

QCD at future facilities

QCD@LHC 2016

ETH Zürich – August 2016

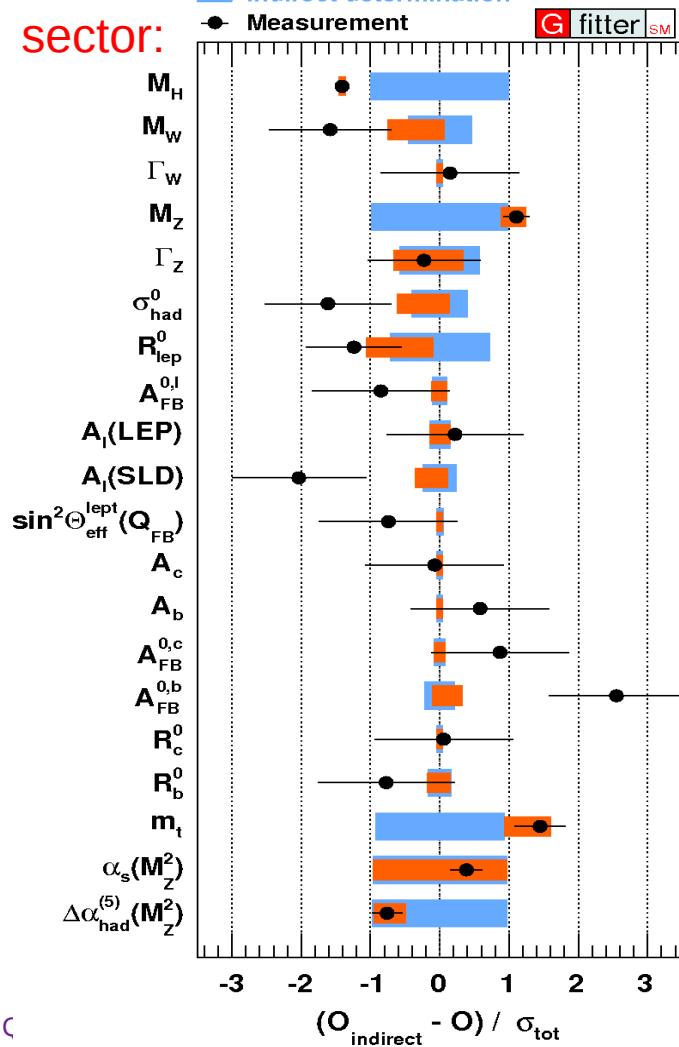
David d'Enterria
CERN

Standard Model of particles & interactions

- Renormalizable QFT of electroweak $SU(2)_L \times U(1)_Y$ & strong $SU(3)_c$ gauge interactions
 $O(20)$ parameters: Couplings, H mass & vev, H-f Yukawa, CKM mixings, CP phases.
 - Experimentally confirmed to great precision for over 40(!) years:

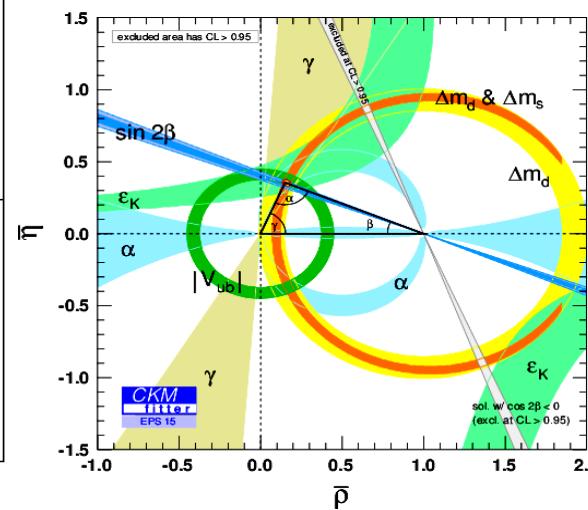
EWK

- Global EW fit
- Indirect determination

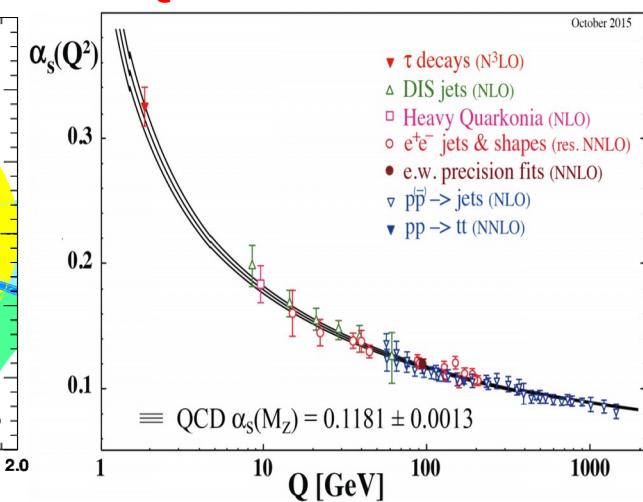


$$\begin{aligned} \mathcal{L} = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) \\ & + (\bar{\nu}_L, \bar{e}_L) \tilde{\sigma}^\mu iD_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R \sigma^\mu iD_\mu e_R + \bar{\nu}_R \sigma^\mu iD_\mu \nu_R + (\text{h.c.}) \\ & - \frac{\sqrt{2}}{v} \left[(\bar{\nu}_L, \bar{e}_L) \phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \right] - \frac{\sqrt{2}}{v} \left[(-\bar{e}_L, \bar{\nu}_L) \phi^* M^\nu \nu_R + \bar{\nu}_R \bar{M}^\nu \phi^T \begin{pmatrix} -e_L \\ \nu_L \end{pmatrix} \right] \\ & + (\bar{u}_L, \bar{d}_L) \tilde{\sigma}^\mu iD_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R \sigma^\mu iD_\mu u_R + \bar{d}_R \sigma^\mu iD_\mu d_R + (\text{h.c.}) \\ & - \frac{\sqrt{2}}{v} \left[(\bar{u}_L, \bar{d}_L) \phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi} \begin{pmatrix} u_L \\ d_L \end{pmatrix} \right] - \frac{\sqrt{2}}{v} \left[(-\bar{d}_L, \bar{u}_L) \phi^* M^u u_R + \bar{u}_R \bar{M}^u \phi^T \begin{pmatrix} -d_L \\ u_L \end{pmatrix} \right] \\ & + (\overline{D_\mu \phi}) D^\mu \phi - m_h^2 [\bar{\phi} \phi - v^2/2]^2 / 2v^2. \end{aligned}$$

Flavour sector:



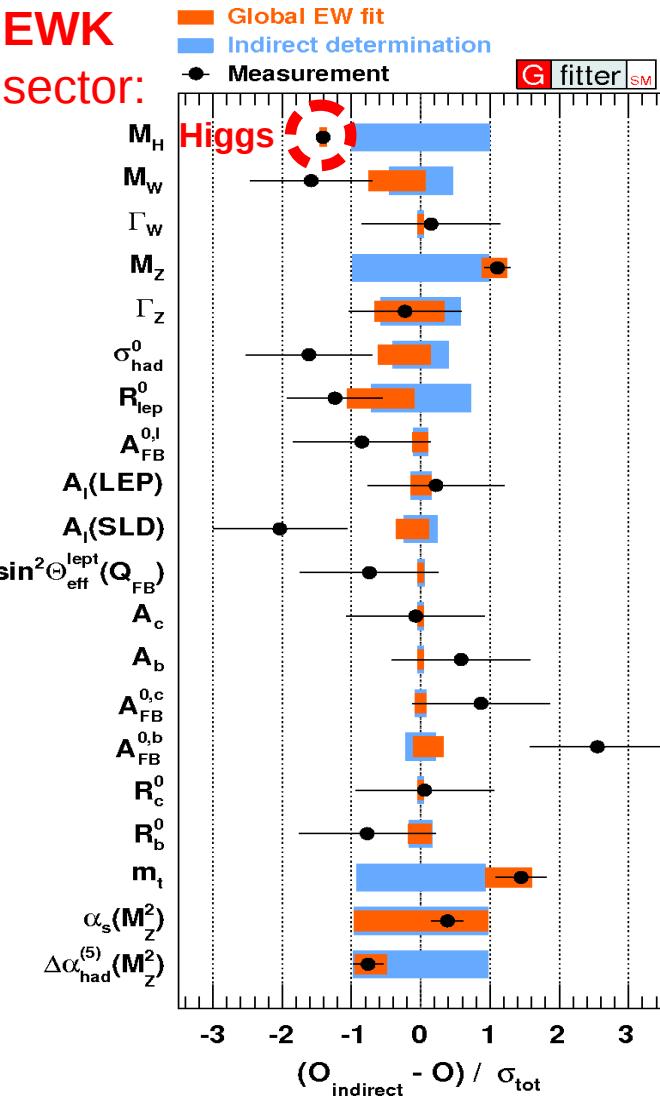
QCD sector:



Standard Model of particles & interactions

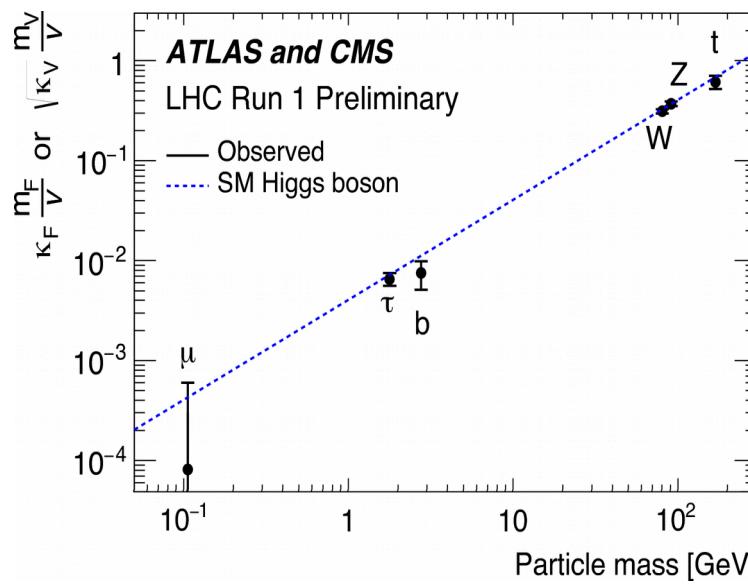
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**EWK
sector:**



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**Higgs
sector:**



Open questions in the SM (1)

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}\text{tr}(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}\text{tr}(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) \quad [\text{Gauge interactions: U(1}_Y, \text{SU(2}}_L, \text{SU(3}}_C]$$

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$$-\frac{\sqrt{2}}{v} \left[(\bar{\nu}_L, \bar{e}_L) \phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \right] - \frac{\sqrt{2}}{v} \left[(-\bar{e}_L, \bar{\nu}_L) \phi^* M^\nu \nu_R + \bar{\nu}_R \bar{M}^\nu \phi^T \begin{pmatrix} -e_L \\ \nu_L \end{pmatrix} \right] \quad [\text{Lepton masses}]$$

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✗ Mass generation: Higgs self-couplings + 1st-generation fermions + all ν's

Open questions in the SM (2)

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}\text{tr}(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}\text{tr}(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) \quad [\text{Gauge interactions: U(1}_Y, \text{SU(2}}_L, \text{SU(3}}_C]$$

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Some/Most(?) of these questions will not be fully answered at the LHC

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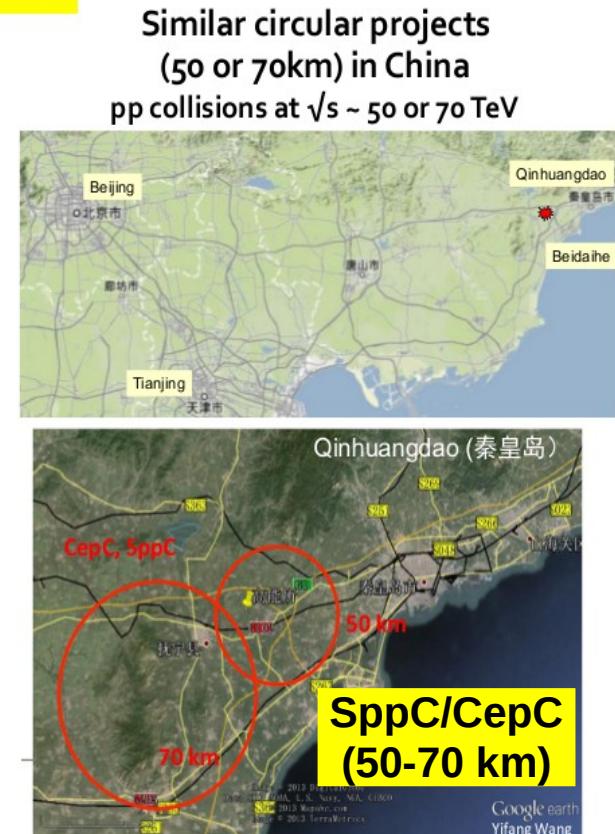
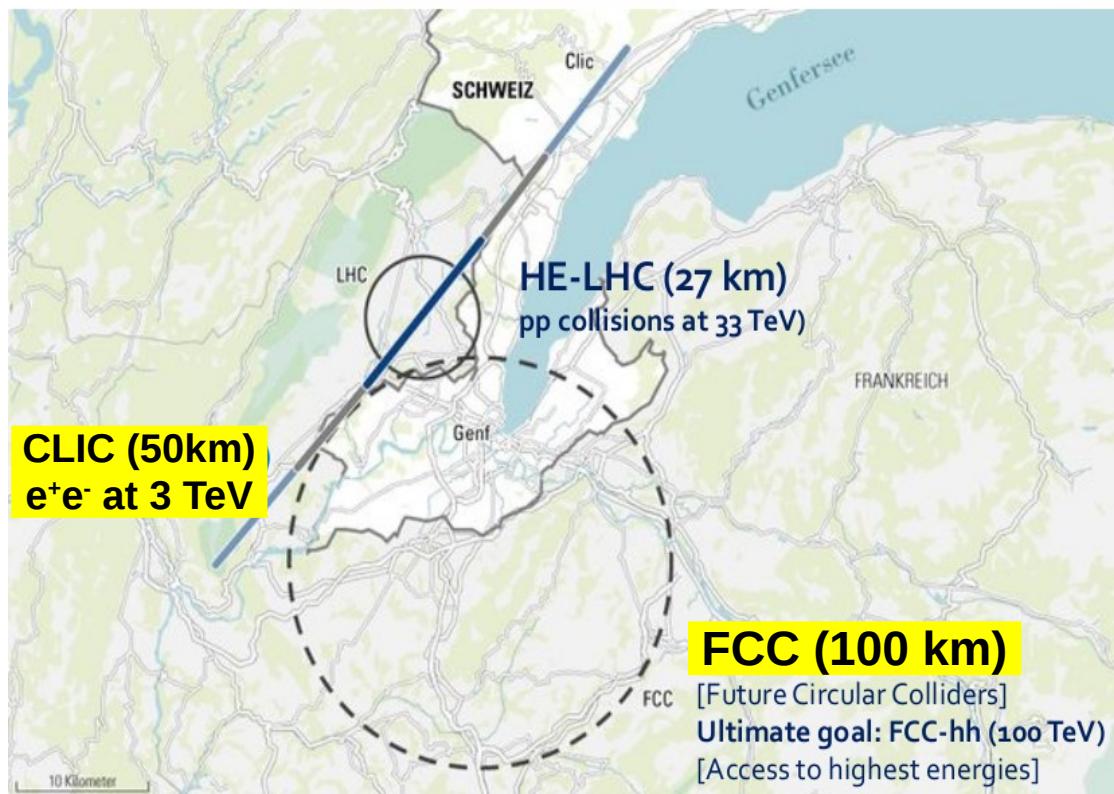
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BSM at new colliders: Direct ($\uparrow \sqrt{s}$) & indirect (\uparrow precision, lumi) searches

EU HEP long-term perspectives (2040-2060)

- Direct new physics searches: **Higher-energy colliders**.
- In May 2013, European Strategy said (very similar statements from US)
 - ◆ Perform R&D and design studies for **high-energy frontier machines** at CERN
 - HE-LHC, a programme for an energy increase to 33 TeV in the LHC tunnel
 - FCC, a 100-km circular ring with a **pp collider** long-term project at $\sqrt{s} = 100$ TeV
 - CLIC, an e^+e^- collider project with \sqrt{s} from 0.3 to 3 TeV



BSM via precision e^+e^- measurements

- Many BSM realizations: SUSY, composite H, extra-D, hidden sectors,...
- Parametrize (B)SM as an Effective Theory:

$$\mathcal{L}_{\text{Eff}} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \dots$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \quad [\mathcal{O}_i] = d$$

