QCD THEORY

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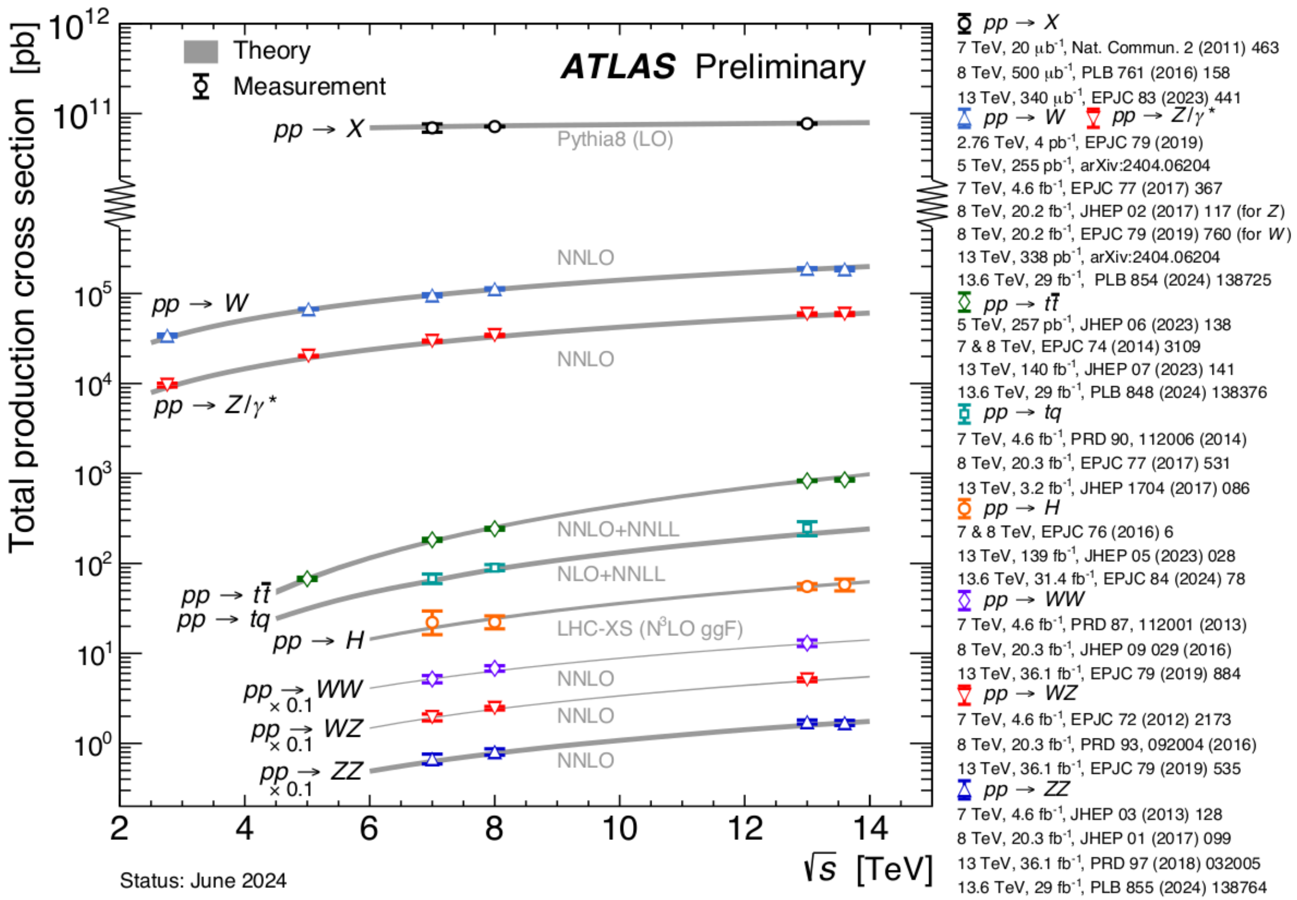
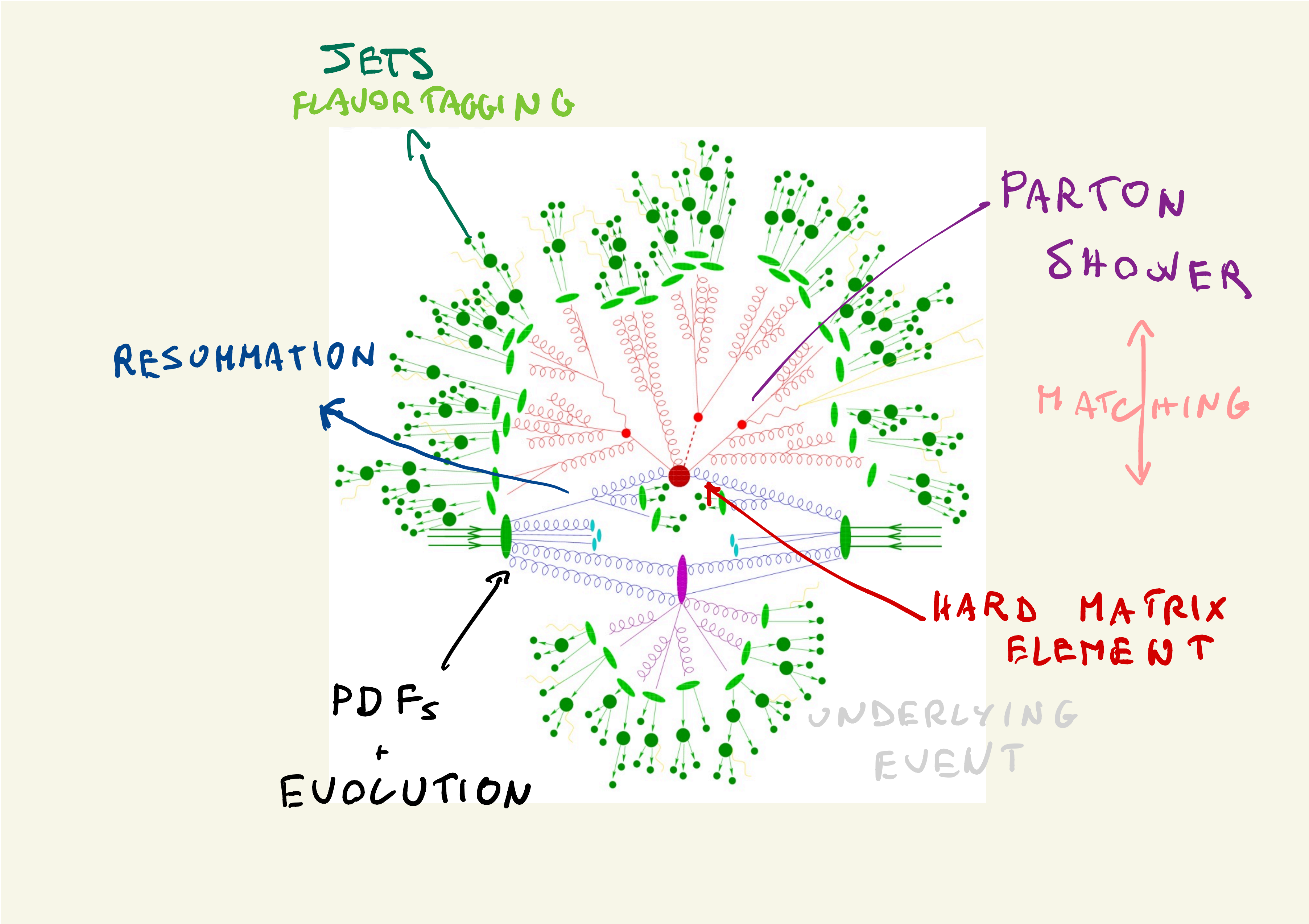
LHC: THE FIRST
PRECISION HADRON COLLIDER!

ATL-PHYS-PUB-2024-011

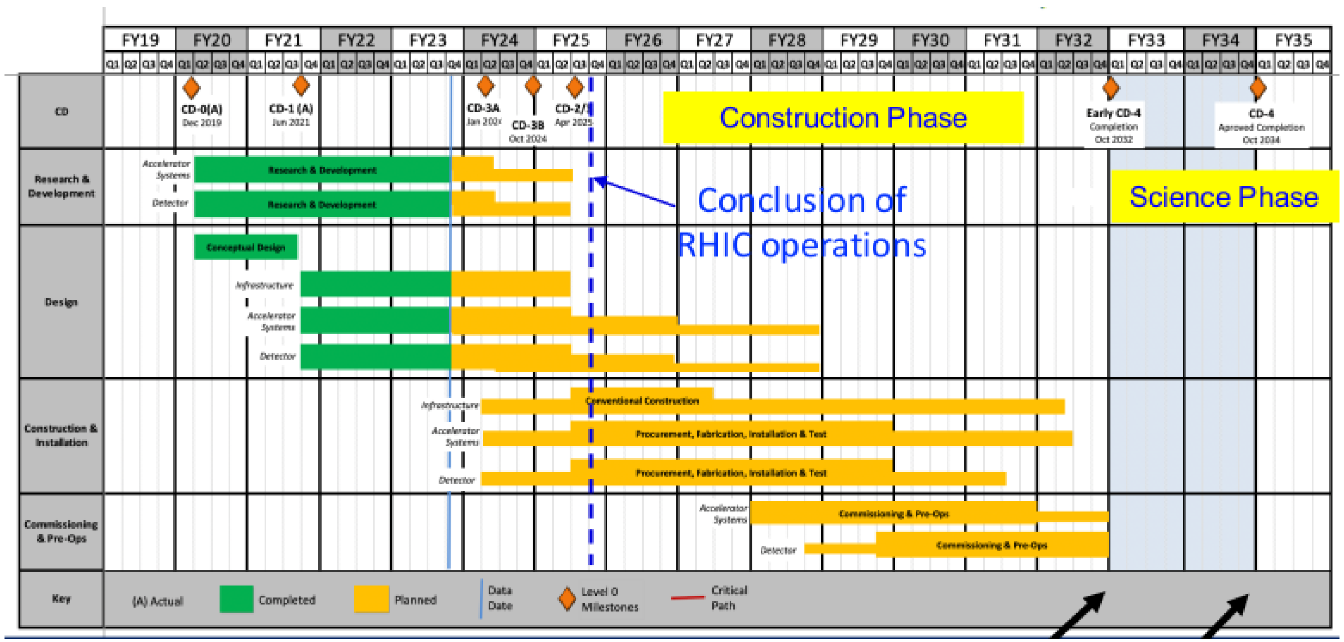


ATLAS 2024

PRECISION FROM QCD!



