THE DETERMINATION OF α_s: STATUS AND PROSPECTS

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WHY α_S?

THE PDG VALUE

$$\alpha_s(M_z) = 0.1181 \pm 0.0011$$

(PDG 2016 rev.: Bethke, Dissertori, Salam)

- $\alpha_s \sim \frac{1}{10}$ AT THE HIGGS MASS: EXPANSION PARAMETER QUITE LARGE
- $\Delta_\alpha \sim 1\% \Rightarrow$ UNCERTAINTY ON PROCESS WHICH STARTS AT, SAY $O(\alpha_s^2)$ (HIGGS IN GLUON FUSION) IS $\sim 2\%$ OF LO+ 3% OF NLO + ...

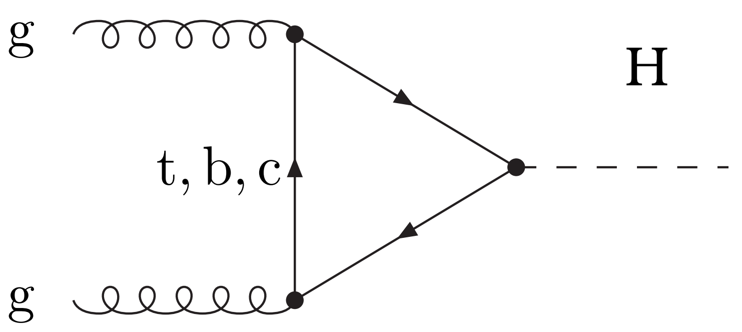
THE GOOD NEWS

"The agreement among so many different ways of measuring α_s is a strong quantitative test of QCD"

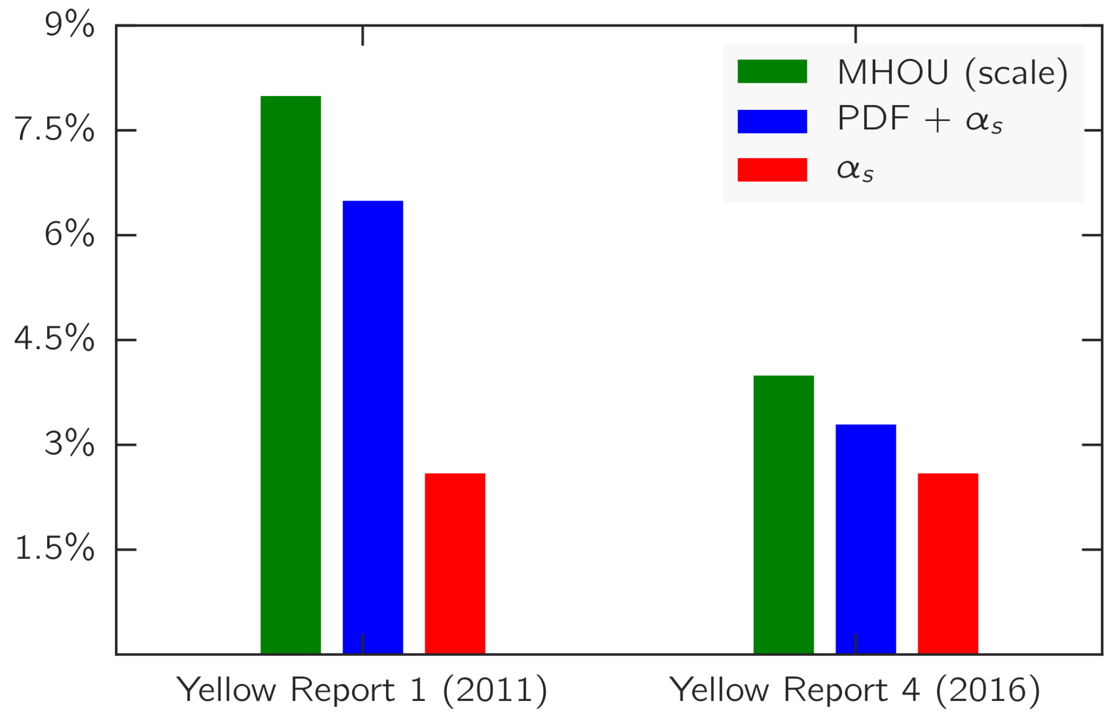
(G. Altarelli, "The QCD running coupling and its measurement", 2013)

THE BAD NEWS
AN EXAMPLE: HIGGS IN GLUON FUSION

- MAIN DISCOVERY CHANNEL; SENSITIVE BSM PROBE (TOP YUKAWA)
- STARTS AT $O(\alpha_s^2)$, 100% NLO CORRECTION
- DRIVEN BY THE GLUON PDF
- ONLY HADRON COLLIDER PROCESS KNOWN UP TO $\mathrm{N^3LO}$ (Anastasiou et al., 2016)



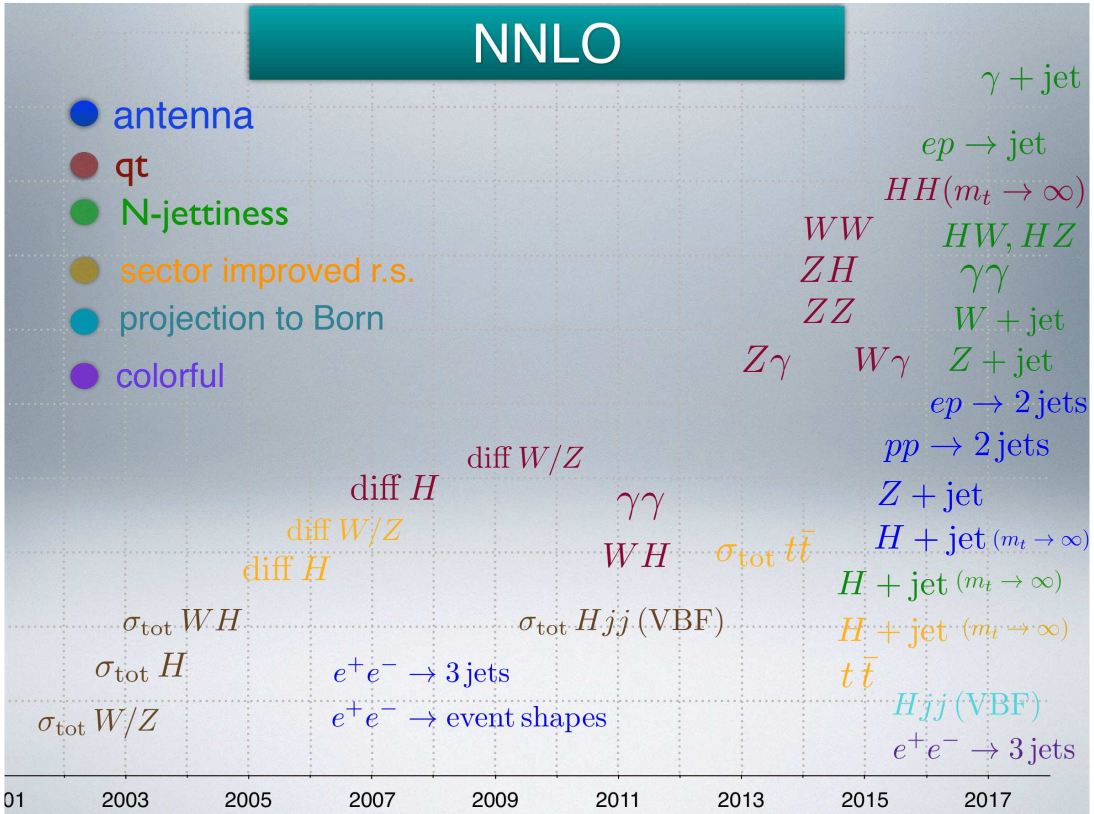
% UNCERTAINTIES ON TOTAL CROSS-SECTION



- MISSING HIGHER ORDER & PDF UNCERTAINTIES CUT BY FACTOR 2 BETWEEN HIGGS DISCOVERY (YR1, 2011) & LHC RUN II (YR4, 2016)
- α_s UNCERTAINTY UNCHANGED

