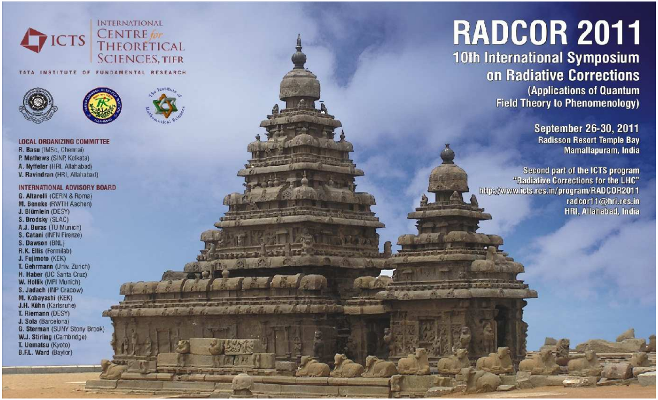
Why Precision ?



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].
- 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
- Constraints on the Higgs 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
- If the Higgs is not there: utmost precise measurements of weak boson scattering cross sections needed: LHC
- Finally reveal New Particles and/or Forces.

Surveys by: J. Katzy (ATLAS), M. Pieri (CMS).

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 $ep, pp \to 3$ 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

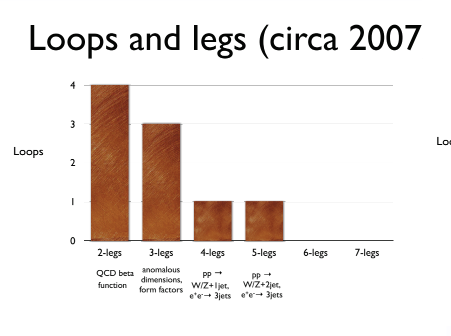
$\Downarrow$

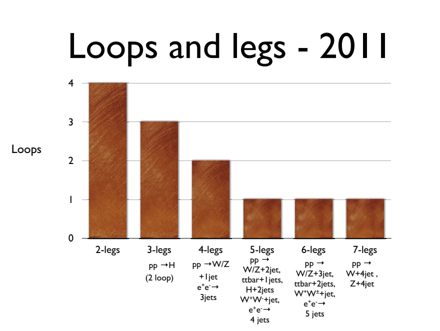
Scattering Cross Sections

$\Uparrow$ $\Uparrow$

Mathematics Algorithmics

Loops versus Legs





(courtesy R.K. Ellis)

Multi-Leg Processes

NLO corrections: - a rapidly developing field $2 \to 4(5)$ processes; > 2009

- $pp \to W^{\pm}(Z) + 3(4)$ jets
- $pp \to t\bar{t}b\bar{b}$
- $pp \to t\bar{t} + 2$ partons
- $pp \to W^{\pm}W^{\pm}b\bar{b}$
- $pp \to b\bar{b}b\bar{b}$
- $e^+e^- \to 5$ jets

Belivaqua, C. Berger, Bern, Binoth Bredenstein, Campbell, Czakon, Denner, Dittmaier, Dixon, R.K. Ellis, Febres Cordero, Forde, Frederix, Frixione, Gleisberg, Greiner, Guffanti, Guillet, Heinrich, Ita, Kallweit, Kosower, Maitre, Melia, Melnikov, Papadopoulos, Pittau, Pozzorini, Reiter, Reuter, Rontsch, Schulze, Uwer, Weinzierl, Williams, Worek, van Hameren, Zanderighi, and others.

Multi-Leg Processes and Monte Carlo

Contributions by:

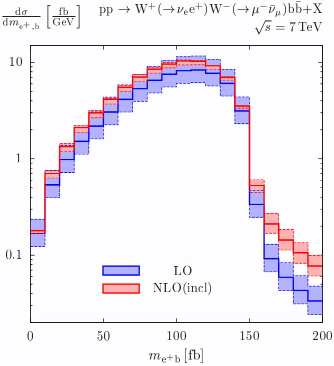
van Hameren:	Hard multi-particle processes at NLO QCD
Pozzorini:	NLO QCD corrections to hadronic $W^+W^-b\bar{b}$ production
Becker:	Multiparton NLO corrections by numerical methods
Englert:	Results in precision multiboson+jet phenomenology
Shivaji:	Multi vector boson production via gluon fusion
Riemann:	Tensor reduction for one loop Feynman integrals (7 point fct.)
Fujimoto:	GRACE
Heinrich:	Golem/Samurai
Melia:	W^+W^-jj NLO
Maierhöfer:	A recursive one-loop algorithm for many-particle amplitudes
Kauer:	Signal-background interference in $gg \to H \to VV$, which is not small (also: Campbell, Ellis, Williams, 1107.5569)
Yost:	Herwiri2.0; EW+QCD corr. to $pp \to Z^*$ + exponentiation
Hirschi:	aMC@NLO
Kubocz:	Alternative NLO subtraction
Badger:	1-loop corrections to multi jets; (Berends-Giele + unitarity method); 12-14 gluons
Gaunt:	Double parton scattering singularity in one-loop integrals; applied to sufficiently hard processes

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:	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:	= CutTools + MadFKS 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
POWEG:	Frixione, Nason, Oleari et al.
Rocket:	Giele, Zanderighi
Samurai:	Mastrolia, Ossola, Reiter, Tramontano
SHERPA:	Gleisberg, Krauss et al.
TeVJet:	Seymour, Tevlin
NLO evo. kernels:	Kusina, Jadach, Skrzypek, Slawinska
more to come:	Lazopoulos; Giele, Kuszt, Winter; Melnikov, Schulze; Gluza, Kajda, Riemann, Yundin

Resummations and Infrared Structure

Resummation of large logs : → recent survey by L. Magnea

- 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, $t\bar{t}$]

Contributions by:

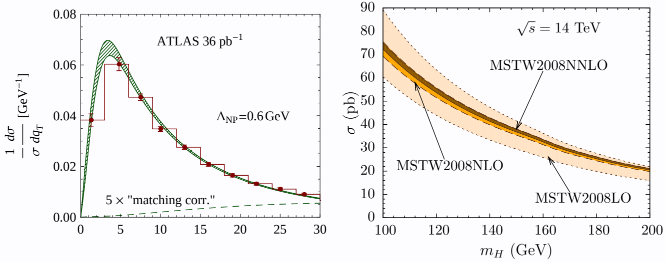
Neubert:	Precision collider physics from SCET
	Higgs, DY: low q_T resummation; transverse pdf
Magnea:	Infrared Singularities at High Energy
	$\rightarrow$ surprisingly simple relation for the anomalous dimensions
	$\rightarrow$ resumming high energy logs (Reggeization)
	$\rightarrow$ very promising scenario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

Other recent contributions by:

Abbate et al., Ahrens, Aybat, Banfi et al., Baur et al., Becher, Beneke et al., 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.,Laenen, Magnea, Mitov, Moch et al., Mantry, Nason, Neubert, Pecjak, Petriello, Ravindran, Salam, Schwartz, Schwinn, Steinhauser Sterman et al., Sumino, Sung, Uwer, Vogelsang, Vogt, White, Yang, Yokoya, Zanderighi

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 $\Longrightarrow a_\mu^{\rm had}$
A. Gauhar:	Improving the K_{l3} formfactor using unitarity and analyticity

Multi-Loop Corrections

- Baikov, Chetyrkin, Kühn, Rittinger:

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

  A new entry in Ellis' histogram at $\#_{\rm leg} = 2$.

- JB, A. De Freitas, W.L. van Neerven:
  $O(\alpha^2)$ massive OME with external massive fermions
  Using local operators the (massive) $e^+e^- \rightarrow Z^0$ cross section can be obtained up to $O(\alpha^2 \ln(s/m_e^2))$; different treatment required for $O(\alpha^2)$.