MORE PRECISION
THE HL-LHC. . . AND THE EIC



QCD

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

MOVING AHEAD THE FRONTIER

- BEYOND CURRENT PRECISION AND ACCURACY
- THE LHC CONFRONTS THE EIC: DIS REDUX
- STRETCHING THE CURRENT THEORY
- THE ERA OF MACHINE LEARNING

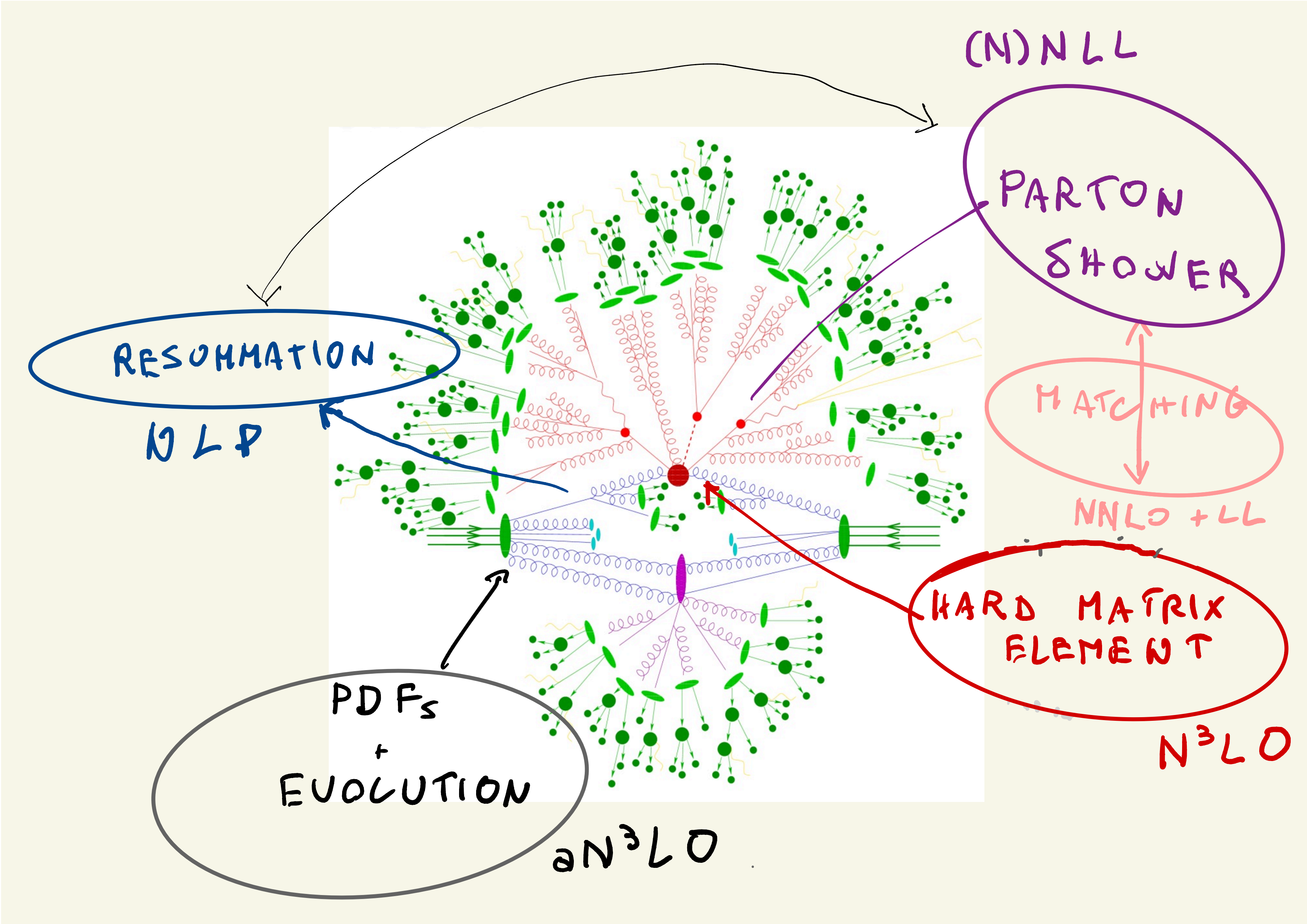
DISCLAIMER

- A PERSONAL SELECTION OF RESULTS
- ONLY RECENT DEVELOPMENTS SINCE EARLY 2023 COVERED

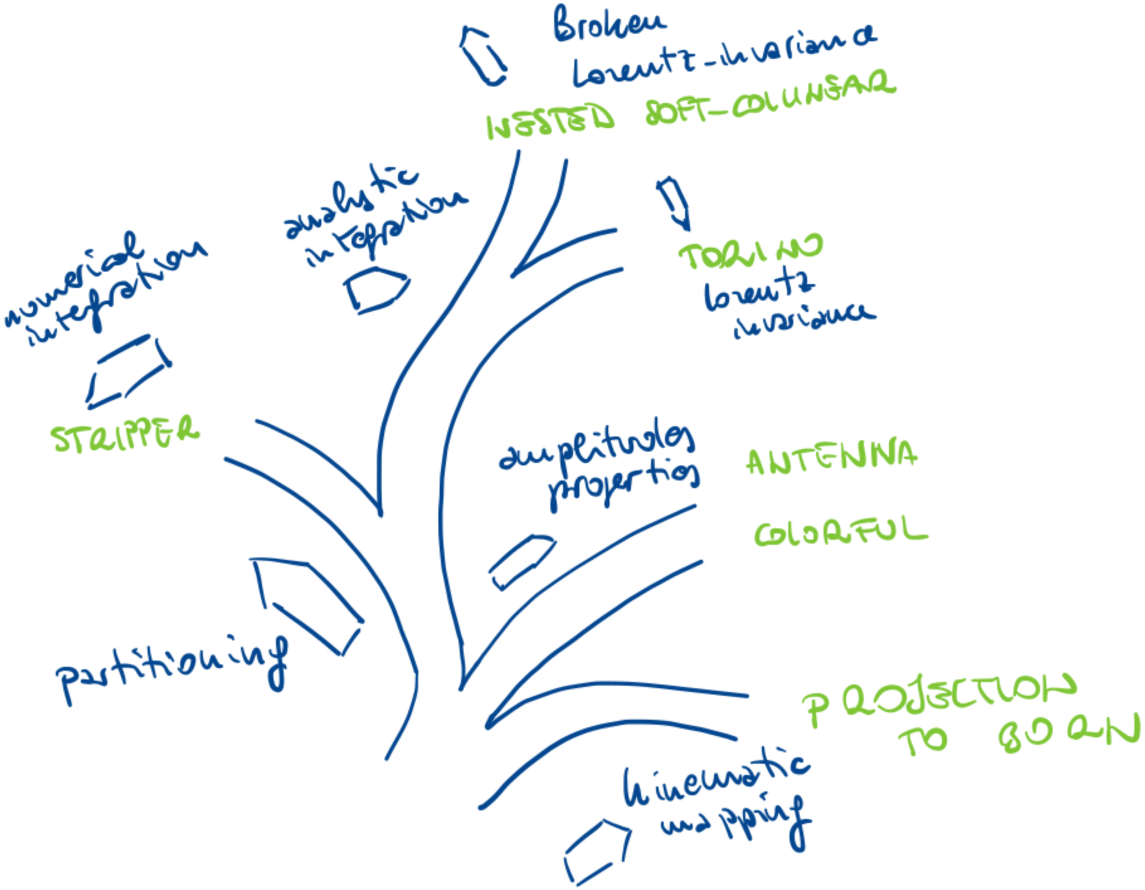
STEFANO CATANI (1958-2024)

HIGHER PRECISION AND ACCURACY

THE PRECISION FRONTIER



THE AMPLITUDE REVOLUTION
NNLO SUBTRACTION METHODS



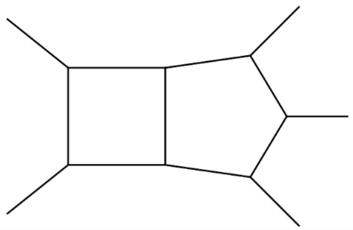
C. Signorile-Signorile

- SUBTRACTION TECHNIQUES ⇔ NNLO UNDER CONTROL

THE AMPLITUDE REVOLUTION

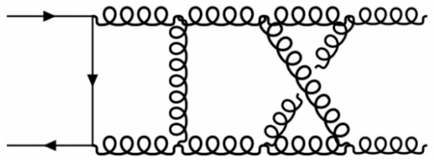
MORE LEGS AND MORE LOOPS

$\mathcal{A}$



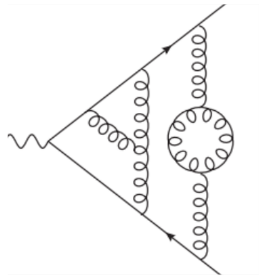
2 loop 5 point

Abreu, Agarwal, Badger, Buccioni, Chawdhry, Chicherin, Czakon, de Laurentis, Febres-Cordero, Gambuti, Gehrmann, Henn, Ita, Lo Presti, Manteuffel, Ma, Mitov, Page, Peraro, Pochelet, Schabinger, Sotnikov, Tancredi, Zhang, ...



3 loop 4 point

Bargiela, Bobadilla, Canko, Caola, Jakubcik, Gambuti, Gehrmann, Henn, Lim, Mella, Mistlberger, Wasser, Manteuffel, Syrrakos, Smirnov, Tancredi, ...



4 loop 3 point

Henn, Lee, Manteuffel, Schabinger, Smirnov, Smirnov, Stainhauser,...

All processes computed in Full Color
Including Planar and Non-Planar diagrams

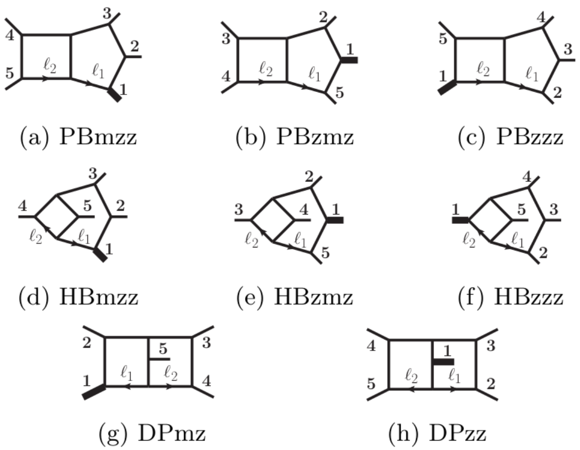
L. Tancredi, QCD@LHC, 2024

THE AMPLITUDE REVOLUTION

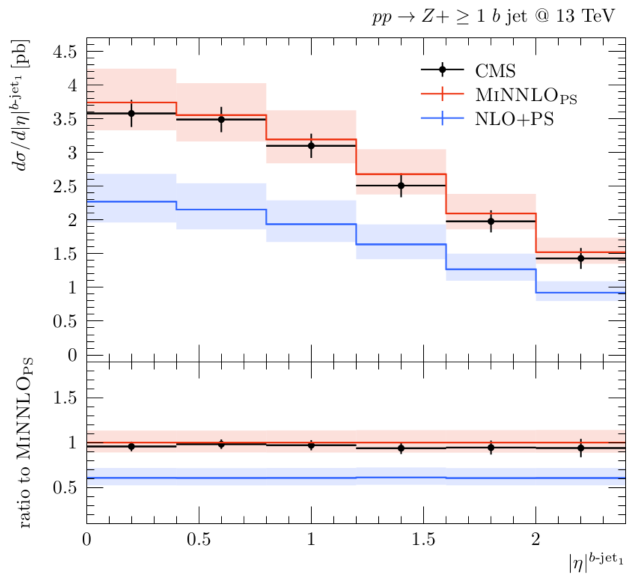
THE COMPLEXITY FRONTIER

$$pp \to \{Vjj\,, Hjj\,, V\gamma\gamma\,, \cdots\}$$

Complete results obtained for **2 loops integrals**



[Abreu, Chicherin, Ita, Page, Sotnikov, Tschernow, Zoia '23]



NNLO corrections to $pp \to Zb\bar{b}$ + PS matching

[Mazzitelli, Sotnikov, Wieseman '24]

L. Tancredi

- 2 MASSLESS 1 MASSIVE AT TWO LOOPS: $pp \to Hjj,\ V\gamma\gamma\ldots$
- MANY RESULTS AT LEADING COLOR (PLANAR), FIRST AT NLC!
- FIRST PHENO STUDIES!