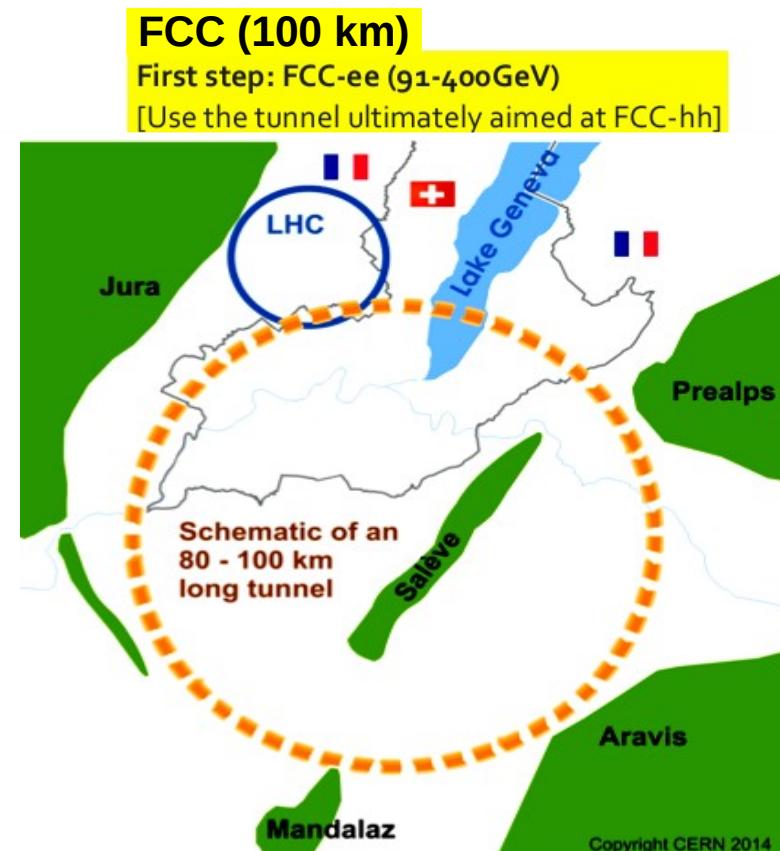
- Indirect (loop) constraints on new physics coupled to scalar sector:

$$\Lambda \gtrsim (1 \text{ TeV}) / \sqrt{(\delta g_{\text{HXX}} / g_{\text{HXX}}^{\text{SM}})} / 5\%$$

- HI-LHC: ~5% deviations of Higgs couplings wrt. SM: $\Lambda > 1 \text{ TeV}$
 - FCC-ee: 0.1% Higgs couplings precision (10^6 Higgs) $\Rightarrow \Lambda > 7 \text{ TeV}$
 - Indirect (loop) constraints on new physics coupled to EWK sector:
- $$\Lambda \propto (1 \text{ TeV}) / \sqrt{\delta X}$$
- Current EWK precision fit: NP excluded below $\Lambda > 3 \text{ TeV}$
 - FCC-ee: $\ll 0.1\%$ precision in properties (10^8 – 10^{12} W,Z) $\Rightarrow \Lambda > 40 \text{ TeV}$

EU HEP mid-term perspectives (2030-2040)

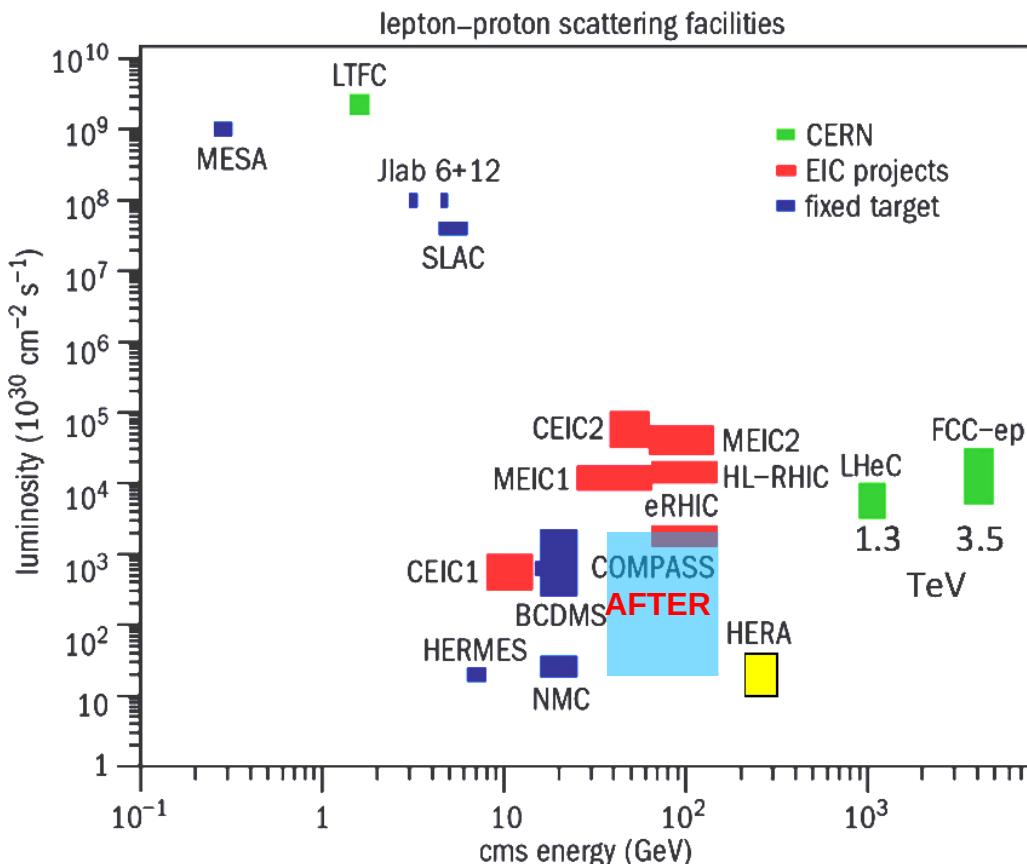
- Indirect new physics searches: Higher-precision/lumi e^+e^- colliders.
- In May 2013, European Strategy said (very similar statements from US)
 - ◆ Acknowledge the strong physics case of e^+e^- colliders with intermediate \sqrt{s}
 - Participate in ILC if Japan government moves forward with the project
 - In the context of the FCC, perform accelerator R&D and design studies
 - In view of a high-luminosity, high-energy, circular e^+e^- collider as a first step



QCD opportunities at future colliders

- Though QCD is *not* the main driving force behind e^+e^- , pp future machines, QCD is crucial for many signals & backgrounds:
 - High-precision α_s needed: SM fits/tests, hadronic cross sections/decays,...
 - High-precision PDFs needed (for hadron colliders)
 - Higher-order pQCD, resummations,... for all hadronic initial/final states
 - Heavy-Quark/Quark/Gluon separation, subjet structure, boosted topologies,...
 - Semihard QCD (for hadron colliders):
low-x gluon saturation, DPS, MPI,... (Note: $Q_0 \sim 10$ GeV at 100 TeV)
 - Soft QCD: e.g. colour reconnection effects (m_{top} , eeWW,..), pileups
 - ...
- I will cover a few of the ongoing dedicated QCD studies:
 - FCC (hh, eh, ee): Multiple studies under investigation.
SppC/CEPC: Similar possibilities as FCC (*not investigated, lower lumi*).
 - ILC (GigaZ option): α_s determination considered.
 - CLIC: photon-photon QCD physics (e.g. γ structure function) considered.

Other proposed QCD-dedicated facilities



■ Fixed target AFTER@LHC:

p-p, p-A, A-p, A-A at $\sqrt{s} = 60\text{--}120 \text{ GeV}$; $L_{\text{int}} \sim 0.2\text{--}1 \text{ fb}^{-1}/\text{yr}$

- 1% of LHC beam **extracted with bent crystal** (LUA9), or ...
- Internal **gas target** similar to SMOG at LHCb

Deep-inelastic e-p,A projects:

■ CERN:

60-GeV Energy Recover Linac

LHeC = ERL+LHC: 1.3 TeV

FCC-eh = ERL+FCC: 3.5 TeV

$L \sim 10^{33}\text{--}10^{34} \text{ cm}^{-2}\text{s}^{-1}$

■ USA e-ion collider: 25–200 GeV

EIC @ Jlab: MEIC1, MEIC2

EIC @ RHIC: eRHIC, HL-RHIC

$L \sim 10^{32}\text{--}10^{34} \text{ cm}^{-2}\text{s}^{-1}$

■ China e-ion collider: 8–60 GeV

CEIC1, CEIC2 (“mini-COMPASS”)

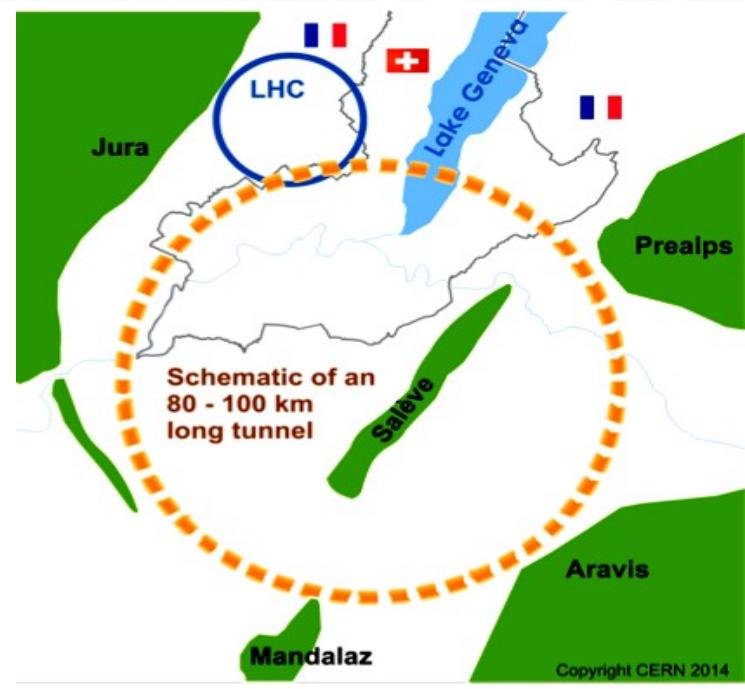
[Note also ion facilities:
FAIR(GSI), NICA(RU)]

CERN Future Circular Collider (FCC) project

- I will mostly focus on the FCC-ee,eh,hh project:



- 100 km ring, Nb₃Sn 16 T magnets,
LHC used as injector:
 - pp at $\sqrt{s}=100$ TeV, $L \sim 2 \times 10^{35}$, $L_{int} \sim 1 \text{ ab}^{-1}/\text{yr}$
(also pPb & PbPb at $\sqrt{s}=39-63$ TeV)
 - e^+e^- option (before pp) at $\sqrt{s}=90-350$ GeV
 $L \sim 10^{35}-4 \cdot 10^{36}$, $L_{int} = 1-40 \text{ ab}^{-1}/\text{yr}$ for H, Z
 - e-h option at $\sqrt{s}=3.5$ TeV, $L \sim 10^{34}$
 $L_{int} \sim 0.1 \text{ ab}^{-1}/\text{yr}$. (also e-Pb at $\sqrt{s} \sim 1-3$ TeV)



QCD studies at future colliders

- (1) QCD coupling** (FCC-ee, FCC-eh, ILC, CLIC)
- (2) Parton densities** (FCC-eh, EIC)
- (3) Beyond DGLAP** (FCC-eh)
- (4) Many body QCD** (FCC-hh)

QCD studies at future colliders

(1) QCD coupling (FCC-ee, FCC-eh, ILC, CLIC)

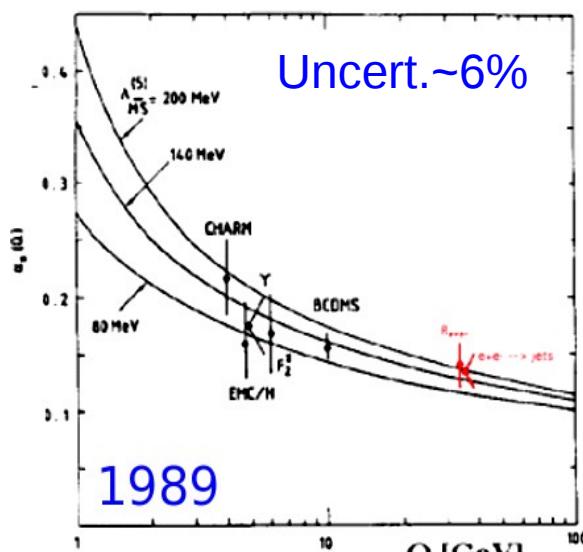
(2) Parton densities (FCC-eh, EIC)

(3) Beyond DGLAP (FCC-eh)

(4) Many body QCD (FCC-hh)

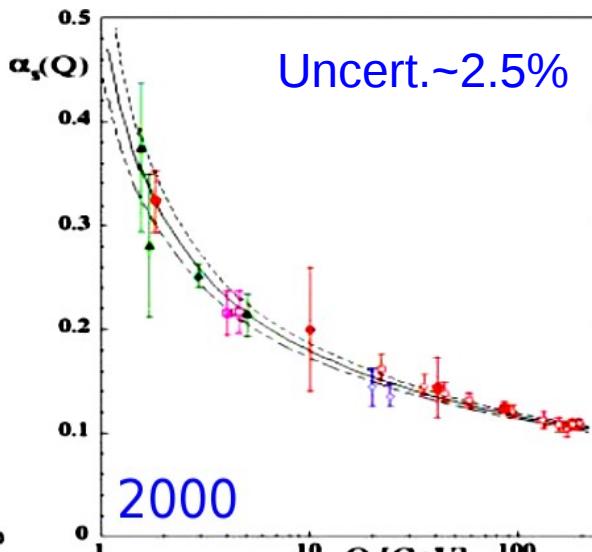
QCD coupling α_s

- 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



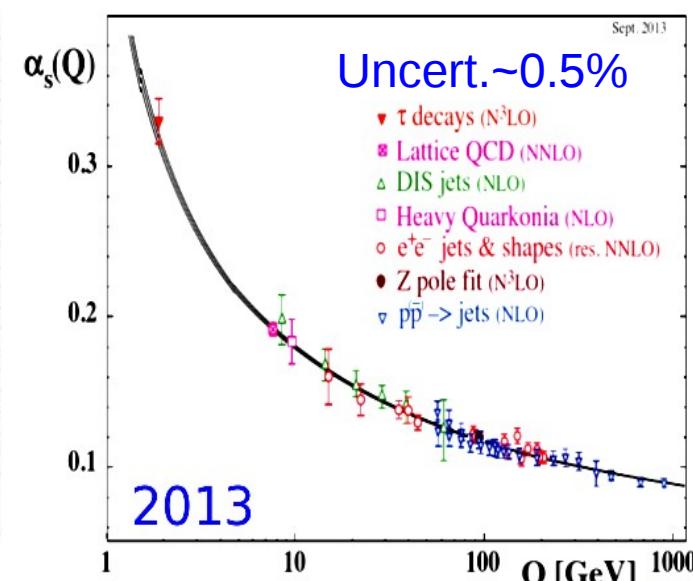
$$\alpha_s(M_Z) = 0.110^{+0.006}_{-0.008} \text{ (NLO)}$$

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



$$\alpha_s(M_Z) = 0.1184 \pm 0.0031 \text{ (NNLO)}$$

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

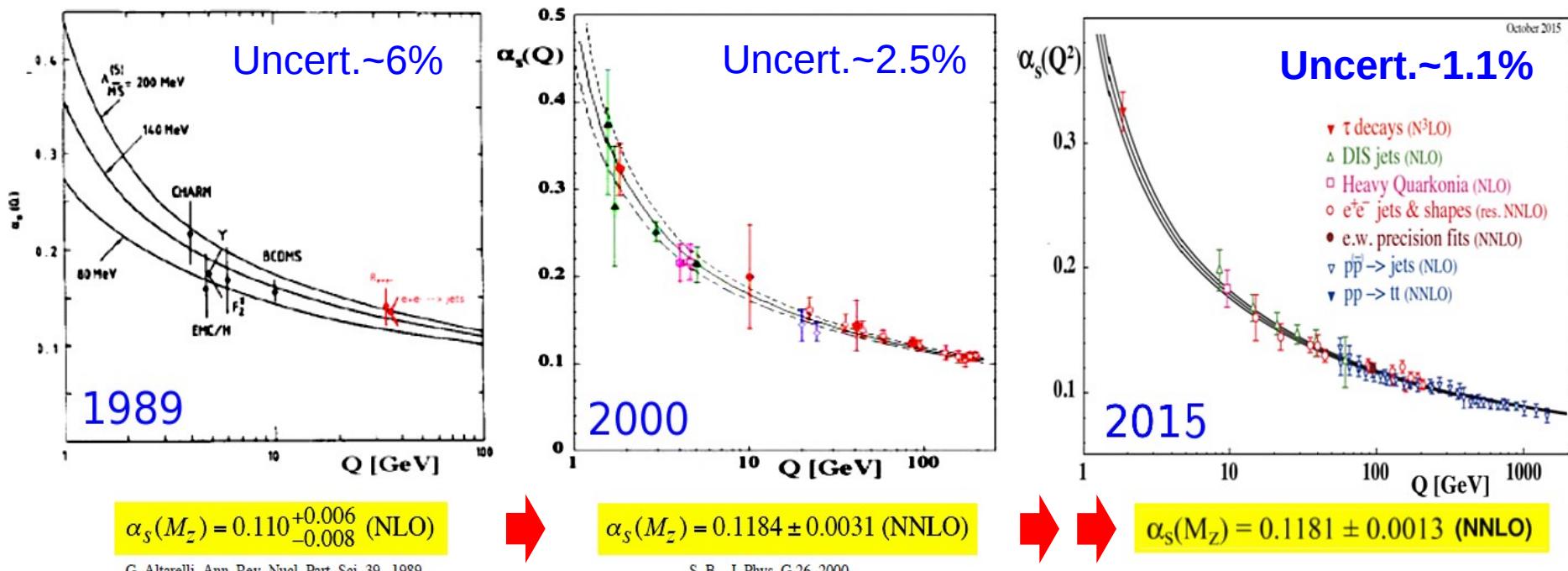


$$\alpha_s(M_Z) = 0.1185 \pm 0.0006 \text{ (NNLO)}$$

David d'Enterria (CERN)

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



→ Least precisely known of all interaction **couplings** !

