New results in CMS using CASTOR

LHCFWD, 2018, CERN

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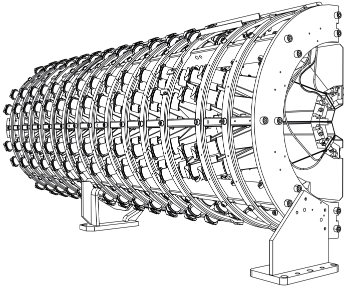
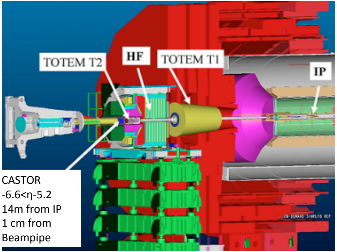
Birds eye view

- CASTOR: very forward calorimeter of CMS. Unique acceptance: $-6.6 < \eta < -5.2$
- Focus on two recent submitted results employing CASTOR
  - FSQ-15-006: measurement of the energy density as a function of pseudorapidity in proton-proton collisions at $\sqrt{s}$= 13 TeV
  - FSQ-17-001: measurement of inclusive very forward jet cross sections in proton-lead collisions at $\sqrt{s_{NN}}$ =5 TeV
- Content talk:
  - Introduction CASTOR
  - Review FSQ-15-006
  - Review FSQ-17-001
  - Conclusions, outlook

The CASTOR calorimeter at CMS





CASTOR at CMS

- CASTOR: EM-hadronic tungsten-quartz calorimeter at CMS
- Most forward conventional calorimeter deployed at the LHC, at 14 m from interaction point. Acceptance: $-6.6 \leq \eta \leq -5.2$
- Longitudinally 14-fold segmentation
- Transversally 16-fold segmentation
- CASTOR has no η segmentation! Consequence: measure energy of jets instead of p_T within its acceptance

Successful data taking campaigns with CASTOR:

- Run I: **p+p** at 0.9, 2.76 and 7 TeV. **Pb+Pb** at 2.76 TeV. **p+Pb** at 5 TeV
- Run II: **p+p** at 5 and 13 TeV. **Pb+Pb** at 5 TeV. **p+Pb** at 5 and 8 TeV

List of papers, submitted papers and prelim. results

- Run I data analyses:
  - Study of the underlying event at forward rapidity in pp collisions at $\sqrt{s}$=0.9,2.76, and 7 TeV: **JHEP 04 (2013) 072**
  - Measurement of energy flow at large pseudorapidities in pp collisions at $\sqrt{s}$=0.9 and 7 TeV: **JHEP 11 (2011) 148**
  - Measurement of diffractive dissociation cross sections in pp collisions at $\sqrt{s}$=7 TeV: **Phys. Rev. D 92, 012003 (2015)**
  - Measurement of inclusive very forward jet cross sections in proton-lead collisions at $\sqrt{s_{NN}}$ =5 TeV: **arXiv:1812.01691**. new!
  - Measurement of the very forward inclusive jet cross section in pp collisions at $\sqrt{s}$ =7 TeV: **CMS-PAS-FSQ-12-023**
  - η and centrality dependence of the forward energy density in PbPb collisions at $\sqrt{s}$=2.76 TeV: **CMS-PAS-HIN-12-006**
- Run II data analyses:
  - Measurement of the inclusive energy spectrum in the very forward direction in proton-proton collisions at $\sqrt{s}$=13 TeV: **JHEP 08 (2017) 046**
  - Measurement of the inelastic proton-proton cross section at $\sqrt{s}$=13 TeV: **JHEP 07 (2018) 161**
  - Measurement of the energy density as a function of pseudorapidity in proton-proton collisions at $\sqrt{s}$= 13 TeV: **arXiv:1812.04095**). new!
  - Measurement of the very forward inclusive jet cross section in pp collisions at $\sqrt{s}$ =13 TeV: **CMS-PAS-FSQ-15-005**
  - **Under construction:** The CASTOR very forward calorimeter of CMS (Run II performance)

Measurement of the energy density as a function of pseudorapidity in proton-proton collisions at $\sqrt{s}$= 13 TeV

