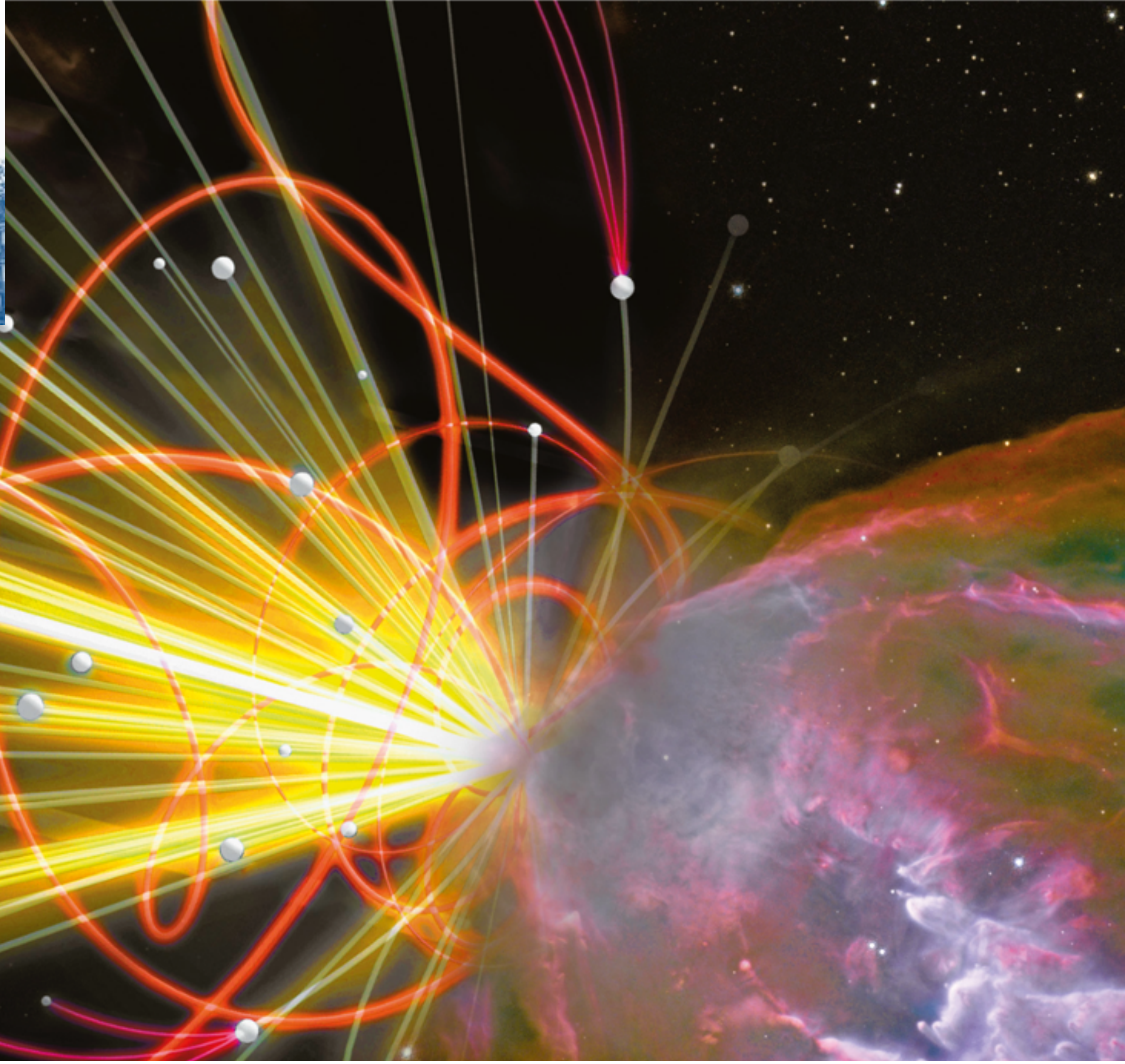
2026 UPDATE
OPEN SYMPOSIUM
European Strategy for Particle Physics

23-27 JUNE 2025

CERN | INFN



Precision QCD and hadron/nuclear structure

Andrea Dainese (INFN Padova),
Cristinel Diaconu (CPPM Marseille),
Chiara Signorile-Signorile (MPP Munich)

for the Strong Interactions Working Group WG2

andrea.dainese@pd.infn.it,
diaconu@cppm.in2p3.fr,
signoril@mpp.mpg.de

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

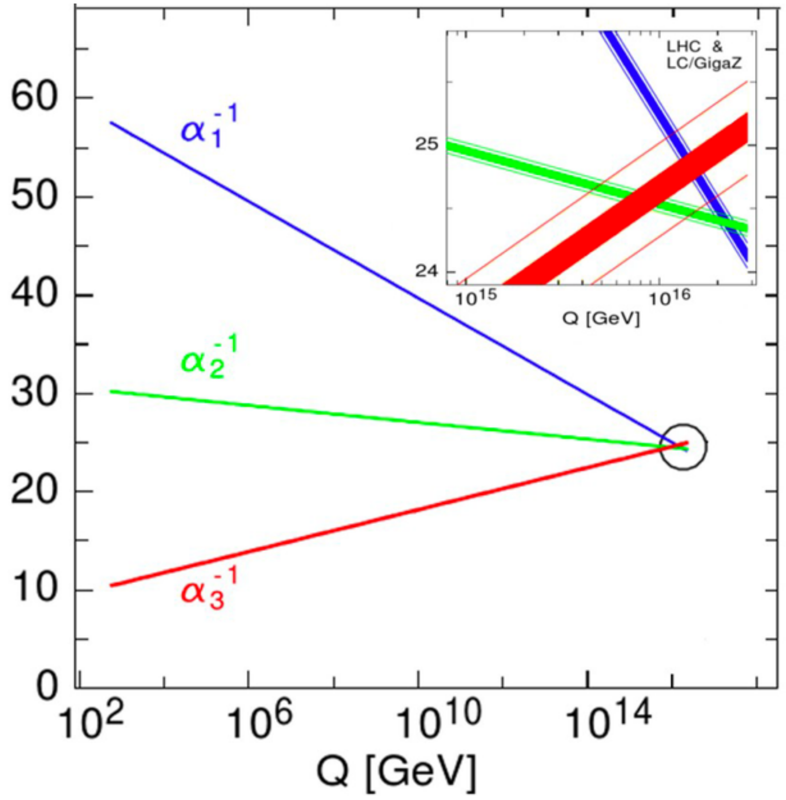
cnrs

IN2P3
Institut national de physique nucléaire et de physique des particules

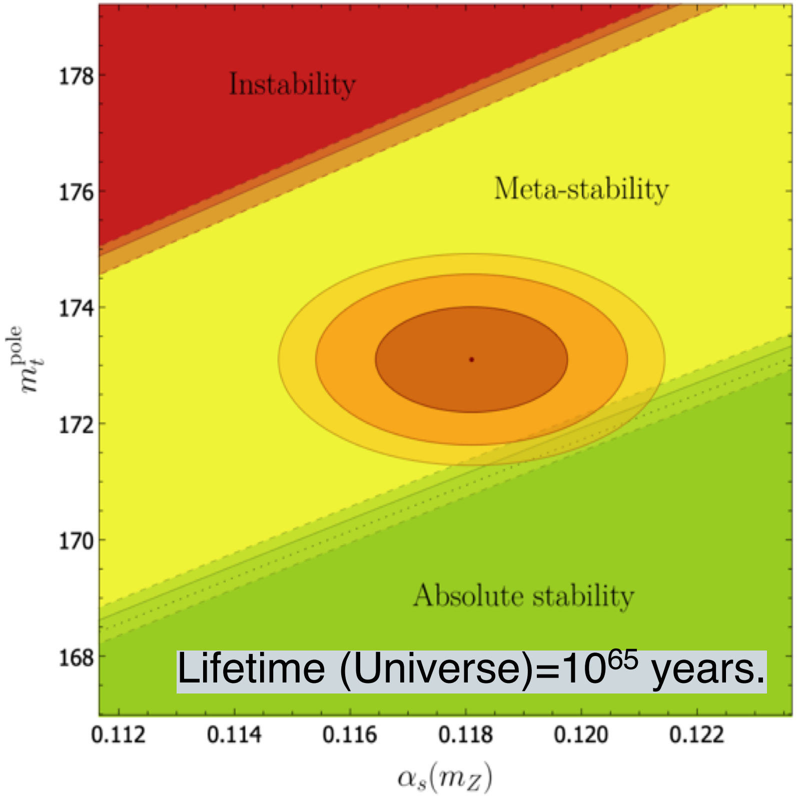
Preamble

- The strong force is everywhere and mainly responsible for the visible nuclear matter composition
- It drives vacuum (asymptotic freedom) as well as collective (confinement) phenomena accessible by experiments ; and maybe the axion?
- The **strong(est)** fundamental coupling is the **least** known amongst the four forces

$$\delta\alpha \approx 10^{-10} \ll \delta G_F \approx 10^{-7} \ll \delta G \approx 10^{-5} \ll \delta\alpha_s \approx 1\%$$



[hep-ph/0410364]



[arXiv:1707.08124]

"To rule out absolute stability to 3sigma confidence
Mtop precision 250 MeV
$\alpha_s(m_Z)$ precision below **0.00025**"

The strong interactions in four questions

European Strategy for Particle Physics

Precision QCD
- The strong coupling
- Precision EW frontier M_W,M_{top}

This talk

QCD connections with hadronic, nuclear and astro(particle) physics
- Exotic hadrons
- Antinuclei in Cosmic Rays

Internal structure of hadrons and nuclei
- (n)PDF

Next Talk

Hot and dense QCD
- Heavy flavour
- Thermal radiation

Strong Interactions WG: physics areas and experts

- **Conveners:**

Andrea Dainese
Cristinel Diaconu

- **Scientific Secretary:**

Chiara Signorile-Signorile

Precision QCD


David d'Enterria, Sven Olaf Moch

Hot and dense QCD



Roberta Arnaldi, Raimond Snellings, Urs Wiedemann

Internal structure of protons and nuclei


Nestor Armesto , Andy Buckley

QCD connections with hadronic, nuclear and astro(particle)physics



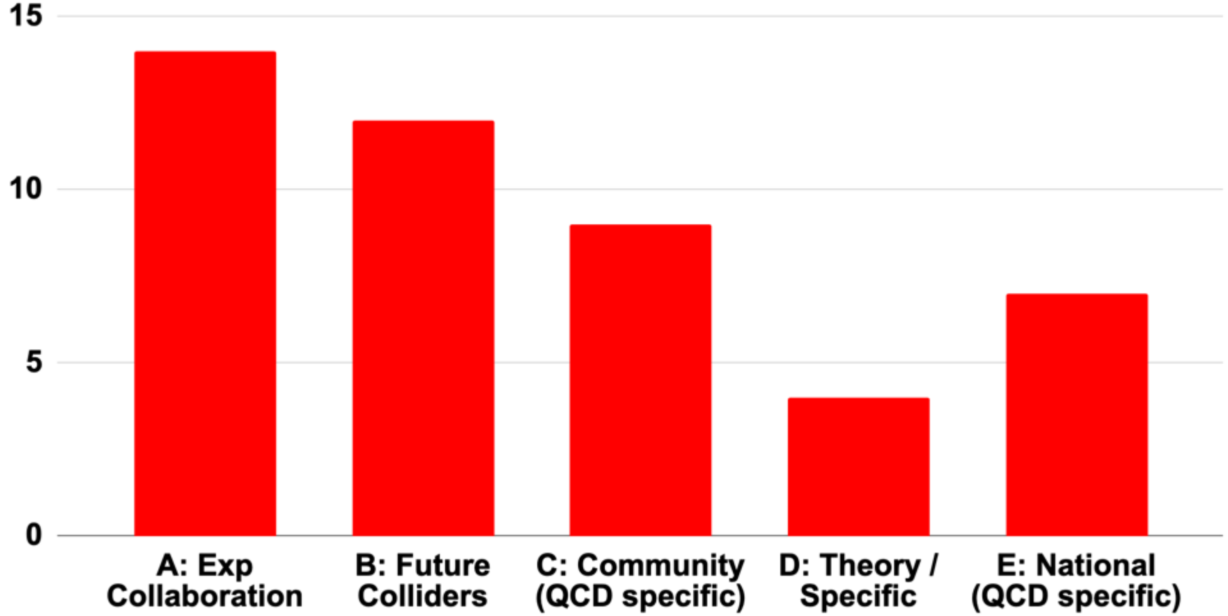
Antoine Gerardin, Valentina Mantovani Sarti, Marco Pappagallo

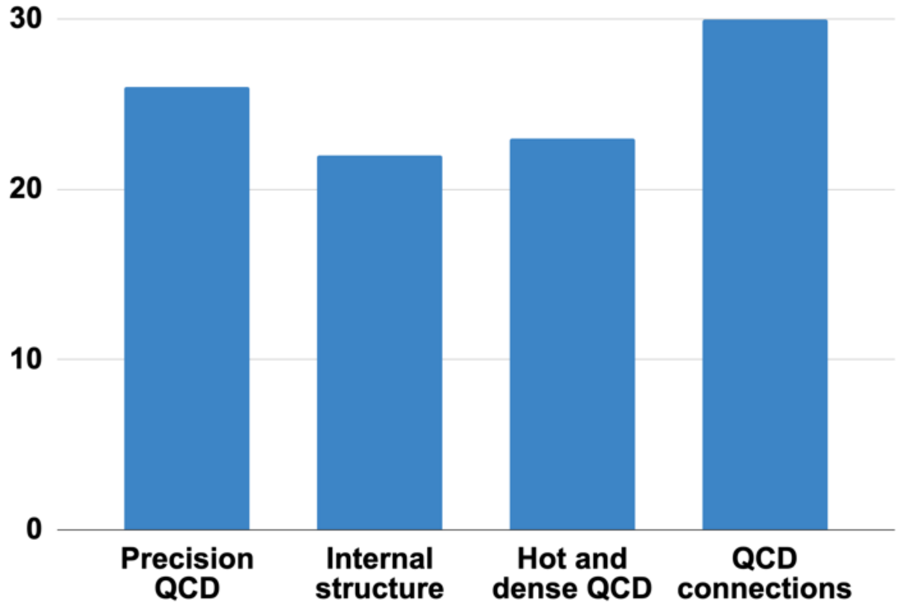
Many thanks to all contributors and in particular: David Dobrigkeit Chinellato, Gianluca Usai Jasmine Therese Brewer, Claire Gwenlan, Maria Ubiali, Thomas Cridge, Hannu Paukkunen Valerio Bertone, Michael Peskin, Pier Francesco Monni, Daniel Britzger, Anselm Vossen,, Win Lin, Marek Karliner, Fiorenza Donato, David Wilson

ESPP 2026 SI Submitted Input Documents

- **47 Input Documents w**as 35 for ESPPU 2020
  - All 2020 physics areas covered, in general more documents per area
  - Most of them from large collaborations and experiments
- **Methodology**
  - Inputs have been assigned to subareas
  - Extra input collected
  - Two open workshops: 14 and 28 Mai 2025
    - https://indico.cern.ch/event/1527574/

Many thanks to all involved people





Future Experiments

- According to the received input and further discussions in the preparatory WG2 open meetings
- If this was *chemistry:*

"Target" \ "Probe"	e	mu	nu	p	A
e	Belle II, FCCee,STCF, LCF,LEP3				
mu	MUonE	mu-coll			
nu			Mu-coll		
p	EIC, LHeC			LHC,FCChh	
A	EIC, LHeC	FPF	FPF	LHC,FCChh	LHC, SPS,FCChh,FAIR

The "lab" is well equiped!

$E_{process}$ ~ GeV ➔ 50 TeV ~6 orders of magnitude

Facility, Experiments	Colliding systems, c.m.s. energy	Timelin	Precision QCD	Partonic dynamics in protons and nucleons	Hot and dense QCD	QCD connections (hadronic, nuclear, astrophysics)
HL-LHC: ALICE 3, ATLAS & CMS pII, LHCb U2, LHCspin	pp 14 TeV AA 5.5 TeV pA 8.8 TeV	> 2035 (ALICE 3, LHCb U2)	$\alpha_s(m_Z^2)$, $\alpha_s(Q^2)$, m_t, m_W	(n)PDF, TMD, small x, intrinsic charm	Precision charm, beauty, and hard e.m. probes, μ_B=0; time evolution	Hadr. int., (hyper/charm)nuclei, Exotica, Cosmic antinuclei, Neutron Star EoS
HL-LHC: FPF	LHC collisions, neutrino-nucleon	> 2031		(n)PDF, small x, intrinsic charm		Cosmic rays (neutrinos)
SPS: NA60+, NA61	pA, AA, 6-17 GeV	> 2030 (NA60+)		nPDF, medium/large x	Charm, dileptons, critical point?, μ_B=200-450MeV	Cosmic antinuclei, neutrinos
FAIR SIS-100: CBM	pA, AA, 2.5-5 GeV	> 2028			Hadrons, dilept., critical point?, μ_B =500-700MeV	(Hyper)nuclei
AMBER	μ,π,K,p(250 GeV)-N	> 2030				K properties, spectroscopy, Cosmic antinuclei
MUonE	μ(160 GeV)-e	> 2030	g-2 (hadronic)			
HIE-ISOLDE upgrades	Radioactive ion beams	> 2029				Nucl. phys. Inputs NS EoS
KEK: Belle II upg.	ee 10 GeV	> 2035	$\alpha_s(m_\tau^2)$			Exotica (c,b)
STCF	ee 2-7 GeV	> 2033	$\alpha_s(m_\tau^2)$			Exotica (c)
EIC	ep, eA 28-140 GeV	> 2036	$\alpha_s(m_Z^2)$, $\alpha_s(Q^2)$	(n)PDF, TMD, GPD, medium/large x		Exotica (c,b)
LHeC	ep, eA 1.2 TeV	> 2043	$\alpha_s(m_Z^2)$, $\alpha_s(Q^2)$	(n)PDF, TMD, GPD, small to large x		Exotica (c,b)
FCC	ee 90-365 GeV pp 85 TeV AA 33.5 TeV pA 53.4 TeV	> 2047 > 2074	$\alpha_s(m_Z^2)$, $\alpha_s(Q^2)$, m_t, Γ_t, m_W	(n)PDF, TMD, small to large x	New probes of time evolution, early times, μ_B=0	Cosmic rays (modeling primary interaction)
LCF CLIC	ee 0.25-1 TeV ee 0.38-1.5 TeV	> 2050	$\alpha_s(m_Z^2)$, $\alpha_s(Q^2)$, m_t, Γ_t, m_W			
LEP3	ee 91-230 GeV	> 2047	$\alpha_s(m_Z^2)$			
Muon Collider	$\mu\mu$ 3-10 TeV	> 2050	$\alpha_s(m_Z^2)$, $\alpha_s(Q^2)$	PDF using sec. neutrino beam		

C. DIACONU
CPPM | CNRS/IN2P3 and Aix Marseille Université

Future Experiments

- According to the received input and further discussions in the preparatory WG2 open meetings
- If this was *chemistry:*

“Target” \ “Probe”	e	mu	nu	p	A
e	Belle II, FCCee,STCF, LCF,LEP3				
mu	MUonE	mu-coll			
nu					
p	EIC, LHeC			LHC,FCChh	
A	EIC, LHeC	FPF Amber	FPF	LHC,FCChh	LHC, SPS,FCChh,FAIR

The “lab” is well equiped!
$E_{process}$ ~ 0,1 GeV ➔ 10^2 TeV ~6 orders of magnitude

Facility, Experiments	Colliding systems, c.m.s. energy	Timeline	Precision QCD	Partonic dynamics in protons and nucleons	Hot and dense QCD	QCD connections (hadronic, nuclear, astrophysics)
HL-LHC: ALICE 3, ATLAS & CMS pII, LHCb U2, LHCspin	pp 14 TeV AA 5.5 TeV pA 8.8 TeV	> 2035 (ALICE 3, LHCb U2)			Precision charm, beauty, hard and e.m. probes, μ_B=0; time evolution	Hadr. int., (hyper/charm)nuclei, Exotica, Cosmic antinuclei, Neutron Star EoS
HL-LHC: FPF	LHC collisions, neutrino-nucleon	> 2031				Cosmic rays (neutrinos)
SPS: NA60+, NA61	pA, AA, 6-17 GeV	> 2030 (NA60+)			Charm, dileptons, critical point?, μ_B=200-450MeV	Cosmic antinuclei, neutrinos
FAIR SIS-100: CBM	pA, AA, 2.5-5 GeV	> 2028			Hadrons, dilept., critical point?, μ_B =500-700MeV	(Hyper)nuclei
AMBER	μ, π, K, p(250 GeV)-N	> 2030				K properties, spectroscopy, Cosmic antinuclei
MUonE	μ(160 GeV)-e	> 2030				
HIE-ISOLDE upgrades	Radioactive ion beams	> 2029				Nucl. phys. Inputs NS EoS
KEK: Belle II upg.	ee 10 GeV	> 2035				Exotica (c,b)
STCF	ee 2-7 GeV	> 2033				Exotica (c)
EIC	ep, eA 28-140 GeV	> 2036				Exotica (c,b)
LHeC	ep, eA 1.2 TeV	> 2043				Exotica (c,b)
FCC	ee 90-365 GeV pp 85 TeV AA 33.5 TeV pA 53.4 TeV	> 2047 > 2074			New probes of time evolution, early times, μ_B=0	Cosmic rays (modeling primary interaction)
LCF CLIC	ee 0.25-1 TeV ee 0.38-1.5 TeV	> 2050				
LEP3	ee 91-230 GeV	> 2047				
Muon Collider	$\mu\mu$ 3-10 TeV	> 2050				

