QCD: FCC e^+e^-, eh, hh complementarity

1st FCC Physics Workshop

CERN, 16th–20th Jan. 2017

David d'Enterria

CERN

QCD is a crucial piece of FCC-xx physics

▶ Though QCD is *not per se* the main driving force behind FCC, QCD is crucial for many FCC measurements (signals & backgrounds):

- High-precision α_s: Affects SM fits/tests, all hadronic cross sections/decays,...
- N^nLO corrs., N^nLL resummations: Needed for all precise QCD initial/final states
- High-precision (n)PDFs: Affects all precision W,Z,H (mid-x) measurements & all searches (high-x) in h-h collisions.
- Heavy-Quark/Quark/Gluon separation, subjet structure, boosted topologies,...: Needed for all precision measurements & searches with final jets.
- Semihard QCD (low-x gluon saturation, multiple hard parton interactions,…): Significant pQCD x-sections at FCC-hh (Note: Q_0~10 GeV at 100 TeV).
- Non-perturbative QCD: Colour reconnection affects e^+e^- jetty final-states: $e^+e^- \rightarrow WW \rightarrow 4j$, $Z \rightarrow 4j$, $t\bar{t}$ (m_{top} extraction); Control of parton fragmentation+ +diffraction+"collective" effects is basic in FCC-pp $\mathcal{O}(1000)$ pileup, backgds,...
- ...

QCD synergies at FCC

(1) QCD coupling (FCC-ee, FCC-eh, FCC-pp)

(2) p,A parton densities (FCC-eh, FCC-hh)

(3) Beyond DGLAP (FCC-eh, FCC-hh)

(4) Gluons & Higgs (FCC-ee, FCC-hh)

(5) Non-perturbative QCD (FCC-ee, FCC-hh)

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Importance of the QCD coupling α_s

- Least-known of couplings: $\delta\alpha \sim 10^{-10} \ll \delta G_F \ll 10^{-7} \ll \delta G \sim 10^{-5} \ll \delta\alpha_s \sim 10^{-3}$
- Impacts all QCD x-sections&decays (H), precision top & param. EWPO:

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
$H \to c\bar{c}$	126	± 7.1	$\pm 0.1\%$	$\pm 2.3\%$
$H \to gg$	126	± 4.1	$\pm 0.1\%$	$\pm 0\%$

Msbar mass error budget (from threshold scan)

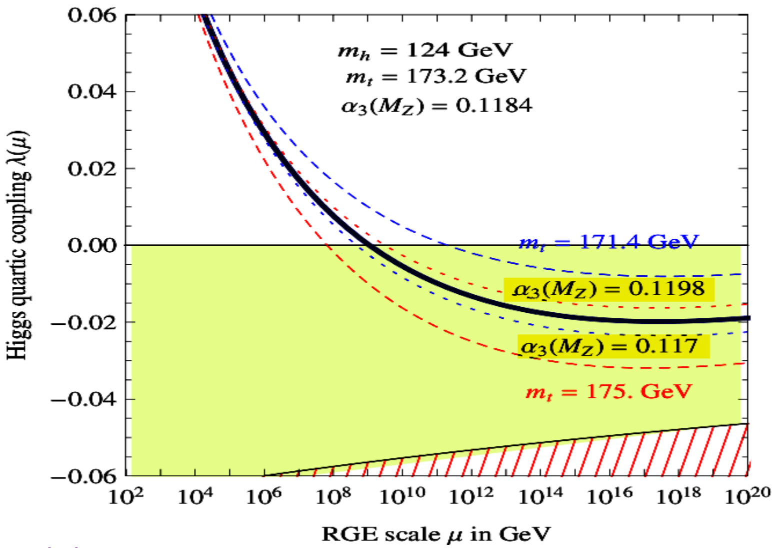
$(\delta M_t^{SD-low})^{exp}$	$(\delta M_t^{SD-low})^{theo}$	$(\delta\overline{m}_t(\overline{m}_t))^{conversion}$	$(\delta\overline{m}_t(\overline{m}_t))^{\alpha_s}$
40 MeV	50 MeV	7 – 23 MeV	70 MeV

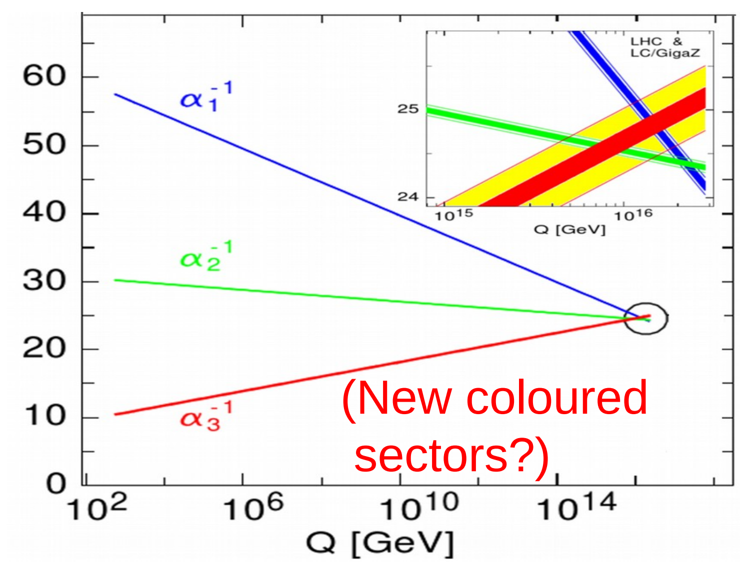
$\Rightarrow$ improvement in α_s crucial $\quad \delta\alpha_s(M_z) = 0.001$

Quantity	FCC-ee	future param.unc.	Main source
Γ_Z [MeV]	0.1	0.1	$\delta\alpha_s$
R_b $[10^{-5}]$	6	< 1	$\delta\alpha_s$
R_ℓ $[10^{-3}]$	1	1.3	$\delta\alpha_s$

Sven Heinemeyer – 1st FCC physics workshop, CERN, 17.01.2017

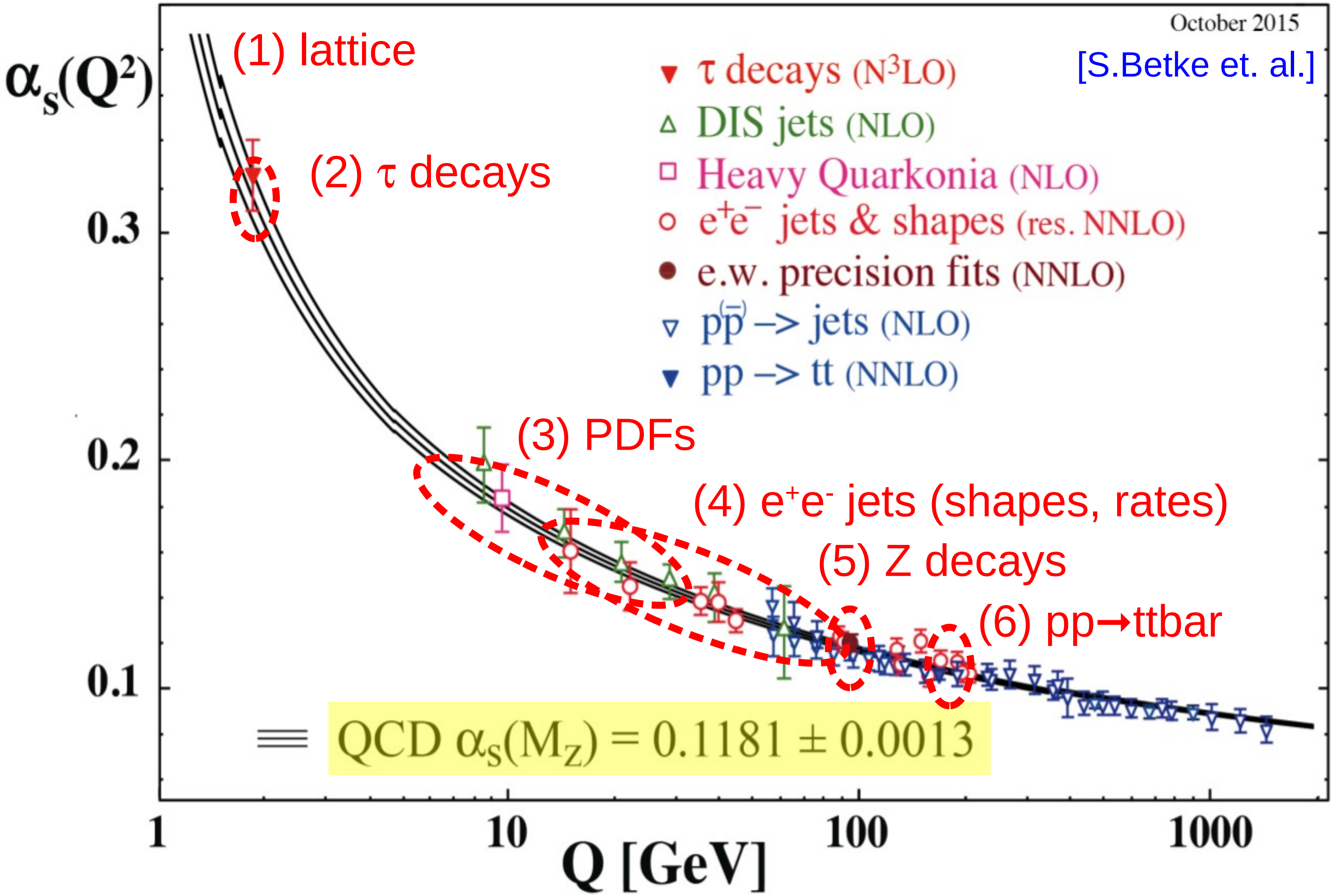
- Impacts physics approaching Planck scale: EW vacuum stability, GUT





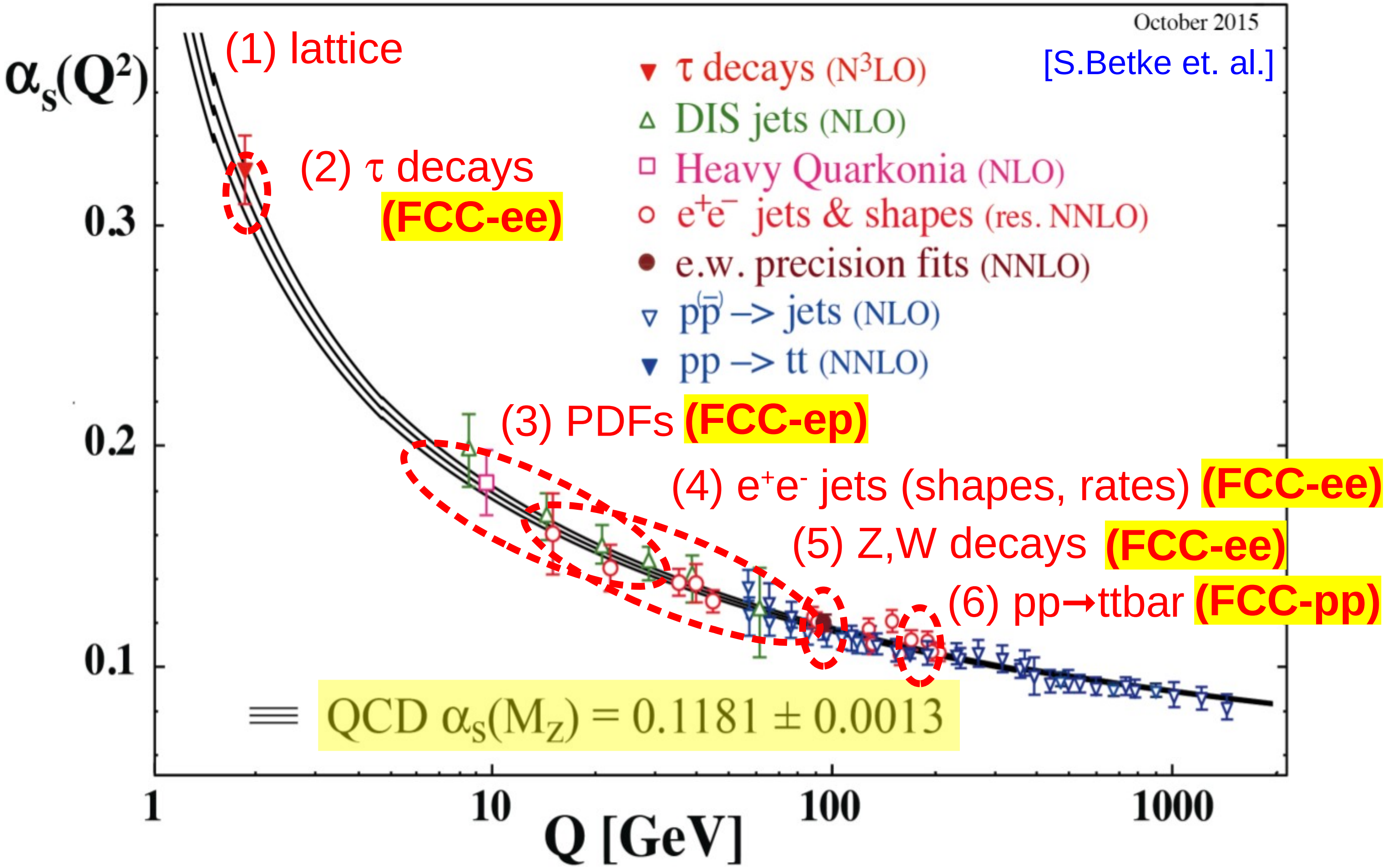
World α_s determination (PDG 2016)

- Determined today by comparing 6 experimental observables to pQCD NNLO,N^{3}LO predictions, plus global average at the Z pole scale:



World α_s determination (PDG 2016)

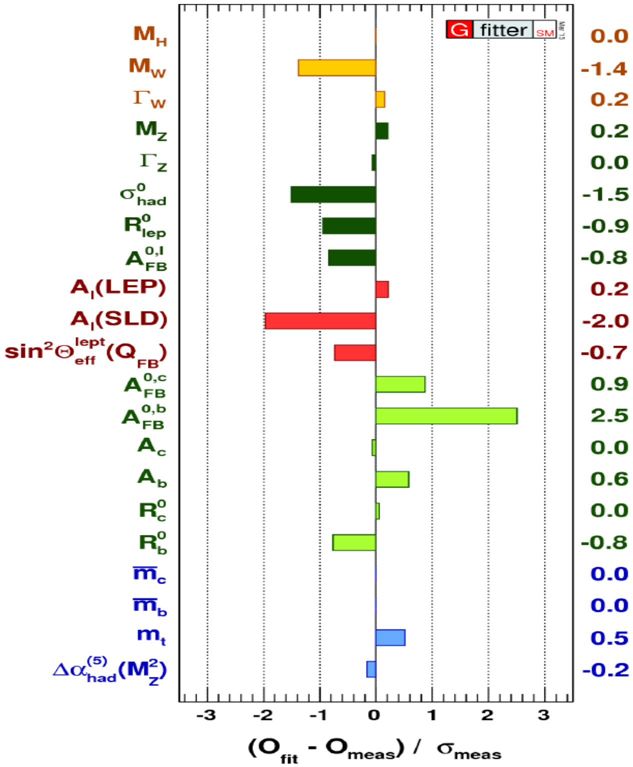
- Determined today by comparing 6 experimental observables to pQCD NNLO,N^3LO predictions, plus global average at the Z pole scale.
  Maximum complementarity among FCC-xx's:

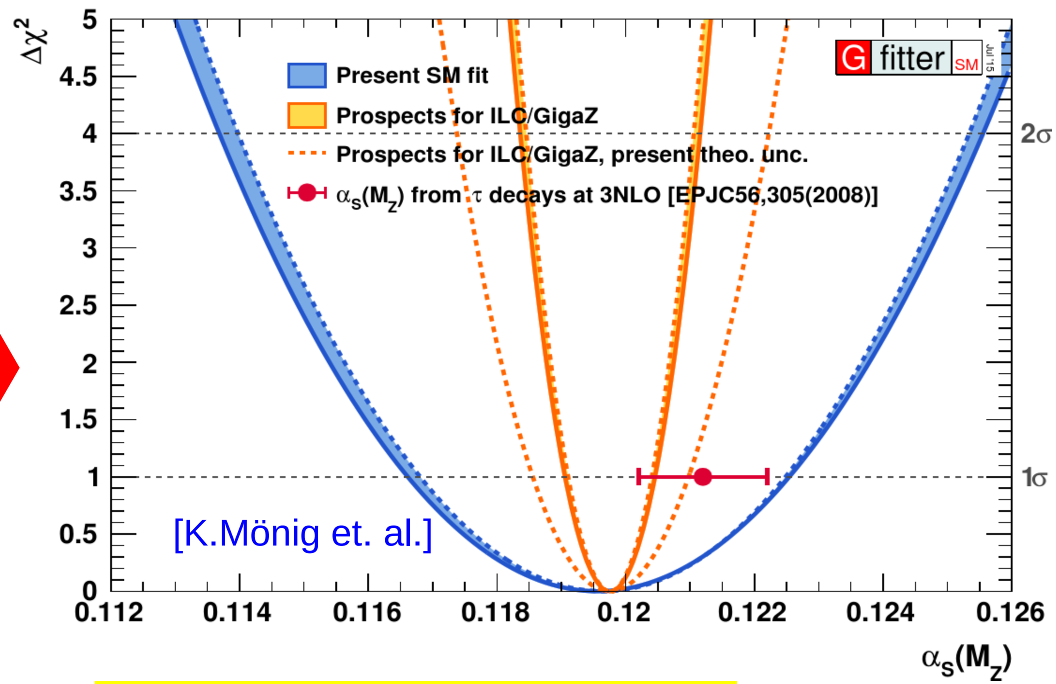


α_s via hadronic Z decays (FCC-ee)

- Computed at N³LO: $R_Z \equiv \frac{\Gamma(Z\to h)}{\Gamma(Z\to l)} = R_Z^{EW} N_C \left(1 + \sum_{n=1}^{4} c_n \left(\frac{\alpha_s}{\pi}\right)^n + \mathcal{O}(\alpha_s^5)\right) + \delta_m + \delta_{np})$
- LEP: 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:





α_s (M_Z) = 0.1196 ± 0.0030 **(±2.5%)**

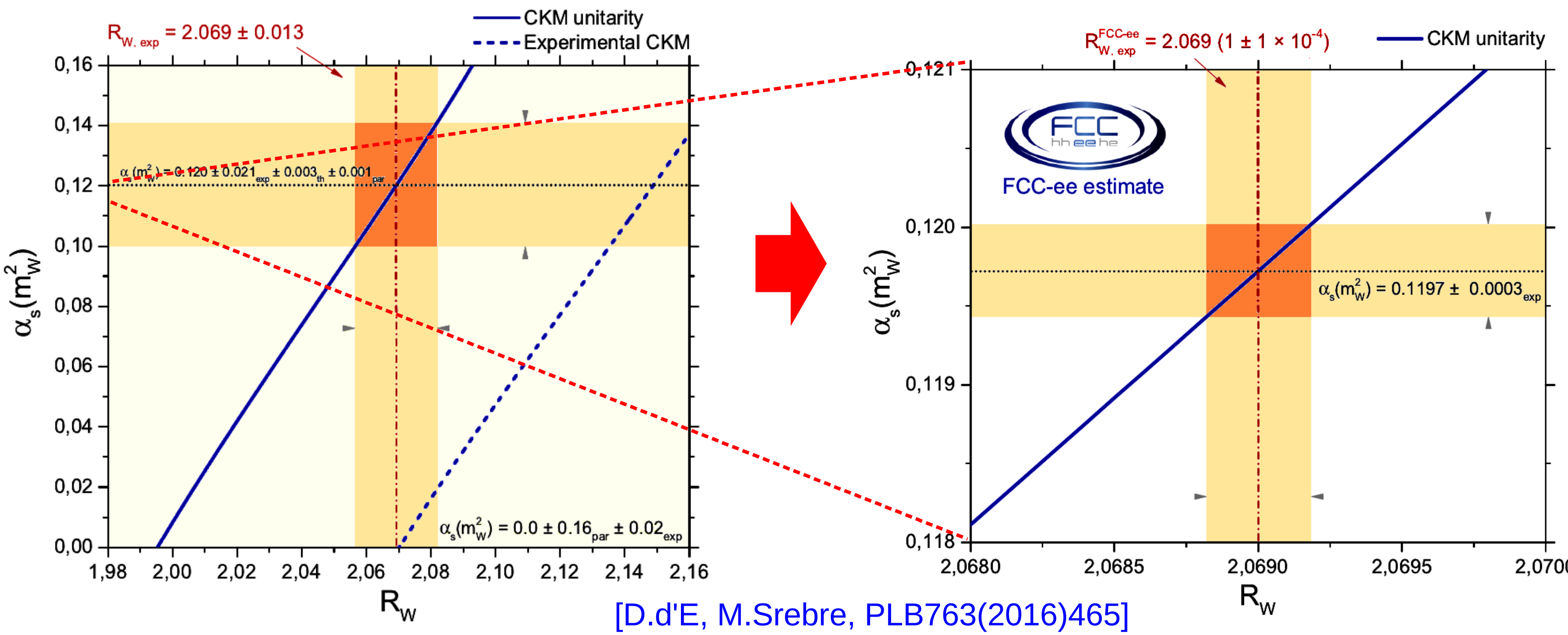
- FCC-ee: – Z stats (×10⁵ LEP) will lead to: **$\delta\alpha_s$ < 0.2%**
  – TH uncertainties: $\sin^2\theta_{eff}$,m_W,m_t. β-function at 5 loops.

α_s via hadronic W decays (FCC-ee)

- Computed at N[2,3]LO: $\Gamma_{\mathrm{W,had}} = \frac{\sqrt{2}}{4\pi} G_F m_W^3 \sum_{\mathrm{quarks\ i,j}} |V_{i,j}|^2 \left[1 + \sum_{k=1}^{4} \left(\frac{\alpha_s}{\pi} \right)^k + \delta_{\mathrm{electroweak}}(\alpha) + \delta_{\mathrm{mixed}}(\alpha\alpha_s) \right]$
- LEP: Γ_W = 1405±29 MeV (±2%), BR_W = 0.6741±0.0027 (±0.4%)

  Extraction with large exp. & parametric (CKM V_{cs}) uncertainties today:

  $\alpha_s(M_z)$ = 0.117 ± 0.040 **(±35%)**



[D.d'E, M.Srebre, PLB763(2016)465]

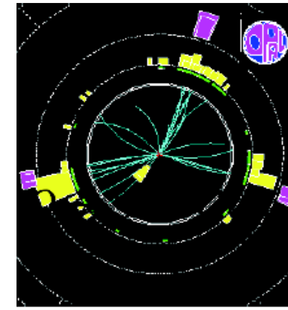
- FCC-ee: – Huge W stats (×10[4] LEP) will lead to: **$\delta\alpha_s$ < 0.3%**

  – TH uncertainty: $|\delta V_{cs}|$ to be significantly improved (10^{-4})

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

- Computed at $N^{2,3}LO+N^{(2)}LL$ accuracy.
- <u>LEP</u> data for thrust, C-parameter, jet shapes, 3-jet x-sections

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

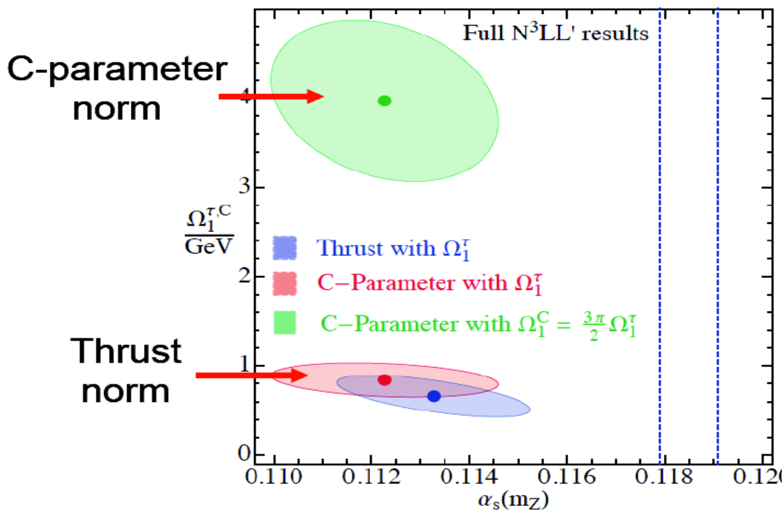


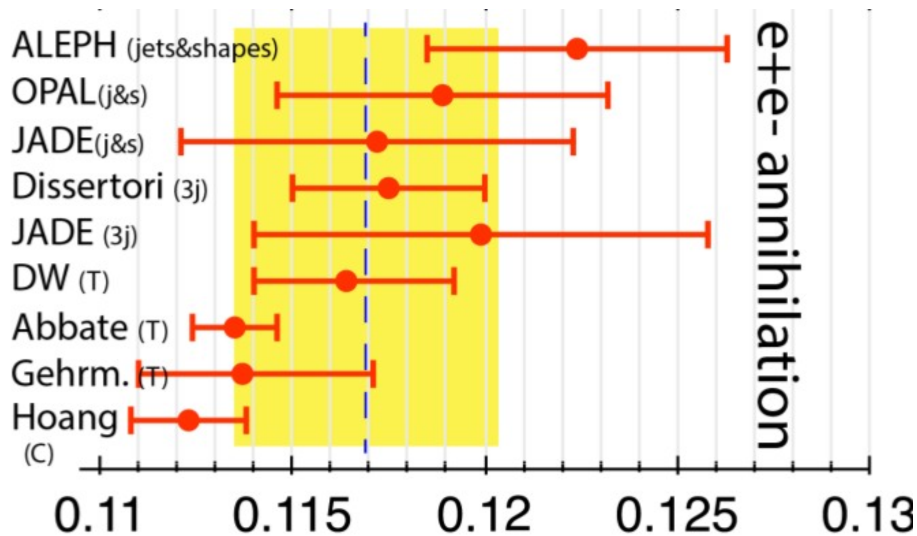
OPAL 3 jet event

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

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

[S.Kluth et al., A.Hoang et. al.]





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

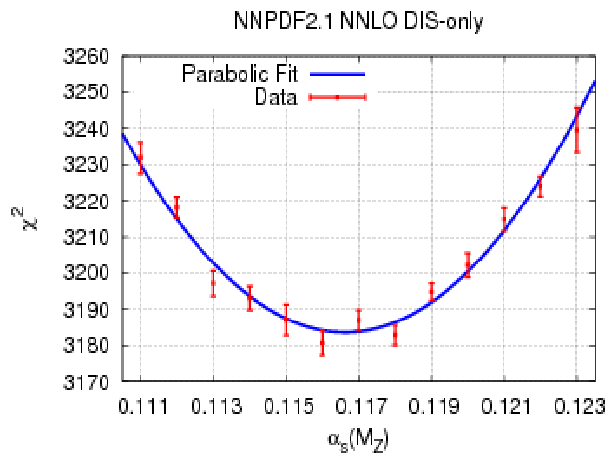
- <u>FCC-ee</u>:
  – Higher-√s data needed for rates (lower-√s for shapes): **$\delta\alpha_s < 1\%$**
  – TH uncert.: Jet rates with improved (NNLL or N^3LL) resummation

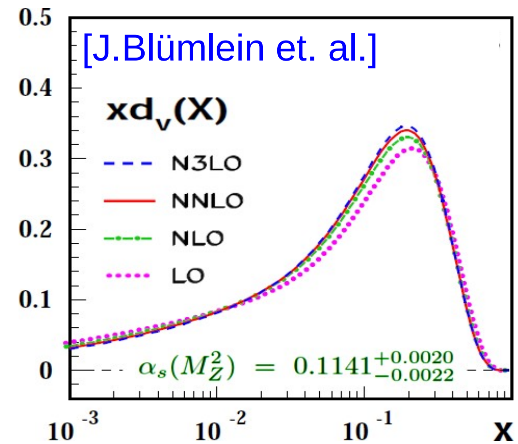
α_s via proton structure functions (HERA+LHC)

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

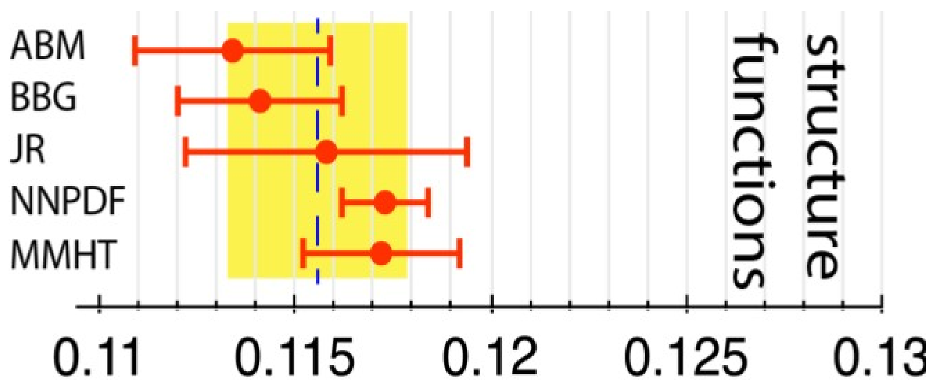
Different approaches:

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%)

α_s via proton structure functions (FCC-ep)

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

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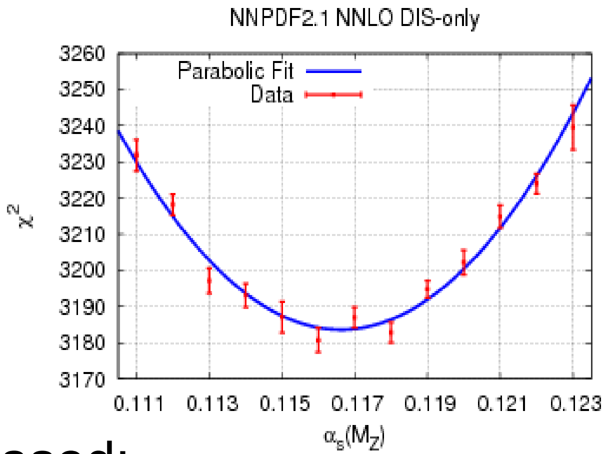

