Fenomenologia del Modello Standard

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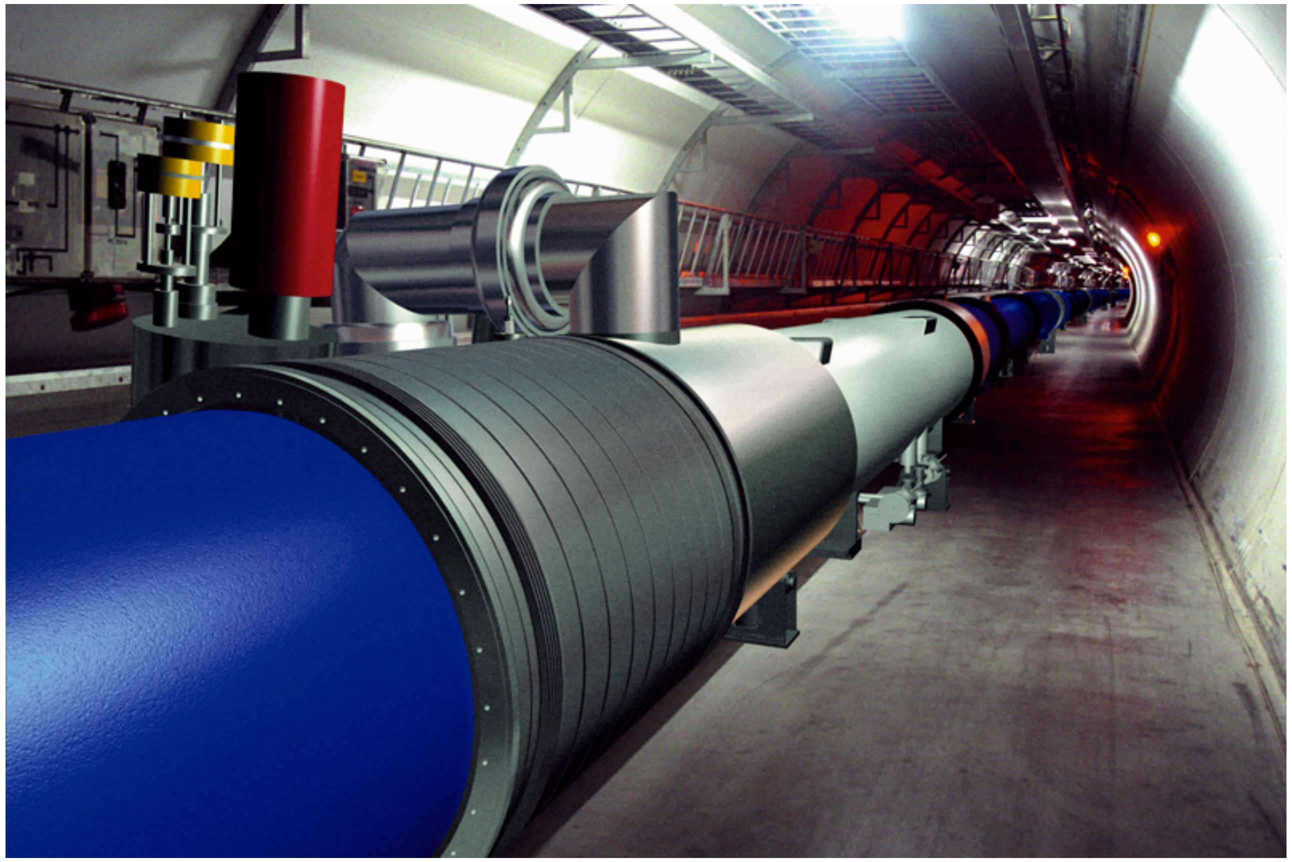
Outline

- Prologue
- EW precision tests
- SM at hadron colliders
  - PDFs
  - Partonic cross section
- Benchmark processes and jets
- α_S & Higgs searches
- Summary

Prologue

After many years of preparation, the LHC has now started its operations and it is successfully colliding proton beams at 7 TeV in the centre-of-mass



The LHC is expected to shed light on the fundamental questions of high energy physics like the origin of mass, the existence of SUSY and the nature of dark matter but....

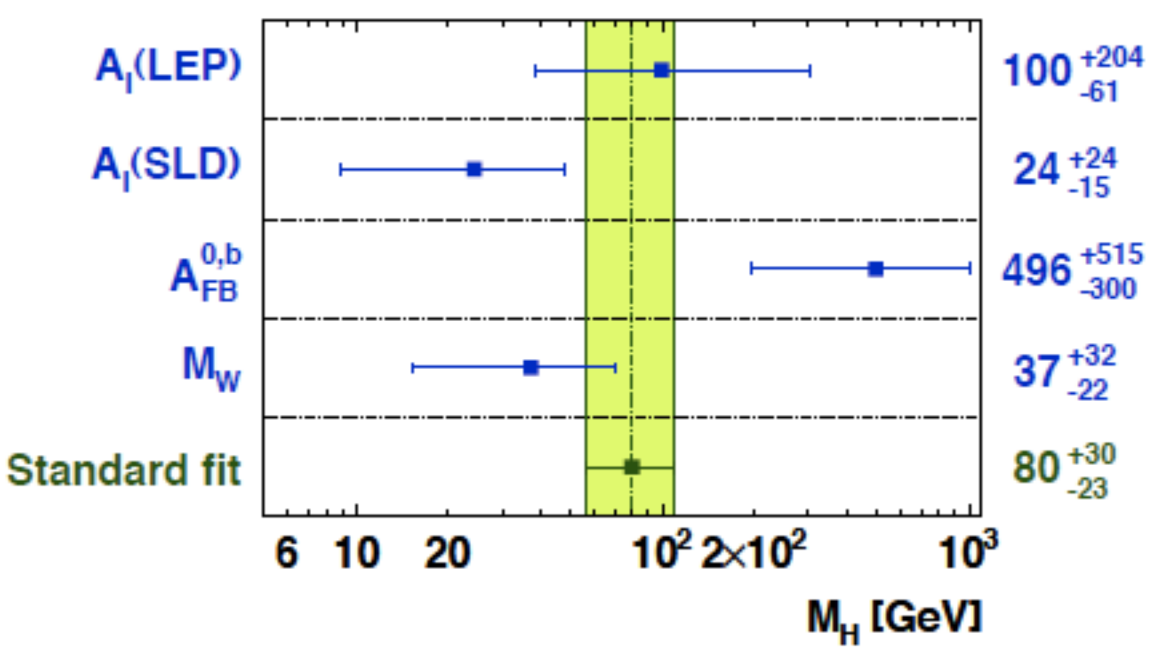
.....for the moment it is rediscovering the Standard Model !

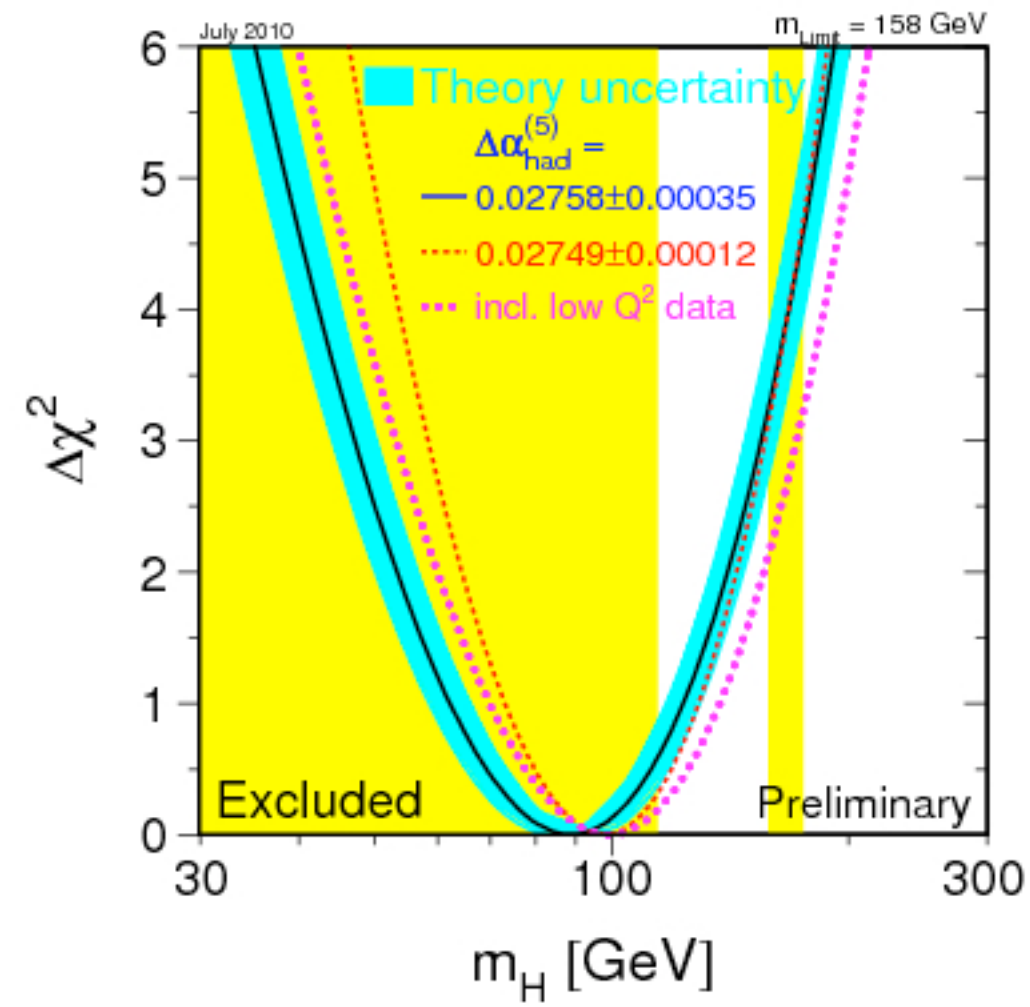
Status of EW tests

EW precision tests and measurement of W and top mass form a very stringent set of constraints

Globally the SM performs rather well

Well known tension from asymmetries





Determination of the Higgs mass excluding all the sensitive observables from the standard fit except one (GFitter)

Improvement from more precise measurements of m_W and m_{top} ($\Delta m_W \sim 0.007\ \Delta m_{top}$ to have same impact in the fit) and from better $\Delta\alpha_{had}$

g-2

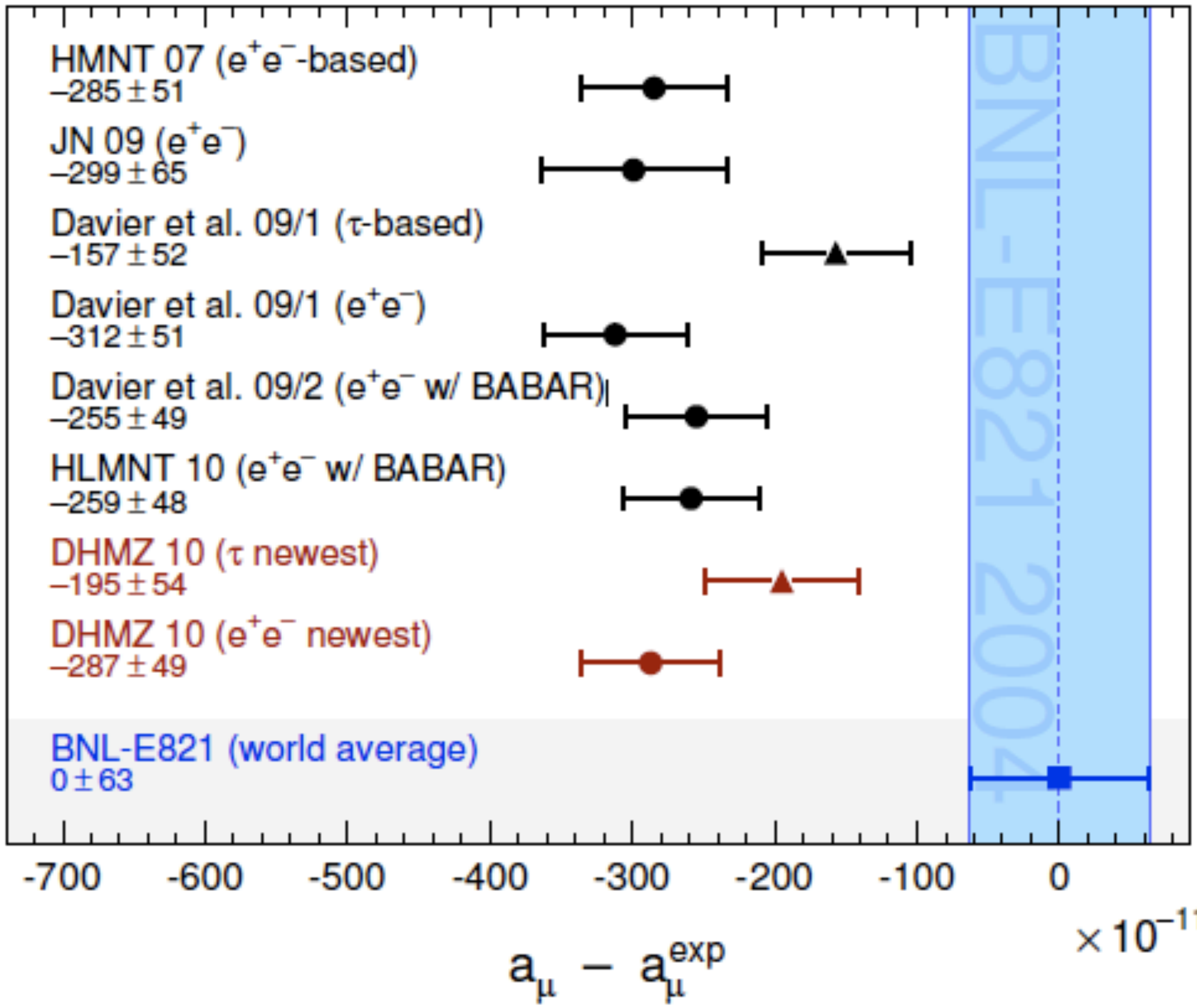
Most recent SM prediction based on $e^+ e^-$ data differs by 3.6 σ from exp. result

