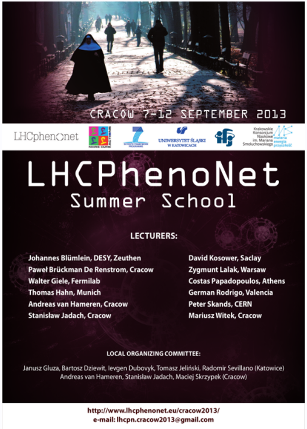
Why Precision ?



Johannes Blümlein, DESY

Contents

Why Precision ? (in experiment and theory)

- T. Brahe (-1601) Detailed measurement of planetary motion. Rudolphine Tables;
  $\Longrightarrow$ J. Kepler (1609, 1618) Laws of planetary orbit;
  $\Longrightarrow$ I. Newton (1686) Classical Gravity.
- A. Michelson (1881) The velocity of light is constant (in flat space).
  $\Longrightarrow$ A. Einstein (1905) Special Relativity. [Possible exception: arXiv:1109.4897]. **measurement error.**
- O. Lummer, E. Pringsheim, H. Rubens, and F. Kurlbaum (1900) measure precisely the Spectrum of the black body radiation.
  $\Longrightarrow$ M. Planck (1900) Quantization of the action.
- O. Stern and O. Frisch (1933) Anomalous magnetic moment of the proton.
  $\Longrightarrow$ SLAC-MIT experiments (1968/69), final discovery:
  The proton consists of quark-gluon partons.
- C. Prescott et. al. (1979) Electro-weak asymmetry in DIS γ-Z interference.
  UA1, UA2 (1983) Production of W and Z bosons.
- M. Veltman (1977) ρ-parameter depends on m_t^2/m_b^2; $\Longleftarrow$SCHOONSHIP
  $\Longrightarrow$ Tevatron (1994/95) Top discovery.
- Precise Loop corrections to the Standard Model
- Discovery of a Higgs-like Boson

The present challenges

Experiment:

- Precision Mass measurements of the top quark: LHC, ILC
- Unraveling neutrino masses and mixing: ν facilities, astrophysics
- Precision measurements of the quark mixing: B-factories
- Precision measurement of the coupling constants $(\alpha_s(M_Z))$: various facilities
- Mass and Width of the Higgs Boson: LHC
- Which Higgs-boson is it? utmost precise measurements are needed LHC
- Finally reveal New Particles and/or Forces.

The present challenges

Theory:

- 4- and 5-loop calculation in QCD for zero-scale quantities (massless and massive)
- Electro-weak, QCD, and MSSM 2-loop calculations: $2 \to n$ processes
- Massless and massive, unpolarized and polarized QCD calculations at the 3-loop level, single differential
- NNLO $ep, pp \to 2$ and 3 jet cross sections
- Always faster analytic resp. numeric ways from diagrams $\Longrightarrow$ cross sections
- Match the experimental precision; QCD: theory errors below 1%
- Precise understanding of all 'backgrounds' to the anticipated discoveries

Scrutinize the known Quantum Field Theories
at the deepest possible level.

Quantum Field Theory

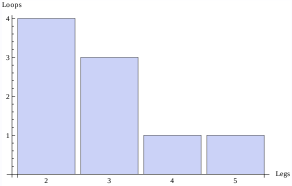
$\Downarrow$

Scattering Cross Sections

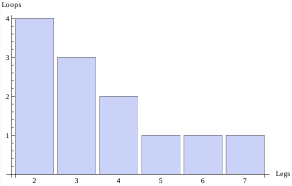
$\Uparrow$ $\Uparrow$

Mathematics Algorithmics

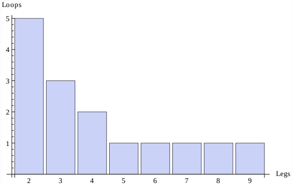
Loops versus Legs



circa 2007



2011



2013

5 Loops, 2 Legs Baikov, Chetyrkin, Kühn, Sturm: 5-loop β-function of QED [1207.2199]
9 Legs,NLO S. Weinzierl et al. $e^+e^- \to 7$ jets [1111.1733]
8 Legs,NLO Z. Bern et al. $pp \to W + 5$ jets [1304.1253]

Multi-Leg Processes

NLO corrections: - a rapidly developing field $2 \to 2 \dots 7$ processes; > 2009

- $pp \to W^{\pm}(Z) + 2 \dots 5$ jets
- $pp \to t\bar{t}b\bar{b}$
- $pp \to t\bar{t} + 2$ partons
- $pp \to W^{\pm}W^{\pm}b\bar{b}$
- $pp \to H + 3$ jets
- $pp \to b\bar{b}b\bar{b}$
- $e^{+}e^{-} \to 7$ jets

