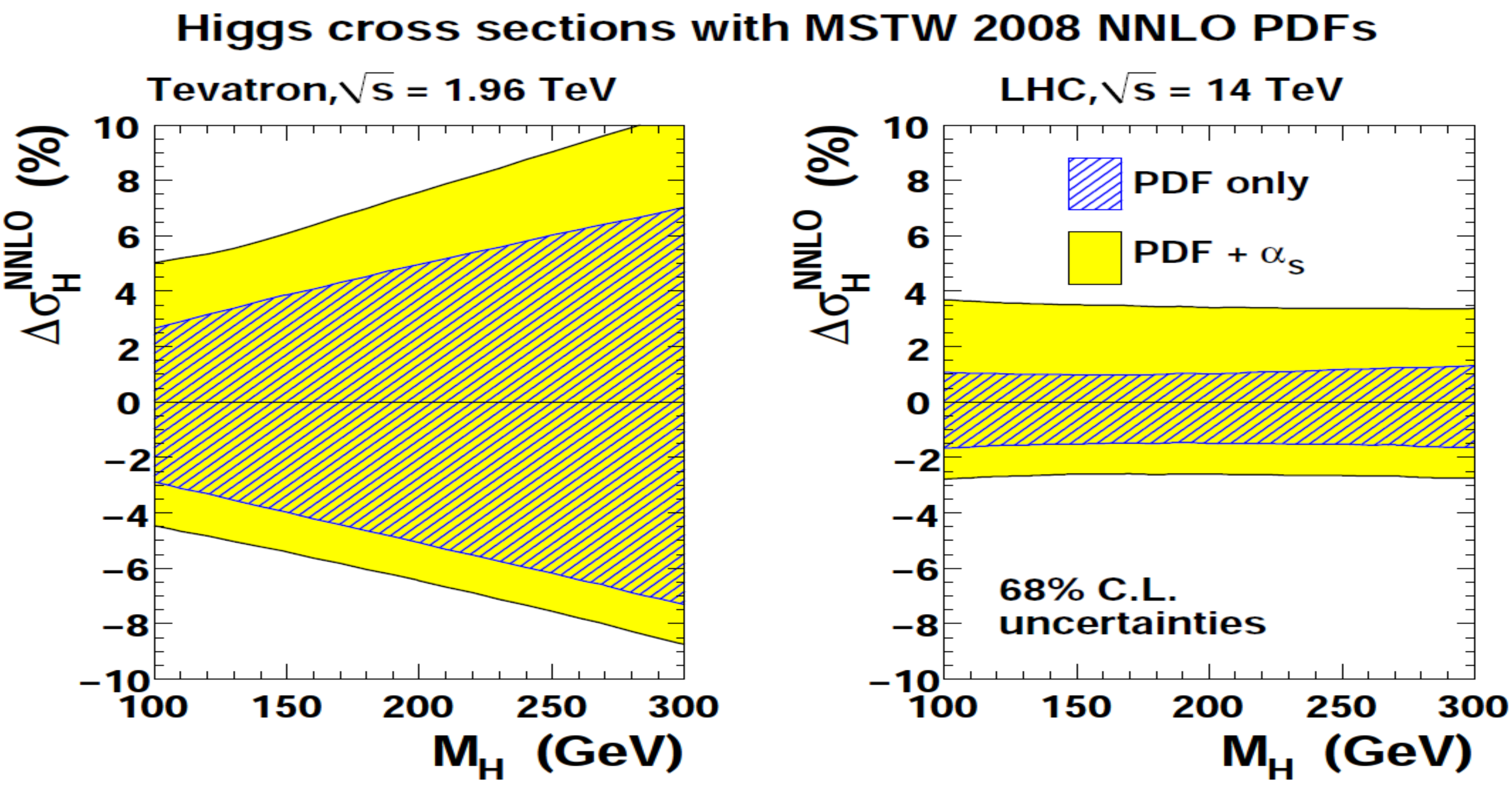

PDF and α_s

- For consistent prediction, PDFs along with appropriate α_s have to be used.
- MSTW does global fits for both PDFs and α_s using DIS data and other hadronic data.
- Also it uses LO, NLO and NNLO corrected cross sections computed in $\overline{MS}$ scheme.

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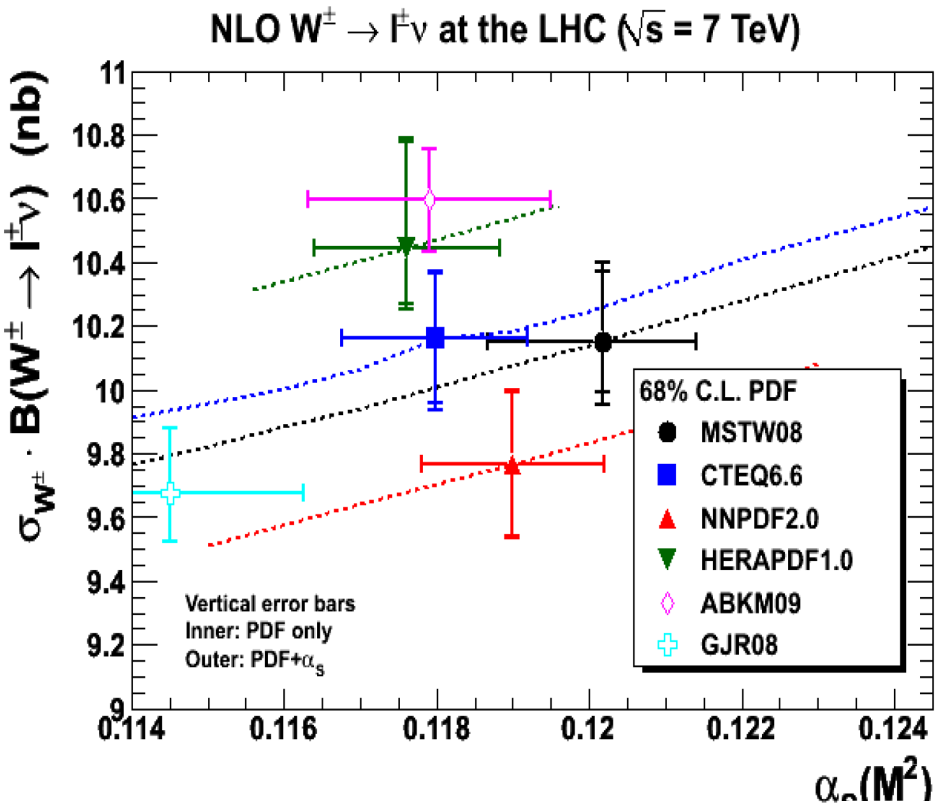
Such a fit gives:

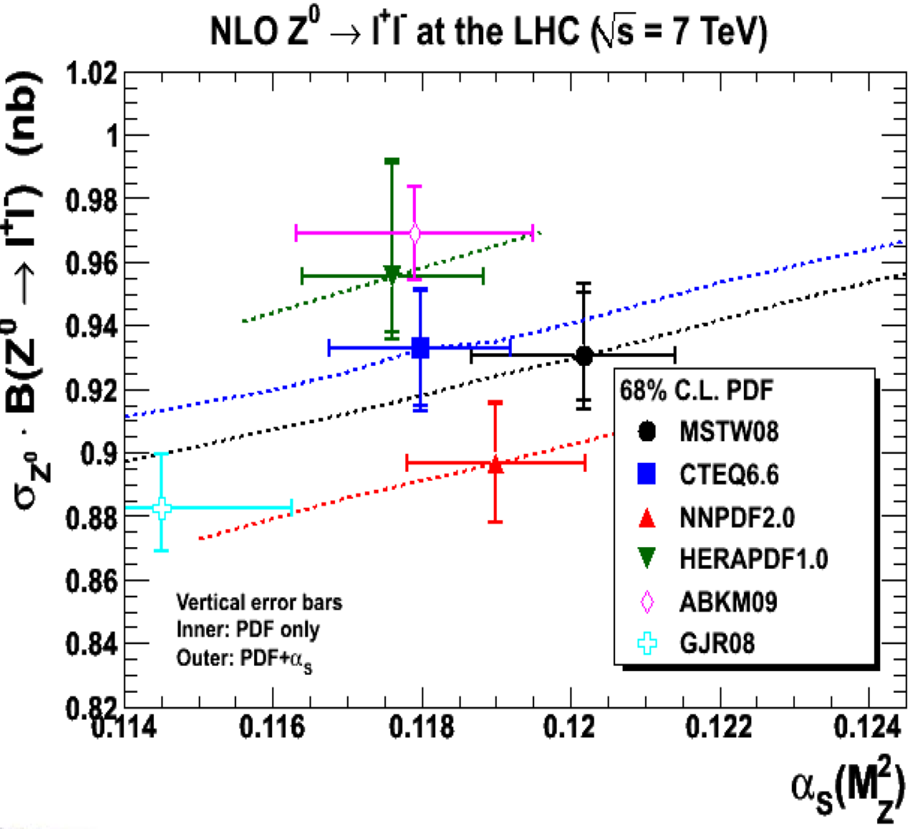
$$NLO : \alpha_s(M_Z^2) \quad = \quad 0.1202^{+0.0012}_{-0.0015}(68\%C.L)^{+0032}_{-0038}(90\%C.L.)$$

$$NLO : \alpha_s(M_Z^2) \quad = \quad 0.1171^{+0.0014}_{-0.0014}(68\%C.L)^{+0034}_{-0034}(90\%C.L.)$$

NNLO	$\alpha_S(M_Z^2)$ (expt. unc. only)
MSTW	$\mathbf{0.1171}$ $^{+0.0014}_{-0.0014}$
AMP	$\mathbf{0.1128}$ $\pm\, 0.0015$
BBG	$\mathbf{0.1134}$ $^{+0.0019}_{-0.0021}$
ABKM	$\mathbf{0.1129}$ $\pm\, 0.0014$
JR	$\mathbf{0.1158}$ $\pm\, 0.0035$

Benchmark cross sections for W and Z





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Benchmark cross sections for Higgs and Top

