ALPHA-S@LHC: Towards the most precise determination of the strong coupling with LHC data

Letter of Intent

Patrick L.S. Connor

Organisation européenne pour la recherche nucléaire

2 July 2025

Introduction

$\Delta\alpha \approx 10^{-10} \ll \Delta G_F \approx 10^{-7} \ll \Delta G \approx 10^{-4} \ll \Delta\alpha_s \approx 0.8\%$

General motivation

- Beside the quark masses, $\alpha_s(m_Z)$ is the **single** free parameter of QCD.
- The α_s is the **least well-known interaction coupling** in the SM.
  $\longrightarrow$ Its large uncertainty propagates to all calculations of observables at LHC [1].
- Its **running** is predicted by QCD.
  $\longrightarrow$ Any deviation could provide a hint to new physics [2].
- "Improving the precision of α_s and m_t by a factor of two to three could be sufficient to **establish or refute SM vacuum stability** at the 5σ level" [3].
  $\longrightarrow$ Is that reachable at LHC?

Introduction

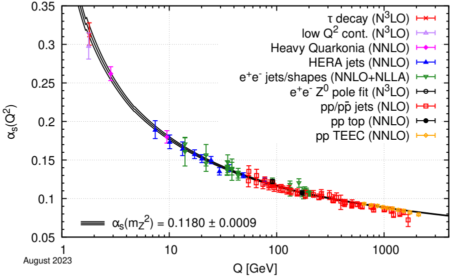
$\Delta\alpha \approx 10^{-10} \ll \Delta G_F \approx 10^{-7} \ll \Delta G \approx 10^{-4} \ll \Delta\alpha_s \approx 0.8\%$

General motivation

- Beside the quark masses, $\alpha_s(m_Z)$ is the **single** free parameter of QCD.
- The α_s is the **least well-known interaction coupling** in the SM.
  $\longrightarrow$ Its large uncertainty propagates to all calculations of observables at LHC [1].
- Its **running** is predicted by QCD.
  $\longrightarrow$ Any deviation could provide a hint to new physics [2].
- "Improving the precision of α_s and m_t by a factor of two to three could be sufficient to **establish or refute SM vacuum stability** at the 5σ level" [3].
  $\longrightarrow$ Is that reachable at LHC?

Introduction

$\Delta\alpha \approx 10^{-10} \ll \Delta G_F \approx 10^{-7} \ll \Delta G \approx 10^{-4} \ll \Delta\alpha_s \approx 0.8\%$

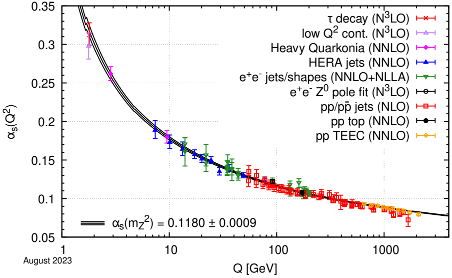


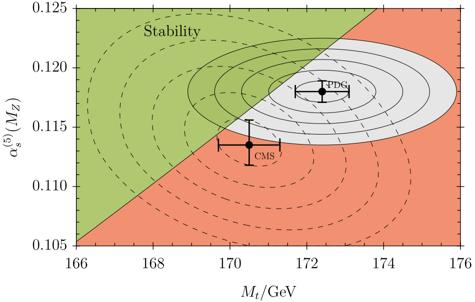
General motivation

- Beside the quark masses, $\alpha_s(m_Z)$ is the **single** free parameter of QCD.
- The α_s is the **least well-known interaction coupling** in the SM.
  $\longrightarrow$ Its large uncertainty propagates to all calculations of observables at LHC [1].
- Its **running** is predicted by QCD.
  $\longrightarrow$ Any deviation could provide a hint to new physics [2].
- "Improving the precision of α_s and m_t by a factor of two to three could be sufficient to **establish or refute SM vacuum stability** at the 5σ level" [3].
  $\longrightarrow$ Is that reachable at LHC?

Introduction

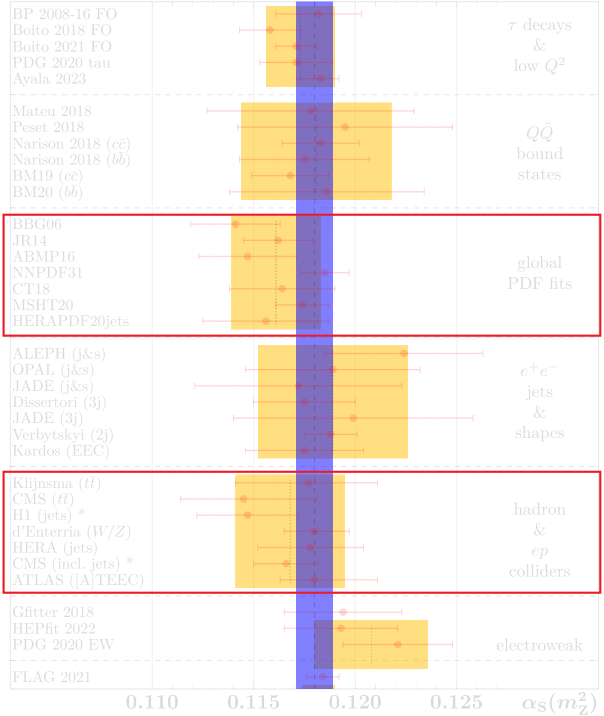
$\Delta\alpha \approx 10^{-10} \ll \Delta G_F \approx 10^{-7} \ll \Delta G \approx 10^{-4} \ll \Delta\alpha_s \approx 0.8\%$





General motivation

- Beside the quark masses, $\alpha_s(m_Z)$ is the **single** free parameter of QCD.
- The α_s is the **least well-known interaction coupling** in the SM.
  $\longrightarrow$ Its large uncertainty propagates to all calculations of observables at LHC [1].
- Its **running** is predicted by QCD.
  $\longrightarrow$ Any deviation could provide a hint to new physics [2].
- "Improving the precision of α_s and m_t by a factor of two to three could be sufficient to **establish or refute SM vacuum stability** at the 5σ level" [3].
  $\longrightarrow$ Is that reachable at LHC?



Research objectives

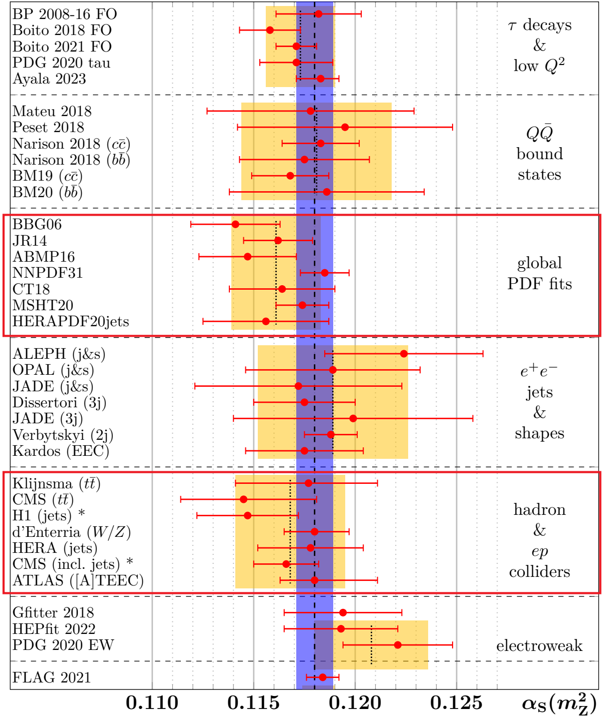
Goal

- **Measure consistently** a large number of observables at the LHC.
- **Determine** $\alpha_s(m_Z)$ with the same precision as the current world average estimate ($< 1\%$).

Expected impact

- Not only reduce the uncertainty from *hadron & ep colliders*...
- ... but also revisit the way the world average is combined across categories.

Research objectives

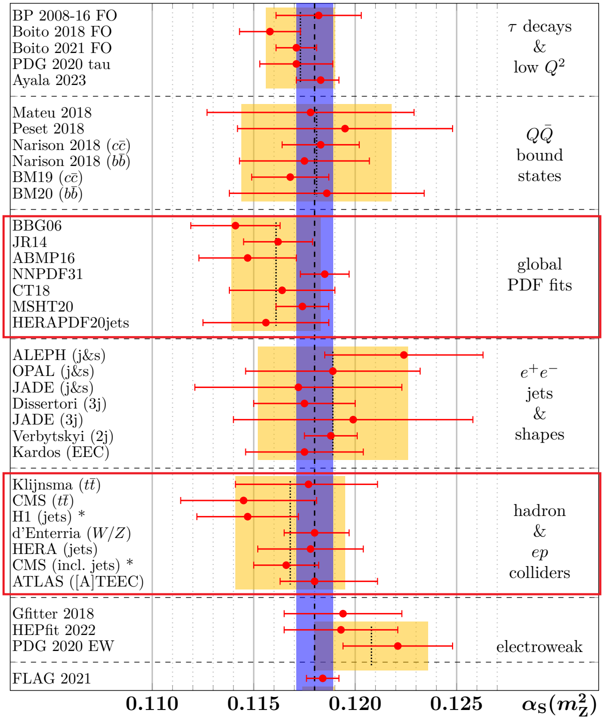


Goal

- **Measure consistently** a large number of observables at the LHC.
- **Determine** $\alpha_s(m_Z)$ with the same precision as the current world average estimate ($< 1\%$).

Expected impact

- Not only reduce the uncertainty from *hadron & ep colliders*...
- ... but also revisit the way the world average is combined across categories.



Research objectives

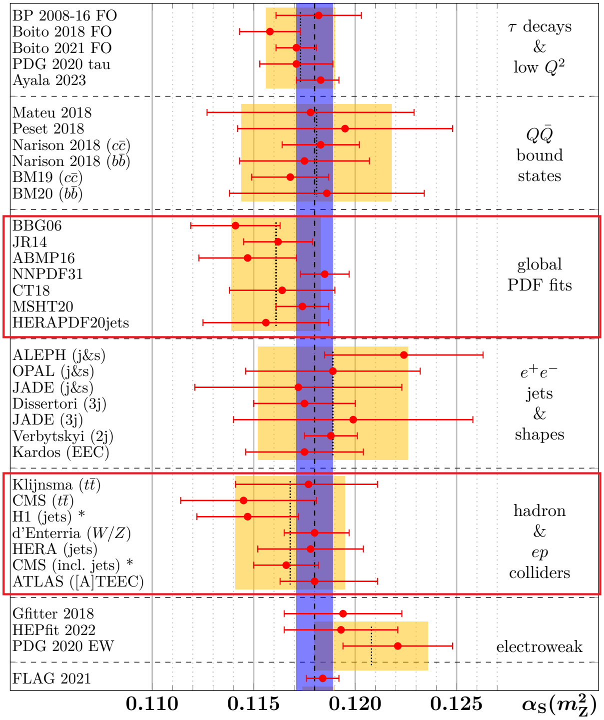
Goal

- **Measure consistently** a large number of observables at the LHC.
- **Determine** $\alpha_s(m_Z)$ with the same precision as the current world average estimate ($< 1\%$).

Expected impact

- Not only **reduce the uncertainty** from *hadron & ep colliders*...
- ... but also **revisit** the way the **world average** is combined across categories.

Research objectives



Goal

- **Measure consistently** a large number of observables at the LHC.
- **Determine** $\alpha_s(m_Z)$ with the same precision as the current world average estimate ($< 1\%$).

Expected impact

- Not only **reduce the uncertainty** from *hadron & ep colliders*...
- ... but also **revisit** the way the **world average** is combined across categories.