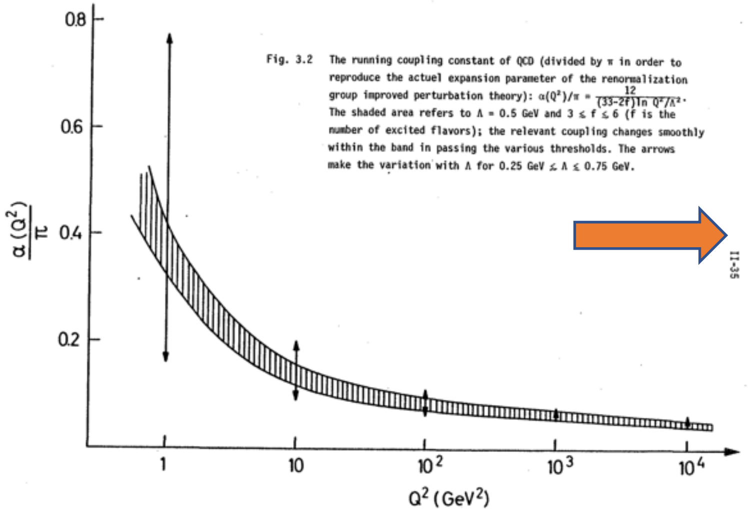
Benchmarks
α_s, M_{top}, M_W
(n) PDF

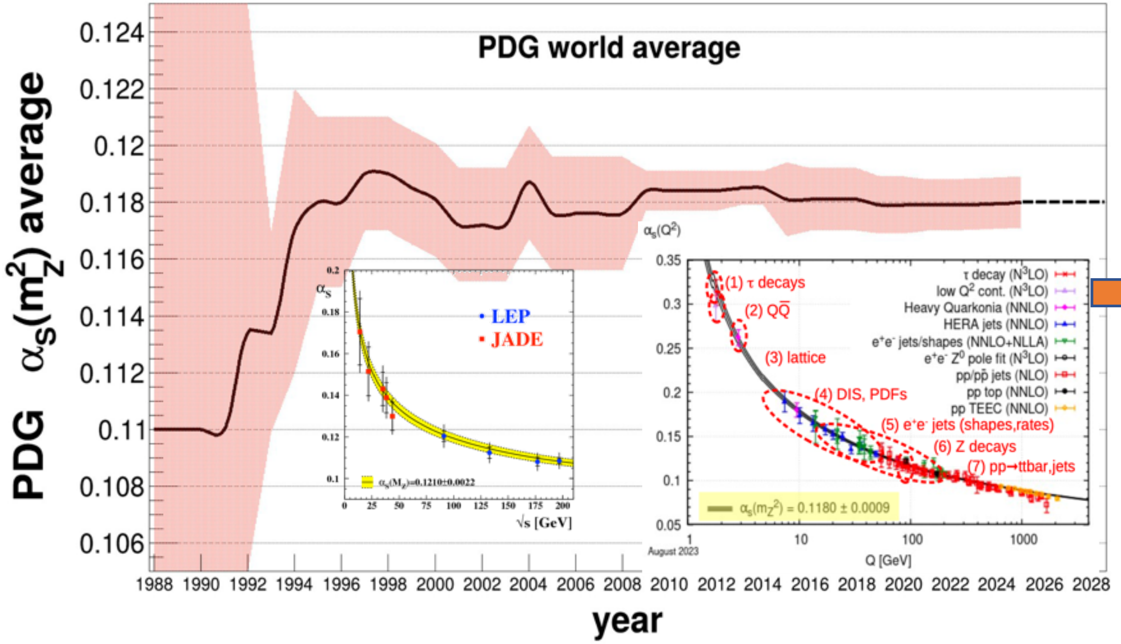
C. DIACONU
CPPM | CNRS/IN2P3 and Aix Marseille Université

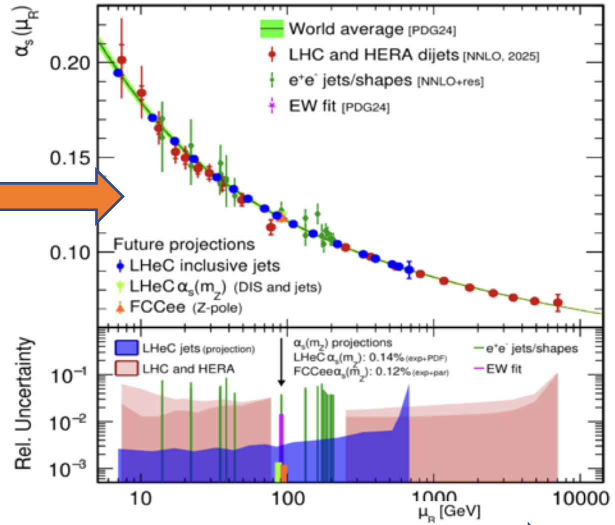
Strong interactions and QCD: the coupling α_s

Measured since > 4 decades
Uncertainty/2 in 25 years

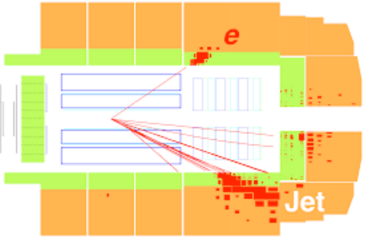
DESY-HERA-80-01, ECFA-80-42

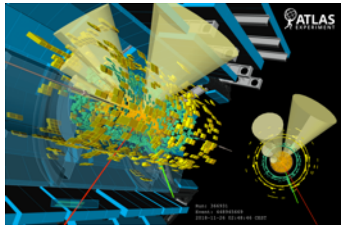






1980 2000 2025 2050





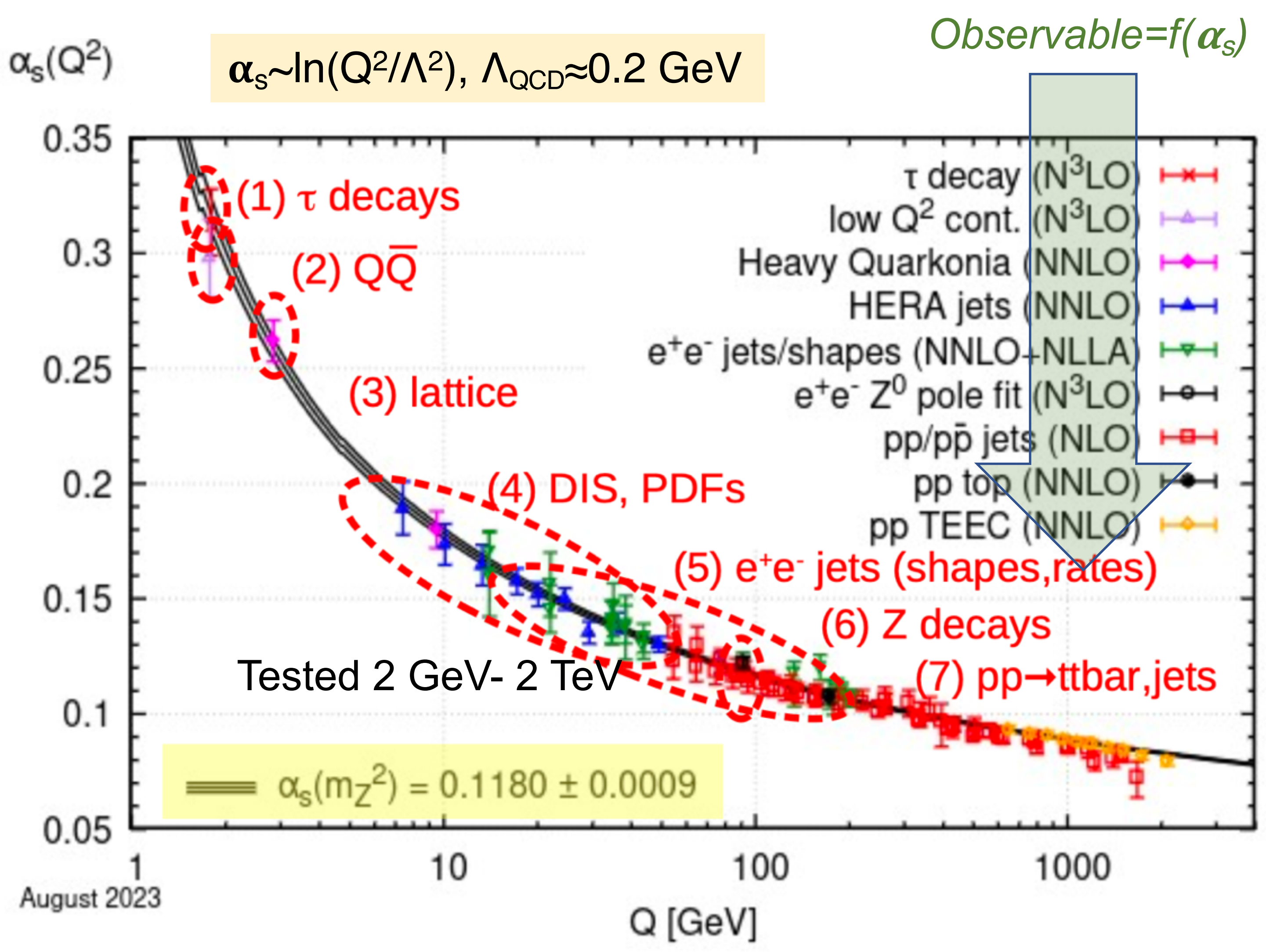
Is it possible to gain an order of magnitude in precision?
When and how?

C. DIACONU
CPPM | CNRS/IN2P3 and Aix Marseille Université

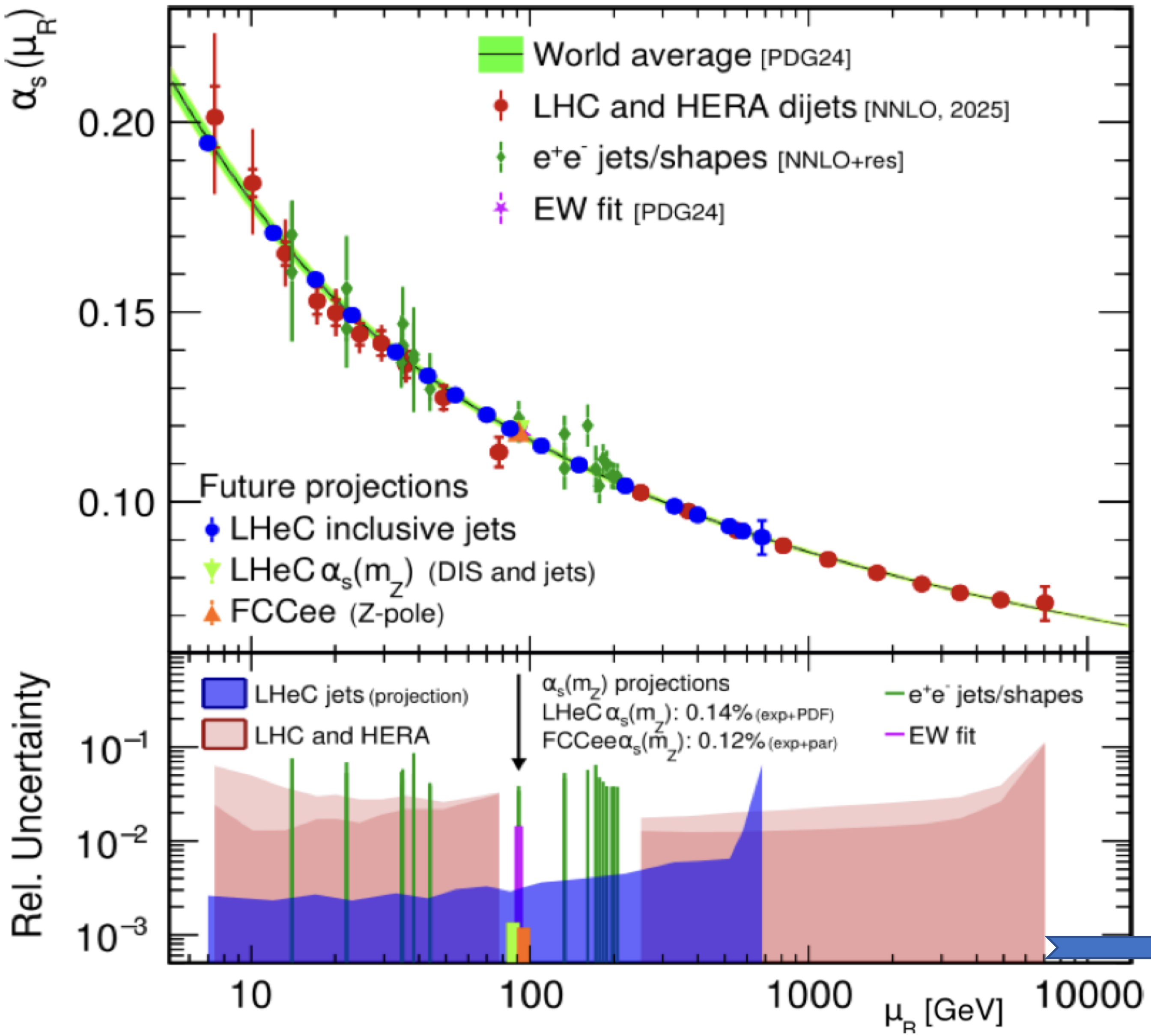
Measure the strong coupling α_s

- 9 methods (e+e-, ep, pp)
- The relation *Observable=f(α_s)* has to be known precisely
- Various methods span different energy scales
- Current world average:
  - $\alpha_s(m_Z^2) = 0.1180 \pm 0.0009$
  - 0.76% uncertainty

1) $\alpha_S(m_Z)$ and its Q^2 dependence.



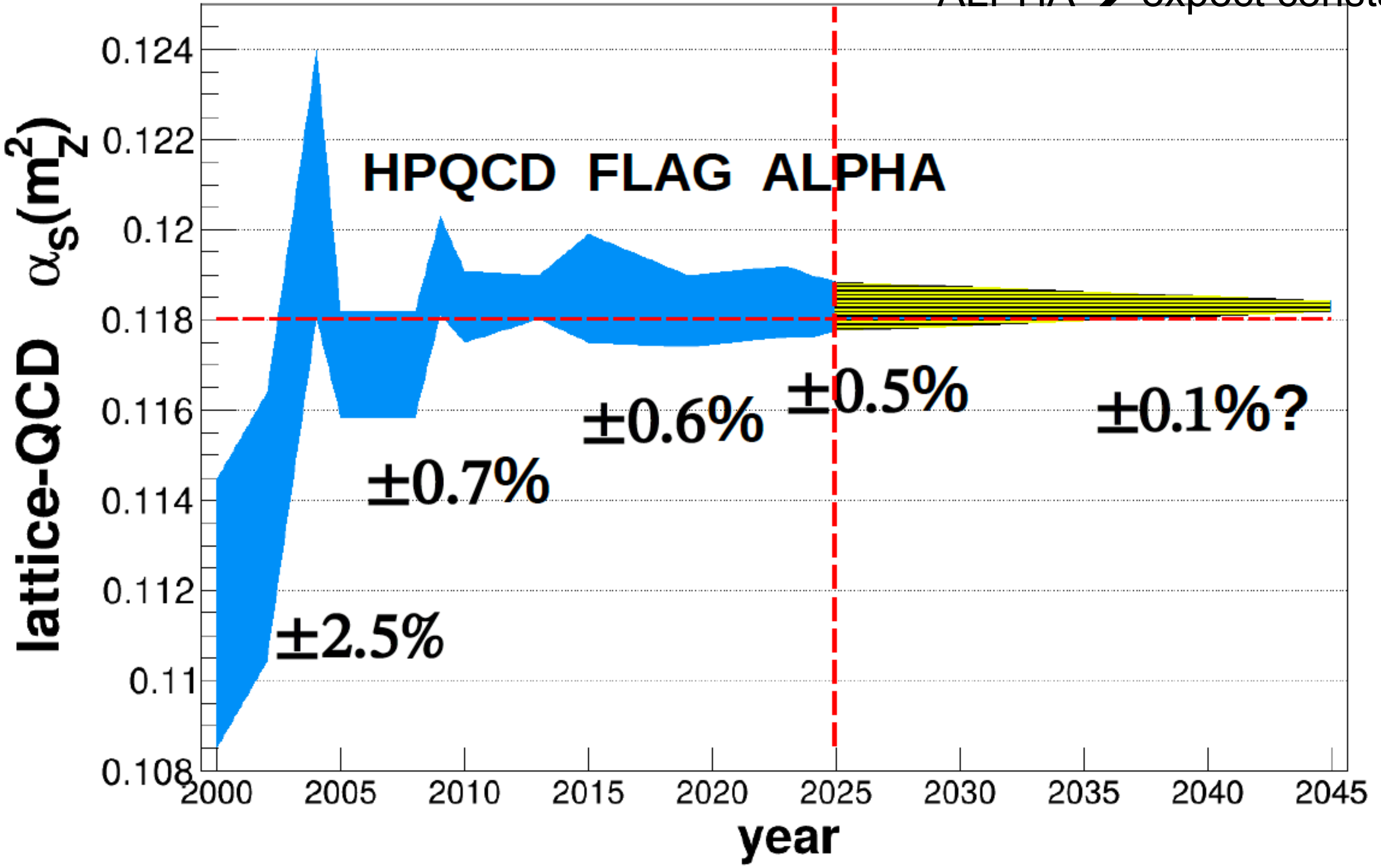
α_s Precision Prospects: experiment and theory



LHeC **5-500 GeV**	Inclusive DIS +jets	0.2% 0.15%		
EIC/ JLAB **3-30 GeV**	Inclusive DIS Observables (deuteron & spin SF): 0.6% Bjorken SR & pol. PDFs.	1% 0.6% 0.6%		
STCF **1.8 GeV**	Tau hadronic	<<1%		
Belle II (u) **1.8-10 GeV**	Tau spectral functions	<<1%		
		FCC	**LC**	**LEP3**
e+e- **91.2 GeV**	Z Pseudo-Observables	0.1%	0.6%	0.2%
80.4 GeV	W hadronic decays	0.2%		0.9%
1.77 GeV	Tau hadronic	<<1	<1%	<1%
20--350 GeV	evt. shapes & jet rates	<<1	<1%	<1%
Lattice 2045		0.1%		
FCChh **→50 TeV**	jet cross sections/fits	<<1%		

Lattice calculations α_s

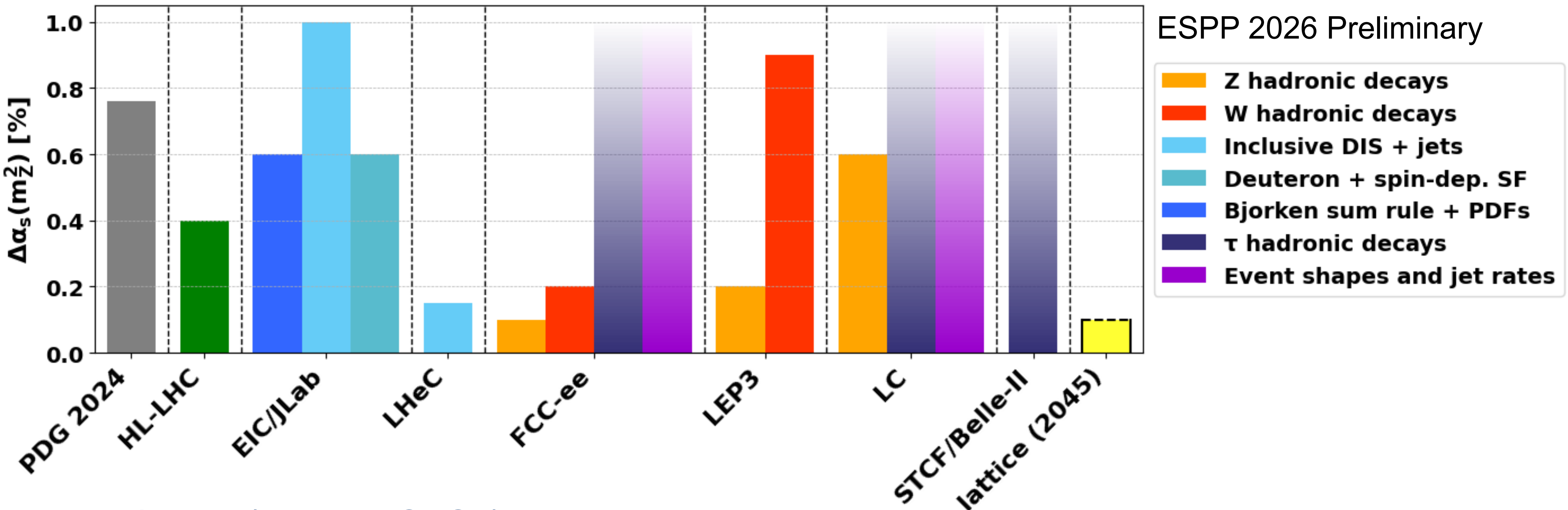
Lattice: FLAG24 + PDG result (0.6% relative error) 0.5
ALPHA ➔ expect constant improvements : 0.1% in 2045 ?



S. Moch / D. d'Enterria

The computing and methodology remain important challenges
– Step-scaling & decoupling are state-of-the-art techniques.
– Stat. uncert.∝(computing power)2 reducible by ~1/2 every 10 yrs
– pQCD observables needed at higher accuracy
– Syst. uncerts. start playing a role: QED, dynamical charm mass,...