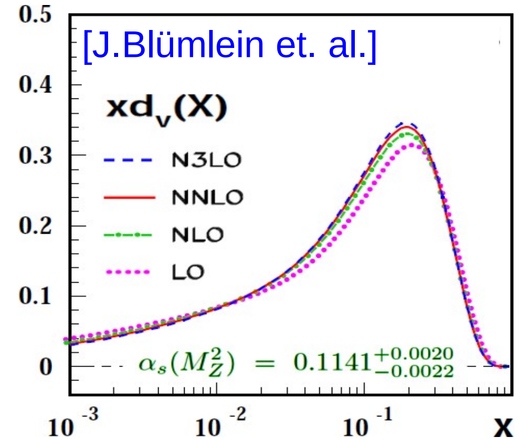

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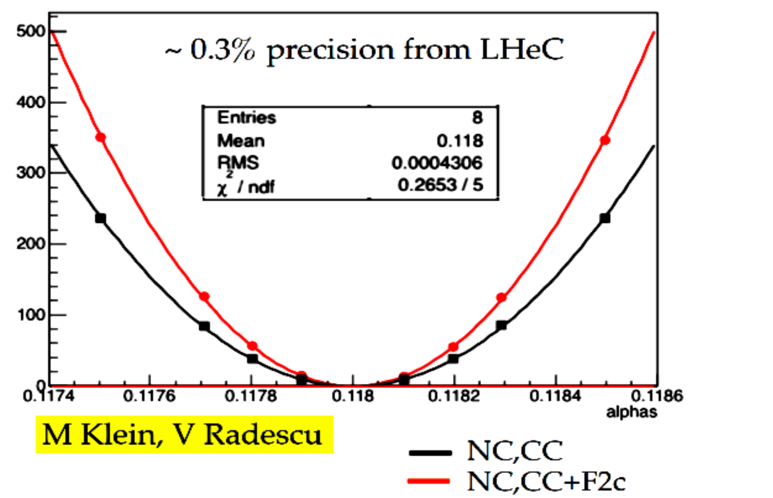
2013 (±1.7%) → 2015 (±2.0%)

combined fit to PDFs+αs using LHeC data



- Upcoming full-NNLO PDF fits including ttbar, jets,... from p-p LHC.
- FCC-ep:
  - Multiple high-precision DIS observables: $\delta\alpha_s$=0.3%
  - TH uncert.: Global fits agreement?

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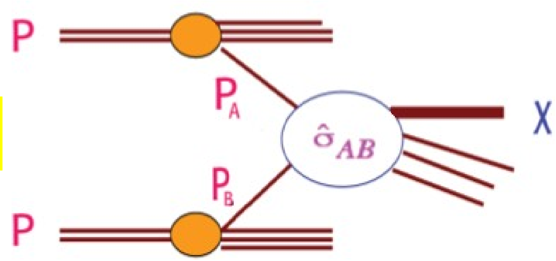
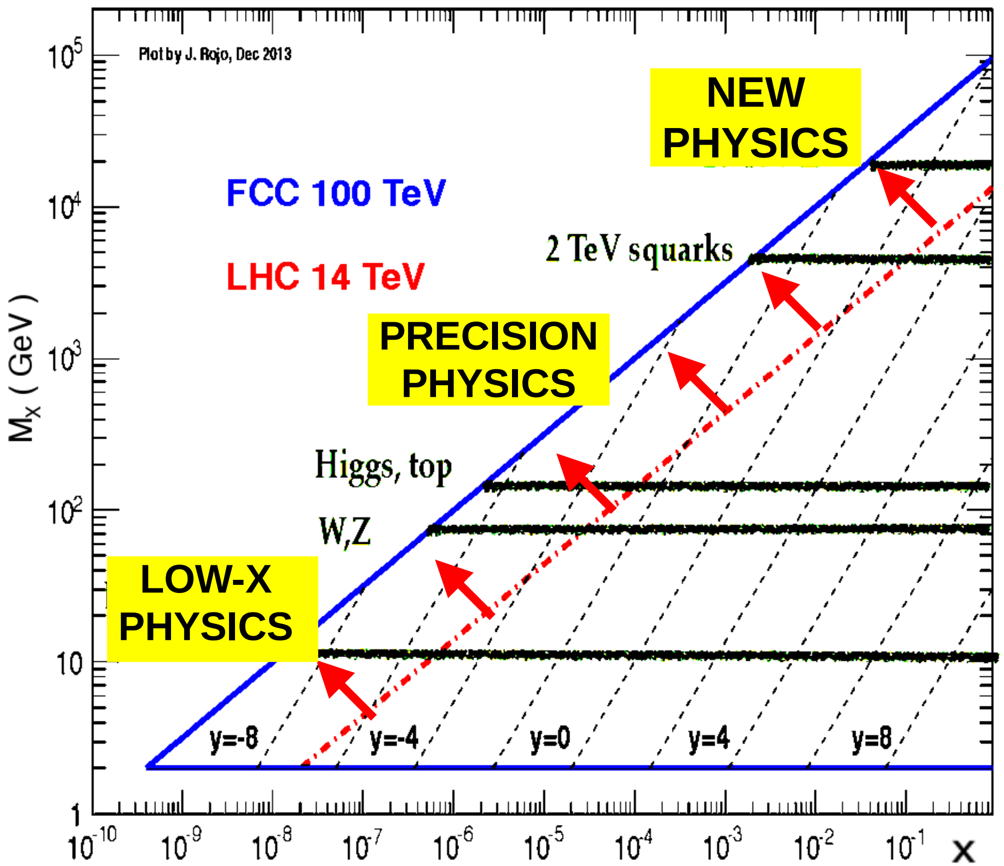
Parton (x,Q²) regions at FCC-pp

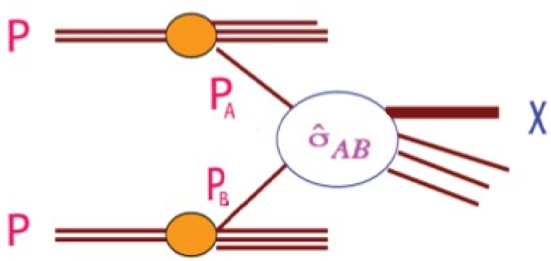
$\sigma = \hat{\sigma} \otimes$ PDF

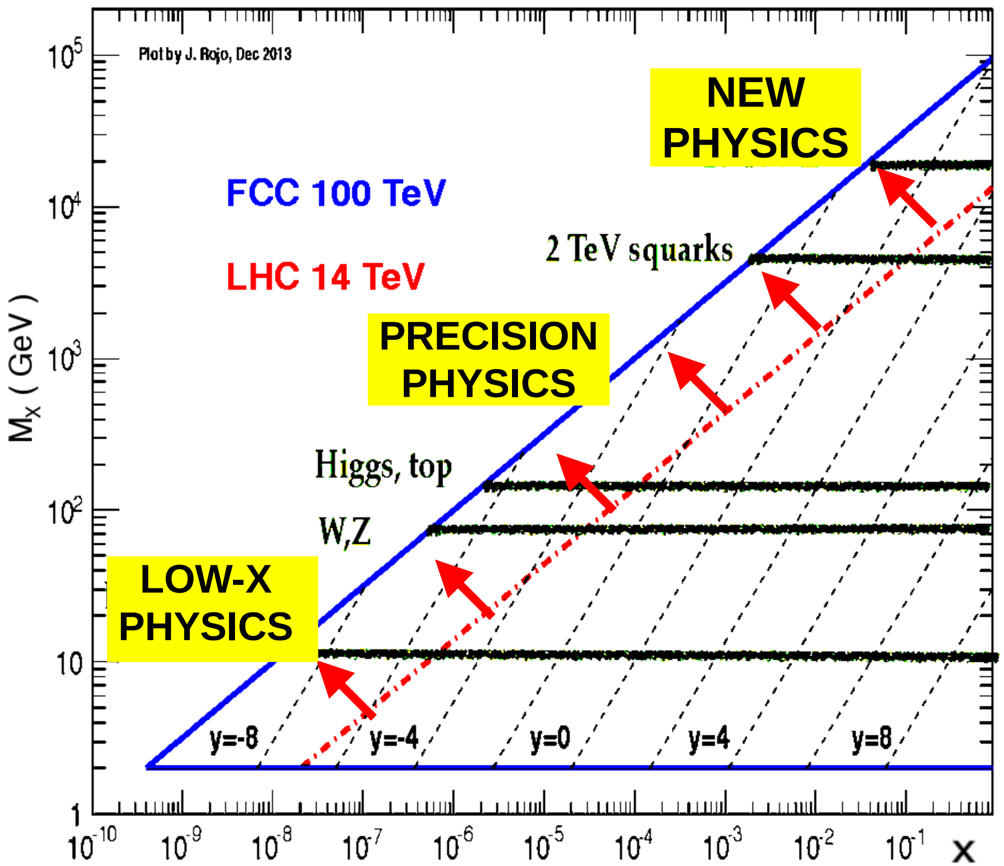




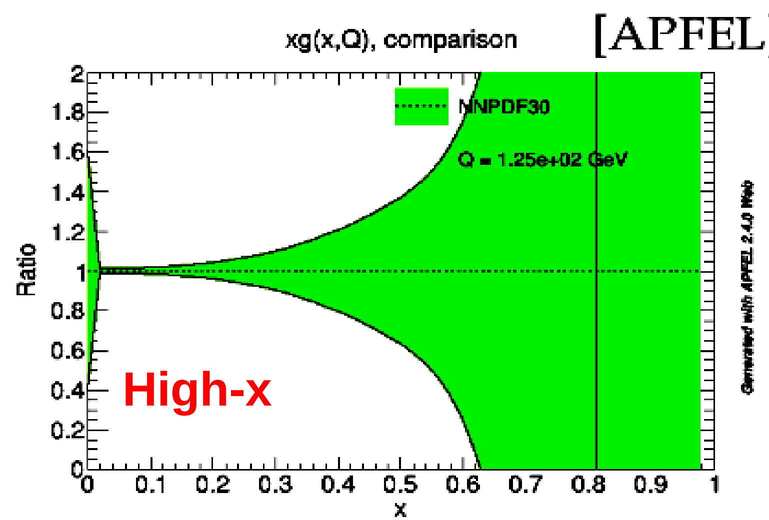
Parton (x,Q^2) regions at FCC-pp

$\sigma = \hat{\sigma} \otimes$ PDF



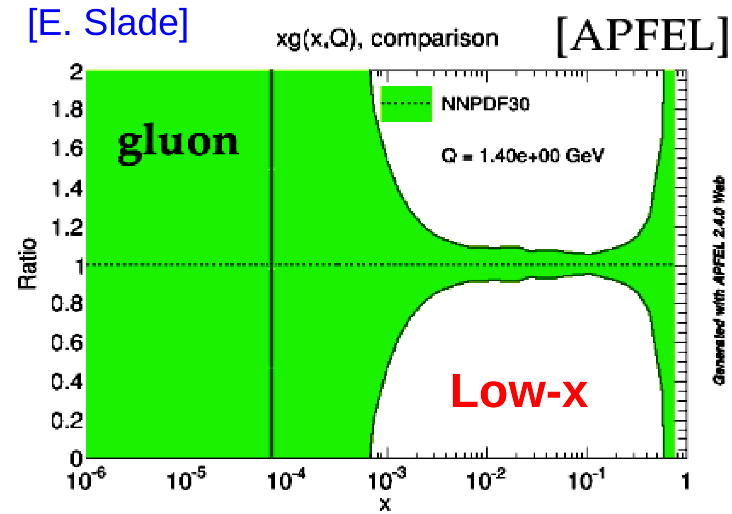


Associated PDFs uncertainties:



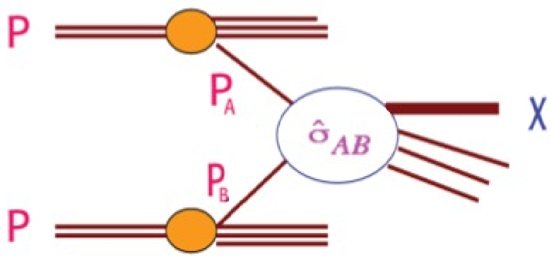
(>100% uncertainty at high- & low-x!)

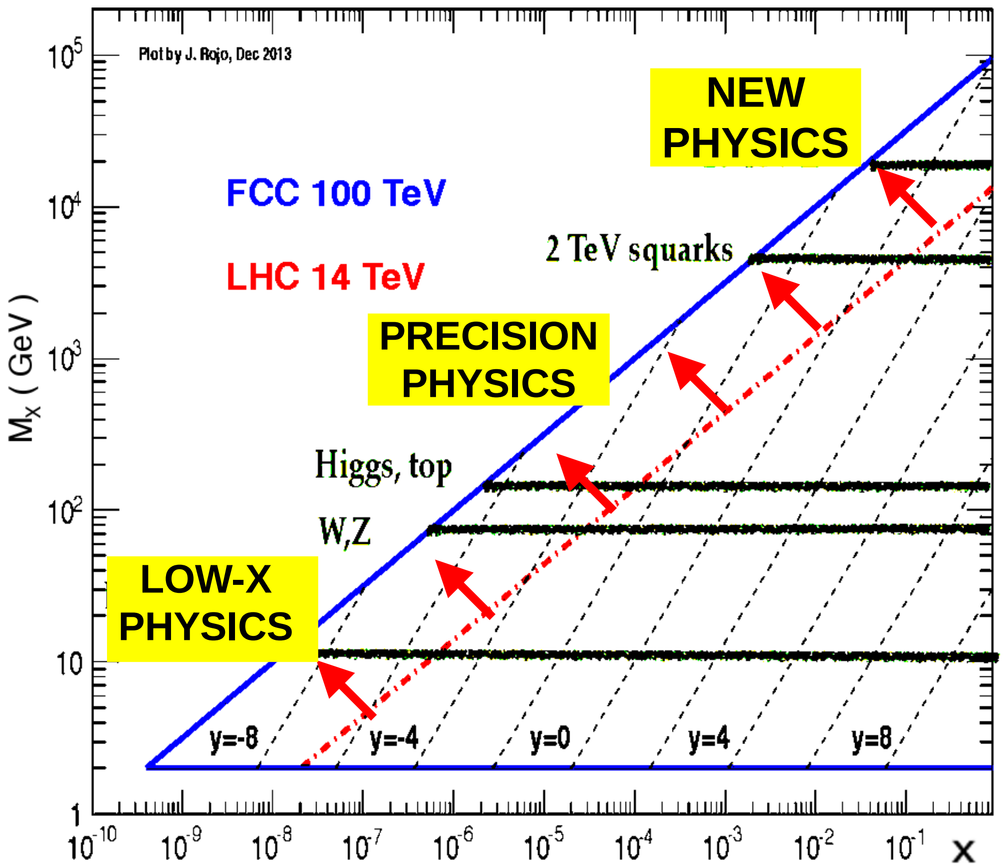
[E. Slade]



