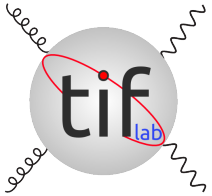


THEORY FRONTIERS

STEFANO FORTE
UNIVERSITÀ DI MILANO & INFN

UNIVERSITÀ DEGLI STUDI DI MILANO
DIPARTIMENTO DI FISICA

extracting α_s@ EIC

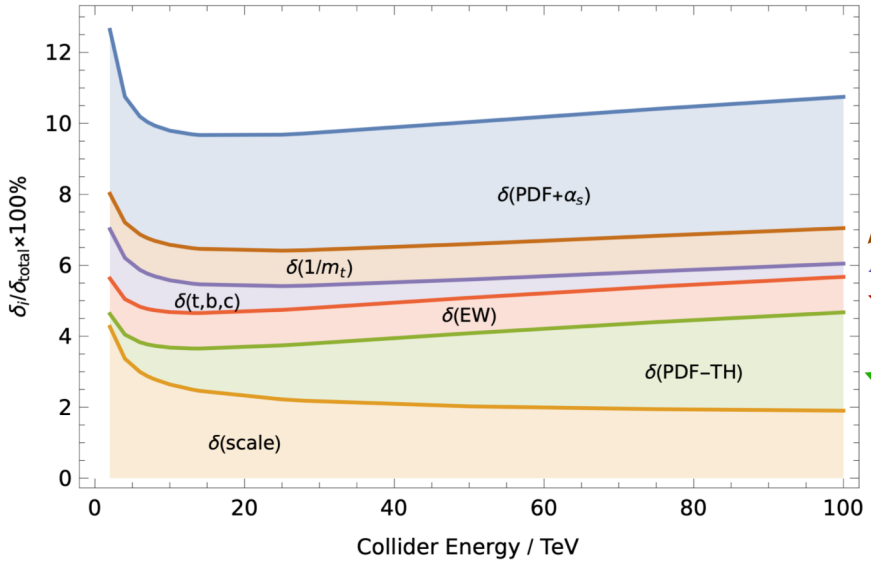
CFNS, Stony Brook, May 7 2025

α_s AND THE PRECISION FRONTIER

HIGGS IN GLUON FUSION: UNCERTAINTIES

Higgs production in gluon fusion

uncertainty budget 6 years ago Dulat, Lazopoulos, Mistlberger '18
N3LO in heavy top limit



see PDF sessions and talk by Valentina Guglielmi

basically removed (NNLO with full top mass)
Czakon, Harlander, Klappert, Niggetiedt '20

t-b interference at NNLO calculated recently
Czakon, Eschment, Niggetiedt, Poncelet, Schellenberger '23, '24

reduced to 0.6%
Bechetti et al '20, '21, Bonetti et al '18, '20, '22

mismatch between PDF (NNLO) and ME (N3LO)
towards N3LO PDFs: MSHT 2207.04739,
NNPDF4.0 2402.18635, Cooper-Sarkar et al. 2406.16188,
Falcioni et al 2302.07593, Guan et al. 2408.03019,
Gehrmann, Manteuffel, Sotnikov, Yang '23, '24

N4LO soft-virtual approx. Das, Moch, Vogt '20;
4-loop form factor Lee, Manteuffel, Schabinger, Smirnov, Smirnov Steinhauser '22,'23

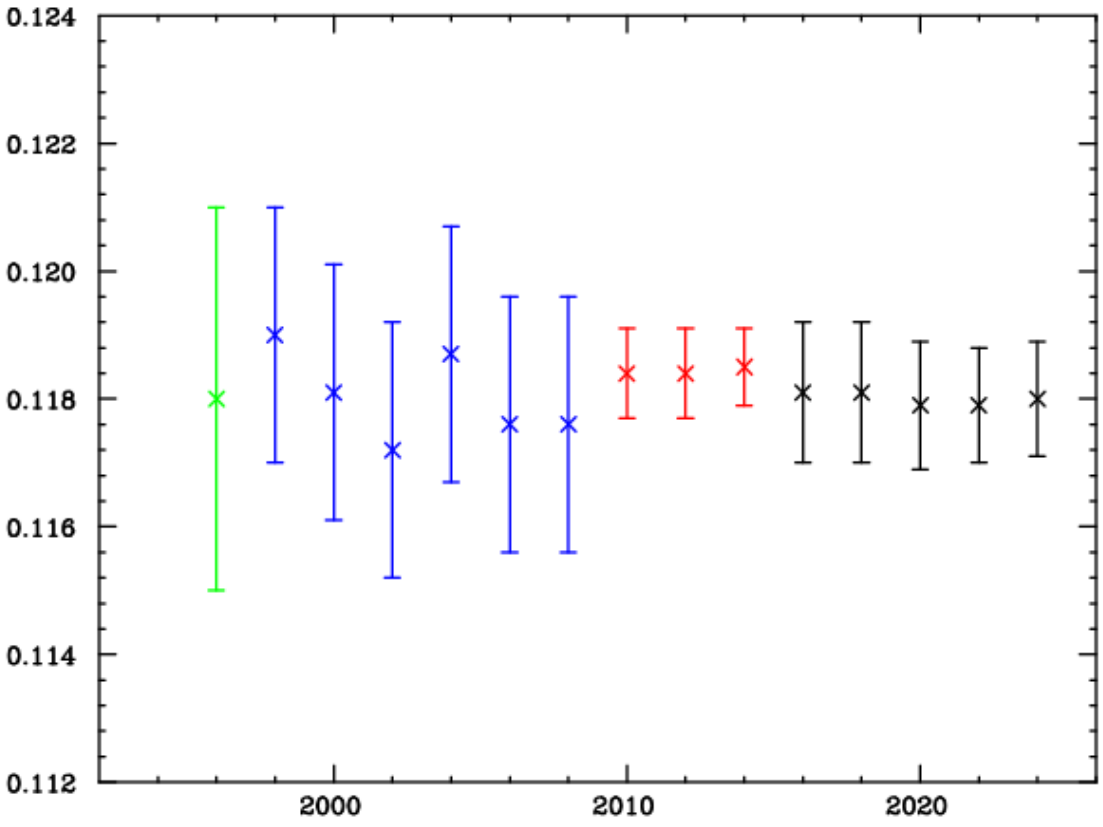
G. Heinrich

UNCERTAINTY ON $\alpha_s \sim 1\% \Rightarrow \sim 3\%$ ON CROSS SECTION

LO$\propto \alpha_s^2$; NLO$\approx$LO$\approx$2NNLO

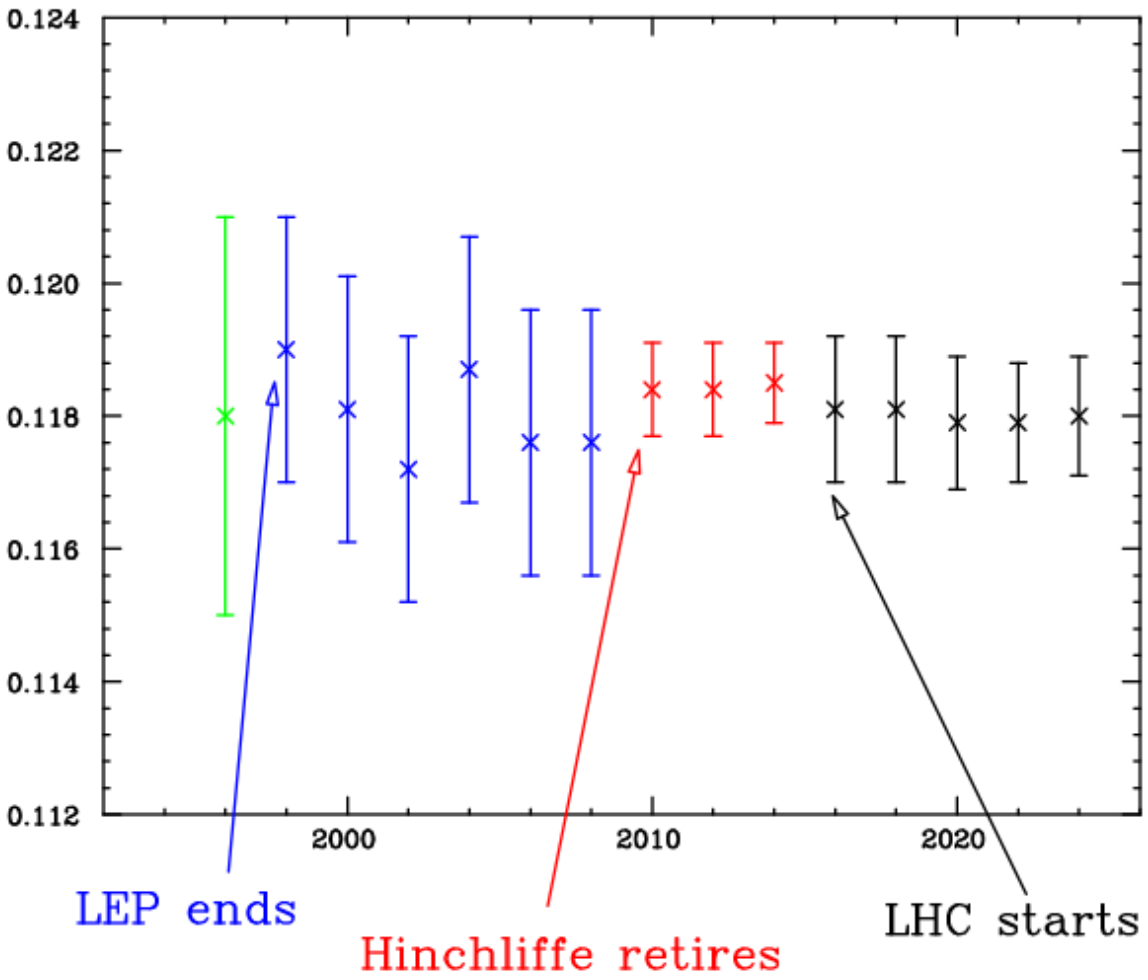
DO WE KNOW THE α_s UNCERTAINTY?

