Measurement of the SM Higgs properties at the LHC

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Based on arXiv:2209.03898

Based on arXiv:2303.HOPESOON

2023 CAU BSM Workshop

Precision SM Higgs @ LHC

- Confirming Higgs properties
  Mass, Width, **Spin**, **CP-property** : **DONE**
  PRD87(2013) 5, 055006, PRD89(2014)034002

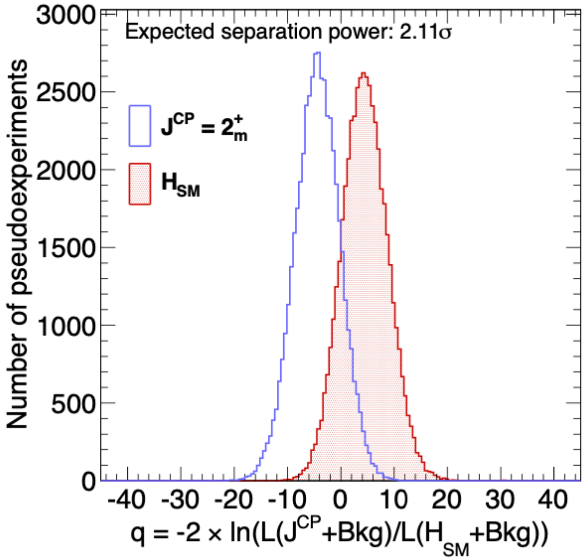
- Confirming a **breaking electroweak symmetry** : **DONE**
  PRL111(2013) 041801

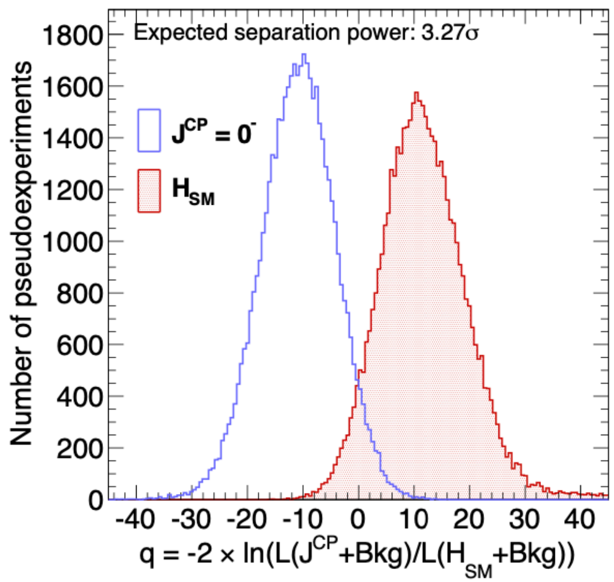
- Confirming Yukawa coupling : **Going well**

- Confirming the **shape of Higgs potential, up to** H^3 : **Going well**
  PRL111(2013) 041801, JHEP 1909(2019) 047

- **Spin, CP-property**

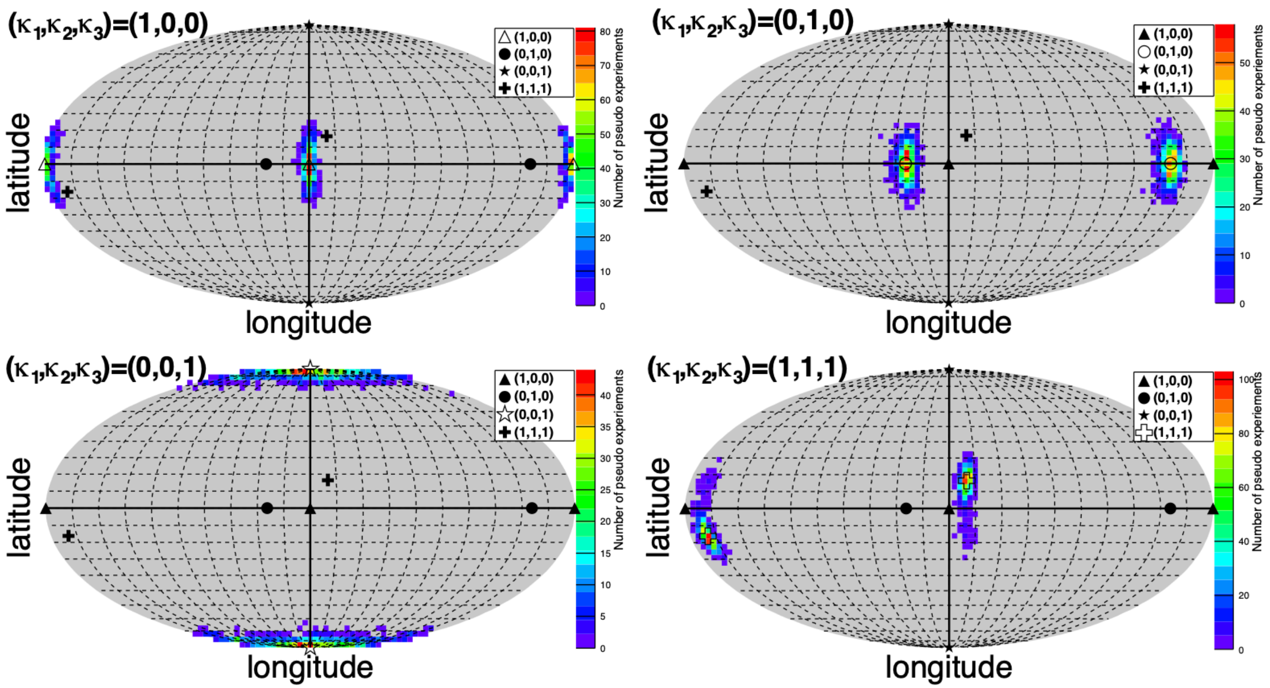
$$KD(A;B) = \ln\left(\frac{|\mathcal{M}_A(a+b\to 4\ell)|^2}{|\mathcal{M}_B(a'+b'\to 4\ell)|^2}\right)$$





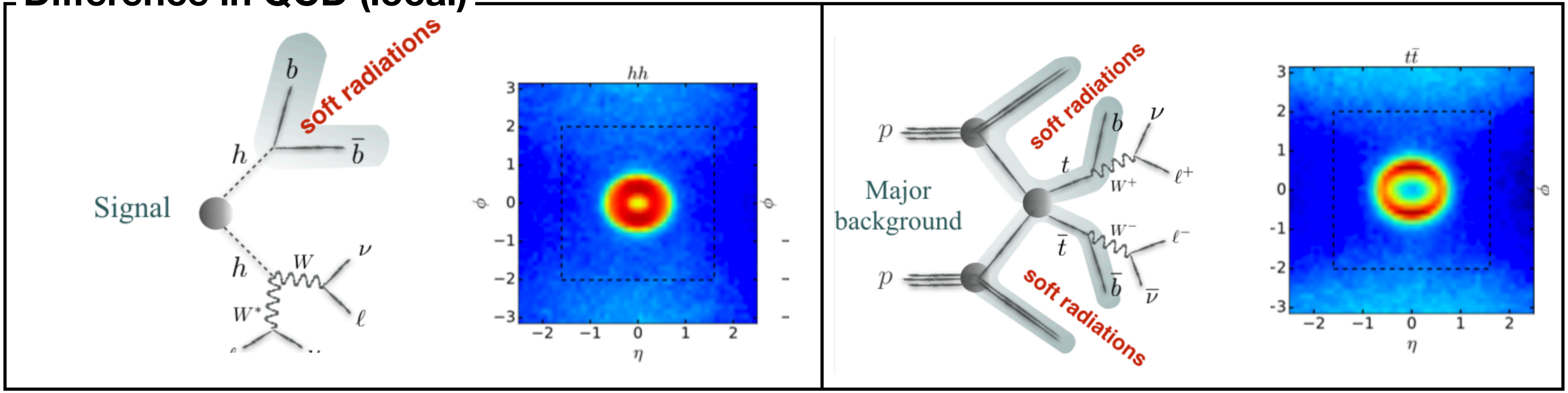
- **breaking electroweak symmetry**

$$\mathcal{L} = -X\left[\kappa_1 \frac{M_Z^2}{v} Z_\mu Z^\mu + \frac{\kappa_2}{2v} F_{\mu\nu} F^{\mu\nu} + \frac{\kappa_3}{2v} F_{\mu\nu} \tilde{F}^{\mu\nu}\right]$$

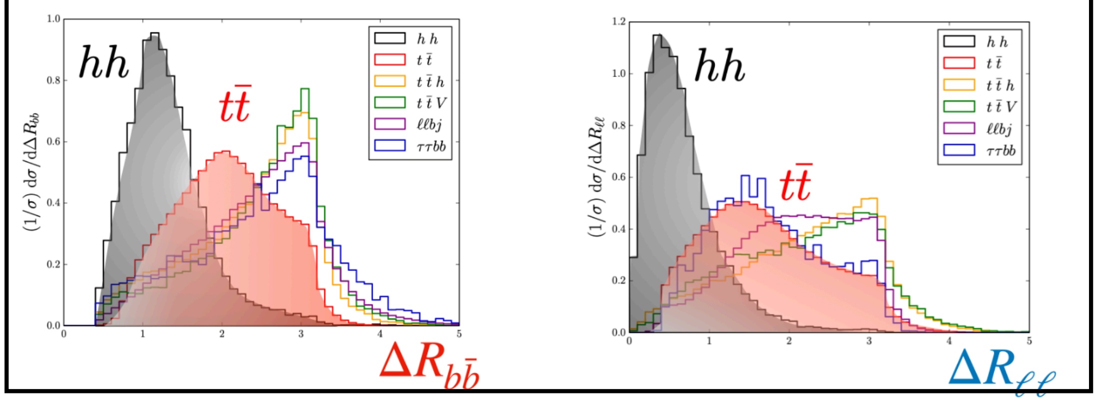


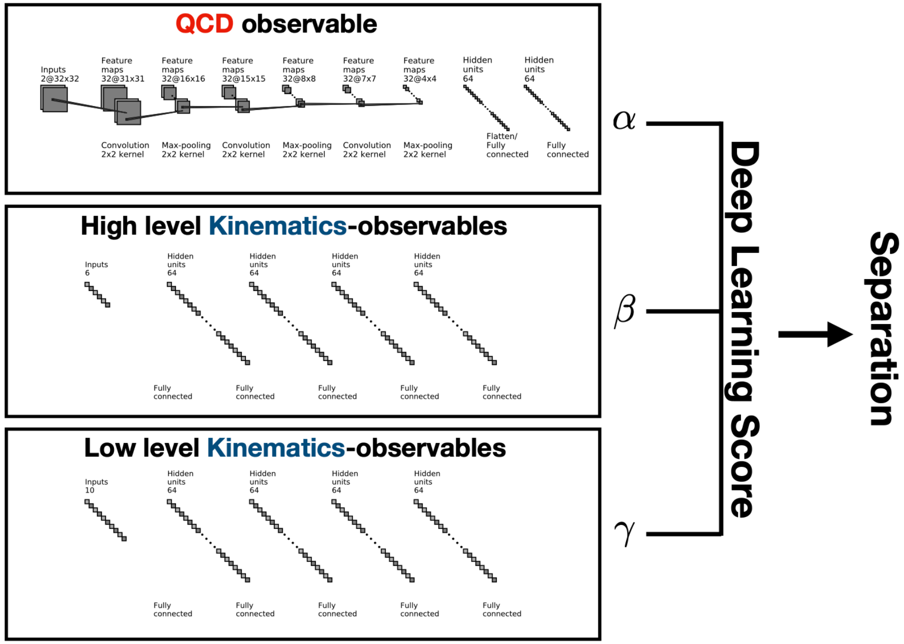
- **shape of Higgs potential, up to H^3**

