Bayesian Analysis in Heavy-Ion Physics

Yi Chen (MIT)
Sep 24, 2022. QCD Town Hall Meeting

How can we test ideas instead of parameters?

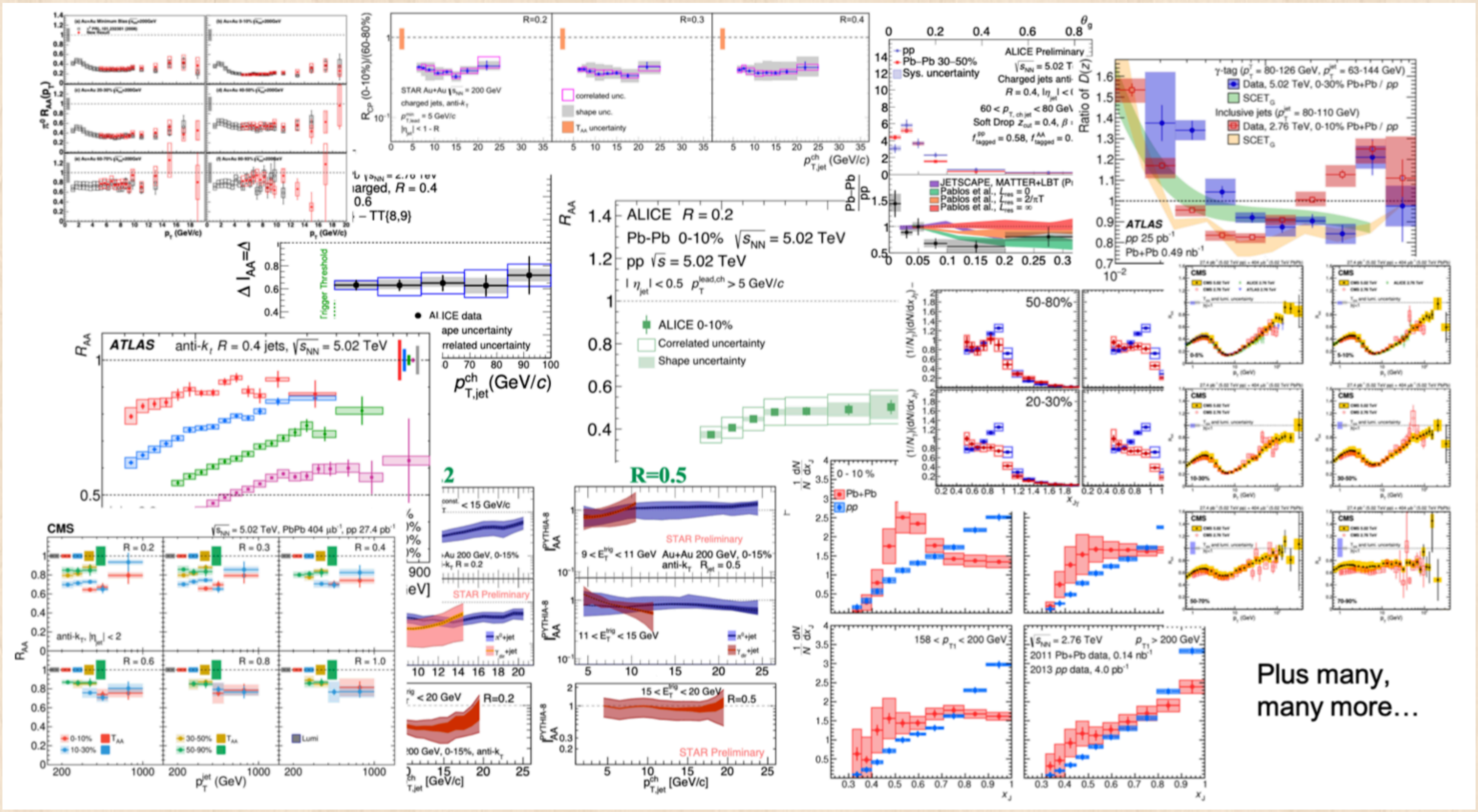
The MITHIG's work is supported by US DOE-NP