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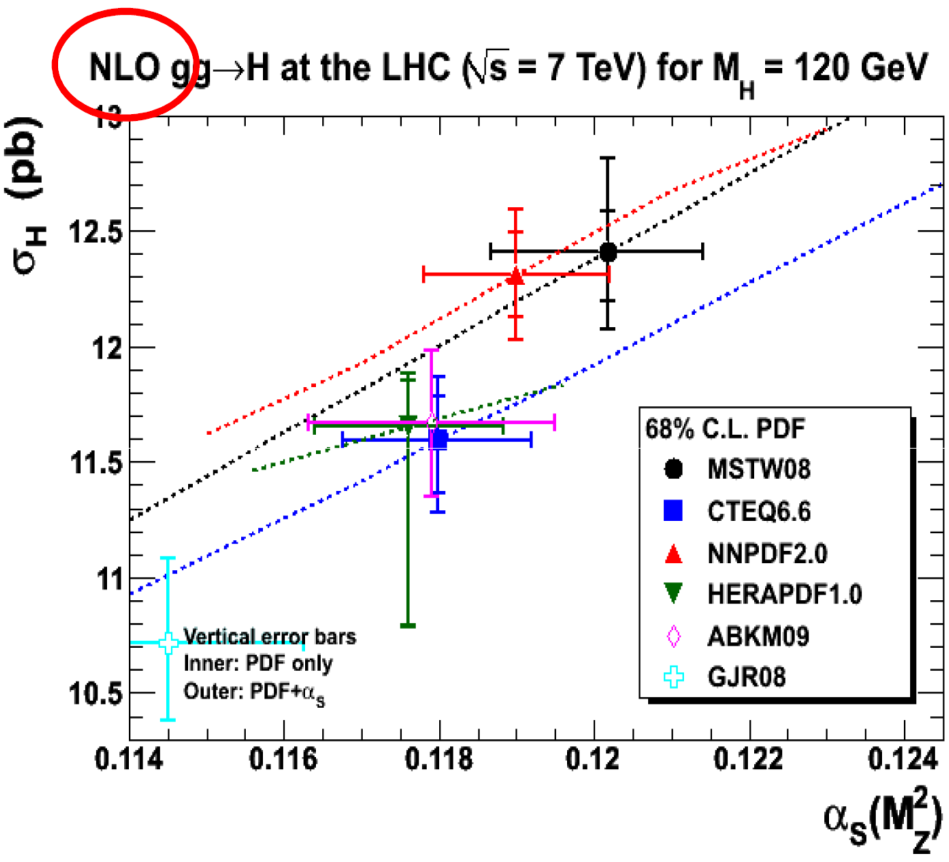
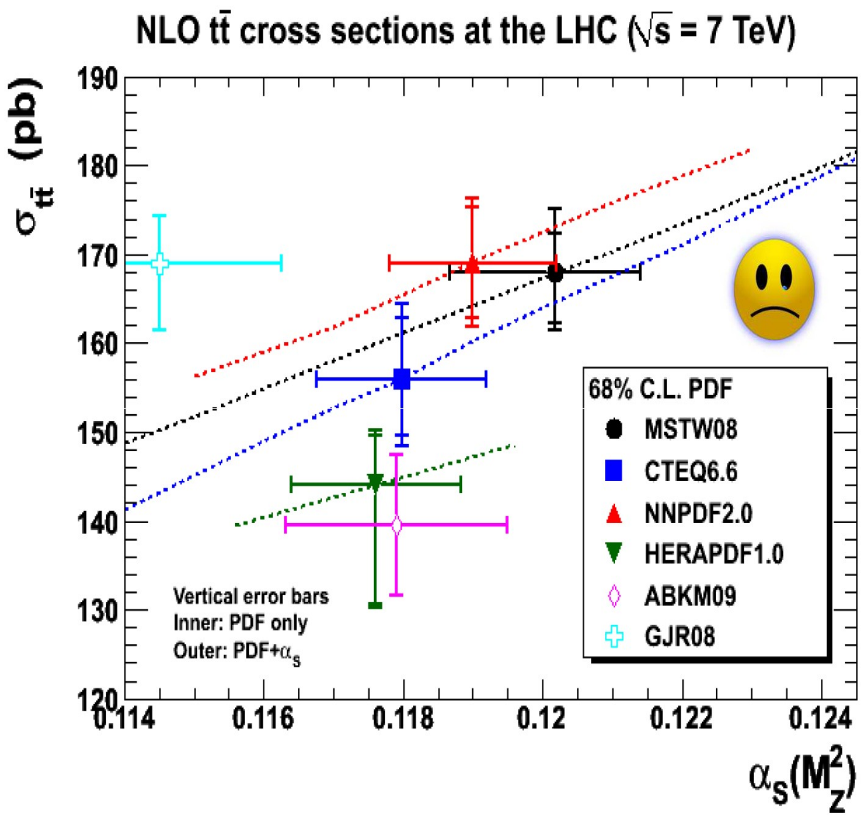
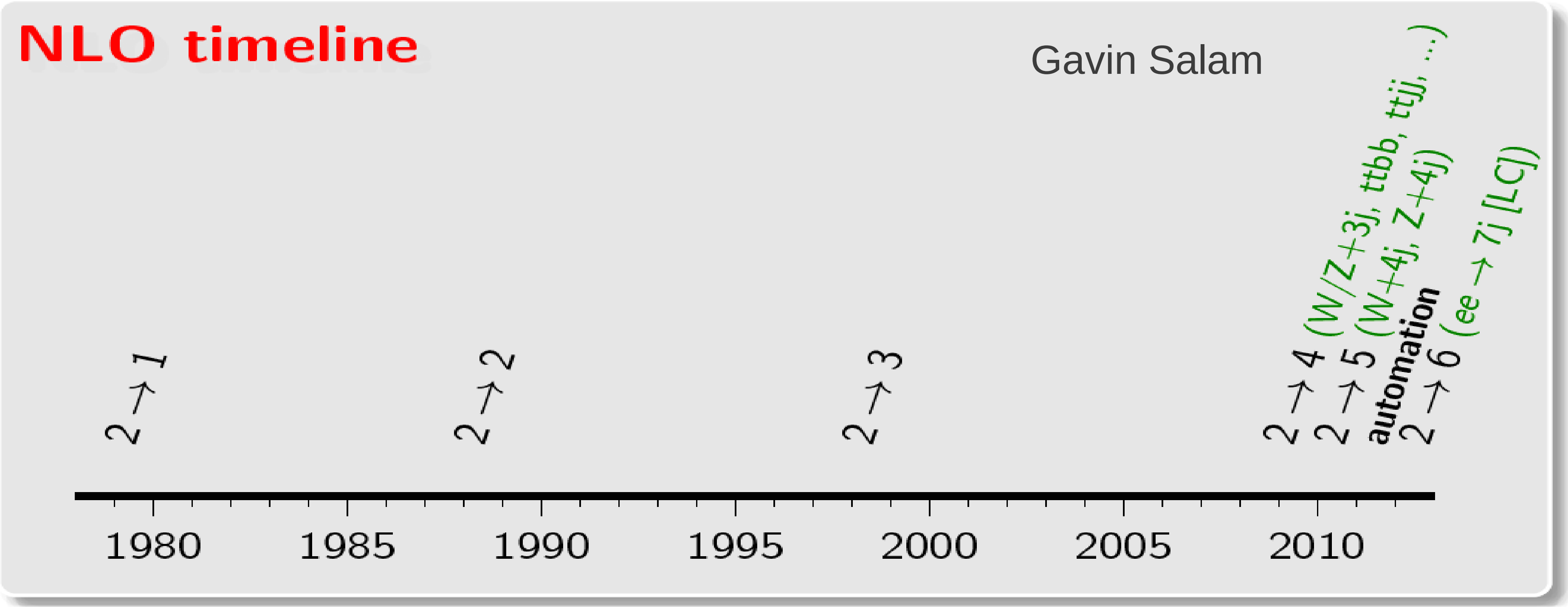




NLO

NLO revolution

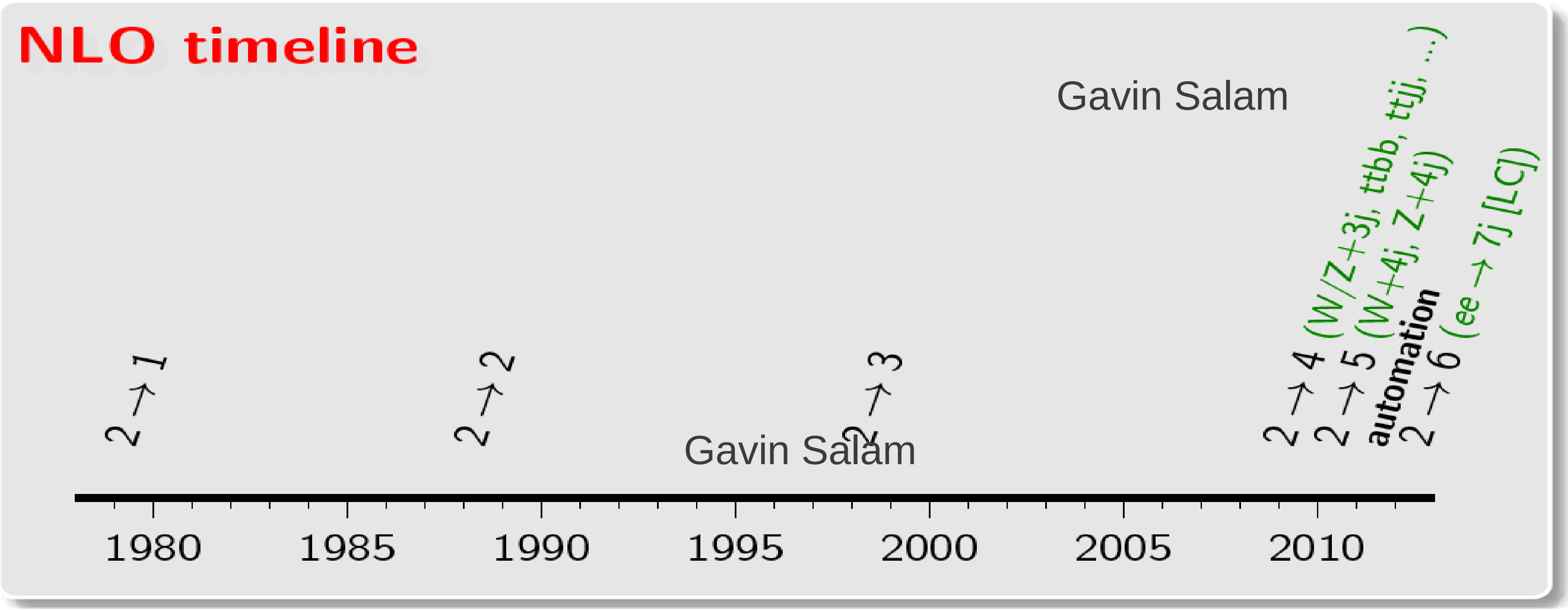


1979: NLO Drell-Yan [Altarelli, Ellis & Martinelli]
1991: NLO $gg \to$ Higgs [Dawson; Djouadi, Spira & Zerwas]

1987: NLO high-p_t photoproduction [Aurenche et al]
1988: NLO $b\bar{b}$, $t\bar{t}$ [Nason et al]
1988: NLO dijets [Aversa et al]
1993: Vj [JETRAD, Giele, Glover & Kosower]

1998: NLO $Wb\bar{b}$ [MCFM: Ellis & Veseli]
2000: NLO $Zb\bar{b}$ [MCFM: Campbell & Ellis]
2001: NLO $3j$ [NLOJet++: Nagy]
...
2007: NLO $t\bar{t}j$ [Dittmaier, Uwer & Weinzierl '07]
...

NLO revolution



2009: NLO $W+3j$ [Rocket: Ellis, Melnikov & Zanderighi]
2009: NLO $W+3j$ [BlackHat+Sherpa: Berger et al]
2009: NLO $t\bar{t}b\bar{b}$ [Bredenstein et al]
2009: NLO $t\bar{t}b\bar{b}$ [HELAC-NLO: Bevilacqua et al]
2009: NLO $q\bar{q} \to b\bar{b}b\bar{b}$ [Golem: Binoth et al]
2010: NLO $t\bar{t}jj$ [HELAC-NLO: Bevilacqua et al]
2010: NLO $Z+3j$ [BlackHat+Sherpa: Berger et al]
...