Overview

- Measurement of energy flow in $3.15 < |\eta| < 5.2$ complemented with $-6.6 < \eta < -5.2$
- Purpose: test models in phase-space relevant to Cosmic Ray physics, review limiting fragmentation hypothesis
- Four event categories studied:
  - Inelastic
  - Non-single diffractive (NSD)
  - Single diffractive (SD)
  - Dedicated limiting fragmentation

Event generators

- Pythia8 **Comput. Phys.Commun. 191 (2015) 159**
  - Based on collinear factorisation, Lund string fragmentation and
  - CUETP8M1, CUETP8S1 and Monash tunes. The CUETP8M1 and CUETP8S1 are tuned to UE data LHC and Tevatron
  - Pythia8 with MBR model: with 4C and CUETP8M1 tune.
- EPOS-LHC and QGSJet. Cosmic Ray models. Combination of Regge-Gribov, perturbative QCD and string fragmentation. **Phys. Rev. C 92, 034906 (2015)**, **Phys.Rev. D83 (2011) 014018**

Definition observables, event categories, and systematics:

Energy Flow

- Definition: $\frac{dE}{d\eta} = \frac{1}{Nevt.} \sum_i E_i \frac{c(\eta)}{\Delta\eta}$
- The correction factor $c(\eta)$ tansforms det. level measurement to particle level
  - Accounts for pileup, noise, and correction detector to particle level
- Systematic model dependence studied with 4 models

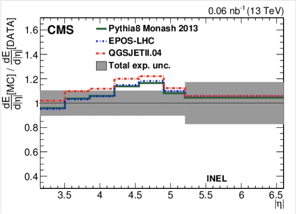
Event categories

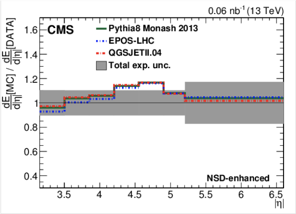
- Four event categories studied using Hadronic Forward (HF) detectors ($3.15 < |\eta| < 5.2$):
  - Inelastic.
    - Require maximal deposit HF >5 GeV
    - Particle level: require $\xi > 10^{-6}$
  - Non-single diffractive (NSD).
    - Fwd and bwd HF detectors both deposit >5 GeV
    - Particle level: particle with $E > 5$ GeV in fwd and bwd HF acceptance
  - Single diffractive (SD)
    - Fwd (bwd) HF detector deposit > 5 GeV, veto bwd (fwd)
    - Particle with $E > 5$ GeV in fwd (bwd) HF acceptance, veto bwd (fwd)
  - Limiting fragmentation
    - Fwd and bwd HF > 4 GeV
    - Particle with E> 4 GeV in fwd and bwd HF acceptance

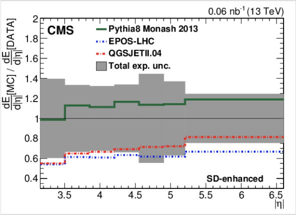
NB: (ξ is max of $\frac{M_X^2}{\sqrt{s}}, \frac{M_Y^2}{\sqrt{s}}$). M_x is mass system Fwd w.r.t. largest pseudorapidity gap)

Compare results to Cosmic Ray models (ratios only)

- Observe none of CR models describe all data. Most pronounced at $\eta = 4.5$
- Largest discepancies with SD measurement



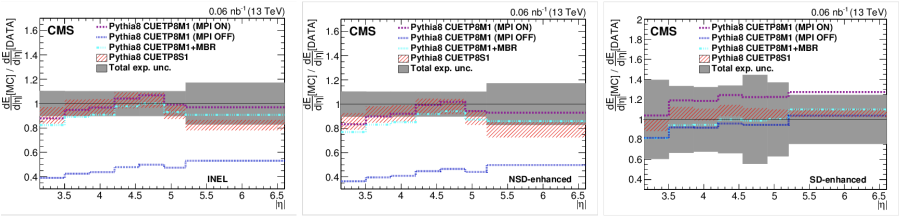




Results

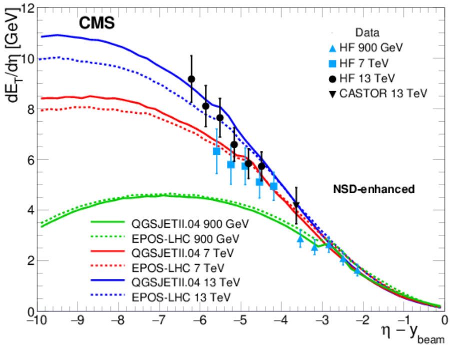
Compare results to Pythia models (ratios only)