Bayesian analysis

The proliferation of data

DATA

Slide from R. Ehlers, QM 2022

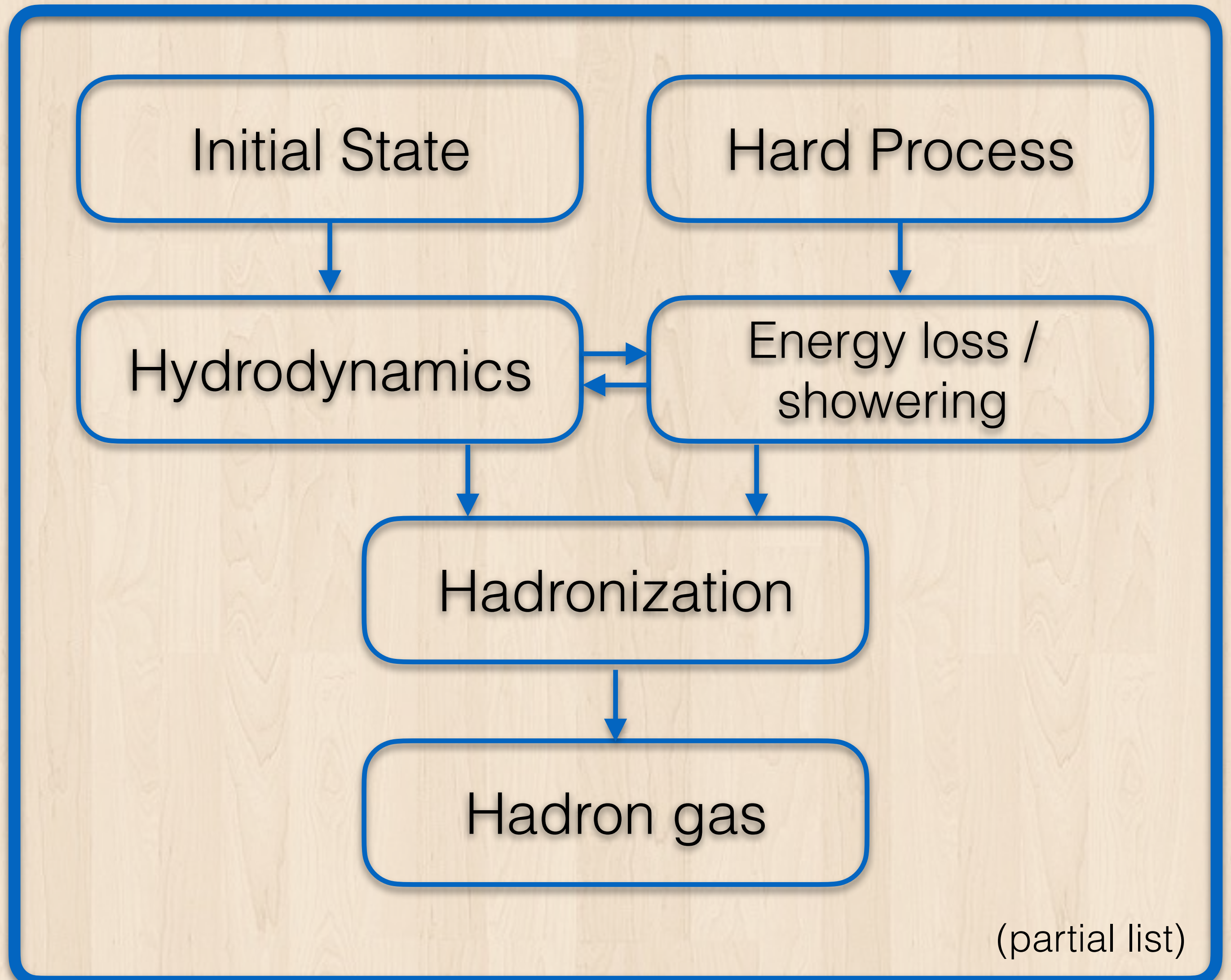


High quality data from experiments come at a high rate

How to best extract physics from them simultaneously?

