

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”

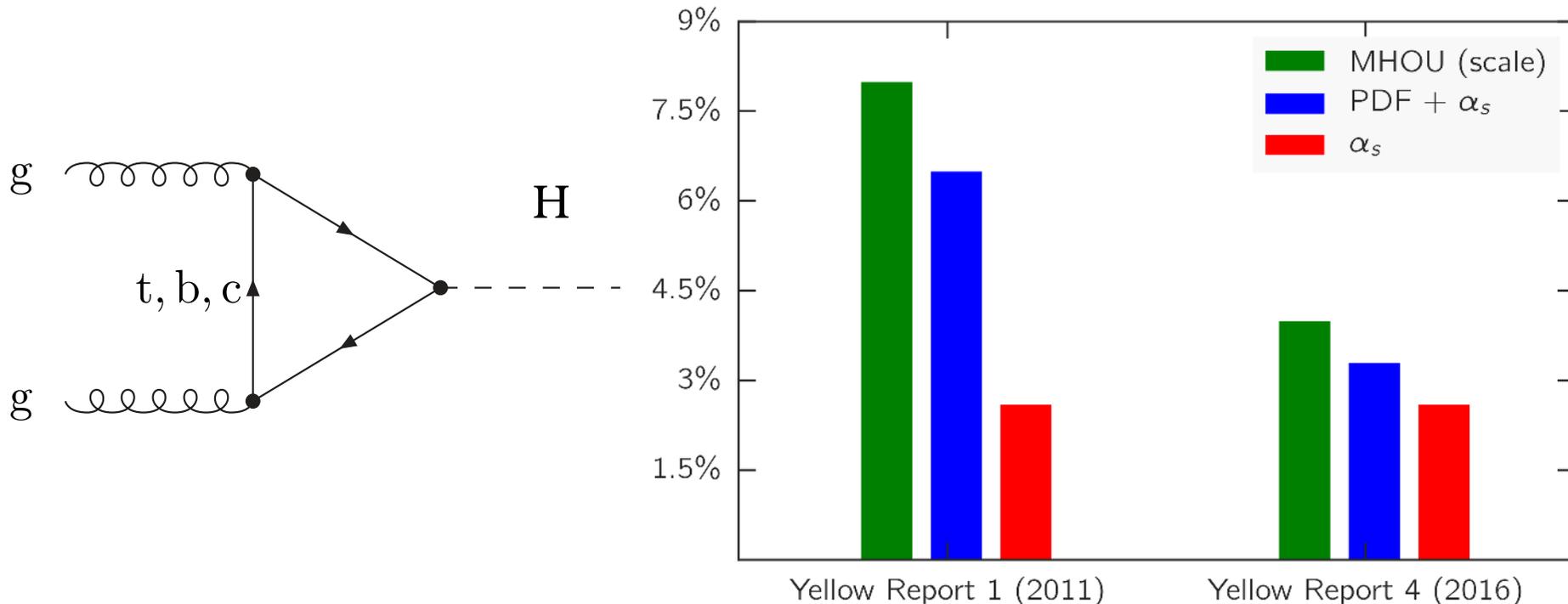
(G. Altarelli, “The QCD running coupling and its measurement”, 2013)

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 N³LO (Anastasiou et al., 2016)

