Precision QCD phenomenology for multi-scale processes at the Large-Hadron-Collider

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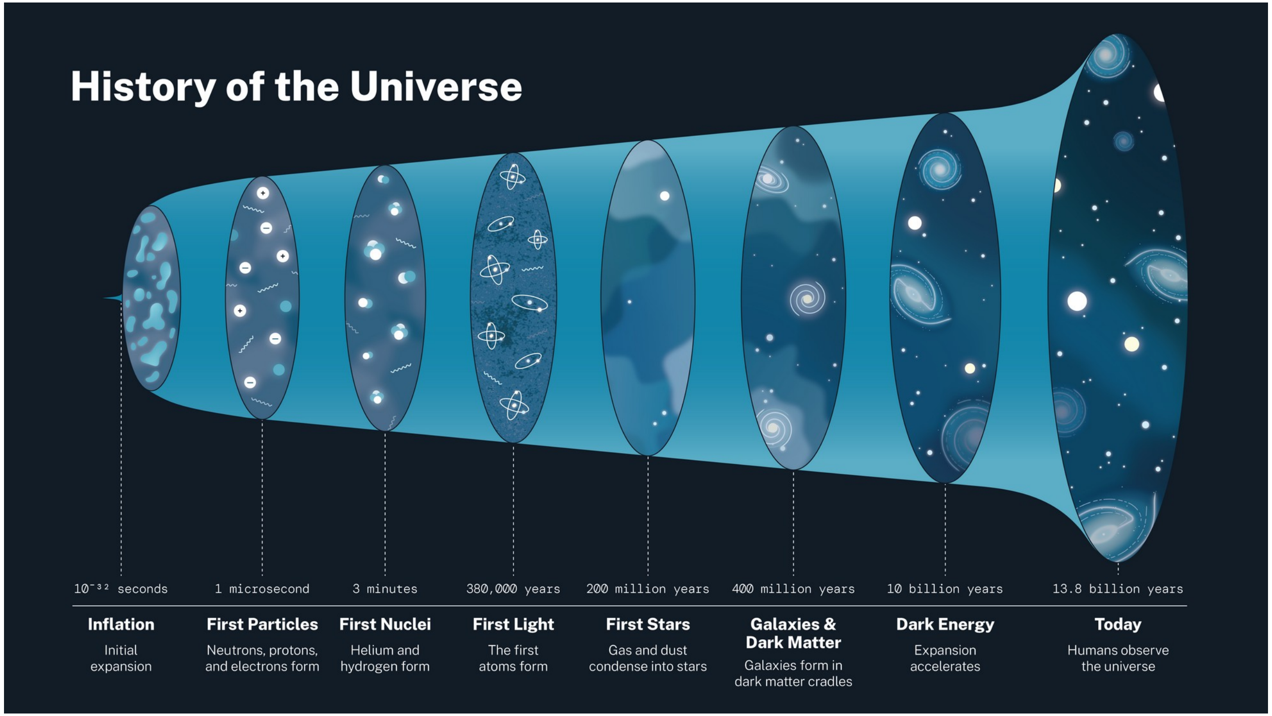
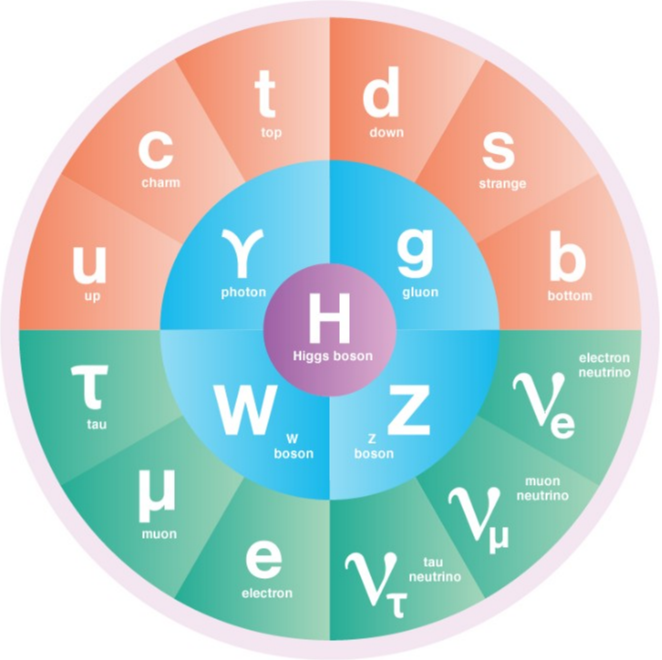
Outline

- Precision phenomenology at the Large Hadron Collider
- Theory predictions with higher-order corrections
- Phenomenology for 2 → 3 processes
- Summary and Outlook

What is the universe made of and where does it come from?



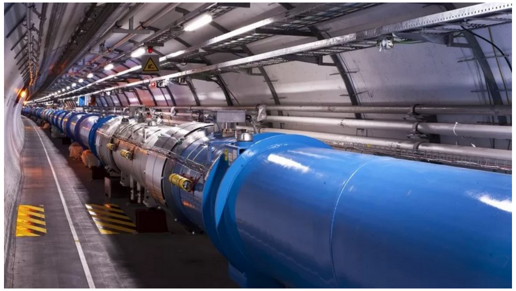
[Credit: NASA]



[Credit: SymmetryMagazine]

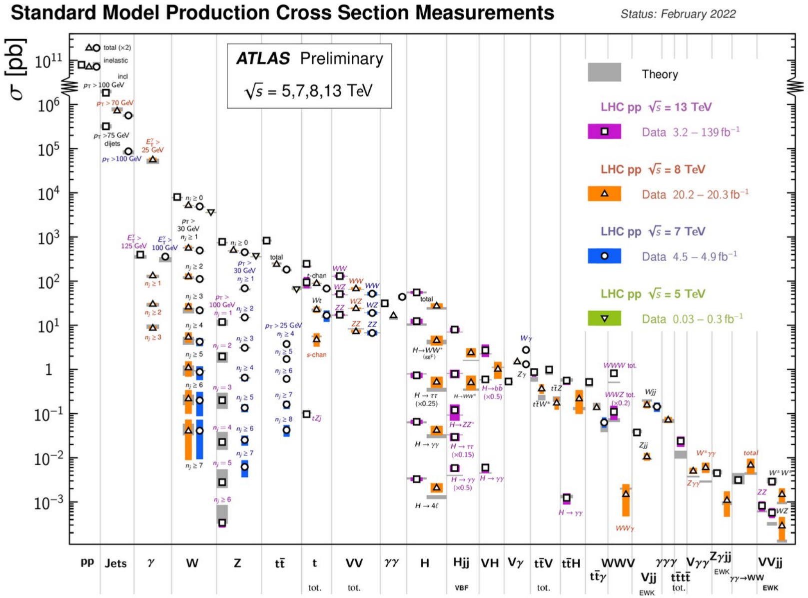
What are the fundamental building blocks of matter?

Scattering experiments



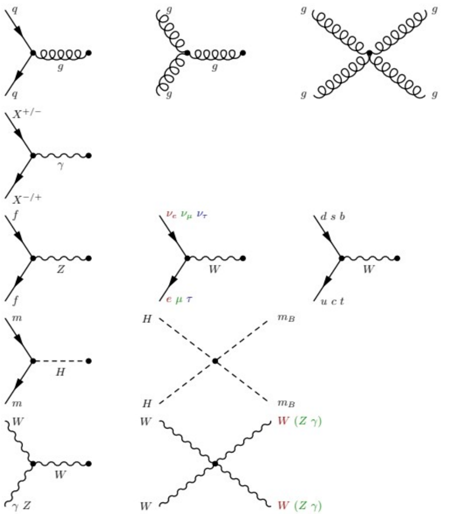
[Credit: CERN]

Collider phenomenology



[Credit: ATLAS]

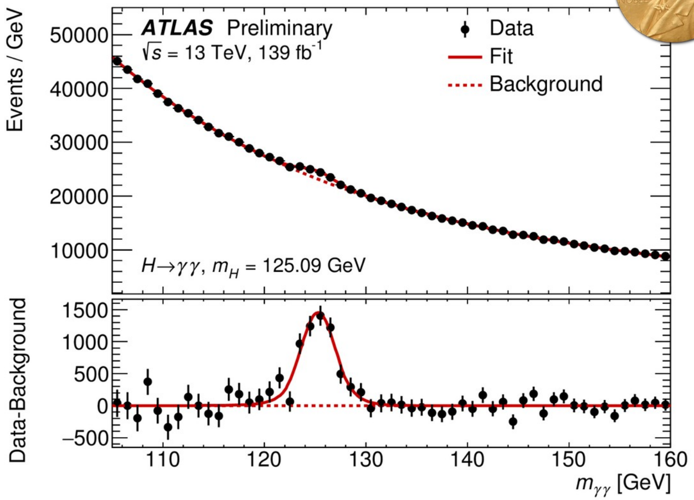
Theory/Model



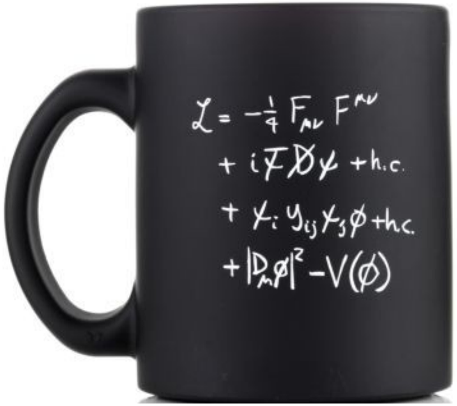
[Credit: Jack Lindon, CERN]

Standard Model of Particle Physics and beyond

Higgs discovery 2012



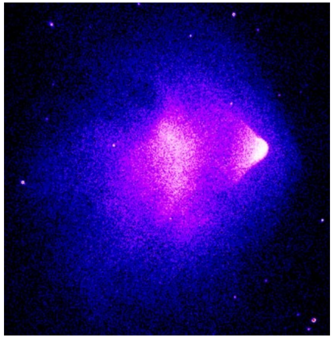
[Credit: ATLAS]



[Credit: CERN]

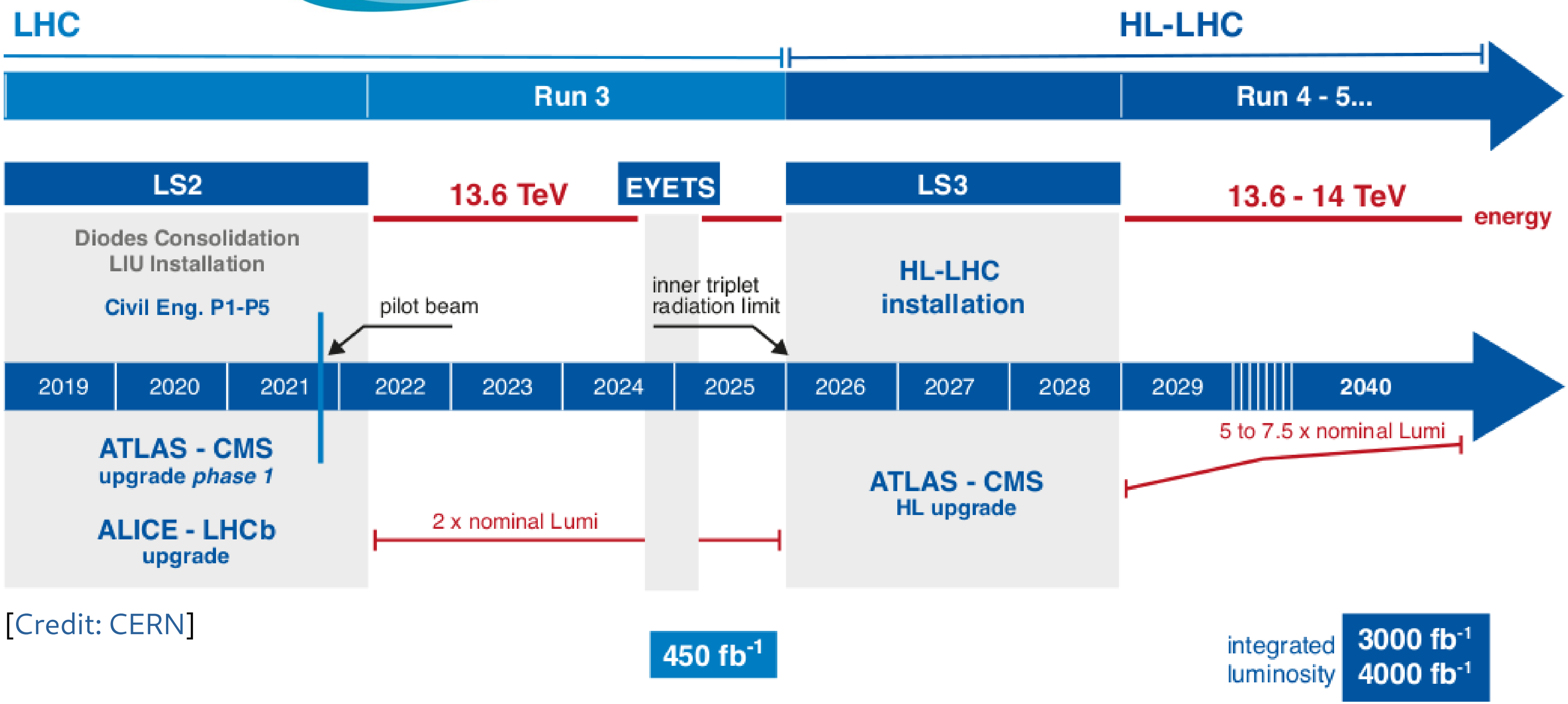
BUT:

- Is the Higgs a fundamental scalar?
- What is dark matter?
- Why is there a matter-anti-matter asymmetry?
- …



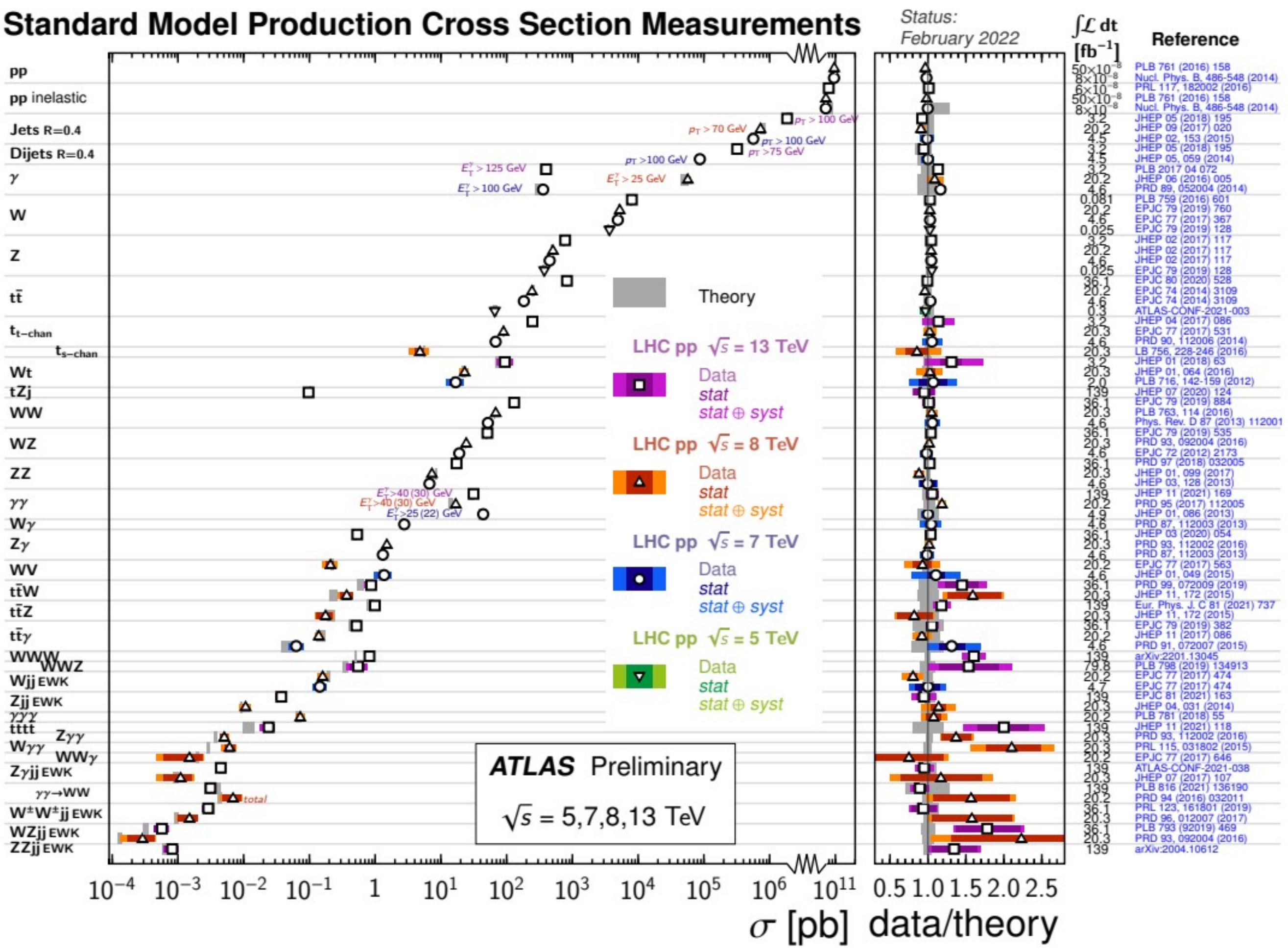
[Credit: NASA]

LHC Precision era and future experiments



[Credit: CERN]