If τ data are used the discrepancy is 2.4 σ

E821 achieved a precision of 0.54 ppm

SM prediction has comparable accuracy

Good news: new Fermilab E989 experiment approved

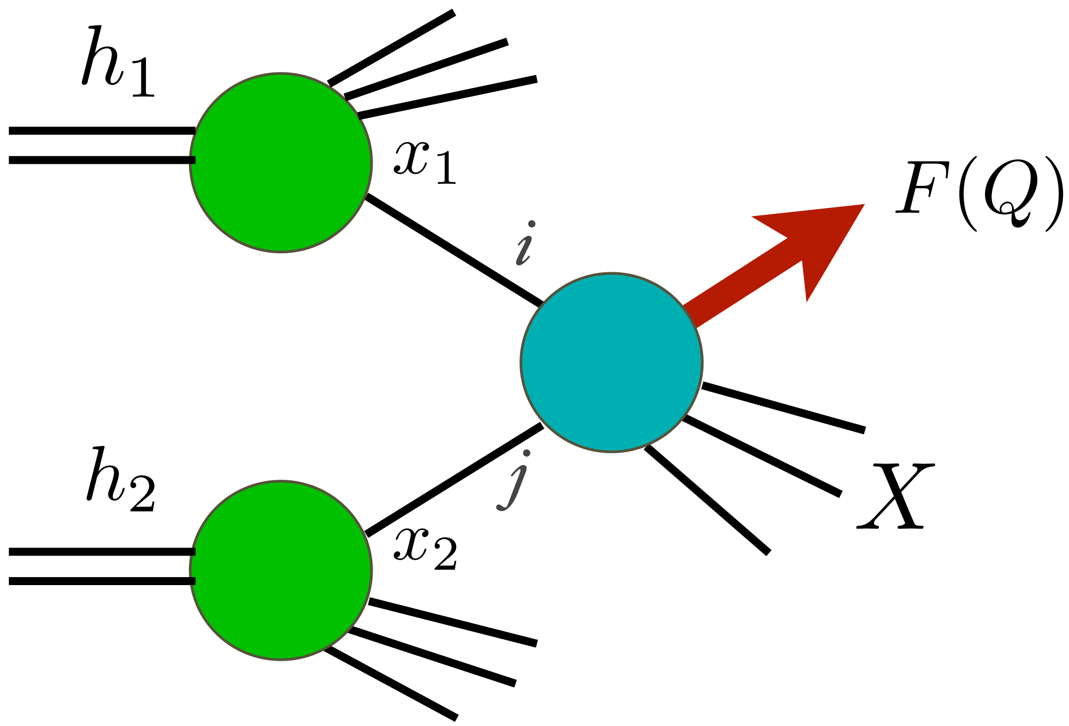


M.Davier et al. (2010)

Should be able to improve the exp. precision to 0.14 ppm !

Will theory be able to achieve a similar improvement ?

Hadron colliders



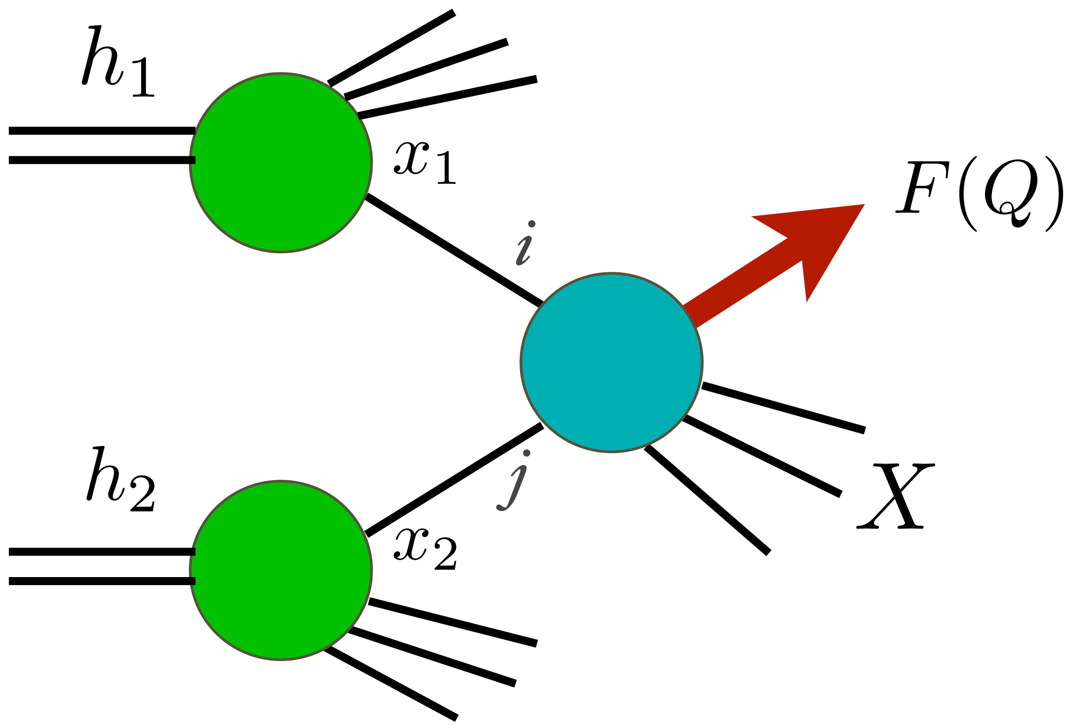
High-p_T interactions are characterized by the presence of a hard scale Q

→ They can be controlled through the factorization theorem

The corresponding cross section can be written as

$$\sigma(P_1,P_2)=\sum_{i,j}\int dx_1 dx_2 f_{i/h_1}(x_1,\mu_F^2) f_{j/h_2}(x_2,\mu_F^2)\hat{\sigma}_{ij}(p_1,p_2,\alpha_S(\mu_R),Q^2;\mu_F^2,\mu_R^2)$$

Hadron colliders



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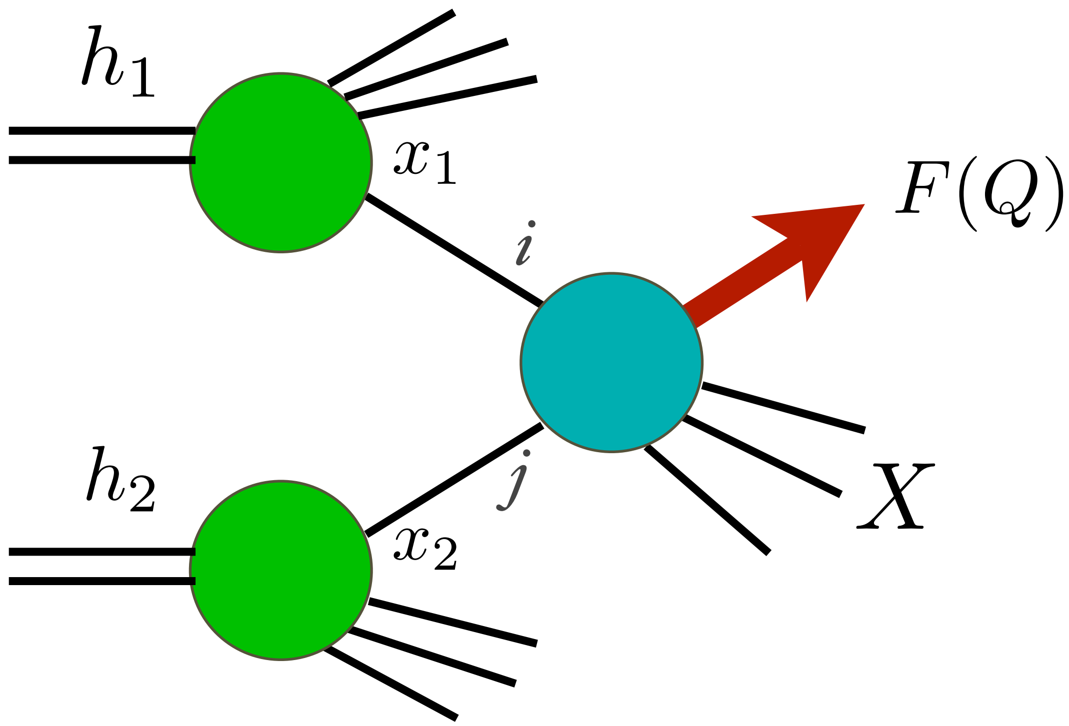
Parton distribution functions (PDFs)

Hadron colliders



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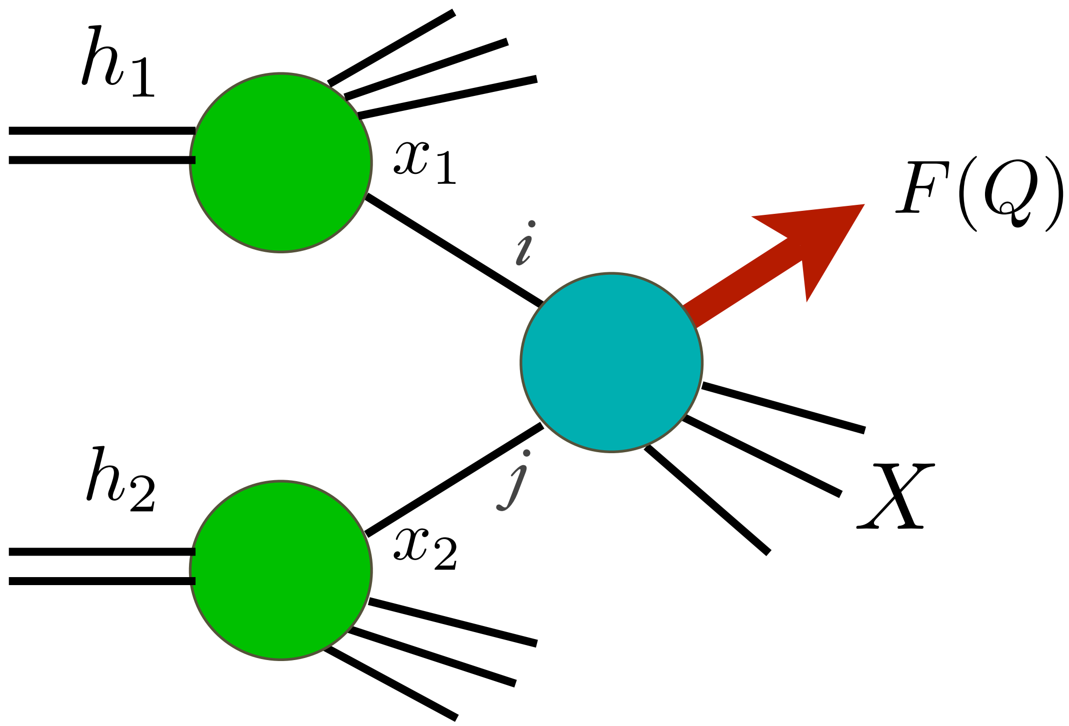

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Parton distribution functions (PDFs)

renormalization scale

Predictions for hadronic cross section depend on knowledge of both $\hat{\sigma}_{ij}$ and $f_{i,h}(x, \mu_F^2)$

factorization scale

PDFs

Determined by global fits to different data sets

Standard procedure:

- Parametrize at input scale $Q_0 = 1 - 4 \text{ GeV}$

$$xf(x, Q_0^2) = Ax^\alpha (1-x)^\beta (1 + \epsilon\sqrt{x} + \gamma x + ...)$$

- Impose momentum sum rule: $\sum_a \int_0^1 dx\, x f_a(x, Q_0^2) = 1$

- Evolve to desired Q^2 through DGLAP equation

$$Q^2 \frac{\partial f_a(x, Q^2)}{\partial Q^2} = \int_x^1 \frac{dz}{z} P_{ab}(\alpha_\mathrm{S}(Q^2), z) f_b(x/z, Q^2)$$

$$P_{ab}(\alpha_S, z) = \frac{\alpha_S}{2\pi} P_{ab}^{(0)}(z) + \left(\frac{\alpha_S}{2\pi}\right)^2 P_{ab}^{(1)}(z) + \left(\frac{\alpha_S}{2\pi}\right)^3 P_{ab}^{(2)}(z) + ...$$

LO (1974) NLO (1980) NNLO (2004: Moch et al.)

- Compute observables and then fit to data to obtain the parameters

PDFs

Main groups: MRST (now MSTW), CTEQ

Now also: NNPDF, Alekhin, Delgado-Reya, HERAPDF......