α_s projected precision

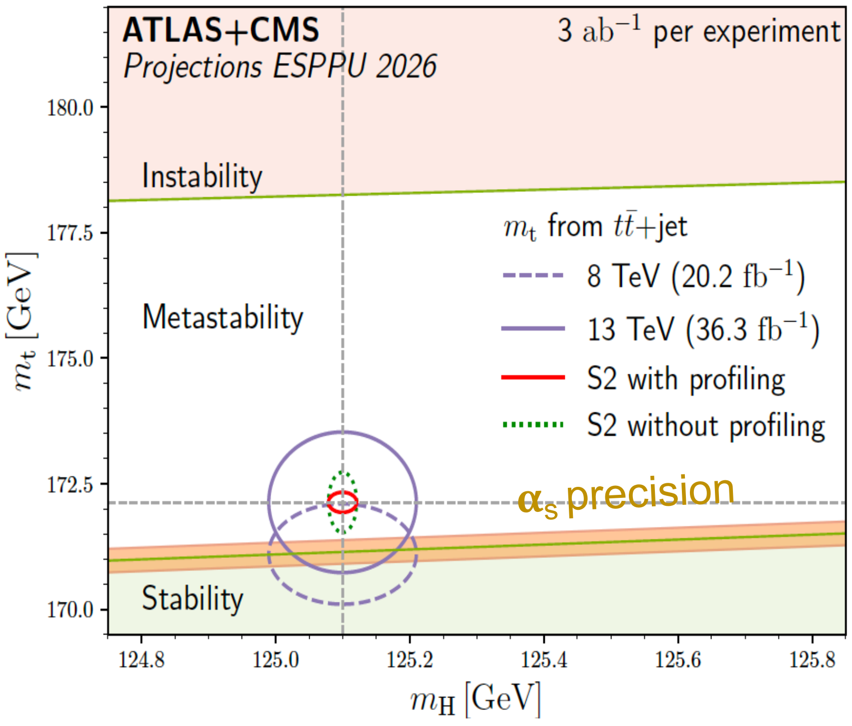


- <1% stat. (Belle-II, STCF) precision reachable at tau facilities.
- O(0.15%) stat. precision reachable at LHeC *(EIC 0.5) ; LEP3 0.2%*
- **<0.1%** (combining extractions) precision reachable at FCC-ee.
- Lattice 0.1% by 2045?
- Theory limitations have to be overcome

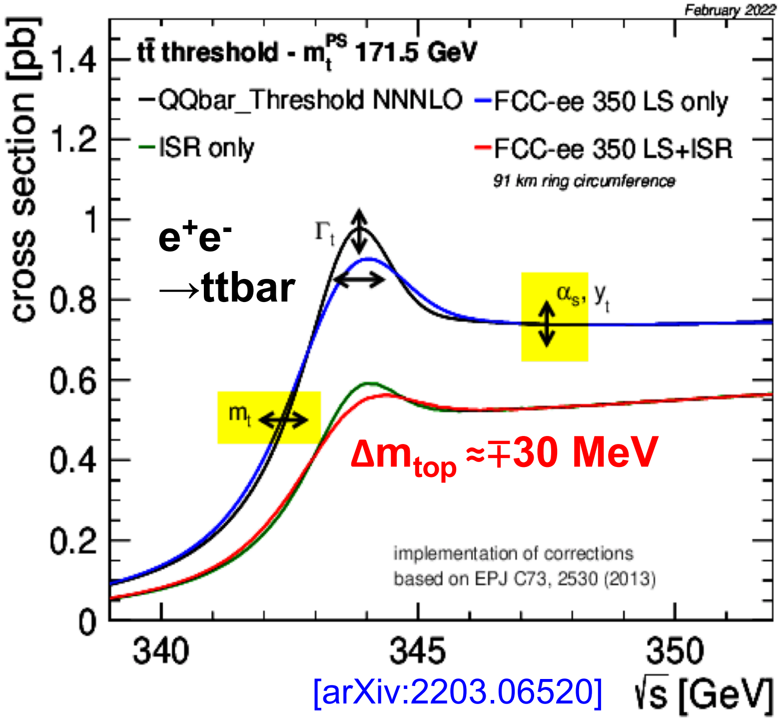
M_{top} Prospects

- HL-LHC :
  - Precise top mass is essential for the SM consistency checks
  - mtop(pole) from ttbar+jet x-sections: 200 MeV (limit Λ_{QCD} for hadronic machines)
  - mtop(MC) from boosted tops: 400 MeV (theoretical interpretation?)
- FCC_{ee} LCF (LC/CLIC)
  - e+e- collisions from threshold scan $\sqrt{s}$ = 340 GeV (FCC-ee)

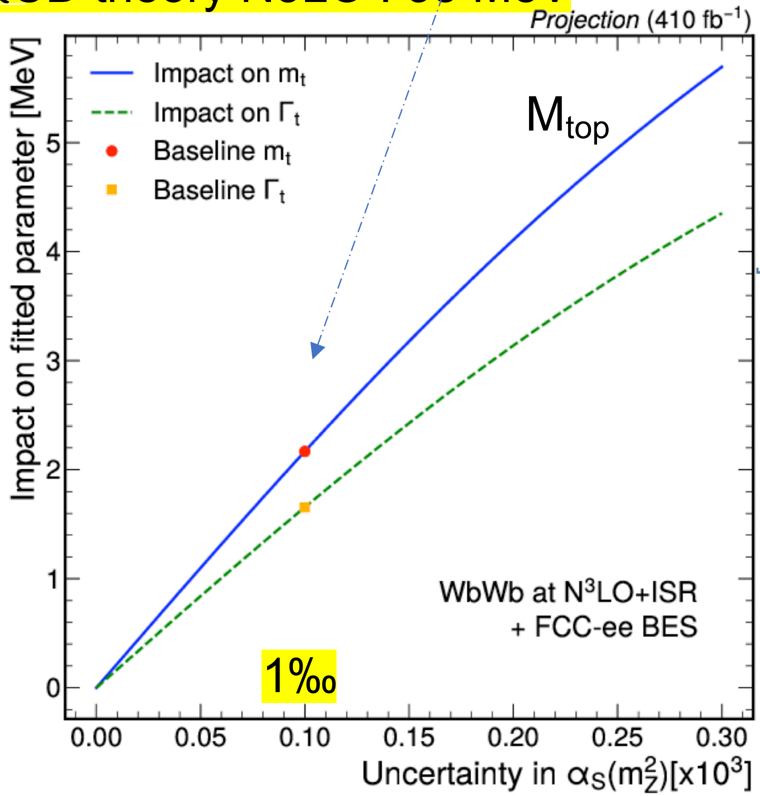
Uncertainties from theory:
- Parametric uncertainty α_s 1‰ ➔ 2 MeV
- QCD theory N3LO : 35 MeV



ATLAS&CMS projections ESPP2026
Vaccum stability predictions adapted arXiv:1507.08833



[arXiv:2203.06520]



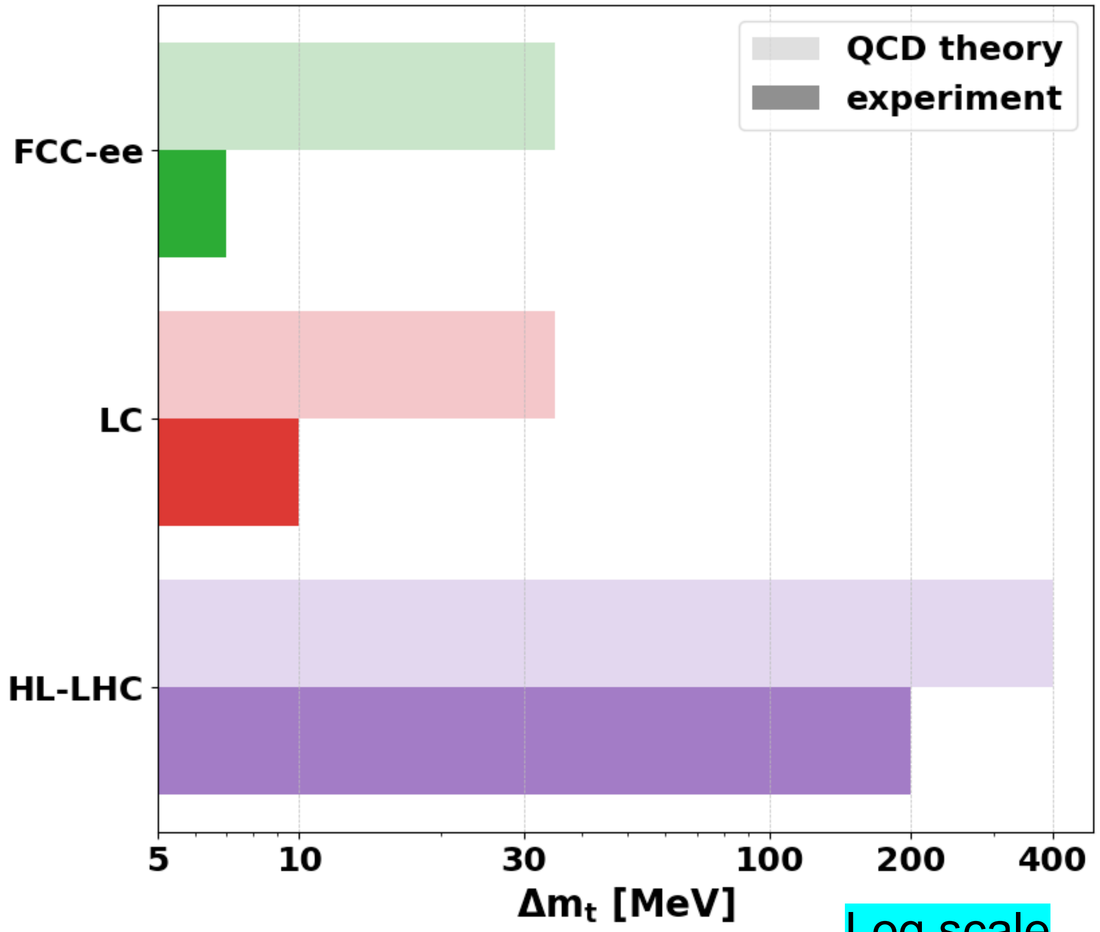
arXiv:2503.18713

C. DIACONU
CPPM | CNRS/IN2P3 and Aix Marseille Université

M_{top} Precision

Table 1.3: Experimental and theoretical uncertainties on m_t and Γ_t expected at HL-LHC, FCC-ee, and LC (CLIC results for 100 fb^{-1} [15] scaled to 400 fb^{-1}). The FCC-ee systematic uncertainties are mostly parametric, of which ± 2.2 MeV (± 1.6 MeV) on m_t (Γ_t) are due to the $\alpha_s(m_Z^2)$ value known with 0.1% precision.

	Collider	Uncertainties	
		Experimental	Theoretical (mostly QCD)
m_t	HL-LHC	± 200 MeV	± 400 MeV
	FCC-ee	± 4.2 MeV (stat.) ± 4.9 MeV (syst.)	± 35 MeV
	LC (CLIC)	± 10 MeV (stat.)	± 35 MeV
Γ_t	FCC-ee	± 10 MeV (stat.) ± 6 MeV (syst.)	± 25 MeV
	LC (CLIC)	± 25 MeV (stat.)	± 25 MeV



Log scale

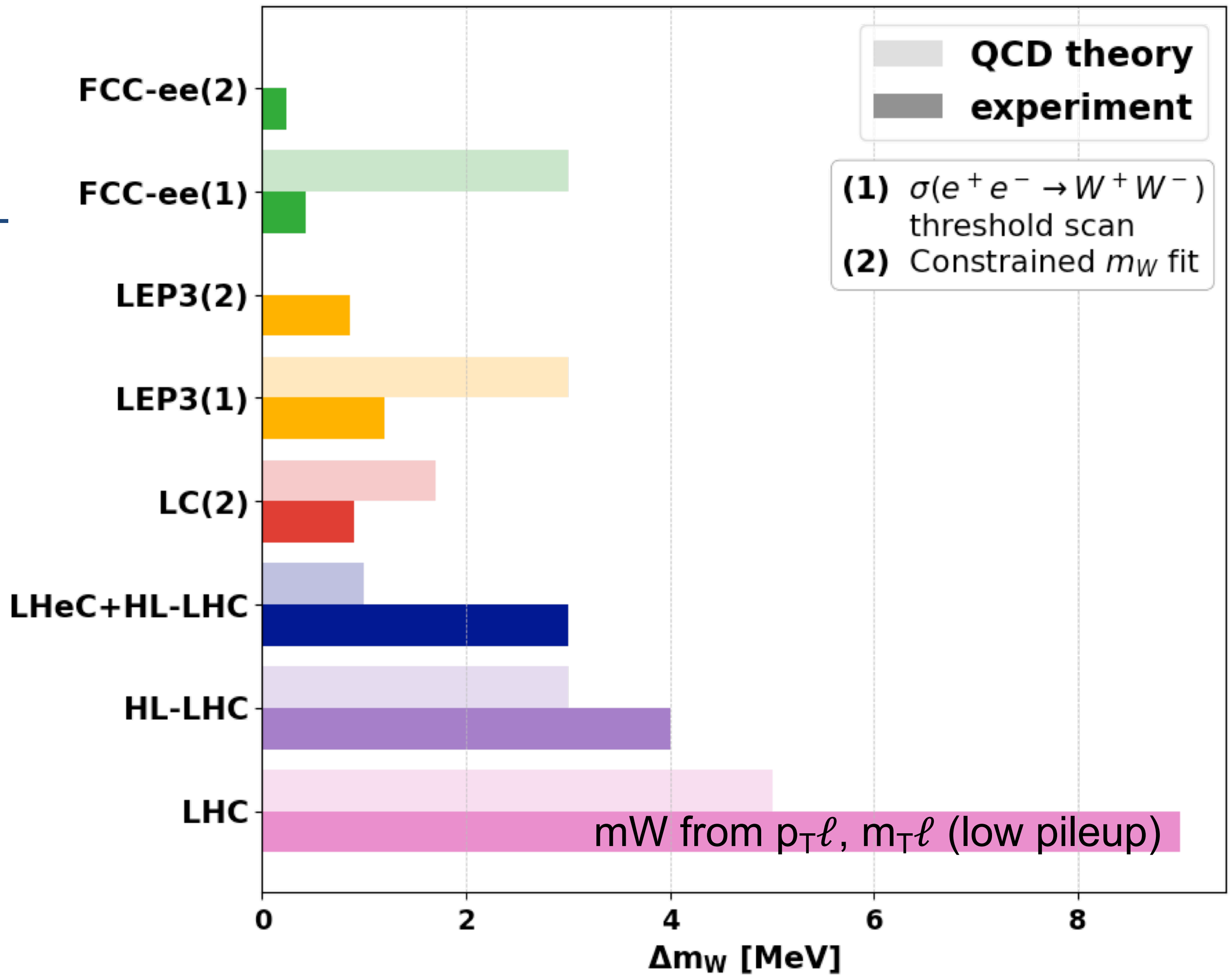
e+e- factor 20-30 improvement in experimental precision

Important pQCD theory developments needed!

σ(e+e-→ttbar) at threshold: N4LO at least

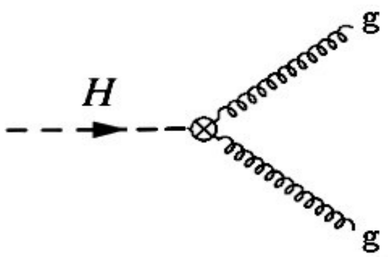
M_W precision prospects

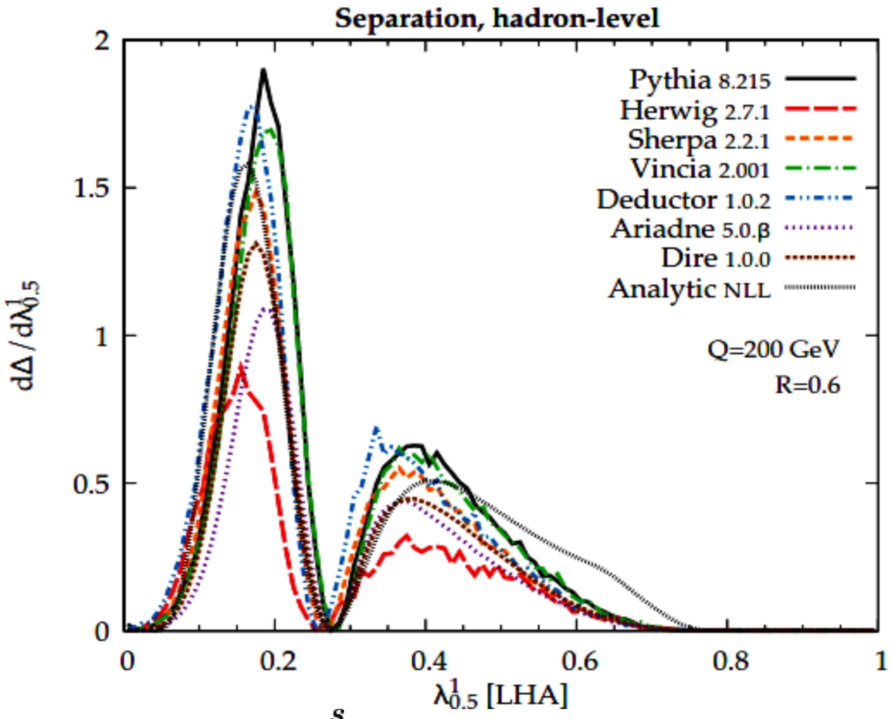
- ~4 MeV in 2045 (HL-LHC)
  - +LHeC reduce PDFs+ α_s errors
  - precision: 3 MeV (QCD 1 MeV)
- $\mathcal{O}$(0.1) MeV reachable with future e+e- projects (FCC_{ee})
- Previsioned theory uncertainties evolve flatter than experiment:
  - stalled at 2-3 MeV
  - Threshold scan x-section: δmW ≈ 5 MeV (-because missing higher-order EW & EW⊗QCD corrections
  - Inv. Mass 4j and jets+l boosted analyses: non-pQCD (Colour reconnection, hadronization) between final-state decay products introduces a δmW ≈ 1 MeV uncertainty.



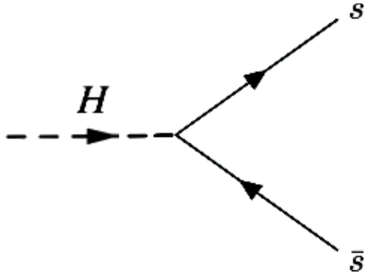
Higgs and QCD

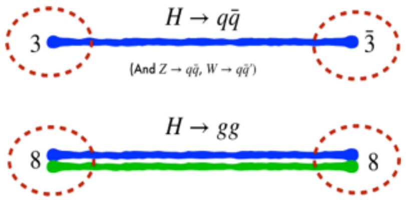
- Precision needed to fully exploit the (B)SM program at Higgs factories requires exquisite control of pQCD & non-pQCD: $\mathcal{B}(H\to had)=80\%$
  - Studying BSM in **Higgs-gluon coupling** within
    - ±0.7% (exp) requires $\alpha_s(mZ)$ within ±0.1%:
  - **Identifying gluon jets** requires significantly improved gluon fragmentation
    - in parton shower (NNLL) MCs:
    - High-stats data samples to be exploited: e+e-→Z→qq(g), e+e-→H(gg)Z
  - **Observing strange-Yukawa** requires significantly improved quark & gluon hadronization





- ☛ Dedicated studies of huge/clean hadronic Z,W→jj samples are key to H→jj physics.
  - Jet tagging, fragmentation, hadronization, Parton showers at N^nLL





Perspectives in Precision QCD

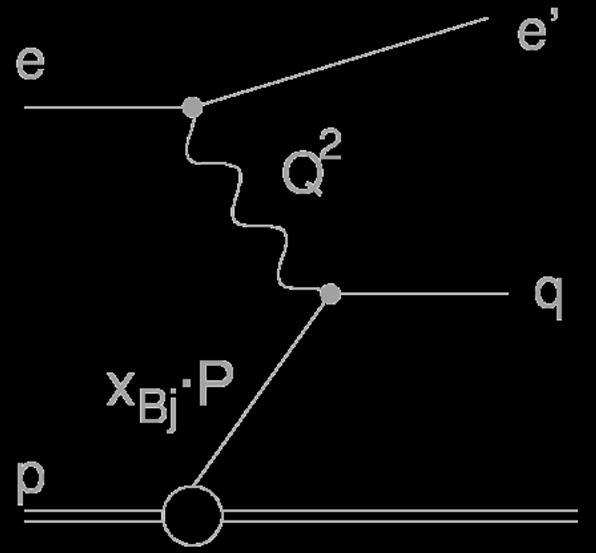
European Strategy for Particle Physics

- The expected experimental accuracy of future colliders requires a significant increase in precision QCD calculation, well beyond the current state of the art
  - Including higher order in QCD (N^5LO…) , Partons Showers(N^3LO…) Fragmentation.
- Lattice calculations will play a crucial role, but have to overcome computational and technical challenges
- Importance of high-performance computer tools
  - software/generators, formal calculations frameworks (FORM), innovation (QIT), AI for hadronization modelling et.