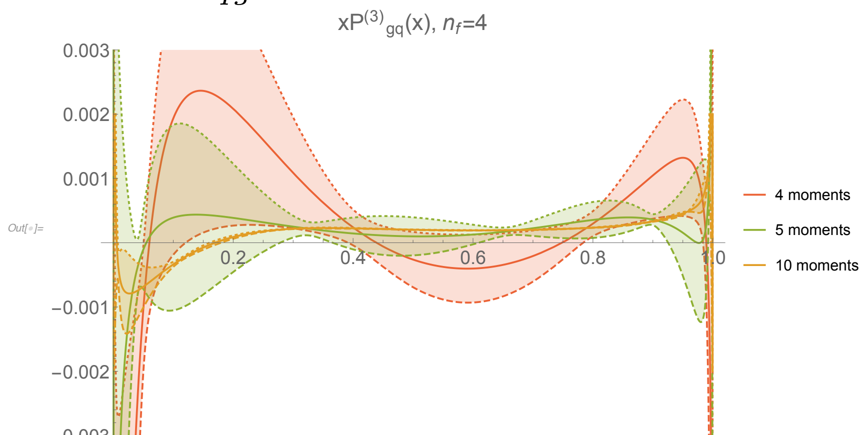
THE AMPLITUDE REVOLUTION
THE N^{3}LO FRONTIER
MATRIX ELEMENTS

- 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, Jakubĉík, 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

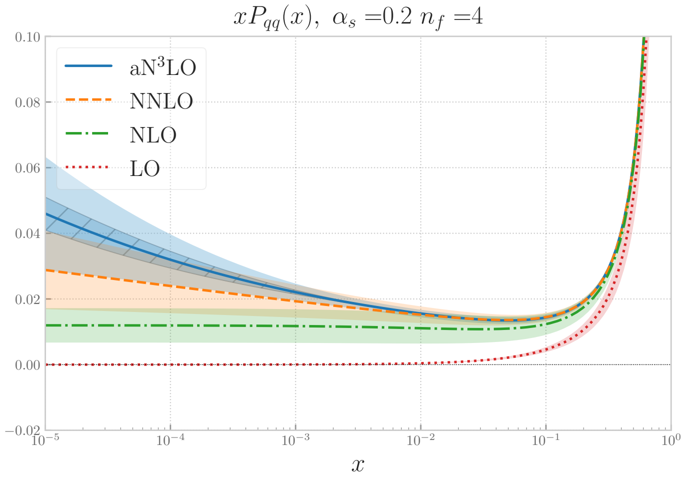


N^3LO SPLITTING FUNCTIONS

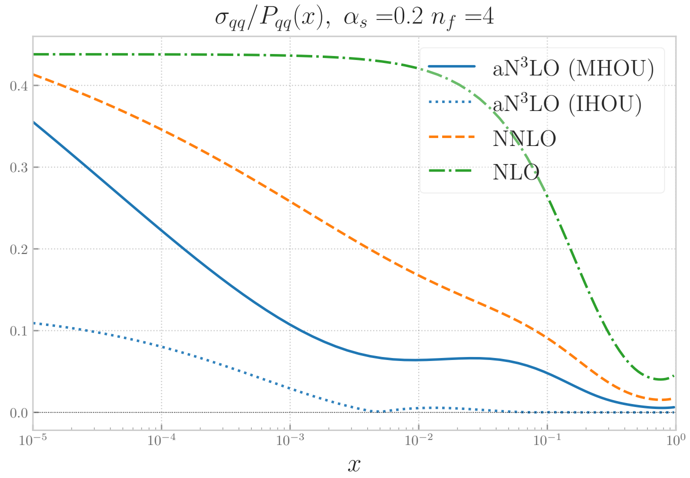
- UNCERTAINTY APPROX (IHOU) $\ll$ MISSING N^4LO UNCERTAINTY (MHOU) $\Rightarrow$ KNOWN EXACTLY FAPP
- FIXED-ORDER N^3LO EVOLUTION KNOWN FAPP

P_{qq}

SPLITTING FCTN



UNCERTAINTY

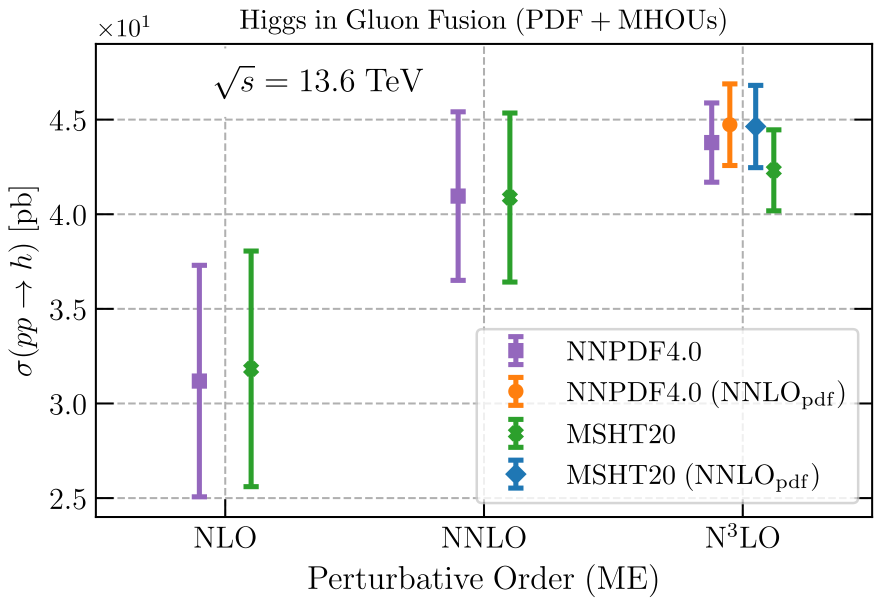


PDFs: N^{3}LO, MHOUs, QED

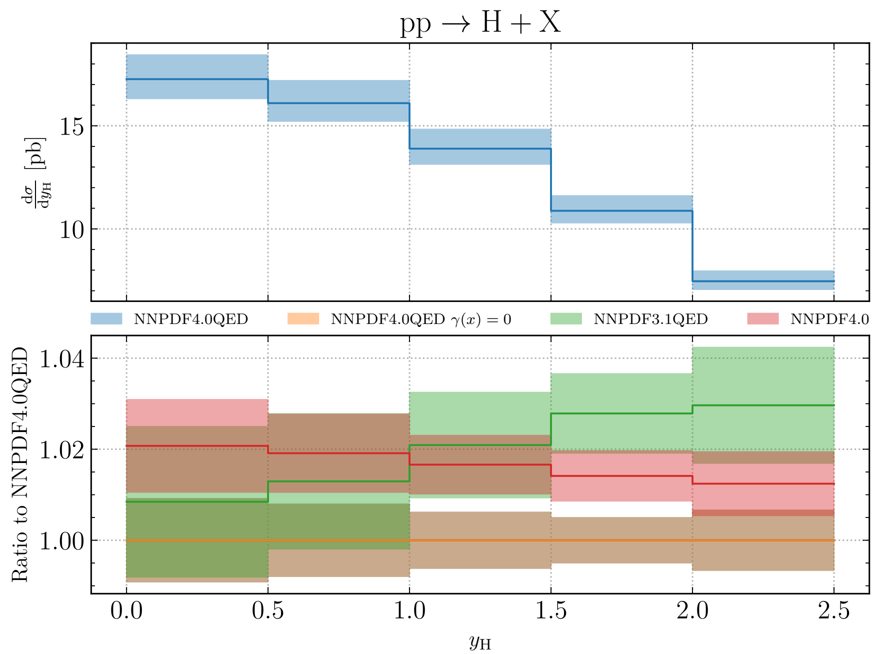
- aN^{3}LO PDF sets now available: MSHT20 (2023), NNPDF4.0 (2024), combination (2024)
  - NNPDF IHOU estimated from theory covariance matrix
  - MSHT IHOU estimated fitting nuisance parms to data
- MHOU on PDF fit available:
  - NNPDF4.0 at any order, from scale variation
  - MSHT20 at aN^{3}LO from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

Higgs in gluon fusion

NNPDF vs MSHT



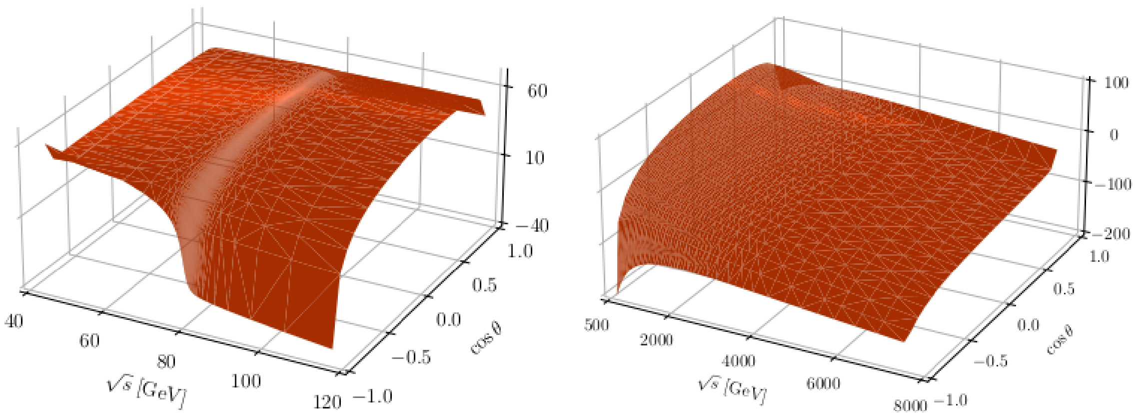
NNPDF: impact of QED



MIXED QCD×EW CORRECTIONS

- $\alpha \sim (\alpha_s(M_Z))^2$ SO $\alpha\alpha_s \sim \alpha_s^3$; NONTRIVIAL INTERFERENCE
- 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)

