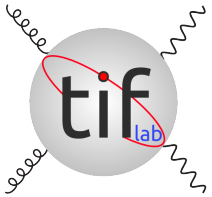


PROSPECTS OF QCD AND TOP PHYSICS

STEFANO FORTE
UNIVERSITÀ DI MILANO & INFN

UNIVERSITÀ DEGLI STUDI DI MILANO
DIPARTIMENTO DI FISICA

Workshop on Future Accelerators

Corfu, 20 May 2024

FUTURE ACCELERATORS

"IT IS DIFFICULT TO MAKE PREDICTIONS, ESPECIALLY ABOUT THE FUTURE"

Niels Bohr, quoting K. K. Steincke

- FIRST HORIZON: HL-LHC & EIC: MID 2030S
  - BEYOND CURRENT PRECISION AND ACCURACY
  - BEYOND CURRENT PROCESSES, OBSERVABLES, AND TECHNIQUES
- SECOND HORIZON: FCC-EE: MID 2040S
  - STRETCHING THE CURRENT THEORY
  - THE ERA OF MACHINE LEARNING
- BEYOND (MY) HORIZON: FCC-PP: MID 2070S
  - 50 YEARS AGO THE SM ARGUABLY DID NOT EXIST

QCD

- A TOOL FOR PRECISION PHYSICS
- A PATH TO THEORETICAL DISCOVERY

DISCLAIMER

- A PERSONAL SELECTION OF RESULTS
- ONLY DEVELOPMENTS SINCE MARCH 2023 COVERED

STEFANO CATANI (1958-2024)

HIGHER PRECISION AND ACCURACY

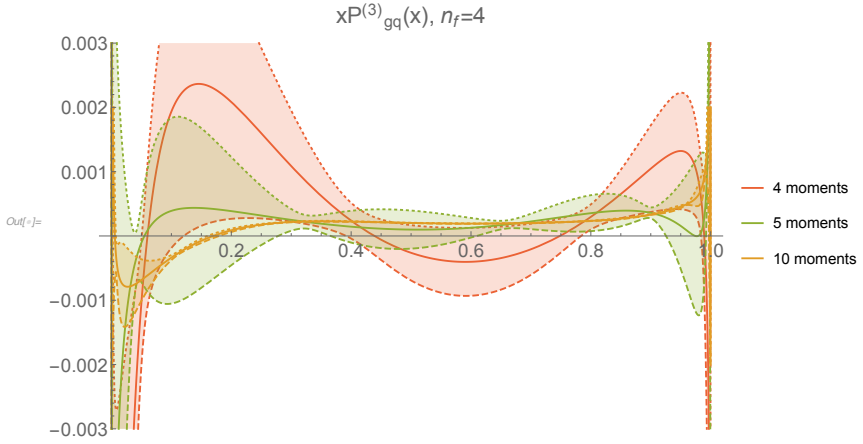
THE AMPLITUDE REVOLUTION AND N^{3}LO

- ENORMOUS PROGRESS IN AMPLITUDE COMPUTATIONS $\Rightarrow$ Papadopoulos, Corfu 2023
- 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
- N^{3}LO SPLITTING FUNCTIONS: GETTING THERE

THE 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 P_{qq}, P_{qg}, P_{gq} SINCE EARLY 2023
  Falcioni, Herzog, Moch, Vogt; + Pelloni, Ruijl, Ueda, Vermaseren
  EXACT N_f^2 TERMS Gehrmann, von Mateuffel, Sotnikov, Yang

P_{qg} WITH 4, 5, 10 MOMENTS

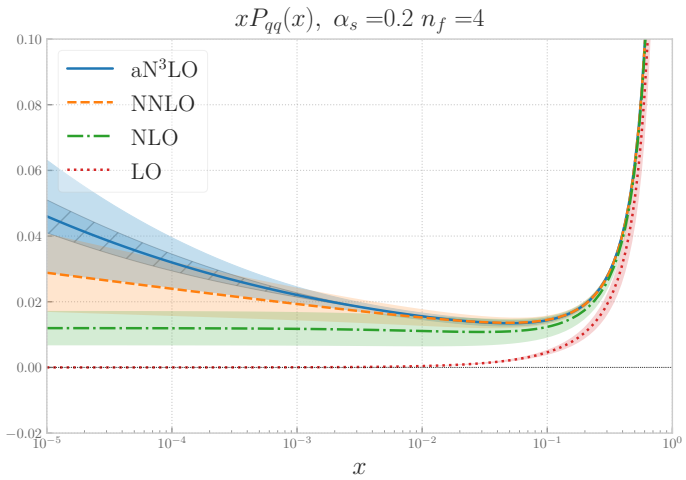


N^{3}LO SPLITTING FUNCTIONS

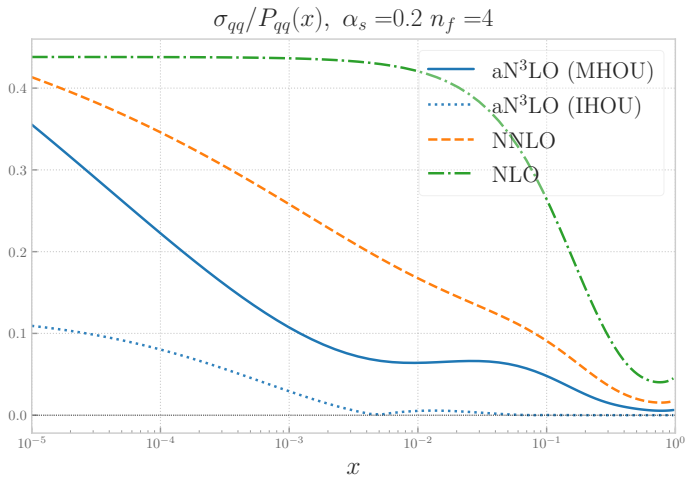
- NONSINGLET & SINGLET QUARK SECTOR P_{qq}, P_{qg}, P_{gq}
  UNCERTAINTY APPROX (IHOU) $\ll$ MISSING N^{4}LO UNCERTAINTY (MHOU) $\Rightarrow$ KNOWN EXACTLY FAPP
- P_{gg} ONLY UNCERTAIN FOR $x \lesssim 0.03 \Rightarrow$ BFKL RESUMMATION REGION
- FIXED-ORDER N^{3}LO EVOLUTION KNOWN FAPP