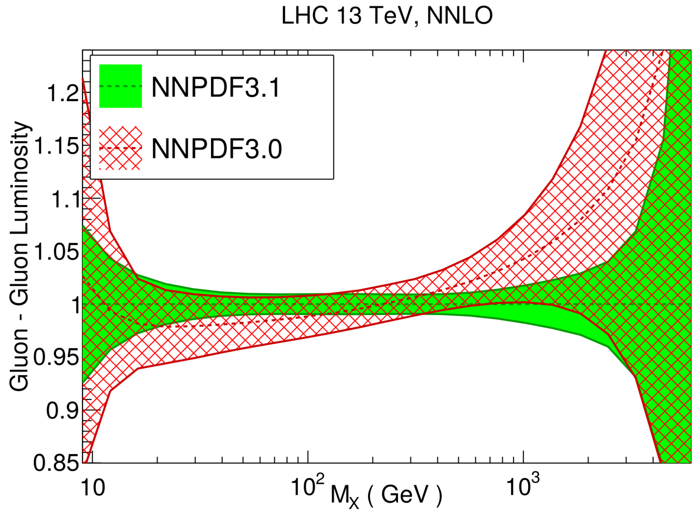
QCD PROGRESS I

NNLO QCD RESULTS



(G. Heinrich, LHCP, May 2017)

GLUON-GLUON PDF LUMINOSITY
NNPDF3.0 (2015) VS.
NNPDF3.1 (2017)



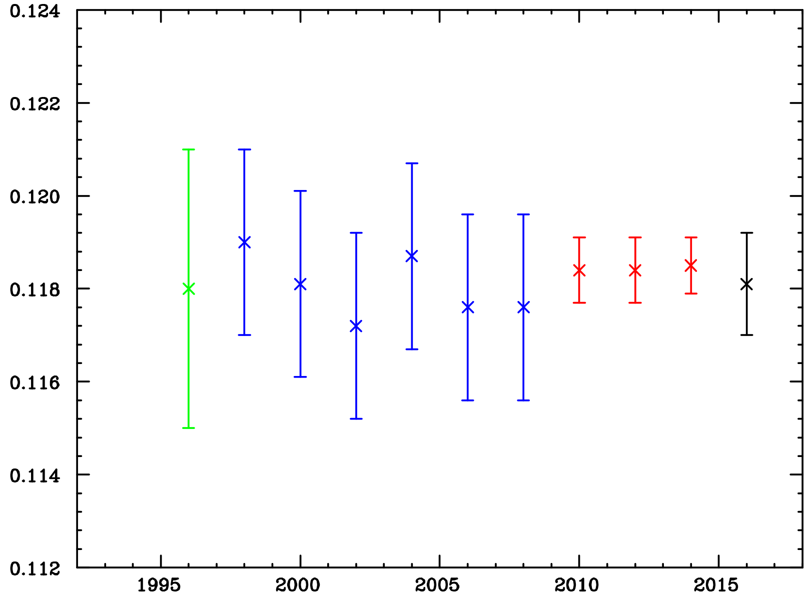
BETWEEN HIGGS DISCOVERY & LHC RUN II

- PERTURBATIVE STANDARD: FROM NLO TO NNLO (& BEYOND)
- PDF STANDARD: UNCERTAINTIES & ACCURACY FROM $6 \div 7\%$ TO $\lesssim 3\%$

QCD PROGRESS II:
PERTURBATIVE ACCURACY & PDFs

- 2000
  - NLO QCD EVOLUTION, MOST PROCESSES KNOWN AT NLO
  - PDF UNCERTAINTIES UNKNOWN
  - DATA-THEORY COMPARISON $\sim 10 - 20\%$
- 2010
  - NNLO QCD EVOLUTION, INCLUSIVE STANDARD CANDLES KNOWN AT NNLO
  - PDF UNCERTAINTIES $\sim 10\%$, ACCURACY?
  - DATA-THEORY COMPARISON $\sim 5 - 10\%$
- 2017
  - NNLO QCD PREDICTIONS INCLUDING FULLY EXCLUSIVE FINAL STATES
  - PDF UNCERTAINTIES $\lesssim 5\%$ WITH RELIABLE ACCURACY
  - DATA-THEORY COMPARISON $\sim 1 - 5\%$

α_s ACCURACY (PDG)



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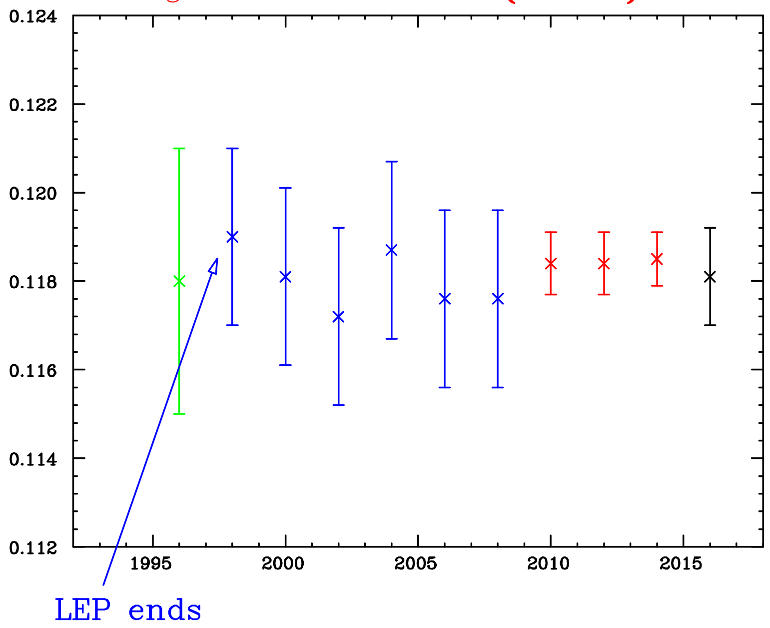