Research objectives

QCD interpretation

Factorisation [4]

$$\underbrace{\sigma_{pp}}_{\text{exp. data}} = \sum_{ij\in gq\bar{q}} \underbrace{f_i(x_i,\mu_F^2,\alpha_s)\otimes f_j(x_j,\mu_F^2,\alpha_s)}_{\text{collinear PDFs}} \otimes \underbrace{\hat{\sigma}_{ij}\left(x_i,x_j,\frac{Q^2}{\mu_F^2},\frac{Q^2}{\mu_R^2},\alpha_s\right)}_{\text{FO predictions in pQCD}}$$

- α_s enters both collinear PDFs and the FO prediction.
- CMS has relied on NNLOJET+fastNLO+xFitter to extract $\alpha_s(m_Z)$ from jet data [5, 6, 7].
- Not shown in this formula: non-perturbative (NP) effects.

Inclusive jet at 13 TeV [8]

$$\alpha_s(m_Z) = 0.1166 \pm 0.0014\ \text{(fit)} \pm 0.0007\ \text{(model)} \pm 0.0004\ \text{(scale)} \pm 0.0001\ \text{(param)}$$
$$= 0.1166 \pm 0.0017\ \text{(total)}$$

$\longrightarrow$ **dominated by the fit (exp. + NP) uncertainty!**

Research objectives

QCD interpretation

Factorisation [4]

$$\underbrace{\sigma_{pp}}_{\text{exp. data}} = \sum_{ij\in gq\bar{q}} \underbrace{f_i(x_i, \mu_F^2, \alpha_s) \otimes f_j(x_j, \mu_F^2, \alpha_s)}_{\text{collinear PDFs}} \otimes \underbrace{\hat{\sigma}_{ij}\left(x_i, x_j, \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}, \alpha_s\right)}_{\text{FO predictions in pQCD}}$$

- α_s enters both collinear PDFs and the FO prediction.
- CMS has relied on NNLOJET+fastNLO+xFitter to extract $\alpha_s(m_Z)$ from jet data [5, 6, 7].
- Not shown in this formula: non-perturbative (NP) effects.

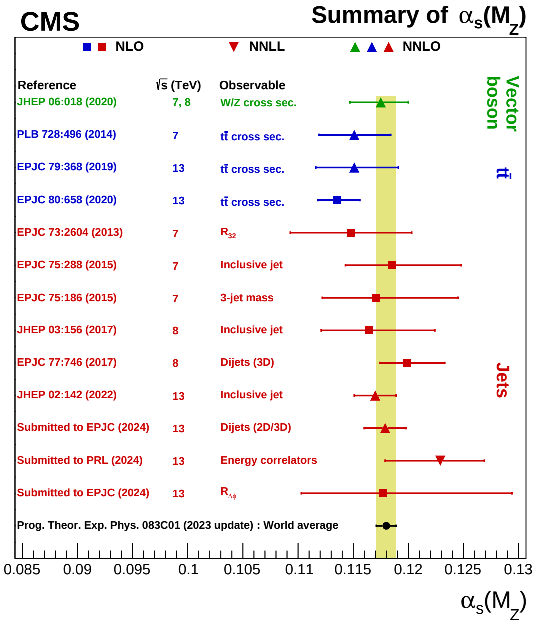
Inclusive jet at 13 TeV [8]

$$\alpha_s(m_Z) = 0.1166 \pm 0.0014 \text{ (fit)} \pm 0.0007 \text{ (model)} \pm 0.0004 \text{ (scale)} \pm 0.0001 \text{ (param)}$$
$$= 0.1166 \pm 0.0017 \text{ (total)}$$

$\longrightarrow$ **dominated by the fit (exp. + NP) uncertainty!**

State of the art

Overview

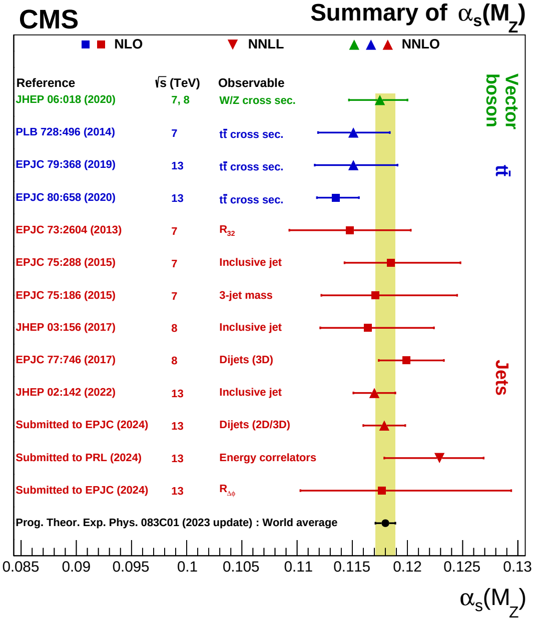


Combination? (Fig. from Ref. [9])

- Inconsistent choices in analysis strategies may lead to tensions in the interpretation.
  $\longrightarrow$ Different ways to mitigate the tensions have been applied, but all reduce the potential sensitivity.
- Statistical correlations between observables obtained from the same data are missing.
  $\longrightarrow$ e.g. between jet and dijet spectra.

State of the art

Overview

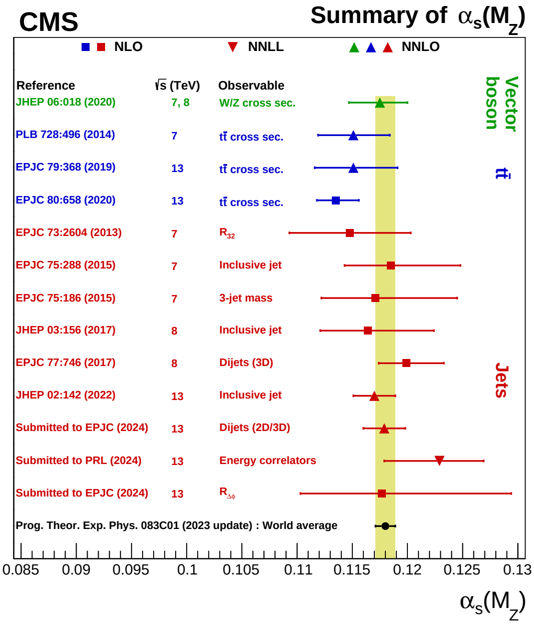


Combination? (Fig. from Ref. [9])

- **Inconsistent choices in analysis strategies** may lead to tensions in the interpretation.
  ⟶ Different ways to mitigate the tensions have been applied, but all reduce the potential sensitivity.
- **Statistical correlations** between observables obtained from the same data are **missing**.
  ⟶ e.g. between jet and dijet spectra.

State of the art

Overview

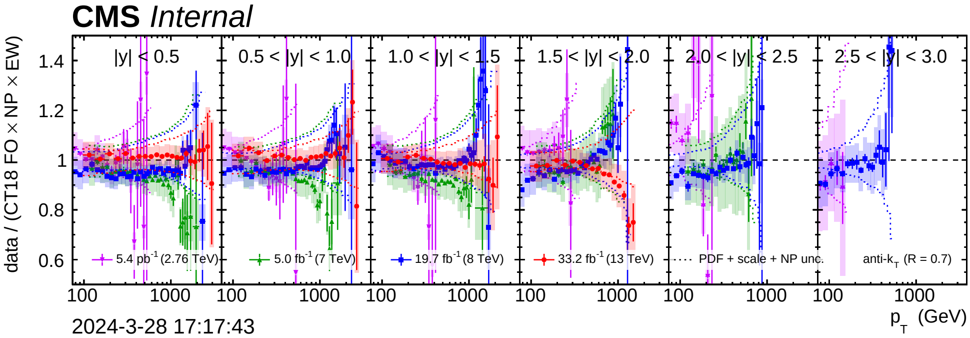


Combination? (Fig. from Ref. [9])

- **Inconsistent choices in analysis strategies** may lead to tensions in the interpretation.
  $\longrightarrow$ Different ways to mitigate the tensions have been applied, but all reduce the potential sensitivity.
- **Statistical correlations** between observables obtained from the same data are **missing**.
  $\longrightarrow$ e.g. between jet and dijet spectra.

State of the art

Latest result



Combined inclusive jet [10]

$$\alpha_s(m_Z) = 0.11759 \pm 0.0009 \text{ (fit)}^{+0.0006}_{-0.0004} \text{ (model)}^{+0.0009}_{-0.0012} \text{ (scale)}^{+0.00000}_{-0.00004} \text{ (param)}$$

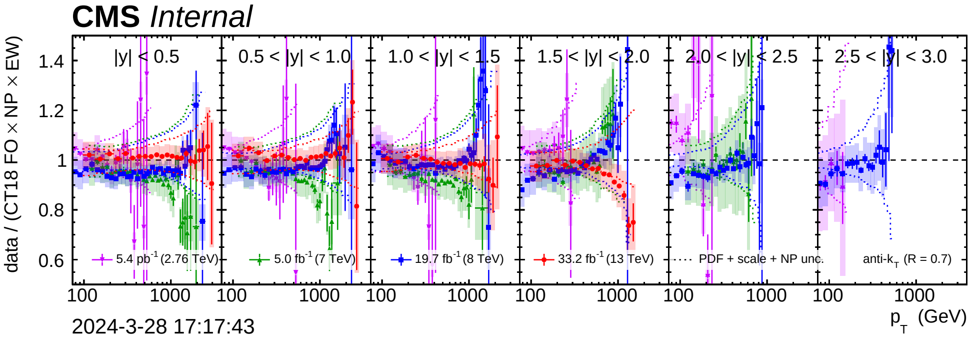
$$= 0.11759^{+0.0014}_{-0.0016} \text{ (total)}$$

$\longrightarrow$ the fit uncertainty was improved

(at the cost of the scale uncertainty & using an aggressive decorrelation scheme among various systematic uncertainties)

State of the art

Latest result



Combined inclusive jet [10]

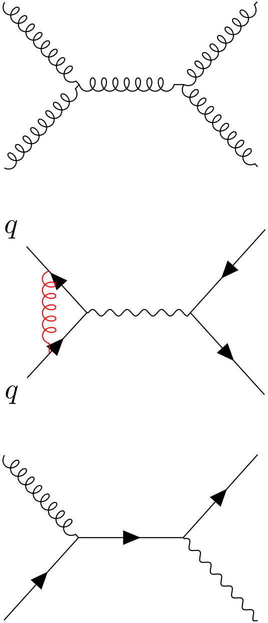
$$\alpha_s(m_Z) = 0.11759 \pm 0.0009\ \text{(fit)}^{+0.0006}_{-0.0004}\ \text{(model)}^{+0.0009}_{-0.0012}\ \text{(scale)}^{+0.00000}_{-0.00004}\ \text{(param)}$$

$$= 0.11759^{+0.0014}_{-0.0016}\ \text{(total)}$$

$\longrightarrow$ the fit uncertainty was improved

(at the cost of the scale uncertainty & using an aggressive decorrelation scheme among various systematic uncertainties)

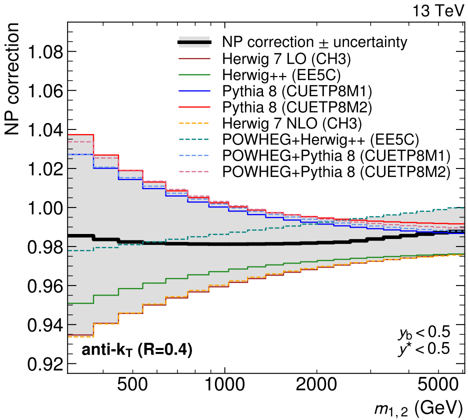
Plan



Work packages

1. Consistently measure a large number of observables sensitive to α_{s} [11, 12],
2. Improve the treatment of non-perturbative (NP) effects [13, 14, 15],
3. Implement "errors on errors" in the minimisation [16, 17].
4. Provide tools that allow extensions (additional final states & other LHC experiments) [18, 19].