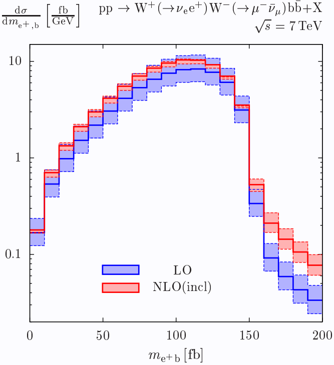
Belivaqua, Badger, Becker, C. Berger, Bern, Binoth Bredenstein, Campanario, Campbell, Czakon, Cullen, Denner, Diana, Dittmaier, Dixon, R.K. Ellis, Englert, Febres Cordero, Fleischer, Forde, Frederix, Frixione, Fujimoto, Gleisberg, Gluza, Goetz, Greiner, Guffanti, Guillet, Heinrich, Hirschi, Höche, Ita, Jadach, Kallweit, Kauer, Kerner, Kosower, Kubocz, Maitre, Maierhöfer, Mastrolia, Melia, Melnikov, Ninh, Ozeren, Papadopoulos, Pittau, Pozzorini, Rauch, Reiter, Reuschle, Reuter, Riemann, Rontsch, Schulze, Schwan, Tramontano, Uwer, Weinzierl, Williams, Worek, van Hameren, Yost, Yundin, Zanderighi, Zeppenfeld, and many others.

NLO Multi-Leg Calculations

Computational Techniques

- MHV amplitudes
- unitarity method
- cutting techniques
- stable numerical implementations for resonances
- stable numerical implementations: 5-, 6-, 7-point functions

One example :



Denner, Dittmaier, Kalweit, Pozzorini: LO (blue) and NLO (red) predictions for the M_{be^+} distribution at the LHC (7TeV). This invariant mass distribution of the visible top-decay products is characterised by a kinematic bound ($M_{eb}^2 < M_t^2 - M_W^2$) that can be exploited for a precision measurement of M_t.

NLO Multi-Leg Tools: virtual corrections, real emission

AutoDipole:	Hasegawa, Moch, Uwer
CutTools:	Ossola, Papadopoulos, Pittau
GOLEM/Gosam:	Binoth, Guillet, Heinrich, Pilon Reiter
GRACE:	Yuasa, Ishikawa, Kurihara, Fujimoto, Shimizu, Hamaguchi, de Doncker, Kato et al.
Helac/Phegas:	Czakon, Papadopoulos, Worek
LoopTools:	Hahn et al. + Feynarts, FormCalc
MadDipole:	Frederix, Greiner, Gehrmann
MadFKS:	Frederix, Frixions, Maltoni, Stelzer
MadLoop:	Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau
MCFM:	Campbell, R.K. Ellis, Williams, et al.
MC@NLO:	Frixione, Webber
NGluon:	Badger, Biedermann, Uwer
NLOJET++:	Nagy, Trocsanyi
OpenLoops:	Cascioli, Maierhöfer, Pozzorini
POWEG:	Frixione, Nason, Oleari et al.
Rocket:	Giele, Zanderighi
Samurai/Gosam:	Mastrolia, Ossola, Reiter, Tramontano
SHERPA:	Gleisberg, Krauss et al.
TeVJet:	Seymour, Tevlin
NLO evo. kernels:	Kusina, Jadach, Skrzypek, Slawinska
and others:	Lazopoulos; Giele, Kuszt, Winter; Melnikov, Schulze; Gluza, Kajda, Riemann, Yundin

Resummations and Infrared Structure

Resummation of large logs : → survey by L. Magnea [2011]

- RGE logs $\alpha^k \ln^k(Q^2/\mu^2)$
- High energy logs $\alpha^k \ln^{k-1}(s/t)$
- Sudakov logs $\alpha^k \ln^{2k-1}(1-z), \quad z = \mu_1^2/\mu_2^2$
- Resummation of Coulomb singularity

Long history :
Bloch, Nordsiek 1937; Grammer, Yennie, Parisi, Curci, Greco, Sen, Collins, Soper, Sterman, Catani, Trentadue, ... 1973-1993.

- Proof of Resummability requested.
- Apply a resummation only when it dominates kinematically.
- Improve a known fixed order result towards higher orders in critical phase space regions.

Resummations and Infrared Structure

- All-order structure of the perturbative exponent is understood

  $d\sigma(\alpha_s, N) = H(\alpha_s)\exp\left[\ln(N) g_1(\alpha_s, N) + g_2(\alpha_s, N) + \alpha_s g_3(\alpha_s, N) + \ldots\right] + O(1/N)$

- New insights from SCET
- Resummation beyond the eikonal approximation
- Vast amount of phenomenological applications
  [hadronic final states, jets, event shapes, Drell-Yan process, Higgs, $t\bar{t}$]

Examples are:

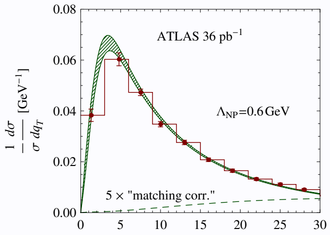
Neubert et al.:	Precision collider physics from SCET
	Higgs, DY: low q_T resummation; transverse pdf
Magnea et al.:	Infrared Singularities at High Energy
	→ surprisingly simple relation for the anomalous dimensions
	→ resumming high energy logs (Reggeization)
	→ very promising scenario to clearly work out the realm of "small x" phyiscs to higher orders
Beneke et al.	NNLL $t\bar{t}$ total cross section; also Coulomb singularity resummation
Vogt et al.	Large x resummation in semi-inclusive e^+e^- annihilation
Ward et al.	Amplitude-Based Resummation in QFT