SM measurements at the LHC



Theory picture of hadron collision events

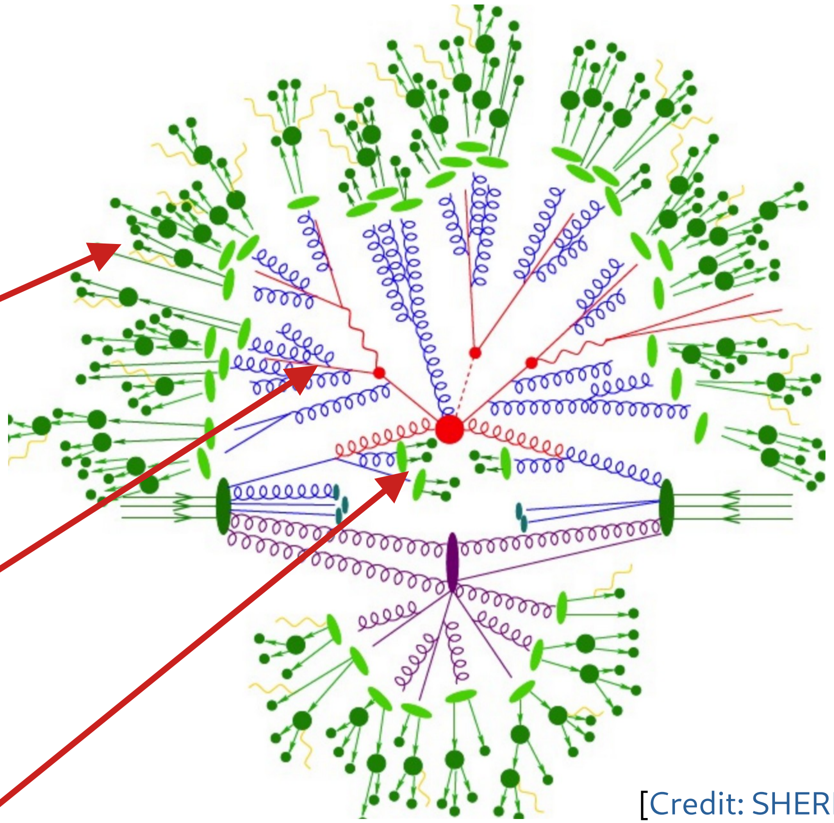
Factorization
"What you see depends on the energy scale"

In Quantum Chromodynamics (QCD):

$Q \sim \Lambda_{\mathrm{QCD}}$ Strong coupling
- Realm of confined states
- non-perturbative physics

$Q \gtrsim \Lambda_{\mathrm{QCD}}$ Transition region
- Parton-shower
- Resummation
- DGLAP / PDF evolution

$Q \gg \Lambda_{\mathrm{QCD}}$ Small coupling → perturbative regime
- Scattering of individual partons



[Credit: SHERPA]

Precision predictions

Fixed order perturbation theory

→ **Core element of event simulation**

→ **Describes high Q regime**

Resummation

Parton-showers

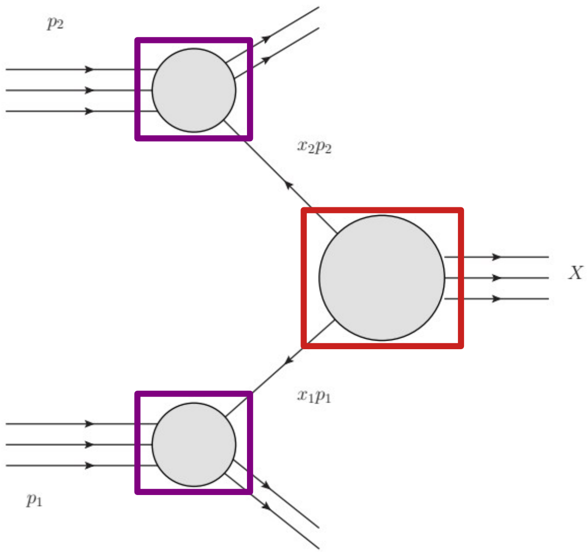
Precision theory predictions

Parametric input:
PDFs, couplings (α_s), ...

Soft physics:
MPI, colour reconnection, ...

Fragmentation/hadronisation

Perturbative QCD



Hadronic cross section in collinear factorization:

$$\sigma_{h_1h_2\to X} = \sum_{ij}\int_0^1\int_0^1 \mathrm{d}x_1\mathrm{d}x_2\phi_{i,h_1}(x_1,\mu_F^2)\phi_{j/h_2}(x_2,\mu_F^2)\hat{\sigma}_{ij\to X}(\alpha_s(\mu_R^2),\mu_R^2,\mu_F^2)$$

Perturbative expansion of partonic cross section:

$$\hat{\sigma}_{ab\to X} = \hat{\sigma}^{(0)}_{ab\to X} + \hat{\sigma}^{(1)}_{ab\to X} + \hat{\sigma}^{(2)}_{ab\to X} + \mathcal{O}(\alpha_s^3)$$

Typical uncertainties from scale variations: δLO O(~100%), δNLO O(~10%), δNNLO (~1%)

(estimate for corrections from missing higher orders based on renormalisation scale invariance $\frac{\mathrm{d}\sigma_{h_1h_2\to X}}{\mathrm{d}\mu} = 0$)

Example: Production of three isolated photons

$$pp \to \gamma\gamma\gamma$$

Theory to data comparison

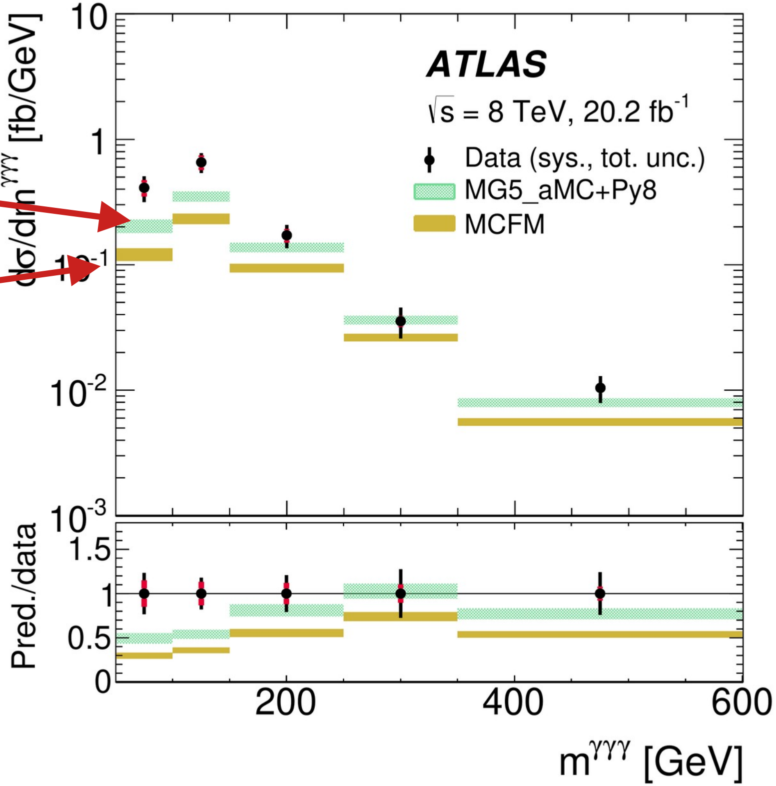
NLO QCD
+ Parton-shower simulation

Fixed-order NLO QCD

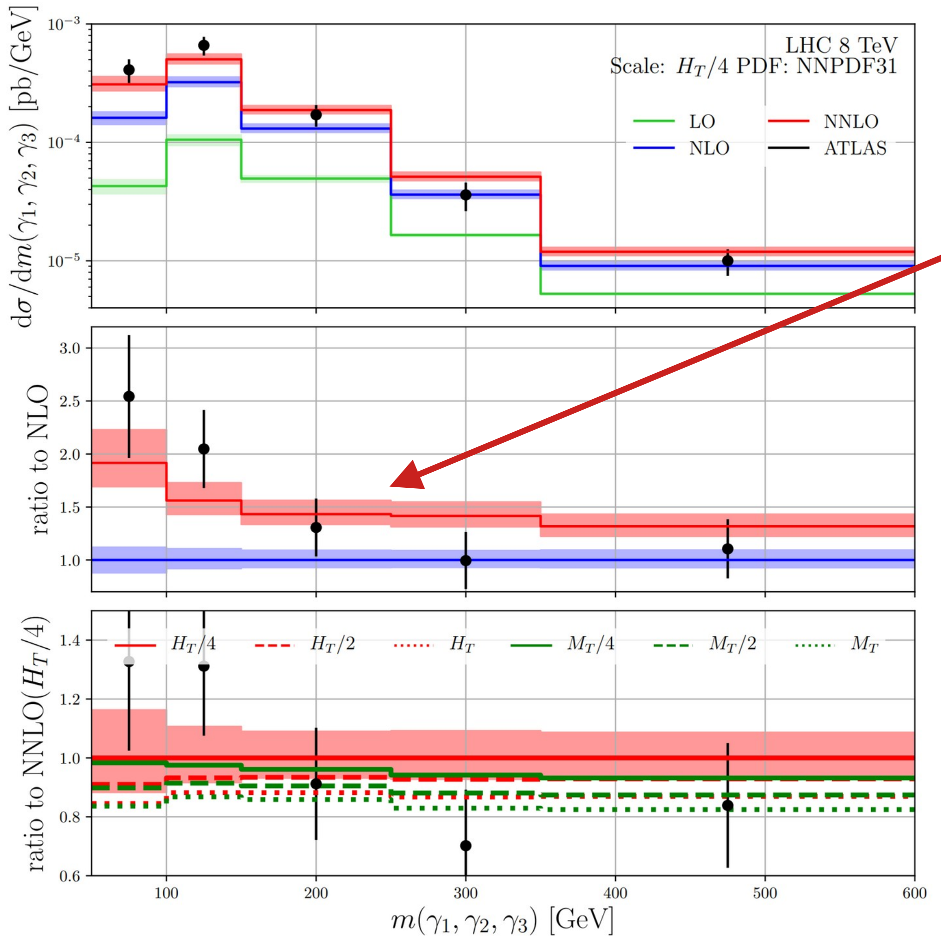
Both fail to describe data (normalization and shape)

Why?
→ NNLO QCD effects!

Measurement of the production cross section of three isolated photons in pp collisions at √s = 8 TeV using the ATLAS detector, ATLAS [1712.07291]



NNLO QCD in three photon production



NNLO QCD corrections to three-photon production at the LHC, Chawdhry, Czakon, Mitov, **Poncelet** [JHEP 02 (2020) 057]

Corrections to **normalization** and **shape**

→ (Much) improved description of data

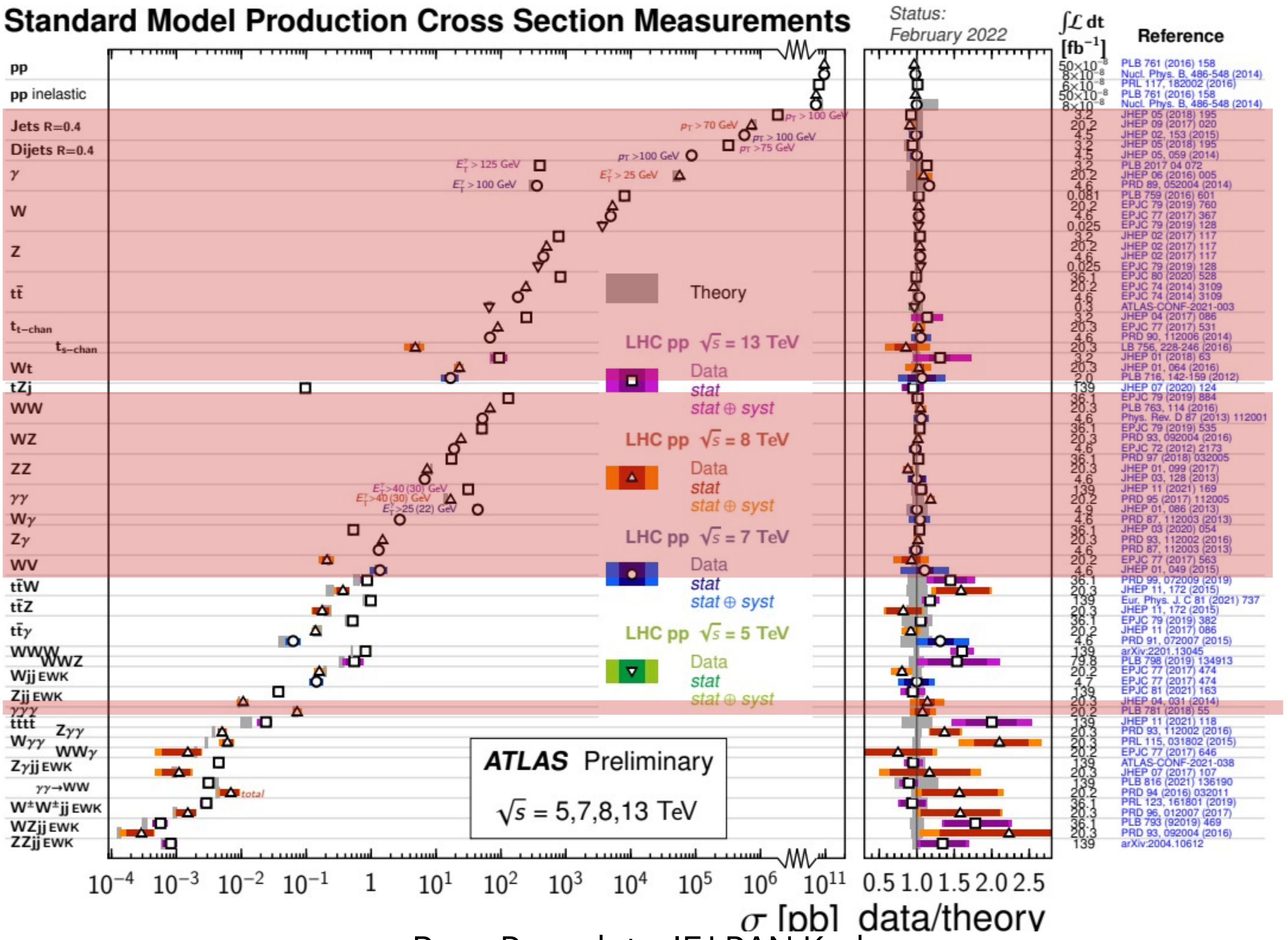
Without NNLO QCD corrections the data

- is not interpretable
  → loss of information

or

- is misleading
  → looks like "New Physics" = data - SM

NNLO QCD coverage



Processes with second-order theory

Theory predictions with higher-order corrections

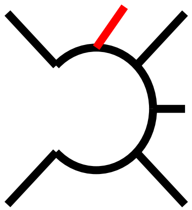
Next-to-leading order case

$$\hat{\sigma}^{(1)}_{ab} = \hat{\sigma}^{\mathrm{R}}_{ab} + \hat{\sigma}^{\mathrm{V}}_{ab} + \hat{\sigma}^{\mathrm{C}}_{ab}$$

KLN theorem
sum is finite for sufficiently inclusive observables and regularization scheme independent

Each term separately infrared (IR) divergent:

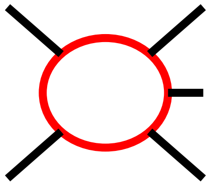
Real corrections:



$$\hat{\sigma}^{\mathrm{R}}_{ab} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n+1} \left\langle \mathcal{M}^{(0)}_{n+1} \middle| \mathcal{M}^{(0)}_{n+1} \right\rangle \mathrm{F}_{n+1}$$

Phase space integration over unresolved configurations

Virtual corrections:

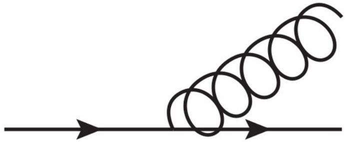


$$\hat{\sigma}^{\mathrm{V}}_{ab} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n}\, 2\mathrm{Re} \left\langle \mathcal{M}^{(0)}_{n} \middle| \mathcal{M}^{(1)}_{n} \right\rangle \mathrm{F}_{n}$$

Integration over loop-momentum
(UV divergences cured by renormalization)

IR singularities in real radiation

$$\hat{\sigma}^{\mathrm{R}}_{ab} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n+1} \left\langle \mathcal{M}^{(0)}_{n+1} \middle| \mathcal{M}^{(0)}_{n+1} \right\rangle \mathrm{F}_{n+1}$$

$\ni \mathrm{d}\Phi_1$ 

$$\sim \int_0 \mathrm{d}E\mathrm{d}\theta \frac{1}{E(1-\cos\theta)} f(E,\cos(\theta))$$

Finite function

Divergent

Regularization in Conventional Dimensional Regularization (CDR) $d = 4 - 2\epsilon$

$$\to \int_0 \mathrm{d}E\mathrm{d}\theta \frac{1}{E^{1-2\epsilon}(1-\cos\theta)^{1-\epsilon}} f(E,\cos(\theta)) \sim \frac{1}{\epsilon^2} + \dots$$

Cancellation against similar divergences in

$$\hat{\sigma}^{\mathrm{V}}_{ab} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_n \, 2\mathrm{Re} \left\langle \mathcal{M}^{(0)}_{n} \middle| \mathcal{M}^{(1)}_{n} \right\rangle \mathrm{F}_{n}$$

How to extract these poles? Slicing and Subtraction

Central idea: Divergences arise from infrared (IR, soft/collinear) limits → Factorization!

