

QCD synergies at FCC

FCC week

Berlin, 29th May – 2nd June 2017

David d'Enterria

CERN

QCD is fundamental for all 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,...
 - **$N^{\text{LO}}+N^{\text{LL}}$ corrections**: Needed for all x-sections with initial/final hadrons
 - **Heavy-Quark/Quark/Gluon separation, subjet structure, boosted topologies,...**: Needed for all precision measurements & searches with jets.
 - **High-precision (n)PDFs**: In h-h collisions, affects all precision W,Z,H (mid-x) measurements, all BSM searches (high-x), & beyond-DGLAP (low-x) studies.
 - **Semihard QCD** (low-x gluon saturation, multiple hard parton interactions,...): Significant pQCD x-sections at FCC-hh (Note: $Q_0 \sim 10$ 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: $\delta\alpha/\alpha \sim 10^{-10} \ll \delta G_F/G_F \ll 10^{-7} \ll \delta G/G \sim 10^{-5} \ll \delta\alpha_s/\alpha_s \sim 10^{-3}$
- Impacts all QCD x-sections & decays (H), precision top & param. EWPO:

Process	σ (pb)	$\delta\alpha_s$ (%)	PDF + α_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 $\rightarrow c\bar{c}$	126	± 7.1	$\pm 0.1\%$	$\pm 2.3\%$
H $\rightarrow gg$	126	± 4.1	$\pm 0.1\%$	$\pm 0\%$

Msbar mass error budget (from threshold scan)

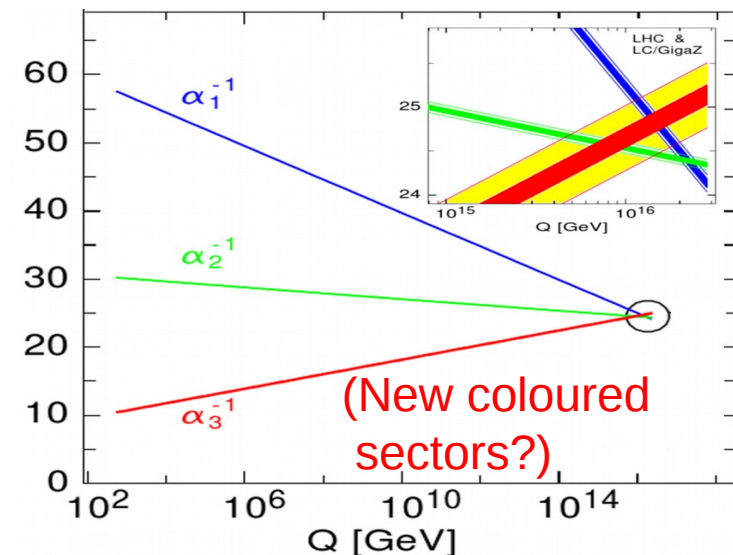
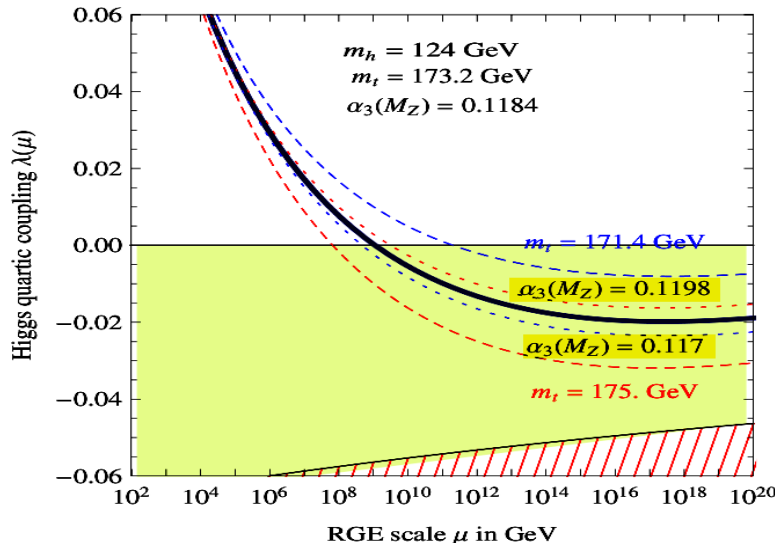
$(\delta M_t^{\text{SD-low}})_{\text{exp}}$	$(\delta M_t^{\text{SD-low}})_{\text{theo}}$	$(\delta \bar{m}_t(\bar{m}_t))_{\text{conversion}}$	$(\delta \bar{m}_t(\bar{m}_t))^{\alpha_s}$
40 MeV	50 MeV	7 - 23 MeV	70 MeV

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

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	$\delta\alpha_s$

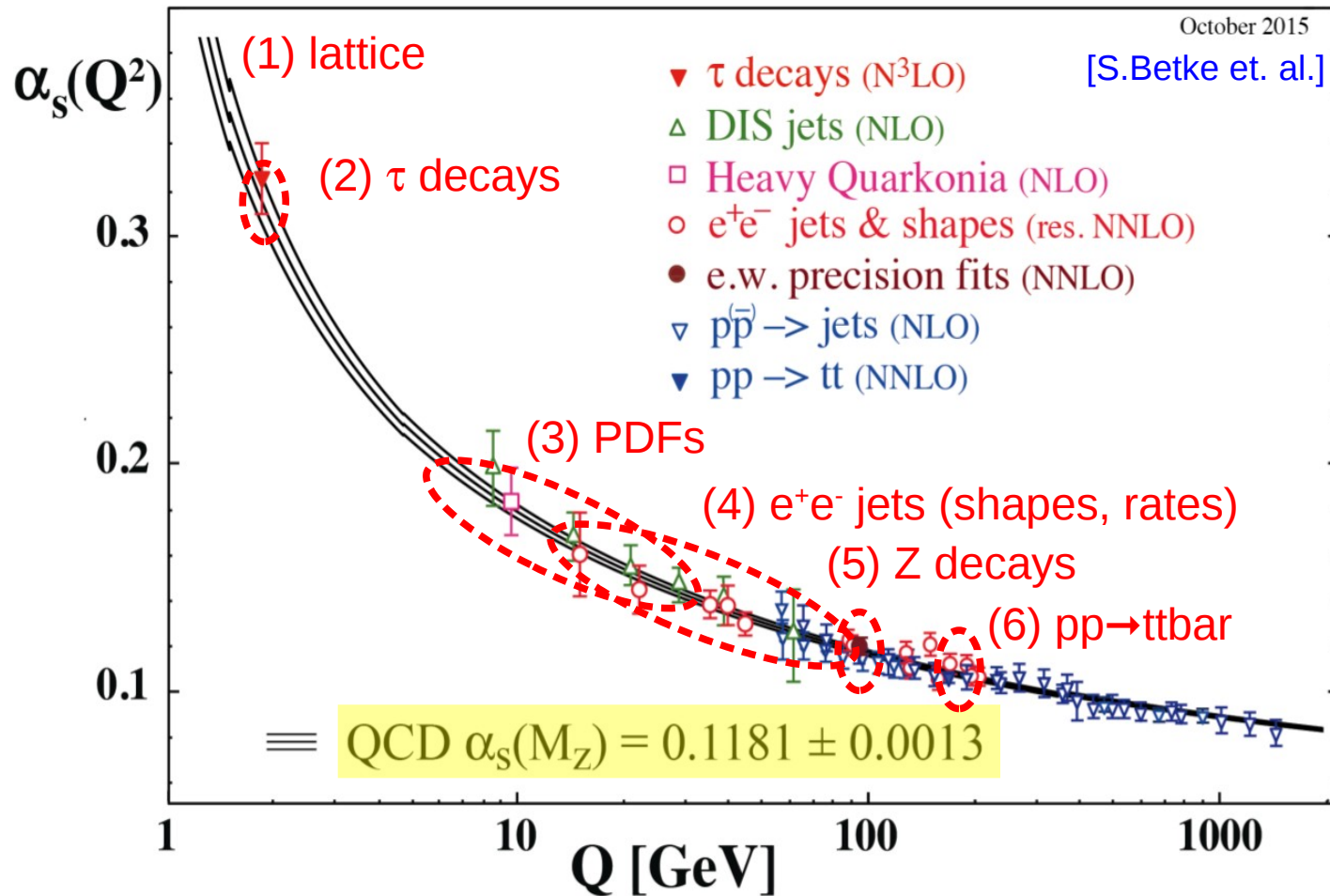
Sven Heinemeyer – 1st FCC physics workshop, CERN, 17.01.2017

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



World α_s determination (PDG 2016)

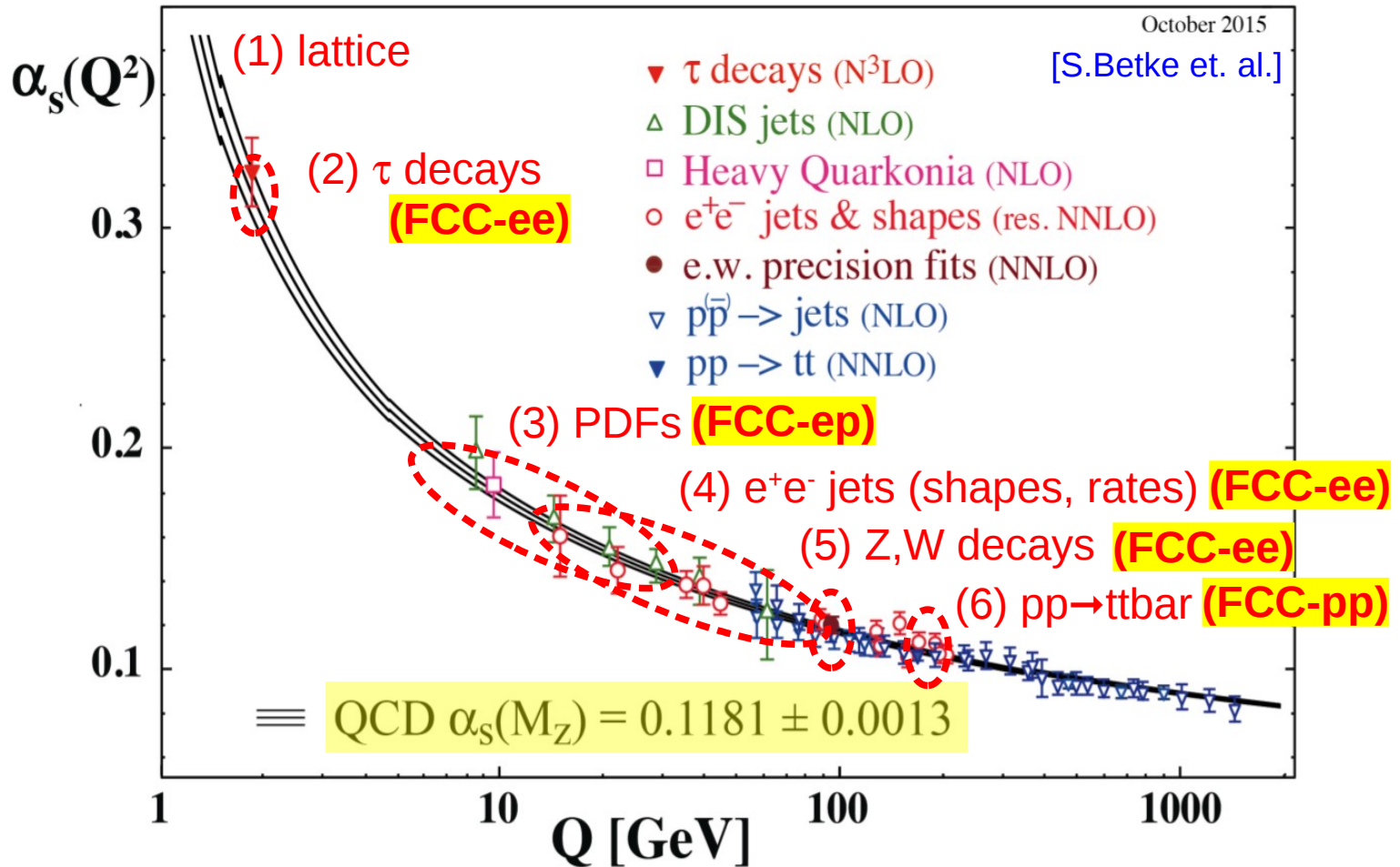
- Determined today by comparing 6 experimental observables to pQCD NNLO, N³LO predictions, plus global average at the Z pole scale:



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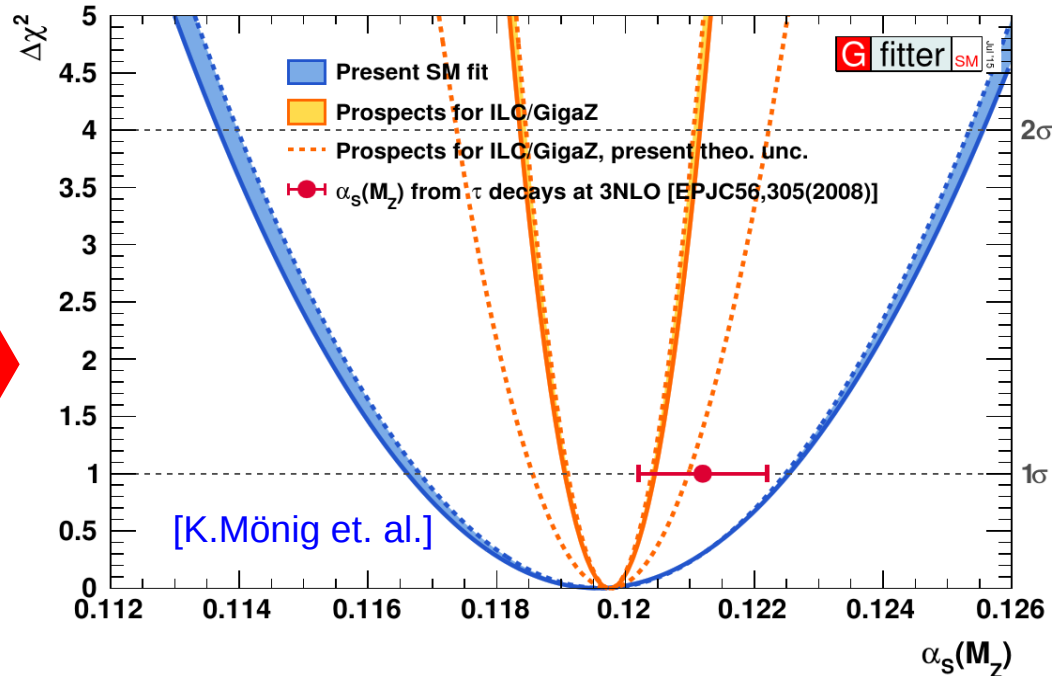
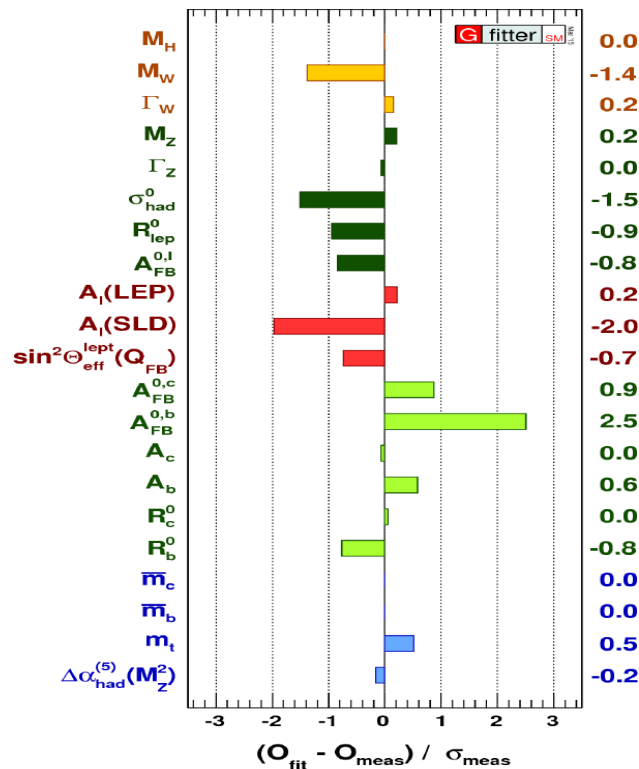
Maximum complementarity among FCC-xx's:



α_s via hadronic Z decays (FCC-ee)

- Computed at **N³LO**: $R_Z \equiv \frac{\Gamma(Z \rightarrow h)}{\Gamma(Z \rightarrow l)} = R_Z^{\text{EW}} N_C (1 + \sum_{n=1}^4 c_n \left(\frac{\alpha_s}{\pi}\right)^n + \mathcal{O}(\alpha_s^5) + \delta_m + \delta_{\text{np}})$
- LEP**: $\Gamma_Z = 2.4952 \pm 0.0023 \text{ GeV } (\pm 0.1\%)$, $R_\ell^0 = \frac{\Gamma_{\text{had}}}{\Gamma_\ell}$, $\sigma_{\text{had}}^0 = \frac{12\pi}{m_Z} \frac{\Gamma_e \Gamma_{\text{had}}}{\Gamma_Z^2}$, $\sigma_\ell^0 = \frac{12\pi}{m_Z} \frac{\Gamma_\ell^2}{\Gamma_Z^2}$

After Higgs discovery, α_s can be directly determined from **full fit of SM**:



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

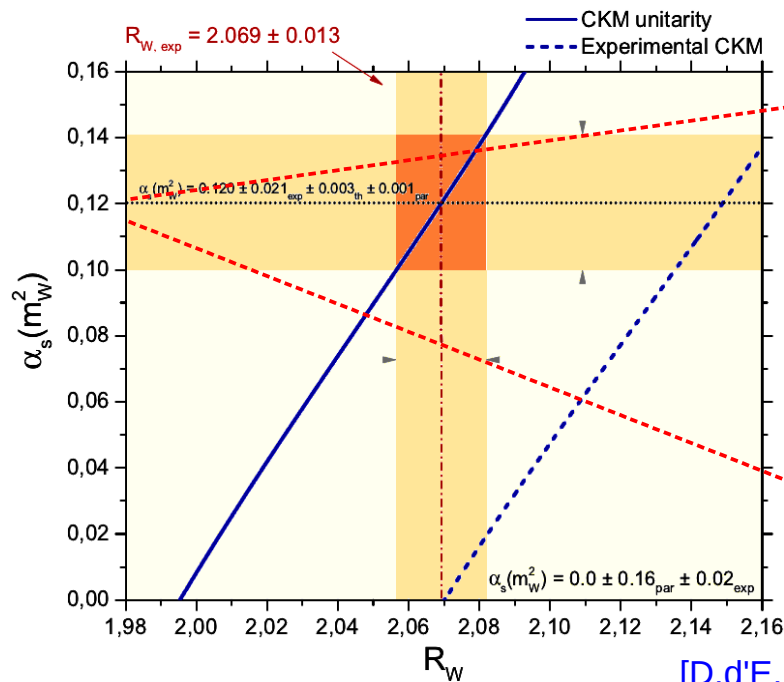
- FCC-ee**: – Z stats ($\times 10^5$ LEP) will lead to: $\delta\alpha_s/\alpha_s < 0.2\%$
- TH param. uncertainties: $\sin^2\theta_{\text{eff}}, m_W, m_t$. β -function at 5 loops now.

α_s via hadronic W decays (FCC-ee)

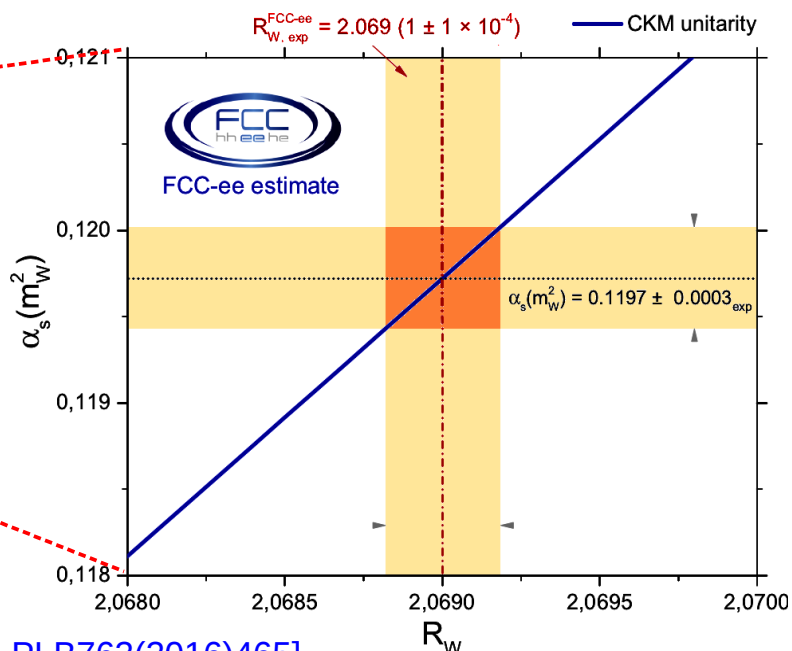
- Computed at **N^{2,3}LO**: $\Gamma_{W,\text{had}} = \frac{\sqrt{2}}{4\pi} G_F m_W^3 \sum_{\text{quarks } i,j} |V_{i,j}|^2 \left[1 + \sum_{k=1}^4 \left(\frac{\alpha_s}{\pi} \right)^k + \delta_{\text{electroweak}}(\alpha) + \delta_{\text{mixed}}(\alpha\alpha_s) \right]$
- LEP**: $\Gamma_W = 1405 \pm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

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

$$\alpha_s(M_Z) = 0.117 \pm 0.040 \quad (\pm 35\%)$$



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



- FCC-ee**: – Huge W stats ($\times 10^4$ LEP) will lead to: $\delta\alpha_s/\alpha_s < 0.3\%$
- TH param. uncertainty: $\delta|V_{CS}|$ to be significantly improved (10^{-4})

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

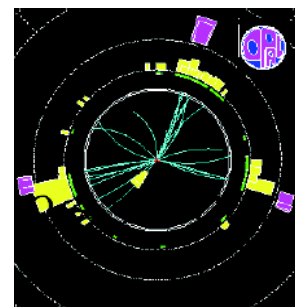
➔ Computed at $N^{2,3}LO+N^{(2)}LL$ accuracy.

➔ LEP data for thrust, C-parameter, jet shapes, 3-jet x-sections

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

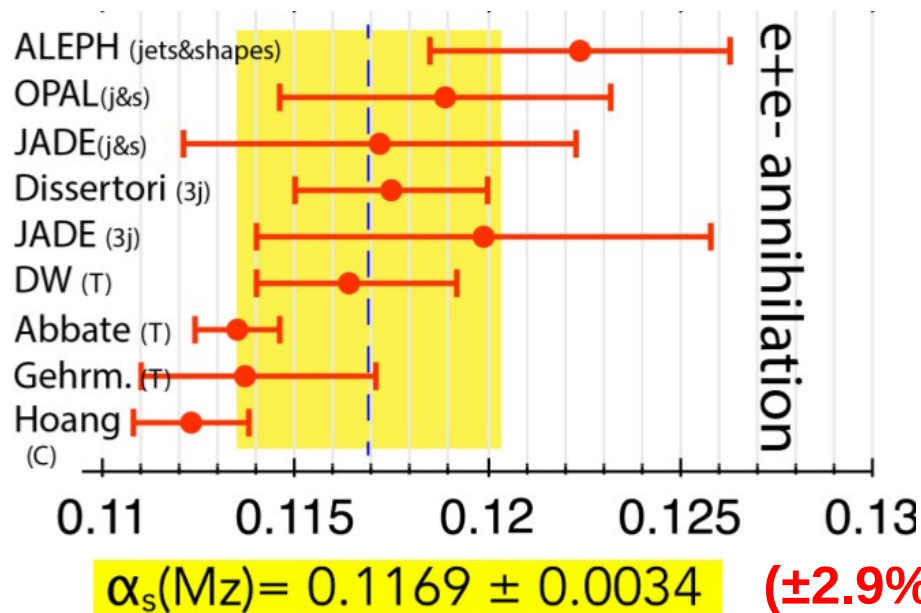
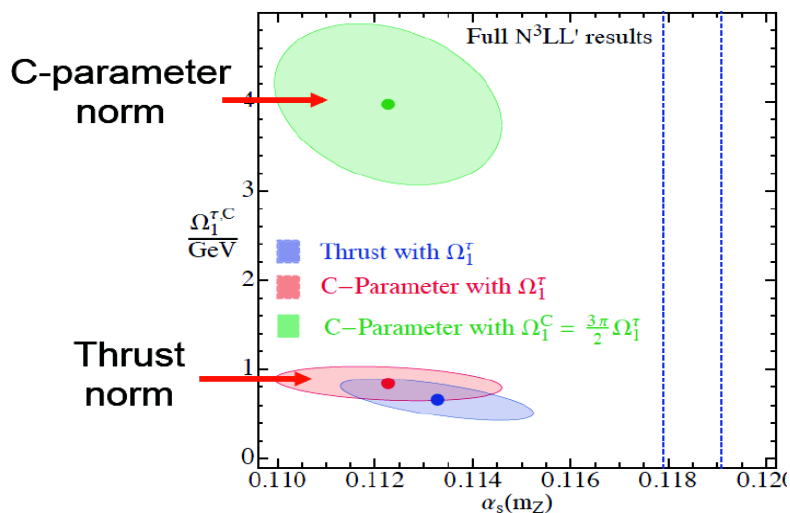
$$\tau = 1 - \max_{\hat{n}} \frac{\sum |\vec{p}_i \cdot \hat{n}|}{\sum |\vec{p}_i|}$$

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



OPAL 3 jet event

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



➔ FCC-ee:

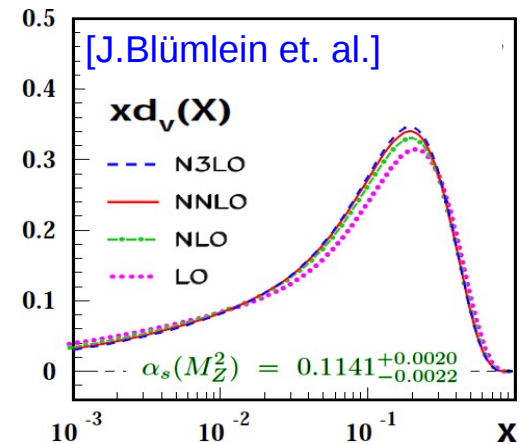
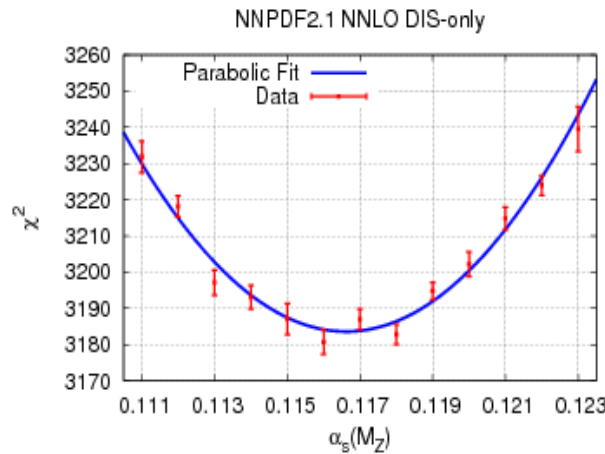
- Higher- \sqrt{s} data needed for rates (lower- \sqrt{s} for shapes): $\delta\alpha_s/\alpha_s < 1\%$
- TH uncert.: Jet rates with improved (NNLL or N^3LL) resummation

α_s via proton structure functions (HERA+LHC)

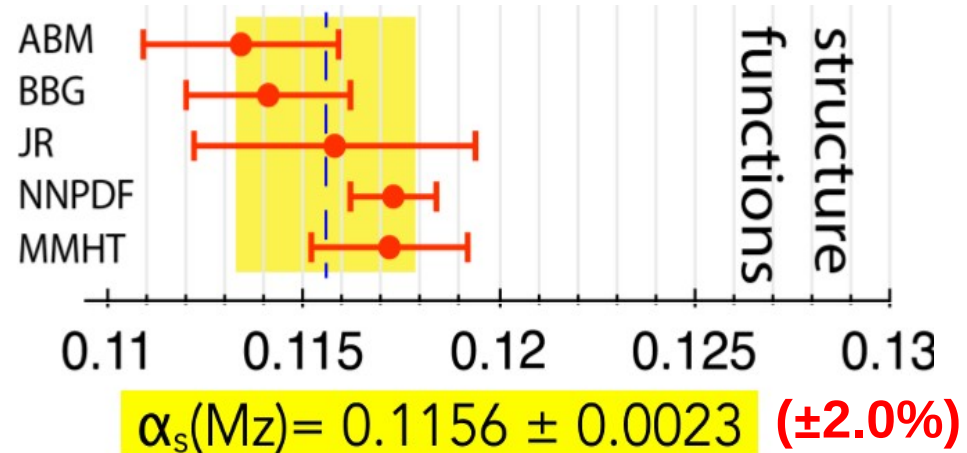
- Computed at **N^{2,3}LO**: $F_2(x, Q^2) = x \sum_{n=0}^{\infty} \frac{\alpha_s^n(\mu_R^2)}{(2\pi)^n} \sum_{i=q,g} \int_x^1 \frac{dz}{z} C_{2,i}^{(n)}(z, Q^2, \mu_R^2, \mu_F^2) f_{i/p}\left(\frac{x}{z}, \mu_F^2\right) + \mathcal{O}\left(\frac{\Lambda^2}{Q^2}\right)$
- HERA**: $F_2(x, Q^2)$, $F_2^c(x, Q^2)$, $F_L(x, Q^2)$, PDFs(x, Q²)

Different **approaches**:

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



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

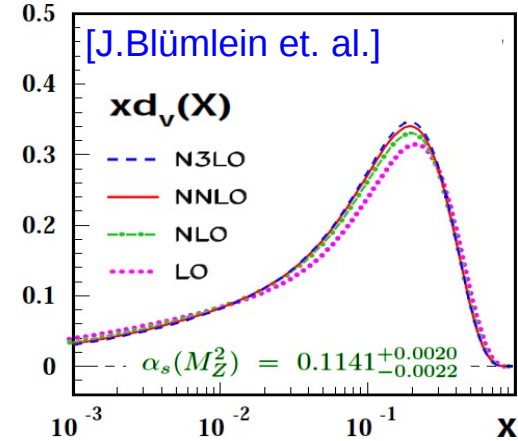
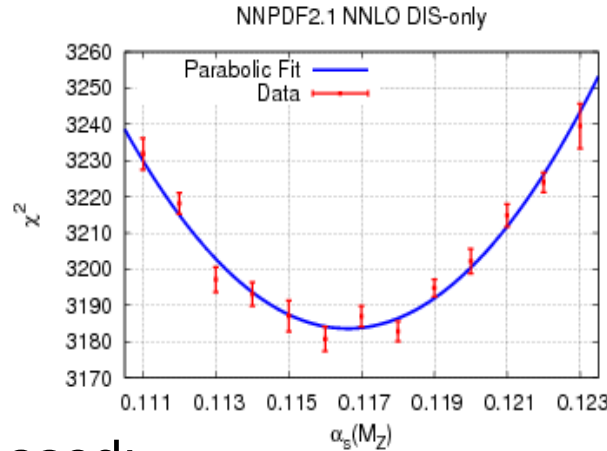


