Leveraging Quantum Annealer to identify event topologies at High energy colliders

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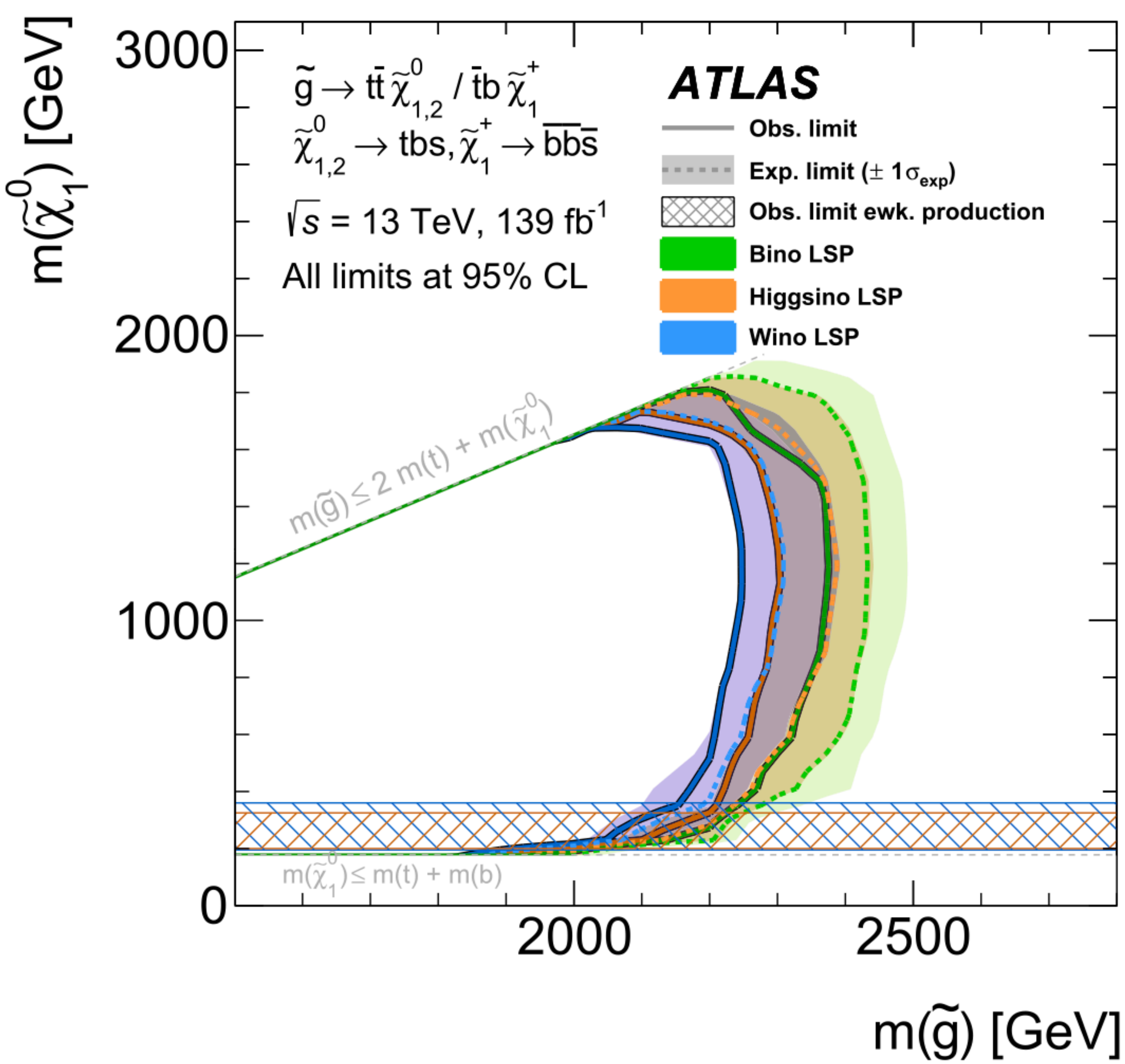
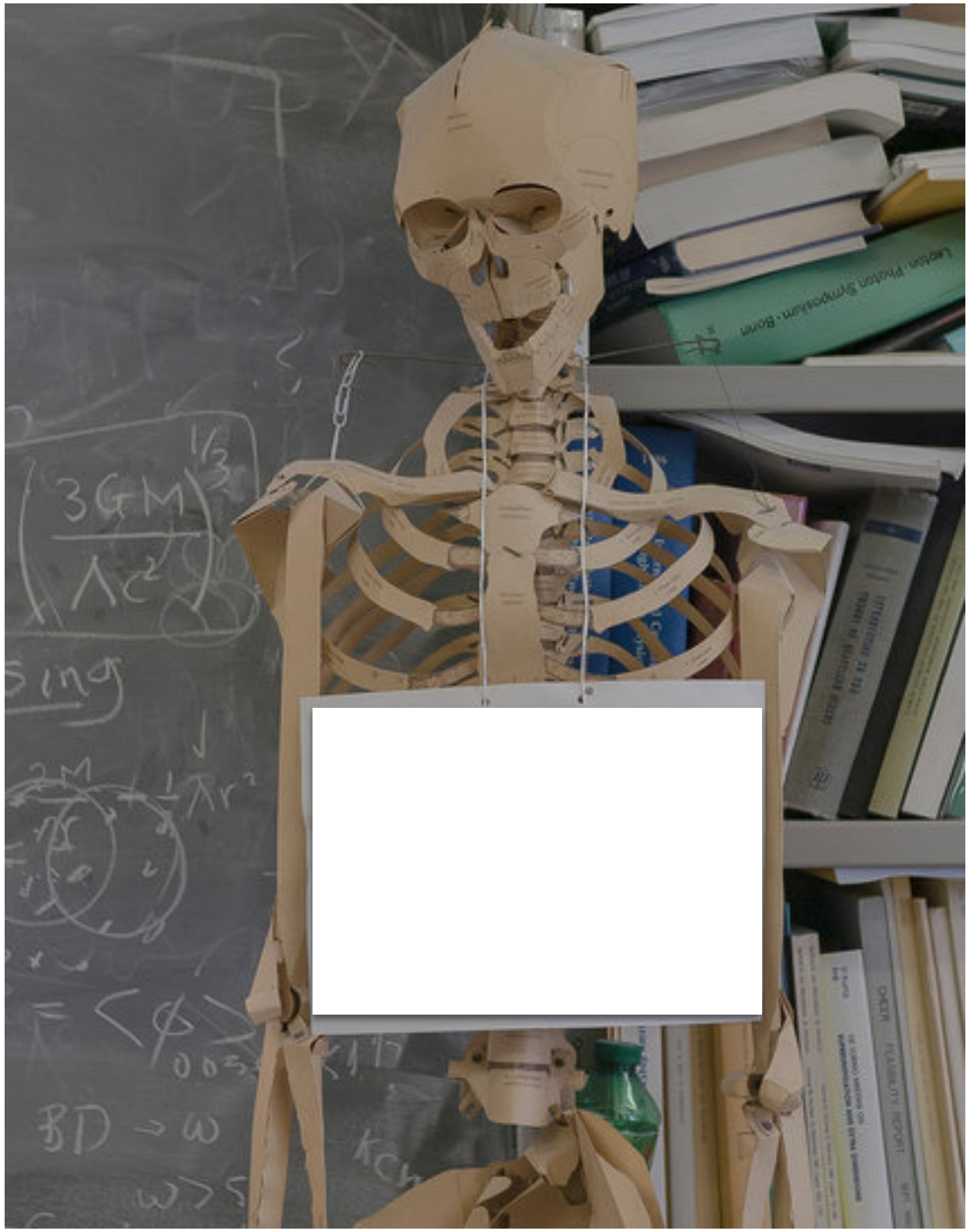
based on arXiv:2111.07806
with Minho Kim, Pyungwon Ko, Jae-hyeon Park

The 2nd Asian-European-Institutes Workshop for BSM (2022)

With the LHC

- The long lived king is **dead**!?