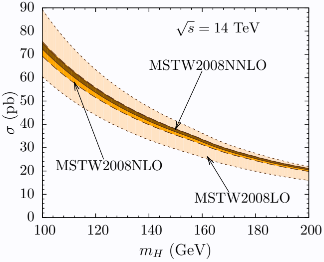
Other recent contributions by:

Abbate et al., Ahrens, Almasy, Aybat, Banfi et al., Baur et al., Becher, Bozzi et al., Cacciari, Catani, Cien, Czakon, de Florian, Dixon, Falgari, Ferroglia, Frixione Gardi, Grazzini, Grunberg, Hagiwara, Kidonakis, Kiyo, Klein, Krämer et al., Kühn, Kulesza et al., LoPresti, Laenen, Magnea, Mitov, Moch et al., Mantry, Nason, Neubert, Pecjak, Petriello, Ravindran, Salam, Schwartz, Schwinn, Steinhauser Sterman et al., Sumino, Sung, Uwer, Vogelsang, White, Yang, Yokoya, Zanderighi and others

Resummations and Infrared Structure

Examples:
DY process & hadronic Higgs production





left: DY q_T resummation @ LHC7: Becher, Neubert, Wilhelm, arXiv:1109.6027

right: $pp \to H^0$ @ LHC14: $\to$ NNLO (N3LL) Ahrens et al. Phys.Lett. B698 (2011) 271.

Precision Calculations for Low-Energy Processes

Important domain of precision physics.

- running of α_{QED}
- $(g\text{-}2)$, Jegerlehner, Marciano, Melnikov, Nyffeler, et al.
- G_F
- QED bound states Czarnecki et al.

Contributions by:

Gluza: High precision luminosity monitor:
NNLO corrections to Bhaba-scattering for lower energy e^+e^- colliders,
GigaZ, ILC, see also Carloni Calame et al. JHEP 1107 (2011) 126

Szafron: ρ-γ mixing and e^+e^- vs τ spectral function:
ρ-width effects in the pion form factor $\Longrightarrow a_\mu^{\rm had}$

Multi-Loop Corrections

Some Recent Results :

- Baikov, Chetyrkin, Kühn, Rittinger:

$$
\begin{aligned}
R(s) &= 3\sum_f Q_f^2 \left[1 + \mathrm{a_s} + \mathrm{a_s^2}\left(1.986 - 0.1153 N_F\right) \right. \\
&\quad \left. - \mathrm{a_s^2}\left(6.637 + 1.200 N_f + 0.00518 N_F^2\right)\right] \\
&\quad - \left(\sum_f Q_f\right)^2 \left[1.2395\,\mathrm{a_s^3} - \left(17.8277 - 0.57489 N_F\right)\mathrm{a_s^4}\right] \\
\beta_{\mathrm{QED}} &= \frac{4}{3}a + 4a^2 - \frac{62}{9}a^3 - \left(\frac{5570}{243} + \frac{832}{9}\zeta_3\right)a^4 \\
&\quad - \left(\frac{195067}{486} + \frac{800}{3}\zeta_3 + \frac{416}{3}\zeta_4 - \frac{6880}{3}\zeta_5\right)a^5
\end{aligned}
$$

- Pak, Rogal, Steinhauser NNLO $pp \to$ (pseudo) scalar Higgs
  $m_{S,P} = 120$ GeV very small mass corr. $m_{S,P} = 300$ GeV: 9% (S); 22% (P)

Jets at Hadron Colliders

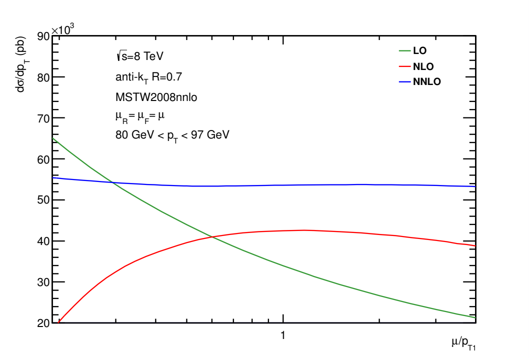
$$d\hat{\sigma}_{ij} = \mathrm{a_s} d\hat{\sigma}_{ij}^{\mathrm{LO}} + \mathrm{a_s^2} d\hat{\sigma}_{ij}^{\mathrm{NLO}} + \mathrm{a_s^3 d}\hat{\sigma}_{\mathrm{ij}}^{\mathrm{NNLO}}$$

- $2 \to 2$ NNLO processes at LHC
  Virtual 2-loop corrections $2 \to 2$:
  - $pp \to 2j$ (C. Anastasiou, N. Glover, C. Oleari, M. Tejeda-Yeomans; Z. Bern, L. Dixon, A. De Freitas)
  - $pp \to V + j$ (L. Garland,T. Gehrmann N. Glover, A. Koukoutsakis, E. Remiddi)
  - $pp \to V\gamma$ (T. Gehrmann, L. Tancredi, E. Weihs)
  - $pp \to H + j$ (T. Gehrmann, N. Glover, M. Jaquier, A. Koukoutsakis)
  - $pp \to t\bar{t}$ (P. Bärnreuther, M. Czakon, P. Fiedler; R. Bonciani, A. Ferroglia, T. Gehrmann, A. von Manteuffel, C. Studerus)

  2-loop corrections $2 \to 3$ (different masses):
  Needed or the 3/2 jet ratio to measure $\alpha_s(M_Z^2)$
- To have $ep \to 3$ jets @ NNLO is of great importance.
  $\Longrightarrow$ the precise HERA jet data await NNLO analysis.