The problem of Heavy Ions

MODEL



Problem of code-base alleviated by e.g. JETSCAPE framework

JETSCAPE

Large amount of moving pieces → parameters

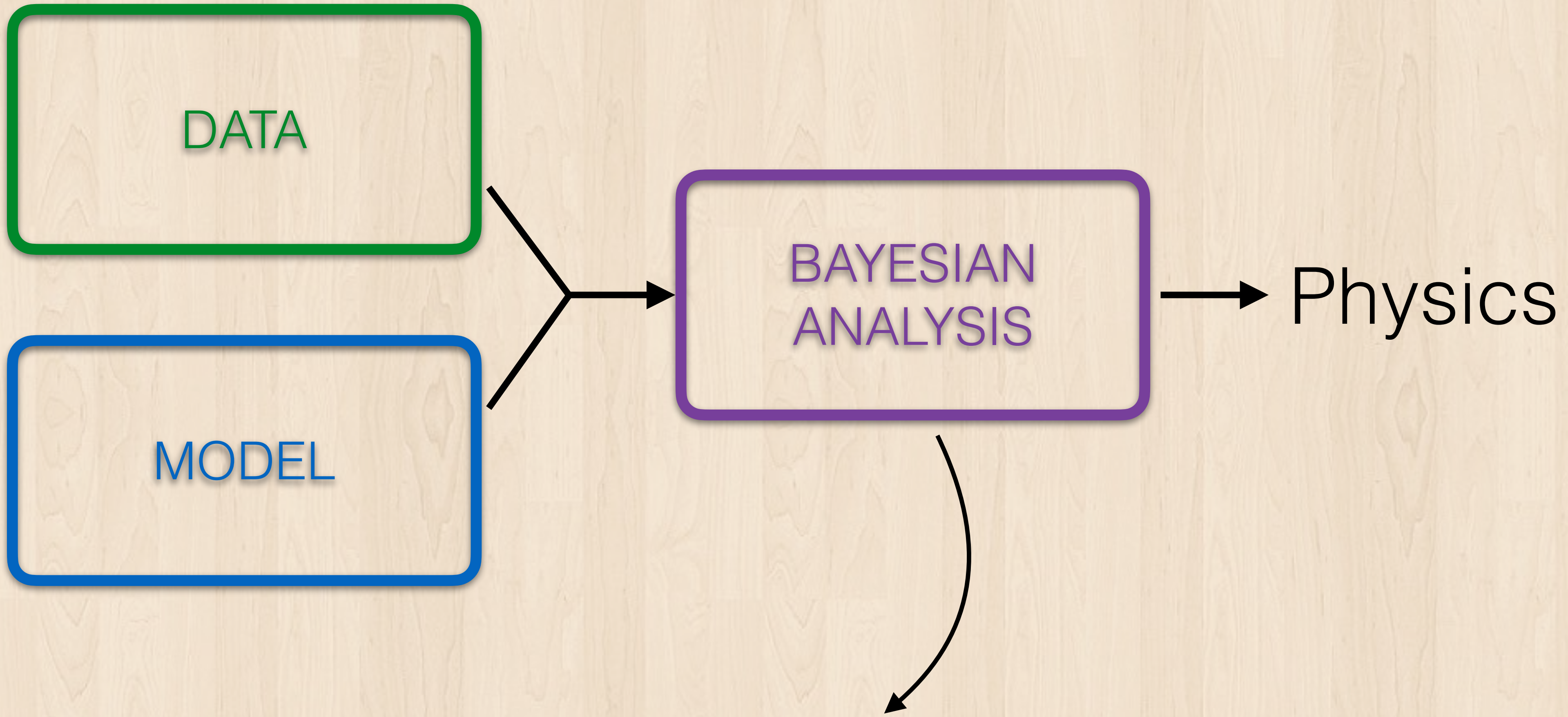
Often different codes

Computing intensive

Quickly becomes non-practical

See also A. Majumder talk on Sep 23

Bayesian analysis



A way to do rigorous data-model comparison

Scales well with problem size

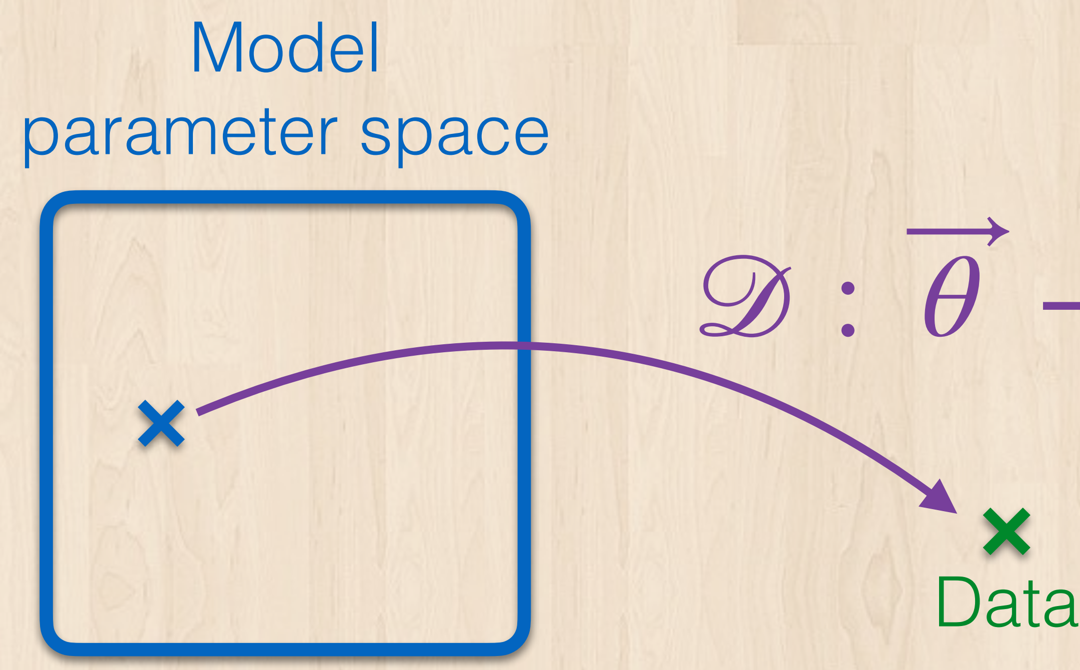
(ps. still need a lot of computing!)

