α_s: status and FCC-ee prospects

FCC week 2016

Rome, 14th April 2016

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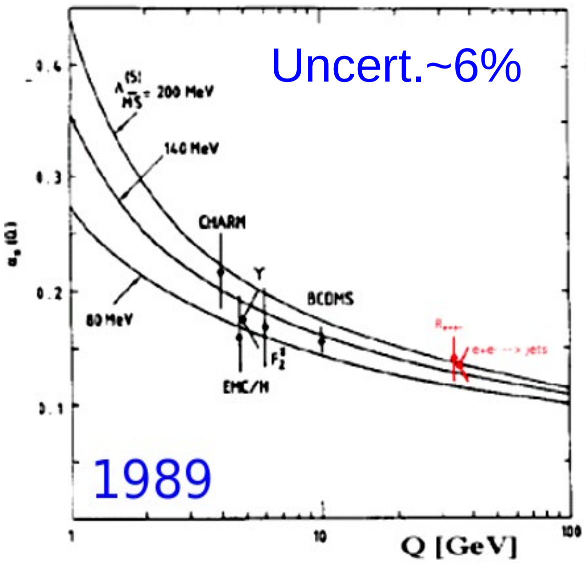
CERN

(*) D. d'Enterria, M. Srebre, "α_s, V_{cs}, and CKM unitarity test from hadronic W boson decays at NNLO", arXiv:1603.06501
D. d'Enterria, P.Z. Skands (eds.), Proceeds. "High-precision α_s from LHC to FCC-ee", CERN Oct. 2015; arXiv:1512.05194

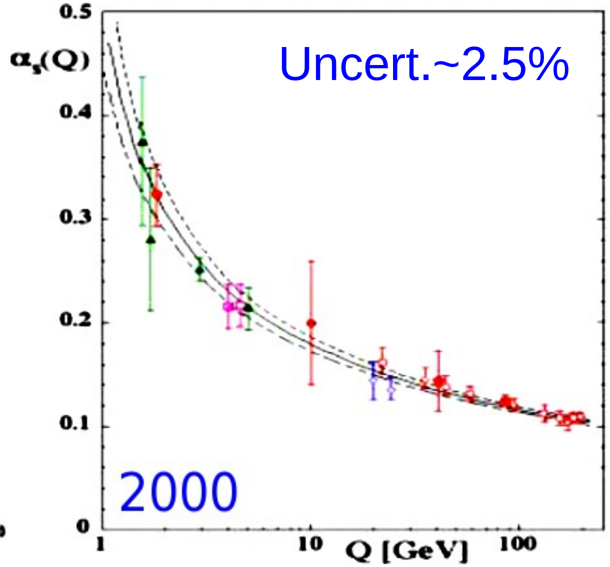
QCD coupling α_s

- Determines strength of the strong interaction between quarks & gluons
- Single free parameter in QCD (in the $m_q \rightarrow 0$ limit)
- Determined at a ref. scale ($Q=m_Z$), decreases as $\alpha_s \sim \ln(Q^2/\Lambda^2)^{-1}$, $\Lambda \sim 0.2$ GeV



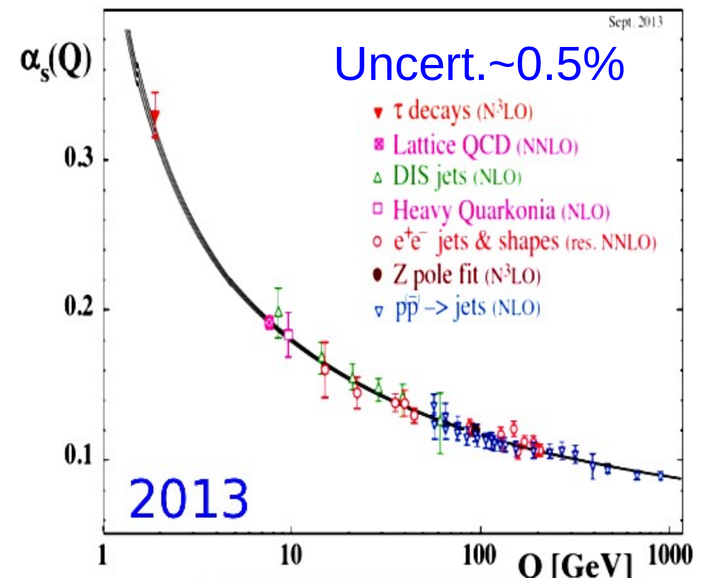
$\alpha_s(M_Z) = 0.110^{+0.006}_{-0.008}$ (NLO)

G. Altarelli, Ann. Rev. Nucl. Part. Sci. 39, 1989



$\alpha_s(M_Z) = 0.1184 \pm 0.0031$ (NNLO)

S. B. , J. Phys. G 26, 2000



$\alpha_s(M_Z) = 0.1185 \pm 0.0006$ (NNLO)

QCD coupling α_s

- Determines strength of the strong interaction between quarks & gluons
- Single free parameter in QCD (in the $m_q \rightarrow 0$ limit)
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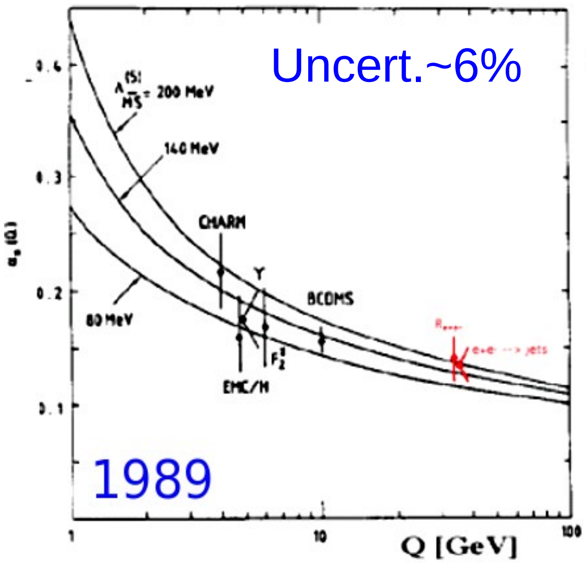

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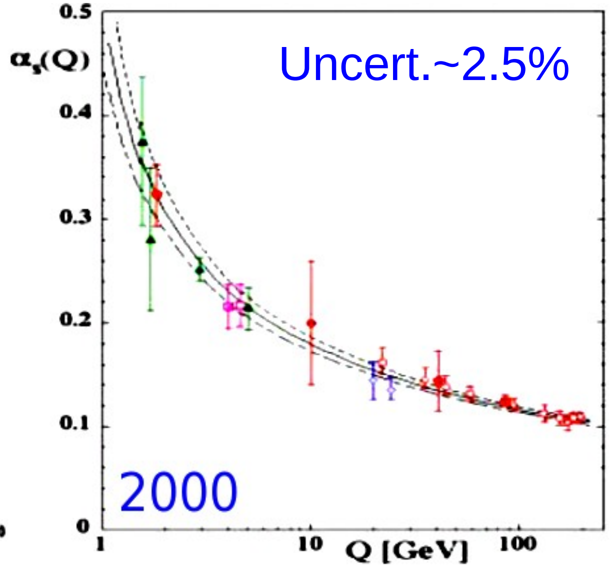

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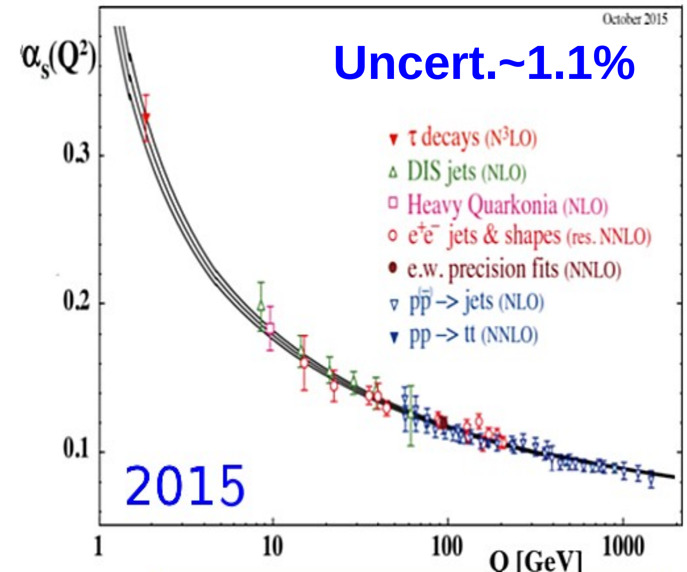


$\alpha_S(M_Z) = 0.1181 \pm 0.0013$ **(NNLO)**

- Least precisely known of all interaction couplings !

$$\delta\alpha \sim 10^{-10} \ll \delta G_F \ll 10^{-7} \ll \delta G \sim 10^{-5} \ll \delta\alpha_s \sim 10^{-3}$$

Importance of the QCD coupling α_s

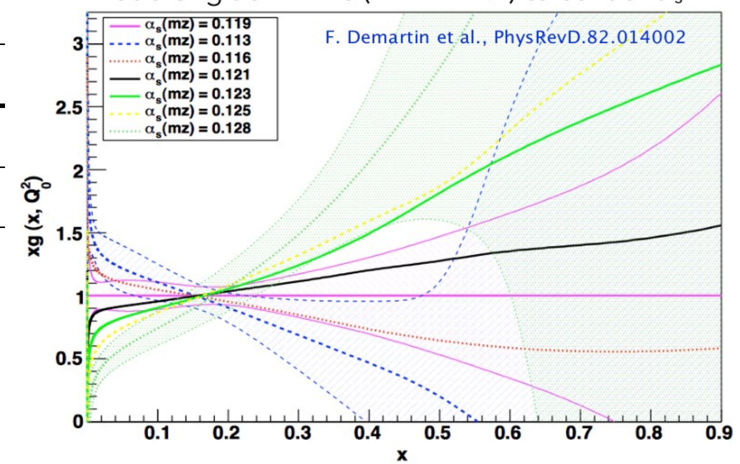
- Impacts all LHC x-sections & QCD decays, chiefly for Higgs:

Uncertainties (update of [LHC HXSWG 2013] for $\sqrt{s} = 14$ TeV)

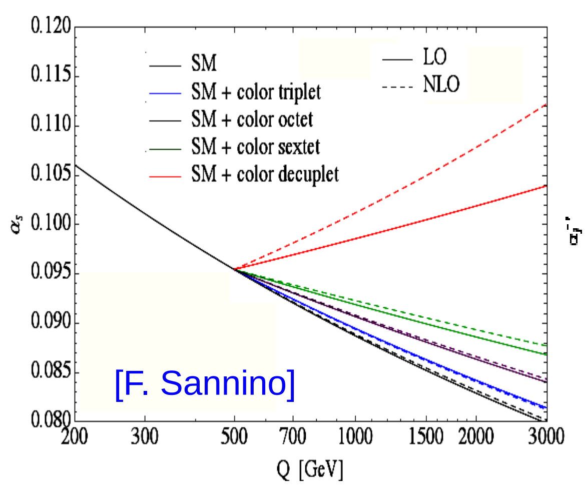
Process	σ (pb)	$\delta\alpha_s(\%)$	PDF $+\alpha_s(\%)$	Scale(%)
ggH	49.87	$\pm$ 3.7	-6.2 +7.4	-2.61 + 0.32
ttH	0.611	$\pm$ 3.0	$\pm$ 8.9	-9.3 + 5.9