Jets at Hadron Colliders

The gg-contribution at NNLO for $pp \to 2$ jets has been completed.

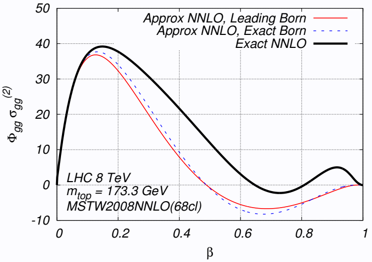


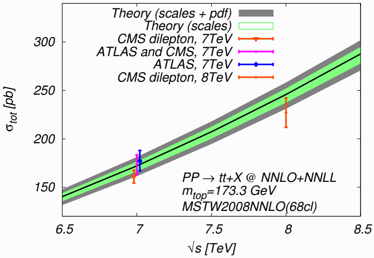
The NNLO scale dependence turns out to be flat and is therefore important for a precise extraction of $\alpha_s(M_Z^2)$ and the gluon distribution from the LHC jet-data.

A. Gehrmann-De Ridder, T. Gehrmann, E.W.N. Glover, J. Pires: Gluonic NNLO corrections to $pp \to 2jets$ [1301.7310]

$t\bar{t}$ Production

Inclusive $t\bar{t}$ production cross section at NNLO has been accomplished by the gg-contributions.





Luminosity-weighted gluonic cross section A prediction for the LHC

M. Czakon, P. Fiedler, A. Mitov: gluonic NNLO corrections to $pp \to t\bar{t}$ [1303.6254]

Mathematical Methods in Feynman Diagram Calculations

Depending on the number of loops, legs & scales, the calculations can be either performed analytically, semi-analytically, or numerically.

Computer Languages

- Numerics/CA: Fortran, C, C++ $\Longrightarrow$ large farms
- CA: FORM: J. Vermaseren
  - as TFORM and PARFORM $\Longrightarrow$ threaded main frames and/or farms
- CA: mathematica, maple: main frames $\leq$ 200 - 300 Gbyte RAM

Result Languages

- Zero dim. quantities: special numbers
  EZVs,MZVs, generalized MZVs over certain number alphabets, cyclotomic extensions, elliptic integrals, ...
- Single dim. quantities: harmonic sums, harmonic polylogarithms, generalized harmonic sums, hyperlogarithms, cyclotomic and other extensions,...

Diagram Generation

- Diagram Generator QGRAF: P. Nogueira
- Graph polynomials: Bogner, Weinzierl

Mathematical Methods in Feynman Diagram Calculations

0-dim quantities: Integration/Summation

- MINCER: Gorishni, Larin, Suguladze,Tkchaov, Vermaseren '89/91
- Baikov's method: Baikov '96
- MATAD: Steinhauser '01
- qexp: Harlander, Seidensticker, Steinhauser '98/99
- SIGMA, EvaluateMultiSums, SumProduction: C. Schneider '01-
- PSLQ methods: Broadhurst; Lee, Smirnov, Smirnov '11
- Hyperlogarithms(∞): F. Brown '08

1-dim and higher quantities:

- Integration by parts
  J. Lagrange 1760/61; G. t Hooft, M. Veltman, '72, K. Chetyrkin, A. Kataev, F. Tkachov, '80, S. Laporta, '00, Anastasiou, Lazopoulos '04 AIR Smirnov '08 FIRE[mathematica], Lee '08,'12, Studerus, von Manteuffel '12 REDUZE 2, + many private codes]; mathematica-based codes are very slow.
- Sector Decomposition
  [Hepp '66; Binoth, Heinrich '00; Nagy, Soper '06; Anastasiou, Beerli, Daleo '07] sector_decomposition [Bogner, Weinzierl '07]; FIESTA2 [Smirnov, Smirnov, Tentyukov '09]; CSectors [Gluza, Kajda, Riemann, Yundin '10]; SecDec [Carter, Heinrich '11]

Mathematical Methods in Feynman Diagram Calculations

- Use of Mellin-Barnes Integrals for Feynman Diagrams
  [Bergere, Lam, '74; Ussyukina, Davydychev '89]
  MB.m, MBasymptotics.m [Czakon, '05,'06]; barnesroutines.m [Kosower '07];
  AMBRE.m [Gluza, Kajda, Riemann '07]; MBresolve [Smirnov, Smirnov '09]
- Differential Equations
  [Kotikov '91, Caffo, Czyz, Laporta, Remiddi '98, Gehrmann, Remiddi, 2000;
  Czyz, Caffo, Remiddi '02]; various applications
- Generalized Hypergeometric and relarted Functions
  [Kalmykov, Ward, Yost, Kniehl, Bytev, 2004–2011]; [Ablinger, JB, Hasselhuhn,
  Klein, Schneider, Wißbrock 2009-]; HypExp, HypExp 2 [Huber, Maitre '08];
  HyperDire [Bytev, Kalmykov, Kniehl '11] half-integer expansions,
  [Weinzierl,2004];
- Difference Equations
  [Moch, Vermasern, Vogt, '99, '04, 05; Bierenbaum, JB, Klein, Schneider, '08;
  JB, Kauers, Klein, Schneider, '09, and various later papers.
- Multiple general sums in difference and product fields:
  SIGMA, EvaluateMultiSums, SumProduction [Schneider '01-],
  ρ-Sum [Round '12]
  Multiple Summation [JB, Klein, Schneider, Stan '10]
- Simplifying HPLs with complicated arguments : Symbol and co-product
  Goncharov, Spradlin, Volovich, Vergu '10; Duhr '12

