QCD

AND

THE EIC-LHC SYNERGY

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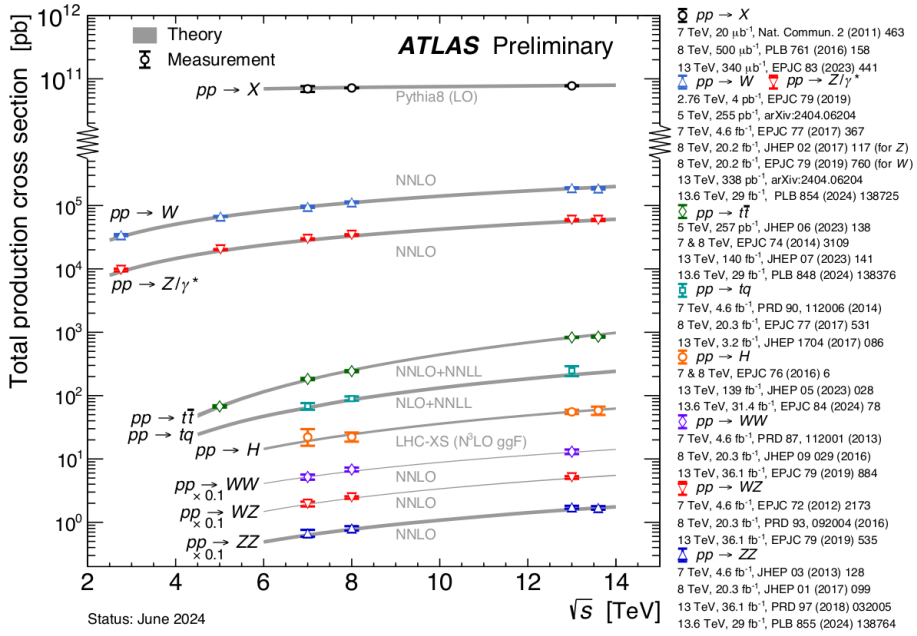
PRECISION PHYSICS
FROM DIS TO HADRON COLLIDERS...

NOT SO LONG AGO....