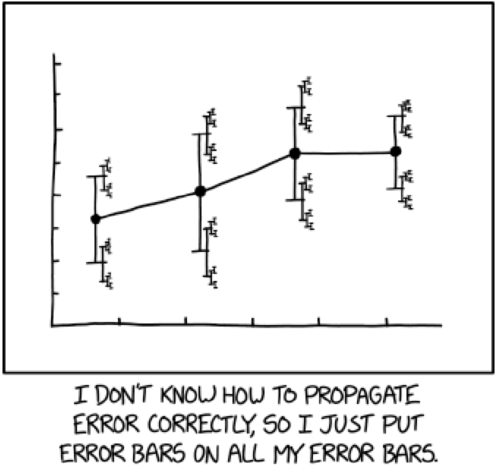
Plan



Work packages

1. Consistently measure a large number of observables sensitive to α_s [11, 12],
2. Improve the treatment of non-perturbative (NP) effects [13, 14, 15],
3. Implement "errors on errors" in the minimisation [16, 17].
4. Provide tools that allow extensions (additional final states & other LHC experiments) [18, 19].

Plan



Work packages

1. Consistently measure a large number of observables sensitive to α_s [11, 12],
2. Improve the treatment of non-perturbative (NP) effects [13, 14, 15],
3. Implement "errors on errors" in the minimisation [16, 17].
4. Provide tools that allow extensions (additional final states & other LHC experiments) [18, 19].

Plan

CMS code

Generic code

Work packages

1. Consistently measure a large number of observables sensitive to α_s [11, 12],
2. Improve the treatment of non-perturbative (NP) effects [13, 14, 15],
3. Implement “errors on errors” in the minimisation [16, 17].
4. Provide tools that allow extensions (additional final states & other LHC experiments) [18, 19].

Request

Connection to TA infrastructure and VA projects

TA infrastructure CERN as hosting institute, as host for the LHC and the CMS experiment.

VA projects Powerful computing clusters (CERN cluster), but also any VAs with pQCD-related computing resources (e.g. NLOAccess, TMDPortal).

Estimated budget request

Total: **330kEUR** (includes administrative overheads & CHF-EUR conversion)

Personnel **130kCHF** per year for two years to pay a postdoc at CERN

Others **50kCHF** to pay participant users per-diem at CERN, travels, and on-site organisation of dedicated workshops

Participating and partner institutions

CMS/ATLAS KIT, Ioaninna, HIP, ULB-IIHE, Zhejiang; LPNHE, MPI Munich

theorists P. Monni & A. Huss (CERN), F. Tackmann & G. Marinelli (DESY), T. Cridge (Antwerp), F. Hekhorn (Jyvaskyla)

QCD PDG editors K. Rabbertz (KIT), G. Zanderighi (MPI Munich)

Request

Connection to TA infrastructure and VA projects

TA infrastructure CERN as hosting institute, as host for the LHC and the CMS experiment.

VA projects Powerful computing clusters (CERN cluster), but also any VAs with pQCD-related computing resources (e.g. NLOAccess, TMDPortal).

Estimated budget request

Total: **330kEUR** (includes administrative overheads & CHF-EUR conversion)

Personnel **130kCHF** per year for two years to pay a postdoc at CERN

Others **50kCHF** to pay participant users per-diem at CERN, travels, and on-site organisation of dedicated workshops

Participating and partner institutions

CMS/ATLAS KIT, Ioaninna, HIP, ULB-IIHE, Zhejiang; LPNHE, MPI Munich

theorists P. Monni & A. Huss (CERN), F. Tackmann & G. Marinelli (DESY), T. Cridge (Antwerp), F. Hekhorn (Jyvaskyla)

QCD PDG editors K. Rabbertz (KIT), G. Zanderighi (MPI Munich)

Request

Connection to TA infrastructure and VA projects

TA infrastructure CERN as hosting institute, as host for the LHC and the CMS experiment.

VA projects Powerful computing clusters (CERN cluster), but also any VAs with pQCD-related computing resources (e.g. NLOAccess, TMDPortal).

Estimated budget request

Total: **330kEUR** (includes administrative overheads & CHF-EUR conversion)

Personnel **130kCHF** per year for two years to pay a postdoc at CERN

Others **50kCHF** to pay participant users per-diem at CERN, travels, and on-site organisation of dedicated workshops

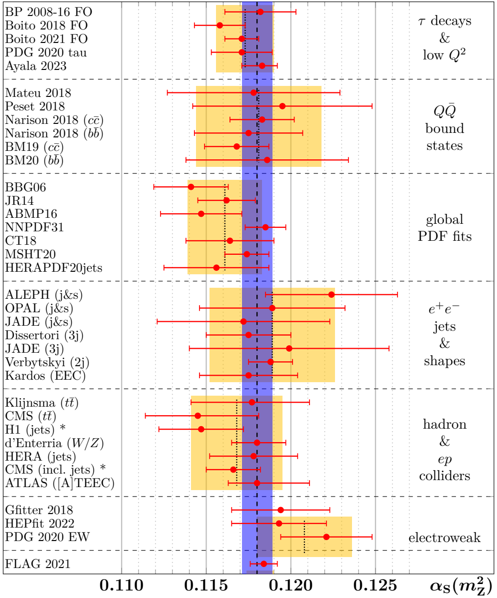
Participating and partner institutions

CMS/ATLAS KIT, Ioaninna, HIP, ULB-IIHE, Zhejiang; LPNHE, MPI Munich

theorists P. Monni & A. Huss (CERN), F. Tackmann & G. Marinelli (DESY), T. Cridge (Antwerp), F. Hekhorn (Jyvaskyla)

QCD PDG editors K. Rabbertz (KIT), G. Zanderighi (MPI Munich)

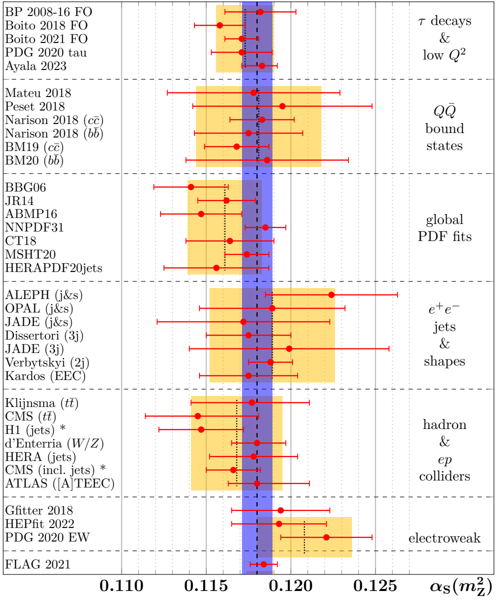
Summary & Conclusions



- **State of the art**: Increasing number of LHC-based $\alpha_s(m_Z)$ extractions, with $\mathcal{O}(2.3\%)$ precision.
- **Task**: Simultaneous $\alpha_s(m_Z)$ extraction, combining multiple LHC observables (CMS first, extendable to other exps.) with proper control of NP effects, improved experimental & theoretical uncertainties, etc.
- **Partners**: leading exp./th. experts on QCD jets and $\alpha_s(m_Z)$.
- **Deliverables**: $\mathcal{O}(1\%)$ $\alpha_s(m_Z)$ extraction from LHC data + public code for analysis & $\alpha_s(m_Z)$ fitting.

Merci pour votre attention!

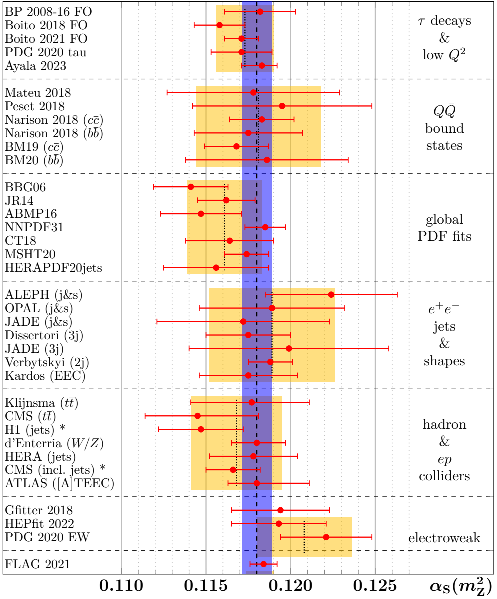
Summary & Conclusions



- **State of the art**: Increasing number of LHC-based $\alpha_s(m_Z)$ extractions, with $\mathcal{O}(2.3\%)$ precision.
- **Task**: Simultaneous $\alpha_s(m_Z)$ extraction, combining multiple LHC observables (CMS first, extendable to other exps.) with proper control of NP effects, improved experimental & theoretical uncertainties, etc.
- **Partners**: leading exp./th. experts on QCD jets and $\alpha_s(m_Z)$.
- **Deliverables**: $\mathcal{O}(1\%)$ $\alpha_s(m_Z)$ extraction from LHC data + public code for analysis & $\alpha_s(m_Z)$ fitting.

Merci pour votre attention!

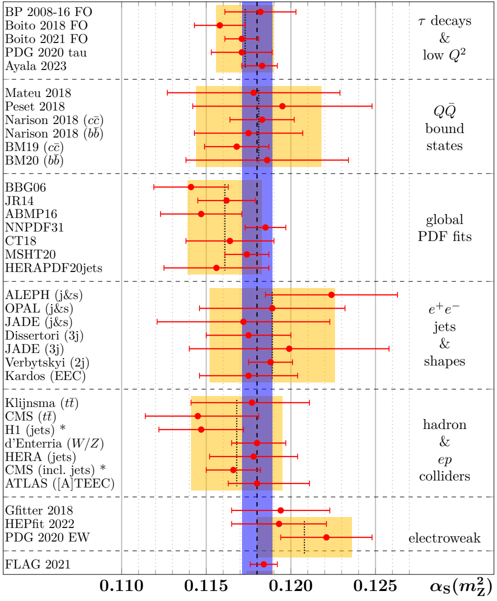
Summary & Conclusions



- **State of the art**: Increasing number of LHC-based $\alpha_s(m_Z)$ extractions, with $\mathcal{O}(2.3\%)$ precision.
- **Task**: Simultaneous $\alpha_s(m_Z)$ extraction, combining multiple LHC observables (CMS first, extendable to other exps.) with proper control of NP effects, improved experimental & theoretical uncertainties, etc.
- **Partners**: leading exp./th. experts on QCD jets and $\alpha_s(m_Z)$.
- **Deliverables**: $\mathcal{O}(1\%)$ $\alpha_s(m_Z)$ extraction from LHC data + public code for analysis & $\alpha_s(m_Z)$ fitting.

Merci pour votre attention!

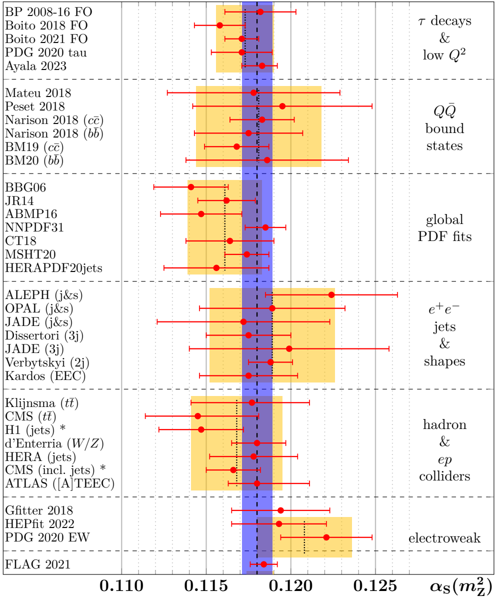
Summary & Conclusions



- **State of the art**: Increasing number of LHC-based $\alpha_s(m_Z)$ extractions, with $\mathcal{O}(2.3\%)$ precision.
- **Task**: Simultaneous $\alpha_s(m_Z)$ extraction, combining multiple LHC observables (CMS first, extendable to other exps.) with proper control of NP effects, improved experimental & theoretical uncertainties, etc.
- **Partners**: leading exp./th. experts on QCD jets and $\alpha_s(m_Z)$.
- **Deliverables**: $\mathcal{O}(1\%)$ $\alpha_s(m_Z)$ extraction from LHC data + public code for analysis & $\alpha_s(m_Z)$ fitting.