α_s via proton structure functions (FCC-ep)

- Computed at **N^{2,3}LO**: $F_2(x, Q^2) = x \sum_{n=0}^{\infty} \frac{\alpha_s^n(\mu_R^2)}{(2\pi)^n} \sum_{i=q,g} \int_x^1 \frac{dz}{z} C_{2,i}^{(n)}(z, Q^2, \mu_R^2, \mu_F^2) f_{i/p}\left(\frac{x}{z}, \mu_F^2\right) + \mathcal{O}\left(\frac{\Lambda^2}{Q^2}\right)$
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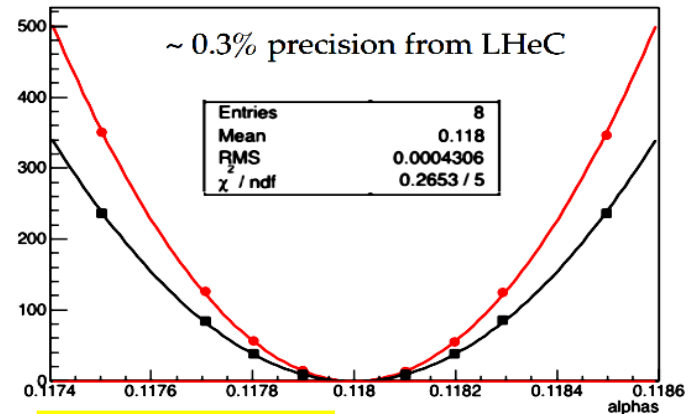
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combined fit to PDFs+ α_s using LHeC data

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



M Klein, V Radescu

— NC,CC
— NC,CC+F2c

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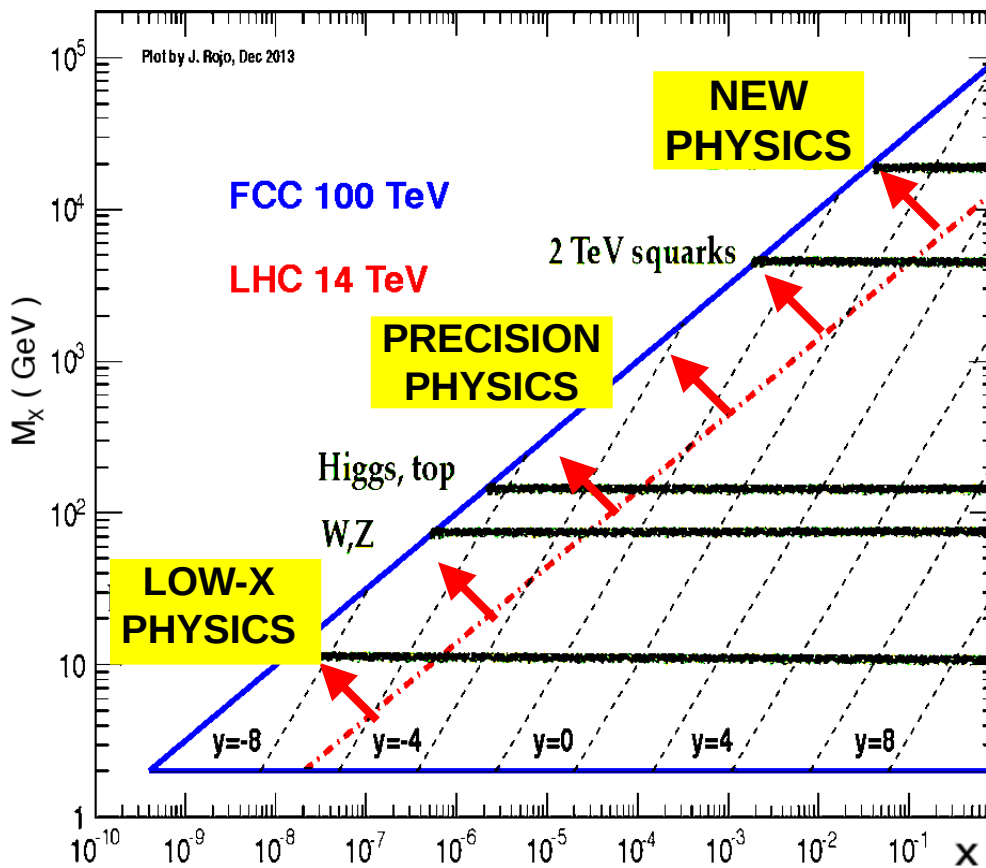
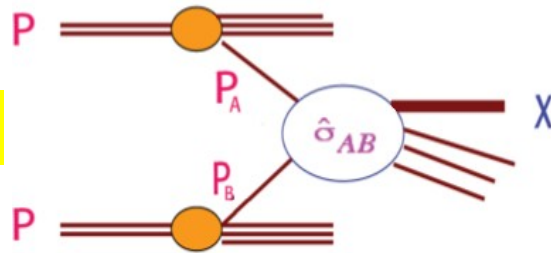
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Parton (x, Q^2) regions at FCC-pp

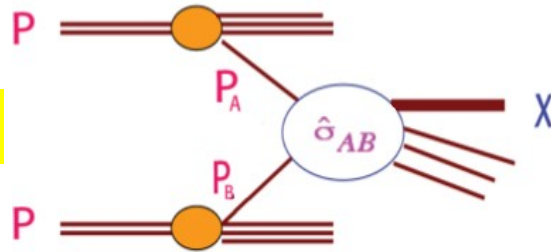
$$\sigma = \hat{\sigma} \otimes \text{PDF}$$



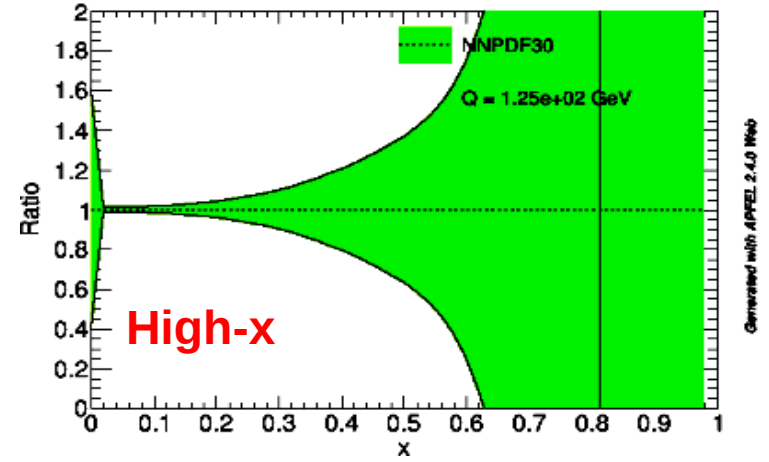
Parton (x, Q^2) regions at FCC-pp

Associated PDFs uncertainties: [APFEL]

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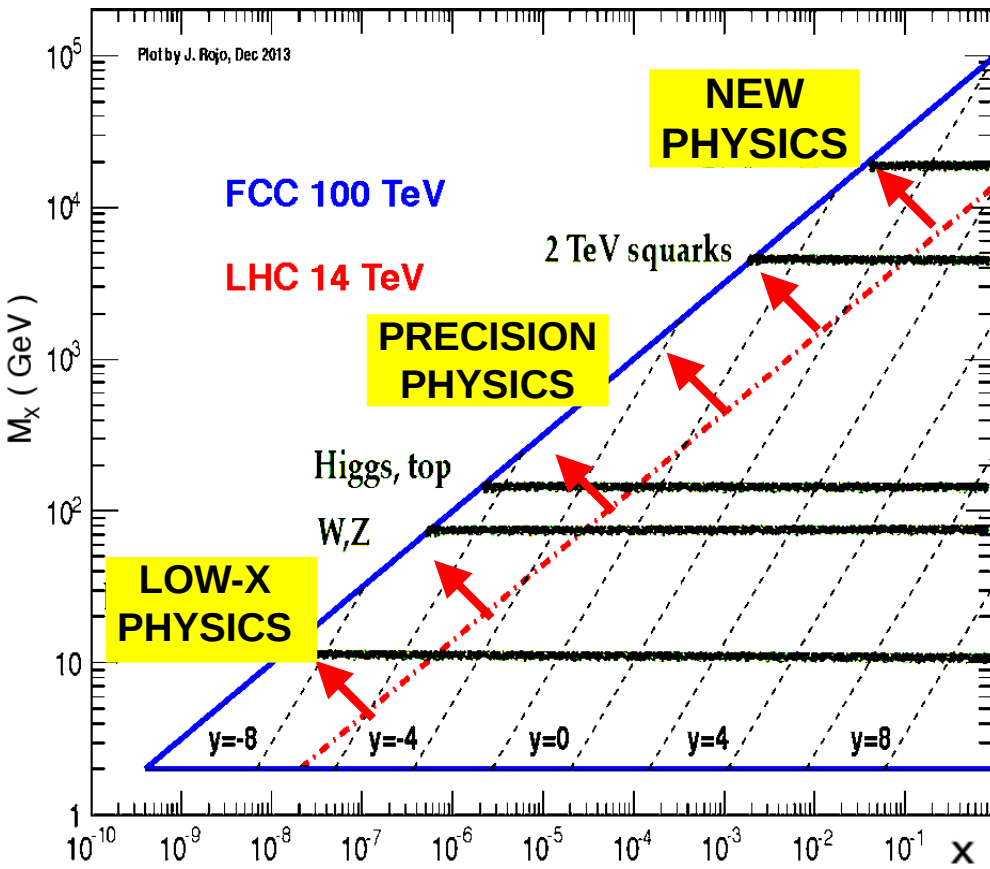
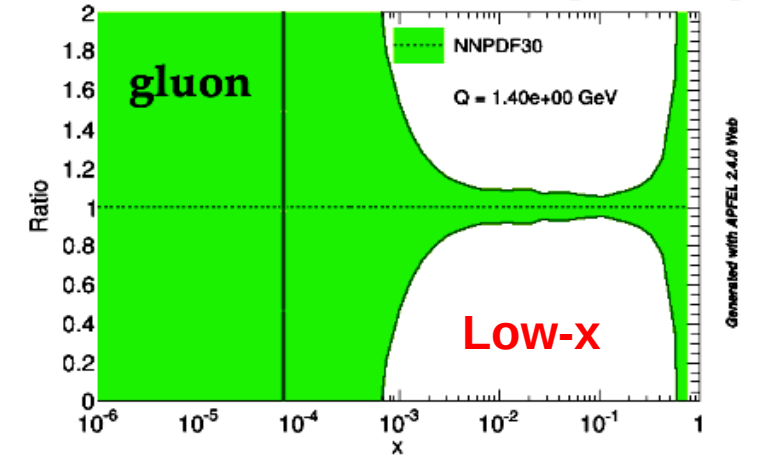


$xg(x, Q)$, comparison [APFEL]



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

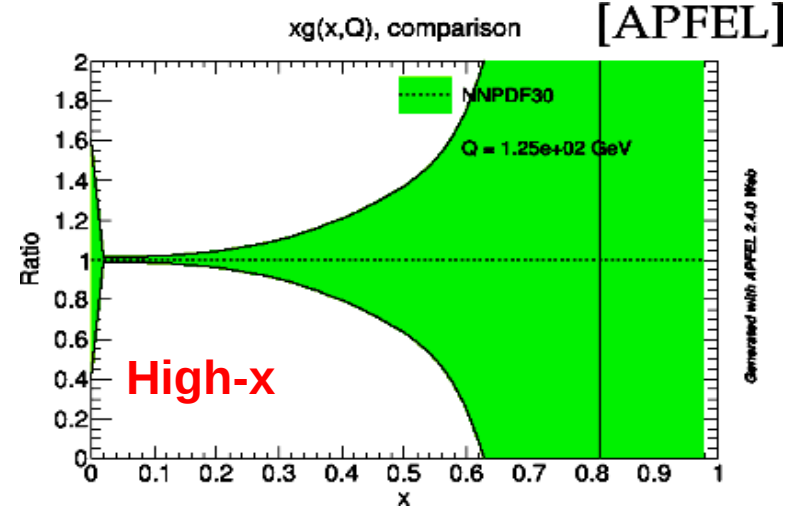
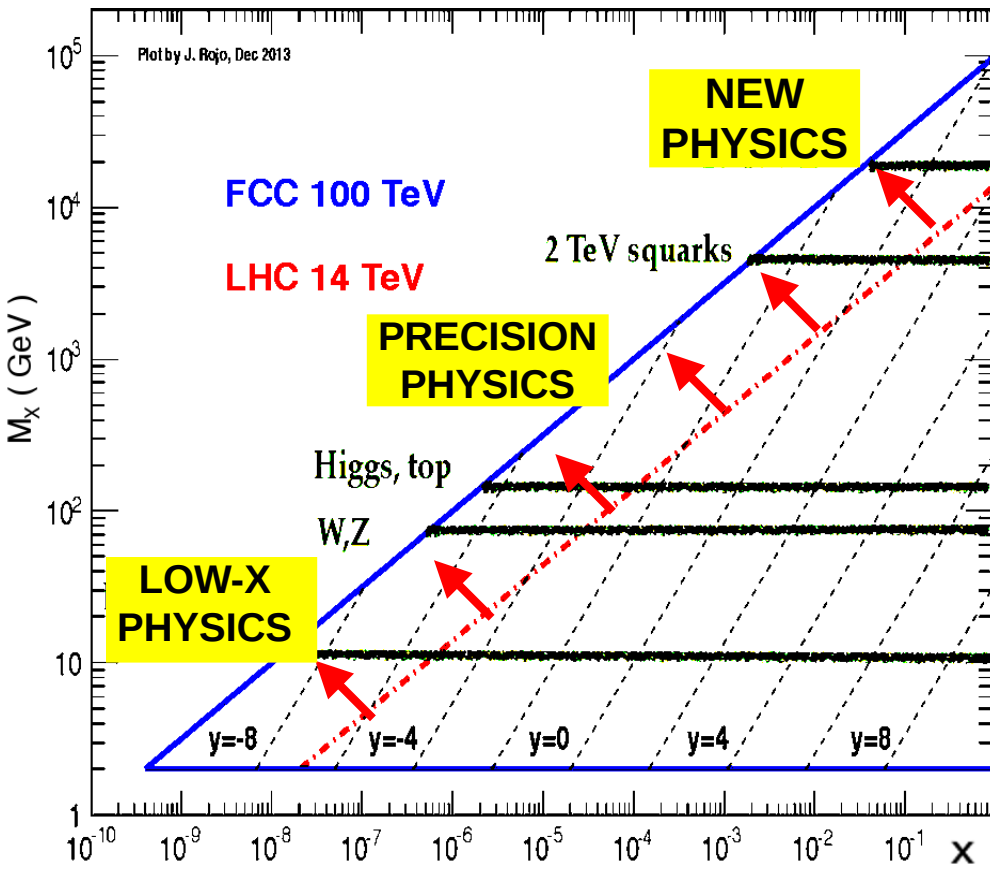
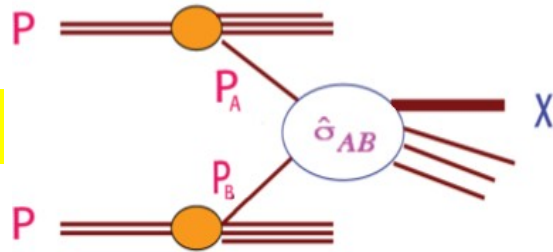
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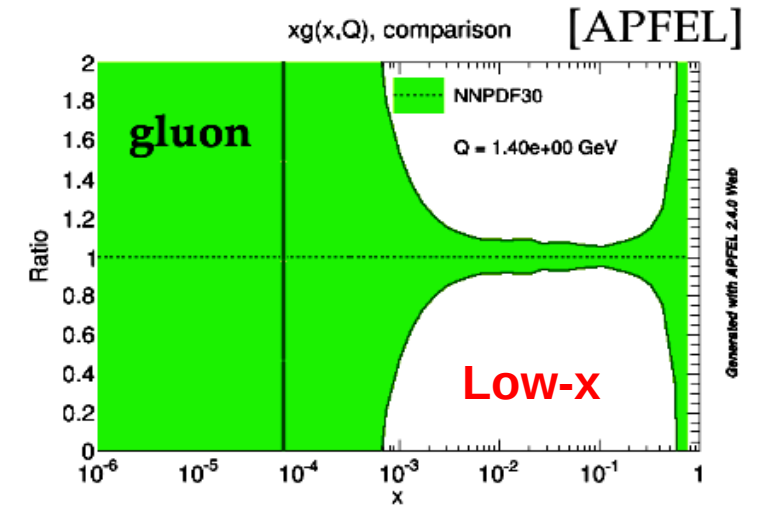
Parton (x, Q^2) regions at FCC-pp