See also e.g. stat part of JETSCAPE

Bayesian analysis: operational view

Function $\mathscr{D}$ maps parameter point to a “distance” to the data

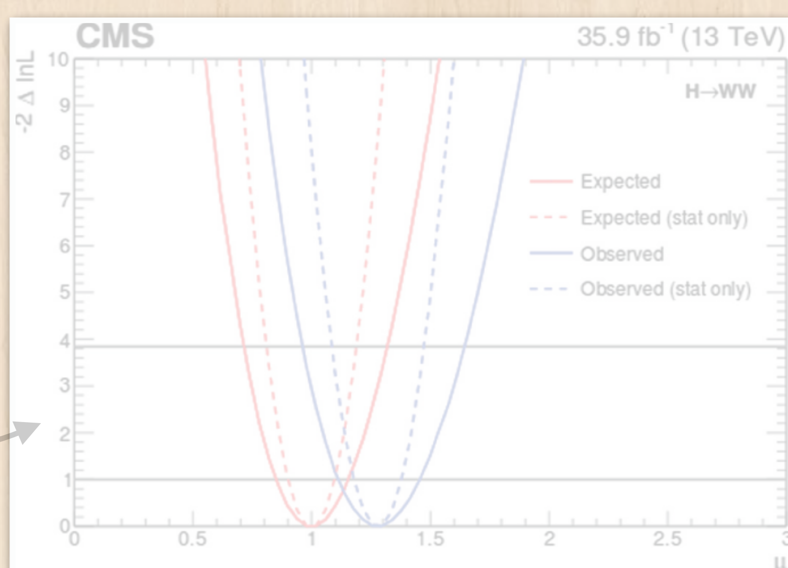
Contains all physics we want to extract



$$\mathscr{D} : \vec{\theta} \to \mathbb{R}$$

$\mathscr{D}$ = the posterior function in the Bayes’ formalism

Similar in spirit

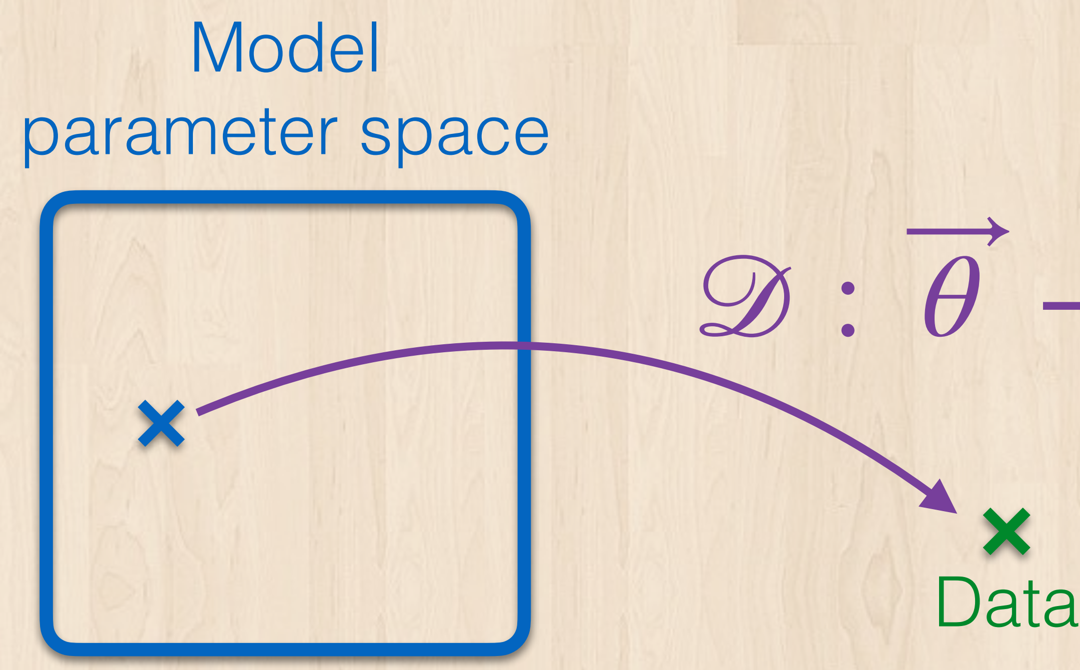


Bayesian analysis provides a way to get to $\mathscr{D}$ efficiently

Bayesian analysis: operational view

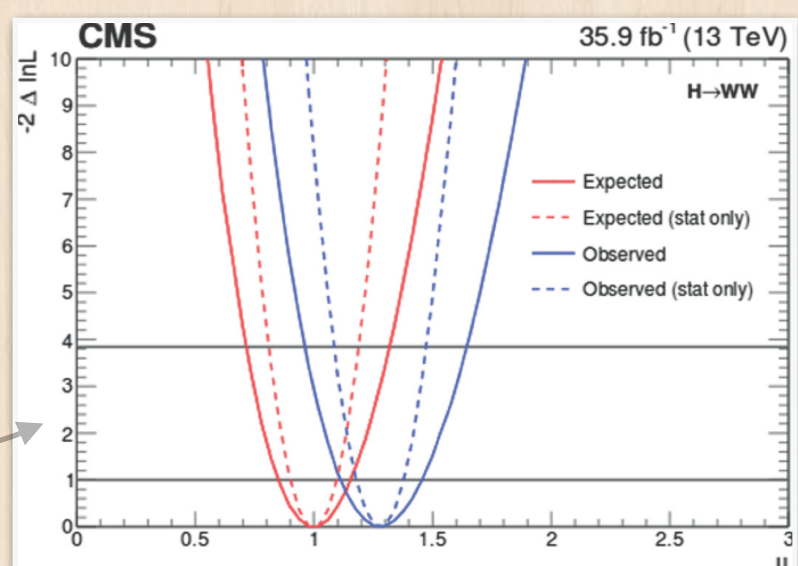
Function $\mathscr{D}$ maps parameter point to a "distance" to the data

Contains all physics we want to extract



$$\mathscr{D} : \overrightarrow{\theta} \to \mathbb{R}$$

Similar in spirit



$\mathscr{D}$ = the posterior function in the Bayes' formalism

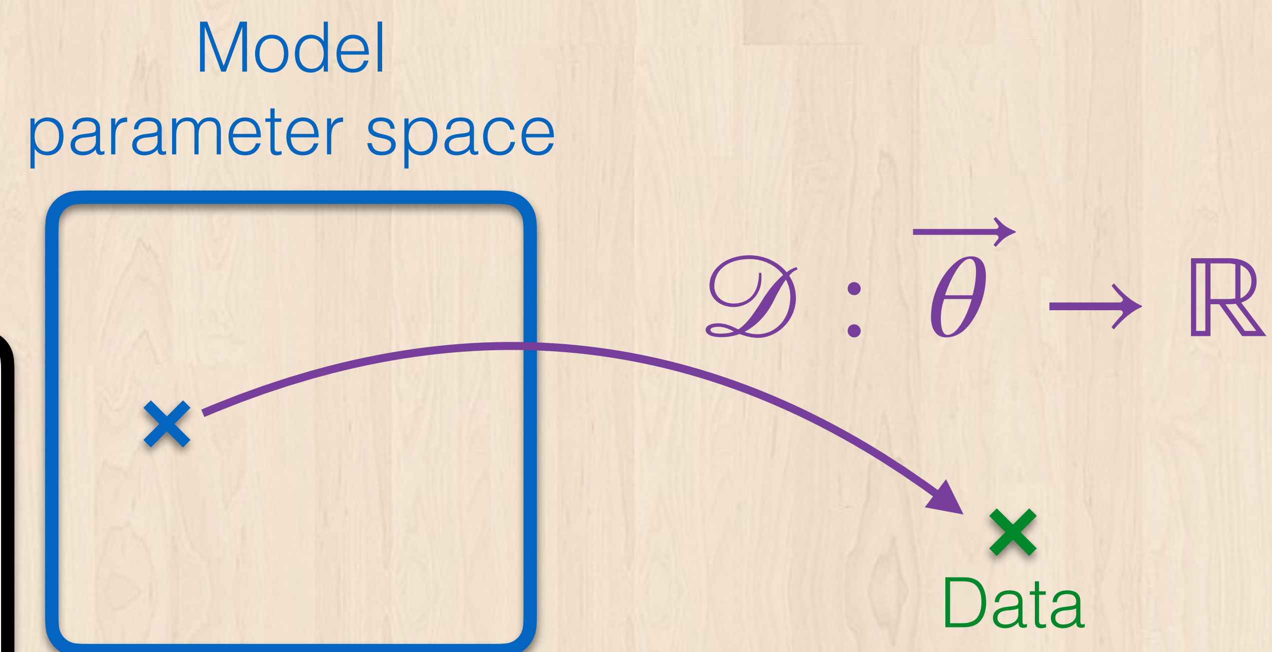
Bayesian analysis provides a way to get to $\mathscr{D}$ efficiently