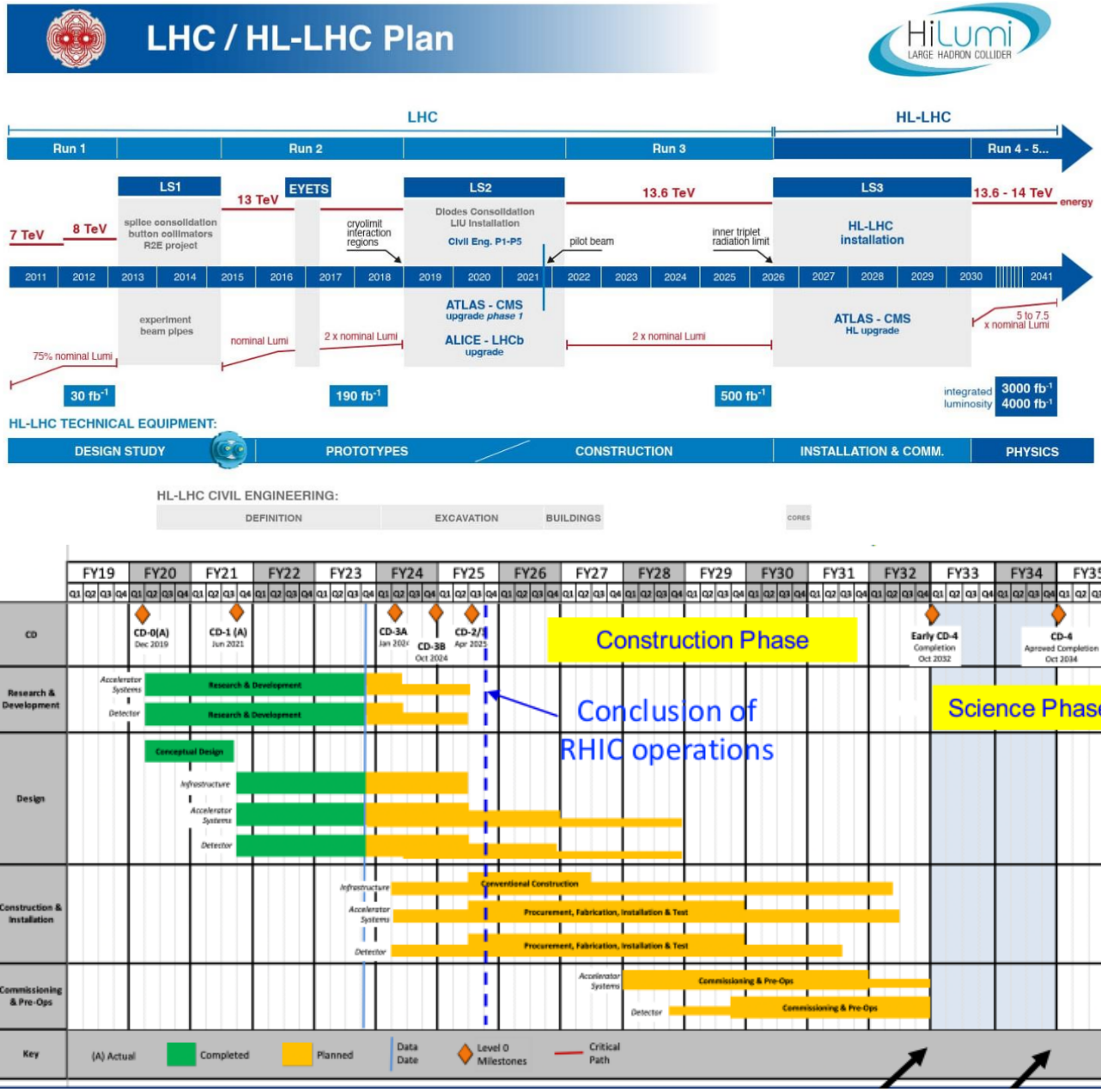
ATL-PHYS-PUB-2024-011

TODAY

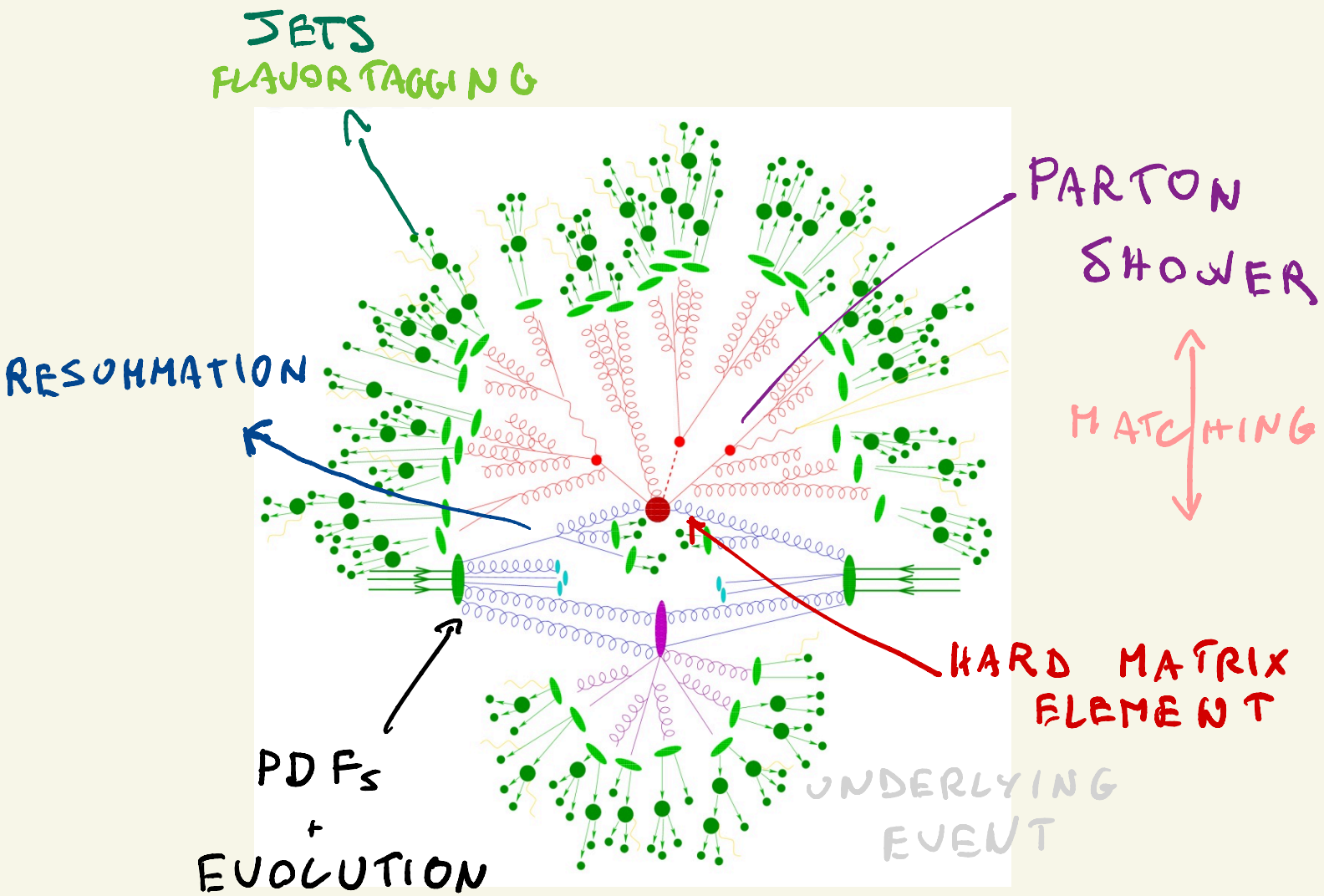


ATLAS 2024

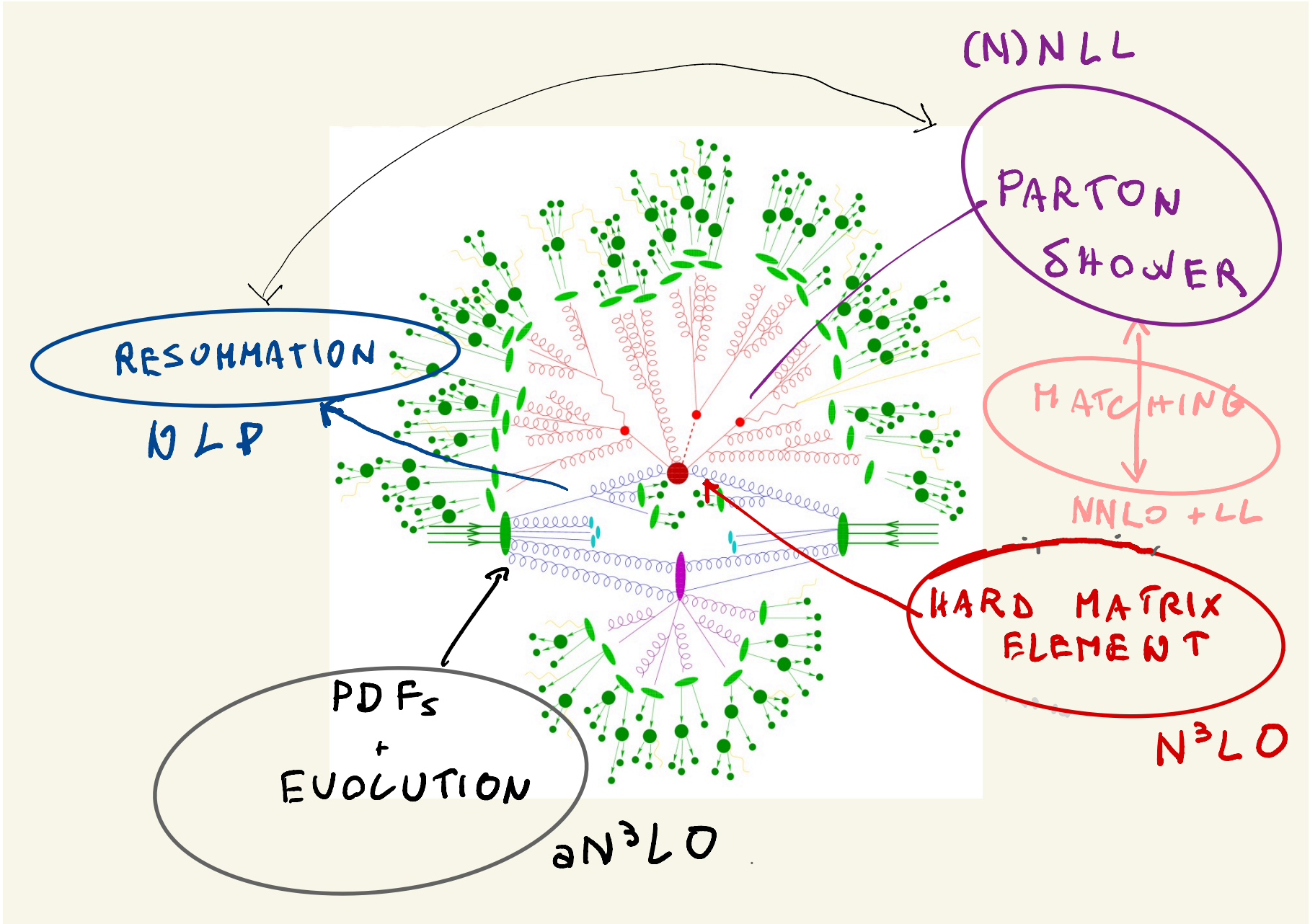
...AND FROM HADRON COLLIDERS TO DIS
THE HL-LHC. . . AND THE EIC



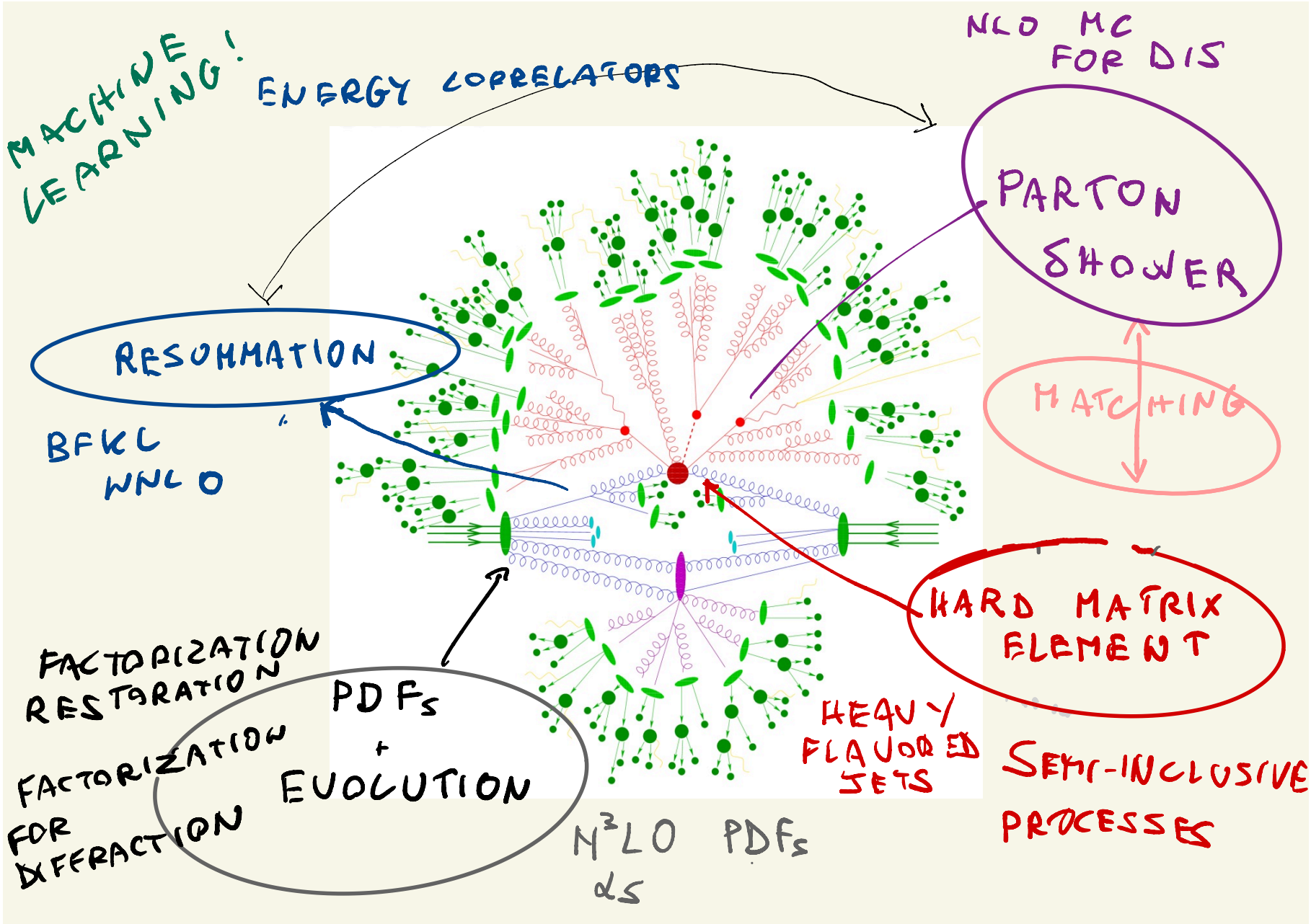
PRECISION QCD PHYSICS



THE LHC FRONTIER



THE DIS - LHC INTERPLAY



SYNERGIES

QCD RESULTS AND METHODS. . .

- LHC $\Rightarrow$DIS

  MOTIVATED BY HADRON COLLIDER PHYSICS IDEAS, NEEDS AND TECHNIQUES, OF RELEVANCE TO DIS

- DIS $\Rightarrow$ LHC

  MOTIVATED BY DIS PHYSICS IDEAS, NEEDS AND TECHNIQUES, OF RELEVANCE TO HADRON COLLIDER PHYSICS

- LHC $\Leftrightarrow$DIS

  DIS $\Leftrightarrow$ LHC

  FROM THE INTERPLAY OF DIS & HADRON COLLIDER PHYSICS

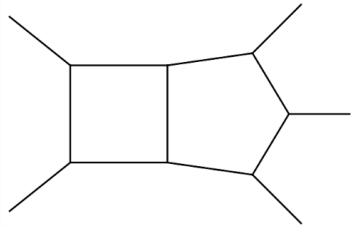
AMPLITUDES

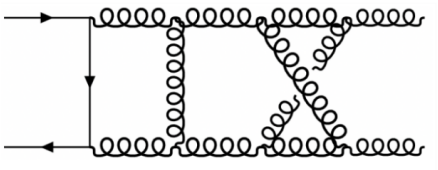
LHC $\Rightarrow$ DIS

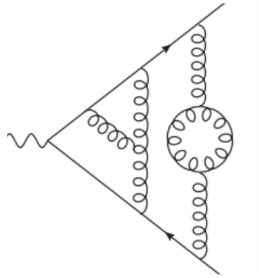
THE AMPLITUDE REVOLUTION

MORE LEGS AND MORE LOOPS

$\mathcal{A}$







2 loop 5 point

3 loop 4 point

4 loop 3 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, ...

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

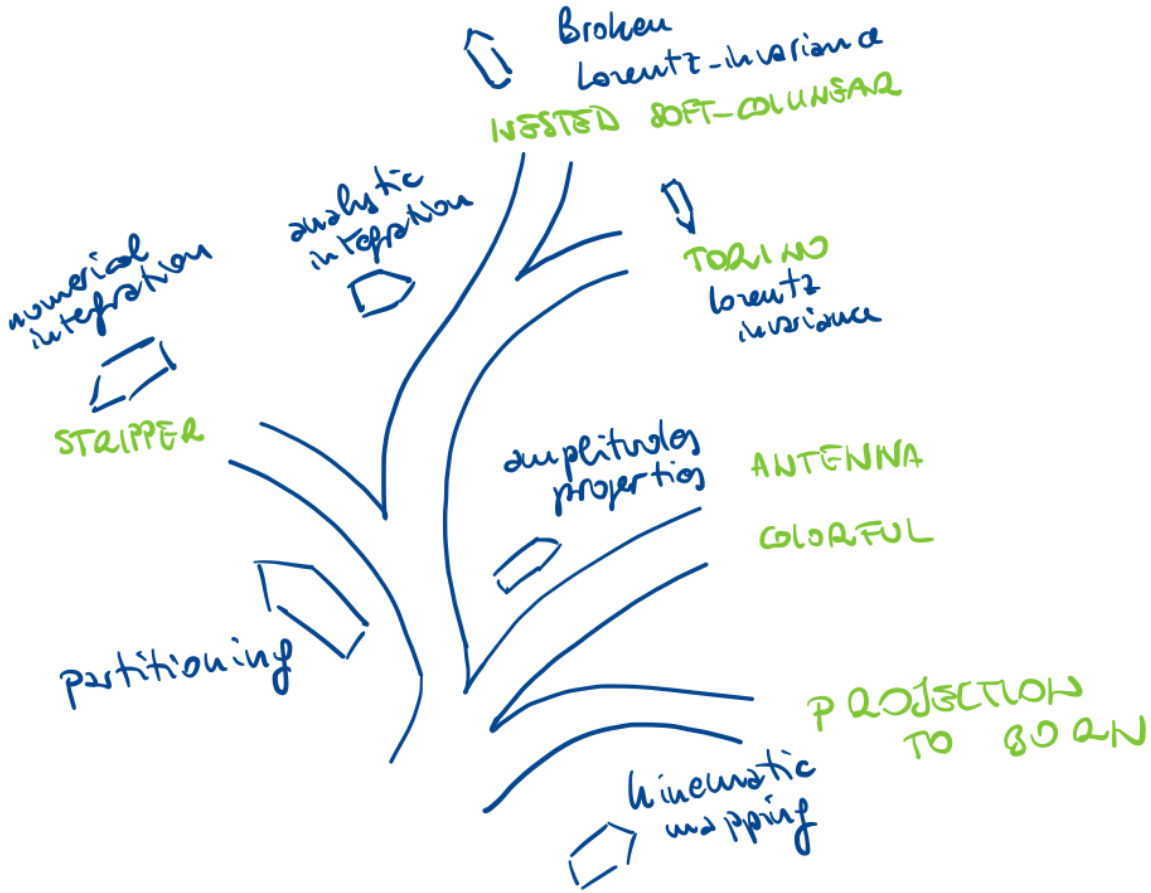
Henn, Lee, Manteuffel, Schabinger, Smirnov, Smirnov, Stainhauser,...