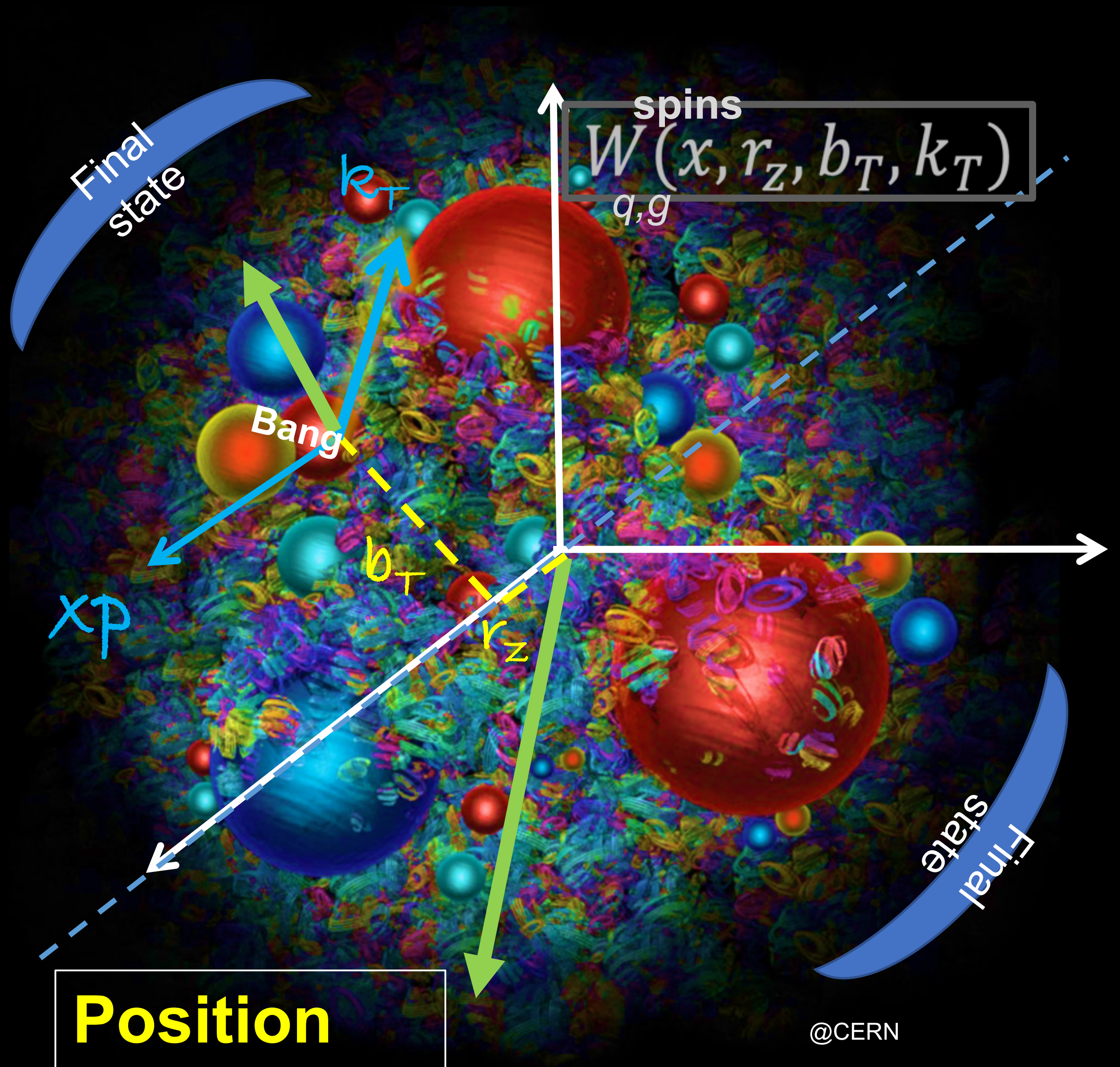
Wish-list

	Observable	Missing higher-order & power-suppressed corrections
$\alpha_s(m_Z)$ in e^+e^-	Hadronic Z width	$\mathcal{O}(\alpha_s^5)$, $\mathcal{O}(\alpha^3)$, $\mathcal{O}(\alpha_s\alpha^3)$, $\mathcal{O}(\alpha_s^2\alpha^2)$
	Hadronic W width	$\mathcal{O}(\alpha_s^5)$, $\mathcal{O}(\alpha^2)$, $\mathcal{O}(\alpha^3)$, $\mathcal{O}(\alpha_s\alpha^2)$, $\mathcal{O}(\alpha_s\alpha^3)$, $\mathcal{O}(\alpha_s^2\alpha^2)$
	Hadronic τ width	$\mathcal{O}(\alpha_s^5)$
	Hadronic event shapes (Z, W, H decays)	N^3LO differential, $N^{3,4}LL$ resummation, power corrections
	Inclusive jet rates	3-jet cross sections at N^3LO, 4-jets at N^2LO, 5-jets at NLO
$\alpha_s(m_Z)$ in latt.	Lattice QCD results	$\mathcal{O}(\alpha_s^6)$ β-function; $\mathcal{O}(\alpha_s^5)$ heavy quark decoupling; $\mathcal{O}(\alpha_s^4)$ static potential
	(α_s extractions; quark masses m_c, m_b)	$\mathcal{O}(\alpha_s^3)$ lattice perturbation theory matching (lattice coupling to $\alpha_s^{\overline{MS}}$ etc.)
m_W, m_{top} in e^+e^-	$\sigma(e^+e^- \to W^+W^-)$ vs. $\sqrt{s}$	EW N^2LO: $\mathcal{O}(\alpha^2)$, Mixed EW-QCD: $\mathcal{O}(\alpha_s\alpha^2)$, $\mathcal{O}(\alpha_s^2\alpha)$
	$\sigma(e^+e^- \to t\bar{t})$ vs. $\sqrt{s}$	NRQCD: $\mathcal{O}(\alpha_s^5)$, Non-resonant: $\mathcal{O}(\alpha_s^5)$,
		$O(\alpha_s^3)$ differential; QED: $\mathcal{O}(\alpha^3)$ at NNLL
QCD in Higgs	$H \to b\bar{b}$ width	N^4LO (massive b-quark); N^4LO differential (massless b-quark)
	$H \to gg$ width	N^5LO (heavy-top limit), N^4LO (massive top)
		N^4LO differential, N^3LO differential (massive top)
e^+e^-,e-p, p-p PS	MC simulations for $e^+e^- \to X$ processes	$N^{2,3}LO$ matched to $N^{2,3}LL$ PS.
		Permille control of non-perturbative QCD effects (hadronization, CR,...)
$\alpha_s(m_Z)$ in DIS	ep $\to$ hadrons (PDF and α_s determination)	$N^{3,4}LO$ evolution equations and inclusive cross sections
	ep $\to$ jets (α_s determination)	N^3LO cross sections

Inside the proton



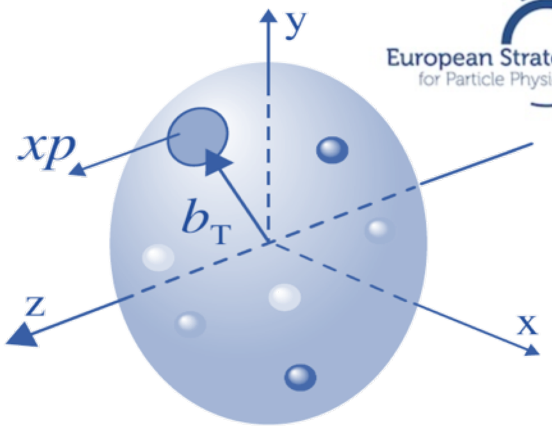
Probe
Resolution~1/Q
Up to 10^{-19}m



Position
Momentum
Spin

Structure Functions

$\int dr_z$ ← $\boxed{W(x, r_z, b_T, k_T)}$ +spin



$W(x, b_T, k_T)$
Wigner distributions

$\int d^2 b_T$ $\int d^2 k_T$

$f(x, k_T)$
transverse momentum distributions (TMDs)
semi–inclusive processes

$f(x, b_T)$
impact parameter distributions

Fourier trf.
$b_T \leftrightarrow \Delta$

$H(x,0,t)$
$t = -\Delta^2$

(Q2 implicit)

$\xi = 0$

$H(x,\xi,t)$
generalized parton distributions (GPDs)
exclusive processes

$\int d^2 k_T$ $\int d^2 b_T$

$\int dx$

$\int dx x^{n-1}$

$f(x)$
parton densities
inclusive and semi–inclusive processes

(n)PDF

$F_1(t)$
form factors
elastic scattering

$A_{n,0}(t) + 4\xi^2 A_{n,2}(t) + \ldots.$
generalized form factors
lattice calculations

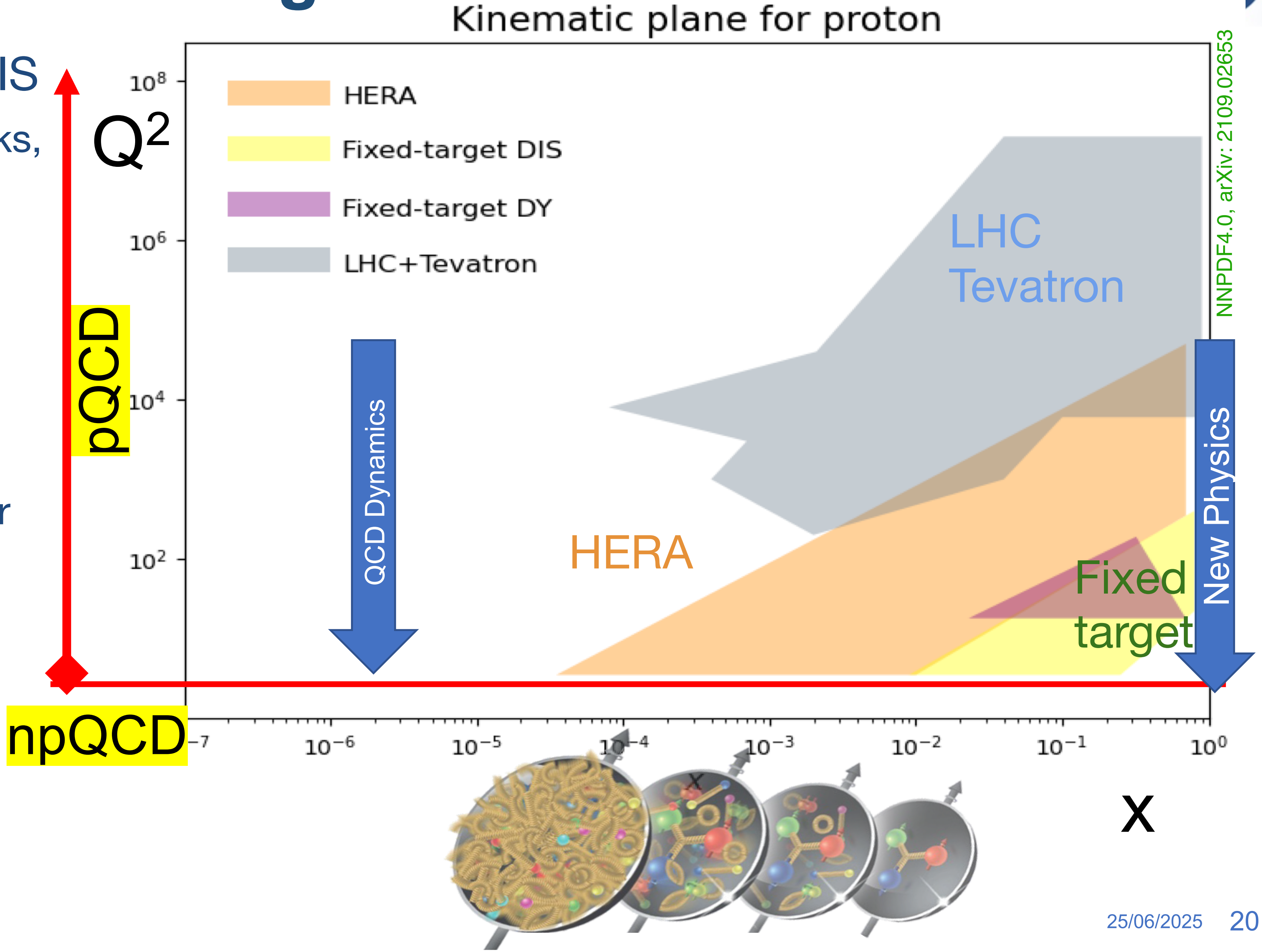
1212.1701

PDFs: messengers ➔ assuming factorisation

σ = Probe(PDF)$\circledast$Interaction$\circledast$Target (PDF)

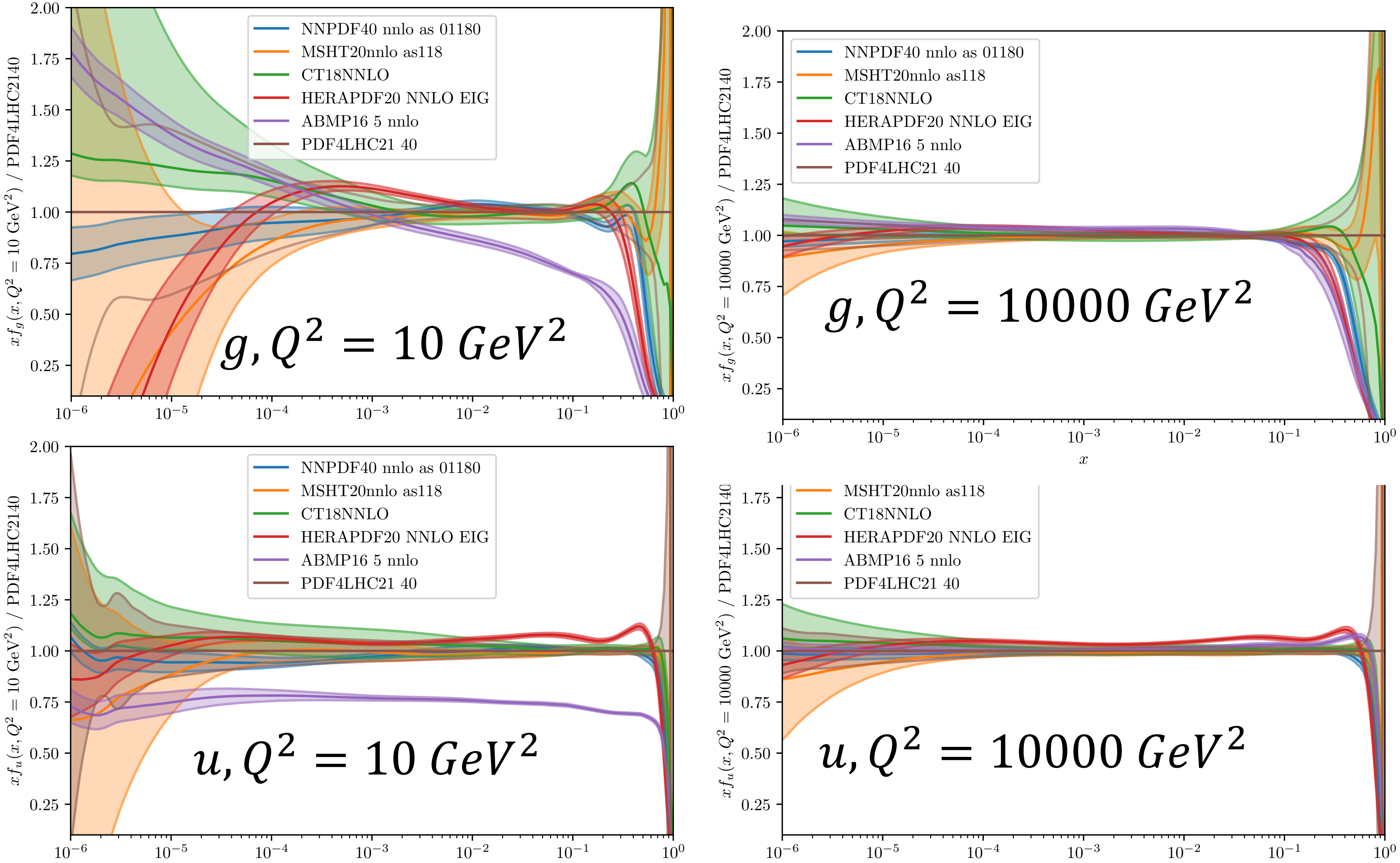
Probing the proton: longitudinal PDFs

- PDFs are measured in DIS
  - HERA e - p Valence quarks, some sea, low x gluon.
  - Fixed Target e,nu - p/A
    - Flavour decomposition.
- Further complementary constrains
  - LHC - Sea quarks, flavour decomposition,
  - medium-large x gluon.



PDFs state of the art

- Low x and high x: more data needed



N.Armesto, June 23rd 2025

Several thousands of data points are understood with few (10-15) parameters and perturbative **QCD**

In more detail:
Differences between PDF sets, profiling delicate, simultaneous PDF+SM parameter fits.

Internal structure of protons and nuclei

Observables=f(PDF)

HERA: NC, CC and jets in DIS

Fixed-target: NC($l^{\pm}$) and CC(ν) DIS + (p (pb) + p/n) DY

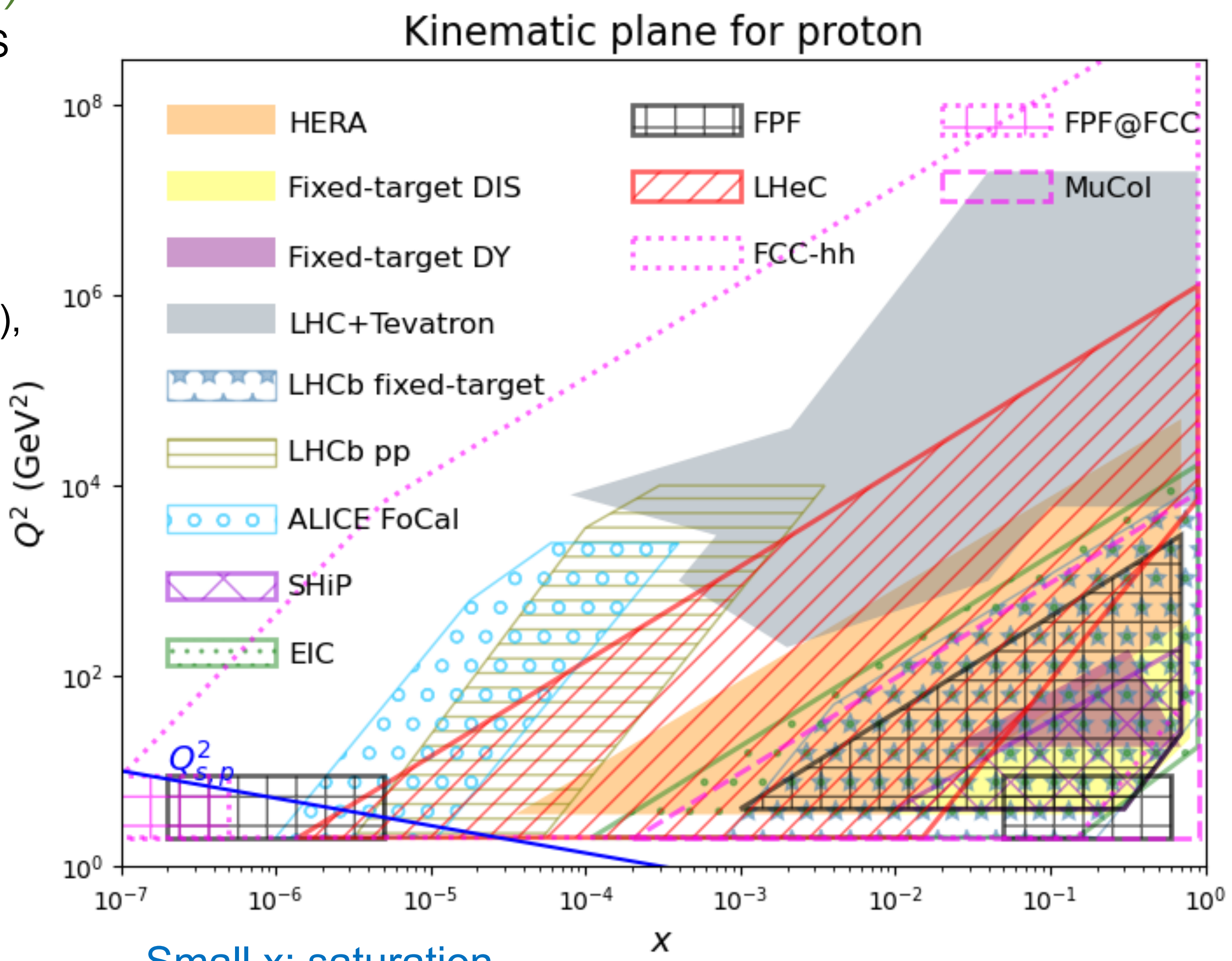
LHC: W(+jet), Z, DY, jets and dijets, single and pair top (+jet), isolated γ
Tevatron: W, Z

LHCb: D, B, quarkonia, light hadrons

ALICE FoCal: γ and jets

SHiP: ν flux from charm, NC and CC DIS (charm tagging)

EIC: NC, CC and jets in DIS, light- and heavy-favour ID



Small x: saturation

FPF: ν NC and CC DIS
FPF@FCC ν NC and CC DIS + charm.