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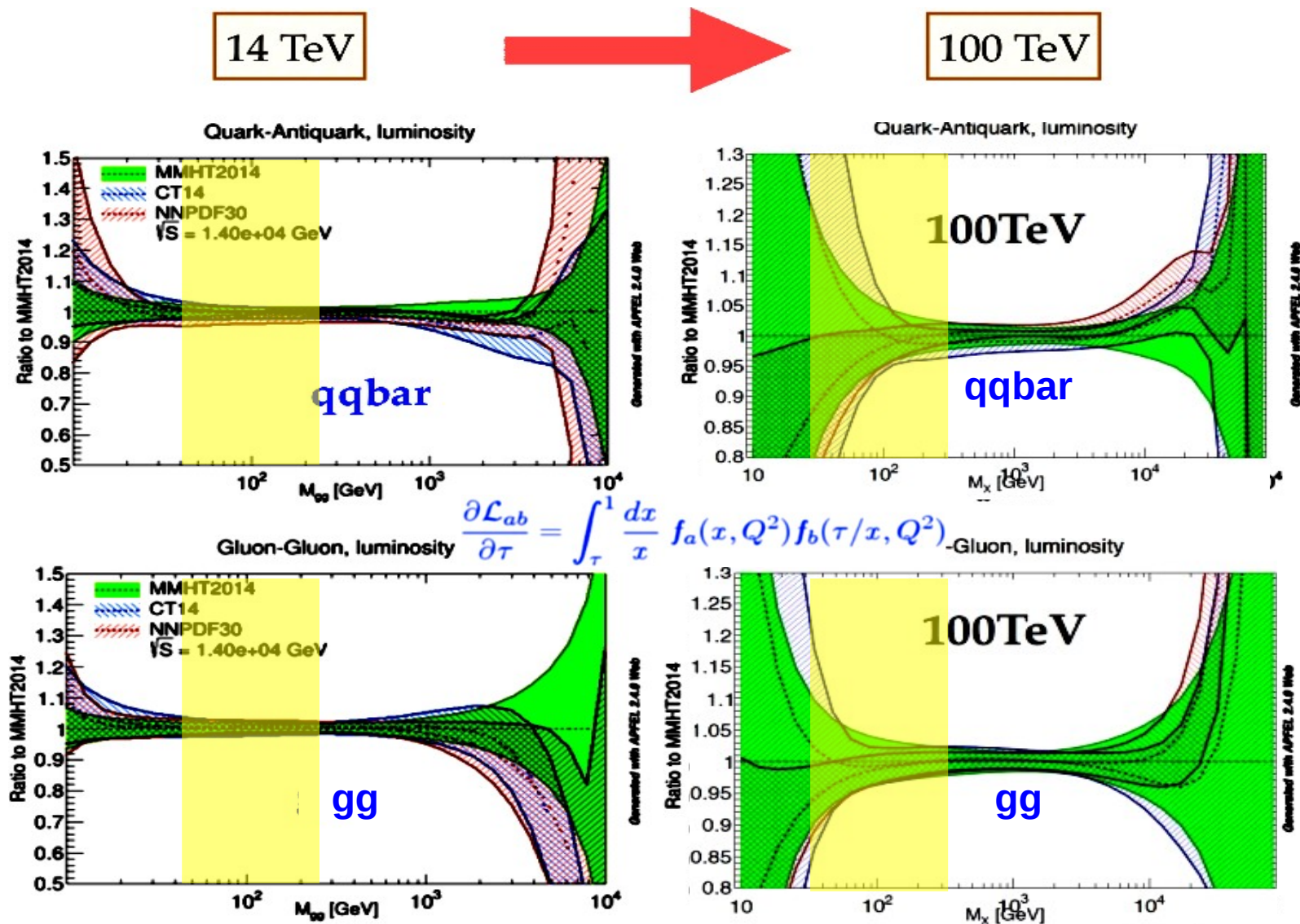


and what about in mid-x region...?



FCC-pp parton lumis in “precision” region

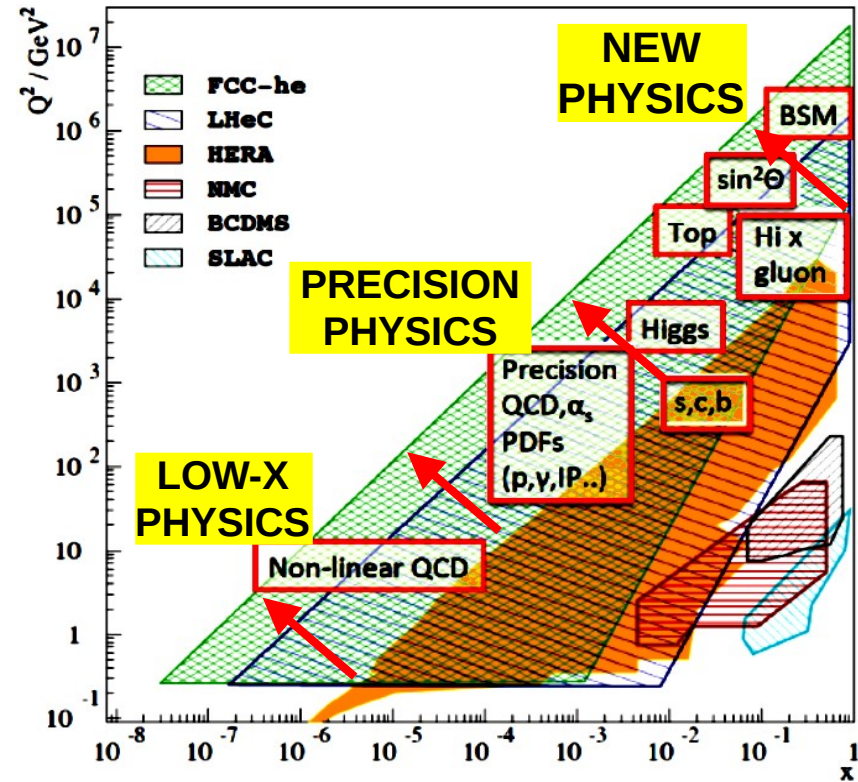
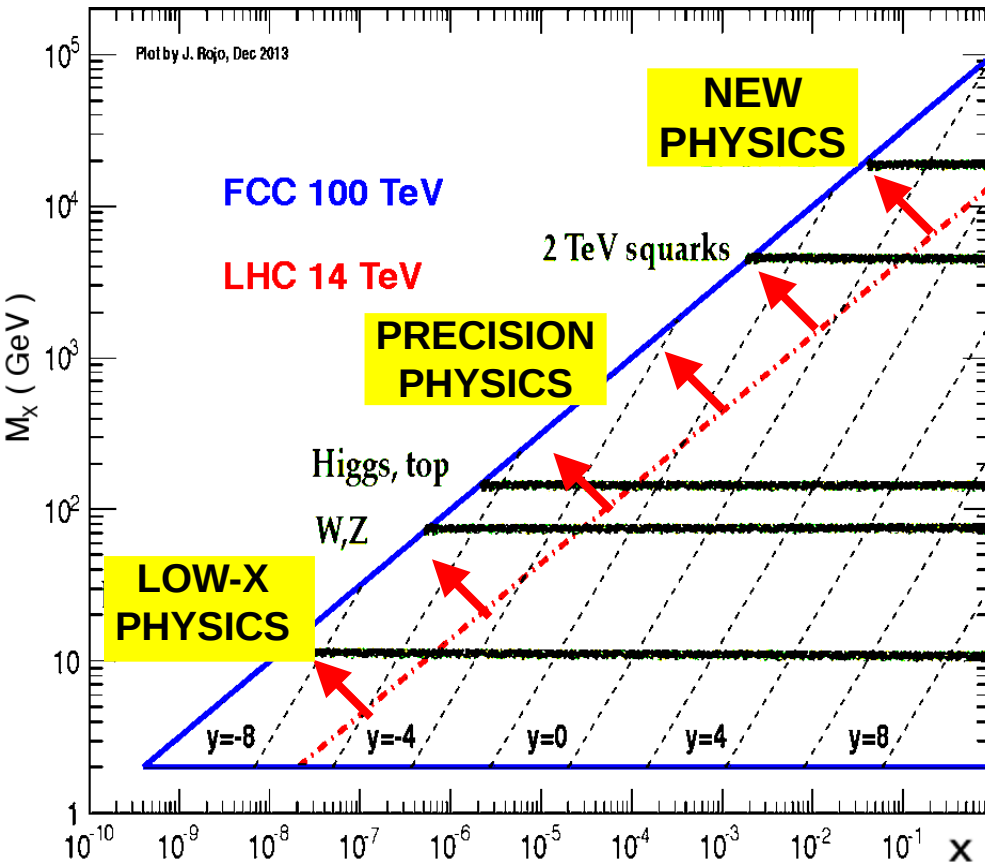
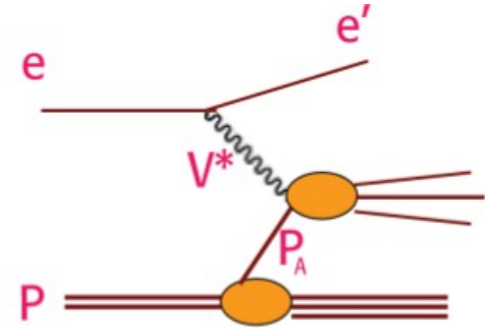
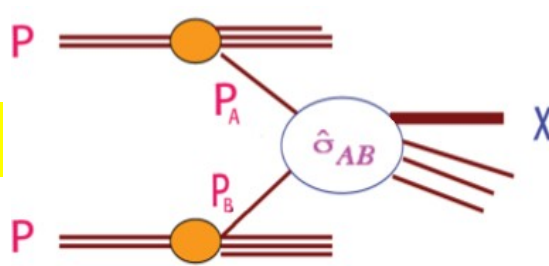
- “Precision” region at FCC-pp: 5–7% PDF uncertainty for $\sigma(W,Z,H)$



FCC-ep “comes to the rescue” of FCC-pp

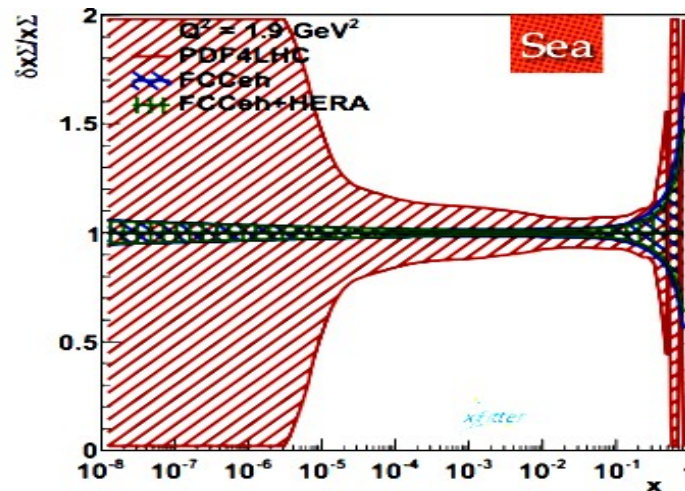
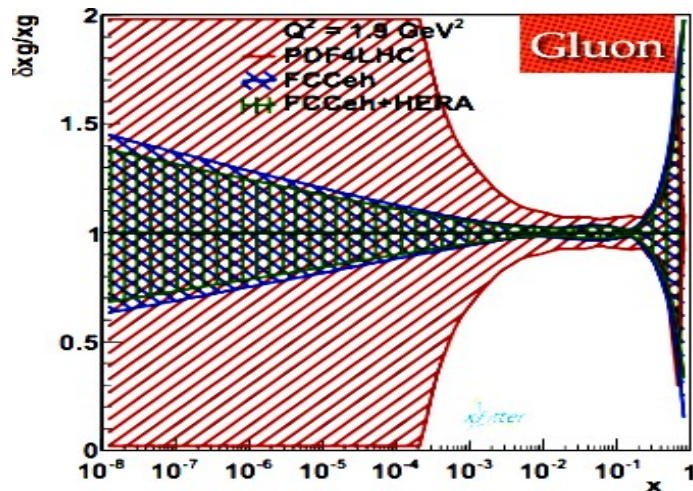
- FCC-ep: Fully complementary with FCC-pp to improve parton densities

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



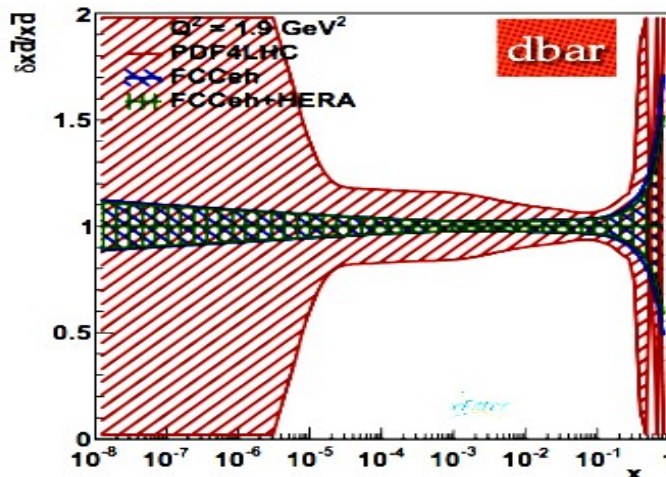
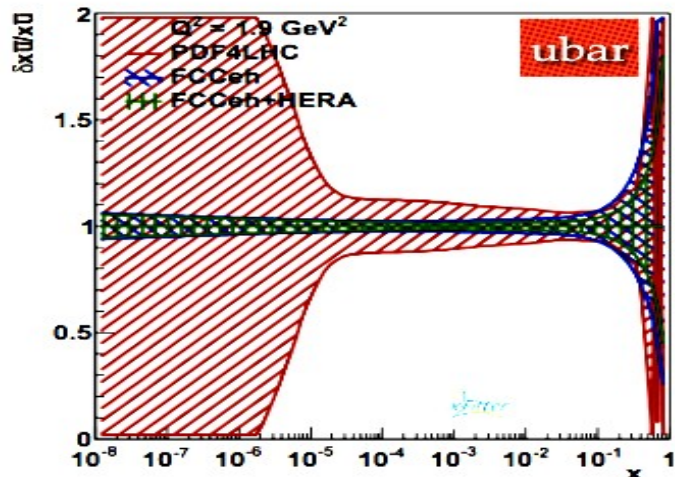
Improved PDFs at all x (FCC-ep)