Mathematical Methods in Feynman Diagram Calculations

- Recurences from moments: guess [Kauers '08-]
- Integrating holonomic functions: [Almkvist, Zeilberger '91]

Functional Representations and Properties:

- Multiple Zeta Values
  MZV data base [JB, Broadhurst, Vermaseren '09]
- Harmonic Sums and Generalizations
  [Vermaseren '98; JB, Kurth '98, Moch, Uwer, Weinzierl '01, JB '03, '09]; summer [Vermaseren '98]; harmol [Remiddi, Vermaseren '99]; hpl [Gehrmann, Remiddi '01]; nestedsums [Weinzierl '02]; numerical ev. of HPL [Vollinga, Weinzierl'04]; HPL [Maitre '06]; XSummer [Moch, Uwer '06]; HarmonicSums [Ablinger '09-]; CHAPLIN [Buehler, Duhr '11];

The package HarmonicSums allows to handle harmonic sums, generalized harmonic sums, (generalized) cyclotomic sums, binomially weighted (generalized) cyclotomic sums and their associated numbers and iterated integrals.

Mathematical Methods in Feynman Diagram Calculations

- Analytic calculations : Do not proliferate !
- Avoid gigantic Zeroes in analytic calculations. They are usually caused by violating the symmetry of the problem using too simple methods: IBP, MB, binomial expansion, and similar others.
- Any reduction has to reduce the problem, but not just to re-order.
- Forming out of a 4-fold integration a 5-fold nested sum constitutes no reduction.

Parton Distribution Functions for the LHC

- All physics at Hadron Colliders (LHC, Tevatron) very sensibly depends on the detailed knowledge of the parton distribution functions.
- The current experimental precision requests to refer to the NNLO PDFs for inclusive observables.

- ABM
- CTEQ
- HERAPDF
- JR
- NNPDF
- MSTW

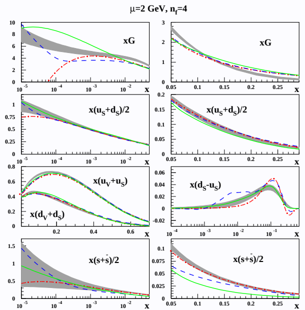


Figure 14: The 1σ band for the 4-flavor NNLO ABM11 PDFs at the scale of $\mu = 2$ GeV versus x obtained in this analysis (shaded area) compared with the ones obtained by other groups (solid lines: JR09, dashed dots: MSTW08, dashes: NN21.

Parton Distribution Functions

Mandatory aspects

- NNLO pdfs (basically achieved by all groups)
- use consistent precision data in fits
- combined H1+ZEUS data (2009) have to be included (ABKM,ABM HERAPDF, JR, NNPDF)
- statistical analysis: $\Delta\chi^2 = 1$ (do not rescale experimental errors)
- correct treatment of systematics (no simple addition in quadrature)
- precision data sets have to be reflected appropriately in the fit result
- first: make predictions for LHC prior just fitting the new data

PDF Moment from the Lattice

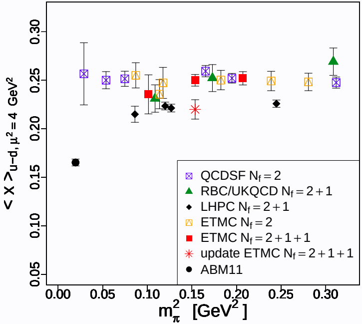
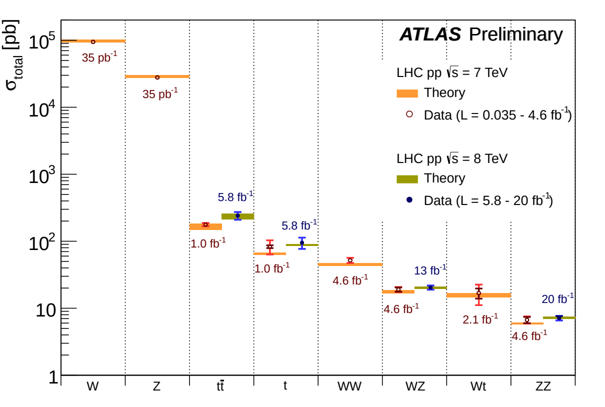


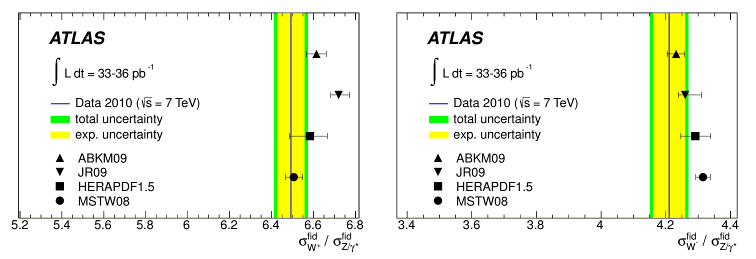
Figure 24: Comparison of lattice computations for the second moment of the non-singlet distribution as a function of the pion mass m_π with the result of ABM11 along with the uncertainties of the respective measurement.

