SUMMARY:

QCD EVERYWHERE

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DIPARTIMENTO DI FISICA

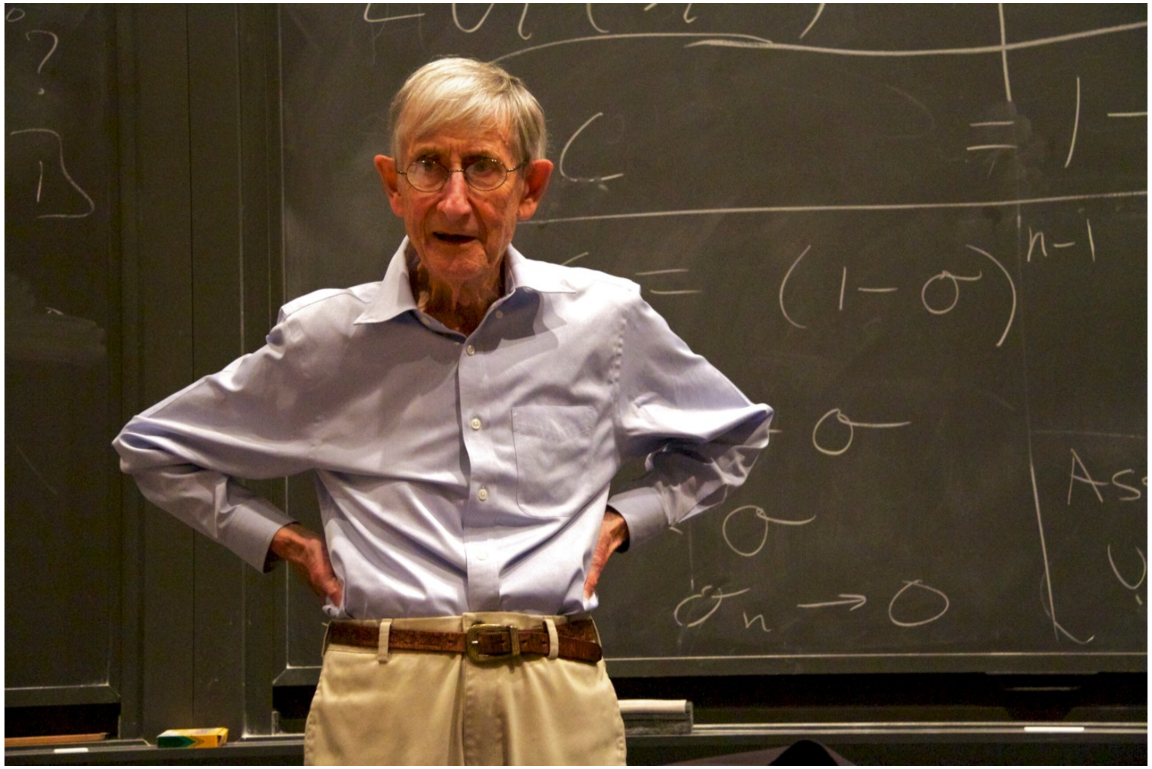
INFN
Istituto Nazionale di Fisica Nucleare

QCD@~~LHC~~ everywhere

Freiburg, 11 october 2024

A HADRON COLLIDER?

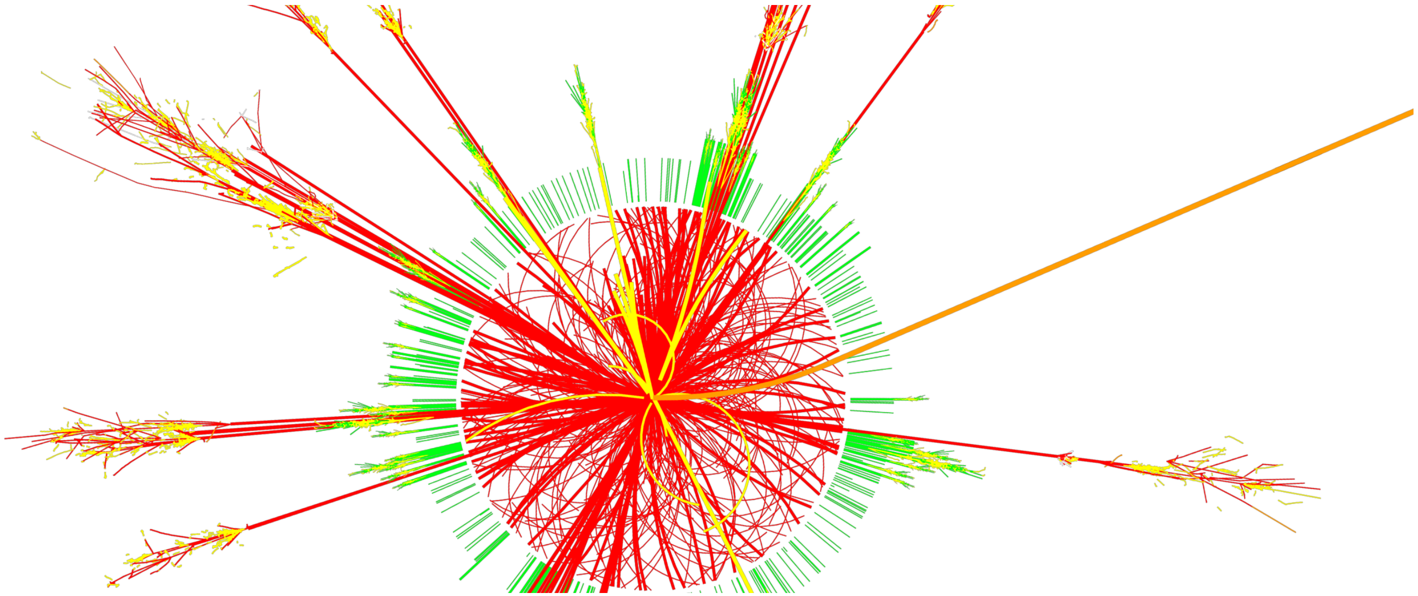
"There are two reasons to be skeptical about the importance of the LHC: one technical and one historical".



Freeman Dyson, 2008

A PRECISION HADRON COLLIDER?

"The technical weakness of the LHC arises from the nature of the collisions that it studies. These are collisions of protons with protons, and they have the unfortunate habit of being messy"



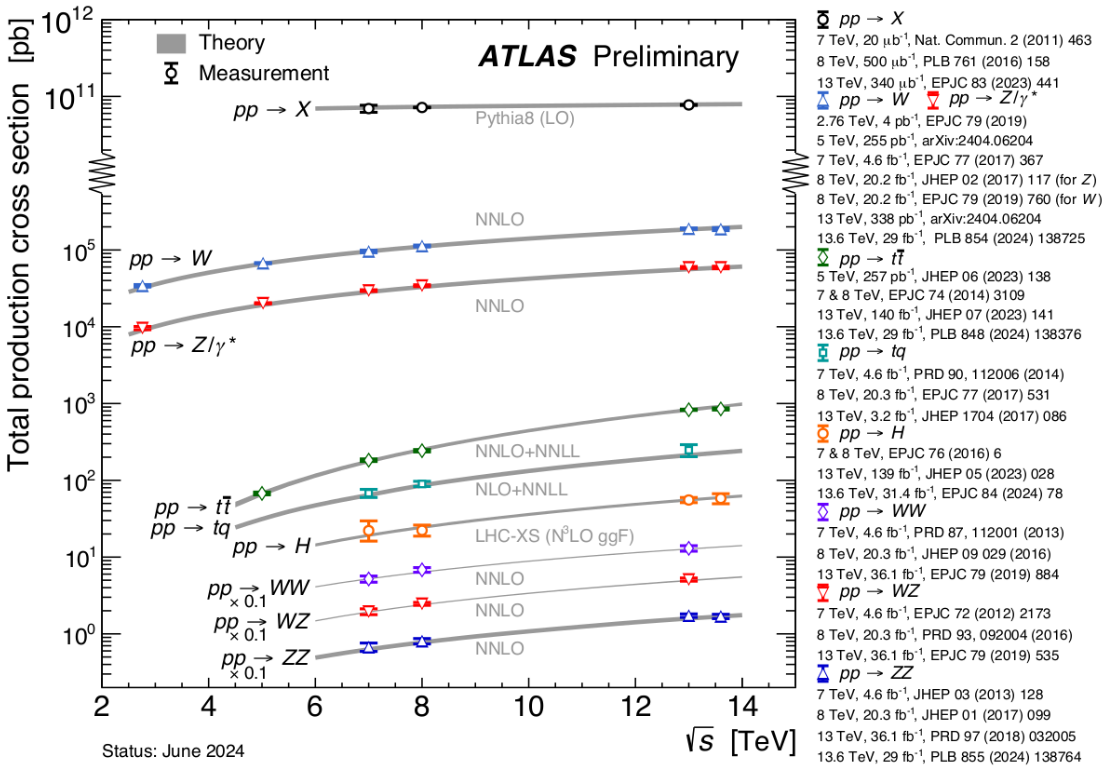
"There have been sixteen important discoveries" (in HEP) "between 1945 and 2008:
four discoveries on the energy frontier,
four on the rarity frontier,
eight on the accuracy frontier"

Freeman Dyson, 2008

A PRECISION HADRON COLLIDER!