THE PDG VALUE OVER TIME



DO WE KNOW THE α_s UNCERTAINTY?

THE PDG VALUE OVER TIME



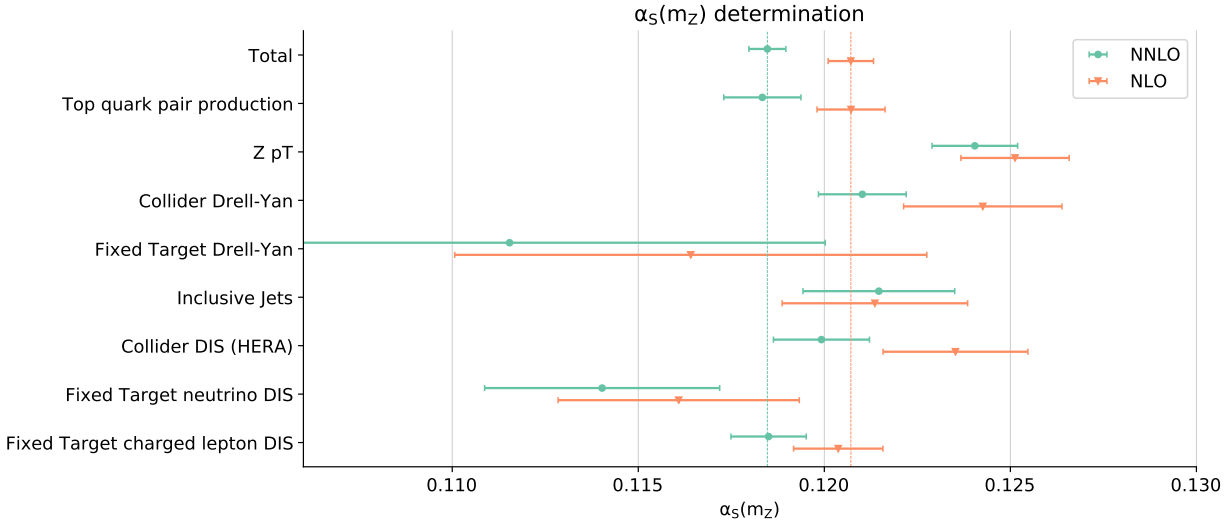
- RESULT DEPENDS ON WHO PERFORMS THE ANALYSIS
- UNCERTAINTY INCREASES WITH NEW DATA

HOW DO WE GET AN ACCURATE DETERMINATION?

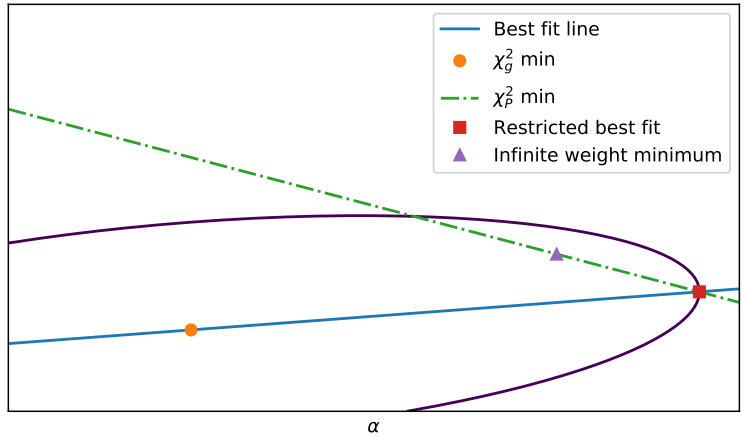
THE NEED TO DETERMINE PDFs

α_s FROM INDIVIDUAL PROCESSES DO NOT AVERAGE TO THE GLOBAL FIT: WHY?

α_s FROM PROFILING OF DATASETS IN GLOBAL FIT



- INDIVIDUAL PROCESSES $\Rightarrow$ FLAT DIRECTIONS
- PROFILING MOVES ALONG A LINE IN PDF SPACE
- MISSES TRUE MINIMUM



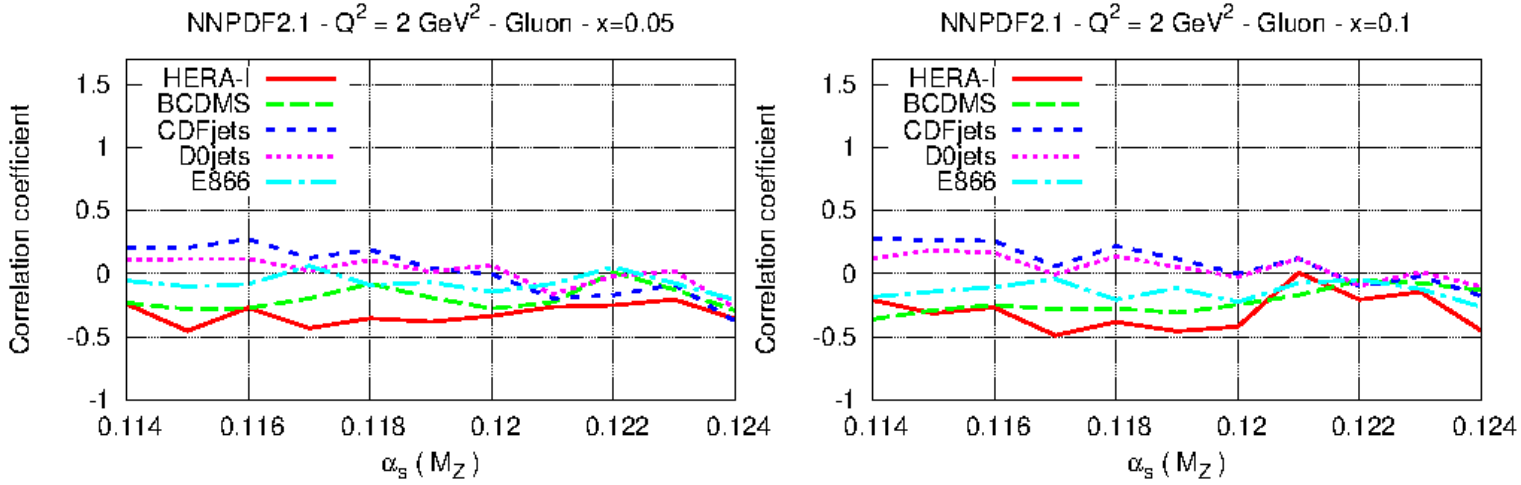
SF, Kassabov, 2020

HOW DO WE GET AN ACCURATE DETERMINATION?

THE NEED FOR A GLOBAL DATASET

α_s FROM DIS HISTORICALLY LOW (Virchaux, Milsztajn, 1992): WHY?

CORRELATION BETWEEN χ^2 AND GLUON



- INDIVIDUAL PROCESSES $\Rightarrow$ RUNAWAY DIRECTIONS
- DIS: LOW χ^2 $\Leftrightarrow$ HIGH GLUON $\Leftrightarrow$ LOW α_s
- QUENCHED BY OTHER DATA (JETS)

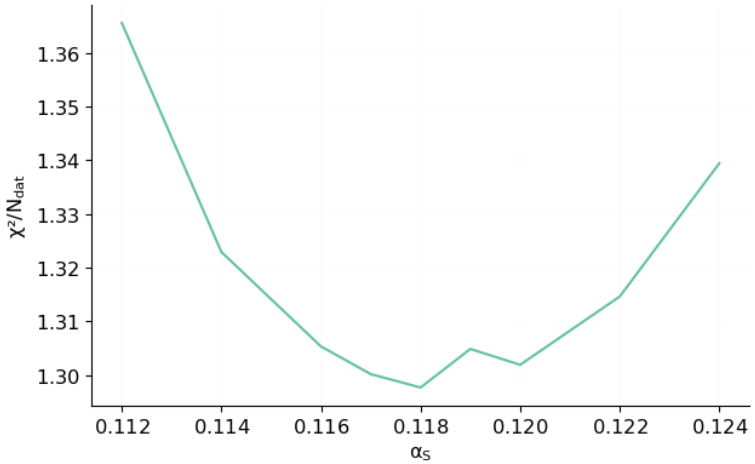
HOW DO WE GET AN ACCURATE DETERMINATION?