Difference in QCD (local)

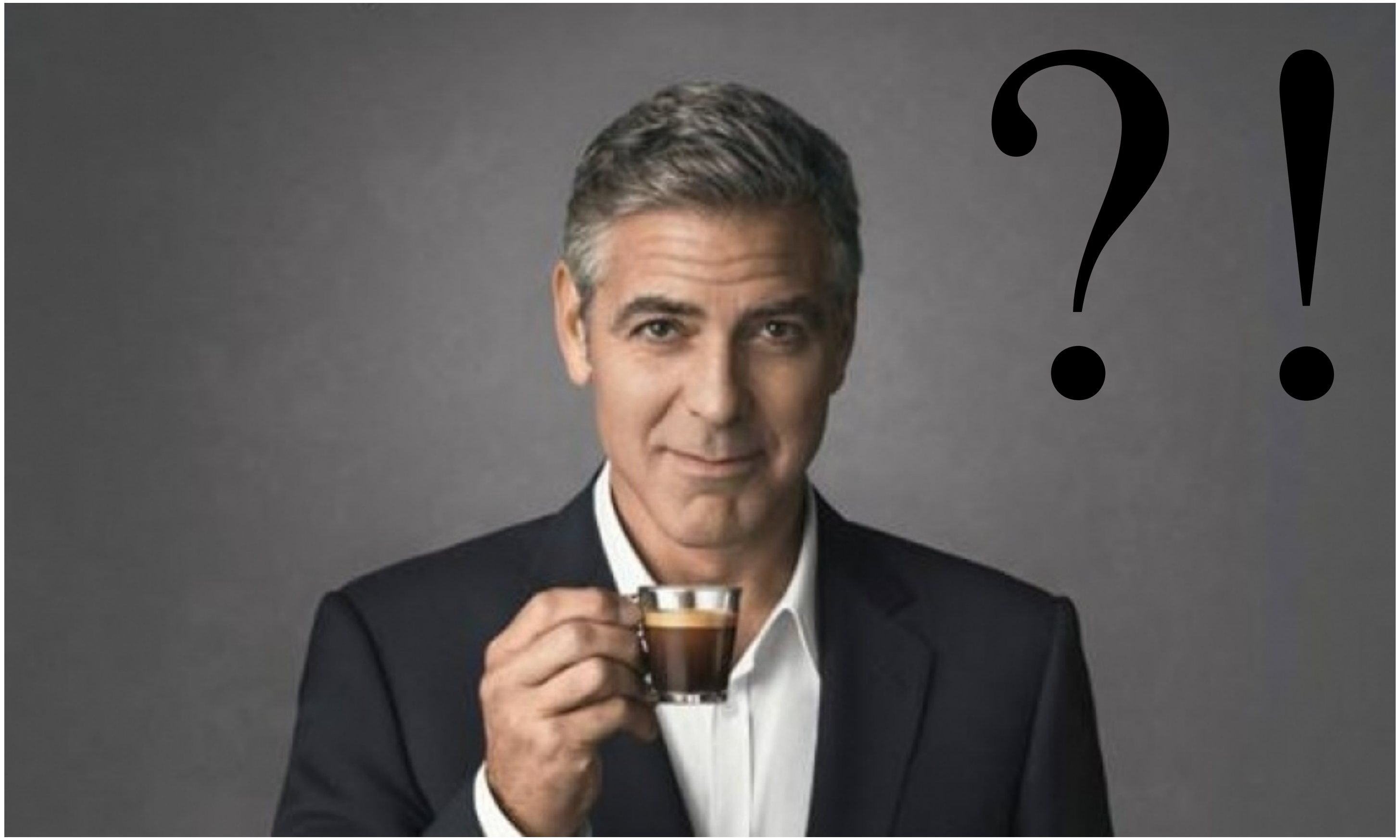


Difference in a phase space (global)





What else?



Color charge of Higgs ?

- Everybody knows SM **Higgs is colorless !**

- But, I decided to check

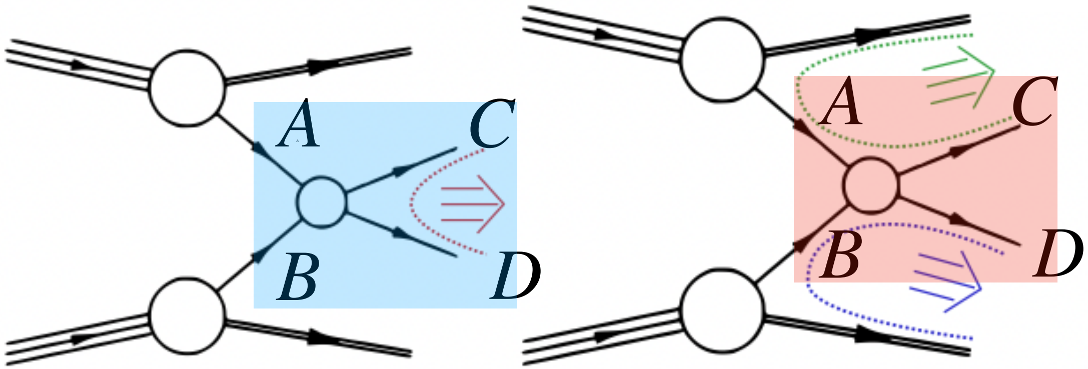
  "how can we **directly measure the color charge of the Higgs" @ the LHC ?**

- We can use this method to separate $H \to b\bar{b}$ from $g \to b\bar{b}$

Basic guide line

- Soft radiations along the color flow

Jason Gallicchio, Matthew D. Schwartz PRL 2010

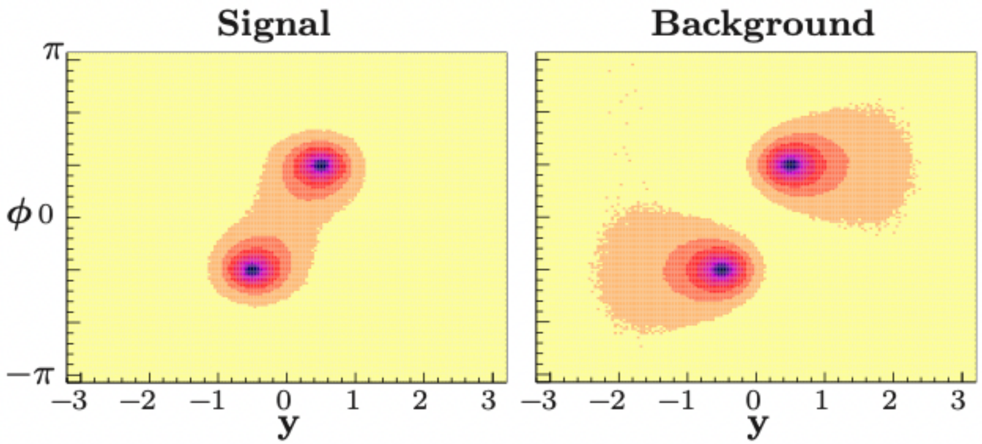


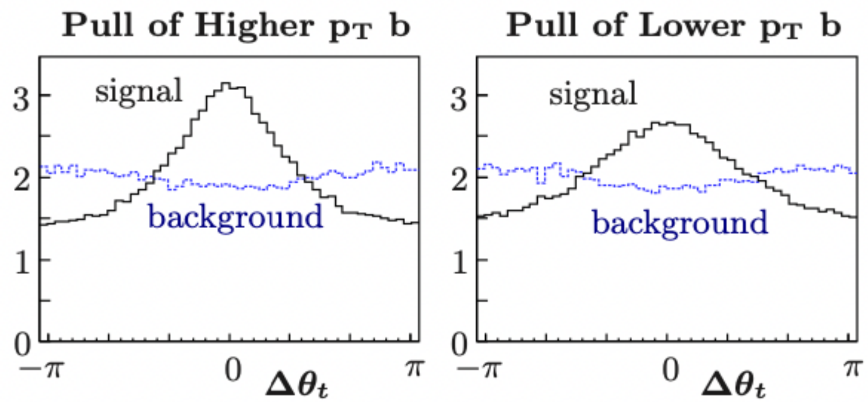
$\mathrm{Tr}[T^A T^B]\mathrm{Tr}[T^C T^D]$

$\mathrm{Tr}[T^A T^C]\mathrm{Tr}[T^B T^D]$

$\mathrm{Tr}[T^A T^D]\mathrm{Tr}[T^B T^C]$

FIG. 1: Possible color connections for signal ($pp \to H \to b\bar{b}$) and for background ($pp \to g \to b\bar{b}$).