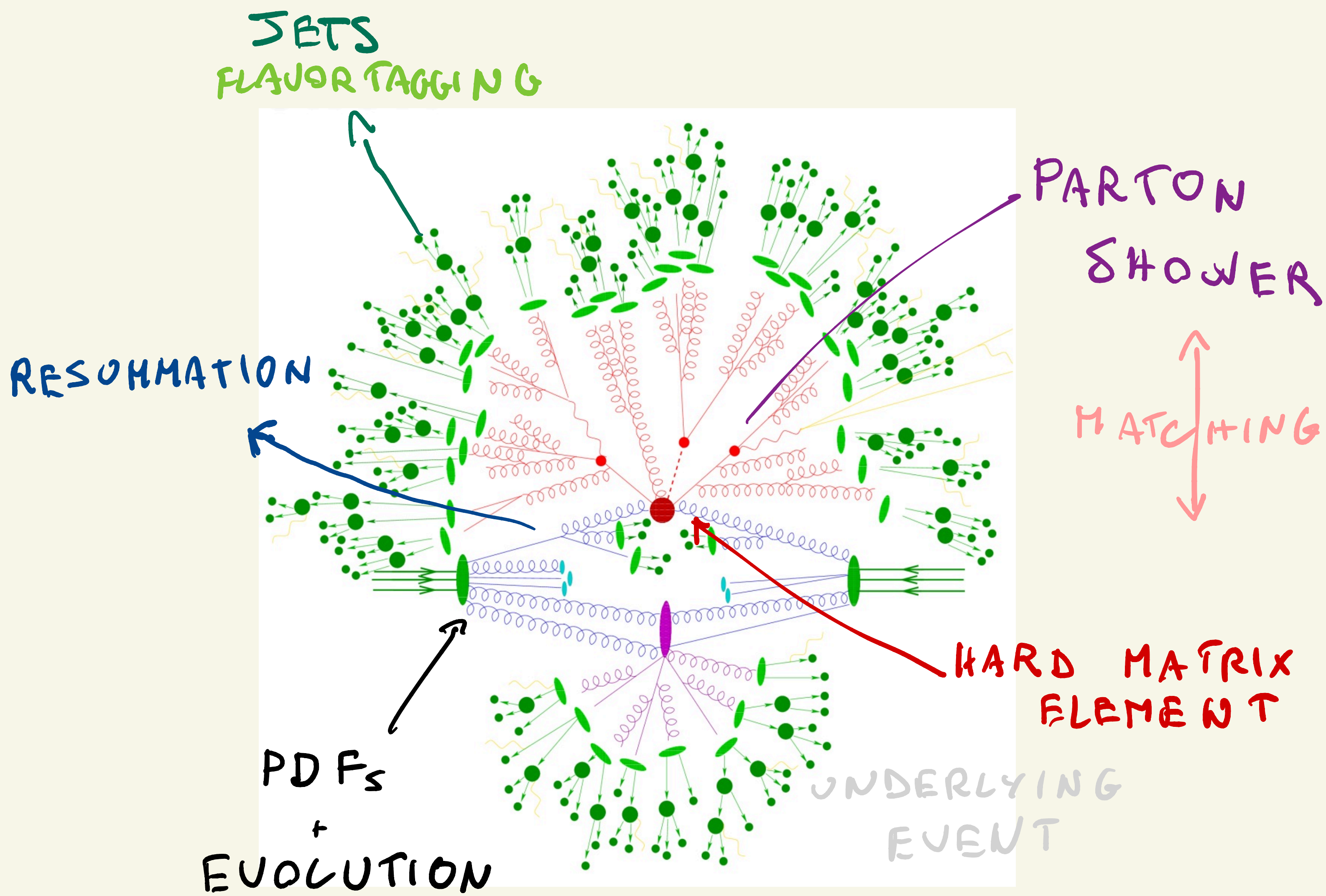
The LHC as a precision hadron collider

ATL-PHYS-PUB-2024-011

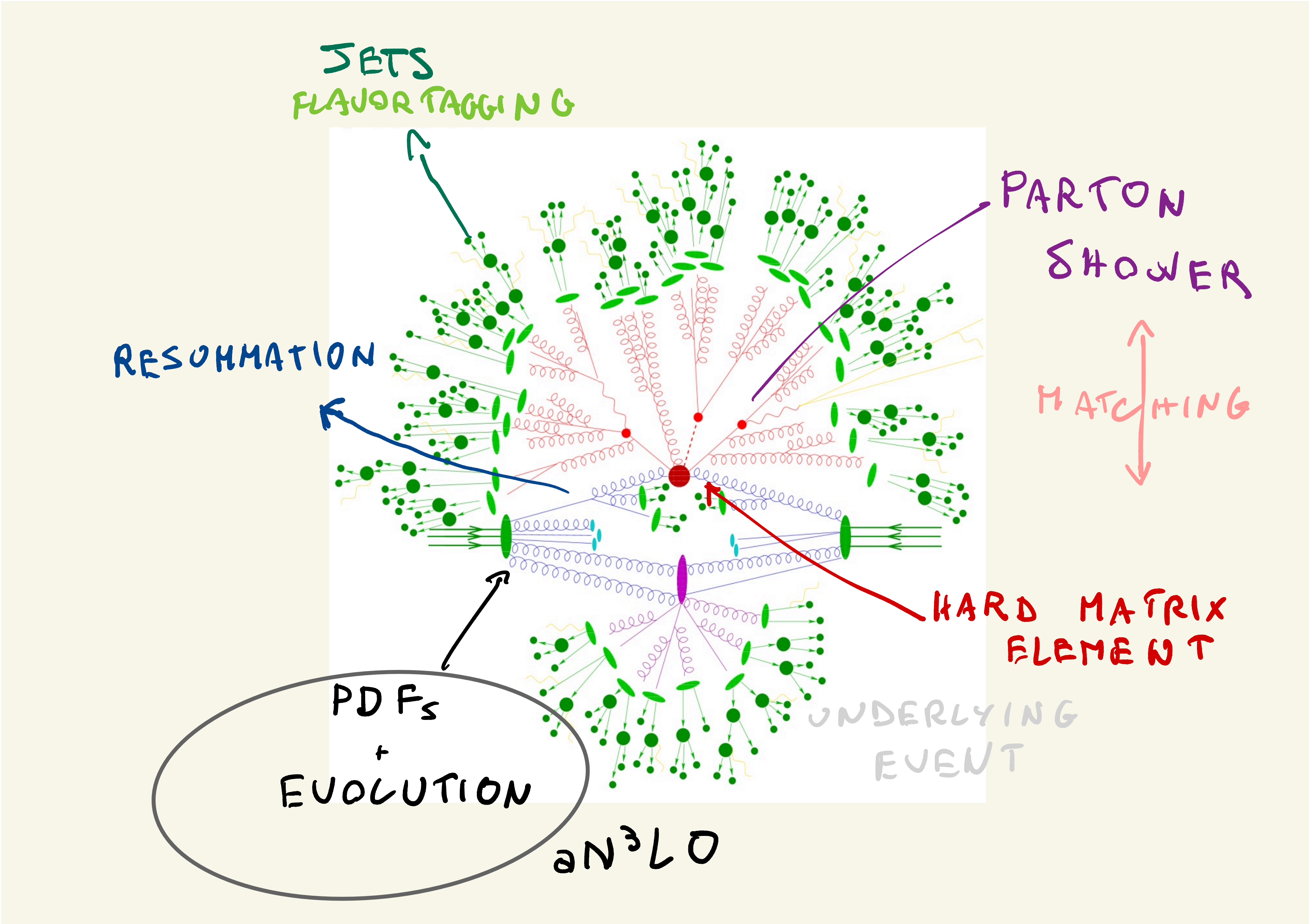


Gudrun Heinrich

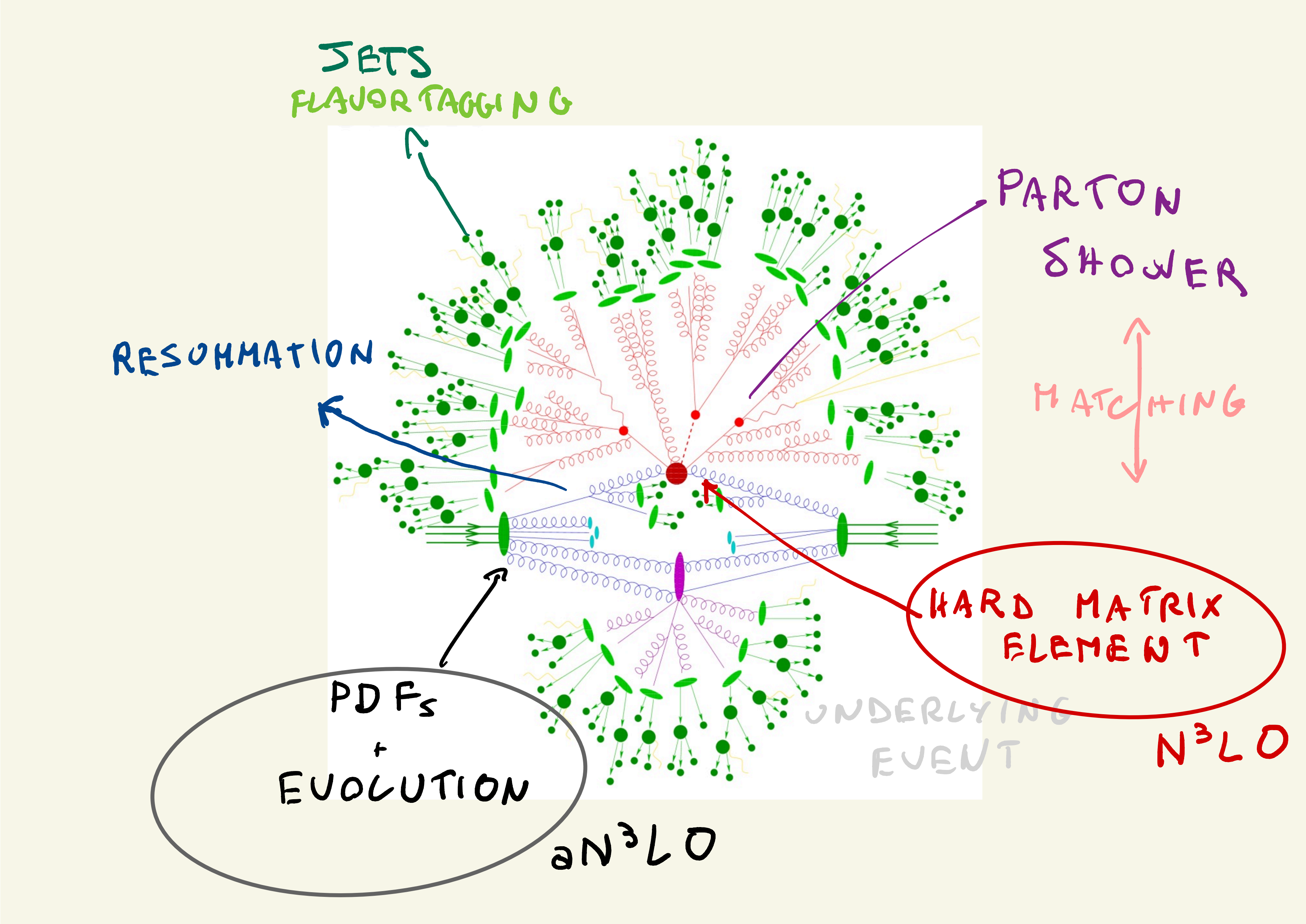
PRECISION QCD TODAY



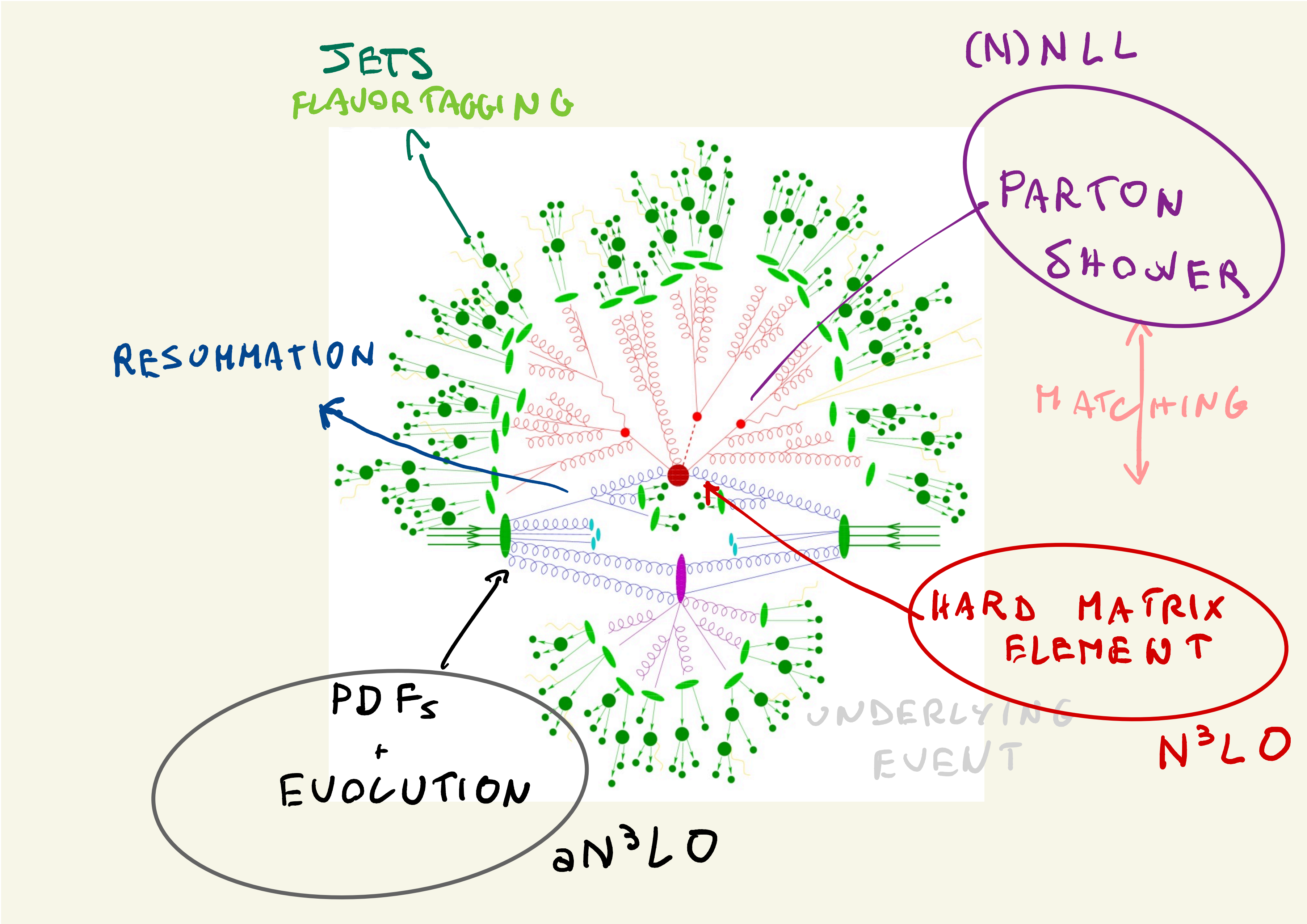
PRECISION QCD TODAY



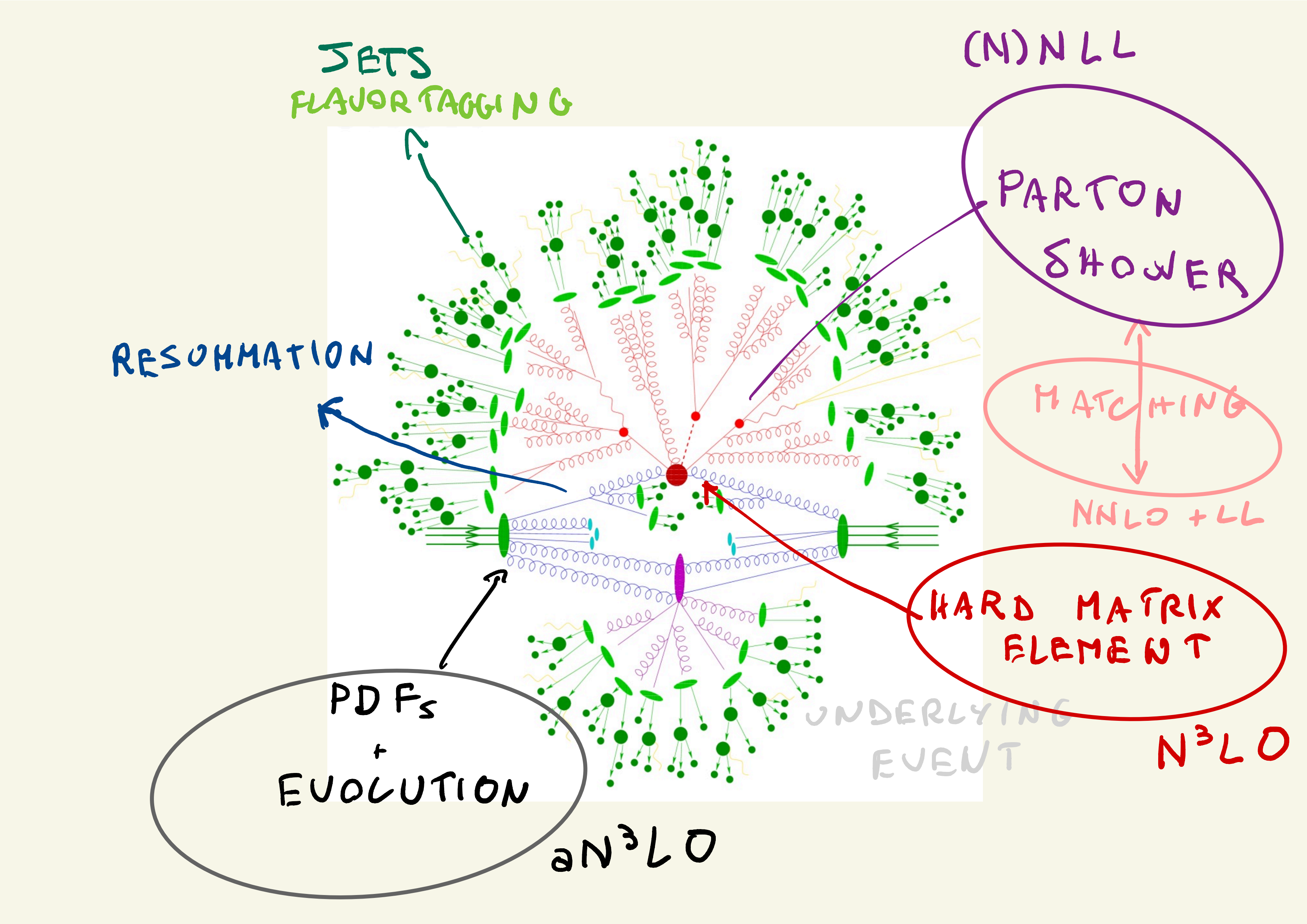
PRECISION QCD TODAY



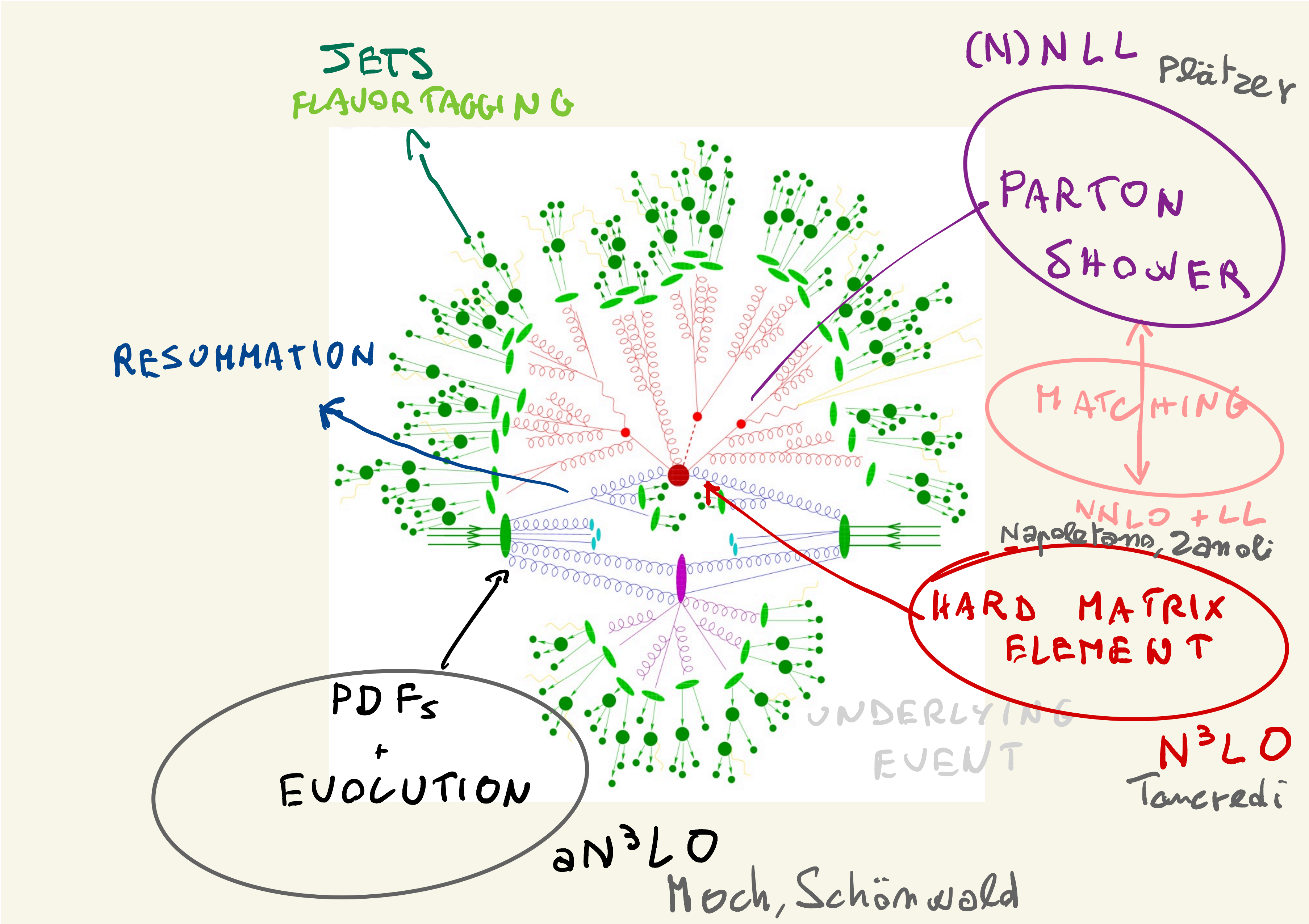
PRECISION QCD TODAY



PRECISION QCD TODAY



PRECISION QCD TODAY



THIS TALK:

- SUPRIZES, TRAPS, ISSUES
- TECHNIQUES, IDEAS, INSIGHTS
- BRIDGES

Disclaimer:

- not a review
- certainly not exhaustive
- names in slides refer to talks at this confetence and are NOT attributions of original authorship

STEFANO CATANI (1958-2024)

''We don't just want to make predictions; we want to quantify uncertainties''

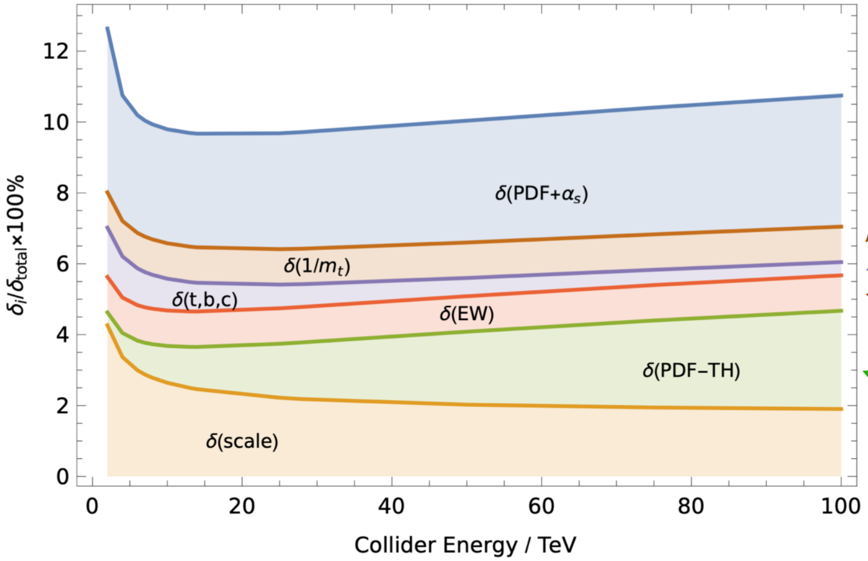
Steffen Schumann

α_s AND ITS UNCERTAINTY

HIGGS IN GLUON FUSION: UNCERTAINTIES

Higgs production in gluon fusion

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



- $\delta(\mathrm{PDF}+\alpha_s)$: see PDF sessions and talk by Valentina Guglielmi