RESUMMATION: THE NLP FRONTIER

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

$$C(\alpha_s, N) = \int_0^1 d\tau \tau^{N-1} C(\alpha_s, \tau)$$

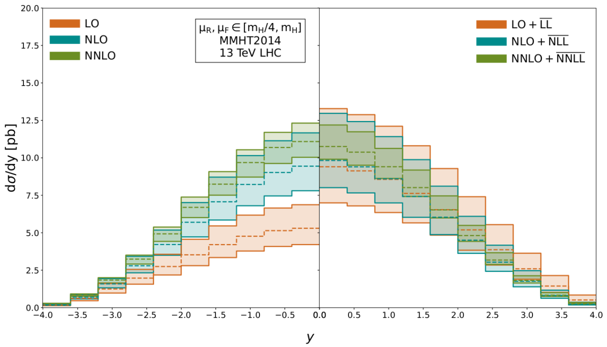
LEADING, NEXT TO LEADING... LOG VS. LEADING, NEXT TO LEADING... POWER: $\lim_{N\to\infty} C^{\rm N^kLO}(\alpha_s, N) \sim$

$$\alpha^k \left[C^{k,LL} \ln^{2k} N + C^{k,NLL} \ln^{2k-1} N + \cdots + g^k + \frac{1}{N} C^{k,NLP}(\ln N) + \ldots \right]$$

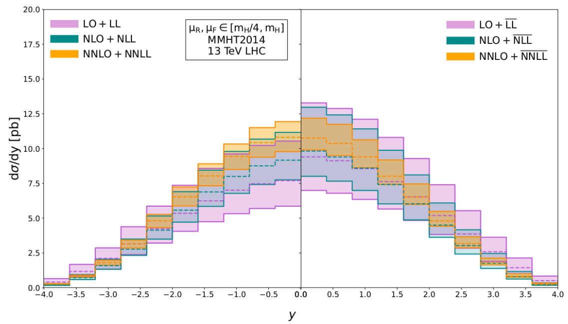
- $\rm N^3LO$ DETERMINES $\rm N^3LL$
- NLP PHENOMENOLOGICALLY RELEVANT FOR M^2 BETWEEN THE GEV AND THE TEV SCALE

HIGGS PRODUCTION LHC

FIXED ORDER VS LOG RESUMMED



LOG VS NLP RESUMMED (PARTIAL)



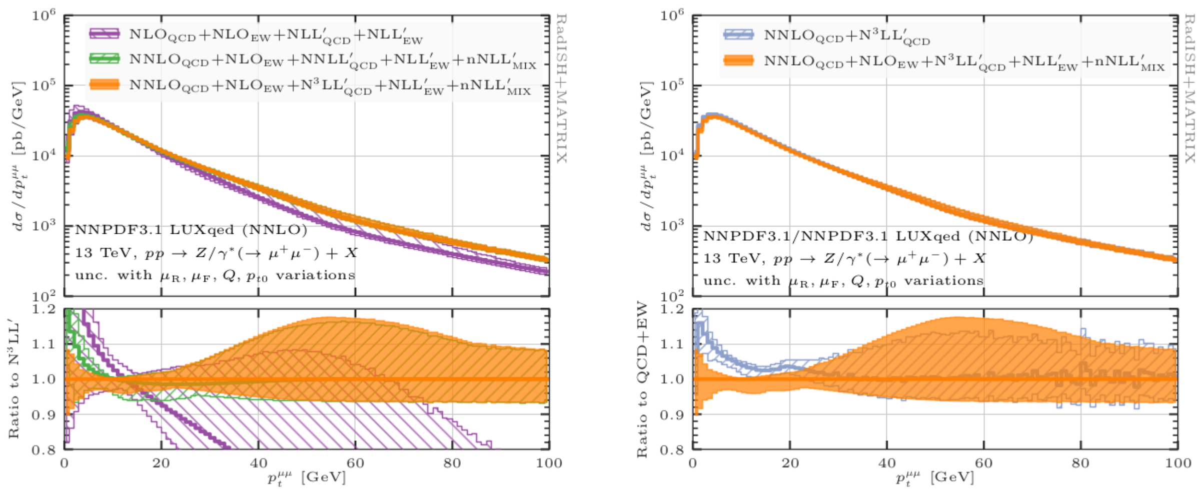
(Ravindran, Sankar, Tiwari, 2022)

- 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)

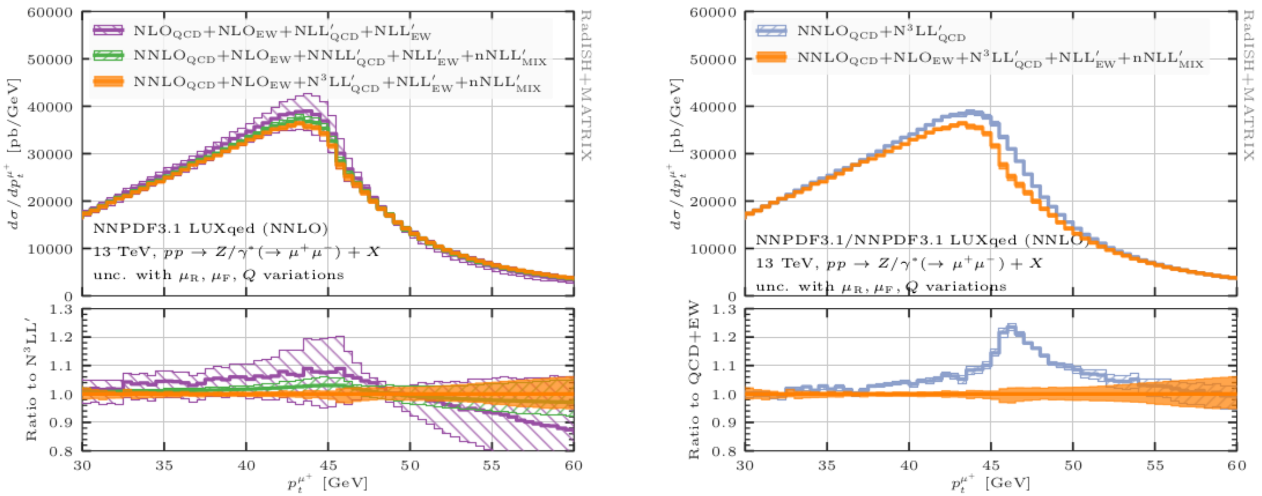
COMBINED QCD-EW RESUMMATION

- 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



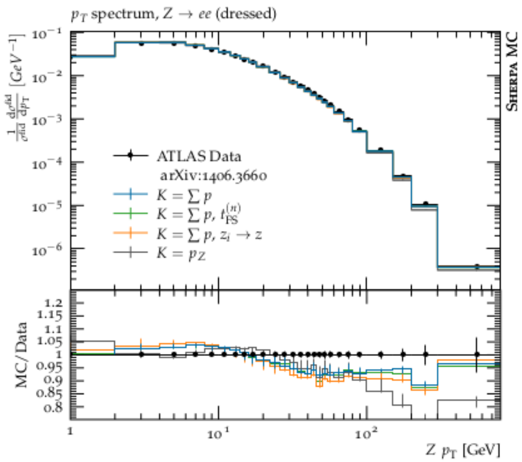
MUON p_T



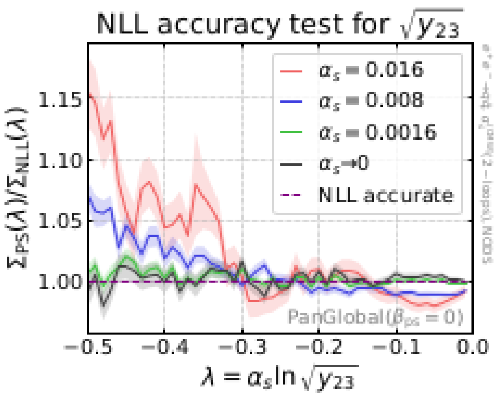
PARTON SHOWER MONTECARLOS: THE PATH TO NN LOGARITHMIC ACCURACY

- 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)
- FULL NNLL ACCURACY FOR JET EVENT SHAPES! (van Beekveld, Dasgupta, El-Menoufi, Ferrario-Ravasio, Helliwell, Hamilton, Karlberg, Monni, Salam, Soto-Ontoso, Sczyboz, Soyez, 2024)

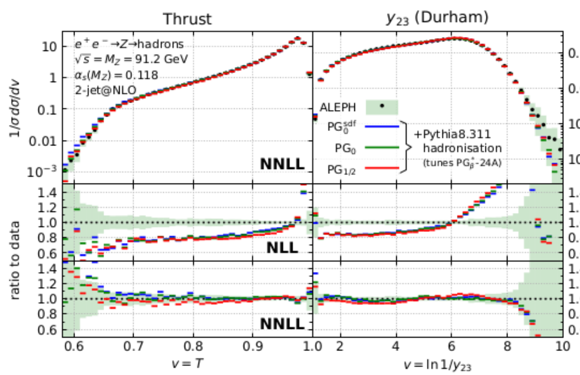
`Alaric`: RECOIL UNCERTAINTY IN DY



`PanScales`: NLL ACCURACY TEST



`PanScales`: NNLL EVENT SHAPES



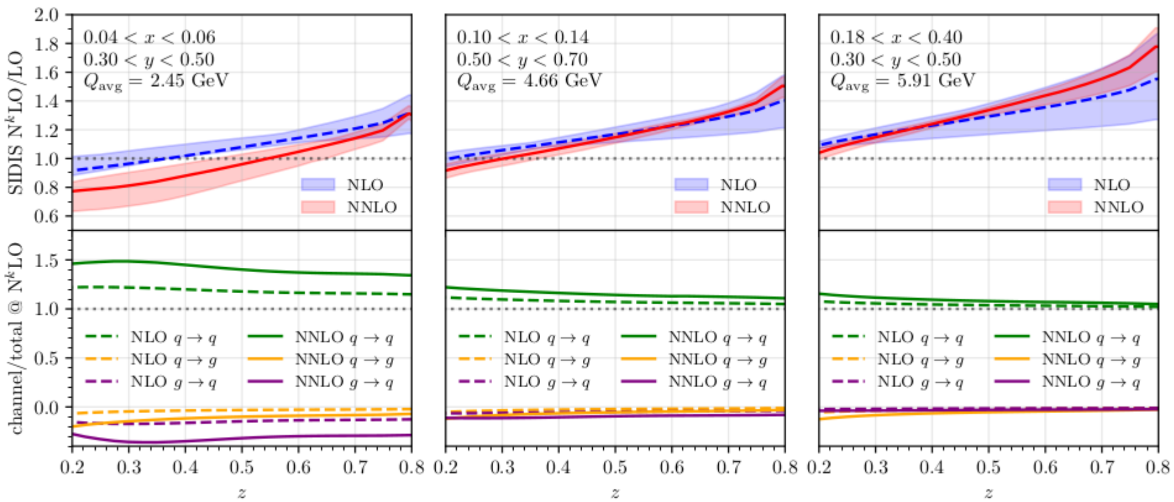
TOWARDS THE EIC:
THE RESURRECTION OF DIS