COLLIDERS AND MULTIPLICATIVE UNCERTAINTIES

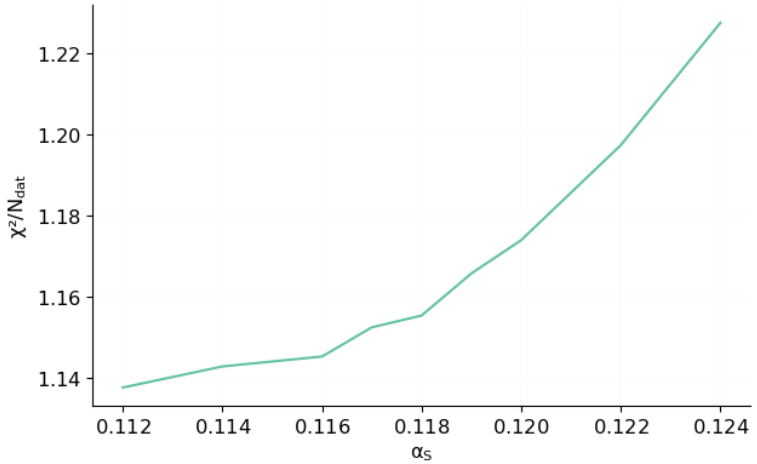
- COLLIDER DATA: MULTIPLICATIVE UNCERTAINTIES IN COVARIANCE MATRIX
- EXPERIMENTAL COVARIANCE MATRIX $\Rightarrow$ BIASED RESULT (d'Agostini, 1994)
- ITERATIVE PROCEDURE NEEDED COVARIANCE MATRIX COMPUTED FROM PREVIOUS FIT

BIASED (COVARIANCE MATRIX)

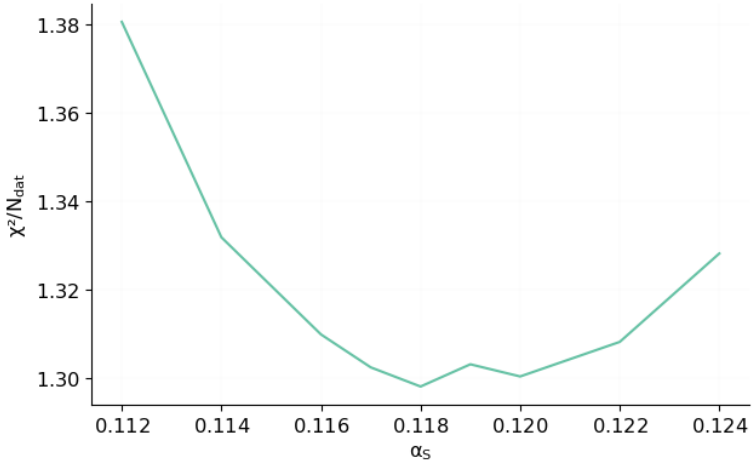
ADDITIVE (NMC, FT)

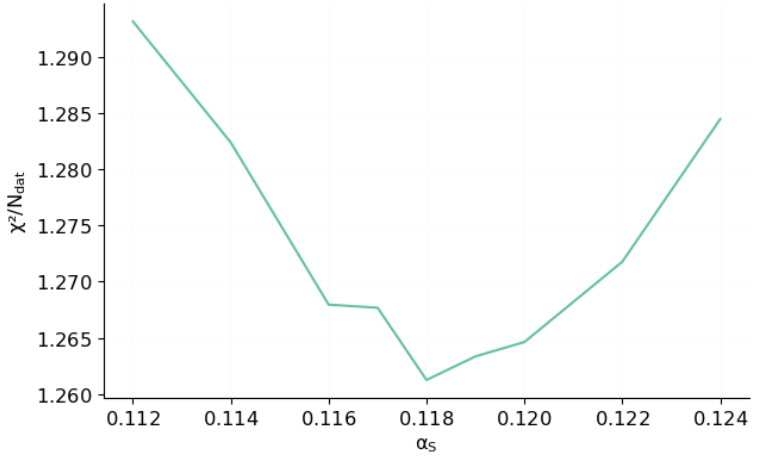


MULTIPLICATIVE (HERA, COLL)



CONSISTENT (ITERATIVE)

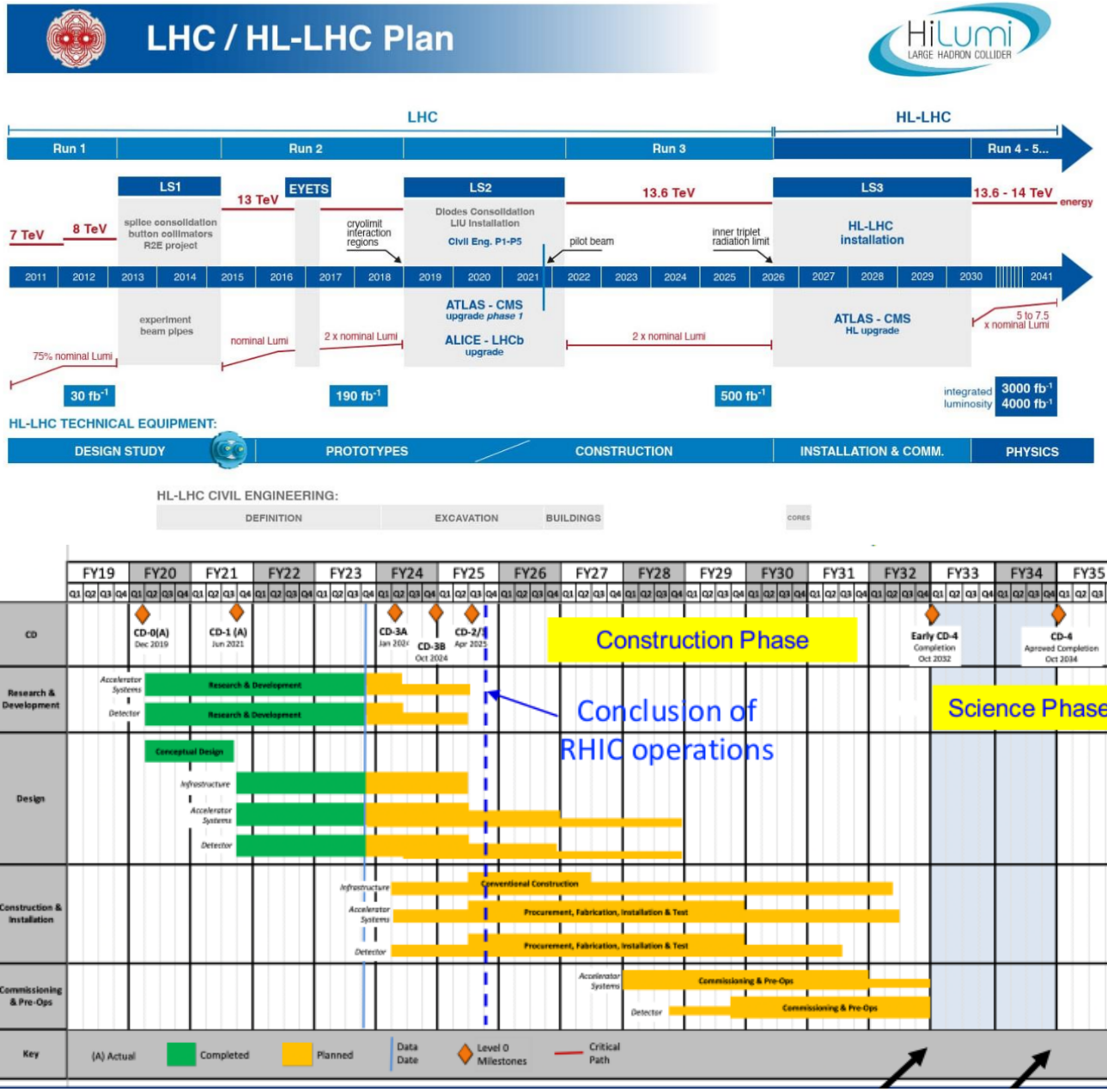




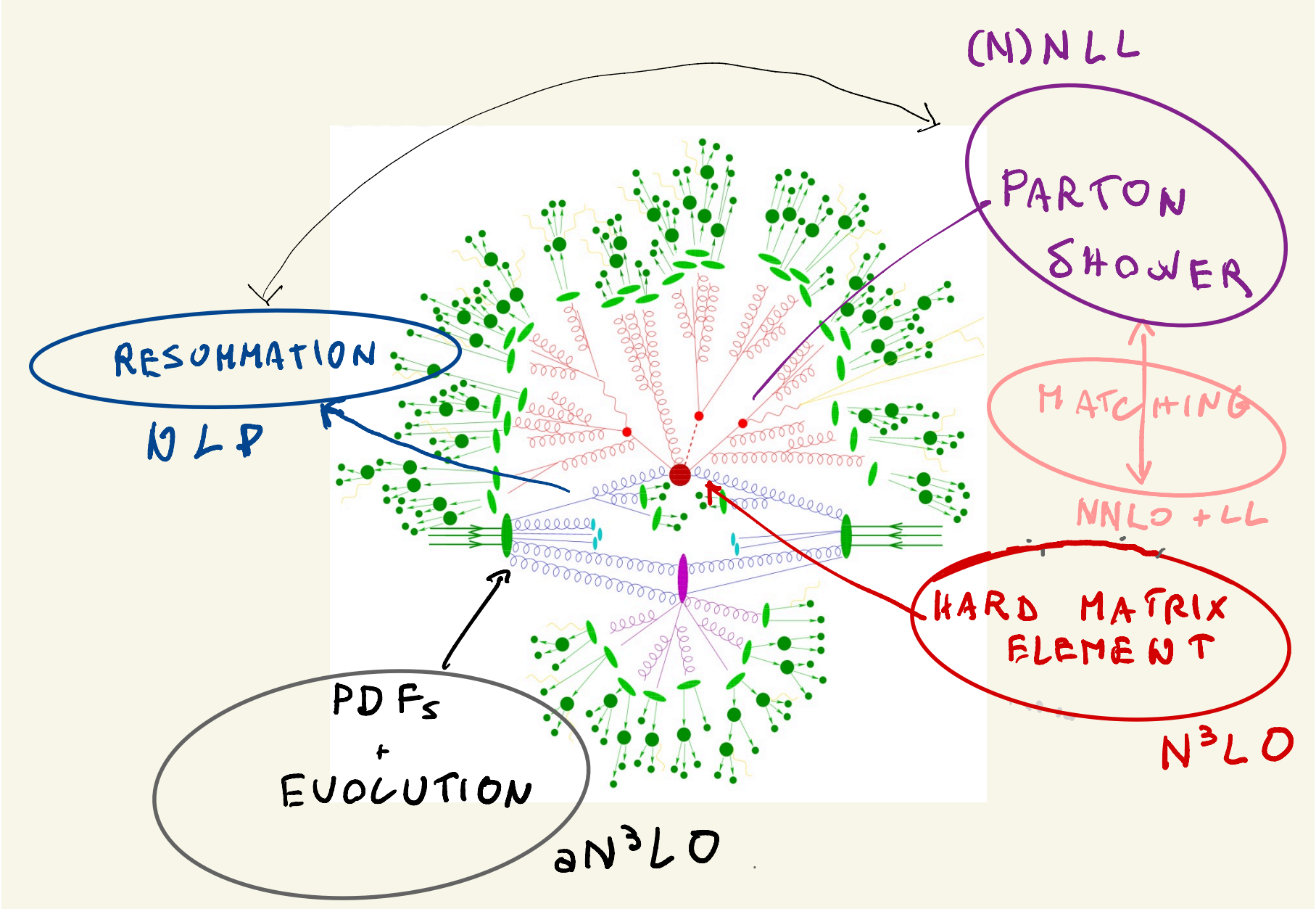
WHAT DO WE NEED FOR AN ACCURATE DETERMINATION?