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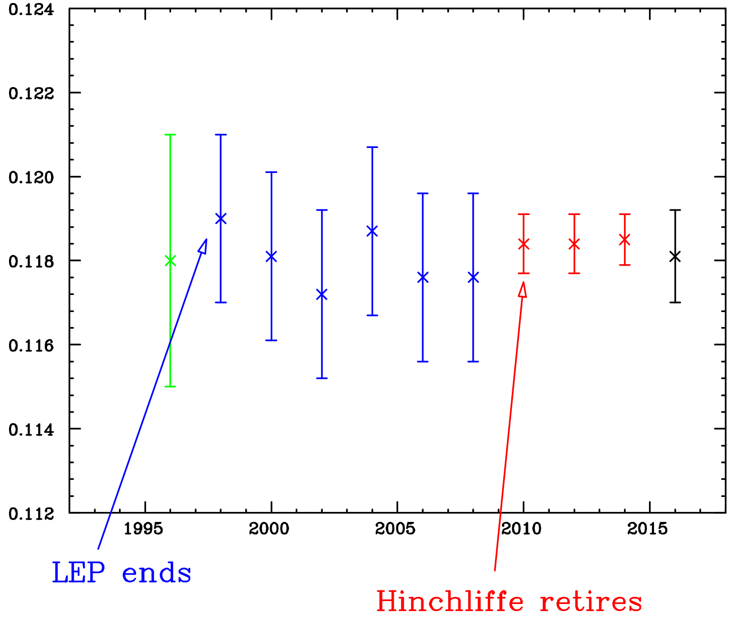
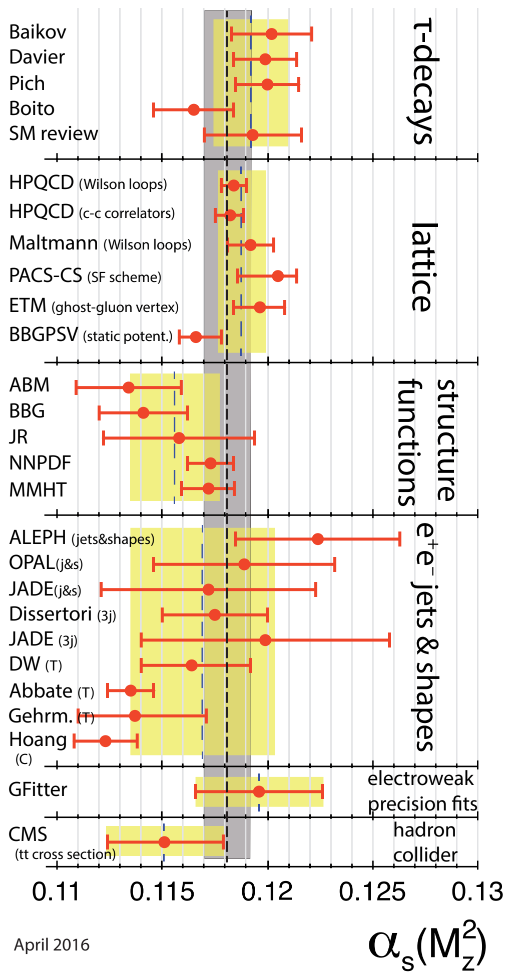


α_S: HOW?

THE PDG AVERAGE
WHERE DOES IT COME FROM?

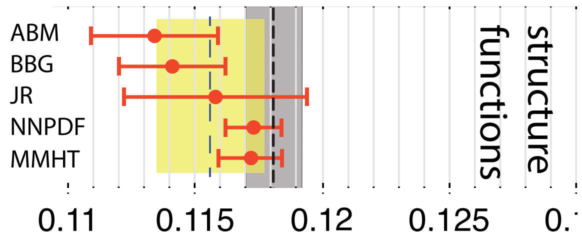
PDG PRE-AVERAGES



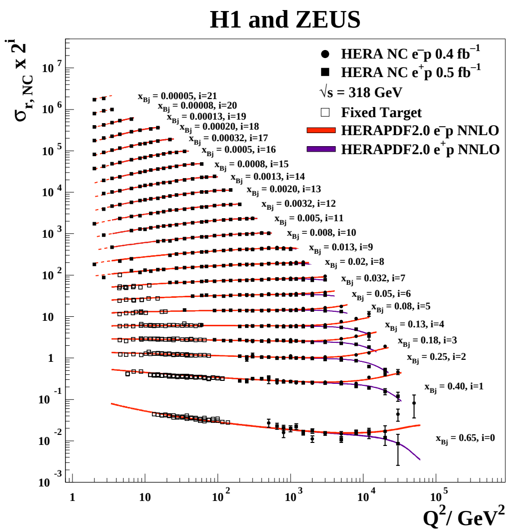
- PDG AVERAGE: χ^2-AVERAGING OF SIX PRE-AVERAGES, CHOSEN TO BE MAXIMALLY UNCORRELATED
- χ^2 AVERAGING $\Rightarrow$ UNCERTAINTIES INFLATED OR CORRELATED UNTIL $\chi^2/dof = 1$
- EACH PRE-AVERAGE IS THE SIMPLE (UNWEIGHTED) AVERAGE OF ITS COMPONENTS, UNCERTAINTY $\leftrightarrow$ AVERAGE OF UNCERTAINTIES (OR STANDARD DEVIATION OF VALUES IF LARGER)
- ONLY PUBLISHED NNLO DETERMINATIONS INCLUDED
- GLOBAL ELECTROWEAK FIT (NO PRE-AVERAGING)
- ONLY ONE LHC DETERMINATION: TOP (NO PRE-AVERAGING)

CASE STUDY I: STRUCTURE FUNCTIONS

- “STRUCTURE FUNCTION”: α_s DETERMINED SIMULTANEOUSLY WITH PDFs IN A MORE OR LESS GLOBAL FIT
- BIG SPREAD OF VALUES, SOME VERY CONTROVERSIAL



BASIC PRINCIPLE:
SCALING VIOLATIONS



- α_s & PDFs (GLUON) STRONGLY CORRELATED
$$\frac{d}{d\ln Q^2}F_2(x,Q^2)\sim\alpha_s(Q^2)F_2(x,Q^2)+\alpha_s(Q^2)G(x,Q^2)$$

MANY SOURCES OF UNCERTAINTY :

- PDF PARAMETRIZATION & PROPAGATION OF PDF UNCERTAINTIES
- TREATMENT OF EXPERIMENTAL SYSTEMATICS IN THE GLOBAL FIT
- HEAVY QUARK MASSES: FFN VS. VFN SCHEMES; PERTURTBATIVE VS. FITTED CHARM; VALUES OF HQ MASSES

- BBG: DRIVEN DOWNWARDS BY NEGLECT OF LARGE NONSINGLET CONTRIBUTION (Martin, 2011)
- ABM: DRIVEN DOWNWARDS BY FIXED-FLAVOR NUMBER TREATMENT OF HEAVY QUARKS (Thorne, 2014)
- JR: BASED ON OBSOLETE PDF FIT
- NNPDF, MMHT: NO SERIOUS ESTIMATE OF THEORY UNCERTAINTIES

CASE STUDY I: ~~STRUCTURE FUNCTIONS~~ GLOBAL PDF FITS

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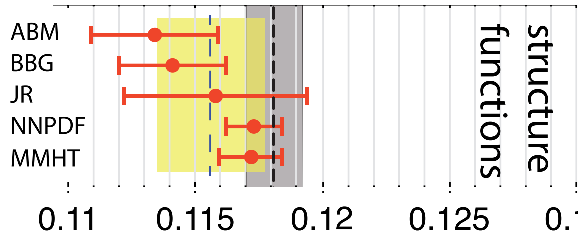

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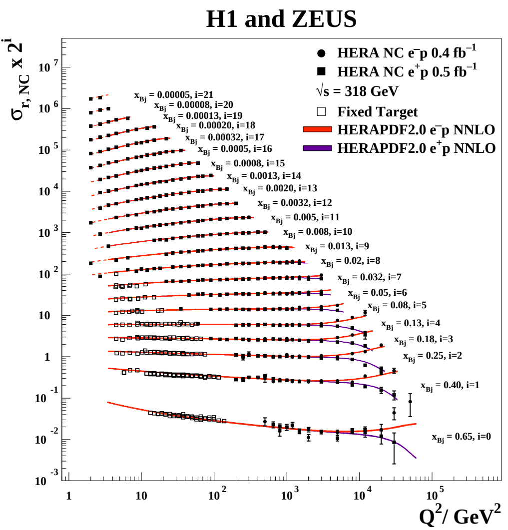