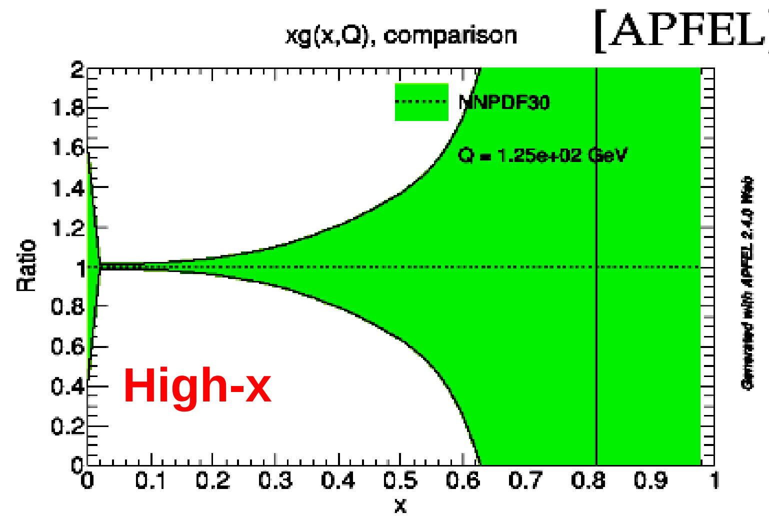
Parton (x,Q²) regions at FCC-pp

$\sigma = \hat{\sigma} \otimes$ PDF

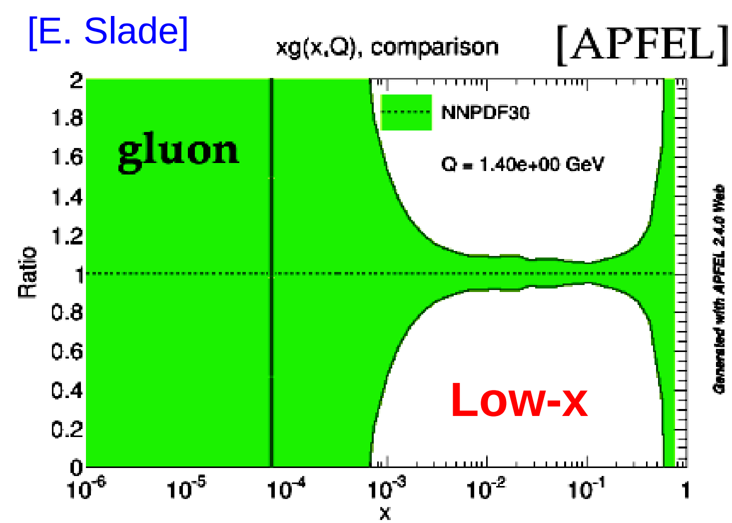




Associated PDFs uncertainties:



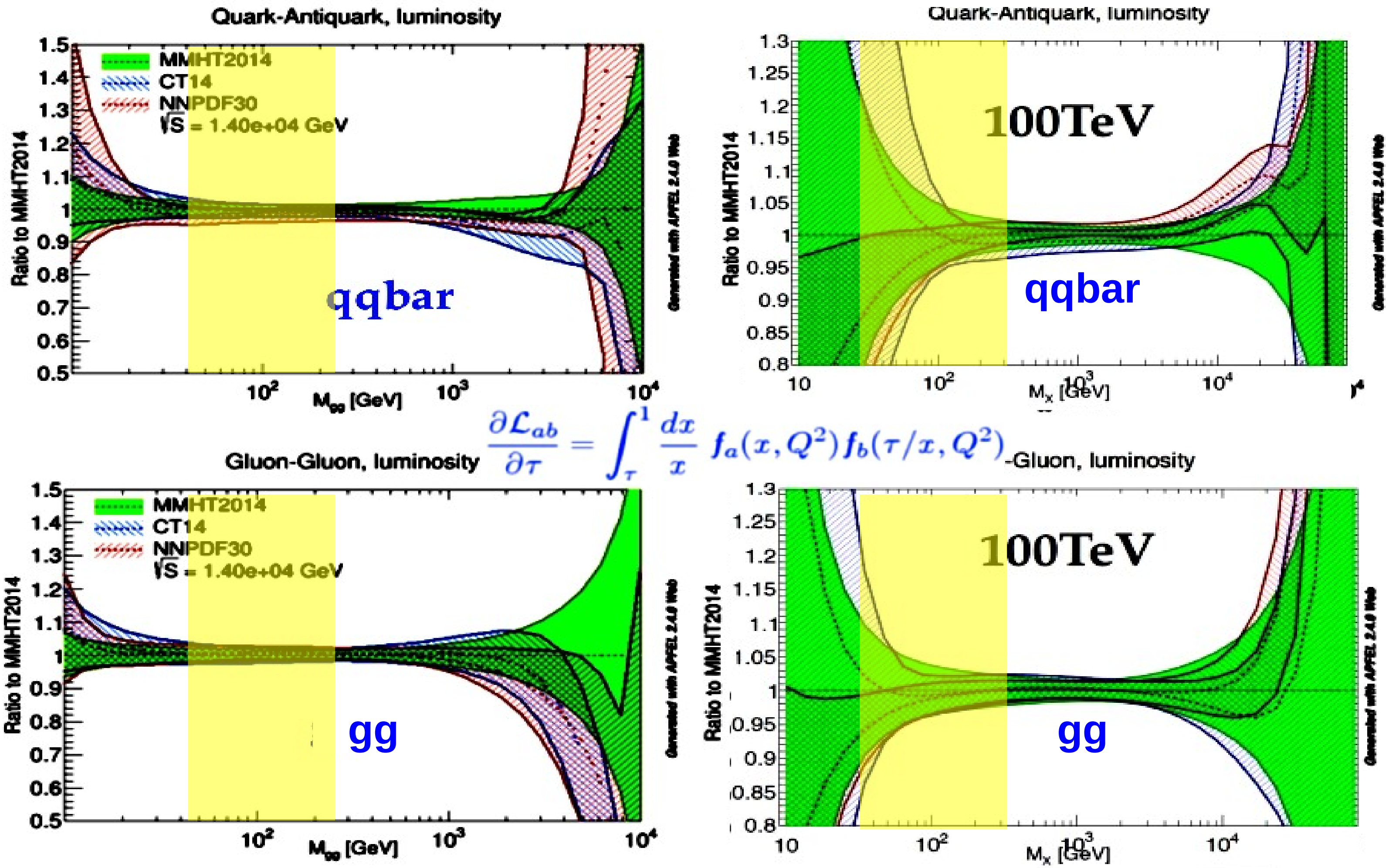
and what about in mid-x region...?



FCC-pp parton lumis in “precision” region

- “Precision” region at FCC-pp: **5–7%** PDF uncertainty for σ(W,Z,H)!

14 TeV → 100 TeV [S.Camarda]

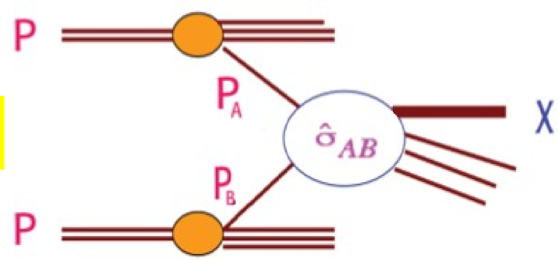


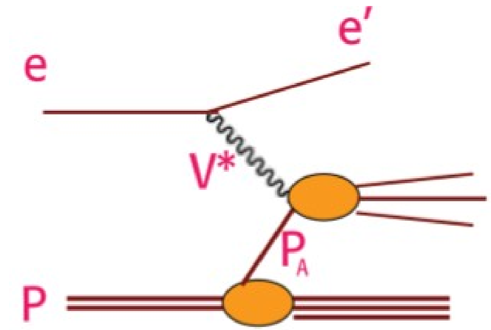
$$\frac{\partial \mathcal{L}_{ab}}{\partial \tau} = \int_{\tau}^{1} \frac{dx}{x}\, f_a(x,Q^2) f_b(\tau/x,Q^2)$$

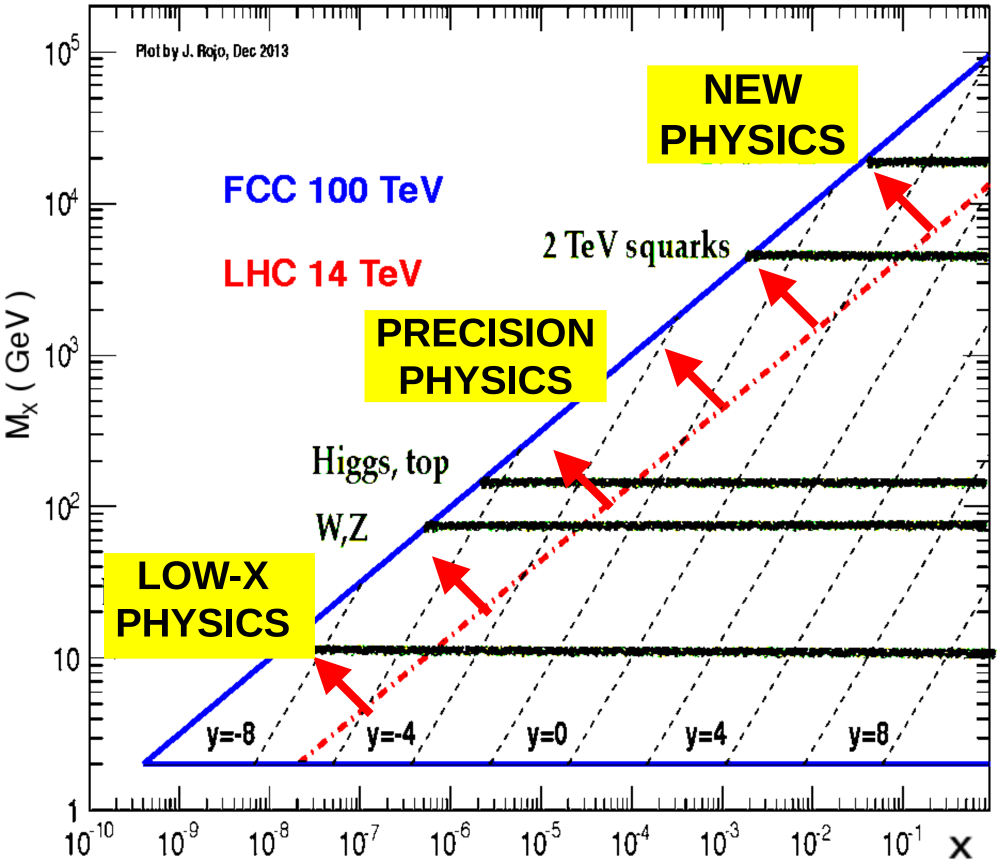
FCC-ep "comes to the rescue" of FCC-pp

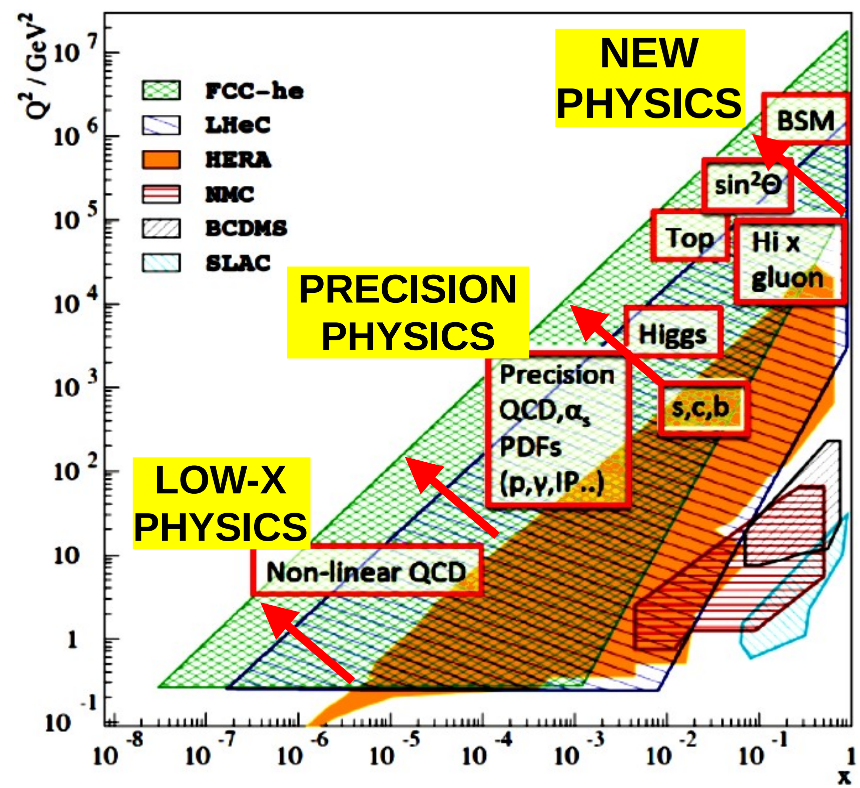
- FCC-ep: Fully complementary with FCC-pp to improve parton densities.