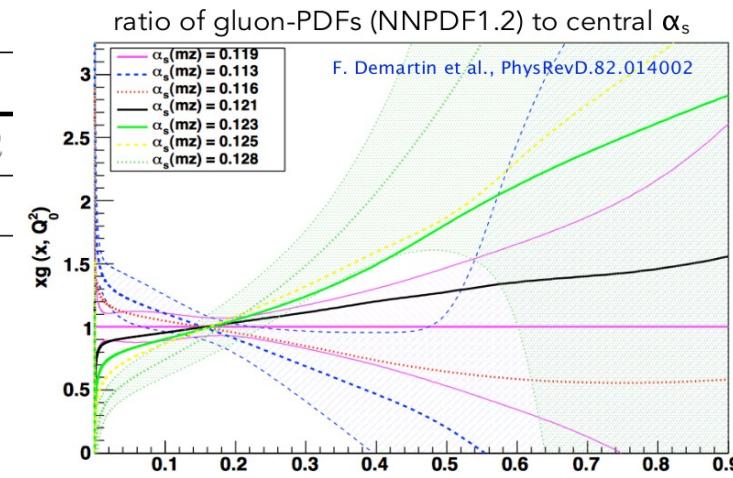
$$\delta\alpha \sim 10^{-10} \ll \delta G_F \ll 10^{-7} \ll \delta G \sim 10^{-5} \ll \delta\alpha_s \sim 10^{-3}$$

Importance of the QCD coupling α_s

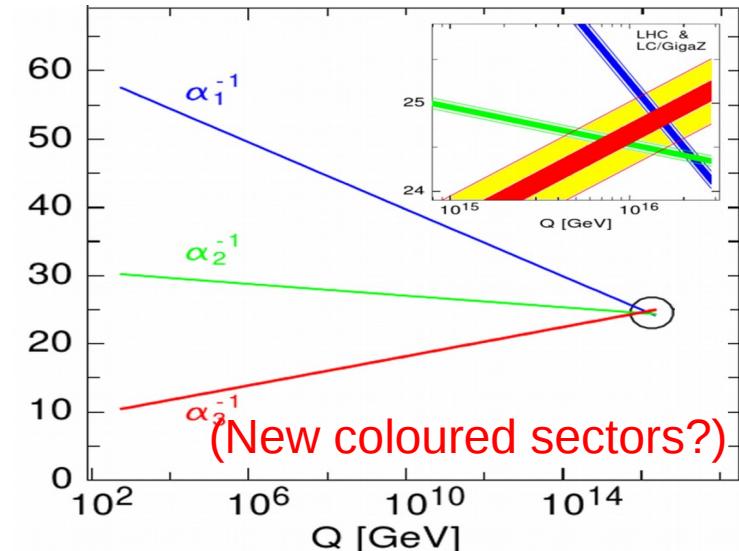
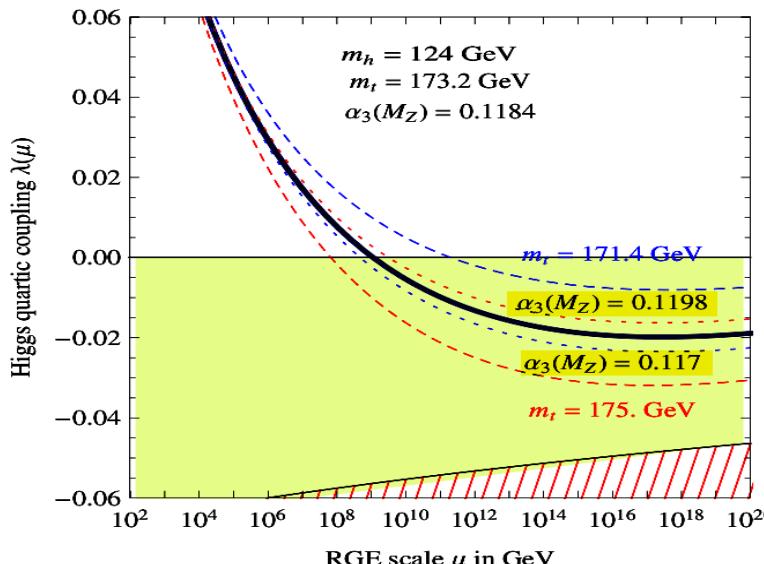
→ Impacts all QCD x-sections & decays, chiefly for Higgs:

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

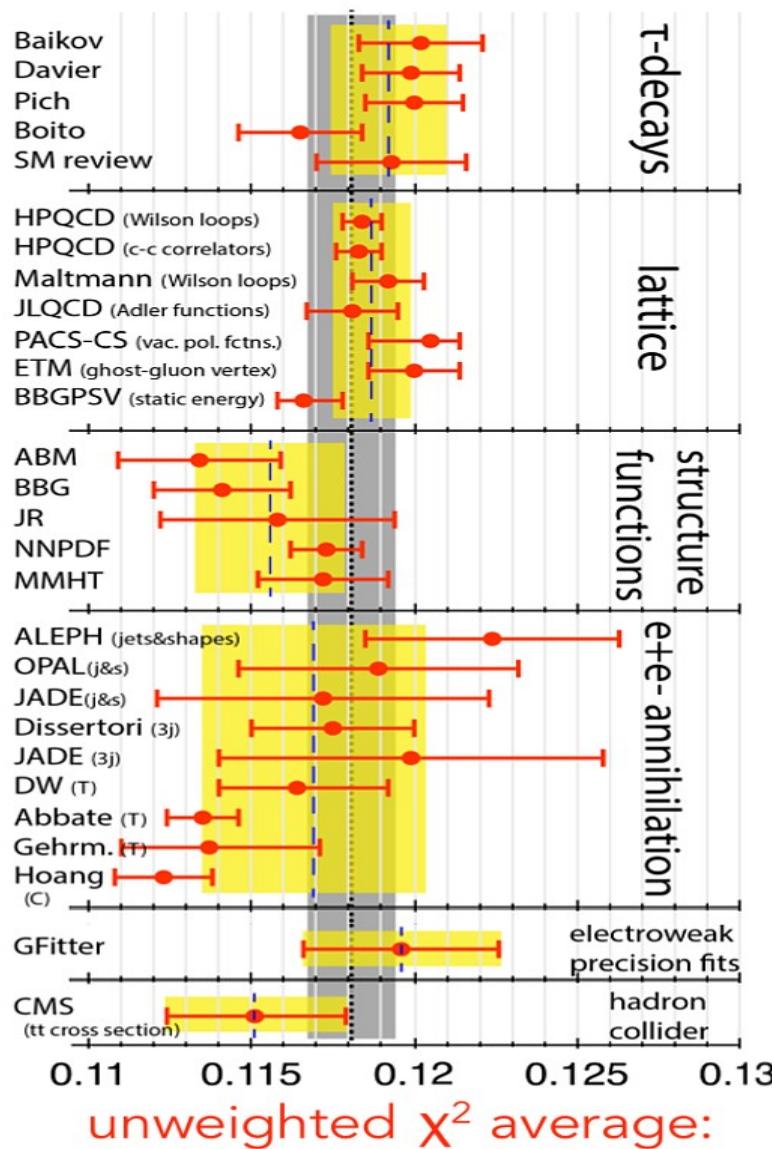
Process	σ (pb)	$\delta\alpha_s(\%)$	PDF + $\alpha_s(\%)$	Scale(%)
ggH	49.87	± 3.7	-6.2 +7.4	-2.61 + 0.32
ttH	0.611	± 3.0	± 8.9	-9.3 + 5.9
Channel	M_H [GeV]	$\delta\alpha_s(\%)$	Δm_b	Δm_c
H → c̄c	126	± 7.1	$\pm 0.1\%$	$\pm 2.3\%$
H → gg	126	± 4.1	$\pm 0.1\%$	$\pm 0\%$



→ Impacts physics approaching Planck scale: EW vacuum stability, GUT



α_s world average (PDG 2016)



class averages:

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

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

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

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

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

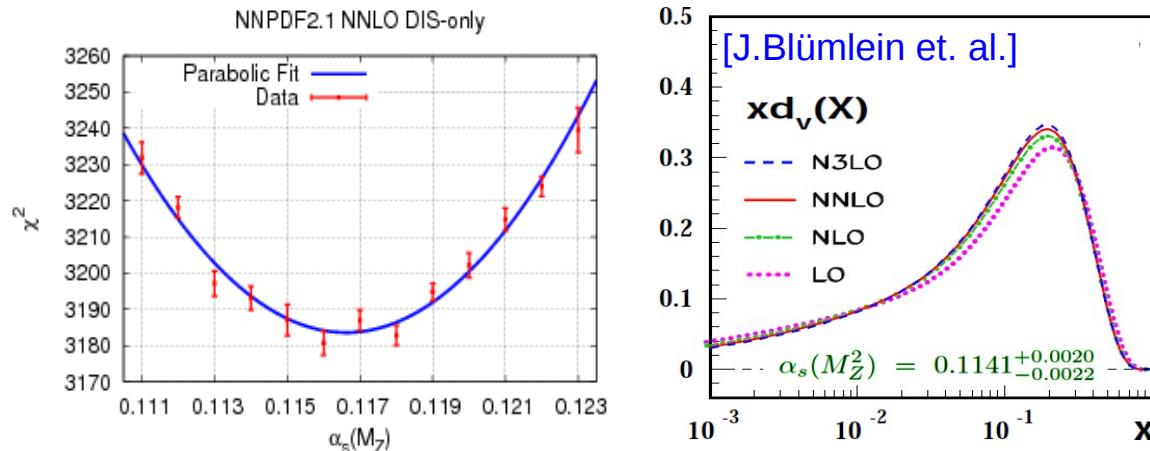
$$\alpha_s(M_Z) = 0.1151 \pm 0.0033 \quad (\pm 2.9\%)$$

$$\alpha_s(M_Z) = 0.1181 \pm 0.0013 \quad (\pm 1.1\%)$$

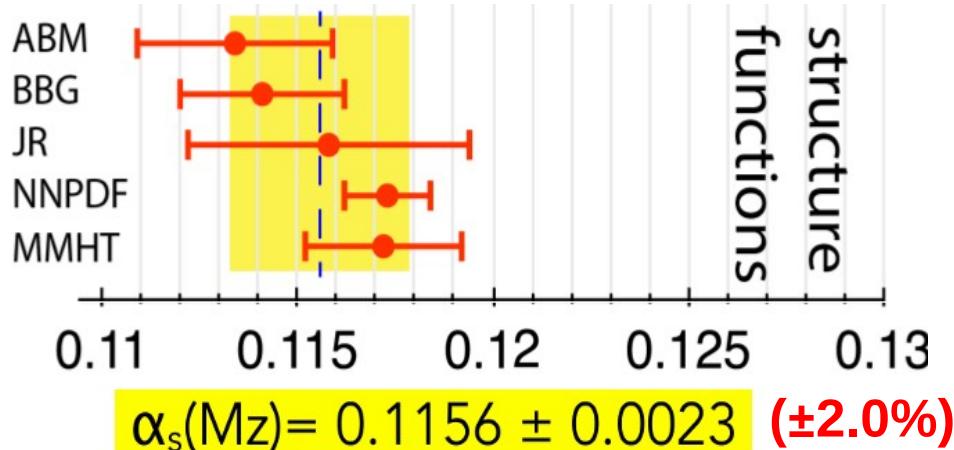
α_s from proton structure functions

- 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: $F_2(x, Q^2)$, $F_2^c(x, Q^2)$, $F_L(x, Q^2)$, PDFs(x, Q^2)

- Different approaches:
Non-singlet fits,
singlet+non-singlet fits,
global fits of PDFs, ...



Uncertainty slightly increased:
2013 ($\pm 1.7\%$) → 2015 ($\pm 2.0\%$)

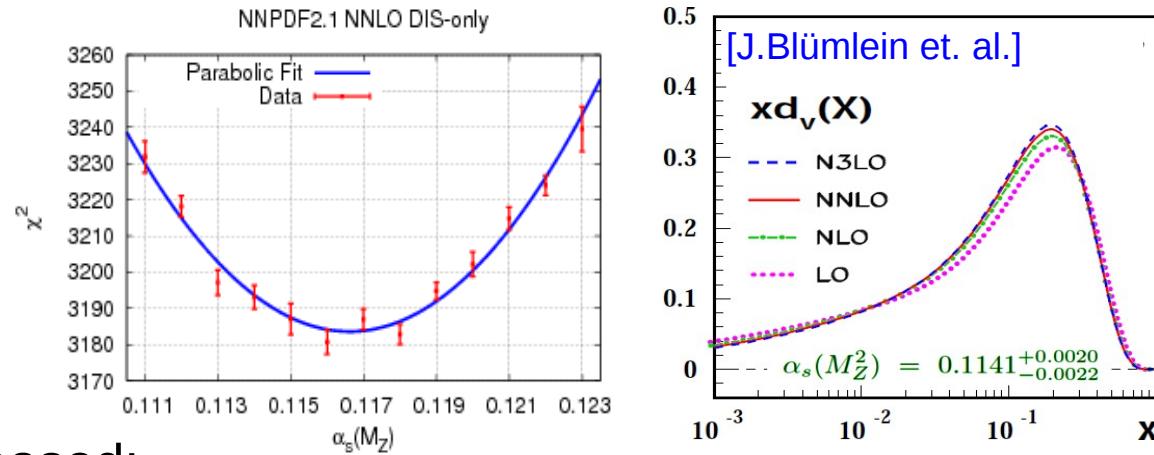


α_s from proton structure functions (FCC-eh)

- 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: $F_2(x, Q^2)$, $F_2^c(x, Q^2)$, $F_L(x, Q^2)$, PDFs(x, Q^2)

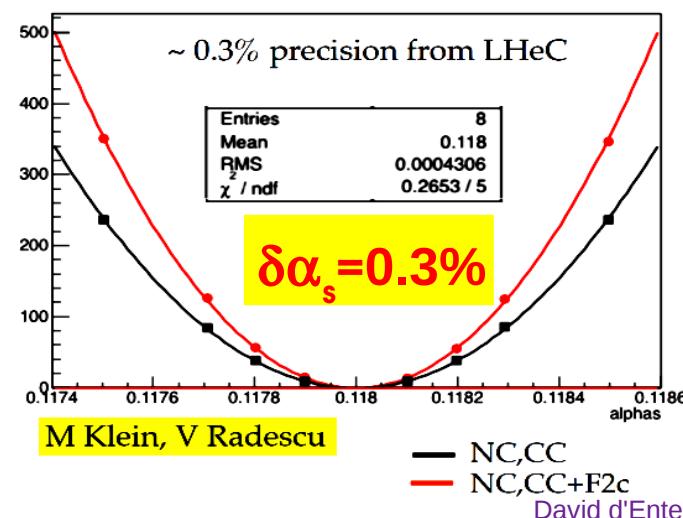
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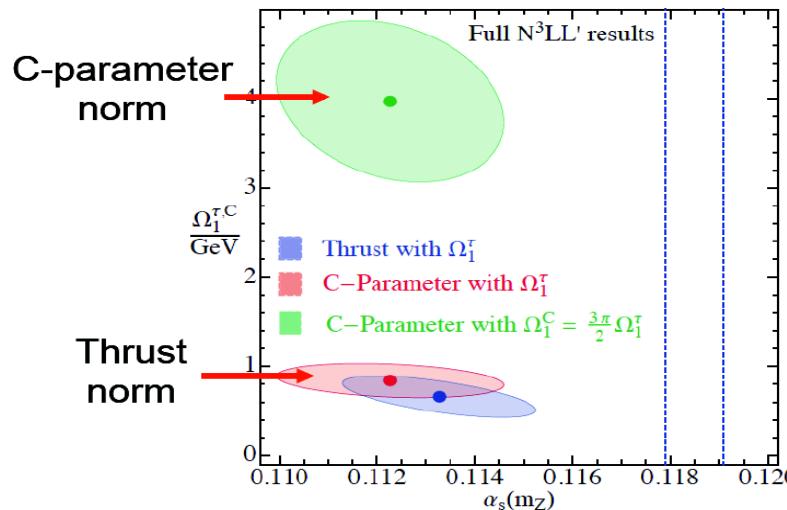
Uncertainty slightly increased:
2013 ($\pm 1.7\%$) → 2015 ($\pm 2.0\%$)