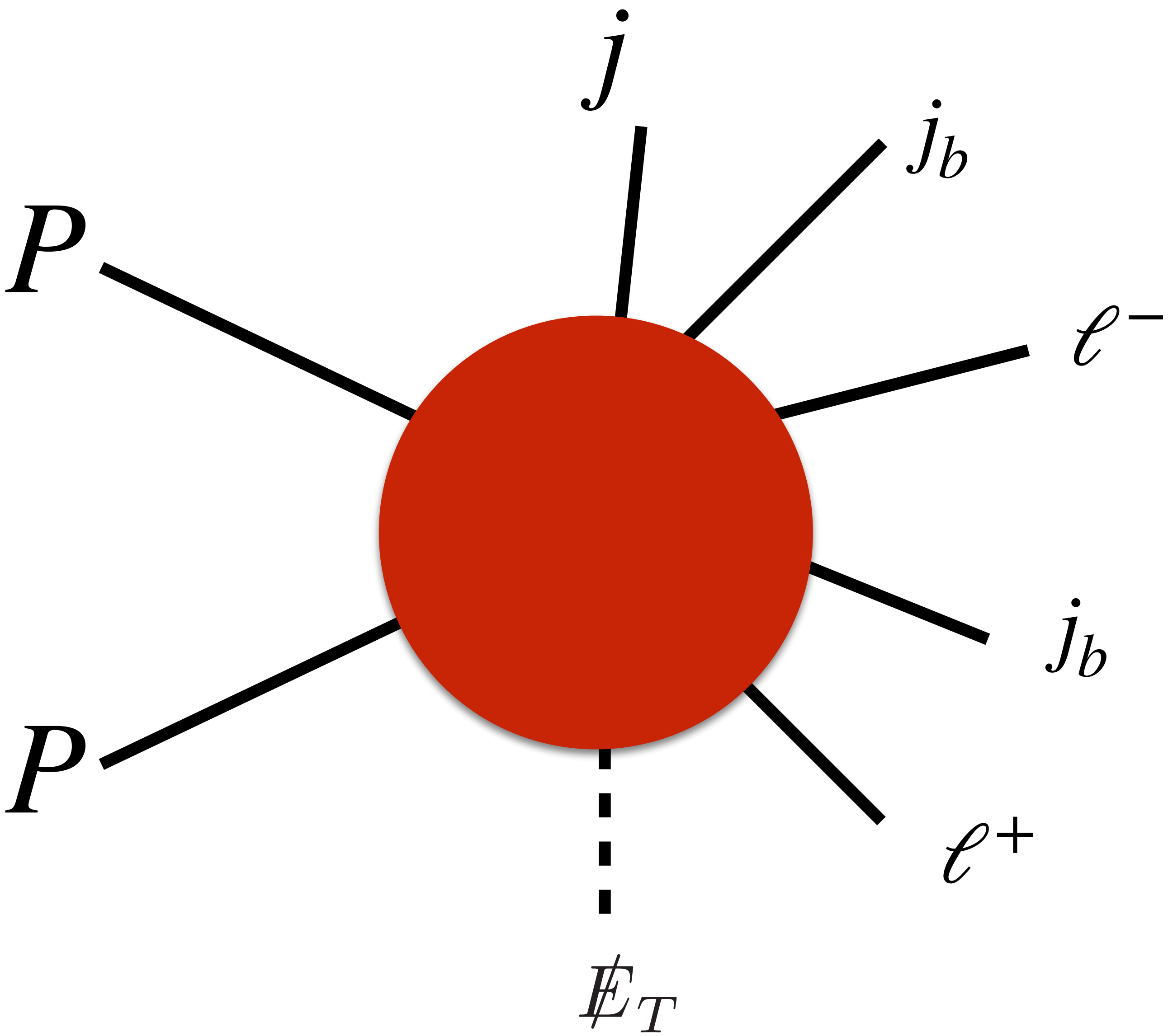
Hunt for new physics afterwards

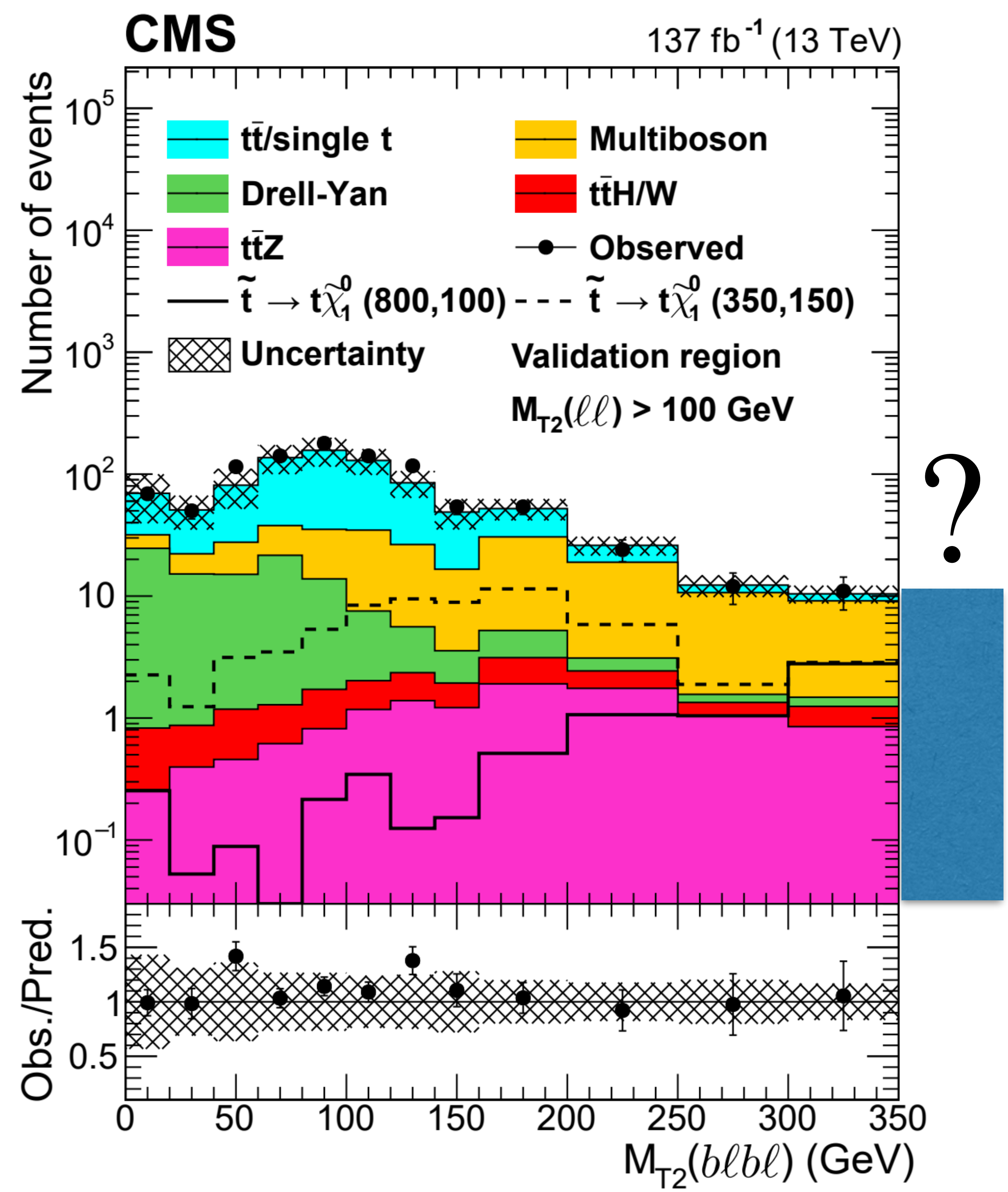
1. **Anomaly detection** (different from SM expectations)
   - Need to have precise tools (importance of MC)

2. Try to interpret a new signal with **various** model assumptions or **Model-independent way** so called simplified model
   - For each model, we start with **specific** "feynman-diagram"
     (**event-topology**, without specific spin assignment.)