Good news

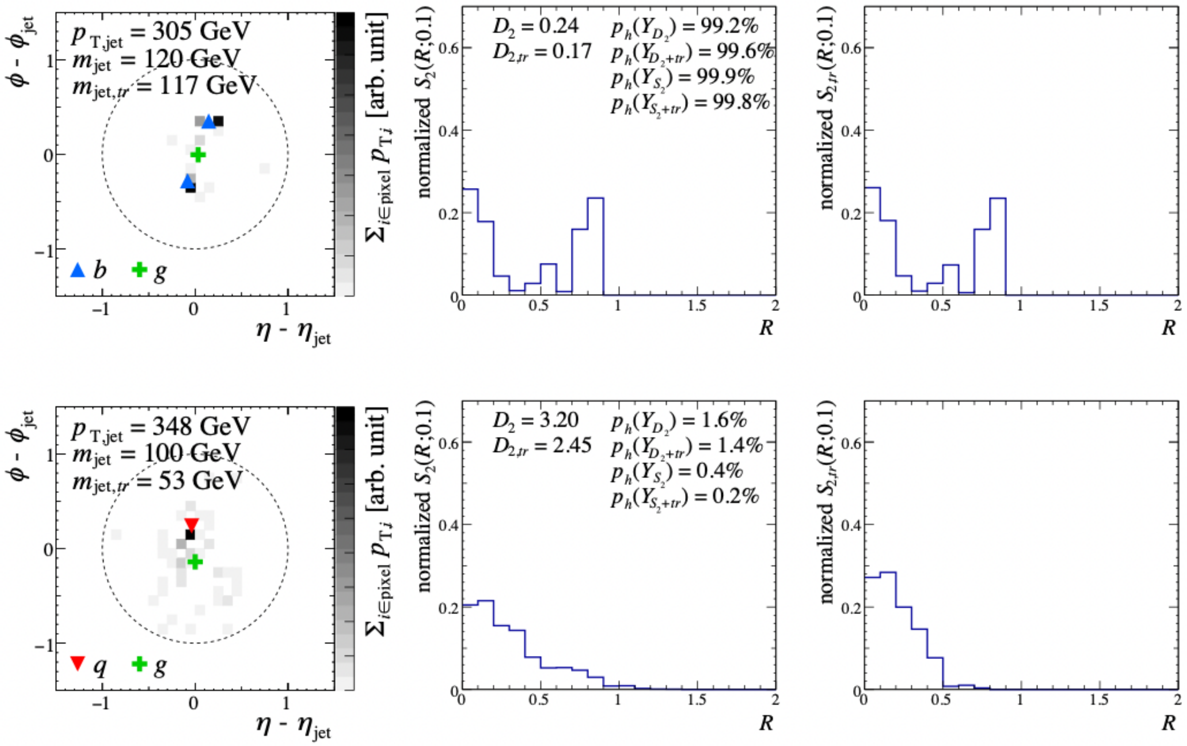
- There have been very good theoretical studies, but

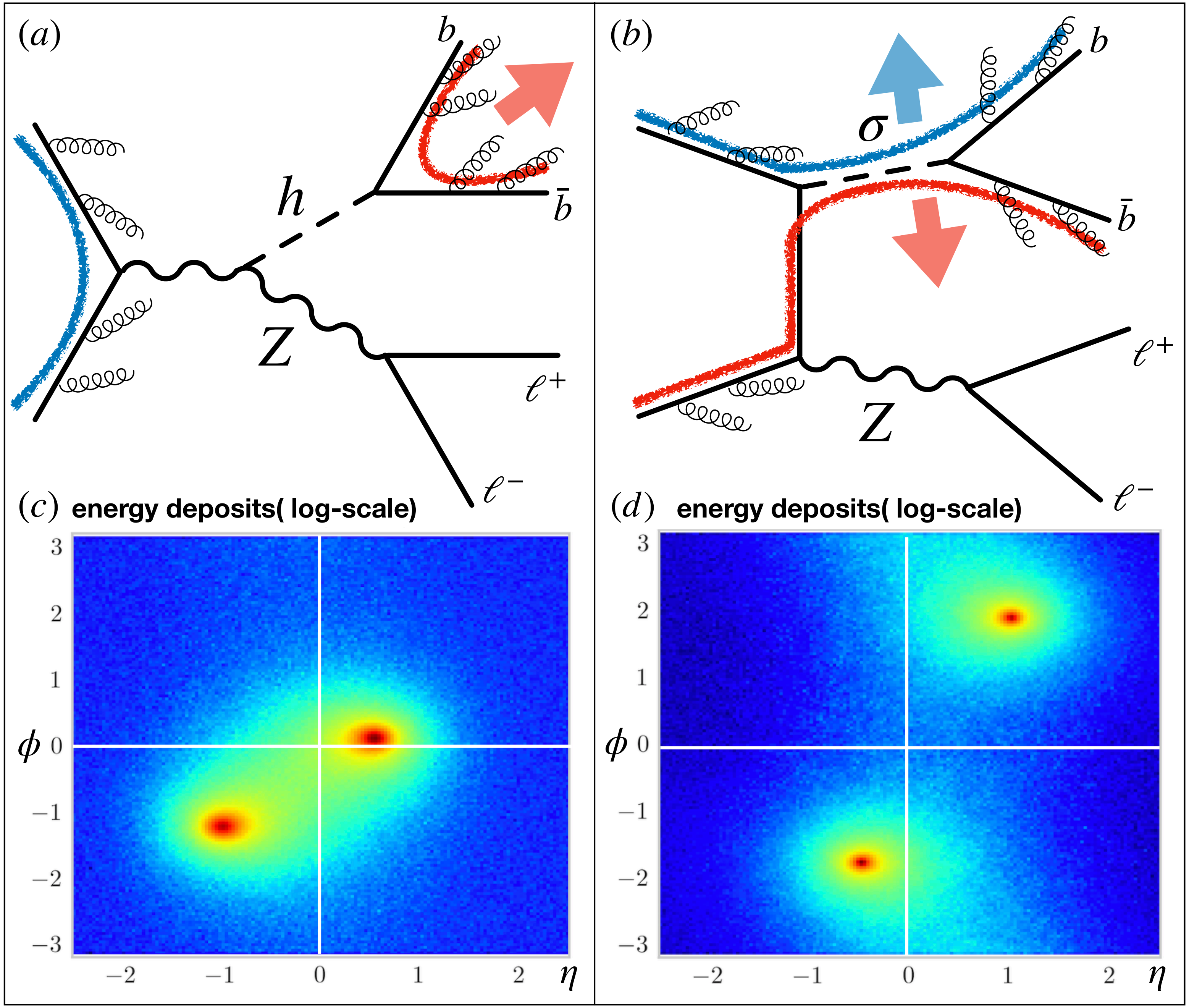
  No consideration about the **"finite" LHC statistics** (up to HL-LHC)

- **Armed with "DEEP and complicated" Neural Network**,
  there have been lots of studies on "jet-tagging" with ML

- Based on "spectral function", $S_2(R, \Delta R) = \frac{1}{\Delta R} \sum_{R_{ij} \in [R, R+\Delta R]} p_{T,i} p_{T,j}$

achieved an "**Understandable**" neural network and get **better performance**...
but in the **BOOSTED region**