- $\delta(1/m_t)$: basically removed (NNLO with full top mass) Czakon, Harlander, Klappert, Niggetiedt '20
- $\delta(\mathrm{t,b,c})$: t-b interference at NNLO calculated recently Czakon, Eschment, Niggetiedt, Poncelet, Schellenberger '23, '24
- $\delta(\mathrm{EW})$: reduced to 0.6% Bechetti et al '20, '21, Bonetti et al '18, '20, '22
- $\delta(\mathrm{PDF-TH})$: mismatch between PDF (NNLO) and ME (N3LO) towards N3LO PDFs: MSHT 2207.04739, NNPDF4.0 2402.18635, Cooper-Sarkar et al. 2406.16188, Falcioni et al 2302.07593, Guan et al. 2408.03019, Gehrmann, Manteuffel, Sotnikov, Yang '23, '24
- $\delta(\mathrm{scale})$: N4LO soft-virtual approx. Das, Moch, Vogt '20; 4-loop form factor Lee, Manteuffel, Schabinger, Smirnov, Smirnov Steinhauser '22,'23

7 QCD@LHC — Precision calculations in the Higgs sector — Gudrun Heinrich

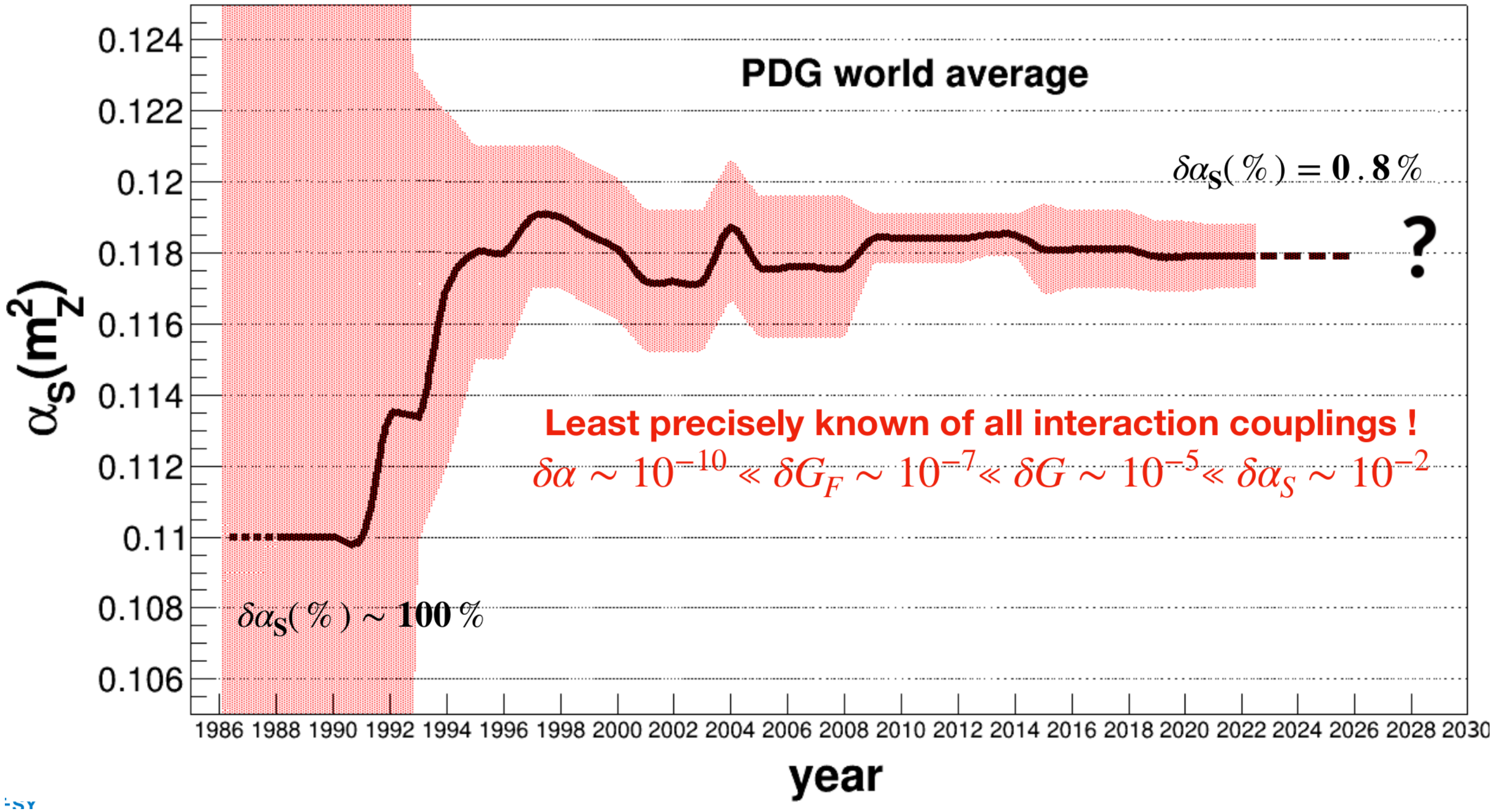
G. Heinrich

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

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

DO WE KNOW THE α_s UNCERTAINTY?

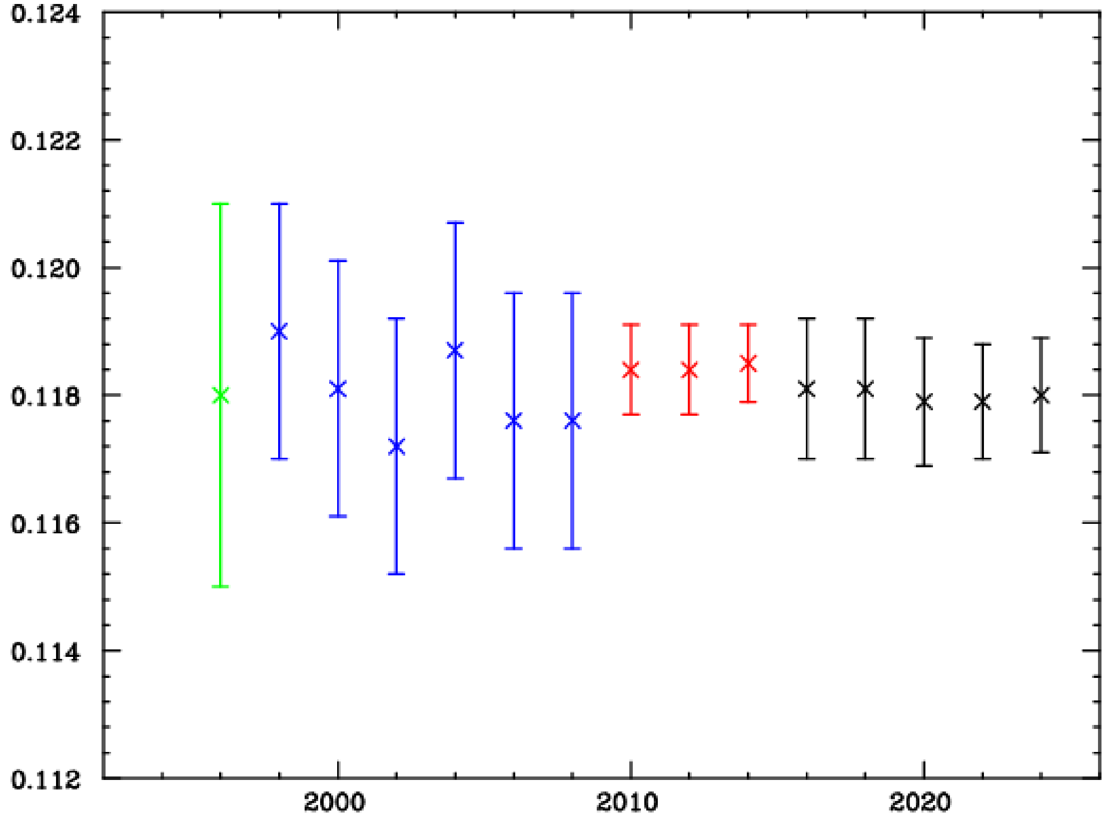
A SUBJECTIVE UNCERTAINTY ESTIMATE



V. Guglielmi

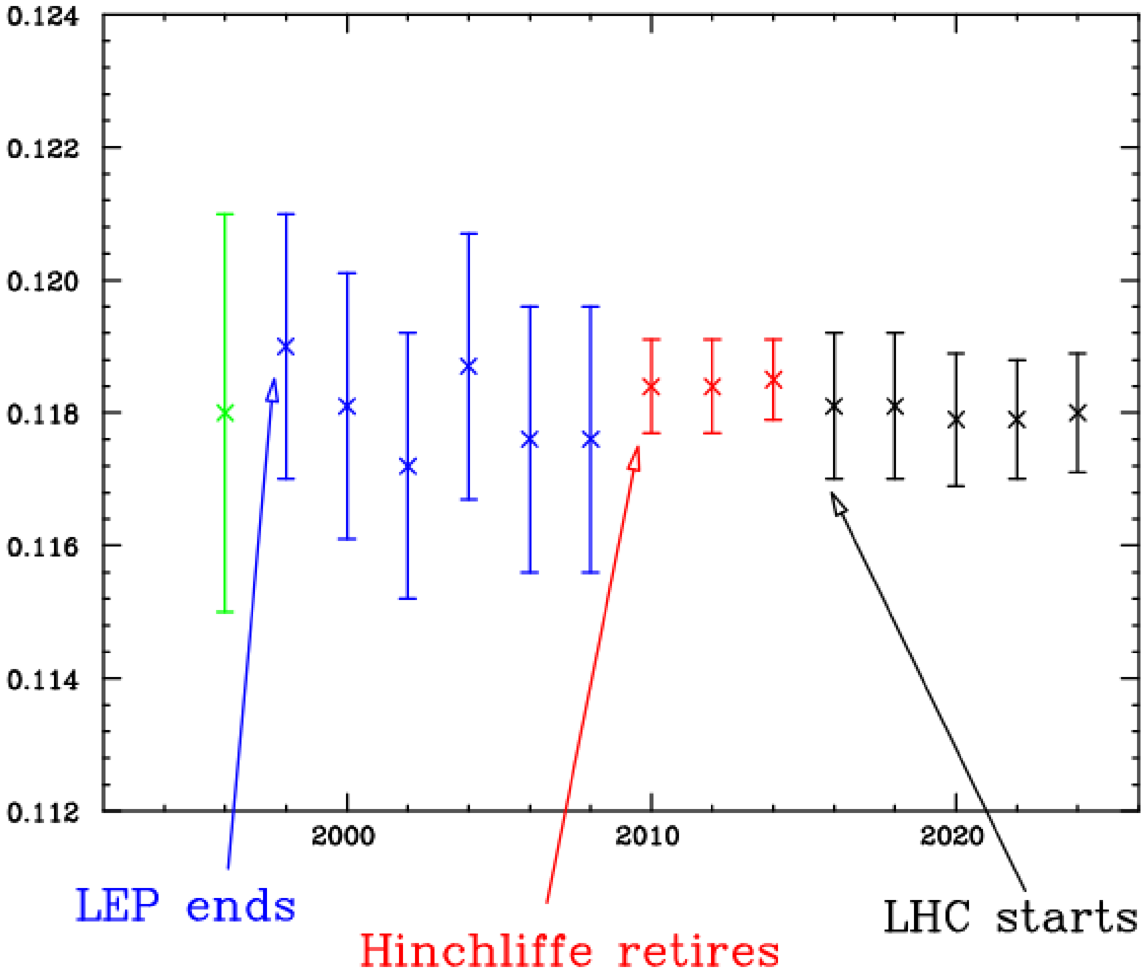
DO WE KNOW THE α_s UNCERTAINTY?