   - Determine parameters (spin, mass) with various methods

Example: anomaly





a simple kinematic variable

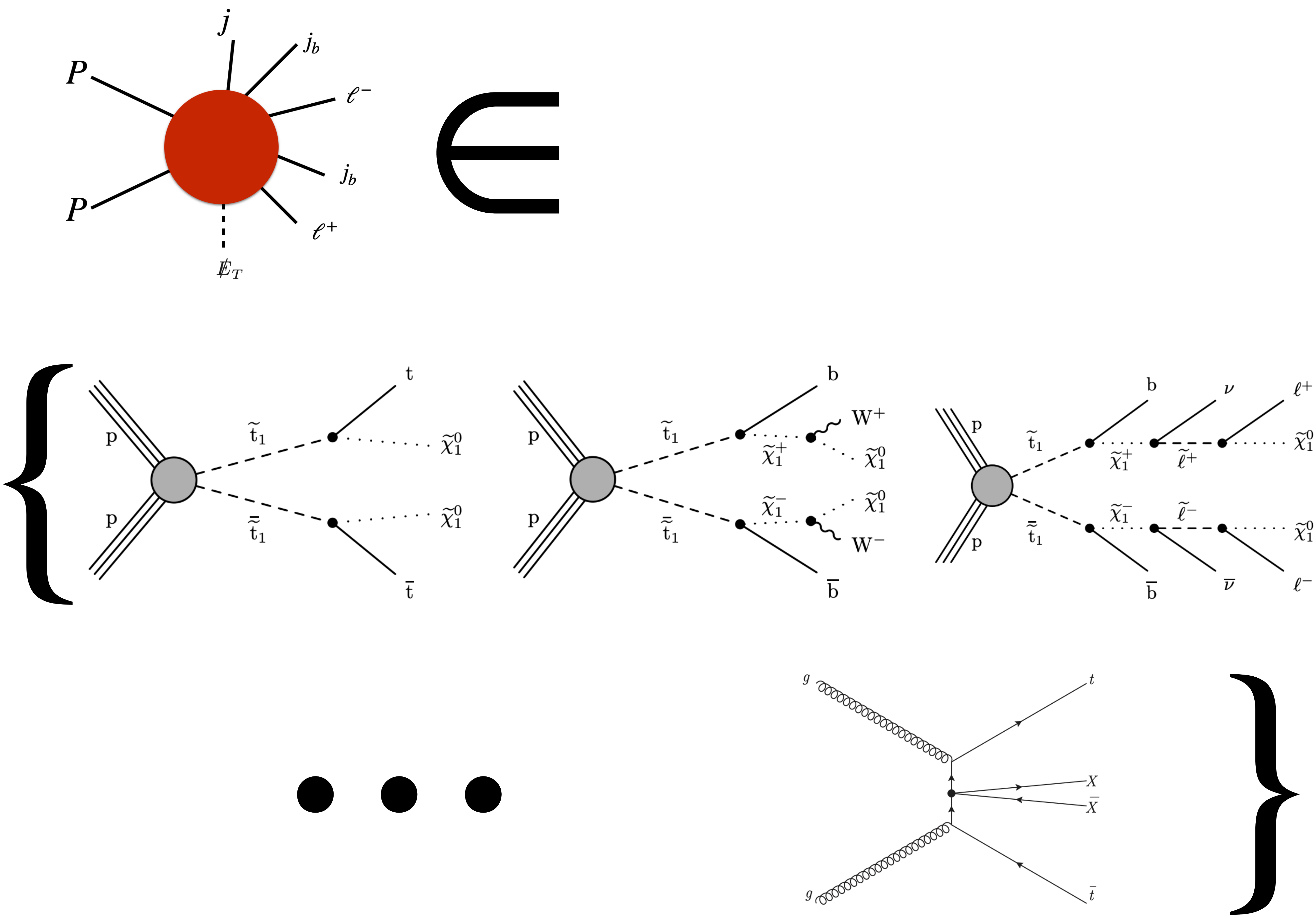


diagram from Lian-Tao Wang et.al. arxiv:1303.6638

Purely bottom-up approach

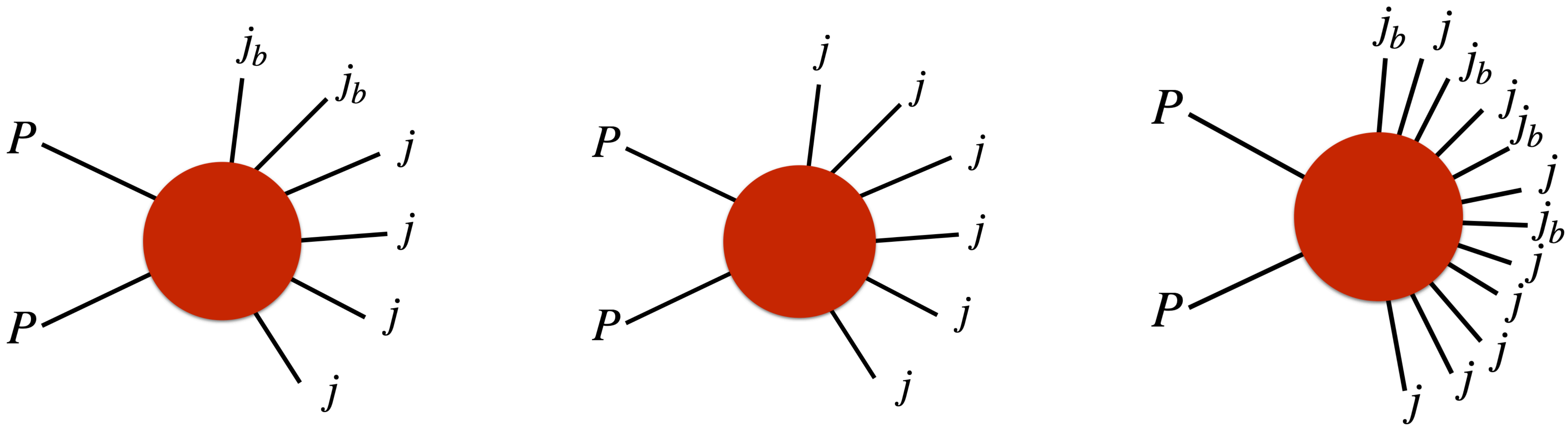
1. **Figure out what is the relevant event-topology behind anomalous (deviation from SM) events.**

2. Check the mass spectrum.

3. Check spin configuration.

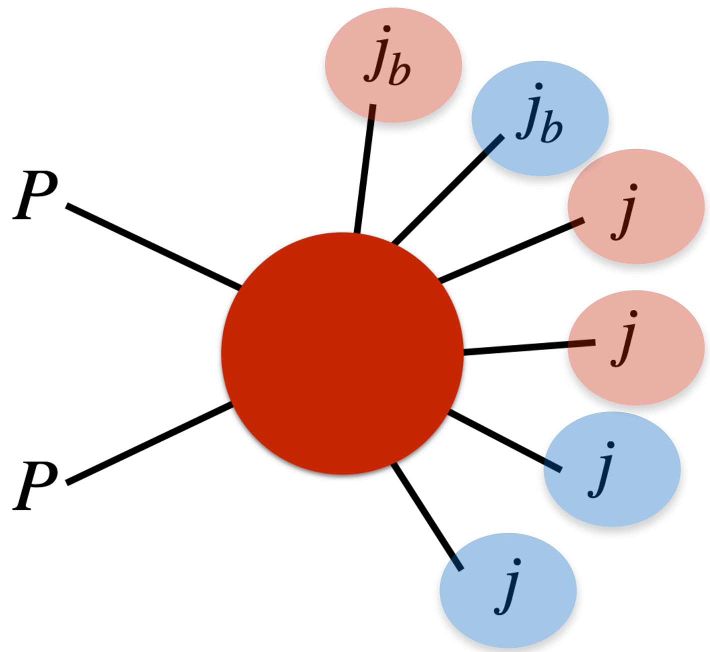
- So far, there are very few literatures for ***#1.***
  Here I will introduce how one can **identify the event-topology**

Our examples (multi-jets)



1. Under the a simple assumption: $pp \to X, Y \to \{j_x\} \cup \{j_y\}$
   (No prejudices on X and Y)

2. Find a right **combination** to reconstruct X and Y particles.
   → Read off information on **Mass** and **Spin** from event reconstruction.



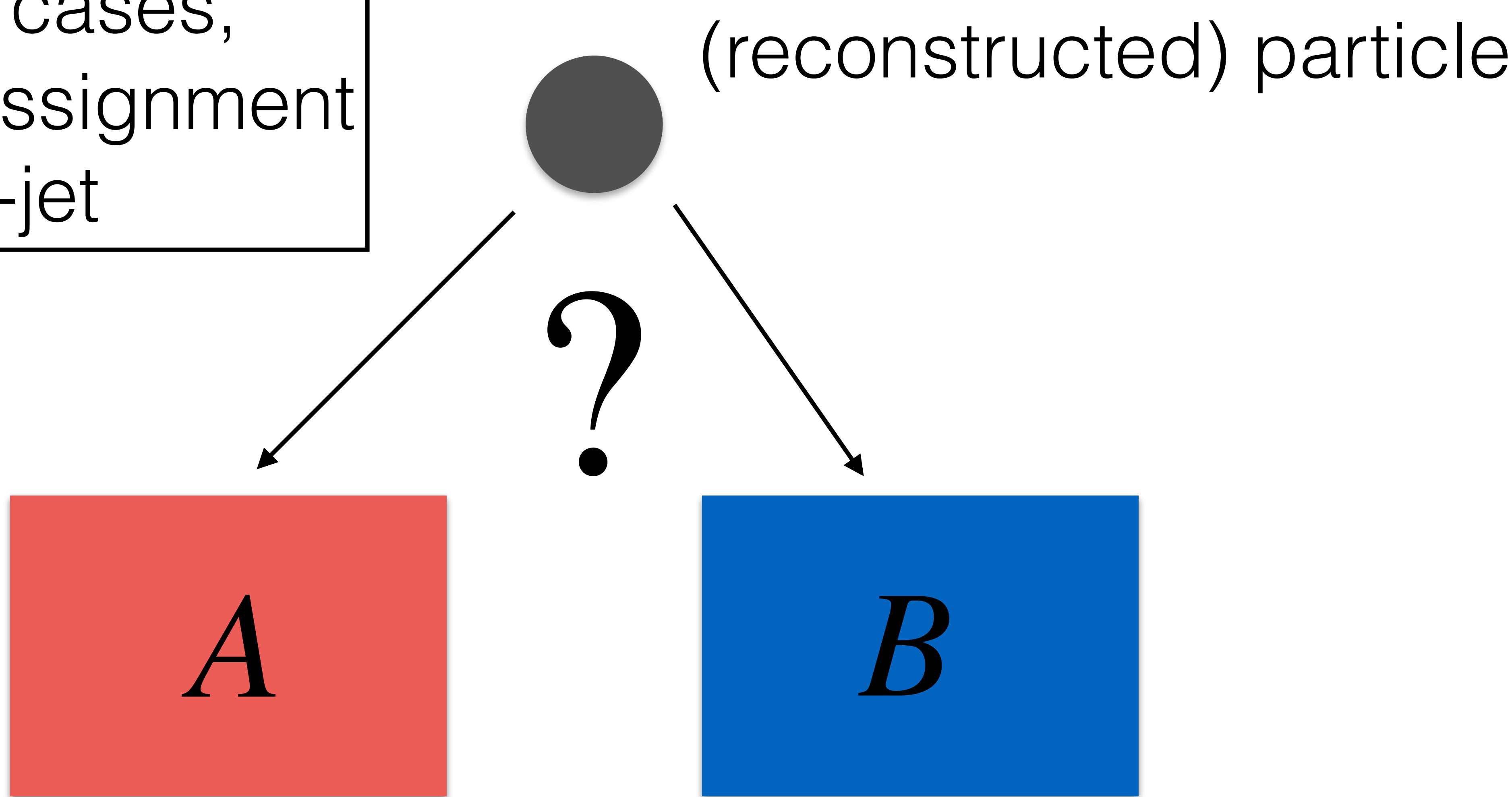
- Standard example of six jets

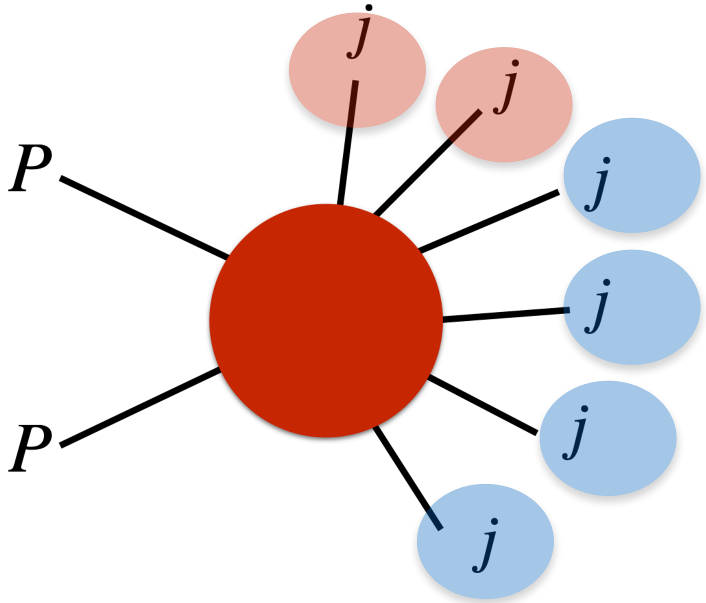
$$pp \to t\bar{t} \to \{j_b, (W \to jj)\} \cup \{j_b, (W \to jj)\}$$

(when A and B have same mass)