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



[JPG39(2012)075001]

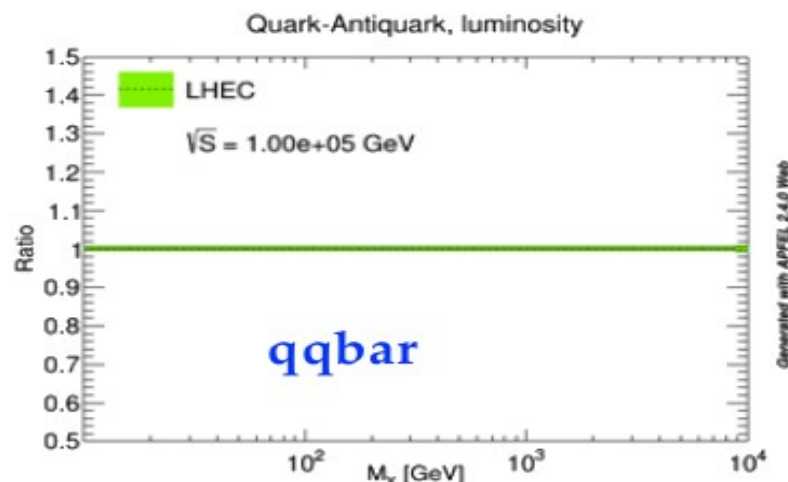
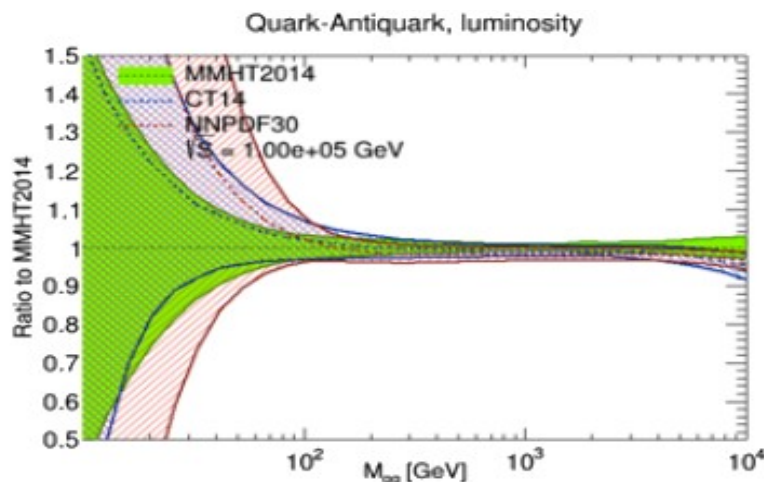
PDF4LHC set
vs. FCC-ep
(+HERA)
at starting
 Q_0 scale



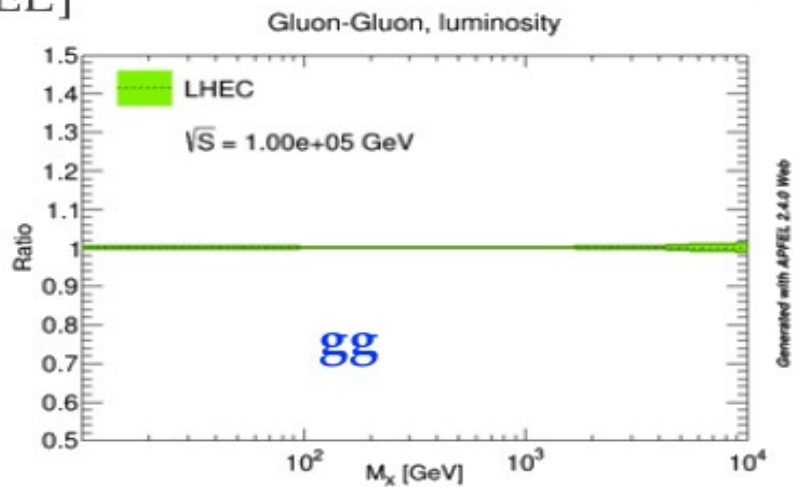
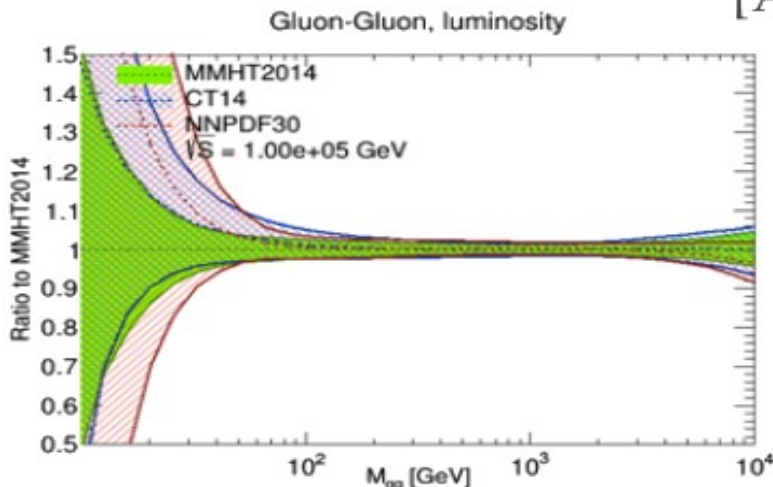
- **Strongly reduced PDF uncertainties** for all flavours (also strange, charm, bottom) at all x (down to 10^{-8})

Parton luminosities: Today vs. FCC-ep

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

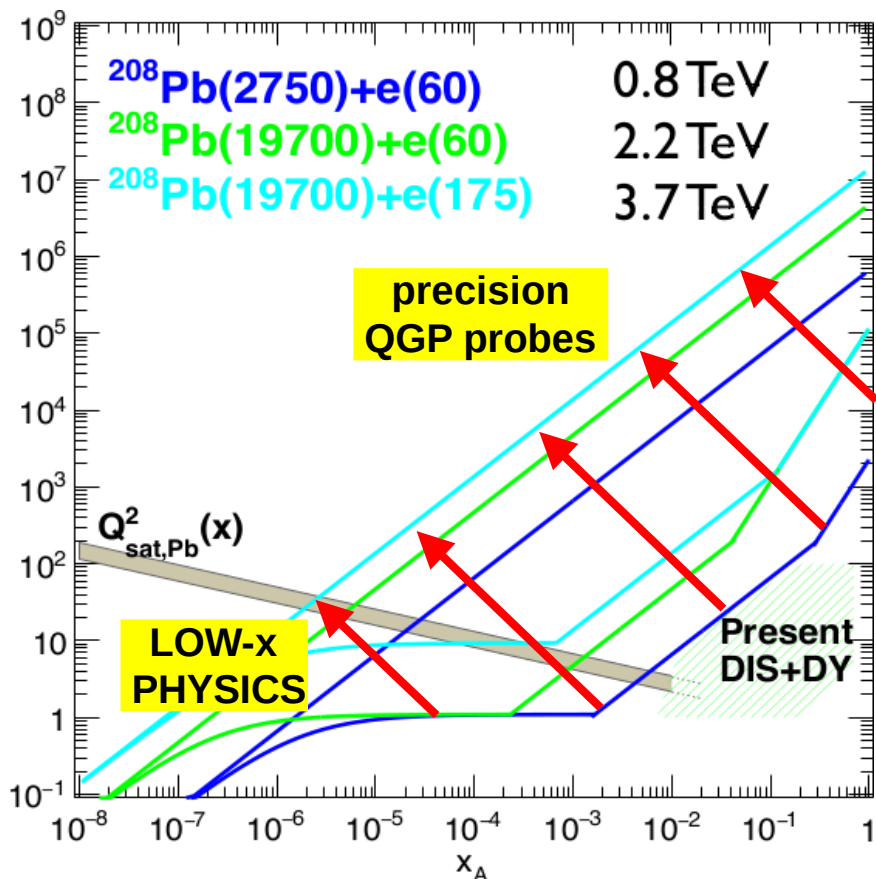
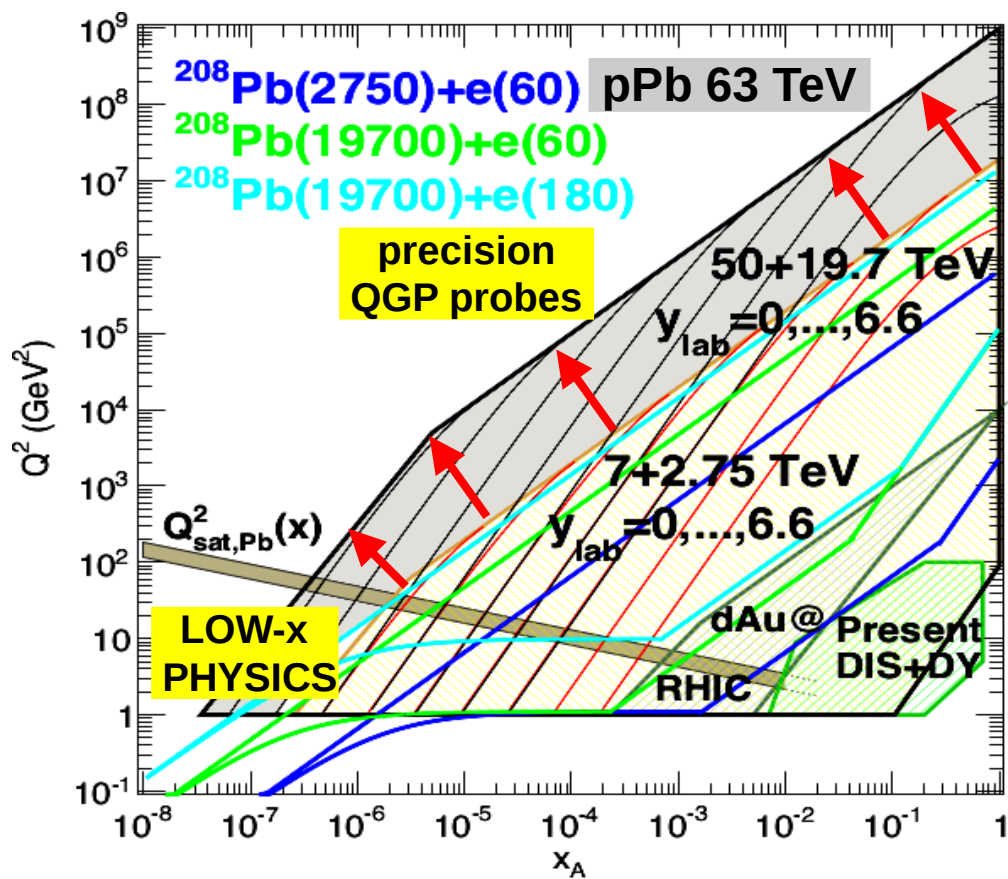
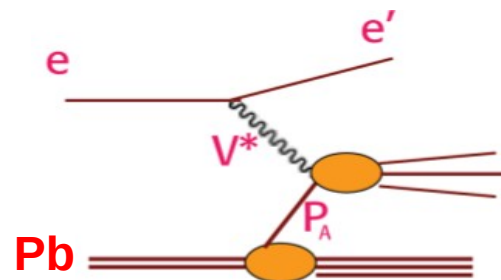
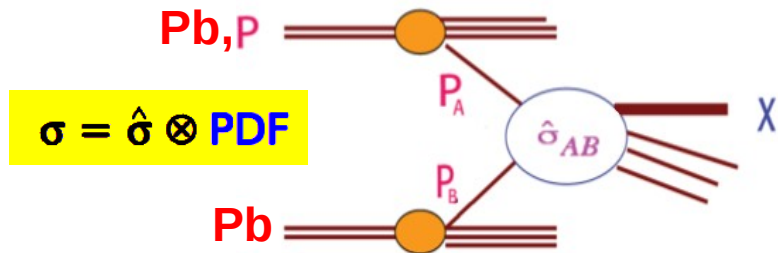


[APFEL]



- FCC-ep required to get **O(1%) PDF uncertainty** for $\sigma(W,Z,H)$ at FCC-pp
(LHC likely to improve PDFs before, but by factor $\times 2(?)$, not $\times 5-10$)

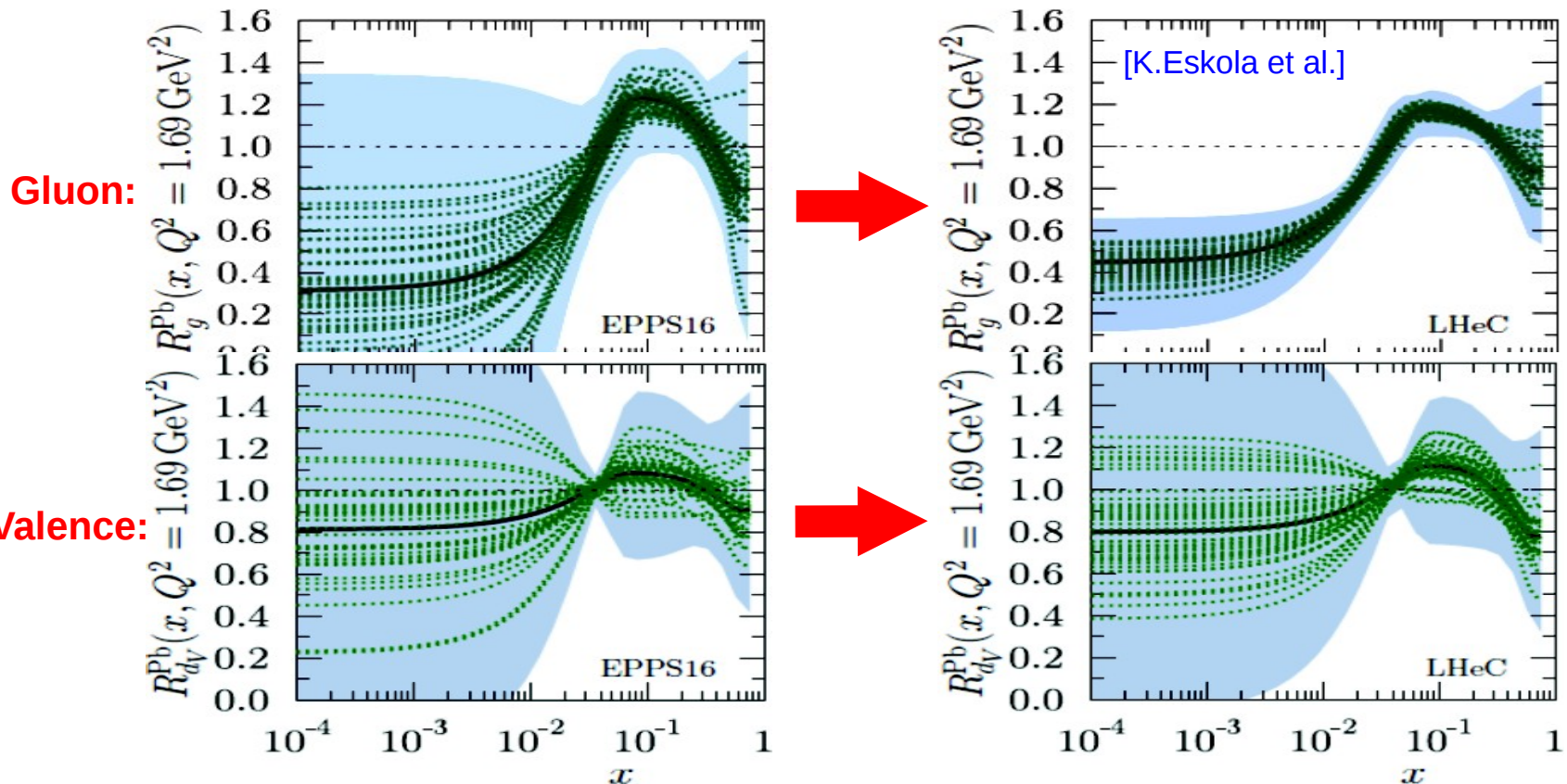
Nuclear parton (x, Q^2) regimes (FCC-eA,-AA)