Advances at NLO

Analytical Methods

- Faster way of generating Feynman diagrams:

  QGRAF

- Sympolic manupulation:

  FORM, Mathematica

- On-shell methods
- Recursion techniques

Merging NLO with Parton Showers:

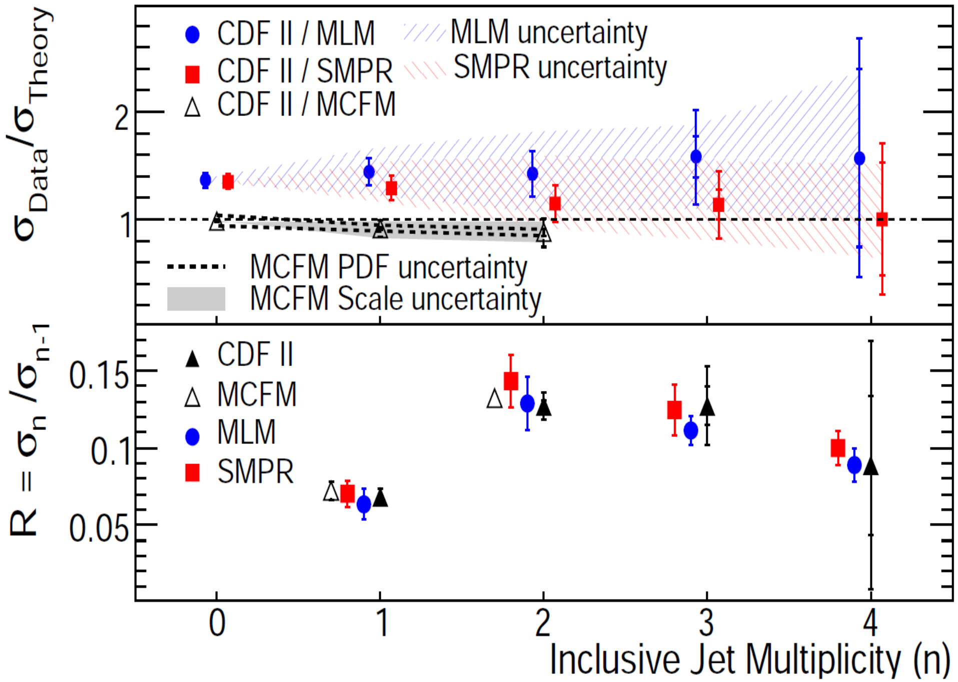
- MC@NLO
- POWEG
- SHERPA
- VINCIA
- GENeVa
- aMC@NLO
- KRKMC

Semi-numerical methods

- Helac-NLO
- CutTools
- BlackHat
- Rocket
- SAMURAI
- MadLoop
- GoSam
- Ngluon

Role of NLO corrections

W + n-jet cross section



- SMPR: Madgraph, Pythia, Jetglu
- MLM: ALPGEN, Herwig, Jetglu
- MCFM: NLO QCD + showering

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W + n-jet cross section

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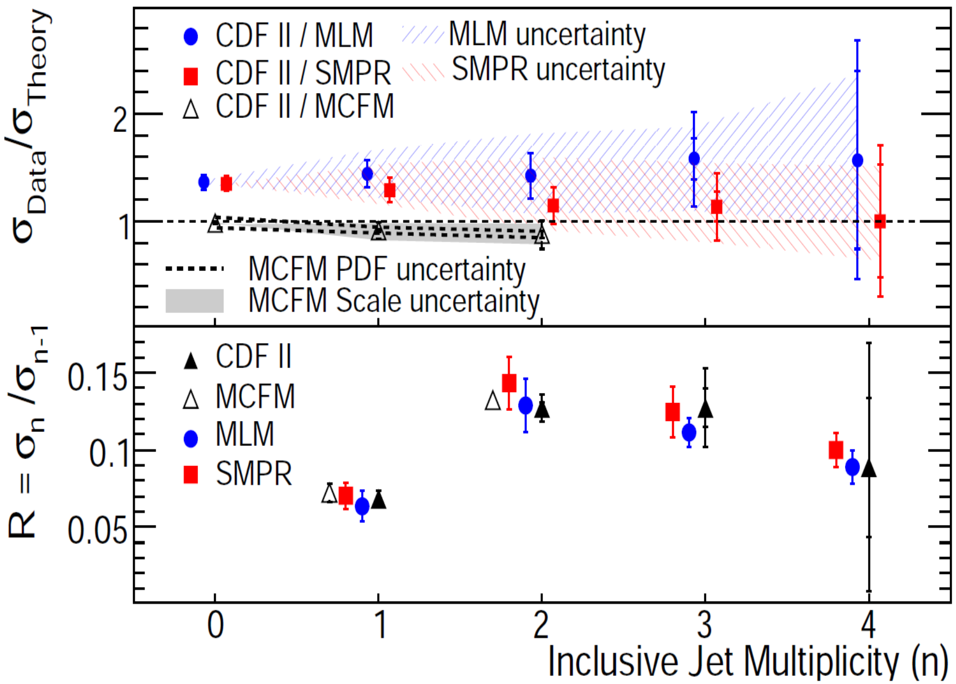
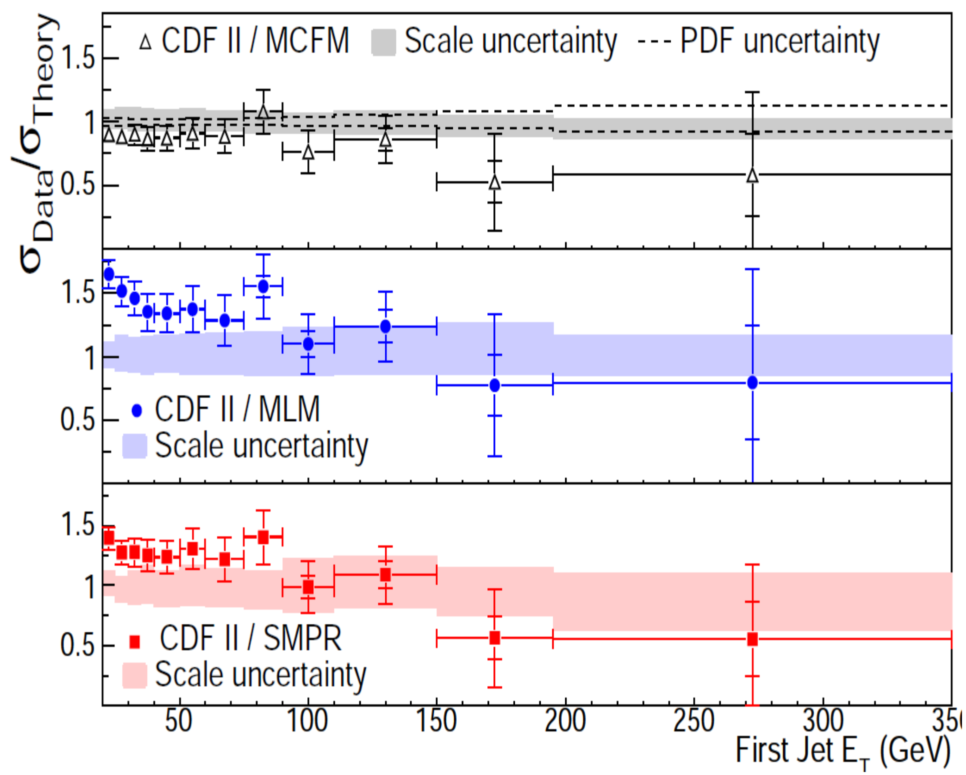
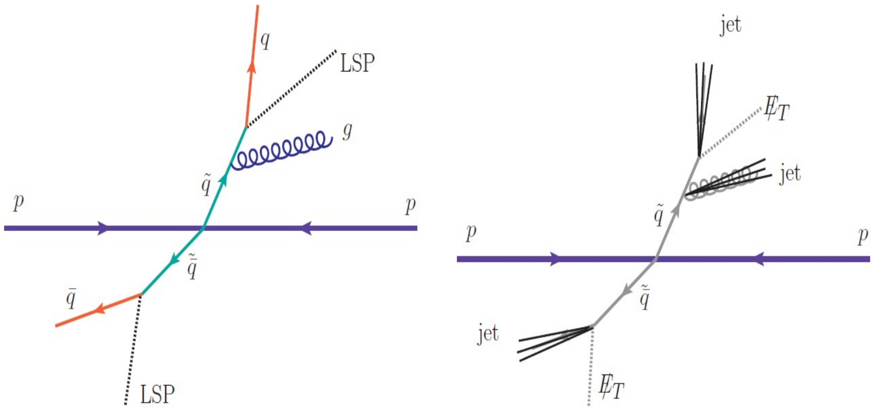




MCFM: NLO QCD works better

Z background to SUSY searches

- Susy searches require estimate on the Z background
- Hard to measure Z background
- Photon rates are 6 times larger easy to measure.
- Use theory to get the ratio $R_{Z/\gamma}$



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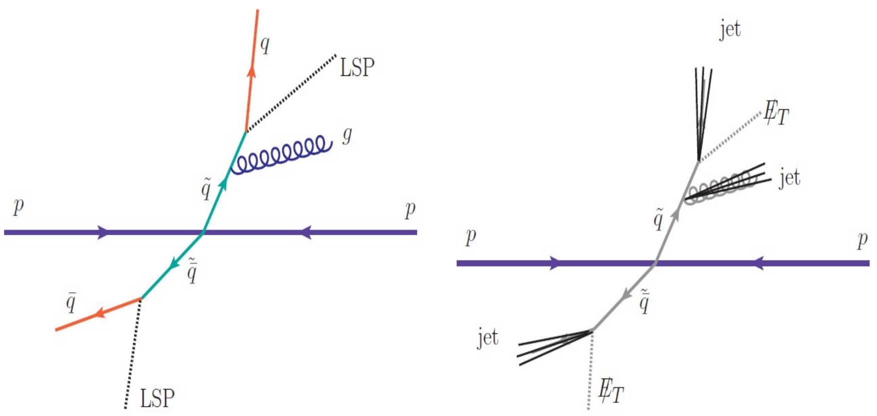

$$\sigma(pp \to Z(\to \nu\bar{\nu}) + \text{jets}) = \sigma(pp \to \gamma + \text{jets}) \times R_{Z/\gamma}$$

Background measured theory

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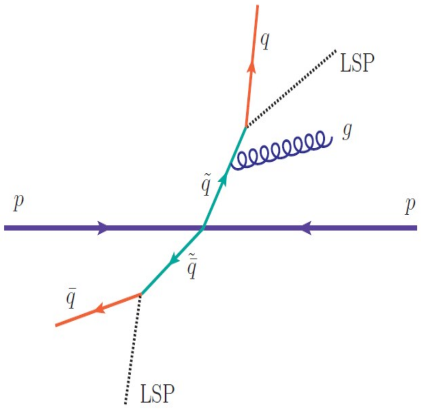
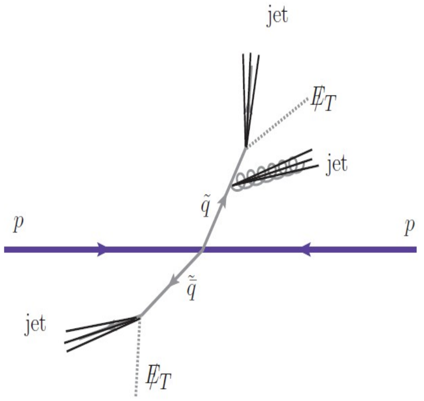
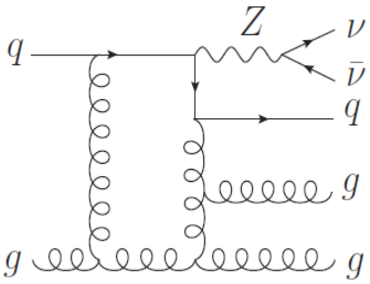
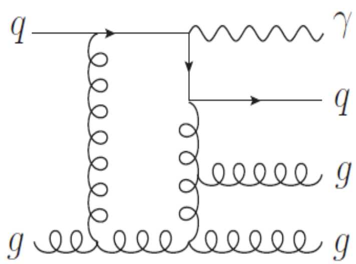




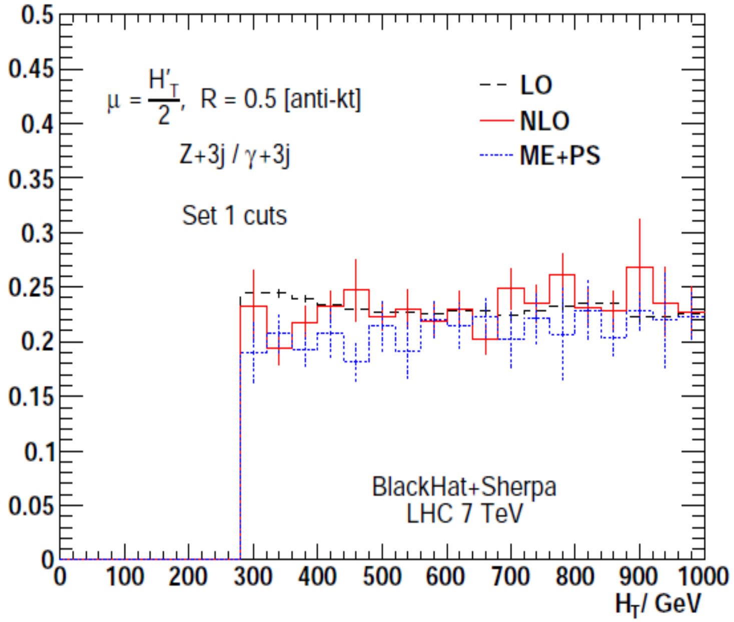
$$\sigma(pp \to Z(\to \nu\bar{\nu}) + \text{jets}) = \sigma(pp \to \gamma + \text{jets}) \times R_{Z/\gamma}$$