Slicing

$$\hat{\sigma}^{\mathrm{R}}_{ab} = \frac{1}{2\hat{s}} \int_{\delta(\Phi)\geq\delta_c} \mathrm{d}\Phi_{n+1} \left\langle \mathcal{M}^{(0)}_{n+1} \middle| \mathcal{M}^{(0)}_{n+1} \right\rangle \mathrm{F}_{n+1} + \frac{1}{2\hat{s}} \int_{\delta(\Phi)<\delta_c} \mathrm{d}\Phi_{n+1} \left\langle \mathcal{M}^{(0)}_{n+1} \middle| \mathcal{M}^{(0)}_{n+1} \right\rangle \mathrm{F}_{n+1}$$

$$\approx \frac{1}{2\hat{s}} \int_{\delta(\Phi)\geq\delta_c} \mathrm{d}\Phi_{n+1} \left\langle \mathcal{M}^{(0)}_{n+1} \middle| \mathcal{M}^{(0)}_{n+1} \right\rangle \mathrm{F}_{n+1} + \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_n \, \tilde{M}(\delta_c) \mathrm{F}_n + \mathcal{O}(\delta_c)$$

$$\ldots + \hat{\sigma}^{\mathrm{V}}_{ab} = \text{finite}$$

Subtraction

$$\hat{\sigma}^{\mathrm{R}}_{ab} = \frac{1}{2\hat{s}} \int \left(\mathrm{d}\Phi_{n+1} \left\langle \mathcal{M}^{(0)}_{n+1} \middle| \mathcal{M}^{(0)}_{n+1} \right\rangle \mathrm{F}_{n+1} - \mathrm{d}\tilde{\Phi}_{n+1} \, \mathcal{S} \mathrm{F}_n \right) + \frac{1}{2\hat{s}} \int \mathrm{d}\tilde{\Phi}_{n+1} \, \mathcal{S} \mathrm{F}_n$$

$$\frac{1}{2\hat{s}} \int \mathrm{d}\tilde{\Phi}_{n+1} \, \mathcal{S} \mathrm{F}_n = \frac{1}{2\hat{s}} \int \underline{\mathrm{d}\Phi_n \, \mathrm{d}\Phi_1} \, \mathcal{S} \mathrm{F}_n$$

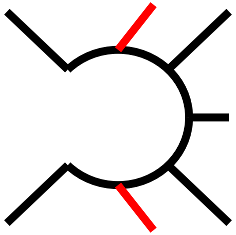
Phase space factorization
→ momentum mappings

Most popular NLO QCD schemes:
CS [hep-ph/9605323],
FKS [hep-ph/9512328]

→ Basis of modern event simulation

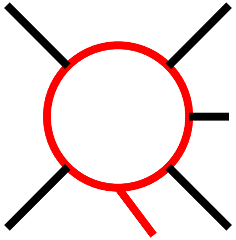
Partonic cross section beyond NLO

$$\hat{\sigma}_{ab}^{(2)} = \hat{\sigma}_{ab}^{\mathrm{VV}} + \hat{\sigma}_{ab}^{\mathrm{RV}} + \hat{\sigma}_{ab}^{\mathrm{RR}} + \hat{\sigma}_{ab}^{\mathrm{C2}} + \hat{\sigma}_{ab}^{\mathrm{C1}}$$



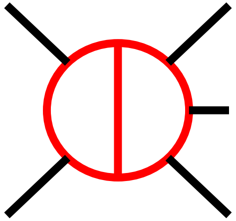
Real-Real

$$\hat{\sigma}_{ab}^{\mathrm{RR}} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n+2} \left\langle \mathcal{M}_{n+2}^{(0)} \middle| \mathcal{M}_{n+2}^{(0)} \right\rangle \mathrm{F}_{n+2}$$



Real-Virtual

$$\hat{\sigma}_{ab}^{\mathrm{RV}} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n+1}\, 2\mathrm{Re} \left\langle \mathcal{M}_{n+1}^{(0)} \middle| \mathcal{M}_{n+1}^{(1)} \right\rangle \mathrm{F}_{n+1}$$



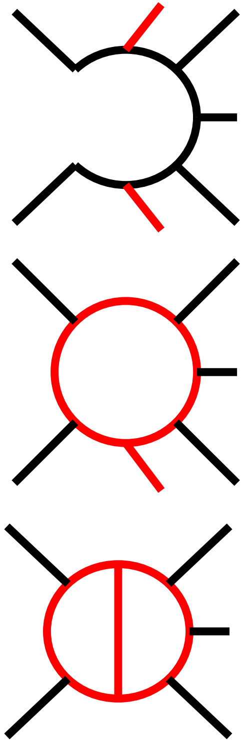
Virtual-Virtual

$$\hat{\sigma}_{ab}^{\mathrm{VV}} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n} \left(2\mathrm{Re} \left\langle \mathcal{M}_{n}^{(0)} \middle| \mathcal{M}_{n}^{(2)} \right\rangle + \left\langle \mathcal{M}_{n}^{(1)} \middle| \mathcal{M}_{n}^{(1)} \right\rangle \right) \mathrm{F}_{n}$$

$\hat{\sigma}_{ab}^{\mathrm{C2}} = (\text{double convolution})\, \mathrm{F}_n$ $\qquad$ $\hat{\sigma}_{ab}^{\mathrm{C1}} = (\text{single convolution})\, \mathrm{F}_{n+1}$

Partonic cross section beyond NLO

$$\hat{\sigma}^{(2)}_{ab} = \hat{\sigma}^{\mathrm{VV}}_{ab} + \hat{\sigma}^{\mathrm{RV}}_{ab} + \hat{\sigma}^{\mathrm{RR}}_{ab} + \hat{\sigma}^{\mathrm{C2}}_{ab} + \hat{\sigma}^{\mathrm{C1}}_{ab}$$



Technically substantially more complicated!

Main bottlenecks:

- Real - real → overlapping singularities
  Many possible limits → good organization principle needed
- Real - virtual → stable matrix elements
- Virtual - virtual → complicated case-by-case analytic treatment

Slicing and Subtraction

Slicing

- Conceptually simple
- Recycling of lower computations
- Non-local cancellations/power-corrections
  → computationally expensive

Subtraction

- Conceptually more difficult
- Local subtraction → efficient
- Better numerical stability
- Choices:
  - Momentum mapping
  - Subtraction terms
  - Numerics vs. analytic

NNLO QCD schemes

qT-slicing [Catani'07],
N-jettiness slicing [Gaunt'15/Boughezal'15]

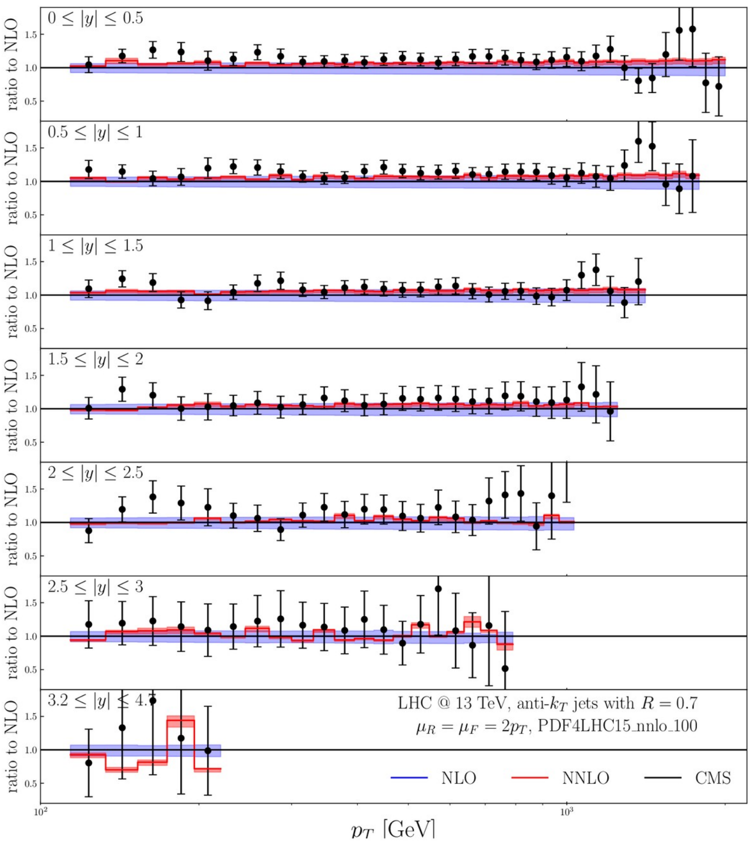
Antenna [Gehrmann'05-'08],
Colorful [DelDuca'05-'15],
Sector-improved residue subtraction [Czakon'10-'14'19]
Projection [Cacciari'15],
Nested collinear [Caola'17],
Geometric [Herzog'18],
Unsubtraction [Aguilera-Verdugo'19],
...

Minimal sector-improved residue subtraction

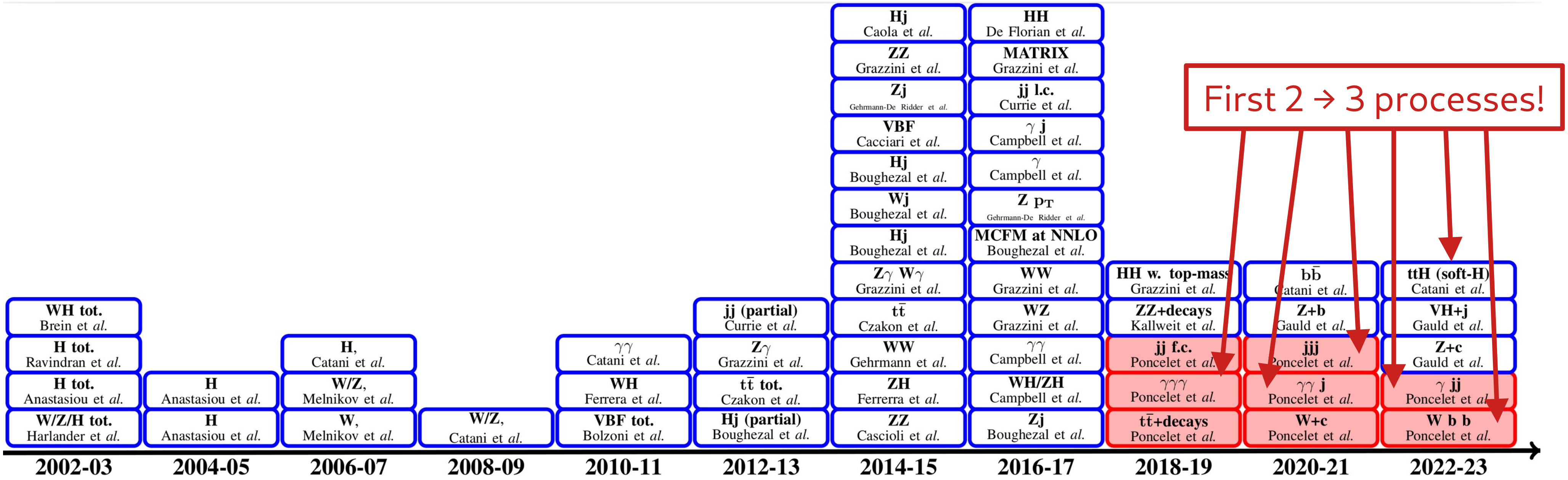
Single-jet inclusive rates with exact color at $\mathcal{O}(\alpha_s^4)$
Czakon,Hameren,Mitov,**Poncelet**, JHEP 10 (2019), 262

Refined formulation of the
sector-improved residue subtraction

- New phase space parametrisation
  → minimization of subtraction kinematics
  → improved computational efficiency/stability
- Improved sector decomposition
- New 4 – dimensional formulation
- First application: inclusive jet production
  → demonstrates that the **scheme is complete**
  → no approximations

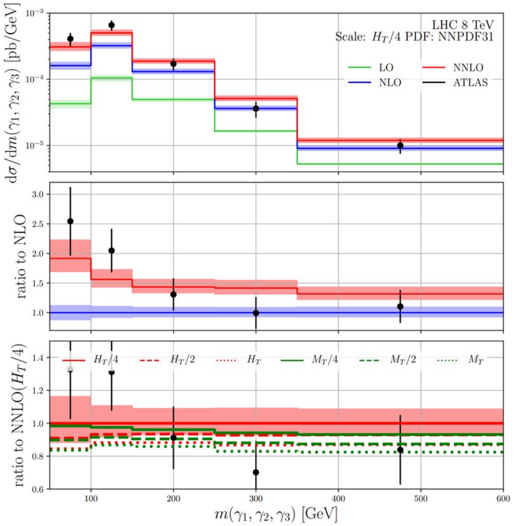


The NNLO QCD revolution



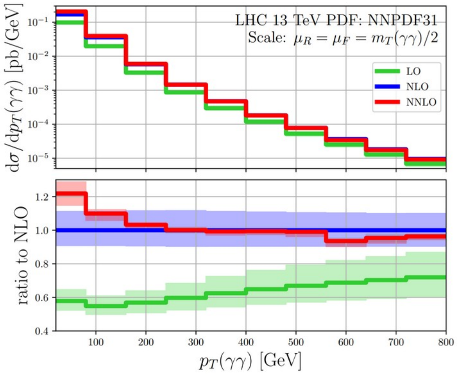
NNLO QCD for massless 2 → 3 processes

$pp \to \gamma\gamma\gamma$



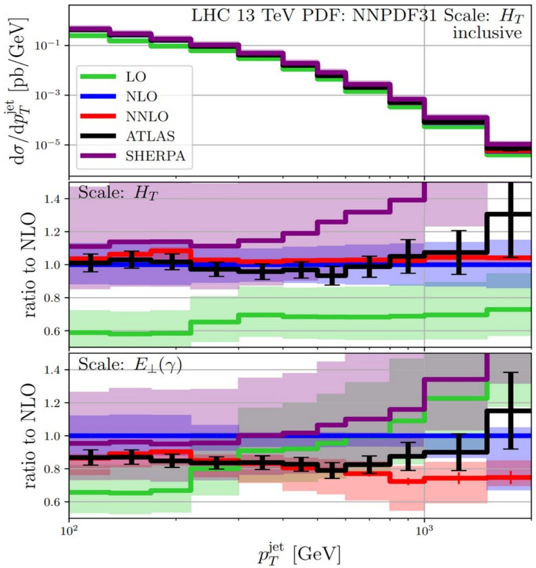
Chawdhry, Czakon, Mitov, **Poncelet** [1911.00479]
Kallweit, Sotnikov, Wiesemann [2010.04681]

$pp \to \gamma\gamma j$



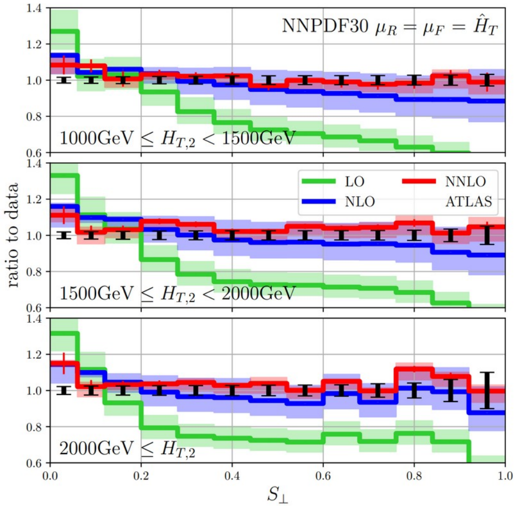
Chawdhry, Czakon, Mitov, **Poncelet** [2103.04319]

$pp \to \gamma jj$



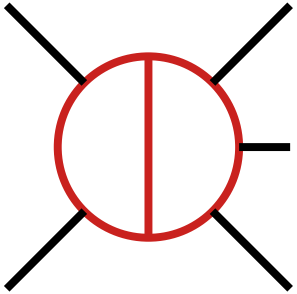
Badger, Czakon, Hartanto, Moodie, Peraro, **Poncelet**, Zoia [2304.06682]

$pp \to jjj$



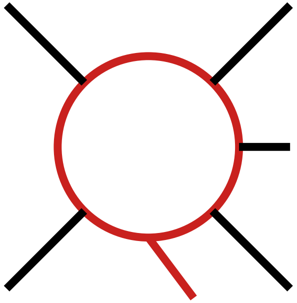
Czakon, Mitov, **Poncelet** [2106.05331]
+ Alvarez, Cantero, Llorente [2301.01086]

NNLO QCD for 2→3 processes - inputs



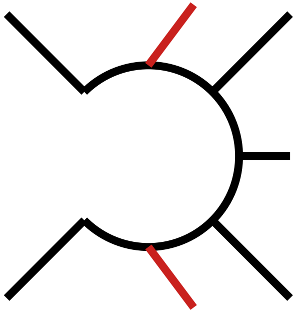
Two-loop amplitudes

- (Non-) planar 5 point massless [Chawdry'19'20'21,Abreu'20'21'23,Agarwal'21,Badger'21'23]
  → triggered by efficient MI representation [Chicherin'20]



One-loop amplitudes → OpenLoops [Buccioni'19]

- Many legs and IR stable (soft and collinear limits)



Double-real Born amplitudes → AvHlib[Bury'15]

- IR finite cross-sections → NNLO subtraction schemes
  qT-slicing [Catani'07], N-jettiness slicing [Gaunt'15/Boughezal'15], Antenna [Gehrmann'05-'08], Colorful [DelDuca'05-'15], Projetction [Cacciari'15], Geometric [Herzog'18], Unsubtraction [Aguilera-Verdugo'19], Nested collinear [Caola'17], Local Analytic [Magnea'18], **Sector-improved residue subtraction** [Czakon'10-'14,'19]

Phenomenology for 2 → 3 processes

Multi-jet observables

Test of pQCD and extraction of strong coupling constant

NLO theory unc. (MHO) > experimental unc.