Merci pour votre attention!

Summary & Conclusions

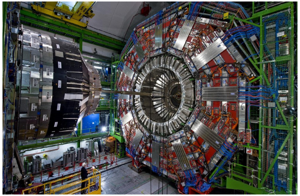
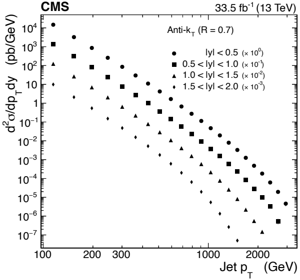


- **State of the art**: Increasing number of LHC-based $\alpha_s(m_Z)$ extractions, with $\mathcal{O}(2.3\%)$ precision.
- **Task**: Simultaneous $\alpha_s(m_Z)$ extraction, combining multiple LHC observables (CMS first, extendable to other exps.) with proper control of NP effects, improved experimental & theoretical uncertainties, etc.
- **Partners**: leading exp./th. experts on QCD jets and $\alpha_s(m_Z)$.
- **Deliverables**: $\mathcal{O}(1\%)$ $\alpha_s(m_Z)$ extraction from LHC data + public code for analysis & $\alpha_s(m_Z)$ fitting.

Merci pour votre attention!

Detailed plan

Simultaneous measurement of many differential observables

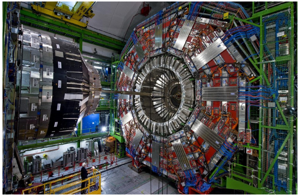
 →  →  → 

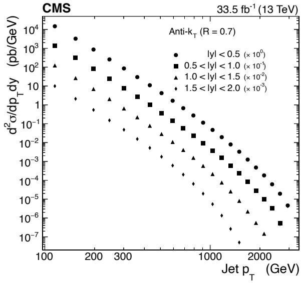
 →

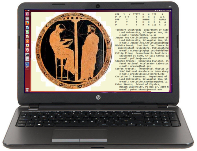
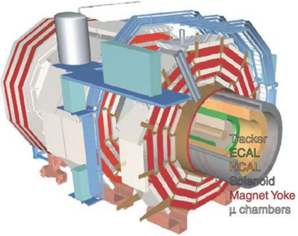
→ →

Detailed plan

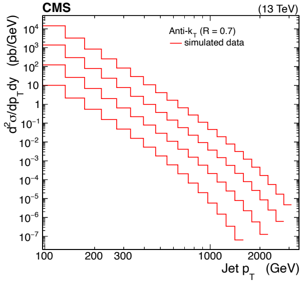
Simultaneous measurement of many differential observables


→

→

→


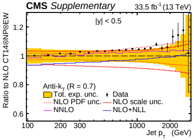

→


→

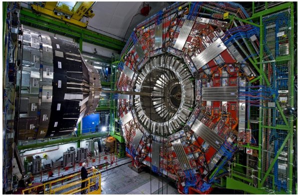
→


Detailed plan

Simultaneous measurement of many differential observables

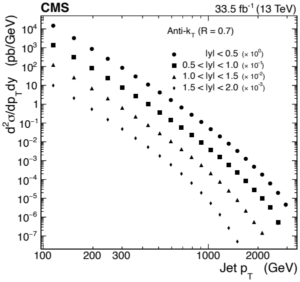


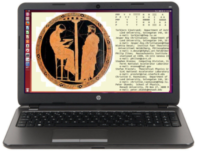
←



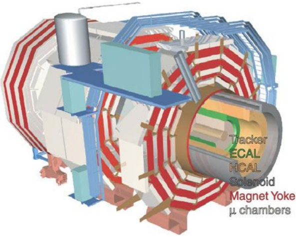
←

←



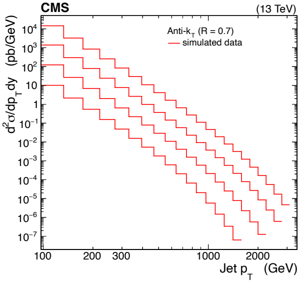


→



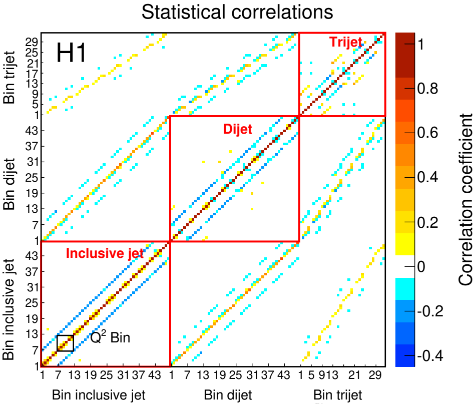
→

→



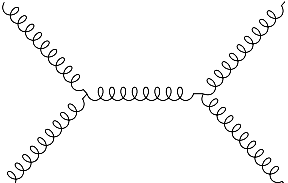
Detailed plan

Simultaneous measurement of many differential observables



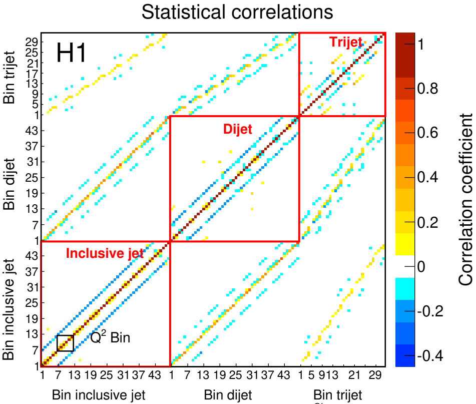
Simultaneous unfolding [12]

1. Start with jet production (WIP), à la H1 [11] (see figure).
2. Extend with V+jet production (LOI).
3. Extend to $t\bar{t}$ (beyond).



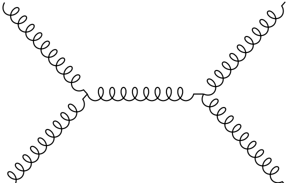
Detailed plan

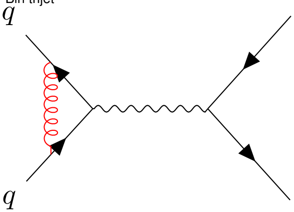
Simultaneous measurement of many differential observables



Simultaneous unfolding [12]

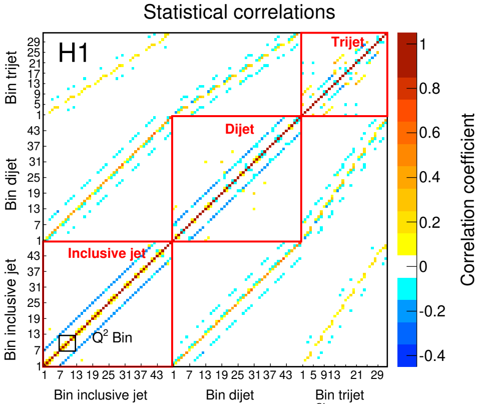
1. Start with jet production (WIP), à la H1 [11] (see figure).
2. Extend with V+jet production (**LOI**).
3. Extend to $t\bar{t}$ (beyond).





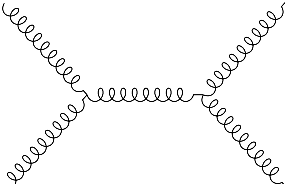
Detailed plan

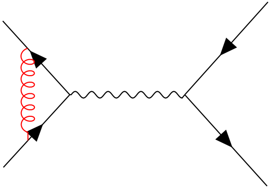
Simultaneous measurement of many differential observables

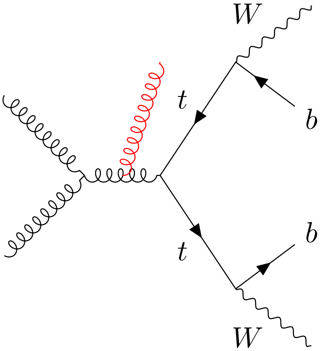


Simultaneous unfolding [12]

1. Start with jet production (WIP), à la H1 [11] (see figure).
2. Extend with V+jet production (**LOI**).
3. Extend to $t\bar{t}$ (beyond).





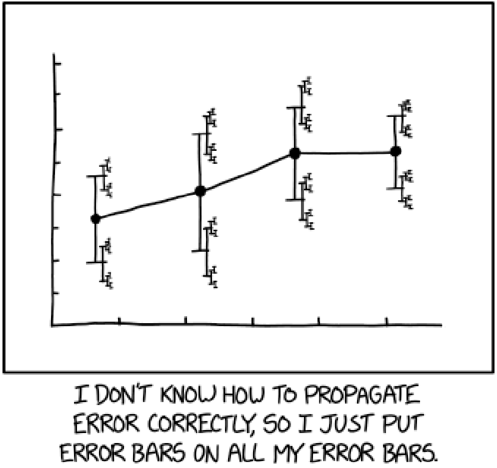


Detailed plan

Upgrade of the fitting tool

"Errors on errors"

- Not all systematic uncertainties are known to the same level of accuracy.
- Novel approach to allow for pulling parameters without preventing fit convergence.
- Need to implement in chosen software.



Detailed plan

Treatment of NP corrections

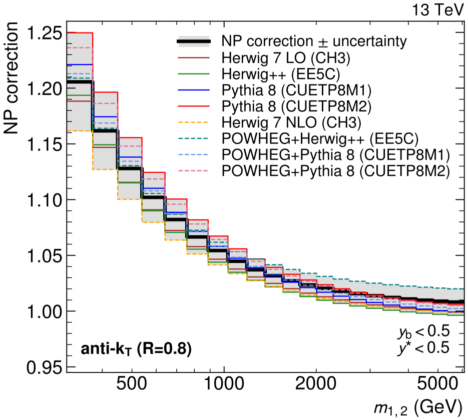
Nature (figure from Ref. [13])

$$\mathrm{NP} = \frac{\sigma_{\mathrm{ME+PS+MPI+HAD}}}{\sigma_{\mathrm{ME+PS}}}$$

- Corrects for HAD and MPI.
- Usually obtained from the envelope of the results obtained with a(n arbitrary) set of MC generators and tunes.

Proposed improvements

1. Better identify the set of MC generators / tunes.
2. Treat effect as migrations rather than with a bin-by-bin correction.
3. Introduce a breakdown of uncertainties.



Detailed plan

Treatment of NP corrections

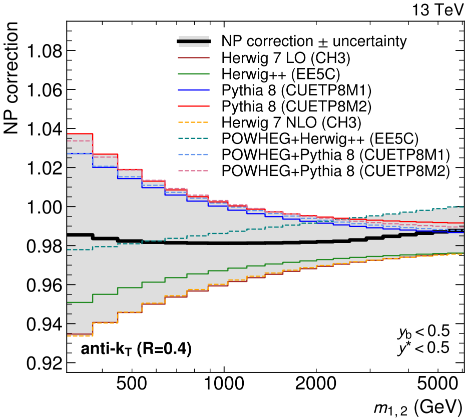
Nature (figure from Ref. [13])

$$\mathrm{NP} = \frac{\sigma_{\mathrm{ME+PS+MPI+HAD}}}{\sigma_{\mathrm{ME+PS}}}$$

- Corrects for HAD and MPI.
- Usually obtained from the envelope of the results obtained with a(n arbitrary) set of MC generators and tunes.

Proposed improvements

1. Better identify the set of MC generators / tunes.
2. Treat effect as migrations rather than with a bin-by-bin correction.
3. Introduce a breakdown of uncertainties.