- COLLIDER DATA
- SEVERAL PROCESSES
- SIMULTANEOUS FIT OF PDFS
- ACCURATE THEORY

COLLIDER DATA:
THE HL-LHC AND THE EIC



ACCURATE THEORY:
THE FRONTIER



THE N^{3}LO FRONTIER

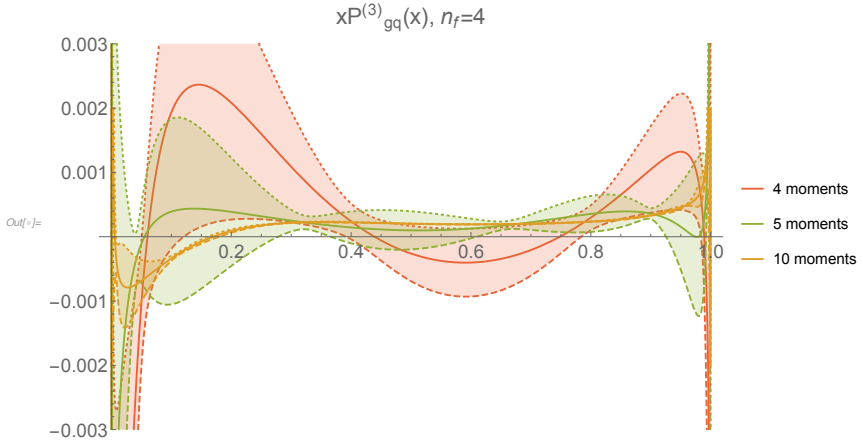
MATRIX ELEMENTS

- TOTAL XSECT: $gg \to H$ (2015), $gg \to HH$ (2020), CC& NC DY (2020-2021)
- FULLY DIFFERENTIAL ggH (2021)
- MORE N^{3}LO MATRIX ELEMENTS:
  HIGGS DECAY TO $b\bar{b}$ OR gg, INDIVIDUAL PARTON CHANNELS UP TO N^{3}LO
  Chen, Jakubčík, Marcoli, Stagnitto, 2024

SPLITTING FUNCTIONS

- LO: 1973 Gross, Wilckzek; NLO: 1979 Floratos, Ross, Sachrajda; Gonzalez-Arroyo, López, Ynduráin; NNLO: 2004 Moch, Vermaseren, Vogt
- N^{3}LO: SUBLEADING LARGE AND SMALL x BEHAVIOUR, INCREASINGLY LARGE NUMBER OF MELLIN MOMENTS (SINCE 2017): FIVE MOMENTS FOR P_{ij} KNOWN (2022)
- FIVE MORE MOMENTS FOR ALL P_{ij} SINCE EARLY 2023
  Falcioni, Herzog, Moch, Vogt; + Pelloni, Ruijl, Ueda, Vermaseren
  EXACT N_f^2 TERMS Gehrmann, von Manteuffel, Sotnikov, Yang
- HEAVY QUARK MATCHING FULLY KNOWN (Ablinger, Behring, Blümlein, De Freitas, von Manteuffel, Schneider, Schönwald, 2024)

P_{qg} WITH 4, 5, 10 MOMENTS

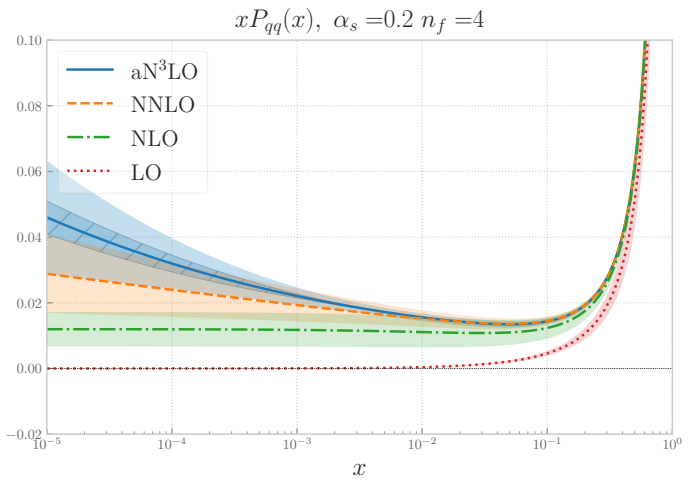


N^{3}LO SPLITTING FUNCTIONS

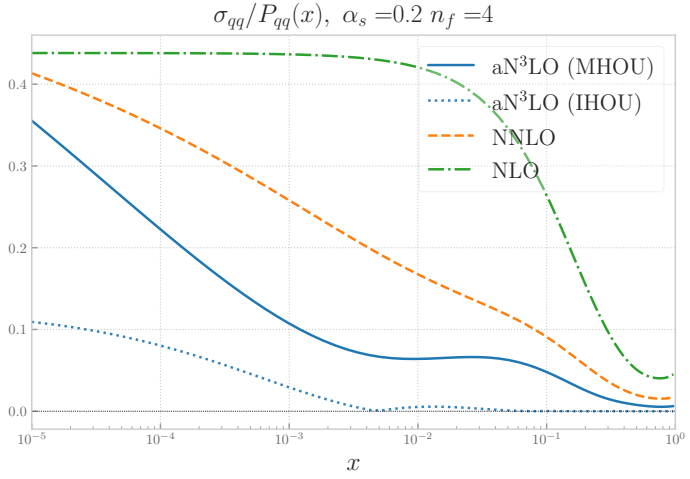
- UNCERTAINTY APPROX (IHOU) $\ll$ MISSING N^{4}LO UNCERTAINTY (MHOU) $\Rightarrow$ KNOWN EXACTLY FAPP
- FIXED-ORDER N^{3}LO EVOLUTION KNOWN FAPP

P_{qq}

SPLITTING FCTN



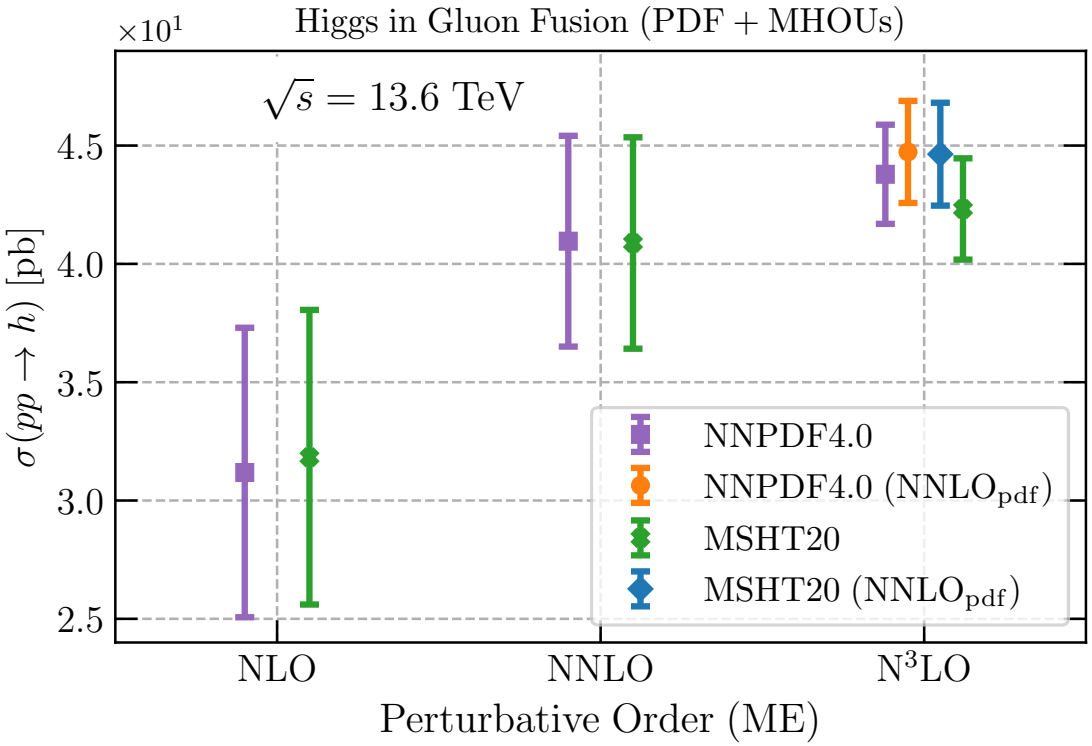
UNCERTAINTY



N^{3}LO PDFs and MHOUs

- aN^{3}LO PDF sets now available: MSHT20 (2023), NNPDF4.0 (2024), combination (2024)
  - NNPDF IHOU estimated from theory covariance matrix
  - MSHT IHOU estimated fitting nuisance parms to data
- MHOU on PDF fit available:
  - NNPDF4.0 at any order, from scale variation
  - MSHT20 at aN^{3}LO from nuisance parms, at NNLO from N^{3}LO-NNLO difference