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

L. Tancredi, QCD@LHC, 2024

LHC $\Rightarrow$ DIS

NNLO SUBTRACTION METHODS



C. Signorile-Signorile

- SUBTRACTION TECHNIQUES $\Leftrightarrow$ NNLO UNDER CONTROL

LHC $\Rightarrow$ DIS

THE STATE OF THE ART

process	known	desired
$pp \to V$	$\mathrm{N^3LO_{QCD}} + \mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$ $\mathrm{NLO_{EW}}$	$\mathrm{N^2LO_{EW}}$
$pp \to VV'$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ + Full $\mathrm{NLO_{QCD}}$ ($gg \to ZZ$), approx. $\mathrm{NLO_{QCD}}$ ($gg \to WW$)	Full $\mathrm{NLO_{QCD}}$ (gg channel, w/ massive loops) $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$
$pp \to V + j$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$	hadronic decays
$pp \to V + 2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (QCD component) $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)	$\mathrm{NNLO_{QCD}}$
$pp \to V + b\bar{b}$	$\mathrm{NLO_{QCD}}$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to W + b\bar{b}$	$\mathrm{NNLO_{QCD}}$	
$pp \to VV' + 1j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$
$pp \to VV' + 2j$	$\mathrm{NLO_{QCD}}$ (QCD component) $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to W^+W^+ + 2j$	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to W^+W^- + 2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)	
$pp \to W^+Z + 2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)	
$pp \to ZZ + 2j$	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to VV'V''$	$\mathrm{NLO_{QCD}}$ +$\mathrm{NLO_{EW}}$ (w/ decays)	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (off-shell)
$pp \to WWW$	$\mathrm{NLO_{QCD}}$ + $\mathrm{NLO_{EW}}$ (off-shell)	
$pp \to W^+W^+(V \to jj)$	$\mathrm{NLO_{QCD}}$ + $\mathrm{NLO_{EW}}$ (off-shell)	
$pp \to WZ(V \to jj)$	$\mathrm{NLO_{QCD}}$ + $\mathrm{NLO_{EW}}$ (off-shell)	
$pp \to \gamma\gamma$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD}}$
$pp \to \gamma + j$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD}}$
$pp \to \gamma\gamma + j$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ + $\mathrm{NLO_{QCD}}$ (gg channel)	
$pp \to \gamma\gamma\gamma$	$\mathrm{NNLO_{QCD}}$	$\mathrm{NLO_{EW}}$

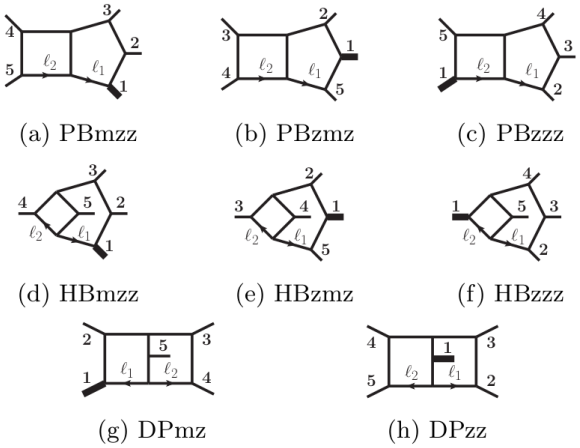
Les Houches 2023 wishlist

LHC $\Rightarrow$ DIS

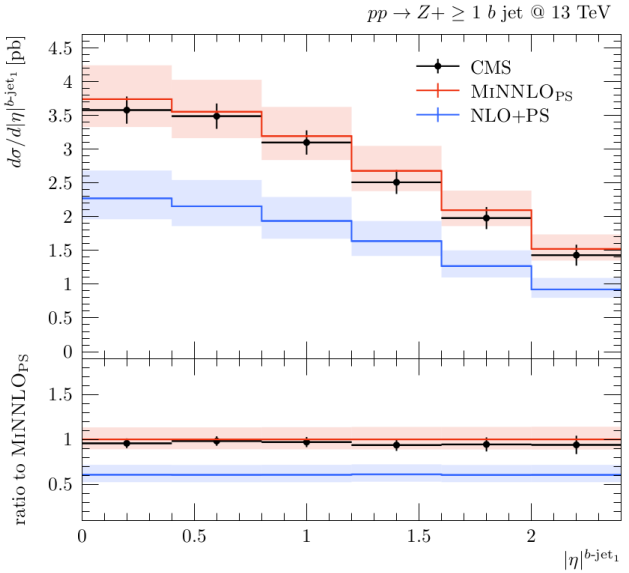
THE COMPLEXITY FRONTIER

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

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!

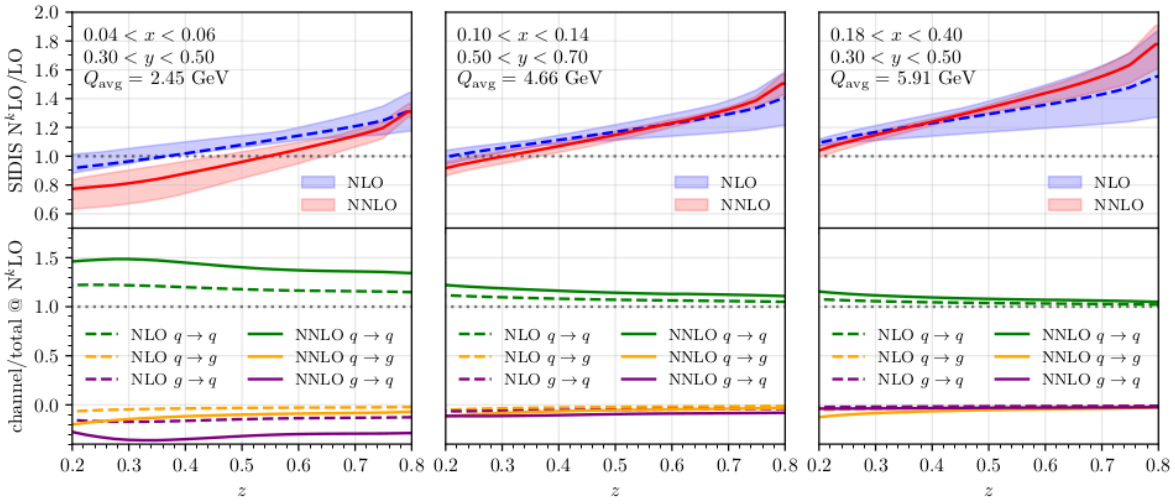
DIS ⇔ LHC

SIDIS AT NNLO

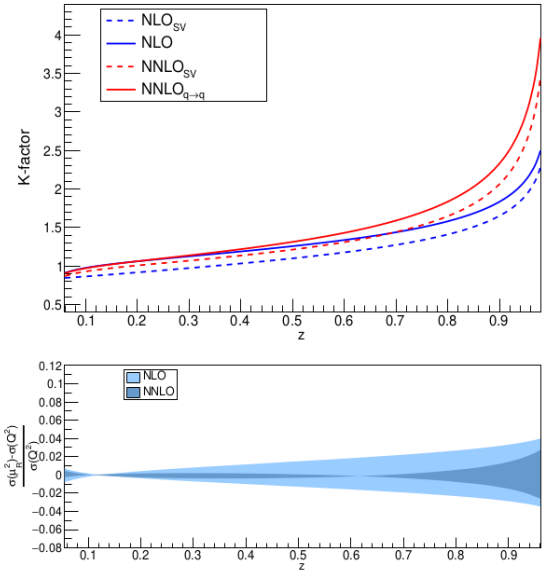
- SEMI-INCLUSIVE DIS: $ep \to h + X$ (TAGGED HADRON IN FINAL STATE)
- SIMULTANEOUS DETERMINATION OF PDF AND FRAGMENTATION FUNCTIONS
  DEPENDS ON TWO MOMENTUM FRACTIONS x & z
  STRINGENT CONSTRAINTS ON PDF FLAVOR SEPARATION
  $\Rightarrow$ NEW PHYSICS SEARCHES AT HL-LHC
- NNLO CORRECTIONS COMPUTED (Bonino, 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
- THRESHOLD RESUMMATION IN DOUBLE-SOFT LIMIT (Abele, de Florian, Vogelsang 2022 $\mathrm{N^3LL}$; Goyal, Moch, Pathak, Rana, Ravindran, 2024) $\mathrm{N^4LL}$ AND SINGLE-SOFT LIMIT (SF, Ridolfi, Ventola, 2025 wip

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

COMPASS X BINS (Bonino et al., 2024)



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



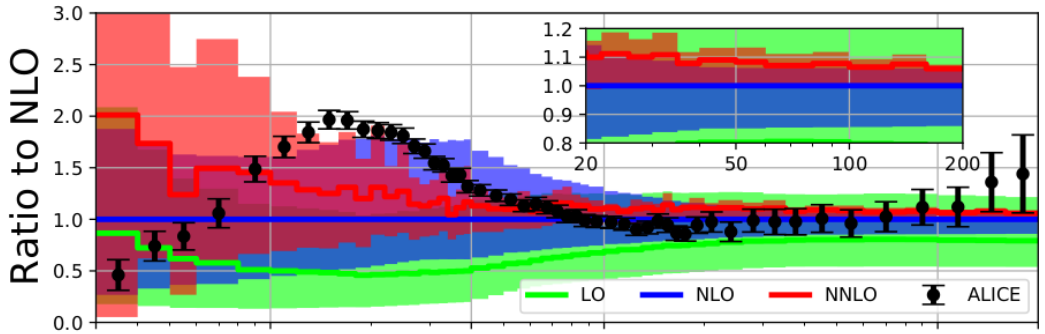
DIS $\Rightarrow$ LHC

NNLO IDENTIFIED HADRON PRODUCTION

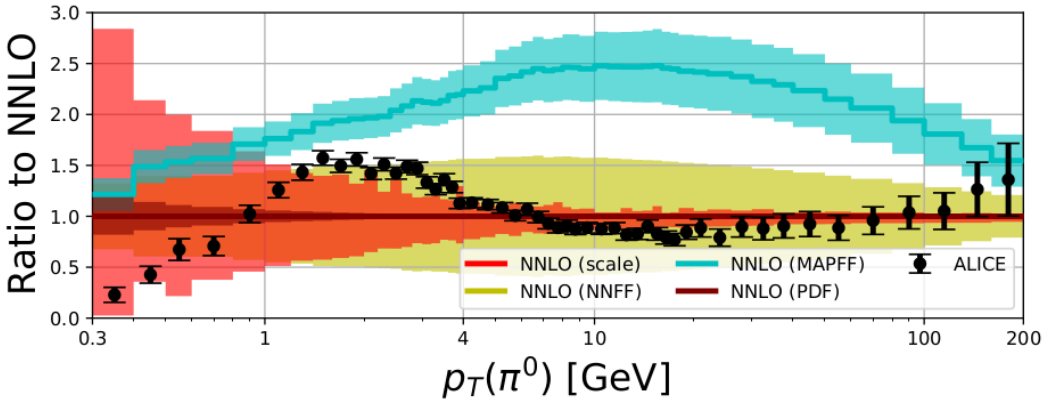
- SEMI-INCLUSIVE: $pp \to h$ AND $pp \to hh$ (TAGGED HADRONS IN FINAL STATE)
- INCLUSIVE π^0 $p+t$ SPECTRUM; DI-PION INVARIANT MASS & CHARGED HADRON DISTRIBN INSIDE JETS COMPUTED AT NNLO (Czakon, Generet, Mitov, Poncelet, 2025)
- GOOD PERTURBATIVE CONVERGENCE
- STRONG DEP. ON FRAGMENTATION FUNCTION