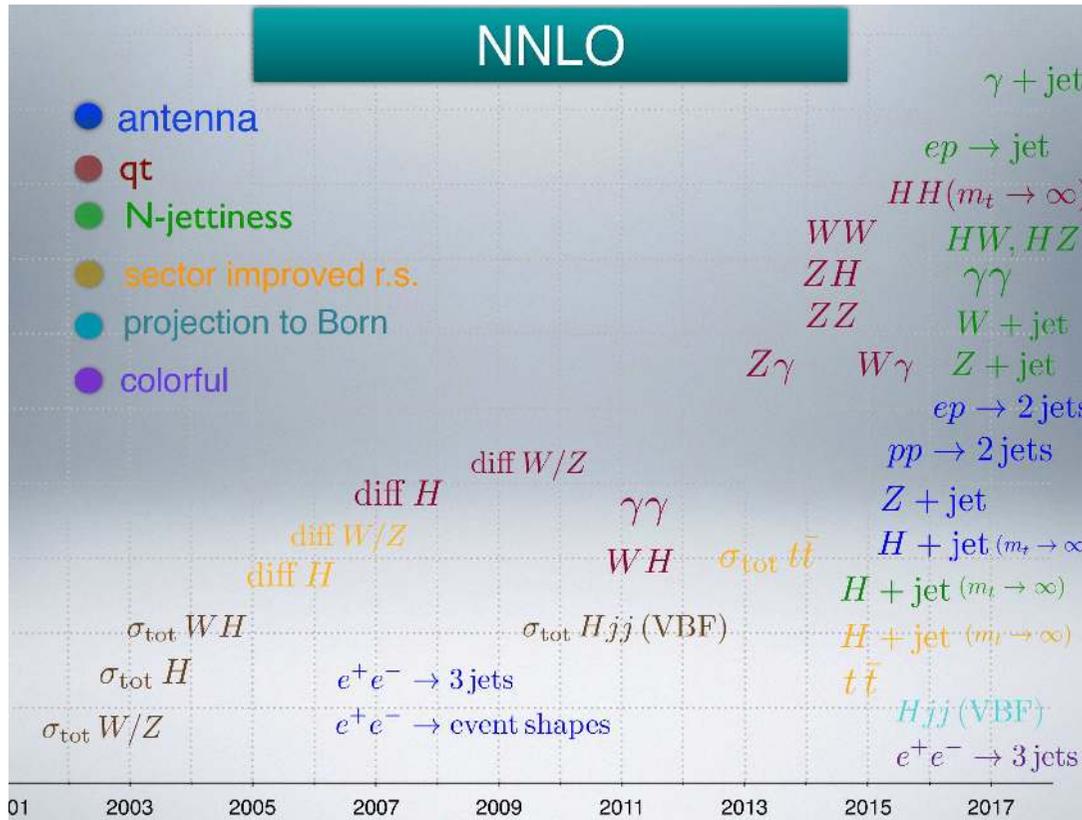
% UNCERTAINTIES ON TOTAL CROSS-SECTION



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

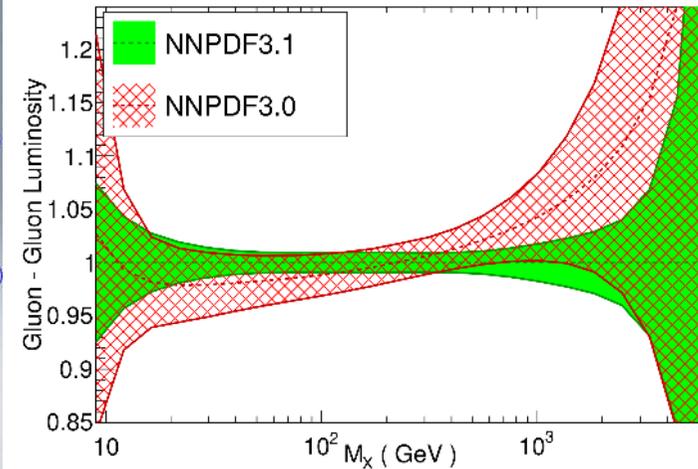
QCD PROGRESS I

NNLO QCD RESULTS



(G. Heinrich, LHCP, May 2017)

GLUON-GLUON PDF LUMINOSITY NNPDF3.0 (2015) VS. NNPDF3.1 (2017) LHC 13 TeV, NNLO

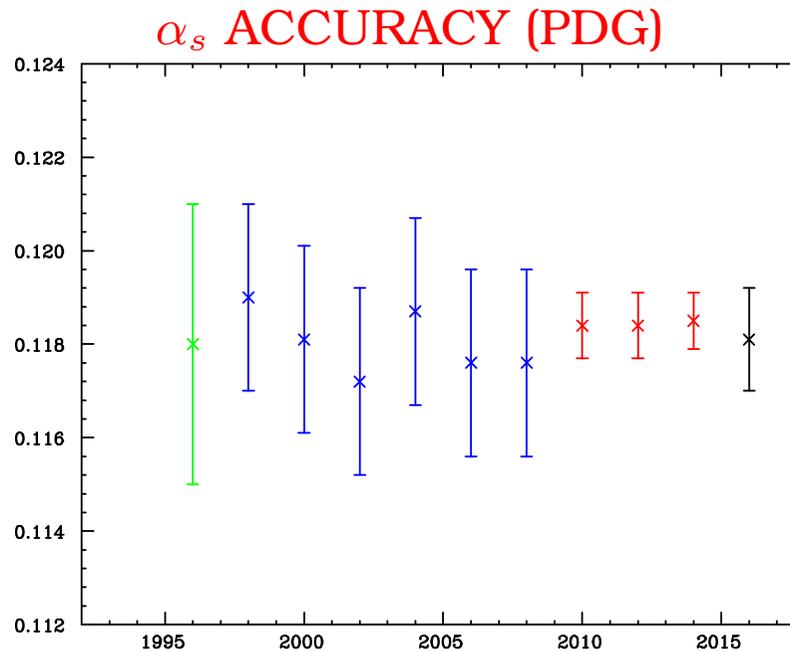


BETWEEN HIGGS DISCOVERY & LHC RUN II

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

QCD PROGRESS II: PERTURBATIVE ACCURACY & PDFs

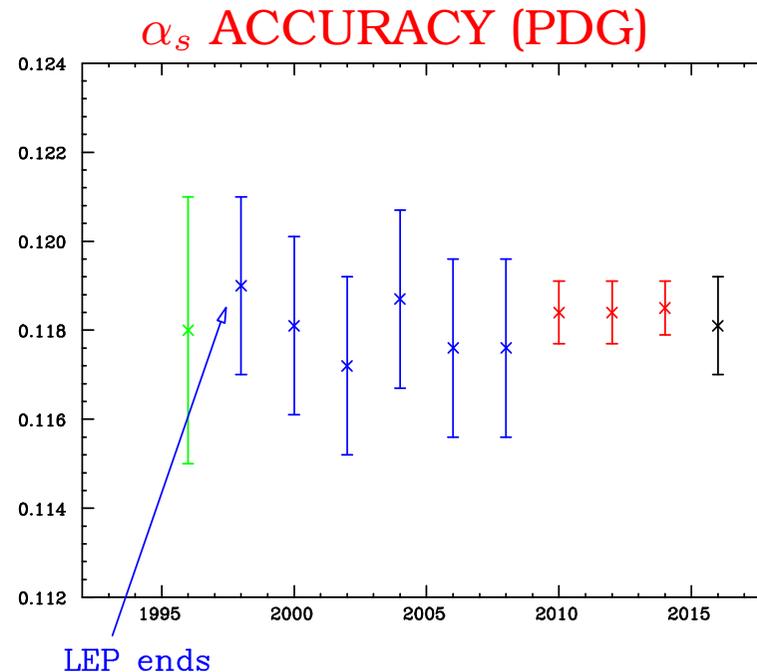
- 2000
 - NLO QCD EVOLUTION, MOST PROCESSES KNOWN AT NLO
 - PDF UNCERTAINTIES UNKNOWN
 - DATA-THEORY COMPARISON $\sim 10 - 20\%$
- 2010
 - NNLO QCD EVOLUTION, INCLUSIVE STANDARD CANDLES KNOWN AT NNLO
 - PDF UNCERTAINTIES $\sim 10\%$, ACCURACY?
 - DATA-THEORY COMPARISON $\sim 5 - 10\%$
- 2017
 - NNLO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