SIDIS AT NNLO

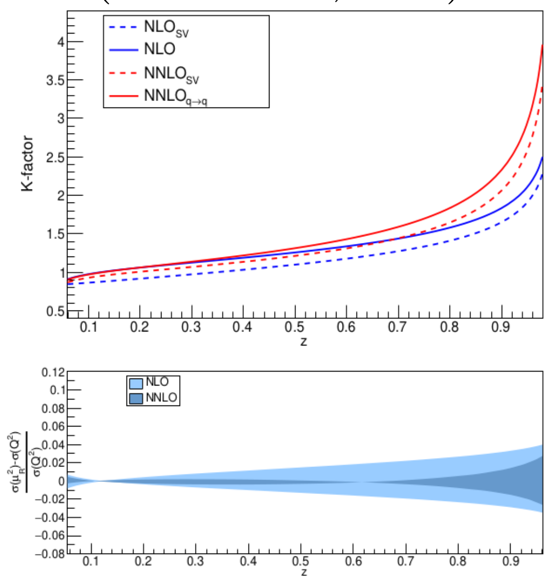
- SEMI-INCLUSIVE DIS: $ep \to h + X$ (TAGGED HADRON IN FINAL STATE)
- WILL BE MEASURED ACCURATELY AT EIC
- SIMULTANEOUS DETERMINATION OF PDF AND FRAGMENTATION FUNCTIONS DEPENDS ON TWO MOMENTUM FRACTIONS x & z
- STRINGENT CONSTRAINTS ON PDF FLAVOR SEPARATION $\Rightarrow$ NEW PHYSICS SEARCHES AT HL-LHC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

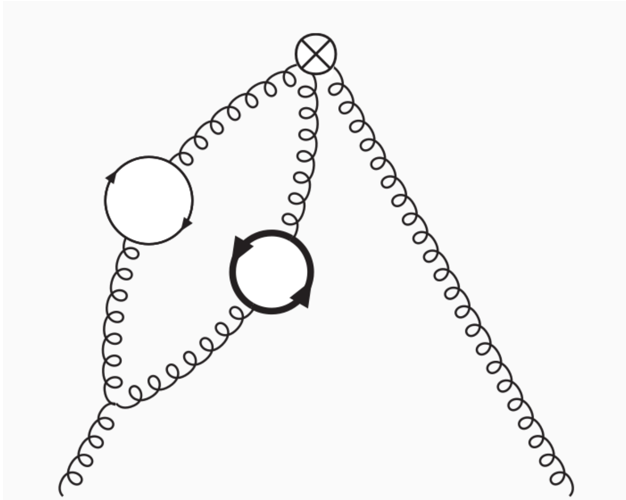
COMPASS X BINS (Bonino et al., 2024)

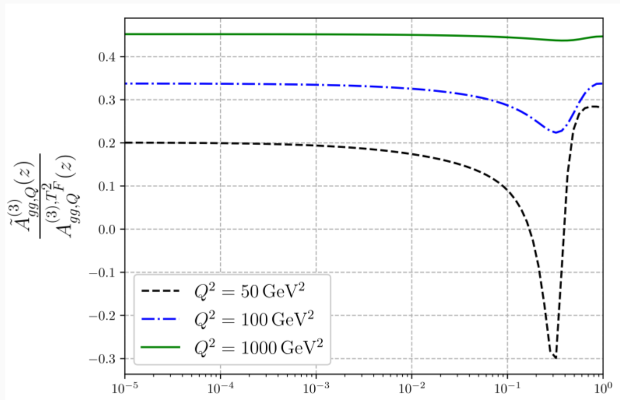


INTEGRATED OVER x FOR EIC (Moch et al., 2024)



HQ MASSES, RESUMMATION





- $m_b \gtrsim m_c \Rightarrow$ 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

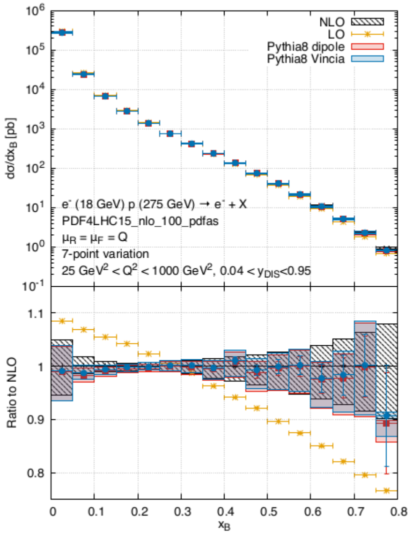
- THRESOLD RESUMMATION GENERALISED TO EIC PROCESSES: SIDIS Abele, de Florian, Vogelsang 2022, DVCS Schoenleber, 2024

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
- RECENTLY EXTENDED TO FINAL-STATE MASSIVE QUARKS
  (Buonocore, Limatola, Nason, Tramontano, 2024)

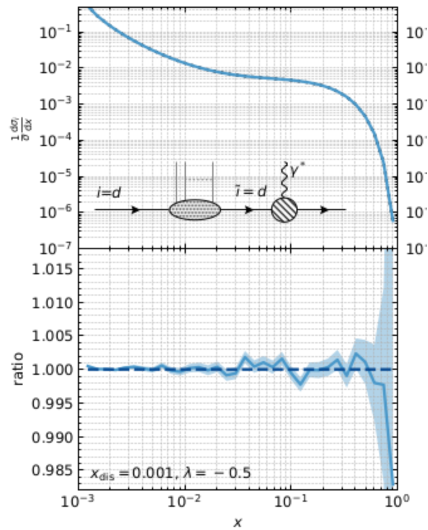
NC DIS AT EIC



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

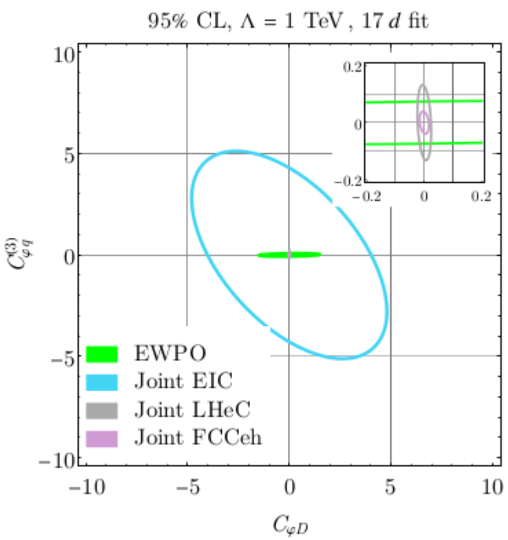
`Panscales` VS HOPPET
PROBABILITY OF PARTON x FOR FIXED x_B



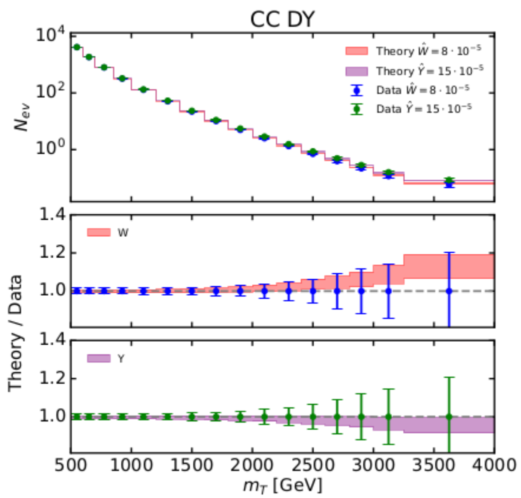
SMEFT, DIS, and PDFs

- 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)

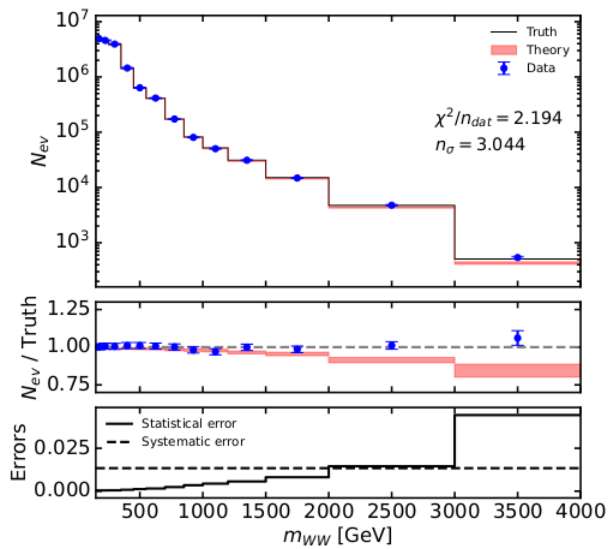
SMEFT fits: impact of future data



contaminated PDFs: CC DY



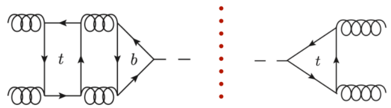
contaminated PDFs WW



STRETCHING THE THEORY

HIGGS IN GLUON FUSION:
TOP-BOTTOM INTERFERENCE

new: top-bottom interference effects at NNLO



Pietrulewicz, Stahlhofen 2302.06623

Niggetiedt, Usowitsch 2312.05297 (3-loop form factor with 3 mass scales)

Czakon, Eschment, Niggetiedt, Poncelet, Schellenberger 2312.09896 (t-b interference), 2407.12413 (OS vs MSbar, 4FS/5FS)

Order	σ_{HEFT} [pb]	$(\sigma_t - \sigma_{\text{HEFT}})$ [pb]	$\sigma_{t\times b}$ [pb]	$\sigma_{t\times b}/\sigma_{\text{HEFT}}$ [%]
		$\sqrt{s} = 13$ TeV		
$\mathcal{O}(\alpha_s^2)$	$+16.30$	–	-1.975	
LO	$16.30^{+4.36}_{-3.10}$	–	$-1.98^{+0.38}_{-0.53}$	-12
$\mathcal{O}(\alpha_s^3)$	$+21.14$	-0.303	$-0.446(1)$	
NLO	$37.44^{+8.42}_{-6.29}$	$-0.303^{+0.10}_{-0.17}$	$-2.42^{+0.19}_{-0.12}$	$-6.5^{+0.9}_{-0.8}$
$\mathcal{O}(\alpha_s^4)$	$+9.72$	$+0.147(1)$	$+0.434(8)$	
NNLO	$47.16^{+4.21}_{-4.77}$	$-0.156(1)^{+0.13}_{-0.03}$	$-1.99(1)^{+0.30}_{-0.15}$	$-4.2^{+0.9}_{-0.8}$

M. Niggetiedt, HP2 2024

t-b interference effect larger than pure top mass effect, also larger than NLO scale uncertainties

…REMEMBER
YR4

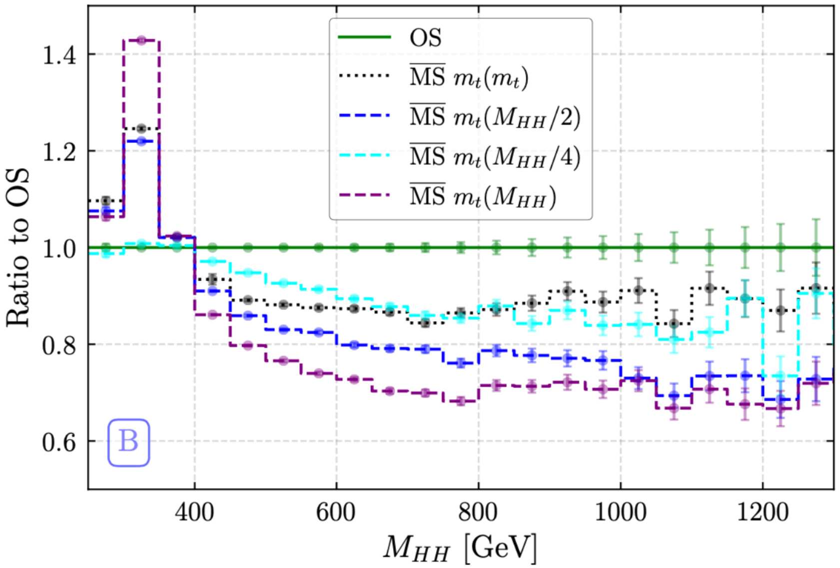
bottom and charm interference correction changes by 0.7 pb if $\overline{\text{MS}}$ or pole heavy quark masses are used.