π p_t DISTRIBUTION

DEPENDENCE ON PERTURBATIVE ORDER



DEPENDENCE ON FRAGMENTATION FUNCTION



PDFs & α_s

DIS $\Rightarrow$ LHC
N^{3}LO EVOLUTION

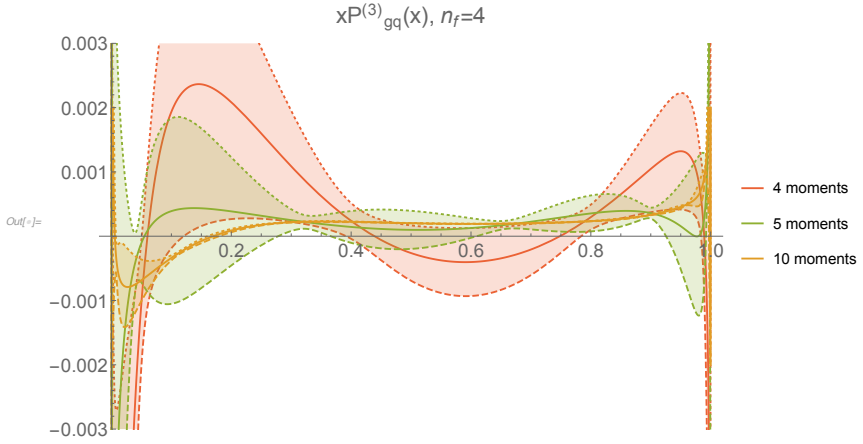
- LO: 1973 Gross, Wilckzek; NLO: 1979 Floratos, Ross, Sachrajda; Gonzalez-Arroyo, López, Ynduráin; NNLO: 2004 Moch, Vermaseren, Vogt

- 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



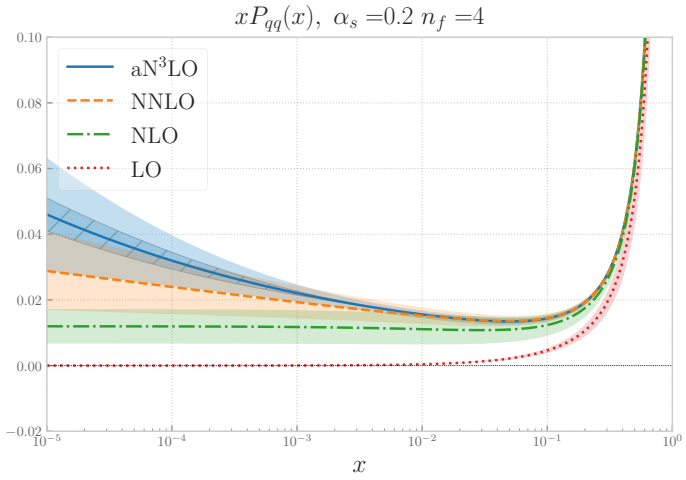
DIS $\Rightarrow$ LHC

THE N^{3}LO SPLITTING FUNCTIONS

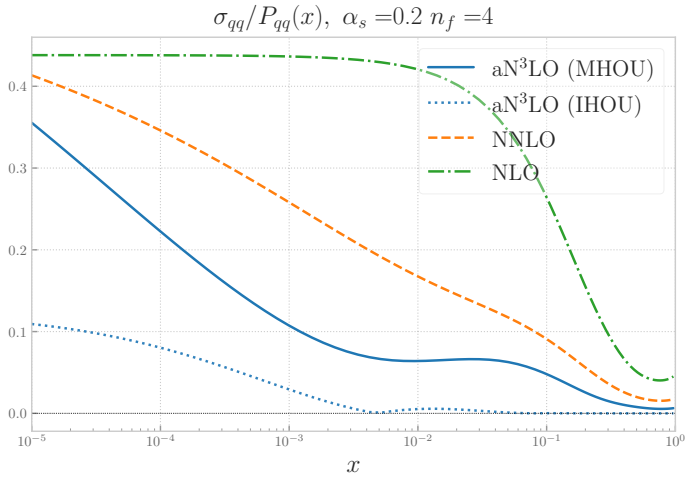
- UNCERTAINTY APPROX (IHOU) $\ll$ MISSING N^{4}LO UNCERTAINTY (MHOU) $\Rightarrow$ KNOWN EXACTLY FAPP
- FIXED-ORDER N^{3}LO EVOLUTION KNOWN FAPP

P_{qq}

SPLITTING FCTN



UNCERTAINTY



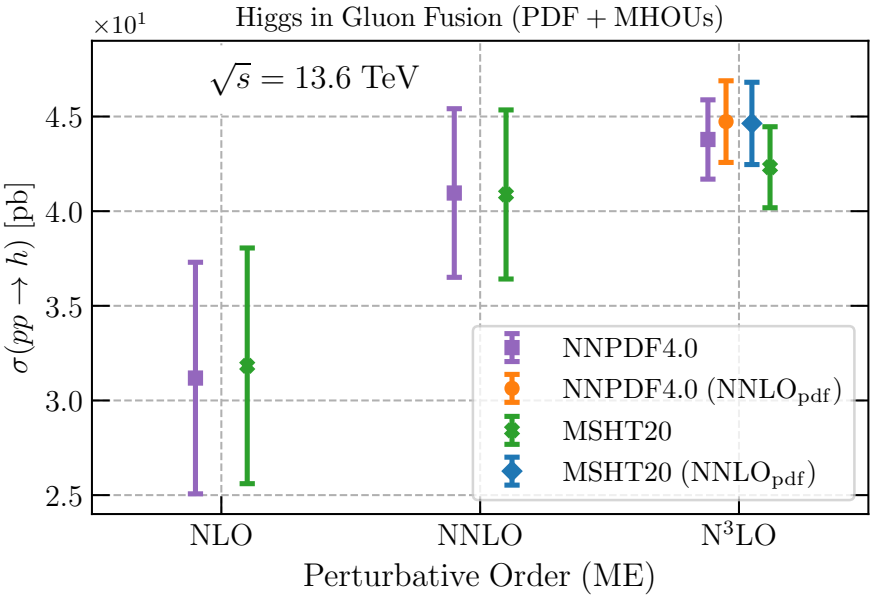
LHC ⇔ DIS

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

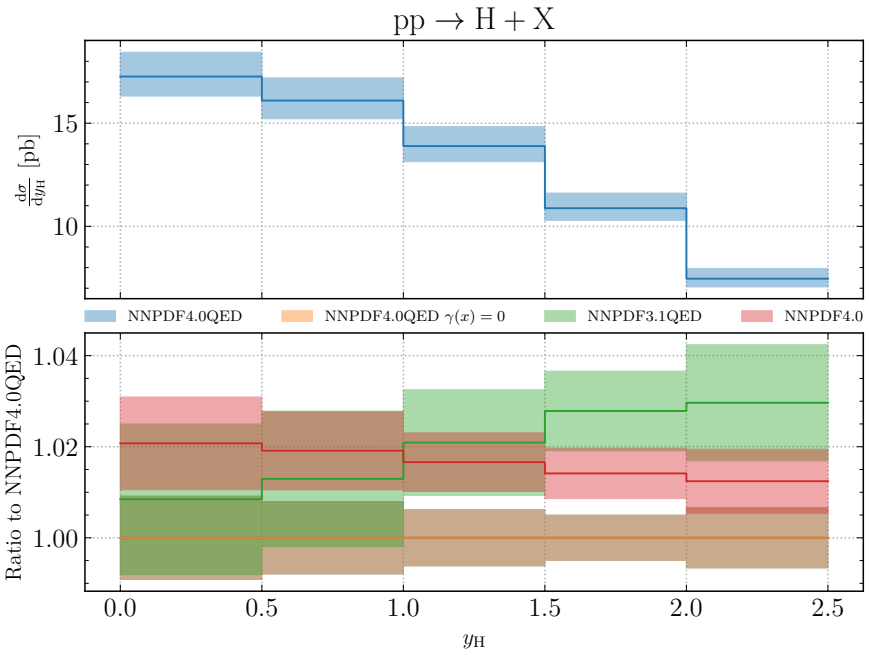
- aN^{3}LO PDF sets now available: MSHT20 (2023), NNPDF4.0 (2024), combination (2024)
  - NNPDF IHOU estimated from theory covariance matrix
  - MSHT IHOU estimated fitting nuisance parms to data
- MHOU on PDF fit available:
  - NNPDF4.0 at any order, from scale variation
  - MSHT20 at aN^{3}LO from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



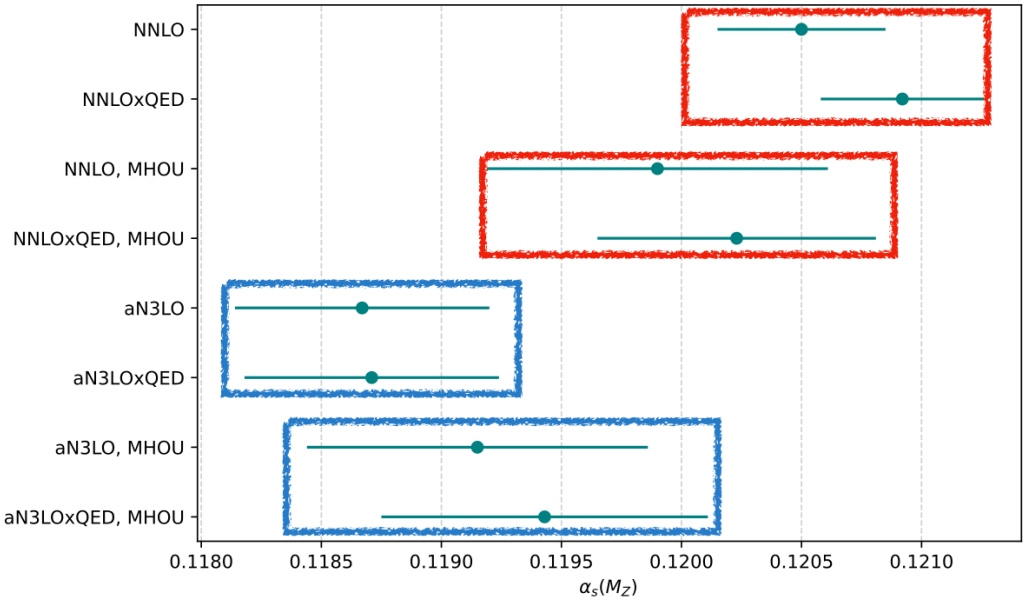
NNPDF: impact of QED



DIS $\Leftrightarrow$ LHC

N^{3}LO α_s IN GLOBAL PDF DETERMINATION

- α_s FROM HADRONIC PROCESSES MUST BE DETERMINED ALONG WITH PDFs (SF, Kassabov, 2020)
- MHOU ON PDF EXTRACTION NEEDED FOR PERTURBATIVE CONSISTENCY
- PHOTON PDF $\Rightarrow$ IMPACT AT $\sim 0.5\%$ LEVEL