- Observe CUETP8S1 is in full agreement with data
- Measurement suggests different η-dependence w.r.t. generators
- Note: MPI interactions amount for approx. 60% of energy flow for INEL and NSD-enhanced. Observe SD rather insensitive



Limiting fragmentation

- Limiting fragmentation predicts longitudinal scaling in terms of shifted $\eta' = \eta - y_{\text{beam}}$
- Measurement transversal energy density E_T, defined $E_T = Ecosh(\eta)$
- Hypothesis predicts invariance of E_T w.r.t. beam energy for $\eta' = 0$
- Plot measurement with results previous measurements. Results support limiting fragmentation. Important results for CR physics!



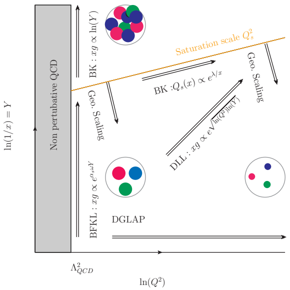
Motivation

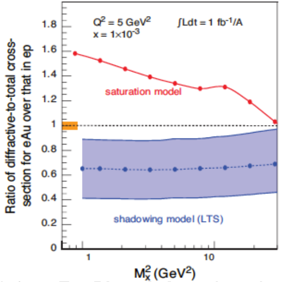
Signals of nonlinear QCD

- At very small momentum fractions x transition from dilute to dense medium. Nonlinear QCD behaviour expected
  - Relevant to cosmic-ray and heavy ion physics
- Saturation scale: $Q_s^2(x) \approx \frac{\alpha_s xg(x, Q_s^2)}{\pi R^2_{had.}}$
  - Geometric interpretation: gluons with area $r^2 \approx 1/Q^2$ "fill up" the hadron area. Fusion reactions ($gg \to g$) expected when overlap occurs
- Saturation has been extensively analysed in past, constitutes a key incentive for future EIC

Status of gluon saturation

- Analyses key measurements comply with saturation hypothesis
- Interpretation of important results diffused though:
  - HERA e+p measurements: the saturation scale close to perturbative limit
  - RHIC d+Au measurements: hard partons projectile at kinematic limit
- LHC results appear to comply with saturation
  - No "smoking gun" signature observed yet though

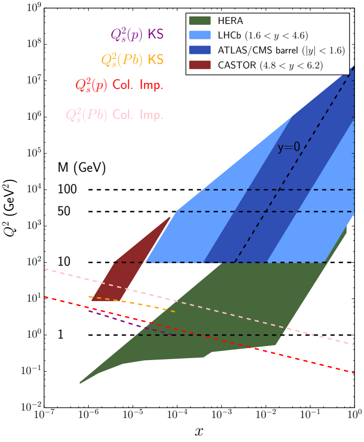




Graph from **Eur.Phys.J. A. 52 (2016) no.9, 268**

Optimal saturation signals

- Saturation scale in ion $\approx N^{1/3}$ larger than proton, ≈ 6 for lead
- For a jet in leading order approximation: $x \approx \frac{p_T \exp^{-\eta}}{\sqrt{s}}$
  $\rightarrow$ Forward low p_T jets in p+Pb collisions sensitive to saturation effects



Forward low pt jets in CASTOR at CMS

- CMS equiped with CASTOR calorimeter:
  - Acceptance: $-6.6 < \eta < -5.2$
  - For jets: $p_T \geq 3$ GeV

  $\rightarrow$ Measurement potentially higly sensitive to saturation, and circumvent adversities previous analyses

Focus of analysis

- Measurement of single-inclusive jet energy spectrum in p+Pb collisions in CASTOR
  - For proton (p+Pb) and ion (Pb+p) to CASTOR
- Interpret results with dedicated saturation models