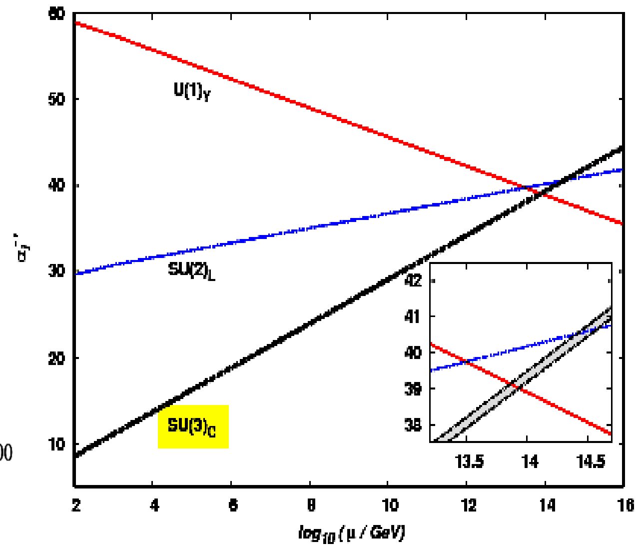
Channel	M_H[GeV]	$\delta\alpha_s(\%)$	Δm_b	Δm_c
$H \to c\bar{c}$	126	$\pm$ 7.1	$\pm$ 0.1%	$\pm$ 2.3 %
$H \to gg$	126	$\pm$ 4.1	$\pm$ 0.1%	$\pm$ 0 %

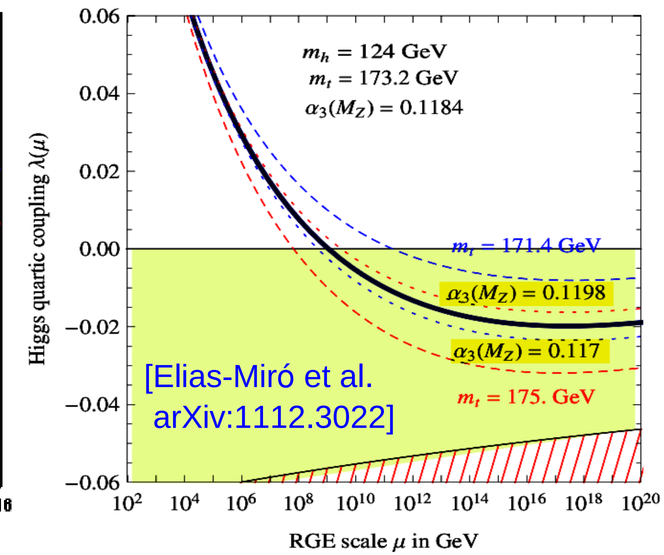
ratio of gluon-PDFs (NNPDF1.2) to central α_s



- Impacts new physics: new colored sectors, GUT, EW vacuum stability

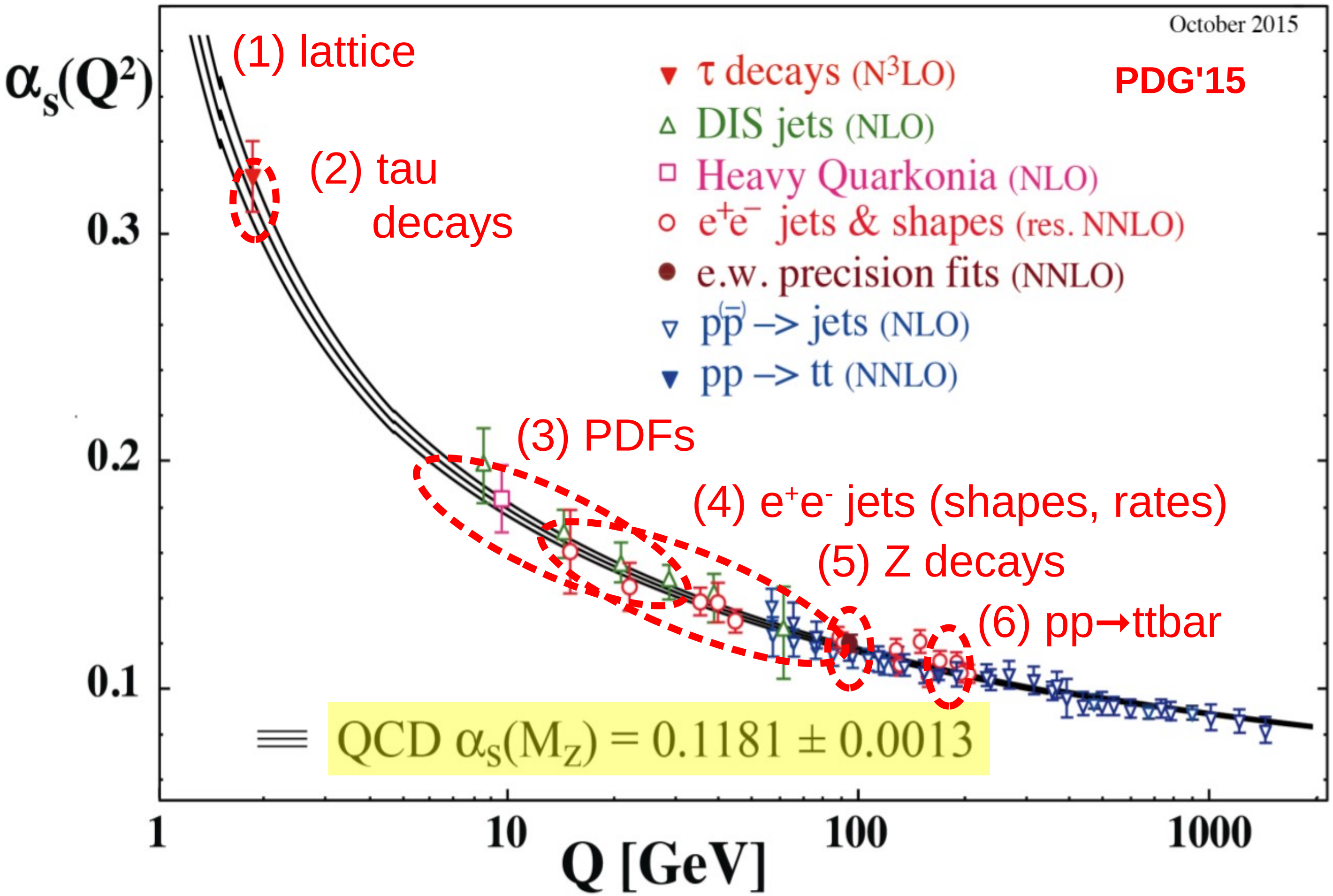






Status of α_s determination (PDG 2015)

- Determined by comparing 6 experimental observables to pQCD NNLO, N^{3}LO predictions, and performing a global average of their propagated values at the Z pole scale:



(1) α_s from lattice QCD

- Comparison of short-distance quantities (Wilson loops, $Q\bar{Q}$ potential, vacuum polariz.,...) computed at NNLO in pQCD, to lattice QCD "data":

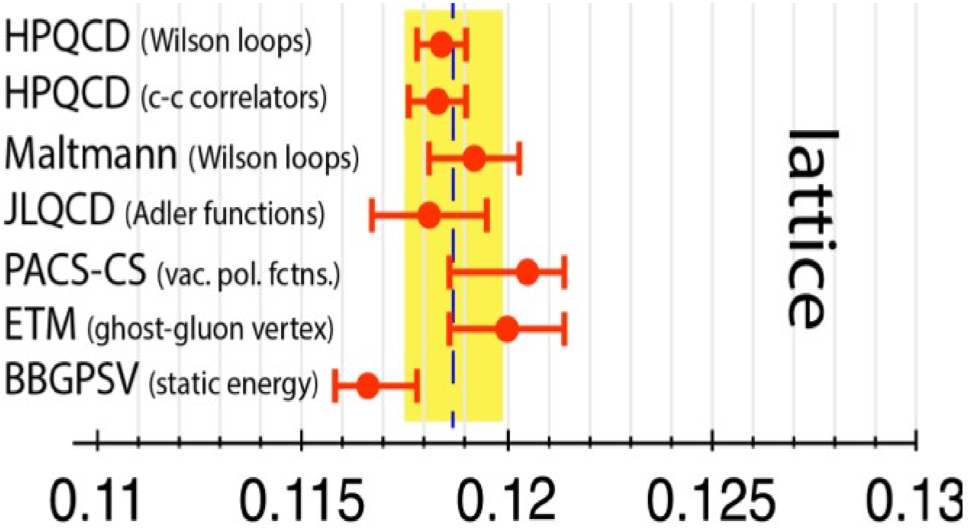
$$K^{\rm NP} = K^{\rm PT} = \sum_{i=0}^{n} c_i \alpha_s^i$$

[FLAG Collab. http://itpwiki.unibe.ch/flag]

- Currently, it's extraction with smallest uncertainties: ±1% (lattice spacing & statistics).

  Extracted value depends on observables:

  Uncertainty increased: 2013 (±0.4%) → 2015 (±1.0%)



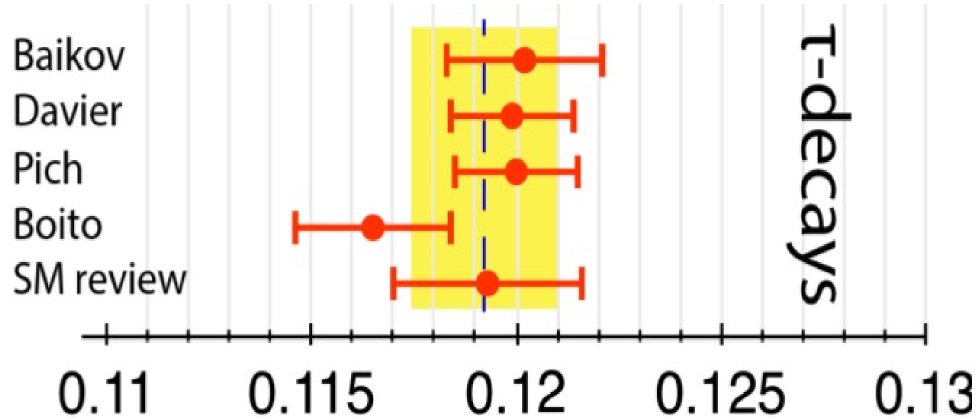
$\alpha_s(M_Z) = 0.1187 \pm 0.0012$ **(±1.0%)**

- Future prospects:
  – Uncertainty in α_s could be halved with (much) better numerical data.
  – Reaching ±0.1% requires 4^{th}-loop perturbation theory (~10 years?)