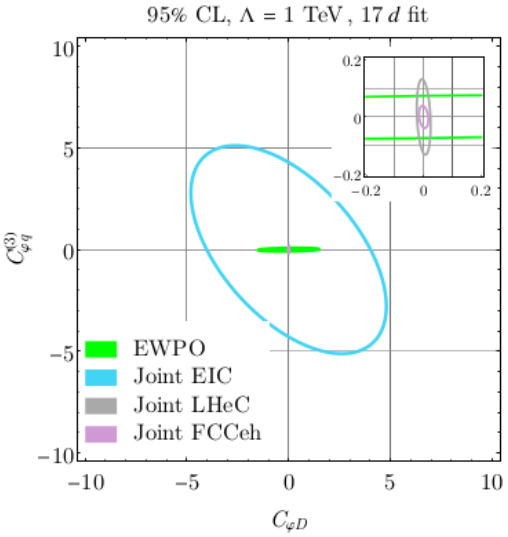
(NNPDF, 2025)

LHC $\Leftrightarrow$ DIS

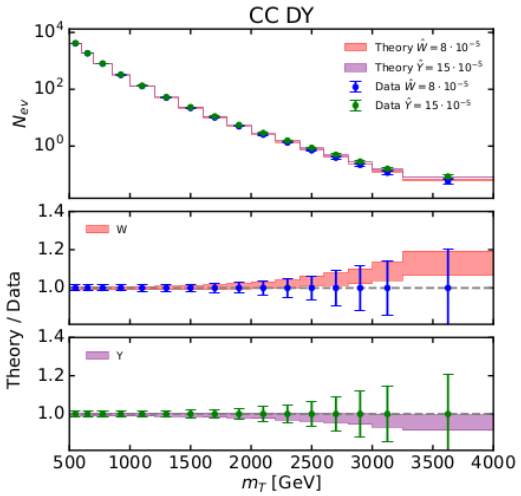
SMEFT, DIS, AND PDFS

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

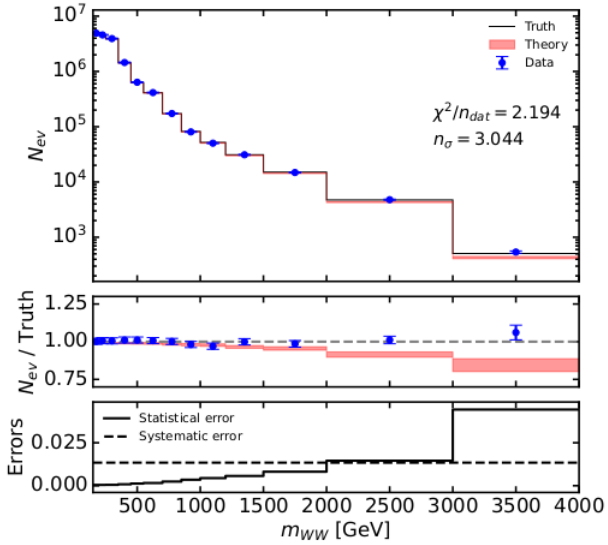
SMEFT FITS: IMPACT OF FUTURE DATA



CONTAMINATED PDFS: CC DY



CONTAMINATED PDFS WW



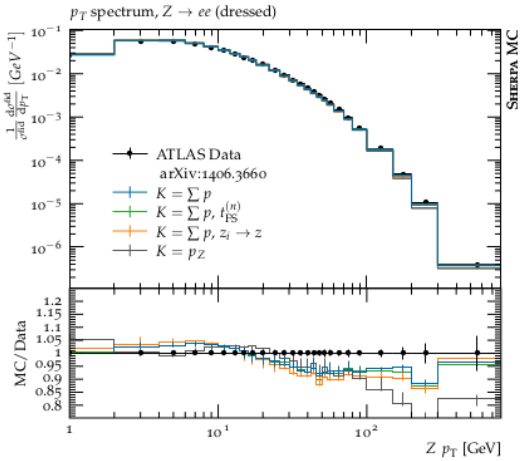
PARTON SHOWER MONTECARLOS

LHC ⇒ DIS

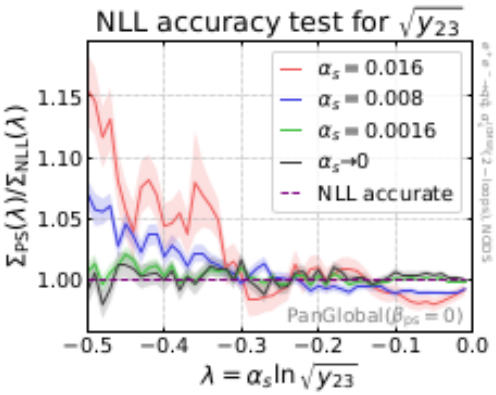
PARTON SHOWER MONTECARLOs: THE PATH TO NN LOGARITHMIC ACCURACY

- 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)

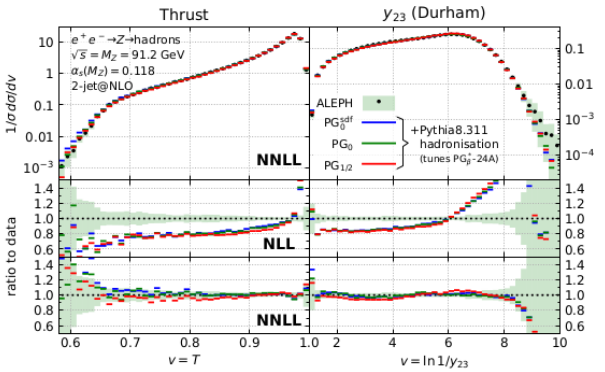
`Alaric`: RECOIL UNCERTAINTY IN DY



`PanScales`: NLL ACCURACY TEST



`PanScales`: NNLL EVENT SHAPES



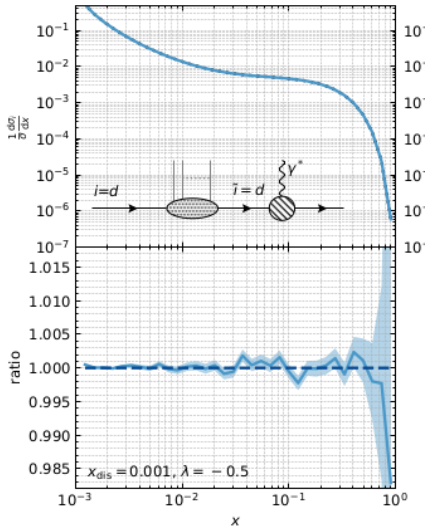
DIS ⇒ LHC

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

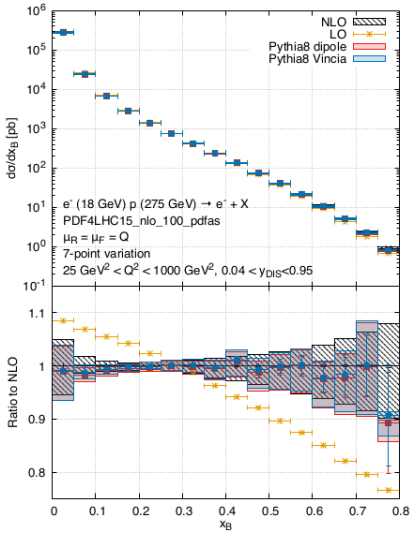
PANSCALES VS HOPPET
PROBABILITY OF PARTON x FOR FIXED x_B



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



HEAVY QUARKS

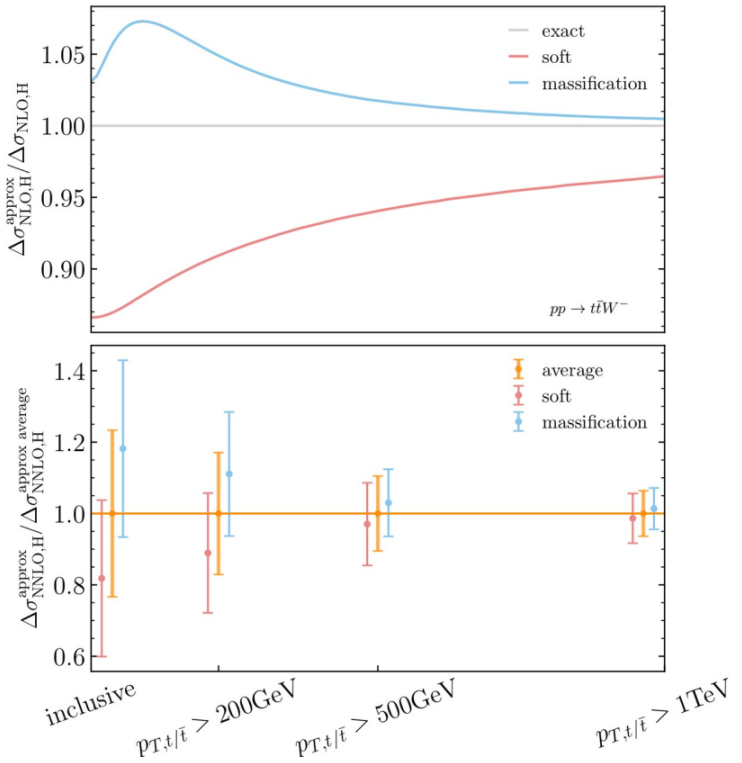
LHC ⇒DIS

TOP MASS IN 2→ 3 PROCESSES

Two strategies have been explored:

- Eikonal approximations: “Soft-Higgs”/”Soft-W”
  - $$\mathcal{M}(\{p_i\}, k; \mu_R, \epsilon) \sim \frac{g}{\sqrt{2}} \left(\frac{p_2 \cdot \varepsilon^*(k)}{p_2 \cdot k} - \frac{p_1 \cdot \varepsilon^*(k)}{p_1 \cdot k} \right) \times \mathcal{M}_L(\{p_i\}; \mu_R, \epsilon) \,,$$ <= qq→tt amps
- ‘Massification’ of V+4j amplitudes
  [Penin’06, Moch Mitov’07, Becher, Melnikov’07]
  - $$|\mathcal{M}^{[p],(m)}> = \prod_i \left[Z_{[i]} \left(\frac{m^2}{\mu^2}, \alpha_s(\mu^2), \epsilon \right) \right]^{1/2} \times |\mathcal{M}^{[p]}> + \mathcal{O}\left(\frac{m^2}{Q^2} \right)$$