QUARK-QUARK

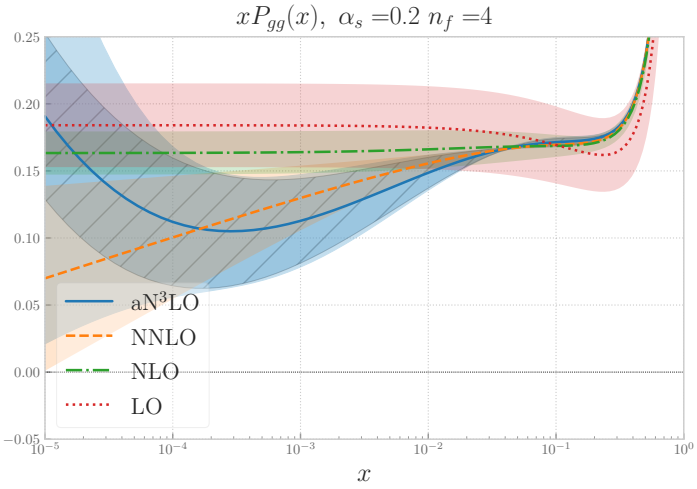
SPLITTING FCTN

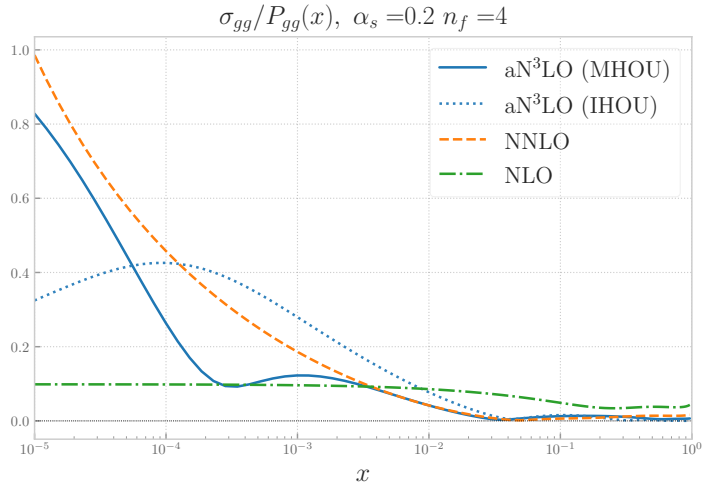


UNCERTAINTY



GLUON-GLUON





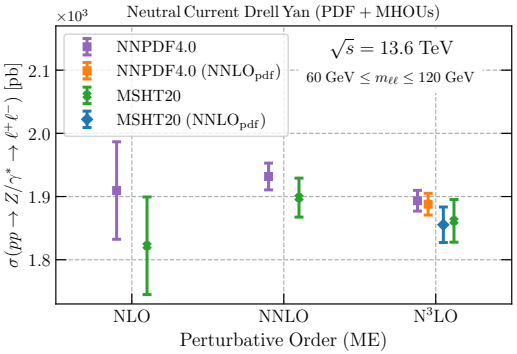
NNPDF 2024, SEE ALSO MOCH, RUIJL, UEDA, VERMASEREN, VOGT 2024

PDFs: N^{3}LO, MHOUs, QED

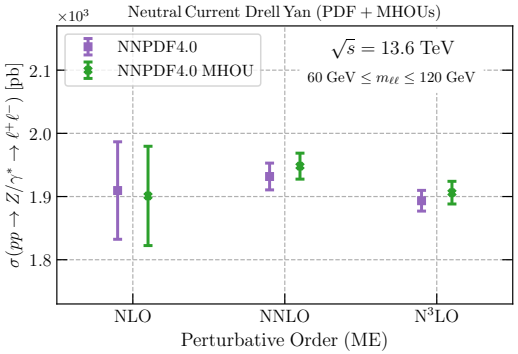
- aN^{3}LO PDF sets now available: MSHT20 (2023), NNPDF4.0 (2024)
  - NNPDF IHOU estimated from theory covariance matrix
  - MSHT IHOU estimated fitting nuisance parms to data
- MHOU on PDF fit available:
  - NNPDF4.0 at any order, from scale variation
  - MSHT20 at aN^{3}LO from nuisance parms, at NNLO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

on-shell Z production

NNPDF vs MSHT

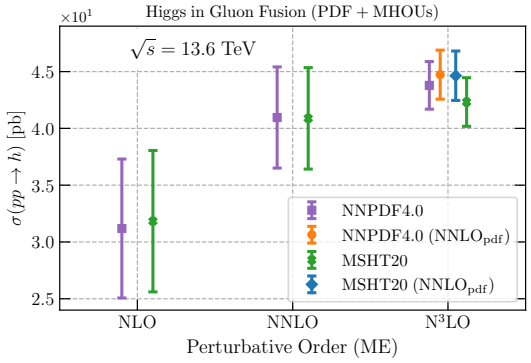


NNPDF: impact of MHOU

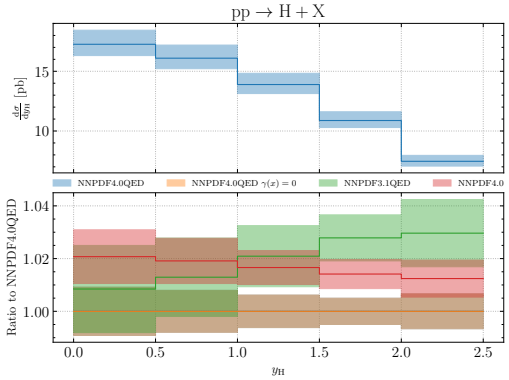


Higgs in gluon fusion

NNPDF vs MSHT



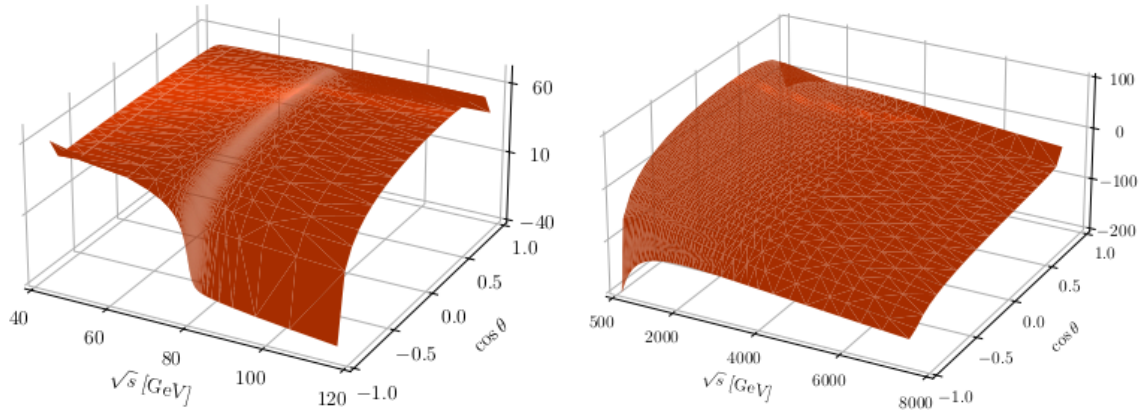
NNPDF: impact of QED



MIXED QCD×EW CORRECTIONS

- $\alpha \sim (\alpha_s(M_Z))^2$ SO $\alpha\alpha_s \sim \alpha_s^3$; NONTRIVIAL INTERFERENCE; RESONANT CONTRIBUTIONS
- FULL TWO LOOP QCD×EW CORRECTIONS TO NC DRELL-YAN INCLUDING DECAY RECENTLY COMPLETED (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, 2023)

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



- PERCENT–LEVEL INTERFERENCE (NEGATIVE)

RESUMMATION: THE NLP FRONTIER

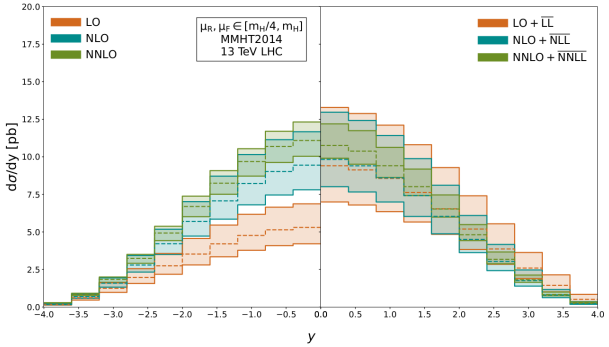
DRELL-YAN, HIGGS CROSS-SECTION: $\sigma(\tau) = \sigma^{\rm LO} C(\alpha_s, \tau)$, $C(\alpha_s, \tau) = 1 + \alpha_s(M^2) C^{\rm NLO} + \ldots$, $\tau = \frac{M^2}{s}$;
$C(\alpha_s, N) = \int_0^1 d\tau \tau^{N-1} C(\alpha_s, \tau)$

LEADING, NEXT TO LEADING... LOG VS. LEADING, NEXT TO LEADING... POWER: $\lim_{N\to\infty} C^{{\rm N^k LO}}(\alpha_s, N) \sim$
$\alpha^k \left[C^{k,LL} \ln^{2k} N + C^{k,NLL} \ln^{2k-1} N + \cdots + g^k + \frac{1}{N} C^{k,NLP} (\ln N) + \ldots \right]$