Detailed plan

Treatment of NP corrections

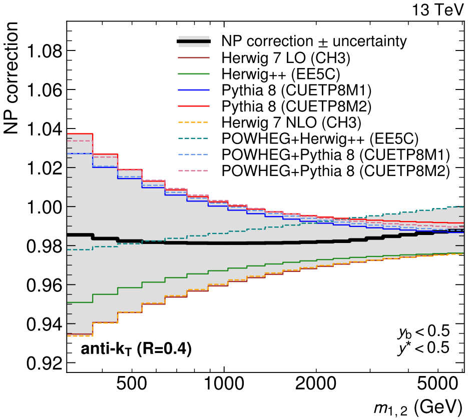
Nature (figure from Ref. [13])

$$\mathrm{NP} = \frac{\sigma_{\mathrm{ME+PS+MPI+HAD}}}{\sigma_{\mathrm{ME+PS}}}$$

- Corrects for HAD and MPI.
- Usually obtained from the envelope of the results obtained with a(n arbitrary) set of MC generators and tunes.

Proposed improvements

1. Better identify the set of MC generators / tunes.
2. Treat effect as migrations rather than with a bin-by-bin correction.
3. Introduce a breakdown of uncertainties.



Expected precision

Wild guess of expected precision

Taking the smallest value in the breakdown of uncertainties from recent published values:

$$\begin{aligned}\alpha_s(m_Z) &= 0.11?? \pm 0.00\mathbf{05}\ \text{(fit)} \pm 0.00\mathbf{02}\ \text{(model)} \\ &\qquad \pm 0.00\mathbf{04}\ \text{(scale)} \pm 0.00\mathbf{01}\ \text{(param)} \\ &= 0.11?? \pm 0.00\mathbf{07}\ \text{(total)}\end{aligned}$$

Caveat: theory uncertainty

- The theory uncertainty based on variations of the scale is known to be a poor approximation.
- In the recent years, theorists have progressed on getting theory nuisance parameters.

⟶ In this LOI, **we focus on the experimental aspects**, but plan to collaborate closely with theorists to apply the most recent developments.

Expected precision

Wild guess of expected precision

Taking the smallest value in the breakdown of uncertainties from recent published values:

$$\begin{aligned}\alpha_s(m_Z) &= 0.11?? \pm 0.00\mathbf{05}\ (\text{fit}) \pm 0.00\mathbf{02}\ (\text{model}) \\ &\quad \pm 0.00\mathbf{04}\ (\text{scale}) \pm 0.00\mathbf{01}\ (\text{param}) \\ &= 0.11?? \pm 0.00\mathbf{07}\ (\text{total})\end{aligned}$$

Caveat: theory uncertainty

- The theory uncertainty based on variations of the scale is known to be a poor approximation.
- In the recent years, theorists have progressed on getting theory nuisance parameters.

$\longrightarrow$ In this LOI, **we focus on the experimental aspects**, but plan to collaborate closely with theorists to apply the most recent developments.

Partners

Participating and partner institutions

CMS Klaus Rabbertz et al. (KIT), Panagiotis Kokkas et al. (Ioaninna), Mikko Voutilainen et al. (HIP), Laurent Favart et al. (ULB-IIHE, Belgium), Xiao Meng et al. (Zhejiang, China)

ATLAS Bogdan Malaescu et al. (LPNHE), Stefan Kluth (MPI)

theorists Pier Monni & Alex Huss (CERN), Frank Tackmann & Giulia Marinelli (DESY), Thomas Cridge (Antwerp), Felix Hekhorn (Jyvaskyla)

QCD PDG editors K. Rabbertz (KIT), G. Zanderighi (MPI Munich)

$\longrightarrow$ include **additional channels** (e.g. $\mathrm{t}\bar{\mathrm{t}}$ +jets), **combining** with ATLAS, **theory nuisance parameters**

Refs.	$\sqrt{s}$	value	fit unc.	PDF unc.	scale unc.	other unc.	PDF	order
R_{32} [20]	7 TeV	0.1148	±0.0014	±0.0018	±0.0050		NNPDF2.1	NLO
2D inclusive jet [21, 22]	7 TeV	0.1185	±0.0019	±0.0028	$^{+0.0053}_{-0.0024}$	±0.0004(NP)	—	NLO
inclusive 3-jet mass [23]	7 TeV	0.1171	±0.0013	±0.0024	$^{+0.0069}_{-0.0040}$	±0.0008(NP)	CT10	NLO
$\mathrm{t\bar{t}}$ [24]	7 TeV	0.1151	$^{+0.0017}_{-0.0018}$	$^{+0.0013}_{-0.0011}$	$^{+0.0009}_{-0.0008}$	$\underbrace{\pm0.0013}_{m_\mathrm{t}}$ $\underbrace{\pm0.0008}_{\sqrt{s}}$	NNPDF2.3	NNLO
2D inclusive jet [25]	8 TeV	0.1185	$^{+0.0019}_{-0.0021}$	$^{+0.0002}_{-0.0015}$ (model) $^{+0.0000}_{-0.0004}$ (param)	$^{+0.0022}_{-0.0018}$		—	NLO
3D dijet mass [26]	8 TeV	0.1199	±0.0015	±0.0002 (model) $^{+0.0002}_{-0.0004}$ (param)	$^{+0.0026}_{-0.0016}$		—	NLO
W/Z [27]	7–8 TeV	0.1163	±0.0018	$^{+0.0016}_{-0.0022}$	±0.0009	±0.0006 (num)	CT14	NNLO
$\mathrm{t\bar{t}}$ (dilepton) [28]	13 TeV	0.1151	±0.0035		$^{+0.0020}_{-0.0002}$		MMHT14	NNLO
normalised $\mathrm{t\bar{t}}$ [29]	13 TeV	0.1135	±0.0016	$^{+0.0002}_{-0.0004}$ (model) $^{+0.0008}_{-0.0001}$ (param)	$^{+0.0011}_{-0.0005}$		—	NLO
2D inclusive jet [8]	13 TeV	0.1166	±0.0014	±0.0007 (model) ±0.0001 (param)	±0.0004		—	NNLO
2D & 3D dijet mass [13]	13 TeV	0.1181	±0.0013	±0.0006 (model) ±0.0002 (param)	±0.0009		—	NNLO
$R_{\Delta\phi}$ [13]	13 TeV	0.1177	±0.0013	±0.0010 (NNPDF3.1) ±0.0020 (choice)	$^{+0.0114}_{-0.0068}$	±0.0011 (NP) ±0.0003 (EW)	NNPDF3.1	NLO
EEC in jets [30]	13 TeV	0.1229	$^{+0.0014}_{-0.0012}$ (stat) $^{+0.0023}_{-0.0036}$ (syst)		$^{+0.0030}_{-0.0033}$		—	aNNLL
comb. 2D inclusive jet [10]		0.1176	±0.0009	$^{+0.0006}_{-0.0004}$ ((model)) $^{+0.0000}_{-0.0000}$ ((param))	$^{+0.0009}_{-0.0012}$		—	NNLO

Refs.	$\sqrt{s}$	value	fit unc.	PDF unc.	scale unc.	other unc.	PDF	order
R_{32} [20]	7 TeV	0.1148	± 0.0014	± 0.0018		± 0.0050	NNPDF2.1	NLO
2D inclusive jet [21, 22]	7 TeV	0.1185	± 0.0019	± 0.0028	$^{+0.0053}_{-0.0024}$	$\pm 0.0004(\text{NP})$	—	NLO
inclusive 3-jet mass [23]	7 TeV	0.1171	± 0.0013	± 0.0024	$^{+0.0069}_{-0.0040}$	$\pm 0.0008(\text{NP})$	CT10	NLO
$\mathrm{t\bar{t}}$ [24]	7 TeV	0.1151	$^{+0.0017}_{-0.0018}$	$^{+0.0013}_{-0.0011}$	$^{+0.0009}_{-0.0008}$	$\underbrace{\pm 0.0013}_{m_\mathrm{t}}\ \underbrace{\pm 0.0008}_{\sqrt{s}}$	NNPDF2.3	NNLO
2D inclusive jet [25]	8 TeV	0.1185	$^{+0.0019}_{-0.0021}$	$\underbrace{^{+0.0002}_{-0.0015}}_{\text{model}}\ \underbrace{^{+0.0000}_{-0.0004}}_{\text{param}}$	$^{+0.0022}_{-0.0018}$		—	NLO
3D dijet mass [26]	8 TeV	0.1199	± 0.0015	$\underbrace{\pm 0.0002}_{\text{model}}\ \underbrace{^{+0.0002}_{-0.0004}}_{\text{param}}$	$^{+0.0026}_{-0.0016}$		—	NLO
W/Z [27]	7–8 TeV	0.1163	± 0.0018	$^{+0.0016}_{-0.0022}$	± 0.0009	$\underbrace{\pm 0.0006}_{\text{num}}$	CT14	NNLO
$\mathrm{t\bar{t}}$ (dilepton) [28]	13 TeV	0.1151	± 0.0035		$^{+0.0020}_{-0.0002}$		MMHT14	NNLO
normalised $\mathrm{t\bar{t}}$ [29]	13 TeV	0.1135	± 0.0016	$\underbrace{^{+0.0002}_{-0.0004}}_{\text{model}}\ \underbrace{^{+0.0008}_{-0.0001}}_{\text{param}}$	$^{+0.0011}_{-0.0005}$		—	NLO
2D inclusive jet [8]	13 TeV	0.1166	± 0.0014	$\underbrace{\pm 0.0007}_{\text{model}}\ \underbrace{\pm 0.0001}_{\text{param}}$	± 0.0004		—	NNLO
2D & 3D dijet mass [13]	13 TeV	0.1181	± 0.0013	$\underbrace{\pm 0.0006}_{\text{model}}\ \underbrace{\pm 0.0002}_{\text{param}}$	± 0.0009		—	NNLO
$R_{\Delta\phi}$ [13]	13 TeV	0.1177	± 0.0013	$\underbrace{\pm 0.0010}_{\text{NNPDF3.1}}\ \underbrace{\pm 0.0020}_{\text{choice}}$	$^{+0.0114}_{-0.0068}$	$\underbrace{\pm 0.0011}_{\text{NP}}\ \underbrace{\pm 0.0003}_{\text{EW}}$	NNPDF3.1	NLO
EEC in jets [30]	13 TeV	0.1229	$\underbrace{^{+0.0014}_{-0.0012}}_{\text{stat}}\ \underbrace{^{+0.0023}_{-0.0036}}_{\text{syst}}$		$^{+0.0030}_{-0.0033}$		—	aNNLL
comb. 2D inclusive jet [10]		0.1176	± 0.0009	$\underbrace{^{+0.0006}_{-0.0004}}_{\text{(model)}}\ \underbrace{^{+0.0000}_{-0.0000}}_{\text{(param)}}$	$^{+0.0009}_{-0.0012}$		—	NNLO