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



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

QCD synergies at FCC

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

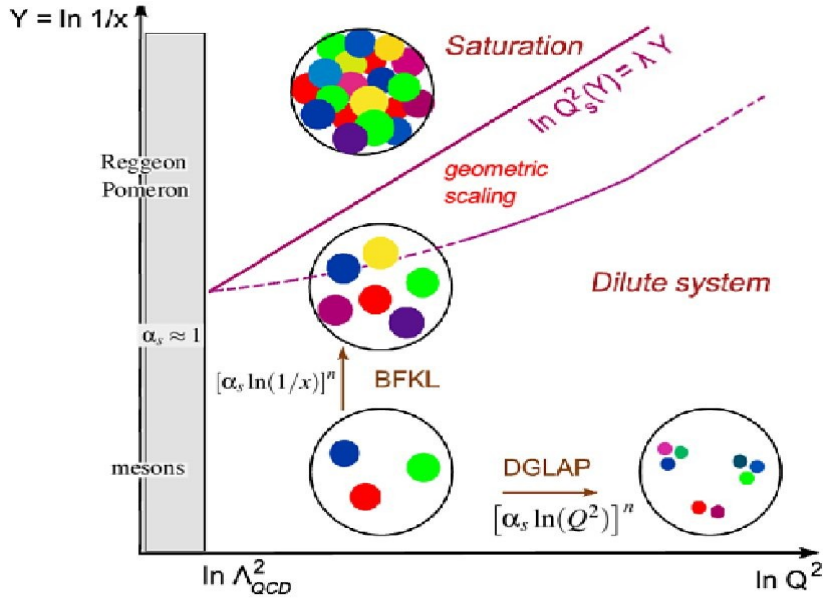
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(3) Beyond DGLAP (FCC-eh, FCC-hh)

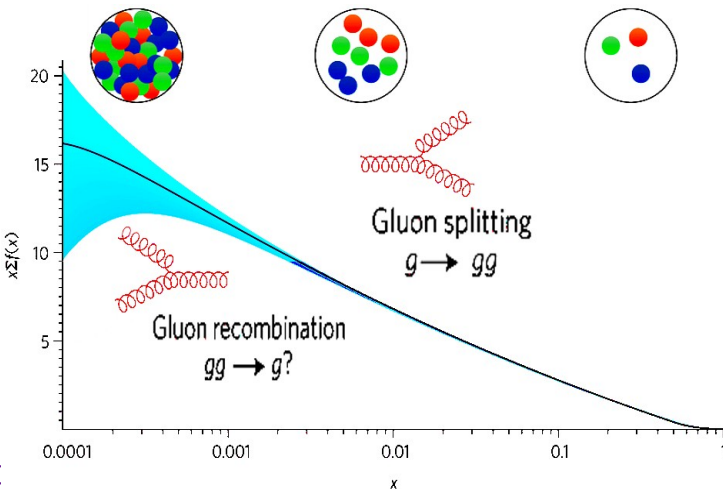
(4) Gluons & Higgs (FCC-ee, FCC-hh)

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

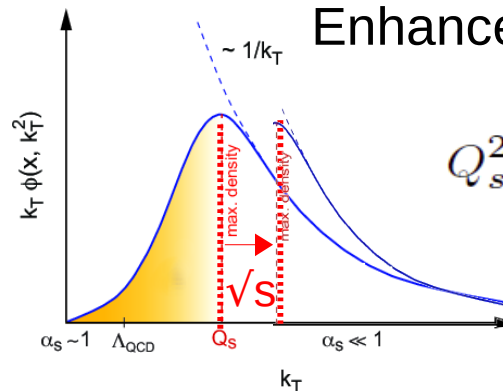
“Beyond DGLAP” low-x phenomena



- ▶ Multiparton interactions
- ▶ Std. collinear factorization broken



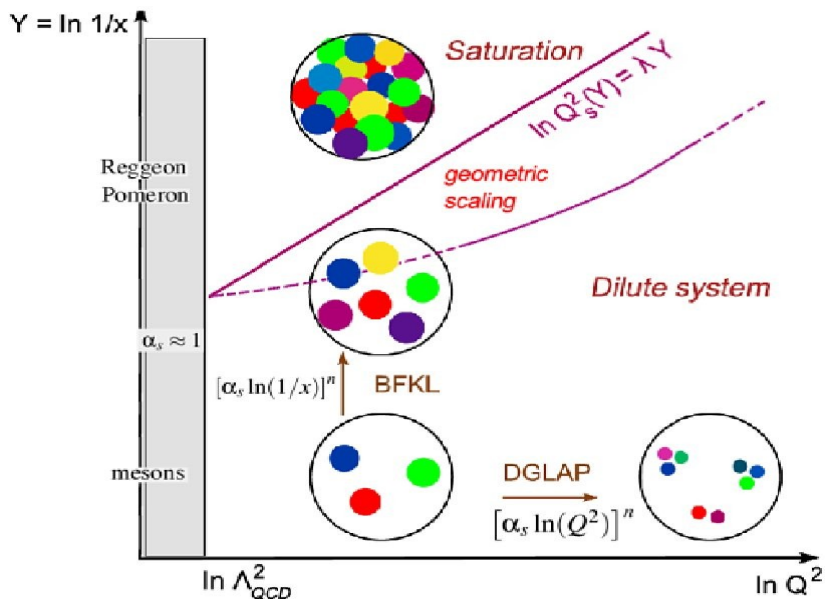
- DGLAP eqs. describe parton radiation as a function of Q^2 :
 $f(Q^2) \sim \alpha_s \ln(Q^2/Q_0^2)^n$
 [fixed-order PDFs, collinear fact.]
- BFKL evolution as a function of x :
 $f(x) \sim \alpha_s \ln(1/x)^n$ [uPDFs, k_T -fact.]
- For increasing \sqrt{s} , non-linear QCD evolution will set in at low 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 key PYTHIA's pQCD cutoff $p_{T,0}$

“Beyond DGLAP” low-x phenomena



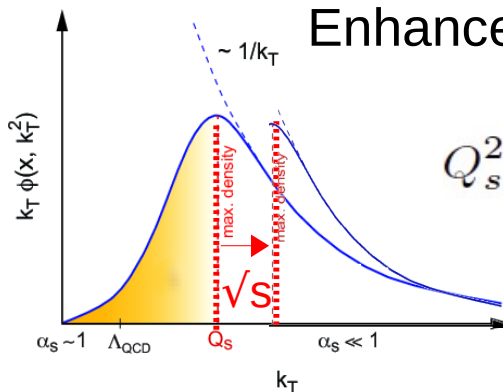
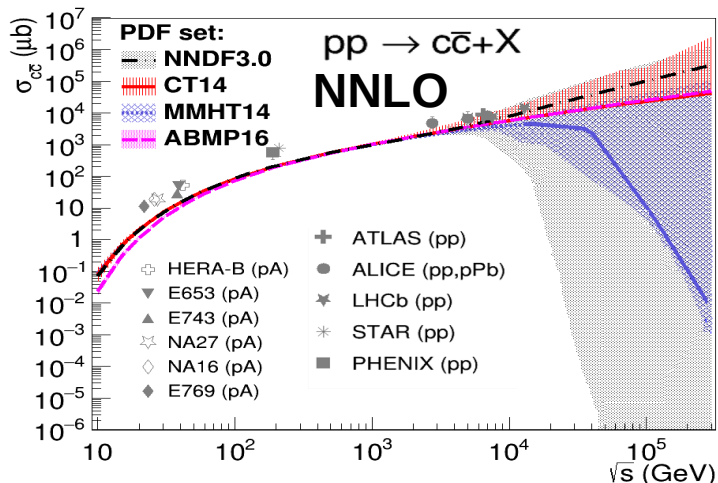
- ▶ Multiparton interactions
- ▶ Std. collinear factorization broken

- 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 \sqrt{s} , non-linear QCD evolution will set in at low x .
 $gg \rightarrow g$ peaks at perturbative “saturation scale” $\mathcal{O}(\text{few GeV})$.

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

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

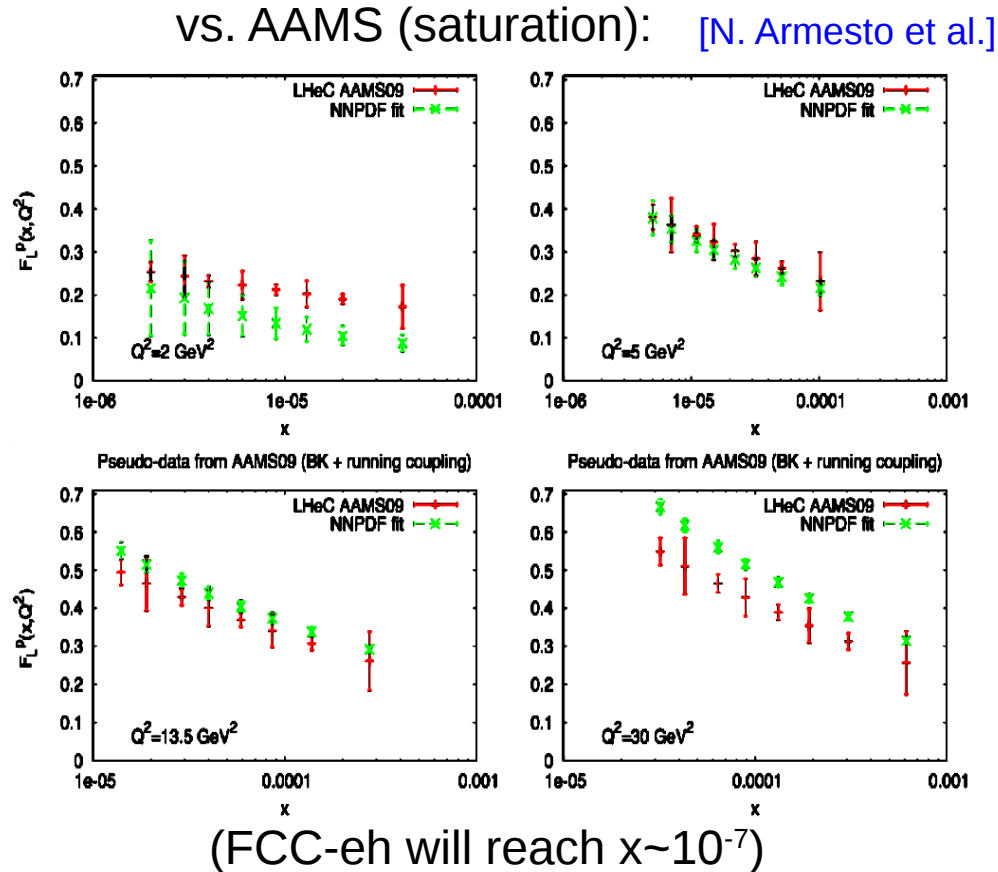
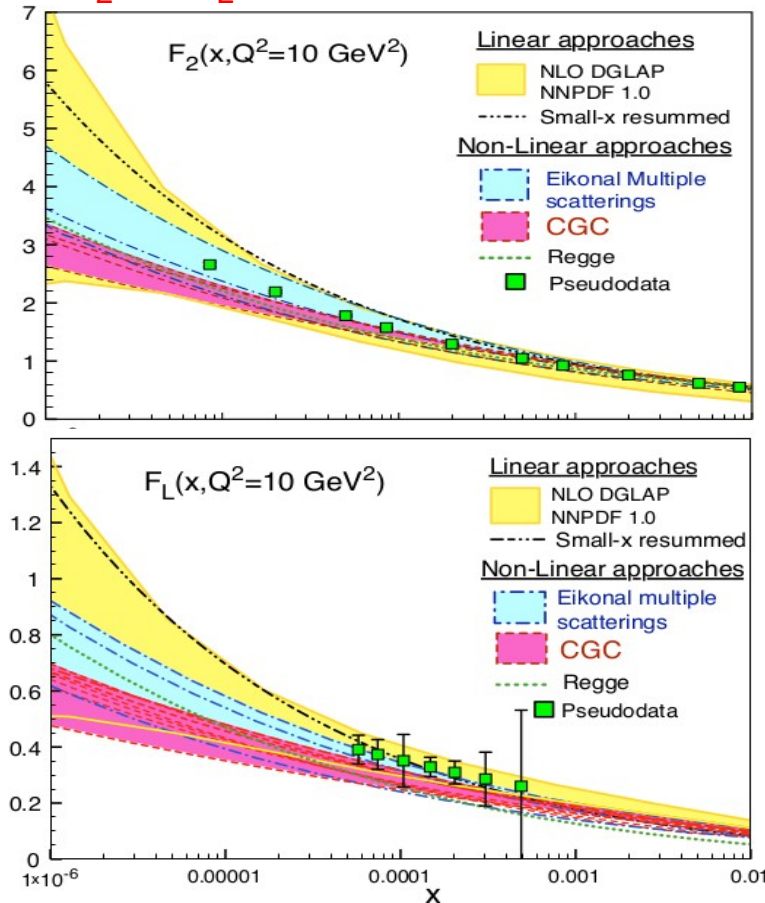
Note: Equivalent to key PYTHIA's pQCD cutoff $p_{T,0}$



“Beyond DGLAP” evolution (FCC-eh)

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

- **FCC-eh** cleanest lab: DGLAP cannot simultaneously accommodate F_2 & F_L if low-x saturation present: F_L pseudodata for NNPDF (DGLAP) vs. AAMS (saturation): [N. Armesto et al.]



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)

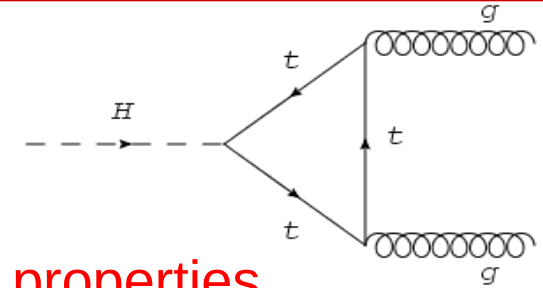
Higgs as a source of pure gluons (FCC-ee)

- FCC-ee $H(gg)$ is a "pure gluon" factory:

$H \rightarrow gg$ (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

$H \rightarrow gg$ vs $Z \rightarrow qq$

Rely on good $H \rightarrow gg$ vs $H \rightarrow bb$ separation;
mandated by Higgs studies requirements anyway?