Background measured theory

Theory predictions

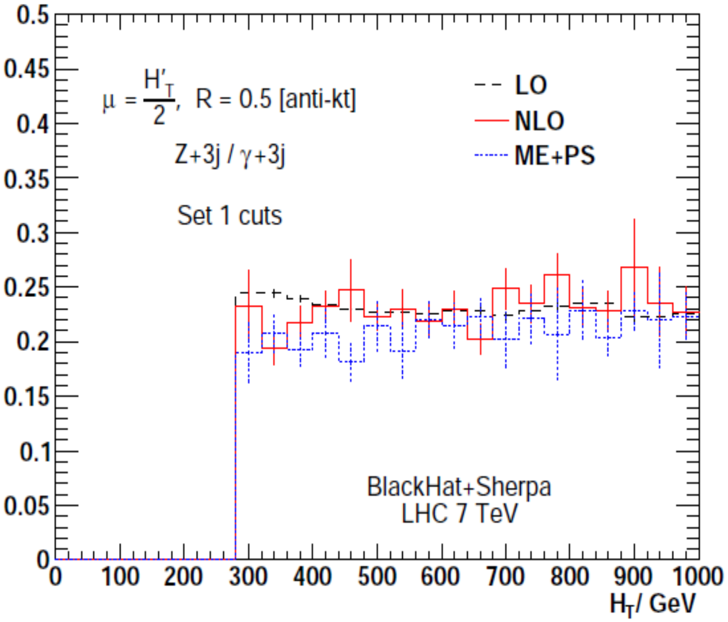


BlackHat

Virtual: On-shell and Unitarity cut techniques
Real : SHERPA

CMS and ALTAS use this
to estimate METZJ background
for SUSY searches

Theory predictions



BlackHat

Virtual: On-shell and Unitarity cut techniques
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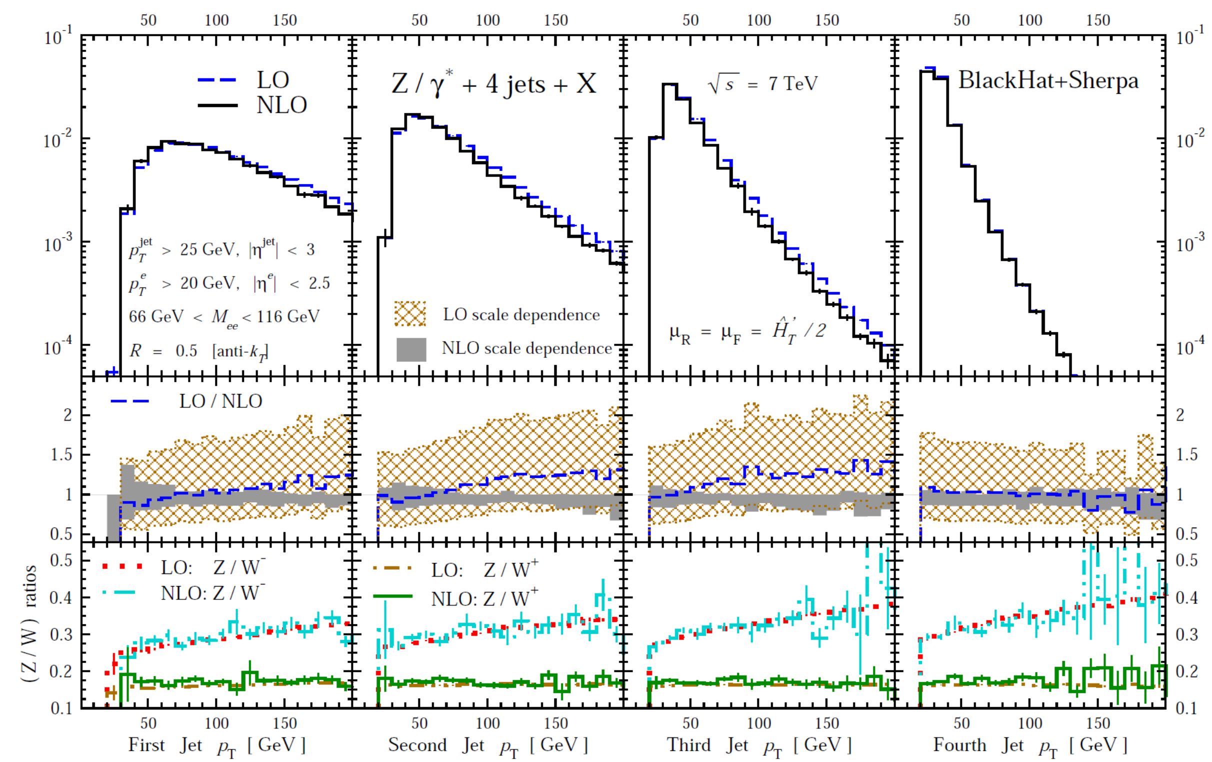
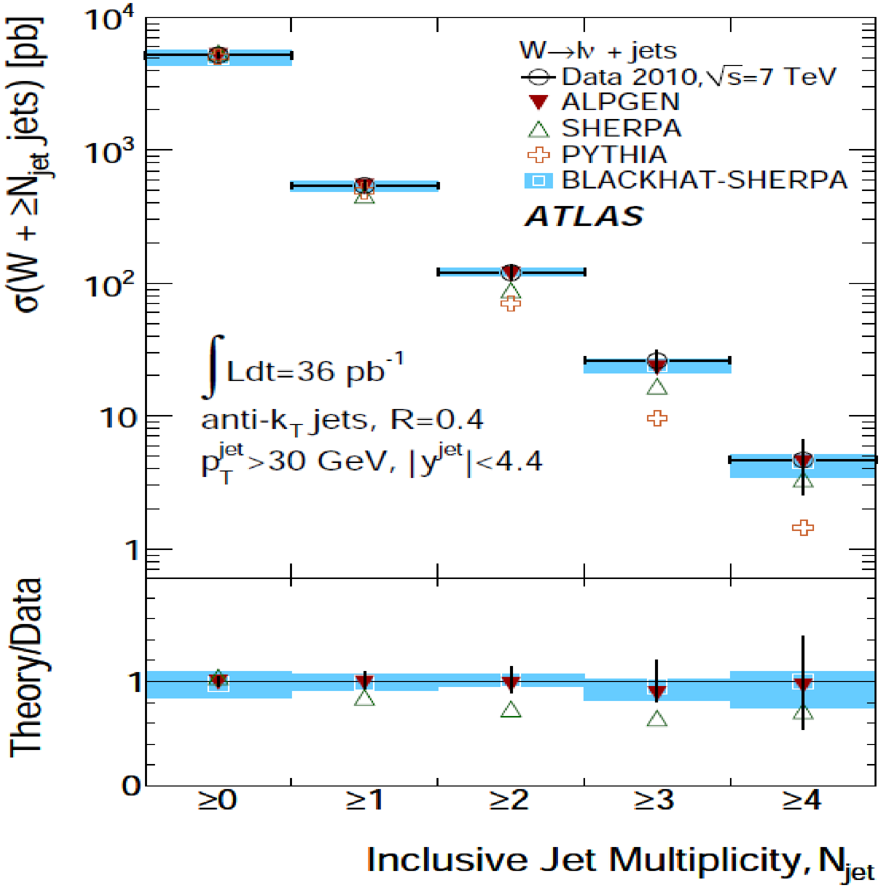


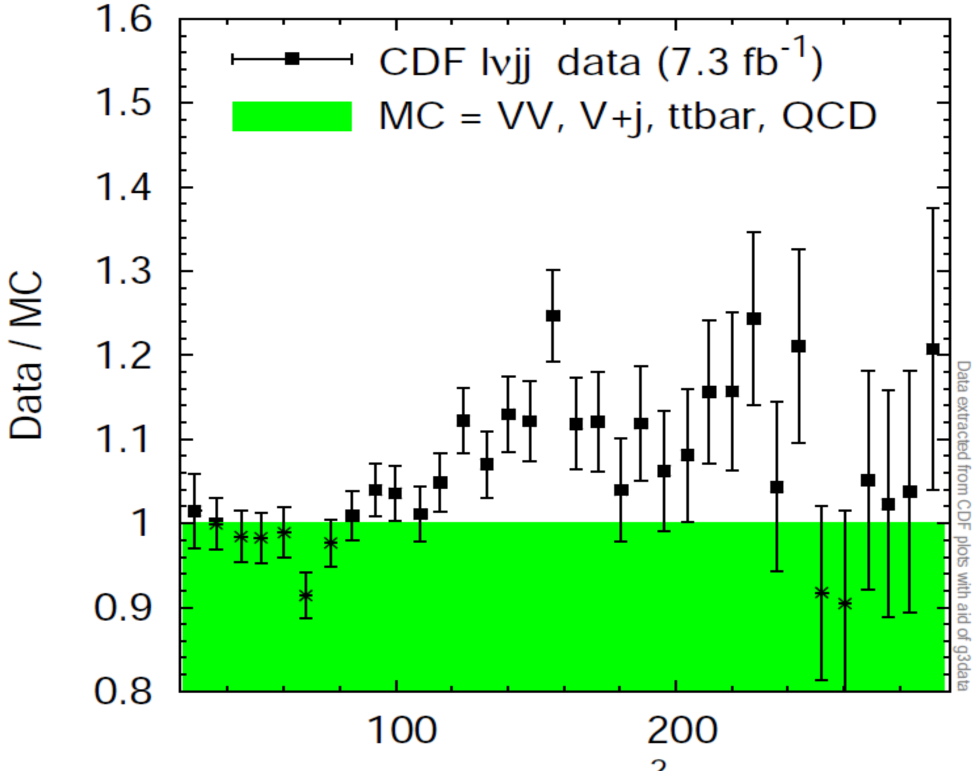
CMS and ALTAS use this
to estimate METZJ background
for SUSY searches

NLO predictions

- NLO tree level matrix elements beyond leading order
- Virtual corrections
- Parton showering
- Good agreement with data

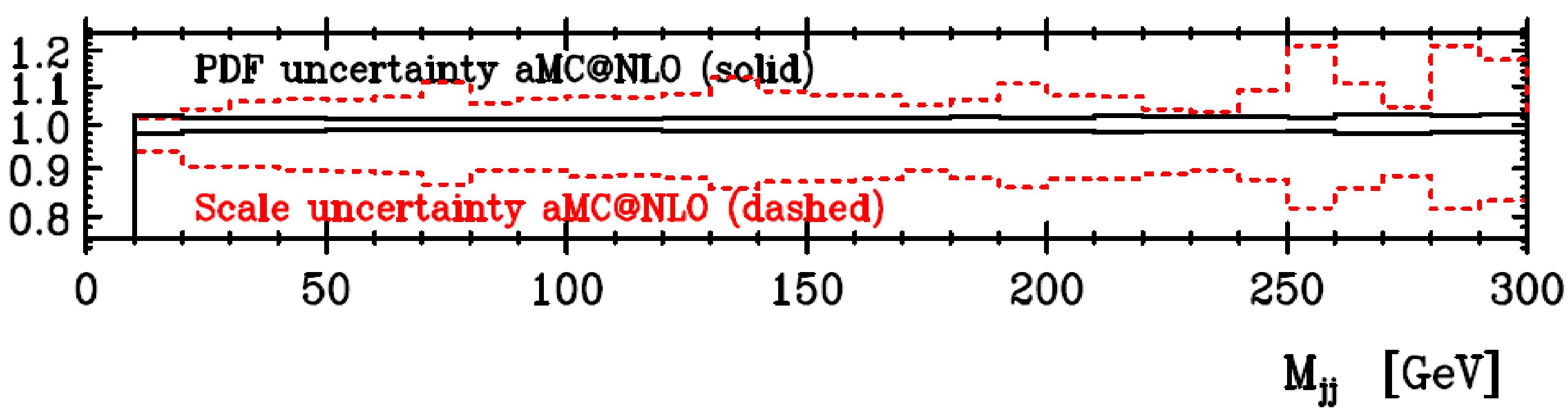


W+2 jet anomaly at CDF – NLO effect?