- Right answer is $(n_A, n_B) = (3,3)$

$2^6 = 64$ cases,
no special assignment
for b-jet



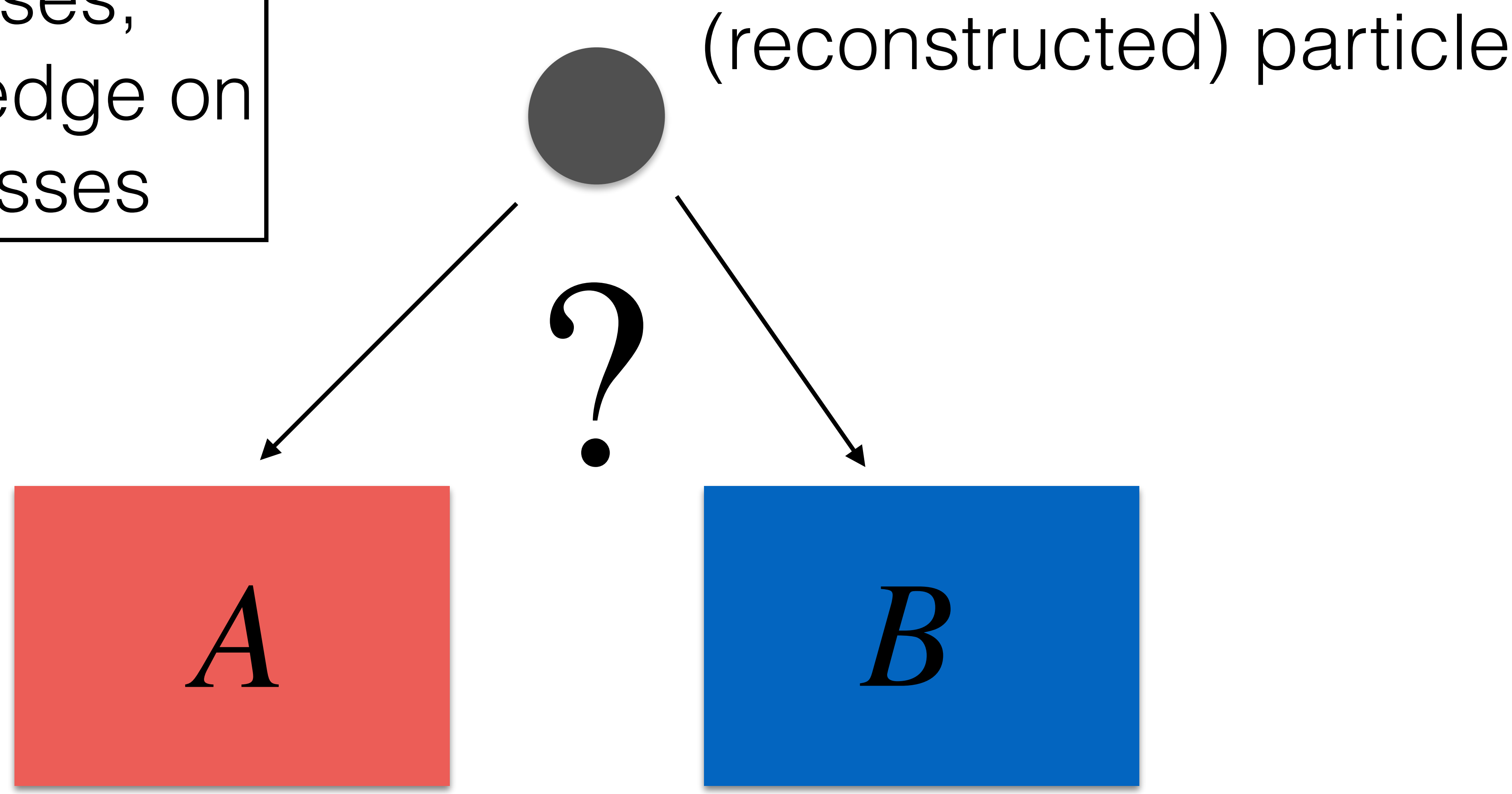


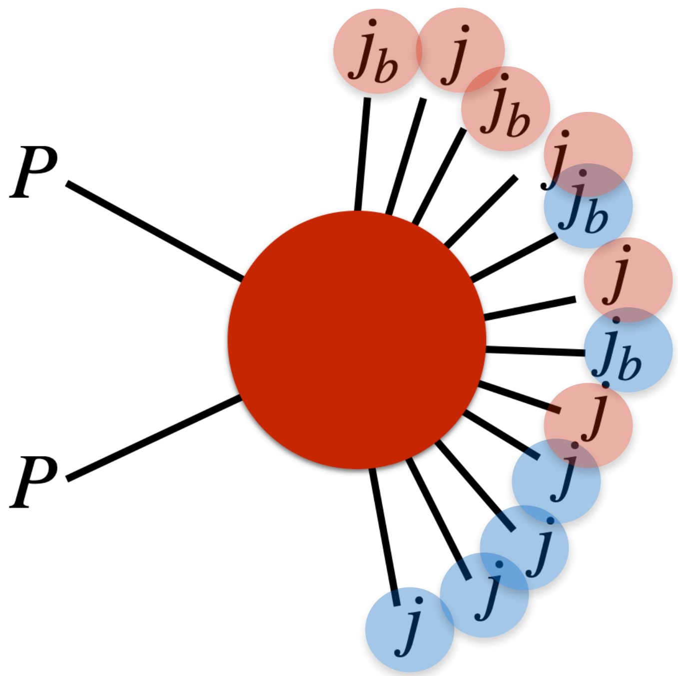
- Different mother particles

$$pp \to ZH \to \{j, j\} \cup \{(W \to jj), (W^* \to jj)\}$$

- Right answer is $(n_A, n_B) = (2,4)$

$2^6 = 64$ cases,
no prior knowledge on
A and B masses





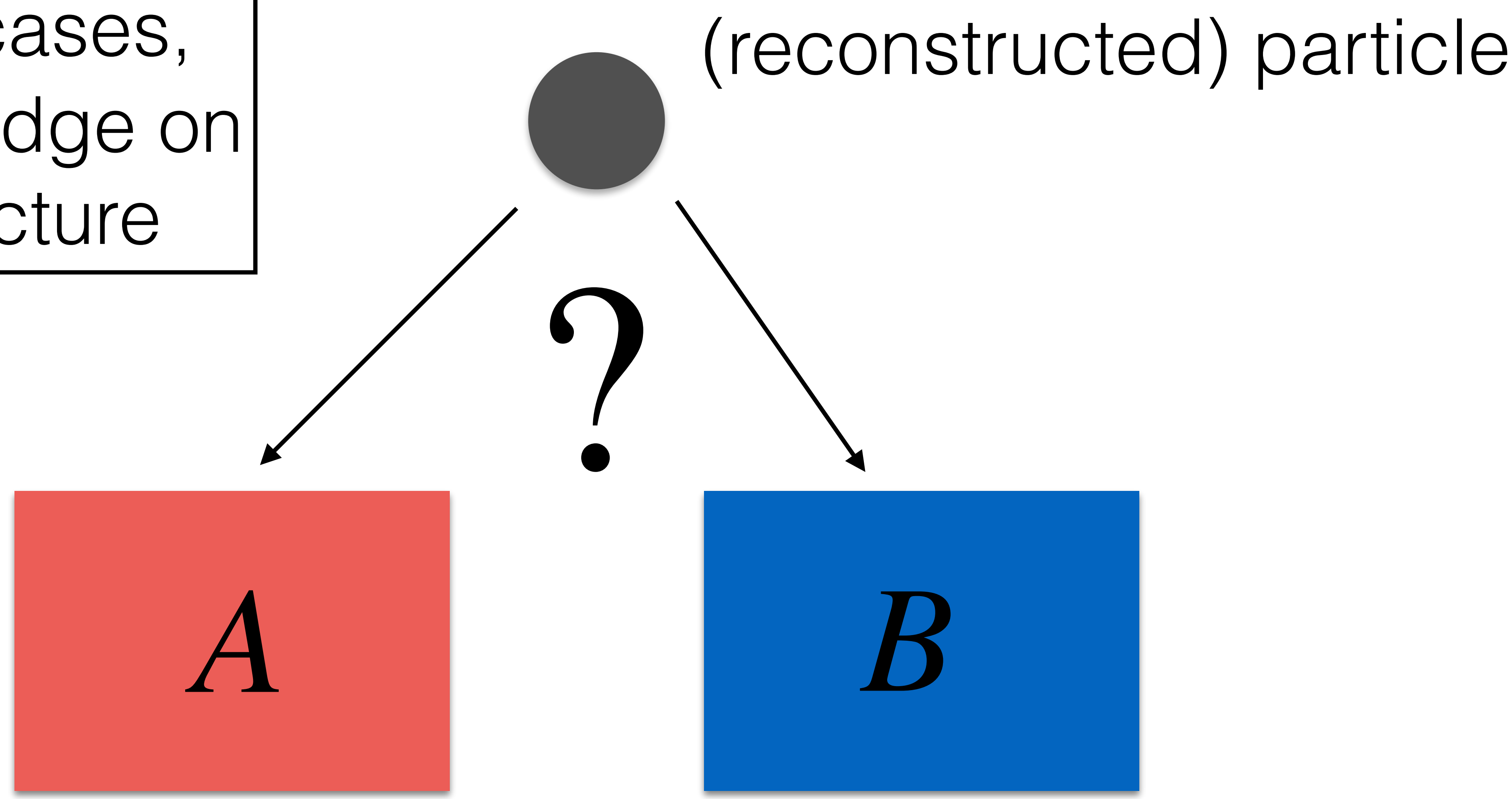
- Complicate situation (12 jets)

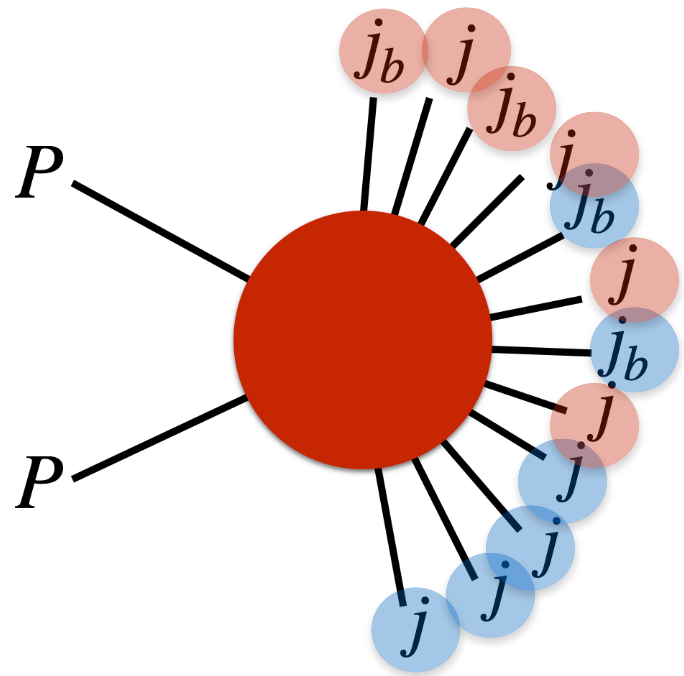
$$pp \to o\tilde{o} \to \{t, \bar{t}\} \cup \{t, \bar{t}\}$$

$$o \to t\bar{t} \to \{j_b, (W \to jj)\} \cup \{j_b, (W \to jj)\}$$

$$\tilde{o} \to t\bar{t} \to \{j_b, (W \to jj)\} \cup \{j_b, (W \to jj)\}$$

$2^{12} = 4096$ cases,
no prior knowledge on
a decay-structure





- Complicate situation (12 jets)