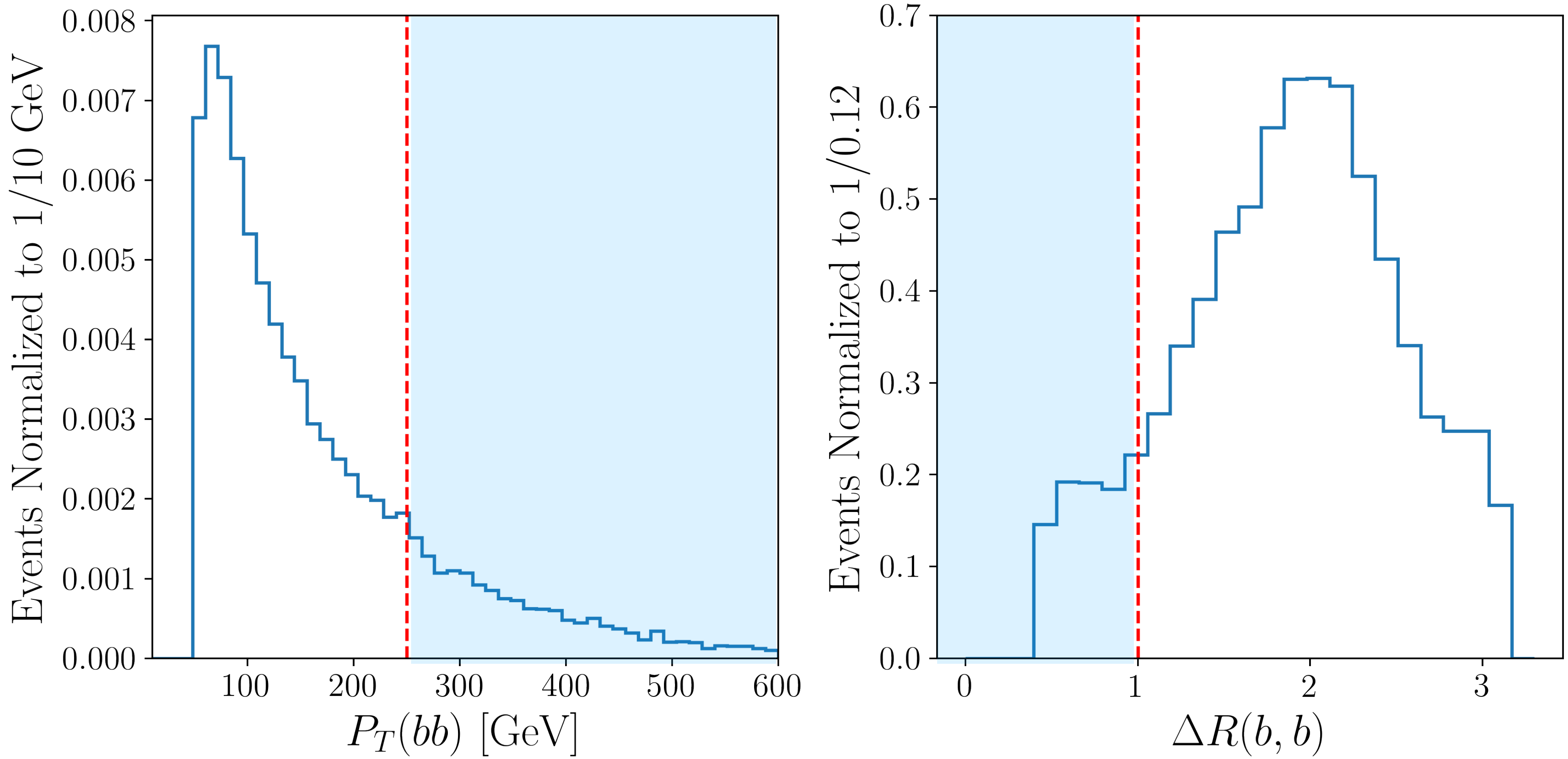




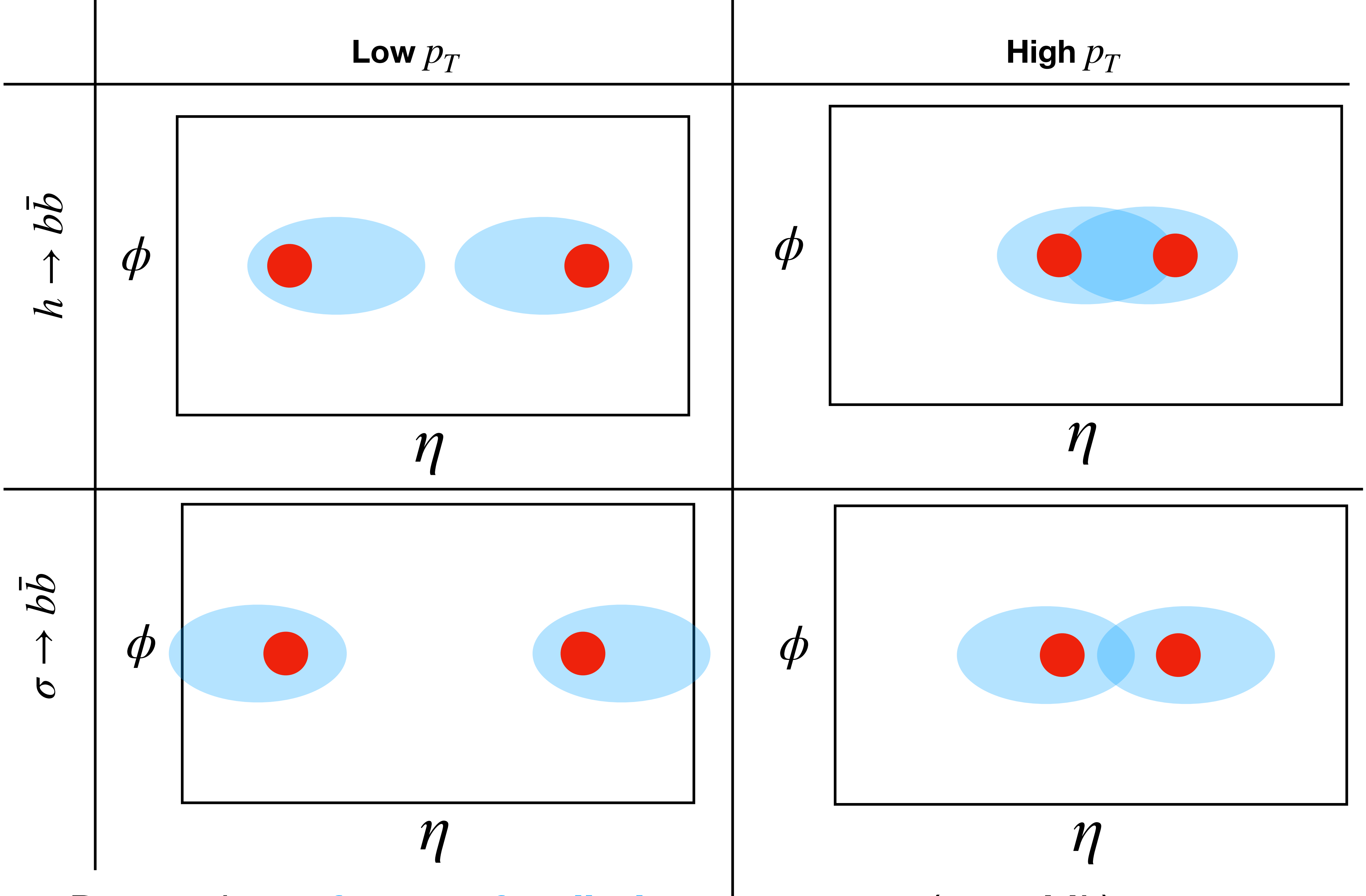
(a)
b
$\bar{b}$
h
Z
ℓ^+
ℓ^-
(b)
σ
(c) energy deposits(log-scale)
(d) energy deposits(log-scale)
φ
η

NOT boosted Higgs?

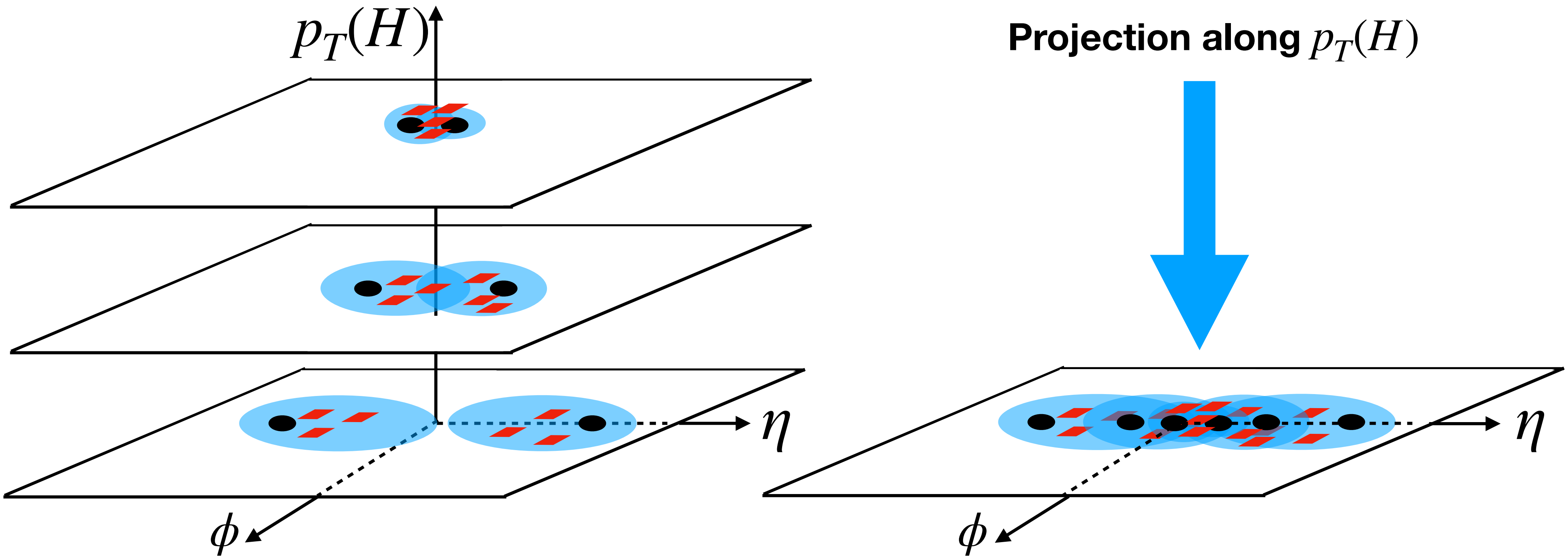
$pp \to HZ$@13TeV LHC



- Of course, we loose STATISTICS



- Due to the **softness of radiations**, everyone (even ML) get focused on **hot cores ($b/\bar{b}$)**



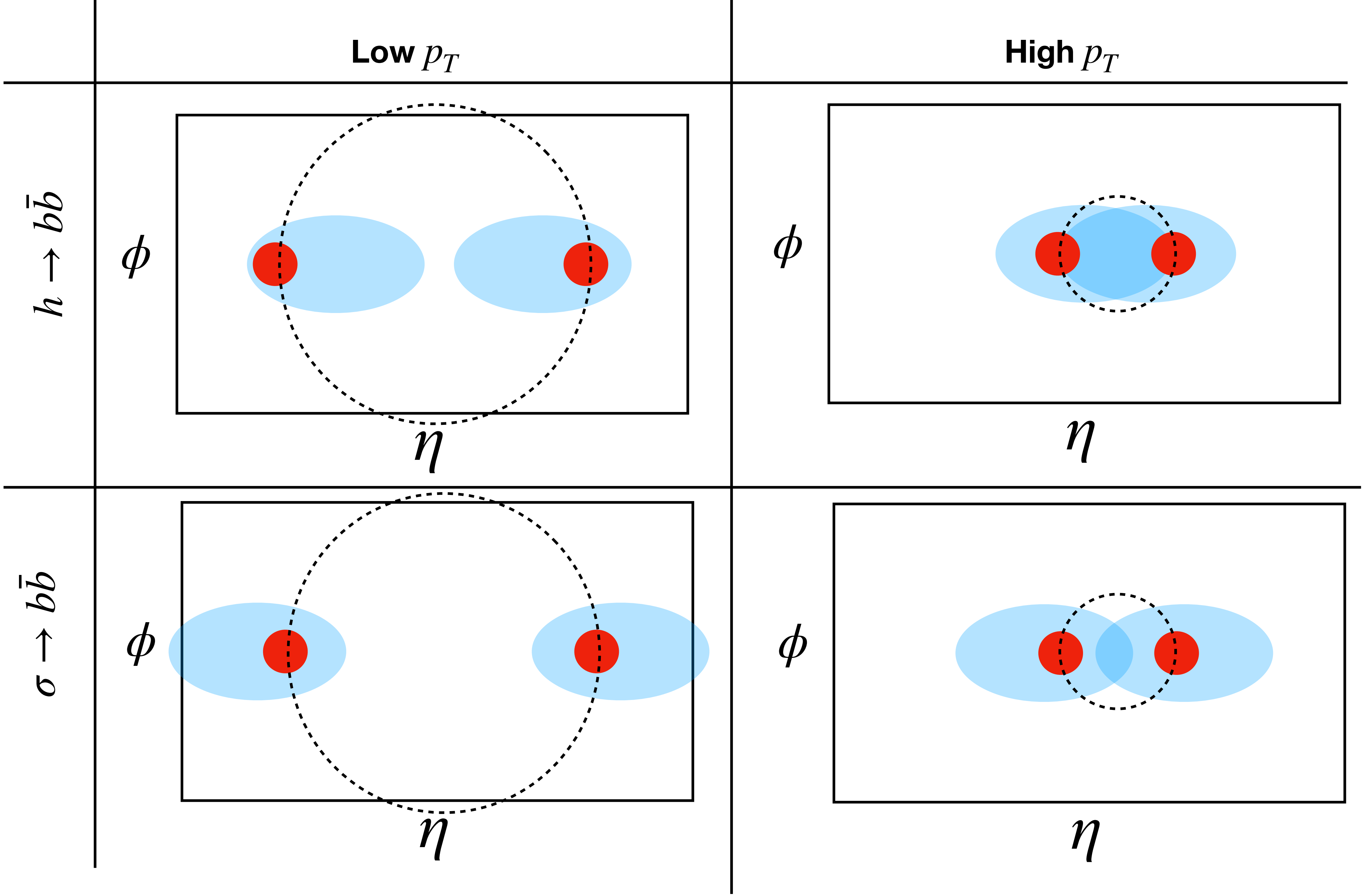
- If one tries to study various $p_T(H)$ ranges,

  even ML will not give a good performance.