Accuracy of Standard Model Processes at LHC



$W^{\pm}$ and Z^0 production cross sections at the LHC

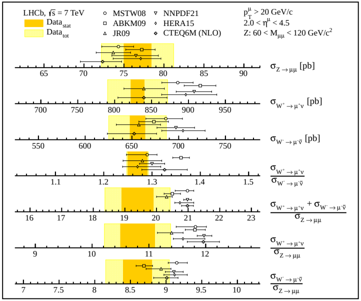
Recent measurements of $W^{\pm}$ and Z-production cross sections at ATLAS
arXiv:1109.5141



$W^{\pm}/Z$ cross section ratios will constrain parton distributions:
ATLAS, CMS, LHCb
Similarly, this is expected from off-resonance Drell-Yan data.

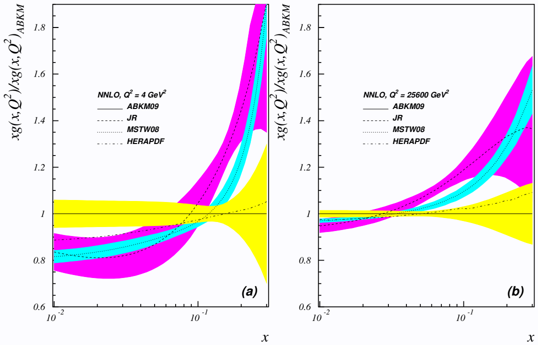
$W^{\pm}$ and Z^{0} production cross sections at the LHC

Recent measurements of $W^{\pm}$ and Z-production cross sections at LHCb arXiv:1204.1620



$W^{\pm}/Z$ cross section ratios will constrain parton distributions:
Observe the different pattern compared e.g. to ATLAS.
$\Longrightarrow$ excellent sensitivity to constrain sea quarks further.

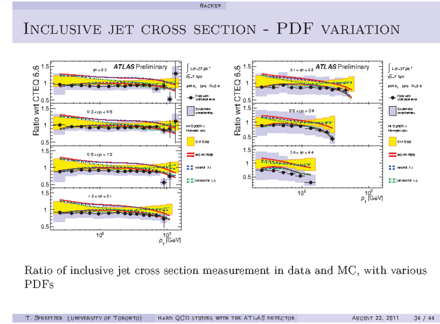
NNLO Gluon Distributions

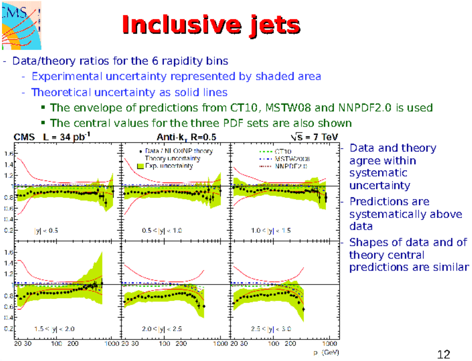


$\Longrightarrow$ Current differences in the gluon densities have significant impact on the jet- and inclusive Higgs production cross sections at Tevatron and LHC.

S. Alekhin, J. Blümlein, P. Jimenez-Delgado, S. Moch, E. Reya, Phys.Lett. B697 (2011) 127.

Jet measurement at LHC

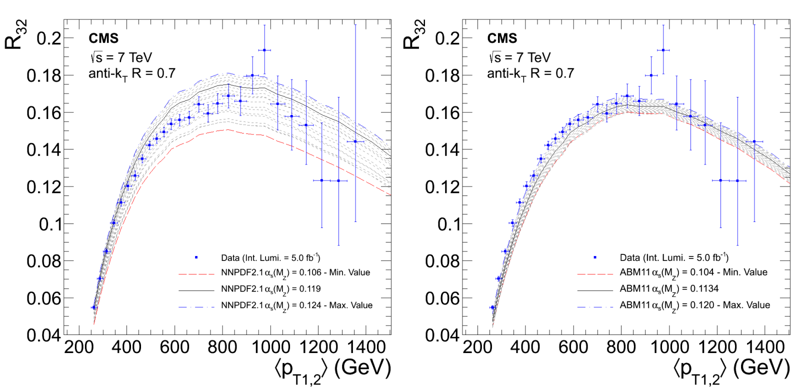




Spreitzer (ATLAS), Lenzi (CMS), St. Andrews 2011

Tevatron-data tuned PDFs somewhat overshoot LHC data.