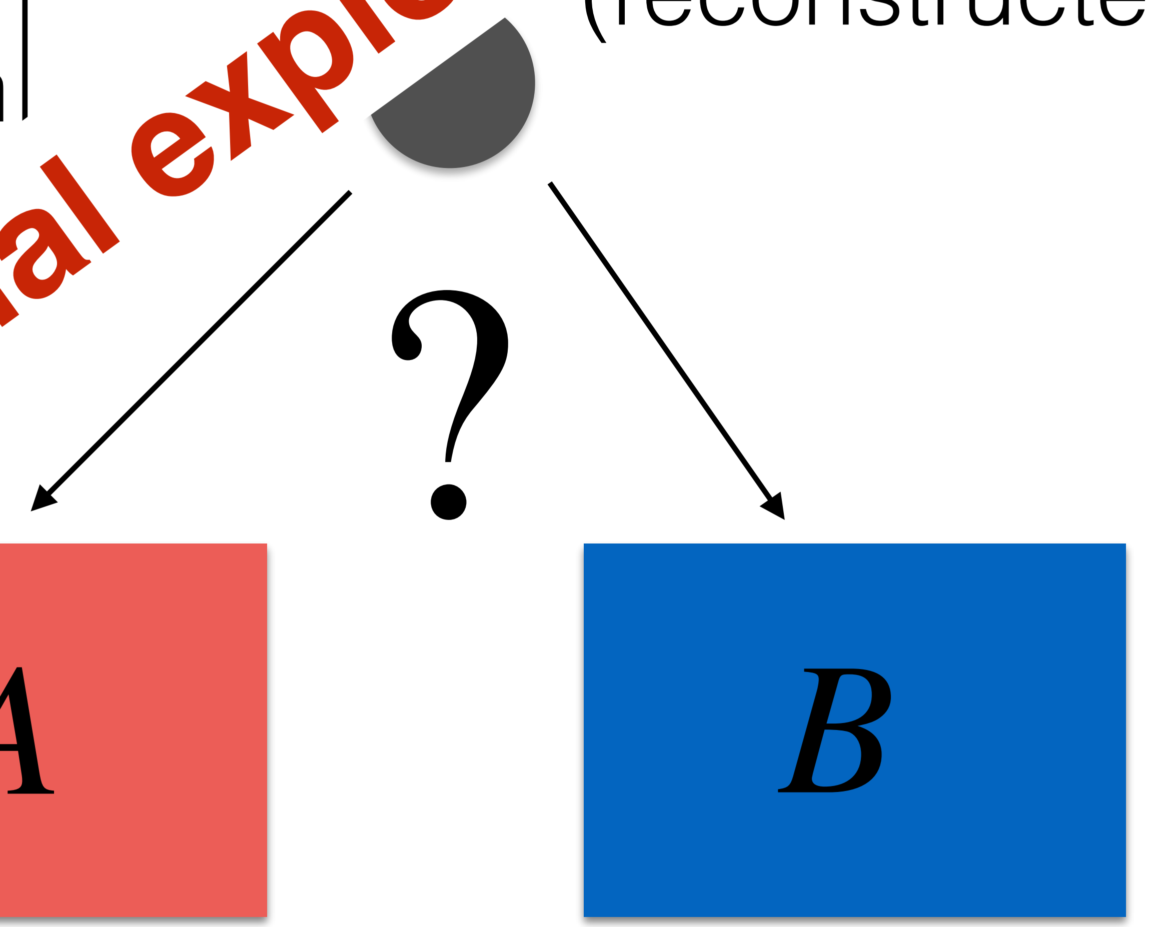
$pp \to o\tilde{o} \to \{t, \bar{t}\} \cup \{t, \bar{t}\}$

$o \to t\bar{t} \to \{j_b, (W \to jj)\}$ ... $(W \to jj)\}$

$\tilde{o} \to t\bar{t} \to \{j_b, (W$ ... $\{j_b, (W \to jj)\}$

$2^{12} = 4096$ cases,
no prior knowledge on
a decay-structure

Combinatorial explosion will occur !



An algorithm ?

- With the only assumption of $2 \rightarrow (2 \rightarrow n)$ process

  - No special treatment on any flavor-tagged particle

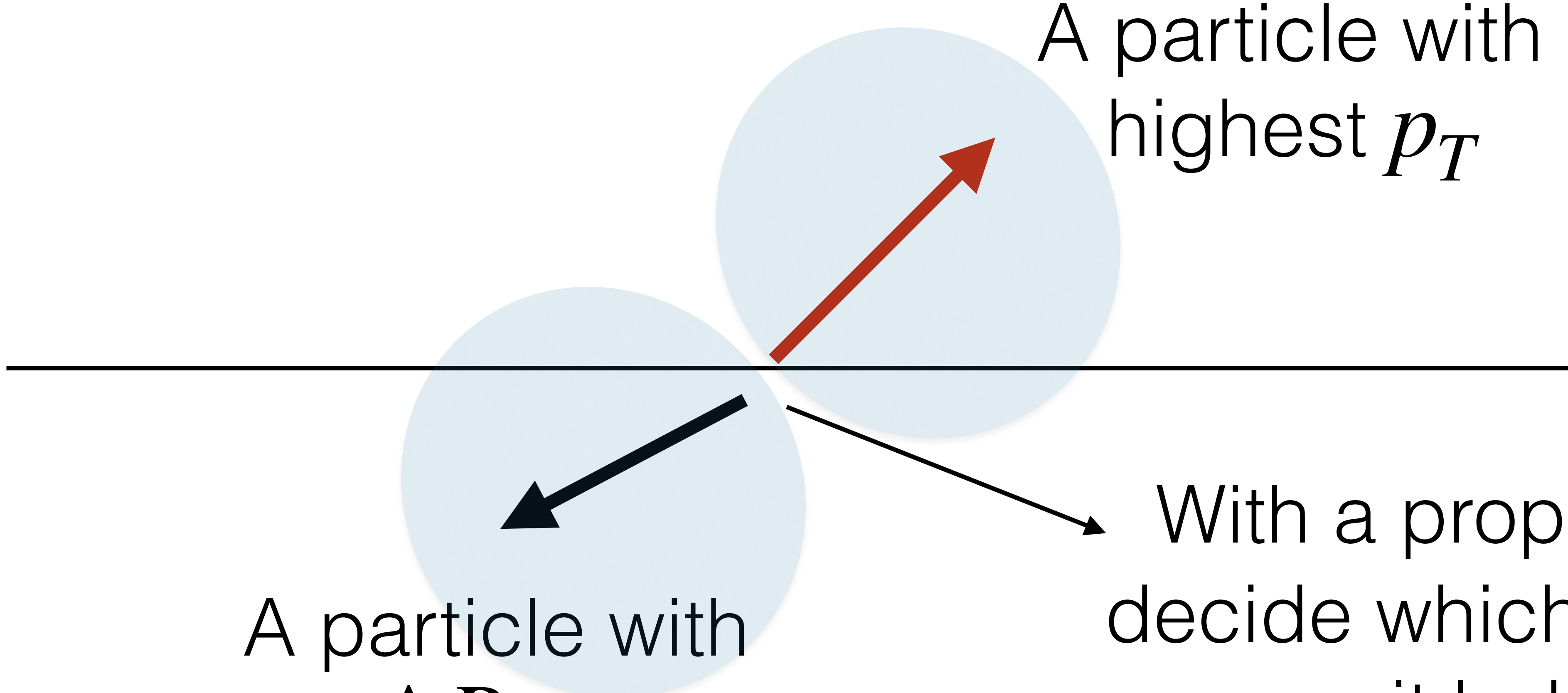
  - No assumption on M_A and M_B

  - No assumption on any decaying structure

- What could be a good guide line ?

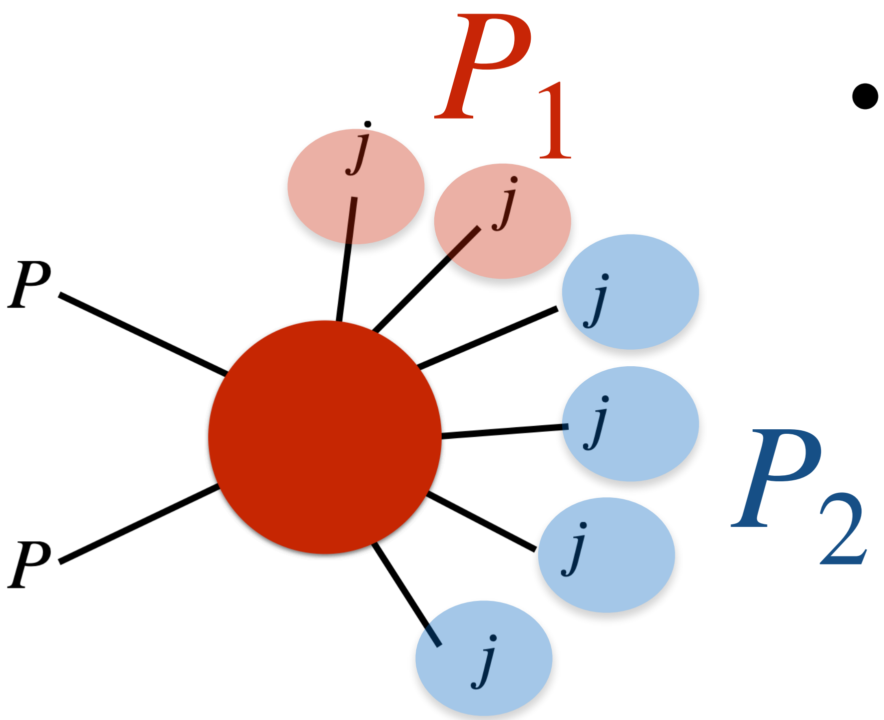
A Classic algorithm

- Hemisphere method: a seed-based method (iterative and converge)