The **F-uncertainty** is estimated as $\Delta_{\text{t,bc}} = \pm 0.4$ pb, i.e. a relative uncertainty of $\pm 0.8\%$, following Sect. I.4.1.a.iii and Ref. [93].

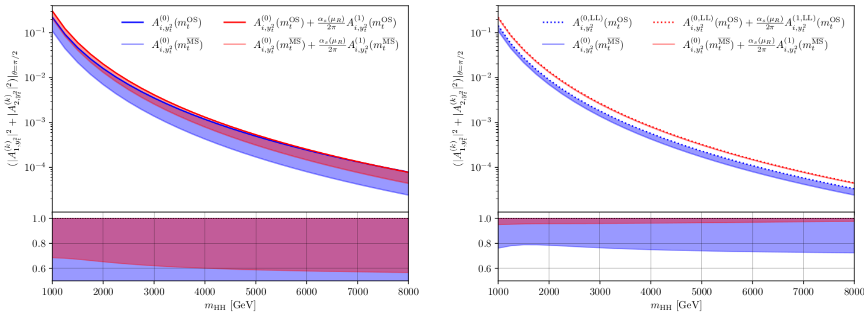
The **G-uncertainty** is estimated taking the scheme dependence of the NLO interference as a reasonably conservative estimate. This leads to $\Delta_{\text{t,bc}} = \pm 0.7$ pb, i.e. a relative uncertainty of $\pm 1.5\%$.

DOUBLE HIGGS PRODUCTION:
TOP MASS DEPENDENCE

- LARGE DIFFERENCE BETWEEN OS AND $\overline{\text{MS}}$ SCHEME RESULTS $\Rightarrow$ LARGEST UNCERTAINTY, UP TO 20% (Bagnaschi, Degrassi, Gröber, 2023)
- REDUCED **?** TO PERCENT LEVEL BY HIGH-ENERGY LL RESUMMATION $\ln \frac{m_t^2}{s}$ (Jaskiewicz, Jones, Szafron, Ulrich, 2025)



Bagnaschi et al, 2023

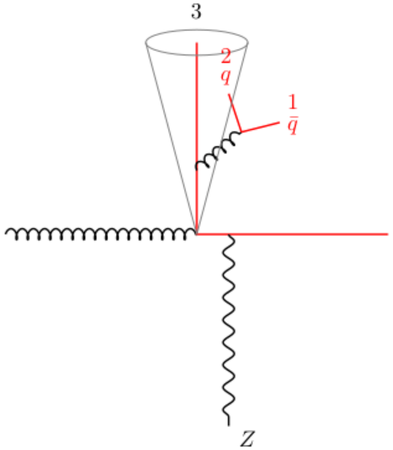


Jaskiewicz et al., 2025

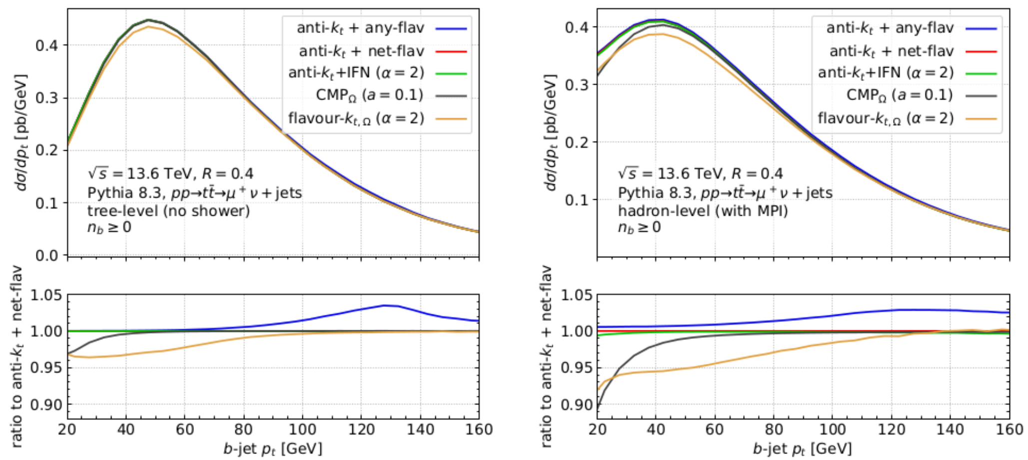
HEAVY FLAVORED JETS

- 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)
- ENABLES HEAVY FLAVORED JET SUBSTRUCTURE STUDIES (Dhani, Fedkevych, Ghira, Marzani, Soyez, 2024)

JET FLAVOR POLLUTION



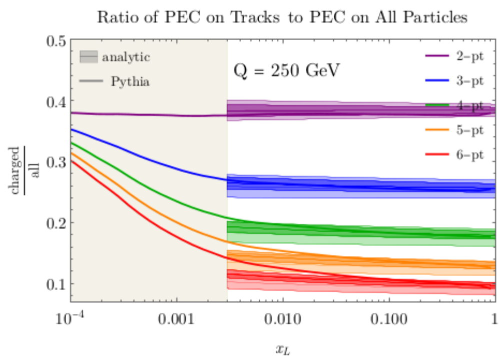
B JET FROM TOP PRODUCTION



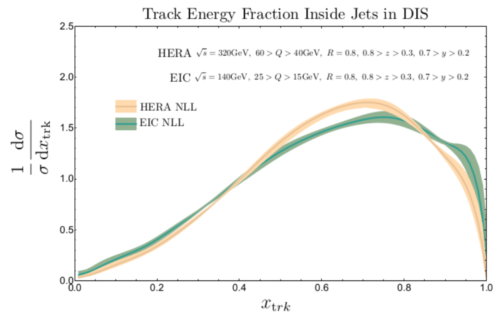
JET SUBSTRUCTURE AND ENERGY CORRELATORS

- 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)

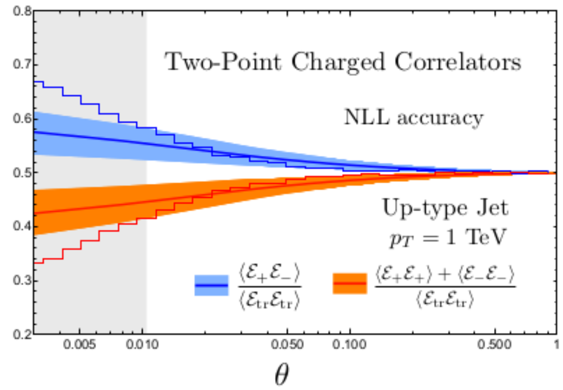
ENERGY CORRELATORS VS ANGULAR SIZE: TRACK TO ALL RATIO
PERTURBATIVE VS. `pythia`



EXTRACTION OF TRACK FUNCTION FROM EIC DIS DATA



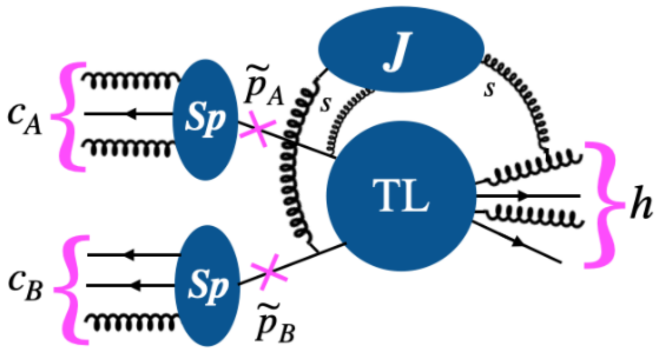
HADRON ENERGY CORRELATORS: SAME VS. DIFFERENT CHARGE



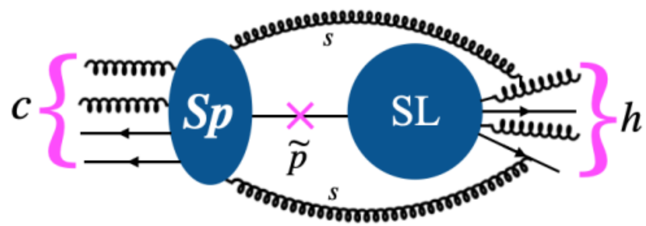
STRETCHING THE LIMITS OF FACTORIZATION

- 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)



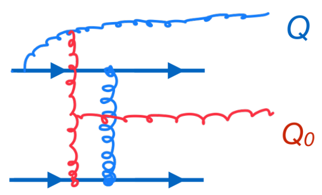
SPACELINE COLLINEAR (INITIAL STATE)



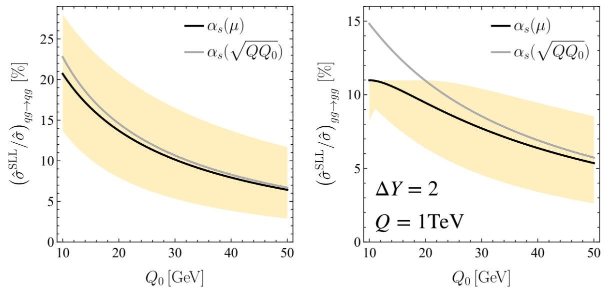
SUPERLEADING LOGS & PDF FACTORIZATION

- NON-GLOBAL OBSERVABLES: GAP BETWEEN JETS, VETO SCALE Q_0
- COLLINEAR LOGS HIGHER ORDER THAN ALTARELLI PARISI $\Rightarrow$ FACTORIZATION VIOLATION
- RESUMMATION (Becher, Neubert, Shao, Stillger, 2023)
- CANCELLED BY GLAUBER GLUONS $\Rightarrow$ PDF FACTORIZATION RESTORATION VERIFIED AT FIXED ORDER (Becher, Hager, Jaskiewicz, Neubert, Schwienbacher, 2024)

SUPERLEADING LOGS



DIJET SLL RESUMMATION



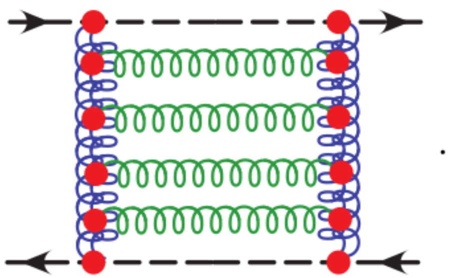
Collinear factorization breaking at $\mu = Q$ **X** soft-collinear factorization breaking by Glauber modes at $\mu = Q_0$