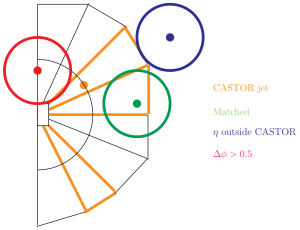
Source of systematic uncertainty

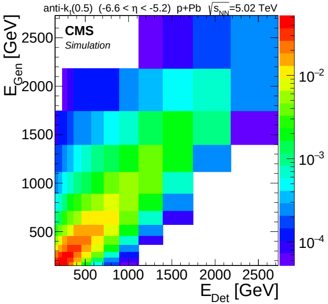
Sources of sys.uncertainty (by magnitude):

- CASTOR energy scale: 15% uncertainty
- Model uncertainty
- Alignment CASTOR known within 2 mm
- Calibration procedure
- Luminosity

Consequences jet matching procedure

- For CASTOR, can only match jets in ϕ
- Two profound consequences:
  - Broad response matrix $\rightarrow$ need regularised unfolding
  - Large mis and fake fractions $\rightarrow$ substantial model dependence unfolding procedure
- NB: unfolding needs 100 (p+Pb) and 720 (Pb+p) Bayesian iterations

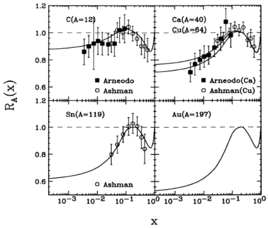




Strategy towards interpreting the data

Two saturation models using Hybrid factorisation:

- Hybrid factorisation for forward production
  - Hard parton via collinear factorisation and DGLAP evolution
  - Soft parton via unintegrated pdf and rcBK equation (linear and nonlinear)
- AAMQS: model soft updf with Colour Glass Condensate assumptions **Phys. Rev. D 94 (2016) 054004**
- Katie KS
  - Use Katie program for offshell matrix elements **Comput. Phys. Commun. 224 (2018) 371**
  - Interfaced with Kutak-Sapeta linear and nonlinear updfs. Evolve with extended BFKL and rcBK equation **Phys. Rev. D 86 (2012) 094043**

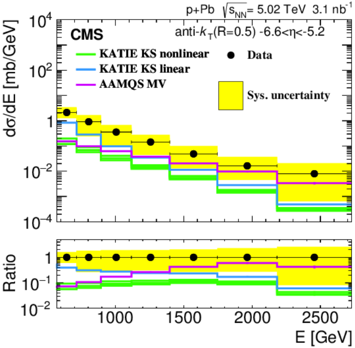


Nuclear modification of structure function from nuclear DIS data used by Hijing. **Phys. Lett. B 202, 603 (1988), ibid. 211, 493 (1988)**

Other event generators:

- Hijing. Applies DGLAP parton evolution via Pythia. Shadowing implemented via suppression of nuclear gluon pdf. Suppressed with fit to nuclear sea quark DIS data **Comput.Phys.Commun.83:307,1994**
- EPOS and QGSJetII_04. CR model. Phenomenological implementations of saturation

The key result: the p+Pb spectrum. Probe ion glue with proton



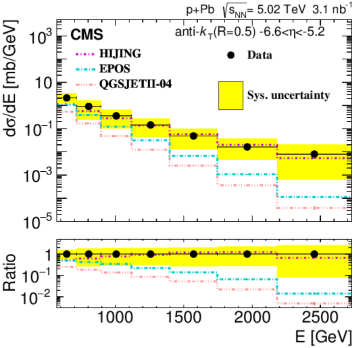
Katie KS

- Measurement potentially highly sensitive to saturation
- Normalisation off. Non-linear shape best

AAMQS prediction

- Underestimates data at low energies
- Shape appears too hard

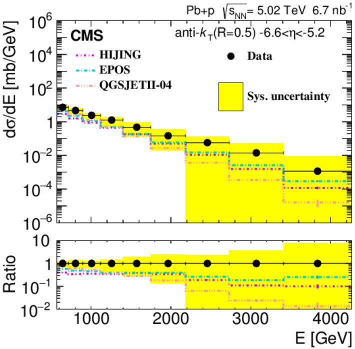
The key result: the p+Pb spectrum. Probe ion glue with proton



Observations

- Hijing describes data well
- EPOS and QGSJet too soft. At 2.5 TeV data and QGSJet deviate by 2.5 orders of magnitude!