CMS hemisphere TDR,
Shigeki Matsumoto, Mihoko M Nojiri, and Daisuke Nomura (2006)

Non-geometric algorithm

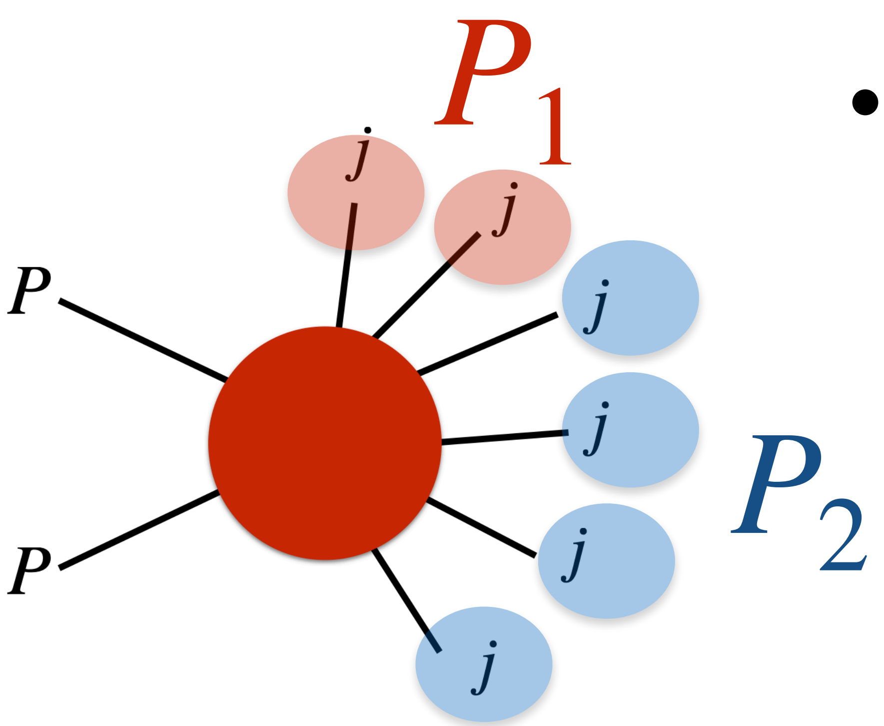


- For each assignment, calculate invariant mass

$$(M_A^2, M_B^2) = (P_1^2, P_2^2)$$

- Try to **minimize** the mass difference $H = (M_A^2 - M_B^2)^2$

Non-geometric algorithm

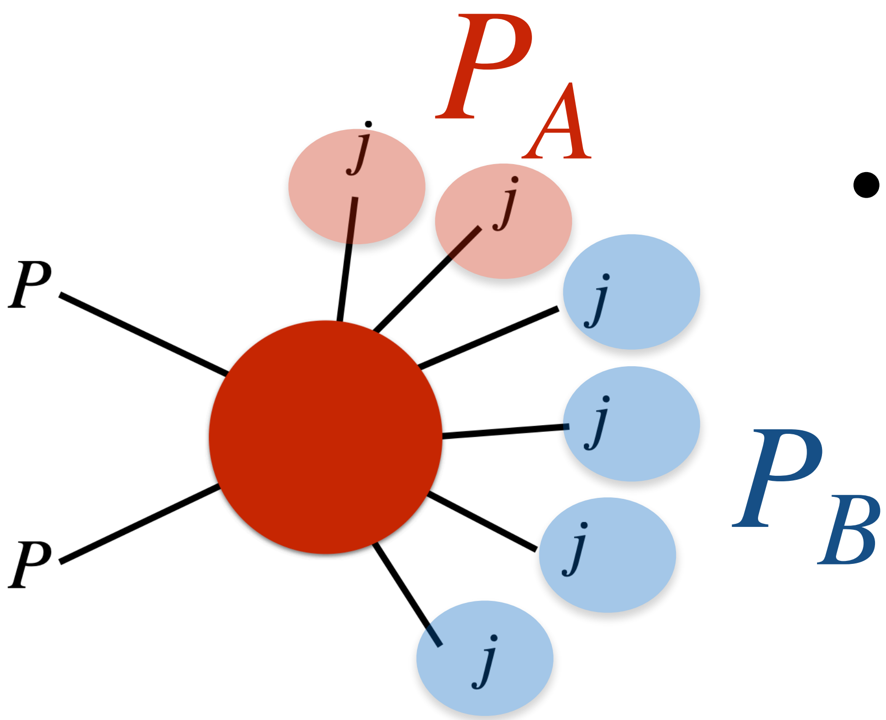


- For each assignment, calculate invariant mass

$$(M_A^2, M_B^2) = (P_1^2, P_2^2)$$

- Try to **minimize** the mass difference $H = (M_A^2 - M_B^2)^2$

- **How can we deal with the case of $M_A \neq M_B$?**



- Try to **minimize** the mass difference

$$H = (M_A^2 - M_B^2)^2$$

- **How can we deal with the case of $M_A \neq M_B$?**

+ (even with $M_A = M_B$) we need to handle
1) off-shell mass due to the width of A and B
2) from smearing effects due to imperfect detectors

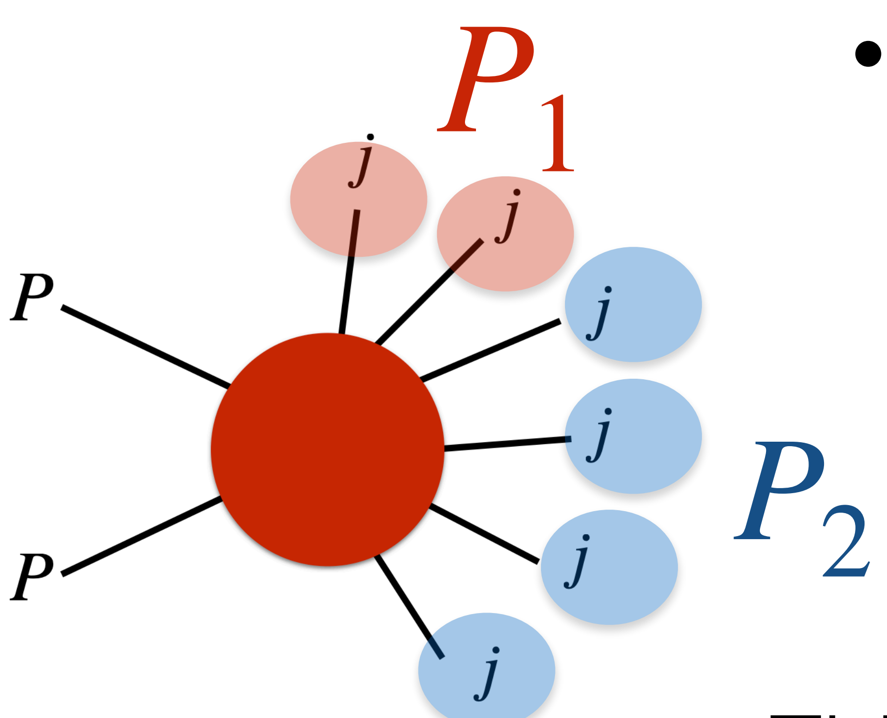
- One suggestion: Add a regularization term of $\lambda(P_1^2 + P_2^2)$

(λ is a dimension full "**hyper-parameter**")

- $2 \to 2$ process: $\{p_i\} \to P_1 \cup P_2$
  Using a binary operation $x_i \in \{0,1\}$

  For p_i to be either in P_1 $(x_i = 1)$ or in P_2 $(x_i = 0)$

$$P_1 = \sum_i p_i x_i \,, \quad P_2 = \sum_i p_i (1 - x_i)$$



- Try to **minimize**

$$H = (P_1^2 - P_2^2)^2 + \lambda (P_1^2 + P_2^2)$$

for each "assignment" ?!

- This problem now becomes well-known...

Minimization using Ising model

- If we replace $x_i \to \dfrac{1+s_i}{2}$ with $s_i \in \{+1, -1\}$

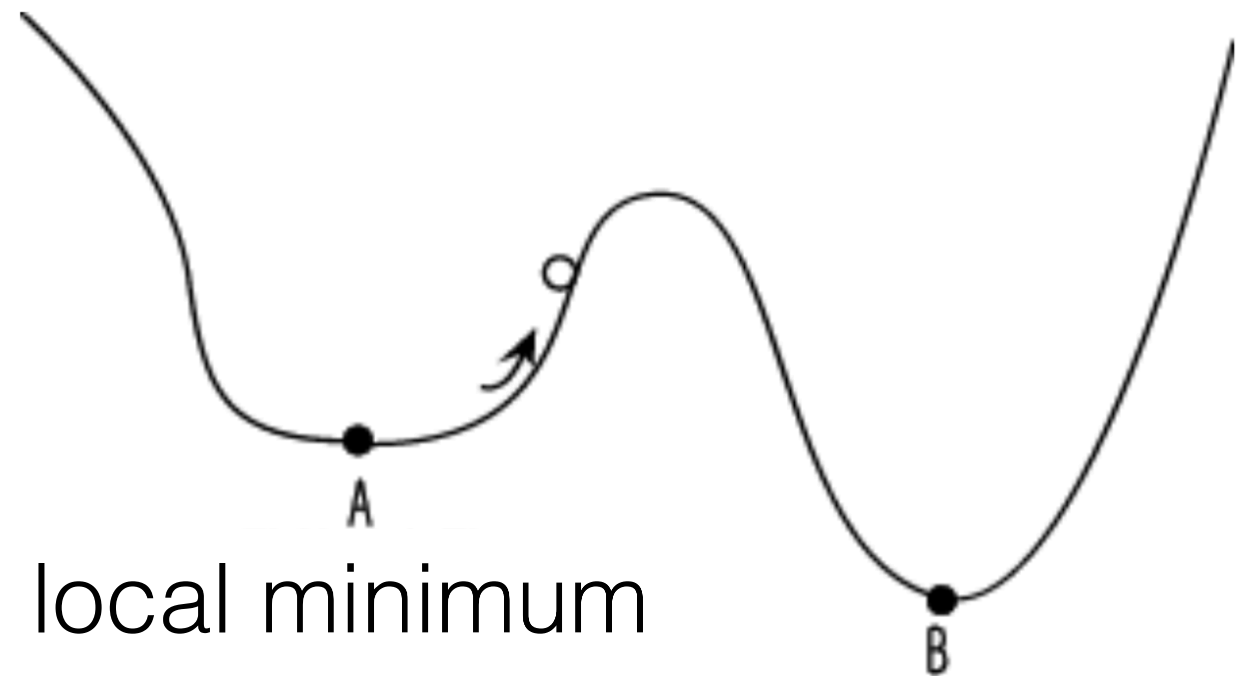
  $$H = \left(P_1^2 - P_2^2\right)^2 \to H + \lambda\left(P_1^2 + P_2^2\right)$$

  $$= \sum_{i,j}\left(C_{ij} + 2\lambda S_{ij}\right)s_i s_j + \sum_i \left(J_i - 2\lambda \sum_j S_{ij}\right)s_i$$