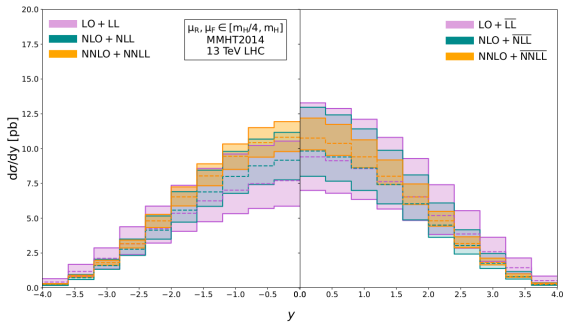
- $\rm N^3LO$ DETERMINES $\rm N^3LL$
- NLP PHENOMENOLOGICALLY RELEVANT FOR M^2 BETWEEN THE GEV AND THE TEV SCALE

HIGGS PRODUCTION LHC

FIXED ORDER VS LOG RESUMMED



LOG VS NLP RESUMMED (PARTIAL)



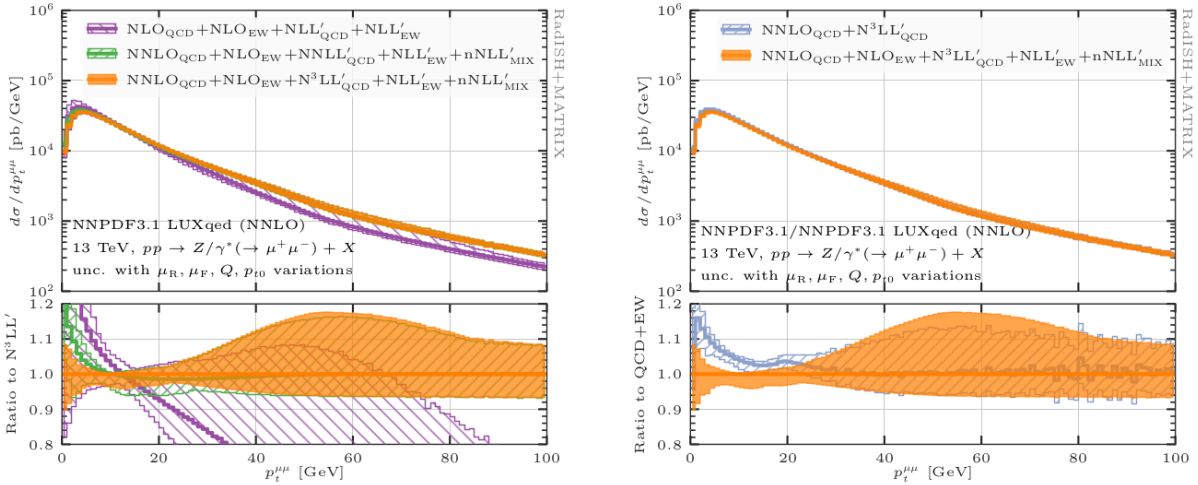
(Ravindran, Sankar, Tiwari, 2022)

- FULL LL, NLP RESUMMATION FOR DY (Bileveld, Laenen, Vernazza, Wang, 2023)
- SOFT QUARK EMISSION GENERALLY RESUMMED (van Beekveld, Vernazza, White, 2023)
- NLP PARTLY RESUMMED FOR JET THRUST AND C-PARM
(Agarwal, van Beehveld, Laenen, Mishra, Mukkopadhyay, Tripathi, 2024)

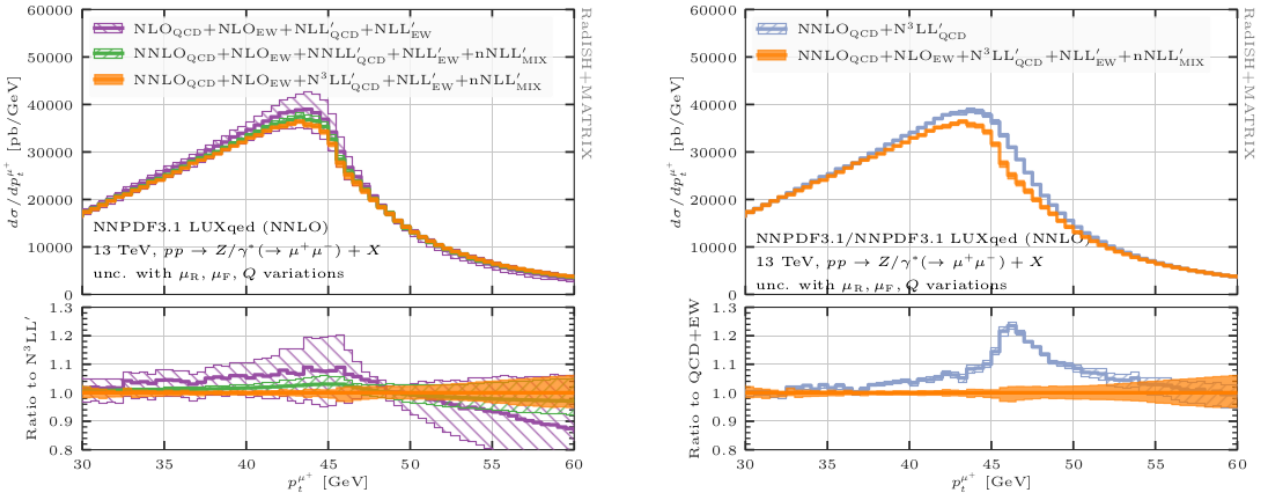
COMBINED QCD-EW RESUMMATION

- 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



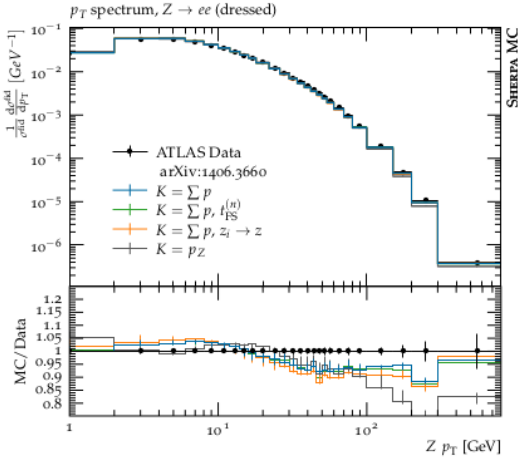
MUON p_T



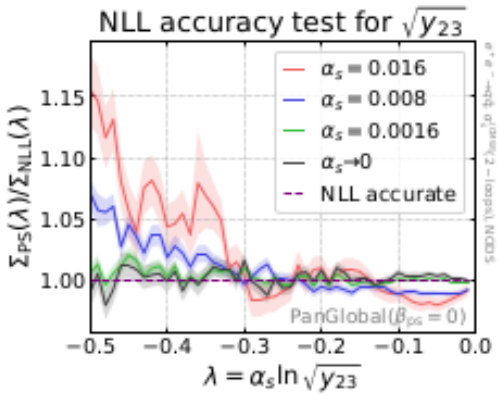
PARTON SHOWER MONTECARLOs: THE PATH TO NN LOGARITHMIC ACCURACY

- 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)
- NNLL EFFECTS INCLUDED IN `PanScales` FOR OBSERVABLES SENSITIVE TO SOFT EMISSION (e^+e^-) (Ferrario-Ravasio, Hamilton, Karlberg, Salam, Sczyboz, Soyez, 2023)
- JET CALCULUS EXTENDED TO NNLL TOWARDS NNLL PS (van Beekveld, Dasgupta, El-Menoufi, Helliwell, Monni, 2024)