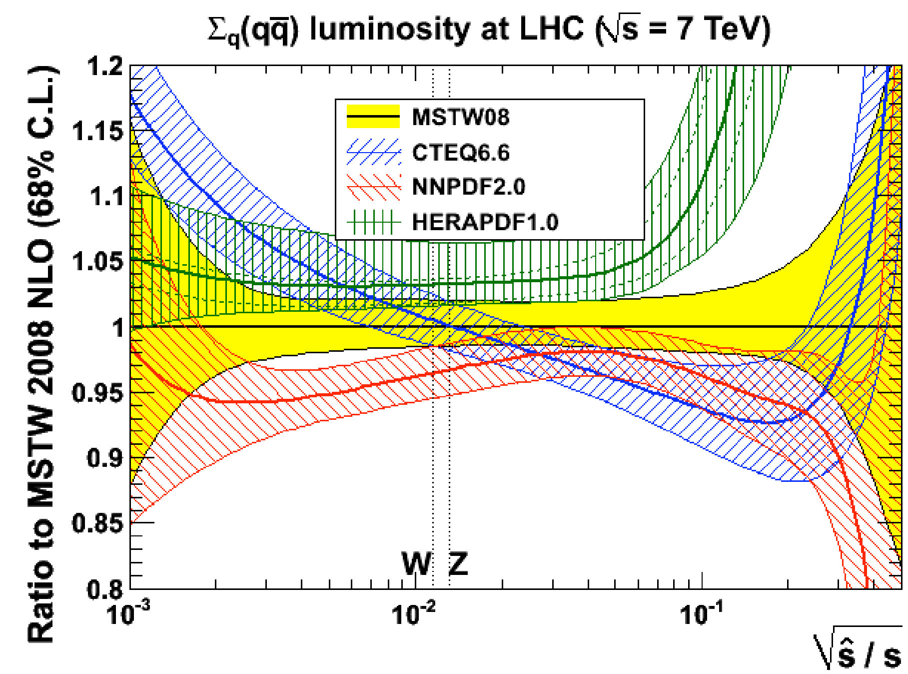
Broad agreement but differences due to:
- choice of data sets
- treatment of errors
- treatment of heavy quarks
- initial parametrization
- theoretical assumptions

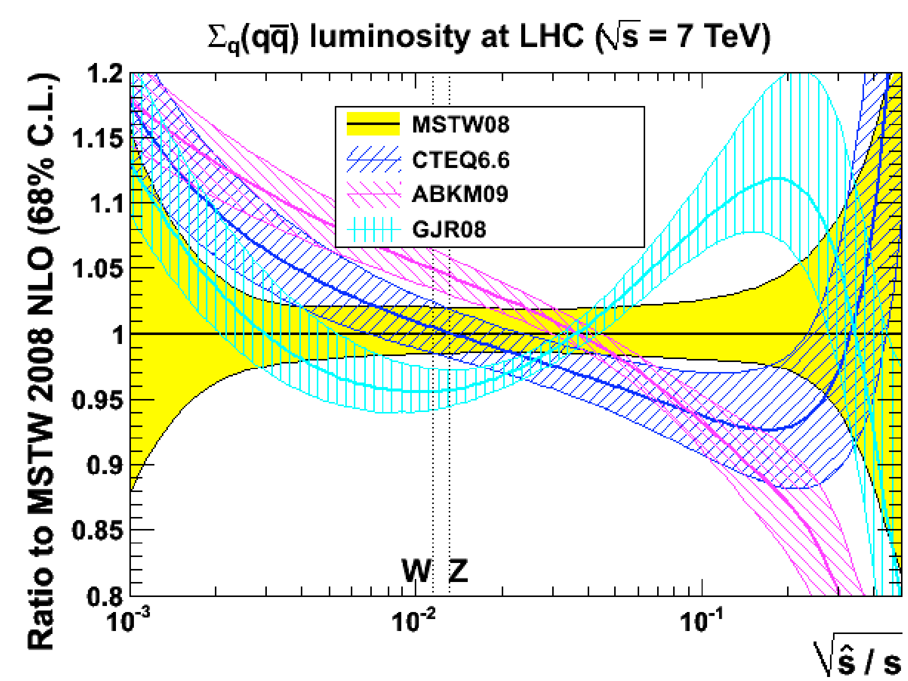
....

Most groups provide PDFs with 'errors'

Such errors come from the experimental uncertainties in the data used in the fit

Theoretical assumptions in the way the fit is set up and performed are more difficult to assess





J.Stirling

What about α_S ?
Come to this point later

Partonic cross section

The partonic cross section for high-p_T processes can be computed as a series expansion in the QCD coupling α_S

$$\hat{\sigma} = \underbrace{\hat{\sigma}^{(0)}}_{\text{LO}} + \frac{\alpha_S}{\pi}\,\underbrace{\hat{\sigma}^{(1)}}_{\text{NLO}} + \left(\frac{\alpha_S}{\pi}\right)^2 \underbrace{\hat{\sigma}^{(2)}}_{\text{NNLO}} + \ldots$$

Leading order (LO) calculations typically give only the order of magnitude of cross sections and distributions: to obtain reliable predictions next-to leading order (NLO) is needed

Example: W(Z)+jets $\Rightarrow$ background for new physics searches

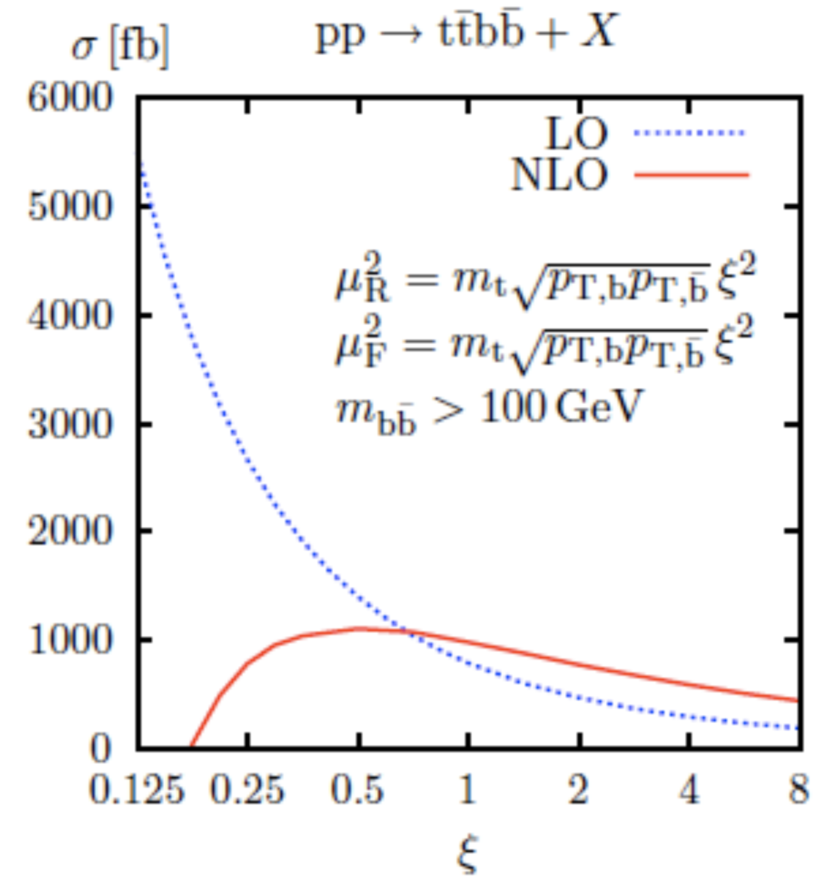
The bottleneck has been for many years the evaluation of the 1 loop correction

This is a field that has seen the most significant advances in the last few years

New NLO calculations with "traditional" Feynman diagrams techniques

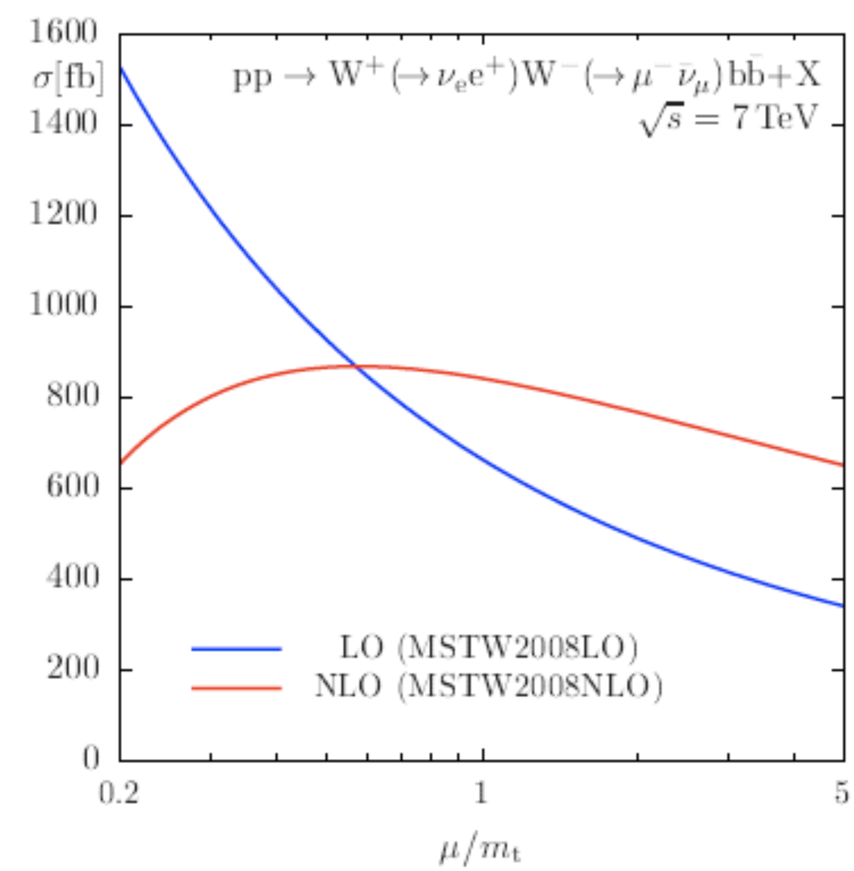
- $pp \to t\bar{t}b\bar{b}$

A. Bredenstein, A.Denner, S.Dittmaier, S. Pozzorini (2010)



- $pp \to WWb\bar{b}$

A.Denner, S.Dittmaier, S.Kallweit, S. Pozzorini (2010)



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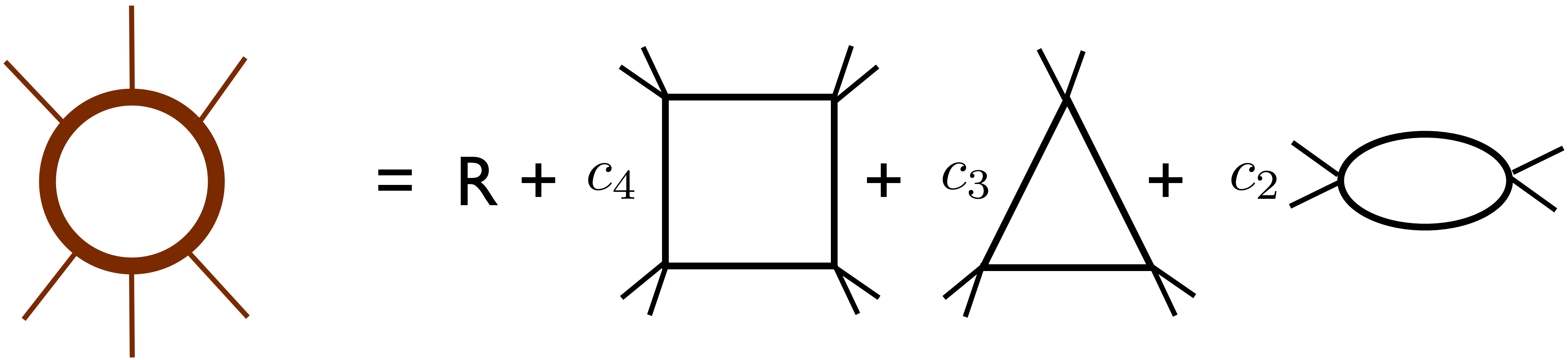
The traditional approach based on Feynman diagrams is now complemented with new powerful methods based on recursion relations and unitarity



General one-loop amplitude expressed as a sum of known boxes, triangles and bubble integrals plus a remainder term