Comparison of approx. cross-sections

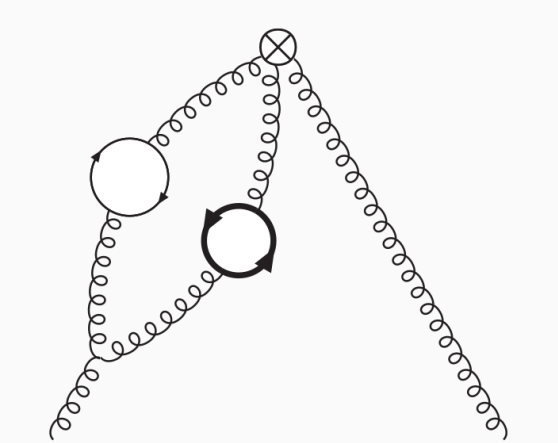


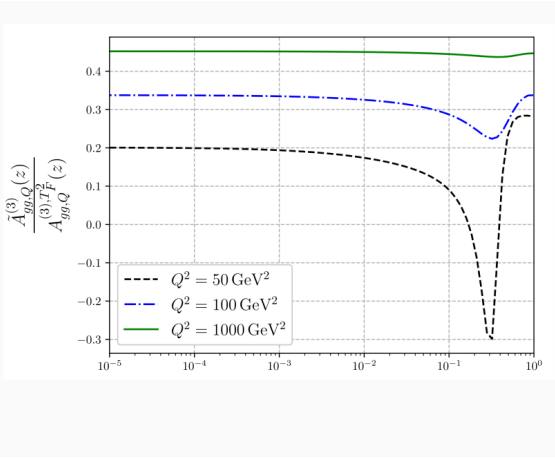
R. Poncelet

- FIRST NNLO ttW, ttH
- EXACT INTERNAL MASSES OUT OF REACH ⇒ APPROXIMATIONS

DIS $\Rightarrow$ LHC

HQ MASSES IN DIS





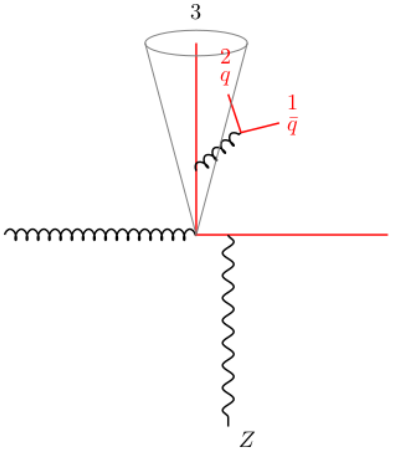
- $m_b \gtrsim m_c \Rightarrow$ MUST INCLUDE BOTH AT ONCE IN VARIABLE-FLAVOR NUMBER SCHEME
- NEW TWO-MASS CONTRIBUTIONS Ablinger, Behring, Blümlein, De Freitas, Manteuffel, Schneider, Schönwald 2024
- SIZABLE WILSON COEFFICIENT AT LOW SCALE, VALENCE PEAK

LHC ⇒DIS

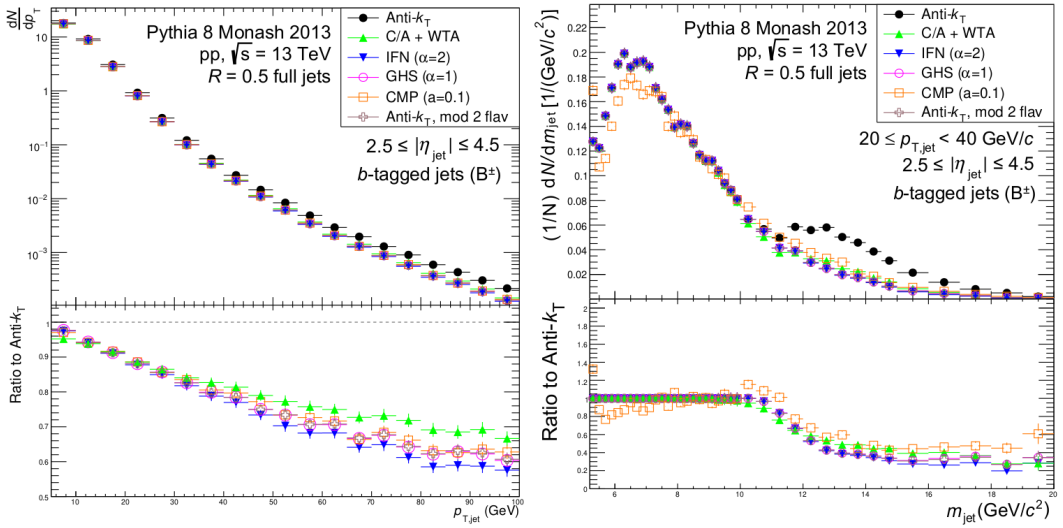
HEAVY FLAVORED JETS

- DEFINITION OF HEAVY FLAVORED JET NONTRIVIAL ⇒ "EXPERIMENTAL" DEFINITION NOT IRC SAFE (LARGE MASS LOGS)
- LONG-STANDING OPEN PROBLEM: SOLUTIONS
  - LIMITED (IRC ONLY AT LOW ORDER)
  - IMPRACTICAL (DIFFICUL TO MERGE WITH ANTI-k_t.)
- MODERN SOLUTIONS
  - SOFT DROP FLAVOR (Caletti, Larkoski, Marzani, Reichelt, 2022)
  - FLAVORED ANTI-k_t (Czakon, Mitov, Poncelet, 2023)
  - FLAVOR DRESSING (Gauld, Huss, Stagnitto, 2023)
  - INTERLEAVED FLAVOR NEUTRALIZATION (Caola, Grabarczyk, Hitt, Salam, Sczyboz, Thaler, 2024)
- DETAILED BENCHMARKING (Behring et al, 2025) ⇒ COMPATIBLE RESULTS
- ENABLES HEAVY FLAVORED JET SUBSTRUCTURE STUDIES (Dhani, Fedkevych, Ghira, Marzani, Soyez, 2024)

JET FLAVOR POLLUTION

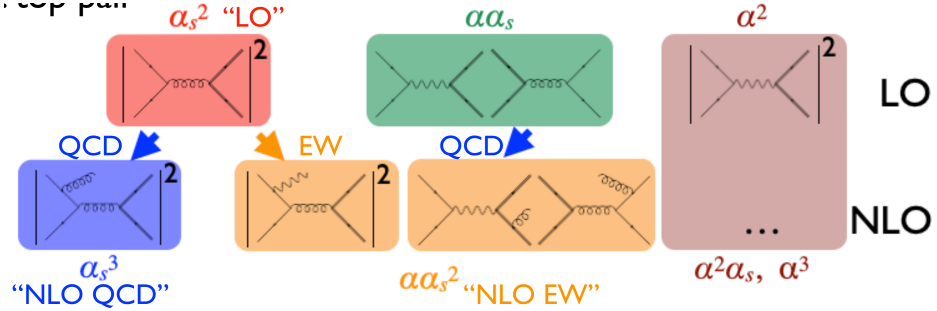


B JET p_T & m_{jet} SPECTRUM



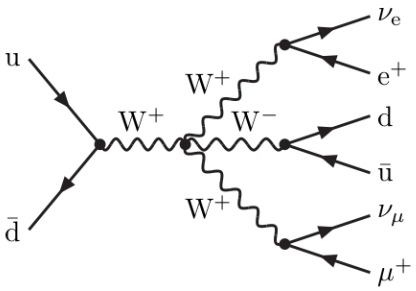
ELECTROWEAK CORRECTIONS

LHC ⇒DIS
QCD vs. EW



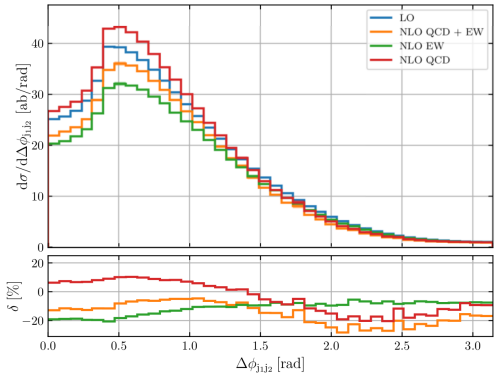
- BEYOND LO CANNOT SEPARATE QCD FROM EW
  ((Frederix, Frixione, Maltoni, Zaro et al., 2014)
- EW EFFECTS CAN BE SIZABLE

AN EXAMPLE: TRIBOSON PRODUCTION



Azimuthal-angle difference of jets for $pp \to e^+\nu_e\mu^+\mu^- jj$

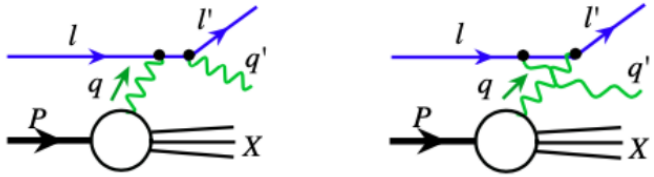
Denner, Lombardi, Lopez, Pelliccioli



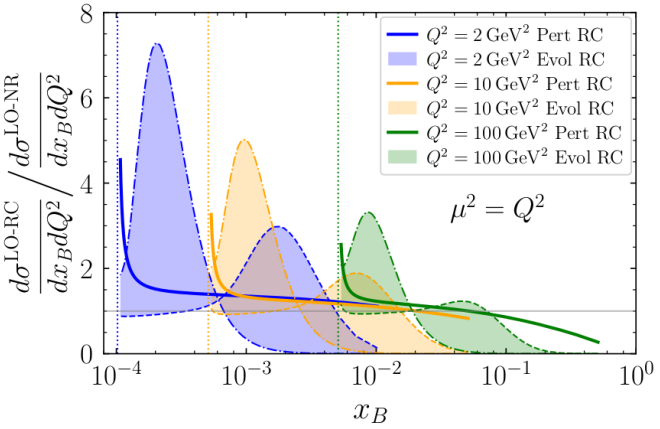
- cancellations between EW and QCD corrections
- corrections vary by 15% and 30%
- small $\Delta\phi_{j_1j_2}$ correlated to large energy of jet pair

DIS $\Rightarrow$ LHC
EW CORRECTIONS TO DIS

- RADIATIVE CORRECTIONS TO DIS $\Rightarrow$ NOW INCLUDED IN EXPT ANALYSIS
- MONTECARLOS `HECTOR, HERACLES, DJANGOH` (Bardin, Spiesberger 1995-2005)
- NLO EW FOR ν DIS AVAILABLE (Diener, Dittmaier, Hollik, 2003)
- FIRST COMPUTATION OF FACTORIZED QCD CORRECTIONS (Cammarota, Qiu, Watanabe, Zhang, 2025) $\Rightarrow$ UP TO 10-20% EIC
- NEED TO GO BEYOND STRUCTURE FUNCTIONS!



PERT. CORRECTED/UNCORRECTED (SOLID LINES)



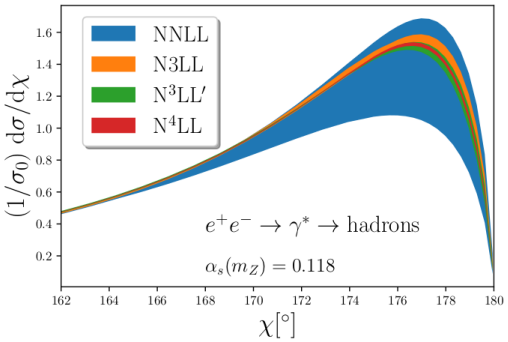
THE LIMITS OF FACTORIZATION

LHC $\Rightarrow$DIS
ENERGY CORRELATORS

Simplest example is the two-point function

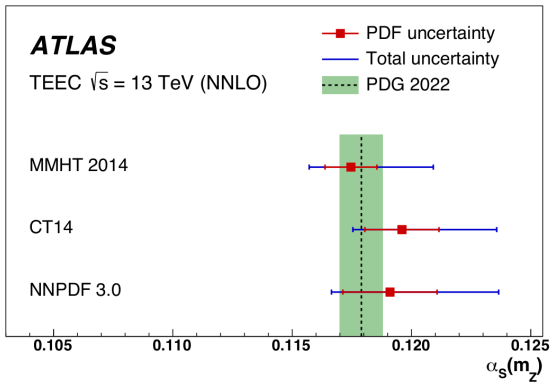
$$\mathrm{EEC}(\chi) = \sum_{a,b} \int \mathrm{d}\sigma_{e^+e^-\to a+b+X} \, \frac{E_a E_b}{Q^2} \, \delta(\cos\chi_{ab} - \cos\chi)$$

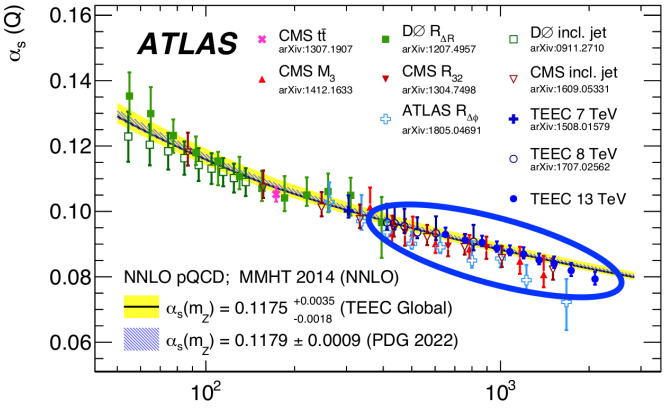
large logarithms both for small and large angles. For large angle N^{4}LL is known!