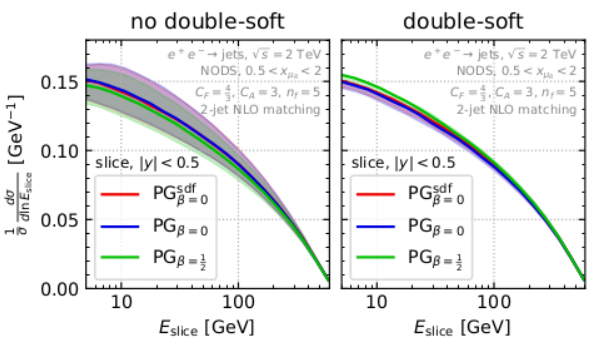
`Alaric`: RECOIL UNCERTAINTY IN DY



`PanScales`: NLL ACCURACY TEST



`PanScales`: UNCERTAINTY REDUCTION AT NNLL



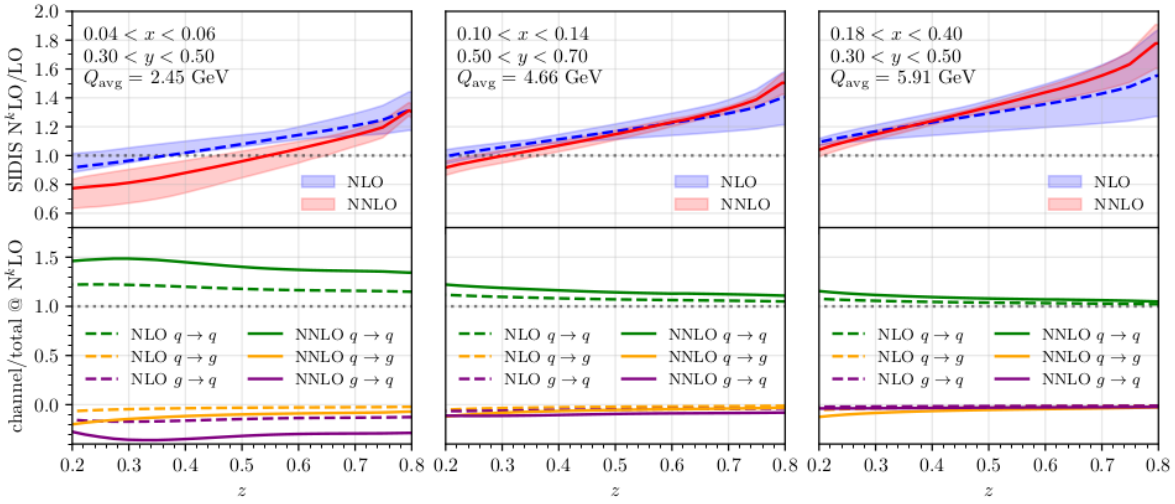
NEW PROCESSES, OBSERVABLES, TECHNIQUES

SIDIS AT NNLO

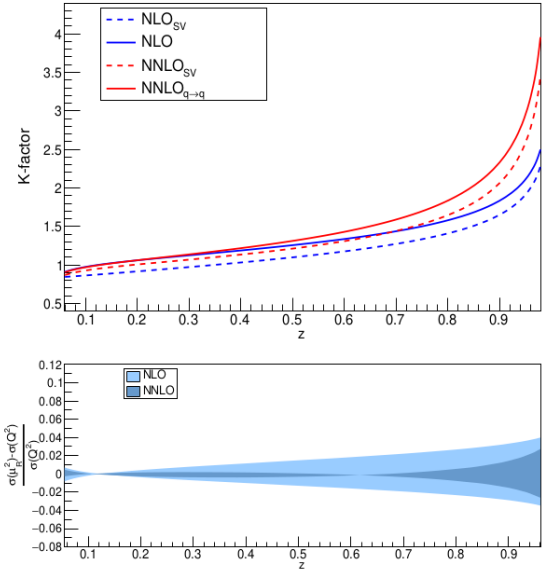
- SEMI-INCLUSIVE DIS: $ep \to h + X$ (TAGGED HADRON IN FINAL STATE)
- WILL BE MEASURED ACCURATELY AT EIC
- SIMULTANEOUS DETERMINATION OF PDF AND FRAGMENTATION FUNCTIONS DEPENDS ON TWO MOMENTUM FRACTIONS x & z
- STRINGENT CONSTRAINTS ON PDF FLAVOR SEPARATION $\Rightarrow$ NEW PHYSICS SEARCHES AT HL-LHC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

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

COMPASS X BINS (Bonino et al., 2024)



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



RESUMMATION: INCREASED COMPLEXITY

NON GLOBAL LOGS

- RADIATION FROM SECONDARY VERTICES $\Rightarrow$ LARGE LOGS IF NON–GLOBAL VETOS
- SUPER–LEADING LOGS DUE TO NONTRIVIAL COLOR STRUCTURE
- FULL RESUMMATION FOR $2 \to M$ JET PROCESSES USING SCET
  (Becher, Neubert, Shao, Stillger, 2023)

JOINT RESUMMATION

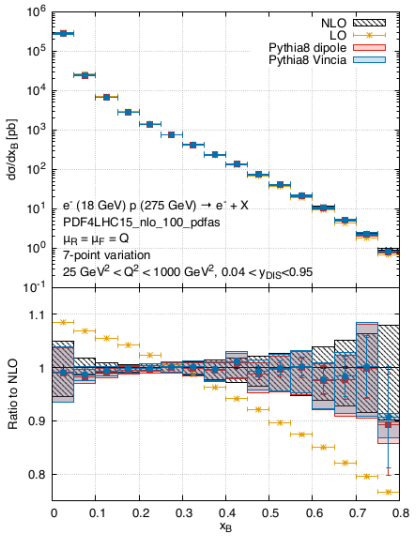
- HEAVY QUARKS $\Rightarrow$ MASSIVE (DECOUPLING) SCHEME (MASS EFFECTS RETAINED) OR MASSLESS ($\overline{\rm MS}$) (MASS LOGS RESUMMED)
- THRESHOLD RESUMMATION POSSIBLE IN EITHER CASE
- RESUMMATION & MASSLESS LIMIT DO NOT COMMUTE
- NONTRIVIAL MATCHING $\Rightarrow$ SIMULTANEOUS RESUMMATION OF MASS & THRESHOLD LOGS
  (Ghira, Marzani, Ridolfi, 2024)

PARTON SHOWER MCs FOR DIS

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
  $\Rightarrow$ MOMENTUM MAPPINGS ADAPTED
  $\Rightarrow$ PRESERVE INCOMING & OUTGOING LEPTON MOMENTA
- NLO CORRECTIONS SIGNIFICANT IN EIC KINEMATICS

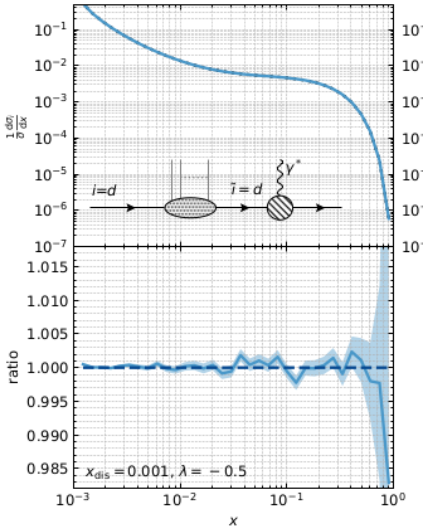
NC DIS AT EIC



NLL SHOWER

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

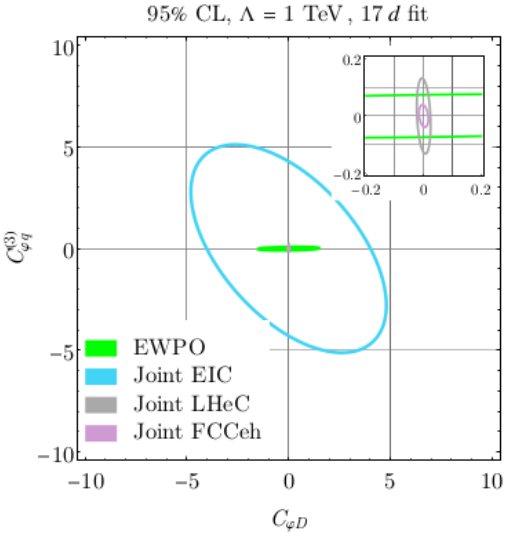
PanScales VS HOPPET
PROBABILITY OF PARTON x FOR FIXED x_B