Jet measurement at LHC



NLO: NNPDF vs ABM

CMS: arXiv:1304.7498

Applications: i) $\alpha_s(M_Z^2)$

$\alpha_s(M_Z^2)$ from NNLO DIS(+) analyses

	$\alpha_s(M_Z^2)$	
BBG	$0.1134\ ^{+0.0019}_{-0.0021}$	valence analysis, NNLO
GRS	0.112	valence analysis, NNLO
ABKM	0.1135 ± 0.0014	HQ: FFNS $N_f = 3$
JR	0.1128 ± 0.0010	dynamical approach
JR	0.1140 ± 0.0006	including NLO-jets
MSTW	0.1171 ± 0.0014	(2009)
MSTW	$0.1155 - 0.1175$	(2013)
ABM11$_J$	$0.1134 - 0.1149 \pm 0.0012$	Tevatron jets (NLO) incl.
ABM13	0.1133 ± 0.0011	
ABM13	0.1132 ± 0.0011	(without jets)
CTEQ	0.1159..0.1162	
CTEQ	0.1140	(without jets)
NN21	$0.1174 \pm 0.0006 \pm 0.0001$	
Gehrmann et al.	$0.1131\ ^{+\ 0.0028}_{-\ 0.0022}$	e^+e^- thrust
Abbate et al.	0.1140 ± 0.0015	e^+e^- thrust
BBG	$0.1141\ ^{+0.0020}_{-0.0022}$	valence analysis, N^{3}LO

$$\Delta_{\rm TH}\alpha_s = \alpha_s({\rm N^3LO}) - \alpha_s({\rm NNLO}) + \Delta_{\rm HQ} = +0.0009 \pm 0.0006_{\rm HQ}$$

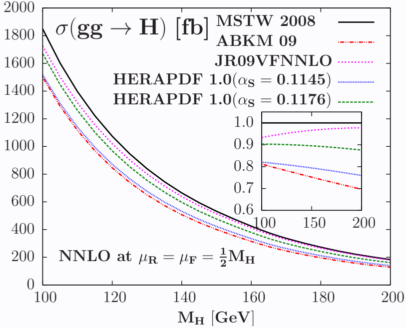
Applications: i) $\alpha_s(M_Z^2)$

$\alpha_s(M_Z^2)$ from further processes

	$\alpha_s(M_Z^2)$	
3 jet rate	0.1175 ± 0.0025	Dissertori et al. 2009
Z-decay	0.1190 ± 0.0026	BCK 2008
τ decays	0.1202 ± 0.0019	BCK 2008
τ decays	0.1212 ± 0.0014	Pich 2010
τ decay	0.1191 ± 0.0022	Boito et al. 2012
lattice	0.1205 ± 0.0010	PACS-CS 2009 (2+1 fl.)
lattice	0.1184 ± 0.0006	HPQCD 2010
lattice	0.1200 ± 0.0014	ETM 2012 (2+1+1 fl.)
lattice	0.1156 ± 0.0022	Brambilla et al. 2012 (2+1 fl.)
lattice	0.1181 ± 0.0014	JLQCD
Average 2012	0.1184 ± 0.0007	S. Bethke

Despite the statistical and systematic errors are getting smaller, there is no final consensus on the value of $\alpha_s(M_Z^2)$ yet.

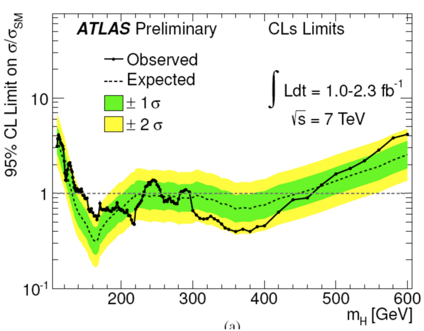
Applications: ii) Higgs Search [2011]



The $gg \to H$ cross section as a function of M_H when the four NNLO PDF sets, MSTW, ABKM, JR and HERAPDF, are used. In the inserts, shown are the deviations with respect to the central MSTW value; Baglio, Djouadi, Godbole, 2011

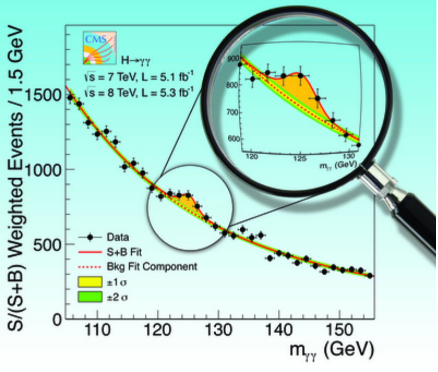
The exclusion limits depend on the pdf's and the value of $\alpha_s(M_Z)$ used. In particular, the predictions vary by up to 40 % for Tevatron.

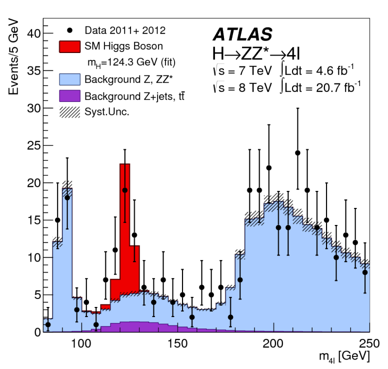
Applications: ii) Higgs Search [2011]



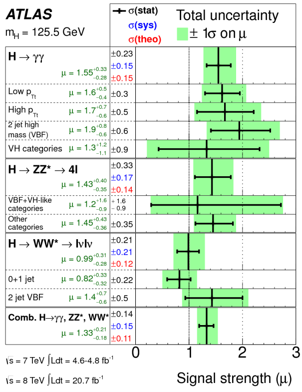
95 % exclusion limits: ATLAS 146-232, 256-282, 296-466 GeV
CMS 145-216, 226-288, 310-340 GeV, LP 2011