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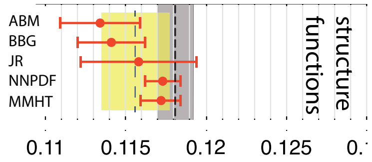
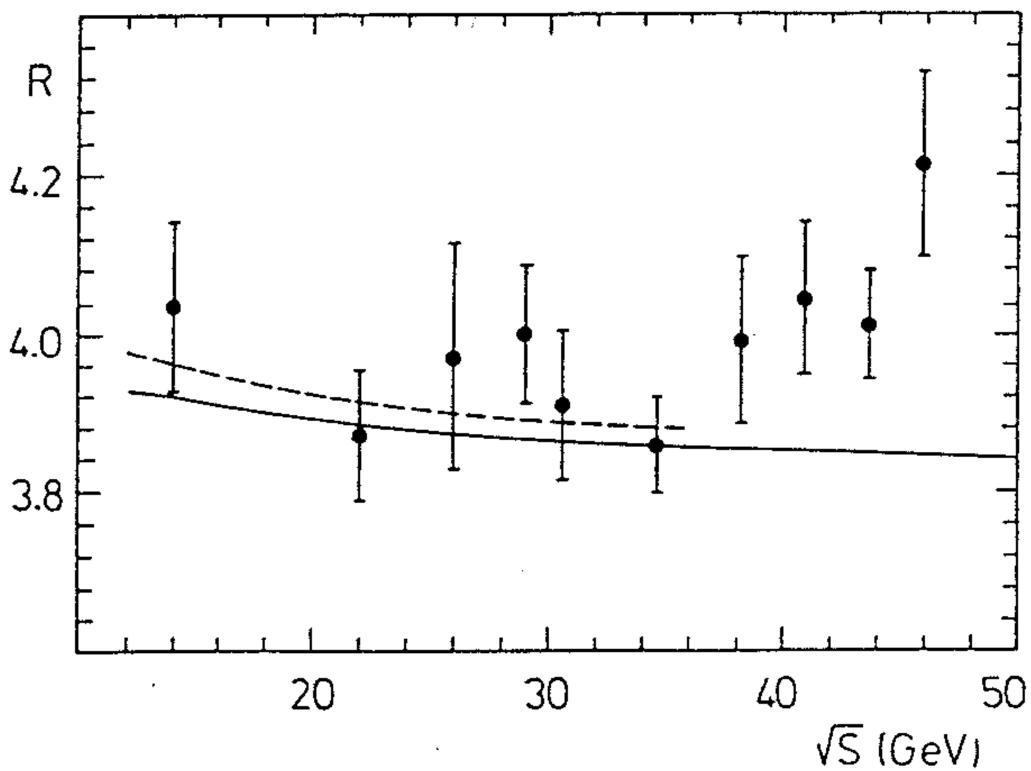


CASE STUDY I: GLOBAL PDF FITS
THE D'AGOSTINI BIAS

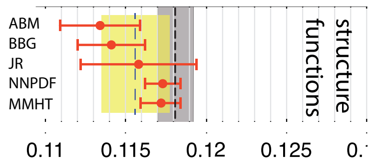
$$R = \frac{e^+e^- \to \text{hadrons}}{e^+e^- \to \mu^+\mu^-}$$



(CELLO collab., 1987)

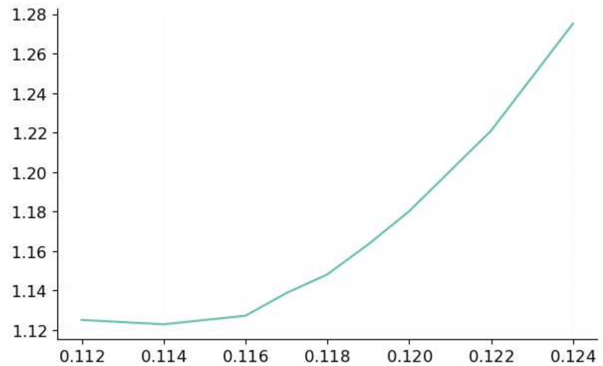
- MULTIPLICATIVE UNCERTAINTIES IN COVARIANCE MATRIX
  $\Rightarrow$ FIT BIASED DOWNWARDS IF DATA INCONSISTENT (d'Agostini, 1994)
  EQUIVALENT TO RESCALING DATA BUT NOT UNCERTAINTIES
- MUST USE ITERATIVE PROCEDURE
  COVARIANCE MATRIX COMPUTED FROM PREVIOUS FIT (NNPDF, 2010)

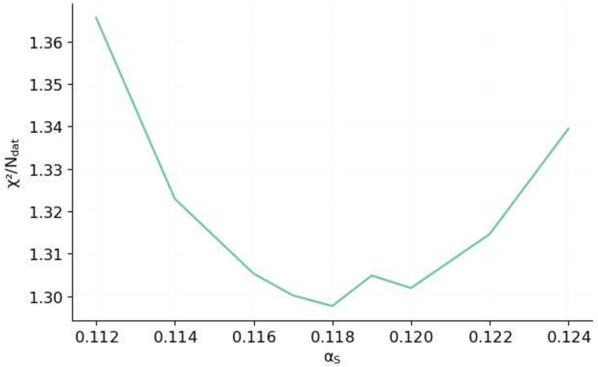
CASE STUDY I: GLOBAL PDF FITS
α_s FROM THE NNPDF3.1 PDF FIT

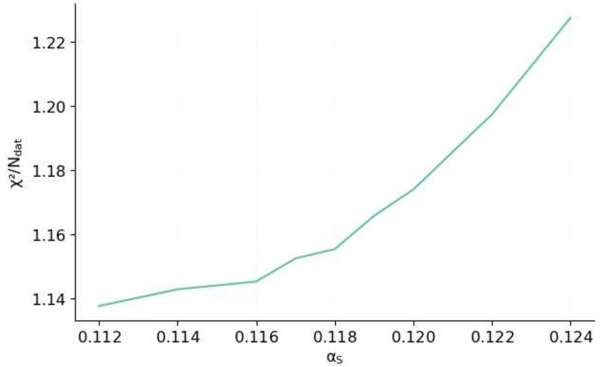


BIASED UNCERTAINTY IN COV. MAT.

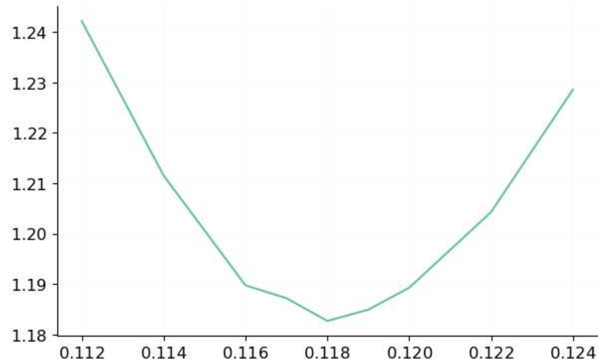
GLOBAL | ADDITIVE (NMC, FT) | MULTIPLICATIVE (HERA, COLL)