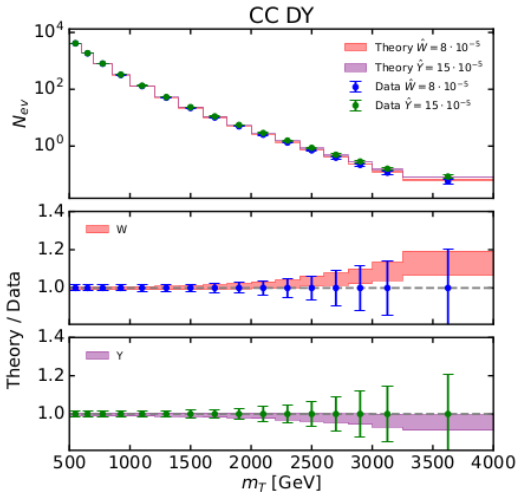
SMEFT, DIS, AND PDFS

- KNOWLEDGE OF QCD SECTOR ⇒ SEARCHES FOR NEW PHYSICS
- DIS CAN RESOLVE DEGENERACIES IN SMEFT FITS,
  BUT EIC ⇒ ∼ 3 TeV (LHEC ∼ 13 TeV; FCC-EH ∼ 18 TeV
  (Bissolotti, Boughezal, Simsek, 2023)
- PDFS CAN BE CONTAMINATED BY NP ⇒ DIFFICULT TO SEE IN CC DY, VISIBLE IN DIBOSON
  (Hammou, Kassabov, Madigan, Mangano, Mantani, Moore, Morales, Ubiali, 2023)
- MUST PERFORM GLOBAL FIT ⇒ OPEN-SOURCE TOOL SIMUnet
  (Costantini, Hammou, Kassabov, Madigan, Mantani, Moore, Morales, Ubiali, 2024)

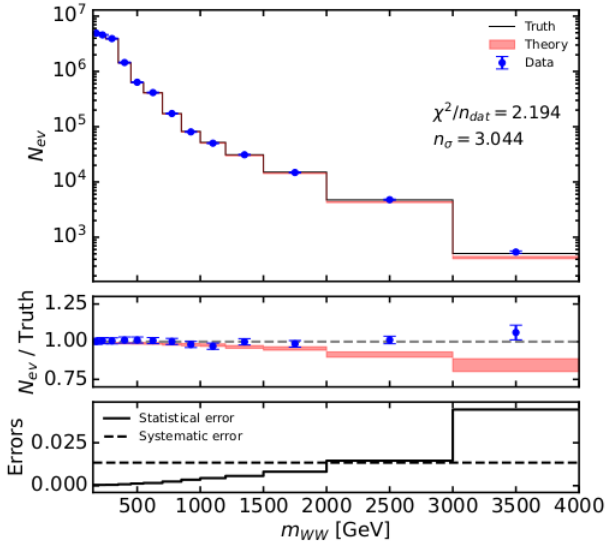
SMEFT FITS: IMPACT OF FUTURE DATA



CONTAMINATED PDFS: CC DY



CONTAMINATED PDFS WW

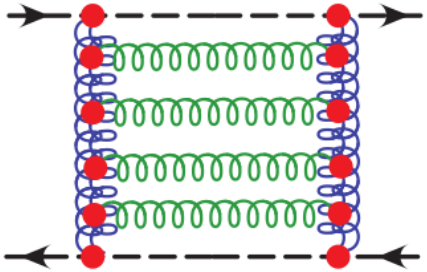


STRETCHING THE THEORY

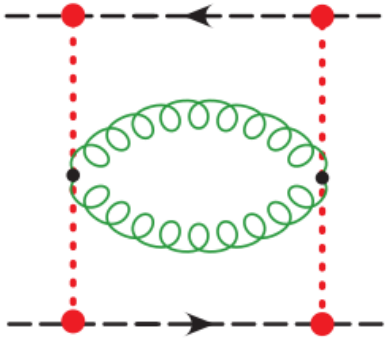
HIGH-ENERGY RESUMMATION

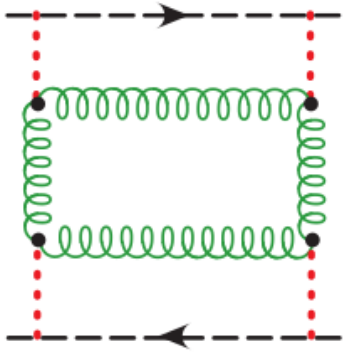
- HIGH ENERGY (BFKL, SMALL x) LOGS $\alpha \ln 1/x$, $x = \frac{M^2}{s}$
  $\Rightarrow$ PARTONIC CROSS-SECTIONS AND ANOMALOUS DIMENSIONS
- ONLY LL FULLY RESUMMED $\rightarrow$ DOMINANT UNCERTAINTY AT $\mathrm{N^3LO}$
- SMALL x EVOLUTION DUAL TO LARGE Q^2 EVOLUTION
- SCET APPROACH $\Rightarrow$ RESUMMATION FROM RGE OF SOFT GLUON OPERATORS
- CONSISTENCY BETWEEN COLLINEAR & SOFT ANOMALOUS DIMENSIONS
  (Gao, Moult, Raman, Ridgway, Stewart 2024)

LIPATOV VERTEX DIAGRAMS IN QCD



GLAUBER GLUON DIAGRAMS IN SCET

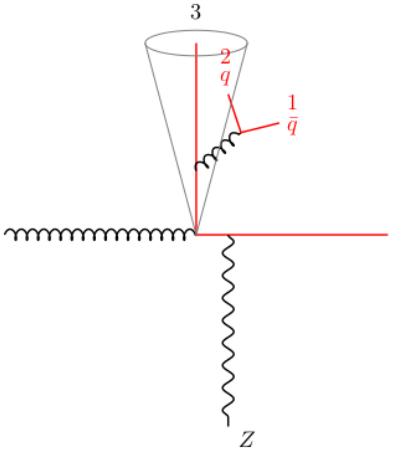




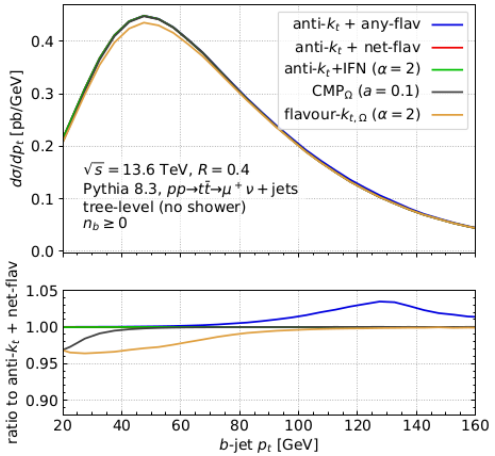
JET FLAVOR

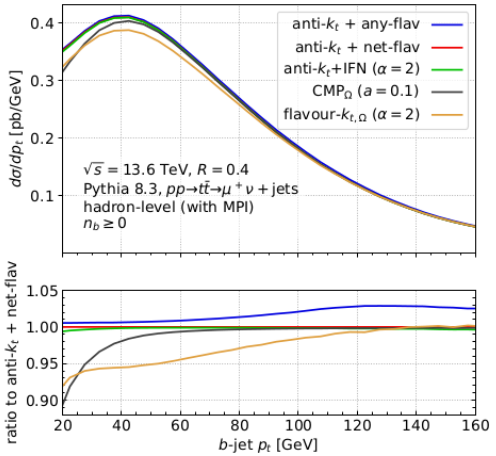
- DEFINITION OF HEAVY FLAVORED JET NONTRIVIAL $\Rightarrow$ "EXPERIMENTAL" DEFINITION NOT IRC SAFE
- LONG-STANDING OPEN PROBLEM: SOLUTIONS
  - LIMITED (IRC ONLY AT LOW ORDER)
  - IMPRACTICAL (DIFFICUL TO MERGE WITH ANTI-k_t.)
- FULL SOLUTION (IFN SCHEME), CONSISTENT WITH ANTI-k_t, ALL-ORDER IRC-SAFETY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