Coefficient of these integrals can be computed by taking suitable multiple cuts

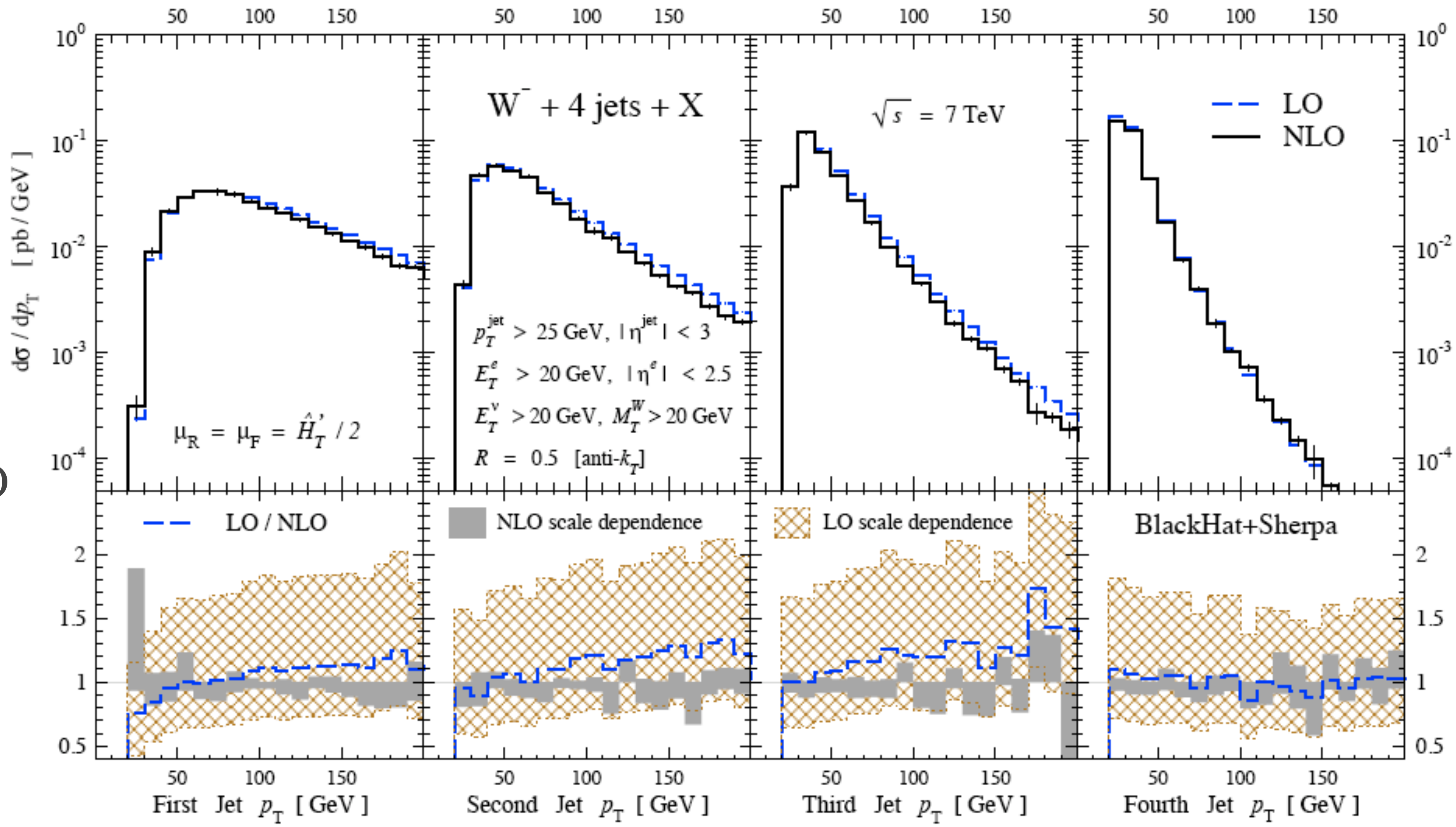
Sew suitable tree-amplitudes

For example c_4 → Simple product of four tree-level amplitudes evaluated at complex momenta

R.Britto, F.Cachazo, B.Feng (2004)

Blackhat coll.: W+4 jets at NLO

Shape difference between LO and NLO results for the first three leading jets



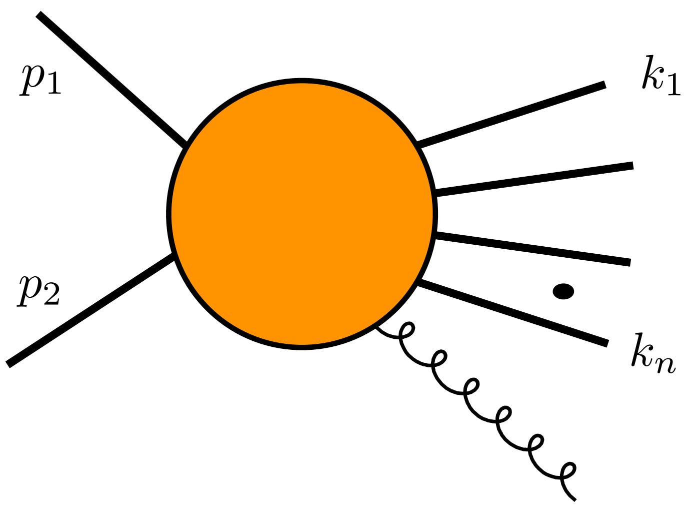
C.F.Berger et al. (2010)

First (almost) complete 2->5 NLO computation

(leading color approximation for the virtual terms)

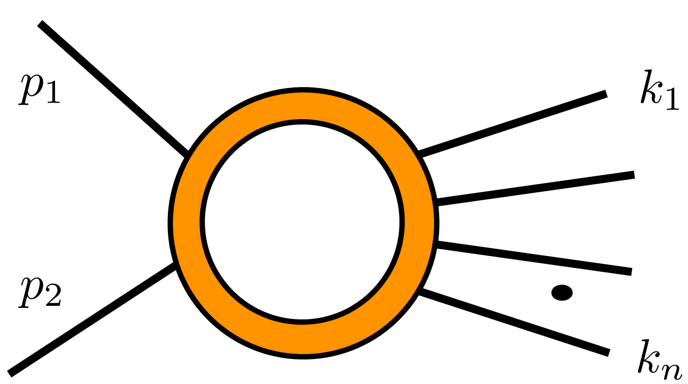
Towards automation of NLO corrections

Combine available methods to compute real corrections.....



with most efficient numerical techniques for virtual corrections

G.Ossola, C.Papadopoulos, R.Pittau (2007)



	Process	μ	n_{lf}	Cross section (pb)	
				LO	NLO
a.1	$pp \to t\bar{t}$	m_{top}	5	123.76 ± 0.05	162.08 ± 0.12
a.2	$pp \to tj$	m_{top}	5	34.78 ± 0.03	41.03 ± 0.07
a.3	$pp \to tjj$	m_{top}	5	11.851 ± 0.006	13.71 ± 0.02
a.4	$pp \to t\bar{b}j$	$m_{top}/4$	4	25.62 ± 0.01	30.96 ± 0.06
a.5	$pp \to t\bar{b}jj$	$m_{top}/4$	4	8.195 ± 0.002	8.91 ± 0.01
b.1	$pp \to (W^+ \to)e^+\nu_e$	m_W	5	5072.5 ± 2.9	6146.2 ± 9.8
b.2	$pp \to (W^+ \to)e^+\nu_e j$	m_W	5	828.4 ± 0.8	1065.3 ± 1.8
b.3	$pp \to (W^+ \to)e^+\nu_e jj$	m_W	5	298.8 ± 0.4	300.3 ± 0.6
b.4	$pp \to (\gamma^*/Z \to)e^+e^-$	m_Z	5	1007.0 ± 0.1	1170.0 ± 2.4
b.5	$pp \to (\gamma^*/Z \to)e^+e^- j$	m_Z	5	156.11 ± 0.03	203.0 ± 0.2
b.6	$pp \to (\gamma^*/Z \to)e^+e^- jj$	m_Z	5	54.24 ± 0.02	56.69 ± 0.07
c.1	$pp \to (W^+ \to)e^+\nu_e b\bar{b}$	$m_W + 2m_b$	4	11.557 ± 0.005	22.95 ± 0.07
c.2	$pp \to (W^+ \to)e^+\nu_e t\bar{t}$	$m_W + 2m_{top}$	5	0.009415 ± 0.000003	0.01159 ± 0.00001
c.3	$pp \to (\gamma^*/Z \to)e^+e^- b\bar{b}$	$m_Z + 2m_b$	4	9.459 ± 0.004	15.31 ± 0.03
c.4	$pp \to (\gamma^*/Z \to)e^+e^- t\bar{t}$	$m_Z + 2m_{top}$	5	0.0035131 ± 0.0000004	0.004876 ± 0.000002
c.5	$pp \to \gamma t\bar{t}$	$2m_{top}$	5	0.2906 ± 0.0001	0.4169 ± 0.0003
d.1	$pp \to W^+W^-$	$2m_W$	4	29.976 ± 0.004	43.92 ± 0.03
d.2	$pp \to W^+W^- j$	$2m_W$	4	11.613 ± 0.002	15.174 ± 0.008
d.3	$pp \to W^+W^+ jj$	$2m_W$	4	0.07048 ± 0.00004	0.1377 ± 0.0005
e.1	$pp \to HW^+$	$m_W + m_H$	5	0.3428 ± 0.0003	0.4455 ± 0.0003
e.2	$pp \to HW^+ j$	$m_W + m_H$	5	0.1223 ± 0.0001	0.1501 ± 0.0002
e.3	$pp \to HZ$	$m_Z + m_H$	5	0.2781 ± 0.0001	0.3659 ± 0.0002
e.4	$pp \to HZj$	$m_Z + m_H$	5	0.0988 ± 0.0001	0.1237 ± 0.0001
e.5	$pp \to Ht\bar{t}$	$m_{top} + m_H$	5	0.08896 ± 0.00001	0.09869 ± 0.00003
e.6	$pp \to Hb\bar{b}$	$m_b + m_H$	4	0.16510 ± 0.00009	0.2099 ± 0.0006
e.7	$pp \to Hjj$	m_H	5	1.104 ± 0.002	1.036 ± 0.002

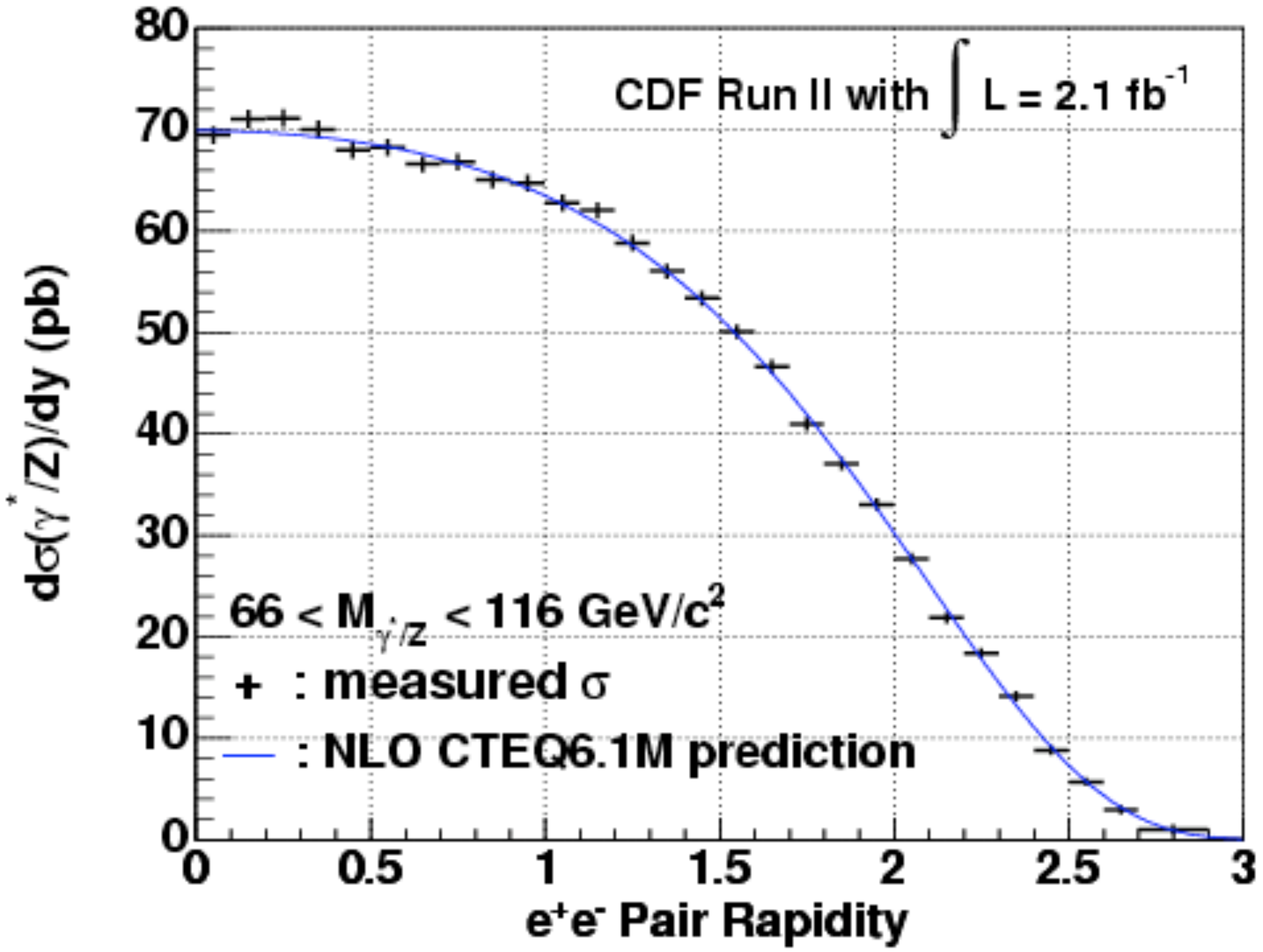
V.Hirschi et al. (2011)