- Future prospects:
 - LHC: Full-NNLO PDF fits (including ttbar, jets,...)
 - LHeC/FCC-eh: Multiple high-precision DIS observables



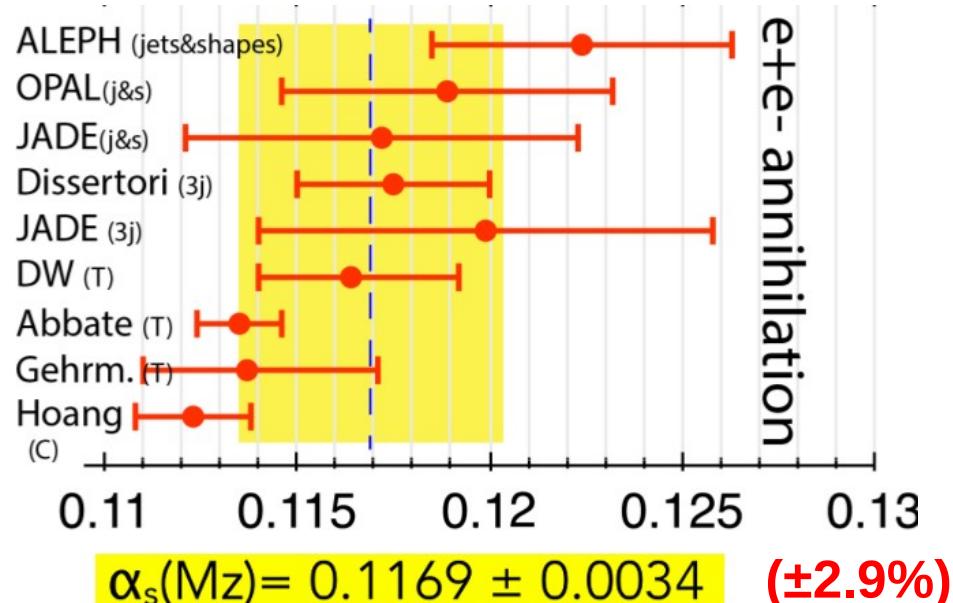
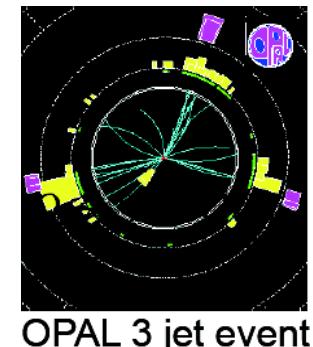
α_s from e^+e^- jet event shapes & rates (FCC-ee)

- Computed at $N^{2,3}\text{LO} + N^{(2)}\text{LL}$ accuracy.
- Experimentally (LEP):
 - Thrust, C-parameter, jet shapes
 - 3-jet x-sections
- Results sensitive to non-pQCD (hadronization) accounted for via MCs or analytically:



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

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



- Future prospects:
 - Jet rates with improved resummation: NNLL or $N^3\text{LL}$
 - New data: lower- \sqrt{s} (Belle-II) for shapes, higher- \sqrt{s} (FCC-ee) for rates

$\delta\alpha_s < 1\%$

α_s from γ QCD structure function (ILC/CLIC)

→ Computed at NNLO: $\int_0^1 dx F_2^\gamma(x, Q^2, P^2) = \frac{\alpha}{4\pi} \frac{1}{2\beta_0} \left\{ \frac{4\pi}{\alpha_s(Q^2)} c_{LO} + c_{NLO} + \frac{\alpha_s(Q^2)}{4\pi} c_{NNLO} + \mathcal{O}(\alpha_s^2) \right\}$

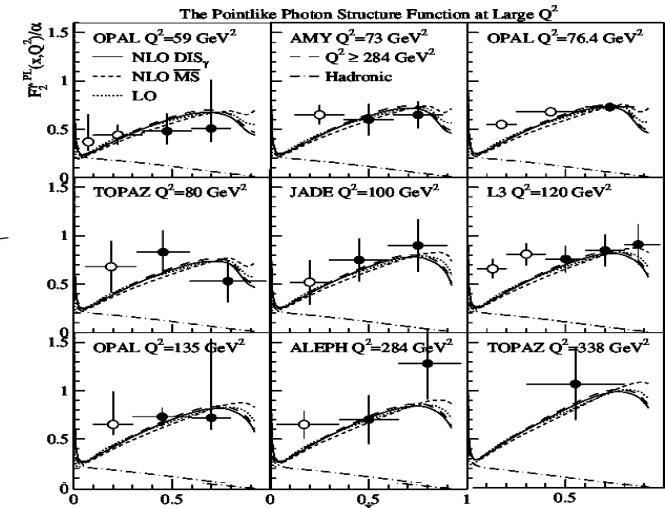
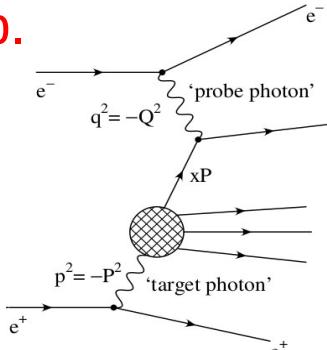
→ Poor $F_\gamma^2(x, Q^2)$ experimental measurements:

→ Extraction (NLO) with large exp. uncertainties today:

$$\alpha_s(M_Z) = 0.1198 \pm 0.0054$$

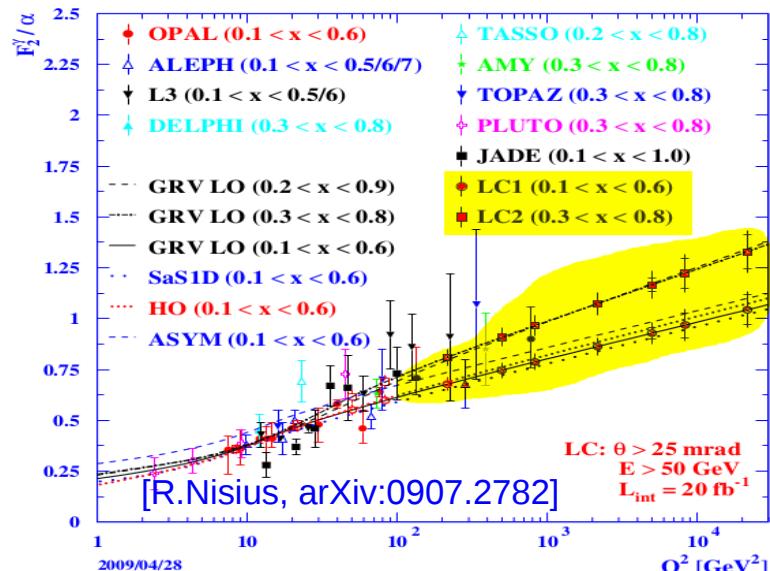
(±4.5%)

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



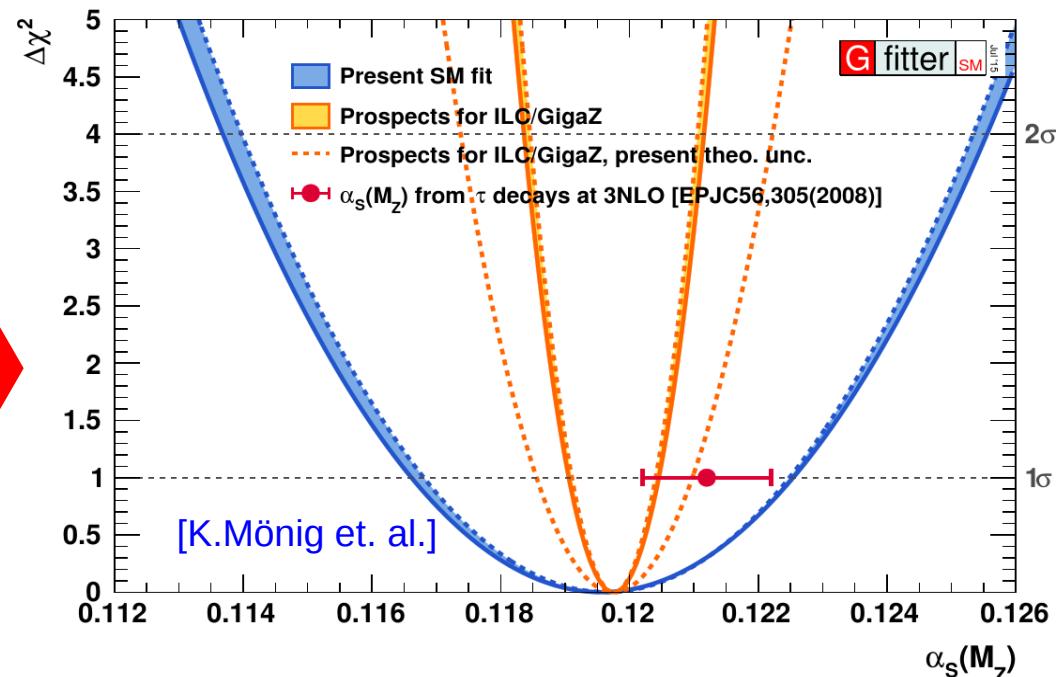
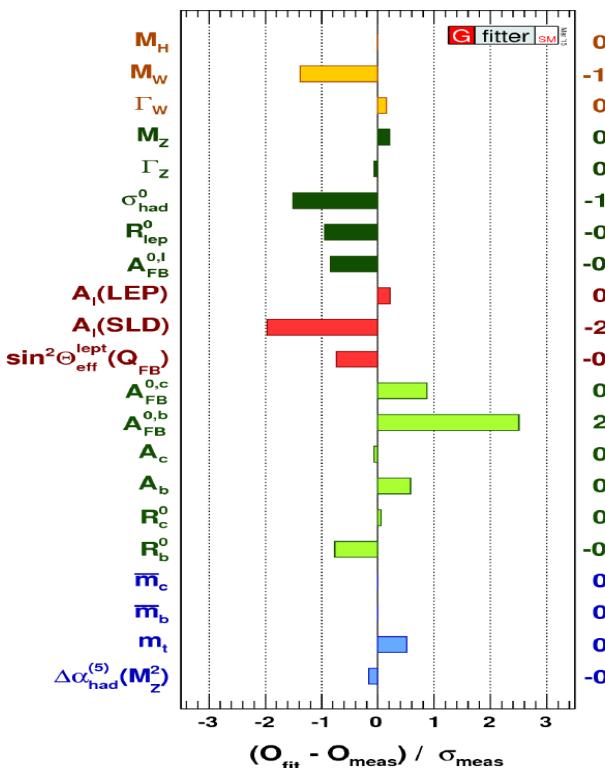
→ Future prospects:

- Better data badly needed.
- Belle-II ?
- Dedicated studies at ILC exist:
- Huge γ (EPA) stats at FCC-ee will lead to: $\delta\alpha_s < 1\%$



α_s from hadronic Z decays (ILC, FCC-ee)

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



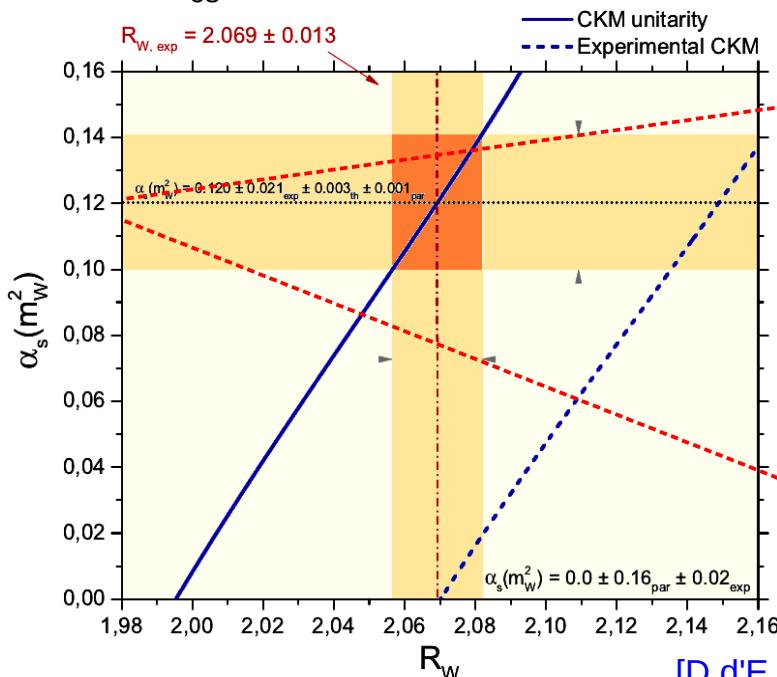
$$\alpha_s(M_Z) = 0.1196 \pm 0.0030 \quad (\pm 2.5\%)$$

- Prospects:
 - Improved $\sin^2\theta_{\text{eff}}, m_W, m_t$. Future β -function at 5 loops.
 - Z stats at ILC-GigaZ, FCC-ee will lead to: $\delta\alpha_s < 1\%, 0.3\%$

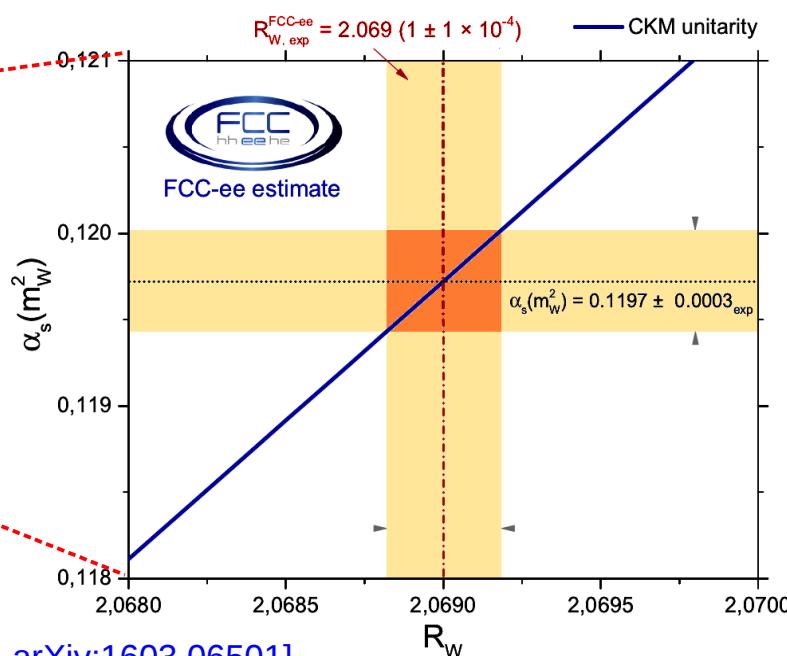
α_s from hadronic W decays (FCC-ee)

- Computed at N^{2,3}LO: $\Gamma_{W,\text{had}} = \frac{\sqrt{2}}{4\pi} G_F m_W^3 \sum_{\text{quarks } i,j} |V_{i,j}|^2 \left[1 + \sum_{k=1}^4 \left(\frac{\alpha_s}{\pi} \right)^k + \delta_{\text{electroweak}}(\alpha) + \delta_{\text{mixed}}(\alpha \alpha_s) \right]$
- Experimentally: $\Gamma_W = 1405 \pm 29 \text{ MeV} (\pm 2\%)$, $\text{BR}_W = 0.6741 \pm 0.0027 (\pm 0.4\%)$
- Extraction with large exp. & parametric (CKM V_{cs}) uncertainties today:

$$\alpha_s(M_Z) = 0.117 \pm 0.020 \quad (\pm 18\%)$$



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



- Future prospects:
 - Huge W stats (10^3 more than LEP) at FCC-ee will lead to: $\delta\alpha_s < 0.3\%$