How can we use

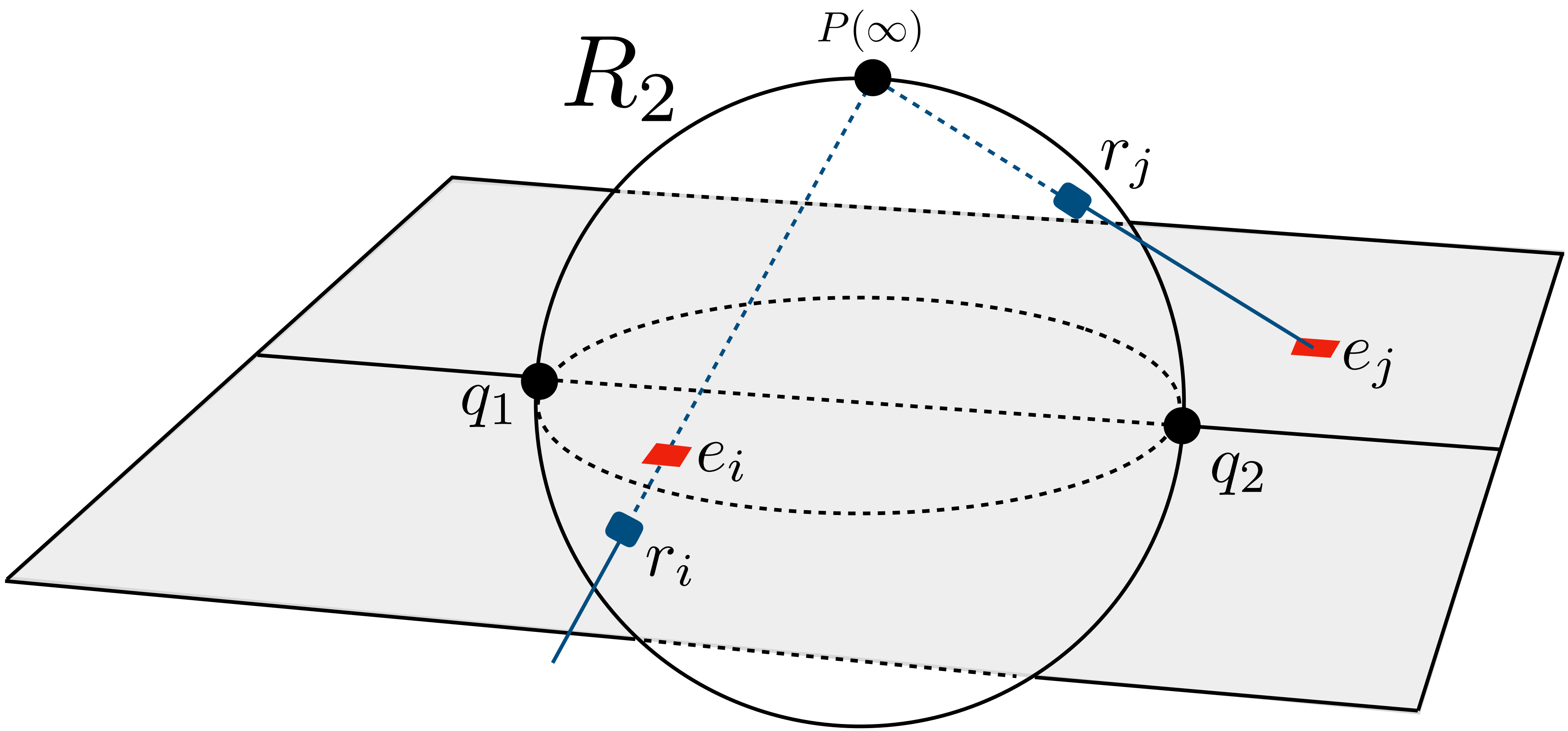
"**full p_T range**" of "Higgs"?

- for the actual LHC test

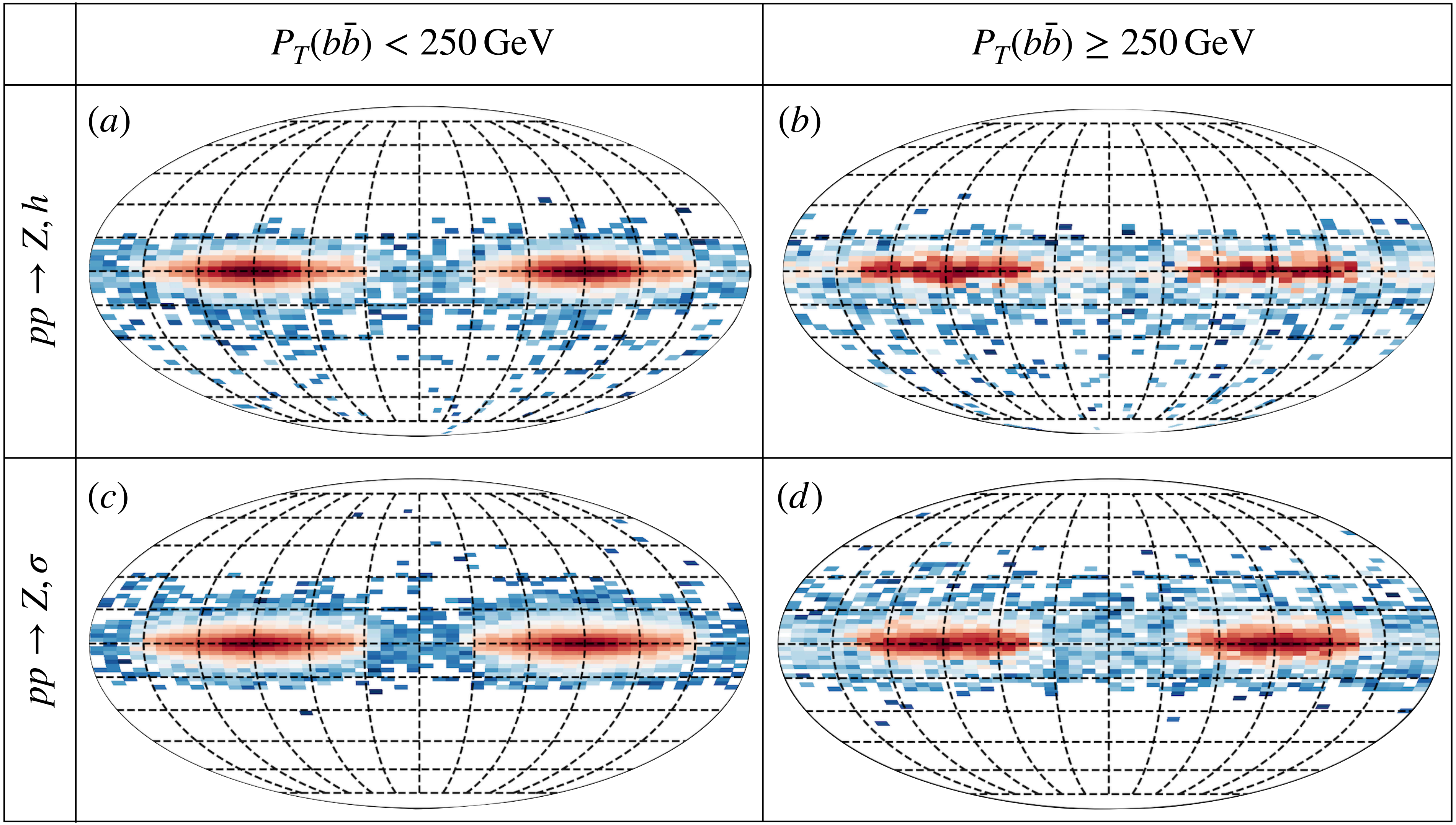


- A binary problem, either "**inside**"or "**outside**" a circle.

Inverse stereographic projection



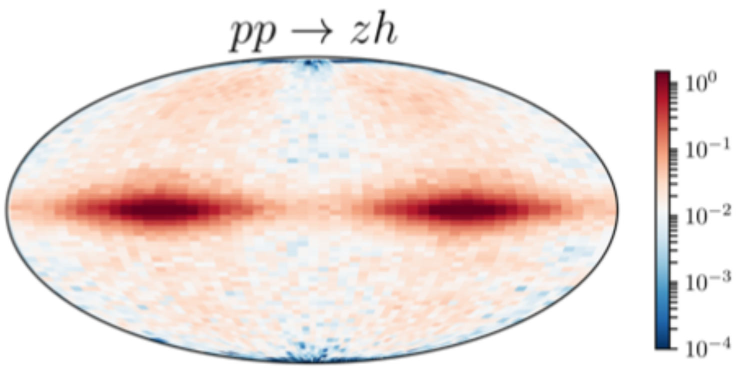
- Soft radiations which are
  inside of a circle $\rightarrow$ Southern hemisphere (H)
  outside of a circle $\rightarrow$ North hemisphere (σ)

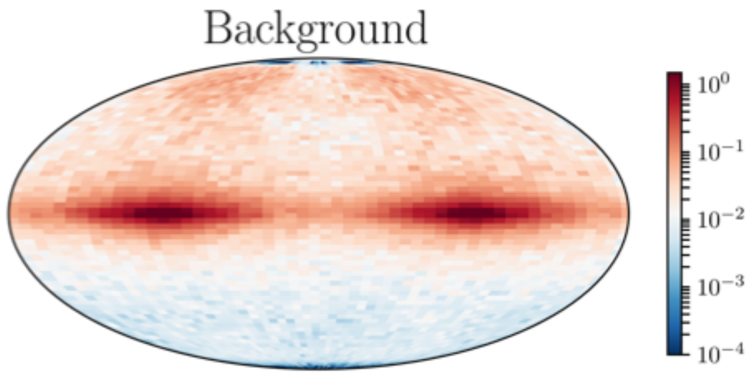


$P_T(b\bar{b}) < 250\,\mathrm{GeV}$
$P_T(b\bar{b}) \geq 250\,\mathrm{GeV}$
$pp \to Z, h$
$pp \to Z, \sigma$
(a)
(b)
(c)
(d)