Higgs in gluon fusion
NNPDF vs MSHT

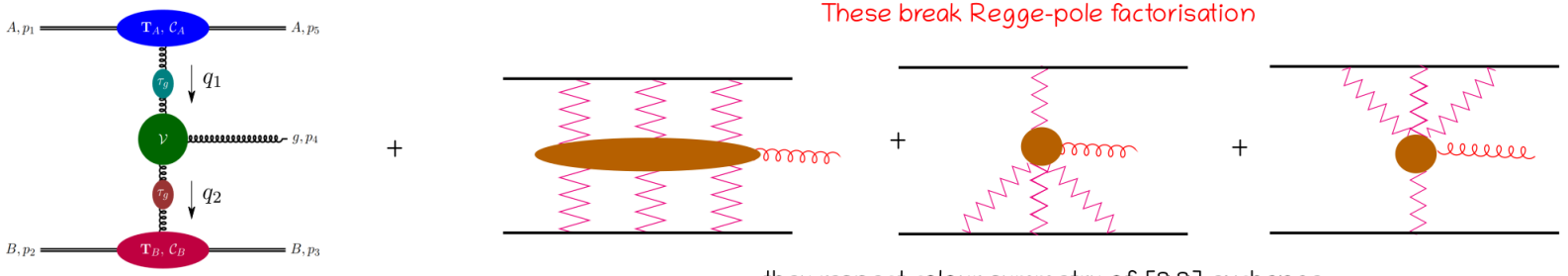


DOMINANT UNCERTAINTY: SMALL x LOGS
TOWARDS NNLO BFKL

- ONLY LL FULLY RESUMMED $\rightarrow$ DOMINANT UNCERTAINTY AT $\mathrm{N^3LO}$
- HIGH ENERGY (BFKL, SMALL x) LOGS $\leftrightarrow$ HIGH-ENERGY BEHAVIOR OF FACTORIZED $2 \rightarrow n$ AMPLITUDES
- BFKL FACTORIZATION BROKEN AT NNLO
- $2 \rightarrow 3$ AMPLITUDE COMPUTED TO TWO LOOPS (Buccioni, Caola, Devoto, Gambuti, 2024; Abreu, De Laurentis, Falcioni, Gardi, Milloy, Vernazza, 2025)
- RESTORED IN COLLINEAR LIMIT BY MULTIGLUON EXCHANGES?

Regge-pole factorisation broken at NNLL for A(-,-):

$$\mathcal{A}_{\lambda}^{AB}(\mathbf{s}) = s_{12}\left[\mathbf{T}_A^a \mathcal{C}_{A,\lambda_A}(s_{51})\right] \frac{\mathcal{R}(s_{45},s_{51})}{s_{51}} \left[f^{aba_4}\ \mathcal{V}_{\lambda_g}(k_\perp,\mathbf{q}_1,\mathbf{q}_2)\right] \frac{\mathcal{R}(s_{34},s_{23})}{s_{23}} \left[\mathbf{T}_B^b \mathcal{C}_{B,\lambda_B}(s_{51})\right] + \text{Multi-Reggeon exchanges}$$



Our goal: recover/show Regge-pole factorisation at NNLL + extract 2-loop CEV

Our strategy:

1. Expand 2-loop five-pt QCD amplitudes in MRK [Agarwal, FB, Devoto, Gambuti, von Manteuffel, Tancredi 2311.09870]
2. Use an effective theory that allows for the calculation/prediction of MR exchanges [Caron-Huot 1309.6521]

✓ 3-loop Regge-Trajectory
[Caola et al 2112.11097, Falcioni et al 2112.11098]

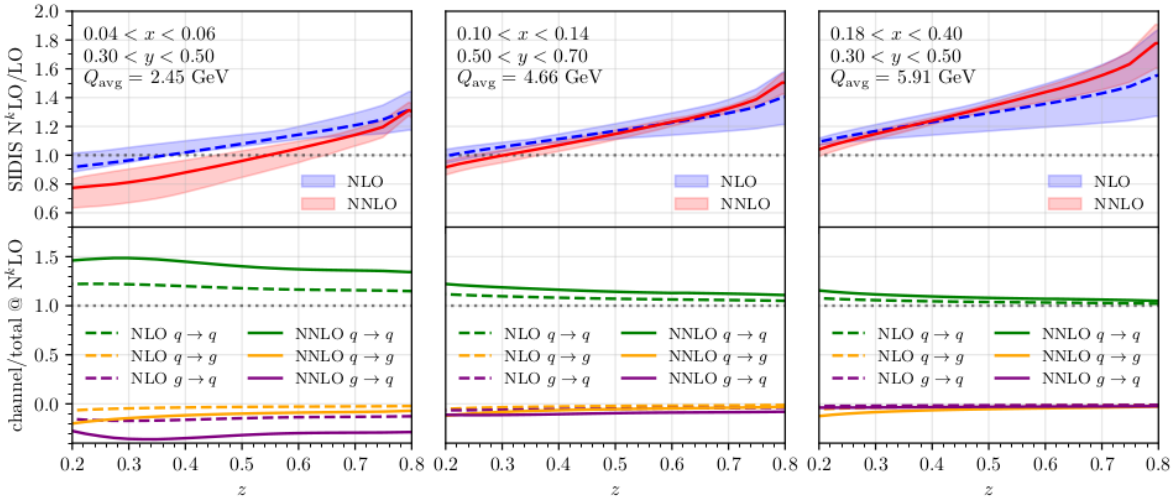
✓ 2-loop impact factors
[taken from Caola et al 2112.11097]

ACCURACY FOR EIC PROCESSES
SIDIS AT NNLO

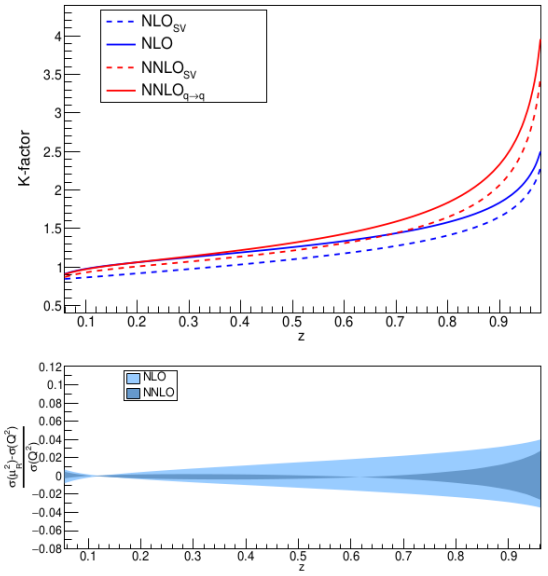
- SEMI-INCLUSIVE DIS: $ep \to h + X$ (TAGGED HADRON IN FINAL STATE)
- SIMULTANEOUS DETERMINATION OF PDF AND FRAGMENTATION FUNCTIONS DEPENDS ON TWO MOMENTUM FRACTIONS x & z
- STRINGENT CONSTRAINTS ON PDF FLAVOR SEPARATION $\Rightarrow$ NEW PHYSICS SEARCHES AT HL-LHC
- NNLO CORRECTIONS COMPUTED (Bonino, Gehrmann, Stagnitto, 2024; Goyal, Moch, Pathak, Rana, Ravindran, 2024), ALSO IN POLARIZED CASE (Bonino, Gehrmann, Stagnitto, 2024)
- SIMILAR IN SIZE TO INCLUSIVE, NONTRIVIAL z DEPENDENCE
- NNLO EXTENDED TO SI PRODUCTION @ LHC (Czakon, Generet, Mitov, Poncelet, 2025)

NNLO/LO & NLO/LO K-FACTORS VS z

COMPASS X BINS (Bonino et al., 2024)

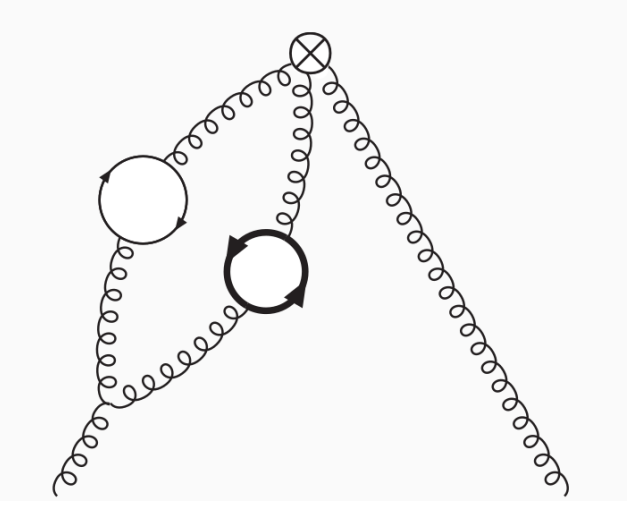


INTEGRATED OVER x FOR EIC (Moch et al., 2024)

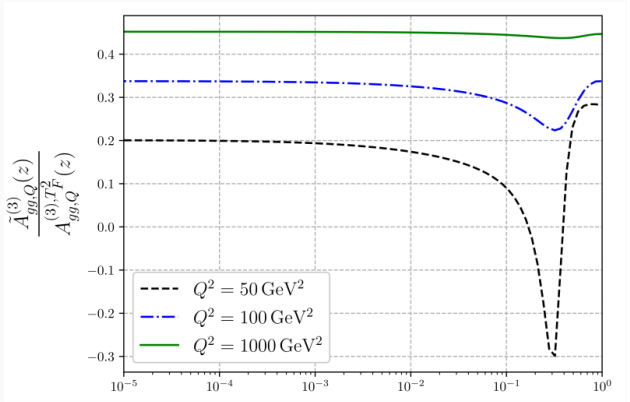


ACCURACY FOR EIC PROCESSES
RESUMMATION, HQ MASSES

- THRESOLD RESUMMATION GENERALISED TO EIC PROCESSES: SIDIS AT NNLO, NLP (Abele, de Florian, Vogelsang 2022), EXTENSION TO ALL NLP (SF, Ventola, in preparation)