$Z \rightarrow bbg$ vs $Z \rightarrow qq(g)$

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

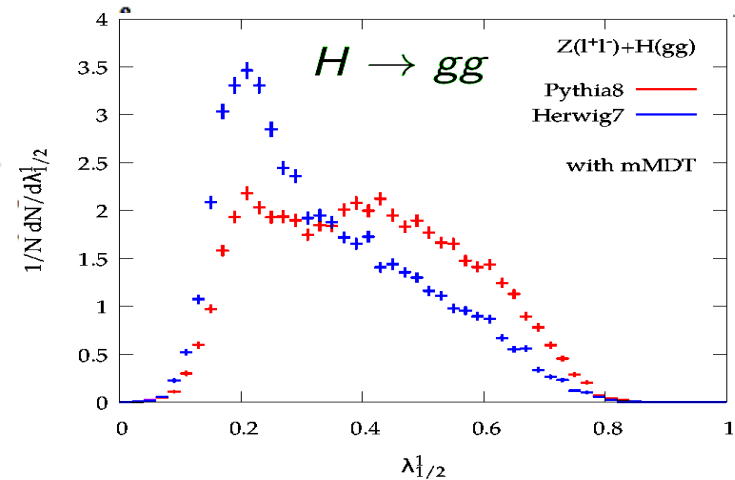
Vary jet radius: small-R → calo resolution

($R \sim 0.1$ also useful for jet substructure)

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

(also useful for FFs & general scaling studies);

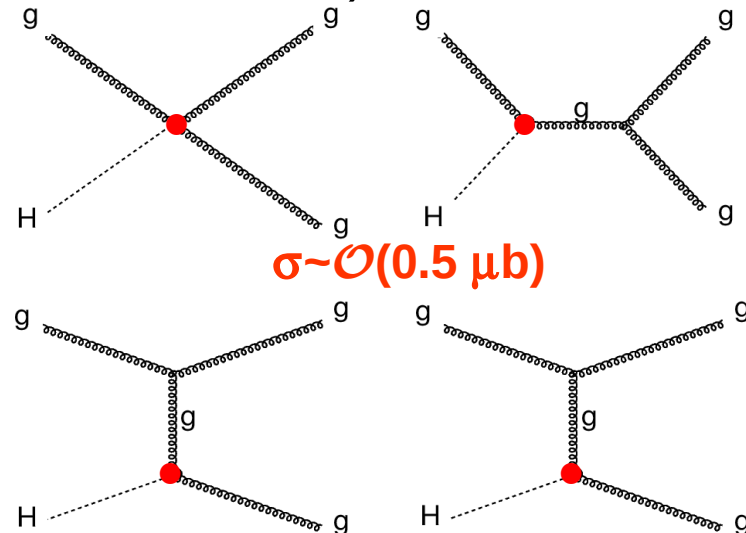
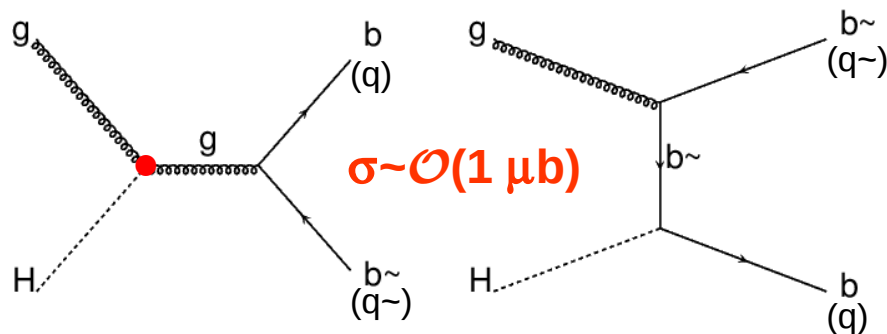
Scaling is **slow**, logarithmic → large lever arm



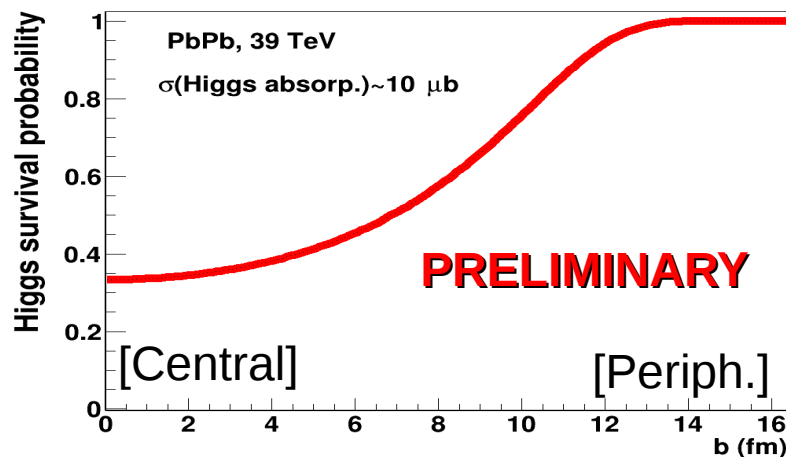
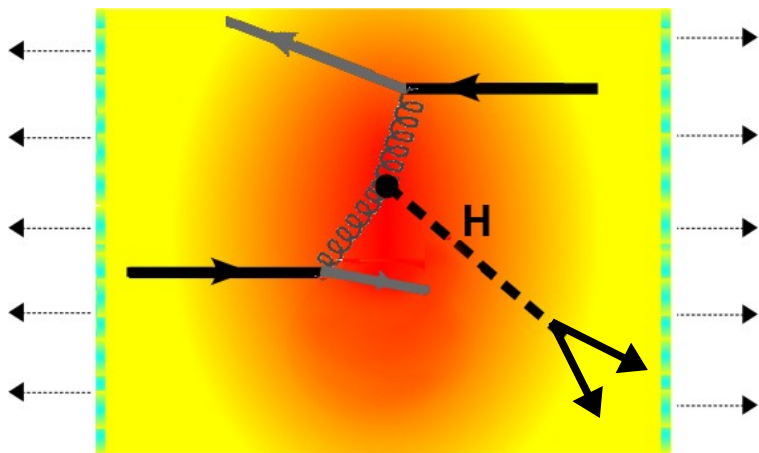
- Check N^n LO antenna functions
- Improve $q/Q/g$ discrim. tools
- Octet neutralization? (zero-charge gluon jet w/ rap-gaps)
- Colour reconnection? Glueballs ?
- Leading η 's, baryons in g jets?

Higgs as a calibrated QGP probe (FCC-AA)

- $gg \rightarrow H$ is the most accurately known pQCD process (N³LO). [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 $\sim 25\%$ quenched in QGP?



QCD synergies at FCC

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- (4) Gluons & Higgs (FCC-ee, FCC-hh)
- (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**: $e^+e^- \rightarrow WW(4j), Z(4j), tt$
- 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.

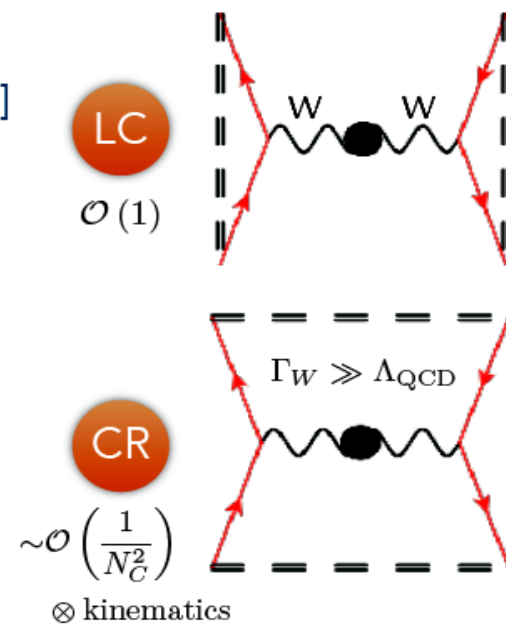
Fundamental to understanding & modeling hadronisation

Follow-up studies now underway at LHC.

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

High-stats ee → other side of story

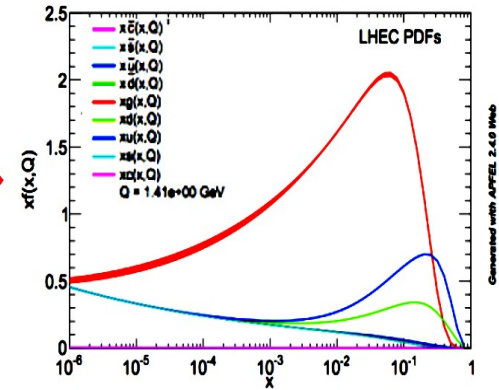
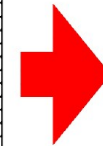
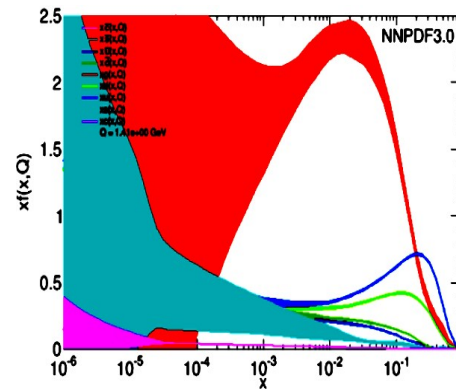
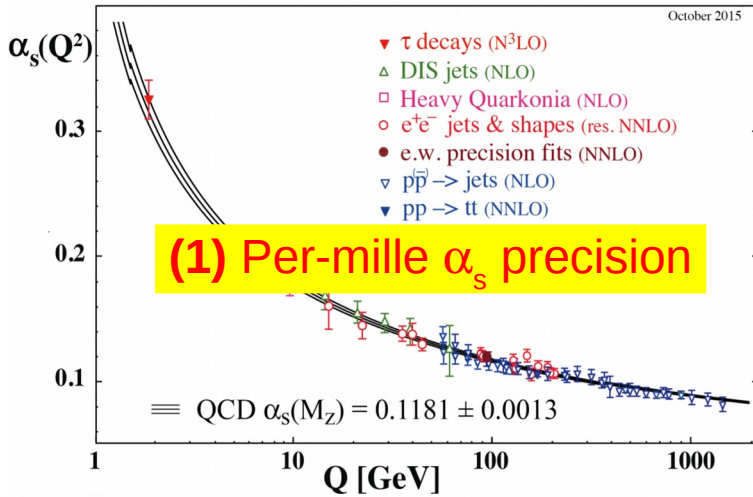
Also relevant in (hadronic) $ee \rightarrow tt$, and $Z \rightarrow 4$ jets



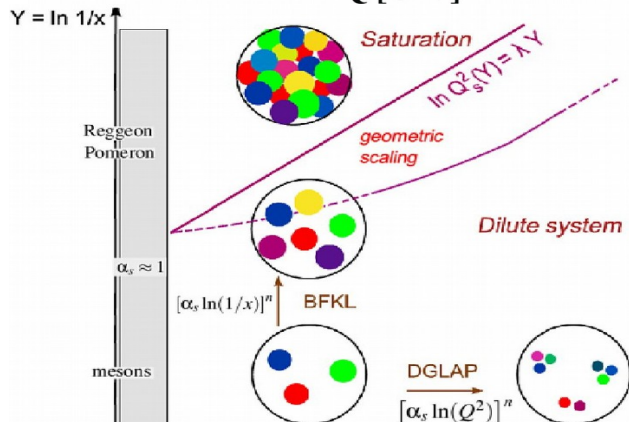
+ Overlaps → interactions?
increased tensions (strangeness)?
breakdown of string picture?

Summary

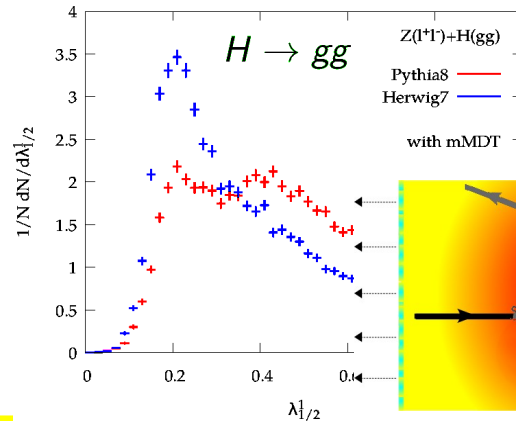
➤ The precision required to fully develop/exploit the FCC ee/pp/ep/eA/AA SM & BSM programs requires exquisite control of QCD via synergistic combinations of measurements at all machines:



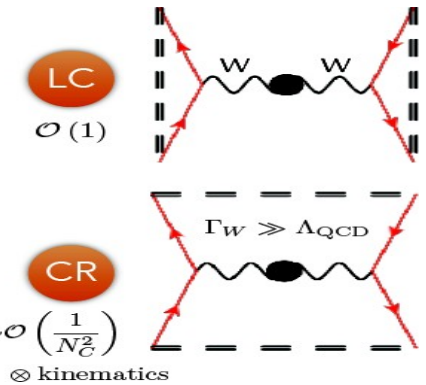
(2) O(1%) PDF uncert. at low/mid/high-x



(3) Collinear factorization corrections/extensions



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



(5) % control of n-pQCD effects

Backup slides

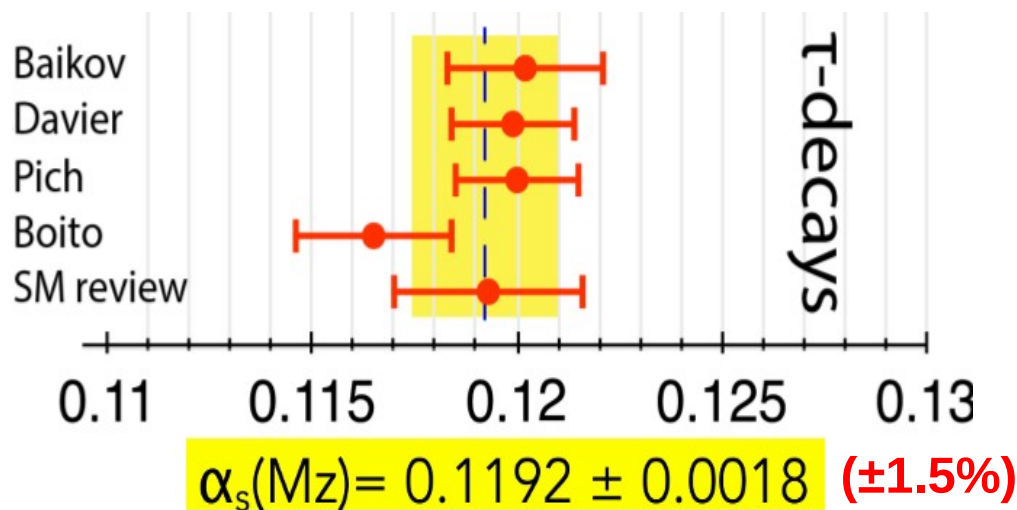
α_s from hadronic τ -lepton decays (FCC-ee)

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

➔ 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 ($\pm 1.3\%$) \rightarrow 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)**.