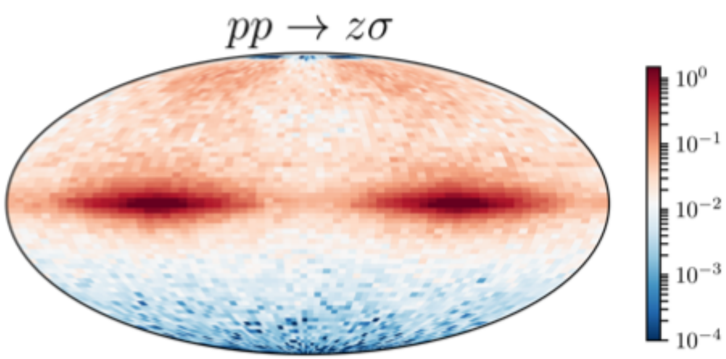
Landscape of Color activity

- Accumulated 5000 events shot



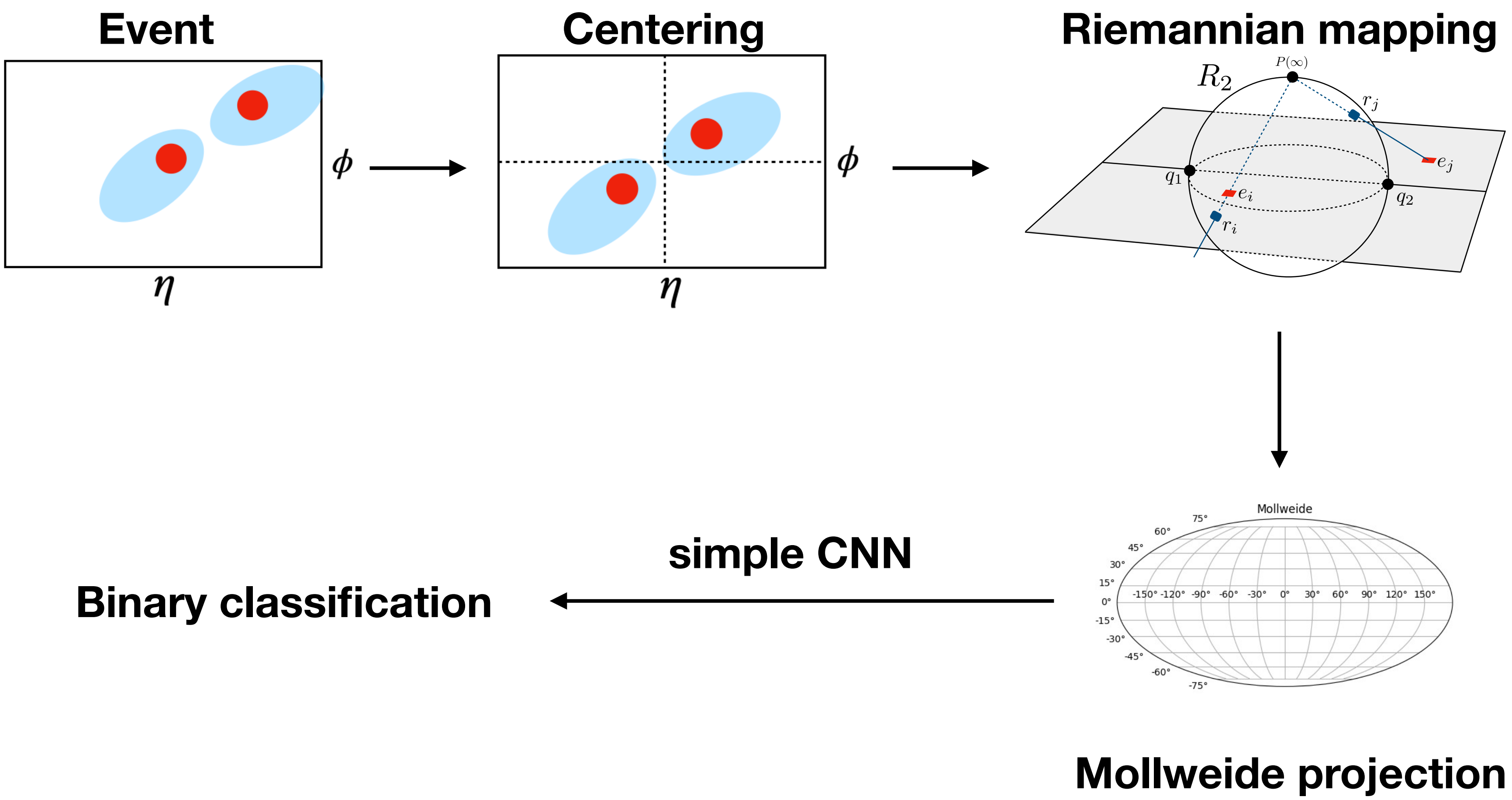


$(V + js,\ t\bar{t},\ t(\bar{t}),\ VV,\ \cdots)$

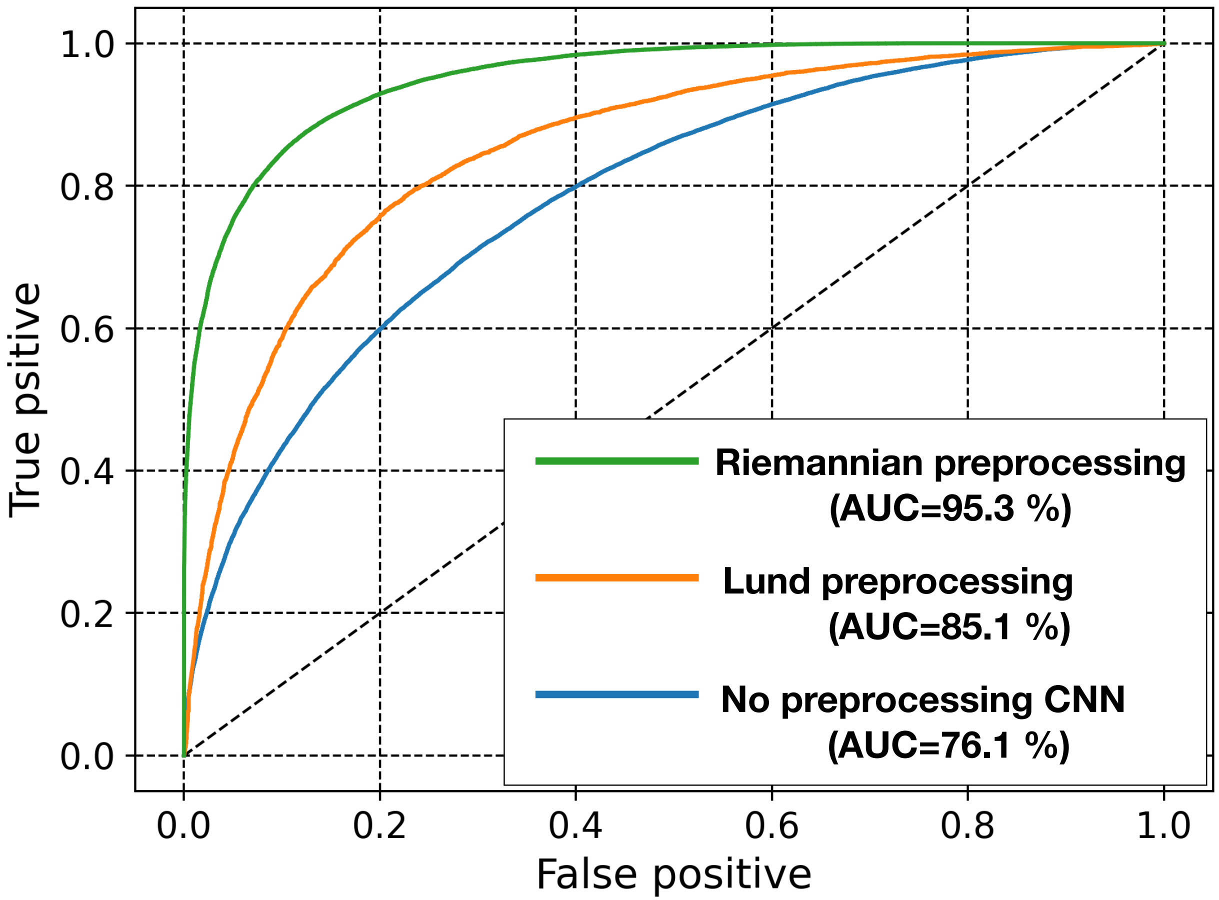


- Corruptions in North hemisphere are from ISR / MPI QCD activities.
- We may utilize this image for SIG / BKG separation too.