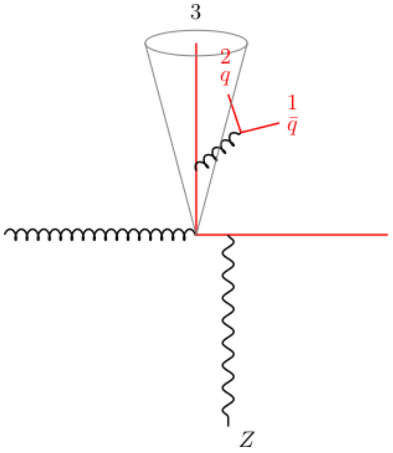
- $m_b \gtrsim m_c \Rightarrow$ MUST INCLUDE BOTH AT ONCE IN VARIABLE-FLAVOR NUMBER SCHEME
- NEW TWO-MASS CONTRIBUTIONS Ablinger, Behring, Blümlein, De Freitas, Manteuffel, Schneider, Schönwald 2024
- SIZABLE WILSON COEFFICIENT AT LOW SCALE, VALENCE PEAK



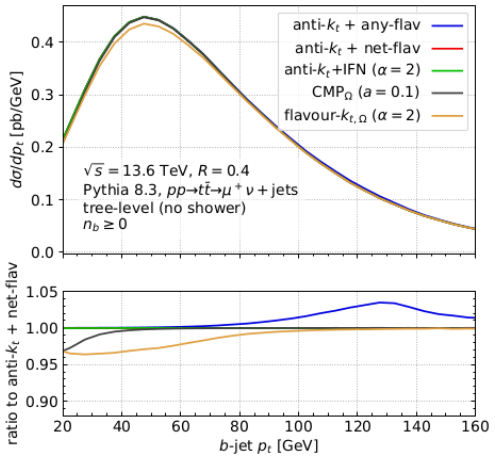
HEAVY QUARK TAGGING
THE PROBLEM OF HEAVY FLAVORED JETS

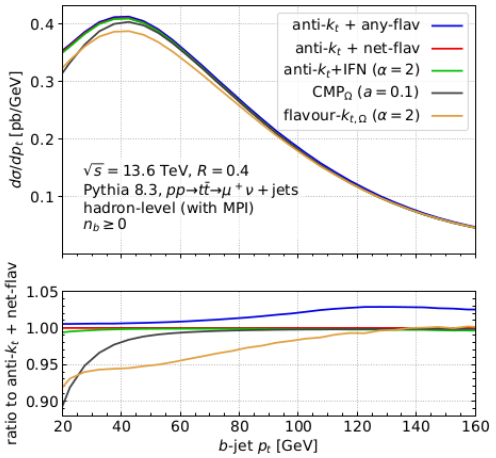
- DEFINITION OF HEAVY FLAVORED JET NONTRIVIAL $\Rightarrow$ "EXPERIMENTAL" DEFINITION NOT IRC SAFE
- LONG-STANDING OPEN PROBLEM: SOLUTIONS
  - LIMITED (IRC ONLY AT LOW ORDER)
  - IMPRACTICAL (DIFFICUL TO MERGE WITH ANTI-k_t.)
- FULL SOLUTION (IFN SCHEME), CONSISTENT WITH ANTI-k_t, ALL-ORDER IRC-SAFETY TEST (Caola, Grabarczyk, Hitt, Salam, Sczyboz, Thaler, 2024)

JET FLAVOR POLLUTION



B JET FROM TOP PRODUCTION

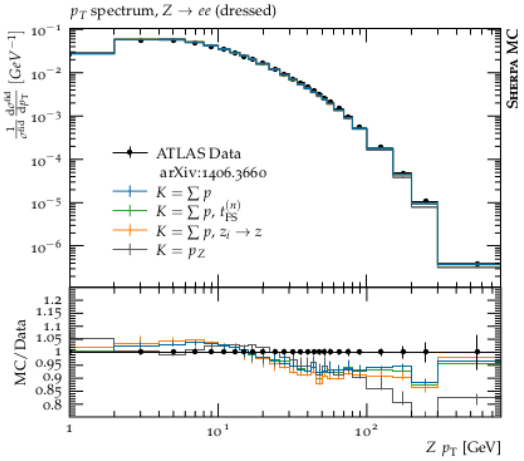




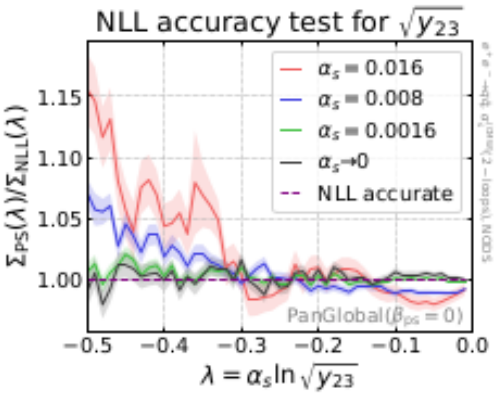
PARTON SHOWER MONTECARLOs: THE PATH TO NN LOGARITHMIC ACCURACY

- CLOSE TO ACHIEVING FULL AGREEMENT WITH NLL ANALYTIC RESUMMATION ⇒ COLOR DIPOLE
  - `Alaric` ⇒ NLL FOR GLOBAL LHC OBSERVABLES (Höche, Krauss, Reichelt, 2024)
  - `PanScales` ⇒ EXACT NLL FOR e^+e^- (van Beekveld et al., 2023)
- INITIAL-STATE MASSIVE QUARK EFFECTS INCLUDED IN `Alaric` (Assi, Höche, 2024)
- FULL NNLL ACCURACY FOR JET EVENT SHAPES! (van Beekveld, Dasgupta, El-Menoufi, Ferrario-Ravasio, Helliwell, Hamilton, Karlberg, Monni, Salam, Soto-Ontoso, Sczyboz, Soyez, 2024)

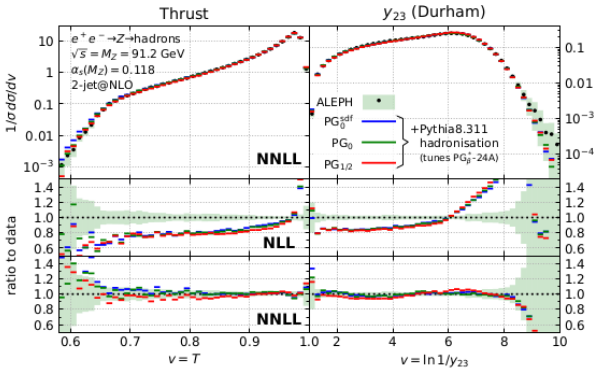
`Alaric`: RECOIL UNCERTAINTY IN DY



`PanScales`: NLL ACCURACY TEST



`PanScales`: NNLL EVENT SHAPES

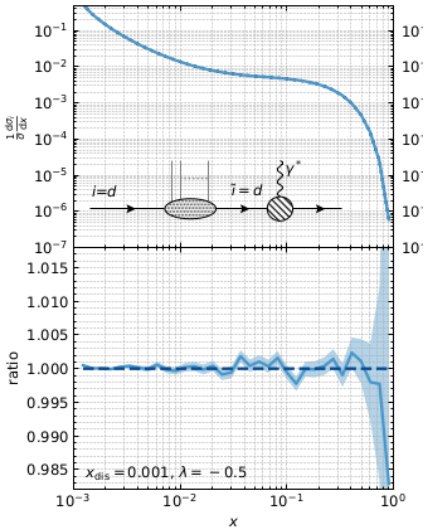


PARTON SHOWER MCs FOR DIS

NLL SHOWER

- PanScales FULLY IMPLEMENTED FOR DIS AND VBF (van Beekveld, Ferrario Ravasio, 2023)
- FIXED-ORDER ⇒ WIDELY SEPARATED EMISSIONS INDEPENDENT
- FIXED-ORDER ⇒ EXACT SUBLEADING COLOR
- ALL-ORDER ⇒ TESTED VS. EXACT NLO EVOLUTION

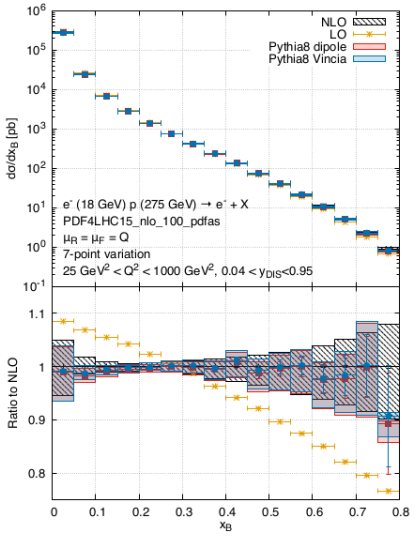
PANSCALES VS HOPPET
PROBABILITY OF PARTON x FOR FIXED x_B