CONCLUSION (1): Per-mille α_s precision requires high-lumi e^+e^- measurements

QCD studies at future colliders

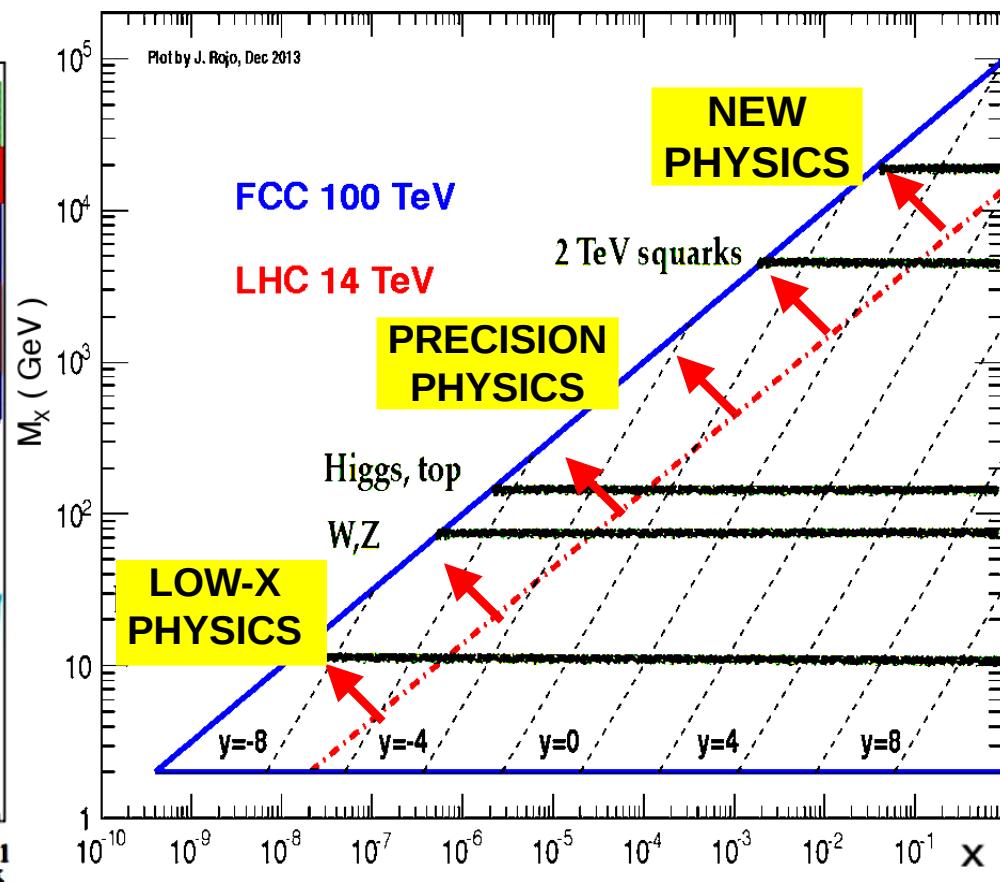
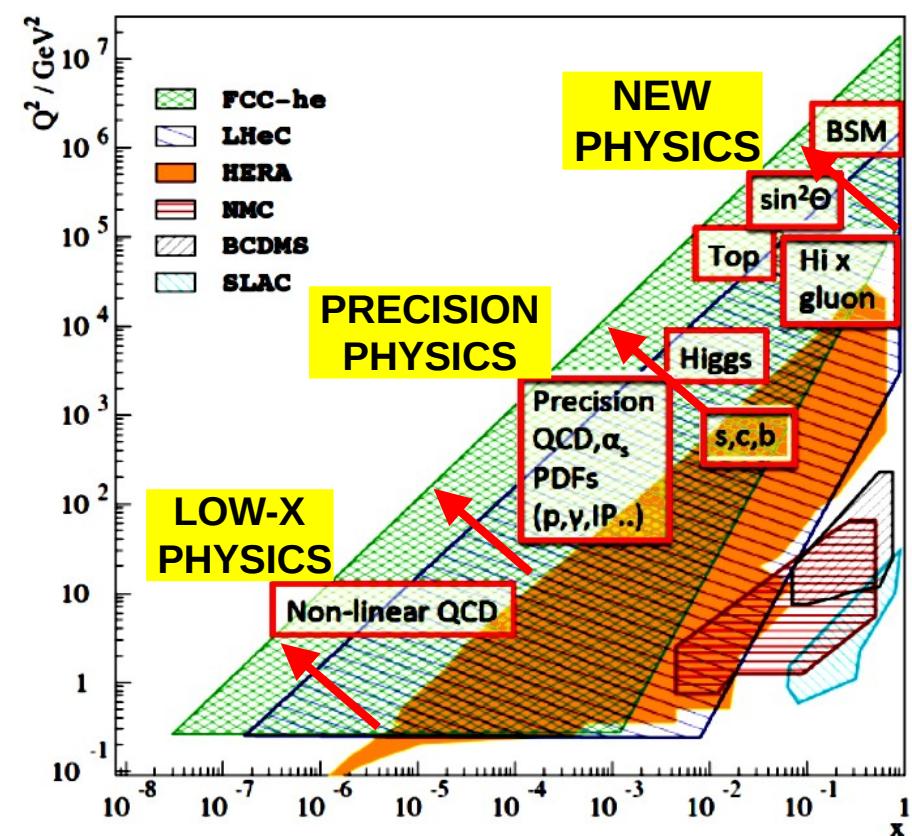
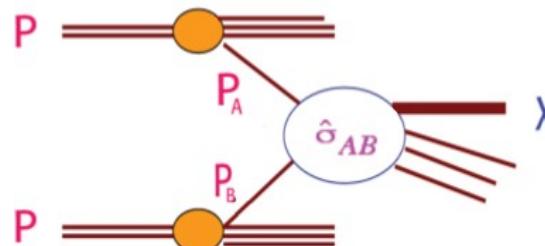
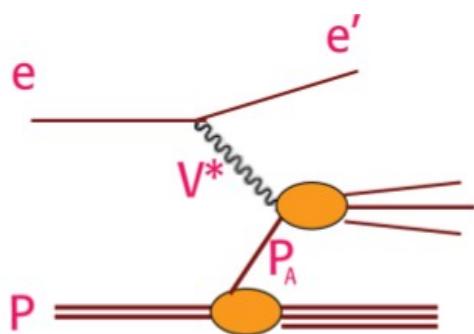
(1) QCD coupling (FCC-ee, FCC-eh, ILC, CLIC)

(2) Parton densities (FCC-eh, EIC)

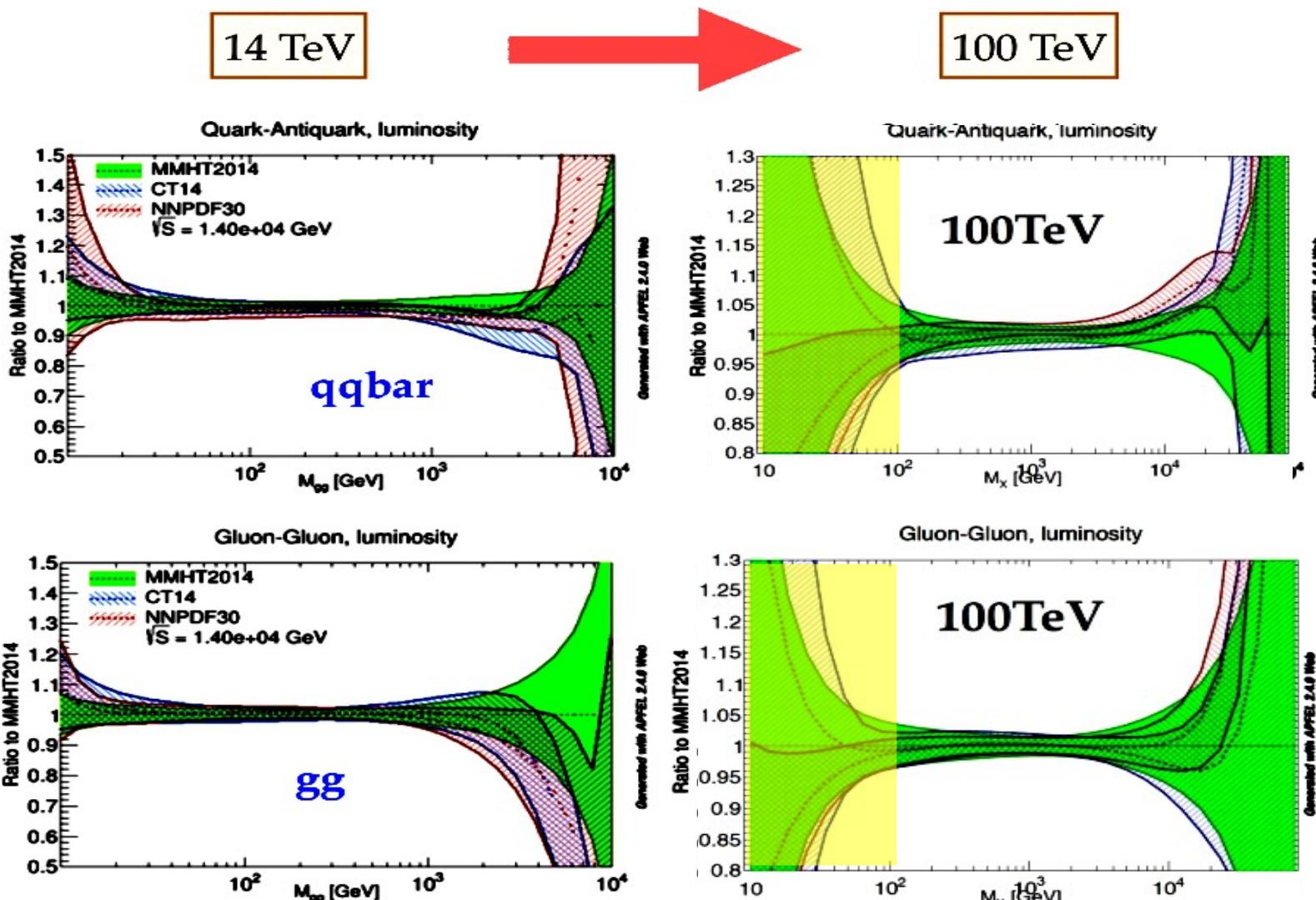
(3) Beyond DGLAP (FCC-eh)

(4) Many body QCD (FCC-hh)

Parton (x, Q^2) kinematics (FCC-ep, FCC-pp)



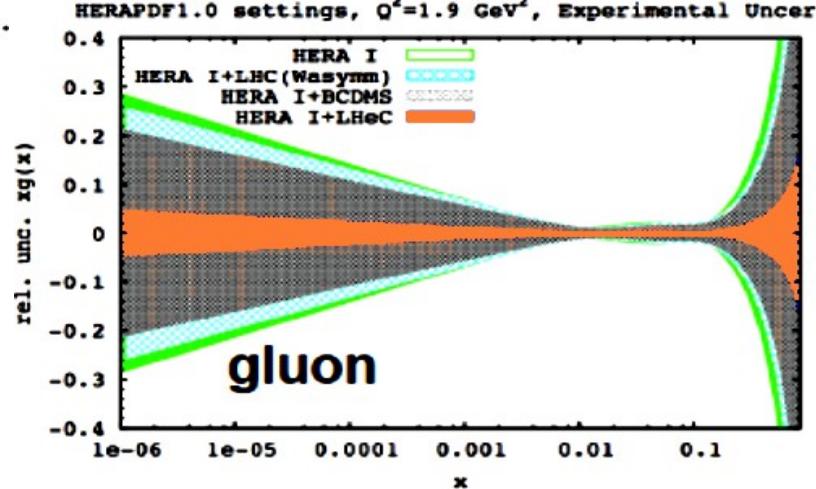
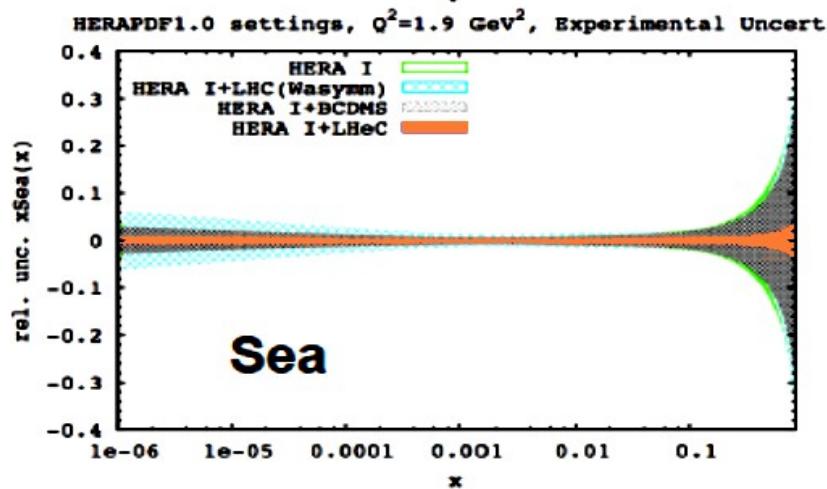
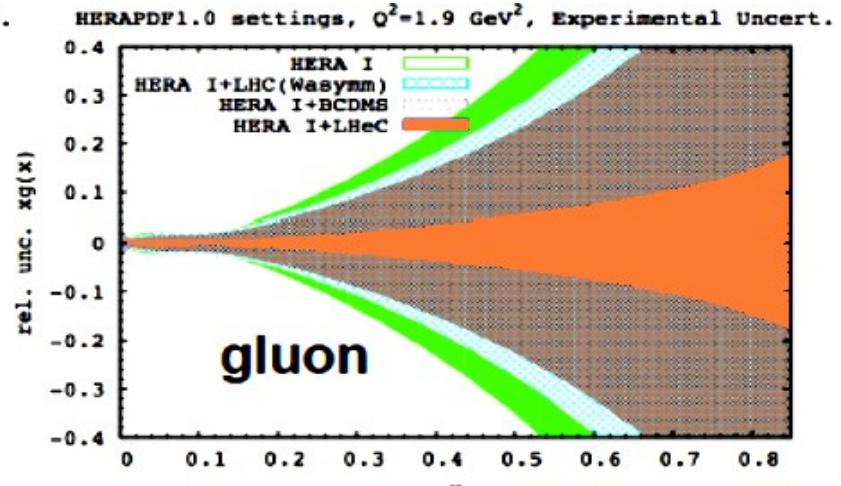
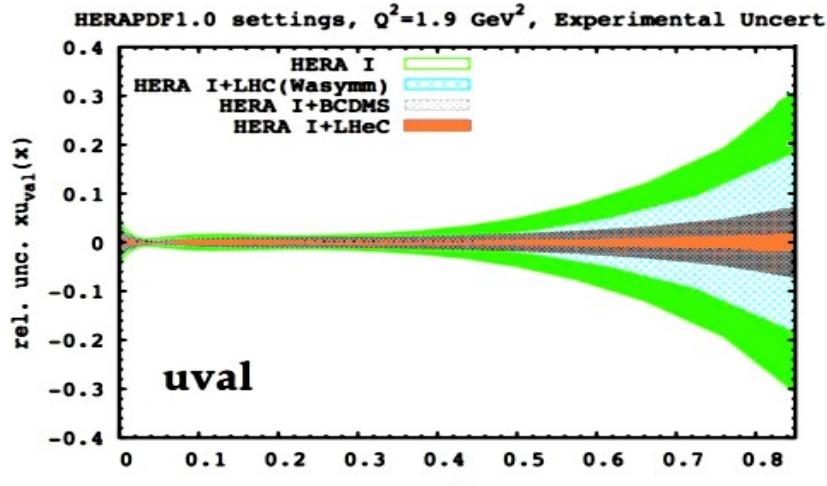
Parton luminosities: LHC vs. FCC-pp



- “Precision” region at FCC-pp: ~10% PDF uncertainty at H,Z scales.
Large increasing PDF uncertainties for masses < 100 GeV.

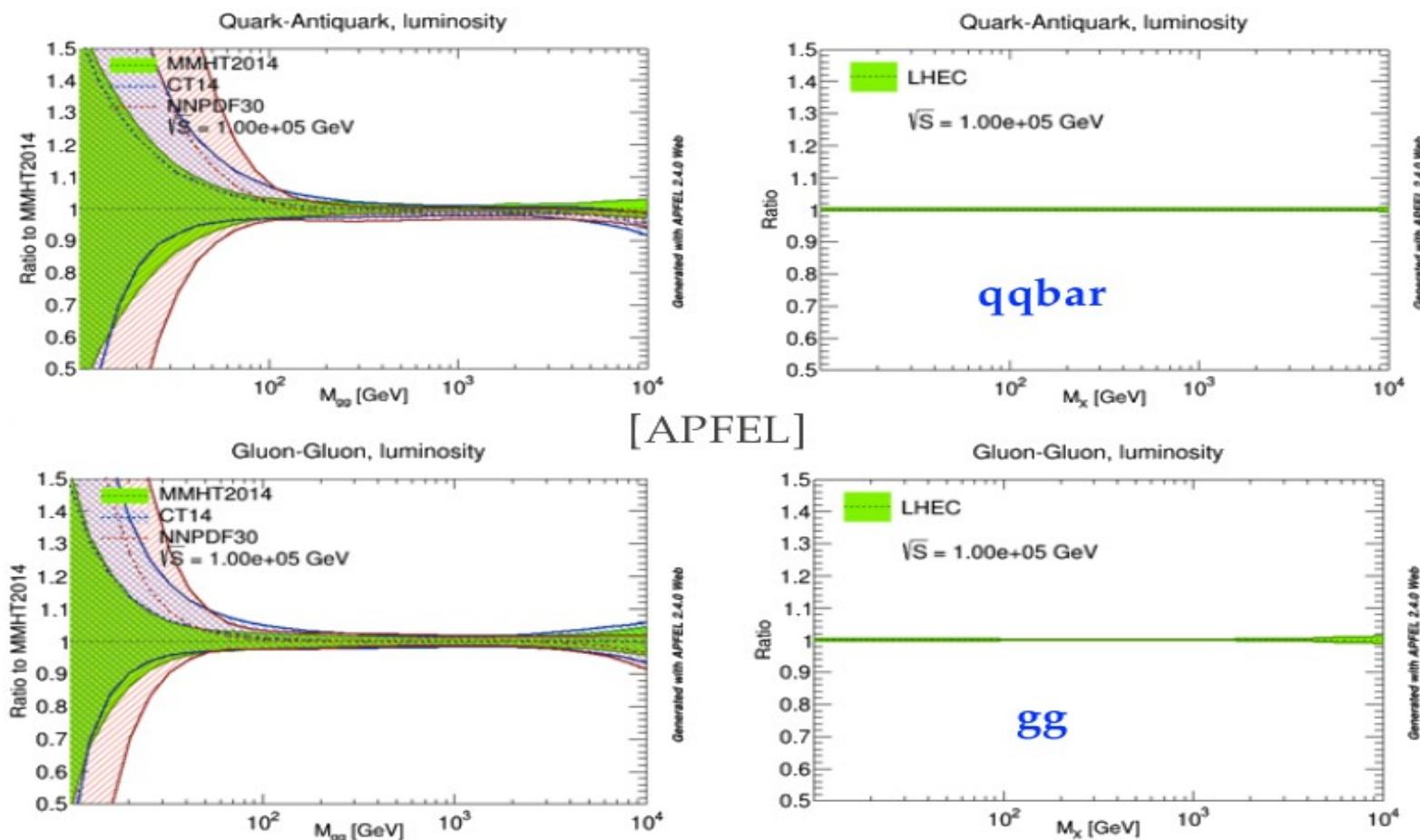
Improved PDFs at all x (FCC-ep)