PROGRESS II

PERTURBATIVE ACCURACY & PDFs

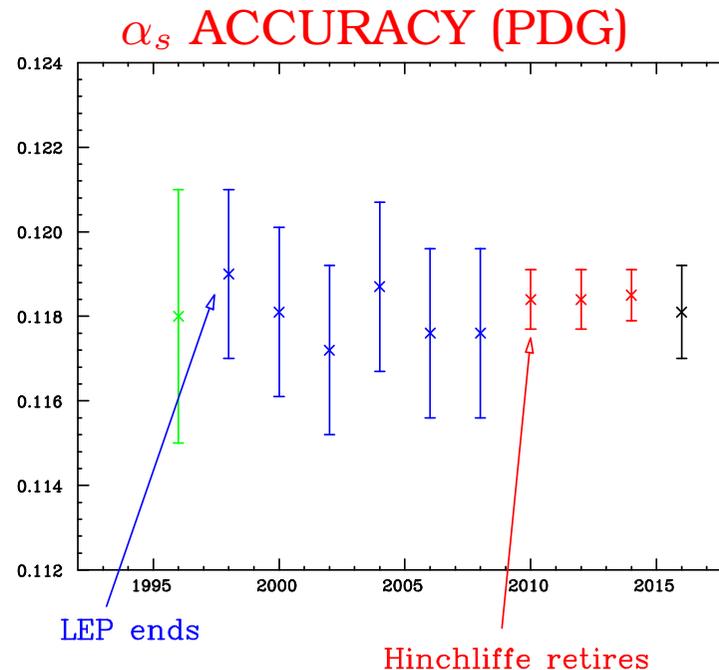
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PROGRESS II

PERTURBATIVE ACCURACY & PDFs

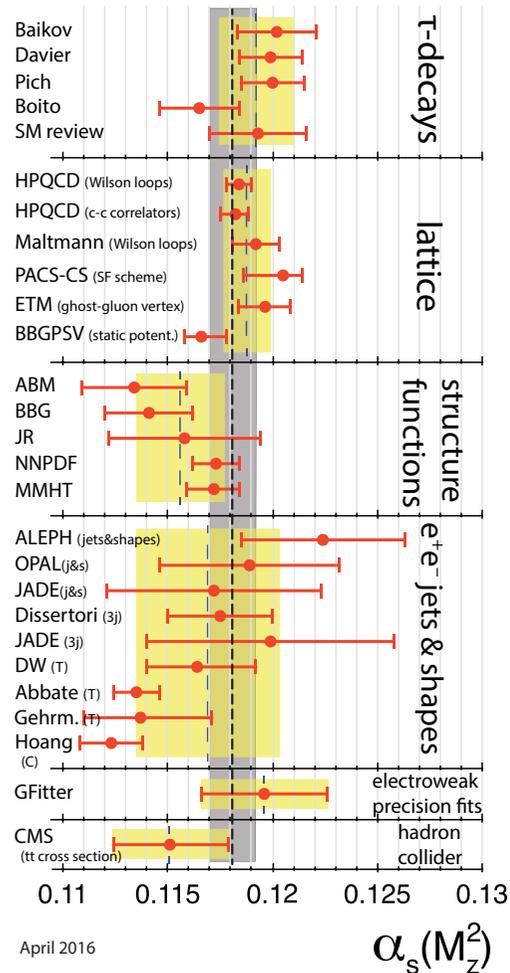
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α_s : HOW?

THE PDG AVERAGE WHERE DOES IT COME FROM?

PDG PRE-AVERAGES



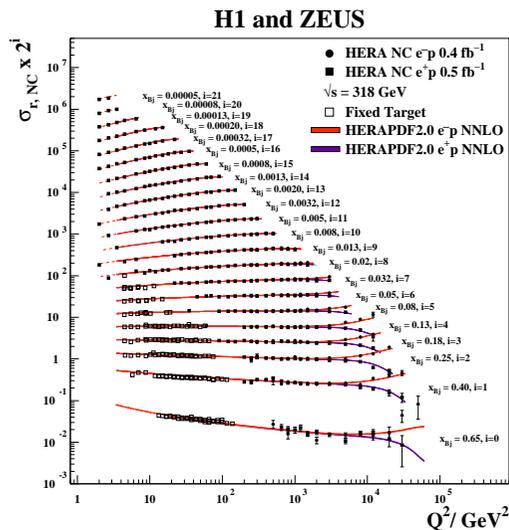
- PDG AVERAGE: χ^2 -AVERAGING OF SIX PRE-AVERAGES, CHOSEN TO BE MAXIMALLY UNCORRELATED
- χ^2 AVERAGING \Rightarrow UNCERTAINTIES INFLATED OR CORRELATED UNTIL $\chi^2/dof = 1$
- EACH PRE-AVERAGE IS THE SIMPLE (UNWEIGHTED) AVERAGE OF ITS COMPONENTS, UNCERTAINTY \leftrightarrow AVERAGE OF UNCERTAINTIES (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

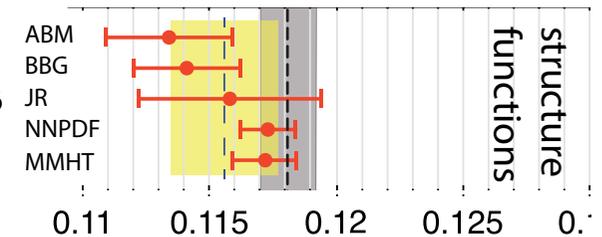


- α_s & PDFs (GLUON) STRONGLY CORRELATED

$$\frac{d}{d \ln Q^2} F_2(x, Q^2) \sim \alpha_s(Q^2) F_2(x, Q^2) + \alpha_s(Q^2) G(x, Q^2)$$

MANY SOURCES OF UNCERTAINTY :

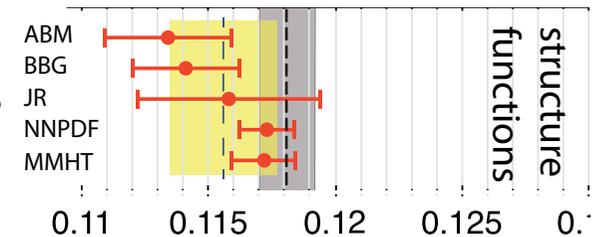
- PDF PARAMETRIZATION & PROPAGATION OF PDF UNCERTAINTIES
- TREATMENT OF EXPERIMENTAL SYSTEMATICS IN THE GLOBAL FIT
- HEAVY QUARK MASSES: FFN vs. VFN SCHEMES; PERTURBATIVE VS. FITTED CHARM; VALUES OF HQ MASSES