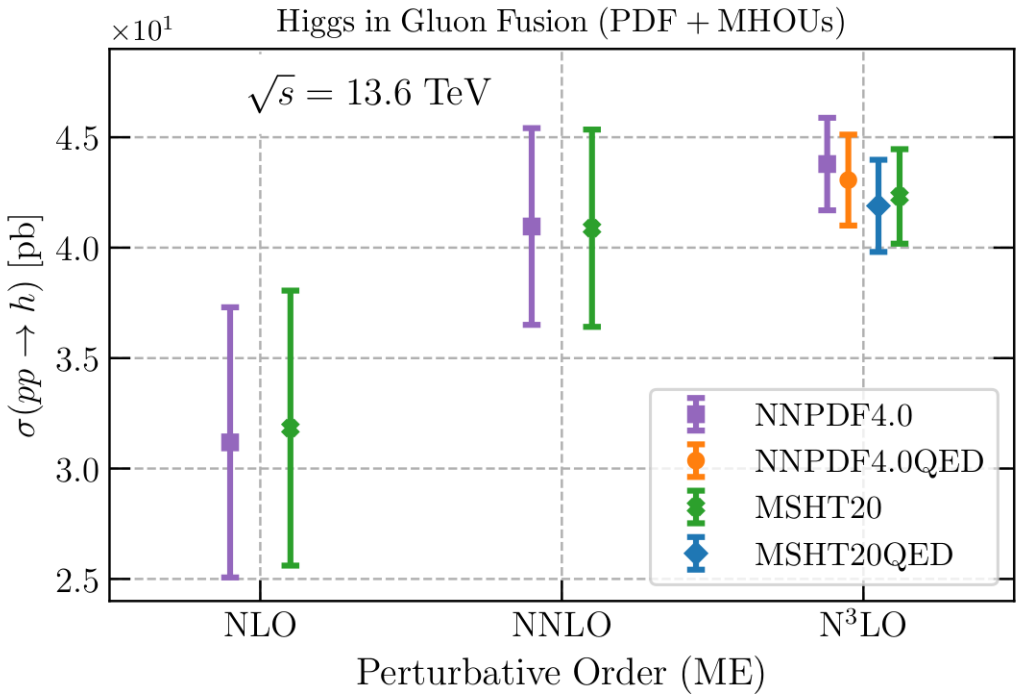
NLO+PS

- NLO+PS EVENT GENERATOR IMPLEMENTED IN POWHEG BOX FOR DIS (Banfi, Ferrario Ravasio, Jäger, Karlberg, Reichenbach, Zanderighi, 2023)
- FSR DOES NOT PRESERVE x_B, y, Q^2
  ⇒ MOMENTUM MAPPINGS ADAPTED
  ⇒ PRESERVE INCOMING & OUTGOING LEPTON MOMENTA
- NLO CORRECTIONS SIGNIFICANT IN EIC KINEMATICS
- EXTENDED TO FINAL-STATE MASSIVE QUARKS (Buonocore, Limatola, Nason, Tramontano, 2024)
- EXTENDED TO NLL+NLO! (van Beekveld, Ferrario-Ravasio, Helliwell, Karlberg, Salam, Scyboz, Soto-Ontoso, Soyez, Zanoli, 2025)

NC DIS AT EIC



WHAT ABOUT QED & EW CORRECTIONS?
THE PHOTON PDF
HIGGS IN GLUON FUSION

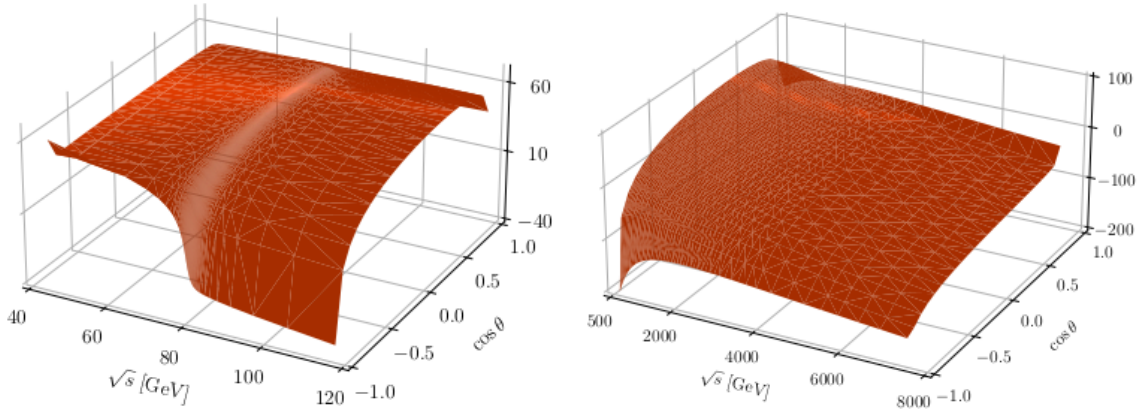


- PHOTON PDF MIXES UPON QCD$\times$ QED EVOLUTION
- SUBTRACTS MOMENTUM FROM GLUON $\Rightarrow$ GLUON SUPPRESSED
- 1-2% EFFECT ON TOTAL GLUON FUSION HIGGS CROSS-SECTION NOT ACCOUNTED FOR & NOT INCLUDED IN UNCERTAINTY IN HXSWG

QED & EW CORRECTIONS LHC
MIXED QCD×EW CORRECTIONS TO DY

- $\alpha \sim (\alpha_s(M_Z))^2$ SO $\alpha\alpha_s \sim \alpha_s^3$; NONTRIVIAL INTERFERENCE
- FULL TWO LOOP QCD×EW CORRECTIONS TO NC DRELL-YAN INCLUDING DECAY RECENTLY COMPLETED, RESONANT AND HIGH-MASS Bonciani et al., Buccioni et al. (2022)
- CC DRELL-YAN AVAILABLE WITH TWO LOOP VIRTUAL CORRECTIONS IN POLE APPROX (2021)
- EXACT TWO-LOOP VIRTUAL CORRECTIONS TO CC NOW AVAILABLE (Armadillo, Bonciani, Devoto, Rana, Vicini, 2024)
- DETAILED PHENO: CORRECTIONS UP TO PERCENT AT HIGH RAPIDITY (Armadillo, et al., 2025)

VIRTUAL TWO–LOOP RATIO TO BORN IN UNITS OF $\alpha\alpha_s$

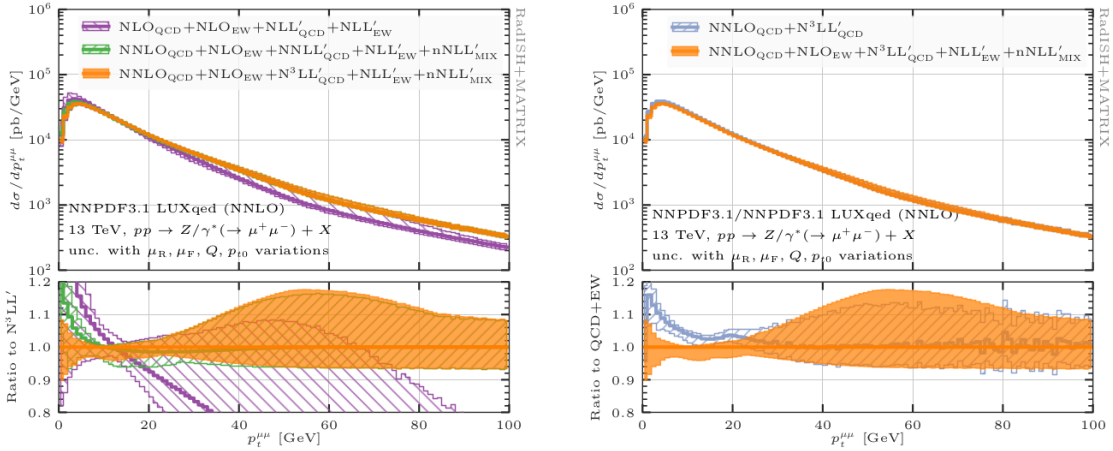


- PERCENT–LEVEL INTERFERENCE (NEGATIVE)

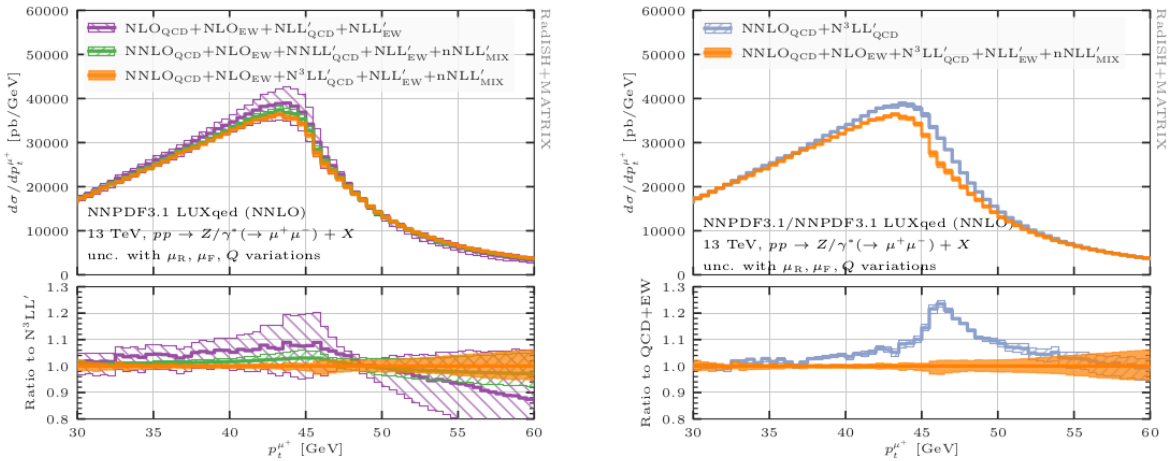
QED & EW CORRECTIONS @ LHC
COMBINED QCD-EW RESUMMATION

- DRELL-YAN FIXED ORDER MIXED QCD+EW COMPUTATION IMPROVED WITH TRANSVERSE MOMENTUM RESUMMATION THROUGH PARTON SHOWERING LONG AGO
- ANALYTIC NLL (EW) x NNLL(QCD) x NLL (MIXED) NOW AVAILABLE
  (Buonocore, Rottoli, Torrielli, 2024)