Duhr, Mistlberger, Vita '22

- e^+e^- $\Rightarrow$ FACTORIZATION AND RESUMMATION TO HIGH ORDER (Duhr, Mistlberger, Vita, 2022)
- $p-p$ $\Rightarrow$ FACTORIZATION IN TERMS OF "DETECTOR" OME (Lee, Meąj, Moult, 2025)
- JET SUBSTRUCTURE $\Rightarrow$ α_s (ATLAS 2024)
- PARISI'S IDEA (1978): $\Rightarrow$ PARTON TO HADRON TRANSITION
  $\Rightarrow$ PDF-INDEPENDENT α_s DETERMINATION



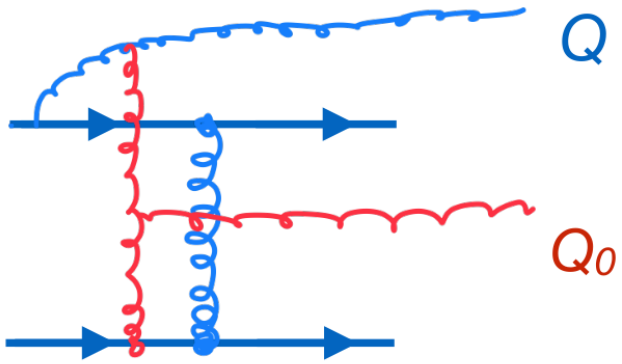


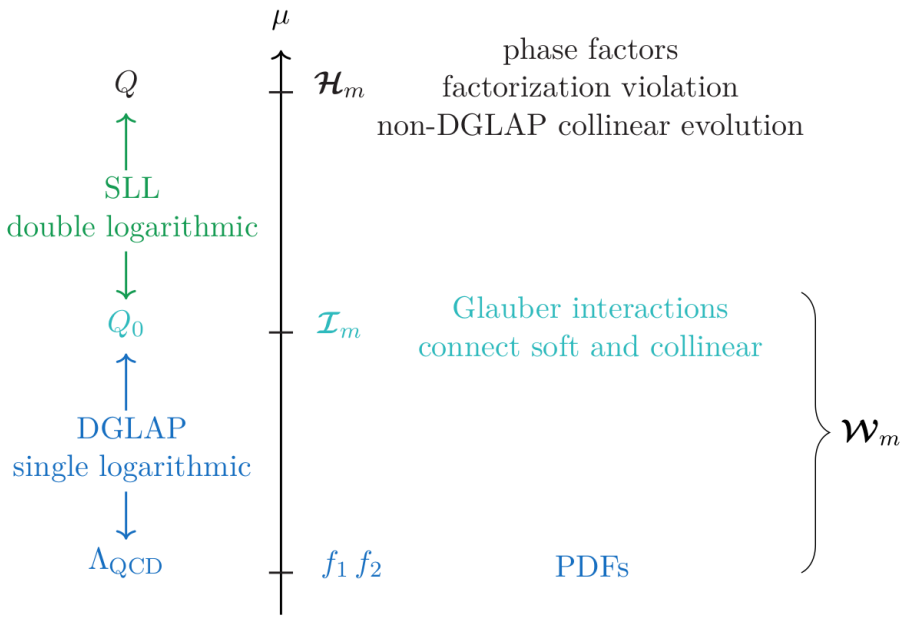
LHC $\Rightarrow$DIS

SUPERLEADING LOGS & PDF FACTORIZATION

- NON-GLOBAL OBSERVABLES: GAP BETWEEN JETS, VETO SCALE Q_0
- COLLINEAR LOGS HIGHER ORDER THAN ALTARELLI PARISI $\Rightarrow$ FACTORIZATION VIOLATION
- CANCELLED BY GLAUBER GLUONS $\Rightarrow$ ALTARELLI PARISI RESTORED
- EXPLICITLY VERIFIED AT FIXED ORDER (Becher, Hager, Jaskiewicz, Neubert, Schwienbacher, 2024-2055)

SUPERLEADING LOGS



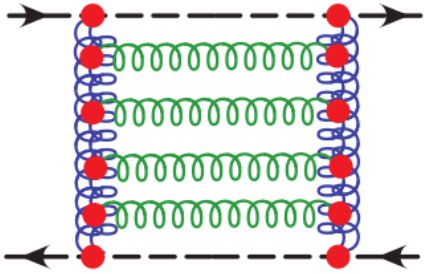


DIS $\Rightarrow$ LHC

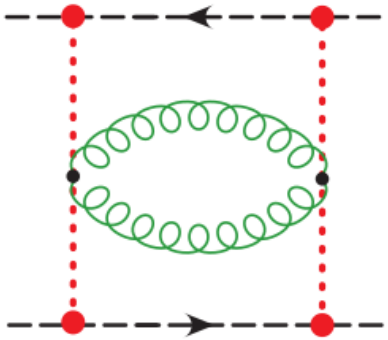
HIGH-ENERGY RESUMMATION

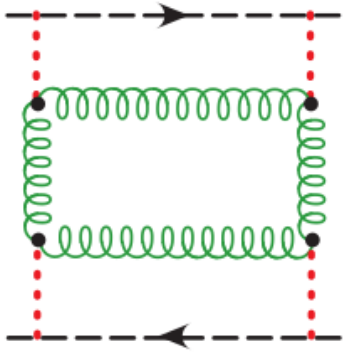
- HIGH ENERGY (BFKL, SMALL x) LOGS $\alpha \ln 1/x$, $x = \frac{M^2}{s}$
  $\Rightarrow$ PARTONIC CROSS-SECTIONS AND ANOMALOUS DIMENSIONS
- SMALL x EVOLUTION DUAL TO LARGE Q^2 EVOLUTION
- SMALL x SPLITTING FUNCTIONS $\Leftrightarrow$ HIGH ENERGY RESUMMATION OF COLLINEAR SPLITTING FUNCTIONS
- SCET APPROACH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





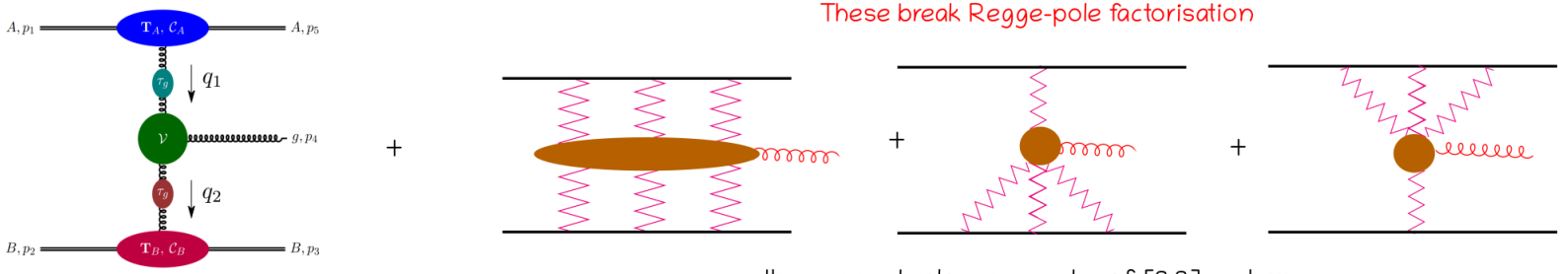
DIS $\Rightarrow$ LHC

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 $2 \to n$ AMPLITUDES
- BFKL FACTORIZATION BROKEN AT NNLO
- $2 \to 3$ 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]

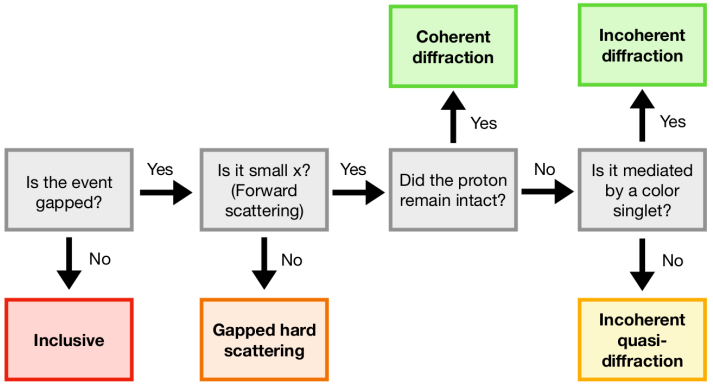
✓ 3-loop Regge-Trajectory
[Caola et al 2112.11097, Falcioni et al 2112.11098]

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

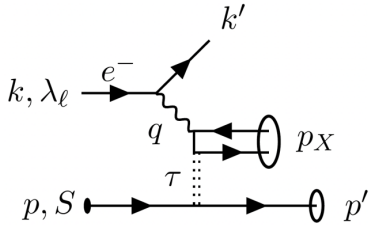
DIS $\Rightarrow$ LHC

FACTORIZATION FOR DIFFRACTIVE DIS

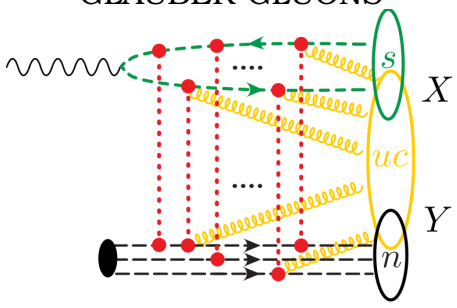
(Lee, Schindler, Stewart, 2025)



- FOUR INDEPENDENT STRUCTURE FUNCTIONS
- STUDY OF EIC KINEMATICS
- SCET FACTORIZATION IN TERMS OF BEAM (NONPERT), SOFT, ULTRASOFT (PERT) FUNCTIONS, DEF. IN TERMS OF OME