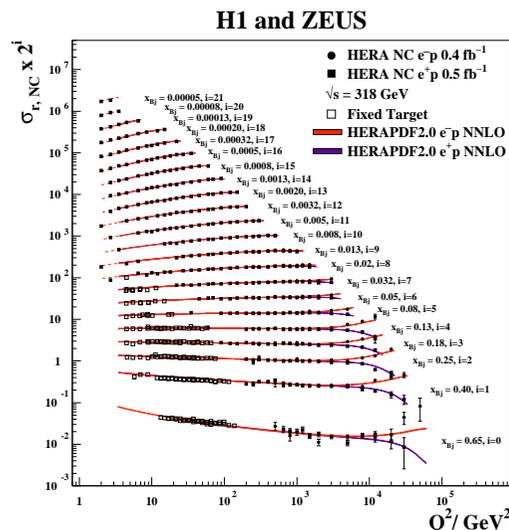
- BBG: DRIVEN DOWNWARDS BY NEGLECT OF LARGE NONSINGLET CONTRIBUTION (Martin, 2011)
- ABM: DRIVEN DOWNWARDS BY FIXED-FLAVOR NUMBER TREATMENT OF HEAVY QUARKS (Thorne, 2014)
- JR: BASED ON OBSOLETE PDF FIT
- NNPDF, MMHT: NO SERIOUS ESTIMATE OF THEORY UNCERTAINTIES

CASE STUDY I: STRUCTURE FUNCTIONS GLOBAL PDF FITS

- “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
- $$\frac{d}{d \ln Q^2} F_2(x, Q^2) \sim \alpha_s(Q^2) F_2(x, Q^2) + \alpha_s(Q^2) G(x, Q^2)$$

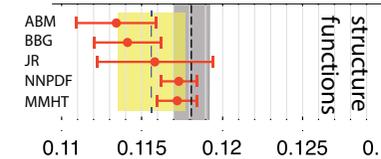
MANY SOURCES OF UNCERTAINTY :

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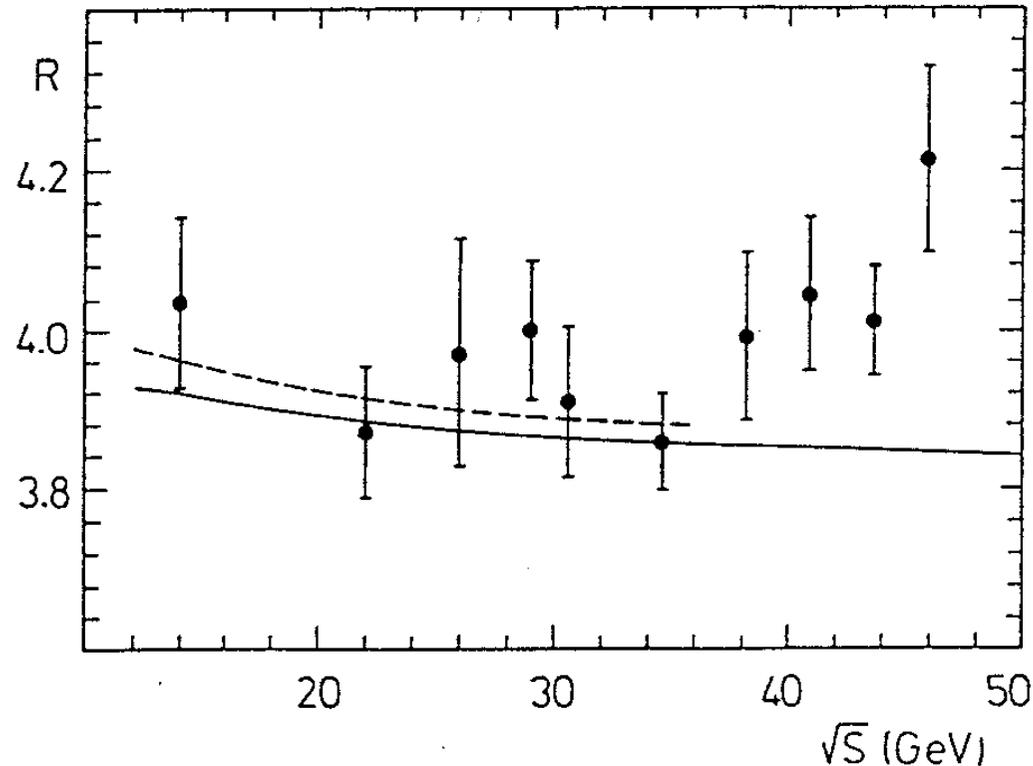
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CASE STUDY I: GLOBAL PDF FITS

THE D'AGOSTINI BIAS



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

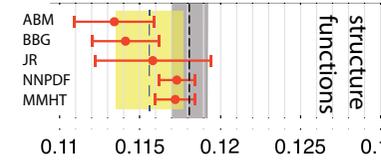


(CELLO collab., 1987)