$\sigma = \hat{\sigma} \otimes \mathrm{PDF}$





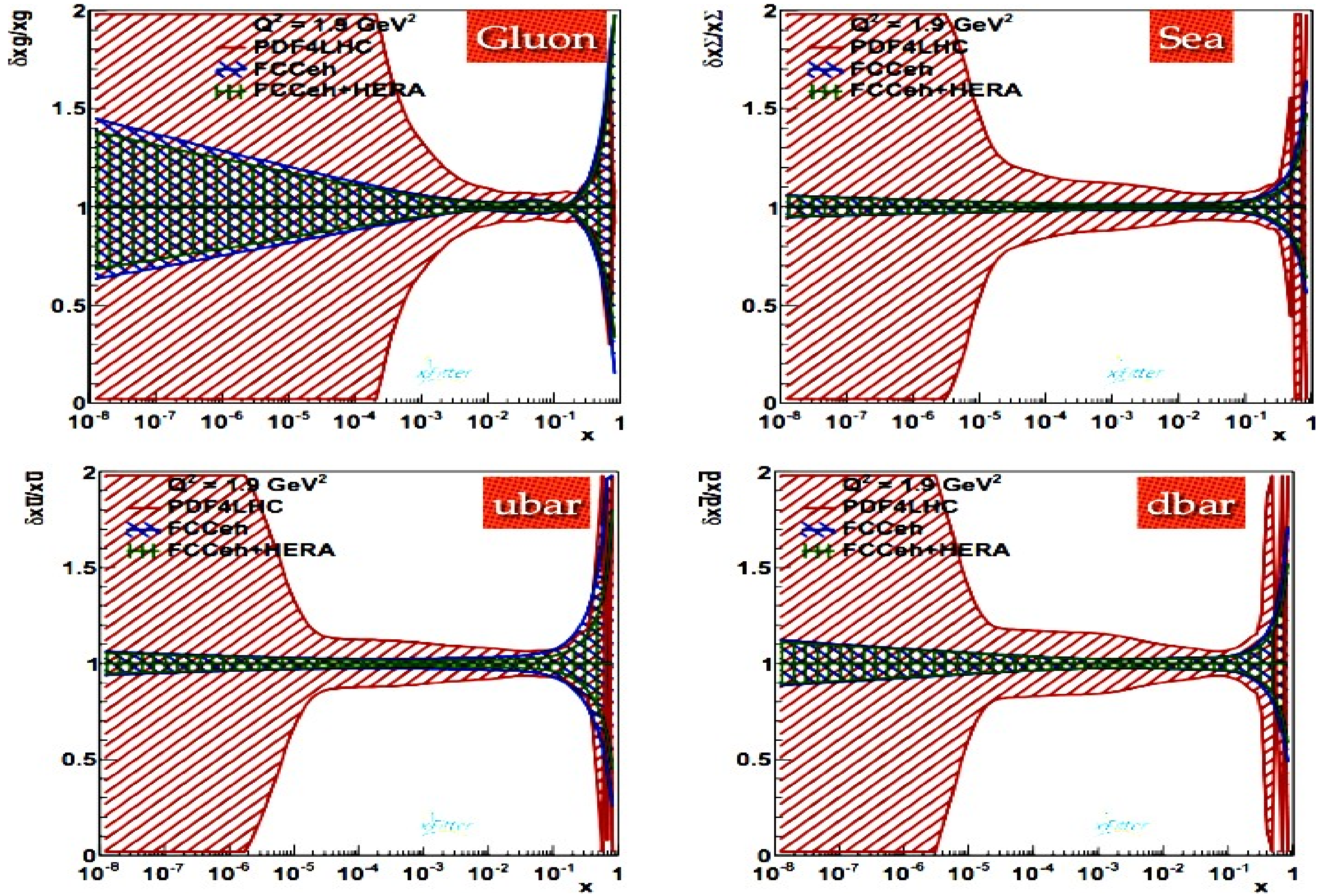




Improved PDFs at all x (FCC-ep)

[S.Camarda]

- Benchmark scenarios: NC & CC $e^{\pm}p$ with P=±0.4, F_2, xF_3, F_L

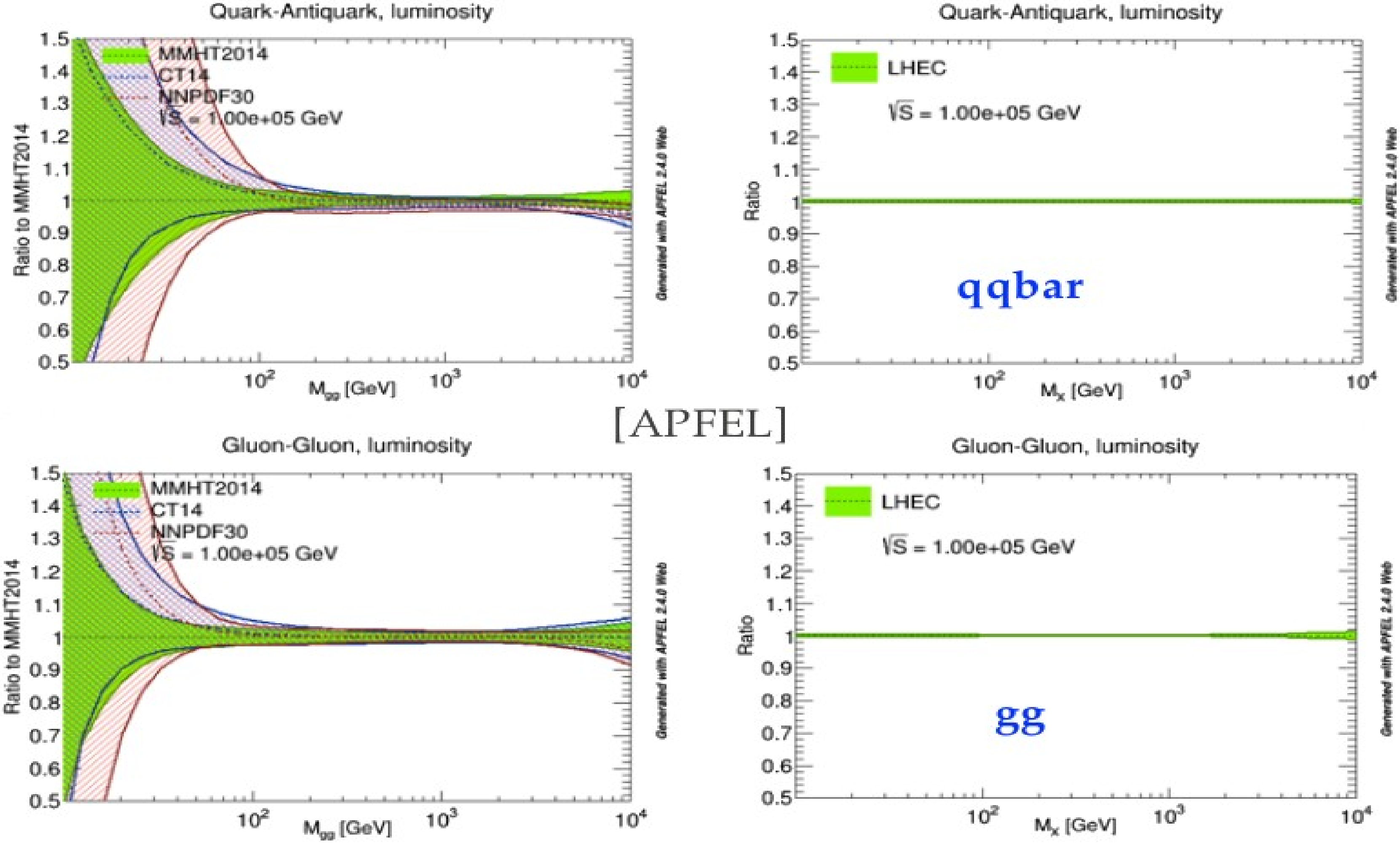


PDF4LHC set vs. FCC-ep (+HERA) at starting Q_0 scale

- Strongly reduced PDF uncertainties for all flavours (also strange, charm, bottom) at all x (down to 10^{-8})

Parton luminosities: Today vs. FCC-ep

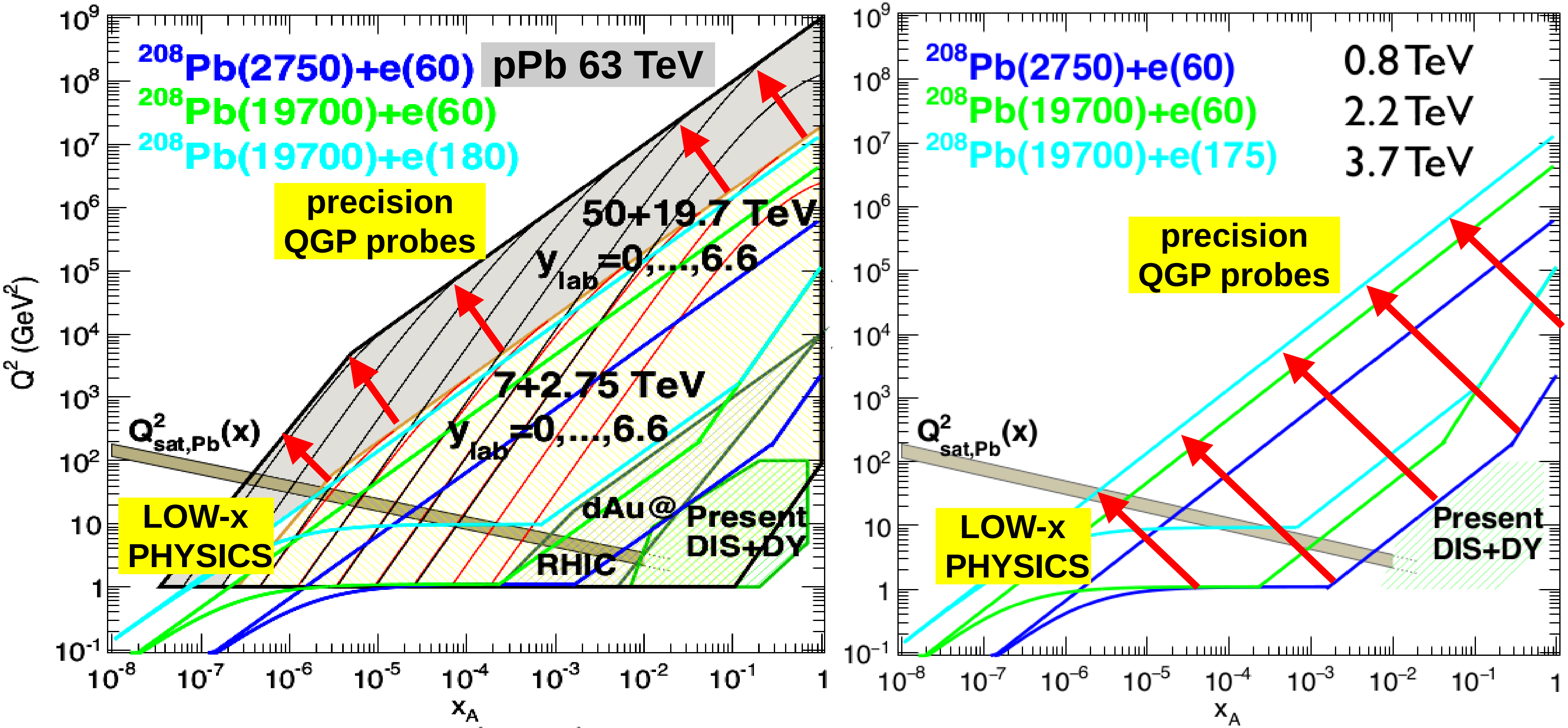
- Strongly reduced parton uncertainties for masses: 10 GeV–10 TeV



- FCC-ep required to get O(1%) PDF uncertainty for σ(W,Z,H) at FCC-pp

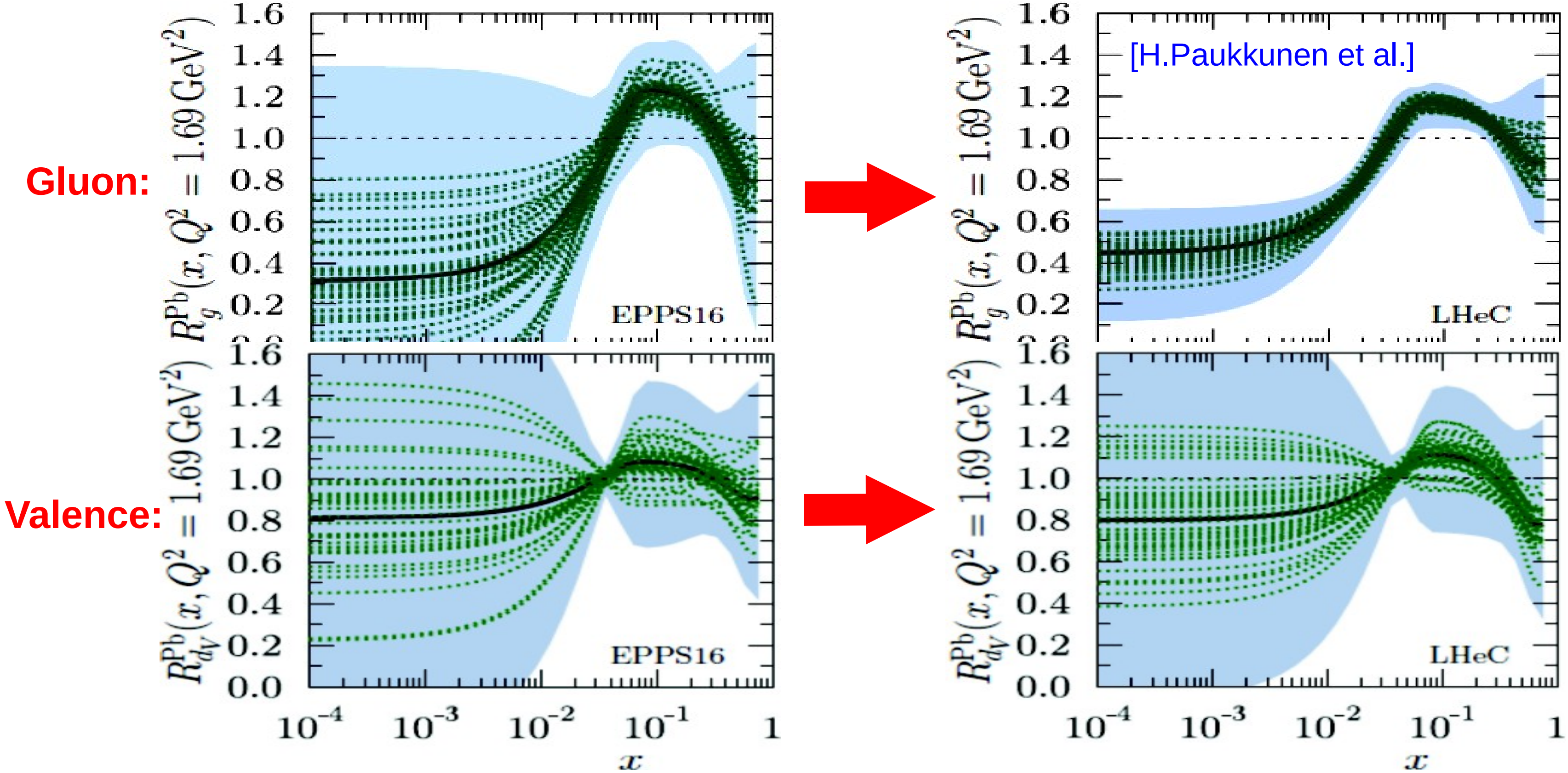
(LHC likely to improve PDFs before FCC by factor ~2(?), not ~5–10).

Nuclear parton (x,Q²) regimes (FCC-eA,-AA)



Improved nuclear PDFs (FCC-eA)

- Very large uncertainties today on nPDFs: Precision study of QGP properties in PbPb jeopardized by initial-state uncertainties.
- eA (60+2760) NC&CC pseudo-data: $R_i^{\rm Pb}(x,Q^2) = \dfrac{f_i^{\rm Pb}(x,Q^2)}{208 f_i^p(x,Q^2)}\,, \quad i = q,\bar{q},g$



- Reduced PDF uncertainties for all flavours (also strange, charm,bottom) at all x (down to 10^{-5}) via multiple clean nuclear DIS measurements.