= PDF factorization for $\mu < Q_0$

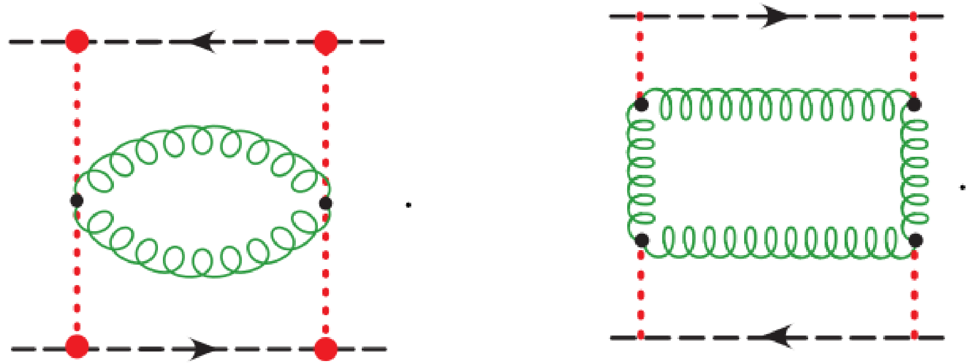
HIGH-ENERGY RESUMMATION

- HIGH ENERGY (BFKL, SMALL x) LOGS $\alpha \ln 1/x$, $x = \frac{M^2}{s}$
  $\Rightarrow$ PARTONIC CROSS-SECTIONS AND ANOMALOUS DIMENSIONS
- SMALL x EVOLUTION DUAL TO LARGE Q^2 EVOLUTION
- SMALL x SPLITTING FUNCTIONS $\Leftrightarrow$ HIGH ENERGY RESUMMATION OF COLLINEAR SPLITTING FUNCTIONS
- 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

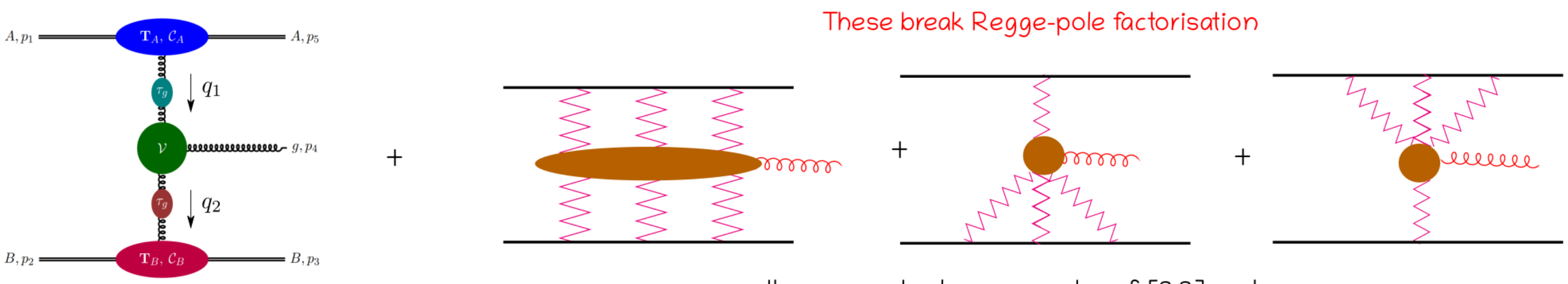


TOWARDS NNLO BFKL

- ONLY LL FULLY RESUMMED $\rightarrow$ DOMINANT UNCERTAINTY AT 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(-,-):

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



they respect colour symmetry of [8,8] exchange

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]

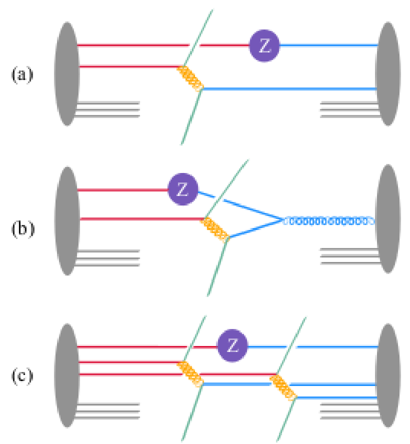
✓ 2-loop impact factors [taken from Caola et al 2112.11097]

F. Buccioni

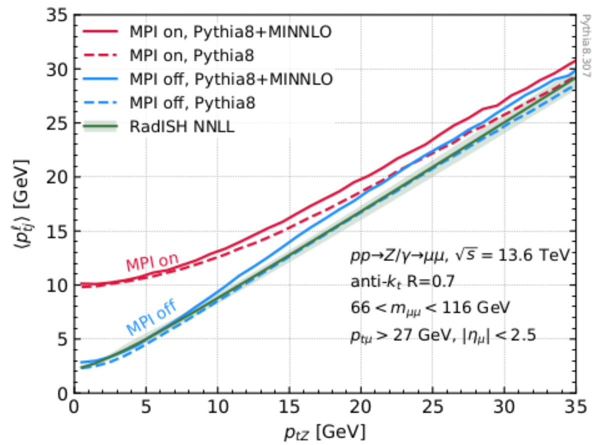
MULTIPARTON INTERACTIONS

- 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 $p_t > p_t^{\min}$

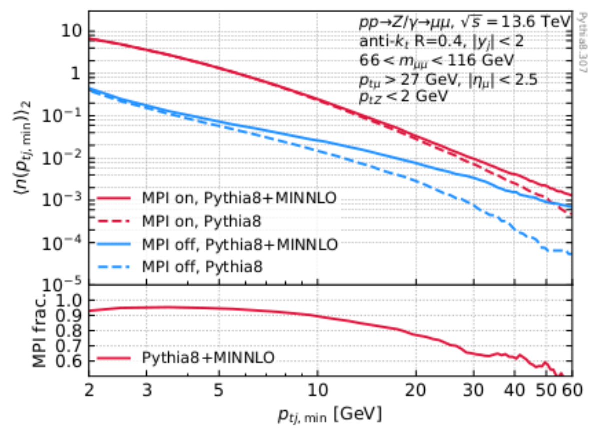
DOUBLE (A,B) AND
TRIPLE (C) PARTON HARD SCATTERING



MPI VS NO MPI VS p_t



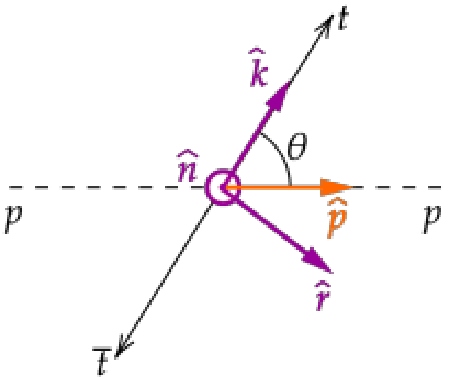
MPI VS NO MPI CUT
CUMULATIVE JET SPECTRUM



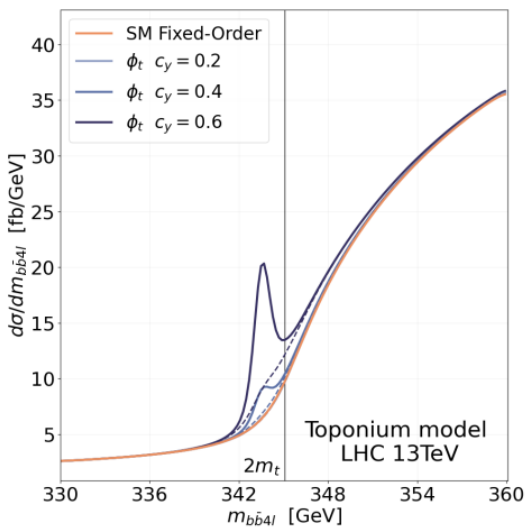
ENTANGLED TOP PAIRS

- TOP PAIRS ENTANGLED ⇒ PATTERN CHANGES BSM
- DEFINE $D^1 = -\operatorname{tr} C_{ij}$ ENTANGLEMENT MARKER ⇒ 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)

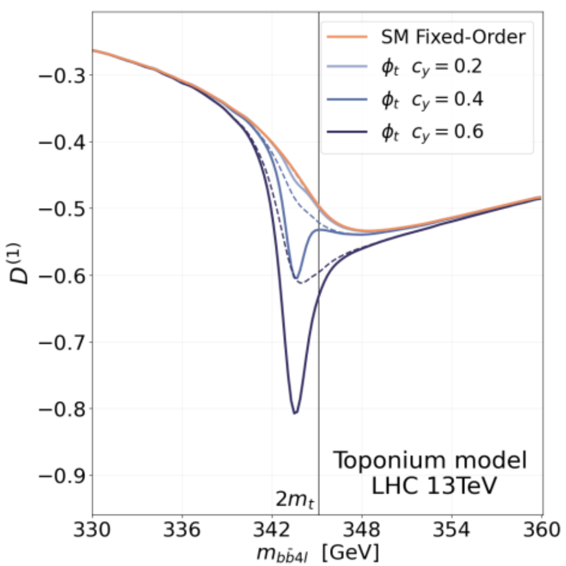
THE HELICITY BASIS



CROSS–SECTION VS FINAL STATE MASS



ENTANGLEMENT MARKER VS FINAL STATE MASS



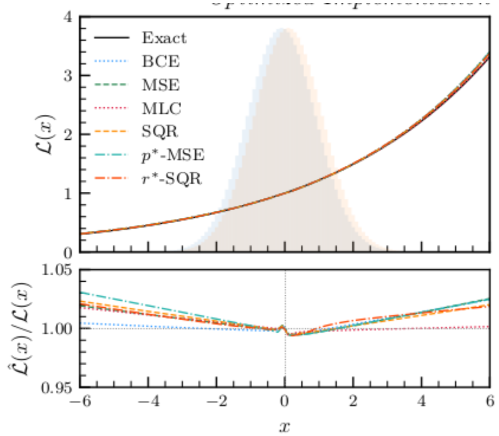
DEEP LEARNING QCD

CLASSIC METHODS

REGRESSION

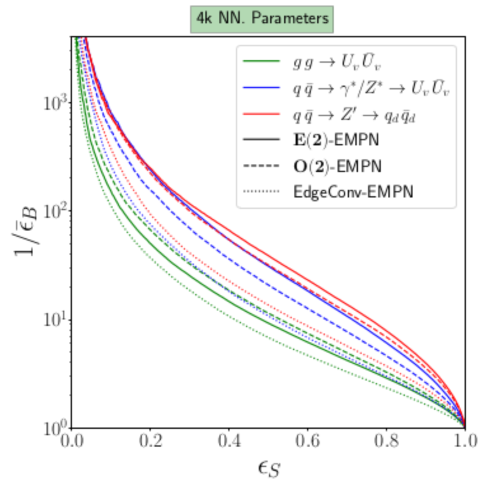
- HYPOTHESIS TESTING $\Rightarrow$ LIKELIHOOD RATIO:
  $\mathcal{L}(x) = \frac{p(x|\theta_0)}{p(x|\theta_1)}$,
  θ_i PARMS OF PROBABILITY
- NEURAL NET FIT
- OPTIMAL NN CLASSIFIER (Rizvu, Pettee, Nachman, 2023)
- MATRIX ELEMENT METHOD: RECONSTRUCTED PROBABILITY FROM UNDERLYING PARTON EVENT
  (Heimel,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