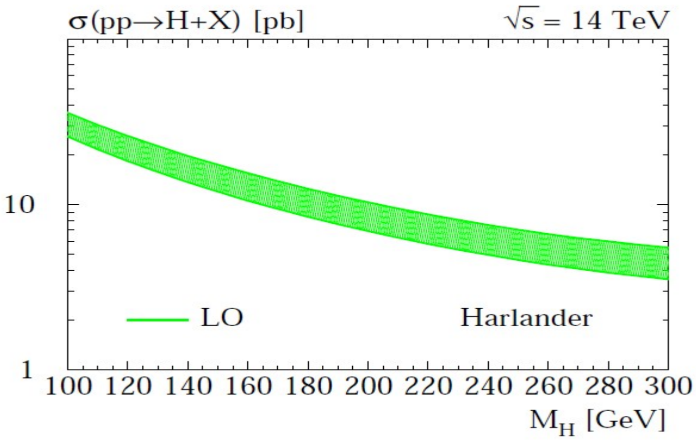
- CDF and D0 use ALPGEN and Parton showering for their analysis
- AMC@NLO Gives the similar prediction
- Theory uncertainty is comparable to Anomaly!

AMC@NLO

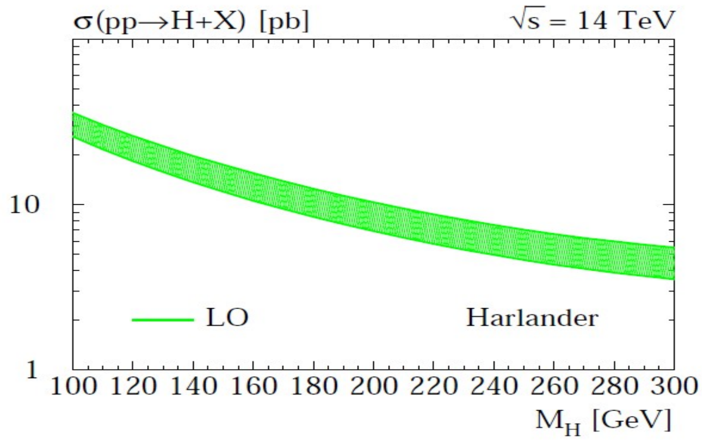


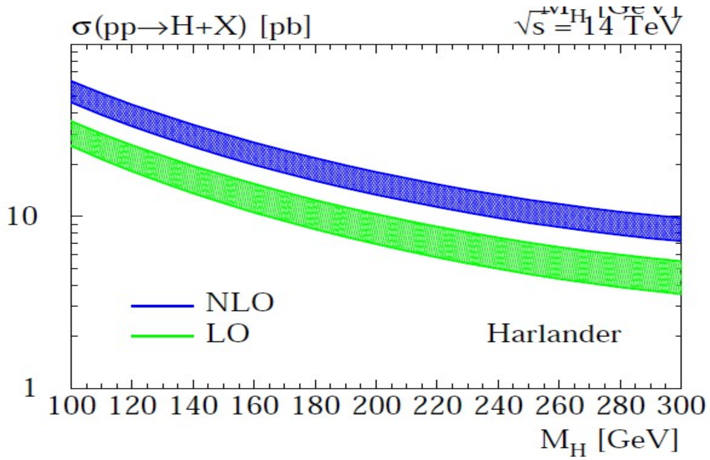
NNLO

Higgs cross section at NNLO

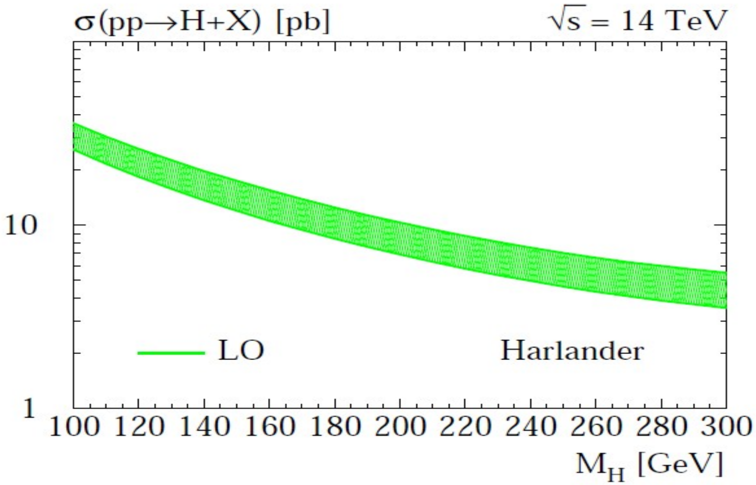


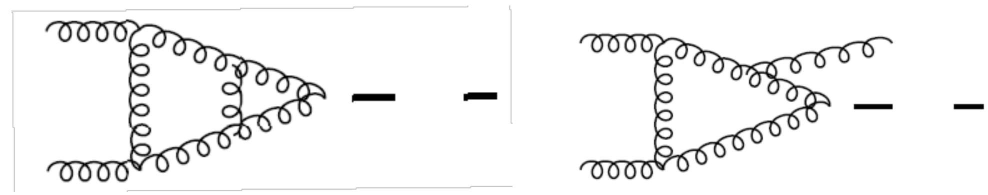
Higgs cross section at NNLO

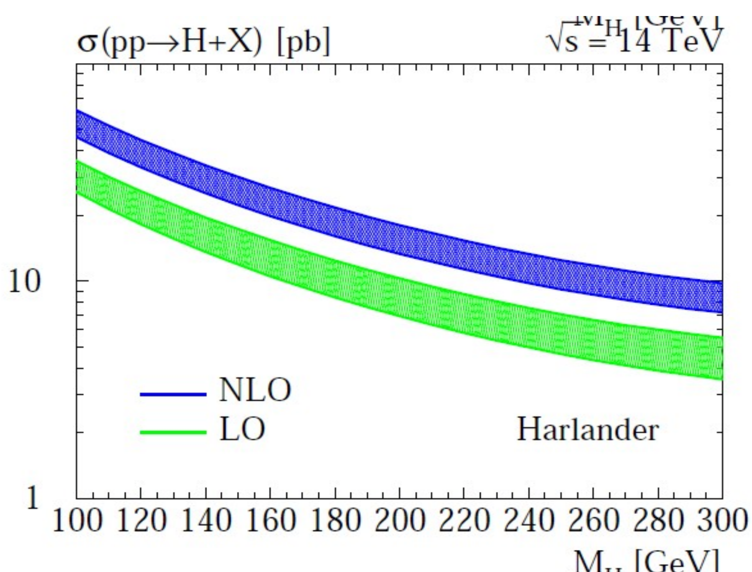


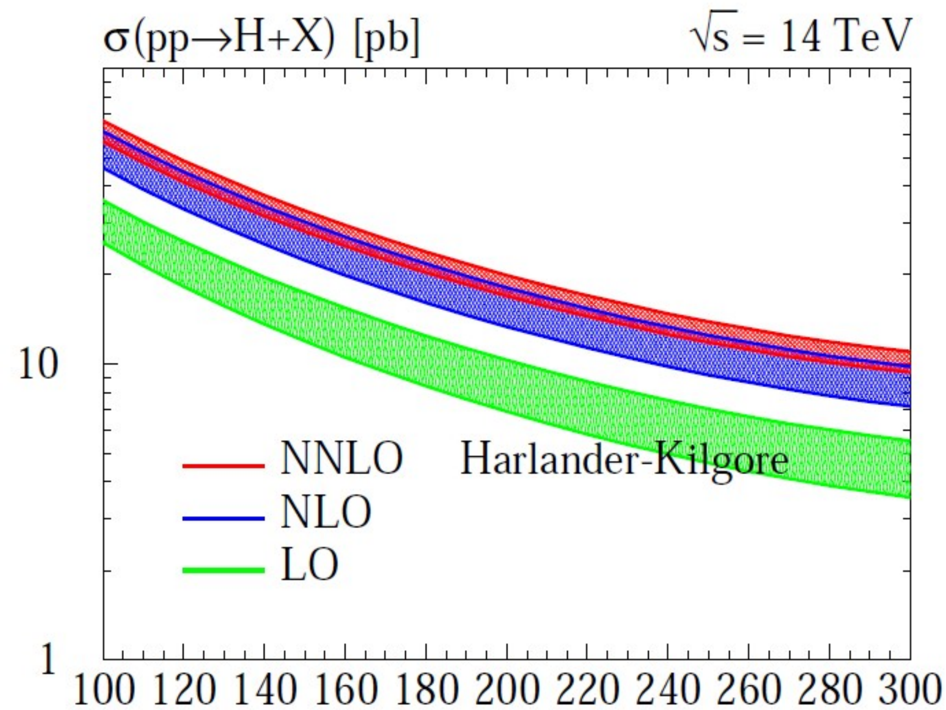


Higgs cross section at NNLO





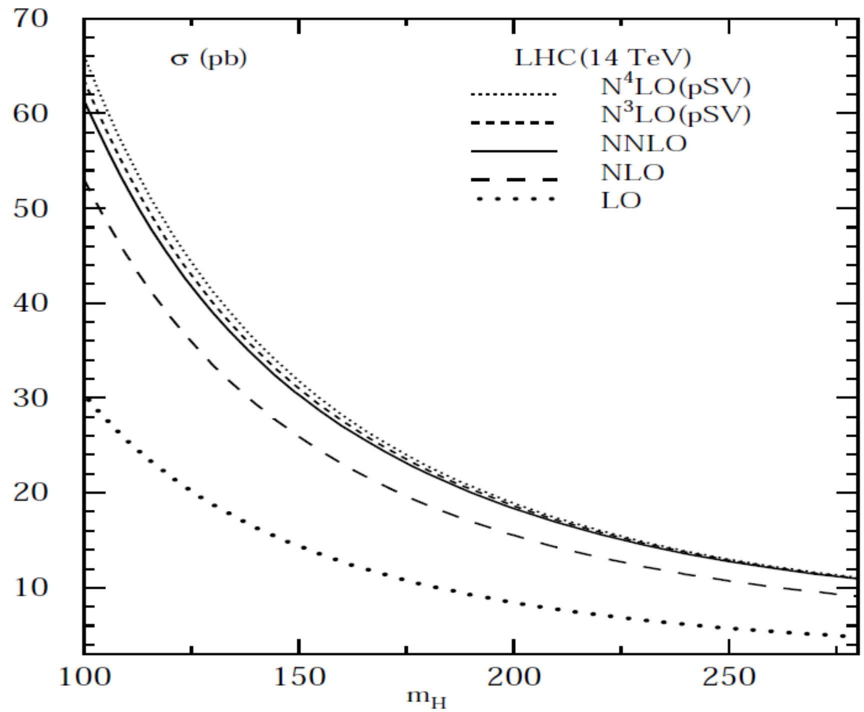


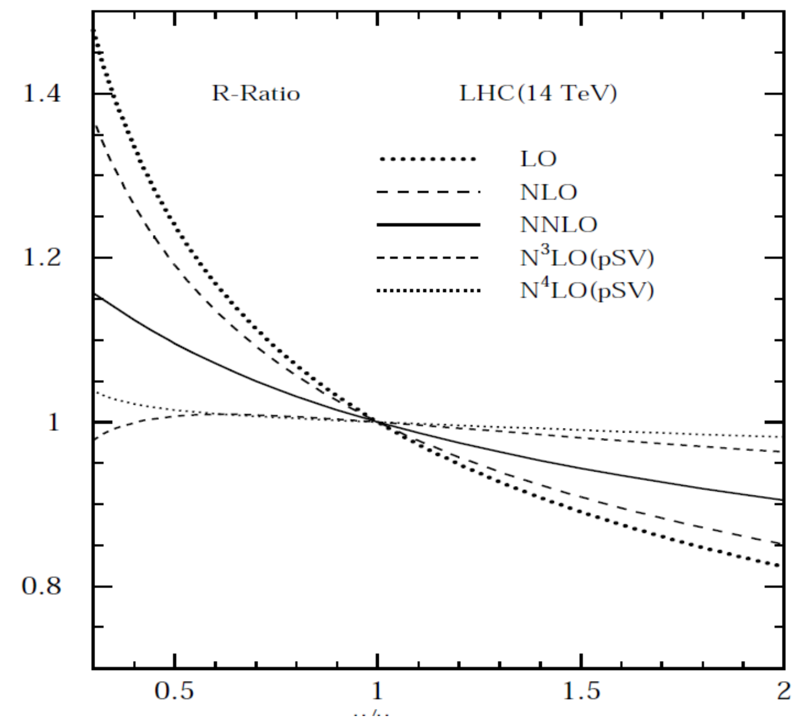


Harlander, Kilgore; Anastasiou, Melnikov; Van Neerven, Smith, VR

Higgs Cross section at NNNLO (approx.)