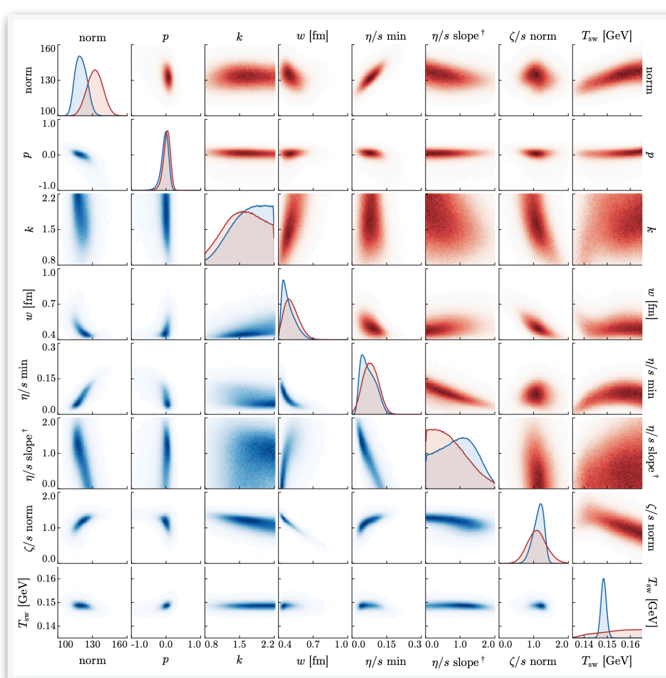
Bayesian analysis: operational view

Function $\mathscr{D}$ maps parameter point to a "distance" to the data

Con…

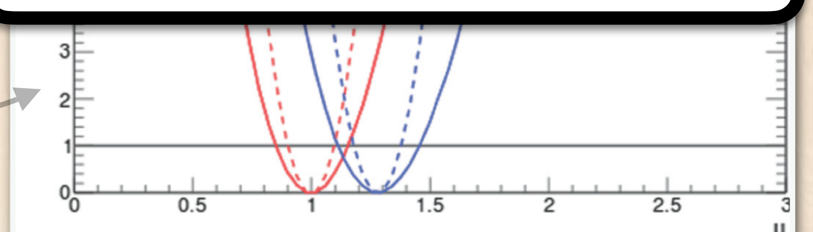
we…





Example for illustrations

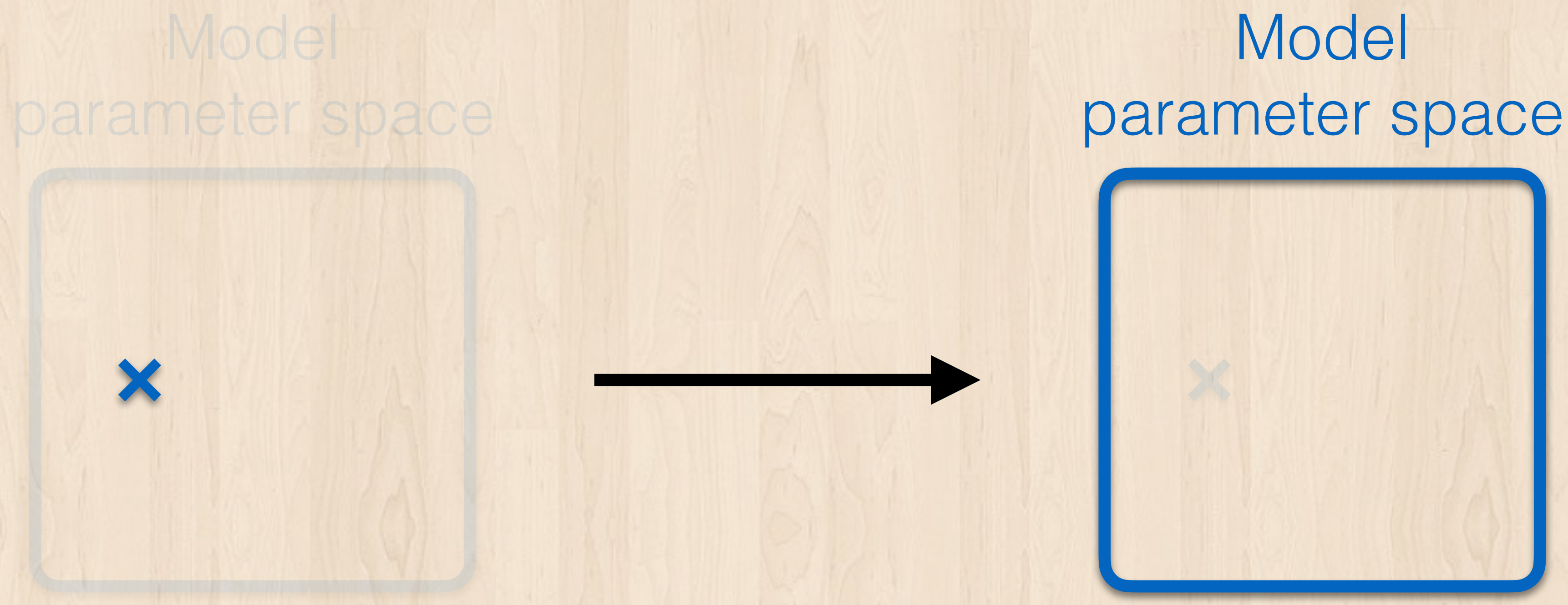
Similar in spirit



$\mathscr{D}$ = the posterior function in the Bayes' formalism

Bayesian analysis provides a way to get to $\mathscr{D}$ efficiently

Conceptual shift



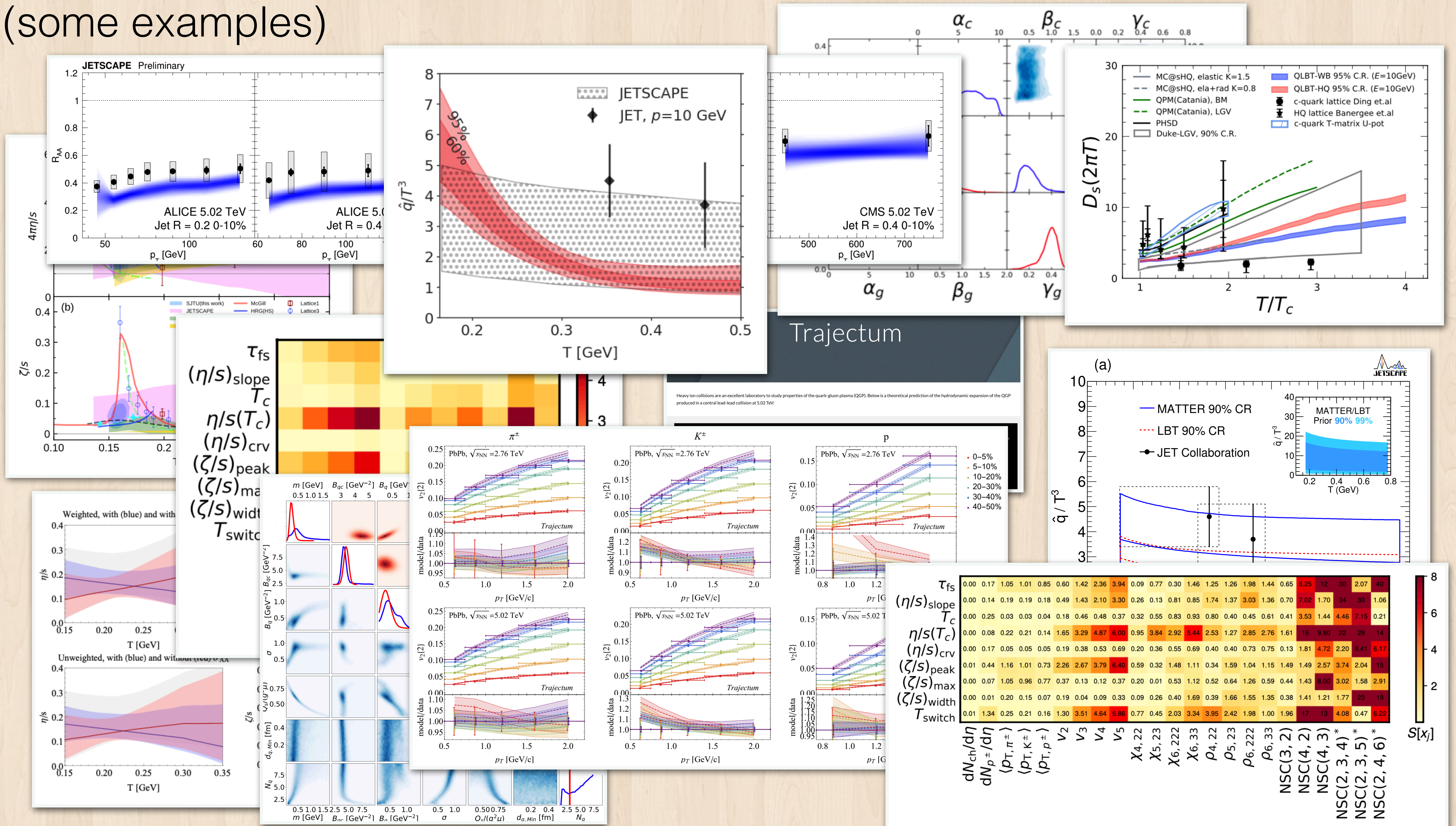
Instead of single parameter, we analyze the model parameter space as a whole

Chance to test models instead of parameters

ideas

A lot of recent results

(some examples)

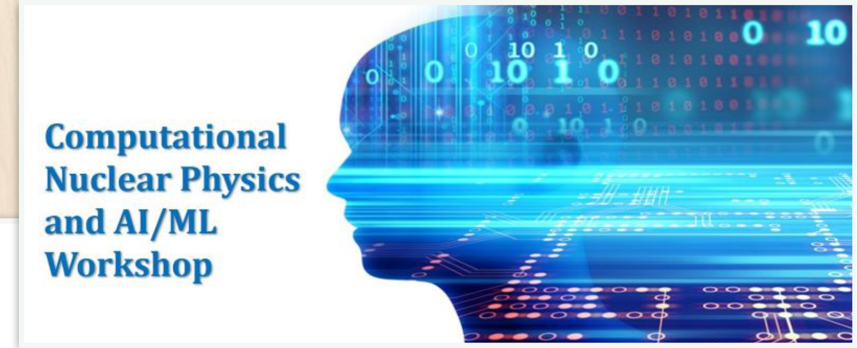


Lots of interest in the field to pursue this type of analysis

Practical requirements

Specific requirements on computing that could differ from the cases for other applications