LHeC: NC, CC and jets in DIS, heavy flavour ID

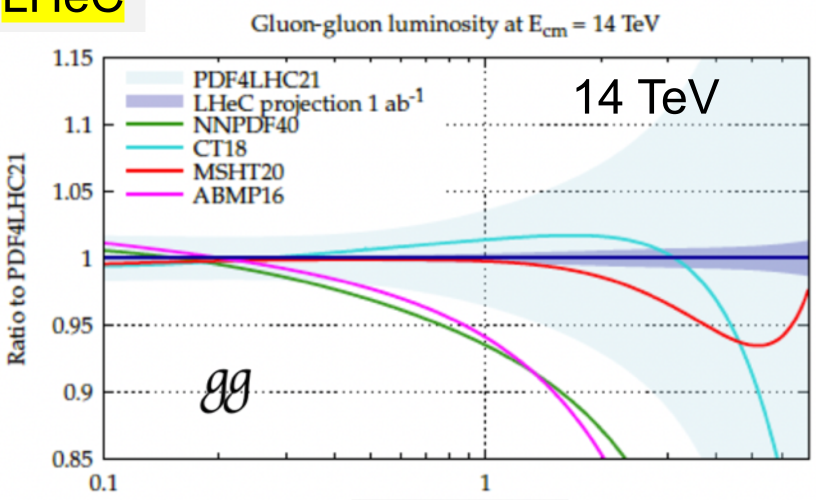
FCC-hh: W, Z, DY, jets and dijets, single and pair top, isolated γ, D, B, quarkonia, light hadrons

MuCol: NC and CC DIS

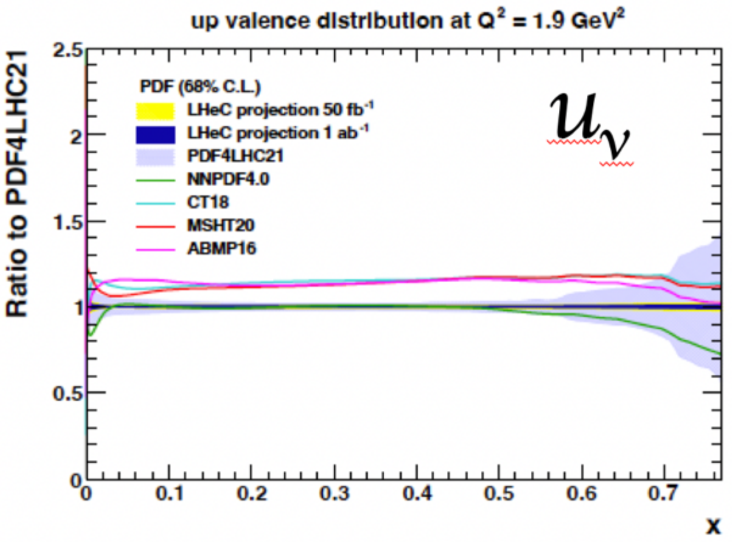
The future: DIS machines

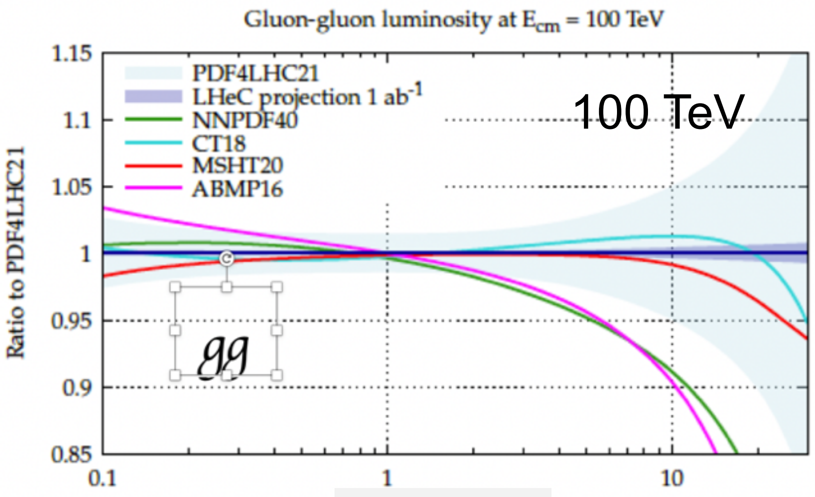
LHeC

2503.17727, **LHeC**

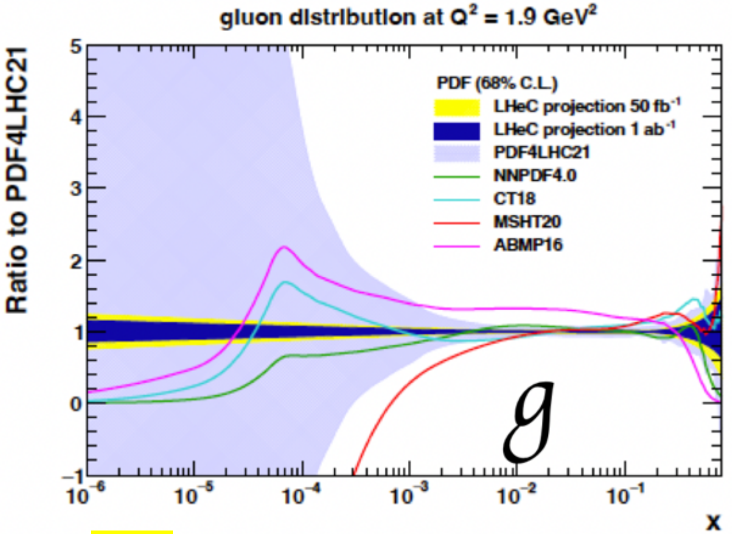


M_X(TeV)





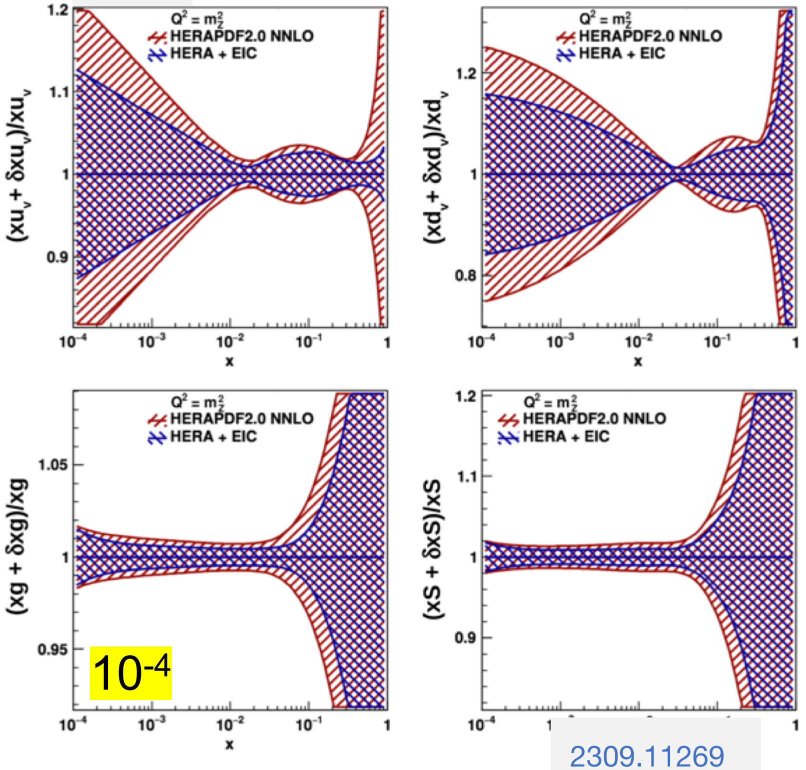
M_X(TeV)



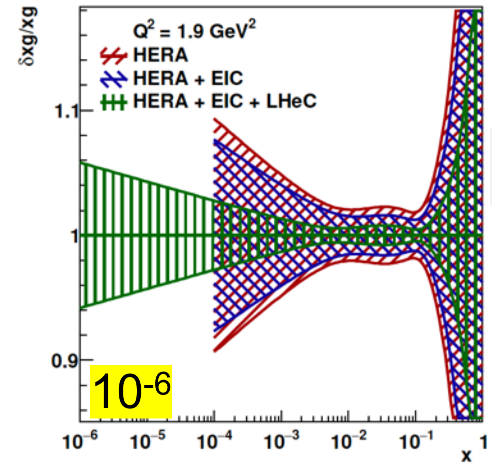
10^{-6}

arXiv:2503.17727

EIC



2309.11269



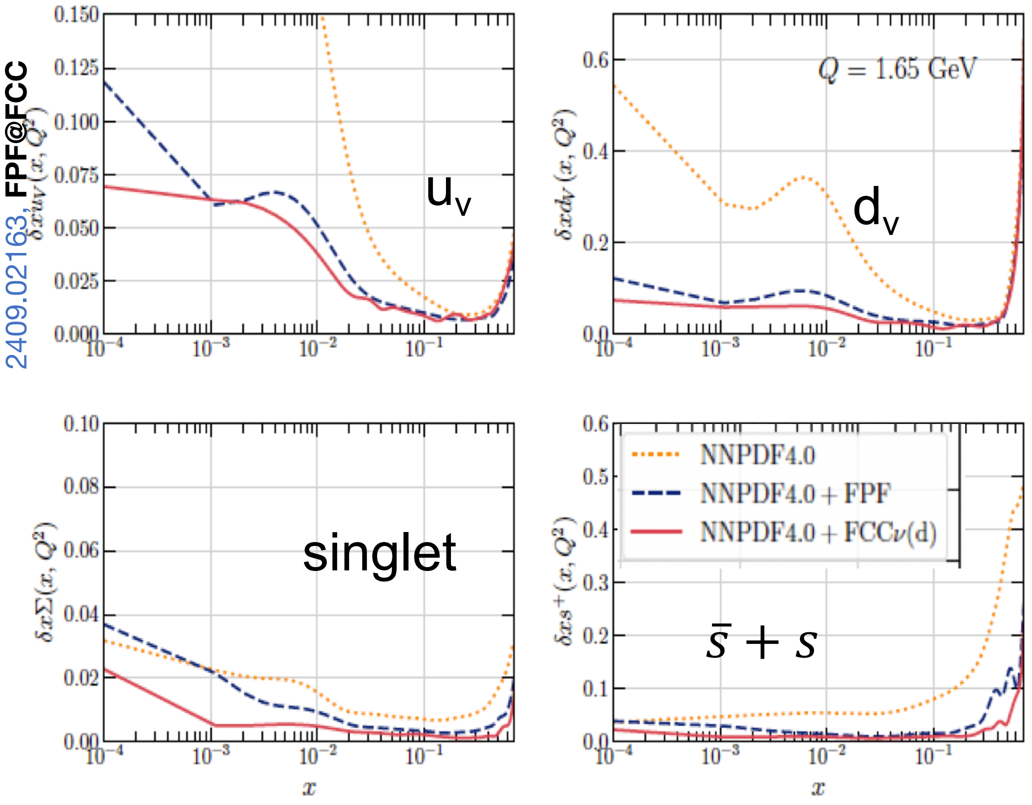
EIC+LHeC

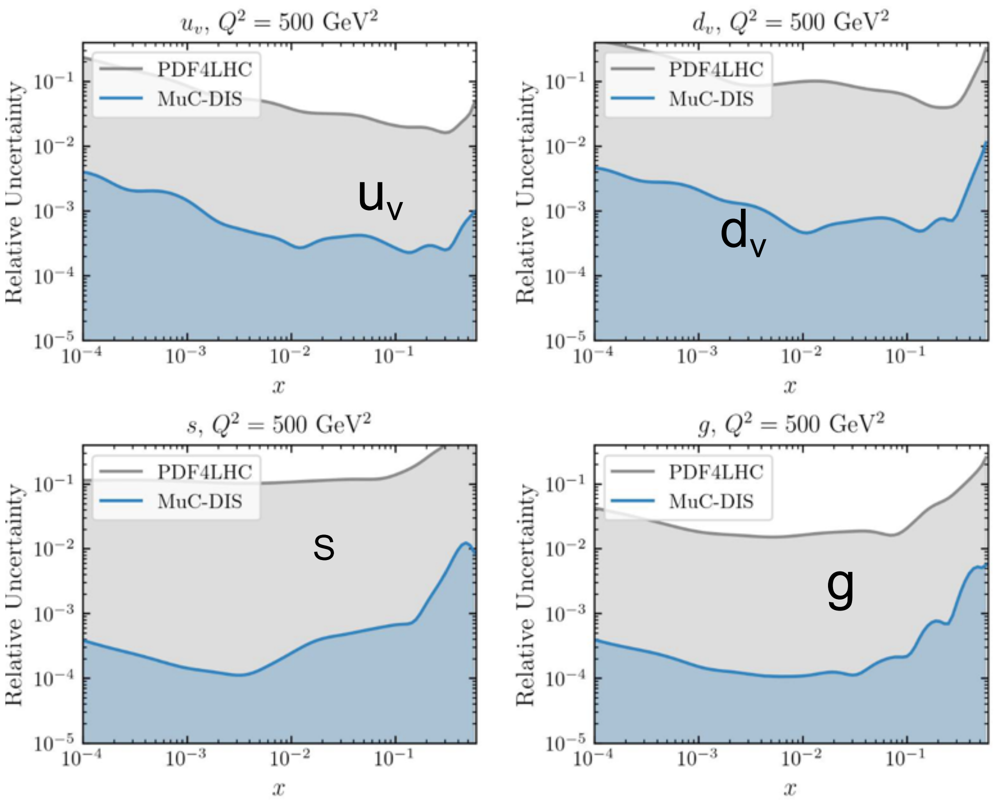
25

C. DIACONU
CPPM | CNRS/IN2P3 and Aix Marseille Université

Distinguish valence quark

2409.02163, FPF@FCC



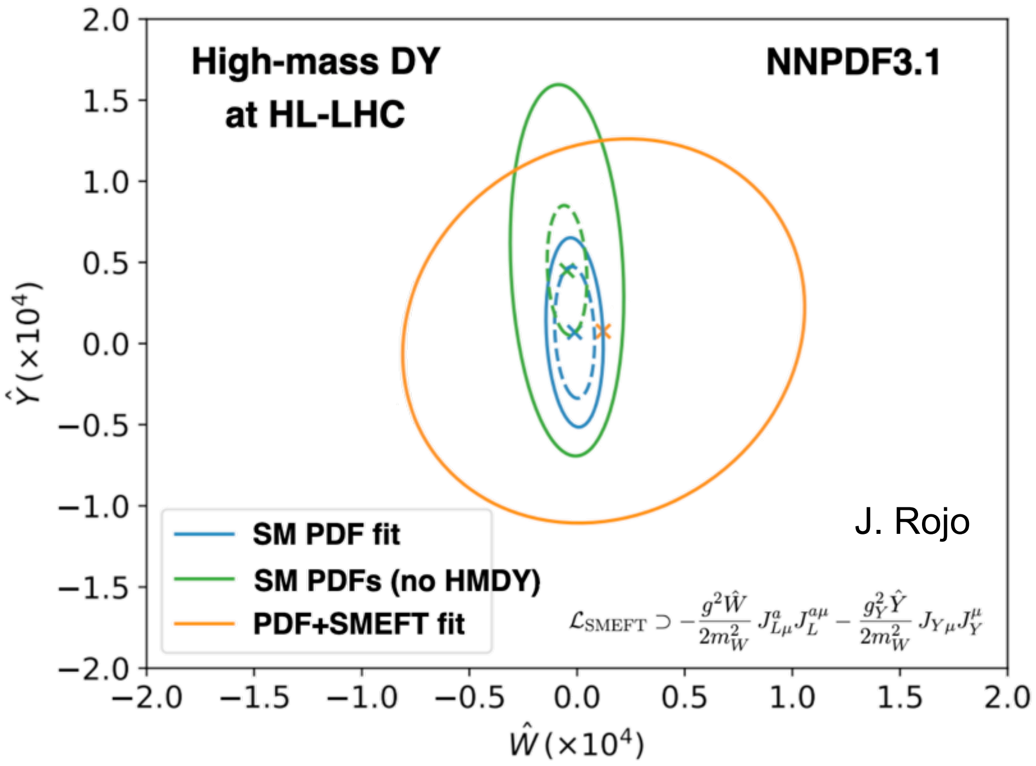


2504.21417, MuCol

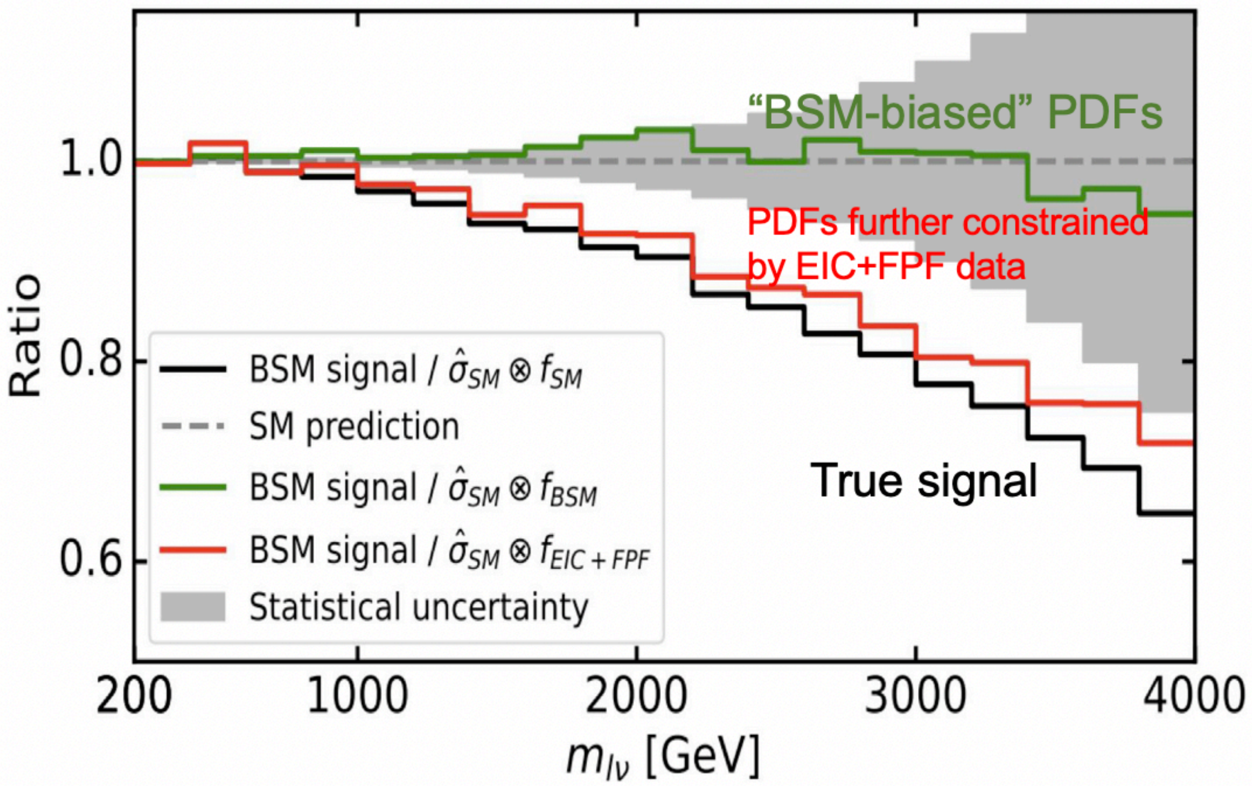
- Sizeable impact from FPF@FCC (valence), close to FPF@HL-LHC.
- Large impact from MuCol (statistics only).

Collinear PDFs and new/precision physics

- PDFs essential for precision physics studies:
- Dominant uncertainty of many SM parameters:
  - ATLAS α_s (0.0005/0.0009), CMS M_W (4.4/9.9 MeV) and $\sin2\theta W$ (0.0027/0.0031).
- High mass (large x): sizable uncertainties, BSM can be hidden in PDF uncertainties.



2410.00963



Internal structure of protons and nuclei - benchmarks

2) Longitudinal and transverse **nuclear** PDF(x,Q^2) Nuclear effects

DIS: CC DIS + NC DIS with electrons and muons

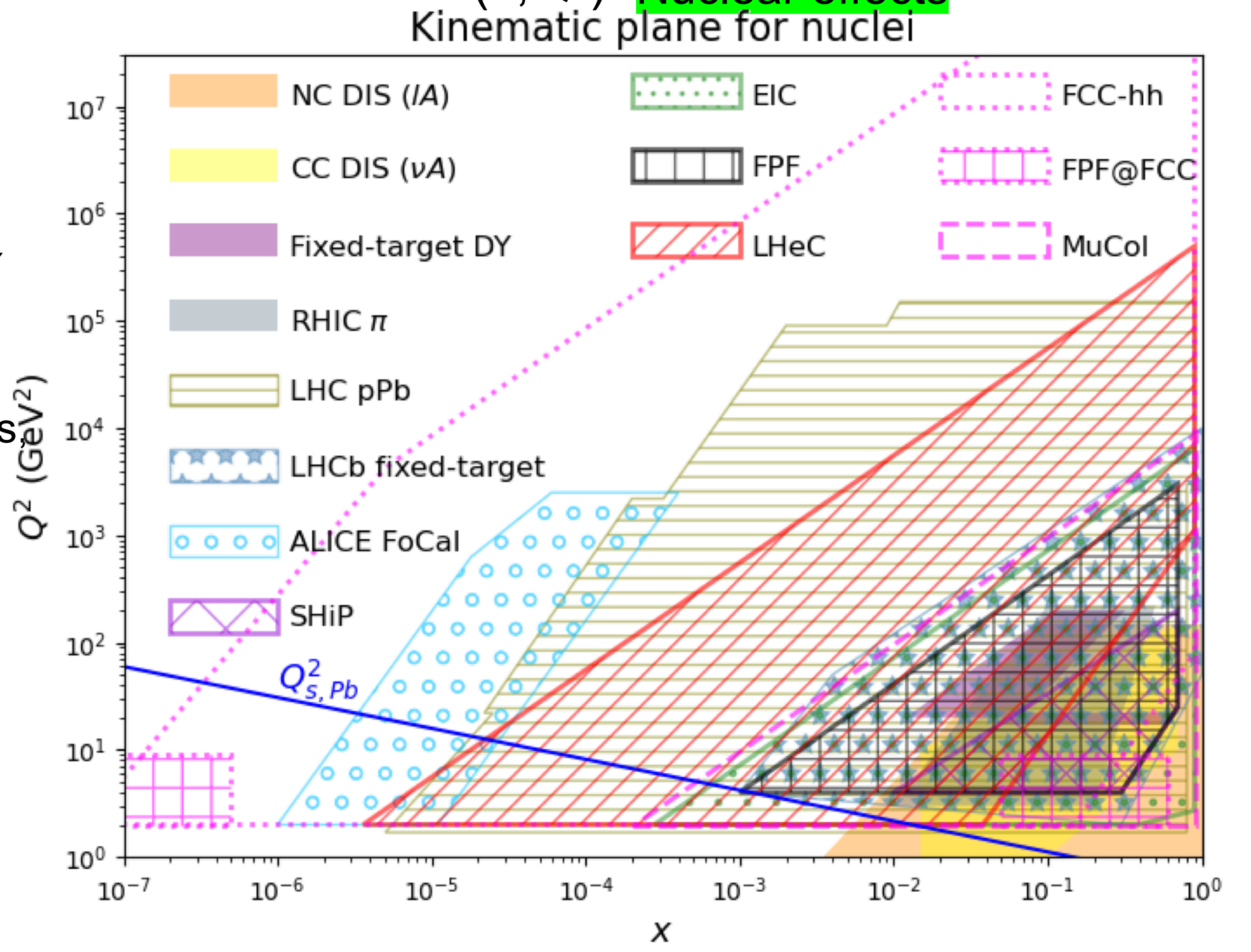
Fixed-target: *pA* and *πA* DY

RICH: pions

LHC: W, Z, jets, light hadrons, isolated γ, D mesons, quarkonia

FoCal: γ and jets

SHiP: **ν** flux from charm, NC and CC DIS (charm tagging)



EIC: NC, CC and jets in DIS, light- and heavy-favour ID

FPF: **ν** NC and CC DIS
FPF@FCC ν NC and CC DIS + charm.