THE PDG VALUE OVER TIME



DO WE KNOW THE α_s UNCERTAINTY?

THE PDG VALUE OVER TIME



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

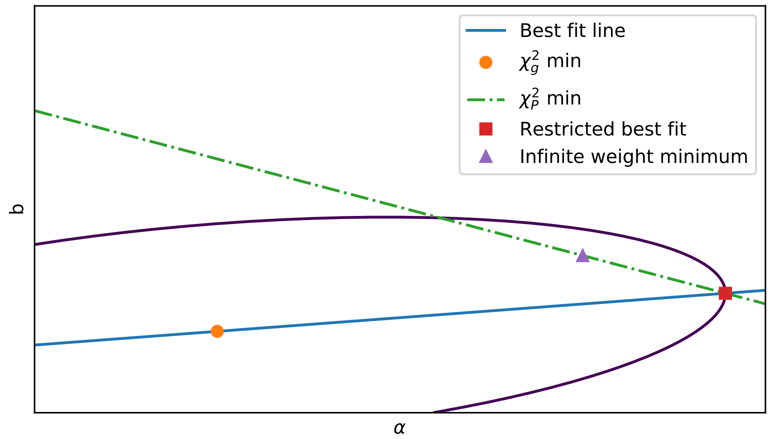
THE PDF CORRELATION TRAP

Two methods to compare σ(exp) to σ(pQCD):

- **Profiling α_S using varying PDF+α_S** (predefined PDF from global PDF)
- **Simultaneous fit of α_S and PDFs**
  - Correlation between PDFs and α_S took into account
  - Reduced bias
  - BUT time consuming

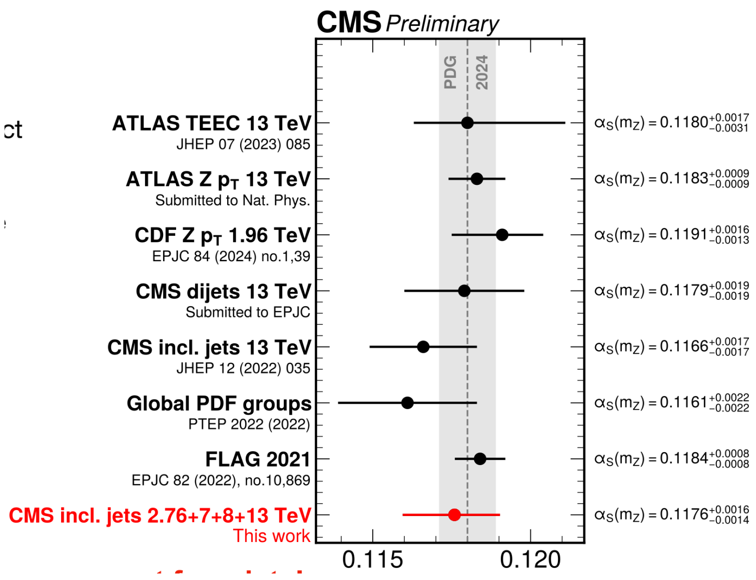
V. Guglielmi

- PROFILING MOVES ALONG A LINE IN PDF SPACE
- MISSES TRUE MINIMUM



SF, Kassabov, 2020

THE α_s COMBINATION TRAP



V. Guglielmi

- CAN A COMBINATION HAVE A LARGER UNCERTAINTY THAN WHAT ENTERS IT?
- GRESHAM'S LAW OF PDFs: THE SMALLEST UNCERTANTY WINS
- A COMMUNITY EFFORT NEEDED SIMILAR TO FLAG FOR LATTICE

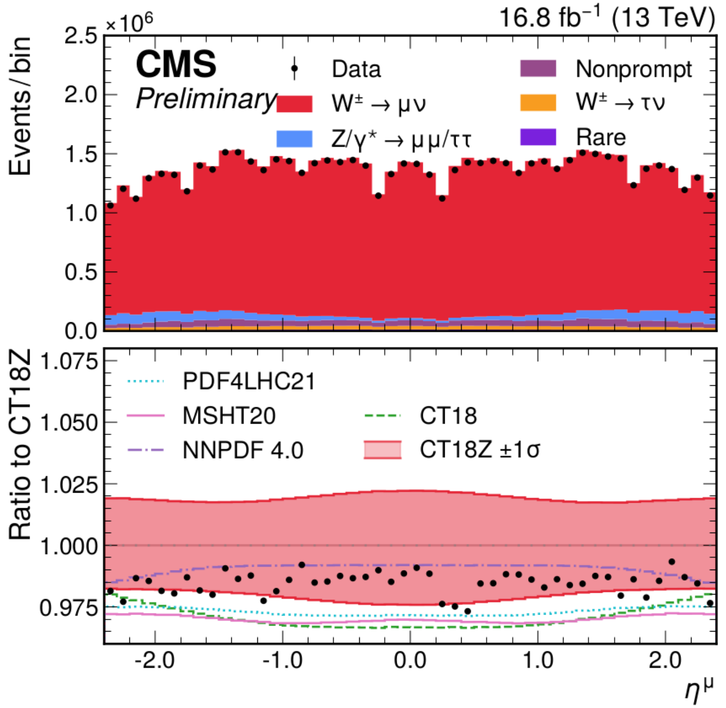
THE PDF CORRELATION TRAP

WHAT ABOUT M_W?

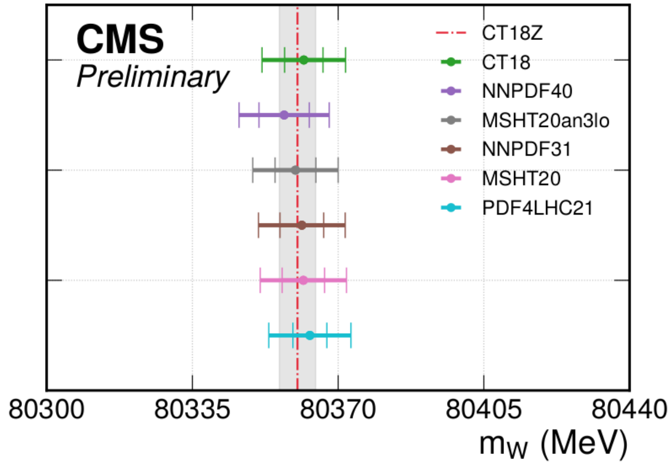
W mass at CMS ($\pm$9.9 MeV): PDF treatment

CMS PAS-SMP

- CT18Z as default PDF, profiling the eigenvectors $\rightarrow \pm$4.4 MeV
- Derive scale factors to cover m_W extracted with all other PDF sets



PDF set	Scale factor	Impact in m_W (MeV) Original σ_{PDF}	Scaled σ_{PDF}
CT18Z	–	4.4	
CT18	–	4.6	
PDF4LHC21	–	4.1	
MSHT20	1.5	4.3	5.1
MSHT20aN3LO	1.5	4.2	4.9
NNPDF3.1	3.0	3.2	5.3
NNPDF4.0	5.0	2.4	6.0



- Very good consistency between PDF sets even before scaling, owed to η^μ
- Difference CT18 vs NNPDF4.0 reduced from 5 MeV to 3 MeV

M. Seidel

TECHNICAL DETAILS

GUDRUN HEINRICH

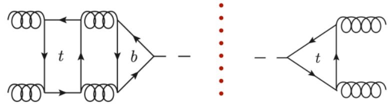
`‘‘ I am not a model bulider,`
`I am a technician’’`

- HEAVY QUARKS
- OFF-SHELL VS. NARROW WIDTH

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]	$(\sigma_t - \sigma_{\mathrm{HEFT}})$ [pb]	$\sigma_{t\times b}$ [pb]	$\sigma_{t\times b}/\sigma_{\mathrm{HEFT}}$ [%]
		$\sqrt{s} = 13$ 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

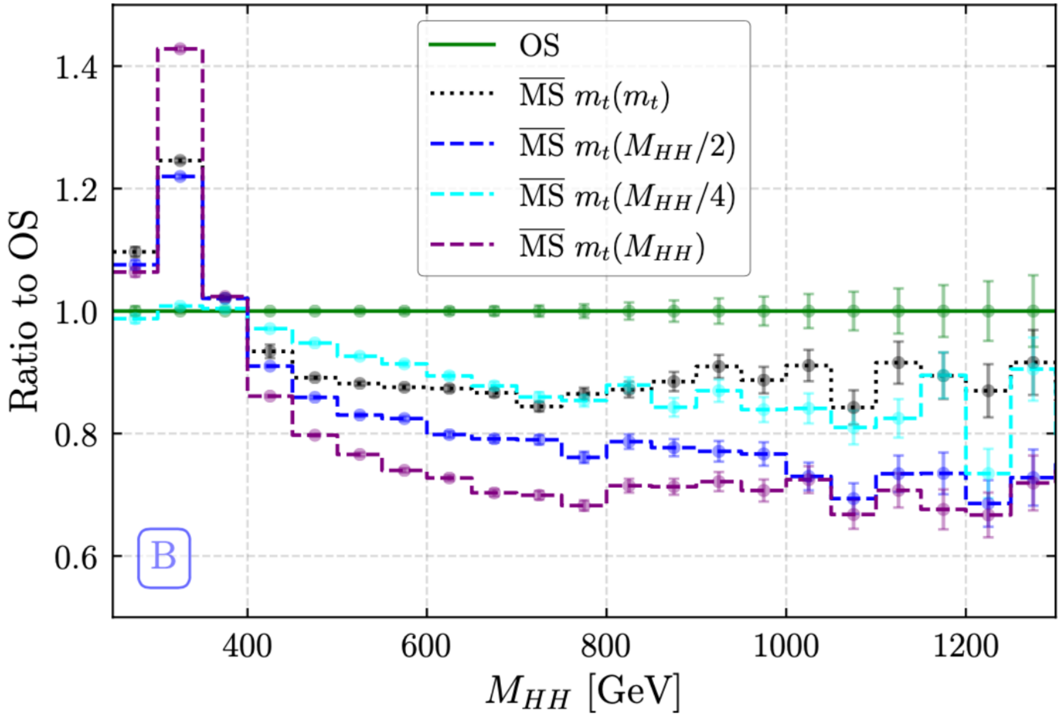
G. Heinrich

…REMEMBER YR4

bottom and charm interference correction changes by 0.7 pb if $\overline{\mathrm{MS}}$ or pole heavy quark masses are used.
The **F-uncertainty** is estimated as $\Delta_{t,bc} = \pm 0.4$ 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 $\Delta_{t,bc} = \pm 0.7$ pb, i.e. a relative uncertainty of $\pm 1.5\%$.

DOUBLE HIGGS PRODUCTION:

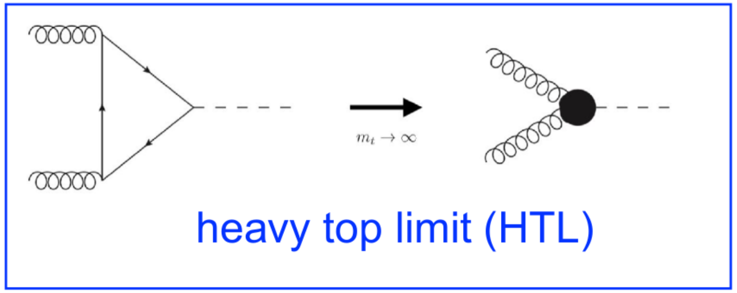
TOP MASS DEPENDENCE



Bagnaschi, Degrassi, Gröber 2309.10525

PDF + α_s uncertainties ~ 2.3%

top mass scheme uncertainty currently largest uncertainty in Higgs boson pair production



- TOP MASS $\Rightarrow$ SETS SCALE OF FORM FACTOR
- $\overline{\text{MS}}$ VS POLE UP TO 20%, MASS VALUE FEW %

G. Heinrich

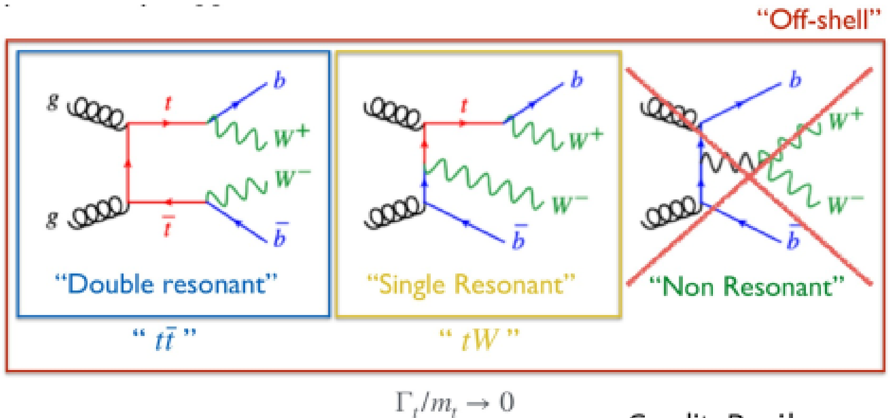
OFF-SHELL EFFECTS IN TOP PAIR PRODUCTION