$$R = \frac{\sigma_{N^iLO}(\mu)}{\sigma_{N^iLO}(\mu_0)}$$

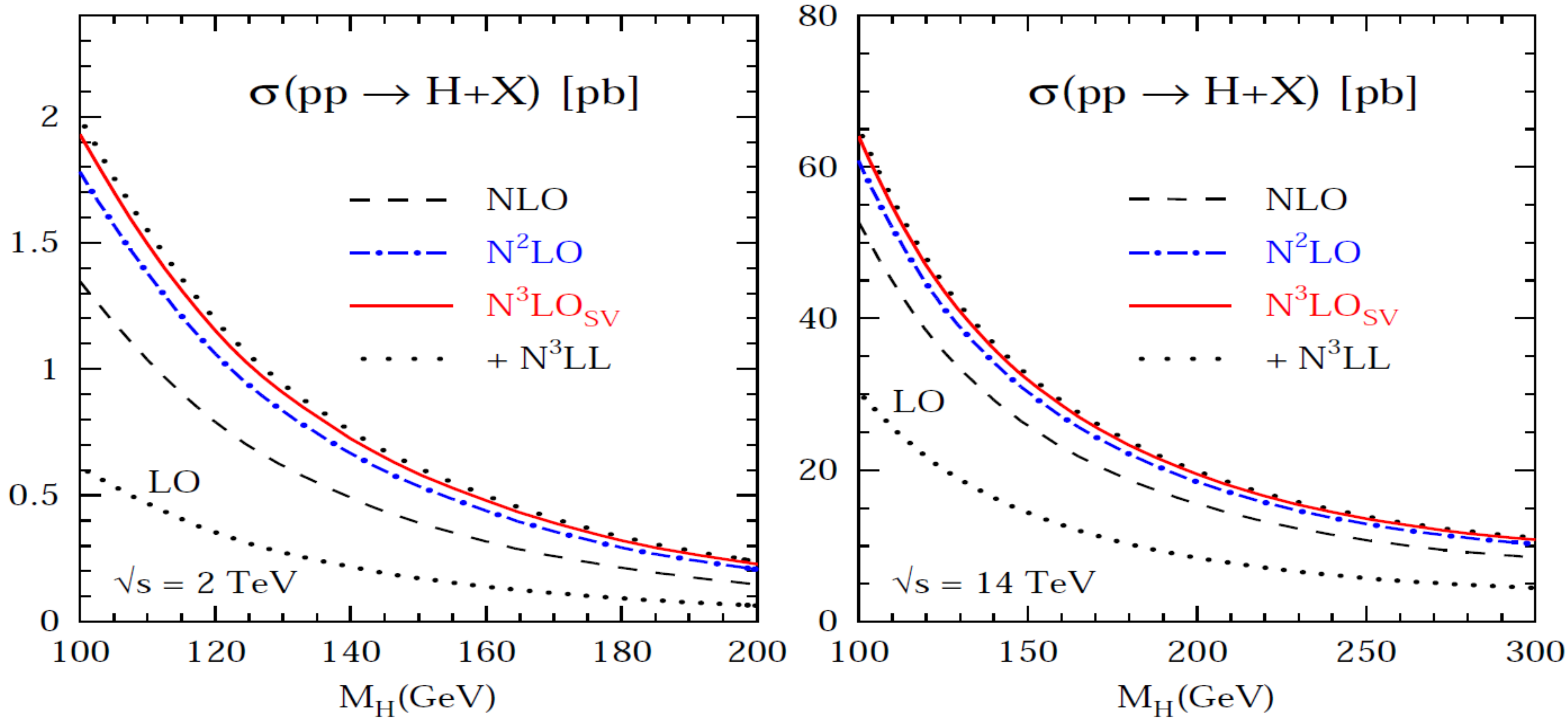




- Scale uncertainity improves a lot
- Additional $\mathbf{7-9\%}$ increase in cross section due to N^3LO soft gluons.

Resummed Higgs cross section

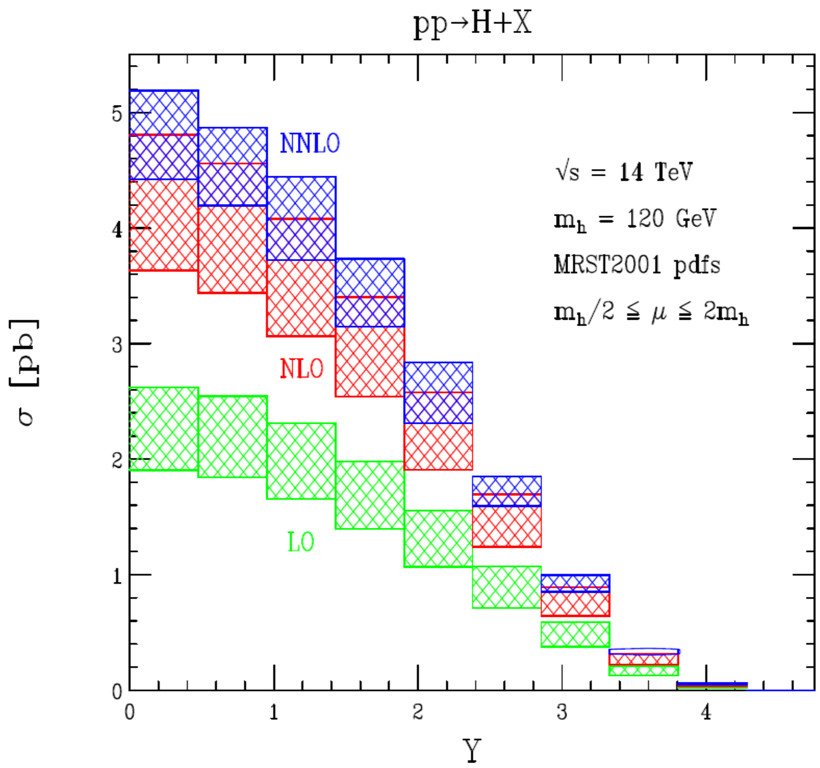
Catani and Grazzini; Vogt and Moch

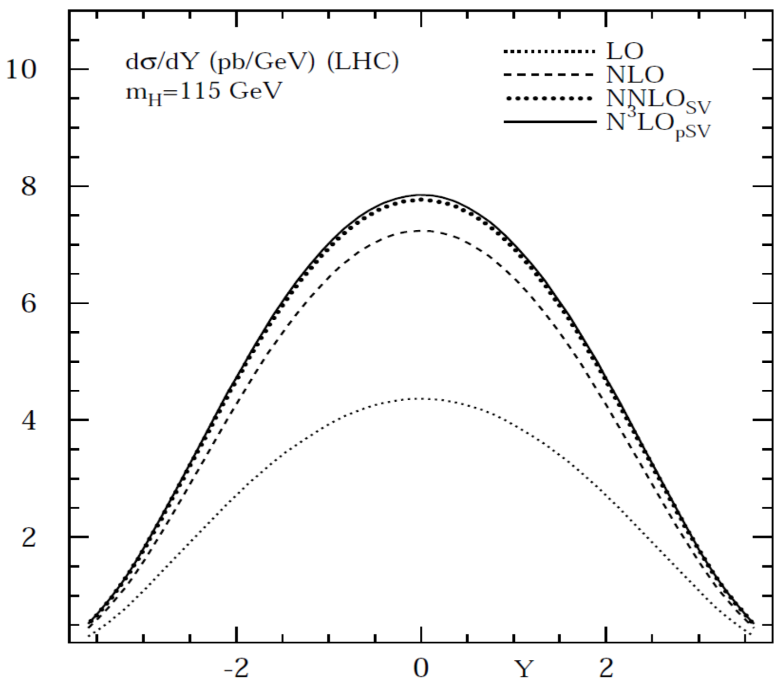


- N^3LL resummation exponents are available now.
- N^3LL resummation does not change the picture much. Fixed order N^3LO_{pSV} is very close to the N^3LL resummed result.