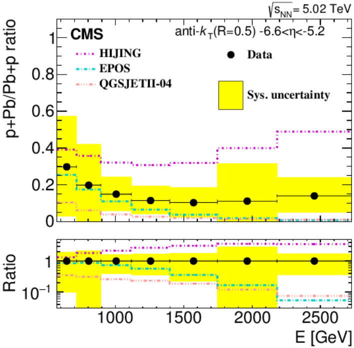
The unfolded Pb+p spectrum



Observations

- Jet algorithm picks contributions beam remnant
- Large sys. uncertainty
- EPOS and Hijing describe shape data reasonably well but norm is off. QGSJet worst description data

The unfolded ratio p+Pb/Pb+p



Data-driven interpretation hard

- Divide results from different cms-frame acceptance
- Ion debris and nuclear effects distort picture

Optimal resolution

- Scale uncertainty partially cancels
- Hijing describes shape well but norm off, due to Pb+p
- EPOS and QGSJet have wrong shape, partially describe data

Conclusions: physics interpretation

Physics interpretation

- Data potentially highly sensitive to saturation effects
  $\rightarrow$ Saturation models, given their current state of art, appear not to describe data in this kinematic regime
- Hijing, based on collinear factorisation and nuclear shadowing, describes p+Pb
  $\rightarrow$ Suggestive k_{T} factorisation may not be needed here. Nuclear effects modelled rather on nucleon that parton level

Experimental progress

- Results on energy flow including CASTOR are consistent with limiting fragmentation hypothesis
- First CASTOR jet paper submitted to Journal. CASTOR jets are an experimental reality
- Implications for saturation models
- CASTOR collected many dataset for different beam setups. Great potential to future (refined) studies!
- Work ongoing on overarching paper performance CASTOR in Run II
- ...Stay tuned!

... Thanks for your attention!

Next steps/discussion

Models

- Discrepancy between AAMQS and Katie non-linear predictions need clarification
  - Dipole amplitude vs offshell matrix elements, effect MPI, hadronisation method, ...
- Shadowing:
  - Currently implemented via fit to data in Hijing
  - Estimate of magnitude effect important

Data-driven conclusion desirable but not straightforward!

- Jets in CASTOR in p+Pb suffer from boost. Can't correct
- Logical next steps (input welcome!)
  - Analyse 5 TeV p+p reference run
  - Study centrality dependence (different dependence shadowing/saturation?)
  - Study of dijets and correlation may enhance sensitivity

Content backup

Content

- References for presentation
- Conclusions on Data and model comparison
- Note on validity results
- References CASTOR papers
- Recent results on forward energy flow
- Detail picture of a CASTOR channel

Conclusions: data and model comparison

Data and model comparison

- Uncertainties for p+Pb and Pb+p large. Scale largely cancels for ratio
  - Max scale uncertainty pA: $^{145\%}_{71\%}$
  - Max scale uncertainty Ap: $^{170\%}_{81\%}$
  - Max scale uncertainty pA/Ap: $^{57\%}_{29\%}$
- p+Pb: significant deviations, progressively larger with jet energy
- Pb+p: model discrepancies smaller than p+Pb, but significant at lower energies
- Ratio: not described by any model. Hijing deviates significantly, through Pb+p deviations
- The RECO level spectra have enhanced discriminative power due to absence model uncertainty

Brief note validity

Validity procedure

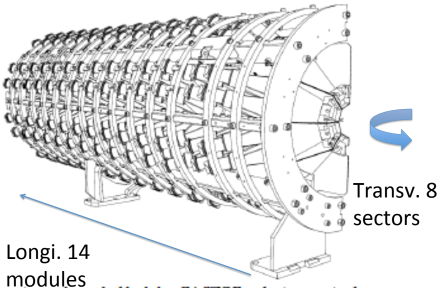
- As cross check, 7 TeV p+p NTuples analysed within p+Pb framework. Convergence reached
- For most parameters, values found are same or comparable with CASTOR p+p jet analyses at 7 and 13 TeV
- Result cross section and systematic uncertainties are reasonably consistent with p+p analyses
- Behaviour on unfolded spectra reasonably comparable with RECO level spectra
- p+Pb actually described by models at low energies
- ... No internal inconsistencies observed