NLO off-shell

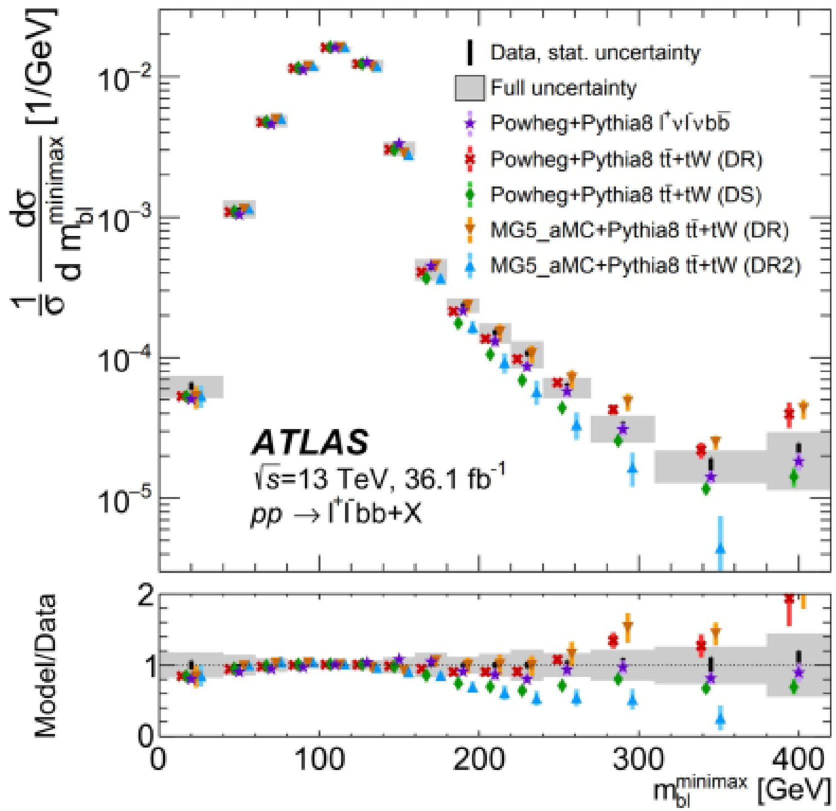
[Bevilacqua, Czakon, Van Hameren, Papadopoulos, Worek '11; Denner, Dittmaier, Kallweit, Pozzorini '11,'12; Cascioli, Kallweit, Maierhöfer, Pozzorini '14 Denner, Pellen '18]

NLO off-shell ⊕ PS

[Jezo, Lindert, Nason, Oleari, Pozzorini '16; Jezo, Lindert, Pozzorini '23]



Credit: Bevilacqua



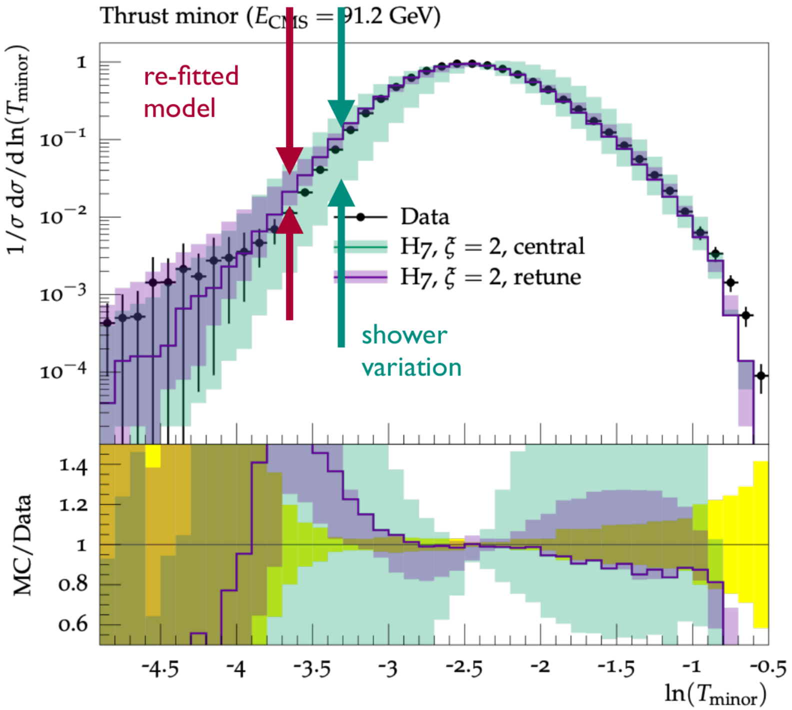
R. Poncelet

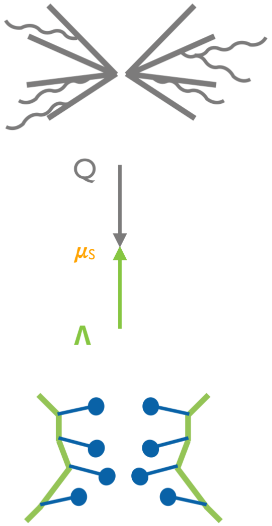
INTERFERENCE WITH IRREDUCIBLE BACKGROUND NEEDED FOR PHENO

HADRONIZATION

‘‘ We should be talking about algorithms, not models’’

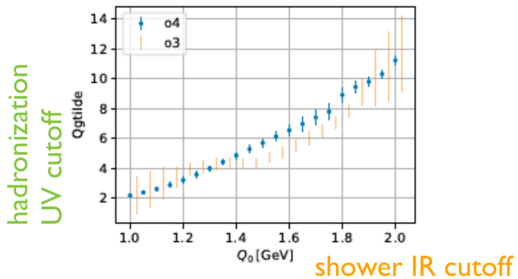
Simon Plätzer





Leads to constructive prescription for “high energy” end of hadronization.

First steps demonstrated:



Lower energy dynamics in the model not sensitive to cutoff anymore.

S. Plätzer

- LARGE DIFFERENCES BETWEEN HADRONIZATION MODELS
- USE SCALE MATCHING TO CONSTRAIN HADRONIZATION

QCD vs EW

Ansgar Denner

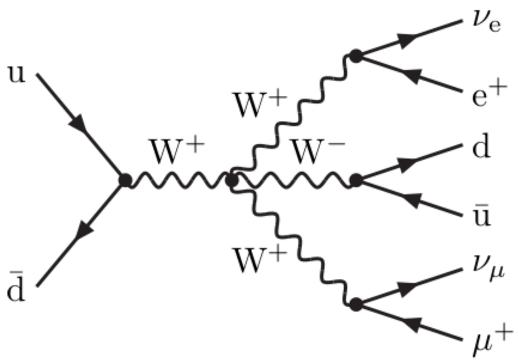
`‘‘ The separation between QCD and EW is not well defined beyond LO’’`

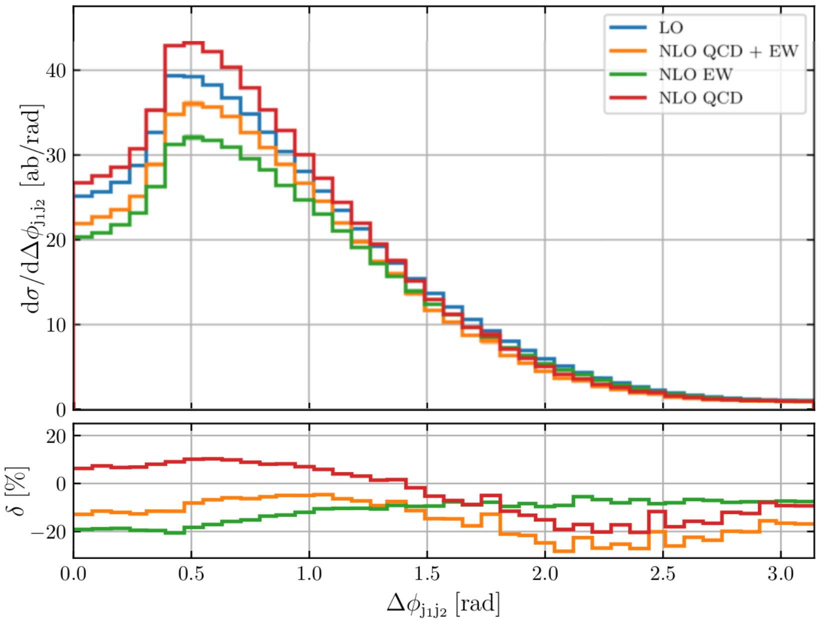
- CANCELLATION AND INTERFERENCE WITH MULTIPARTICLE FINAL STATES
- THE PHOTON PDF AND HIGGS

TRIBOSON PRODUCTION

Azimuthal-angle difference of jets for $\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\mu^+\mu^-\mathrm{jj}$

Denner, Lombardi, Lopez, Pellicciolі

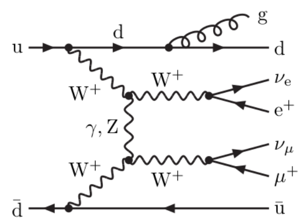




- cancellations between EW and QCD corrections
- corrections vary by 15% and 30%
- small $\Delta\phi_{\mathrm{j_1 j_2}}$ correlated to large energy of jet pair

on-shell contr. 3% 4%

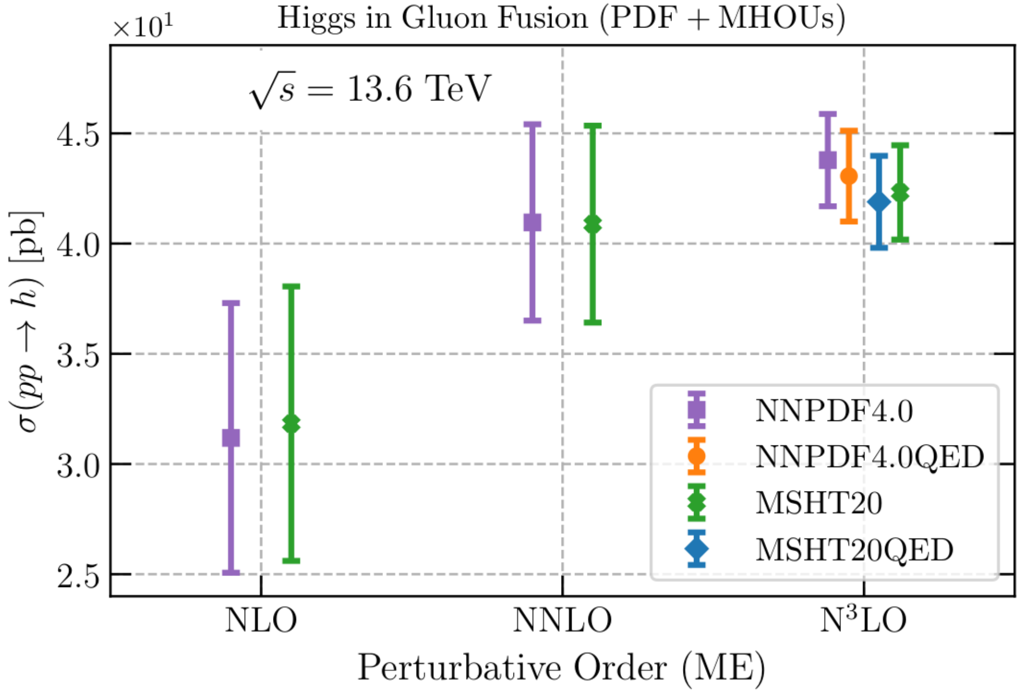
- large NLO contribution of VBS
  owing to events where radiated gluon plays role
  of leading jet evading $M_{\mathrm{jj}} < 160\,\mathrm{GeV}$ cut



- no QCD corrections to decays included in on-shell calculations

THE PHOTON PDF

HIGGS IN GLUON FUSION



R. Stegeman

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

``We must think how to use calculations in a clever way ''

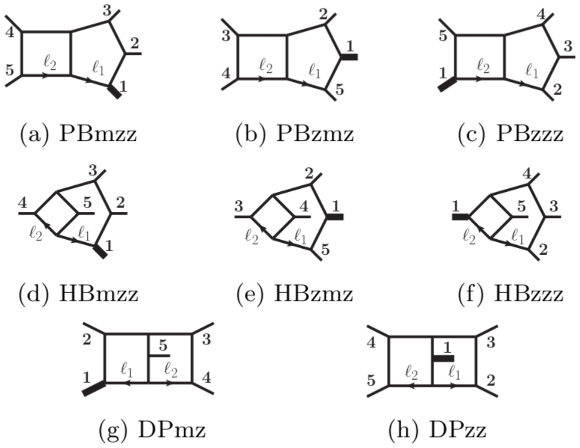
Lorenzo

Tancredi

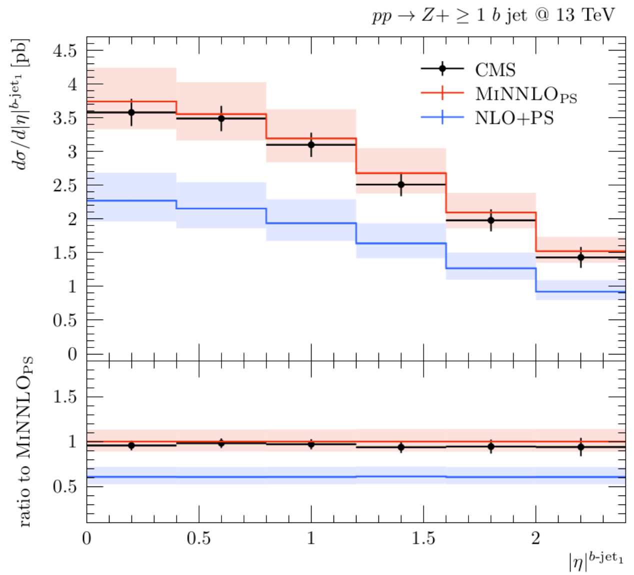
THE COMPLEXITY FRONTIER

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

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!

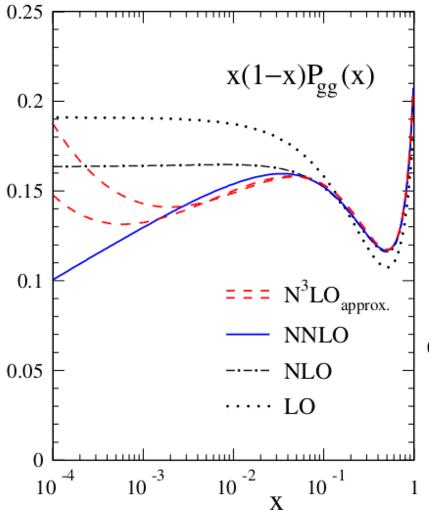
RESUMMATION AND SCALES

THOMAS BECHER

`‘‘ Resummation is about treating the soft and collinear regions’’`

- N^3LO EVOLUTION
- NNLO BFKL
- COLLINEAR VS. PDF FACTORIZATION
- SUPERLEADING LOGS

N^3LO PERTURBATIVE EVOLUTION!