Multi-Loop Corrections

- DESY-RISC-RWTH: $O(\alpha_s^3)$ Massive DIS Wilson Coefficients $Q^2 \gg m^2$
  General values of N: first 2 of 5 Wilson Coefficients completed; arrived at the calculation of ladder topologies.
- 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)
- Anastasiou, Buehler, Lazopoulos: `iHixs`: NNLO inclusive Higgs production, $+b\bar{b}$, width effects
- Bozzi, Catani, Cieri, de Florian, Ferrera, Grazzini, Tramontano Higher order QCD correction for the DY process; fully differential NNLO cross section + resummations also: [Melnikov, Petriello, '06]
- Anastasiou, Herzog, Lazopoulos Disentangling Infrared Singularities
  Factorizing overlapping singularities using special non-linear Feynman-parameter mapping cf. also Hamberg & van Neerven, 1991
- von Manteuffel: Reduze 2 and non-planar massive double box
  Representations in terms of Cyclotomic and Generalized Harmonic Polylogarithms $\to$ [Ablinger, J.B., Schneider, 2011a,b] are obtained (up to cyclotomy 6). More and more interesting structures of this type are expected to occur in massive calculations.
  A numerical study: Y. Fujimoto et al. GRACE 1109.4213

Multi-Loop Corrections

- $2 \to 2$ NNLO processes at LHC
  Glover, Boughezal, Currie, Jimenez Delegado, Gehrmann-De Ridder, Gehrmann, Heinrich, Luisoni, Monni, Pires, Ritzmann, Wells

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

- Massive reduction of theoretical error expected
- Various technologies needed were developed calculating $e^+e^- \to 3$ jets
- Aim to have 'leading color gluons only' $pp \to 2$ jet very soon
- Various other technical aspects in good progress
- STRIPPER Czakon
- To have $ep \to 3$ jets @ NNLO is of great importance.
  $\Longrightarrow$ the precise HERA jet data await NNLO analysis.
- NNLO $t\bar{t}$ hadro-production: - work in progress (virtual & real corrections) Abelof, Anastasiou, Aybat, Bonciani, Czakon, Ferroglia, A+T Gehrmann, Kniehl, Körner, Merebashvili, Mitov, Moch, Neubert, Pecjak, Ritzmann, Rogal, Studerus, v. Manteuffel, Yang $\to$ recent survey by S. Moch

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: C. Schneider '01-
- PSLQ methods: Broadhurst; Lee, Smirnov, Smirnov '11
- Hyperlogarithms(∞): F. Brown '08

1-dim and higher quantities:

- 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
  [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 [Schneider '01-]
  Multiple Summation [JB, Klein, Schneider, Stan '10]
- Recurences from moments:
  guess [Kauers '08-]
- Integrating holonomic functions: [Almkvist, Zeilberger '91]

Mathematical Methods in Feynman Diagram Calculations

Functional Representations and Properties:

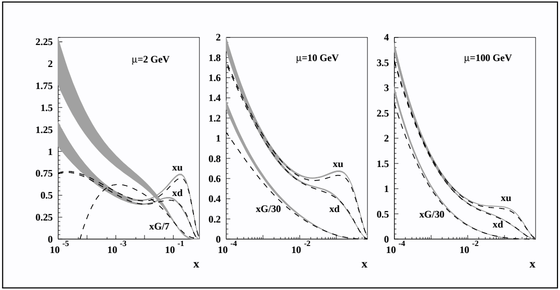
- Harmonic Sums and Generalizations
  [Vermaseren '98; JB, Kurth '98, Moch, Uwer, Weinzierl '01, JB '03, '09];
  `summer` [Vermaseren '98]; `harmol` [Remiddi, Vermaseren '99]; `hpl` [Gehrmann, Remiddi '01]; `nestedsums` [Weinzierl '02]; numerical ev. of HPL [Vollinga, Weinzierl'04]; `HPL` [Maitre '06];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

- 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.

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



ABKM09 vs MSTW08: differences for light partons (Phys. Rev. **D81** (2010) 014032.)

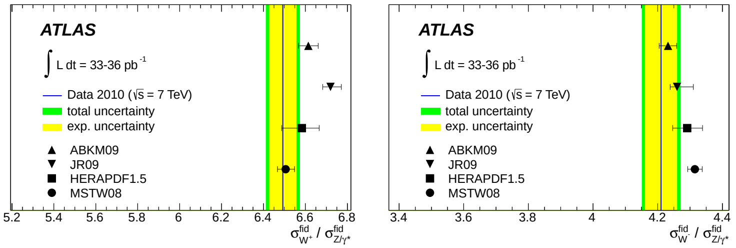
Parton Distribution Functions

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, 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

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

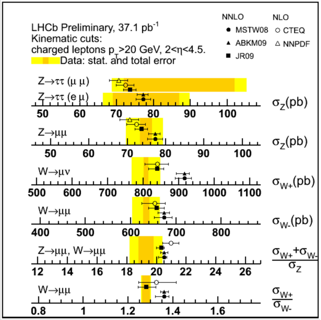
Recent measurements of $W^{\pm}$ and Z-production cross sections at ATLAS arXiv:1109.5141 (Monday)



$W^{\pm}/Z$ 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:1109.3371 (Anderson et al.)