JET FLAVOR POLLUTION



B JET FROM TOP PRODUCTION



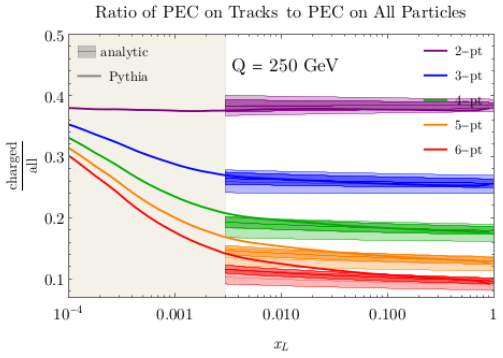


JET SUBSTRUCTURE AND ENERGY CORRELATORS

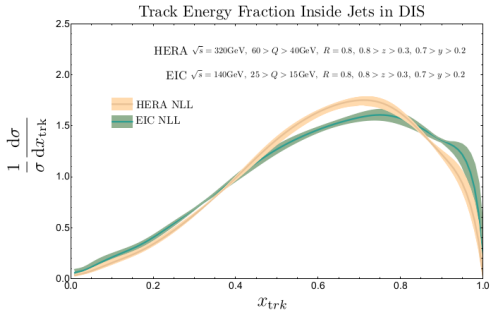
- PARISI'S IDEA (1978): ENERGY CORRELATORS ⇒ PARTON TO HADRON TRANSITION
- COMPUTABLE ⇒ FACTORIZED TRACK FUNCTIONS; NONPERTURBATIVE, PERTURBATIVE RGE (Jaarsma, Li, Moult, Waalewijn, Zhu, 2023)
- TRACK FUNCTIONS (PROPERTY OF FINAL STATE) MATCHED TO TRACK JET FUNCTION (PROPERTIES OF IDENTIFIED JETS) ⇒ JET SUBSTRUCTURE FROM DATA (Lee, Moult, Ringer, Waalewijn 2023)
- CORRELATIONS BETWEEN DIFFERENT HADRONS ⇒ DECONFINEMENT (Lee, Moult, 2023)
- SPECTRAL FUNCTIONS ⇒ METRIC IN JET SPACE (& IN THEORY SPACE?) (Larkoski, Thaler, 2023)

ENERGY CORRELATORS VS ANGULAR SIZE: TRACK TO ALL RATIO

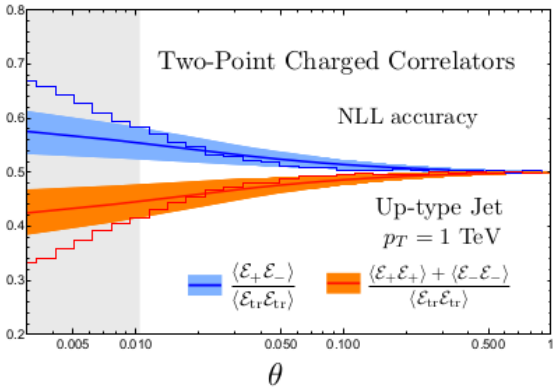
PERTURBATIVE VS. `pythia`



EXTRACTION OF TRACK FUNCTION FROM EIC DIS DATA



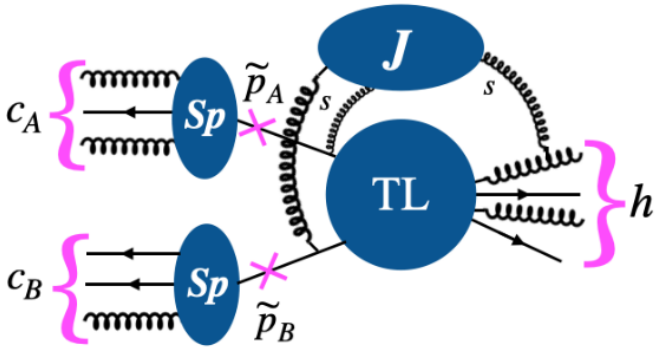
HADRON ENERGY CORRELATORS: SAME VS. DIFFERENT CHARGE



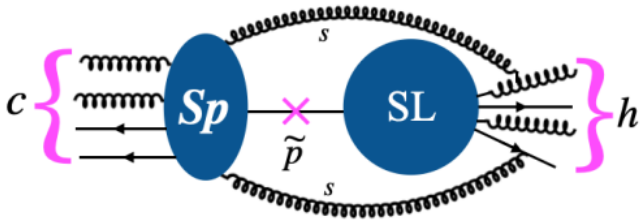
STRETCHING THE LIMITS OF FACTORIZATION

- ALL-ORDER EXTENSION OF SOFT-GLUON EFFECTIVE COUPLING
  $\Rightarrow$ ALL-ORDER EXACT RESULTS IN LARGE n_f LIMIT $\Rightarrow$ CUSP ANOMALOUS DIMENSION
  (Catani, de Florian, Devoto, Grazzini, Mazzitelli, 2023)
- UNIVERSALITY OF FACTORIZATION VIOLATED BY INITIAL-STATE COLLINEAR CONFIGURATIONS $\Rightarrow$
  COLLINEAR FACTORIZATION ENDANGERED AT $\mathrm{N^3LO}$ AND BEYOND
- SOFT-PHOTON THEOREM MODIFIED IN QCD (Ma, Sterman, Venkata, 2024)
- Catani's GENERALIZED FACTORIZATION FOR SPACELIKE COLLINEAR EMISSION
  (Cieri, Dhani, Rodrigo, 2024)

TIMELIKE COLLINEAR (FINAL STATE)



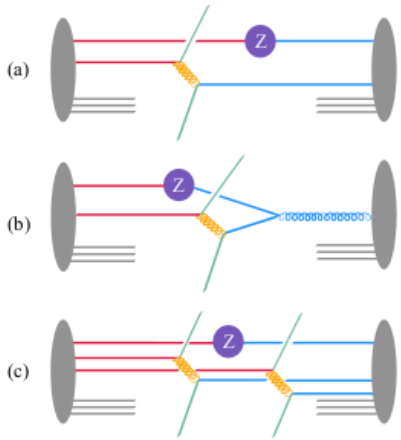
SPACELINE COLLINEAR (INITIAL STATE)



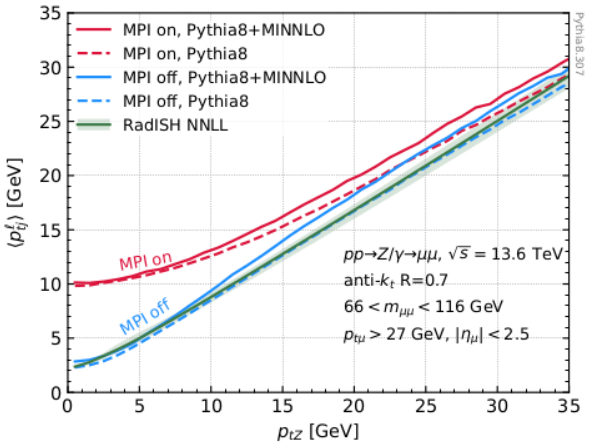
MULTIPARTON INTERACTIONS

- SIZABLE CONTRIBUTION, FACTORIZABLE IN HARD SCATTERING
- DISENTANGLE THROUGH p_t CUTS (Andersen, Monni, Rottoli, Salam, Soto-Ontoso 2023)
- DOMINANT CONTRIBUTION TO DY AT SMALL p_T
- ENHANCED IN CUMULATIVE INTEGRATED JET SPECTRUM $p_t > p_t^{\min}$