LHeC: NC, CC and jets in DIS, heavy flavour ID

FCC-eh: NC, CC and jets in DIS, heavy flavour ID

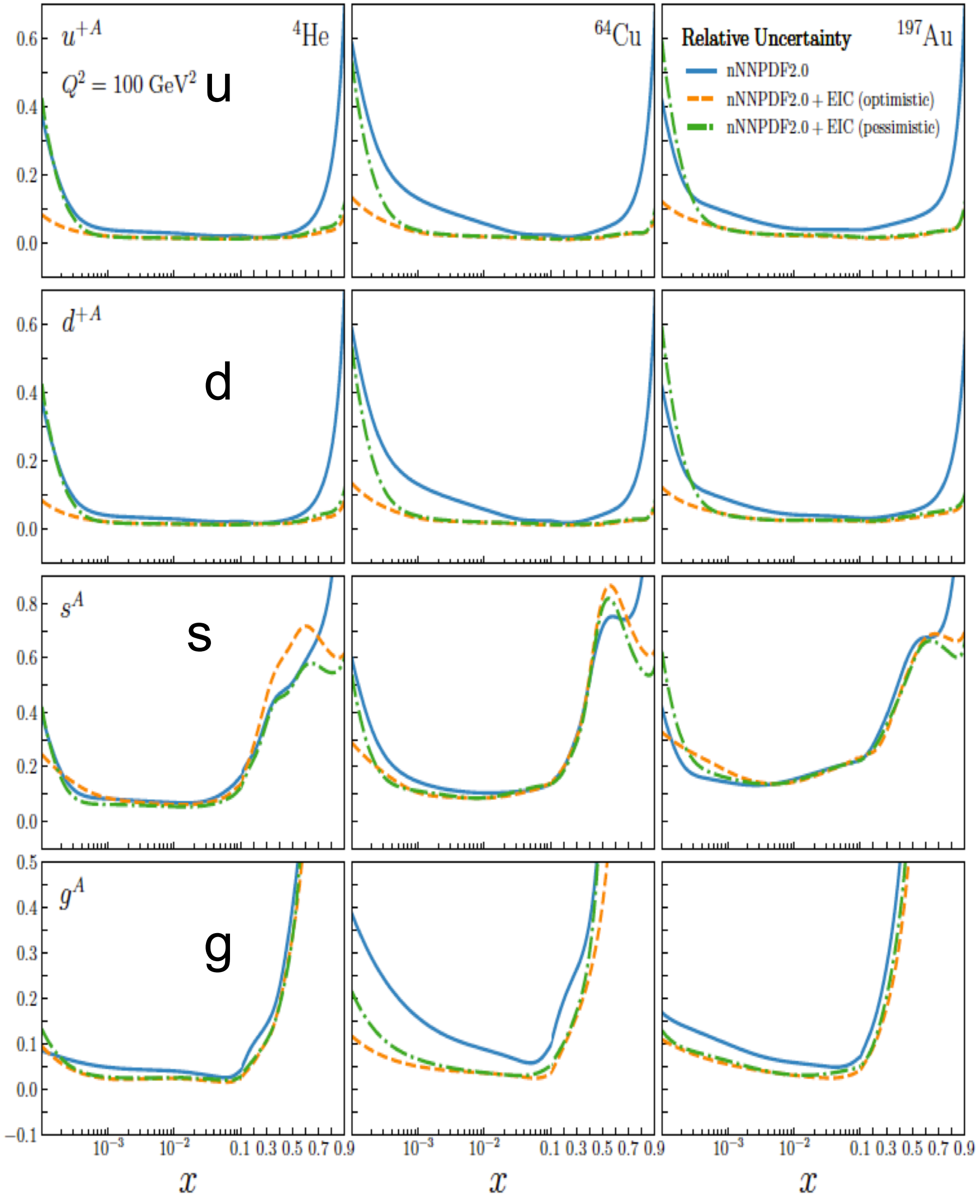
FCC-hh: W, Z, DY, jets and dijets, single and pair top, isolated γ, D, B, quarkonia, light hadrons

MuCol: NC and CC DIS

- Small x : Saturation more visible in nuclei: GBW, scaled by $A^{1/3}$~6 for a Pb nucleus.
  - PPS2 at CMS in the HL-LHC, diffractive observables at the EIC and LHeC, photon-photon at LEP3/FCC-ee/CEPC/LC, FCC-hh and FCC-eh, …

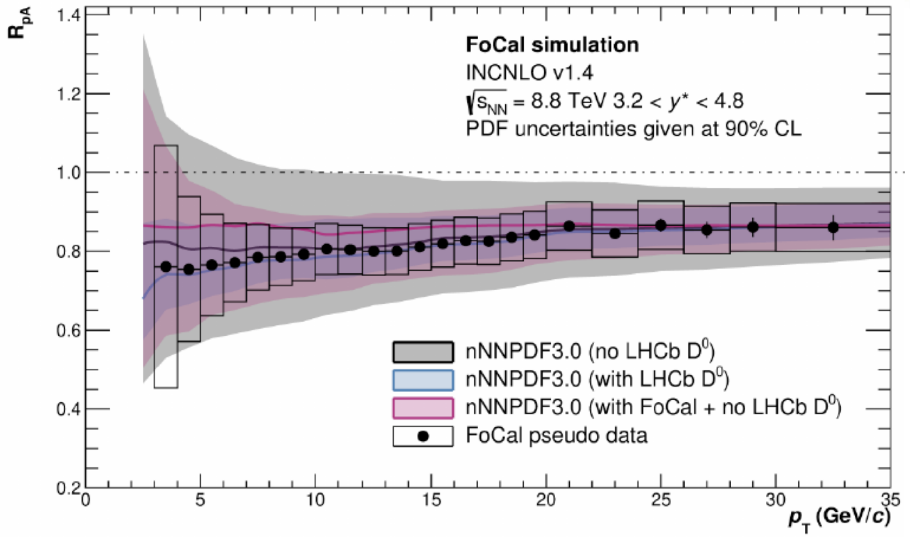
Kinematic planes for nuclei

2102.00018

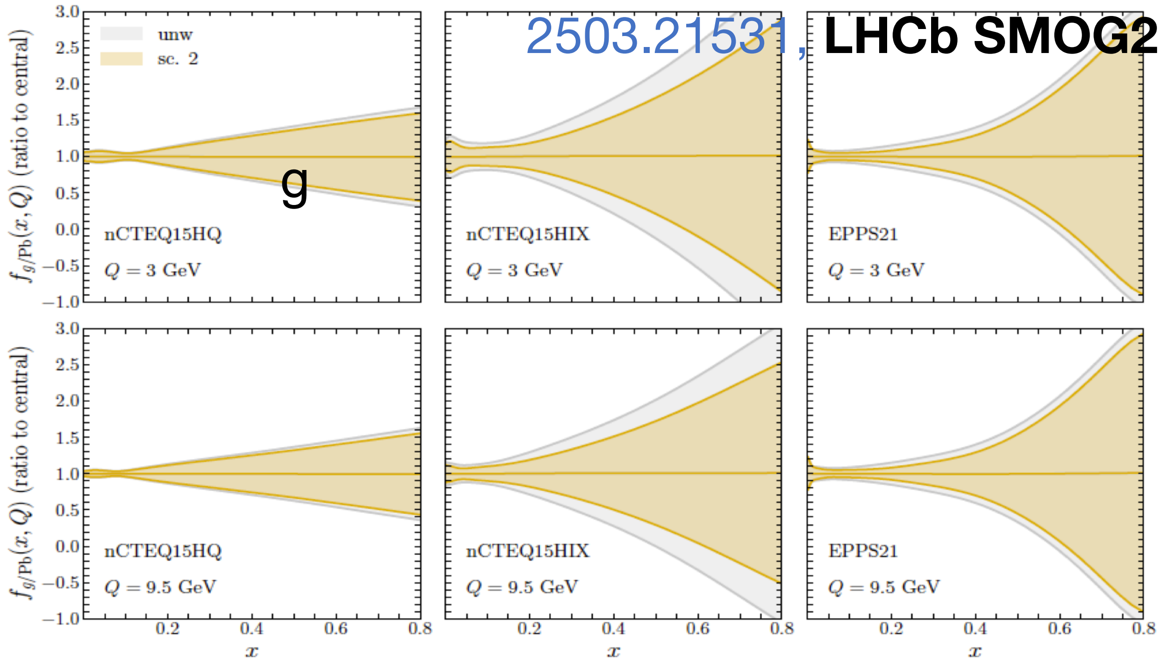


- Large impact from EIC.
- Sizable impact from LHCb SMOG2 and ALICE FoCal ($\gamma's \sim \mathrm{D}'s$).

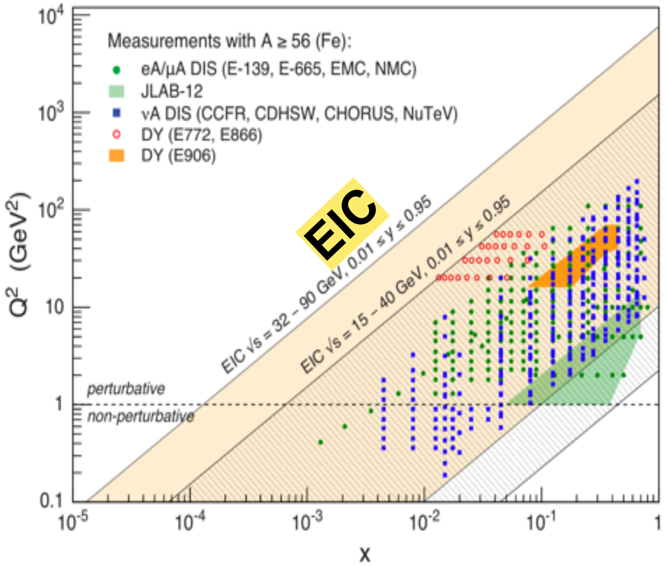
2407.13058, γ@ALICE **FoCal**



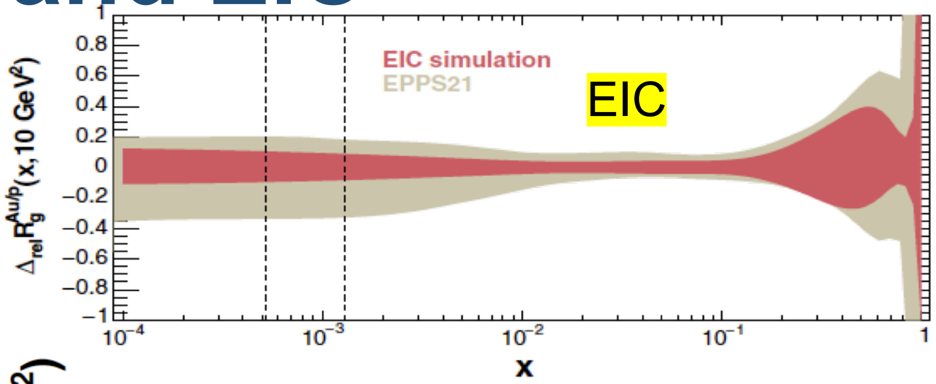
2503.21531, **LHCb SMOG2**

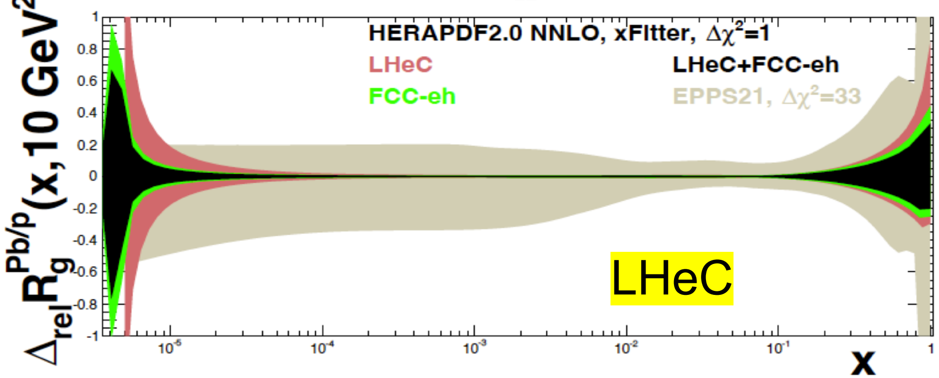


nPDFs LHeC and EIC

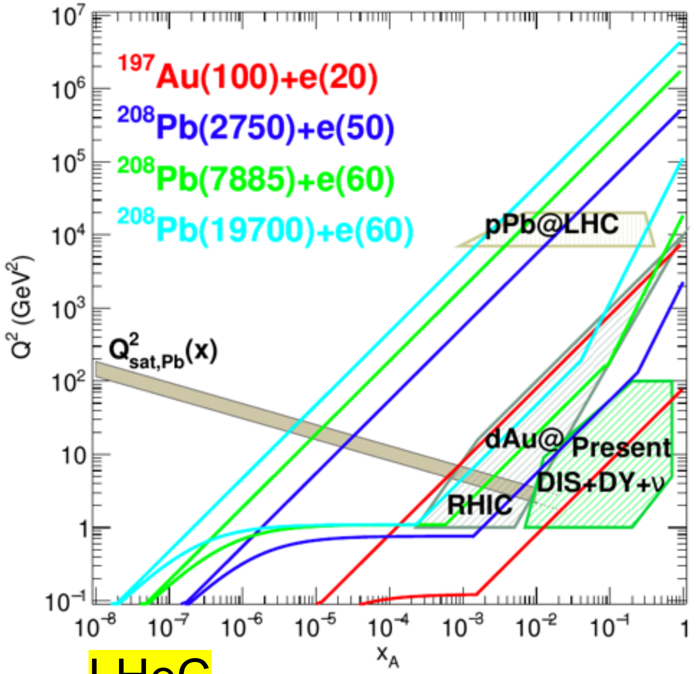


EIC

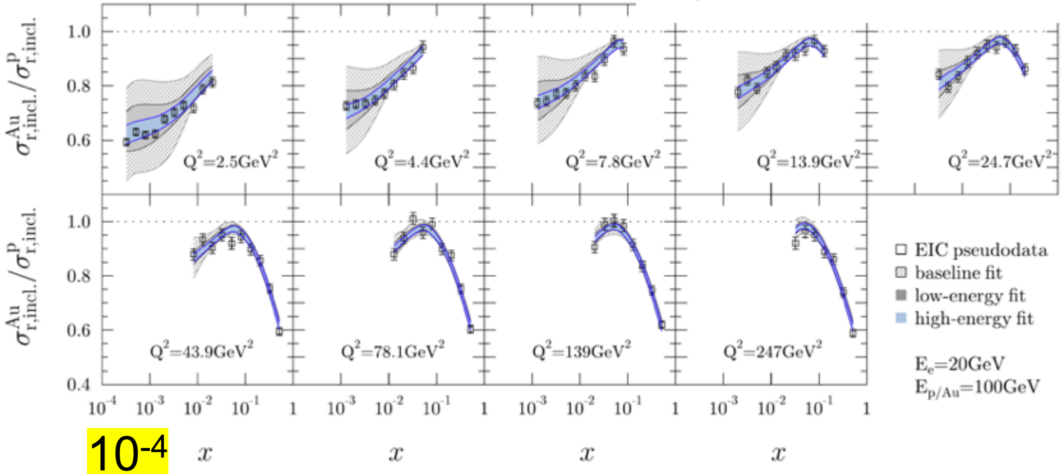




2309.11269

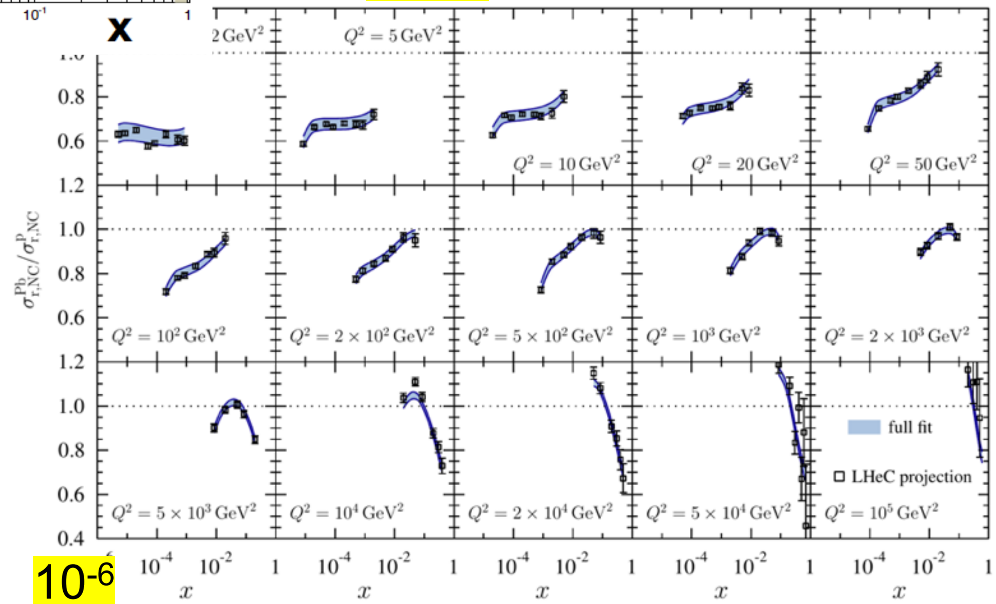


LHeC



10⁻⁴

[PHYS.REV.D 96 (2017) 11, 114005]



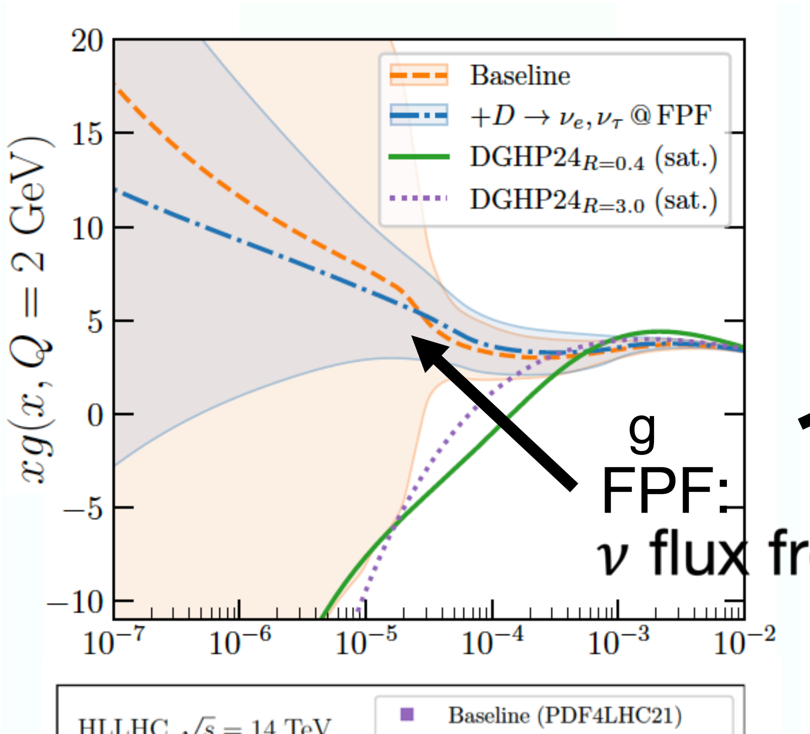
10⁻⁶

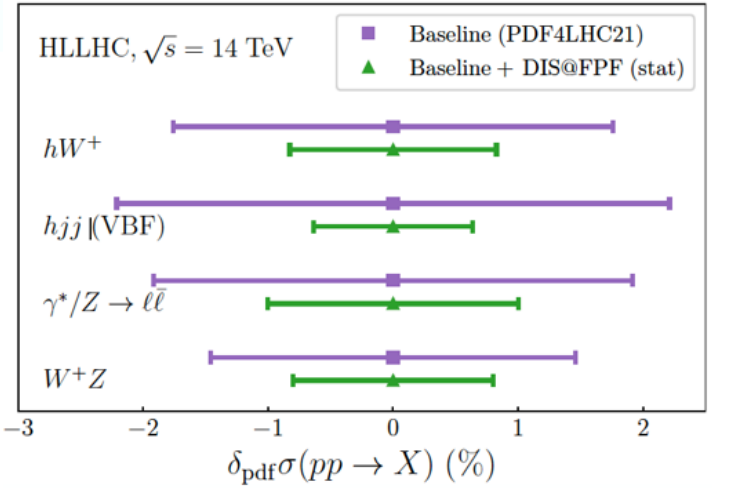
[J.PHYS.G 48 (2021) 11, 110501]