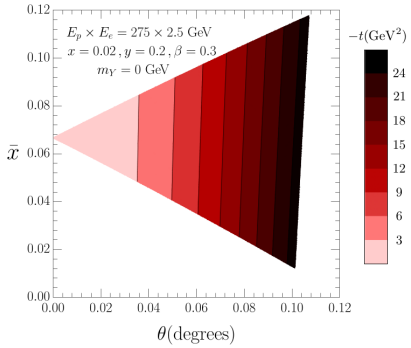


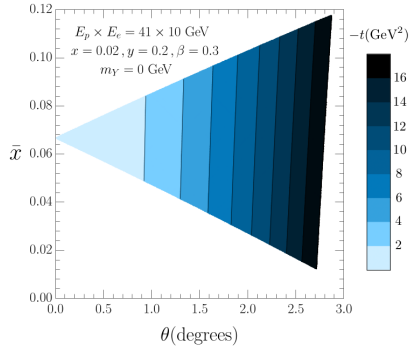
GLAUBER GLUONS



KINEMATIC REGIONS EIC

$$\bar{x} = \frac{k\cdot\tau}{k\cdot}$$





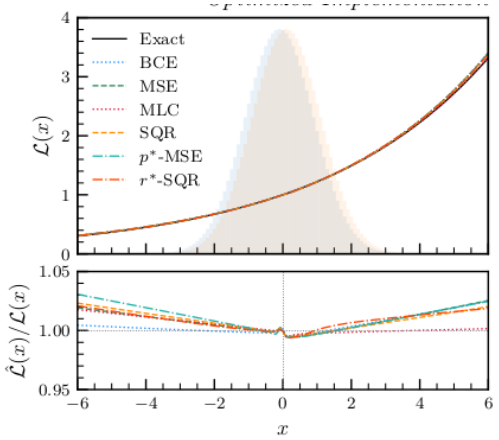
MACHINE LEARNING

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)

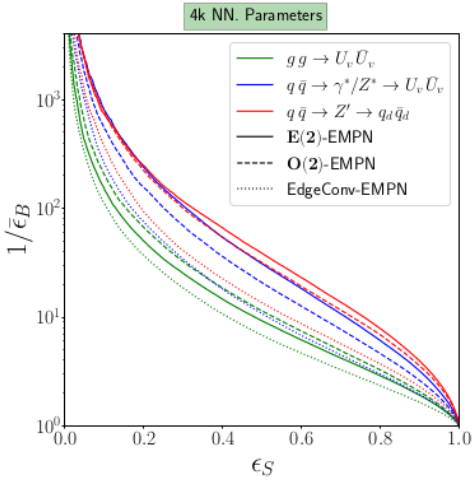
LIKELIHOOD RATIO: DISPLACED GAUSSIAN FITTED VS TRUE



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)

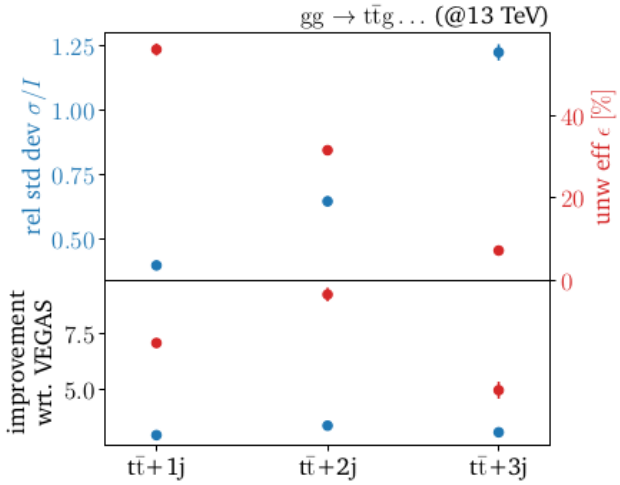
1/(FALSE POSITIVE) VS TRUE POSITIVE NEW PHYSICS SIGNALS



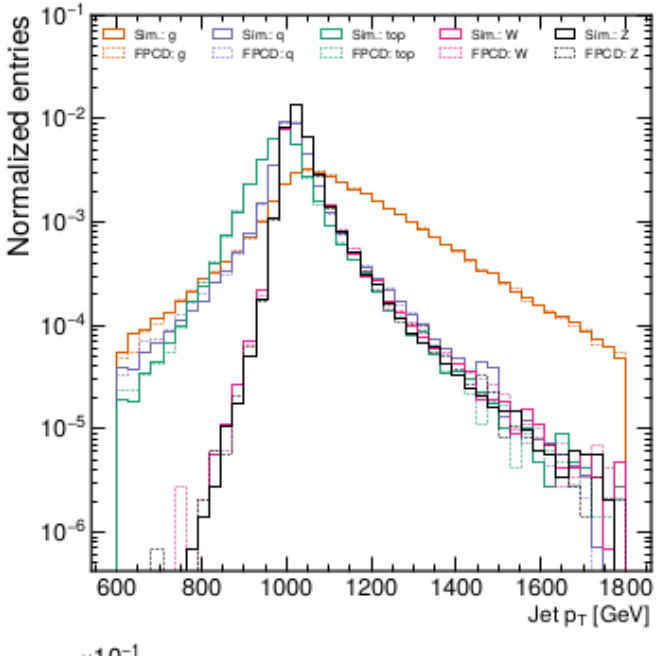
CONTEMPORARY METHODS
GENERATIVE METHODS

- 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)

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



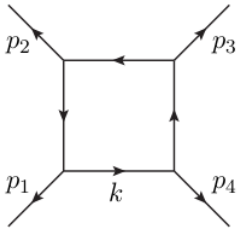
JET p_T: GENERATED VS SIMULATED



TOWARDS THE FUTURE
LEARNING FEYNMAN INTEGRALS

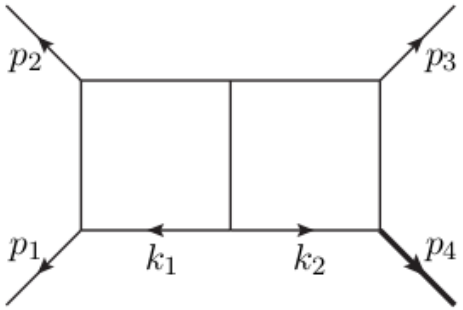
- MASSLESS BOX INTEGRAL FAMILY: $I_{\vec{a}} = \int \frac{d^d k}{i\pi^{d/2}} \frac{\mu^{4-d}}{D_1^{a_1} D_2^{a_2} D_3^{a_3} D_4^{a_4}}$
- FINITE NUMBER LIN. INDEP. $\Rightarrow$ MASTER INTEGRALS $\vec{F}(s,t,\epsilon)$
- DIFFERENTIAL EQUATIONS $\frac{\partial}{\partial s} F^i(s,t,\epsilon) = \epsilon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

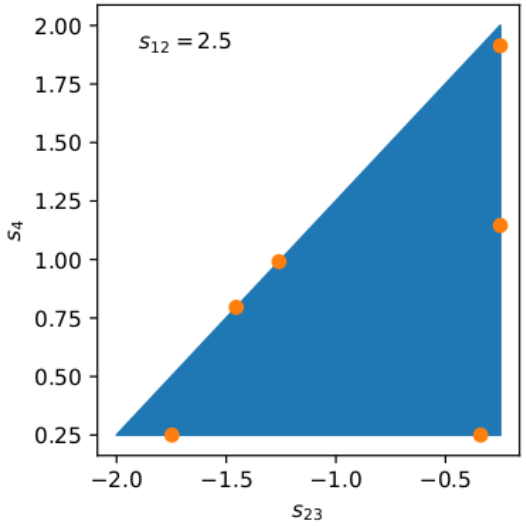


SIMILAR PROBLEM: DETERMINE PHASE OF AMPLITUDE FROM XSECT FROM OPTICAL THM $\Rightarrow$ INTEGRAL EQN (Dersy, Schwartz, Zhiboedov, 2023)

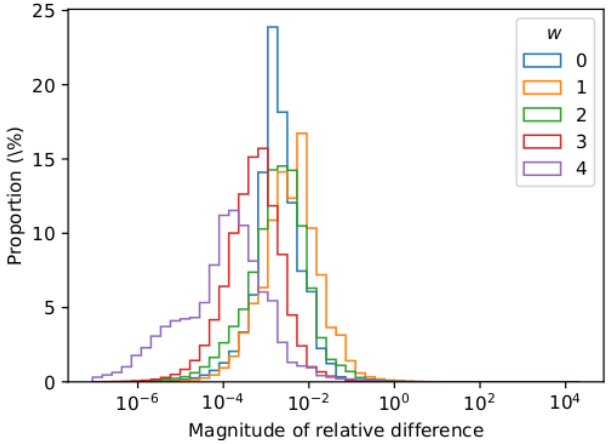
THE DOUBLE BOX



BOUNDARY POINTS



APPROX ERROR FOR DIFFERENT POWERS OF ϵ

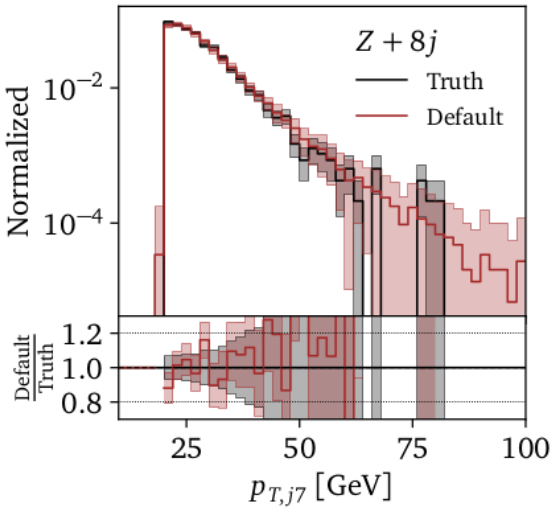


THE FUTURE?

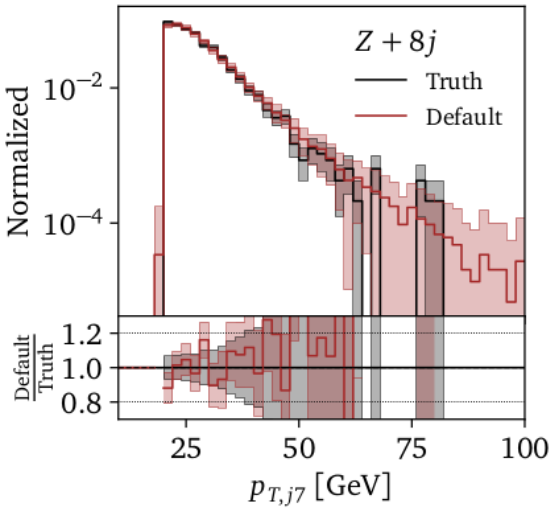
TRANSFORMERS: LEARNING AMPLITUDES

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

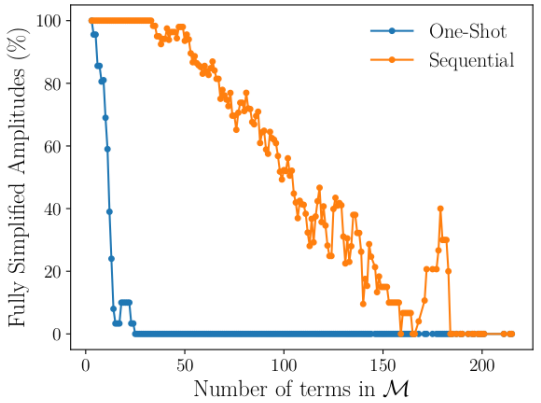
LEARNING JETS



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