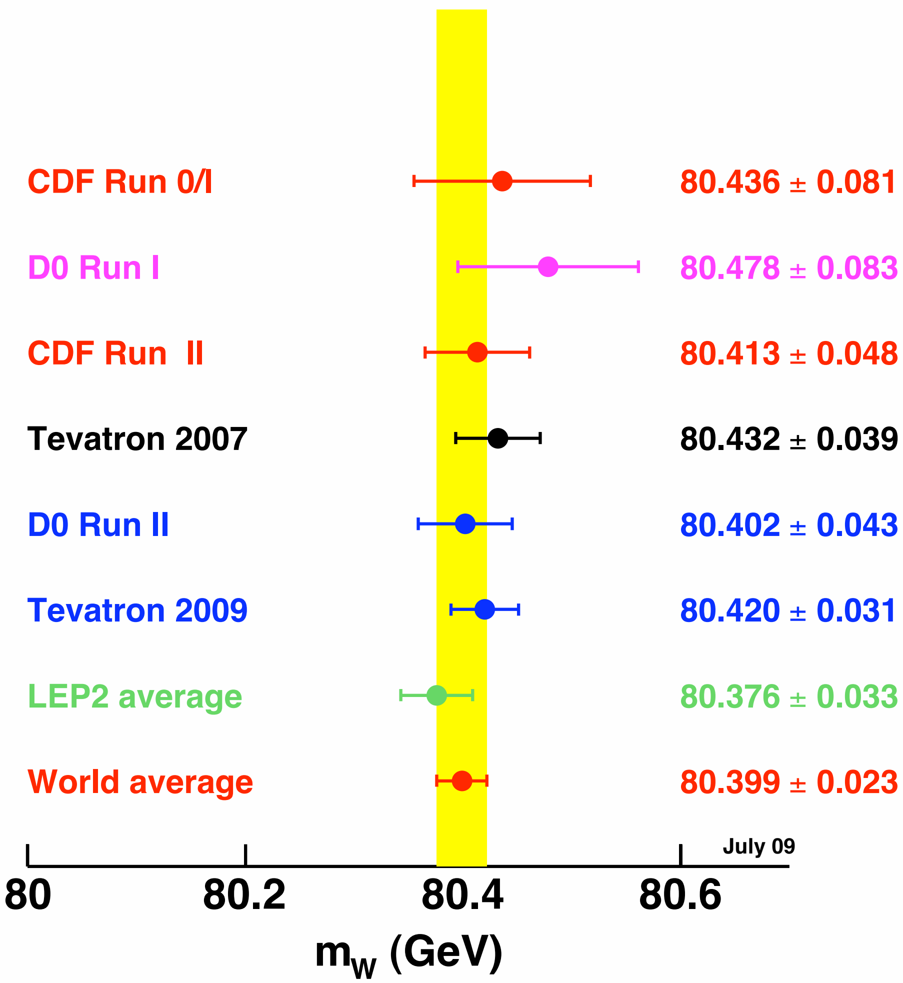
Benchmarks: W, Z

W and Z production are benchmarks processes at hadron colliders

- large production rates and clean signatures
- standard candles for detector calibration
- stringent constraints for PDFs extraction
- W mass

....





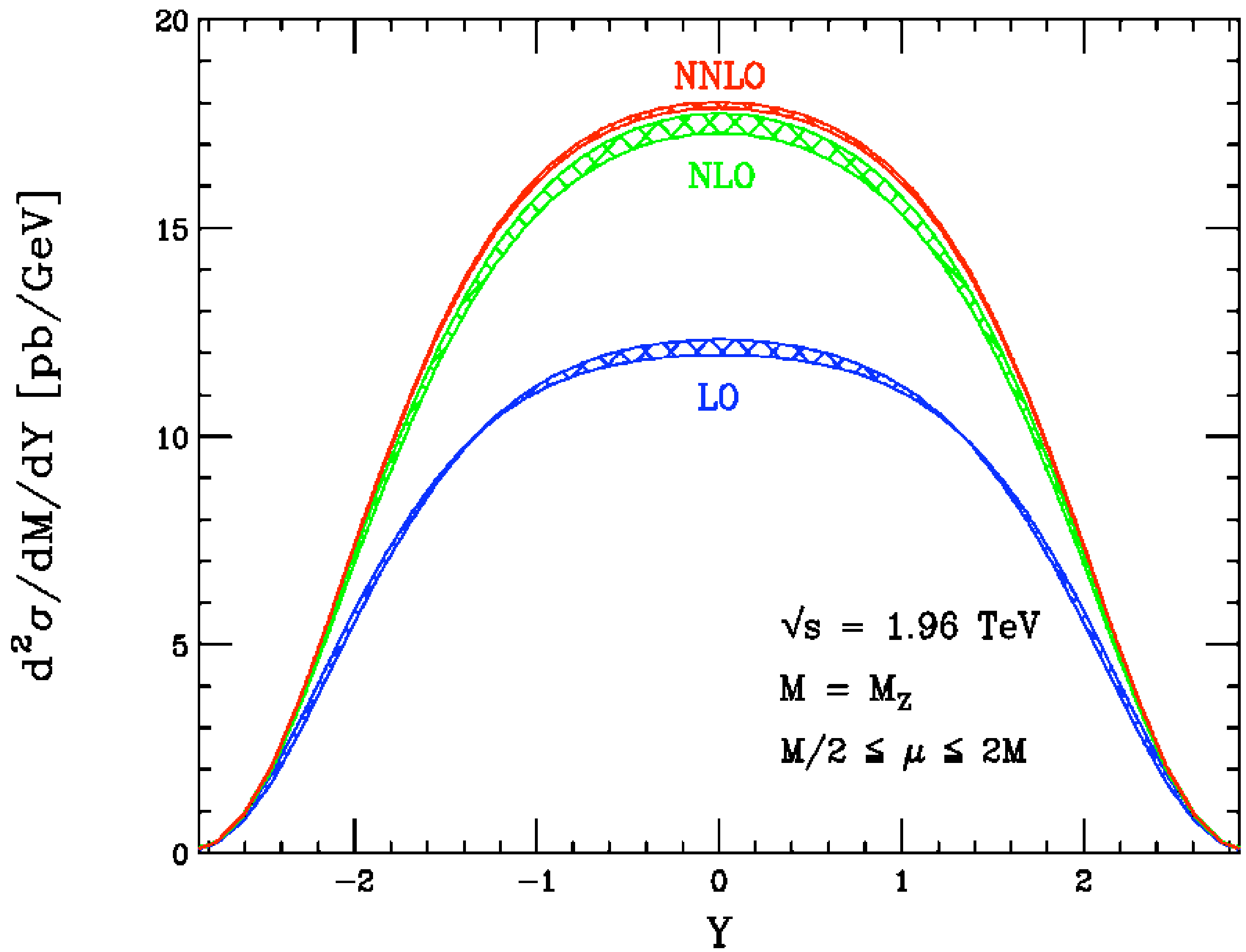
Benchmarks: W, Z

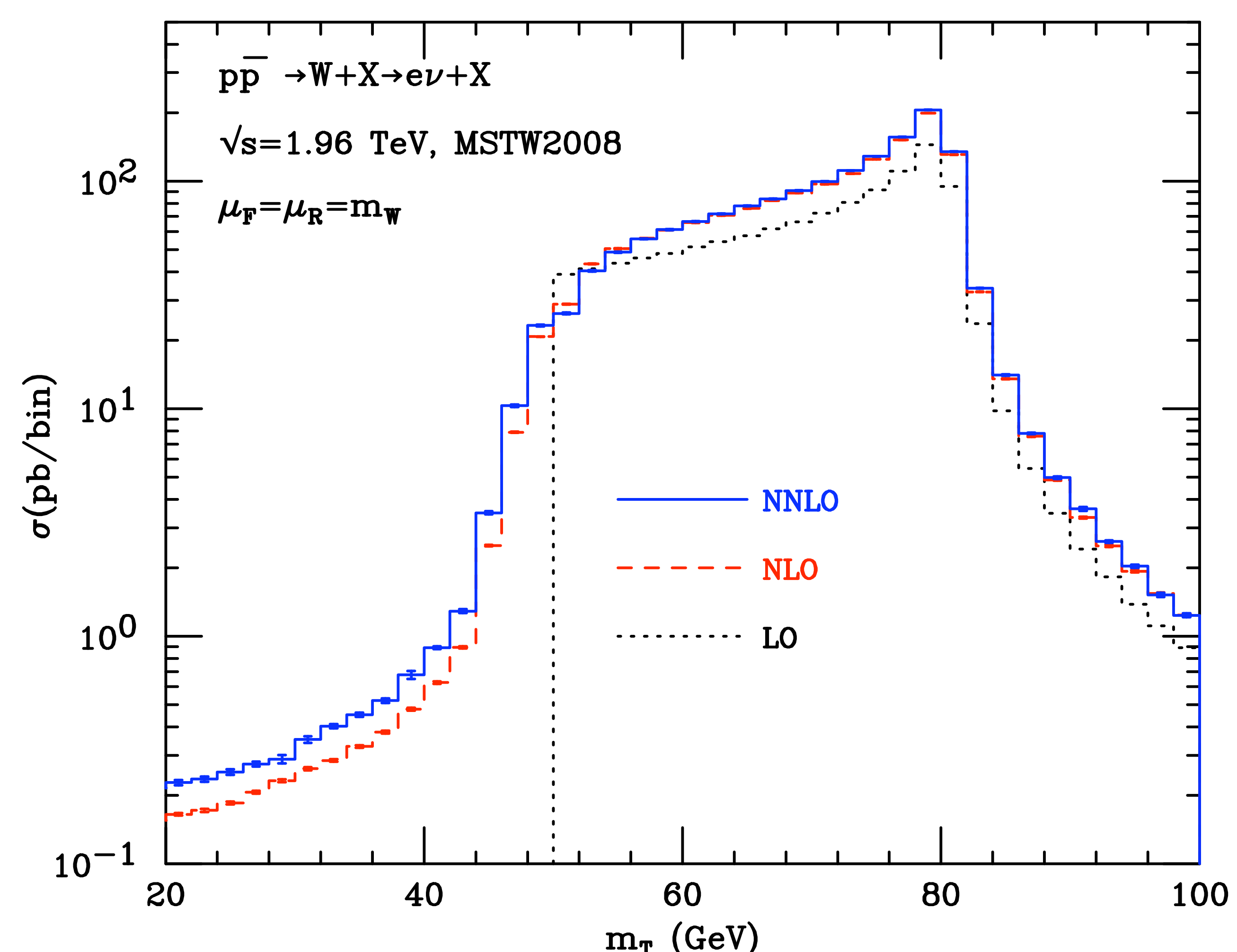
Here theory has done well !

QCD corrections to the total cross section and rapidity distribution known up to NNLO

R.Hamberg, W.Van Neerven, T.Matsuura (1991)

C.Anastasiou, K.Melnikov, L.Dixon,F.Petriello (2003)





Now also fully exclusive NNLO computation available

K.Melnikov, F.Petriello (2004)

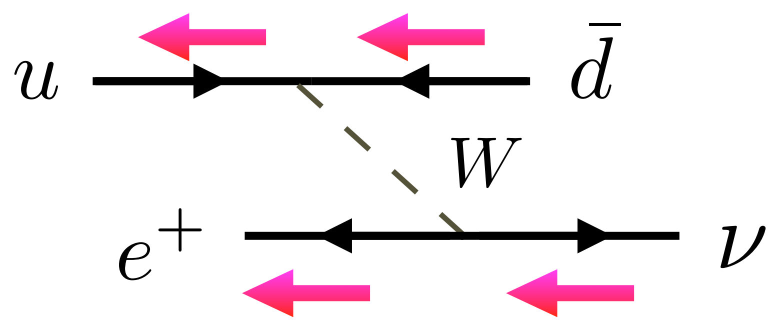
S. Catani et al. (2009)

One application: first NNLO computation of the lepton charge asymmetry

S. Catani, G.Ferrera, MG (2010)

W asymmetry gives important information on u and d quarks in the proton

(u carries more momentum than d)