- **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

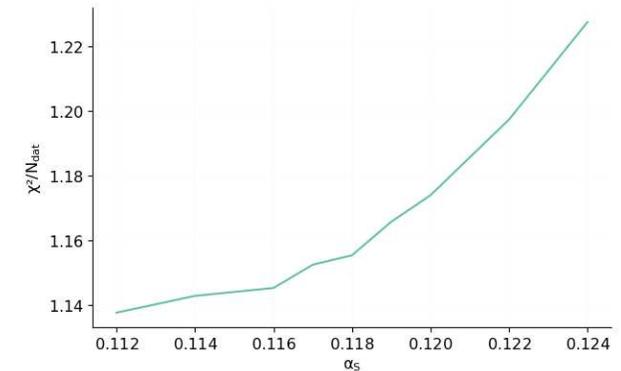
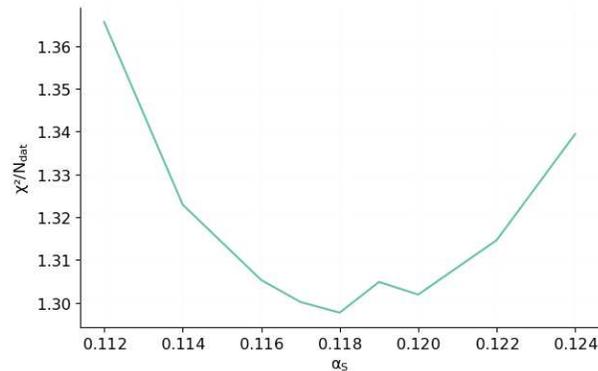
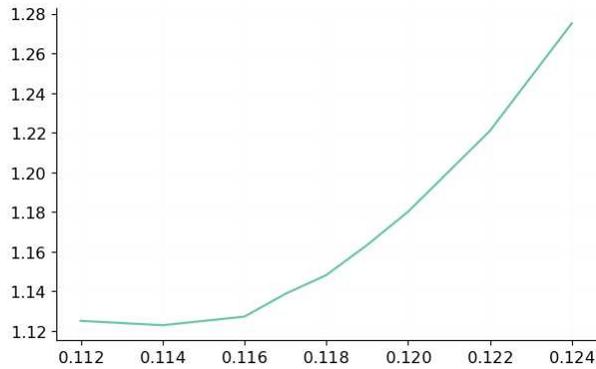
α_s FROM THE NNPDF3.1 PDF FIT



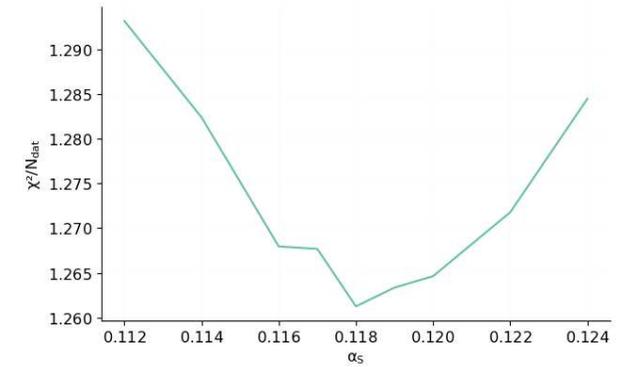
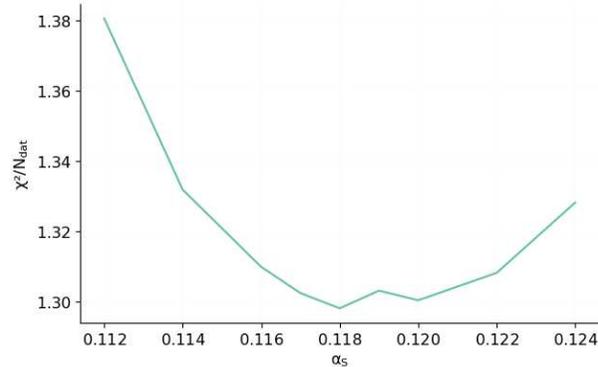
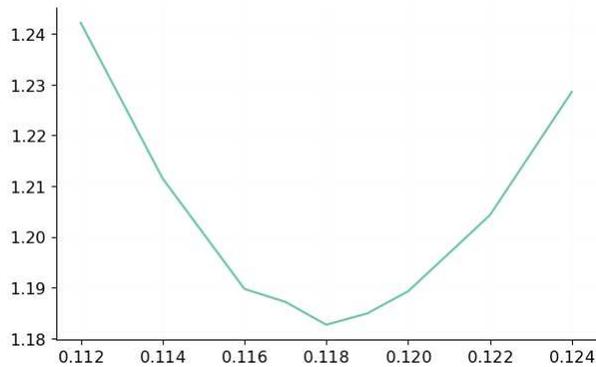
BIASED UNCERTAINTY IN COV. MAT.
ADDITIVE (NMC, FT)

GLOBAL

MULTIPLICATIVE (HERA, COLL)



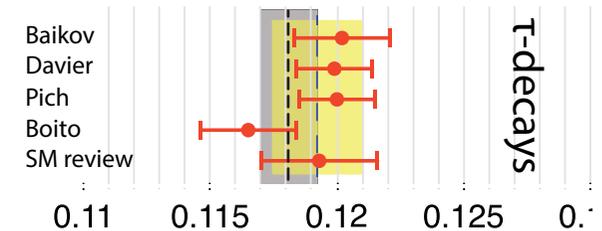
CONSISTENT (ITERATIVE)



- 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 INITIAL 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**



- HADRONIC WIDTH $\Leftrightarrow W$ **SELF-ENERGY** $\Pi(q^2)$

$$\Pi^{\mu\nu}(q) = i \int d^4x e^{iqx} \langle T (J_\mu(x) J_\nu^\dagger(0)) \rangle$$

- 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)

BASIC PRINCIPLE:

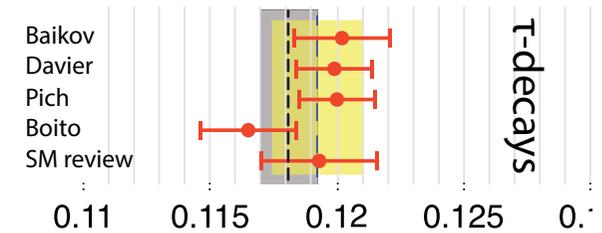
HADRONIC DECAY WIDTH

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

$$= f(\alpha_s(m_\tau))$$

CASE STUDY II: τ DECAYS

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

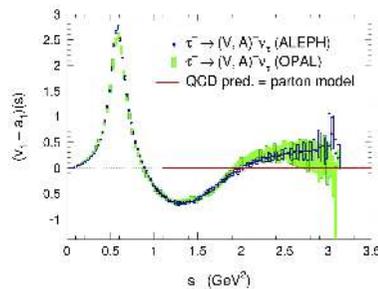


PERTURBATIVE UNCERTAINTIES

- 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 $\propto \frac{\langle O_4 \rangle}{m_\tau^4}$
 RENORMALON-INDUCED CONTRIBUTION $\propto \frac{\Lambda^2}{m_\tau^2}$?
- **CIPT AND FOPT AVERAGED**,
 \Rightarrow **DIFFERENCE** IN $\alpha_s(M_z)$ OF ORDER OF $\sim 1.5 - 2\%$

NONPERTURBATIVE UNCERTAINTIES

V+A SPECTRAL FCTN.