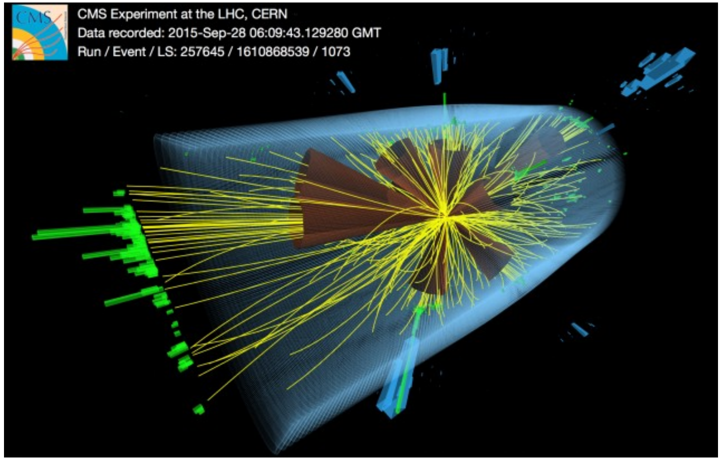
- NNLO QCD needed for precise theory-data comparisons
  → Restricted to two-jet data [Currie'17+later][Czakon'19]
- New NNLO QCD three-jet → access to more observables
  - Jet ratios

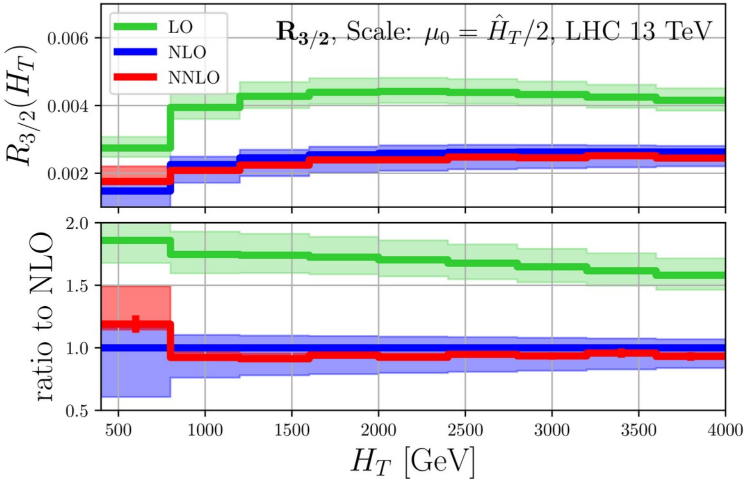
Next-to-Next-to-Leading Order Study of Three-Jet Production at the LHC
Czakon, Mitov, **Poncelet** Phys.Rev.Lett. 127 (2021) 15, 152001

$$R^i(\mu_R, \mu_F, \mathrm{PDF}, \alpha_{S,0}) = \frac{\mathrm{d}\sigma_3^i(\mu_R, \mu_F, \mathrm{PDF}, \alpha_{S,0})}{\mathrm{d}\sigma_2^i(\mu_R, \mu_F, \mathrm{PDF}, \alpha_{S,0})}$$

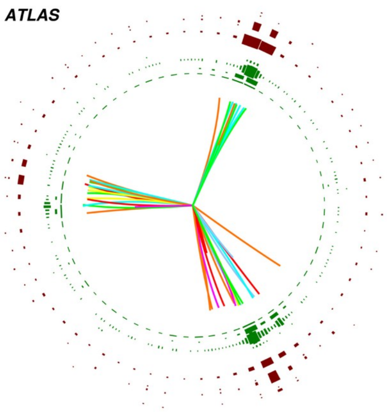
  - Event shapes

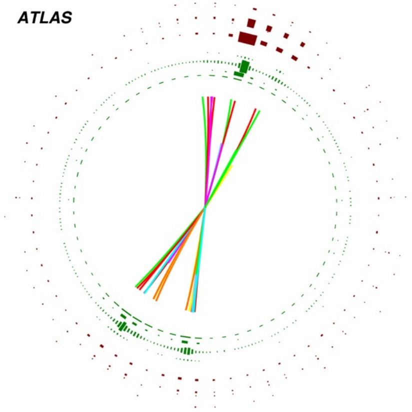
NNLO QCD corrections to event shapes at the LHC
Alvarez, Cantero, Czakon, Llorente, Mitov, **Poncelet** JHEP 03 (2023) 129





Encoding QCD dynamics in event shapes





Using (global) event information to separate different regimes of QCD event evolution:

Energy-energy correlators

$$\frac{1}{\sigma_2}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\Delta\phi} = \frac{1}{\sigma_2}\sum_{ij}\int \frac{\mathrm{d}\sigma\, x_{\perp,i}x_{\perp,j}}{\mathrm{d}x_{\perp,i}\mathrm{d}x_{\perp,j}\mathrm{d}\cos\Delta\phi_{ij}}\delta(\cos\Delta\phi - \cos\Delta\phi_{ij})\mathrm{d}x_{\perp,i}\mathrm{d}x_{\perp,j}\mathrm{d}\cos\Delta\phi_{ij}\,,$$

Separation of energy scales: $H_{T,2} = p_{T,1} + p_{T,2}$

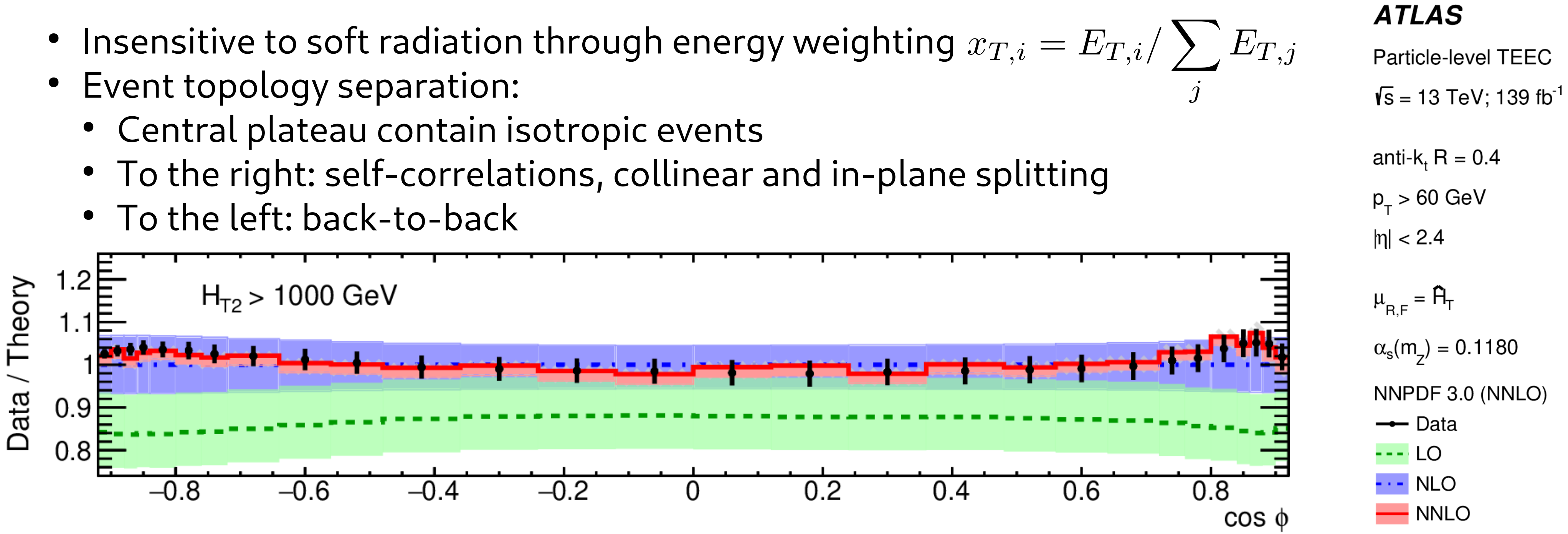
Ratio to 2-jet: $R^i(\mu_R,\mu_F,\mathrm{PDF},\alpha_{S,0}) = \frac{\mathrm{d}\sigma_3^i(\mu_R,\mu_F,\mathrm{PDF},\alpha_{S,0})}{\mathrm{d}\sigma_2^i(\mu_R,\mu_F,\mathrm{PDF},\alpha_{S,0})}$

Here: jets as input → experimentally advantageous (better calibrated, smaller non-pert.)

The transverse energy-energy correlator

$$\frac{1}{\sigma_2}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\Delta\phi} = \frac{1}{\sigma_2}\sum_{ij}\int \frac{\mathrm{d}\sigma\; x_{\perp,i}x_{\perp,j}}{\mathrm{d}x_{\perp,i}\mathrm{d}x_{\perp,j}\mathrm{d}\cos\Delta\phi_{ij}}\delta(\cos\Delta\phi - \cos\Delta\phi_{ij})\mathrm{d}x_{\perp,i}\mathrm{d}x_{\perp,j}\mathrm{d}\cos\Delta\phi_{ij}\,,$$

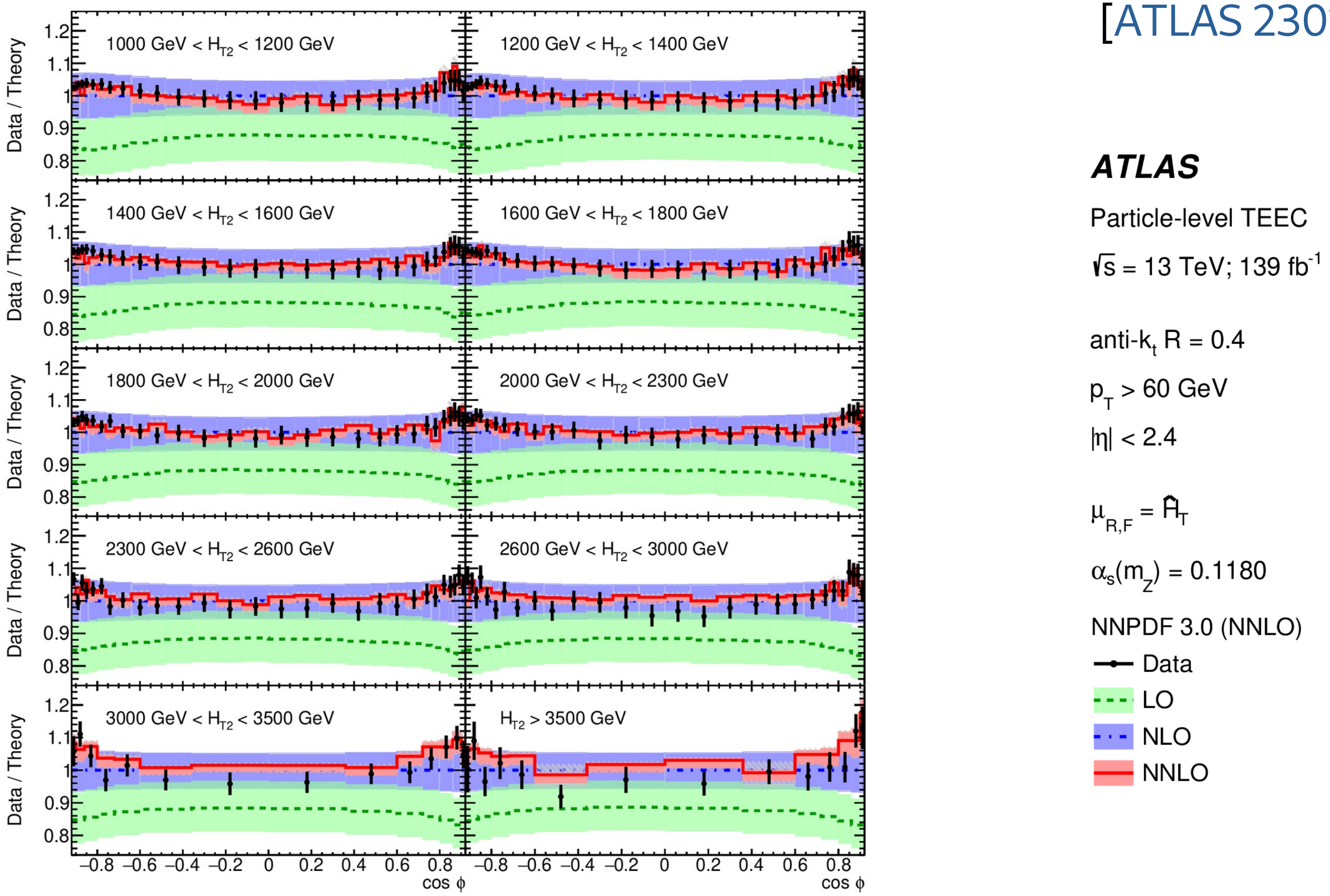
- Insensitive to soft radiation through energy weighting $x_{T,i} = E_{T,i}/\sum_j E_{T,j}$
- Event topology separation:
  - Central plateau contain isotropic events
  - To the right: self-correlations, collinear and in-plane splitting
  - To the left: back-to-back



[ATLAS 2301.09351]

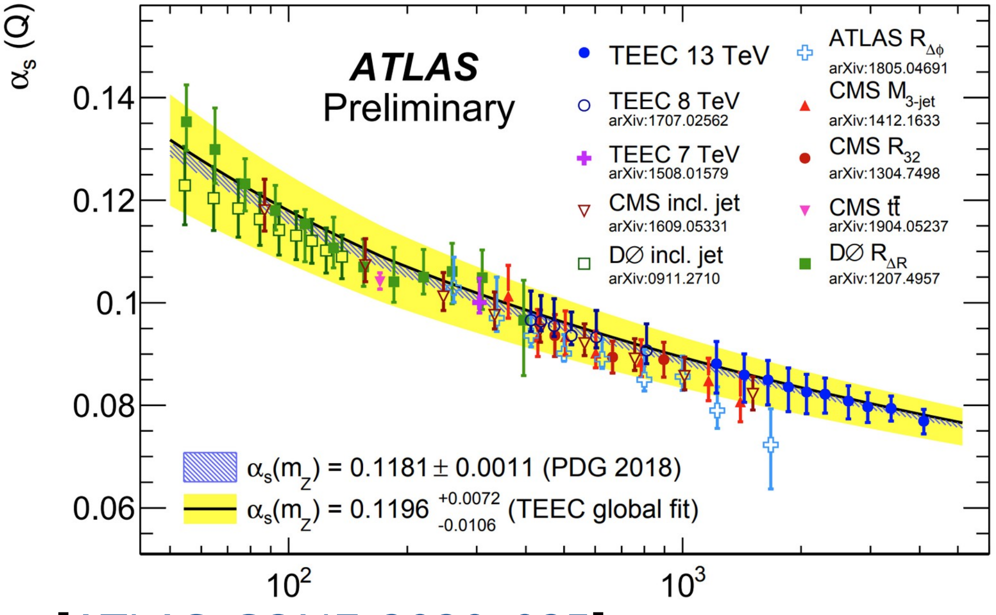
Double differential TEEC

[ATLAS 2301.09351]



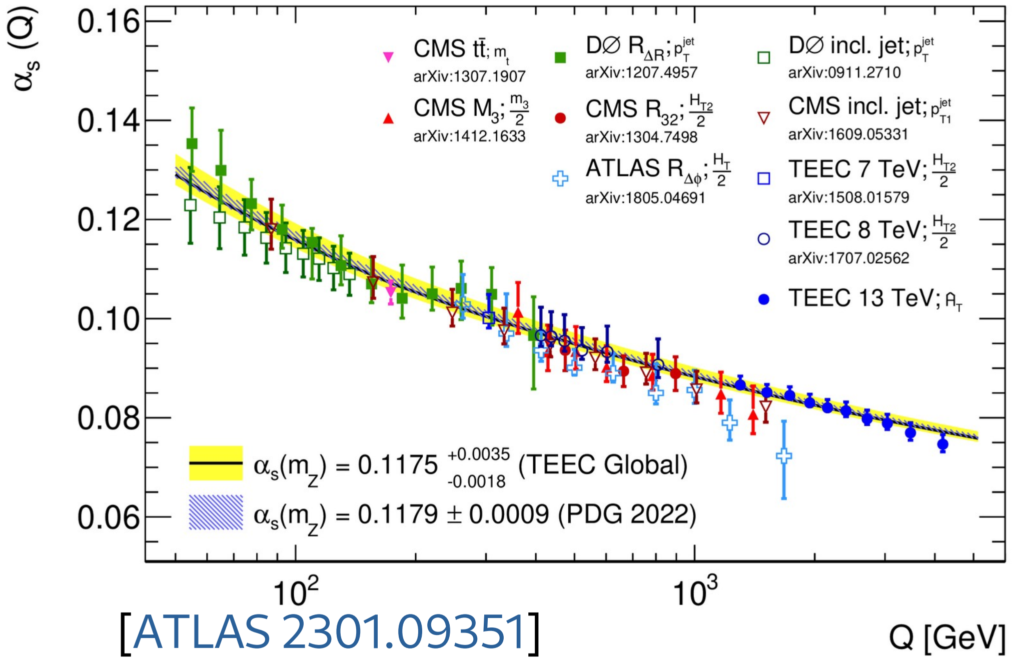
Running of α_S

NLO QCD



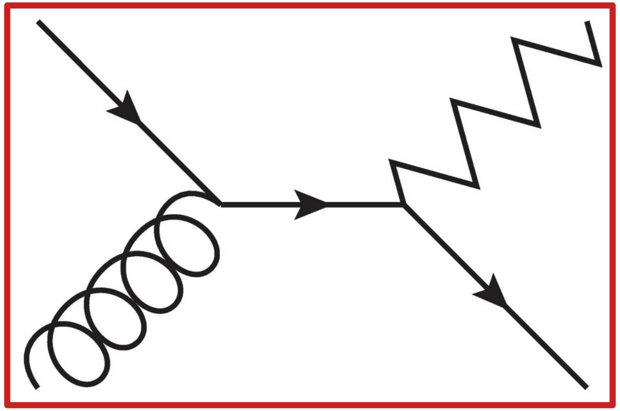
[ATLAS-CONF-2020-025]

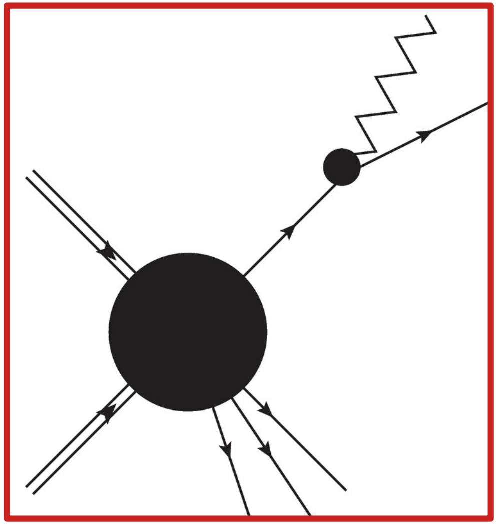
NNLO QCD



[ATLAS 2301.09351]

Prompt photon production

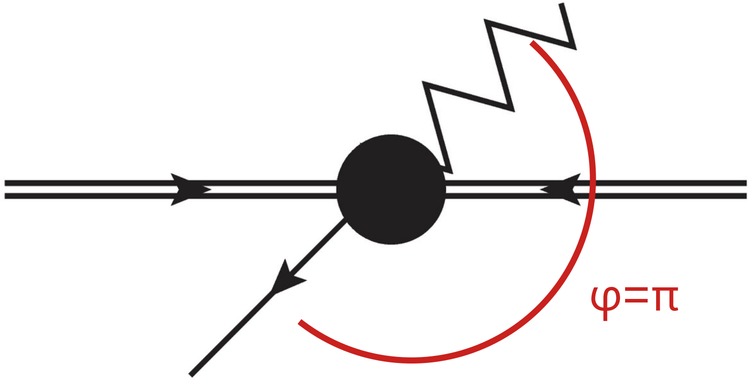


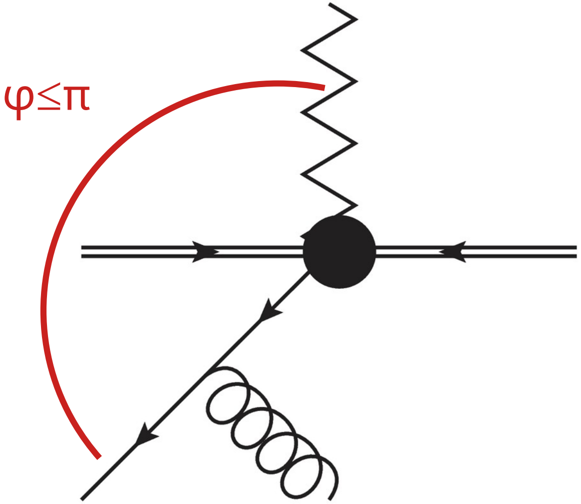


Direct production
- Test of perturbative QCD
- Gluon PDF sensitivity
- Estimates for BSM backgrounds

Fragmentation
- Depends on non-perturbative fragmentation functions
- Separation from “direct” not unique

Why photon plus a jet pair?