(2) α_s from hadronic τ-lepton decays

- Computed at N^{3}LO: $R_\tau \equiv \frac{\Gamma(\tau^- \to \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)} = S_{\rm EW} N_C (1 + \sum_{n=1}^{4} c_n \left(\frac{\alpha_s}{\pi}\right)^n + \mathcal{O}(\alpha_s^5) + \delta_{\rm np})$
- Experimentally: $R_{\tau,\mathrm{exp}} = 3.4697 \pm 0.0080$ (±0.23%)
- Various pQCD approaches (FOPT vs CIPT) & treatment of non-pQCD contributions, yield different results.

  Uncertainty slightly increased: 2013 (±1.3%) → 2015 (±1.5%)



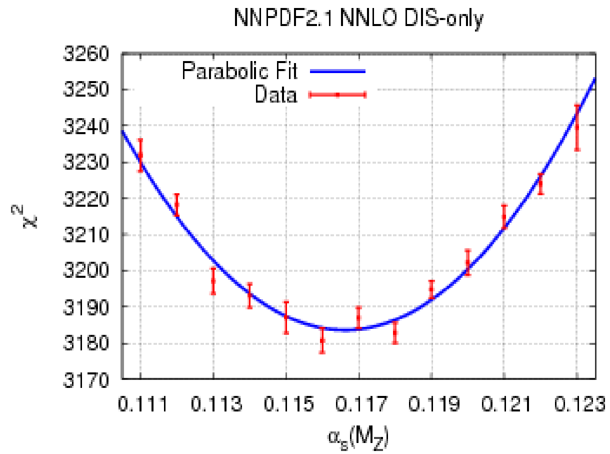
$\alpha_s(M_Z) = 0.1192 \pm 0.0018$ (±1.5%)

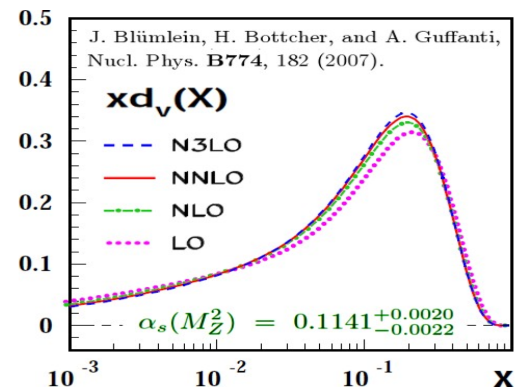
- Future prospects:
  – Better understanding of FOPT vs. CIPT differences.
  – Better spectral functions needed (high stats & precision): B-factories (BELLE-2), future (ILC, FCC-ee).

(3) α_s from proton structure functions

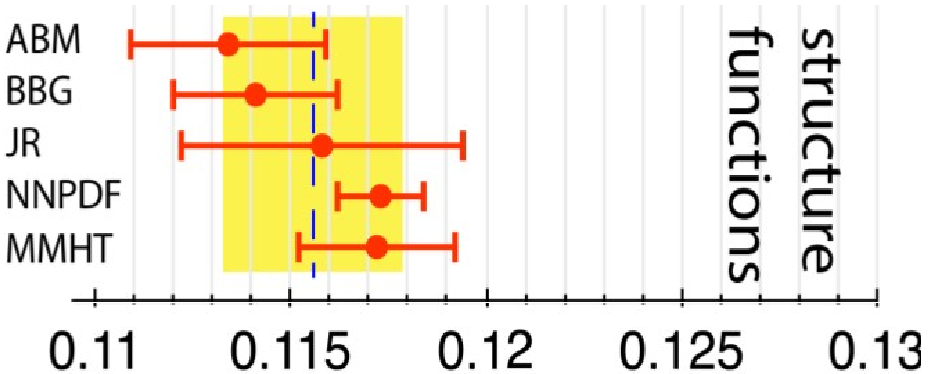
- Computed at N[2,3]LO: $F_2(x,Q^2) = x \sum_{n=0}^{\infty} \frac{\alpha_s^n(\mu_R^2)}{(2\pi)^n} \sum_{i=q,g} \int_x^1 \frac{dz}{z} C_{2,i}^{(n)}(z,Q^2,\mu_R^2,\mu_F^2)\, f_{i/p}\left(\frac{x}{z},\mu_F^2\right) + \mathcal{O}\left(\frac{\Lambda^2}{Q^2}\right)$
- Experimentally: Multiple $F_2(x,Q^2)$, $F^c_2(x,Q^2)$, $F_L(x,Q^2)$, PDFs(x,Q^2)
- Different approaches:

  Non-singlet fits,
  singlet+non-singlet fits,
  global fits of PDFs, …





Uncertainty slightly increased:
2013 (±1.7%) → 2015 (±2.0%)



$\alpha_s(M_Z) = 0.1156 \pm 0.0023$ (±2.0%)

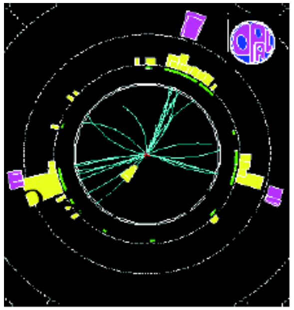
- Future prospects:
  – Full-NNLO PDF fits (including ttbar, jets,...)

(4) α_s from e^+e^- jets (event shapes & rates)

- Computed at $N^{2,3}LO+N^{(2)}LL$ accuracy.
- Experimentally (LEP):
  Thrust, C-parameter, jet shapes
  3-jet x-sections

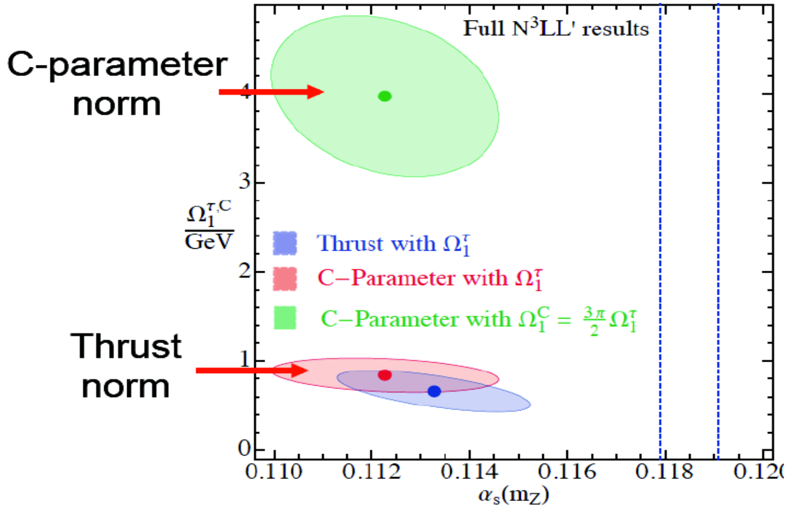
$$\tau = 1 - \max_{\hat{n}} \frac{\sum |\vec{p}_i \cdot \hat{n}|}{\sum |\vec{p}_i|}$$

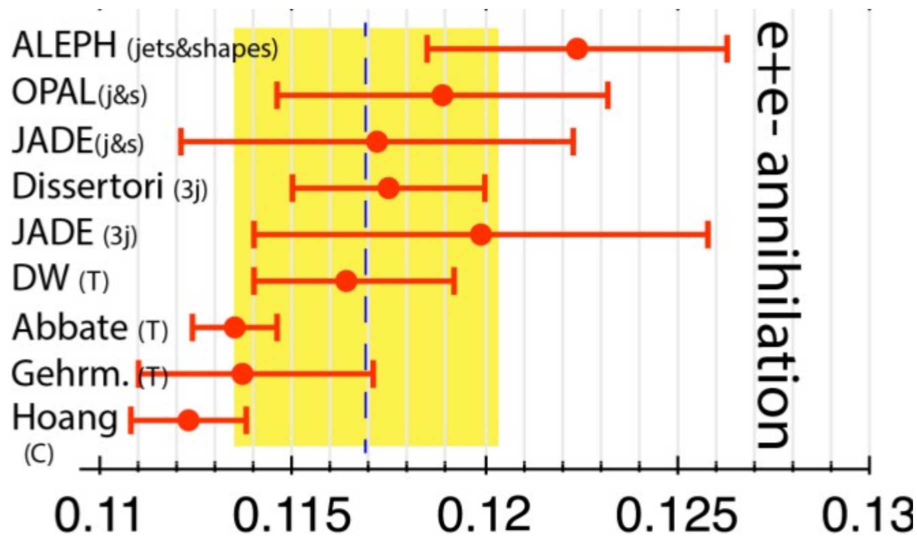
$$C = \frac{3}{2} \frac{\sum_{i,j} |\vec{p}_i||\vec{p}_j| \sin^2 \theta_{ij}}{\left(\sum_i |\vec{p}_i|\right)^2}$$



OPAL 3 jet event

- Results sensitive to non-pQCD (hadronization) accounted for via MCs or analytically:



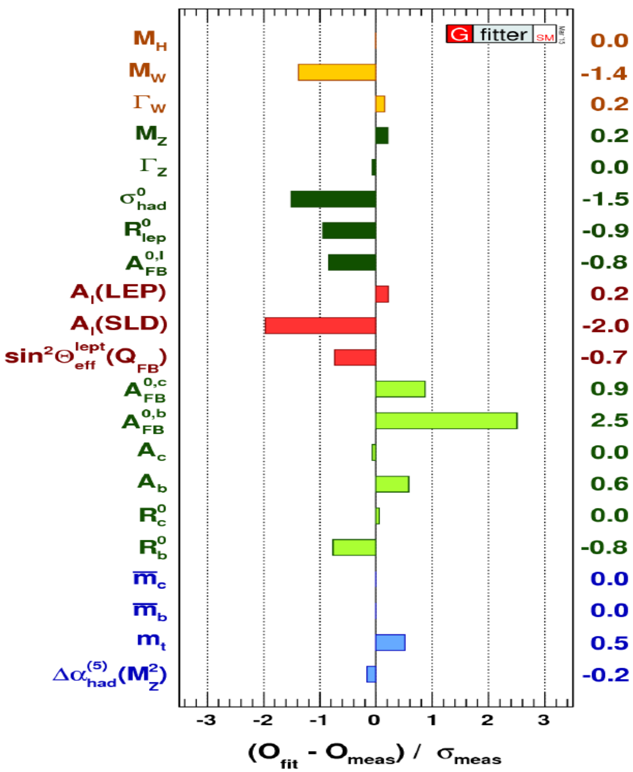


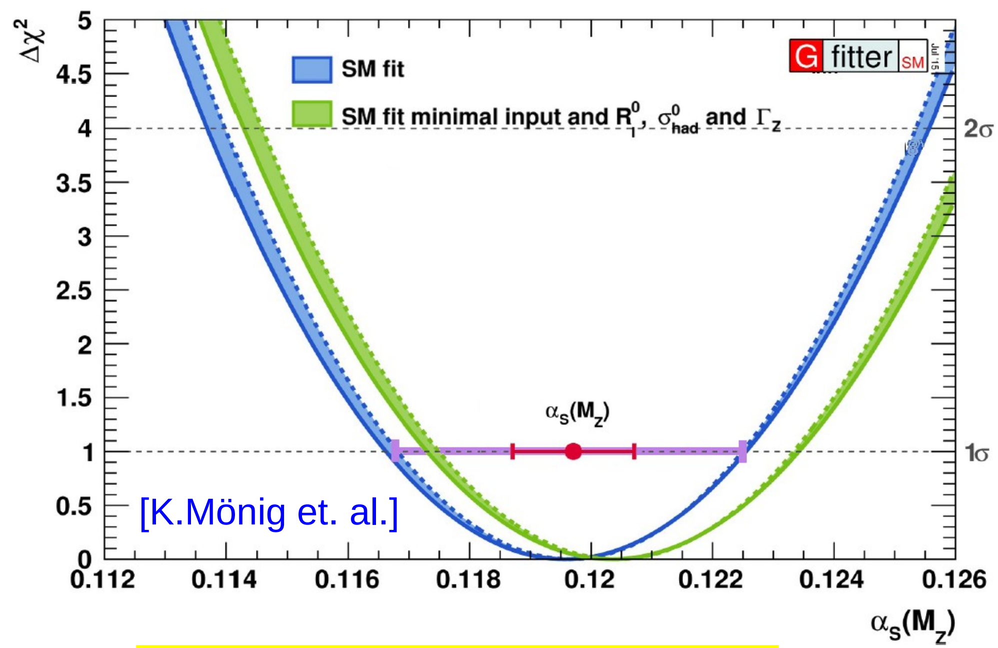
$\alpha_s(M_Z) = 0.1169 \pm 0.0034$ (±2.9%)

- Prospects:
  – New e^+e^- data: low-$\sqrt{s}$ (Belle-II) for shapes, high-$\sqrt{s}$ (FCC-ee) for rates
  – Jet rates with improved resummation: NNLL or N^3LL

(5) α_s from hadronic Z decays

- Computed at N[3]LO: $R_Z \equiv \frac{\Gamma(Z \to h)}{\Gamma(Z \to l)} = R_Z^{EW} N_C (1 + \sum_{n=1}^{4} c_n \left(\frac{\alpha_s}{\pi}\right)^n + \mathcal{O}(\alpha_s^5) + \delta_m + \delta_{np})$
- Experim.: Γ_Z = 2.4952±0.0023 GeV (±0.1%), $R_\ell^0 = \frac{\Gamma_{had}}{\Gamma_\ell}$, $\sigma_{had}^0 = \frac{12\pi}{m_Z} \frac{\Gamma_e \Gamma_{had}}{\Gamma_Z^2}$, $\sigma_\ell^0 = \frac{12\pi}{m_Z} \frac{\Gamma_\ell^2}{\Gamma_Z^2}$
- After Higgs discovery, α_s can be directly determined from full fit of SM:



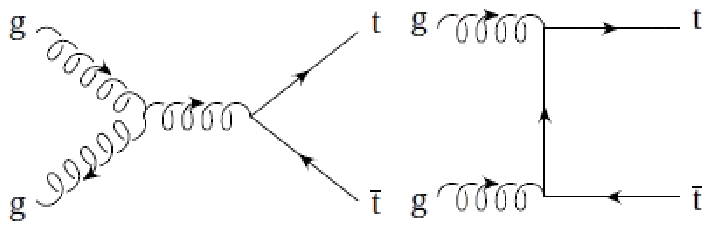


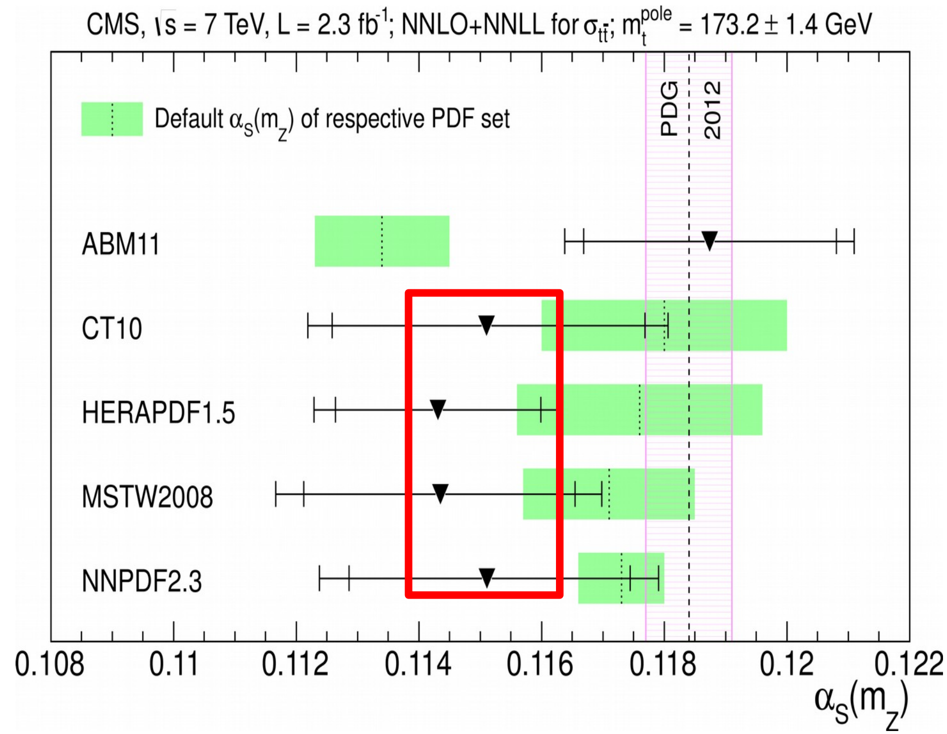
$\alpha_s (M_Z) = 0.1196 \pm 0.0030$ (±2.5%)

- Prospects: – Huge Z stats at FCC-ee will lead to: $\delta\alpha_s < 0.3\%$
  – Improved parametric ($\sin^2\theta_{eff}$, m_W, m_t) and TH (N[4]LO, EW, mixed) uncert.

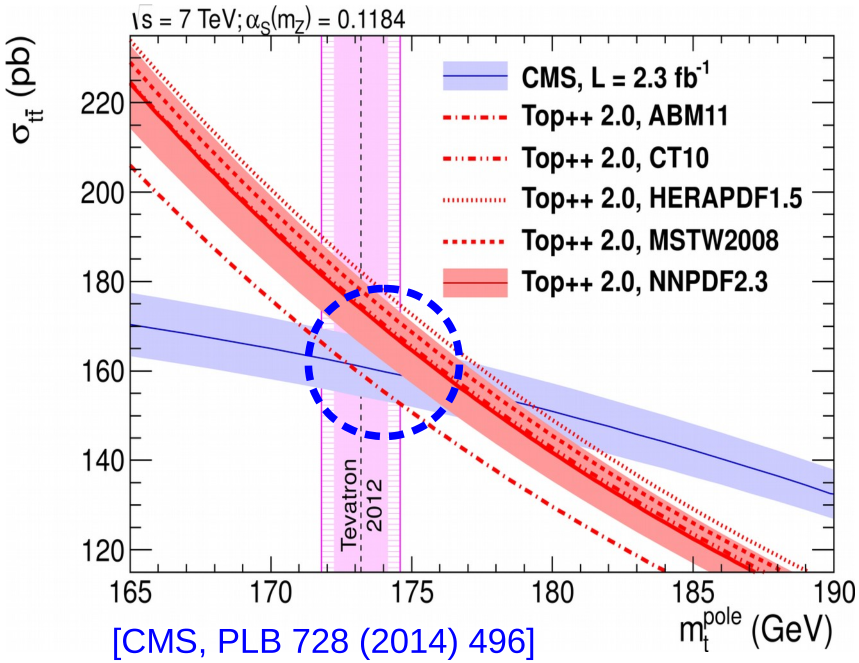
(6) α_s from top-pair p-p cross sections

- Total top-antitop cross section (known at NNLO+NNLL) is the 1st p-p collider observable to constrain α_s at NNLO accuracy:





Data-theory x-section comparison for varying PDF+α_s as a function of m_{top}:



[CMS, PLB 728 (2014) 496]

Precise measurement dominated by associated PDF uncertainty (±2.5%)

$$\alpha_s(M_Z^2) = 0.1151^{+0.0028}_{-0.0027}$$

(6) α_s from top-pair p-p cross sections

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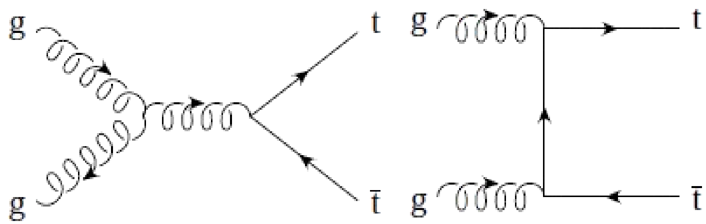

[G.Salam et al. arXiv:1512.05194]