- MELLIN MOMENTS UP YO $N = 20$ KNOWN FOR ALL SPLITTING FUNCTIONS
- ACCURATE APPROXIMATIONS COMBINING WITH SMALL AND LARGE x RESUMMATION $\Rightarrow$ UNCERTAINTY NEGLIGIBLE EXCEPT AT SMALL x
- FIRST ANALYTIC INSIGHT

- Reconstruction of analytic all-N expressions for ζ_5 terms from solution of Diophantine equations
  - example for $\gamma_{\rm gg}^{(3)}$ with $\eta = \frac{1}{N} - \frac{1}{N+1}$ and $\nu = \frac{1}{N-1} - \frac{1}{N+2}$

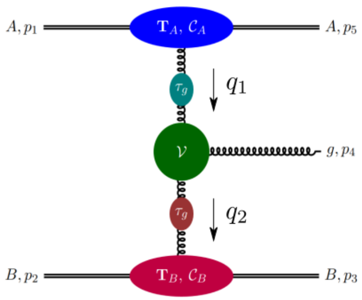
$$\gamma_{\rm gg}^{(3)}(N)\Big|_{\zeta_5\, d_{AA}^{(4)}/n_A} = \frac{64}{3}\Big(30\,(12\,\eta^2 - 4\,\nu^2 - S_1(4\,S_1 + 8\,\eta - 8\,\nu - 11) - 7\nu) + 188\,\eta - \frac{751}{3} - \frac{1}{6}\,N\,(N+1)\Big)$$

S. Moch

TOWARDS NNLO BFKL

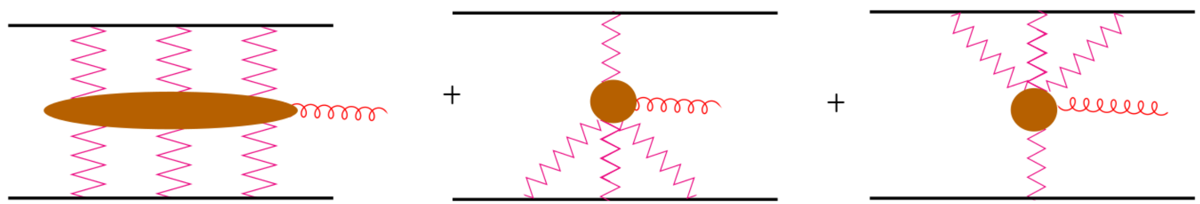
Regge-pole factorisation broken at NNLL for A(-,-):

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



+

These break Regge-pole factorisation



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

- SMALL x SPLITTING FUNCTIONS $\Leftrightarrow$ HIGH ENERGY RESUMMATION OF COLLINEAR SPLITTING FUNCTIONS
- BFKL FACTORIZATION BROKEN AT NNLO
- RESTORED IN COLLINEAR LIMIT BY MULTIGLUON EXCHANGES

COLLINEAR VS PDF FACTORIZATION

Collinear factorization breaking at $\mu = Q$

X

soft-collinear factorization breaking by Glauber modes at $\mu = Q_0$

=

PDF factorization for $\mu < Q_0$

"factorization restoration"

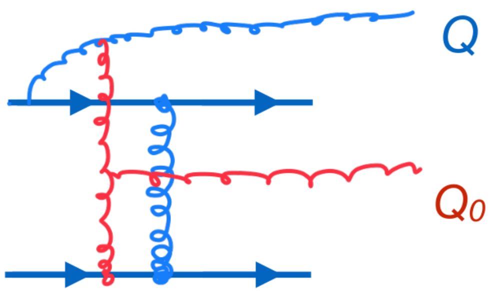
TB, Hager, Jaskiewicz, Neubert, Schwienbacher '24

T. Becher

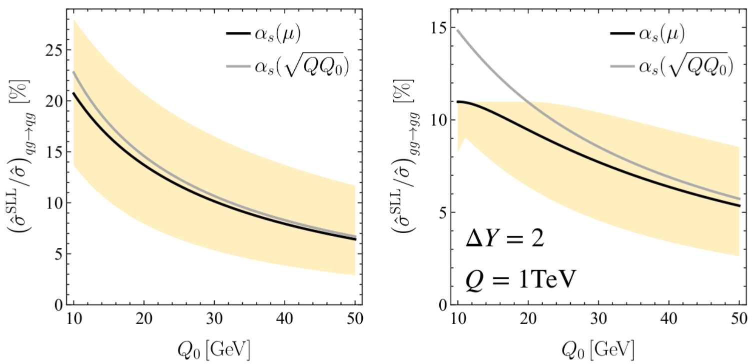
- COLLINEAR FACTORIZATION BROKEN BY INITIAL-STATE SPACELIKE SPLITTING (Catani 2011)
- DOUBLE NON-UNIVERSAL SUPERLEADING (HIGHER THAN ALTARELLI-PARISI) LOGS
- CANCELLED BY GLAUBER GLUONS
- PDF REMAINS UNIVERSAL (PDF FACTORIZATION)

SUPERLEADING LOGS

- COLLINEAR FACTORIZATION VIOLATION ⇒ HIGHER THAN ALTARELLI PARISI
- RESUMMATION
- PDF FACTORIZATION RESTORATION VERIFIED AT FIXED ORDER



First resummations for SLLs



Super-leading logs (SLLs)

- Glauber phases spoil collinear cancellations

Small effects for $pp \to Z/H$, $pp \to Z/H + j$, but sizable for dijet production TB, Neubert, Shao '21 + Stillger '23

T. Becher

HEAVY QUARKS

``The biggest challenge is two loops with masses''

René Poncelet

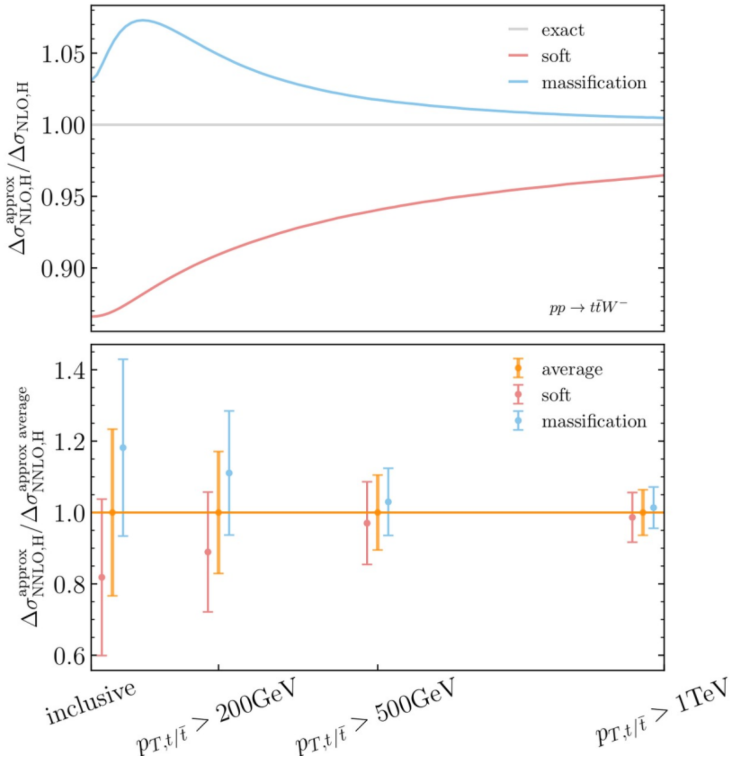
- APPROXIMATE MASS TREATMENT IN TOP PRODUCTION
- TWO-MASS EFFECTS IN DEEP-INELASTIC SCATTERING
- FLAVORED JETS

TOP MASS IN 2$\rightarrow$ 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 $\Rightarrow$ APPROXIMATIONS

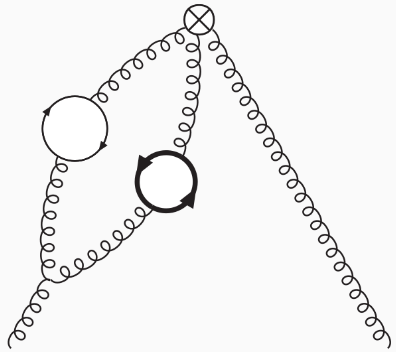
TWO-MASS TERMS IN WILSON COEFFICIENTS FOR DIS

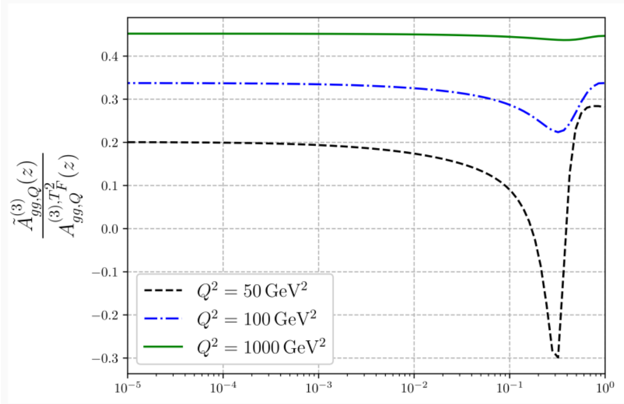
$Q^2 \gg m_b^2 \gg m_c^2$

- Decouple charm, then decouple bottom while considering the charm as massless.
- No new ingredients appear in the asymptotic representation.
- Universal power corrections in $\sqrt{\eta} = \frac{m_c}{m_b} \sim 0.3$ are not accounted for.

$Q^2 \gg m_b^2 \sim m_c^2$

- Decouple charm and bottom together.
- New OMEs with both massive quarks present simultaneously appear.
- All two-mass OMEs exept A_{Qg} already calculated.



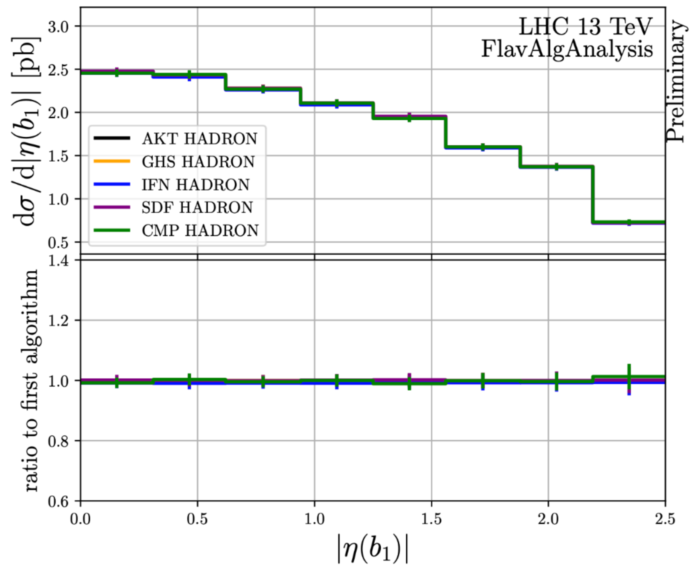


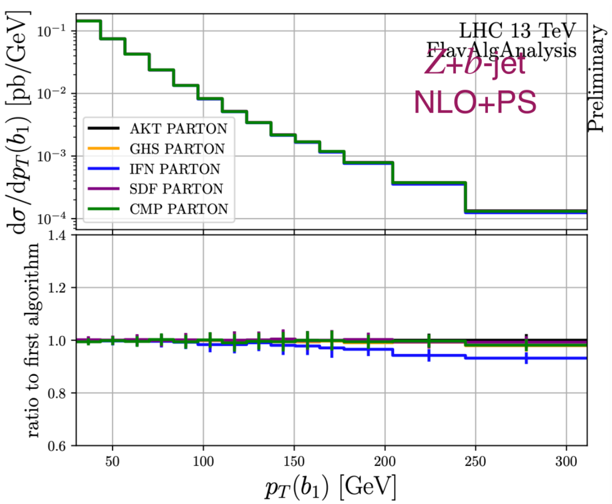
K. Schönwald

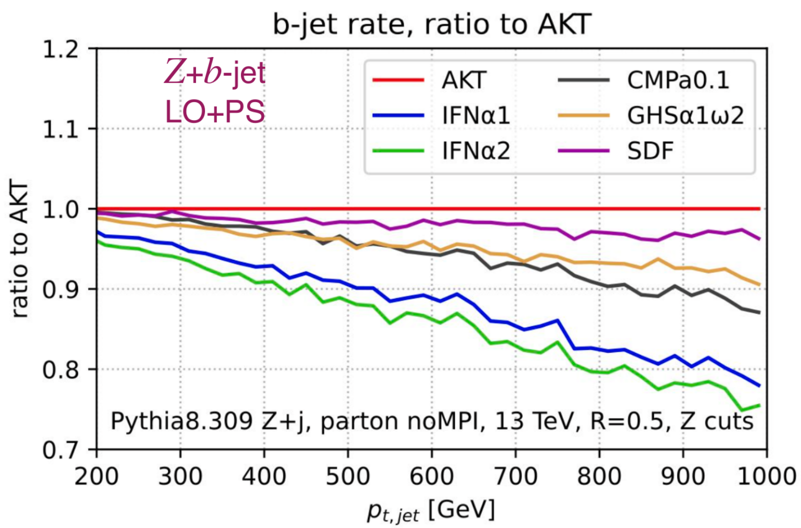
- $m_b \gtrsim m_c \Rightarrow$ MUST INCLUDE BOTH AT ONCE IN VARIABLE-FLAVOR NUMBER SCHEME
- NEW TWO-MASS CONTRIBUTIONS
- SIZABLE WILSON COEFFICIENT AT LOW SCALE, VALENCE PEAK

JET FLAVOR TAGGING

- ALL-ORDER IRC SAFE DEFINITION OF HEAVY FLAVORED JET NONTRIVIAL
- SEVERAL INEQUIVALENT ALGORITHMS AVAILABLE
- BENCHMARKING $\Rightarrow$ EFFICIENCY?