Example: jet energy loss calculation through events
→ Pre-calculated hydrodynamic profile? (**I/O**)
→ Hydrodynamic evolution / feedback from jet? (**CPU**)
→ Storing outputs (**I/O & storage**)
…



discussion across disciplines

Workshop Resolution

High-performance computing is essential to advance nuclear physics on the experimental and theory frontiers. Increased investments in computational nuclear physics will facilitate discoveries and capitalize on previous progress. Thus, we recommend a targeted program to ensure the utilization of ever-evolving HPC hardware via software and algorithmic development, which includes taking advantage of novel capabilities offered by AI/ML.

link to meeting

Recent developments

Examples

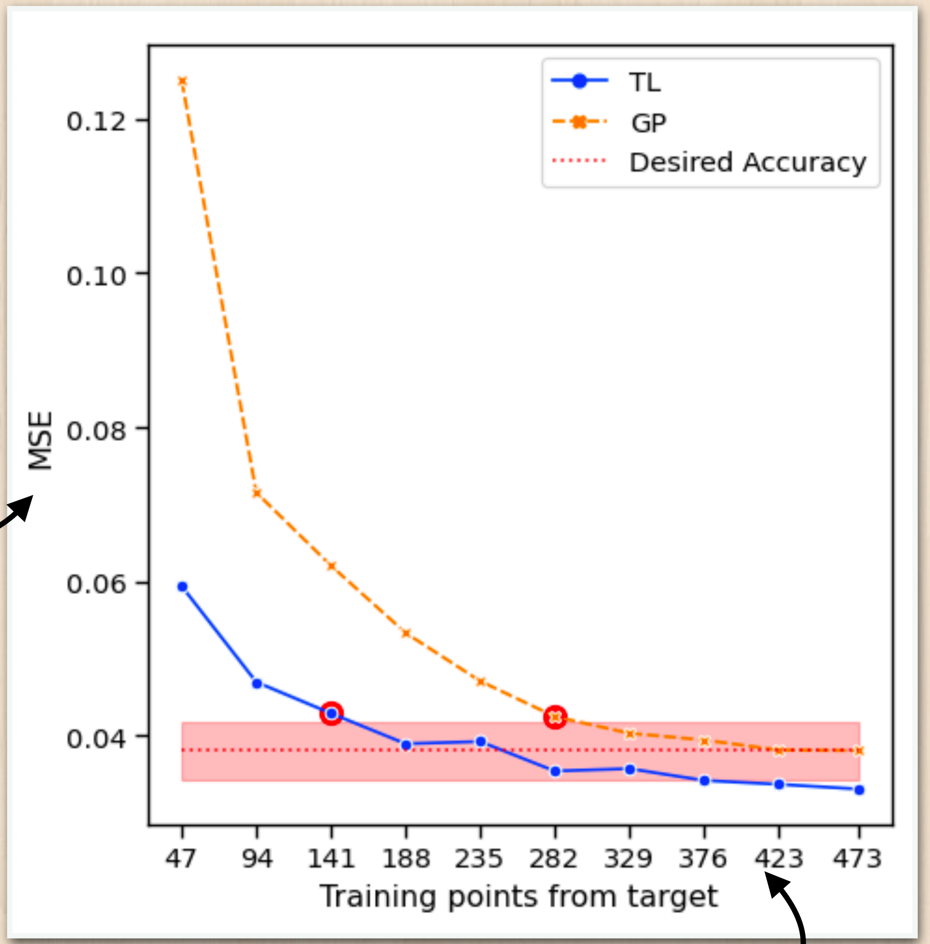
Transfer learning

In addition to the nominal analysis, many developments in the analysis side as well