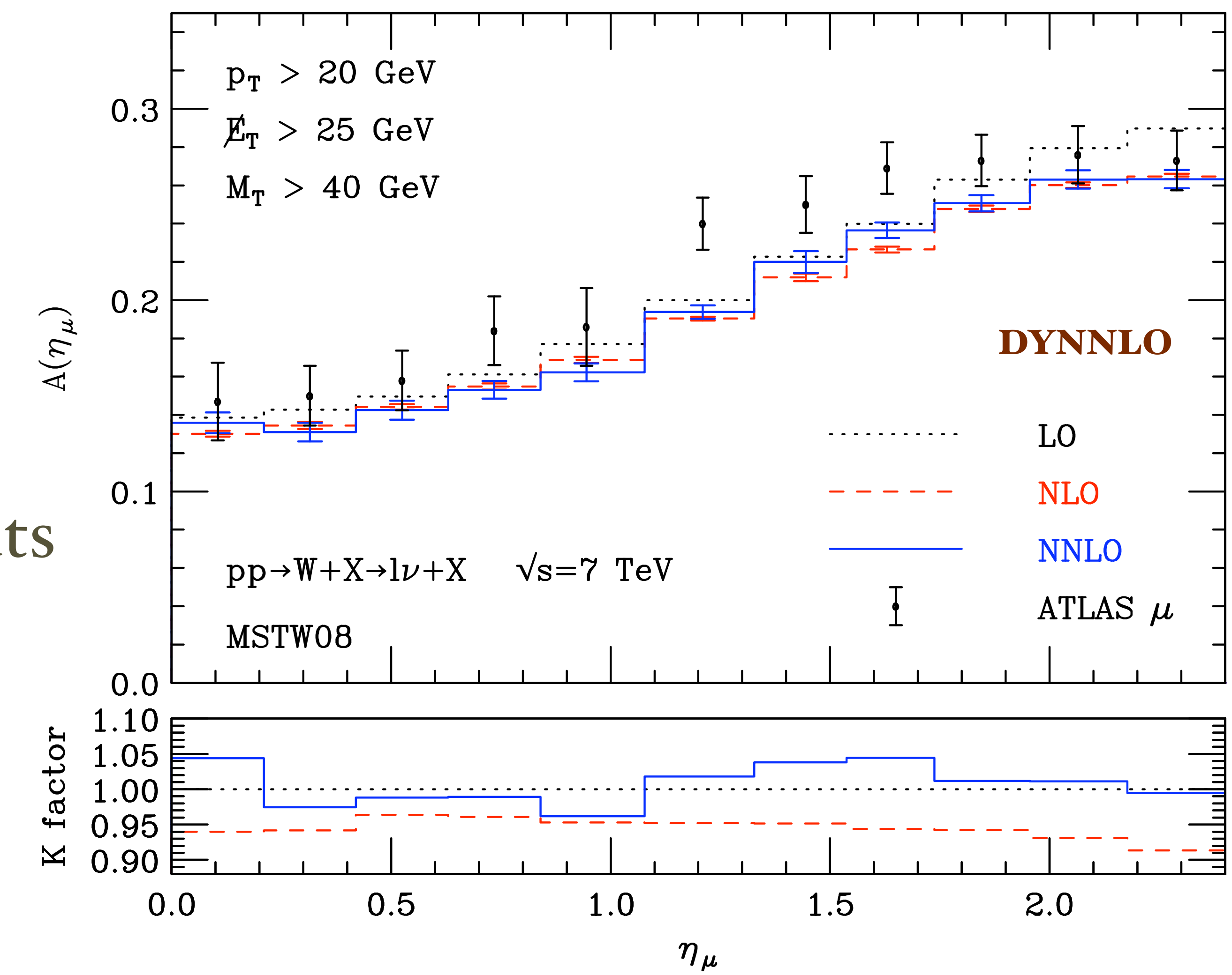


W production and decay mechanisms are correlated

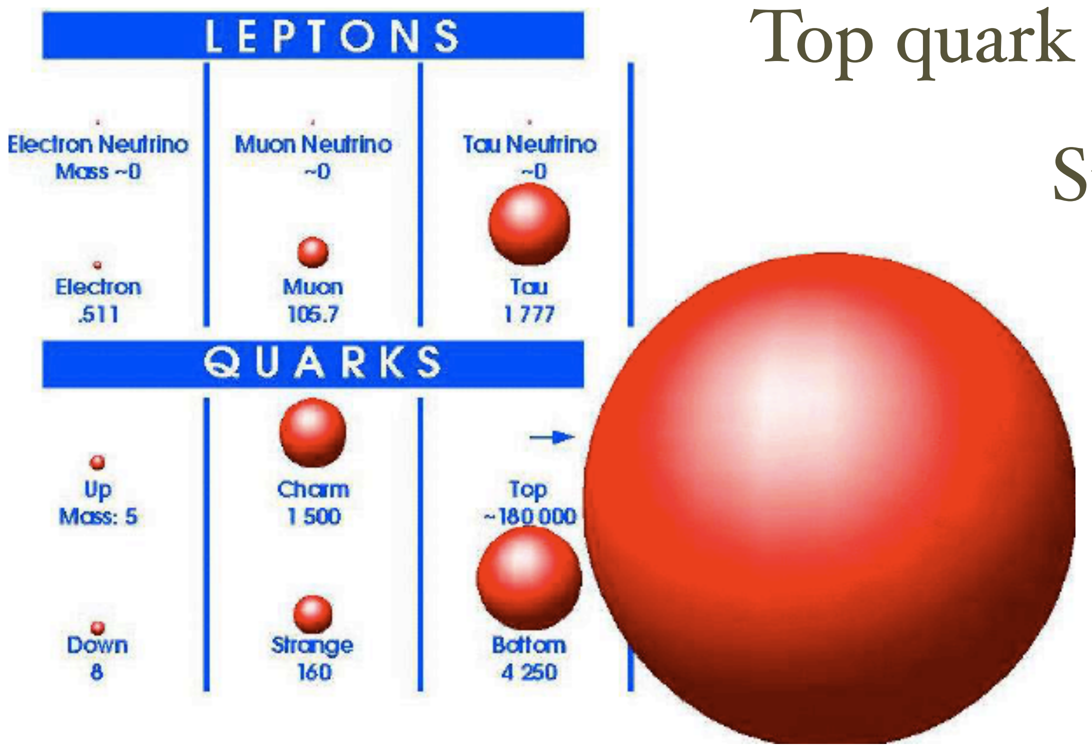
Angular momentum conservation: the charged lepton is mainly produced in the direction of the down quark

The calculation takes into account all cuts used in the analysis

First LHC data already impact PDF determinations



Benchmarks: top



Top quark is the heaviest fundamental particle we know

Strongly coupled to the Higgs sector $m_t \sim \lambda_t v$

➡ The Yukawa coupling λ_t must be large !

$A_{FB}^{t\bar{t}}$ recent measurement vs NLO QCD

	$M_{t\bar{t}} < 450$ GeV	$M_{t\bar{t}} > 450$ GeV
CDF	-0.116 ± 0.154	0.475 ± 0.114
MCFM	0.040 ± 0.006	0.088 ± 0.013

Asymmetry vanishes at LO

➡ NLO calculation for $A_{FB}^{t\bar{t}}$ effectively LO

Huge effort towards ttbar at NNLO

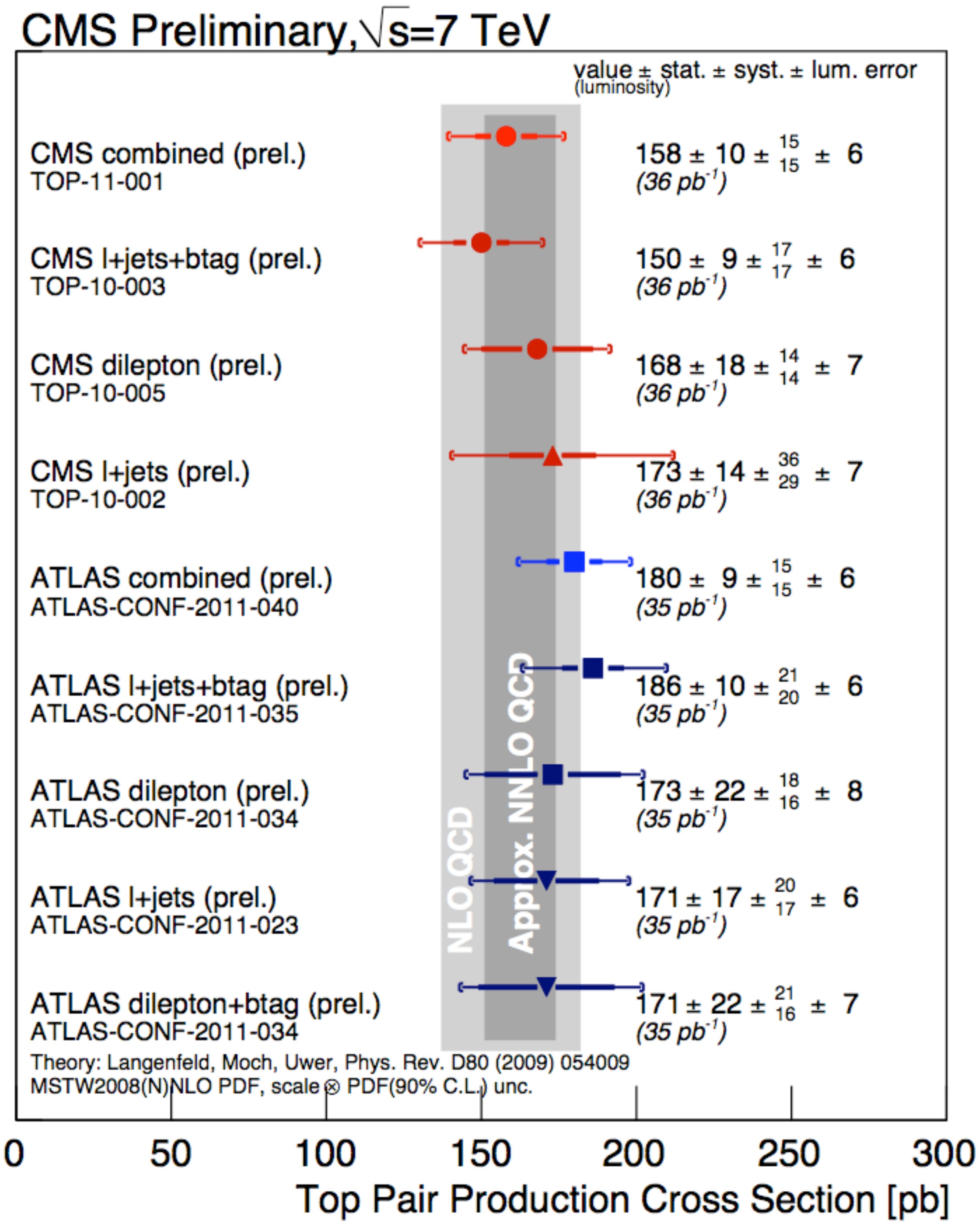
- ttbar+jet at NLO done
- one loop squared known
- two loop amplitude in progress

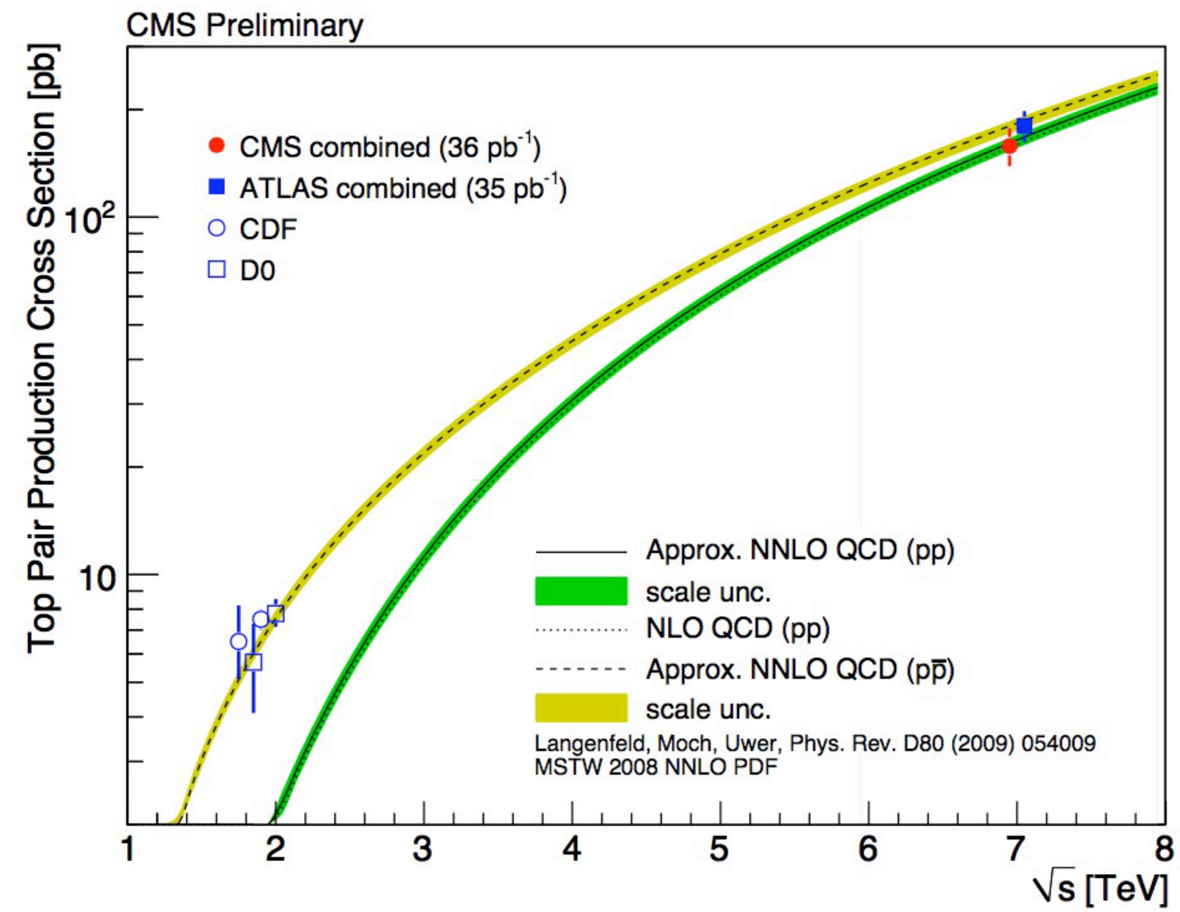
S. Dittmaier et al. (2007)

M.Rogal et al. (2008)
C.Anastasiou, Aybat (2008)