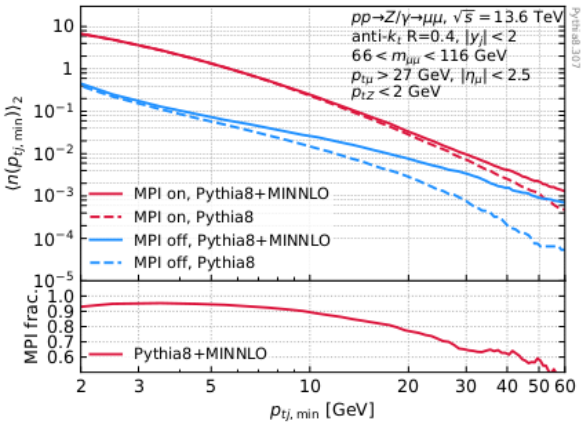
DOUBLE (A,B) AND
TRIPLE (C) PARTON HARD SCATTERING



MPI VS NO MPI VS p_t



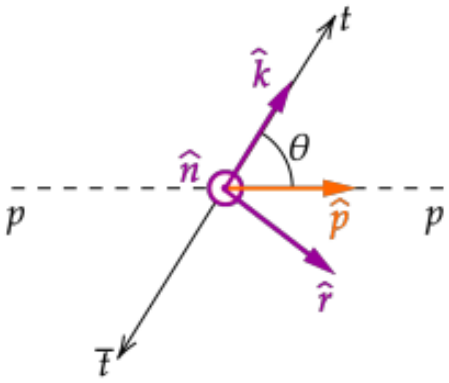
MPI VS NO MPI CUT
CUMULATIVE JET SPECTRUM



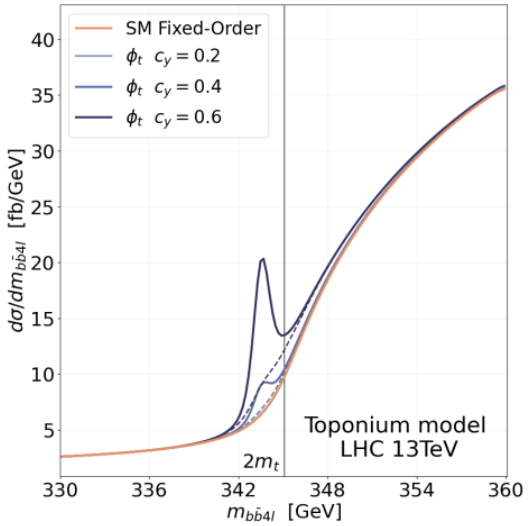
ENTANGLED TOP PAIRS

- TOP PAIRS ENTANGLED $\Rightarrow$ PATTERN CHANGES BSM
- DEFINE $D^1 = -\operatorname{tr} C_{ij}$ ENTANGLEMENT MARKER $\Rightarrow$ TRACE OF $t\bar{t}$ SPIN CORRELATION MATRIX IN HELICITY BASIS
- ENTANGLEMENT SENSITIVE TO BSM PSEUDOSCALAR RESONANCE ϕ (Maltoni, Severi, Tentori, Vryonidou 2024)
- ALSO EW DIBOSON PRODUCTION (Aoude, Madge, Maltoni, Mantani 2024)

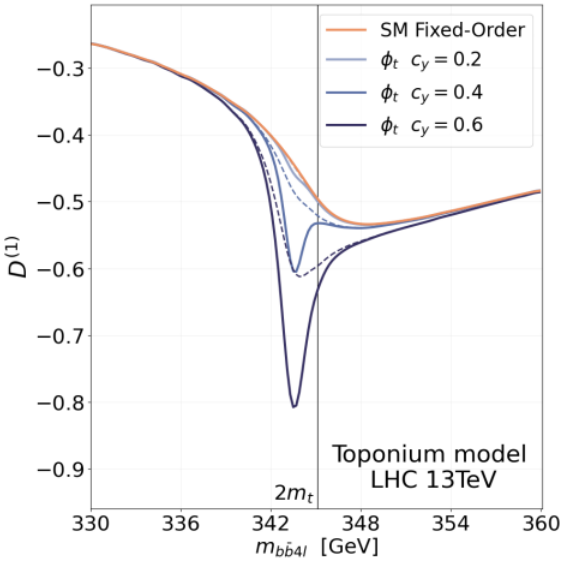
THE HELICITY BASIS



CROSS–SECTION VS FINAL STATE MASS



ENTANGLEMENT MARKER VS FINAL STATE MASS



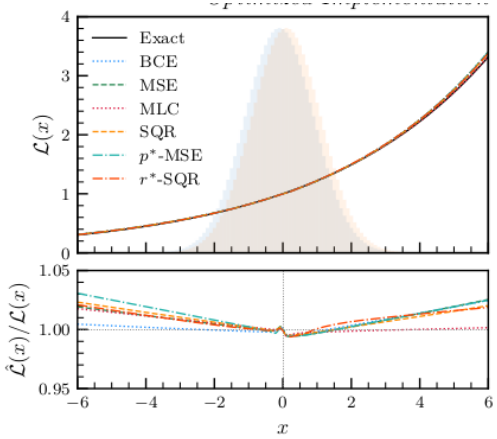
DEEP LEARNING QCD

CLASSIC METHODS

REGRESSION

- HYPOTHESIS TESTING $\Rightarrow$ LIKELIHOOD RATIO:
  $\mathcal{L}(x) = \frac{p(x|\theta_0)}{p(x|\theta_1)}$,
  θ_i PARMS OF PROBABILITY
- NEURAL NET FIT
- OPTIMAL NN CLASSIFIER (Rizvu, Pettee, Nachman, 2023)
- MATRIX ELEMENT METHOD: RECONSTRUCTED PROBABILITY FROM UNDERLYING PARTON EVENT
  (Heimel, Huetsch, Winterhalder, Plehn, Butter 2023)

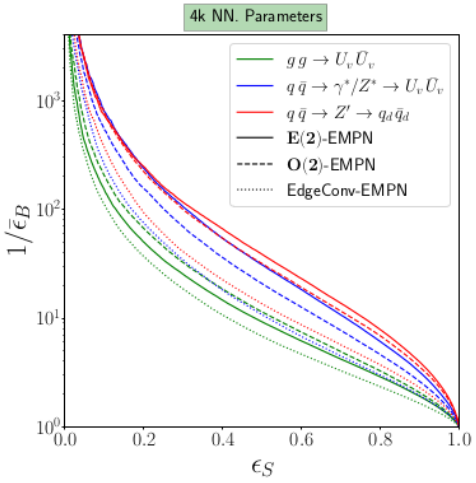
LIKELIHOOD RATIO: DISPLACED GAUSSIAN FITTED VS TRUE



TAGGING

- TRAIN NEURAL NET $\Rightarrow$ TAG SIGNAL FROM BACKGROUND
- STANDARD IN TOP TAGGING, EXTENDED TO JETS
- GRAPH & CONVOLUTIONAL NN $\Rightarrow$ EQUIVARIANCE
- JET TAGGING FOR NP SIGNALS
  (Bhardwaj, Englert, Naskar, Ngairangbam, Spannowsky, 2024)