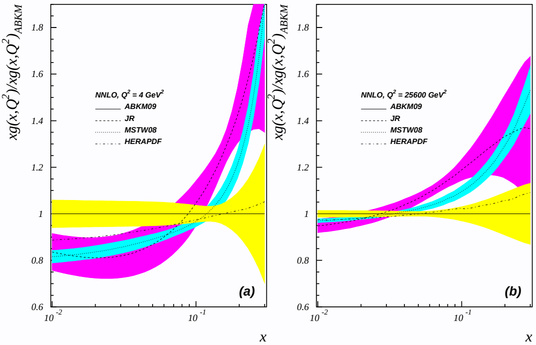


$W^{\pm}/Z$ cross section ratios will constrain parton distributions:

Observe the different pattern compared e.g. to ATLAS.

$\Longrightarrow$ excellent sensitivity to constrain sea quarks further.

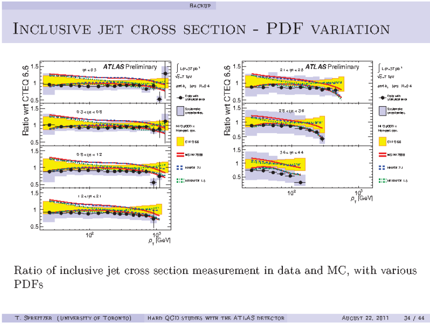
NNLO Gluon Distributions

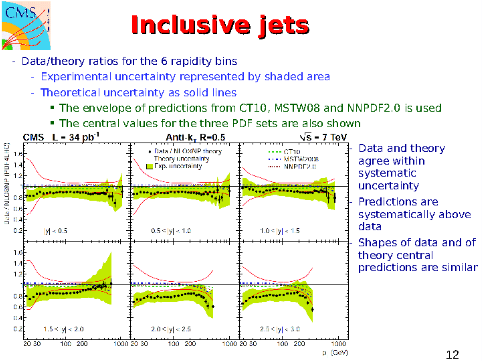


$\Longrightarrow$ Current differences in the gluon densities have significant impact on the jet- and inclusive Higgs production cross sections at Tevatron and LHC.

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

Jet measurement at LHC

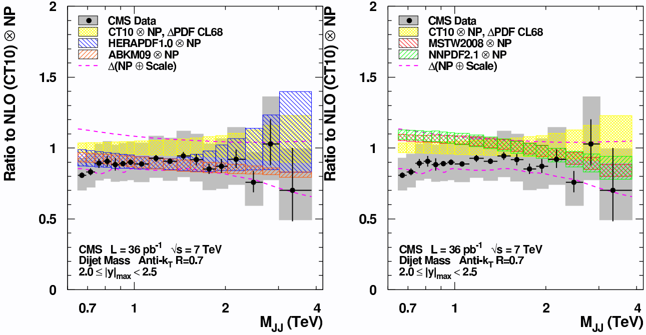




Spreitzer (ATLAS), Lenzi (CMS), St. Andrews 2011

Tevatron-data tuned PDFs somewhat overshoot LHC data.

Jet measurement at LHC



ABKM $\rightarrow$ a prediction

CMS di-jet data (Analysis by K. Rabbertz, CERN-CMS-NOTE-2011-004, June 11, 2011)

Parton Distribution Functions

Contributions by:

Bertone: PDFs from NNPDF
Uematsu: SUSY QCD and photon structure function
Watanabe: Mass effects of photon structure functions
Mukherjee: Photon GPDs

- Photon Structure Functions form an interesting laboratory for QCD (non-perturbative and perturbative contributions)
  $\Longrightarrow$

$$\int_0^1 dx\, g_1^{\mathrm{NLO}}(x, P^2, m^2) = 0$$

- Generalized parton distribution add an interesting degree of freedom: non-forwardness: $\Longrightarrow$ angular momentum.