- Non-back-to-back Born configurations
  → access to angular correlations between the photon and jets
- Access to different kinematic regimes through distinguishable photon
  → enhance direct, high- or low-z fragmentation
- Background process for BSM: $pp \to \gamma + Y(\to jj)$

Photon plus jet pair

Measurement of isolated-photon plus two-jet production in pp collisions at sqrt(s) = 13 TeV with the ATLAS detector [1912.09866]

Requirements on photon	$E_T^\gamma > 150$ GeV, $\lvert\eta^\gamma\rvert < 2.37$ (excluding $1.37 < \lvert\eta^\gamma\rvert < 1.56$) $E_T^{\text{iso}} < 0.0042 \cdot E_T^\gamma + 4.8$ GeV (reconstruction level) $E_T^{\text{iso}} < 0.0042 \cdot E_T^\gamma + 10$ GeV (particle level)		
Requirements on jets	at least two jets using anti-k_t algorithm with $R = 0.4$ $p_T^{\text{jet}} > 100$ GeV, $\lvert y^{\text{jet}}\rvert < 2.5$, $\Delta R^{\gamma-\text{jet}} > 0.8$		
Phase space	**total**	**fragmentation enriched** $E_T^\gamma < p_T^{\text{jet2}}$	**direct enriched** $E_T^\gamma > p_T^{\text{jet1}}$
Number of events	755 270	111 666	386 846

Modelled with hybrid isolation

$$E_\perp(r) \leq E_{\perp\max}(r) = 0.1\, E_\perp(\gamma) \left(\frac{1-\cos(r)}{1-\cos(R_{\max})} \right)^2 \quad \text{for} \quad r \leq R_{\max} = 0.1$$

+

$$E_\perp(r) \leq E_{\perp\max} = 0.0042\, E_\perp(\gamma) + 10 \text{ GeV} \quad \text{for} \quad r \leq R_{\max} = 0.4$$

No fragmentation contribution
→ Purely pQCD through NNLO
→ focus on "inclusive" and "direct" PS

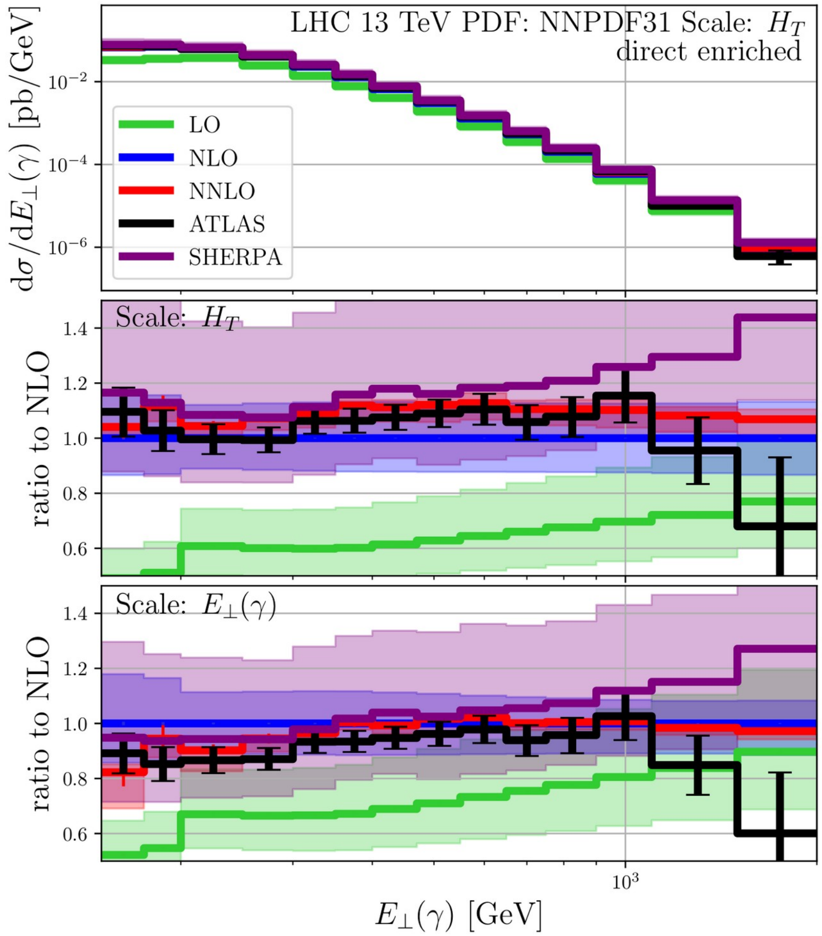
Theory - data comparisons

NNLO QCD

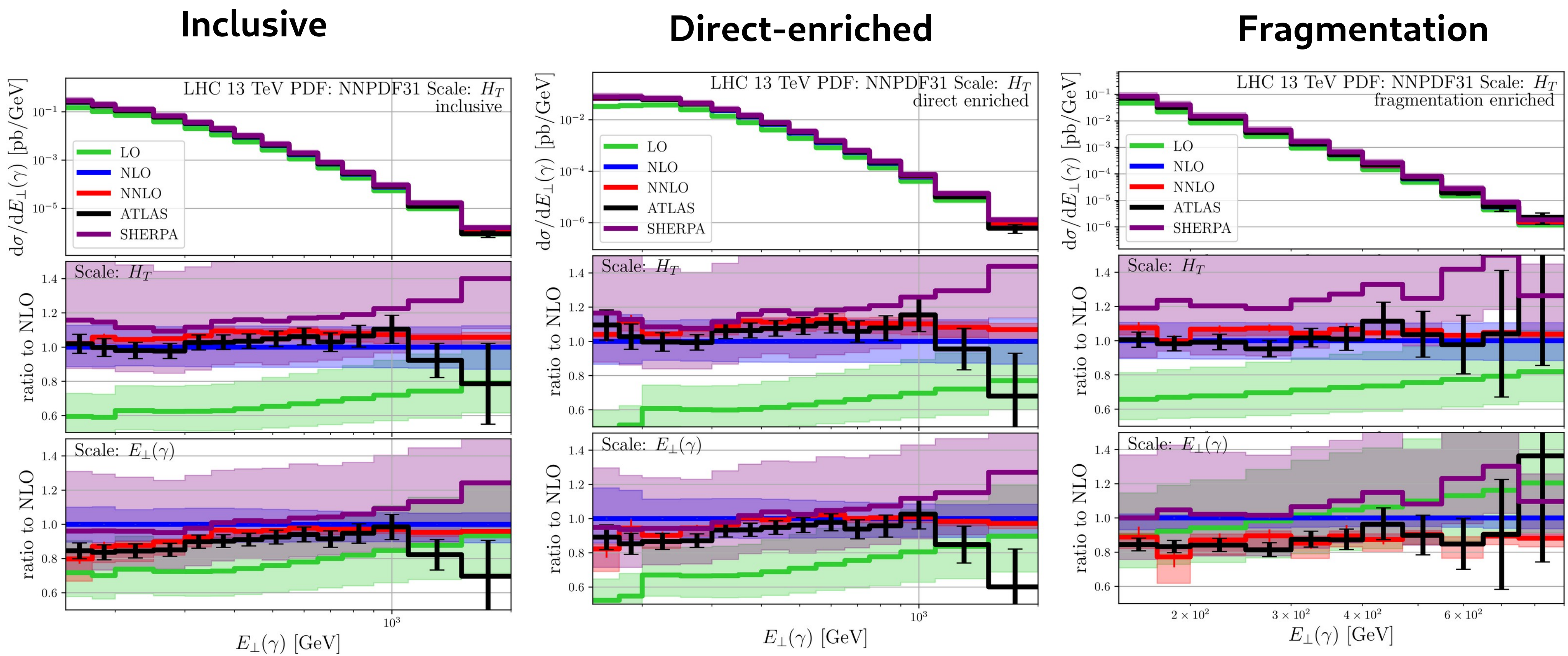
- Describes data well
- Improvements on the shape
- Small corrections
- Small remaining scale dependence

Comment on the SHERPA predictions

- Large NLO scale uncertainties
- The shape is not well described
- Maybe an artefact of multi-jet merging?



Inclusive vs. direct vs. fragmentation



Transverse photon energy

Scale choice

Full tree kinematics

$$\mu_R = \mu_F = H_T = E_\perp(\gamma) + p_T(j_1) + p_T(j_2)$$

$$\mu_R = \mu_F = E_\perp(\gamma) \ ,$$

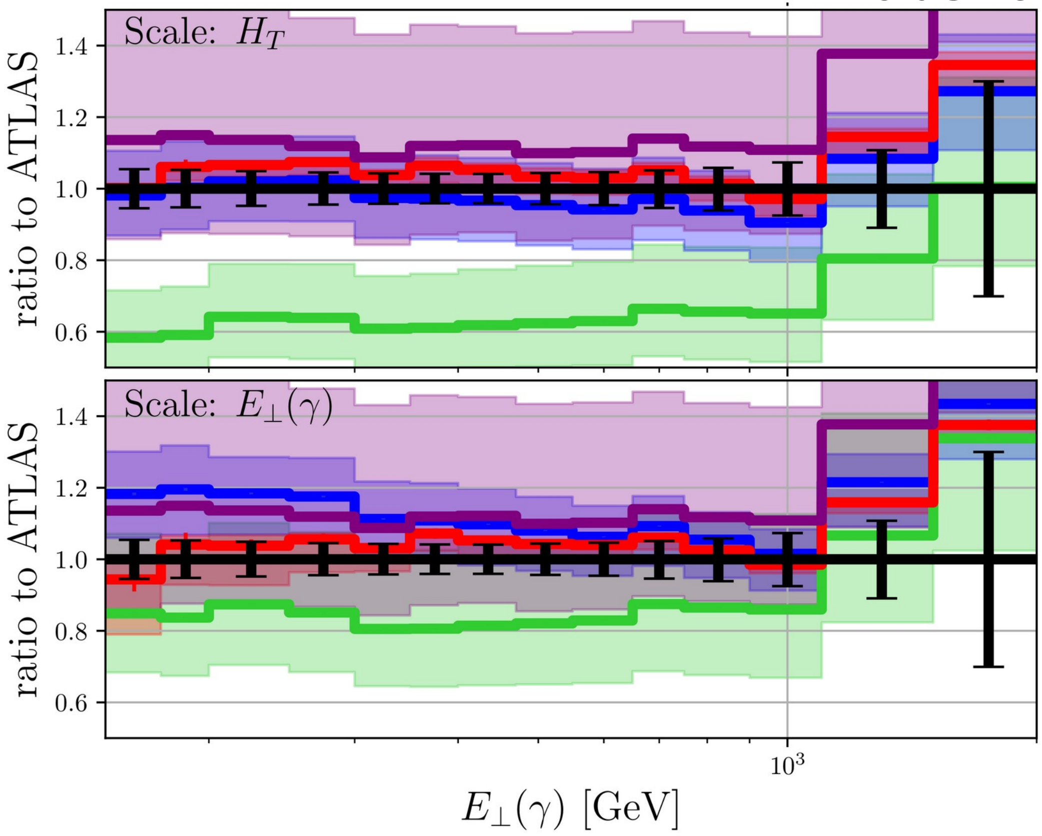
Only photon

Perturbative convergence

NNLO result similar **but** $E_\perp(\gamma)$

- Larger (negative) NNLO corrections
- Larger scale dependence (for jet obs.)

Inclusive



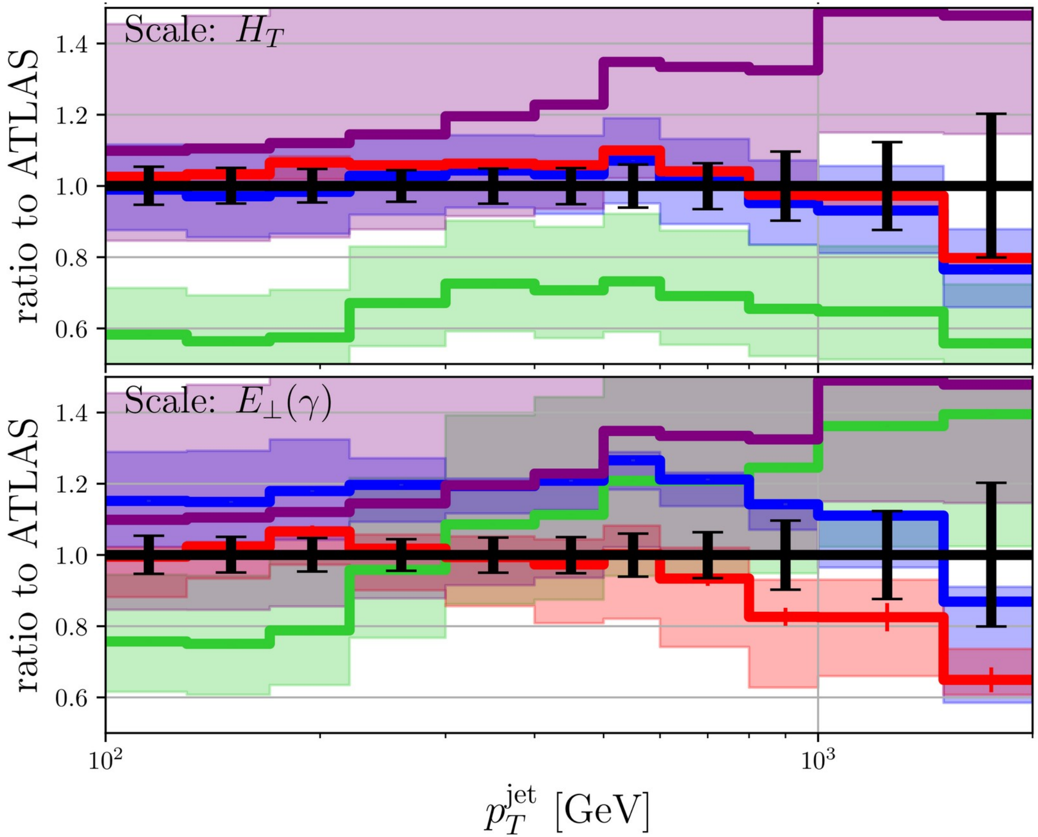
Scale choice

Full tree kinematics

$$\mu_R = \mu_F = H_T = E_\perp(\gamma) + p_T(j_1) + p_T(j_2)$$

$$\mu_R = \mu_F = E_\perp(\gamma)\ ,$$

Only photon



<u>Perturbative convergence</u>

NNLO result similar **but** $E_\perp(\gamma)$

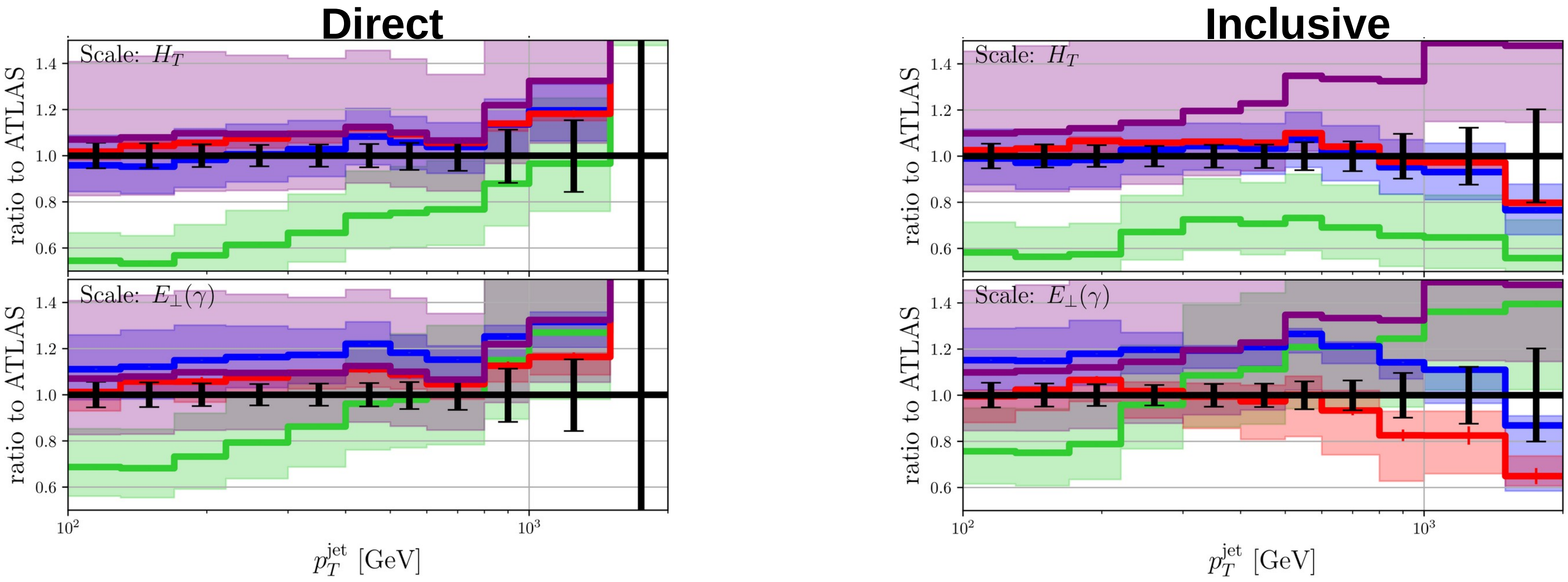
- Larger (negative) NNLO corrections
- Larger scale dependence (for jet obs.)