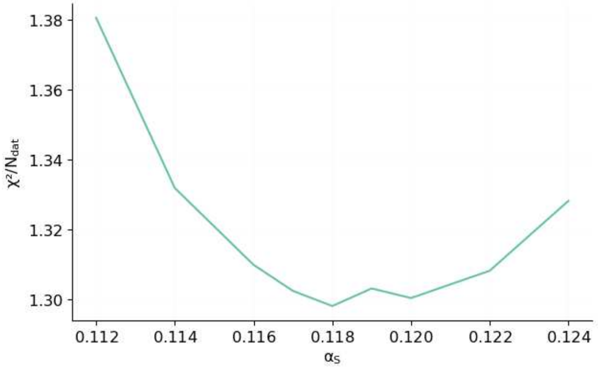


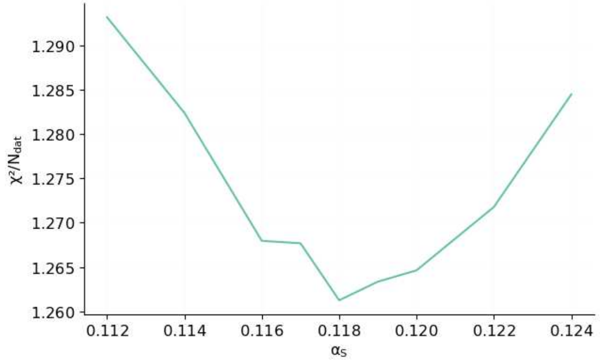




CONSISTENT (ITERATIVE)



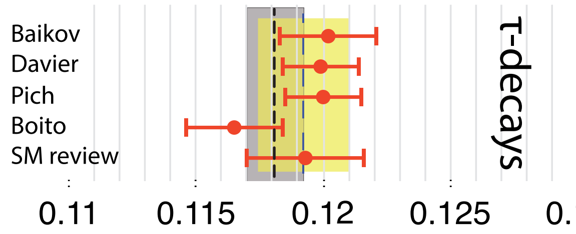




- χ^2 COMPUTED FROM COVARIANCE MATRIX $\Rightarrow$ BIASED LOW FIT FAVORED
- LESS EVOLUTION $\Leftrightarrow$ LOW α_s
- ONLY WHEN MULTIPLICATIVE UNCERTAINTIES DOMINATE
  COLLIDER ONLY, NOT FIXED TARGET

CASE STUDY II: τ DECAYS

- LEPTONIC INTIAL STATE: NO DEPENDENCE ON PDFs
- LOW SCALE ($m_\tau = 1.78$ GeV):
  - UNCERTAINTY AT HIGH SCALE M_z SHRINKS
  - LARGE PERTURBATIVE & NONPERTURBATIVE CORRECTIONS
- SPREAD OF VALUES DUE TO NONPERTURBATIVE TREATMENT

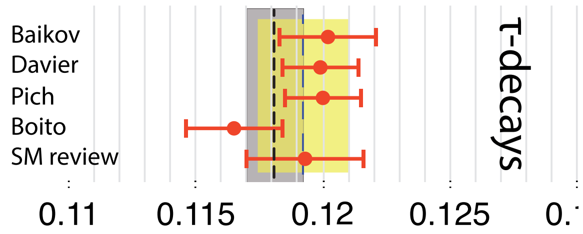


BASIC PRINCIPLE:
HADRONIC DECAY WIDTH

$$R_\tau = \frac{\Gamma(\tau^- \to \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)}$$
$$= f(\alpha_s(m_\tau))$$

- HADRONIC WIDTH $\Leftrightarrow$ W SELF-ENERGY $\Pi(q^2)$
  $\Pi^{\mu\nu}(q) = i \int d^4 x e^{iqx} \langle T\left(J_\mu(x) J_\nu^\dagger(0)\right)\rangle$
- EXPRESSED USING ANALYTICITY IN TERMS OF INTEGRAL OVER $\Pi(s)$ IN COMPLEX s PLANE ON THE CIRCLE $|s| = m_\tau^2$
- LEADING ORDER WILSON COEFFN. PERTURBATIVELY KNOWN UP TO $O(\alpha_s^4)$ (Baikov, Chetyrkin, Kühn, 2008)

CASE STUDY II: τ DECAYS



- $R_\tau = \dfrac{\Gamma(\tau^- \to \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)}$
- $\Pi^{\mu\nu}(q) = i \int d^4x e^{iqx} \langle T\left(J_\mu(x) J_\nu^\dagger(0)\right)\rangle$

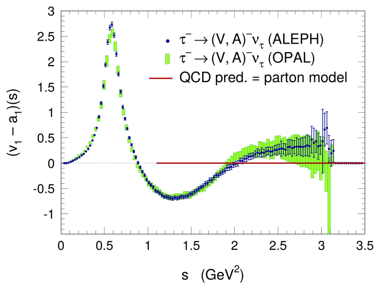
PERTURBATIVE UNCERTAINTIES

- EXPANSION IN α_s OF CONTOUR INTEGRAL (FOPT) VS EXPANSION OF THE INTEGRAND (CIPT)
  $\Rightarrow$ FOPT IS A NON-CONVERGENT SERIES, BUT CIPT MAY CONTAIN RENORMALONS
- FIRST SUBLEADING OPERATOR FOR $\Pi(q^2)$ IS DIMENSION 4 $\propto \dfrac{\langle O_4 \rangle}{m_\tau^4}$

  RENORMALON-INDUCED CONTRIBUTION $\propto \dfrac{\Lambda^2}{m_\tau^2}$?
- CIPT AND FOPT AVERAGED,
  $\Rightarrow$ DIFFERENCE IN $\alpha_s(M_z)$ OF ORDER OF $\sim 1.5 - 2\%$

NONPERTURBATIVE UNCERTAINTIES

V+A SPECTRAL FCTN.

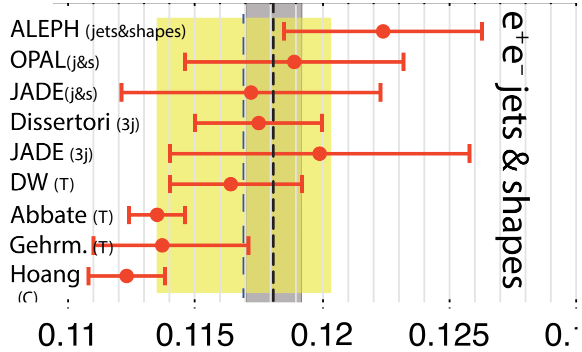


(Davier, Höcker, Zhang, 2006)

- MOMENTS OF THE DECAY INVARIANT-MASS DISTRIBUTION $\Leftrightarrow$ WEIGHTED INTEGRALS OF THE SPECTRAL FUNCTION
- NP CORRECTIONS EXTRACTED BY COMPARISON
- RESONANCE CONTRIBUTIONS TO INTEGRAL: SUPPRESSED BY CHOICE OF WEIGHT OR MODELED?
- $\Rightarrow$ DIFFERENCE IN $\alpha_s(M_z)$ OF ORDER OF $\sim 3\%$

CASE STUDY III: e^+e^- JETS & SHAPES

- LEP (& PETRA) JETS: LEPTONIC INITIAL STATE, WIDE SET OF DATA AND OBSERVABLES
- FINAL STATE HADRONS $\Rightarrow$ NONPERTURBATIVE PHYSICS
- OUTLIER DETERMINATION, VERY SMALL UNCERTAINTY



BASIC PRINCIPLE:
JET RATES & SHAPE
THRUST:

$$T = \max_{\vec{n}} \frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |\vec{p}_i|}$$

C-PARAMETER:

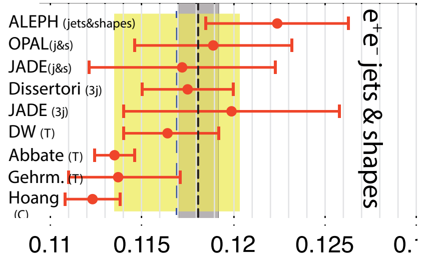
$$C = \frac{3}{2} \frac{\sum_{i,j} |\vec{p}_i||\vec{p}_j| \sin^2 \theta_{ij}}{(\sum_i |\vec{p}_i|)^2}$$

broadening, jet mass, two-to-three jet transition; three-jet rate

- NNLO+NLL PERTURBATIVE COMPUTATION MATCHED TO MONTE CARLO HADRONIZATION:
  - SIMULTANEOUS FIT TO SIX EVENT SHAPES: ALEPH, OPAL (LEP), JADE (PETRA)
  - THREE-JET RATES: ALEPH (NNLO ONLY), JADE
- NNLO+N^{k}LL MATCHED TO NONPERTURBATIVE MODELING:
  - NNLO+NLL EFFECTIVE COUPLING (THRUST)
  - NNLO+NNLL DISPERSIVE MODEL (THRUST)
  - NNLO+N^{3}LL (PADÉ) SCET FITTED SHAPE FUNCTION (THRUST & C-PARAMETER)

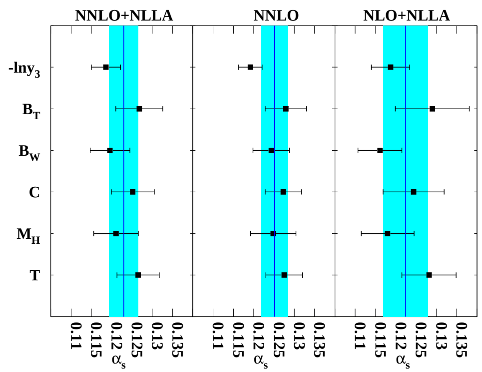
CASE STUDY III:
e^+e^- JETS & SHAPES

UNCERTAINTIES (CONSERVATIVE): ALEPH EVENT SHAPES



- STAT. (BINNED χ^2 FIT) & EXP. UNCERTAINTIES (VARY CUTS) SMALL
- PERTURBATIVE AND NONPERTURBATIVE UNCERTAINTIES DOMINANT

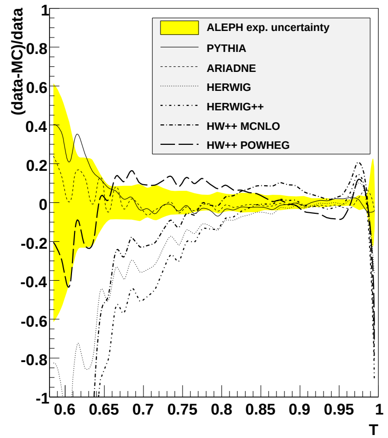
PERTURBATIVE UNCERTAINTIES



- RESUMMATION NEEDED FOR ACCURATE PREDICTIONS IN WIDE RANGE
  $\Rightarrow$ REDUCED DISPERSION OF RESULTS
- INCOMPLETE SCALE CANCELLATION WHEN NNLO MATCHED TO NLL (NEED NNLL)
  $\Rightarrow$ INCREASED UNCERTAINTY
- $\Delta\alpha_s(M_z) \sim 3.5\%$

NONPERTURBATIVE UNCERTAINTIES

MC VARIATION VS. EXP UNC.



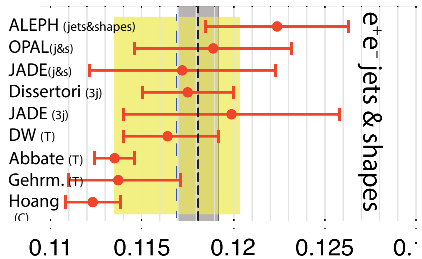
- MC REANALYSIS USING MODERN PS (MC@NLO & POWEG)
  $\Rightarrow$ DISCREPANCY (TUNING ISSUES?)
- PYTHIA & HERWIG HADRONIZATION: SOME OBSERVABLES (THRUST, C PARM.) $\Rightarrow$ UNDERESTIMATED HADR. CORRECTIONS?
- $\Delta\alpha_s(M_z) \gtrsim 1\%$

(Dissertori et al., 2009)

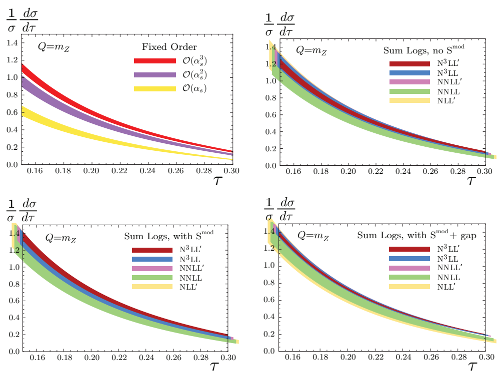
CASE STUDY III: e^+e^- JETS & SHAPES

UNCERTAINTIES (AGGRESSIVE): THRUST FROM SCET

- GLOBAL FIT TO VERY LARGE NUMBER OF THRUST DATA (AMY@KEK; TASSO, JADE@PETRA; SLC; ALEPH, OPAL, DELPI, L3 @ LEP)
- PERMILLE EXPERIMENTAL, HADRONIZATION & PERTURBATIVE UNCERTAINTIES



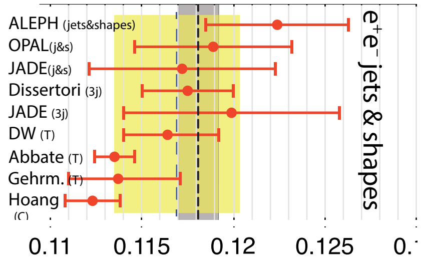
PERTURBATIVE UNCERTAINTIES



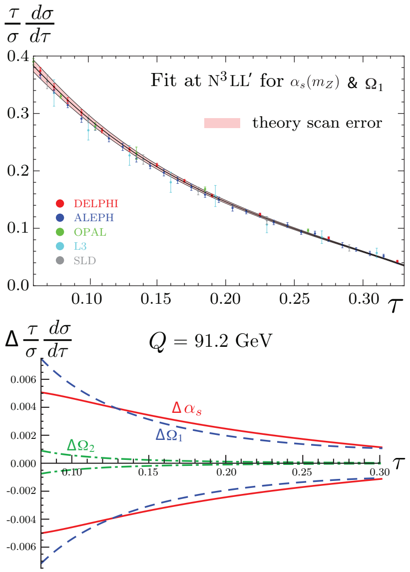
- RESUMMATION (N^{3}LL PADÉ), NONPERTURBATIVE FUNCTION & RENORMALON SUBTRACTION ADDED TO FIXED ORDER
- "THEORY SCAN" UNCERTAINTY: TWO-PARAMETER α_s, Ω_1 FIT WITH 12 THEORY PARMS VARIED $\Rightarrow$ CONSTANT DECREASE OF SPREAD
- $\Delta\alpha_s(M_z) \lesssim 1\%$

CASE STUDY III: e^+e^- JETS & SHAPES

UNCERTAINTIES (AGGRESSIVE): THRUST FROM SCET



- GLOBAL FIT TO VERY LARGE NUMBER OF THRUST DATA (AMY@KEK; TASSO, JADE@PETRA; SLC; ALEPH, OPAL, DELPI, L3 @ LEP)
- PERMILLE EXPT., HADR. & PERT. UNCERTAINTIES



NONPERTURBATIVE UNCERTAINTIES

- ONE-SIGMA ELLIPSE OF TWO-PARAMETER FIT $\Rightarrow$ HADRONIZATION UNCERTAINTY
- LARGE STATISTICS, VERY SMALL UNCERTAINTY: $\Delta\alpha_s(M_z) \sim 0.5\%$
- WHY IS THE CENTRAL VALUE SO LOW?