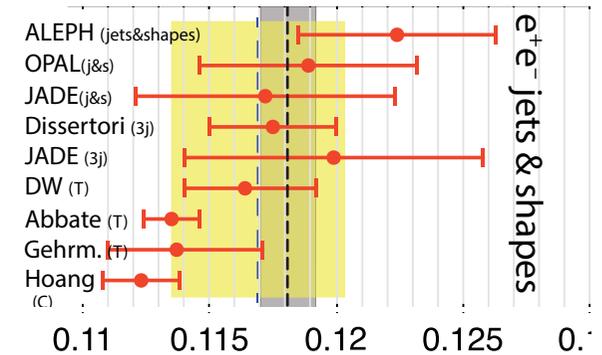


(Davier, Höcker, Zhang,
2006)

- **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:

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

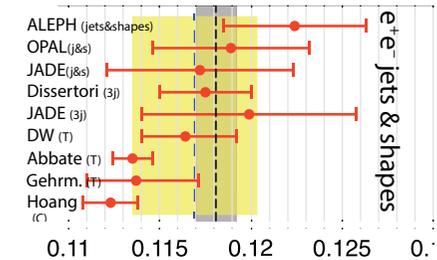
broadening, jet mass,
two-to-three jet transition;
three-jet rate

- **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^kLL** MATCHED TO **NONPERTURBATIVE MODELING:**
 - NNLO+NLL EFFECTIVE COUPLING (**THRUST**)
 - NNLO+NNLL DISPERSIVE MODEL (**THRUST**)
 - NNLO+N³LL (PADÉ) SCET FITTED SHAPE FUNCTION (**THRUST & C-PARAMETER**)

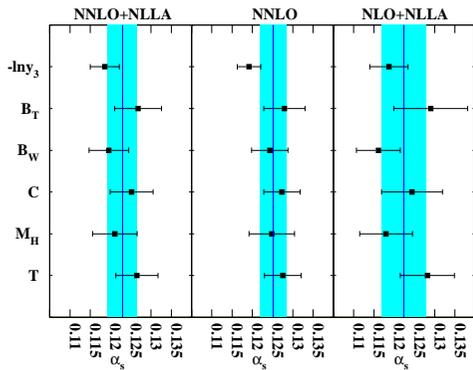
CASE STUDY III: e^+e^- JETS & SHAPES

UNCERTAINTIES (CONSERVATIVE): ALEPH EVENT SHAPES

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



PERTURBATIVE UNCERTAINTIES



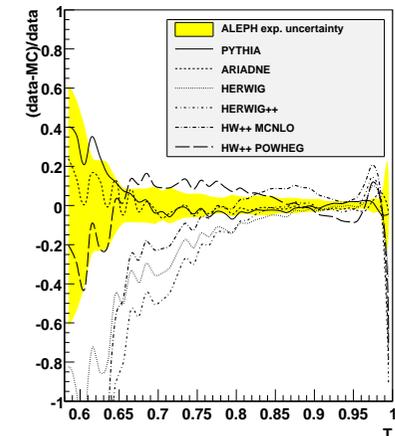
- RESUMMATION NEEDED FOR ACCURATE PREDICTIONS IN WIDE RANGE
⇒ REDUCED DISPERSION OF RESULTS
- INCOMPLETE SCALE CANCELLATION WHEN NNLO MATCHED TO NLL (NEED NNLL)
⇒ INCREASED UNCERTAINTY
- $\Delta\alpha_s(M_z) \sim 3.5\%$

NONPERTURBATIVE UNCERTAINTIES

MC VARIATION VS. EXP UNC.

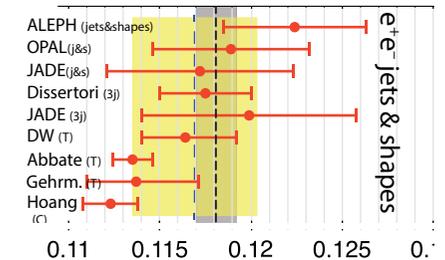
- MC REANALYSIS USING MODERN PS (MC@NLO & POWEG)
⇒ DISCREPANCY (TUNING ISSUES?)
- PYTHIA & HERWIG HADRONIZATION: SOME OBSERVABLES (THRUST, C PARM.) ⇒ UNDERESTIMATED HADR. CORRECTIONS?
- $\Delta\alpha_s(M_z) \gtrsim 1\%$

(Dissertori et al., 2009)

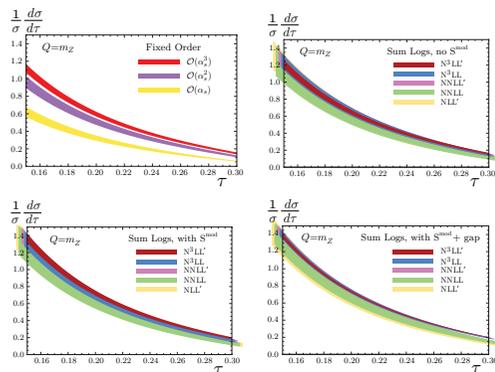


CASE STUDY III: e^+e^- JETS & SHAPES UNCERTAINTIES (**AGGRESSIVE**): THRUST FROM SCET

- 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



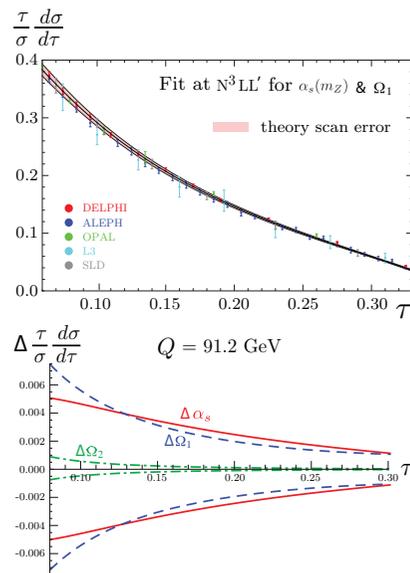
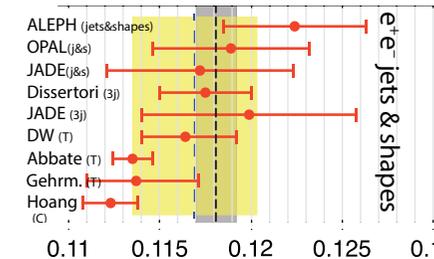
PERTURBATIVE UNCERTAINTIES