Scale choice

$E_\perp(\gamma)$ **does not capture relevant scales** for $pp \to \gamma + 2j$

- Better for "direct" enriched phase space $p_T(\gamma) > p_T(j_1)$
  → $E_\perp(\gamma)$ closer to $H_T = p_T(\gamma) + p_T(j_1) + p_T(j_2)$

NNLO QCD needed for this conclusion



Summary & Outlook

Overview 2 → 3 massless cross sections

$pp \to \gamma\gamma\gamma$

Sector-improved RS [1911.00479]
MATRIX [2010.04681]

$pp \to \gamma\gamma j$

Sector-improved RS [2105.06940]

$pp \to jjj$

Sector-improved RS
[2106.05331]
[2301.01086]
NNLOJET (gluons only)
[2203.13531]

Cross sections

$pp \to \gamma jj$

Sector-improved RS
[2304.06682]

Overview 2 → 3 massless amplitudes

$pp \to \gamma\gamma j$
[2102.01820]
[2103.04319]
[2105.04585]

$pp \to \gamma\gamma\gamma$
[1911.00479]
[2010.15834]
[2012.13553]

$pp \to jjj$
[1904.00945]
[2102.13609]
[2306.15431]

Integral representation in terms of **“Pentagon functions”** [2009.07803]

Amplitudes

Full colour

$pp \to \gamma jj$
[2304.06682]

→ $pp \to \gamma jj$ **first computation with full colour two-loop** matrix elements

Take home messages

- Precision phenomenology is stable of LHC physics
  → but requires higher-order corrections!
  → NNLO QCD or even higher orders are needed to keep up with experimental precision

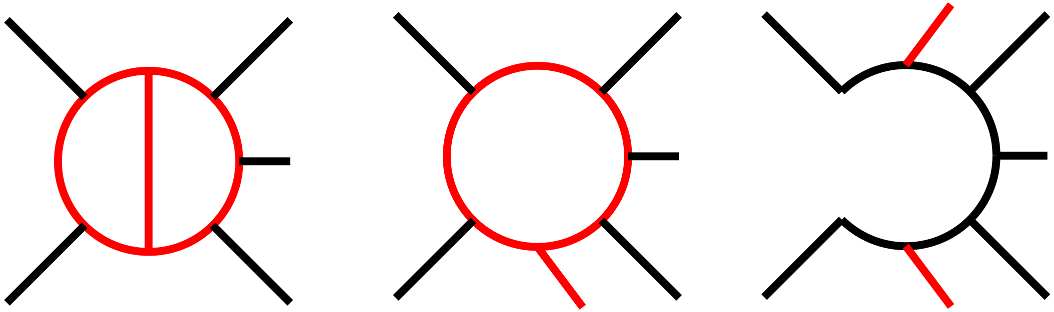
- Completion of massless 2→ 3 processes at hadron colliders through NNLO QCD

$$pp \to \gamma\gamma\gamma \qquad pp \to \gamma\gamma j \qquad pp \to \gamma j j \qquad pp \to jjj$$

- Most important bottlenecks from theory side:
  → Real radiation contributions
  (subtraction, Monte Carlo methods, efficiency, automation,…)
  → Two-loop amplitudes
  (including external/internal masses are the current frontier)

Backup

Sector-improved residue subtraction



Sector decomposition I

Considering working in CDR:

→ Virtuals are usually done in this regularization: $\hat{\sigma}_{ab}^{VV} = \sum_{i=-4}^{0} c_i \epsilon^i + \mathcal{O}(\epsilon)$

→ Can we write the real radiation as such expansion?

→ Difficult integrals, analytical impractical (except very simple observables)!

→ Numerics not possible, integrals are divergent → ε-poles!

How to extract these poles? → Sector decomposition!

Divide and conquer the phase space:

$$1 = \sum_{i,j} \left[\sum_k \mathcal{S}_{ij,k} + \sum_{k,l} \mathcal{S}_{i,k;j,l} \right] \quad \rightarrow \quad \hat{\sigma}_{ab}^{\mathrm{RR}} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n+2} \sum_{i,j} \left[\sum_k \mathcal{S}_{ij,k} + \sum_{k,l} \mathcal{S}_{i,k;j,l} \right] \left\langle \mathcal{M}_{n+2}^{(0)} \middle| \mathcal{M}_{n+2}^{(0)} \right\rangle \mathrm{F}_{n+2}$$

Sector decomposition II

Divide and conquer the phase space

- Each $\mathcal{S}_{i,k}$ (NLO), $\mathcal{S}_{ij,k}/\mathcal{S}_{i,k;j,l}$ (NNLO) has simpler divergences:
  - Soft limits of partons i and j
  - Collinear w.r.t partons k (and l) of partons i and j

$$\mathcal{S}_{i,k} = \frac{1}{D_1 d_{i,k}} \quad D_1 = \sum_{ik} \frac{1}{d_{i,k}} \qquad d_{i,k} = \frac{E_i}{\sqrt{s}}(1 - \cos\theta_{ik})$$

- Parametrization w.r.t. reference parton makes divergences explicit

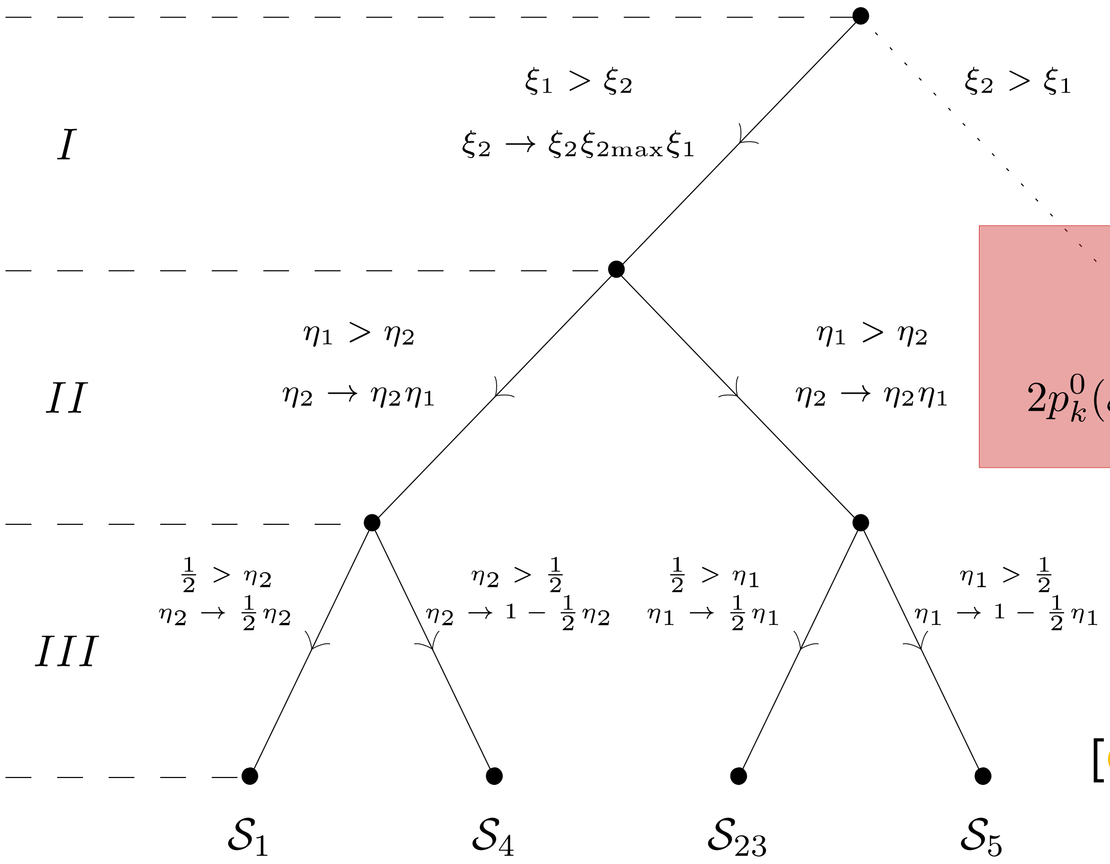
$$\hat{\eta}_i = \tfrac{1}{2}(1 - \cos\theta_{ik}) \in [0,1] \qquad \hat{\xi}_i = \frac{u_i^0}{u_{\max}^0} \in [0,1]$$

- Example: Splitting function

$$\sim \frac{1}{s_{ik}} P(z) \qquad s_{ik} = (p_i + p_k)^2 = 2p_k^0 u_{\max}^0 \xi_i \eta_i \qquad \sim \frac{1}{\eta_i \xi_i}$$

Sector decomposition II – triple collinear factorization

Three particle invariant does not factorize trivially:



Double soft factorization:

$$\theta(u_i^0 - u_j^0) + \theta(u_i^0 - u_j^0)$$

$$(p_k + u_i + u_j)^2 =$$

$$2p_k^0(\xi_i \eta_i u_{\max}^{0,i} + \xi_j \eta_j u_{\max}^{0,j} + \xi_i \xi_j \frac{u_{max}^{0,i} u_{max}^{0,j}}{p_k^0} \angle(u_i, u_j))$$

[Czakon'10,Caola'17]

Sector decomposition III

Factorized singular limits in each sector:

$$\frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n+2}\, \mathcal{S}_{kl,m} \left\langle \mathcal{M}^{(0)}_{n+2} \middle| \mathcal{M}^{(0)}_{n+2} \right\rangle \mathrm{F}_{n+2} = \sum_{\text{sub-sec.}} \int \mathrm{d}\Phi_n \prod \mathrm{d}x_i \underbrace{x_i^{-1-b_i\epsilon}}_{\text{singular}} \mathrm{d}\tilde{\mu}(\{x_i\}) \underbrace{\prod x_i^{a_i+1} \langle \mathcal{M}_{n+2} | \mathcal{M}_{n+2} \rangle}_{\text{regular}} \mathrm{F}_{n+2}$$

$$x_i \in \{\eta_1, \xi_1, \eta_2, \xi_2\}$$

Regularization of divergences:

$$x^{-1-b\epsilon} = \underbrace{\frac{-1}{b\epsilon}}_{\text{pole term}} + \underbrace{\left[x^{-1-b\epsilon}\right]_+}_{\text{reg. + sub.}}$$

$$\int_0^1 \mathrm{d}x \left[x^{-1-b\epsilon}\right]_+ f(x) = \int_0^1 \frac{f(x) - f(0)}{x^{1+b\epsilon}}$$

Finite NNLO cross section

$$\hat{\sigma}_{ab}^{\mathrm{RR}} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n+2} \left\langle \mathcal{M}_{n+2}^{(0)} \middle| \mathcal{M}_{n+2}^{(0)} \right\rangle \mathrm{F}_{n+2}$$

$$\hat{\sigma}_{ab}^{\mathrm{RV}} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n+1}\, 2\mathrm{Re} \left\langle \mathcal{M}_{n+1}^{(0)} \middle| \mathcal{M}_{n+1}^{(1)} \right\rangle \mathrm{F}_{n+1}$$

$$\hat{\sigma}_{ab}^{\mathrm{VV}} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n} \left(2\mathrm{Re} \left\langle \mathcal{M}_{n}^{(0)} \middle| \mathcal{M}_{n}^{(2)} \right\rangle + \left\langle \mathcal{M}_{n}^{(1)} \middle| \mathcal{M}_{n}^{(1)} \right\rangle \right) \mathrm{F}_{n}$$

$$\hat{\sigma}_{ab}^{\mathrm{C1}} = (\text{single convolution})\, \mathrm{F}_{n+1}$$

$$\hat{\sigma}_{ab}^{\mathrm{C2}} = (\text{double convolution})\, \mathrm{F}_{n}$$

sector decomposition and master formula

$$x^{-1-b\epsilon} = \underbrace{\frac{-1}{b\epsilon}}_{\text{pole term}} + \underbrace{\left[x^{-1-b\epsilon}\right]_+}_{\text{reg. + sub.}}$$

$$(\sigma_F^{RR}, \sigma_{SU}^{RR}, \sigma_{DU}^{RR}) \quad (\sigma_F^{RV}, \sigma_{SU}^{RV}, \sigma_{DU}^{RV}) \quad (\sigma_F^{VV}, \sigma_{DU}^{VV}, \sigma_{FR}^{VV}) \quad (\sigma_{SU}^{C1}, \sigma_{DU}^{C1}) \quad (\sigma_{DU}^{C2}, \sigma_{FR}^{C2})$$

re-arrangement of terms → 4-dim. formulation [Czakon'14, Czakon'19]

$$(\sigma_F^{RR}) \quad (\sigma_F^{RV}) \quad (\sigma_F^{VV}) \quad (\sigma_{SU}^{RR}, \sigma_{SU}^{RV}, \sigma_{SU}^{C1}) \quad (\sigma_{DU}^{RR}, \sigma_{DU}^{RV}, \sigma_{DU}^{VV}, \sigma_{DU}^{C1}, \sigma_{DU}^{C2}) \quad (\sigma_{FR}^{RV}, \sigma_{FR}^{VV}, \sigma_{FR}^{C2})$$

separately finite: ε poles cancel

Improved phase space generation

Phase space cut and differential observable introduce

mis-binning : mismatch between kinematics in subtraction terms

→ leads to increased variance of the integrand

→ slow Monte Carlo convergence

New phase space parametrization [Czakon'19]:

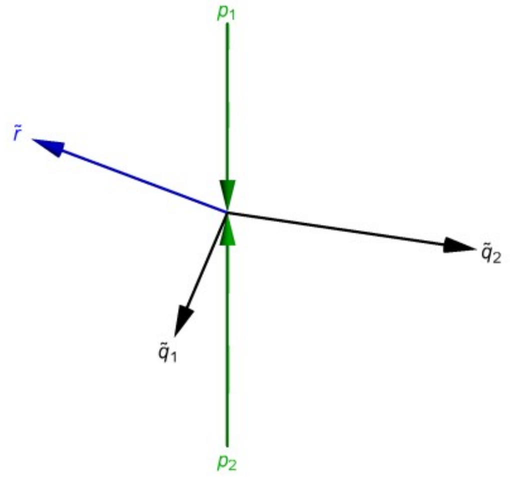
Minimization of # of different subtraction kinematics in each sector

Improved phase space generation

New phase space parametrization:

Minimization of # of different subtraction kinematics in each sector

Mapping from n+2 to n particle phase space: $\{P, r_j, u_k\} \to \left\{\tilde{P}, \tilde{r}_j\right\}$



Requirements:

- Keep direction of reference r fixed
- Invertible for fixed u_i : $\left\{\tilde{P}, \tilde{r}_j, u_k\right\} \to \{P, r_j, u_k\}$
- Preserve Born invariant mass: $q^2 = \tilde{q}^2\,, \quad \tilde{q} = \tilde{P} - \sum_{j=1}^{n_{fr}} \tilde{r}_j$

Main steps:

- Generate Born configuration
- Generate unresolved partons u_i
- Rescale reference momentum $r = x\tilde{r}$
- Boost non-reference momenta of the Born configuration

Improved phase space generation

New phase space parametrization:

Minimization of # of different subtraction kinematics in each sector

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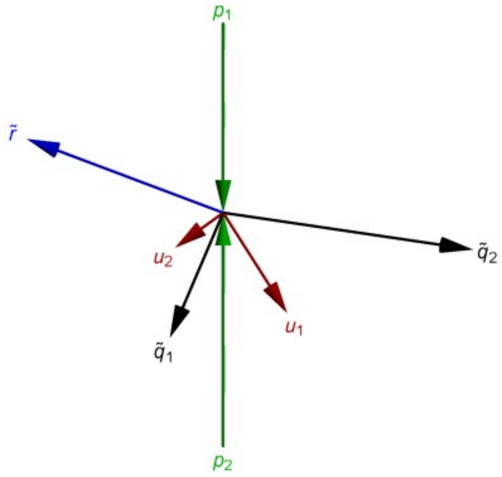

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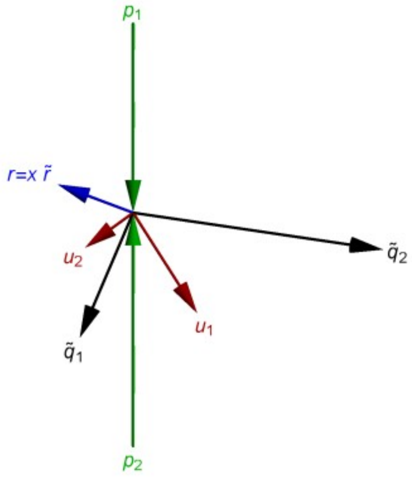

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- Invertible for fixed u_i: $\left\{\tilde{P}, \tilde{r}_j, u_k\right\} \to \{P, r_j, u_k\}$
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Main steps:

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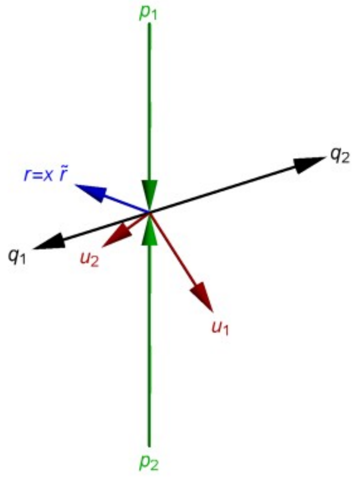


Requirements:

- Keep direction of reference r fixed
- Invertible for fixed u_i: $\left\{\tilde{P}, \tilde{r}_j, u_k\right\} \to \{P, r_j, u_k\}$
- Preserve Born invariant mass: $q^2 = \tilde{q}^2\,,\quad \tilde{q} = \tilde{P} - \sum_{j=1}^{n_{fr}} \tilde{r}_j$

Main steps:

- Generate Born configuration
- Generate unresolved partons u_i
- Rescale reference momentum $r = x\tilde{r}$
- Boost non-reference momenta of the Born configuration

t'HV corrections

Observables: Implemented by infrared safe measurement function (MF) F_m

Infrared property in STRIPPER context:

- $\{x_i\} \to 0 \leftrightarrow$ single unresolved limit
  $\Rightarrow \mathrm{F}_{n+2} \to \mathrm{F}_{n+1}$
- $\{x_i\} \to 0 \leftrightarrow$ double unresolved limit
  $\Rightarrow \mathrm{F}_{n+2} \to \mathrm{F}_n$
  $\Rightarrow \mathrm{F}_{n+1} \to \mathrm{F}_n$

Tool for new formulation in the 't Hooft Veltman scheme:

Parameterized MF $\mathrm{F}^{\alpha}_{n+1}$

- $\mathrm{F}^{\alpha}_n \equiv 0$ for $\alpha \neq 0$
  (NLO MF)
- 'arbitrary' F^0_n
  (NNLO MF)
- $\alpha \neq 0 \Rightarrow$ DU $= 0$ and SU separately finite