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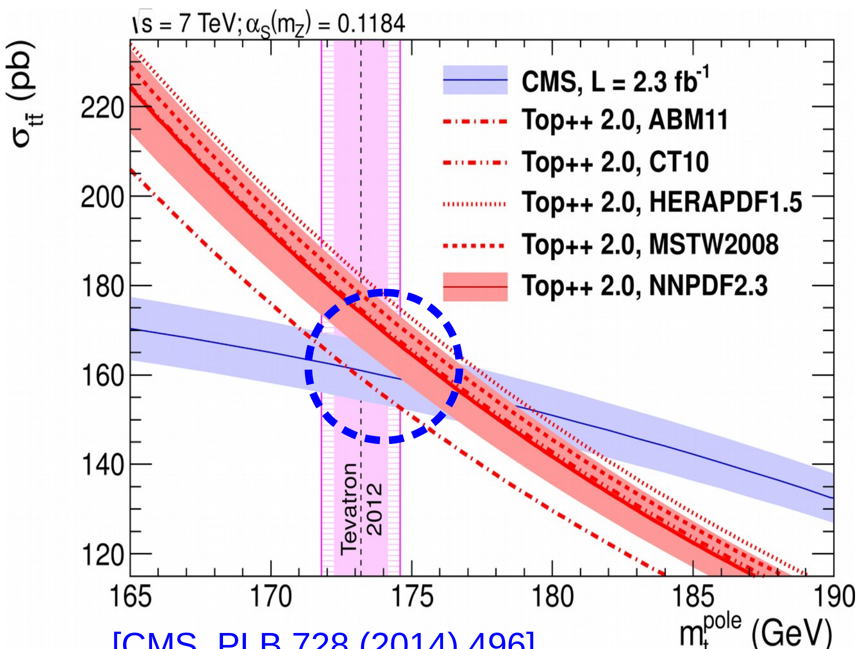
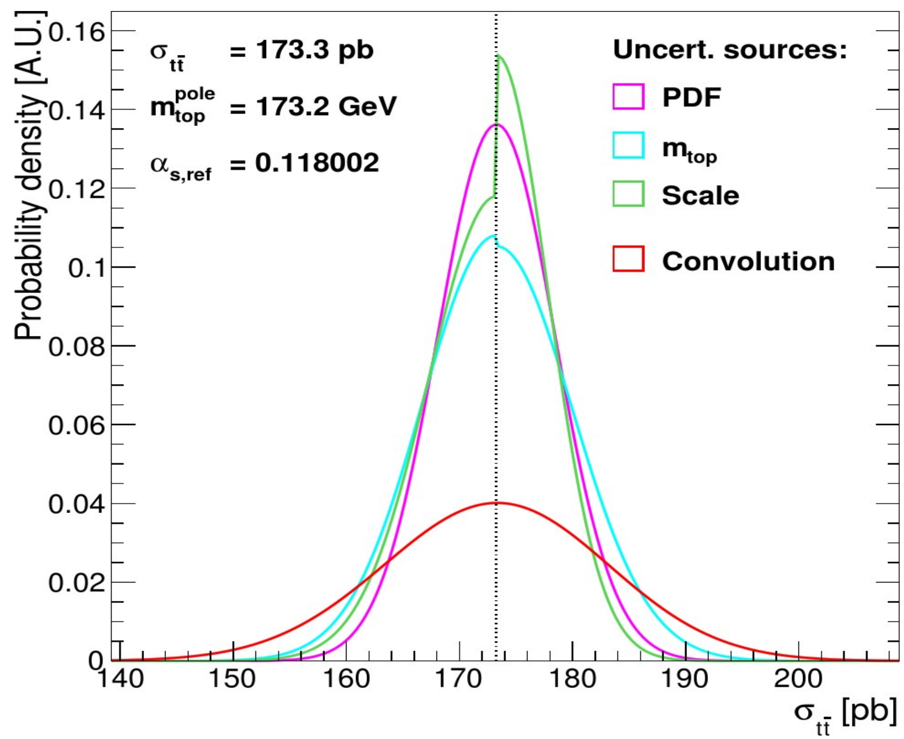


[CMS, PLB 728 (2014) 496]

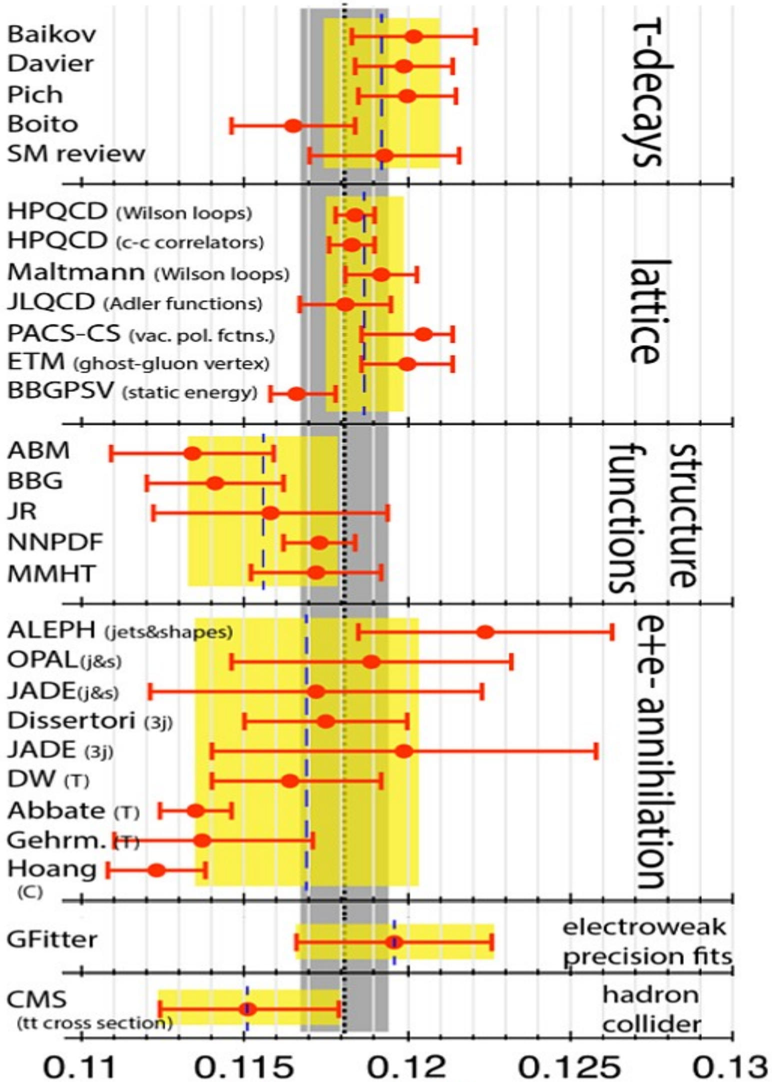


Inclusion of full set of t-tbar data increases $\alpha_s(m_Z)$ & uncertainty:

$\alpha_s(M_Z) = 0.1186 \pm 0.0033$ (±2.9%)

PDG 2015 α_s world average (NNLO)

[S.Bethke, Feb'16]



class averages:

$\alpha_s(M_z) = 0.1192 \pm 0.0018$ (±1.5%)

$\alpha_s(M_z) = 0.1187 \pm 0.0012$ (±1.0%)

$\alpha_s(M_z) = 0.1156 \pm 0.0023$ (±2.0%)

$\alpha_s(M_z) = 0.1169 \pm 0.0034$ (±2.9%)

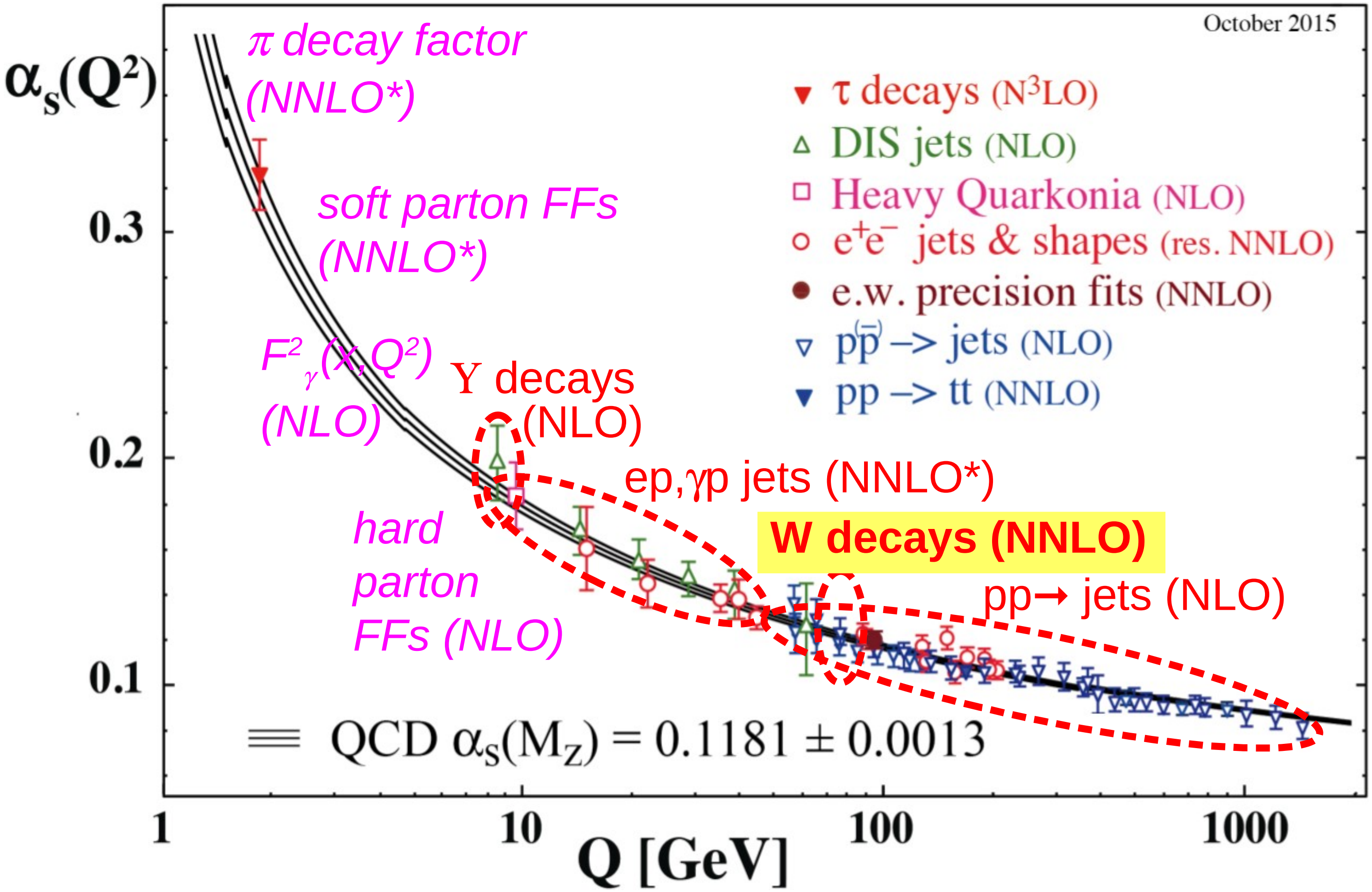
$\alpha_s(M_z) = 0.1196 \pm 0.0030$ (±2.5%)

$\alpha_s(M_z) = 0.1151 \pm 0.0033$ (±2.9%)

unweighted χ^2 average: $\alpha_s(M_z) = 0.1181 \pm 0.0013$ (±1.1%)

Other α_s extractions (not *yet* in world average)

- There exist at least 8 other classes of α_s observables (mostly of lower NLO, NNLO* accuracy) used to extract the QCD coupling:



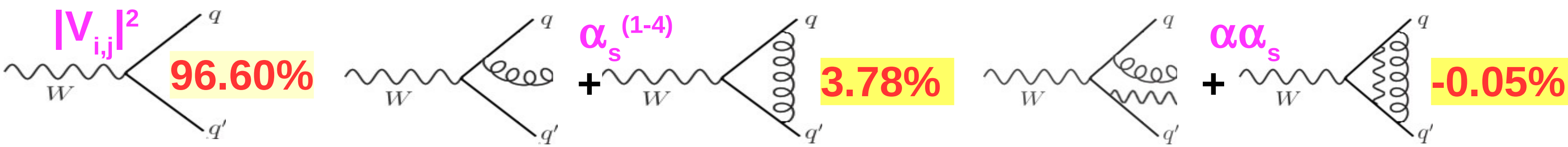
Hadronic W width & branching ratio

[D.d'E, M.Srebre, arXiv:1603.06501]

- Width (BR) known at N^3LO (NNLO). Small sensitivity to α_s (beyond Born)

$$\Gamma_{\mathrm{W,had}} = \frac{\sqrt{2}}{4\pi} G_F m_W^3 \sum_{\text{quarks i,j}} |V_{i,j}|^2 \left[1 + \sum_{k=1}^{4} \left(\frac{\alpha_s}{\pi}\right)^k + \delta_{\mathrm{electroweak}}(\alpha) + \delta_{\mathrm{mixed}}(\alpha\alpha_s) \right]$$

[EWK: -0.35%]



- TH improvements: finite quark-mass effects included (LO), updated PDG values, careful evaluation of parametric ($V_{i,j}$, m_W) & theoretical uncert.