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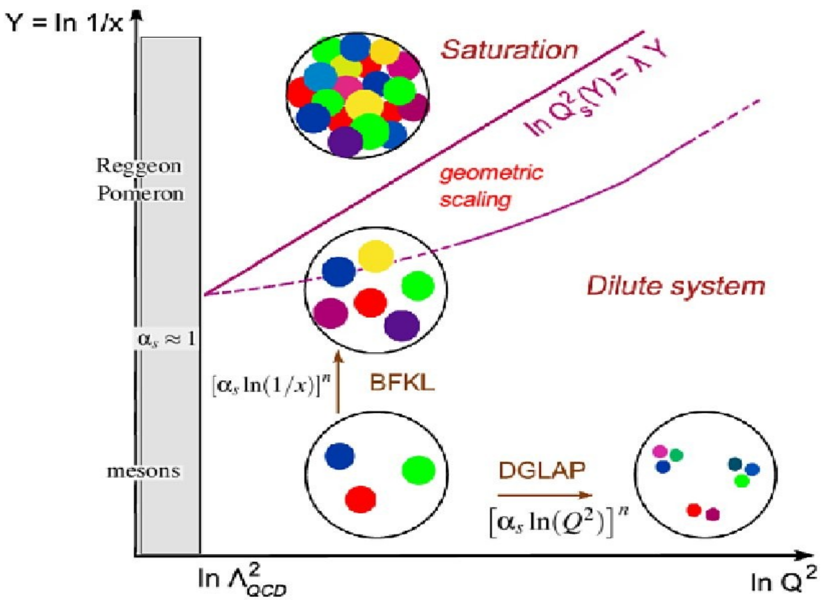
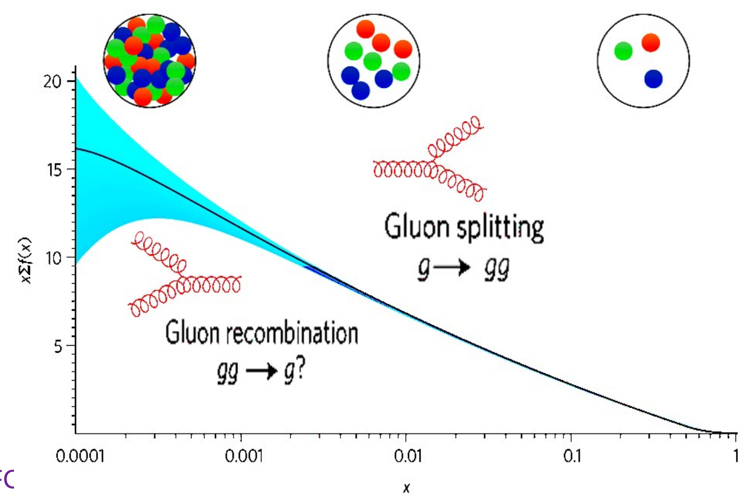
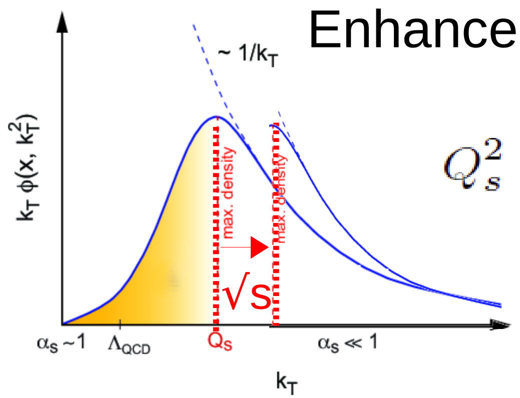
"Beyond DGLAP" phenomena



- ▶ Multiparton interactions
- ▶ Std. collinear factorization broken





- 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-fact.]
- For increasing √s, non-linear QCD evolution will set in at low x.
  gg→g peaks at perturbative "saturation scale" $\mathcal{O}$(few GeV).
  Enhanced in nuclei (~$A^{1/3}$).

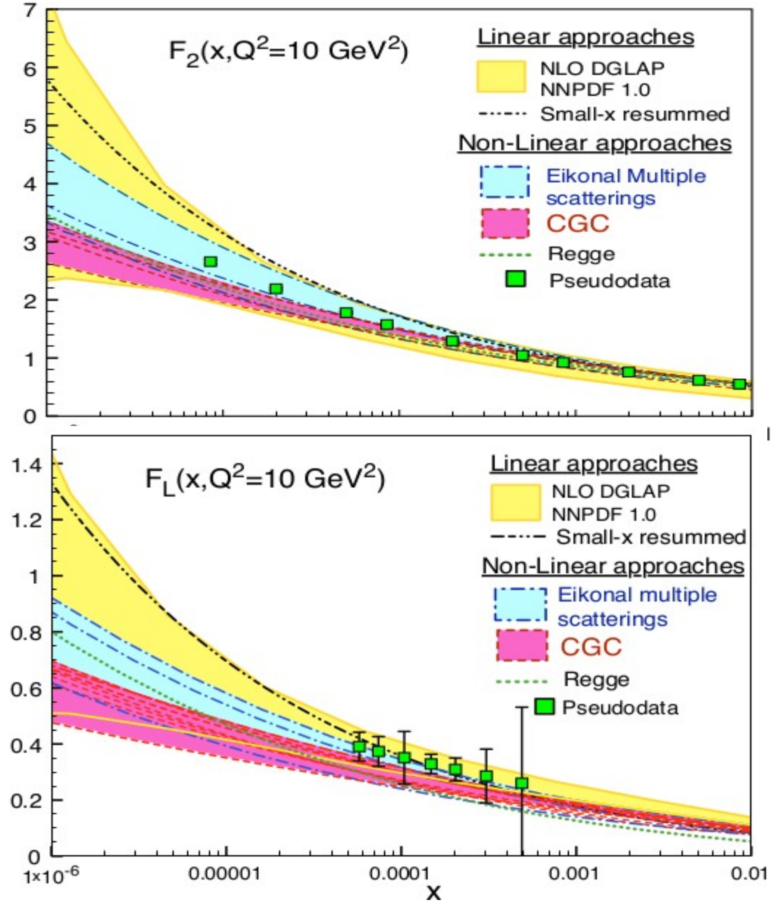
$$Q_s^2 \sim A^{1/3} Q_0^2 \left(\frac{1}{x}\right)^{\lambda} \sim (\sqrt{s})^{\lambda}$$

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

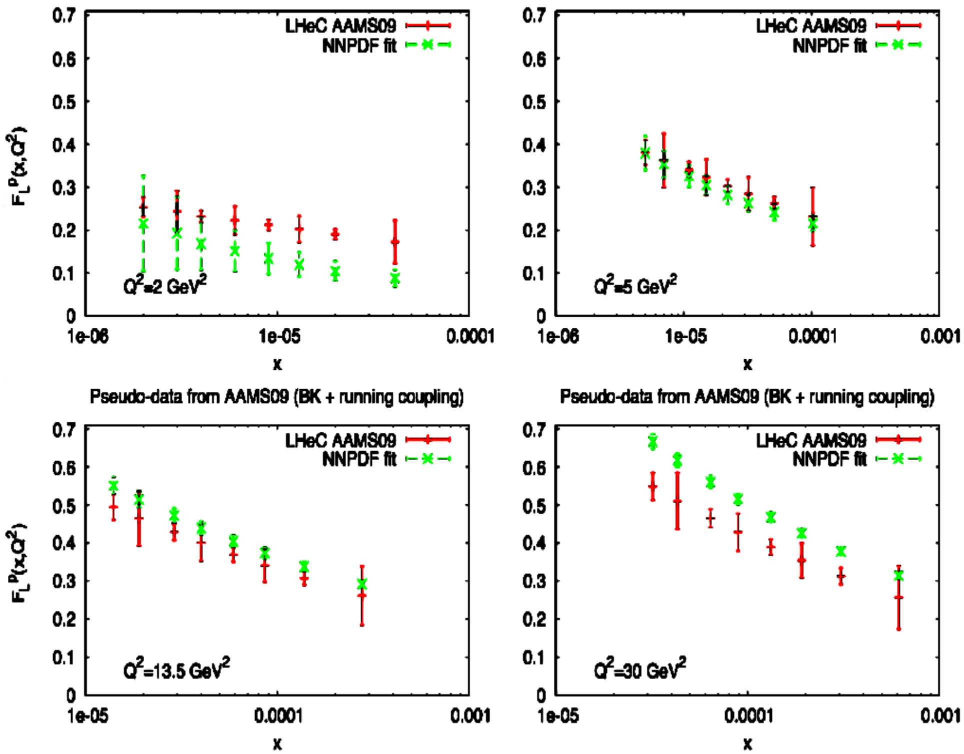
“Beyond DGLAP” evolution (FCC-eh)

- Beyond collinear factorization phenomena (MPIs, g saturation?) dominate particle production up to ~10 GeV (c,b) at FCC-hh.

- FCC-eh clean ab: DGLAP cannot simultaneously accommodate F_2 & F_L if low-x saturation present:



F_L pseudodata for NNPDF (DGLAP) vs. AAMS (saturation): [N. Armesto]



(FCC-eh will reach $x \sim 10^{-7}$)

QCD synergies at FCC

(1) QCD coupling (FCC-ee, FCC-eh, FCC-pp)

(2) p,A parton densities (FCC-eh, FCC-hh)

(3) Beyond DGLAP (FCC-eh, FCC-hh)

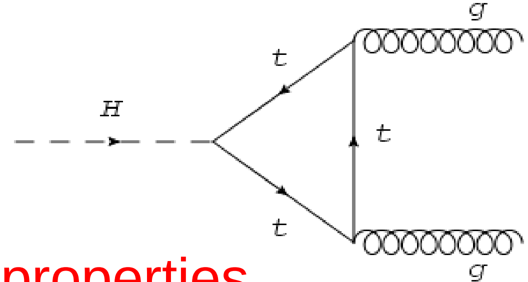
(4) Gluons & Higgs (FCC-ee, FCC-hh)

(5) Non-perturbative QCD (FCC-ee, FCC-hh)

Higgs as a source of pure gluons (FCC-ee)

- FCC-ee H(gg) is a "pure gluon" factory:
  H→gg (BR~10% accurately know) provides
  O(200.000) extra-clean digluon events:

→High-precision study of gluon radiation & g-jet properties



Handles to split degeneracies

G. Soyez, K. Hamacher, G. Rauco, S. Tokar, Y. Sakaki

H→gg vs Z→qq

Rely on good **H→gg vs H→bb** separation;
mandated by Higgs studies requirements anyway?

Z→bbg vs Z→qq(g)

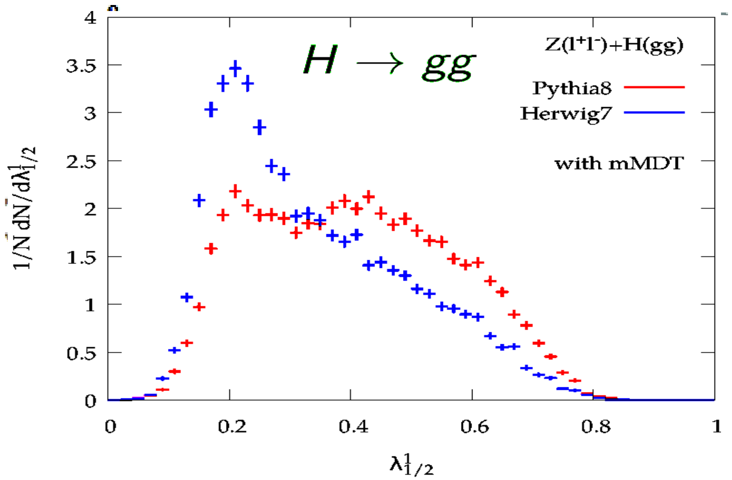
g in one hemisphere recoils against two b-jets in other hemisphere: **b tagging**

Vary jet radius: small-R → calo resolution

(R ~ 0.1 also useful for jet substructure)

Vary E_{CM} range : below m_Z : radiative events
→ **forward** boosted

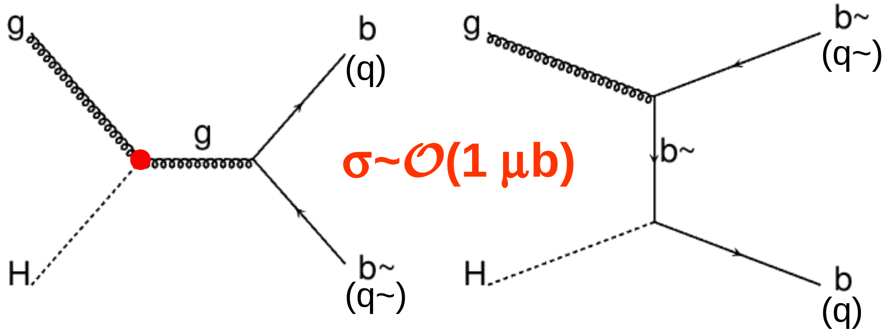
(also useful for FFs & general scaling studies);
Scaling is **slow**, logarithmic → large lever arm

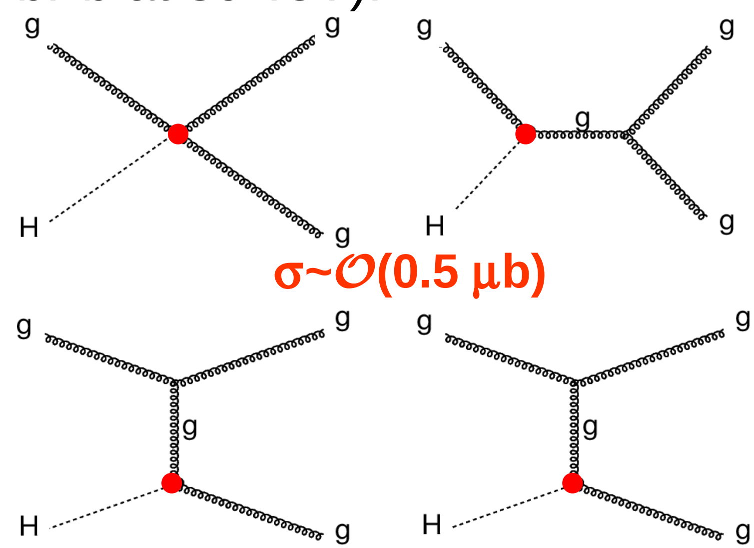


– Check N^nLO antenna functions
– Improve q/Q/g discrim. tools
– Octet neutralization? (zero-charge gluon jet w/ rap-gaps)
– Colour reconnection? Glueballs ?
– Leading η's,baryons in g jets?

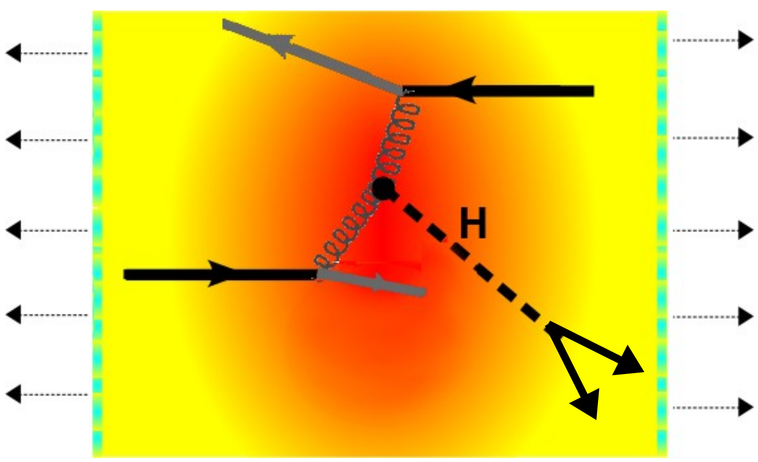
Higgs as a calibrated QGP probe (FCC-AA)

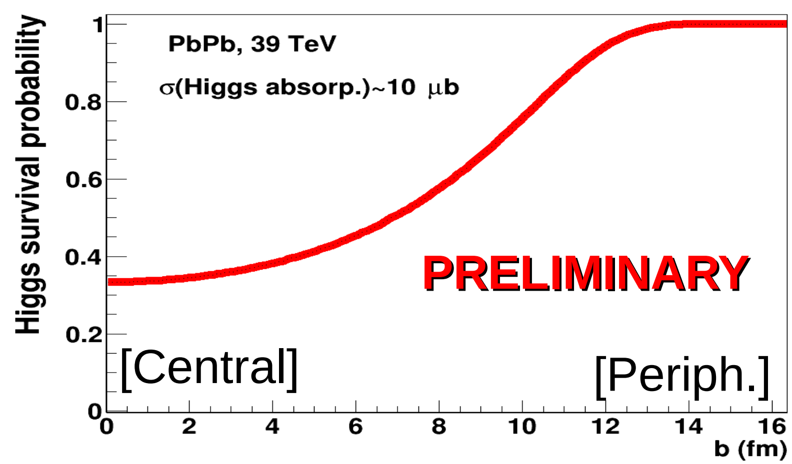
- gg→H is the most accurately known pQCD process (N^3LO). [DdE,C.Loizides]
  Let's "rotate" its production diagrams to "tomographically" study the QGP...
- Gluon-Higgs scatterings cross sections (PbPb at 39 TeV):





- H yields ~25% quenched in QGP?