List of papers, CMS PAS (Physics Analysis Summary) and performance notes with CASTOR

- Underlying event at forward rapidity at 0.9, 2.76, and 7 TeV p+p: **JHEP 04 (2013) 072**
- Forward energy flow at 13 TeV p+p: **JHEP 08 (2017) 046**
- η and centrality dependence of the forward energy density in PbPb collisions at $\sqrt{s}$=2.76 TeV: **CMS-PAS-HIN-12-006**
- Diffractive Dissociative Cross section at 7 TeV p+p: **Phys. Rev. D 92, 012003 (2015)**
- Inelastic cross section at 13 TeV p+p : **CMS PAS FSQ-15-005**
- Inclusive CASTOR jet cross section at 13 TeV p+p: **CMS PAS FSQ-16-003**
- Inclusive CASTOR jet cross section at 7 TeV p+p: **CMS-PAS-FSQ-12-023**
- Inclusive CASTOR jet cross section at 5 TeV p+Pb: **CMS-PAS-FSQ-17-001**

Theory predictions

- Katie-KS predictions:
  - Katie: textbfComput. Phys. Commun. 224 (2018) 371
  - Kutak-Sapeta updf: textbfPhys. Rev. D 86 (2012) 094043
- AAMQS predictions:
  - The predictions are based on the framework described in **Phys. Rev. D 94 (2016) 054004**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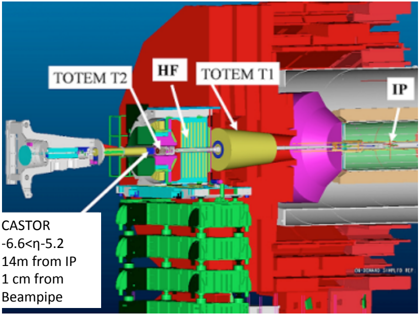
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HF
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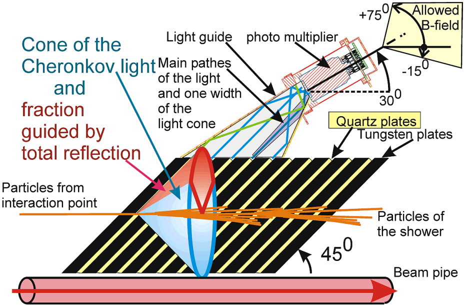
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and one width
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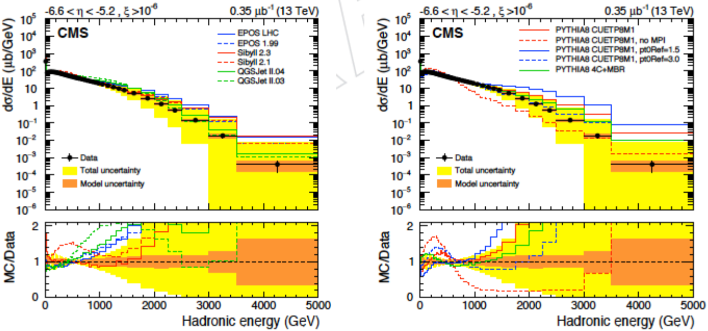
+75⁰
Allowed
B-field
-15⁰
30⁰
Quartz plates
Tungsten plates
Particles from
interaction point
Particles of
the shower
45⁰
Beam pipe

Results

- Energy flow $\frac{dN}{dE}$ measured at CASTOR at 13 TeV proton+proton collisions
- Measurement possesses large systematics error (mainly due to scale). Nonetheless, none of models describes all features of the data
- Cosmic Ray models tuned to LHC give best description
- Spectra very sensitive to MPI cutoff.
  → Forward energy flow measurement at CASTOR allows for tuning MPI and improving understanding muon production in air showers
- Results can be found at JHEP 08 (2017) 046



Condition number definition

Results

- Condition number is a reflection of how broad the response matrix K is
- $\mathrm{cond}(K) = \sigma_{\max}/\max(0, \sigma_{\min})$, where $\sigma_{\max}$ is the largest and $\sigma_{\min}$ is the smallest singular value of K
- Large condition number implies many Bayesian iterations are needed for sufficient regularization