Refs.	$\sqrt{s}$	value	fit unc.	PDF unc.	scale unc.	other unc.	PDF	order
R_{32} [20]	7 TeV	0.1148	± 0.0014	± 0.0018		± 0.0050	NNPDF2.1	NLO
2D inclusive jet [21, 22]	7 TeV	0.1185	± 0.0019	± 0.0028	$^{+0.0053}_{-0.0024}$	± 0.0004(NP)	—	NLO
inclusive 3-jet mass [23]	7 TeV	0.1171	± 0.0013	± 0.0024	$^{+0.0069}_{-0.0040}$	± 0.0008(NP)	CT10	NLO
$t\bar{t}$ [24]	7 TeV	0.1151	$^{+0.0017}_{-0.0018}$	$^{+0.0013}_{-0.0011}$	$^{+0.0009}_{-0.0008}$	$\underbrace{\pm 0.0013}_{m_t}$ $\underbrace{\pm 0.0008}_{\sqrt{s}}$	NNPDF2.3	NNLO
2D inclusive jet [25]	8 TeV	0.1185	$^{+0.0019}_{-0.0021}$	$\underbrace{^{+0.0002}_{-0.0015}}_{\text{model}}$ $\underbrace{^{+0.0000}_{-0.0004}}_{\text{param}}$	$^{+0.0022}_{-0.0018}$		—	NLO
3D dijet mass [26]	8 TeV	0.1199	± 0.0015	$\underbrace{\pm 0.0002}_{\text{model}}$ $\underbrace{^{+0.0002}_{-0.0004}}_{\text{param}}$	$^{+0.0026}_{-0.0016}$		—	NLO
W/Z [27]	7–8 TeV	0.1163	± 0.0018	$^{+0.0016}_{-0.0022}$	± 0.0009	$\underbrace{\pm 0.0006}_{\text{num}}$	CT14	NNLO
$t\bar{t}$ (dilepton) [28]	13 TeV	0.1151	± 0.0035		$^{+0.0020}_{-0.0002}$		MMHT14	NNLO
normalised $t\bar{t}$ [29]	13 TeV	0.1135	± 0.0016	$\underbrace{^{+0.0002}_{-0.0004}}_{\text{model}}$ $\underbrace{^{+0.0008}_{-0.0001}}_{\text{param}}$	$^{+0.0011}_{-0.0005}$		—	NLO
2D inclusive jet [8]	13 TeV	0.1166	± 0.0014	$\underbrace{\pm 0.0007}_{\text{model}}$ $\underbrace{\pm 0.0001}_{\text{param}}$	± 0.0004		—	NNLO
2D & 3D dijet mass [13]	13 TeV	0.1181	± 0.0013	$\underbrace{\pm 0.0006}_{\text{model}}$ $\underbrace{\pm 0.0002}_{\text{param}}$	± 0.0009		—	NNLO
$R_{\Delta\phi}$ [13]	13 TeV	0.1177	± 0.0013	$\underbrace{\pm 0.0010}_{\text{NNPDF3.1}}$ $\underbrace{\pm 0.0020}_{\text{choice}}$	$^{+0.0114}_{-0.0068}$	$\underbrace{\pm 0.0011}_{\text{NP}}$ $\underbrace{\pm 0.0003}_{\text{EW}}$	NNPDF3.1	NLO
EEC in jets [30]	13 TeV	0.1229	$\underbrace{^{+0.0014}_{-0.0012}}_{\text{stat}}$ $\underbrace{^{+0.0023}_{-0.0036}}_{\text{syst}}$		$^{+0.0030}_{-0.0033}$		—	aNNLL
comb. 2D inclusive jet [10]		0.1176	± 0.0009	$\underbrace{^{+0.0006}_{-0.0004}}_{\text{(model)}}$ $\underbrace{^{+0.0000}_{-0.0000}}_{\text{(param)}}$	$^{+0.0009}_{-0.0012}$		—	NNLO

Refs.	$\sqrt{s}$	value	fit unc.	PDF unc.	scale unc.	other unc.	PDF	order
R_{32} [20]	7 TeV	0.1148	± 0.0014	± 0.0018		± 0.0050	NNPDF2.1	NLO
2D inclusive jet [21, 22]	7 TeV	0.1185	± 0.0019	± 0.0028	$^{+0.0053}_{-0.0024}$	± 0.0004(NP)	—	NLO
inclusive 3-jet mass [23]	7 TeV	0.1171	± 0.0013	± 0.0024	$^{+0.0069}_{-0.0040}$	± 0.0008(NP)	CT10	NLO
$t\bar{t}$ [24]	7 TeV	0.1151	$^{+0.0017}_{-0.0018}$	$^{+0.0013}_{-0.0011}$	$^{+0.0009}_{-0.0008}$	± 0.0013 (m_t) ± 0.0008 ($\sqrt{s}$)	NNPDF2.3	NNLO
2D inclusive jet [25]	8 TeV	0.1185	$^{+0.0019}_{-0.0021}$	$^{+0.0002}_{-0.0015}$ (model) $^{+0.0000}_{-0.0004}$ (param)	$^{+0.0022}_{-0.0018}$		—	NLO
3D dijet mass [26]	8 TeV	0.1199	± 0.0015	± 0.0002 (model) $^{+0.0002}_{-0.0004}$ (param)	$^{+0.0026}_{-0.0016}$		—	NLO
W/Z [27]	7–8 TeV	0.1163	± 0.0018	$^{+0.0016}_{-0.0022}$	± 0.0009	± 0.0006 (num)	CT14	NNLO
$t\bar{t}$ (dilepton) [28]	13 TeV	0.1151	± 0.0035		$^{+0.0020}_{-0.0002}$		MMHT14	NNLO
normalised $t\bar{t}$ [29]	13 TeV	0.1135	± 0.0016	$^{+0.0002}_{-0.0004}$ (model) $^{+0.0008}_{-0.0001}$ (param)	$^{+0.0011}_{-0.0005}$		—	NLO
2D inclusive jet [8]	13 TeV	0.1166	± 0.0014	± 0.0007 (model) ± 0.0001 (param)	± 0.0004		—	NNLO
2D & 3D dijet mass [13]	13 TeV	0.1181	± 0.0013	± 0.0006 (model) ± 0.0002 (param)	± 0.0009		—	NNLO
$R_{\Delta\phi}$ [13]	13 TeV	0.1177	± 0.0013	± 0.0010 (NNPDF3.1) ± 0.0020 (choice)	$^{+0.0114}_{-0.0068}$	± 0.0011 (NP) ± 0.0003 (EW)	NNPDF3.1	NLO
EEC in jets [30]	13 TeV	0.1229	$^{+0.0014}_{-0.0012}$ (stat) $^{+0.0023}_{-0.0036}$ (syst)		$^{+0.0030}_{-0.0033}$		—	aNNLL
comb. 2D inclusive jet [10]		0.1176	± 0.0009	$^{+0.0006}_{-0.0004}$ (model) $^{+0.0000}_{-0.0000}$ (param)	$^{+0.0009}_{-0.0012}$		—	NNLO

Refs.	$\sqrt{s}$	value	fit unc.	PDF unc.	scale unc.	other unc.	PDF	order
R_{32} [20]	7 TeV	0.1148	± 0.0014	± 0.0018		± 0.0050	NNPDF2.1	NLO
2D inclusive jet [21, 22]	7 TeV	0.1185	± 0.0019	± 0.0028	$^{+0.0053}_{-0.0024}$	± 0.0004(NP)	—	NLO
inclusive 3-jet mass [23]	7 TeV	0.1171	± 0.0013	± 0.0024	$^{+0.0069}_{-0.0040}$	± 0.0008(NP)	CT10	NLO
$t\bar{t}$ [24]	7 TeV	0.1151	$^{+0.0017}_{-0.0018}$	$^{+0.0013}_{-0.0011}$	$^{+0.0009}_{-0.0008}$	$\underbrace{\pm 0.0013}_{m_t}$ $\underbrace{\pm 0.0008}_{\sqrt{s}}$	NNPDF2.3	NNLO
2D inclusive jet [25]	8 TeV	0.1185	$^{+0.0019}_{-0.0021}$	$\underbrace{^{+0.0002}_{-0.0015}}_{\text{model}}$ $\underbrace{^{+0.0000}_{-0.0004}}_{\text{param}}$	$^{+0.0022}_{-0.0018}$		—	NLO
3D dijet mass [26]	8 TeV	0.1199	± 0.0015	$\underbrace{\pm 0.0002}_{\text{model}}$ $\underbrace{^{+0.0002}_{-0.0004}}_{\text{param}}$	$^{+0.0026}_{-0.0016}$		—	NLO
W/Z [27]	7–8 TeV	0.1163	± 0.0018	$^{+0.0016}_{-0.0022}$	± 0.0009	$\underbrace{\pm 0.0006}_{\text{num}}$	CT14	NNLO
$t\bar{t}$ (dilepton) [28]	13 TeV	0.1151	± 0.0035		$^{+0.0020}_{-0.0002}$		MMHT14	NNLO
normalised $t\bar{t}$ [29]	13 TeV	0.1135	± 0.0016	$\underbrace{^{+0.0002}_{-0.0004}}_{\text{model}}$ $\underbrace{^{+0.0008}_{-0.0001}}_{\text{param}}$	$^{+0.0011}_{-0.0005}$		—	NLO
2D inclusive jet [8]	13 TeV	0.1166	± 0.0014	$\underbrace{\pm 0.0007}_{\text{model}}$ $\underbrace{\pm 0.0001}_{\text{param}}$	± 0.0004		—	NNLO
2D & 3D dijet mass [13]	13 TeV	0.1181	± 0.0013	$\underbrace{\pm 0.0006}_{\text{model}}$ $\underbrace{\pm 0.0002}_{\text{param}}$	± 0.0009		—	NNLO
$R_{\Delta\phi}$ [13]	13 TeV	0.1177	± 0.0013	$\underbrace{\pm 0.0010}_{\text{NNPDF3.1}}$ $\underbrace{\pm 0.0020}_{\text{choice}}$	$^{+0.0114}_{-0.0068}$	$\underbrace{\pm 0.0011}_{\text{NP}}$ $\underbrace{\pm 0.0003}_{\text{EW}}$	NNPDF3.1	NLO
EEC in jets [30]	13 TeV	0.1229	$\underbrace{^{+0.0014}_{-0.0012}}_{\text{stat}}$ $\underbrace{^{+0.0023}_{-0.0036}}_{\text{syst}}$		$^{+0.0030}_{-0.0033}$		—	aNNLL
comb. 2D inclusive jet [10]		0.1176	± 0.0009	$\underbrace{^{+0.0006}_{-0.0004}}_{\text{(model)}}$ $\underbrace{^{+0.0000}_{-0.0000}}_{\text{(param)}}$	$^{+0.0009}_{-0.0012}$		—	NNLO

Simultaneous unfolding

Typical analysis strategy

Data reduction in a nutshell

1. Apply a common selection to real and simulated samples.
2. Calibrate the samples.
3. Use simulated samples to construct a migration matrix.
4. Invert this migration matrix and apply to real data (unfolding).

Unfolding

$$\mathbf{A}\mathbf{x} = \mathbf{y}$$

- $\mathbf{x}$ (unknown) unbiased measurement
- $\mathbf{y}$ biased measurement
- $\mathbf{A}$ migration matrix

Simultaneous unfolding

Typical analysis strategy

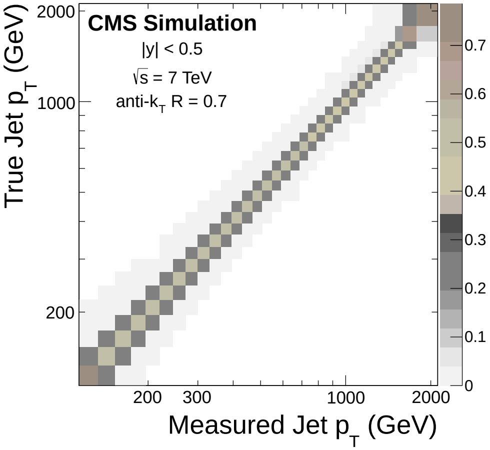
Data reduction in a nutshell

1. Apply a common selection to real and simulated samples.
2. Calibrate the samples.
3. Use simulated samples to construct a migration matrix.
4. Invert this migration matrix and apply to real data (unfolding).