- Benchmark scenarios: NC, CC $e^\pm p$ with $P=\pm 0.4$, F_2 , xF_3 , F_L [CDR, JPG39(2012)075001]



- Strongly reduced PDF uncertainties for all flavours (also strange, charm, bottom) at all x (down to 10^{-6})

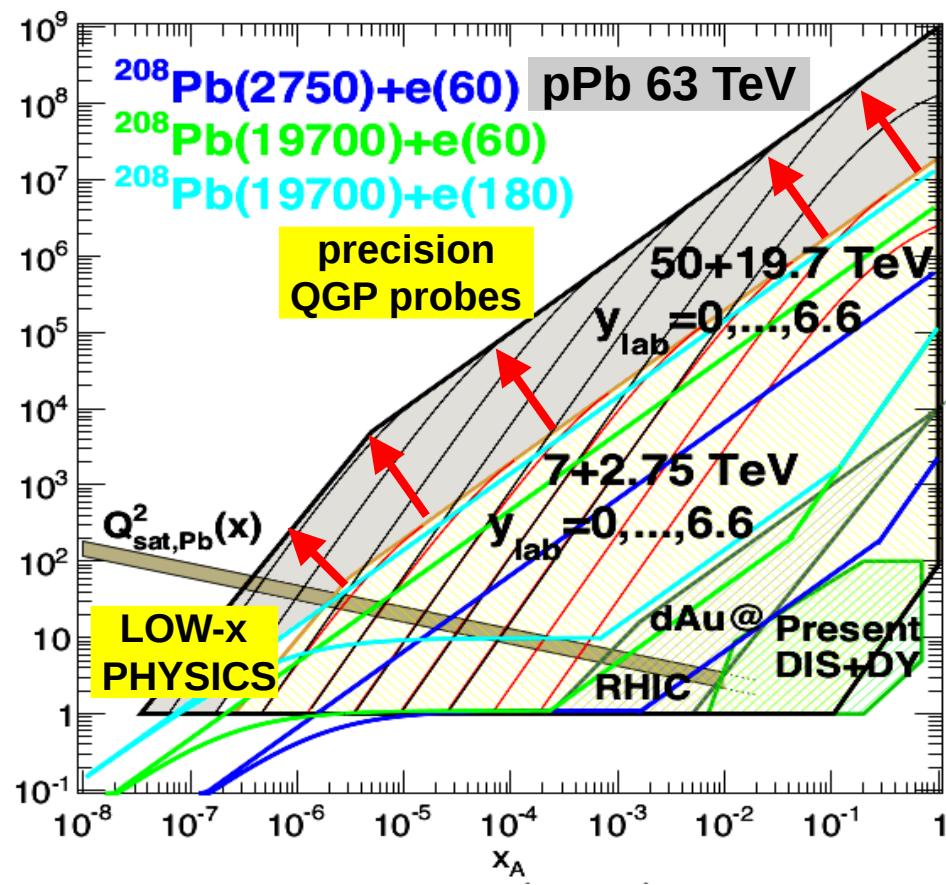
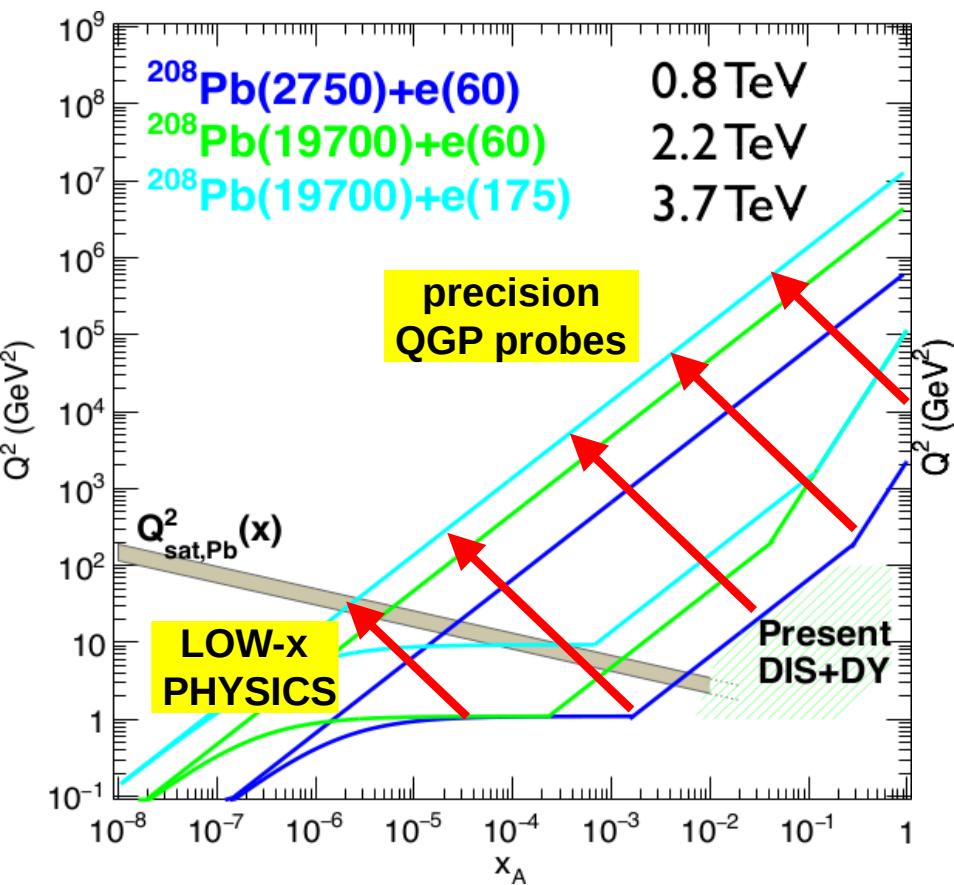
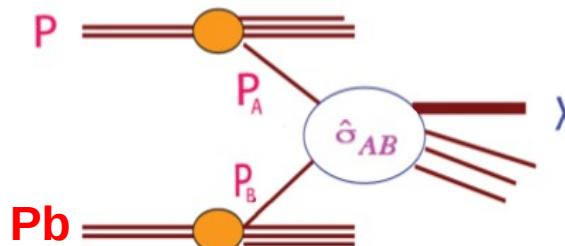
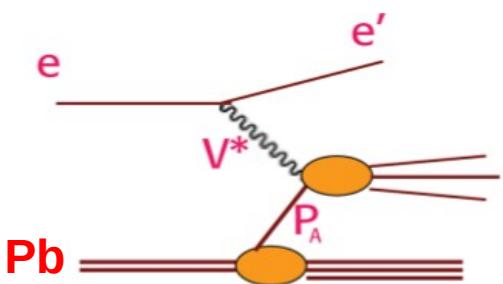
Parton luminosities: LHC vs. FCC-ep



- “Precision” region at FCC-pp: <1% PDF uncertainty at H,Z scales.
Strongly reduced parton uncertainties for masses: 10 GeV–10 TeV

CONCLUSION (2a): <1% PDF precision requires high- \sqrt{s} e-p collider

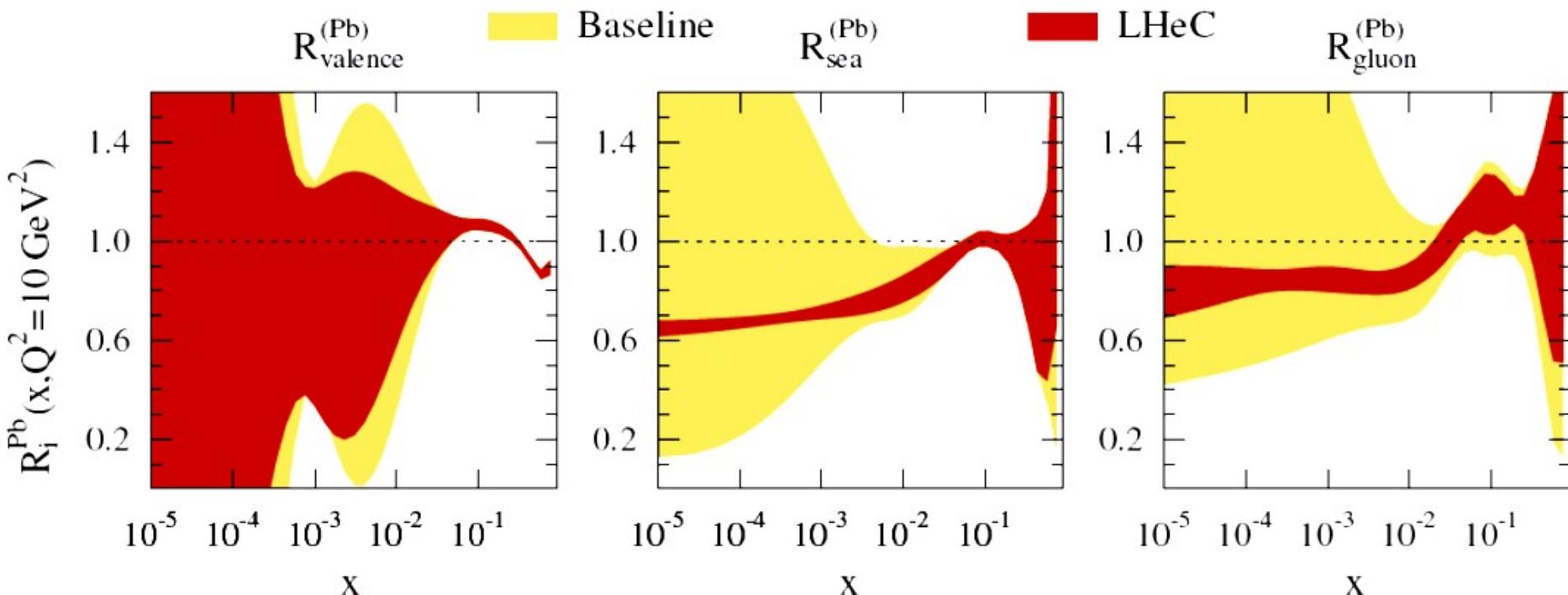
Parton (x, Q^2) kinematics (FCC-eA, FCC-pA)



Improved nuclear PDFs (FCC-eA)

- Very large uncertainties today on nPDFs: Precision study of QGP properties in PbPb jeopardized by initial-state uncertainties.

$$R_i^{\text{Pb}}(x, Q^2) = \frac{f_i^{\text{Pb}}(x, Q^2)}{208 f_i^p(x, Q^2)}, \quad i = q, \bar{q}, g$$

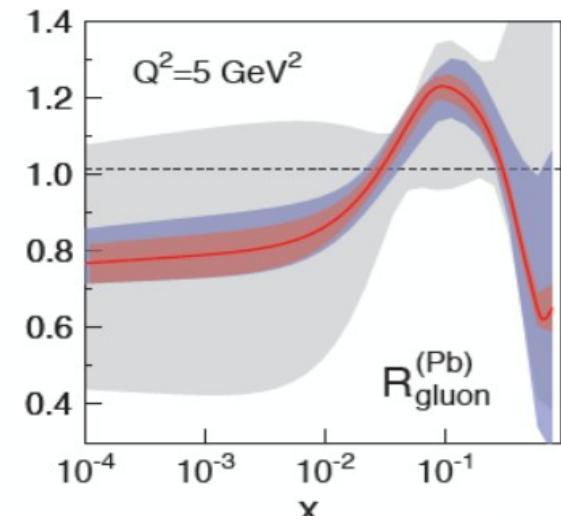
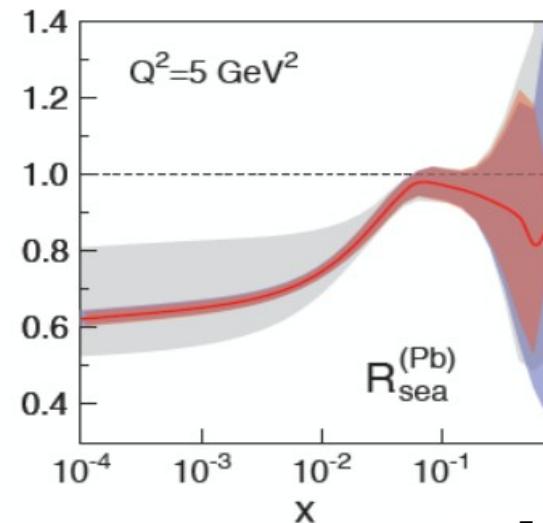
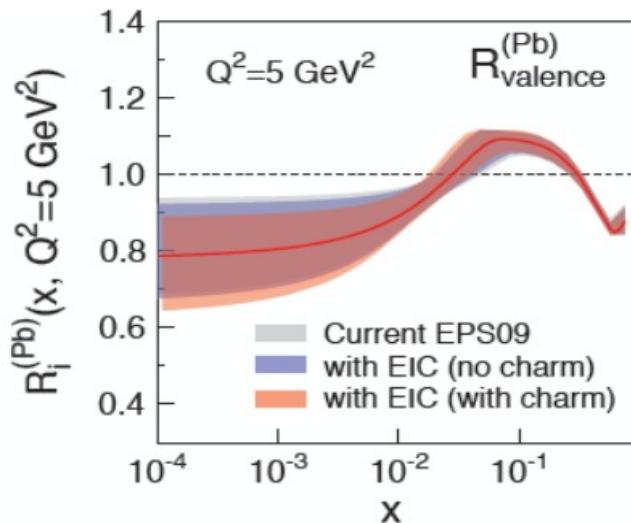


- Strongly reduced PDF uncertainties for all flavours (also strange, charm, bottom) at all x (down to 10^{-5}) via multiple DIS measurements (**NC pseudodata**, CC+c,b to be added).

Improved nuclear PDFs (EIC)

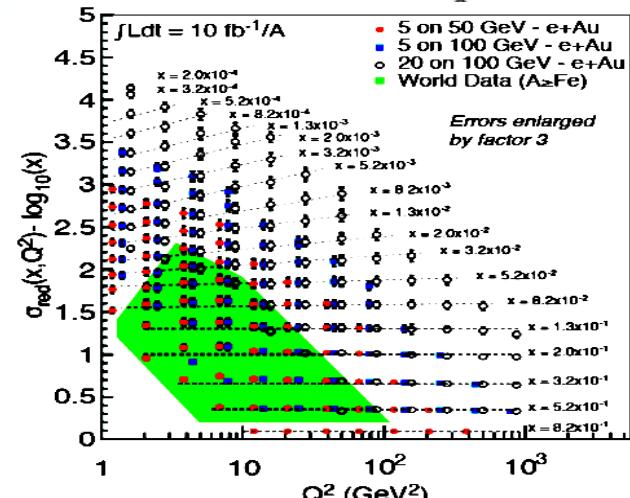
- Very large uncertainties today on nPDFs: Precision study of QGP properties in PbPb jeopardized by initial-state uncertainties.

$$R_i^{\text{Pb}}(x, Q^2) = \frac{f_i^{\text{Pb}}(x, Q^2)}{208 f_i^p(x, Q^2)}, \quad i = q, \bar{q}, g$$



- EIC (e-Au at 10–100 GeV): Strongly reduced PDF uncertainties for all flavours down to $x \sim 10^{-4}$