Rapidity of Higgs and its scale dependence at $NNLO, N^3LO$

Anastaiou et al

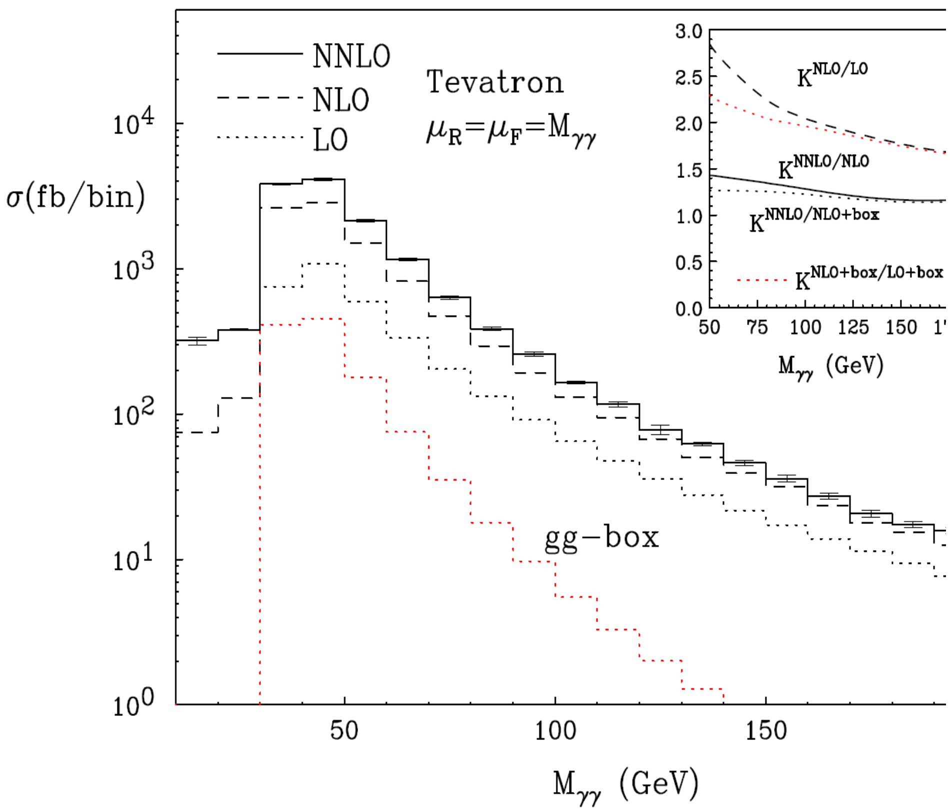


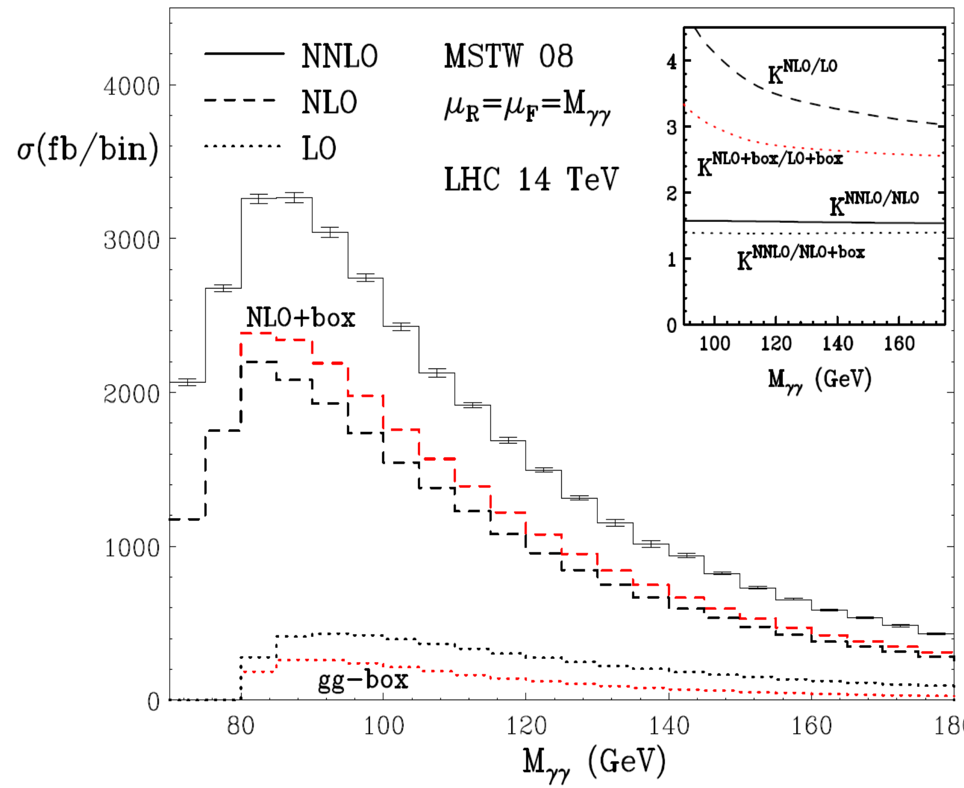


- NNLO exact in the large top limit reduces the scale uncertainity significantly
- One of the most difficult computations in QCD. Is it the end?

Di-photon at NNLO

Tevatron LHC Catani et al.





Cross section increases by 30-40%

Top quark production at NNLO

Percent level precision physics at the Tevatron: first genuine NNLO QCD corrections to $q\bar{q} \to t\bar{t} + X$

Peter Bärnreuther and Michał Czakon
Institut für Theoretische Teilchenphysik und Kosmologie, RWTH Aachen University, D-52056 Aachen, Germany

Alexander Mitov
Theory Division, CERN, CH-1211 Geneva 23, Switzerland
(Dated: April 25, 2012)

The total top quark pair production cross-section at hadron colliders through $\mathcal{O}(\alpha_S^4)$

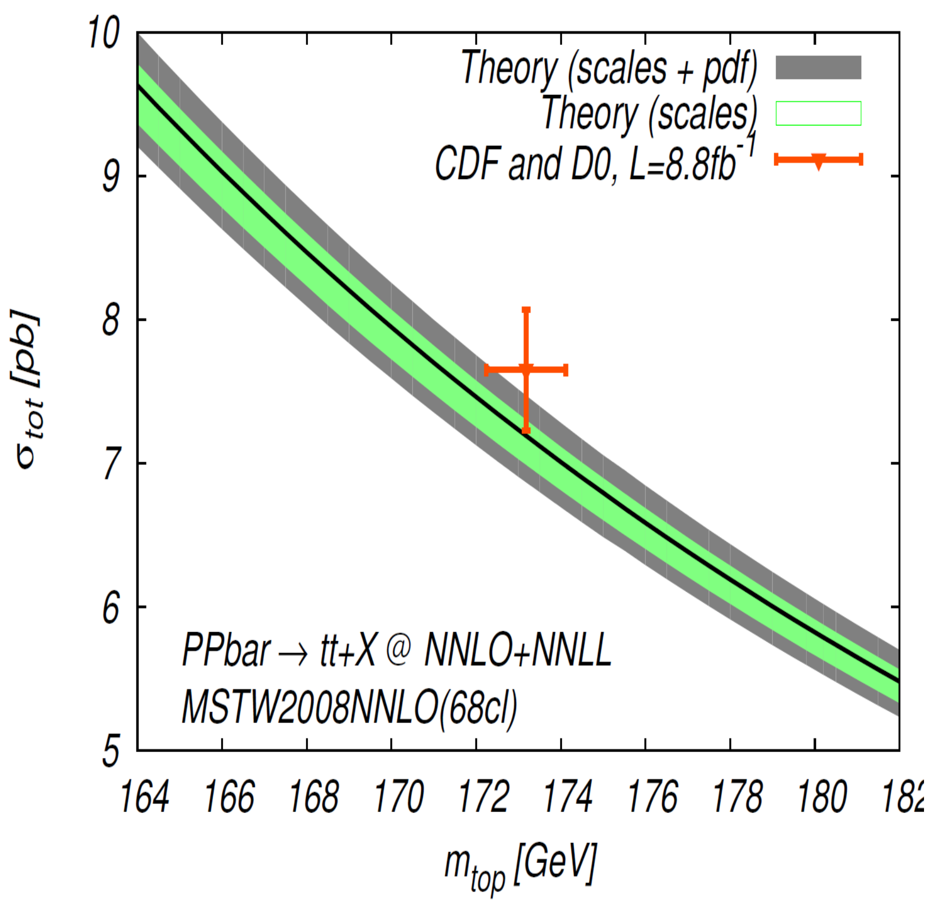
Michał Czakon and Paul Fiedler
Institut für Theoretische Teilchenphysik und Kosmologie, RWTH Aachen University, D-52056 Aachen, Germany

Alexander Mitov
Theory Division, CERN, CH-1211 Geneva 23, Switzerland
(Dated: March 26, 2013)

Top@Tevatron and LHC

Czakon et al.

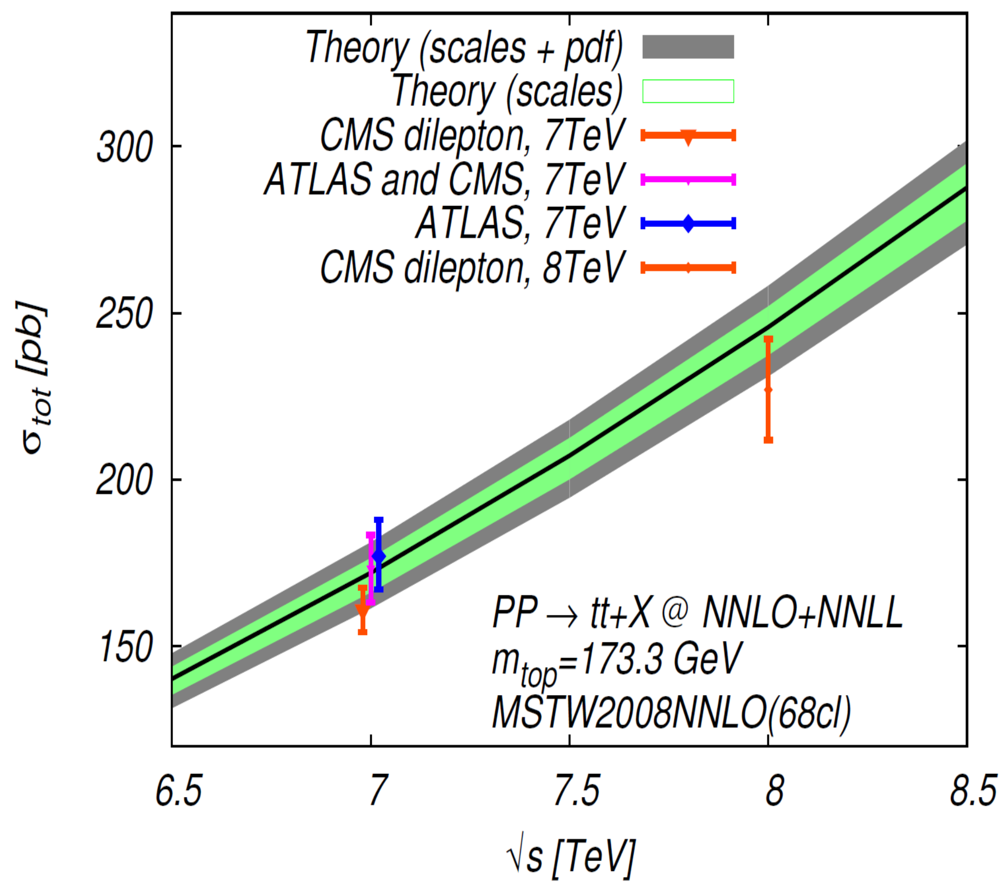
Tevatron



Scale dependence decreases 3-4 times
Compared NLO+ results

Scale uncertainty is 2.2%

LHC

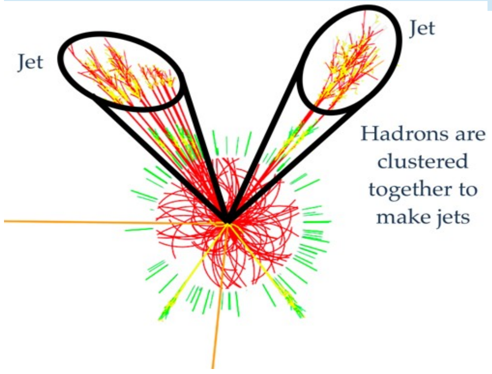


Scale dependence decreases 2-4 times
Compared to NLO+ results

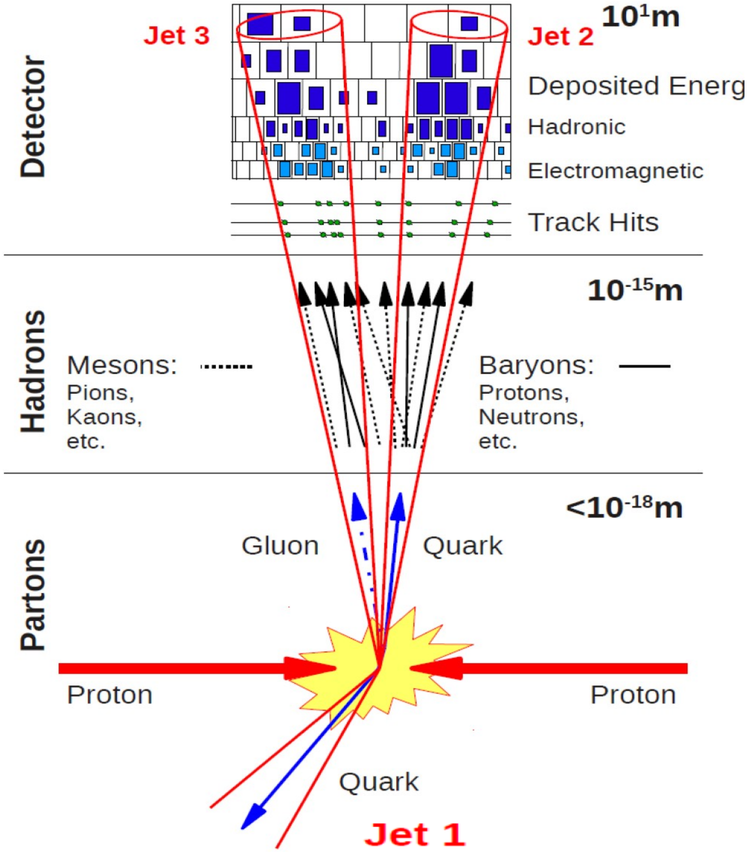
Scale uncertainty is 3%

Jets

Infra-red safe observables



- We do not see quarks and gluons, we see only
- hadrons/bunch of hadrons (jets), leptons, photons, weak b



- Infra-red Safe observables are the only measurabl
- How to construct infra-red safe quatities in QCD?
- Example: What is a Jet

Infra-red safe definition of a Jet

Algorithm

Collection of partons → Collection of hadrons (Jets)

Jet Agorithms

- k_t Algorithm
- Cambride/Aachen algorithm
- Anti - k_t algorithm

SIS Cone
ATLAS Cone
CMS Iterative Cone
GetJet
....
....