Unfolding

$$\mathbf{Ax} = \mathbf{y}$$

- $\mathbf{x}$ (unknown) unbiased measurement
- $\mathbf{y}$ biased measurement
- $\mathbf{A}$ migration matrix



Simultaneous unfolding

Typical analysis strategy

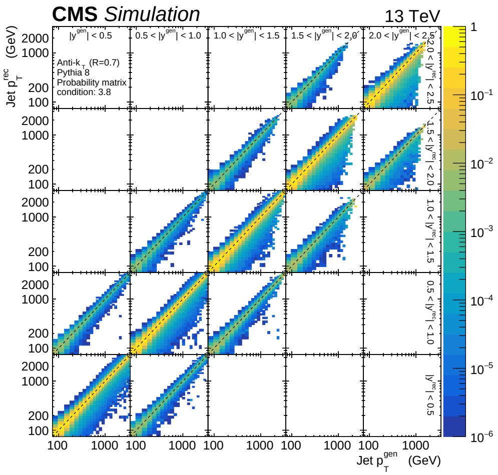
Data reduction in a nutshell

1. Apply a common selection to real and simulated samples.
2. Calibrate the samples.
3. Use simulated samples to construct a migration matrix.
4. Invert this migration matrix and apply to real data (unfolding).

Unfolding

$$\mathbf{A}\mathbf{x} = \mathbf{y}$$

- $\mathbf{x}$ (unknown) unbiased measurement
- $\mathbf{y}$ biased measurement
- $\mathbf{A}$ migration matrix



Application

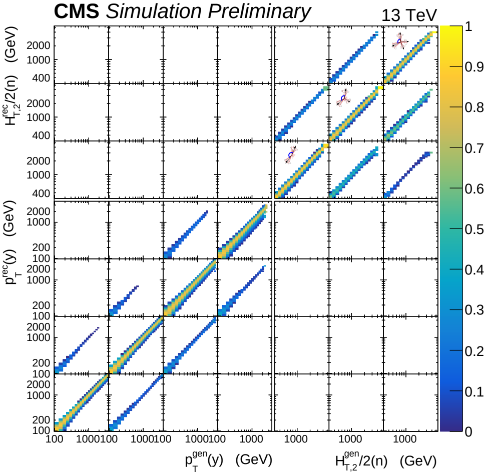
Migrations

$H_{\mathrm{T},2}$ spectra (3×3 block)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}H_{\mathrm{T},2}/2}(n) = \frac{1}{\mathcal{L}} \frac{N^{\text{eff}}_{n-\text{jets}}}{\Delta H_{\mathrm{T},2}/2}$$

Inclusive jet (4×4 block)

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_\mathrm{T}\ \mathrm{d}y} = \frac{1}{\mathcal{L}} \frac{N^{\text{eff}}_{\text{jets}}}{\Delta p_\mathrm{T}\,\Delta y}$$



Application

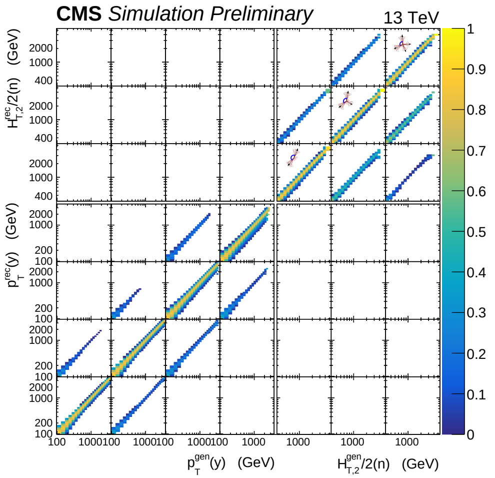
Migrations

$H_{\mathrm{T},2}$ spectra $(3 \times 3$ block)

$$\frac{d\sigma}{dH_{\mathrm{T},2}/2}(n) = \frac{1}{\mathcal{L}} \frac{N^{\mathrm{eff}}_{n-\mathrm{jets}}}{\Delta H_{\mathrm{T},2}/2}$$

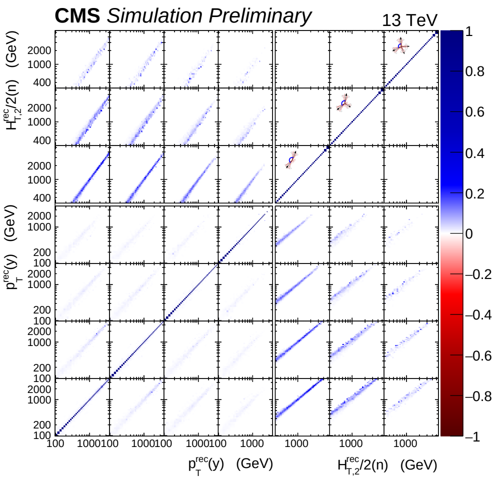
Inclusive jet $(4 \times 4$ block)

$$\frac{d^2\sigma}{dp_{\mathrm{T}}\ dy} = \frac{1}{\mathcal{L}} \frac{N^{\mathrm{eff}}_{\mathrm{jets}}}{\Delta p_{\mathrm{T}}\,\Delta y}$$



Application

Pre-unfolding correlations



Statistical correlations in real data

upper 3×3 block 1D inclusive jet in bins of multiplicity.

lower 4×4 block kinematic bins of 2D inclusive jet (multi-count observable).

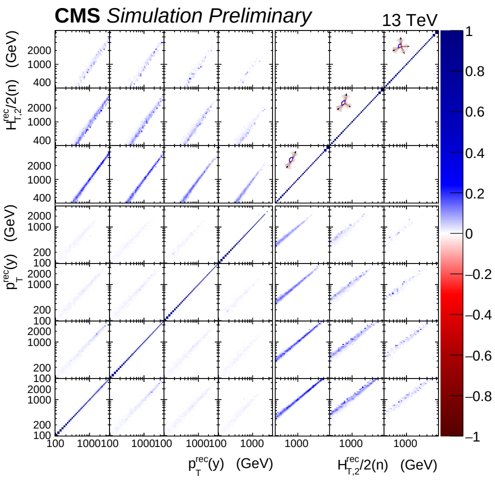
off-diagonal blocks correlations among the bins of the respective observables.

For the present exercise: simple least-square minimisation

$$\chi^2 = \min_{\mathbf{x}} \left[(\mathbf{A}\mathbf{x} - \mathbf{y})^\intercal \mathbf{V_y}^{-1} (\mathbf{A}\mathbf{x} - \mathbf{y}) \right]$$ where $\mathbf{V_y}$ is the covariance matrix

Application

Pre-unfolding correlations



Statistical correlations in real data

- **upper 3×3 block**: 1D inclusive jet in bins of multiplicity.
- **lower 4×4 block**: kinematic bins of 2D inclusive jet (multi-count observable).
- **off-diagonal blocks**: correlations among the bins of the respective observables.

For the present exercise: simple least-square minimisation

$$\chi^2 = \min_{\mathbf{x}} \left[(\mathbf{A}\mathbf{x} - \mathbf{y})^\intercal \mathbf{V_y}^{-1} (\mathbf{A}\mathbf{x} - \mathbf{y}) \right]$$

where $\mathbf{V_y}$ is the covariance matrix

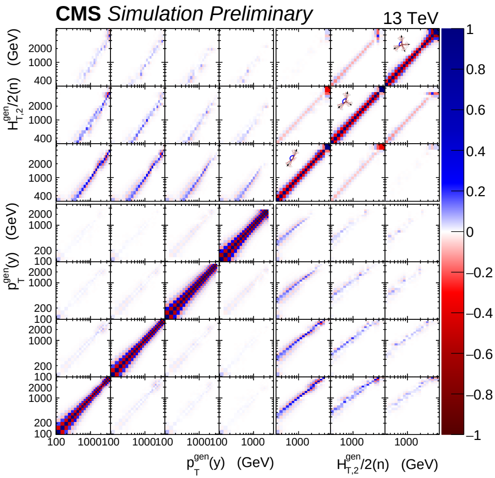
Application

Post-unfolding correlations

Result (unless regularisation is needed)

$$\mathbf{x} = (\mathbf{A}^\intercal \mathbf{V_y}^{-1} \mathbf{A})^{-1} \mathbf{A}^\intercal \mathbf{V_y}^{-1} \mathbf{y}$$

$$\mathbf{V_x} = \mathbf{A}^{-1} \mathbf{V_y} \mathbf{A}^{\intercal -1}$$



From the simulated data

- With infinitely large statistics, one can use independent statistical samples to construct the different sectors of the migration matrix.
- Else repeat unfolding using alternative migration matrices with additional event weights $\sim$ Pois(1):

$$\mathbf{V}'_\mathbf{x} = \left(\frac{1}{N} \sum_{n=1}^{N} \mathbf{x}_n \cdot \mathbf{x}_n^\intercal \right) - \frac{1}{N^2} \left(\sum_{n=1}^{N} \mathbf{x}_n \right) \cdot \left(\sum_{n=1}^{N} \mathbf{x}_n \right)^\intercal$$

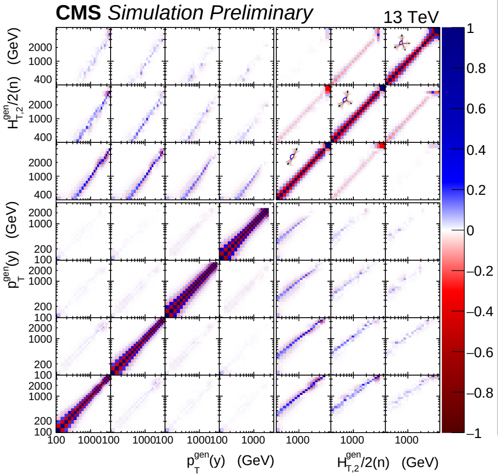
Application

Post-unfolding correlations

Result (unless regularisation is needed)

$$\mathbf{x} = \left(\mathbf{A}^\intercal \mathbf{V_y}^{-1} \mathbf{A}\right)^{-1} \mathbf{A}^\intercal \mathbf{V_y}^{-1}\, \mathbf{y}$$

$$\mathbf{V_x} = \mathbf{A}^{-1} \mathbf{V_y} \mathbf{A}^{\intercal -1}$$



From the simulated data

- With infinitely large statistics, one can use independent statistical samples to construct the different sectors of the migration matrix.
- Else repeat unfolding using alternative migration matrices with additional event weights $\sim \mathrm{Pois}(1)$:

$$\mathbf{V}'_\mathbf{x} = \left(\frac{1}{N} \sum_{n=1}^{N} \mathbf{x}_n \cdot \mathbf{x}_n^\intercal \right) - \frac{1}{N^2} \left(\sum_{n=1}^{N} \mathbf{x}_n \right) \cdot \left(\sum_{n=1}^{N} \mathbf{x}_n \right)^\intercal$$

CERN

Application

Final correlations

From H_{T} spectra to R_{ij}

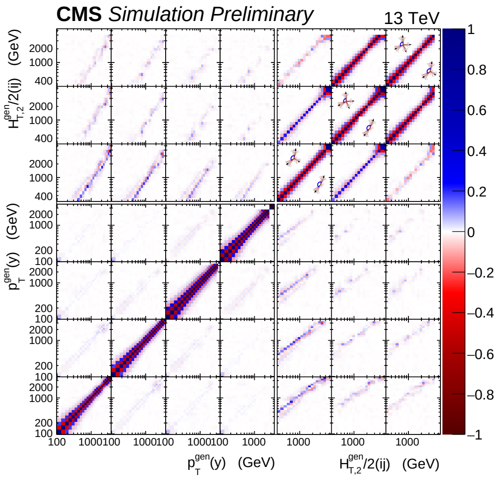
- Goal is to extract $\mathbf{z} = \mathbf{f}(\mathbf{x})$ and its correlations.
- Apply a rotation R to diagonalise $\mathbf{V_x}$ and generate N events $\mathbf{z}_n$:

$$\delta'_{n,i} \sim \mathcal{N}\left(0, \sqrt{\max(0, k_i)}\right)$$
$$\mathbf{z}_n = \mathbf{f}\left(\mathbf{x} + \mathbf{R}^{-1}\boldsymbol{\delta}'_n\right)$$

- Under the Gaussian hypothesis, the covariance may be obtained using the formula given on the last slices.