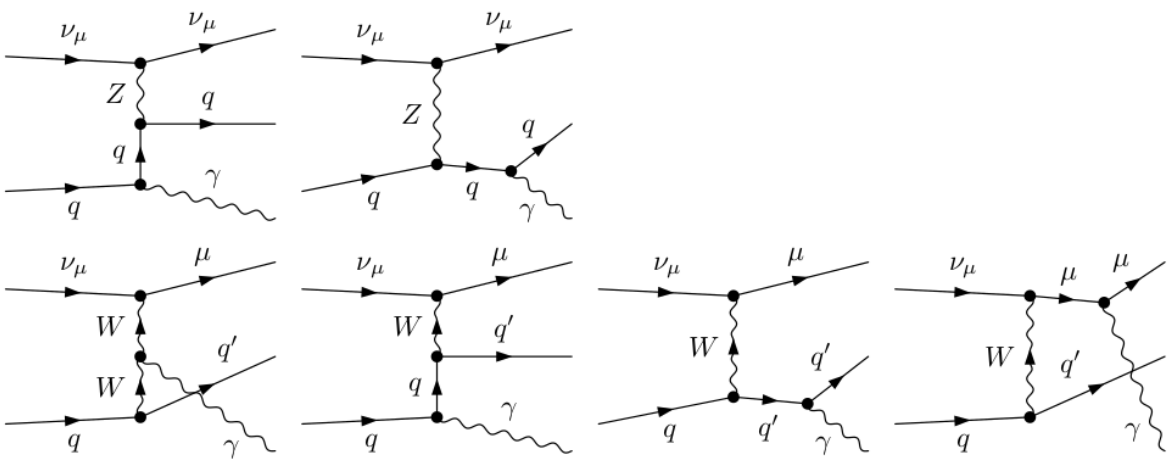
NEUTRAL CURRENT
DIMUON p_T



MUON p_T



QED & EW CORRECTIONS @ EIC?



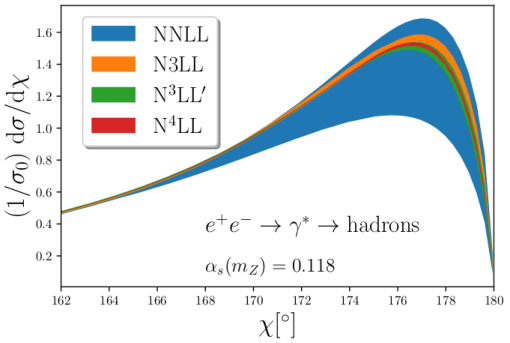
- RADIATIVE CORRECTIONS TO DIS $\Rightarrow$ INCLUDED IN EXPT ANALYSIS
- MONTECARLOS `HECTOR`, `HERACLES`, `DJANGOH` (Bardin, Spiesberger 1995-2005)
- NLO EW FOR ν DIS AVAILABLE (Diener, Dittmaier, Hollik, 2003)
- NEED TO GO BEYOND STRUCTURE FUNCTIONS!

α_s WITHOUT PDFs
ENERGY CORRELATORS

Simplest example is the two-point function

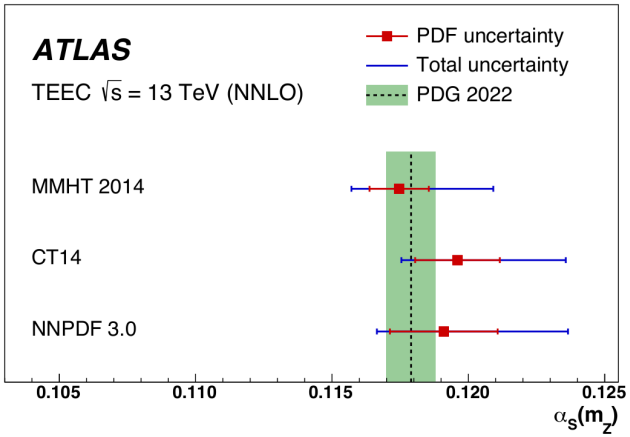
$$\mathrm{EEC}(\chi) = \sum_{a,b} \int \mathrm{d}\sigma_{e^+e^-\to a+b+X} \, \frac{E_a E_b}{Q^2} \, \delta(\cos\chi_{ab} - \cos\chi)$$

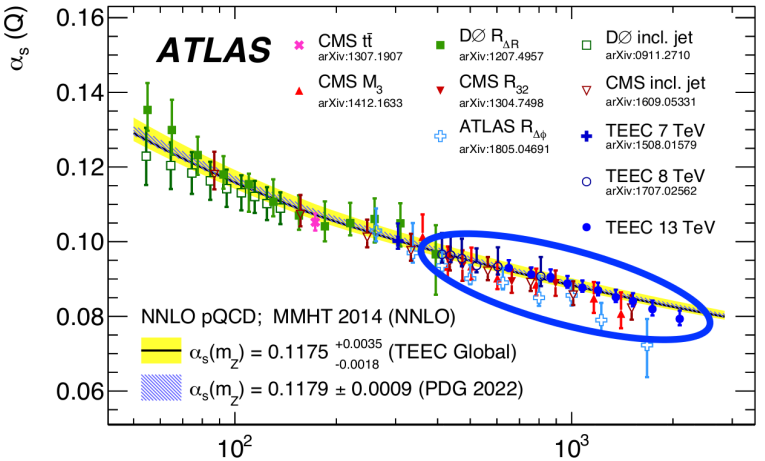
large logarithms both for small and large angles. For large angle N^{4}LL is known!



Duhr, Mistlberger, Vita '22

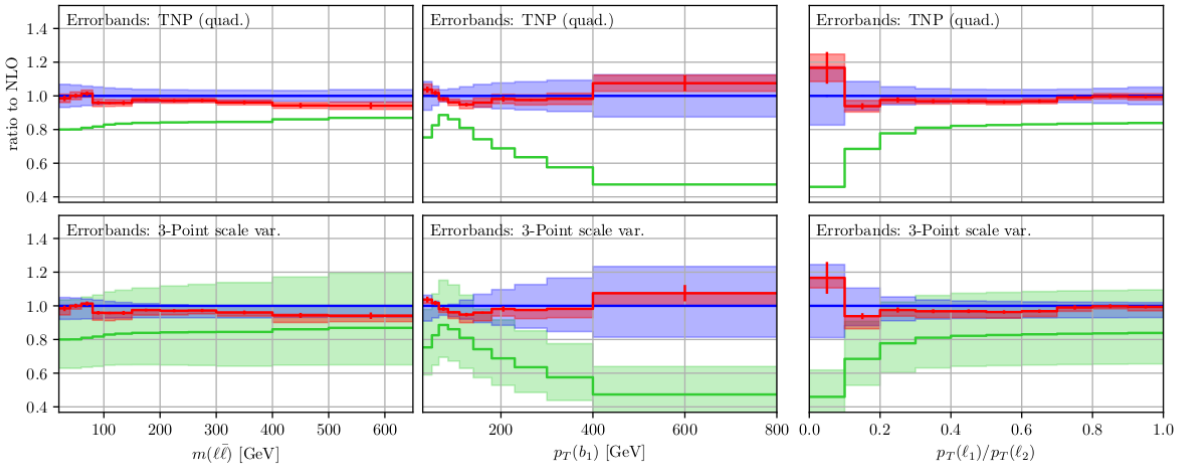
- FACTORIZATION AND RESUMMATION TO HIGH ORDER
- CURRENTLY $\Rightarrow$ JET SUBSTRUCTURE $\Rightarrow$ α_s (ATLAS, CMS)
- PARISI'S IDEA (1978): $\Rightarrow$ PARTON TO HADRON TRANSITION $\Rightarrow$ PDF-INDEPENDENT α_s DETERMINATION





FAITHFUL ERROR ESTIMATION

- MHO TERMS ⇒ COVMAT / NUISANCE PARAMETERS
  (NNPDF, 2019; Tackmann, 2024; Lim, Poncelet, 2024)
- EXTRACT BEHAVIOR FROM KNOWN INFORMATION



MACHINE LEARNING AMPLITUDES

- TRANSFORMERS ⇒ LARGE LANGUAGE MODELS ⇔ ATTENTION (TOKENS)
- PREDICT ANSWER TO QUESTION ⇒ PREDICT ITEM IN SEQUENCE
- PREDICT $n + k$-JET RADIATION FEATURES FROM n-JET RADIATION (Butter, Charton, Villadamigo, Ore, Plehn, Spinner, 2024)
- PREDICT COEFFICIENTS OF SPECIFIC HIGHER-ORDER TERMS IN AMPLITUDES (Cai, Merz, Charton, Nolte, Wilhelm, K. Cranmer, Dixon, 2024)

SUMMARY

THEORY AT THE HL-LHC & EIC START?

- SAME ACCURACY FOR STANDARD CANDLES @ LHC (DY, TOP, HIGGS) & EIC (DIS, SIDIS)
- N^3LO QCD+ N(N)LO EW FIXED ORDER; NLP SOFT (SUDAKOV) RESUMMATION; N(N)LO HIGH-ENERGY BFKL RESUMMATION; NNLO PARTON SHOWER MATCHED TO N(N)LO
- INCREASING ROLE OF ML: MHOUS & MODELING UNCERTAINTIES

$\Rightarrow$ RELIABLE FEW PERMILLE α_s

HOWEVER

BEWARE OF GRESHAM'S LAW OF α_s DETERMINATION

"Bad determinations drive our good determinations"

(T. Gresham, 1519-1579)

- ACCURATELY ASSESSED UNCERTAINTY $\Rightarrow$ LARGER!
- DETERMINATIONS WITH LARGE UNCERTAINTY ARE DISFAVORED W.R. TO SMALL UNCERTAINTY