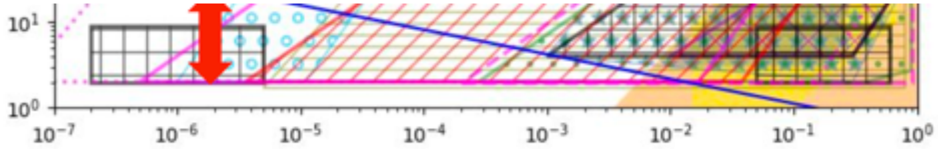
C. DIACONU
CPPM | CNRS/IN2P3 and Aix Marseille Université

Nuclear PDFs : constrains from FPF (FCC)

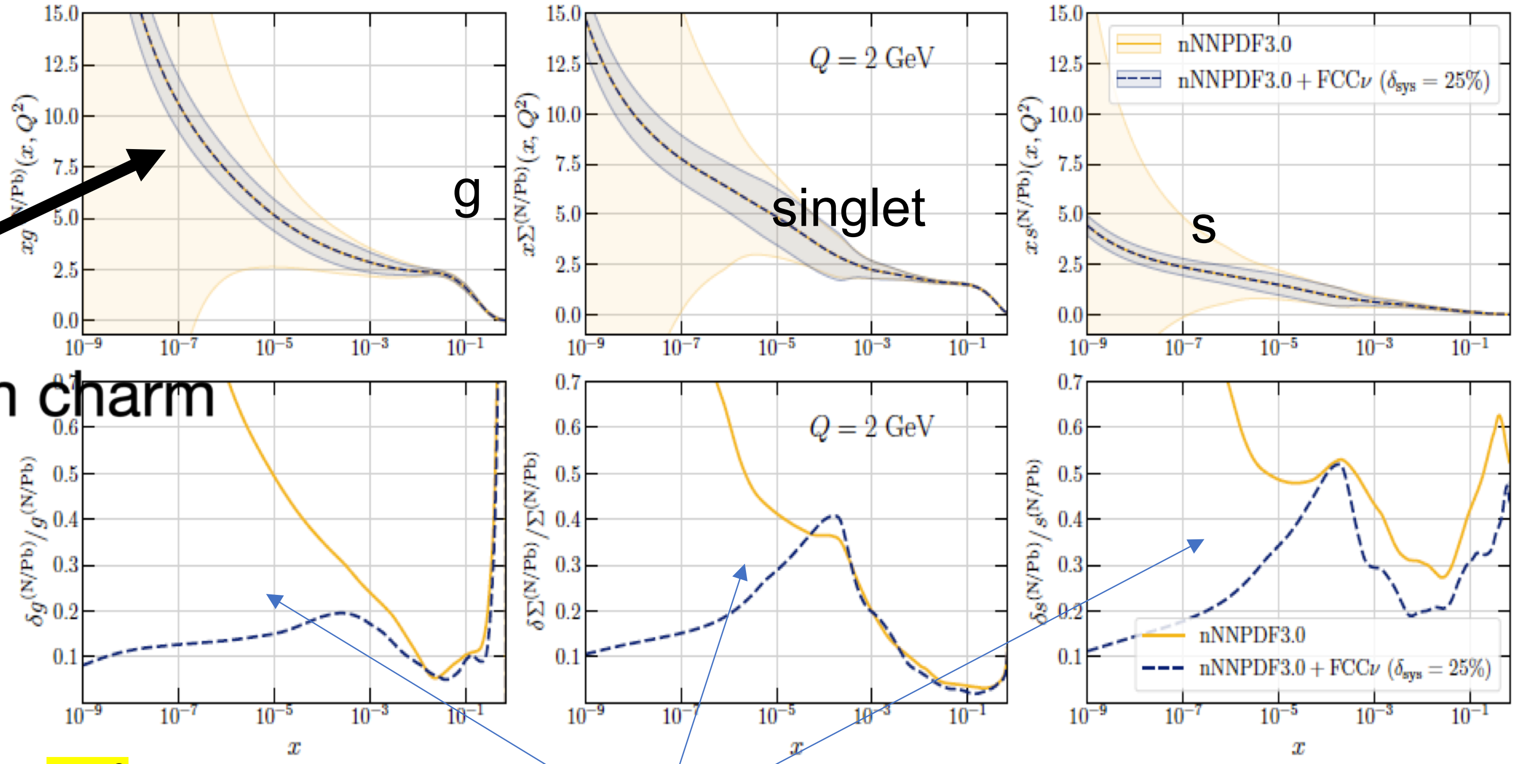
European Strategy for Particle Physics







g
FPF:
ν flux from charm



10^{-9}

2409.02163, **FPF@FCC**

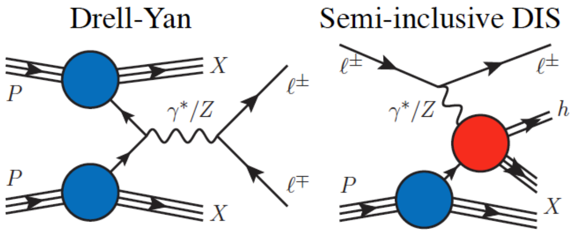
TMDs

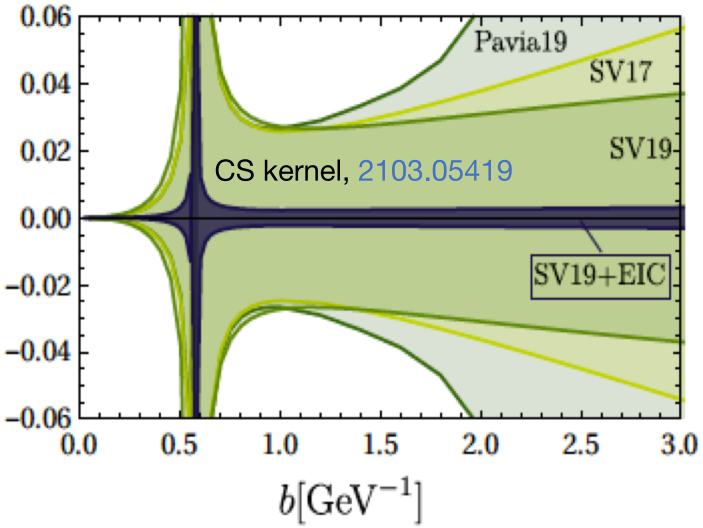
1601.01813

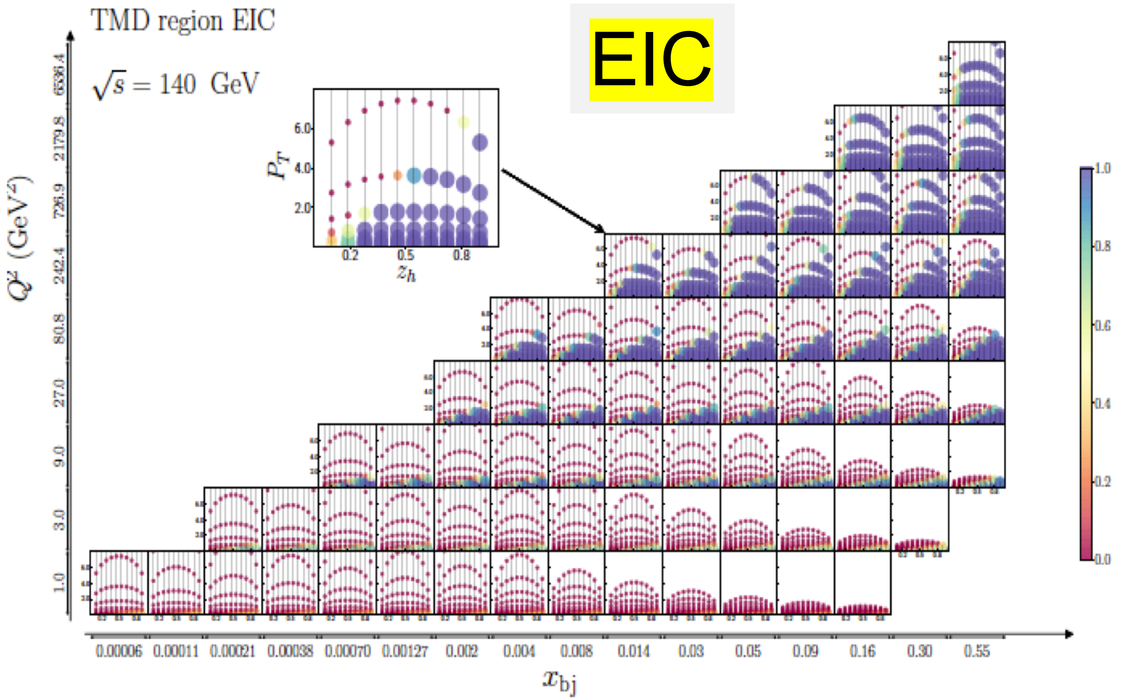
- TMD factorisation appears in **two-scale problems,** e.g., Q and q_T in DY.
- TMDs contain perturbative & non-perturbative pieces; linked to collinear PDFs/FFs.
- Numerous sets/approaches, large perturbative accuracy (N4LL, required by data).
- Potential impact in precision measurements (e.g. $p_T(Z)$ 2203.05394)

	DIS & DY	SIDIS	$pA \to hX$	$pA \to \gamma\,\text{jet}\,X$	Dijet in DIS	Dijet in pA
$f_1^{g\,[+,+]}$ (WW)	×	×	×	×	√	√
$f_1^{g\,[+,-]}$ (DP)	√	√	√	√	×	√
Gluon unpol. and lin. pol. TMDs	LHC, FCC-hh, EIC, LHeC,	EIC, LHeC	LHC, FCC-hh		EIC, LHeC	LHC, FCC-hh

	DIS & DY	SIDIS	$pA \to hX$	$pA \to \gamma\,\text{jet}\,X$	Dijet in DIS	Dijet in pA
$h_1^{\perp g\,[+,+]}$ (WW)	×	×	×	×	√	√
$h_1^{\perp g\,[+,-]}$ (DP)	×	×	×	×	×	√

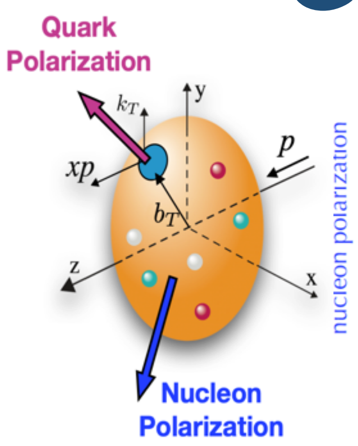






C. DIACONU
CPPM | CNRS/IN2P3 and Aix Marseille Université

GPDs



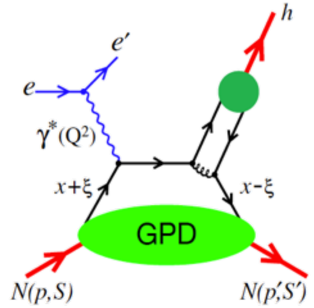
quark polarization (columns); nucleon polarization (rows)

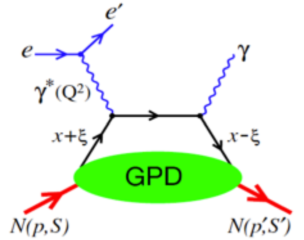
GPD	U	L	T
U	H		$\mathcal{E}_T$
L		$\tilde{H}$	$\tilde{E}_T$
T	E	$\tilde{E}$	H_T, $\tilde{H}_T$

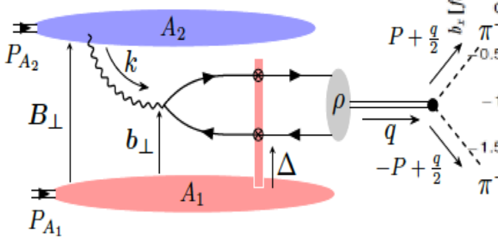
B. Pasquini at DIS2025

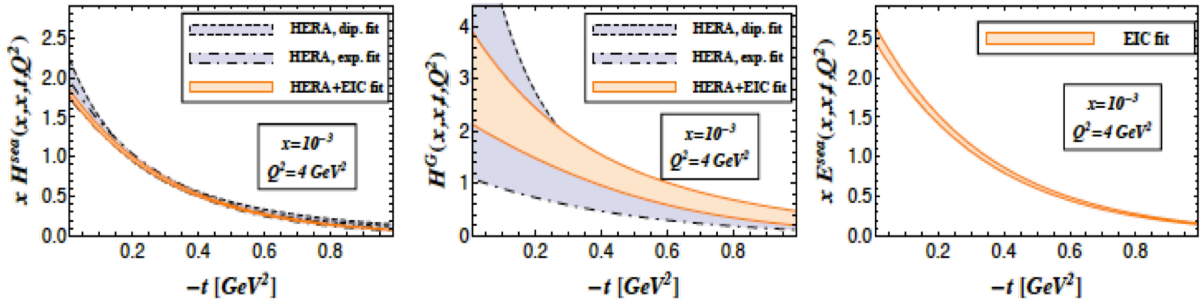
- Measured in exclusive processes:
  - DVCS, TCS (NNLO), exclusive VM production (NLO?), DDVCS, 2 to 3 processes like $\gamma\gamma$ or γ-meson, transition GPDs/DAs,...
- The partonic profile of hadrons can be extracted dependent on x.

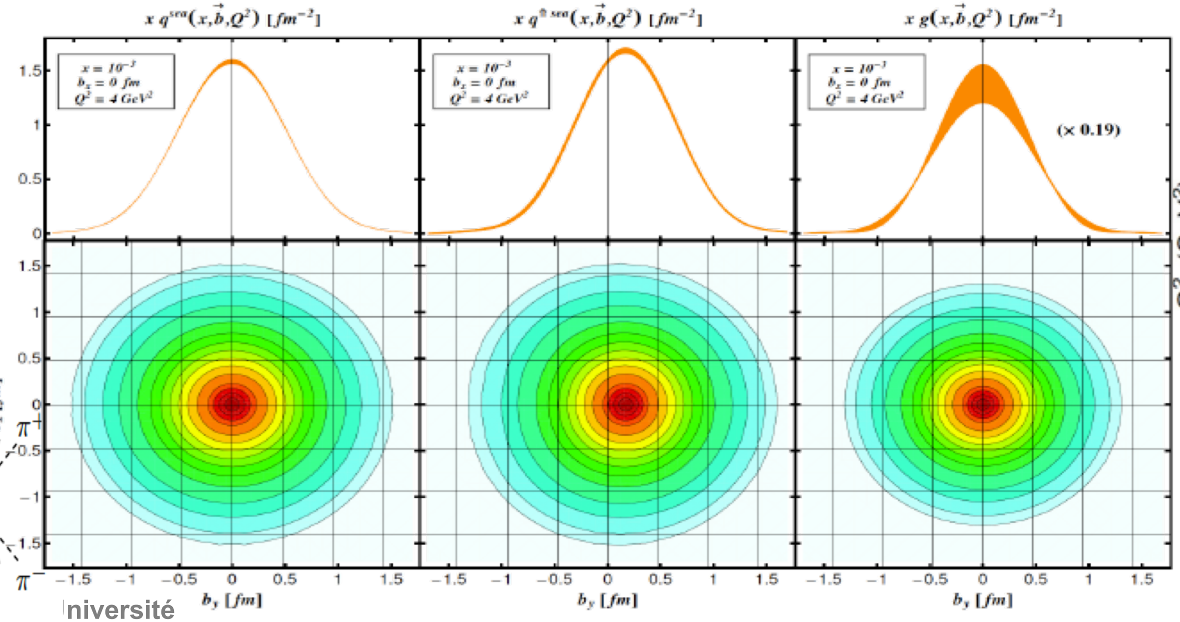
Experiment red = ESPP submissions	Observable	Access to
HL-LHC in collider and fixed-target mode	Exclusive quarkonium production and TCS in UPCs	Quark and gluon GPDs
LHCspin	TSSA in UPCs	
EIC	DVCS, exclusive VM production	Quark and gluon GPDs
LHeC	DVCS, exclusive VM production	Quark and gluon GPDs
FAIR	N+N⟶N+π(90º)+B	Transition GPDs
Electron-Ion Collider in China	DVCS, DVMP	Quark and gluon GPDs
CLAS12 luminosity upgrade	Proton, neutron and nuclear DVCS, TCS, DVMP	Quark and gluon GPDs
SoLID	DVCS, TCS, DDVCS, exclusive meson production on polarised proton and nuclear targets	Quark and gluon GPDs
JLab22	DVCS, …	Quark and gluon GPDs



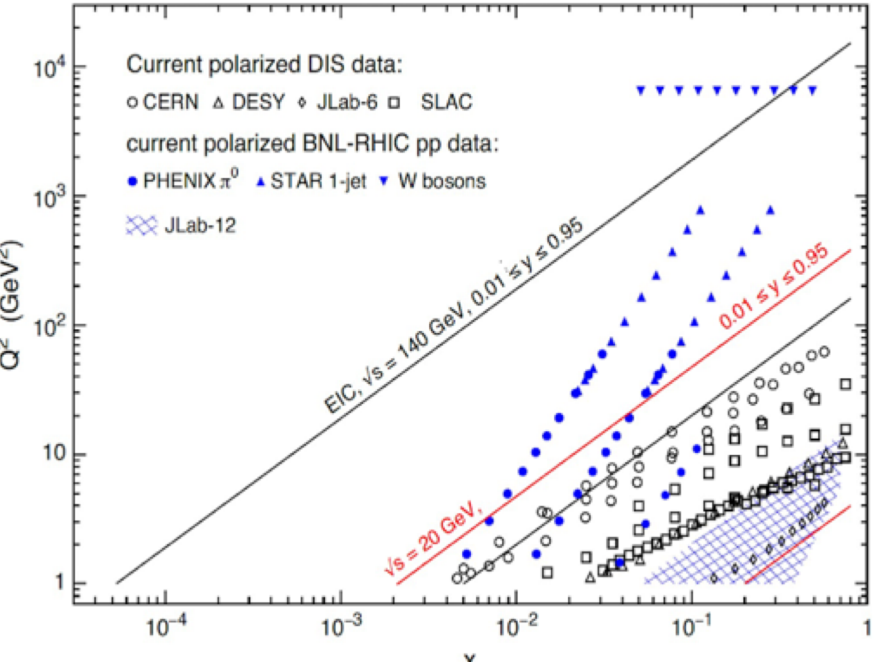








niversité

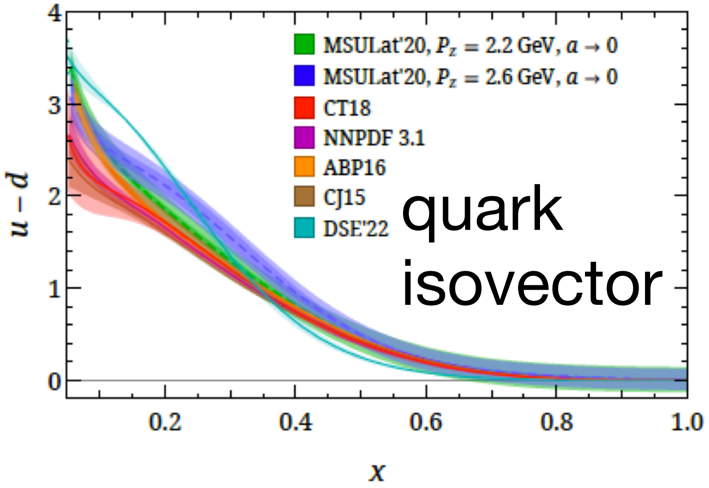


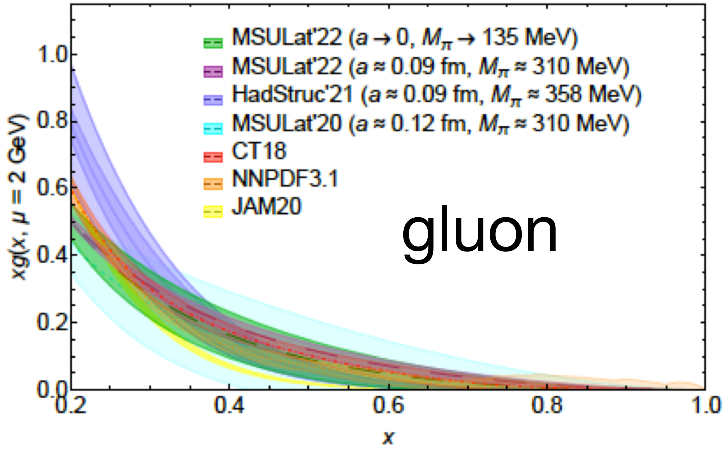
Lattice: state-of-the-art and challenges

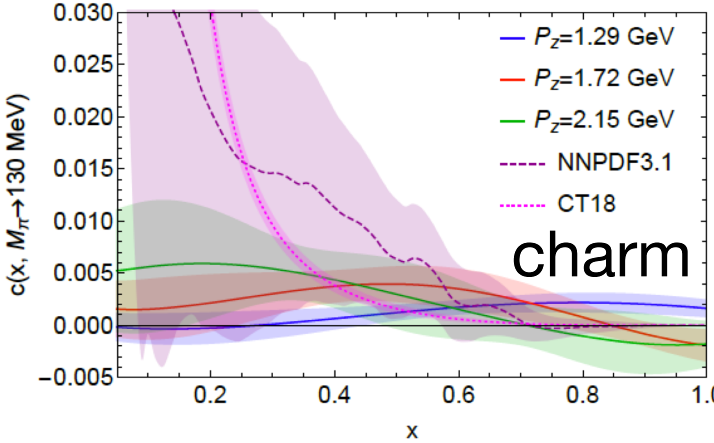
- Lattice QCD :1st-principles PDFs, TMDs and GPDs.
- 2+1(+1) flavors (physical mπ for some quantities).