α_s from γ QCD structure function (FCC-ee)

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

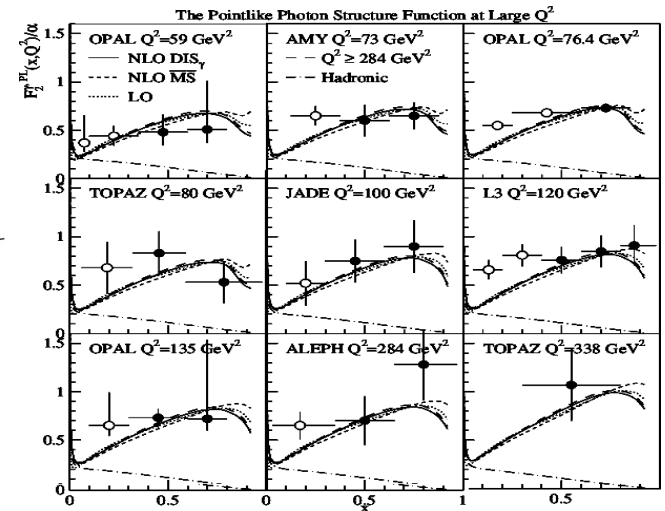
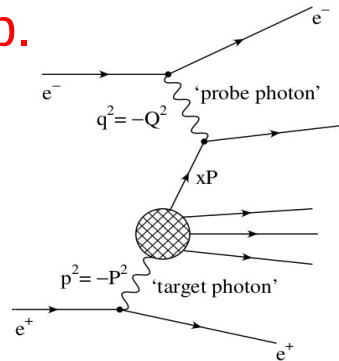
➔ Poor $F_2^\gamma(x, Q^2)$ experimental measurements:

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

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

(±4.5%)

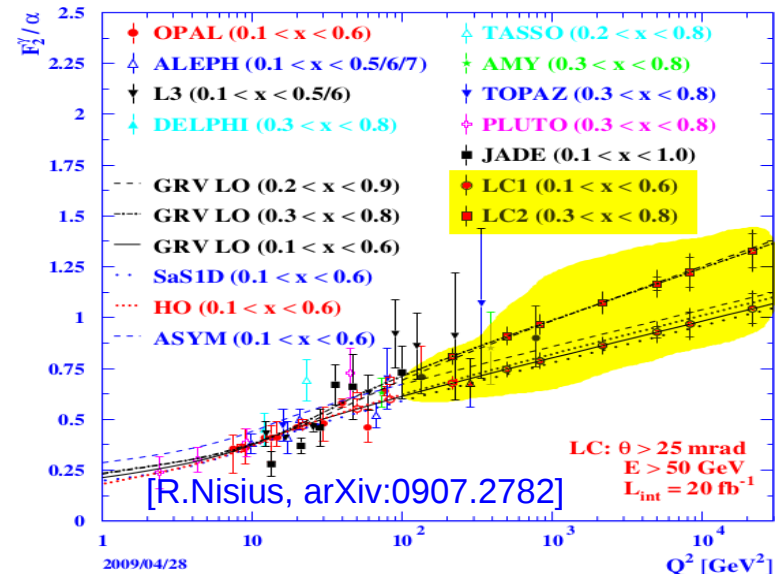
[M.Klasen et al. PRL89 (2002)122004]



➔ Future prospects:

- Better data badly needed.
- Belle-II ?
- Dedicated studies at ILC exist:
- Huge $\gamma\gamma$ (EPA) stats at

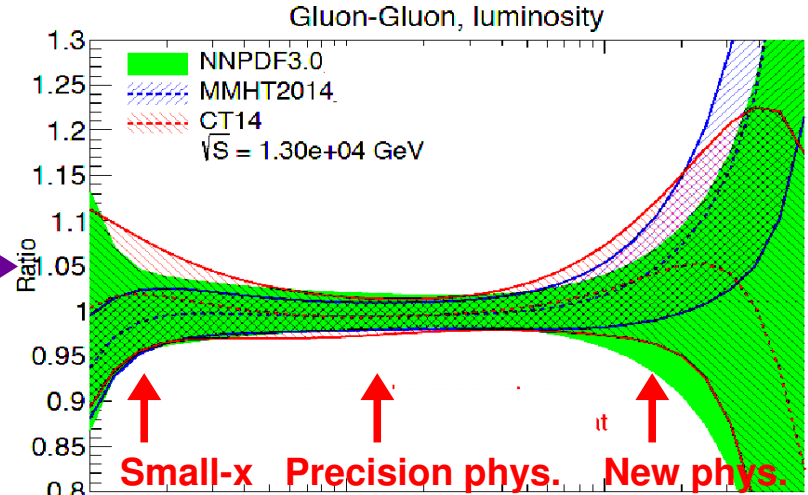
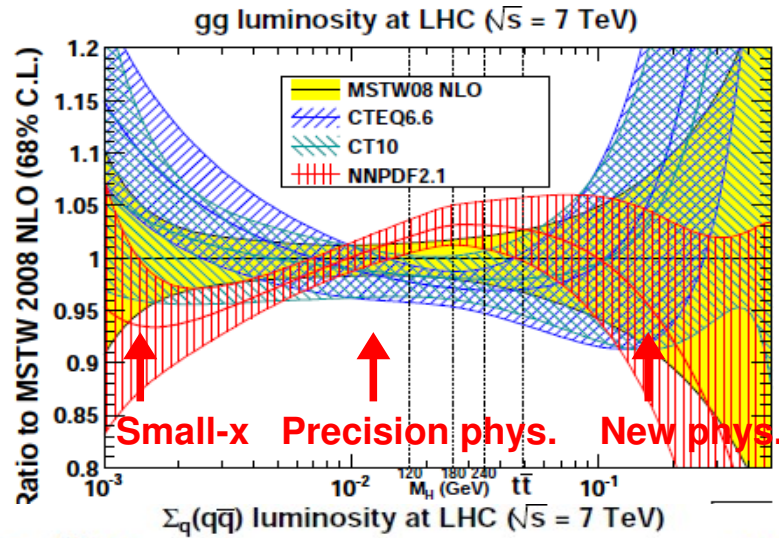
FCC-ee will lead to: $\delta\alpha_s < 1\%$



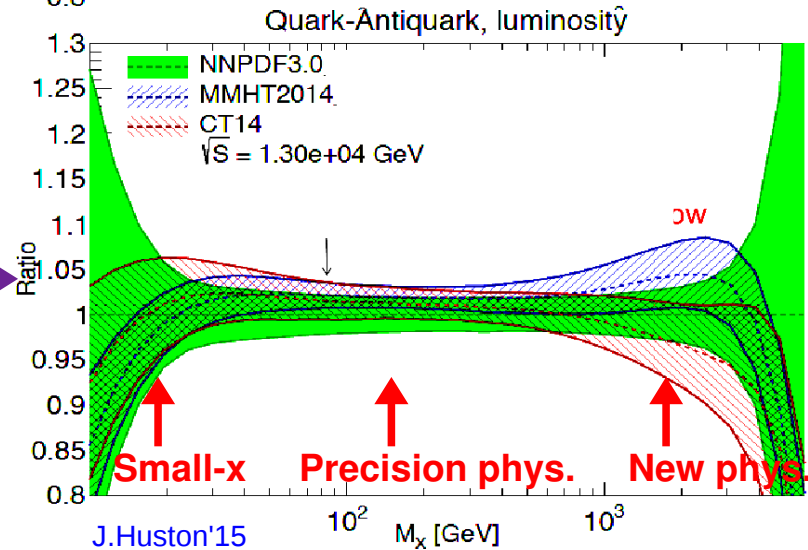
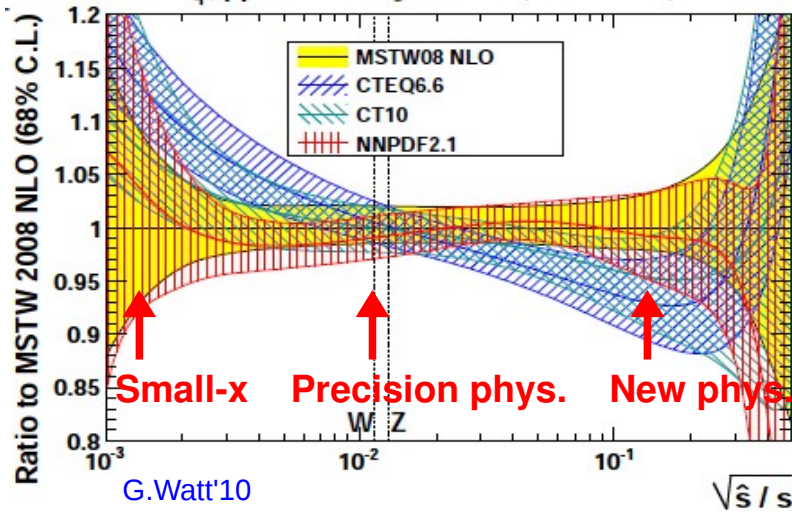
Parton densities

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

GLUONS



QUARKS



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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**:

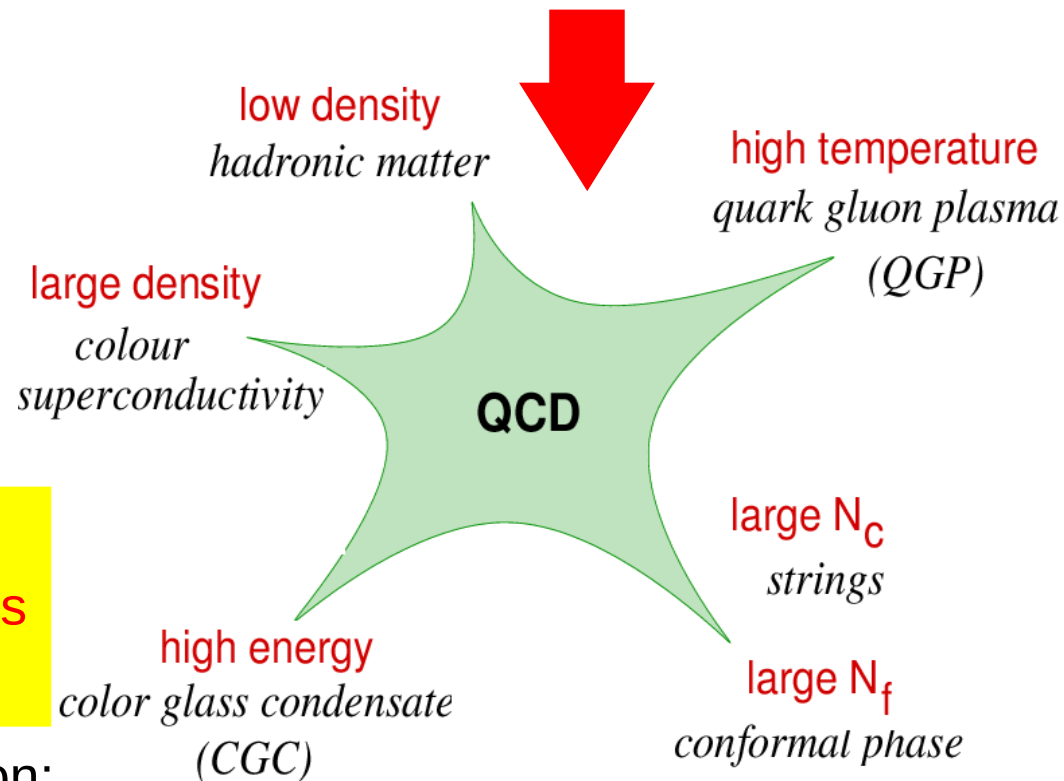
- QCD = **ONLY non-Abelian QFT whose collective dynamics can be studied in the lab !**

Insight for EWK phase transition:

Hydrodynamics expansion? New (quasiparticle) degrees of freedom?

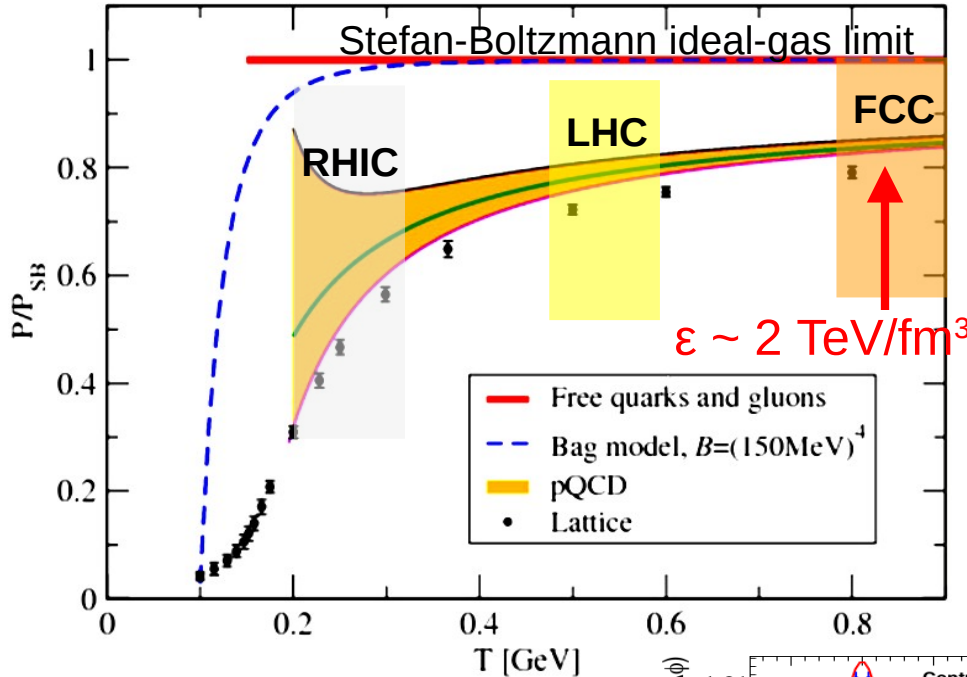
$$\mathcal{L} = \frac{1}{4g^2} G_{\mu\nu}^a G_{\mu\nu}^a + \sum_f \bar{\psi}_f (i\gamma^\mu D_\mu + m_f) \psi_f$$

where $G_{\mu\nu}^a \equiv \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + f_{bc}^a A_\mu^b A_\nu^c$
and $D_\mu \equiv \partial_\mu + i t^a A_\mu^a$

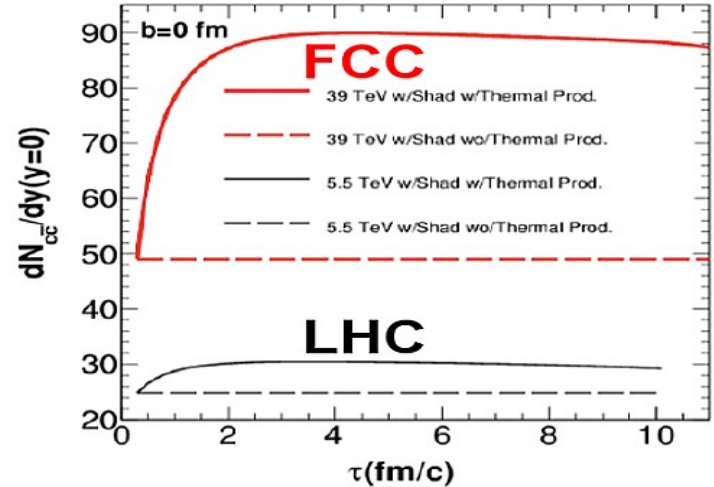


Many-body QCD (FCC-AA)

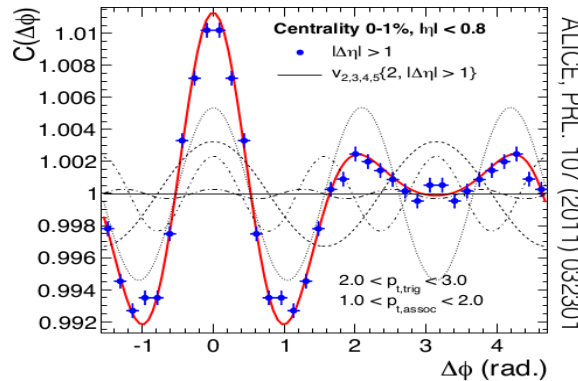
■ QCD Equation-Of-State probed at TeV/fm^3 : Even heavy-Q thermalize...



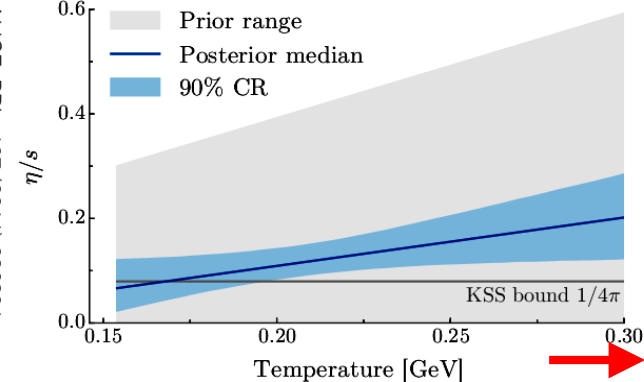
PbPb(39TeV): Very abundant pQCD probes: $gg \rightarrow c\bar{c}$, $q\bar{q} \rightarrow c\bar{c}$



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



QGP viscosity J. E. Bernhard et al, arXiv: 1605.03954



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