Example: $F^{\alpha}_{n+1} = F_{n+1}\Theta_{\alpha}(\{\alpha_i\})$
with $\Theta_{\alpha} = 0$ if some $\alpha_i < \alpha$

t'HV corrections

$$\sigma_{SU} = \sigma_{SU}^{RR} + \sigma_{SU}^{RV} + \sigma_{SU}^{C1} \qquad \text{where} \qquad \sigma_{SU}^{c} = \int \mathrm{d}\Phi_{n+1} \left(I_{n+1}^{\mathrm{c}} F_{n+1} + I_{n}^{\mathrm{c}} F_{n} \right)$$

NLO measurement function ($\alpha \neq 0$):

$$\int \mathrm{d}\Phi_{n+1} \left(I_{n+1}^{\mathrm{RR}} + I_{n+1}^{\mathrm{RV}} + I_{n+1}^{\mathrm{C1}} \right) F_{n+1}^{\alpha} = \text{finite in 4 dim.}$$

All divergences cancel in d-dimensions:

$$\sum_{c} \int \mathrm{d}\Phi_{n+1} \left[\frac{I_{n+1}^{c,(-2)}}{\epsilon^2} + \frac{I_{n+1}^{c,(-1)}}{\epsilon} \right] F_{n+1}^{\alpha} \equiv \sum_{c} \mathcal{I}^{c} = 0$$

t'HV corrections

$$\sigma_{SU} = \sigma_{SU}^{RR} + \sigma_{SU}^{RV} + \sigma_{SU}^{C1} \underbrace{-\mathcal{I}^{RR} - \mathcal{I}^{RV} - \mathcal{I}^{C1}}_{=0}$$

$$\begin{aligned}
\sigma_{SU}^{c} - \mathcal{I}^{c} &= \int \mathrm{d}\Phi_{n+1} \left\{ \left[\frac{I_{n+1}^{c,(-2)}}{\epsilon^2} + \frac{I_{n+1}^{c,(-1)}}{\epsilon} + I_{n+1}^{c,(0)} \right] F_{n+1} + \left[\frac{I_{n}^{c,(-2)}}{\epsilon^2} + \frac{I_{n}^{c,(-1)}}{\epsilon} + I_{n}^{c,(0)} \right] F_{n} \right\} \\
&\quad - \int \mathrm{d}\Phi_{n+1} \left[\frac{I_{n+1}^{c,(-2)}}{\epsilon^2} + \frac{I_{n+1}^{c,(-1)}}{\epsilon} \right] F_{n+1}\Theta_{\alpha}(\{\alpha_i\}) \\
&= \int \mathrm{d}\Phi_{n+1} \left[\frac{I_{n+1}^{c,(-2)} F_{n+1} + I_{n}^{c,(-2)} F_{n}}{\epsilon^2} + \frac{I_{n+1}^{c,(-1)} F_{n+1} + I_{n}^{c,(-1)} F_{n}}{\epsilon} \right] (1 - \Theta_{\alpha}(\{\alpha_i\})) \\
&\quad + \int \mathrm{d}\Phi_{n+1} \left[I_{n+1}^{c,(0)} F_{n+1} + I_{n}^{c,(0)} F_{n} \right] + \int \mathrm{d}\Phi_{n+1} \left[\frac{I_{n}^{c,(-2)}}{\epsilon^2} + \frac{I_{n}^{c,(-1)}}{\epsilon} \right] F_{n}\Theta_{\alpha}(\{\alpha_i\})
\end{aligned}$$

$$=: \underbrace{Z^{c}(\alpha)}_{\text{integrable, zero volume for } \alpha \to 0} + \underbrace{C^{c}}_{\text{no divergencies}} + \underbrace{N^{c}(\alpha)}_{\text{only } F_n \to \text{DU}}$$

t'HV corrections

Looks like slicing, but it is slicing *only* for divergences
$\rightarrow$ no actual slicing parameter in result

Powerlog-expansion:

$$N^c(\alpha) = \sum_{k=0}^{\ell_{\max}} \ln^k(\alpha) N_k^c(\alpha)$$

- all $N_k^c(\alpha)$ regular in α
- start expression independent of $\alpha \Rightarrow$ all logs cancel
- only $N_0^c(0)$ relevant

Putting parts together:

$$\sigma_{SU} - \sum_c N_0^c(0) \text{ and } \sigma_{DU} + \sum_c N_0^c(0)$$

are finite in 4 dimension

$\Downarrow$

SU contribution: $\sigma_{SU} - \sum_c N_0^c = \sum_c C^c$
original expression σ_{SU} in 4-dim without poles, no further ϵ pole cancellation

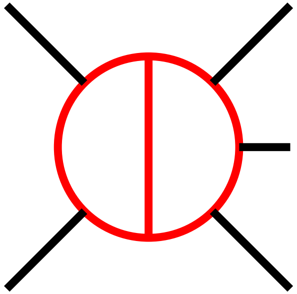
C++ framework

- Formulation allows efficient algorithmic implementation → STRIPPER
- **High degree of automation**:
  - Partonic processes (taking into account all symmetries)
  - Sectors and subtraction terms
  - Interfaces to Matrix-element providers + O(100) hardcoded:
    AvH, OpenLoops, Recola, NJET, HardCoded

    → In practice: Only two-loop matrix elements required
- **Broad range of applications** through additional facilities:
  - Narrow-Width & Double-Pole Approximation
  - Fragmentation
  - Polarised intermediate massive bosons
  - (Partial) Unweighting → Event generation for **HighTEA**
  - Interfaces: FastNLO, FastJet

Two-loop five-point amplitudes

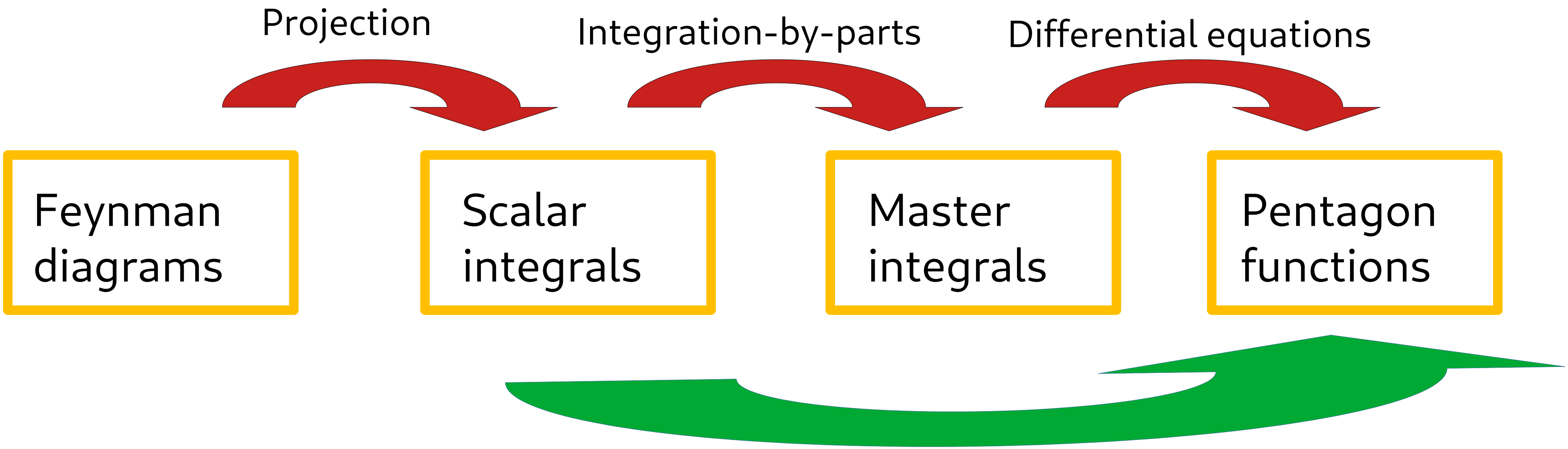
Massless:
[Chawdry'19'20'21] (3A+2j,2A+3j)
[Abreu'20'21] (3A+2j,5j)
[Agarwal'21] (2A+3j)
[Badger'21'23] (5j,gggAA,jjjjA)



1 external mass:
[Abreu'21] (W+4j)
[Badger'21'22] (Hqqgg,W4q,Wajjj)
[Hartanto'22] (W4q)

Overview

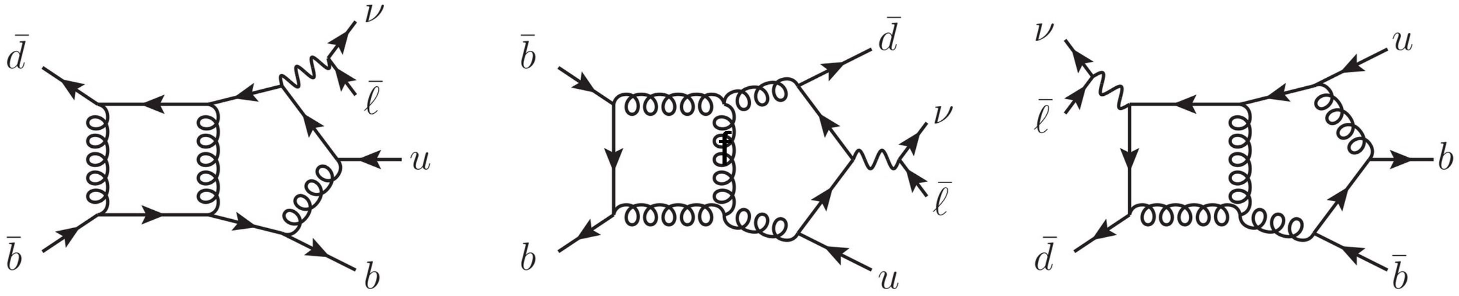
Old school approach:



Automated framework using finite fields to avoid expression swell based on FiniteFlow [Peraro'19]

Projection to scalar integrals

Generate diagrams (contributing to leading-colour) with QGRAF



Factorizing decay: $A_6^{(L)} = A_5^{(L)\mu} D_\mu P$ $\qquad$ $M_6^{2(L)} = \sum_{\text{spin}} A_6^{(0)^*} A_6^{(L)} = M_5^{(L)\mu\nu} D_{\mu\nu} |P|^2$

Projection on scalar functions (FORM+Mathematica):
→ anti-commuting γ_5 + Larin prescription

$$M_5^{(L)\mu\nu} = \sum_{i=1}^{16} a_i^{(L)} v_i^{\mu\nu}$$

$$a_i^{(L)} = a_i^{(L),\text{even}} + \text{tr}_5 a_i^{(L),\text{odd}} \qquad a_i^{(L),p} = \sum_i c_{j,i}(\{p\},\epsilon)\mathcal{I}(\{p\},\epsilon)$$

Integration-By-Parts reduction

$$a_i^{(L),p} = \sum_i c_{j,i}(\{p\},\epsilon)\mathcal{I}(\{p\},\epsilon)$$

→ prohibitively large number of integrals

$$\mathcal{I}_i(\{p\},\epsilon) \equiv \mathcal{I}(\vec{n_i},\{p\},\epsilon) = \int \frac{\mathrm{d}^d k_1}{(2\pi)^d}\frac{\mathrm{d}^d k_2}{(2\pi)^d}\prod_{k=1}^{11} D_k^{-n_{i,k}}(\{p\},\{k\})$$

Integration-By-Parts identities connect different integrals → system of equations
→ only a small number of independent "master" integrals

$$0 = \int \frac{\mathrm{d}^d k_1}{(2\pi)^d}\frac{\mathrm{d}^d k_2}{(2\pi)^d} l_\mu \frac{\partial}{\partial l^\mu}\prod_{k=1}^{11} D_k^{-n_{i,k}}(\{p\},\{k\}) \quad \text{with} \quad l \in \{p\} \cap \{k\}$$

LiteRed (+ Finite Fields)

→

$$a_i^{(L),p} = \sum_i d_{j,i}(\{p\},\epsilon)\mathrm{MI}(\{p\},\epsilon)$$

Master integrals & finite remainder

Differential Equations: $\mathrm{d}\vec{\mathrm{MI}} = \mathrm{d}A(\{p\},\epsilon)\vec{\mathrm{MI}}$

Canonical basis: $\mathrm{d}\vec{\mathrm{MI}} = \epsilon \mathrm{d}\tilde{A}(\{p\})\vec{\mathrm{MI}}$

[Remiddi, 97]
[Gehrmann, Remiddi, 99]
[Henn, 13]

Simple iterative solution

$$\mathrm{MI}_i = \sum_w \epsilon^w \tilde{\mathrm{MI}}_i^w \quad \text{with} \quad \tilde{\mathrm{MI}}_i^w = \sum_j c_{i,j} m_j$$

Chen-iterated integrals
"Pentagon"-functions

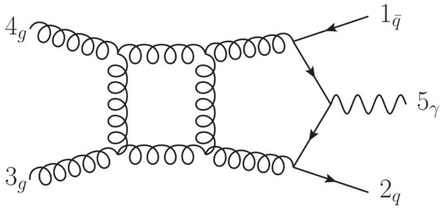
[Chicherin, Sotnikov, 20]
[Chicherin, Sotnikov, Zoia, 21]

Putting everything together (and removing of IR poles):

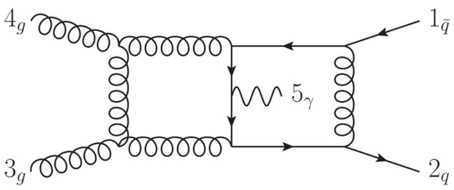
$$f_i^{(L),p} = a_i^{(L),p} - \text{poles} \qquad f_i^{(L),p} = \sum_j c_{i,j}(\{p\}) m_j + \mathcal{O}(\epsilon)$$

Reconstruction of Amplitudes

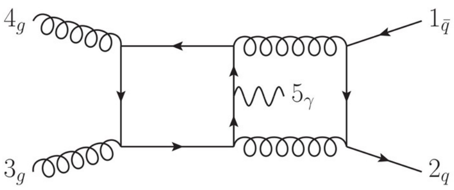
[Badger'21]



$A^{(2),N_c^2}_{34;q}, A^{(2),N_c}_{\delta;q}$



$A^{(2),1}_{34;q}, A^{(2),N_c}_{\delta;q}, A^{(2),1/N_c}_{\delta;q}$



$A^{(2),N_c}_{34;l}, A^{(2),1/N_c}_{34;l}, A^{(2),1/N_c^2}_{\delta;l}$

New optimizations

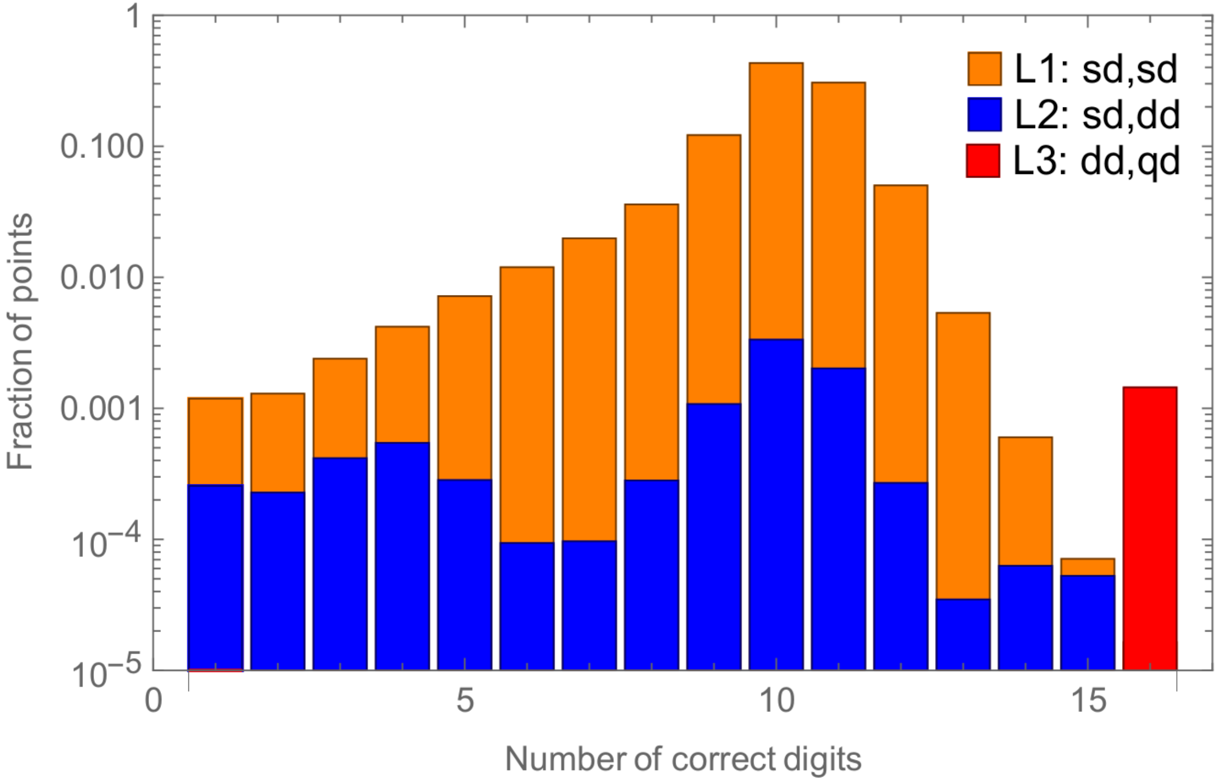
- Syzygy's to simplify IBPs
- Exploitation of Q-linear relations
- Denominator Ansaetze
- On-the-fly partial fractioning

amplitude	helicity	original	stage 1	stage 2	stage 3	stage 4
$A^{(2),1}_{34;q}$	$-++-+$	94/91	74/71	74/0	22/18	22/0
$A^{(2),1}_{34;q}$	$-+-++$	93/89	90/86	90/0	24/14	18/0
$A^{(2),1/N_c^2}_{34;q}$	$-++-+$	90/88	73/71	73/0	23/18	22/0
$A^{(2),1/N_c^2}_{34;q}$	$-+-++$	90/86	86/82	86/0	24/14	19/0
$A^{(2),1/N_c}_{34;l}$	$-+-++$	89/82	74/67	73/0	27/14	20/0
$A^{(2),1/N_c}_{34;l}$	$-++-+$	85/81	61/58	60/0	27/18	20/0
$A^{(2),N_c^2}_{34;q}$	$-+-++$	58/55	54/51	53/0	20/16	20/0