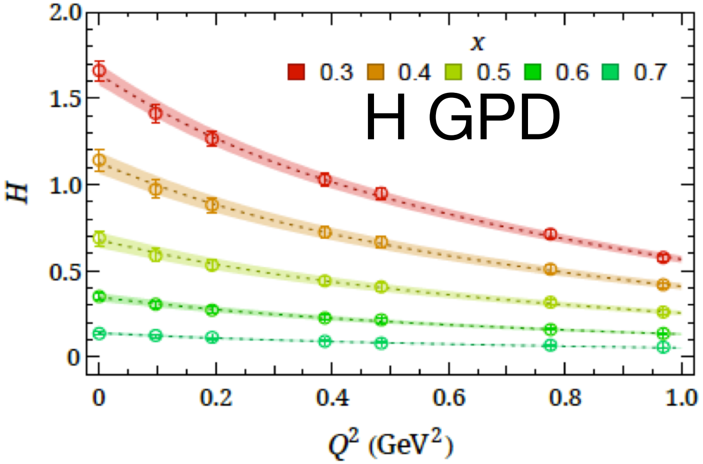
- Challenges:
  - signal-to-noise ratios, extrapolation to physical mπ
  - uncertainties for large and small x;
  - include in global fits

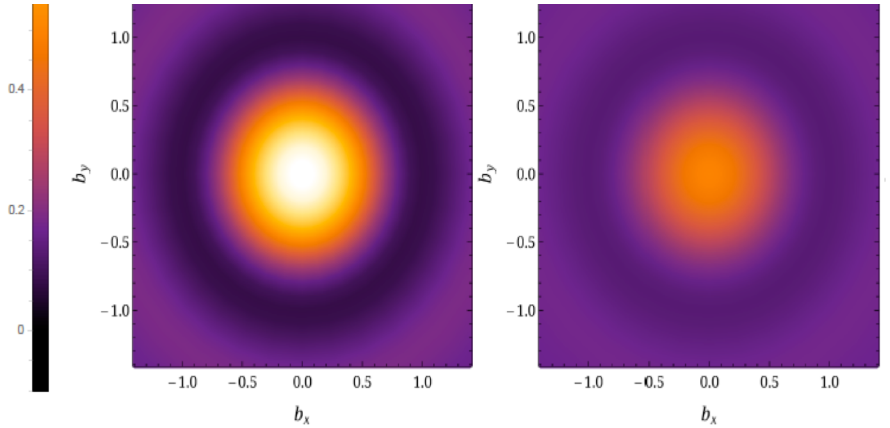
arXiv:2506.05025











$$q(x, b) = \int \frac{\mathrm{d}\mathbf{q}}{(2\pi)^2} H(x, \xi = 0, t = -\mathbf{q}^2) e^{i\mathbf{q}\cdot\mathbf{b}}$$

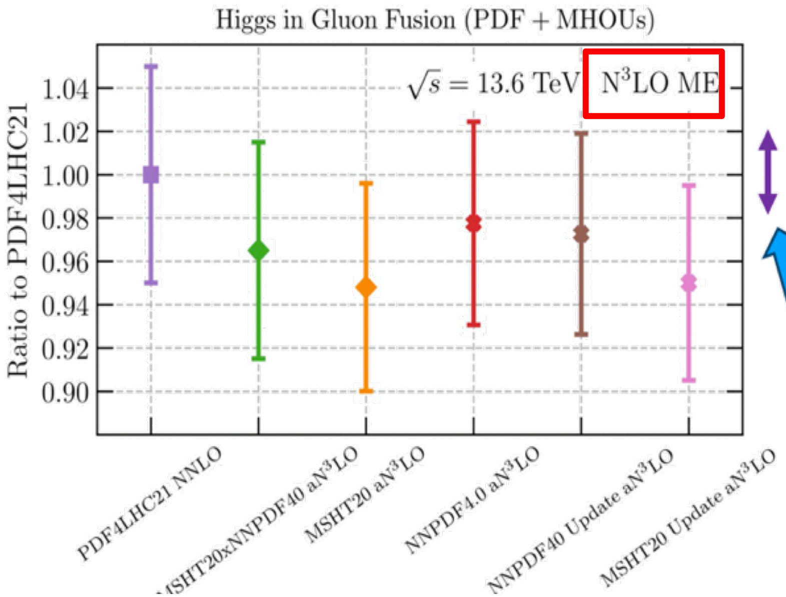
Comparing different projects

Quantity or question/ experiment	LHC in fixed target mode D, B, quarkonium, light hadrons	(HL)LHC in collider mode D, B, quarkonium, light hadrons, UPCs, DY	Alice FoCal Photons and jets	SHiP ν flux from charm, NC and CC DIS	EIC NC, CC and jets in DIS, light and heavy flavour ID, exclusive diffraction	FPF ν flux from charm, NC and CC DIS	LHeC NC, CC and jets in DIS, heavy flavour ID, exclusive diffraction	FCC-ee/ LEP3/ CEPC/LC FFs of light and heavy quarks, jets, $\gamma\gamma$	MuCol ν flux from muons	FCC-hh D, B, quarkonium, light hadrons, UPCs, DY
PDFs		Most information available	Simultaneous fits of proton and nuclei	Simultaneous fits of proton and nuclei; F_4, F_5	Covered by HERA	Simultaneous fits of proton and nuclei; F_4, F_5			Simultaneous fits of proton and nuclei	Kinematic reach
nPDFs		Most information available	Region overlapping with current pPb							Kinematic reach
TMDs		DY, jets	Little PID			No prospects	Little PID in current project	FFs needed for PDFs, and TMD in jets		DY, jets
GPDs		Currently UPCs	No prospects			Little PID in current project				Currently UPCs
Small-*x* dynamics	Large x needed for small x			Large x needed for small x	Kinematic reach	Kinermatic reach		$\gamma\gamma$	Large x needed for small x	

Dark green: Highest precision/breadth; Light green: strong/focussed contributions; White: no contribution.

Future: PDFs impact on physics observable

2411.05373

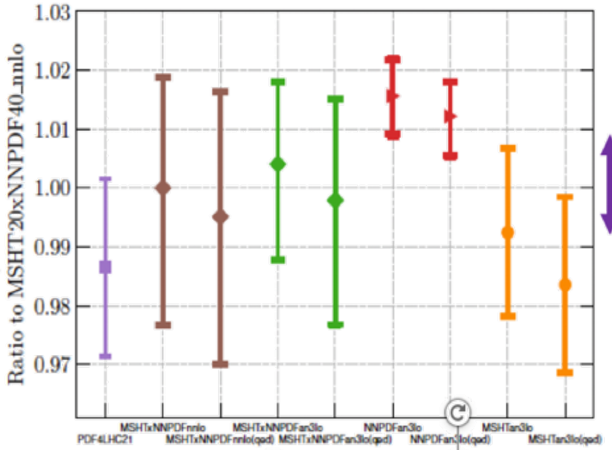


2309.11269,
MSHT20+EIC total/PDF

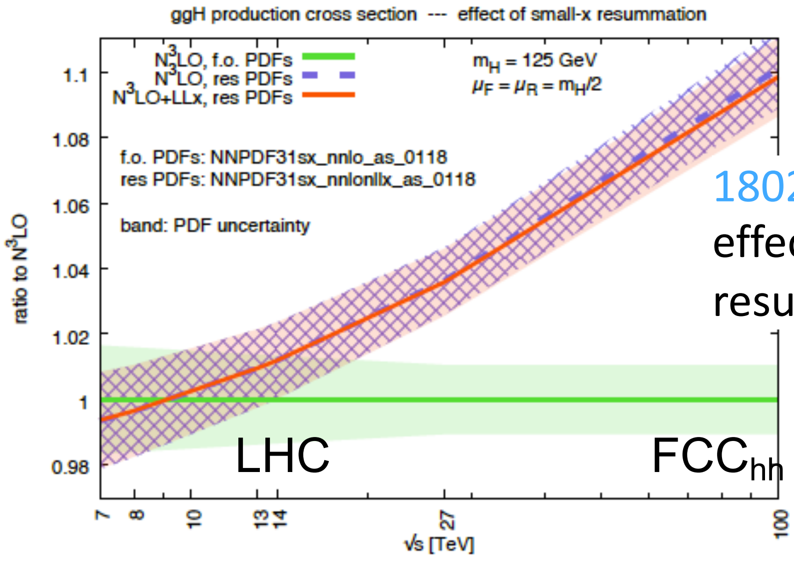
2503.17727, LHeC
total/PDF+α_s

Higgs cross section at 14 TeV:
$gg \to H$ and HW$^+$ (VBF).

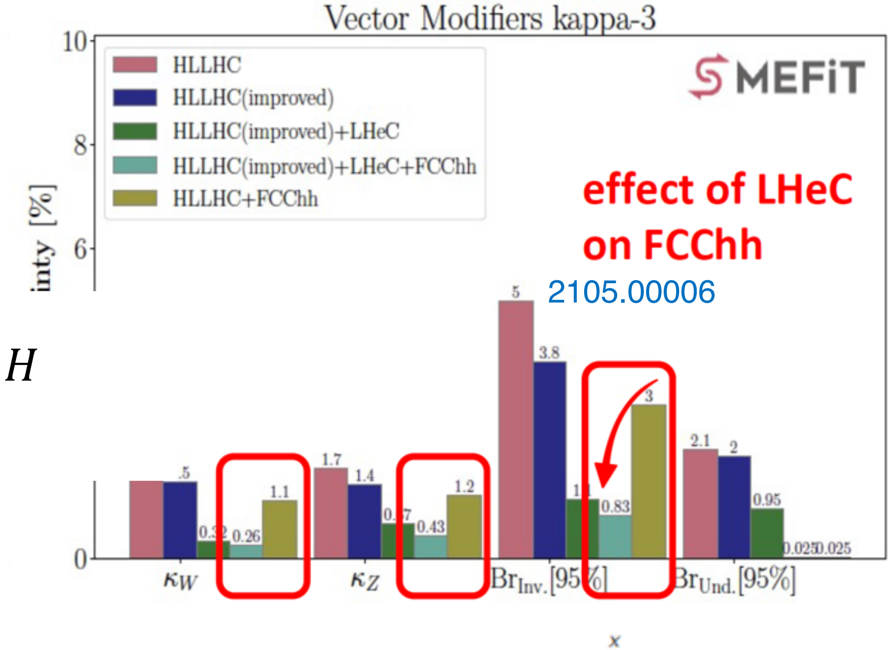
2411.05373



2503.19010,
DIS@FPF (stat.)



1802.07758,
effect of small-x resummation on $gg \to H$



Conclusions

- The strong coupling is the least known amongst the four forces, “the permille plan”:
  - Reaching 0.1% requires FCCee (10^{12} Z bosons), Lattice, LHeC
- Precision stress tests of the SM (EW, Higgs Yukawas/BSM, top) require N^nLO+N^nLL pQCQ and significant progress in NP-QCD (had, color rec.)
- Hadron structure is a fundamental scientific question and limits important EW measurements and searches
  - DIS machines EIC, LHeC will refine the measurements and step into unexplored areas
  - The phase space will be further explored processes/experiments (neutrinos)
- The strong force is an unique laboratory for the interface between perturbative and non-perturbative and collective effects (low x/saturation, nPDFs, HI)

- A very dynamic field of research
  - Significant progress expected and necessary in the next 20-40 years
  - A common vision for QCD theory and experiment needs to be developed

Backup

Experimental Collaborations

				Precision QCD	Internal structure	Hot and dense QCD	Connections (hadr,nucl,astr)	
6	Input for the EUROPEAN STRATEGY FOR PARTICLE PHYSICS UPDATE 2026 compiled by THE ISOLDE COLLABORATION COMMITTEE	A: Exp Collaboration	ISOLDE				X	A: Exp Collaboration
205	The Belle II Experiment at SuperKEKB	A: Exp Collaboration	KEK Belle II	X			X	
68	Input from the ALICE Collaboration	A: Exp Collaboration	LHC ALICE		X	X	X	
170	Highlights of the HL-LHC physics projections by ATLAS and CMS	A: Exp Collaboration	LHC ATLAS+CMS	X	X			
23	Prospects and Opportunities with an upgraded FASER Neutrino Detector during the HL-LHC era: Input to the EPPSU	A: Exp Collaboration	LHC FASER		X		X	
19	The Forward Physics Facility at the Large Hadron Collider	A: Exp Collaboration	LHC FPF		X		X	
81	Discovery potential of LHCb Upgrade II	A: Exp Collaboration	LHC LHCb				X	
82	Heavy ion physics with LHCb Upgrade II	A: Exp Collaboration	LHC LHCb		X	X	X	
213	LHCspin: a Polarized Gas Target for LHC	A: Exp Collaboration	LHC LHCspin		X			
245	MUonE Contribution to the European Strategy: status of the project	A: Exp Collaboration	mu CERN MUonE	X				
131	European Strategy for Particle Physics 2026: the NA60+/DiCE experiment at the SPS	A: Exp Collaboration	SPS NA60+/DiCE			X		
171	Proposal from the NA61/SHINE Collaboration for the update of the European Strategy for Particle Physics	A: Exp Collaboration	SPS NA61/SHINE			X	X	
231	Super Tau Charm Facility	A: Exp Collaboration	STCF China	X			X	

Future Colliders

				Precision QCD	Internal structure	Hot and dense QCD	Connections (hadr,nucl,astr)	
114	Synergies between a U.S.-based Electron-Ion Collider and European Research in Particle Physics	B: Future Colliders	eh: EIC USA	X	X			B: Future Colliders
214	The Large Hadron electron Collider (LHeC) as a bridge project for CERN	B: Future Colliders	eh: LHeC	X	X			
209	FCC: QCD physics	B: Future Colliders	FCC	X	X	X	X	
227	Prospects for physics at FCC-hh	B: Future Colliders	FCC	X	X	X	X	
233	FCC Integrated Programme Stage 1: The FCC-ee	B: Future Colliders	FCC	X				
241	The FCC integrated programme: a physics manifesto	B: Future Colliders	FCC	X	X	X	X	
247	FCC Integrated Programme Stage 2: The FCC-hh	B: Future Colliders	FCC	X	X	X	X	
141	The ECFA Higgs/Electroweak/Top Factory Study	B: Future Colliders	FCC/LC/CLIC/MuCol	X				
275	Status of the International Linear Collider	B: Future Colliders	ILC	X				
188	LEP3: A High-Luminosity e+e− Higgs & Electroweak Factory in the LHC Tunnel	B: Future Colliders	LEP3	X				
152	United States Muon Collider Community White Paper for the European Strategy for Particle Physics Update	B: Future Colliders	Muon Collider		X			
207	The Muon Collider	B: Future Colliders	Muon Collider		X			

Community (QCD specific)

				Precision QCD	Internal structure	Hot and dense QCD	Connections (hadr,nucl, astr)	
224	Community Support for Physics with high-luminosity proton-nucleus collisions at the LHC	C: Community (specific)	HI at HL-LHC		X	X	X	C: Community (specific)
2	Light Ion Collisions at the LHC	C: Community (specific)	HI Light ions LHC		X	X	X	
7	Conclusions of the Town Meeting: Heavy Ion and QGP Physics at CERN	C: Community (specific)	HI physics CERN			X		
55	Kaon Physics: A Cornerstone for Future Discoveries	C: Community (specific)	Kaon Phyiscs				X	
29	Strategy for the Future of Lattice QCD	C: Community (specific)	Lattice QCD		X	X	X	
103	Nuclear Physics and the European Particle Physics Strategy Update 2026	C: Community (specific)	NuPECC		X	X	X	
235	Summary Report of the Physics Beyond Colliders Study at CERN	A: Exp Collaboration	Phyiscs Beyond Colliders	X	X	X	X	
89	Precision cross-sections for advancing cosmic-ray physics	C: Community (specific)	Cross sections for cosmics	.			X	
201	Statement of the Pierre Auger Collaboration as input for the 2026 European Particle Physics Strategy		HI for cosmics (AUGER)	.			X	

Theory / Specific

				Precision QCD	Internal structure	Hot and dense QCD	Connections (hadr,nucl, astr)	
174	Phase-One LHeC	D: Theory / Specific	Personal input LHeC/HL-LHC	X	X			D: Theory / Specific
33	Computer Algebra for Precision Calculations in Particle Physics: the FORM project	D: Theory / Specific	QCD theory/computing	X				
35	Cusp Spectroscopy, Hyperon-Nucleon Scattering, and Femtoscopy: Pioneering Tools for Next-Generation Hadron Interaction Studies	D: Theory / Specific	QCD theory/computing	.			X	
113	Quantum Information meets High-Energy Physics: Input to the update of the European Strategy for Particle Physics	D: Theory / Specific	Quantum Computing	X			X	

National (QCD specific)

				Precision QCD	Internal structure	Hot and dense QCD	Connections (hadr,nucl,astr)	
5	Prospective report of the French QCD community to the ESPPU 2025 with respect to the program of the LHC Run 5 and beyond and future colliders at CERN	E: National (specific)	France QCD	X	X	X		
126	Input to ESPPU by the German Astroparticle Community	E: National (specific)	Germany Astroparticle	.			X	
183	Input of the German Nuclear and Hadron Physics Community to the ESPPU 2026 Regarding the Programs at CERN, at FAIR, and Related Activities	E: National (specific)	Germany Hadronic and Nuclear	.		X	X	**E: National (specific)**
117	The INFN National Scientific Committee for Theoretical Physics	E: National (specific)	Italy Theory	X		X	X	
51	Ultra-relativistic Heavy-Ion Collisions: Inputs of the Italian community for the ESPP 2026	E: National (specific)	Italy HI	.		X		
76	Input on the update of the European Strategy for Particle Physics by the INFN Nuclear and Hadron Phyiscs Community	E: National (specific)	Italy Nuclear Phys	.		X	X	
246	U.S. interest in high-energy nuclear physics at the LHC	E: National (specific)	US LHC HI community	.		X		

Benchmark measurements

2 Strong Interactions

The benchmark measurements in the area of the strong interaction are reported in the following for the four main physics research directions. Clearly, this is not an exclusive list of the observables and measurements that the working group will cover. The input documents are anticipated to have a much broader coverage, which will be taken into account. The list of benchmarks will be used to summarise and highlight the complementarity and strengths of the future measurements at existing (e.g. SPS, HL-LHC) and proposed colliders (leptonic, hadronic, electron–hadron). The presentation of results will be organised by the working group in communication with the contact persons of submitted inputs.

- Precision QCD
  - $\alpha_S(m_Z)$ and its Q^2 dependence;
  - Strong interaction effects for precision measurements of top and W masses (see comments at the end of the section);
    - Comment on top and W masses: while these are formally EW parameters, the strong-interaction aspects are important for their experimental and theoretical determination. For example, we propose to report the expected experimental performance for the following approaches to t and W mass measurements.
      - ee collisions: m_t from threshold scan around $\sqrt{s} = 340$ GeV; m_W from threshold scan for W^+W^- production (leptonic decays);
      - ep collisions: m_t from heavy-quark DIS (top-quark structure function measurements); m_W from inclusive DIS (charged-current structure function measurements);
      - pp collisions: m_t from $t\bar{t}$ production rates, multi-differential in $m_{t\bar{t}}, y_{t\bar{t}}$; m_W from p_T^ℓ distributions.
- Inner structure of protons and nuclei
  - Longitudinal and transverse proton PDF(x, Q^2): parton flavours, Bjorken-x and Q^2 ranges for which new constraints and reduction of uncertainties are expected;
  - Longitudinal and transverse nuclear PDF(x, Q^2); same as above;
- Hot and dense QCD
  - Heavy-flavour and quarkonium hadron production (rare states, kinematic coverage): expected novel access to low-cross-section open and hidden heavy-flavour hadrons, multi-differential observables (such as correlations), transverse momentum and rapidity ranges;
  - QGP transport coefficients (heavy quarks, jets): expected precision for observables that constrain the transport coefficients that characterise parton energy loss and heavy-quark interactions in the QGP;
  - QGP thermal radiation, sensitivity to temperature: expected precision for measurements of thermal radiation and parameters that map to the temperature of the hot and dense system formed in heavy-ion collisions at different centre-of-mass energies and regions of the QCD phase diagram;
- QCD connections with hadronic, nuclear and astro(particle) physics
  - Constraints on nature of exotic hadrons from spectroscopy and h-h correlations; expected measurements that can help understanding the structure of exotic heavy-flavour hadrons (e.g. compact tetraquark vs. hadron molecule), including direct measurements of yields, resonant states, kinematic distributions in different collision systems, and hadron-hadron momentum correlation functions that have sensitivity to bound states;
  - Precision on anti-nuclei production and absorption relevant for cosmic-ray physics: production of light anti-nuclei (e.g. $\bar{p}$, $\bar{d}$, $^3\bar{He}$) that constrain production processes and kinematic distributions in primary cosmic-ray interactions; annihilation cross sections for anti-nuclei on nuclei, relevant for the propagation of cosmic anti-nuclei in space (e.g. from Dark Matter decays);