G. Stagnitto

EXPERIMENT ⇔ THEORY

GIOVANNI STAGNITTO

``I'll talk about experimental fesibility like a poor theory guy''

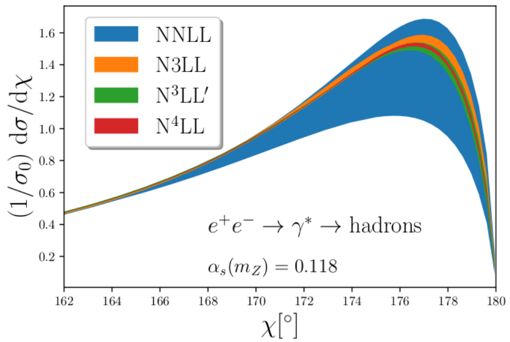
- JET OBSERVABLES
- ANGULAR DEPENDENCE AND SPIN CORRELATIONS
- MACHINE LEARNING

ENERGY CORRELATORS

Simplest example is the two-point function

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

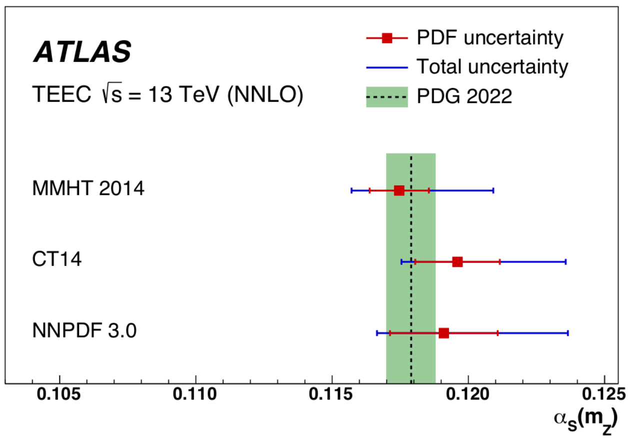
large logarithms both for small and large angles. For large angle N⁴LL is known!

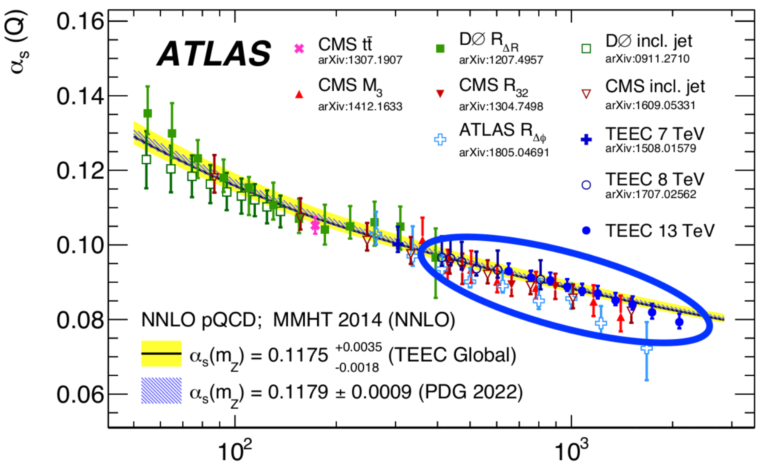


Duhr, Mistlberger, Vita '22

T. Becher

- FACTORIZATION AND RESUMMATION TO HIGH ORDER
- PDF-INDEPENDENT α_s DETERMINATION





F. Castillo

ANGULAR COEFFICIENTS:
THE Z p_T AND RAPIDITY (ATLAS)

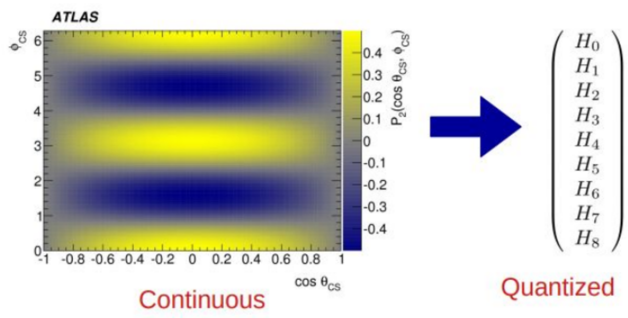
Measure θ and ϕ distributions defined in the Collin-Soper frame and **extract the free parameters** (A_i,σ^{U+L}) from a fit in , p_T -y bins

- ○ $d\sigma/dp_T$: transverse dynamics
- ○ $d\sigma/dy$: longitudinal dynamics (PDFs)

$$\frac{d\sigma}{dpdq} = \frac{d^3\sigma^{U+L}}{dp_T dydm}\left(1+\cos^2\theta+\sum_{i=0}^{7}A_i(y,p_T,m)P_i(\cos\theta,\phi)\right)$$

Measuring A_i → a "quantized" representation of ($cos(\theta)$, ϕ) from the construction of a synthetic model

- ○ allow to control uncertainties while accounting for correlations
- ○ provide analytic extrapolation of lepton cuts and enables a richer interpretation programme



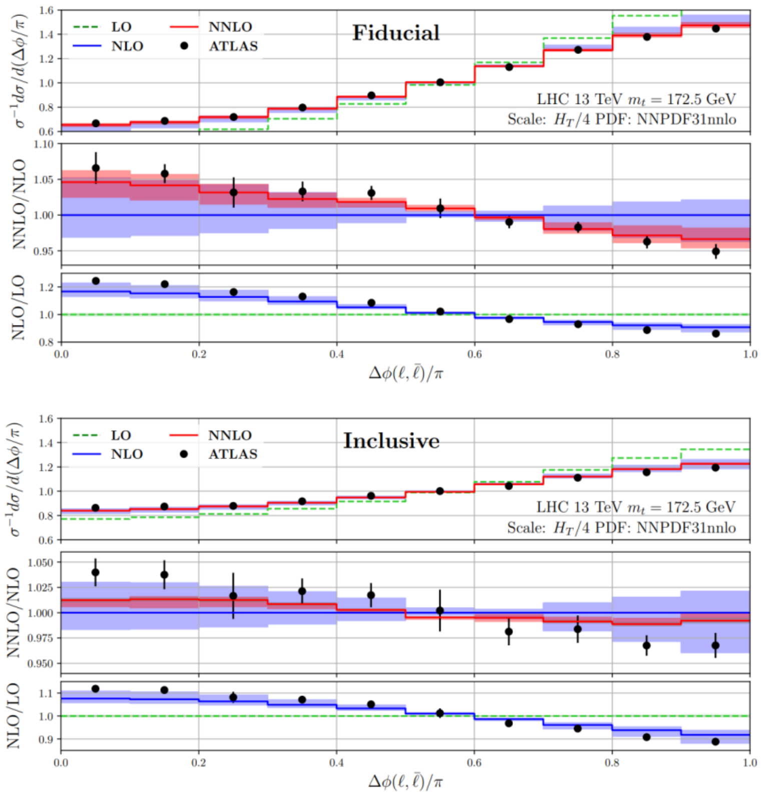
F. Castillo

- MOST GENERAL ANGULAR DEPENDENCE OF DISTRIBUTION ⇒ FINITE NUMBER OF SPERICAL HARMONICS
- EXTRAPOLATION TO SIDEBANDS FIXED

SPIN CORRELATIONS IN TOP PRODUCTION

Azimuthal correlations for leptons

[Behring, Czakon, Mitov, Papanastasiou, Poncelet '19
Czakon, Mitov, Poncelet '21]



Spin-density-matrix

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta_1^i\,\mathrm{d}\cos\theta_2^j} = \frac{1}{4}\left(1 + B_1^i\cos\theta_1^i + B_2^j\cos\theta_2^j - C_{ij}\cos\theta_1^i\cos\theta_2^j\right)$$

Coefficient	LO ($\times 10^3$)	NLO ($\times 10^3$)	NNLO ($\times 10^3$)	CMS ($\times 10^3$)
B_1^k	1^{+0}_{-0} [sc] ± 1 [mc]	1^{+0}_{-1} [sc] ± 2 [mc]	-1^{+0}_{-1} [sc] ± 4 [mc]	5 ± 23
B_1^r	0^{+0}_{-0} [sc] ± 1 [mc]	0^{+1}_{-0} [sc] ± 2 [mc]	0^{+1}_{-2} [sc] ± 2 [mc]	-23 ± 17
B_1^n	0^{+0}_{-0} [sc] ± 1 [mc]	3^{+1}_{-1} [sc] ± 1 [mc]	4^{+1}_{-0} [sc] ± 3 [mc]	6 ± 13
B_2^k	0^{+0}_{-0} [sc] ± 1 [mc]	0^{+0}_{-1} [sc] ± 1 [mc]	-5^{+2}_{-3} [sc] ± 3 [mc]	7 ± 23
B_2^r	0^{+0}_{-0} [sc] ± 1 [mc]	0^{+2}_{-0} [sc] ± 1 [mc]	-2^{+0}_{-1} [sc] ± 2 [mc]	-10 ± 20
B_2^n	0^{+0}_{-0} [sc] ± 1 [mc]	-2^{+0}_{-1} [sc] ± 1 [mc]	-3^{+1}_{-0} [sc] ± 3 [mc]	17 ± 13
C_{kk}	324^{+7}_{-7} [sc] ± 1 [mc]	330^{+2}_{-2} [sc] ± 3 [mc]	323^{+2}_{-5} [sc] ± 6 [mc]	300 ± 38
C_{rr}	6^{+5}_{-5} [sc] ± 1 [mc]	58^{+18}_{-12} [sc] ± 2 [mc]	69^{+8}_{-7} [sc] ± 3 [mc]	81 ± 32
C_{nn}	332^{+1}_{-0} [sc] ± 1 [mc]	330^{+1}_{-1} [sc] ± 2 [mc]	326^{+1}_{-1} [sc] ± 4 [mc]	329 ± 20
$C_{nr}+C_{rn}$	1^{+0}_{-0} [sc] ± 1 [mc]	-1^{+1}_{-0} [sc] ± 3 [mc]	-4^{+4}_{-0} [sc] ± 6 [mc]	-4 ± 37
$C_{nr}-C_{rn}$	0^{+0}_{-1} [sc] ± 1 [mc]	-1^{+1}_{-0} [sc] ± 2 [mc]	2^{+4}_{-2} [sc] ± 8 [mc]	-1 ± 38
$C_{nk}+C_{kn}$	0^{+0}_{-0} [sc] ± 1 [mc]	2^{+1}_{-0} [sc] ± 1 [mc]	3^{+4}_{-1} [sc] ± 3 [mc]	-43 ± 41
$C_{nk}-C_{kn}$	1^{+0}_{-0} [sc] ± 1 [mc]	1^{+1}_{-1} [sc] ± 2 [mc]	6^{+0}_{-2} [sc] ± 7 [mc]	40 ± 29
$C_{rk}+C_{kr}$	-229^{+4}_{-4} [sc] ± 1 [mc]	-203^{+9}_{-7} [sc] ± 2 [mc]	-194^{+8}_{-6} [sc] ± 7 [mc]	-193 ± 64
$C_{rk}-C_{kr}$	1^{+0}_{-0} [sc] ± 1 [mc]	1^{+0}_{-1} [sc] ± 4 [mc]	-1^{+1}_{-3} [sc] ± 5 [mc]	57 ± 46

[CMS 1907.03729]

Higher-order corrections and entanglement measurements?

R. Poncelet

- DENSITY MATRIX ⇔ LEPTON AZIMUTHAL CORRELATIONS
- ENTANGLEMENT ⇔ BSM SEARCHES

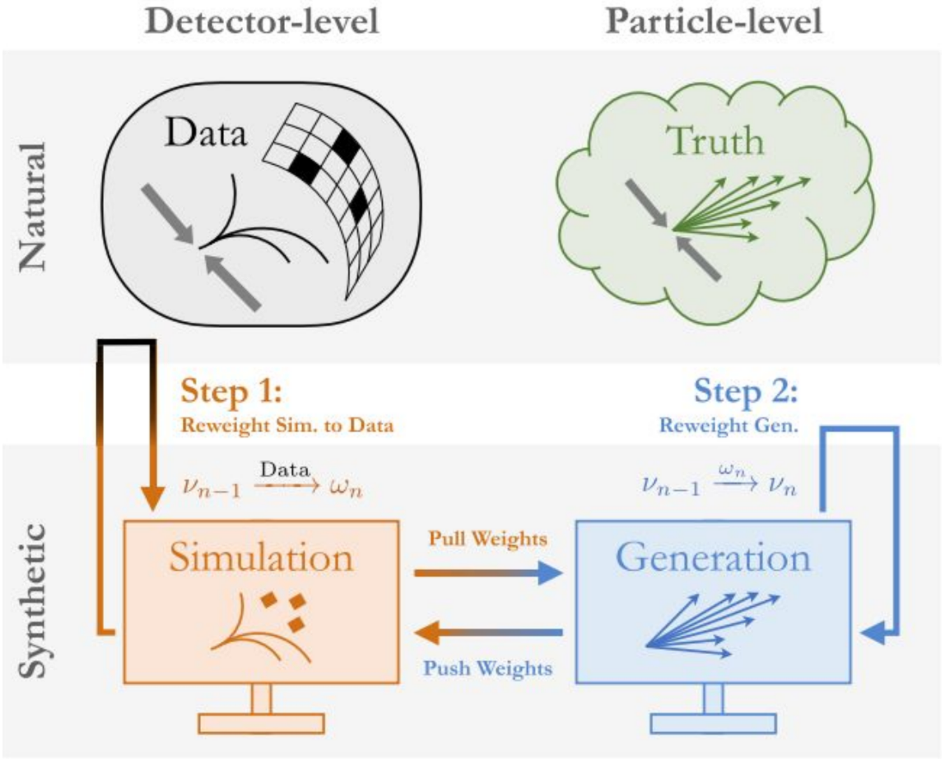
MACHINE LEARNING EXPERIMENT

BYPASSING UNFOLDING

Omnifold Z+jets

arXiv:2405.20041

Schema from Phys. Rev. Lett. 124, 182001 (2020)



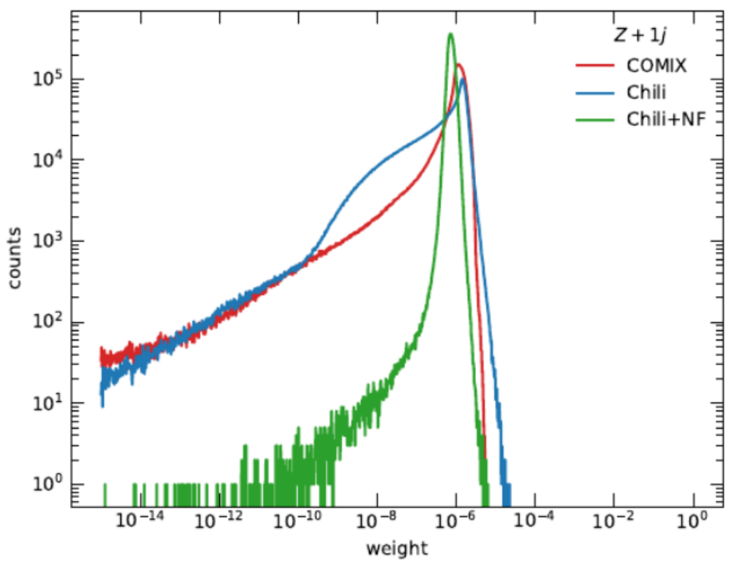
- OmniFold weights particle-level Gen to be consistent with Data once passed through the detector
  - This technique bypass the current unfolding (fixed binned data, not feasible for unfolding multiples dimensions)
- Advantages of Omnifold
  - Can capture all detector effects
  - Unbinned: final result is a list of events with a weight, user can construct any binning and any possible variable
- *The output of OmniFold is an* ***event-by-event reweighting function*** *that adjusts the Generation to match the Truth.*