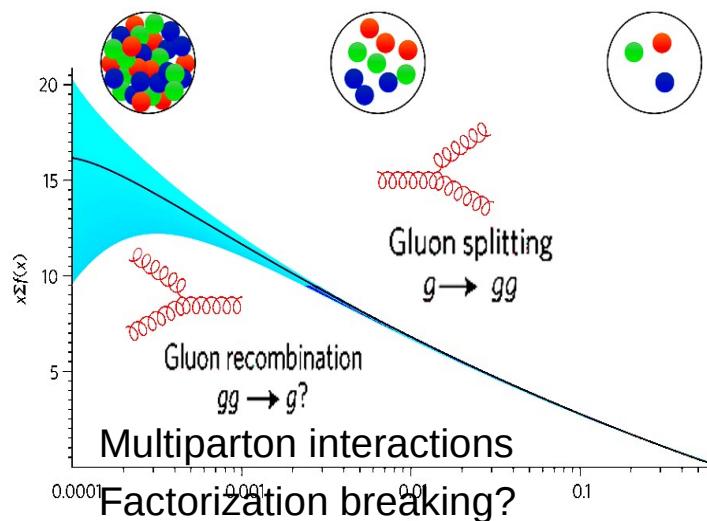
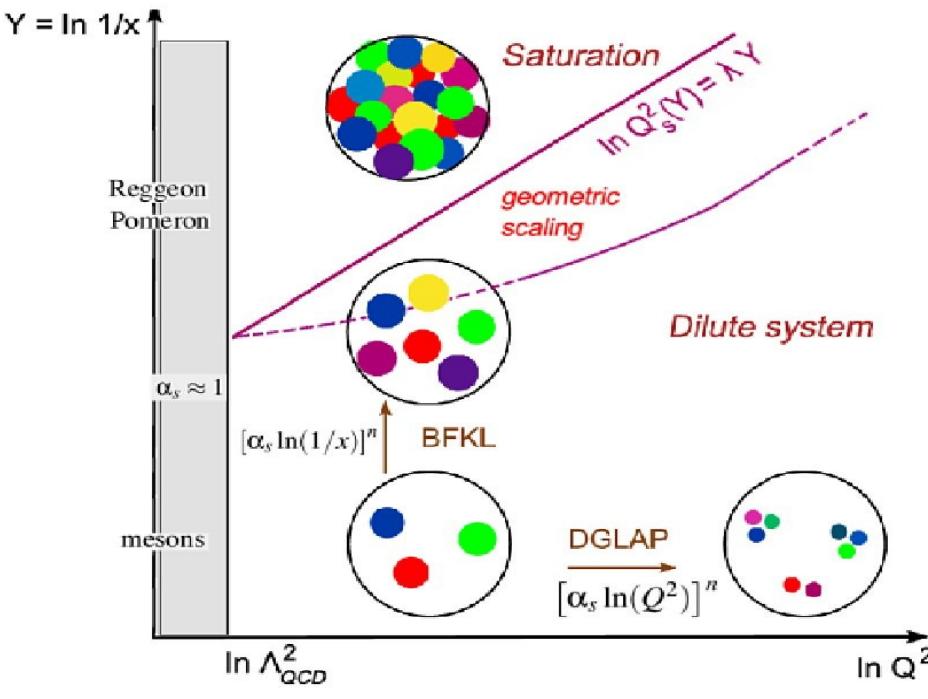
CONCLUSION (2b): Few-% nuclear PDF precision requires high-lumi e-A collider



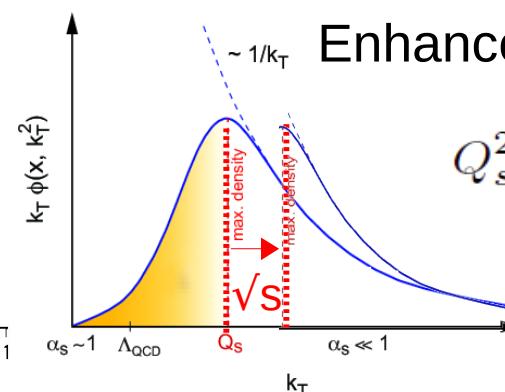
QCD studies at future colliders

- (1) QCD coupling (FCC-ee, FCC-eh, ILC, CLIC)
- (2) Parton densities (FCC-eh, EIC)
- (3) Beyond DGLAP (FCC-eh)**
- (4) Many body QCD (FCC-hh)

“Beyond DGLAP” evolution



- DGLAP eqs. describe parton radiation as a function of Q^2 :
 $f(Q^2) \sim \alpha_s \ln(Q^2/Q_0^2)^n$
[fixed-order PDFs, collinear fact.]
- BFKL evolution as a function of x :
 $f(x) \sim \alpha_s \ln(1/x)^n$
[uPDFs, k_T -factorization]
- Non-linear evolution eqs. at low x
 $gg \rightarrow g$ peaks at perturbative
“saturation scale” $\mathcal{O}(\text{few GeV})$.



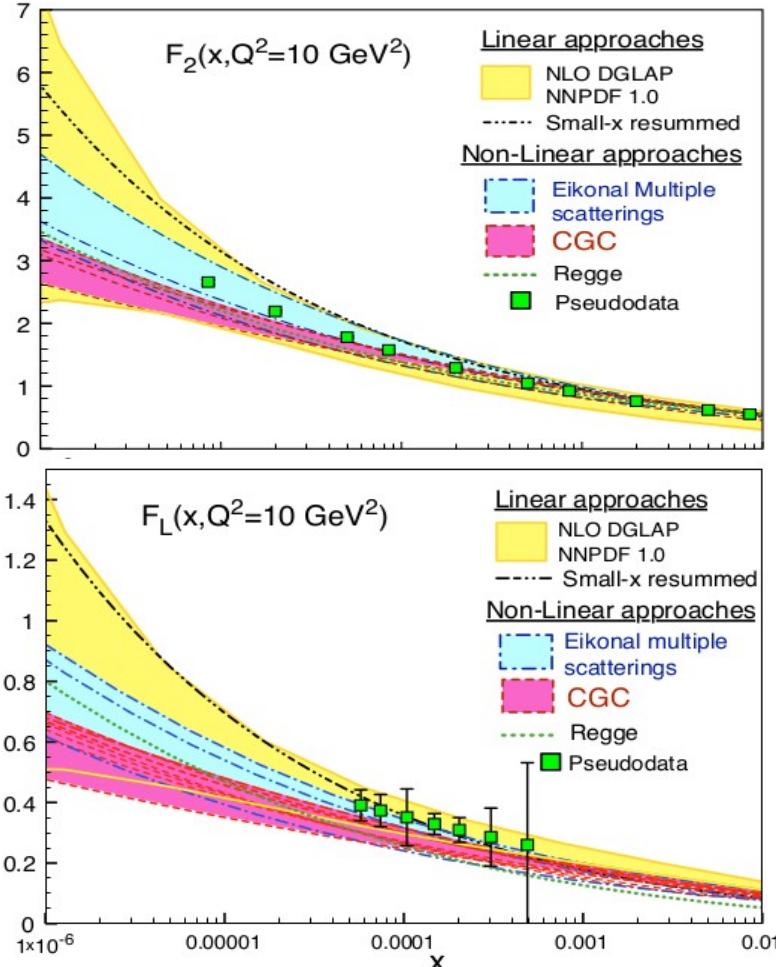
Enhanced in nuclei ($\sim A^{1/3}$).

$$Q_s^2 \sim A^{1/3} Q_0^2 \left(\frac{1}{x}\right)^\lambda \sim (\sqrt{s})^\lambda$$

Note: Equivalent to PYTHIA's pQCD cutoff $p_{T,0}$

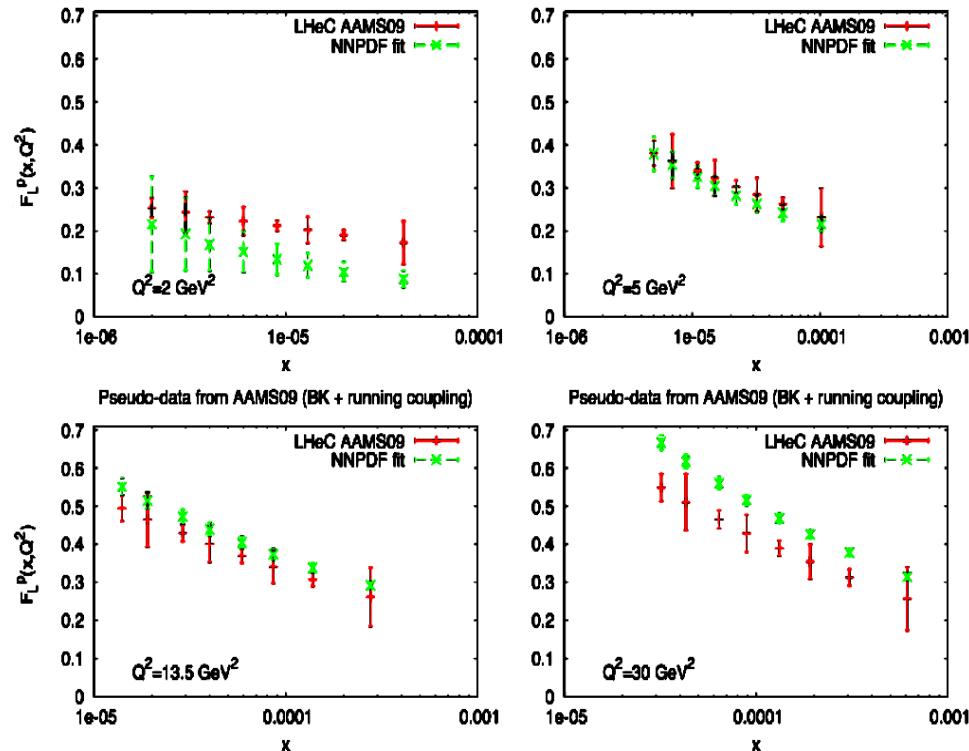
“Beyond DGLAP” evolution (FCC-eh)

- NLO DGLAP cannot simultaneously accommodate LHeC F_2 & F_L if low- x gluon saturation present:



(CGC: “Color Glass Condensate” effective theory with non-linear BK/JIMWLK evolution eqs.)

- LHeC pseudodata for F_L for NNPDF (DGLAP) vs. AAMS (saturation):



CONCLUSION (3): Evidence for non-linear QCD requires high- \sqrt{s} e-p,A

QCD studies at future colliders

- (1) QCD coupling** (FCC-ee, FCC-eh, ILC, CLIC)
- (2) Parton densities** (FCC-eh, EIC)
- (3) Beyond DGLAP** (FCC-eh)
- (4) Many body QCD** (FCC-hh)

Quantum Chromo (many-body) Dynamics

- QCD = Quantum-field theory with **very rich dynamical** content:
asymptotic freedom, confinement,
(approx.) χ -symmetry, non-trivial
vacuum, $U_A(1)$ anomaly,
CP problem, ...

- QCD = very diverse **many-body phenomenology** at various **limits**:

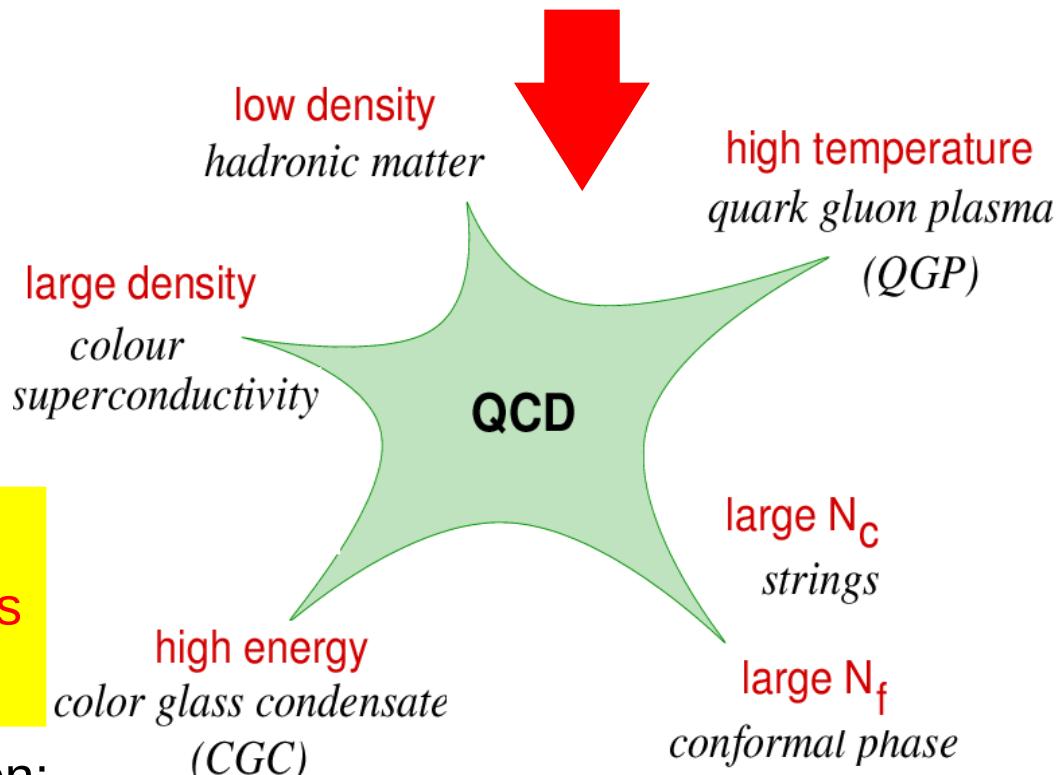
- QCD = **ONLY** non-Abelian QFT whose collective dynamics can be studied in the lab !

Insight for EWK phase transition:

Hydrodynamics expansion? New (quasiparticle) degrees of freedom?

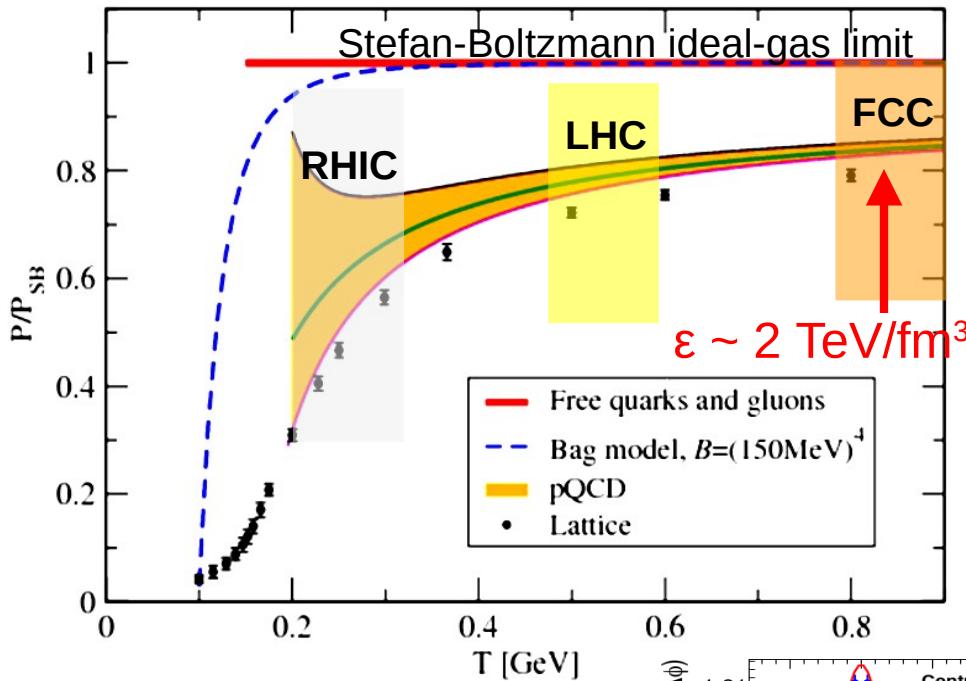
$$\mathcal{L} = \frac{1}{4g^2} G_{\mu\nu}^\alpha G_{\mu\nu}^\alpha + \sum_j \bar{q}_j (i \gamma^\mu D_\mu + m_j) q_j$$

where $G_{\mu\nu}^\alpha = \partial_\mu A_\nu^\alpha - \partial_\nu A_\mu^\alpha + g_{\mu\nu}^{ab} A_a^b A_b^\alpha$
and $D_\mu = \partial_\mu + i e A_\mu^\alpha \gamma_\alpha$

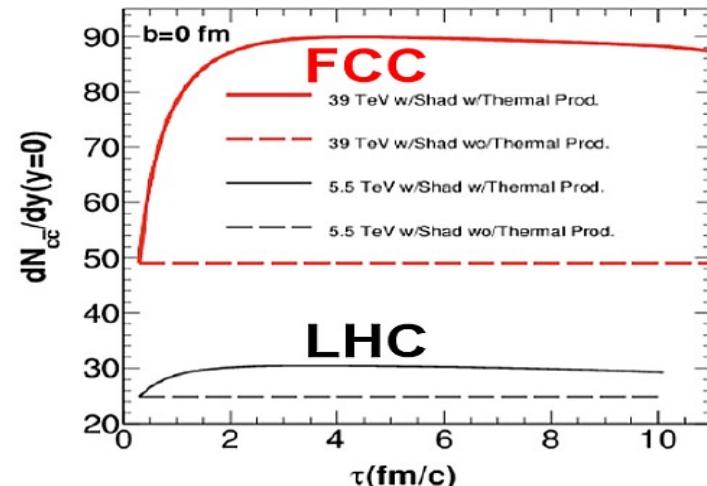


Many-body QCD (FCC-AA)

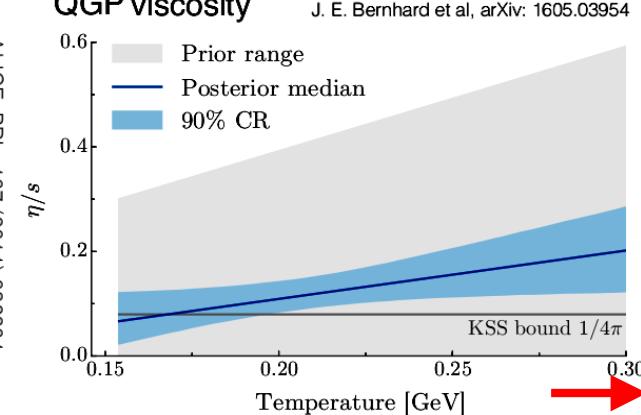
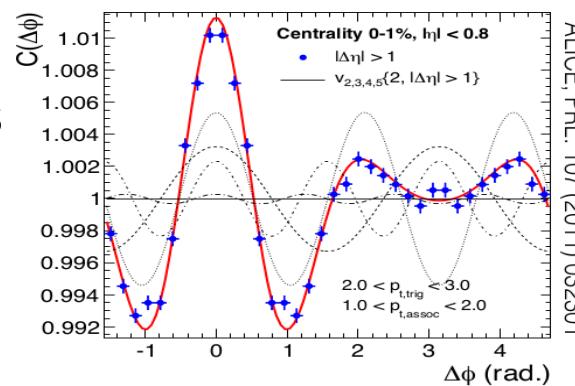
- QCD Equation-Of-State probed at TeV/fm^3 : Even heavy-Q thermalize...