Gain

We now have two observables with distinct properties obtained from the same data.
$\longrightarrow$ R_{ij} offers additional control on α_{s}.



Application
Final correlations

From H_{T} spectra to R_{ij}

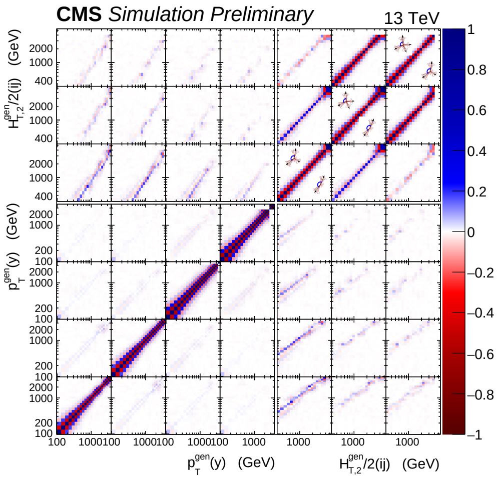
- Goal is to extract $\mathbf{z} = \mathbf{f}(\mathbf{x})$ and its correlations.
- Apply a rotation R to diagonalise $\mathbf{V}_{\mathbf{x}}$ and generate N events $\mathbf{z}_n$:

$$\delta'_{n,i} \sim \mathcal{N}\left(0, \sqrt{\max(0,k_i)}\right)$$
$$\mathbf{z}_n = \mathbf{f}\left(\mathbf{x} + \mathbf{R}^{-1}\boldsymbol{\delta}'_n\right)$$

- Under the Gaussian hypothesis, the covariance may be obtained using the formula given on the last slices.

Gain

We now have two observables with distinct properties obtained from the same data.
$\longrightarrow$ R_{ij} offers additional control on α_{S}.



Acronyms I

ATLAS A Toroidal LHC ApparatuS. 21–23, 41

CERN European Organisation for Nuclear Research. 21–23

CMS Compact Muon Solenoid. 10, 11, 20–28, 41

EEC energy energy correlator. 42–46

FO fixed order. 10, 11

HAD hadronisation. 36–38

LHC Large Hadron Collider. 2–9, 17–28

LOI letter of intent. 32–34, 39, 40

MC Monte Carlo. 36–38

ME matrix element. 36–38

MPI multi-parton interaction. 36–38

NP non-perturbative. 10, 11, 17–20, 24–28, 36–38

PDF parton distribution function. 10, 11, 42–46

PDG Particle Data Group. 21–23, 41

pQCD perturbative QCD. 10, 11, 21–23

PS parton shower. 36–38

QCD quantum chromodynamics. 2–5, 21–28, 41

SM standard model. 2–5

TA transnational access. 21–23

VA virtual access. 21–23

WIP work in progress. 32–34

References I

[1] D. de Florian et al. "Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector". In: 2/2017 (Oct. 2016). DOI: 10.23731/CYRM-2017-002. arXiv: 1610.07922 [hep-ph].

[2] Paul Langacker. "Grand Unified Theories and Proton Decay". In: **Phys. Rept.** 72 (1981), p. 185. DOI: 10.1016/0370-1573(81)90059-4.

[3] Gudrun Hiller et al. "Vacuum stability in the Standard Model and beyond". In: **Phys. Rev. D** 110.11 (2024), p. 115017. DOI: 10.1103/PhysRevD.110.115017. arXiv: 2401.08811 [hep-ph].

[4] John C. Collins, Davison E. Soper, and George F. Sterman. "Factorization of Hard Processes in QCD". In: **Adv. Ser. Direct. High Energy Phys.** 5 (1989), pp. 1–91. DOI: 10.1142/9789814503266_0001. arXiv: hep-ph/0409313.

[5] T. Gehrmann et al. "Jet cross sections and transverse momentum distributions with NNLOJET". In: **PoS** RADCOR2017 (2018). Ed. by Andre Hoang and Carsten Schneider, p. 074. DOI: 10.22323/1.290.0074. arXiv: 1801.06415 [hep-ph].

[6] Daniel Britzger et al. "New features in version 2 of the fastNLO project". In: **20th International Workshop on Deep-Inelastic Scattering and Related Subjects**. 2012, p. 217. DOI: 10.3204/DESY-PROC-2012-02/165. arXiv: 1208.3641 [hep-ph].

References II

[7] V. Bertone et al. "xFitter 2.0.0: An Open Source QCD Fit Framework". In: **PoS** DIS2017 (2018). Ed. by Uta Klein, p. 203. DOI: 10.22323/1.297.0203. arXiv: 1709.01151 [hep-ph].

[8] Armen Tumasyan et al. "Measurement and QCD analysis of double-differential inclusive jet cross sections in proton-proton collisions at $\sqrt{s} = 13$ TeV". In: **JHEP** 02 (2022). [Addendum: JHEP 12, 035 (2022)], p. 142. DOI: 10.1007/JHEP02(2022)142. arXiv: 2111.10431 [hep-ex].

[9] Aram Hayrapetyan et al. "Stairway to discovery: a report on the CMS programme of cross section measurements from millibarns to femtobarns". In: (May 2024). arXiv: 2405.18661 [hep-ex].

[10] Vladimir Chekhovsky et al. "Determination of the strong coupling and its running from measurements of inclusive jet production". In: (Dec. 2024). arXiv: 2412.16665 [hep-ex].

[11] V. Andreev et al. "Measurement of multijet production in ep collisions at high Q^2 and determination of the strong coupling α_s". In: **Eur. Phys. J. C** 75.2 (2015), p. 65. DOI: 10.1140/epjc/s10052-014-3223-6. arXiv: 1406.4709 [hep-ex].

[12] CMS Collaboration. **Simultaneous determination of several differential observables with statistical correlations**. Tech. rep. Geneva: CERN, 2024. URL: https://cds.cern.ch/record/2888301.

References III

[13] Aram Hayrapetyan et al. "Measurement of multidifferential cross sections for dijet production in proton-proton collisions at $\sqrt{s} = 13$ TeV". Dec. 2023. arXiv: 2312.16669 [hep-ex].

[14] Maximilian Horzela and Cedric Verstege. **MC-Run**. 2023. URL: https://zenodo.org/records/12721769 (visited on 10/13/2024).

[15] Stefan Gieseke et al. "Nonperturbative effects in triple-differential dijet and Z+jet production at the LHC". In: (Dec. 2024). arXiv: 2412.19694 [hep-ph].

[16] Glen Cowan. "Statistical Models with Uncertain Error Parameters". In: **Eur. Phys. J. C** 79.2 (2019), p. 133. DOI: 10.1140/epjc/s10052-019-6644-4. arXiv: 1809.05778 [physics.data-an].

[17] Enzo Canonero and Glen Cowan. "Correlated Systematic Uncertainties and Errors-on-Errors in Measurement Combinations: Methodology and Application to the 7-8 TeV ATLAS-CMS Top Quark Mass Combination". In: (July 2024). arXiv: 2407.05322 [hep-ex].

[18] Patrick L.S. Connor and Louis Moureaux. **Proto/Darwin**. 2023. URL: http://protodarwin.docs.cern.ch (visited on 10/12/2024).

[19] CMS Collaboration. **Das Analysis System**. 2018. URL: http://dasanalysissystem.docs.cern.ch.

References IV

[20] Serguei Chatrchyan et al. "Measurement of the ratio of the inclusive 3-jet cross section to the inclusive 2-jet cross section in pp collisions at $\sqrt{s} = 7$ TeV and first determination of the strong coupling constant in the TeV range". In: **Eur. Phys. J. C** 73 (2013), p. 2604. DOI: 10.1140/epjc/s10052-013-2604-6. hep-ex: 1304.7498. URL: http://cdsweb.cern.ch/record/1544428.

[21] Serguei Chatrchyan et al. "Measurements of Differential Jet Cross Sections in Proton-Proton Collisions at $\sqrt{s} = 7$ TeV with the CMS Detector". In: **Phys. Rev. D** 87 (2013). [Erratum: Phys.Rev.D 87, 119902 (2013)], p. 112002. DOI: 10.1103/PhysRevD.87.112002. arXiv: 1212.6660 [hep-ex].

[22] Vardan Khachatryan et al. "Constraints on parton distribution functions and extraction of the strong coupling constant from the inclusive jet cross section in pp collisions at $\sqrt{s} = 7$ TeV". In: **Eur. Phys. J. C** 75 (2015), p. 288. DOI: 10.1140/epjc/s10052-015-3499-1. hep-ex: 1410.6765. URL: http://cdsweb.cern.ch/record/1957365.

[23] Vardan Khachatryan et al. "Measurement of the inclusive 3-jet production differential cross section in proton-proton collisions at 7 TeV and determination of the strong coupling constant in the TeV range". In: **Eur. Phys. J. C** 75 (2015), p. 186. DOI: 10.1140/epjc/s10052-015-3376-y. hep-ex: 1412.1633. URL: http://cdsweb.cern.ch/record/1974165.

References V

[24] Serguei Chatrchyan et al. "Determination of the top quark pole mass and strong coupling constant from the $t\bar{t}$ production cross section in pp Collisions at $\sqrt{s} = 7$ TeV". In: **Phys. Lett. B** 728 (2014). [Erratum: Phys.Lett.B 738, 526–528 (2014)], p. 496. DOI: 10.1016/j.physletb.2013.12.009. arXiv: 1307.1907 [hep-ex].

[25] Vardan Khachatryan et al. "Measurement and QCD analysis of double-differential inclusive jet cross sections in pp collisions at $\sqrt{s} = 8$ TeV and cross section ratios to 2.76 and 7 TeV". In: **JHEP** 03 (2017), p. 156. DOI: 10.1007/JHEP03(2017)156. arXiv: 1609.05331 [hep-ex].

[26] Albert M Sirunyan et al. "Measurement of the triple-differential dijet cross section in proton-proton collisions at $\sqrt{s} = 8$ TeV and constraints on parton distribution functions". In: **Eur. Phys. J. C** 77.11 (2017), p. 746. DOI: 10.1140/epjc/s10052-017-5286-7. arXiv: 1705.02628 [hep-ex].

[27] Albert M Sirunyan et al. "Determination of the strong coupling constant $\alpha_S(m_Z)$ from measurements of inclusive $W^{\pm}$ and Z boson production cross sections in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV". In: **JHEP** 06 (2020), p. 018. DOI: 10.1007/JHEP06(2020)018. arXiv: 1912.04387 [hep-ex].

[28] Albert M Sirunyan et al. "Measurement of the $t\bar{t}$ production cross section, the top quark mass, and the strong coupling constant using dilepton events in pp collisions at $\sqrt{s} = 13$ TeV". In: **Eur. Phys. J. C** 79 (2019), p. 368. DOI: 10.1140/epjc/s10052-019-6863-8. arXiv: 1812.10505 [hep-ex].

References VI

[29] Albert M Sirunyan et al. "Measurement of $\mathrm{t\bar{t}}$ normalised multi-differential cross sections in pp collisions at $\sqrt{s} = 13$ TeV, and simultaneous determination of the strong coupling strength, top quark pole mass, and parton distribution functions". In: **Eur. Phys. J. C** 80 (2020), p. 658. DOI: 10.1140/epjc/s10052-020-7917-7. arXiv: 1904.05237 [hep-ex].

[30] Aram Hayrapetyan et al. "Measurement of Energy Correlators inside Jets and Determination of the Strong Coupling αS(mZ)". In: **Phys. Rev. Lett.** 133.7 (2024), p. 071903. DOI: 10.1103/PhysRevLett.133.071903. arXiv: 2402.13864 [hep-ex].

Patrick L.S. Connor

patrick.connor@cern.ch
CERN, 40/A1-016