Massive reduction of complexity

Two-loop matrix element stability

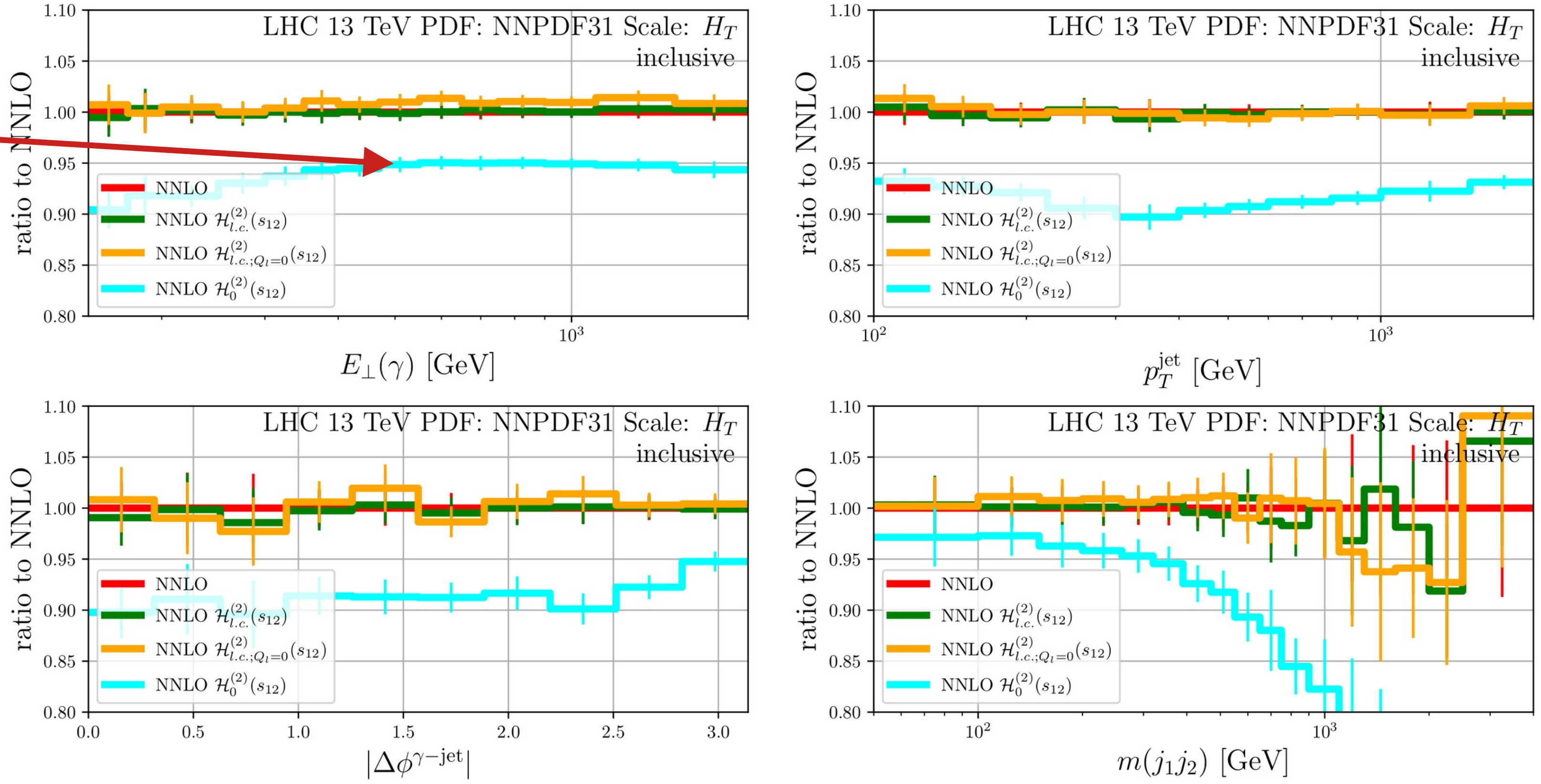
- Stable evaluation requires high floating point precision for rational functions
- In rarer cases higher precision “Pentagon” functions necessary
- 2.2 million events needed → fast evaluation essential



Quality of leading colour the approximation

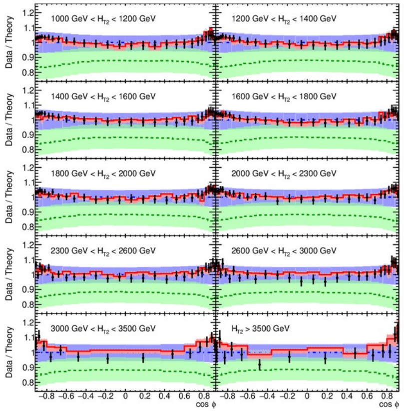
Two-loop
contribution
~ 5-10%
wrt. full NNLO
(scheme dep.)

“Leading colour”
Approximation
”Error” = O(~1%)
wrt full NNLO



HighTEA

HighTEA



= ~100 MCPUh

How to make this more efficient/environment-friendly/ accessible/faster?

high tea
for your freshly brewed analysis

https://www.precision.hep.phy.cam.ac.uk/hightea

HighTEA: **High energy Theory Event Analyser**
[2304.05993]

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Basic idea

- Database of precomputed “Theory Events”
  - **Equivalent to a full fledged computation**
  - Currently this means partonic fixed order events
  - Extensions to included showered/resummed/hadronized events is feasible
  - (Partially) Unweighting to increase efficiency
- Analysis of the data through an user interface
  - Easy-to-use
  - Fast
  - Flexible:
    - Observables from basic 4-momenta
    - Free specification of bins
    - Renormalization/Factorization Scale variation
    - PDF (member) variation
    - Specify phase space cuts

Not so new idea:
LHE [Alwall et al ‘06],
Ntuple [BlackHat ‘08’13],

Factorizations

Factorizing renormalization and factorization scale dependence:

$$w_s^{i,j} = w_{\mathrm{PDF}}(\mu_F, x_1, x_2) w_{\alpha_s}(\mu_R) \left(\sum_{i,j} c_{i,j} \ln\left(\mu_R^2\right)^i \ln\left(\mu_F^2\right)^j \right)$$

PDF dependence:

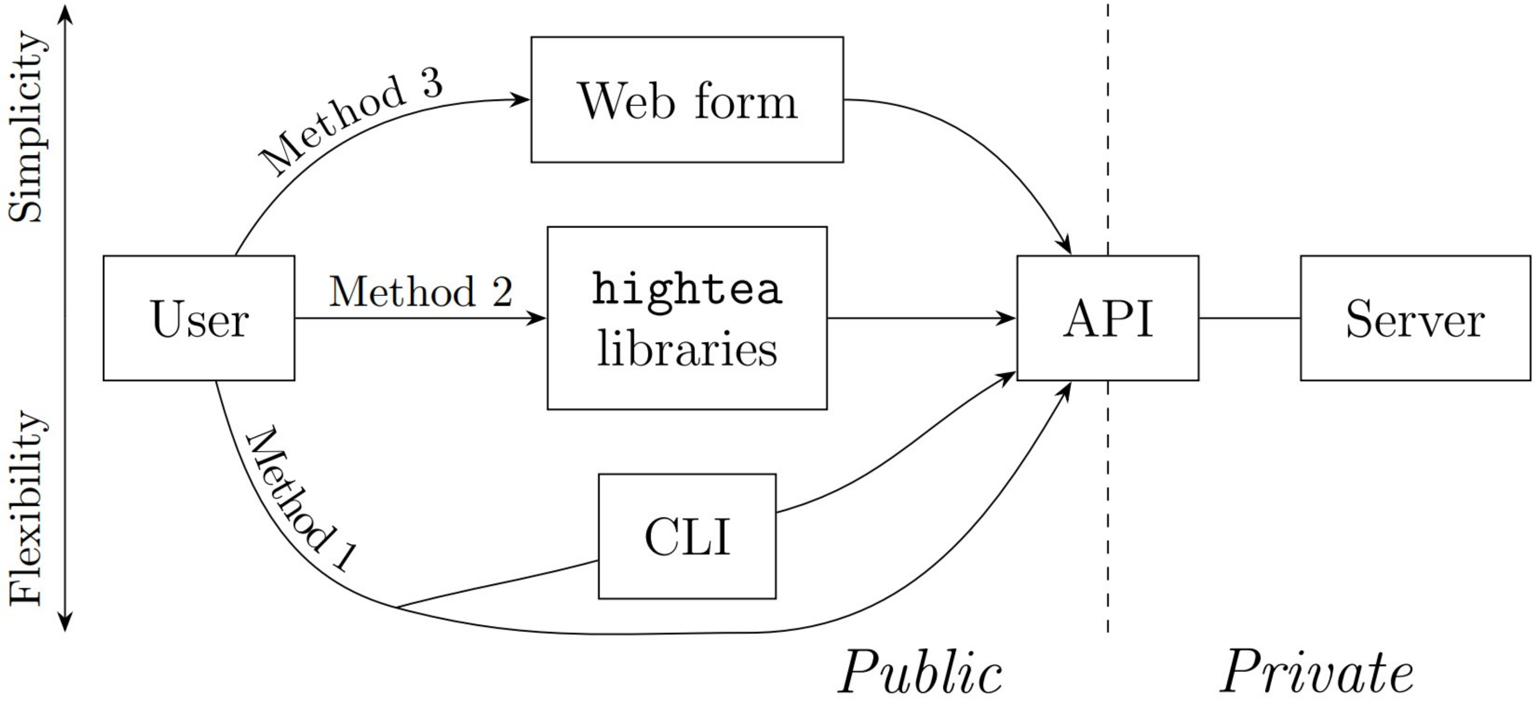
$$w_{\mathrm{PDF}}(\mu, x_1, x_2) = \sum_{ab \in \mathrm{channel}} f_a(x_1, \mu) f_b(x_2, \mu)$$

α_s dependence:

$$w_{\alpha_s}(\mu) = (\alpha_s(\mu))^m$$

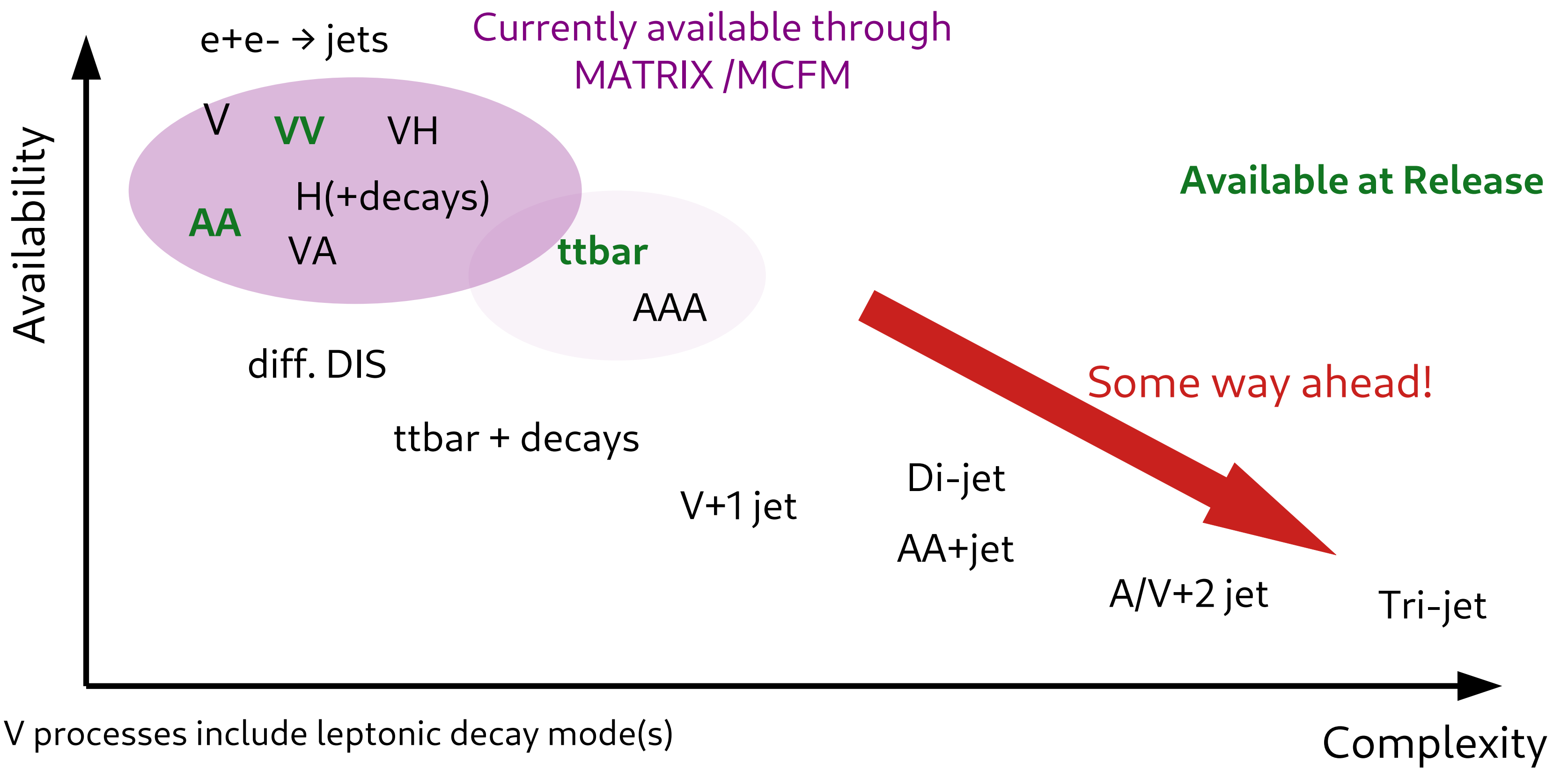
Allows **full control over scales and PDF**

HighTEA interface



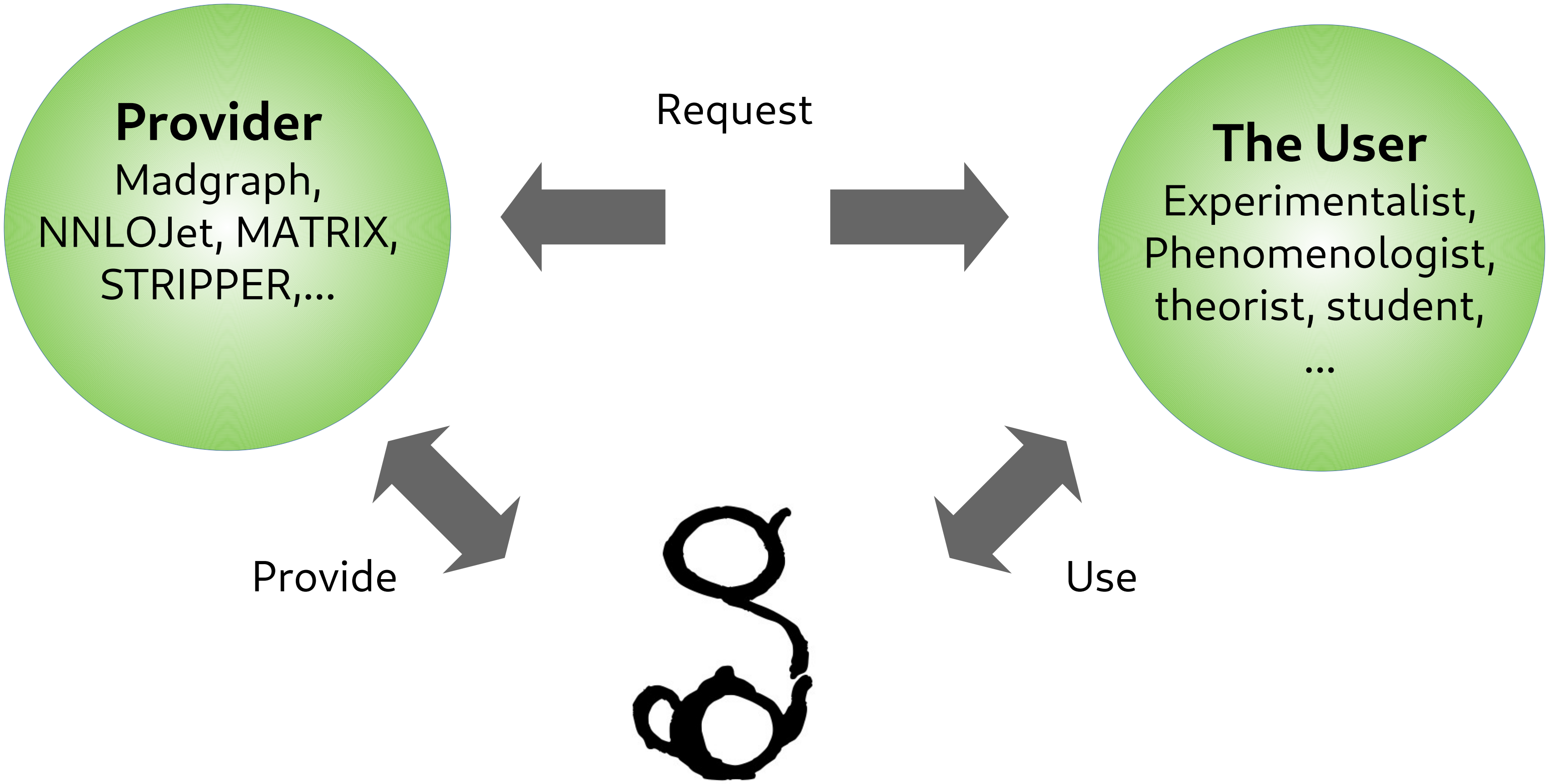
Available Processes

Processes currently implemented in our STRIPPER framework through NNLO QCD



* V processes include leptonic decay mode(s)

The Vision


Provider
Madgraph,
NNLOJet, MATRIX,
STRIPPER,…
Request
The User
Experimentalist,
Phenomenologist,
theorist, student,
…
Provide
Use

Transverse Thrust @ NNLO QCD

NNLO QCD corrections to event shapes at the LHC
Alvarez, Cantero, Czakon, Llorente, Mitov, Poncelet [2301.01086]

ATLAS [2007.12600]