Transfer analysis "knowledge" across similar tasks

Case study: transfer from 2.76 TeV Pb+Pb to 200 GeV Au+Au

Precision



Amount of computing needed

PRC 105, 034910 (2022)

Multi-fidelity approach

Model 1

Cheap to run
Does not capture full physics

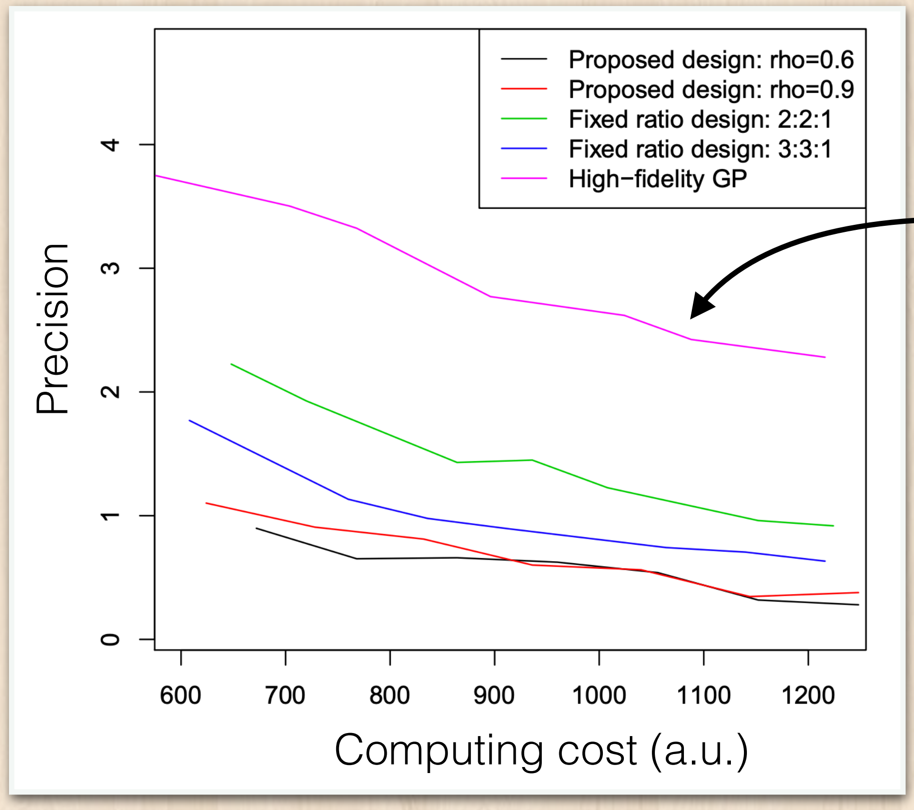
e.g. LO

Model 2

Expensive to run
Precise

e.g. NLO, or even NNLO

Strategy: use model 1 to learn the "big structure" and model 2 to refine



Use only model 2

Multi-fidelity approach

Reduces CPU cost needed to achieve same level of precision

arXiv: 2108.00306

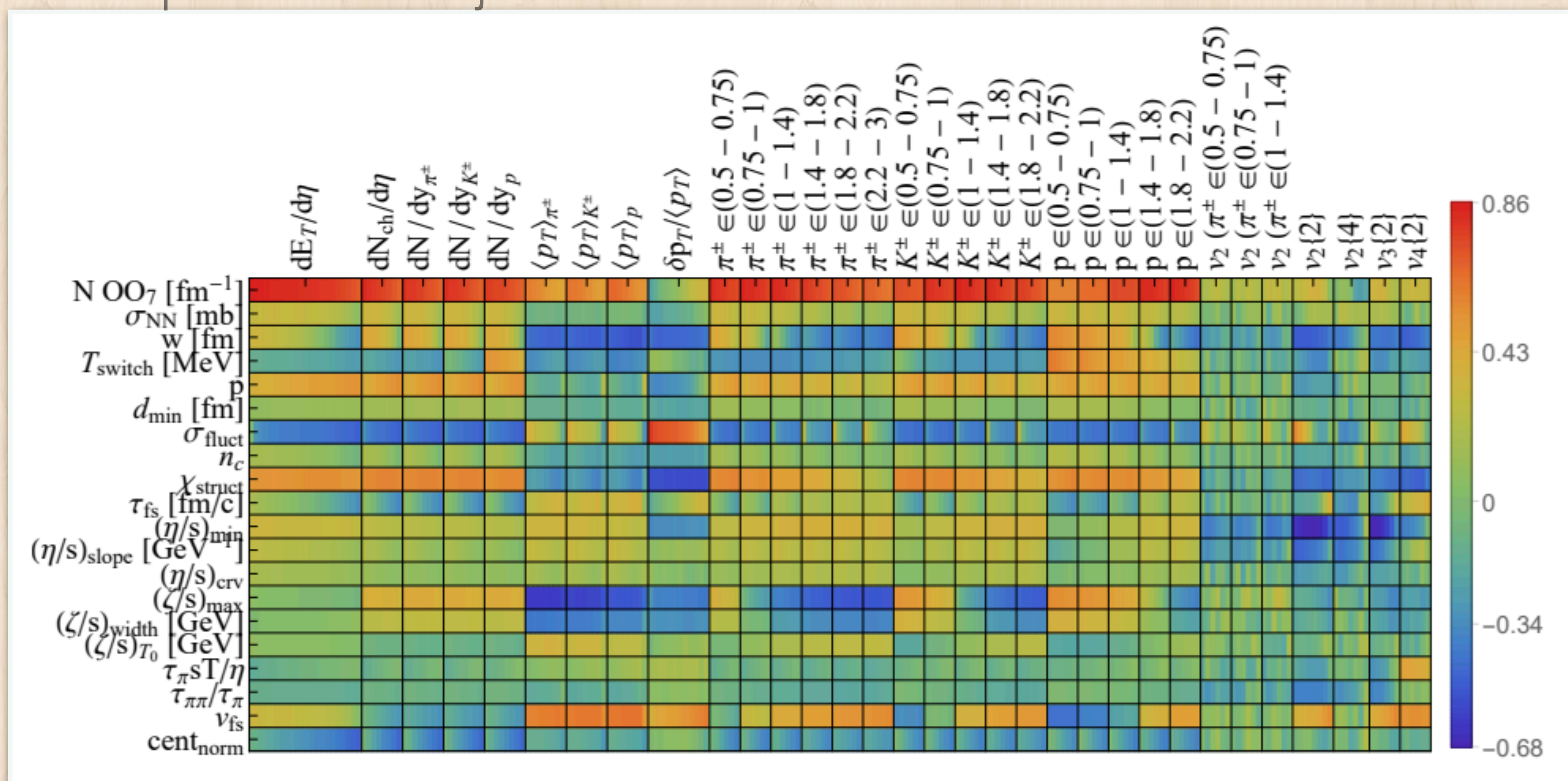
Beyond simple parameter extraction

Examples

Sensitivity study

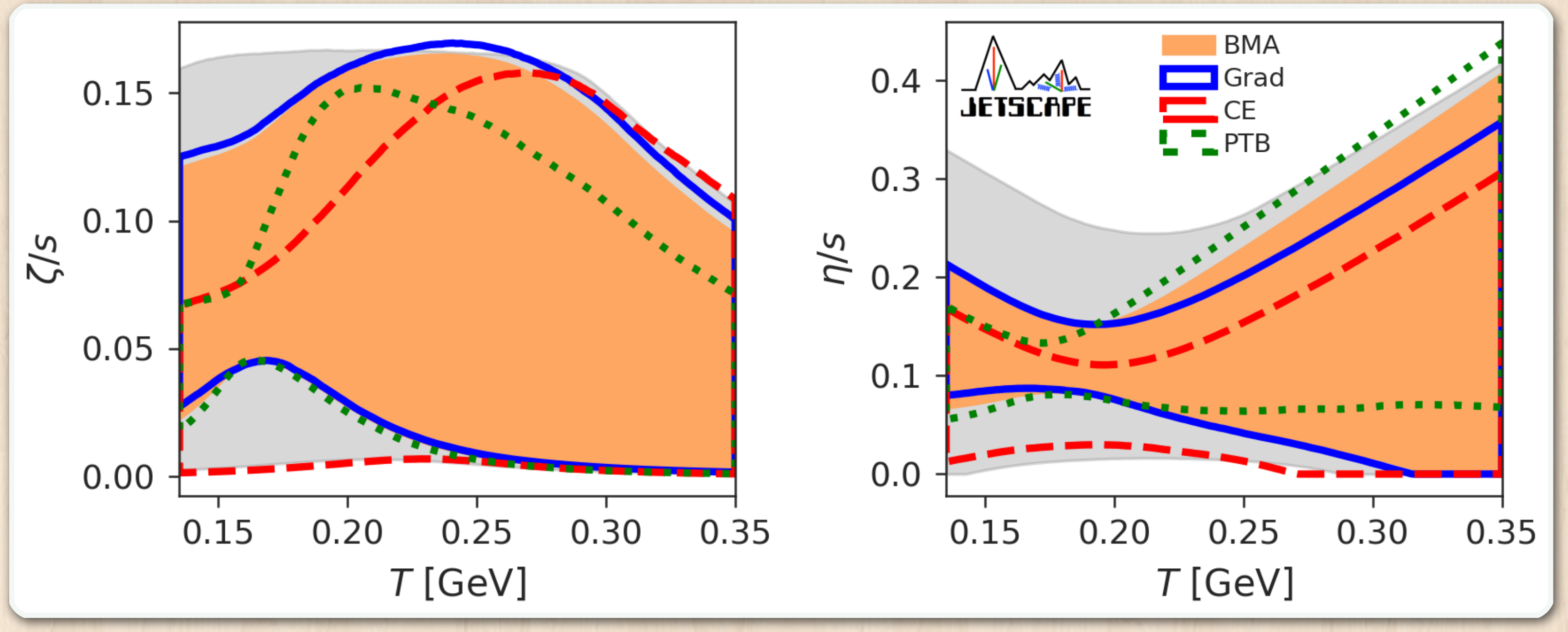
Quantify sensitivity of parameters to observables

Example from Trajectum



Build physics intuition and guide future efforts

Combining: model averaging



Grad/CE/PTB: different particlization models

What is the “combined” prediction of all models?

Rigorous data-driven way to combine the models

BAND framework: goal to provide a “toolkit” for the community including multi-model prediction

Event generation

Typical flow

Data $\xrightarrow{\text{Tuning}}$ Parameter $\xrightarrow{\text{Input}}$ Generator $\longrightarrow$ Events

With Bayesian analysis

Data $\xrightarrow{\text{Bayesian analysis}}$ Full parameter space $\xrightarrow{\text{Sample per event}}$ Generator $\longrightarrow$ Events

Directly embed the full correlation into event generation

Concluding Remarks

Moving forward

- Even though (current) Bayesian analysis makes a lot of things possible, in the long term it is still **limited by computing resources**

- Continuous **improvements in the analysis** and likely some breakthroughs needed

  - → Concerted effort across disciplines

- Case for improved **computing resources and facilities**

Summary

- Bayesian analysis: rigorous data-model comparison
  - From parameter point to parameter space
  - Test models (→ ideas) instead of parameters
  - Essential for the future of the field
- Fast-growing in the field, good synergy with others
- Many additional possible applications

Backup Slides Ahead