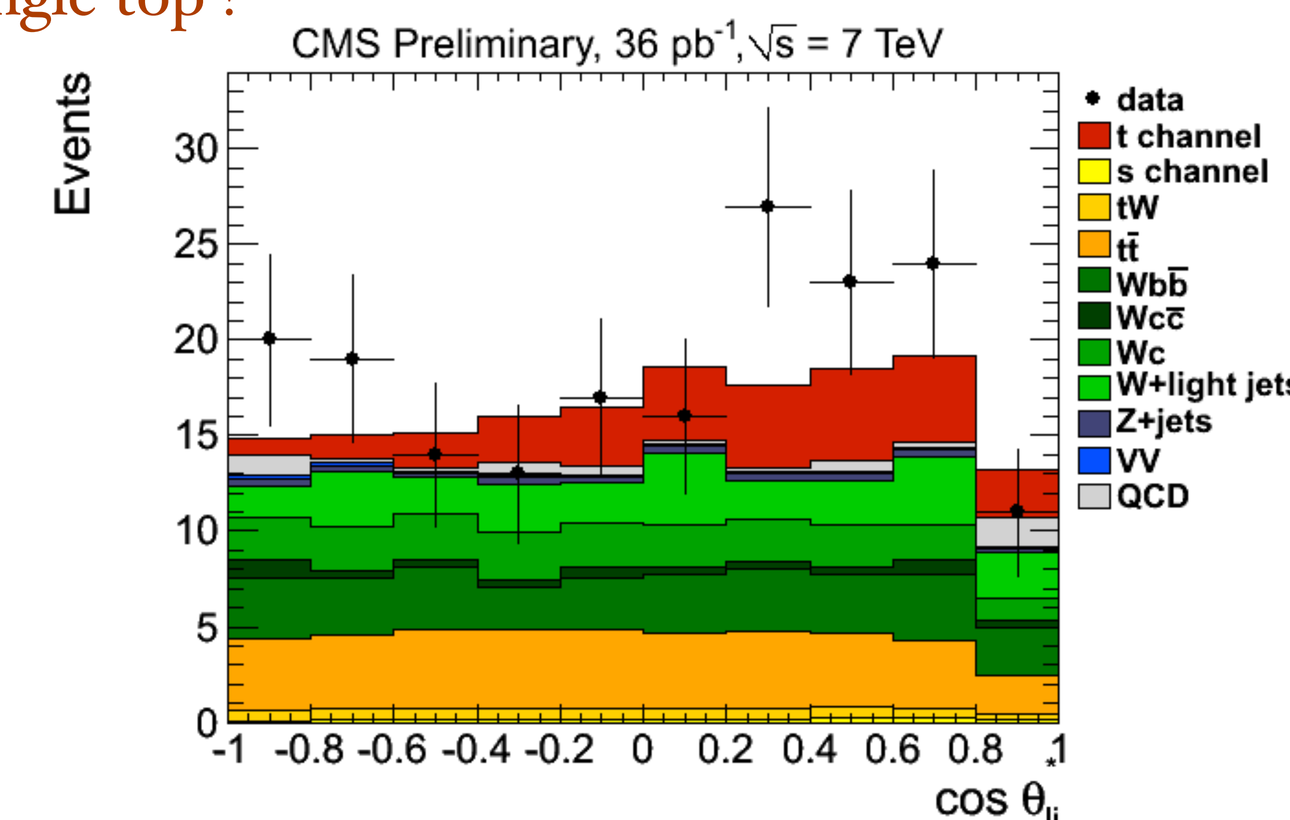
M. Czakon (2008)
R. Bonciani et al. (2010)

Benchmarks: top





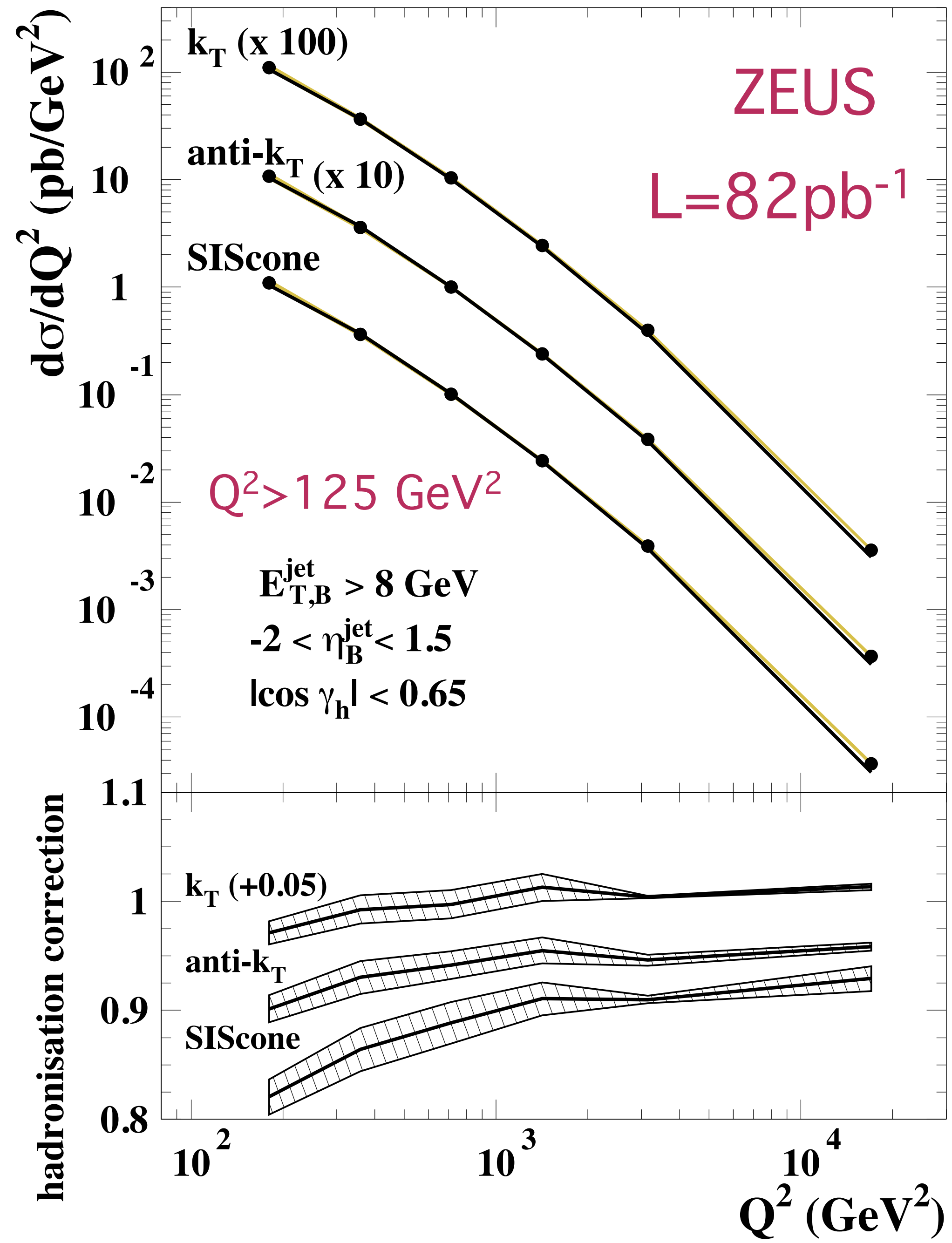
Single top !



Jets

Problem: the traditional (cone) algorithms used at hadron colliders are often IR unsafe

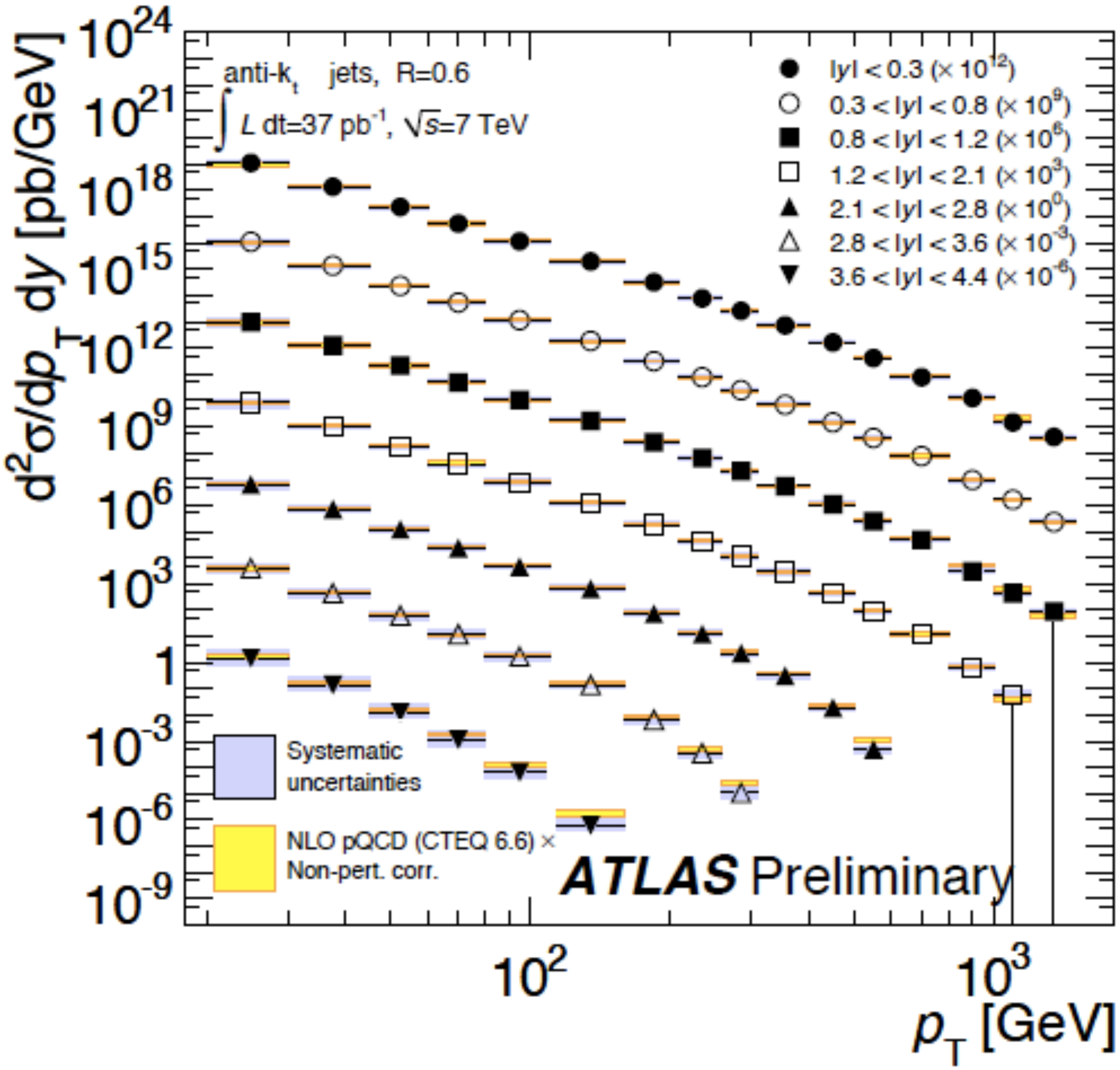
Sensitive to the emission of additional soft particles or to the splitting in two collinear particles

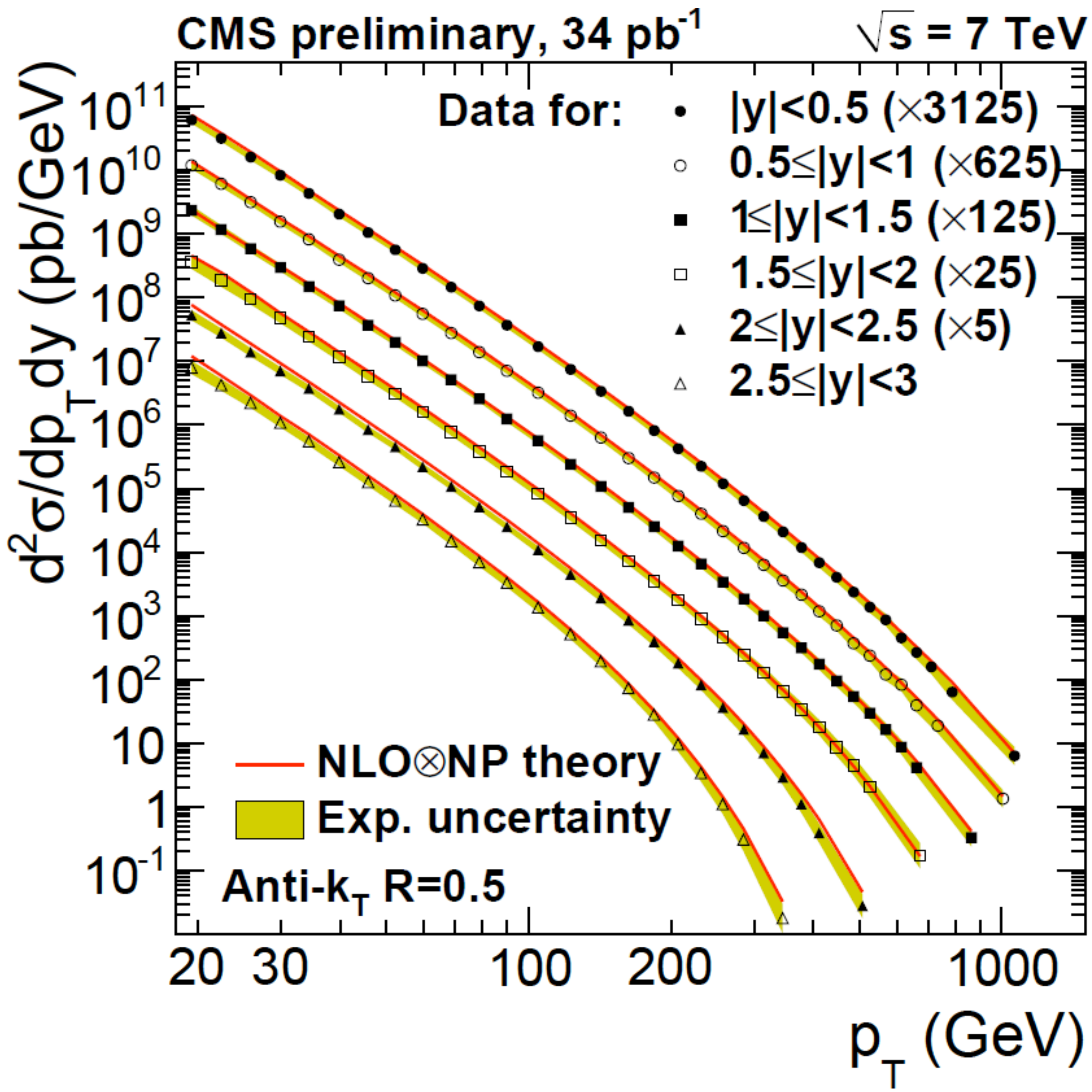


Sequential recombination algorithms (e.g. k_T) solve this problem (clustering sequence closely follows QCD soft and collinear splitting)