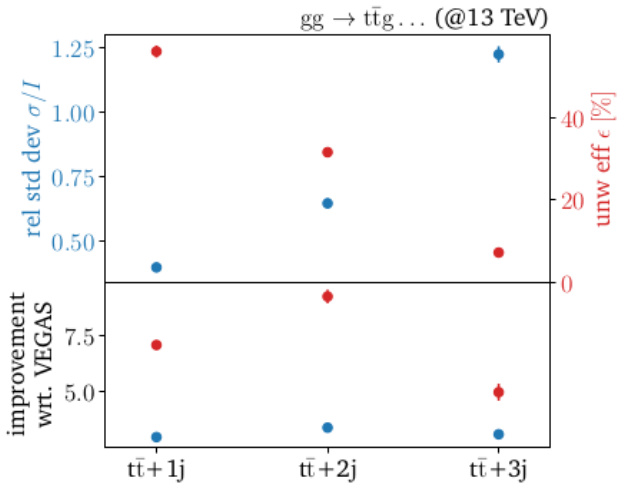
1/(FALSE POSITIVE) VS TRUE POSITIVE NEW PHYSICS SIGNALS



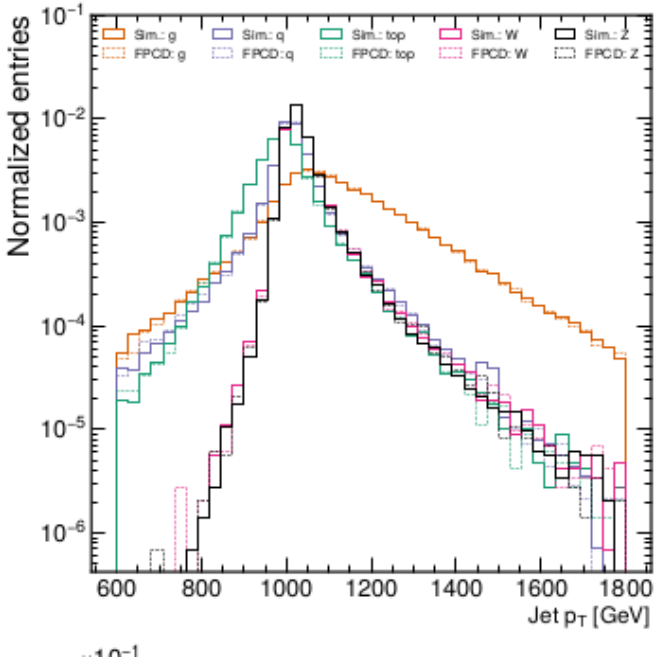
CONTEMPORARY METHODS
GENERATIVE METHODS

- GENERATIVE METHODS ⇒ ARTIFICIAL IMAGES
- IMPORTANCE SAMPLING ⇒ `MadNIS` NEURAL IMPORTANCE SAMPLING IN `Madgraph` (Heimel, Huetsch, Maltoni, Mattelaer, Plehn, Winterhalder, 2023)
- HEP EVENTS ⇒ CONTINUOUS VARIABLES (NOT PIXELS), SYMMETRIES
- DIFFUSION MODELS ⇒ GENERATE PROBABILITY USED FOR SAMPLING: FPCD (FAST POINT CLOUD DIFFUSION) FOR JETS (Mikuni, Nachman, Pettee, 2023)

$T t\bar{t}$ + jet: `MadNIS` VS. VEGAS



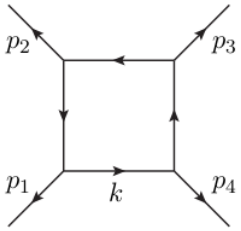
JET p_T: GENERATED VS SIMULATED



TOWARDS THE FUTURE
LEARNING FEYNMAN INTEGRALS

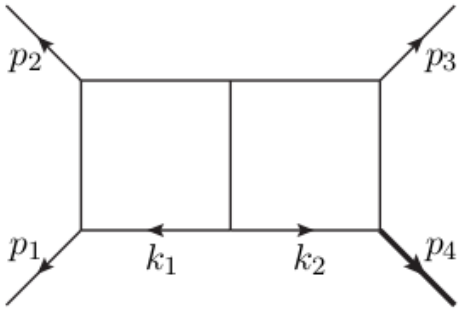
- MASSLESS BOX INTEGRAL FAMILY: $I_{\vec{a}} = \int \frac{d^d k}{i\pi^{d/2}} \frac{\mu^{4-d}}{D_1^{a_1} D_2^{a_2} D_3^{a_3} D_4^{a_4}}$
- FINITE NUMBER LIN. INDEP. $\Rightarrow$ MASTER INTEGRALS $\vec{F}(s,t,\epsilon)$
- DIFFERENTIAL EQUATIONS $\frac{\partial}{\partial s} F^i(s,t,\epsilon) = \epsilon A_s^{ij}(s,t) F^j(s,t,\epsilon) \Rightarrow$ DETERMINE $\vec{F}$ SOLVING EQN., B.C. FROM NUMERICAL EVALUATION
- PHYSICS-INSPIRED DEEP LEARNING: TRAIN NN
  LOSS: DIFFERENCE BETWEEN TWO SIDE OF EQN + BOUNDARY VALUES
  (Calisto, Moodie, Zoia, 2023)

THE BOX DIAGRAM

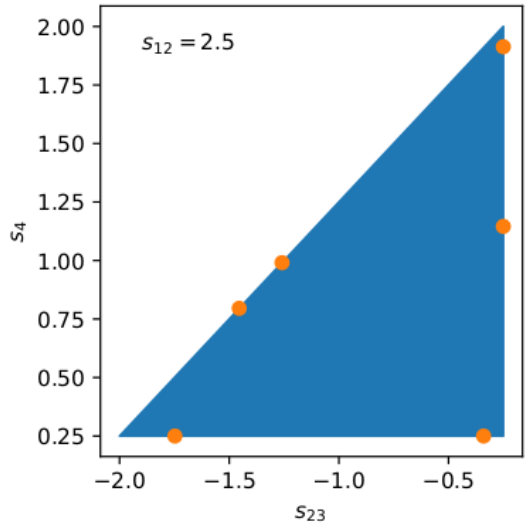


SIMILAR PROBLEM: DETERMINE PHASE OF AMPLITUDE FROM XSECT FROM OPTICAL THM $\Rightarrow$ INTEGRAL EQN (Dersy, Schwartz, Zhiboedov, 2023)

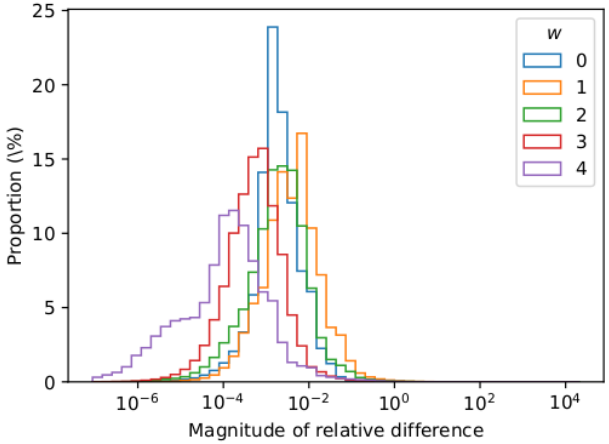
THE DOUBLE BOX



BOUNDARY POINTS



APPROX ERROR FOR DIFFERENT POWERS OF ϵ



THE FUTURE?

LEARNING AMPLITUDES

- TRANSFORMERS $\Rightarrow$ LARGE LANGUAGE MODELS $\Leftrightarrow$ ATTENTION (TOKENS)
- PREDICT ANSWER TO QUESTION $\Rightarrow$ PREDICT ITEM IN SEQUENCE
- EXPRESS AMPLITUDES IN TERMS OF POLYLOGS $\Rightarrow$ SYMBOLS (ITERATED INTEGRALS)
- PREDICT MISSING TERMS OF SYMBOLS
- PREDICT HIGHER LOOPS
- TEST IMPLEMENTATION FOR $N = 4$ SYM
  (Cai, Merz, Charton, Nolte, Whilhelm, K. Cranmer, Dixon, 2024) $\Rightarrow$
  FOUNDATION MODEL FOR QCD OR QFT?

SUMMARY

THE TWO HORIZONS

- MID 2030S: SUB-PERCENT ACCURACY AND PRECISION
  - N^3LO+ N(N)LO EW STANDARD CANDLES; NLP RESUMMATION, NNLO PARTON SHOWER
  - LEVERAGING THE HL-LHC EIC SYNERGY
- MID 2040S: THE TRIUMPH OF QCD
  - FULL UNDERSTANDING OF QCD FACTORIZATION
  - MACHINE LEARNING FOR INFERENCE