- Calculation dominated by ±1.5% parametric (mostly V_{cs}) uncertainty:

Γ_W(MeV) = $1428.67 \pm 22.40_{(par)} \pm 0.04_{(th)}$ (exp. CKM)

$1411.40 \pm 0.96_{(par)} \pm 0.04_{(th)}$ (CKM=1)

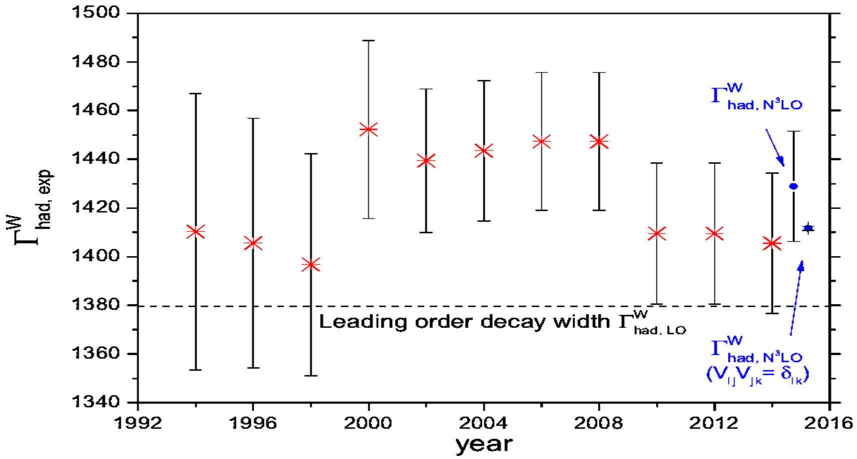
$BR_W = \Gamma_W/\Gamma_{tot}$ = $0.6820 \pm 0.0110_{(par)} \pm 0.0002_{(th)}$ (exp. CKM)

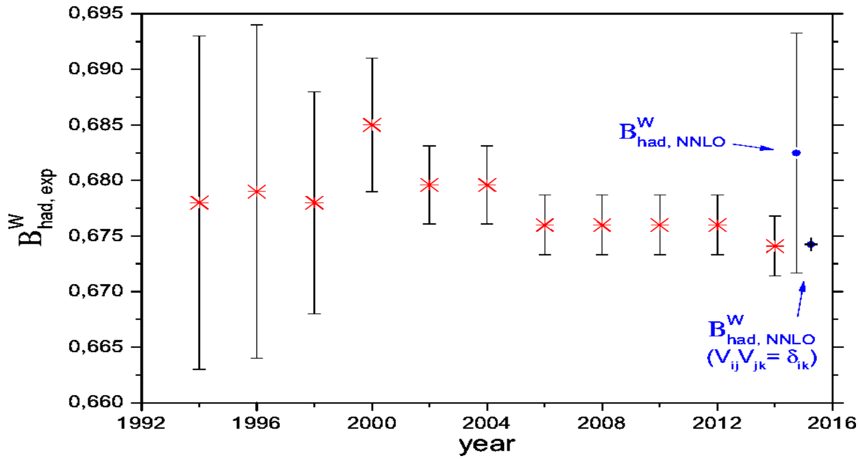
$0.6742 \pm 0.0001_{(par)} \pm 0.0002_{(th)}$ (CKM=1)

- TH uncertainty (missing α_s^5 terms, non-pQCD $(\Lambda_{QCD}/m_W)^4$ power corrs., finite quark masses beyond LO, CKM matrix renorm. scheme): ±0.03%

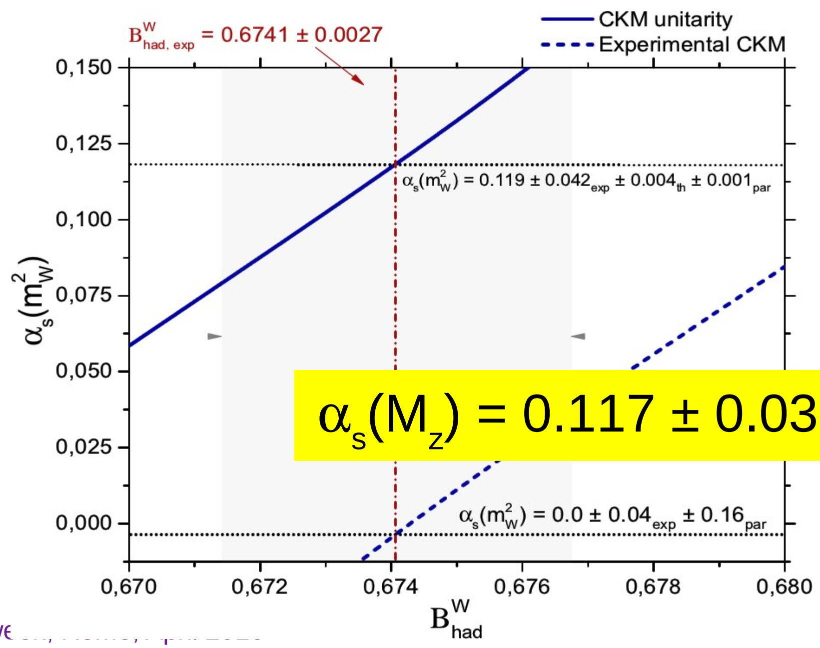
α_s from hadronic W decays

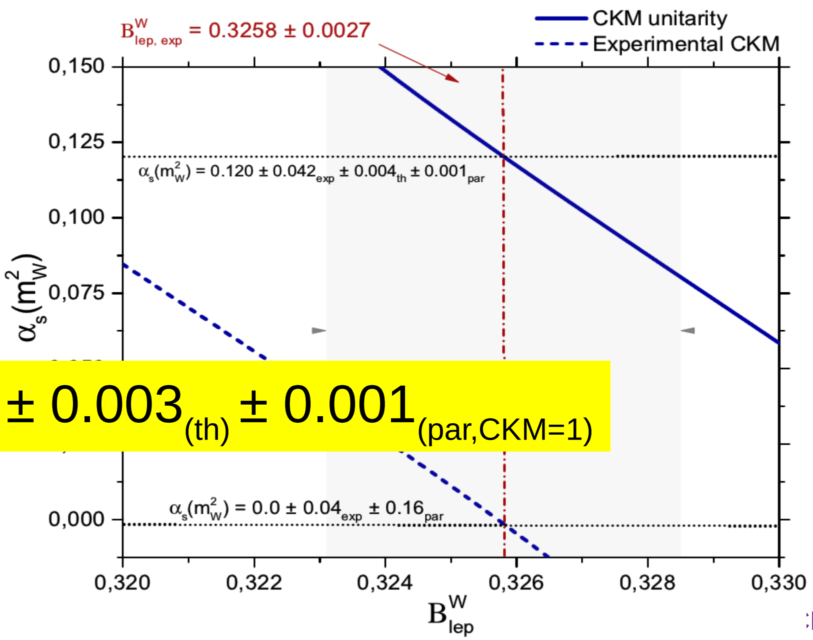
- TH vs. EXP: Γ_W = 1405±29 MeV (±2%), BR_W = 0.6741±0.0027 (±0.4%)





- Extraction with large exp. & parametric uncertainties (±25%) today:





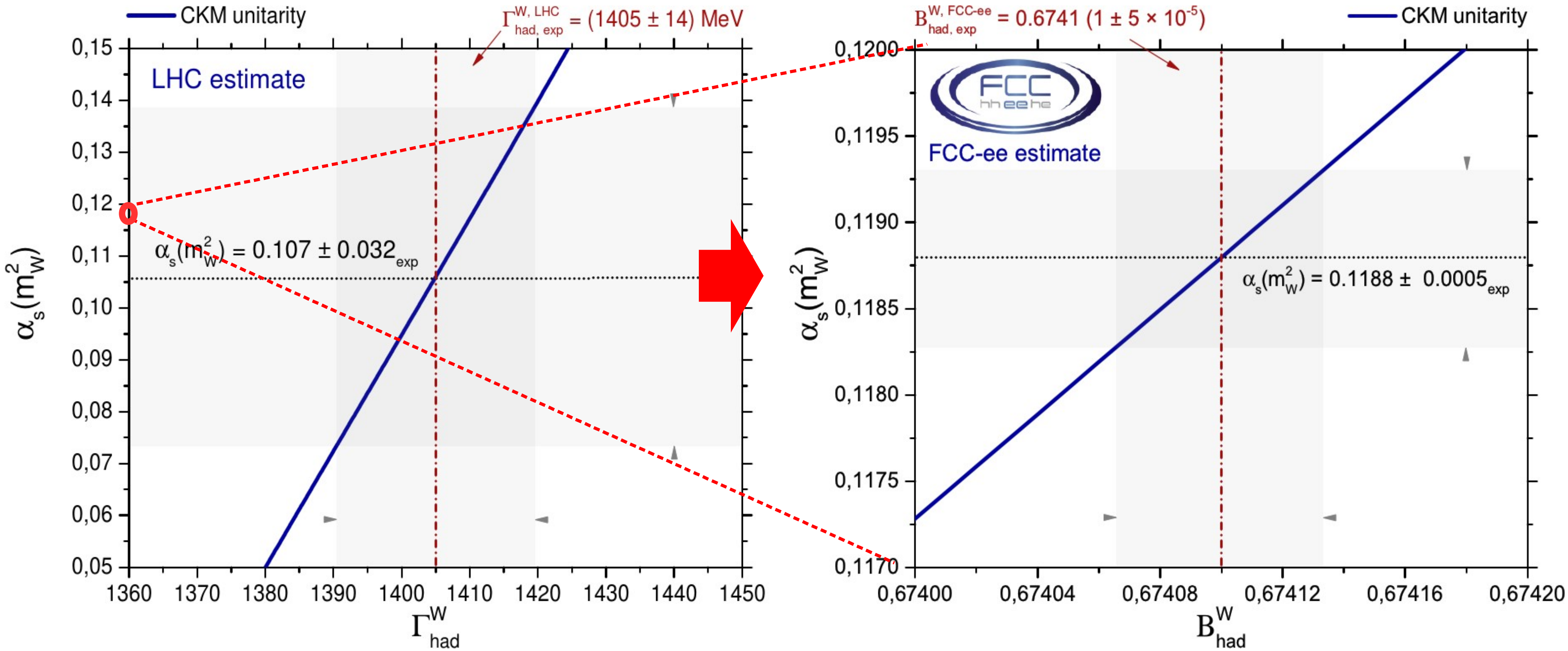
$$\alpha_s(M_Z) = 0.117 \pm 0.030_{(exp)} \pm 0.003_{(th)} \pm 0.001_{(par,CKM=1)}$$