Recent important developments: SIScone, anti-k_T

Jets





anti-k$_T$: repeatedly combine pairs with smallest $d_{ij}=\Delta R^2/\max(k^2_{Ti}, k^2_{Tj})$

Cone-like jets but through a sequential (IR safe) algorithm

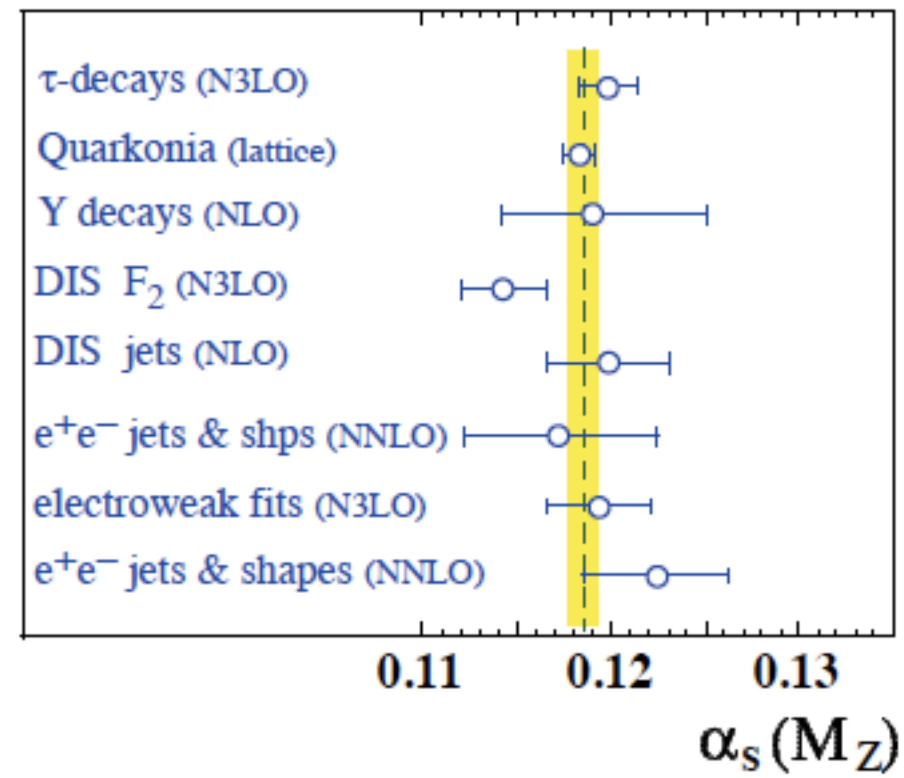
M.Cacciari, G.Salam, G.Soyez (2008)

The α_S riddle

What is the value of α_S ?

World average $\alpha_S = 0.1184 \pm 0.0007$

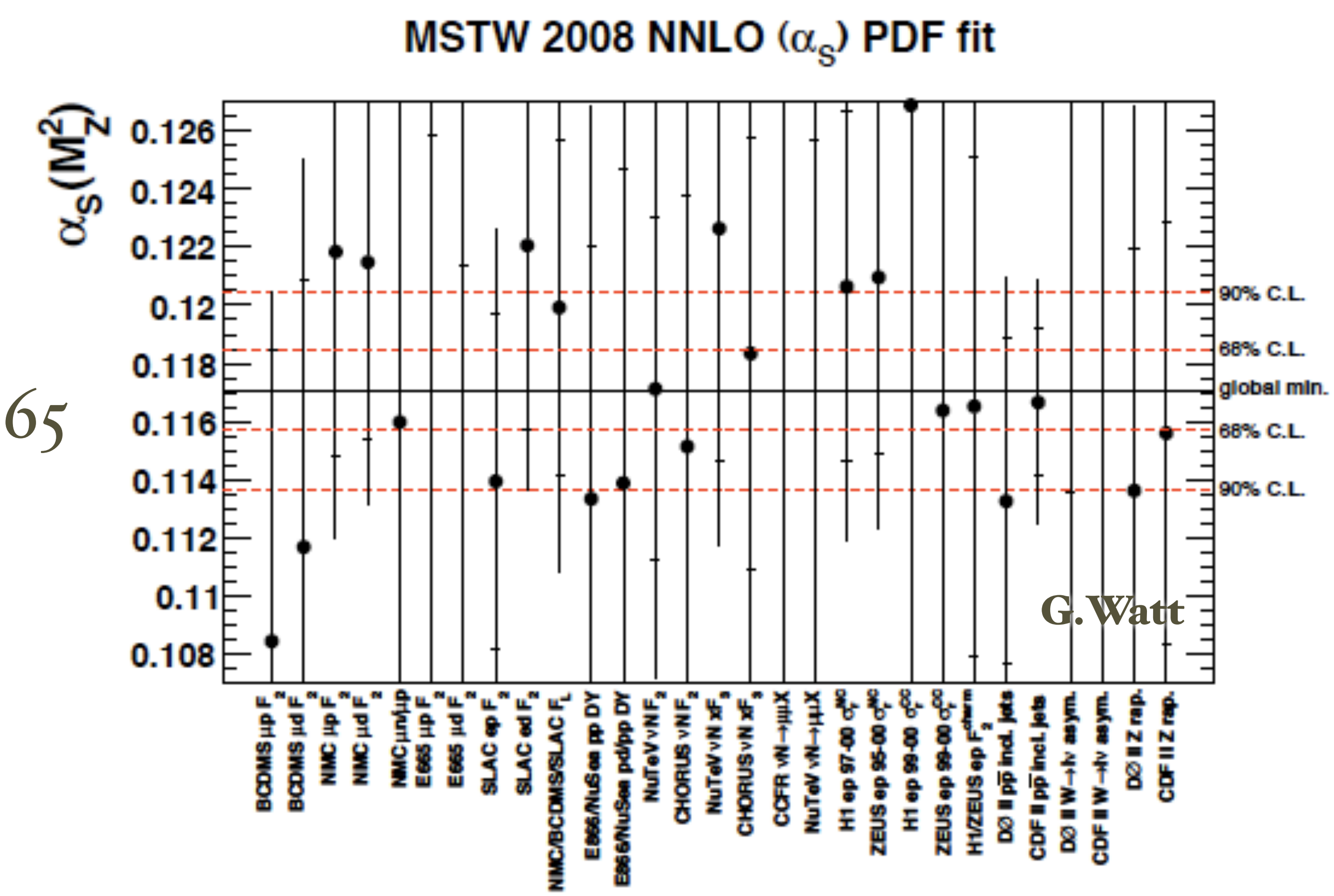
S. Bethke (2009)



Exclude older and less precise measurements → The α_S scandal ! (S. Forte, DIS2010)

Should we trust this result ?
Common lore: DIS data prefer lower α_S

Apparently true only for BCDMS, E665 and SLAC ep data



The α_S riddle

MSTW2008 result $\alpha_S(m_Z) = 0.11707$ at NNLO

Recent claim: this high α_S could be due to mistreatment of NMC data

S. Alekhin et al. (2011)

No such effect seen by MSTW
Similar stability found by NNPDF at NLO and at NNLO

MSTW: impact of Tevatron jet data crucial to get high-x gluon right and thus higher α_S

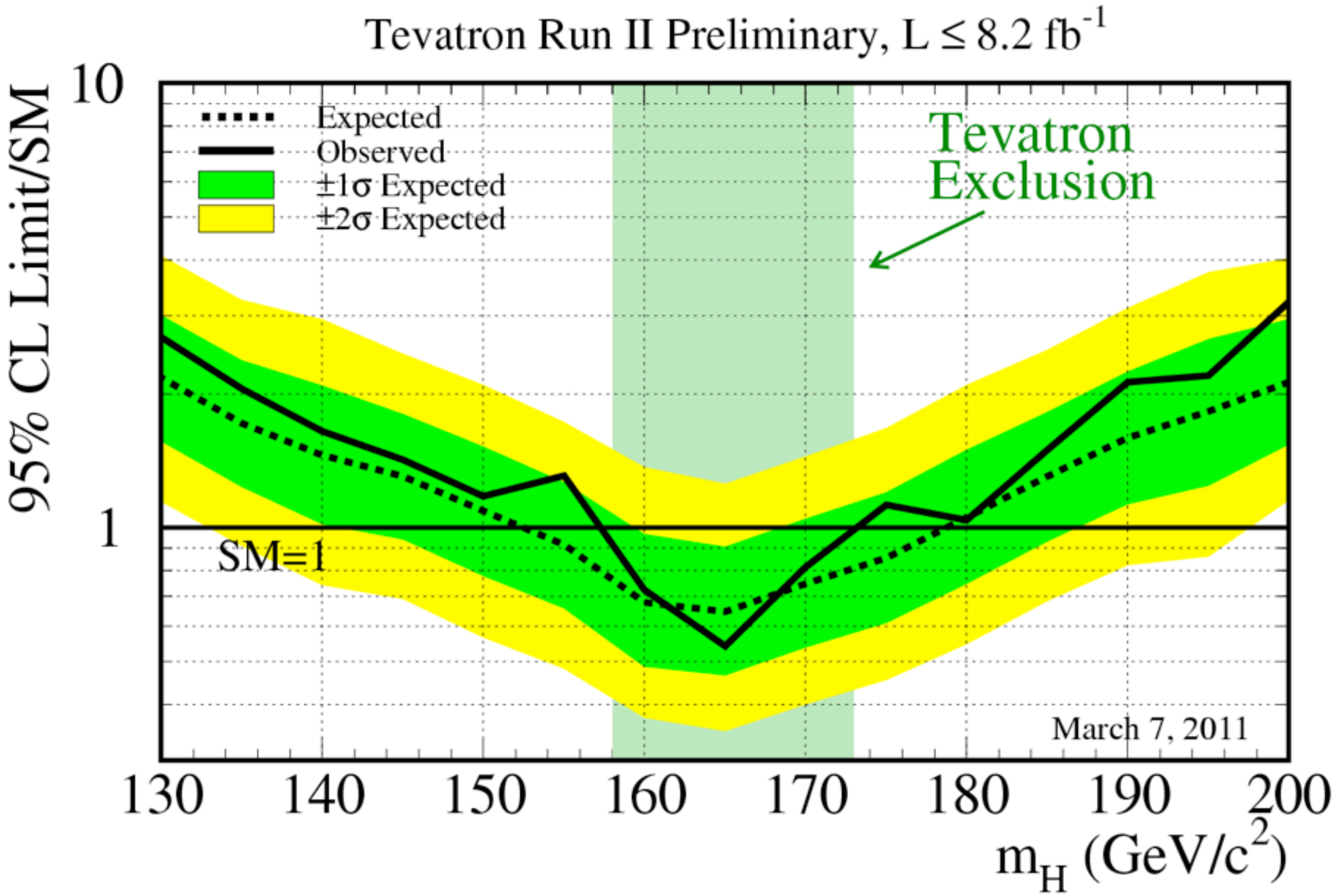
It is a fact that all NNLO fits (except MSTW) have lower $\alpha_S(m_Z)$

	$\alpha_s(M_Z^2)$	
BBG	$0.1134\ ^{+0.0019}_{-0.0021}$	valence analysis, NNLO [1]
GRS	0.112	valence analysis, NNLO [2]
ABKM	0.1135 ± 0.0014	HQ: FFNS $N_f = 3$ [3]
ABKM	0.1129 ± 0.0014	HQ: BSMN-approach [3]
JR	0.1124 ± 0.0020	dynamical approach [4]
JR	0.1158 ± 0.0035	standard fit [4]
MSTW	0.1171 ± 0.0014	[5]
ABM	0.1147 ± 0.0012	FFNS, incl. combined H1/ZEUS data [6]
Gehrmann et al.	$0.1153 \pm 0.0017 \pm 0.0023$	e^+e^- thrust [7]
Abbate et al.	$0.1135 \pm 0.0011 \pm 0.0006$	e^+e^- thrust [8]
BBG	$0.1141\ ^{+0.0020}_{-0.0022}$	valence analysis, N^3LO [1]
world average	0.1184 ± 0.0007	[9]

S. Alekhin, J.Blumlein, H. Bottcher, S.Moch (2011)

You think this is boring ?
Let's see implications for Higgs search

Higgs



Recent Tevatron combination excludes a SM Higgs boson with 158 GeV $\leq m_H \leq$ 173 GeV

Based on our computation of $gg \to H$ cross section including all known higher order effects done with MSTW2008 PDFs

D. de Florian, MG (2009)

Exclusion challenged by Djouadi et al.

Computation using ABKM or HERAPDFs leads to a cross section smaller by 20-50 % !

Preliminary NNPDF2.5 NNLO support MSTW2008 and thus the Tevatron exclusion

Summary

- Despite its (well) known problems the SM is still in good shape
- Few tensions (EW fit, g-2, top asymmetry.....) could hide new physics but difficult to say at present
- In the meanwhile the SM is being rediscovered at the LHC

  ➡ Impressive collection of new results already with 2010 data !

- Lot of progress in theoretical predictions and tools
- We need a conservative (and reliable) average for $\alpha_S(m_Z)$

EAGERLY WAITING FOR THE NEW LHC RESULTS IN 2011 !