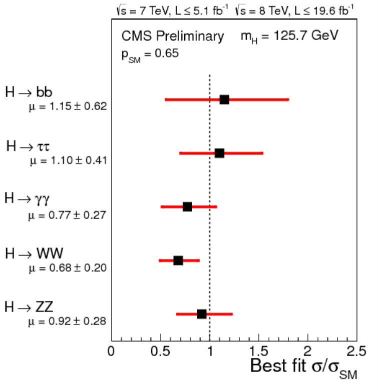
Applications: ii) Higgs Search: Branchings [2013]



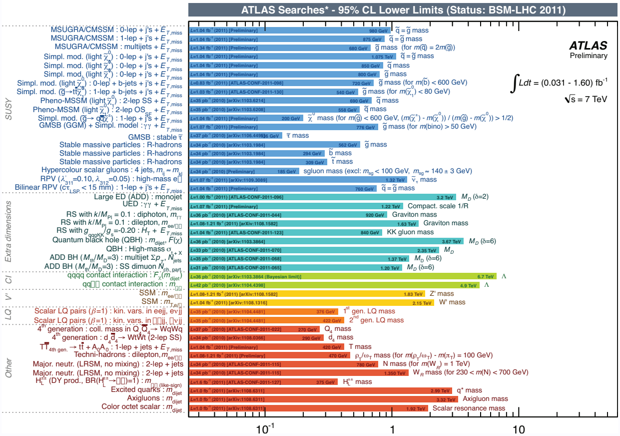


Applications: ii) Higgs Search: Signals [2013]



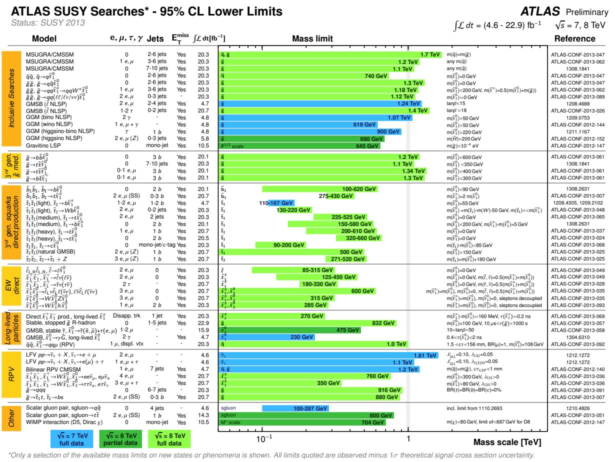


Beyond the Standard Model [2011]



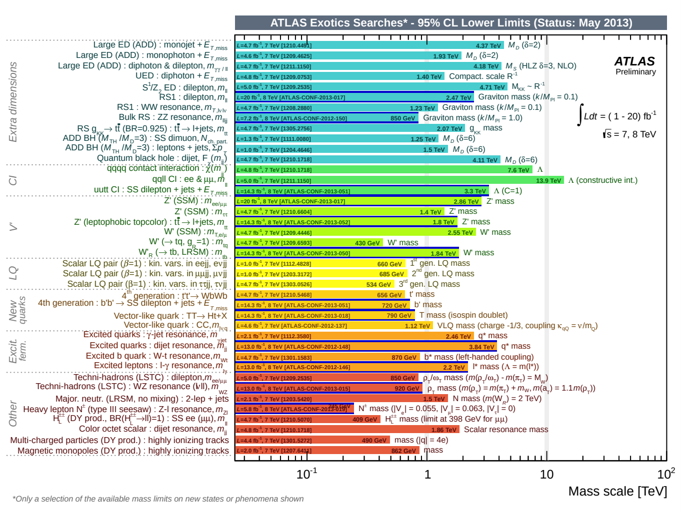
SUSY exclusion reaches masses ∼ 1 TeV, ATLAS, BEM-LHC, Trieste, 2011

Beyond the Standard Model [2013]



SUSY exclusion reaches masses ~ 1 TeV in more channels

Beyond the Standard Model [2013]



Higher limits for other exotica

Beyond the Standard Model

- SUSY: 2-loop corrections, multi-leg processes at NLO; important to search for possible signals
- increasing number of studies using higher order corrections for other BSM processes
- No signals yet.

Key questions :

- How exactly are the fundamental masses are generated ?
- Do the Higgs couplings come out right ?
- Is the neutrino sector special ?
- Do the fundamental forces unify and where ?
- The particle spectrum of potential new fundamental states.
- What is the role of gravity ?

High Precision High Energy Physics

- The field is in good shape.
- Many more precison measurements will be performed at various colliders. (LHC, lower energy facilities, JPARC; planned: B-factory, EIC, ILC).
- Calculational tools do vastly evolve (NLO automation; highly efficient numerical computing; intense use of computer algebra; new mathematical technologies).
- NLO reached 9 point functions.
- Resummations are needed in many places; bridging to non-perturbative regions.
- Many NNLO calculations, including masses; 5 loop 2-leg calculations.
- 4-loop QCD corrections started and more are to come.
- Renormalizable QFTs start to request Tbyte CPUs to solve problems analytically.
- Sophisticated integrations turn more and more into algebraic problems.

We all enjoy to contribute to and to witness these facinating and groundbreaking computations in one of the most fundamental fields of science.