QCD synergies at FCC

(1) QCD coupling (FCC-ee, FCC-eh, FCC-pp)

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(5) Non-perturbative QCD (FCC-ee, FCC-hh)

Colour reconnection in multi-jets at FCC-ee

- Colour reconnection among partons in e^+e^- = Source of uncertainty in m_W, m_{top}, aGC extractions in multijet final-states: $e^+e^- \to WW(4j)$, $Z(4j)$, tt
- Use e^+e^- leptonic final-states to learn about CR:

At LEP 2: hot topic (by QCD standards)**: 'string drag' effect on W mass**

Non-zero effect convincingly demonstrated at LEP-2

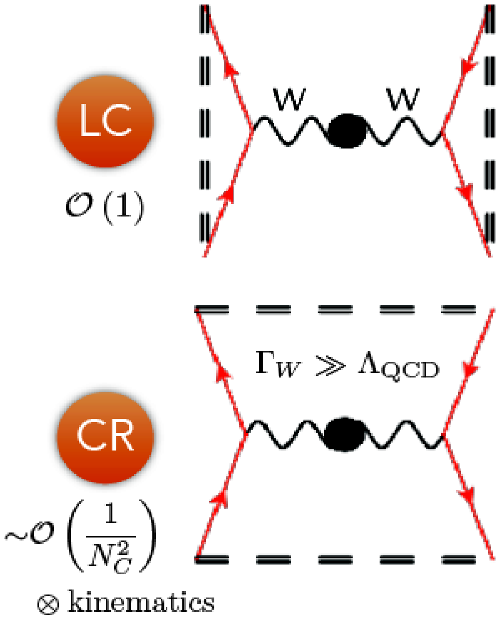
No-CR excluded at 99.5% CL [Phys.Rept. 532 (2013) 119]

But not much detailed (differential) information

Thousand times more WW at FCC-ee

Sjöstrand: turn the W mass problem around; use huge sample of semi-leptonic events to measure m_W

→ use as constraint to measure CR in hadronic WW



Has become even hotter topic at LHC

It appears jet universality is under heavy attack.
Fundamental to understanding & modeling hadronisation

Follow-up studies now underway at LHC.

T. Sjöstrand, W. Metzger, S. Kluth, C. Bierlich

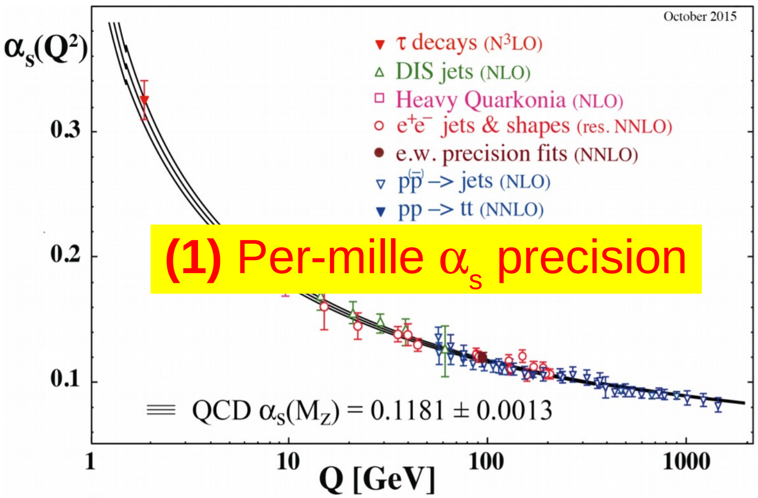
High-stats ee → other side of story

Also relevant in (hadronic) ee→tt, and Z→4 jets

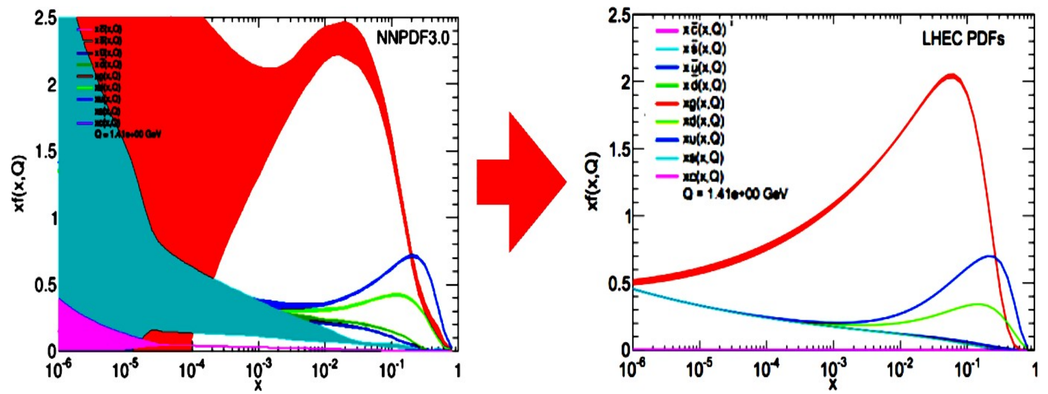
+ Overlaps → interactions?
increased tensions (strangeness)?
breakdown of string picture?

Summary

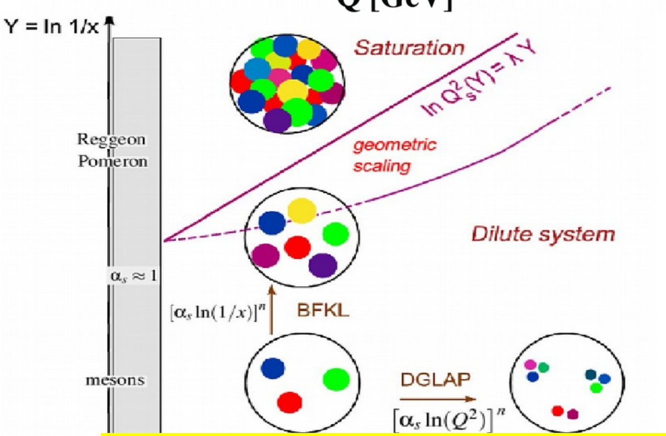
☛ The precision required to fully develop/exploit the FCC ee/pp/ep/eA/AA SM & BSM programs requires exquisite control of QCD via synergistic combinations of measurements at all machines:



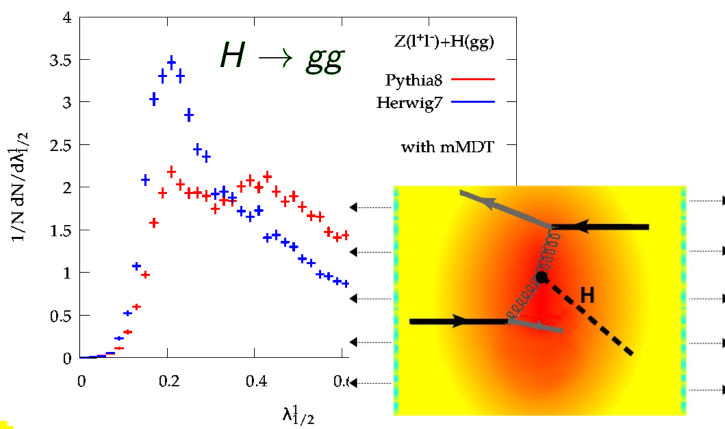
(1) Per-mille α_s precision



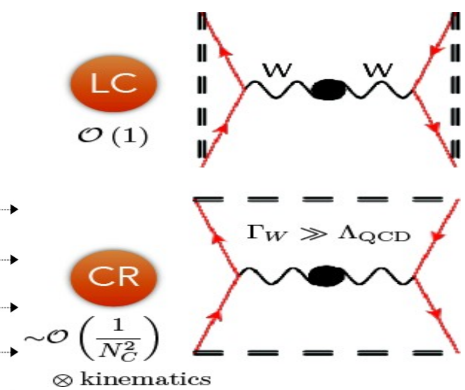
(2) O(1%) PDF uncert. at low/mid/high-x



(3) Collinear factorization corrections/extensions



(4) Novel&precise probes of gluon & QGP properties



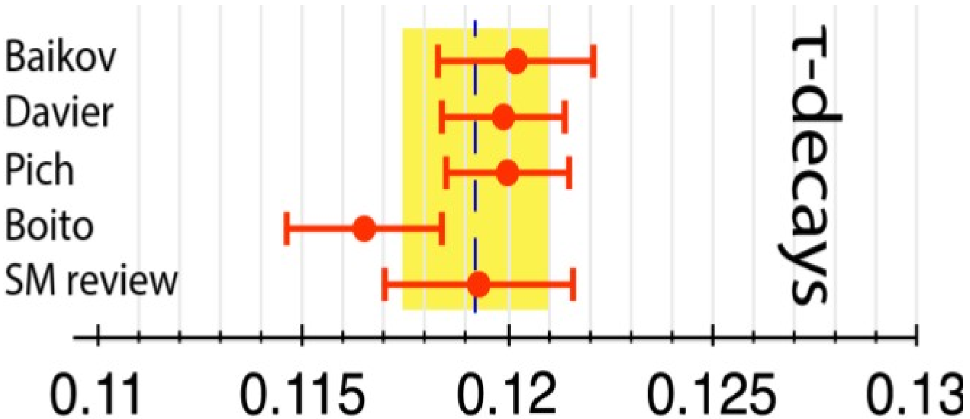
(5) <1% control of n-pQCD effects

Backup slides

α_s from hadronic τ-lepton decays (FCC-ee)

- Computed at N³LO: $R_\tau \equiv \frac{\Gamma(\tau^- \to \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)} = S_{\rm EW} N_C (1 + \sum_{n=1}^{4} c_n \left(\frac{\alpha_s}{\pi}\right)^n + \mathcal{O}(\alpha_s^5) + \delta_{\rm np})$
- Experimentally: $R_{\tau,exp}$ = 3.4697 ± 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 ± 0.0018 **(±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).

α_s from γ QCD structure function (FCC-ee)

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

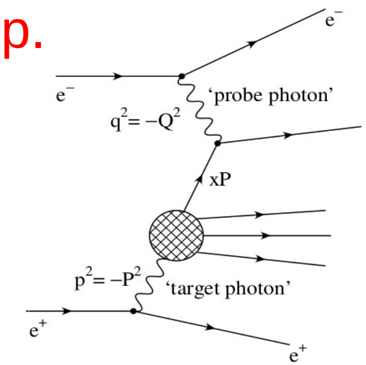
- Poor $F^2_\gamma(x,Q^2)$ experimental measurements:

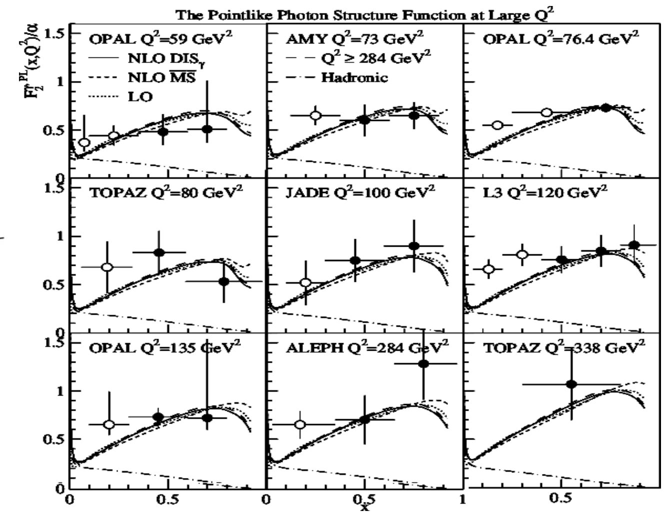
- Extraction (NLO) with large exp. uncertainties today:

α_s (M_z) = 0.1198 ± 0.0054

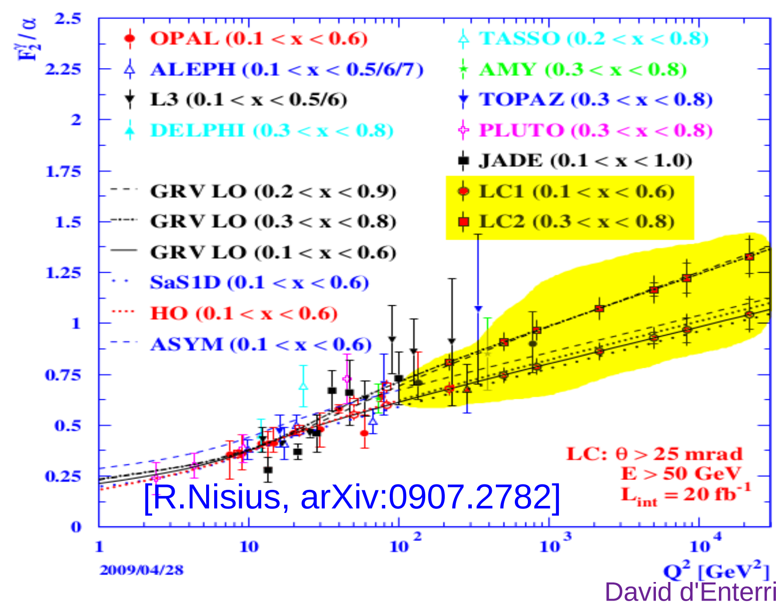
(±4.5%)