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	0.1124 ± 0.0020	dynamical approach
JR	0.1158 ± 0.0035	standard fit
MSTW	0.1171 ± 0.0014	
ABM	0.1147 ± 0.0012	FFNS, incl. combined H1/ZEUS data
$\mathrm{ABM11}_J$	$0.1134 - 0.1149 \pm 0.0012$	Tevatron jets (NLO) incl.
CTEQ	0.118 ± 0.005	
NNPDF	$0.1174 \pm 0.0006 \pm 0.0001$	
Gehrmann et al.	$0.1153 \pm 0.0017 \pm 0.0023$	e^+e^- thrust
Abbate et al.	$0.1135 \pm 0.0011 \pm 0.0006$	e^+e^- thrust
BBG	$0.1141\ {}^{+0.0020}_{-0.0022}$	valence analysis, $\mathrm{N^3LO}$

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

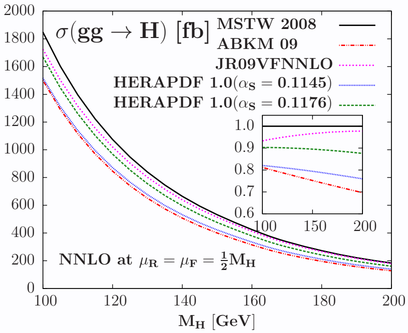
Applications: i) $\alpha_s(M_Z^2)$

$\alpha_s(M_Z^2)$ 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 decays	0.1180 ± 0.0008	Beneke, Jamin 2008
lattice	0.1183 ± 0.0008	HPQCD 2008
Average 2011	0.1185 ± 0.0008	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.

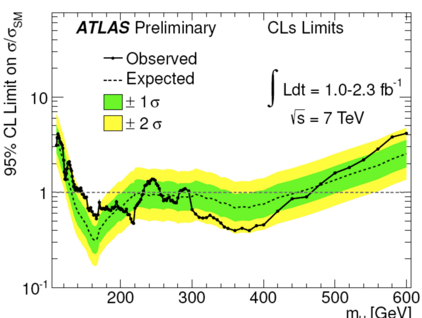
Applications: ii) Higgs Search



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

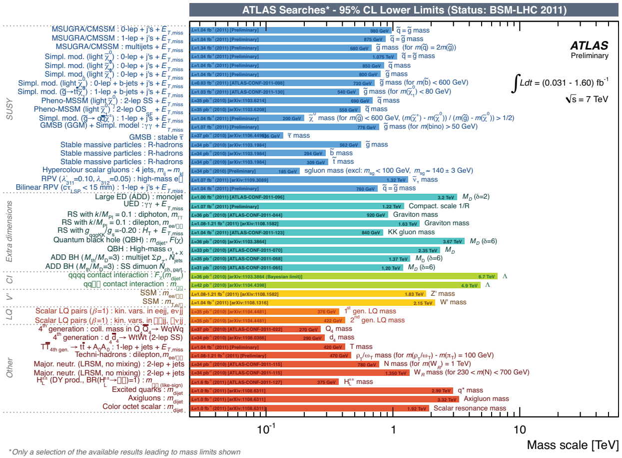


(a)

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

J. Katzy, M. Pieri

Beyond the Standard Model



SUSY exclusion reaches masses $\sim$ 1 TeV   ATLAS, BEM-LHC, Trieste, 2011

Beyond the Standard Model

Contributions by: Herrero, Majhi, Niessen: SUSY corrections;
Ravindran, Mathews, Mitra, Seth, Sridhar, Tripathi: KK and large EDMs

- 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 :

- Are masses generated by the Higgs mechanism ?
- 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 7 point functions.
- Resummations are needed in many places; bridging to non-perturbative regions.
- Many NNLO calculations, including masses.
- 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.

We cordially thank the organizers of RADCOR 2011

R. Basu, D. Indumathi, P. Mathews, A. Nyffeler, and V. Ravindran and their team, for the splendid organization of a highly interesting conference.

The meeting will be continued

http://en.wikipedia.org/wiki/Lumley_Castle

at Lumley Castle, UK, 22-27 September 2013.