- RESUMMATION (N^3LL 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^3LL 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)



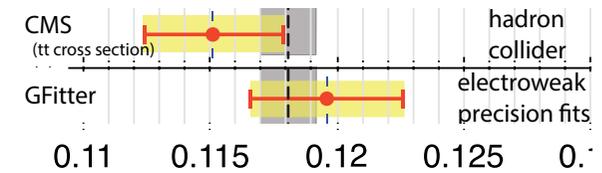
LESSONS LEARNT

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

WHICH α_s ?

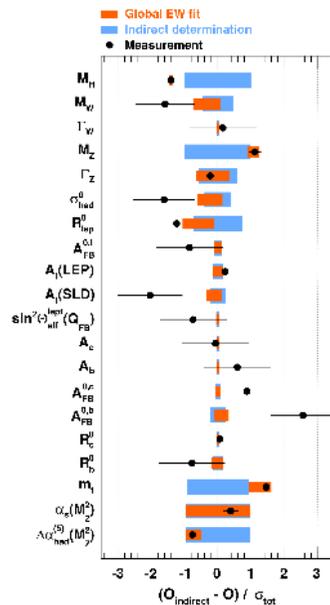
THE MEANING OF THE α_s UNCERTAINTY

- 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?

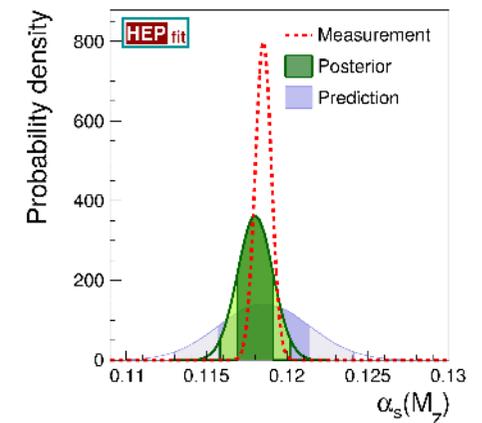


EASY (CONSERVATIVE?) UNCERTAINTY ESTIMATE: THE GLOBAL ELECTROWEAK FIT

- 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



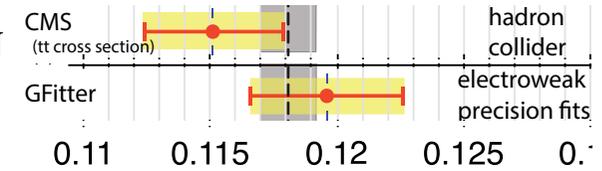
(Gfitter, 2014)



(HEPfit, de Blas et al., 2016)

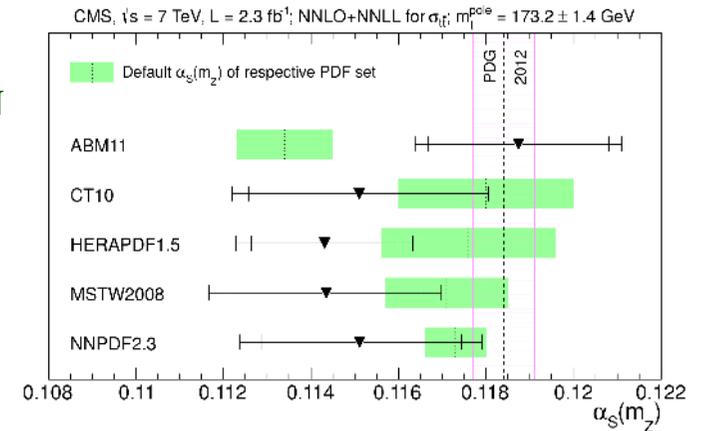
THE MEANING OF THE α_s UNCERTAINTY

- 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?

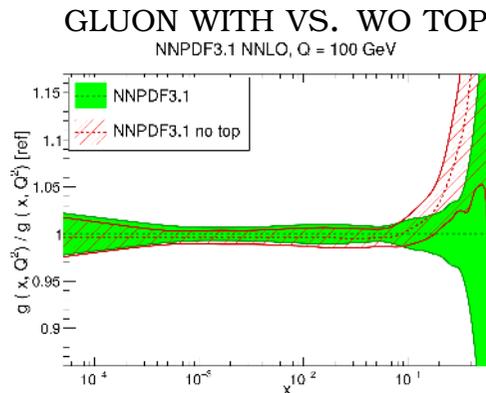


DIFFICULT (AGGRESSIVE?) UNCERTAINTY ESTIMATE: TOP PAIR PRODUCTION AT THE LHC

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



(CMS, 2014)