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





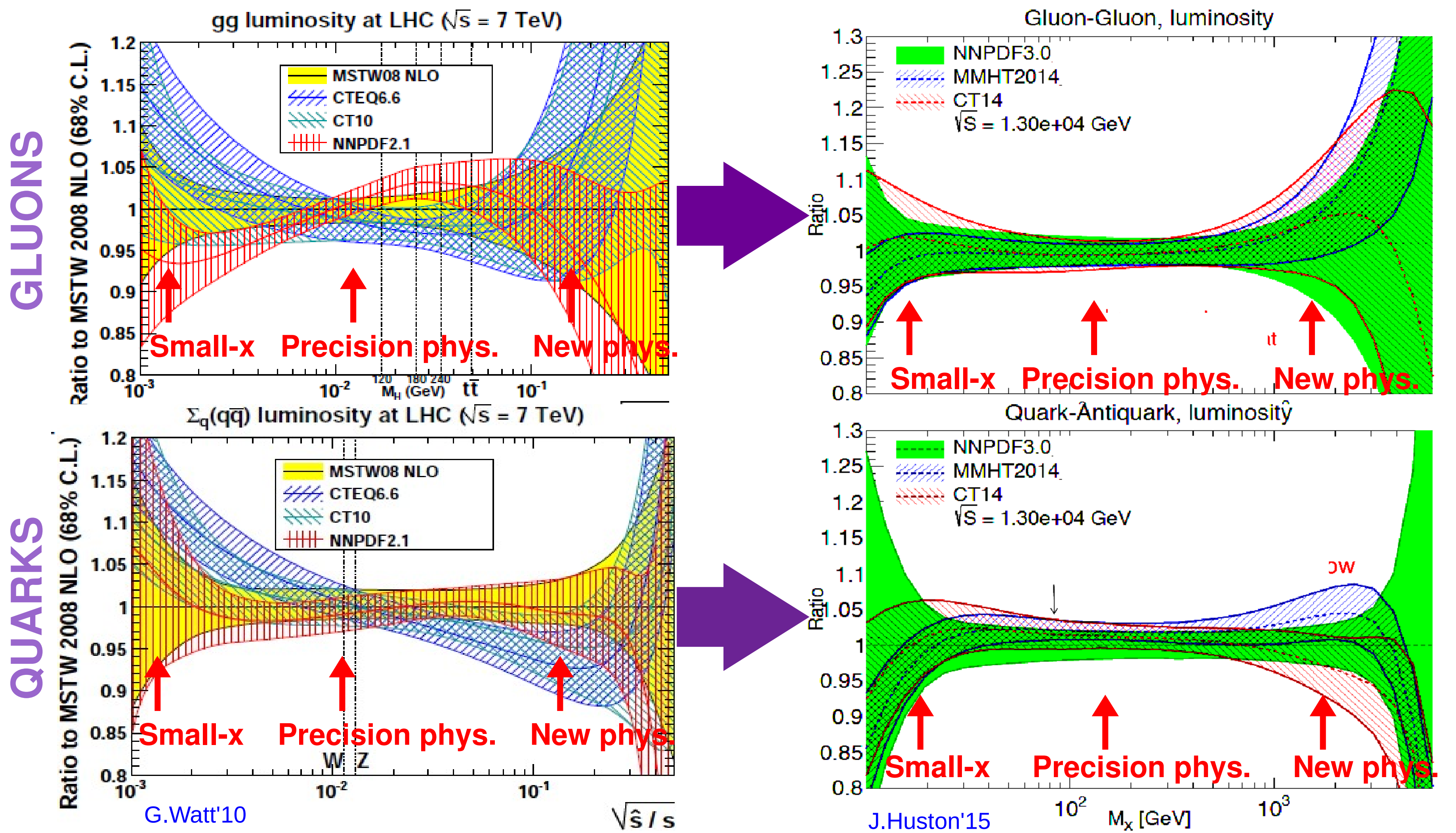
- Future prospects:
  - Better data badly needed.
  - Belle-II ?
  - Dedicated studies at ILC exist:
  - Huge γγ (EPA) stats at FCC-ee will lead to: **$\delta\alpha_s$ < 1%**



[R.Nisius, arXiv:0907.2782]

Parton densities

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



QCD studies at future colliders

(1) QCD coupling (FCC-ee, FCC-eh, FCC-pp)

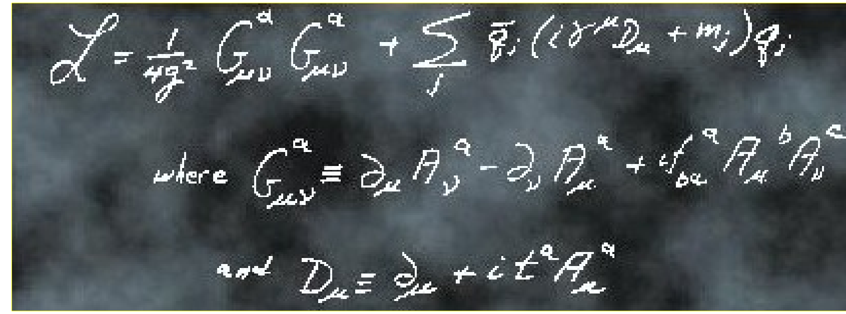
(2) Parton densities (FCC-eh, FCC-pp)

(3) Beyond DGLAP (FCC-eh)

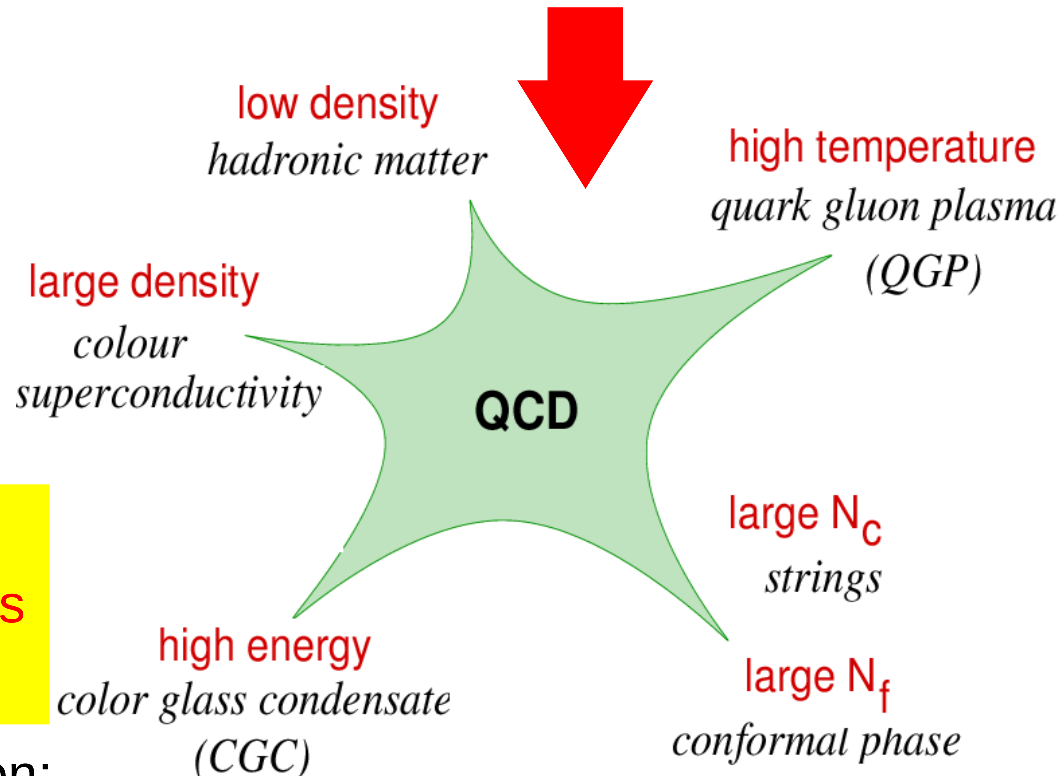
(4) Many body QCD (FCC-hh)

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:

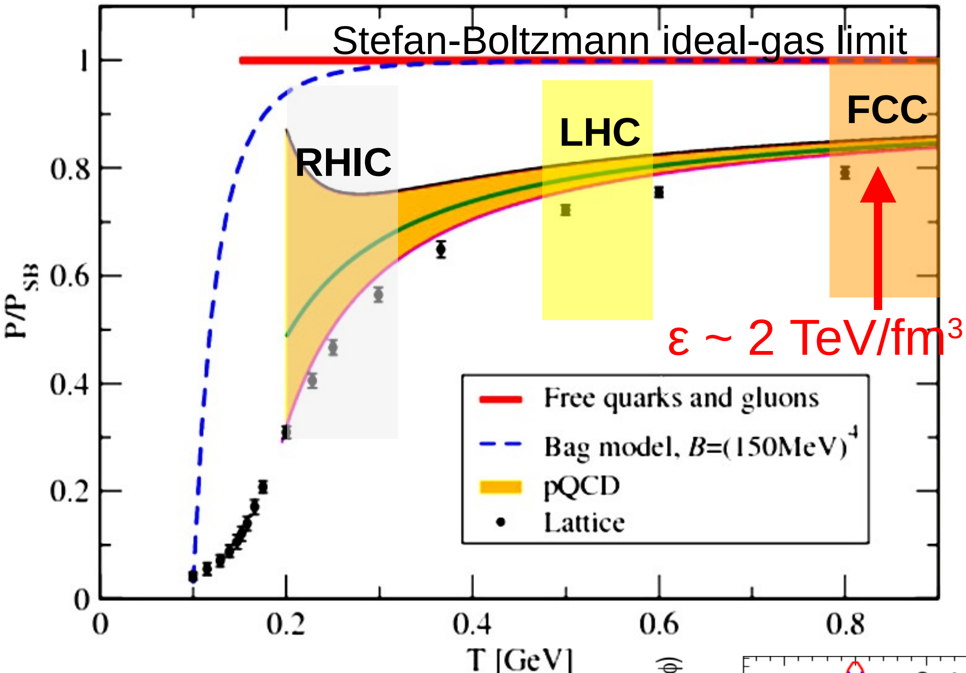


- QCD = ONLY non-Abelian QFT whose collective dynamics can be studied in the lab !

Insight for EWK phase transition:
Hydrodynamics expansion? New (quasiparticle) degrees of freedom?

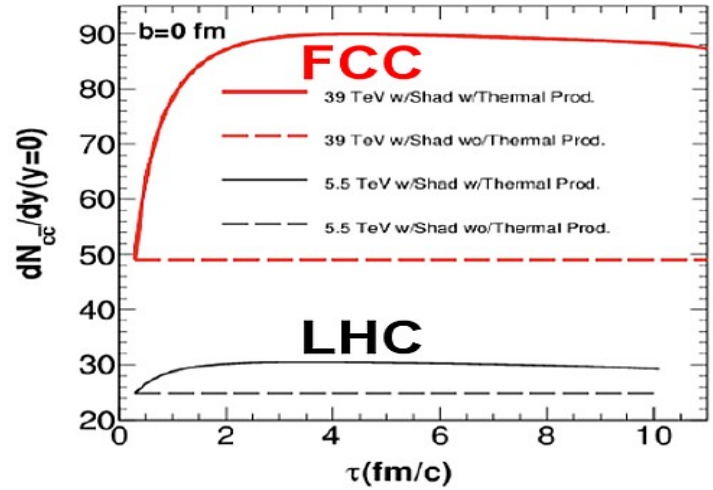
Many-body QCD (FCC-AA)

- QCD Equation-Of-State probed at TeV/fm³:

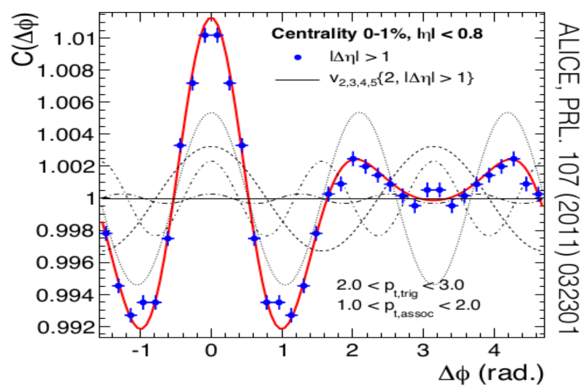


Even heavy-Q thermalize...

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

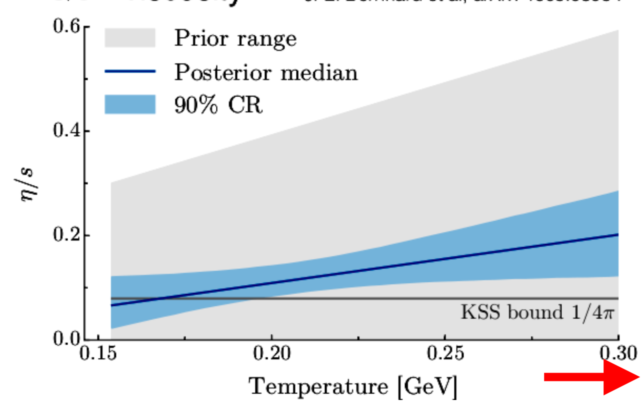


- Transport properties (viscosity) probed at $T \sim 5 \times T_c$:



QGP viscosity

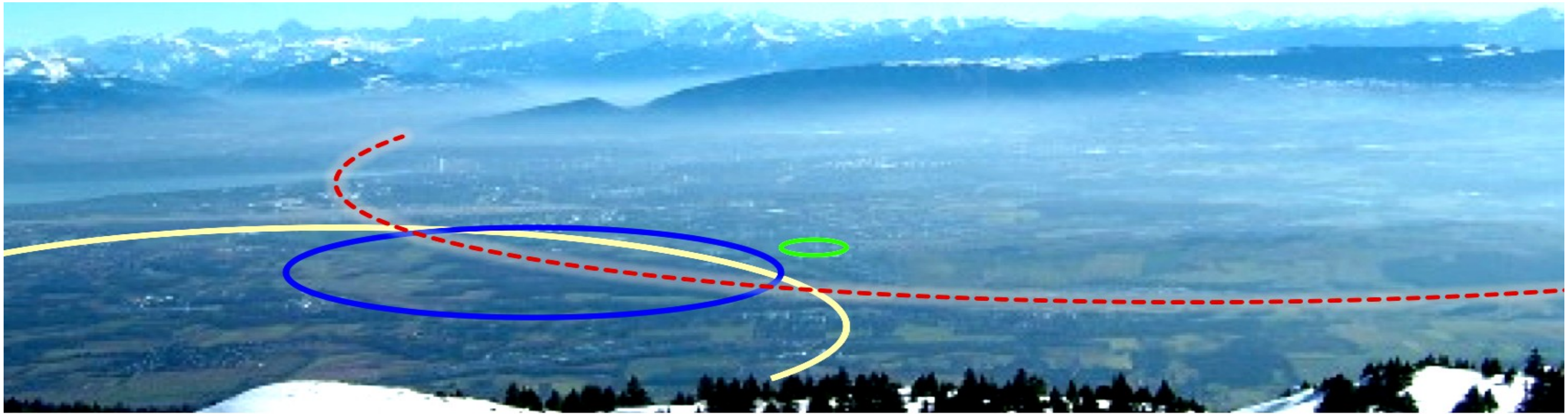
J. E. Bernhard et al, arXiv: 1605.03954



CONCLUSION (4): Study of QGP at TeV/fm³ requires high-√s AA collider

CERN Future Circular Collider (FCC) project

- FCC European Design Study, CDR expected by end 2018



- 100 km ring, Nb_3Sn 16 T magnets, LHC used as injector:
  - pp at √s=100 TeV, L~2x10^{35}, L_{int} ~ 1 ab^{-1}/yr (also pPb & PbPb at √s=39–63 TeV)
  - e^+e^- option (before pp) at √s=90–350 GeV L~10^{35}–4·10^{36}, L_{int}=1–40 ab^{-1}/yr for H, Z
  - e-h option at √s=3.5 TeV, L~10^{34} L_{int} ~ 0.1 ab^{-1}/yr. (also e-Pb at √s~1–3 TeV)