- To maintain the importance of original H,

  we take $\lambda = \dfrac{\min\left(C_{ij}\right)}{\max\left(S_{ij}\right)}$

"Classic" minimization method (for ising hamiltonian)



local minimum

global minimum

Simulated annealing

- Go to the next spin state $s_n \rightarrow s_{n+1}$

  1) If $E_n > E_{n+1}$: go to the lower energy

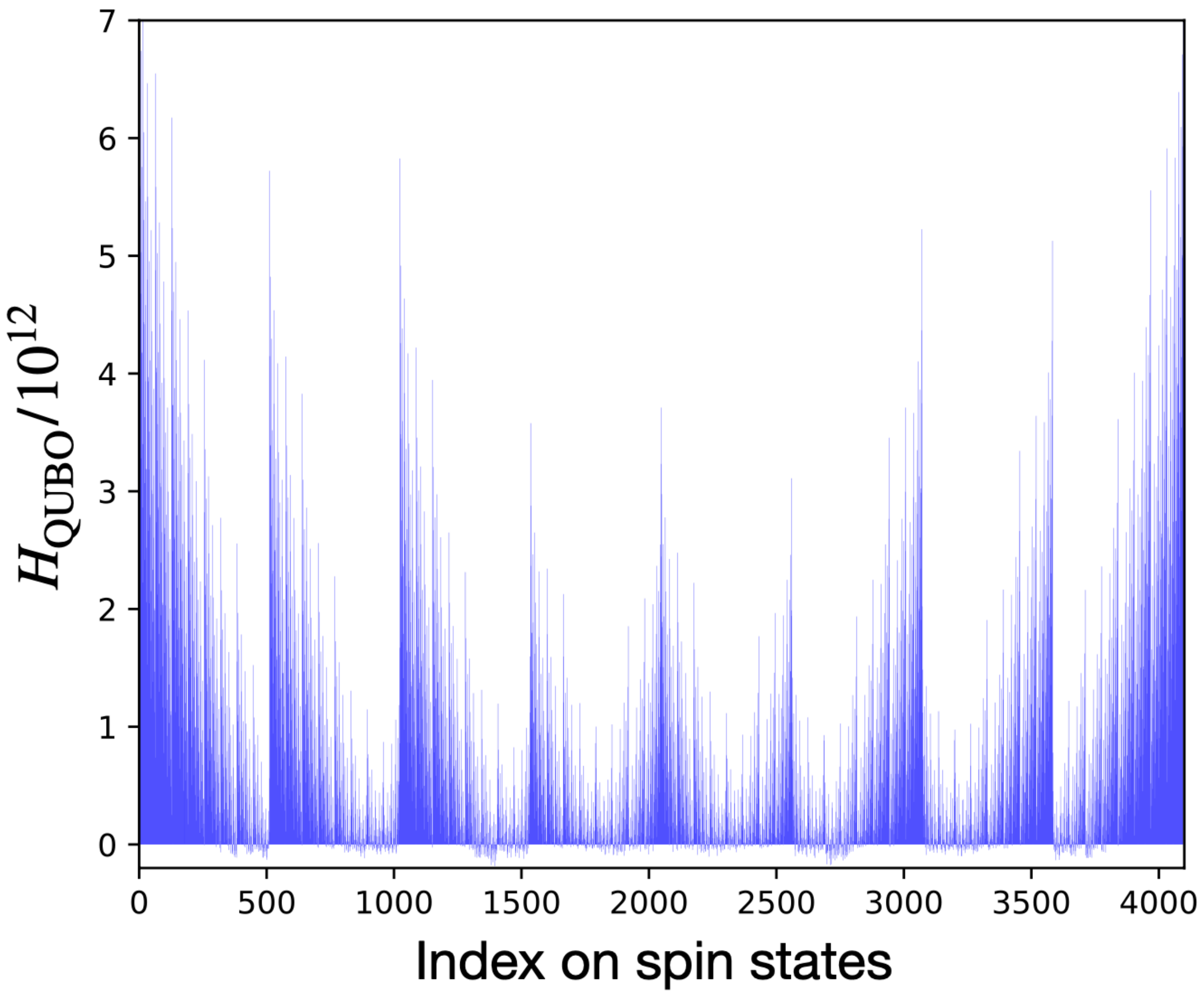
  2) If $E_n < E_{n+1}$, go with a probability of $e^{-\frac{E_{n+1} - E_n}{k_B T}}$ to **jump out**

(A "temperate $T \rightarrow 0$. With large T, SA can jump out local minimum)

But our "mindless"
=**minimally assumed** Collider example
is **not so easy**
for a classical SM

Combinatorial complexity arises (for a random Ising model)

Landscape of energy distribution



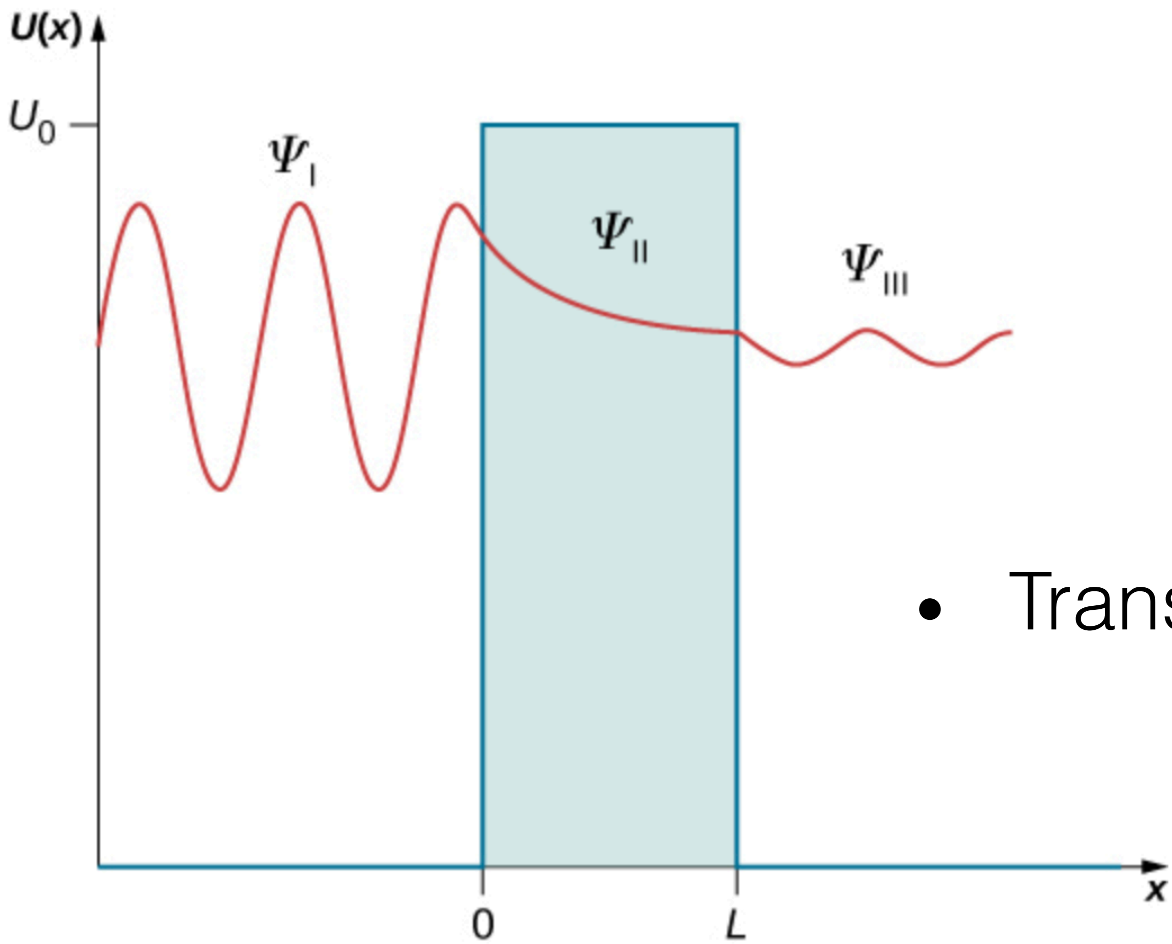
$$\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow \rightarrow \uparrow\uparrow\uparrow\uparrow\uparrow\downarrow \rightarrow \cdots \rightarrow \downarrow\downarrow\downarrow\downarrow\downarrow\downarrow \quad (n_{\mathrm{spin}} = 2^{12} = 4096)$$

SA cannot jump this random potential!

Any solution
we can have?

The Quantum thing...

- In the class of **undergraduate QM**, we learned



- Transmission coefficient $T \propto e^{-2L\sqrt{U_0 - E}}$

1) The effect of energy difference becomes mild

2) Effective for **shallow barrier** !