PbPb(39TeV): Very abundant pQCD probes: $gg \rightarrow c\bar{c}$, $q\bar{q} \rightarrow c\bar{c}$



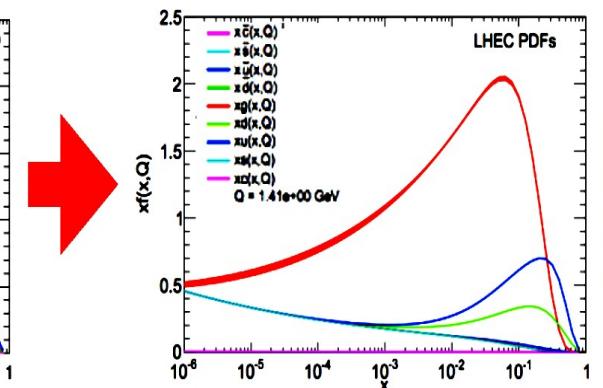
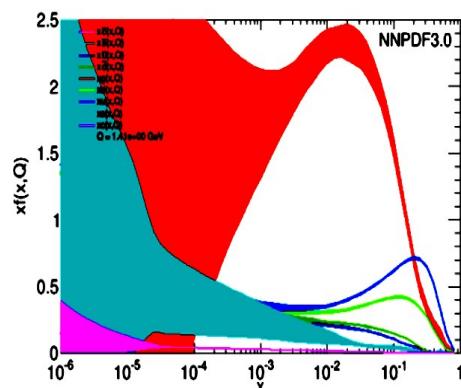
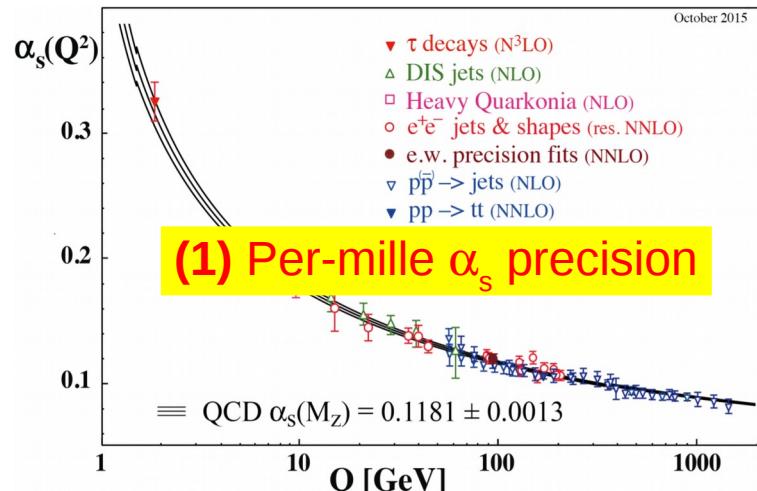
- Transport properties (viscosity) probed at $T \sim 5 \times T_c$:



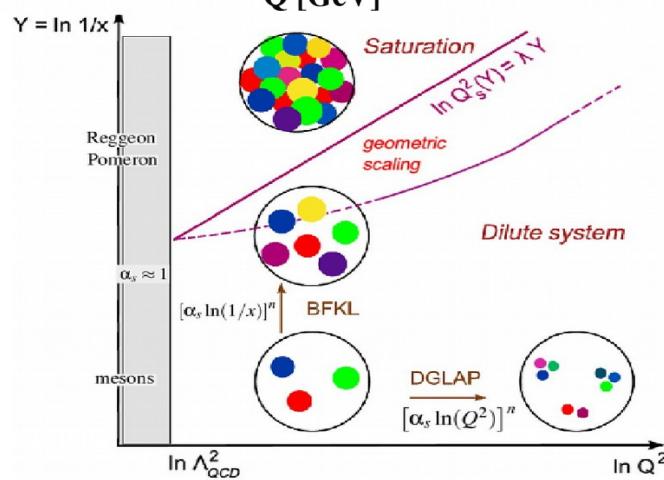
CONCLUSION (4): Study of QGP at TeV/fm^3 requires high- \sqrt{s} AA collider

Summary

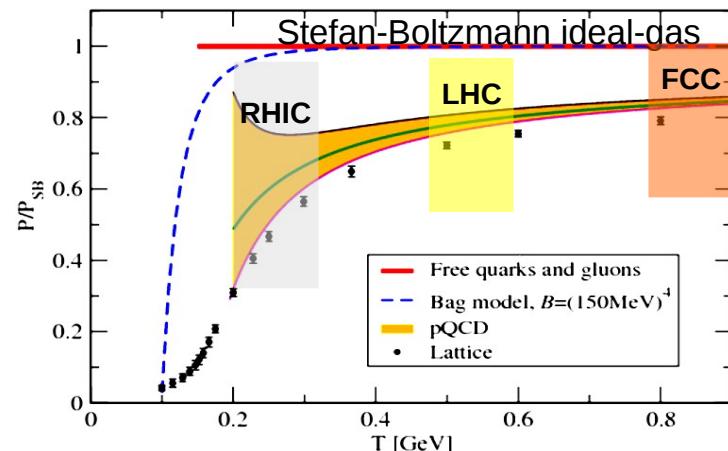
- Many fundamental HEP questions will *not* be fully answered at the LHC.
- New (ee, pp) colliders with higher \sqrt{s} , luminosity & precision are needed.
- Crucial QCD studies needed to fully exploit SM & BSM physics, e.g. ...



(2) Sub-% PDF precision



(3) Non-linear QCD limit

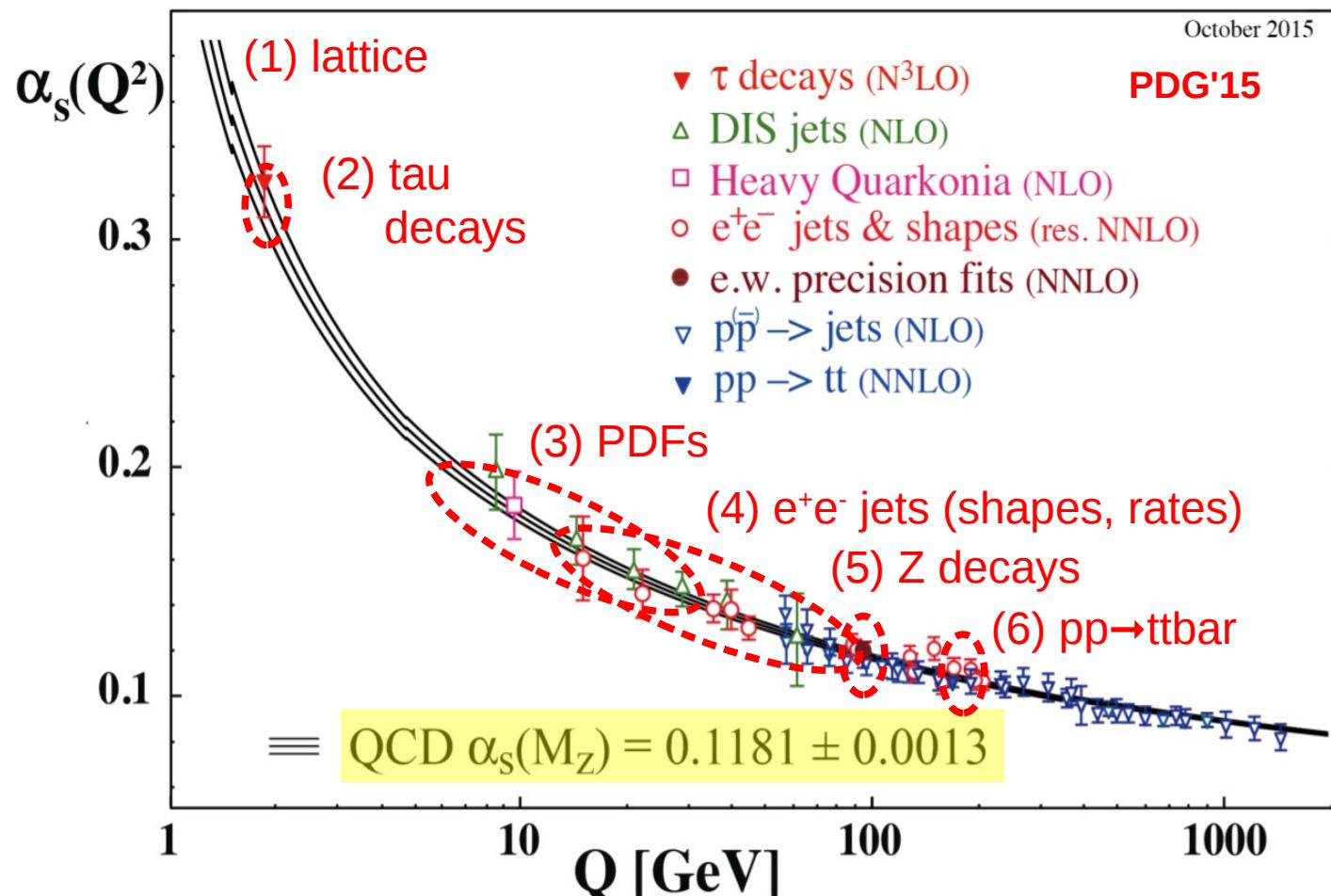


(4) TeV/fm³ QCD thermodynamics

Backup slides

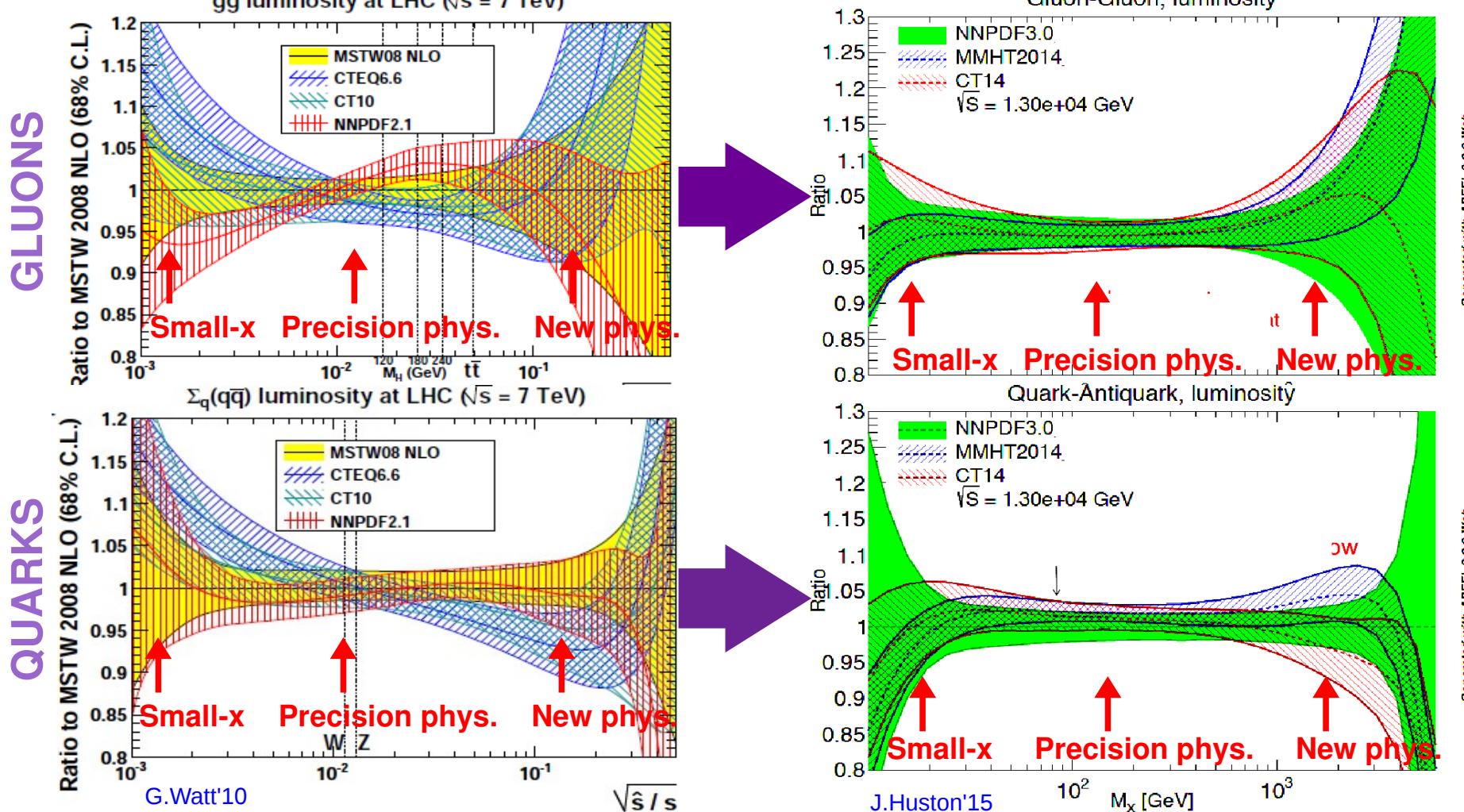
Status of α_s determination (PDG 2016)

- Determined by comparing **6 experimental observables** to pQCD NNLO,N³LO predictions, plus performing a **global average** of their propagated values at the Z pole scale:



Parton densities

■ Parton-parton luminosities pre- and post-LHC Run-1:



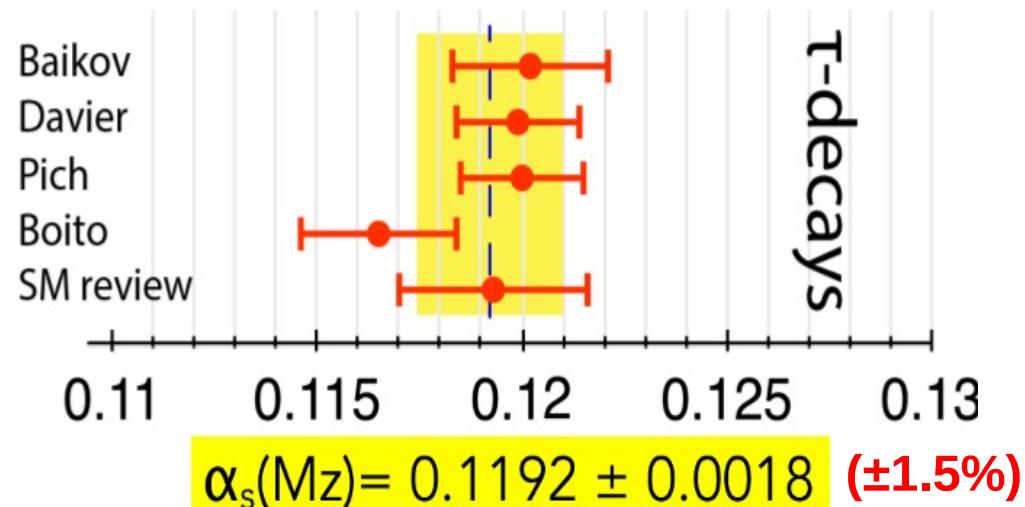
α_s from hadronic τ -lepton decays

→ Computed at **N³LO**: $R_\tau \equiv \frac{\Gamma(\tau^- \rightarrow \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \rightarrow \nu_\tau e^- \bar{\nu}_e)} = S_{\text{EW}} N_C (1 + \sum_{n=1}^4 c_n \left(\frac{\alpha_s}{\pi}\right)^n + \mathcal{O}(\alpha_s^5) + \delta_{\text{np}})$

→ Experimentally: $R_{\tau, \text{exp}} = 3.4697 \pm 0.0080 (\pm 0.23\%)$

→ Various pQCD approaches (**FOPT vs CIPT**) & treatment of non-pQCD contributions, yield different results.

Uncertainty slightly increased:
2013 ($\pm 1.3\%$) → 2015 ($\pm 1.5\%$)



→ Future prospects:

- Better understanding of **FOPT vs CIPT differences**.
- **Better spectral functions needed** (high stats & better precision):
B-factories (BELLE-II), **high-statistics τ samples** (ILC, FCC-ee).

(1) QCD coupling at future facilities

(2) Parton densities at future facilities

(3) Beyond DGLAP at future facilities

(4) Many-body QCD at future facilities