Riemannian preprocessing with CNN



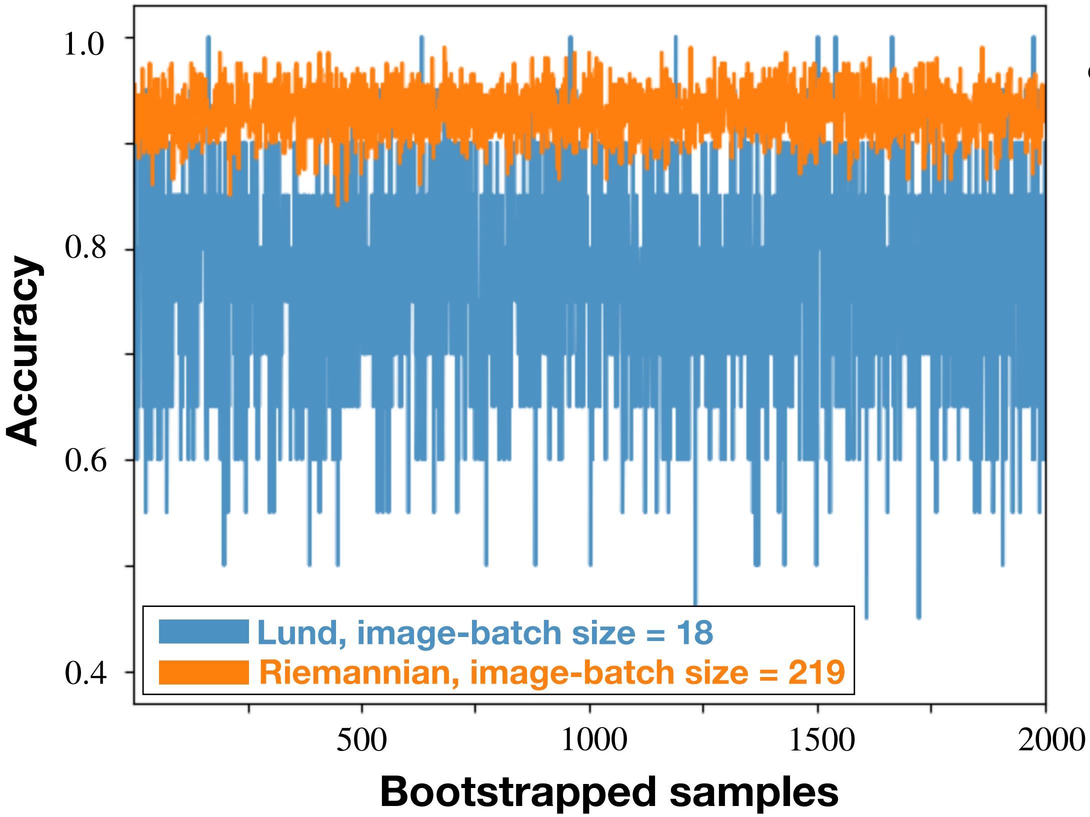
Performance test



- With 100,000 MC data sample each for (1) whole p_T range and for (2) boosted p_T (60% training, 20% validation, 20% test),
  Riemannian preprocessing has a outperformance.

- Lund preprocessing ("double-logarithmic plane") is from [arXiv:2105.03989] for a boosted Higgs (Data preprocessing with selected QCD features)

Applying NN to the LHC

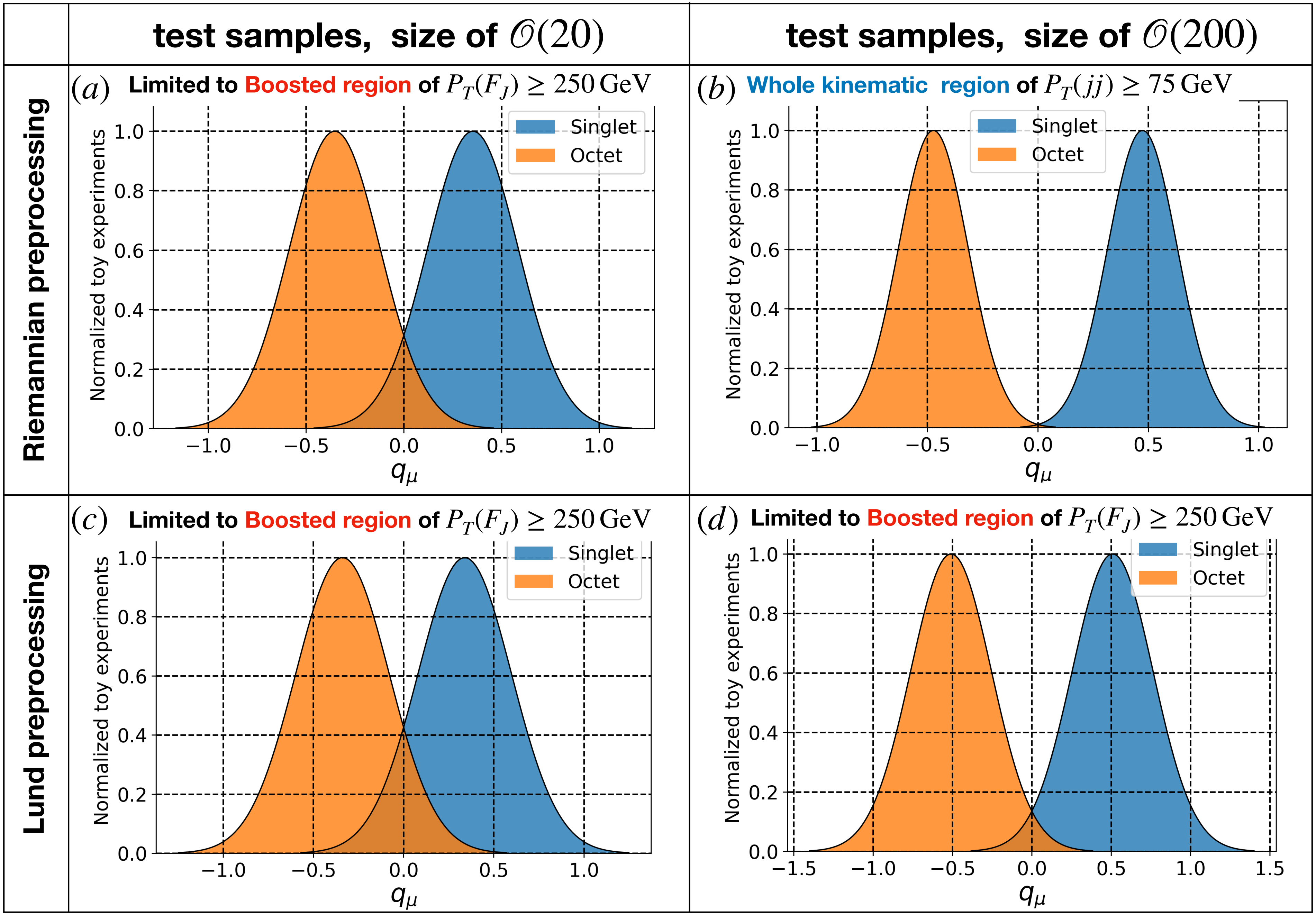


- Based on the ATLAS work (Measurement of WH/ZH in $H \to b\bar{b}$, 13TeV with $139\mathrm{fb}^{-1}$: arXiv:2007.02873)

  Number of Higgs samples after selection cuts : 219
  Number of Higgs samples in the boosted region ($p_T > 250\mathrm{GeV}$) : 18

- With well-trained Neural Network, we may suffer from **"statistical fluctuation"** in the real battle of the LHC.

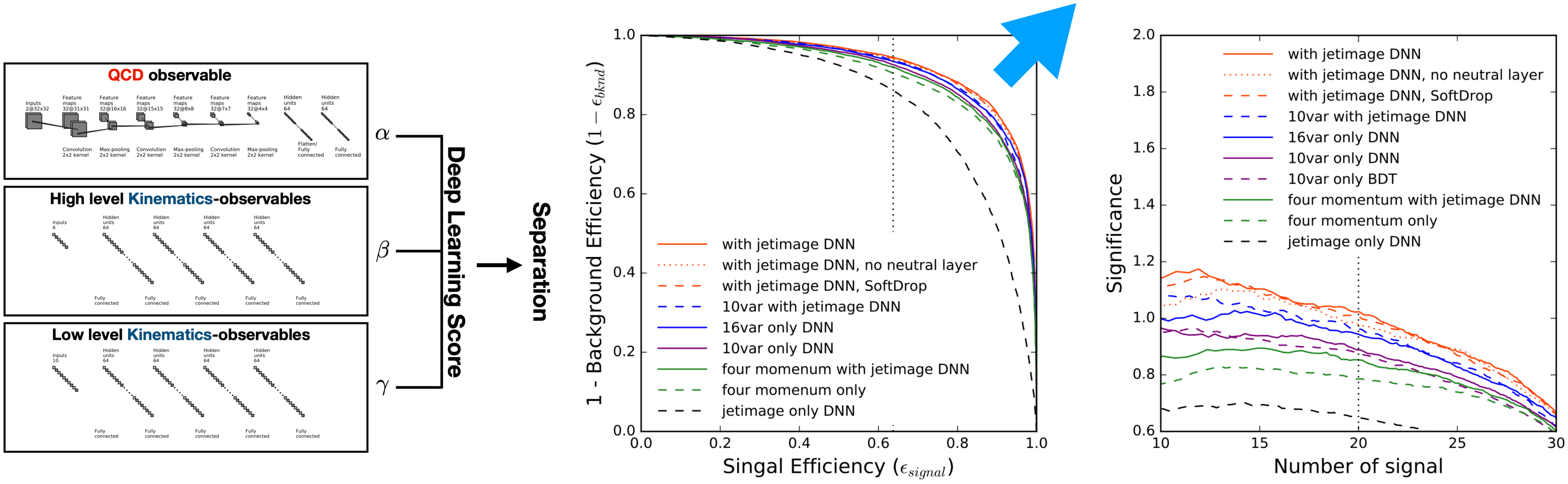
- Thus, the method with wide range of $p_T(h)$ would be better



- Our simple mapping is better even with the same statistics.

Further studies?

1. Combining two regions (local and global)



- Combining QCD observable with kinematics **does not** provide a BIG improvement... **why???**

2. ML with a few training data

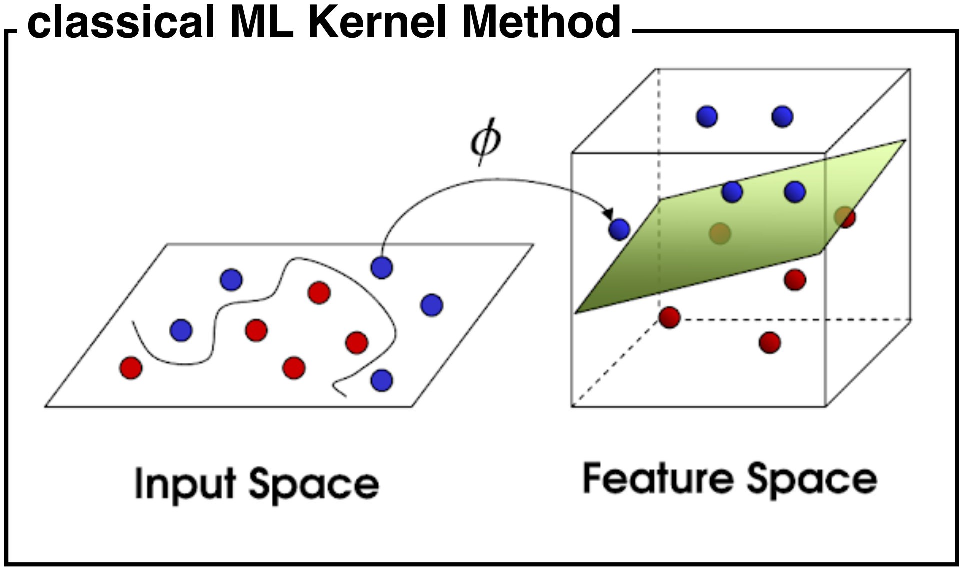
- Current ML technologies require "Big DATA" to train the "sophisticated" neural network.