LIKELIHOOD RATIO: DISPLACED GAUSSIAN
FITTED VS TRUE



TAGGING

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

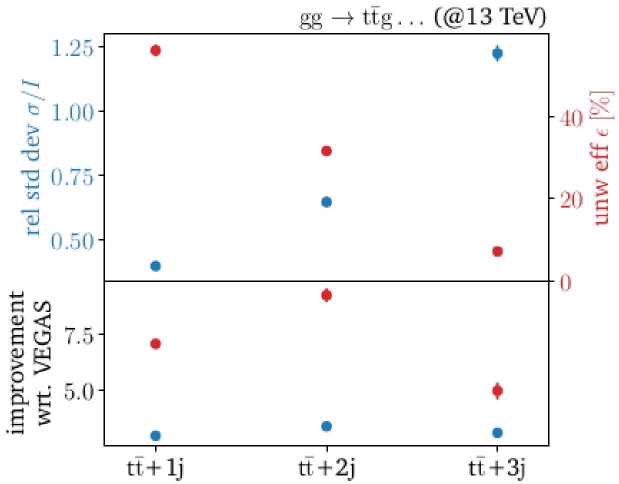


- TRAIN NEURAL NET $\Rightarrow$ TAG SIGNAL FROM BACKGROUND
- STANDARD IN TOP TAGGING, EXTENDED TO JETS
- GRAPH & CONVOLUTIONAL NN $\Rightarrow$ EQUIVARIANCE
- JET TAGGING FOR NP SIGNALS
  (Bhardwaj, Englert, Naskar, Ngairangbam, Spannowsky, 2024)

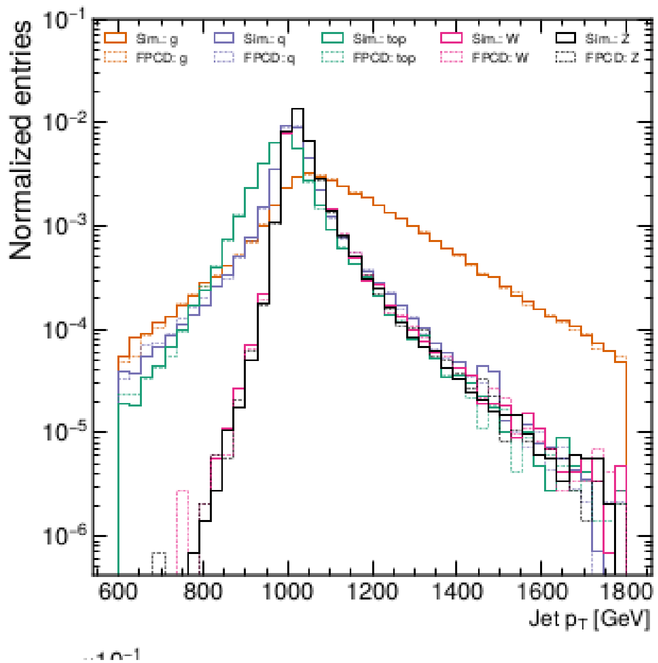
GENERATIVE METHODS

- 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)

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



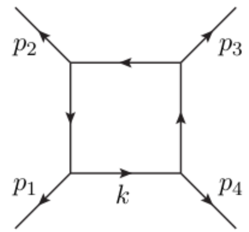
JET p_T: GENERATED VS SIMULATED



TOWARDS THE FUTURE
LEARNING FEYNMAN INTEGRALS

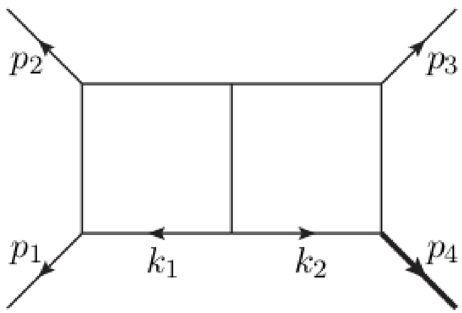
- MASSLESS BOX INTEGRAL FAMILY: $I_{\vec{a}} = \int \frac{d^d k}{i\pi^{d/2}} \frac{\mu^{4-d}}{D_1^{a_1} D_2^{a_2} D_3^{a_3} D_4^{a_4}}$
- FINITE NUMBER LIN. INDEP. $\Rightarrow$ MASTER INTEGRALS $\vec{F}(s,t,\epsilon)$
- DIFFERENTIAL EQUATIONS $\frac{\partial}{\partial s} F^i(s,t,\epsilon) = \epsilon A_s^{ij}(s,t) F^j(s,t,\epsilon) \Rightarrow$
  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

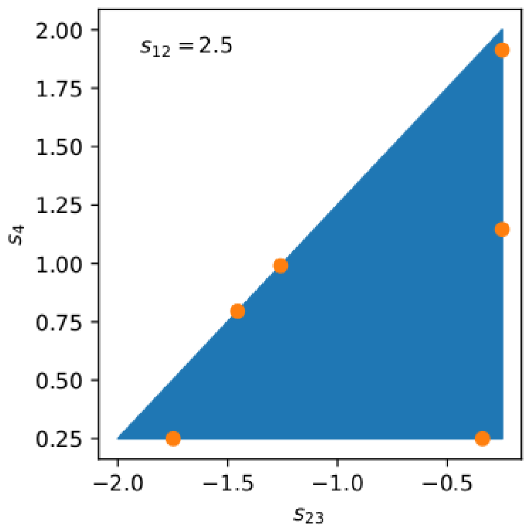


SIMILAR PROBLEM: DETERMINE PHASE OF AMPLITUDE FROM XSECT FROM OPTICAL THM $\Rightarrow$ INTEGRAL EQN (Dersy, Schwartz, Zhiboedov, 2023)

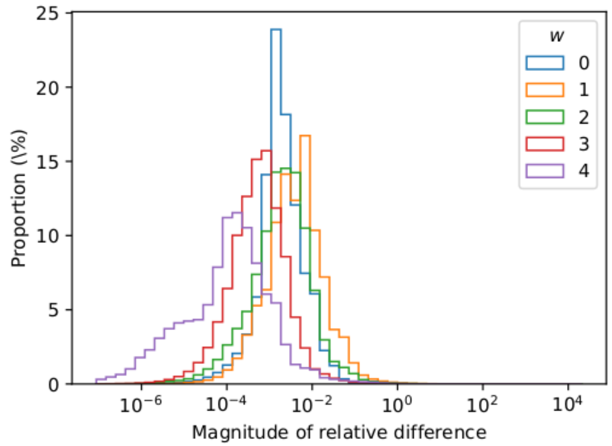
THE DOUBLE BOX



BOUNDARY POINTS



APPROX ERROR FOR DIFFERENT POWERS OF ϵ

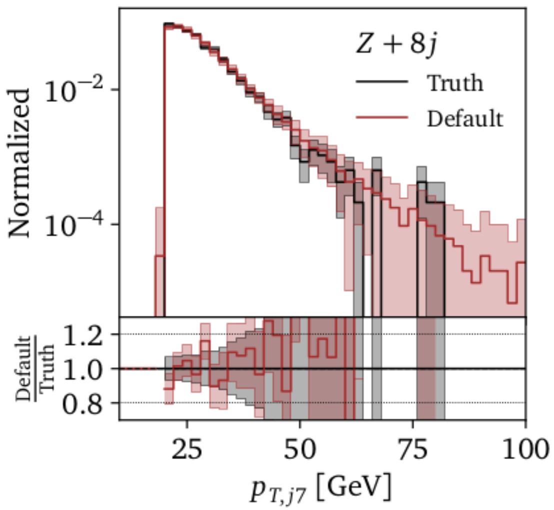


THE FUTURE?

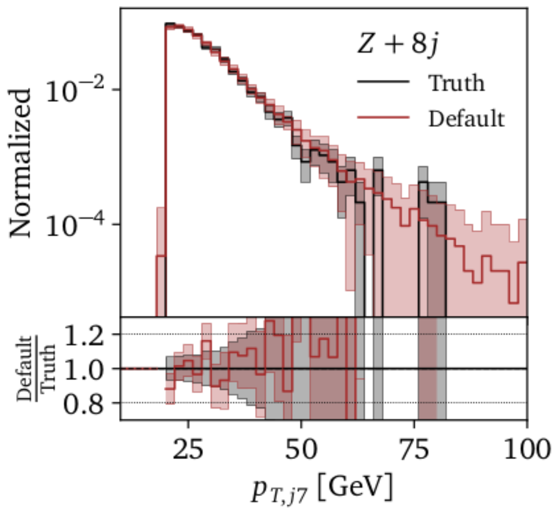
TRANSFORMERS: LEARNING AMPLITUDES

- TRANSFORMERS $\Rightarrow$ LARGE LANGUAGE MODELS $\Leftrightarrow$ ATTENTION (TOKENS)
- PREDICT ANSWER TO QUESTION $\Rightarrow$ PREDICT ITEM IN SEQUENCE

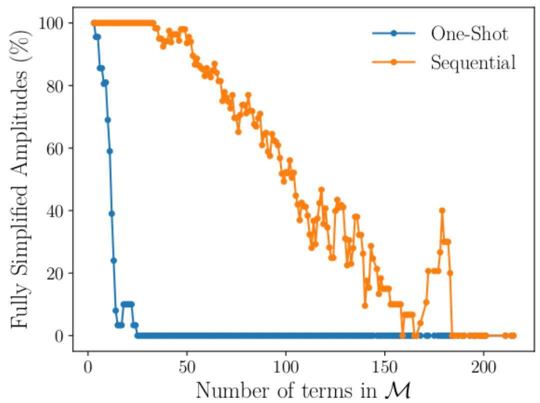
LEARNING JETS



EXTRAPOLATING JETS



SIMPLIFICATION EFFICIENCY



- PREDICT $n+k$-JET RADIATION FEATURES FROM n-JET RADIATION (Butter, Charton, Villadamigo, ore, Plehn, Spinner, 2024)
- SIMPLIFY AMPLITUDES WITH ~ 100 TERMS (Cheung, Dersy, Schwartz, 2024)
- PREDICT COEFFICIENTS OF SPECIFIC HIGHER-ORDER TERMS IN AMPLITUDES (Cai, Merz, Charton, Nolte, Whilhelm, K. Cranmer, Dixon, 2024)

SUMMARY

THE TWO HORIZONS

- 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
- 2040: THE TRIUMPH OF QCD
  - FULL UNDERSTANDING OF QCD FACTORIZATION
  - MACHINE LEARNING FOR INFERENCE