Successively Recombine the nearby partons

$$d_{ij} = \min(k_{t,i}^{2p}, k_{t,j}^{2p})(\Delta y_{ij}^2 + \Delta\phi_{ij}^2)$$

$p = 1$: k_t algorithm [Catani, Dokshitzer, Seymour, Webber, 93]

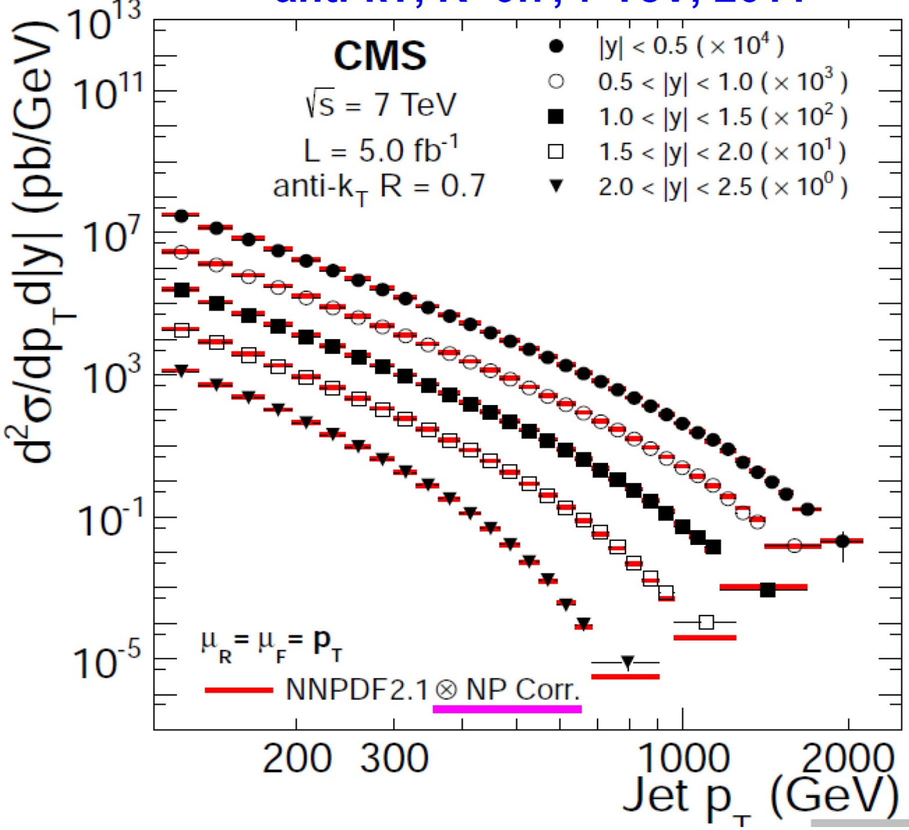
$p = 0$: Cambridge/Aachen (C/A) algorithm [Dokshitzer, Leder, Moretti, Webber, 93]

$p = -1$: anti-k_t algorithm [Cacciari, Salam, GS, 08]

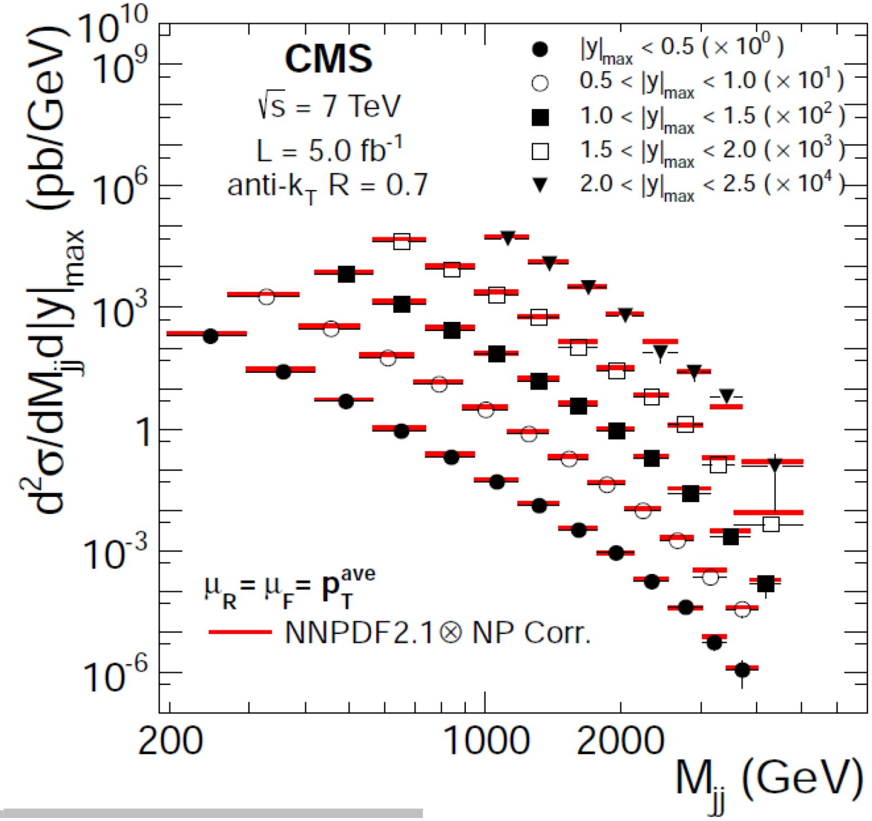
Cone: $\approx$ flow of energy in a cone (of fixed R) centred on the cone centre: SISCone [Salam, GS, 07]

High Pt and invariant mass distributions of jets

anti-kT, R=0.7, 7 TeV, 2011



anti-kT, R=0.7, 7 TeV, 2011



Excellent agreement with NLO QCD predictions

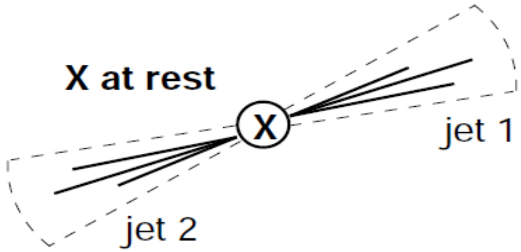
Fine Jets and Boosted Jets

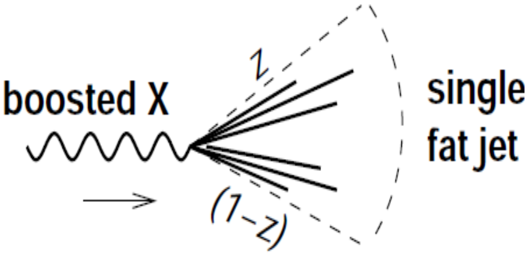
Filtering: undo the last recombination, keep the subjets

Trimming: remove low energetic deposits near a jet

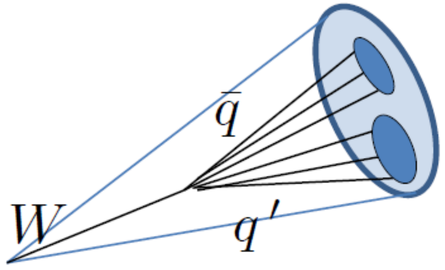
Pruning: recluster each jet in way wide angle recombinatio are absent

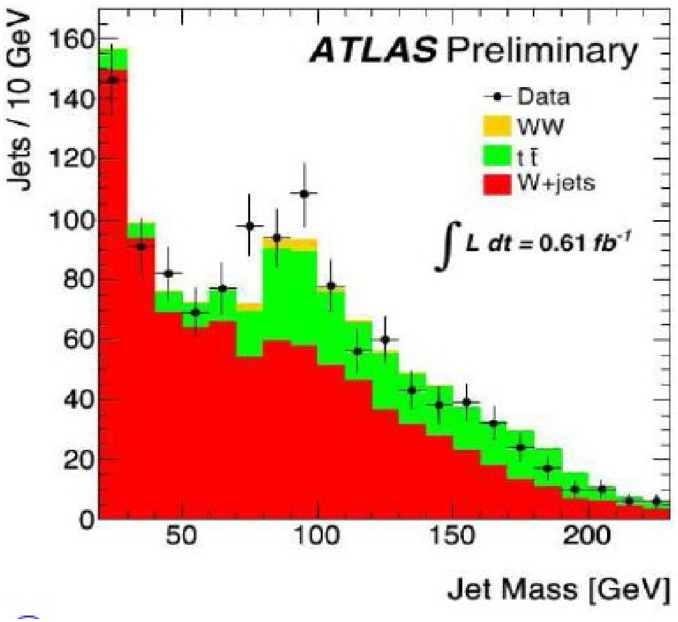
Boosted jets can probe Heavy states: new physics



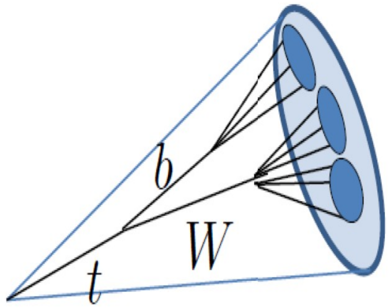


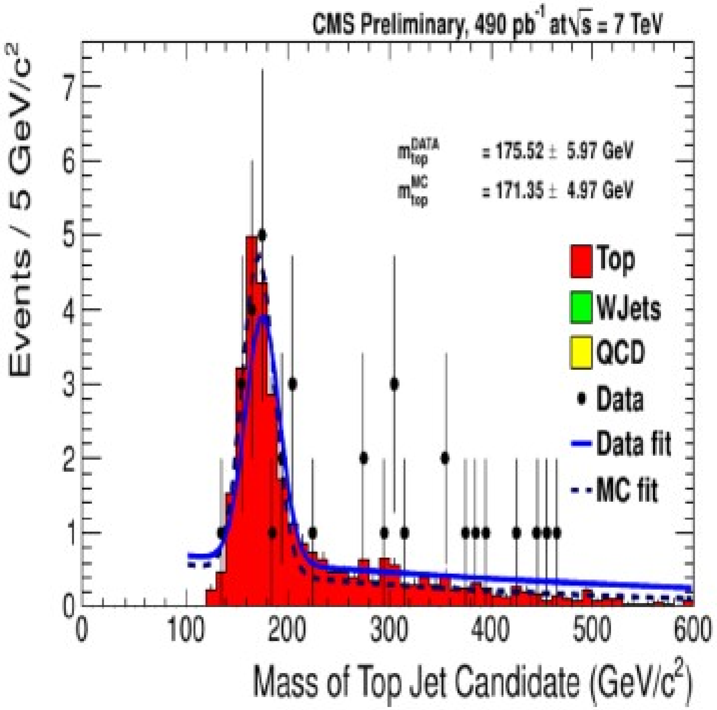
Boosted Jet from W Boson





Boosted Jet from top quark





Conclusions

- QCD is a tool kit at Hadron Colliders
- Factorisation plays an important role for predictions
- Strong coupling constant and PDFs are under control
- Many NLO and few NNLO results are available to test SM and new physics
- Jet physics provides alternate ground for probing new physics.