(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

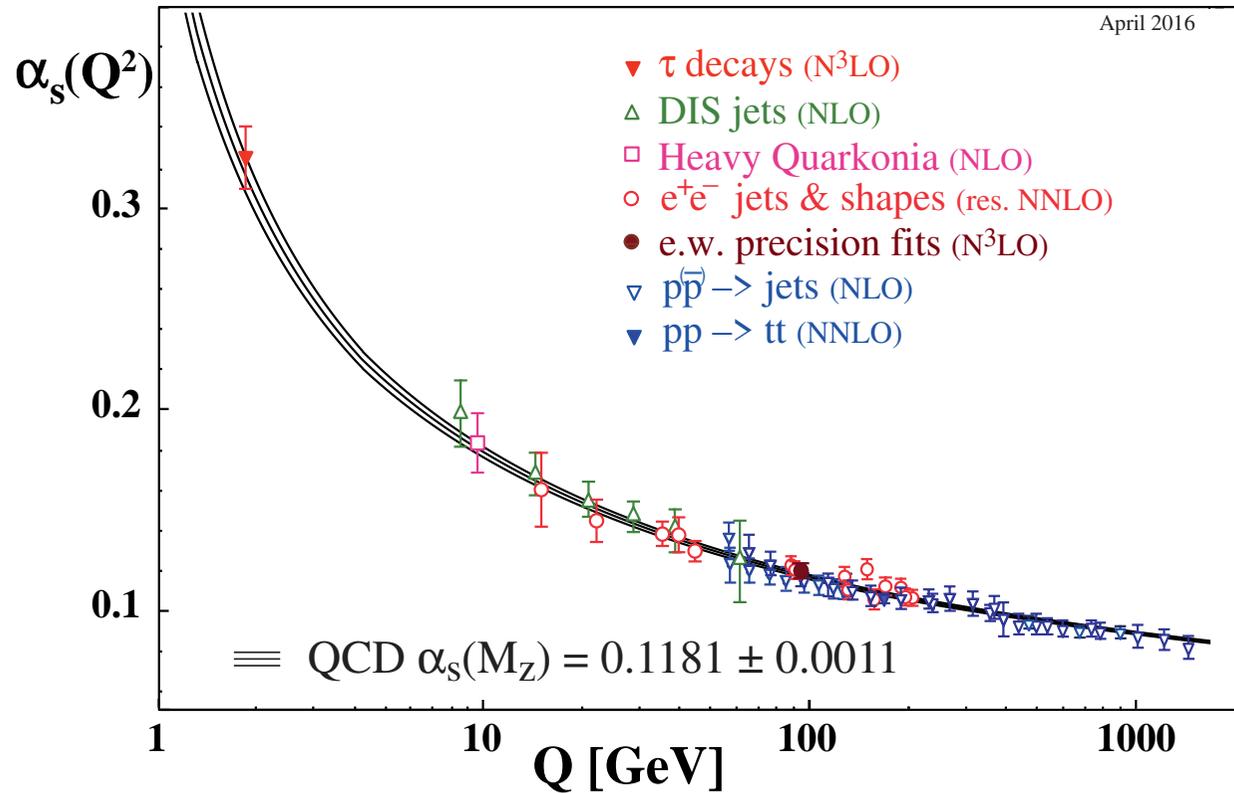
- SURPRISING **LACK OF PROGRESS**:
 - **NO SINGLE** RELIABLE AND ACCURATE DETERMINATION
 - **OUTLIERS** NOT FULLY UNDERSTOOD
- **FUTURE IMPROVEMENTS**:
 - **LHC-RUN II & HL-LHC** DATA \Rightarrow GLOBAL EW FIT, PDFs
 - **LATTICE** AS AN INDEPENDENT HANDLE \Rightarrow **OUTLIERS DISCARDED**

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

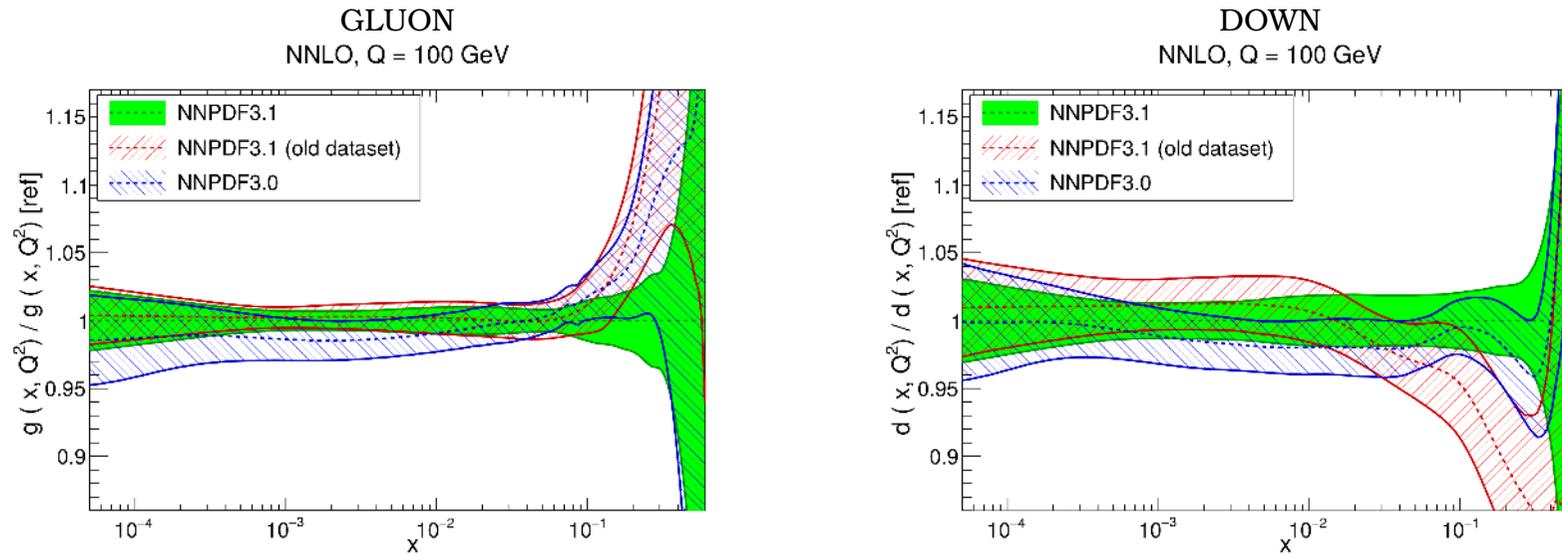


(PDG, 2016)

- 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 RAPIDITY, Z p_T , LHCb & ATLAS W & Z PRODUCTION



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