α_s from hadronic W decays

[D.d'E, M.Srebre, arXiv:1603.06501]

- LHC prospects:
  Improved measurement of Γ_W:
  $\delta\alpha_s \sim 10\%$

- FCC-ee prospects:
  Huge ee→WW stats (10^8, $\times 10^3$ LEP):
  $\delta\alpha_s < 0.2\%$

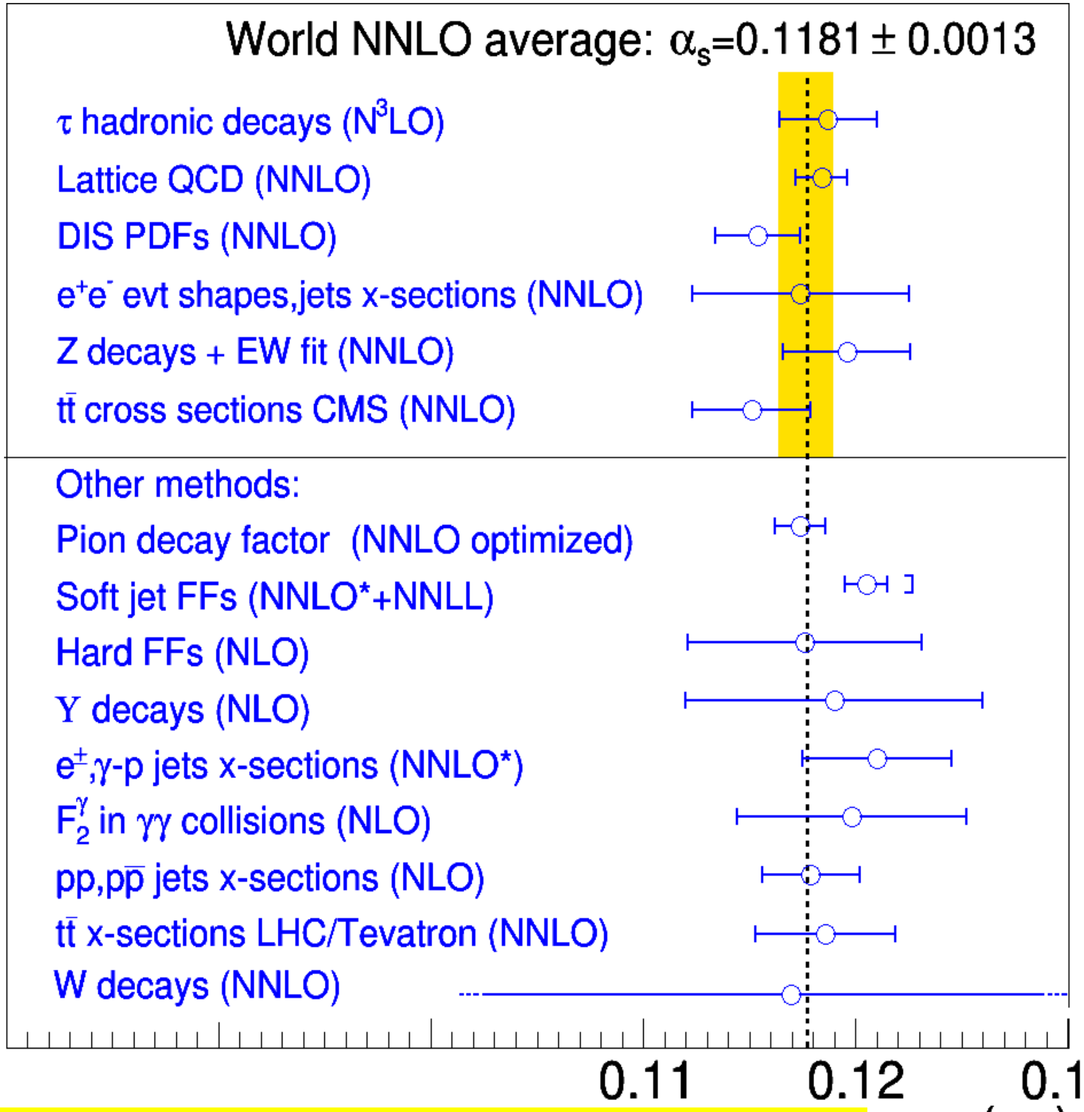


- Combined FCC-ee from W & Z decays: $\alpha_s(M_Z) = 0.1190 \pm 0.0002$

$\delta\alpha_s$(exp) < 0.15%. Parametric ($V_{i,j}$, m_W) & TH uncert. to be improved too.

Summary: α_s status & FCC-ee prospects

- World-average QCD coupling at NNLO:
  - Determined from 6 observables with 1.1% uncertainty *(least well-known coupling).*
  - Impacts all LHC x-sections & QCD decays.
  - Role beyond SM: *Couplings unification* *EWK vacuum stability* *New? colored sectors*
- Detailed study of NNLO extraction via W decays: ±25% exp.uncertainty today



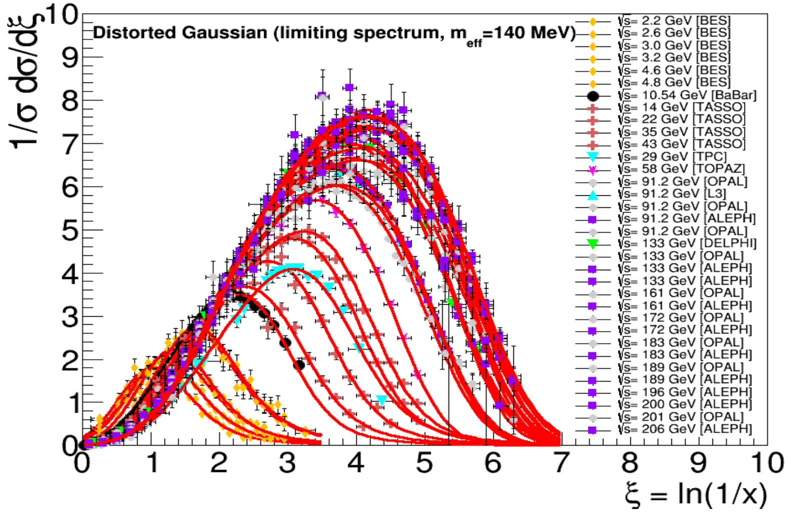
- O(0.1%) uncertainty only reachable w/ W,Z decays at FCC-ee

Backup slides

Other α_s extractions (NLO, NNLO*)

- Soft parton-to-hadron FFs (NNLO*+NNLL):

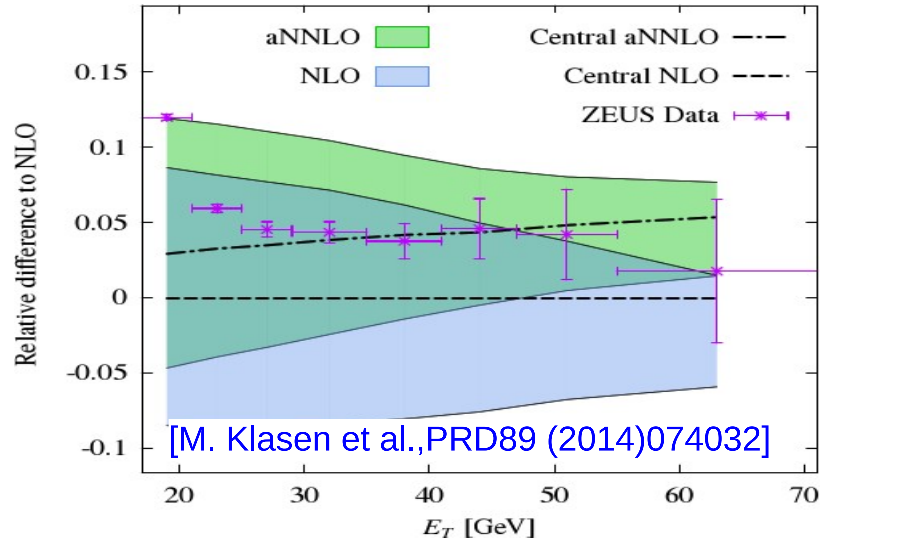
$\alpha_s(m_Z) = 0.1205 \pm 0.0022$ (±2%)



[D.d'E.,R.Perez-Ramos, arXiv:0505.02624]

- Jet x-sections in e,γ-p (NNLO*):

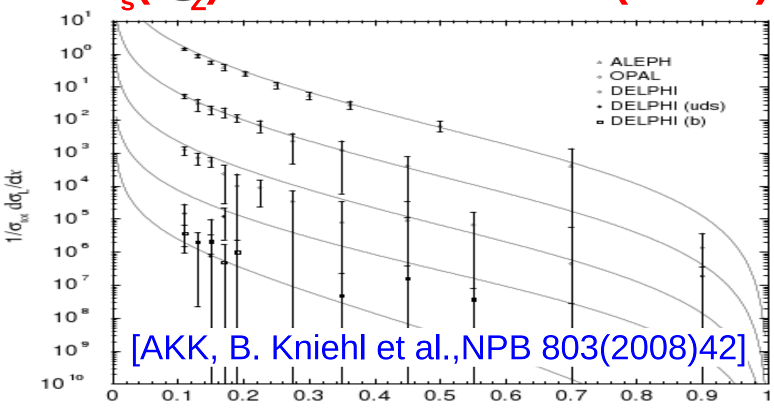
$\alpha_s(m_Z) = 0.112 \pm 0.002 \pm 0.003$ (±4%)



[M. Klasen et al.,PRD89 (2014)074032]

- Hard parton-to-hadron FFs (NLO):

$\alpha_s(m_Z) = 0.1176 \pm 0.0055$ (±4.7%)



[AKK, B. Kniehl et al.,NPB 803(2008)42]

- π decay factor (N³LO, RGOPT):

$\alpha_s(m_Z) = 0.1174 \pm 0.0017$ (±1.5%)