(Abbate et al., 2010)

- DISPERSIVE MODEL+STANDARD QCD LEADS TO $\Delta\alpha_s(M_z) \sim 3\%$ (ONLY ALEPH, L3, TASSO) NO RENORMALONS, NO N^{3}LL PADÉ)

(Gehrmann, Luisoni, Monni et al., 2012)

- ARE RESULTS STABLE UPON REBINNING?

"I think that this is a good example of an underestimated error which is obtained within a given machinery without considering the limits of the method itself"

(G.Altarelli, 2013)

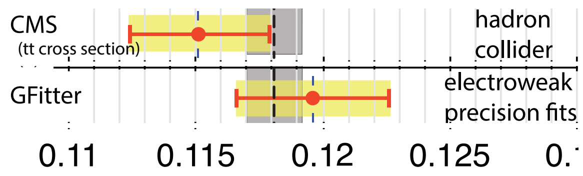
LESSONS LEARNT

- COMPLEX ANALYSIS LEADS TO MANY SOURCES OF UNCERTAINTY, SOME UNEXPECTED
- NONPERTURBATIVE & PDF UNCERTAINTIES HARD TO ESTIMATE
- AGGRESSIVE ERROR ESTIMATE SIGNALED BY WIDE DISPERSION OF RESULTS

WHICH α_s?

THE MEANING OF THE α_s UNCERTAINTY

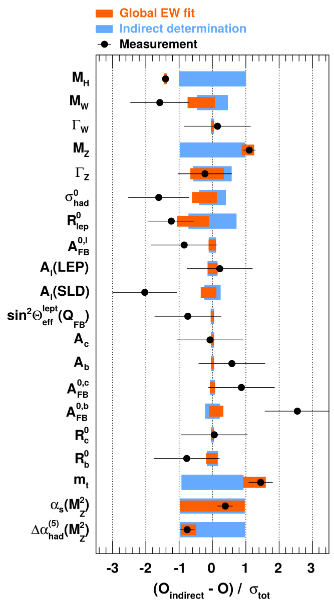
- TWO DETERMINATIONS IN PDG NOT PRE-AVERAGED:
  GLOBAL ELECTROWEAK FIT &
  TOP-PAIR TOTAL CROSS SECTION @ LHC
  (ONLY HADRON COLLIDER DETERMINATION IN PDG AVERAGE)



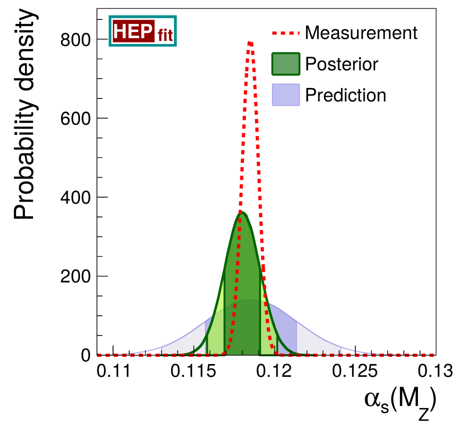
- BOTH HAVE 3% UNCERTAINTY
- DO THEY HAVE THE SAME UNCERTAINTY?

EASY (CONSERVATIVE?) UNCERTAINTY ESTIMATE: THE GLOBAL ELECTROWEAK FIT

- MUST ASSUME STANDARD MODEL
- FIT HIGHLY CONSTRAINED & CONSISTENT
  (14 d.o.f., $\chi^2 = 17.8$) (ALL ANOMALIES GONE)
- GOOD CONSISTENCY OF VALUES FROM GLOBAL FIT
  (α_s ONE OF THE FIT PARAMETERS)
  & PREDICTION (α_s NOT A FIT PARAMETER)
- CONSTANT IMPROVEMENT
- NOW HIGGS MASS ADDED TO FIT



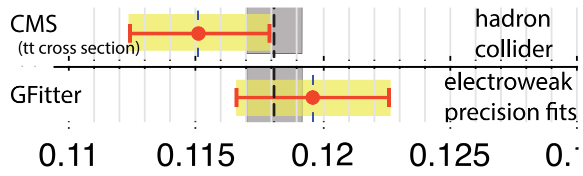
(Gfitter, 2014)



(HEPFit, de Blas et al., 2016)

THE MEANING OF THE α_s UNCERTAINTY

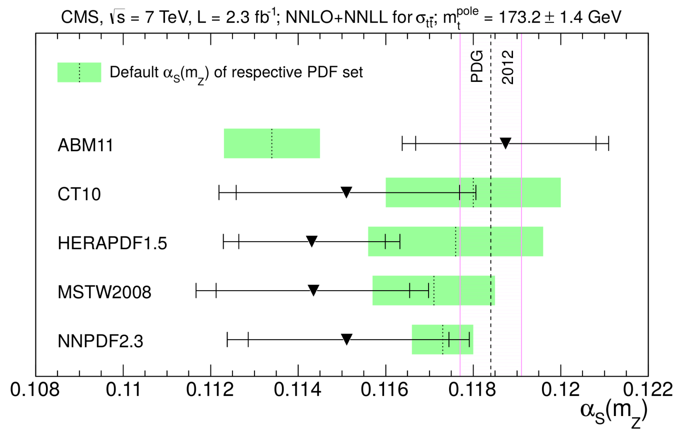
- TWO DETERMINATIONS IN PDG NOT PRE-AVERAGED: GLOBAL ELECTROWEAK FIT & TOP-PAIR TOTAL CROSS SECTION @ LHC (ONLY HADRON COLLIDER DETERMINATION IN PDG AVERAGE)



- BOTH HAVE 3% UNCERTAINTY
- DO THEY HAVE THE SAME UNCERTAINTY?

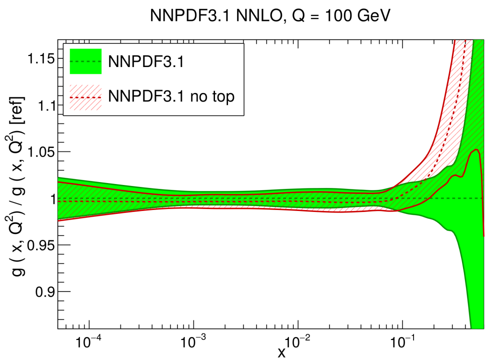
DIFFICULT (AGGRESSIVE?) UNCERTAINTY ESTIMATE: TOP PAIR PRODUCTION AT THE LHC

- INCLUSIVE "STANDARD CANDLE", CROSS-SECTION KNOWN TO NNLO+NNLL
- DEPENDS ON α_s & PDFs
- BAYESIAN UPDATE OF PRIOR DISTRIBUTION $f(\sigma_{t\bar{t}})$ $\Rightarrow$ JOINT POSTERIOR FOR $\sigma_{t\bar{t}}$, m_t & α_s FOLDING WITH PROBABILITIES FOR PDF & THEORY UNCERTAINTY



(CMS, 2014)

GLUON WITH VS. WO TOP



(NNPDF3.1, 2017)

- DO WE FULLY CONTROL THE PDF UNCERTAINTY?
- DOES THE LOW α_s VALUE REFLECT AN OVERESTIMATED GLUON PDF?

Gresham's Law of α_s determination

"Bad determinations drive our good determinations"

(T. Gresham, 1519-1579)

- ACCURATELY ASSESSED UNCERTAINTY $\Rightarrow$ LARGER!
- DETERMINATIONS WITH LARGE UNCERTAINTY ARE DISFAVORED W.R. TO SMALL UNCERTAINTY

"CONSERVATIVE" α_s?

"In my opinion one should select few theoretically simplest processes for measuring α_s and consider all other ways as tests of the theory."