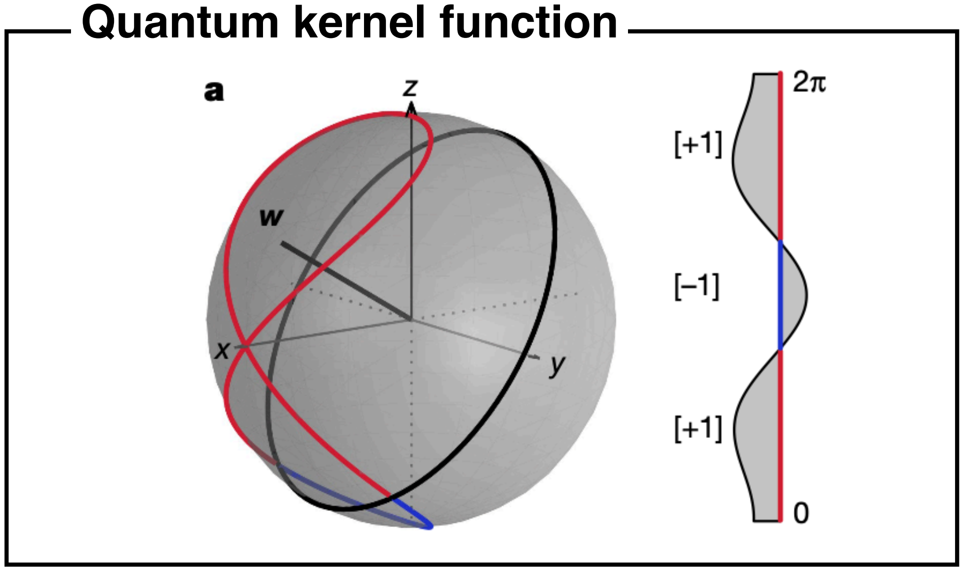
  - Big data from MC simulations...

  - With a few data, we can "augment" existing data :self-supervised

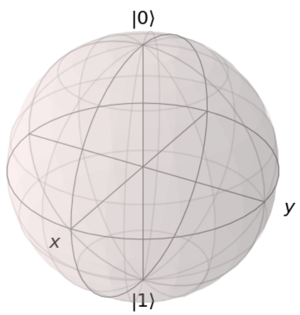
- Algorithm based on Quantum Information can do this job !

Quantum Hilbert space

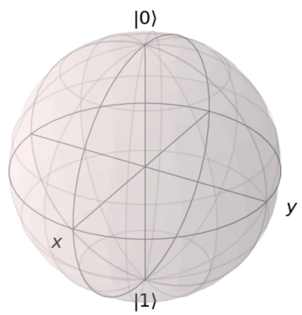




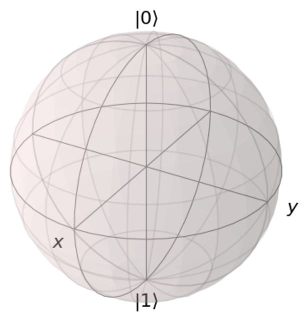
$$|\Psi\rangle = \sum a_{i_1 i_2 \cdots i_n}$$



$\otimes$



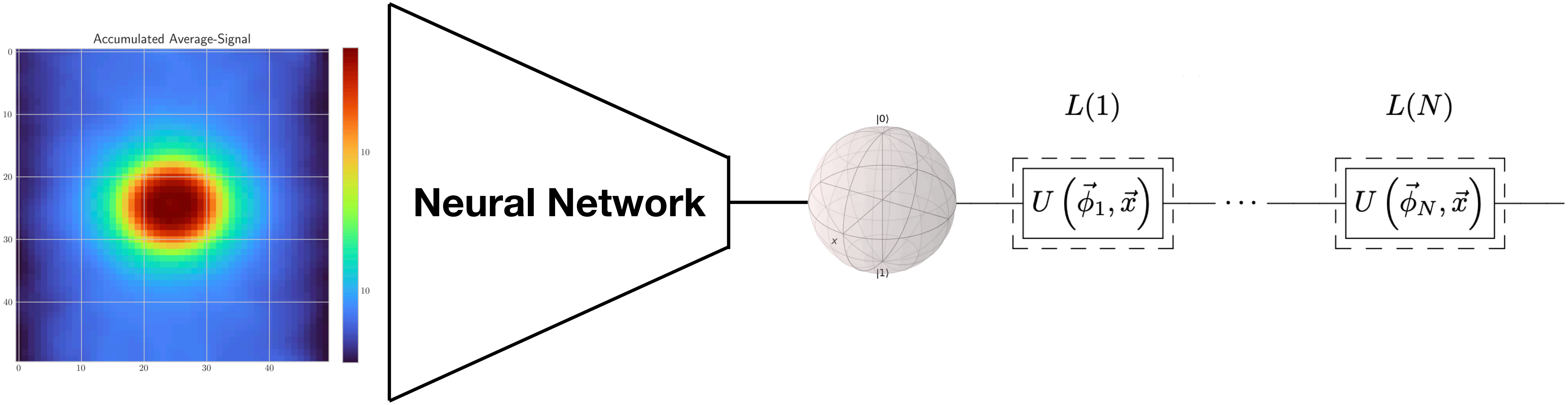
$\cdots \otimes$

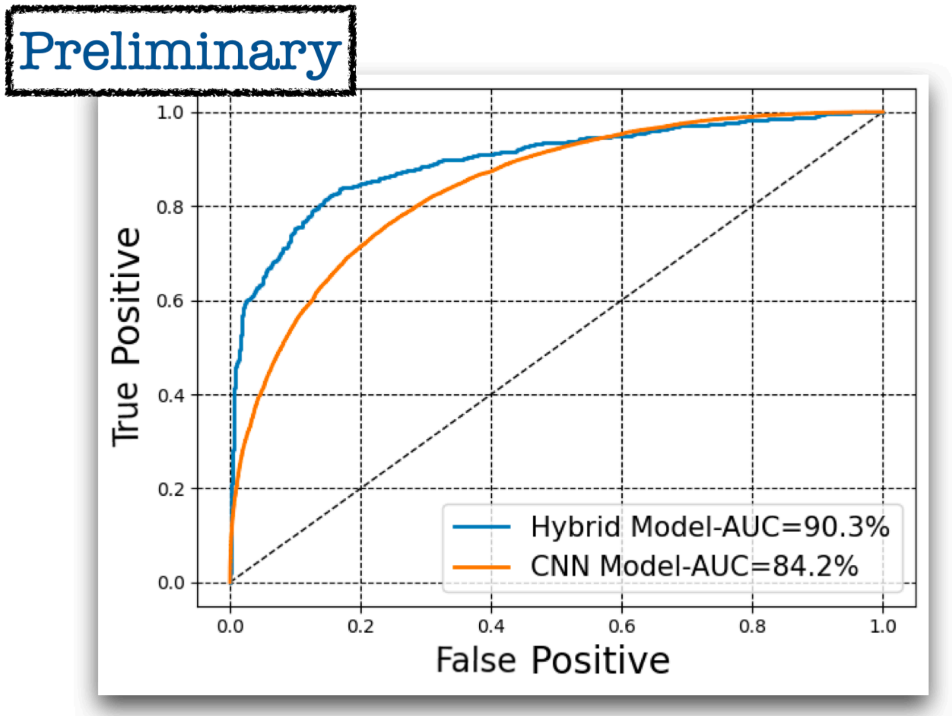


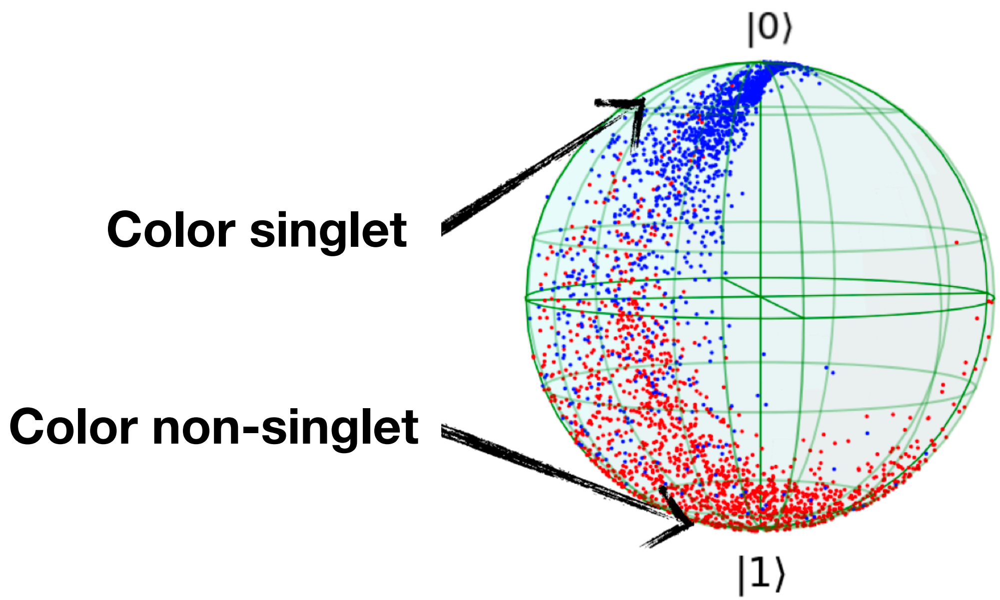
- Expressing and manipulating input data in an **exponentially large (2^n) and "compact" Quantum Hilbert Space**.
- We can **linearly separate** different objects with a "kernel method"

- With one qubit,

Dimensional Reduction







Conclusion

- The Standard Model Higgs precision requires advanced computing methods.

- Thanks to the LHC, we have improved the physics of QCD dramatically.

  - Precision physics with soft patterns armed with ML
  - But current focuses are in the boosted analyses.

- Here, I present how we can utilize (local) QCD features in "non-boosted" region: Need to resolve effects from different kinematics

  TO DO
  1. Efficient way to combine local (QCD) and global (Kinematics)
  2. Utilize Quantum Information in Machine Learning algorithms.