[Kneur&Neveu,PRD81(2010)125012]

- Υ decay (NLO): [Mambrilla et al. PRD75(07)074014]

$\alpha_s(m_Z) = 0.1190 \pm 0.007$ (±6%)

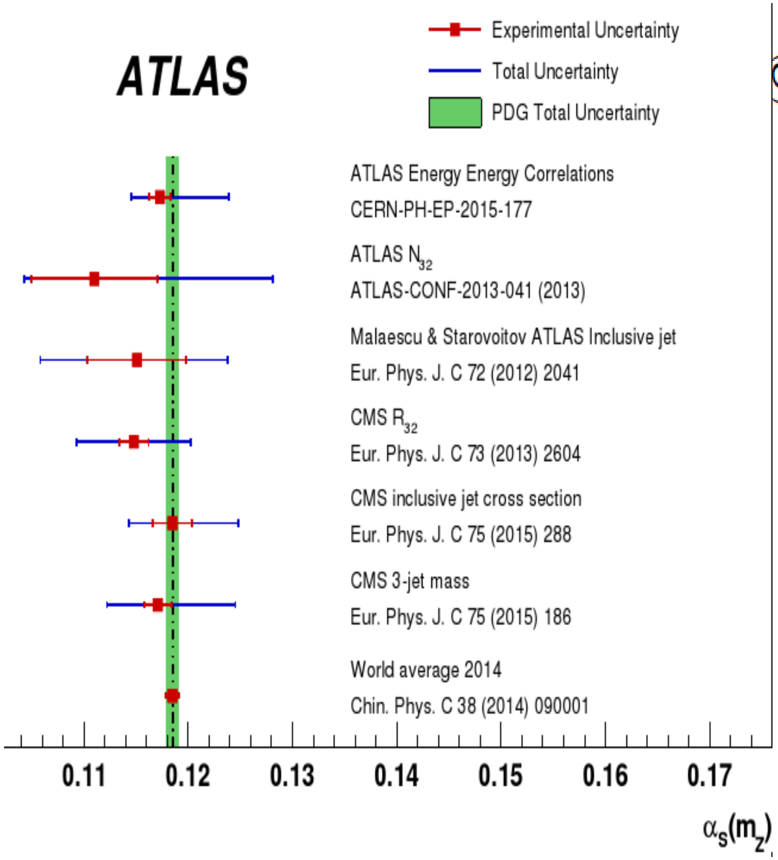
- Photon structure function F^2_γ (NLO):

$\alpha_s(m_Z) = 0.1198 \pm 0.0054$ (±4.5%)

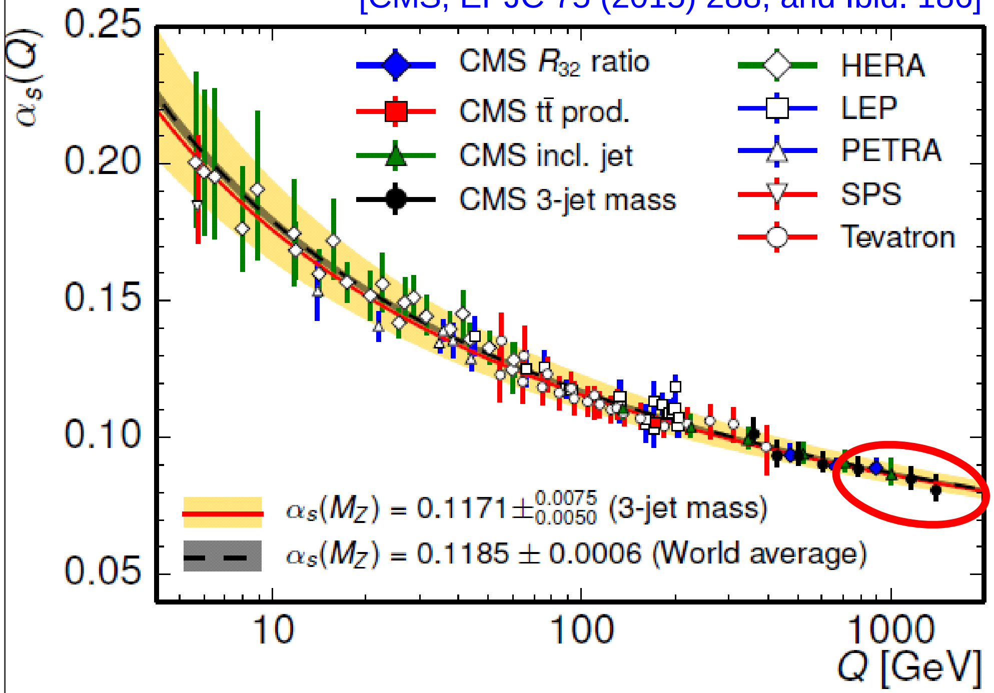
[M.Klasen et al. PRL89 (2002)122004]

α_s coupling from LHC pp → jets (NLO)

- Ratio of 3-jets of 2-jets, 3-jet mass & inclusive jets x-sections constrain α_s (NLO only) up to so-far unprobed scales Q ~ 1.4 TeV:



[CMS, EPJC 75 (2015) 288, and Ibid. 186]

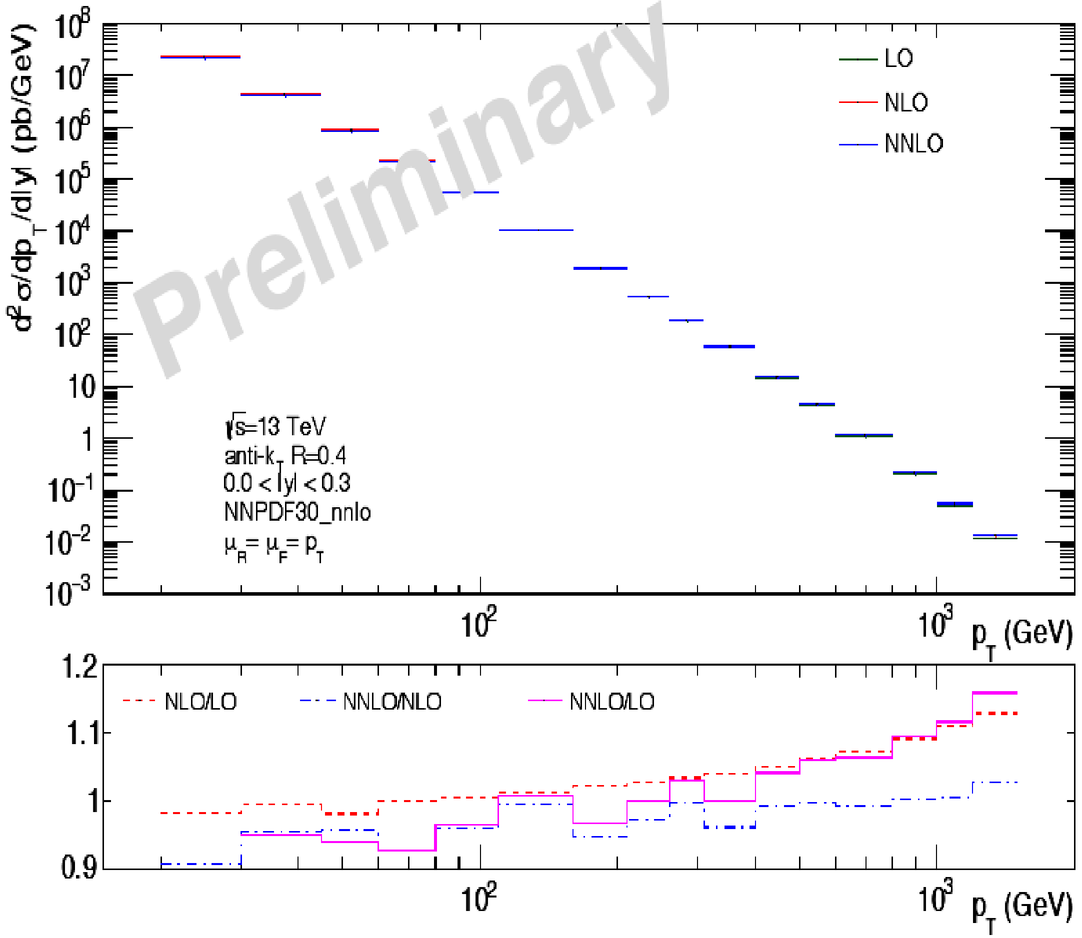


➧ 1st time asymptotic freedom is probed at the TeV scale!

➧ Upcoming NNLO jet cross sections (changes x-section by -10%, +1%. Reduced scale uncertainty): Important pQCD breakthrough!

α_s from p-p jets cross sections (NNLO)

[J.Pires]



moderate corrections of -10% that rise to 1% at high-p_T with respect to NLO

➧ NNLO jet cross sections will have a large impact in many α_s extractions: PDFs, FFs, jets in DIS/photoprod.,...

α_s from pion and Υ decays

[J.L.Kneur]

$$F_\pi^2(pert)_{\overline{MS}} = N_c \frac{m^2}{2\pi^2}\left[-L + \frac{\alpha_S}{4\pi}(8L^2 + \frac{4}{3}L + \frac{1}{6}) + (\frac{\alpha_S}{4\pi})^2[f_{30}(n_f)L^3 + f_{31}(n_f)L + f_{32}(n_f)L + f_{33}(n_f)] + \mathcal{O}(\alpha_S^3)\right]$$

$L \equiv \ln\frac{m}{\mu}$, $n_f = 2(3)$

$$\overline{\alpha}_S(m_Z) = 0.1174^{+.0010}_{-.0005}(\text{rgopt th}) \pm .0010|_{(F_\pi/F_0)} \pm .0005_{evol}$$

Issues:

- Too low scale for pQCD? Optimization approach,...
- Intriguing agreement with world average.

α_s = 0.1174±0.0017 (±1.5%)

[J. Soto]

$$R_\gamma \equiv \frac{\Gamma(\Upsilon(1S)\to\gamma X)}{\Gamma(\Upsilon(1S)\to X)} = \frac{36}{5}\frac{e_b^2\alpha}{\alpha_s}\frac{N}{D},$$

$$N,\, D = 1 + \mathcal{O}(\alpha_s) + \mathcal{O}(v^2) + \mathcal{O}(\frac{v^4}{\alpha_s}) + \mathcal{O}({\alpha_s}^2) + \mathcal{O}(\alpha_s v^2) + \mathcal{O}(\alpha_s\frac{v^4}{\alpha_s}) + \mathcal{O}(v^4) + \mathcal{O}(\frac{v^6}{\alpha_s})$$

α_s(NLO)= 0.1190±0.007 (±6%)

- A NNLO extraction of α_s appears feasible in the coming years, the key ingredients being:
  - More precise data for the $\Upsilon(1S)$ photon spectrum (and total hadronic width)
  - Non-trivial higher order perturbative calculations