(G.Altarelli, 2013)

- TAKE, FOR SAKE OF ARGUMENT, PDF-INDEPENDENT DETERMINATIONS, WITH CONSERVATIVE UNCERTAINTIES:
  - τ DECAYS $\Rightarrow \alpha_s(M_z) = 0.119 \pm 0.002$
  - EW FIT (HEPfit) $\Rightarrow \alpha_s(M_z) = 0.1185 \pm 0.0028$
- COMBINED RESULT: $\alpha_s(M_z) = 0.1188 \pm 0.0016$

OUTLOOK

- SURPRISING LACK OF PROGRESS:
  - NO SINGLE RELIABLE AND ACCURATE DETERMINATION
  - OUTLIERS NOT FULLY UNDERSTOOD

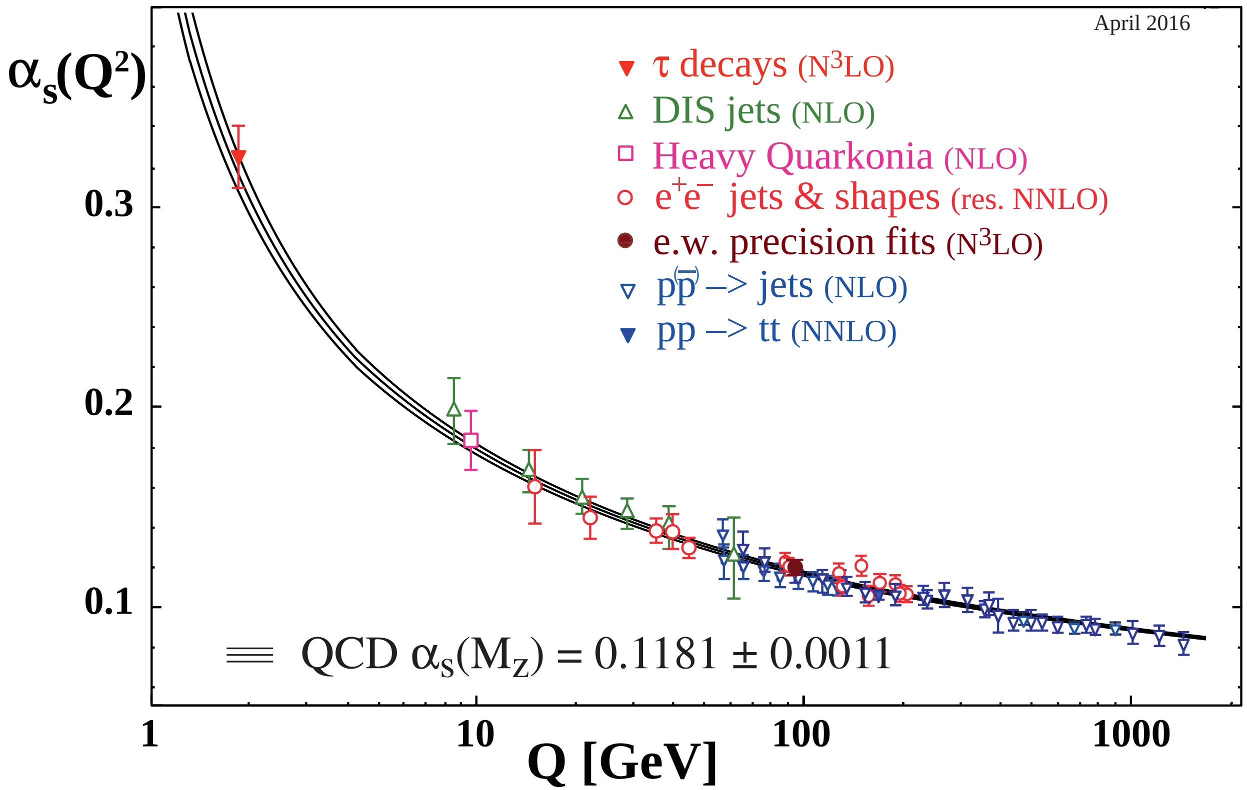
- FUTURE IMPROVEMENTS:
  - LHC-RUN II & HL-LHC DATA $\Rightarrow$ GLOBAL EW FIT, PDFs
  - LATTICE AS AN INDEPENDENT HANDLE $\Rightarrow$ OUTLIERS DISCARDED

there is nothing new under the sun
but there are lots of old things we don’t know

Ambrose Bierce

EXTRAS

THE RUNNING OF α_s



(PDG, 2016)

- CONSISTENT SCALE DEPENDENCE OVER THREE ORDERS OF MAGNITUDE
- RUNNING KNOWN TO FIVE LOOPS (Baikov, Chetyrkin, Kühn, 2016)

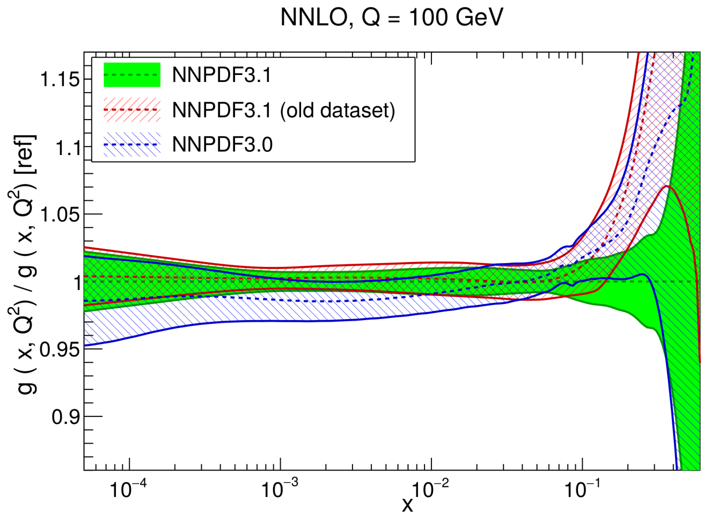
PDFs

PRECISION VS. ACCURACY

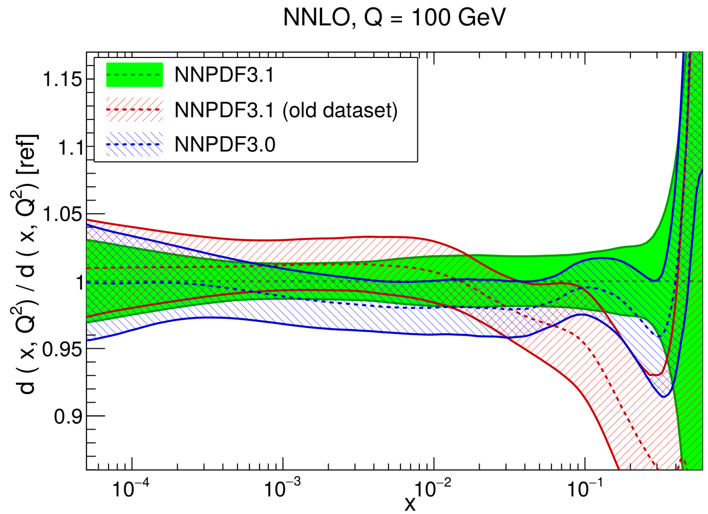
NNPDF3.1 VS. 3.0

- METHODOLOGY: INDEPENDENTLY PARAMETRIZED CHARM PDF
- LHC DATA : TOP RAPIDIDITY, Z p_T, LHCB & ATLAS W & Z PRODUCTION

GLUON



DOWN



- FITTING CHARM ENHANCES GLUON IN GGF RANGE BY SEVERAL PERCENT
- NEW DATA (ESPECIALLY LHCB & ATLAS w z 2011) ENHANCE QUARKS IN VALENCE REGION