MACHINE LEARNING THEORY
SUSTAINABLE SIMULATION

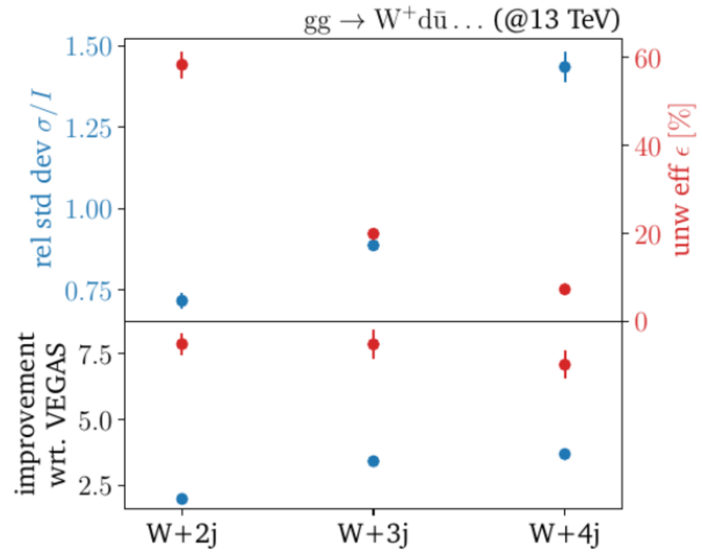
ML-assisted phase-space sampling – closing in on production

- implementation in SHERPA framework
  [Gao *et al.*, PRD 101 (2020) no.7, 076002] [Bothmann *et al.*, SciPost Phys. 15 (2023) 4]
- MADNIS multi-channel sampler for MADGRAPH
  [Heimel *et al.*, SciPost Phys. 15 (2023) 141 & 17 (2024) 23]

SHERPA $Z + 1j$



MADNIS



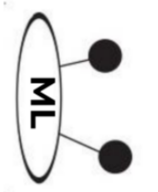
⇝ new powerful integration/sampling methods

⇝ enormous potential for other applications, e.g. loop calcs

MACHINE LEARNING HADRONIZATION

One approach: 'fit' hadronisation using neural networks.
E.g. HadML, uses Generative Adversarial Network (GAN)

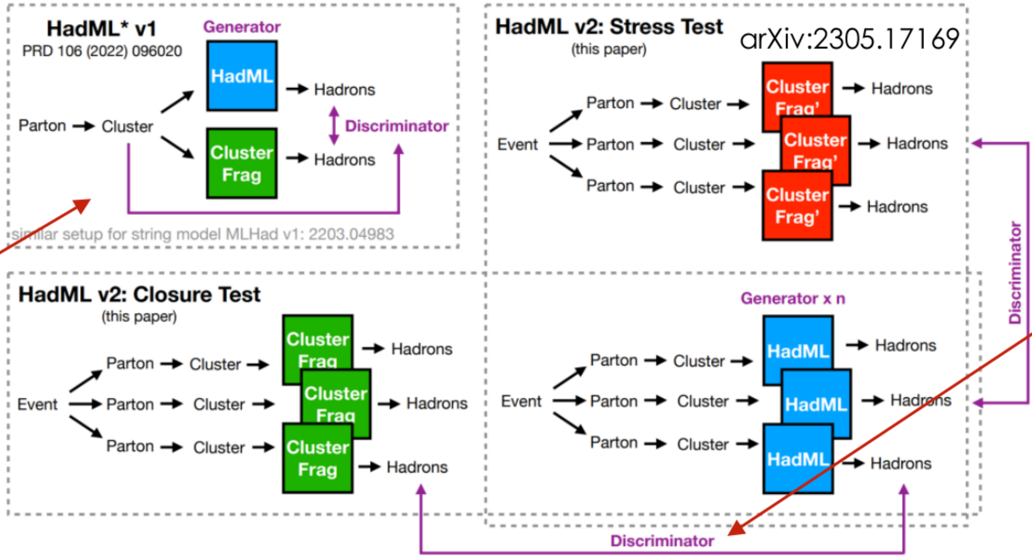
Chan, Ghosh, Ju, Kania, Nachman, Sangli, Siodmok



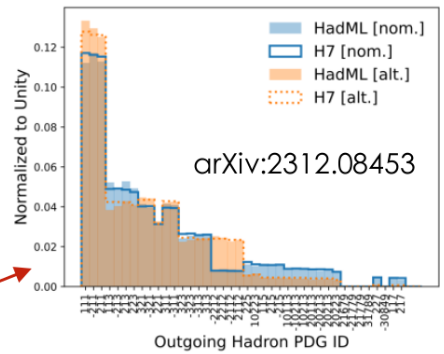
NN describes cluster decay to 2 hadrons

Discriminator compared HadML output to data at level of clusters (not possible for actual exp data)

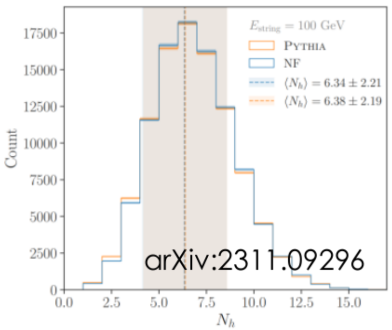
rXiv:2203.12660



Now discriminator compares at level of events



Now fitting both kinematics and particle flavour



Alternative approach: MLHad. "MAGIC" training method that can use event-level data

Bierlich, Ilten, Menzo, Mrenna, Szewc, Wilkinson, Youssef, Zupan

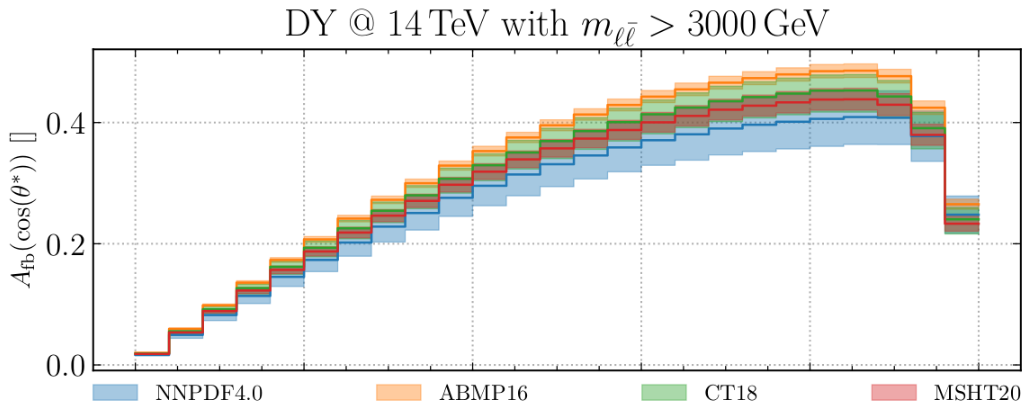
J. Gaunt

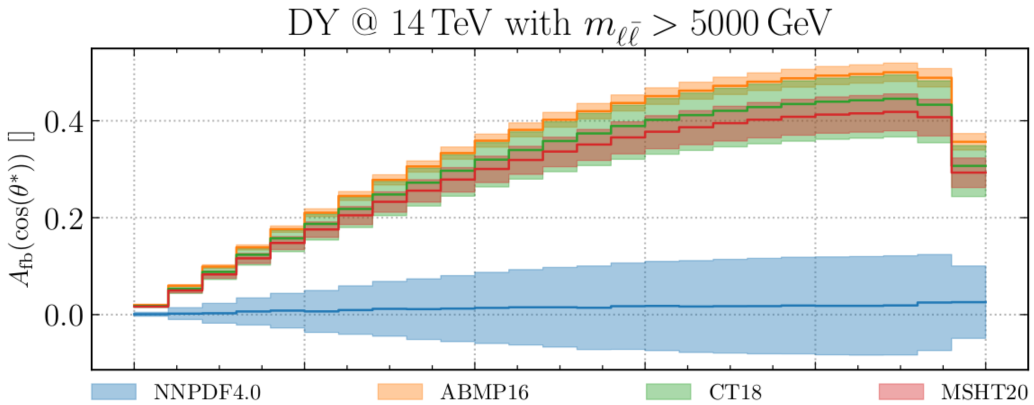
‘‘QCD is what will keep us busy for the next 100 years’’

Yasmine Amhis

QCD ⇒ BSM

LARGE x PDFs





J. Cruz Martínez

HIGH-MASS A_{FB} IN Z PRODUCTION DETERMINED BY UNDETERMINED LARGE x PDFS

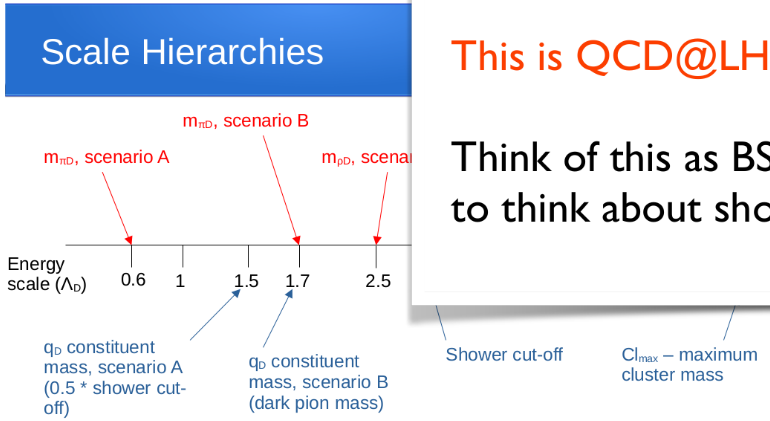
BSM ⇒ QCD

DARK SECTOR SHOWERS

QCD-like dark sectors can in principle build on existing QCD showering. Hadronization and scale hierarchy can differ significantly: no safe territory.

Interactions beyond QCD

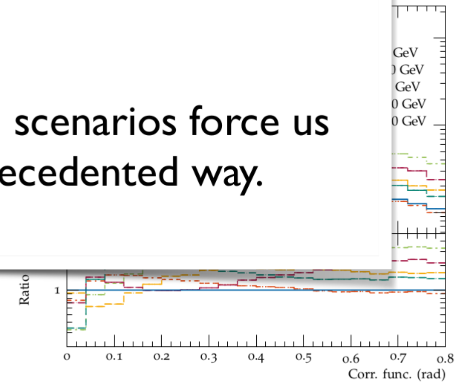
New in Herwig and the cluster model — more investigations and pheno to follow.



This is QCD@LHC — why bother?

Think of this as BSM4QCD: all of QED, EW and BSM scenarios force us to think about showers and hadronisation in an unprecedented way.

$$\frac{1}{N_\gamma}\sum_{i<j\in\text{jet}}(E_iE_j)^\gamma\delta(\Delta R_{ij}-\rho)$$



[Stafford at PSR '24]

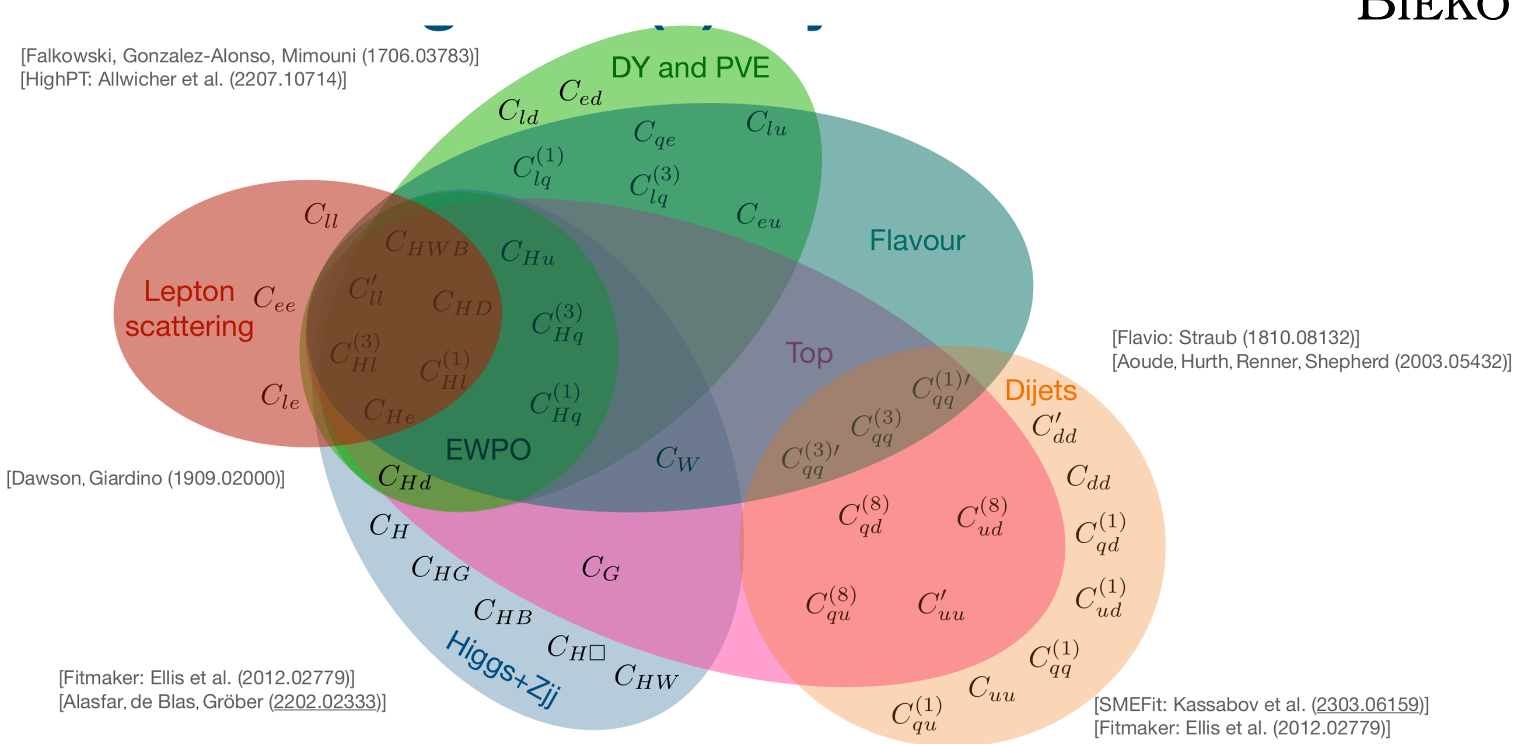
[Kulkarni, Masouminia, Plätzer, Stafford — '24]

S. Plätzer

THE SMEFT CONNECTION

Anke Biekötter

``Leading order calculations will not impress this community''



A. Biekötter

WHAT LIES AHEAD

BRANDON
REGNERY

'' We look at two experiments that from the outside look the same, but everything inside is different''