- If there is a **machine which can realize** **Quantum tunneling**,

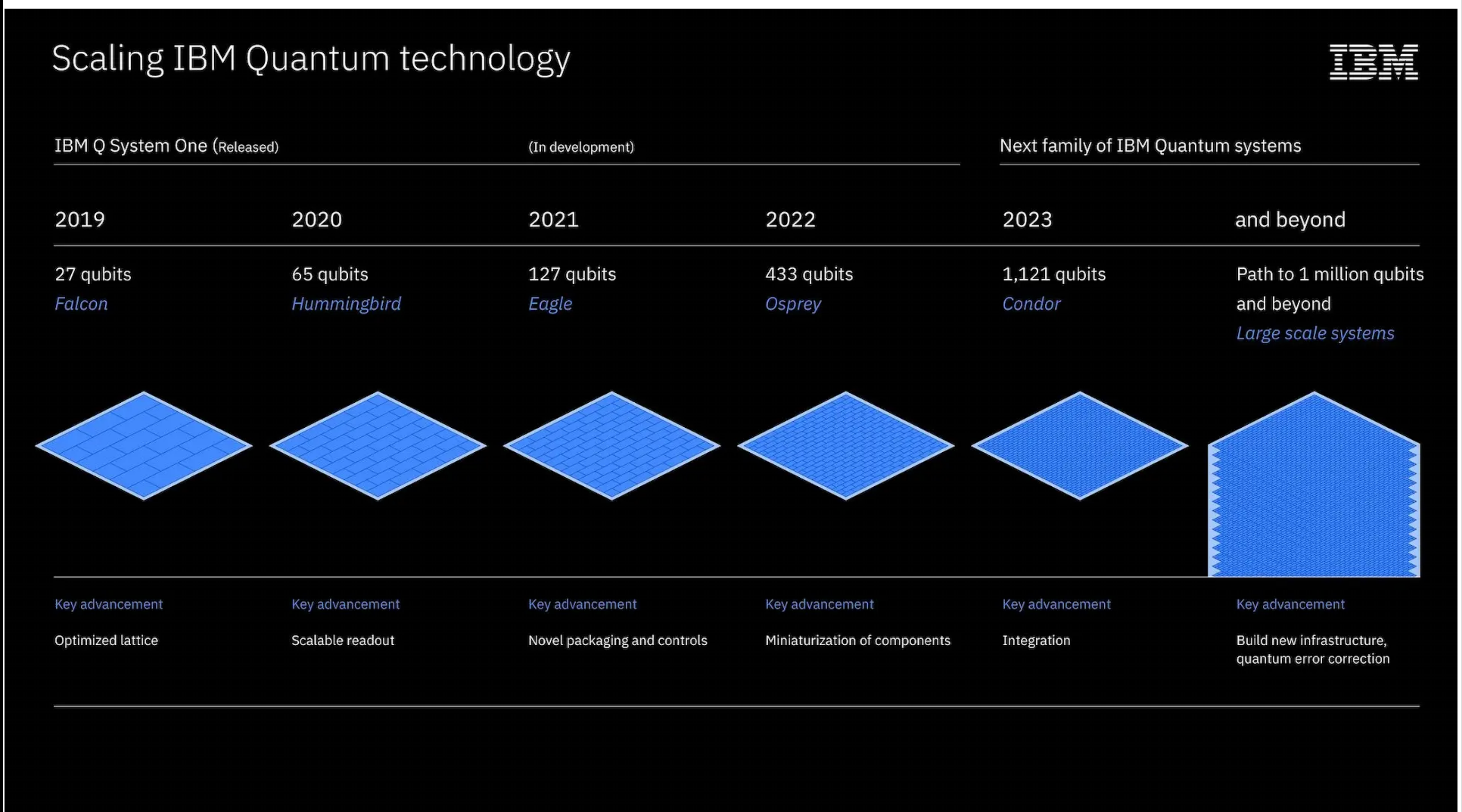
  our problem is a **simple and good example** to demonstrate an **advantage from Quantum tunneling**

Quantum Computer

- Gate type : IBM just announced **433 qubit** QPU. (**An application of this type: Yamazaki's talk**)

- **Quantum annealer**: over 5000 qubits **(Here)**

currently 433 Qubits (IBM Eagle)



Quantum Annealer

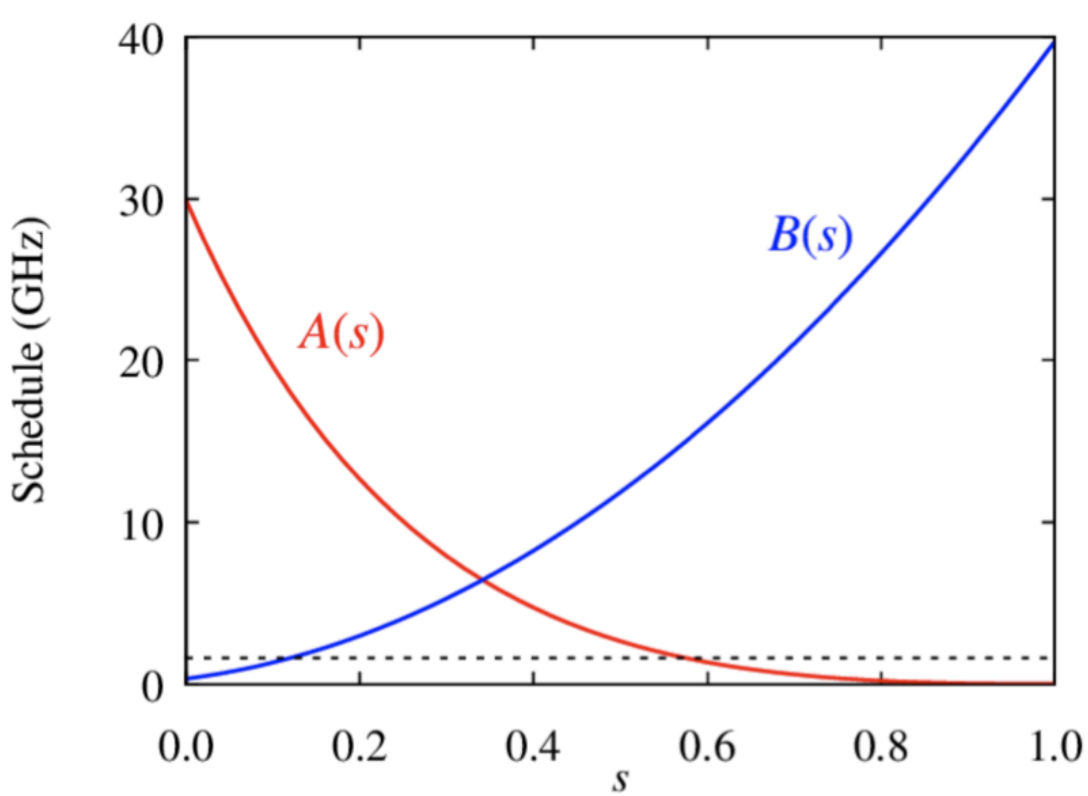
Temperature: below$1.5 \times 10^{-2}\mathrm{K}$
dimension: $3\mathrm{m} \times 2.1\mathrm{m} \times 3\mathrm{m}$
Weight: $3800\mathrm{kg}$
Power: (max) $25\mathrm{kW}$

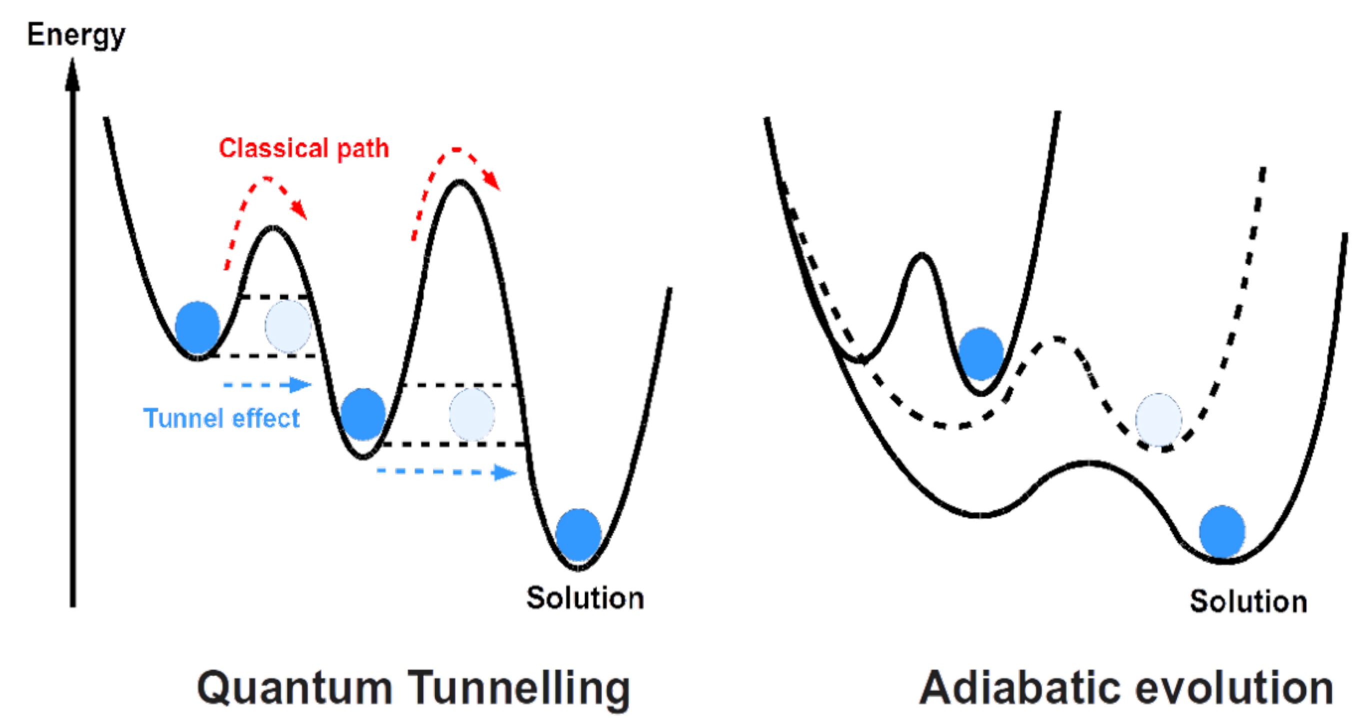
Quantum Annealing method

- With adiabatic theorem, we can find the ground state of a complicate hamiltonian H_{QUBO} starting from simple H_0.

$$H_{\mathrm{QA}} = A(s)\,H_0 + B(s)\,H_{\mathrm{QUBO}} \quad \text{with } H_0 = \sum \sigma_i^x \text{ and } H_{\mathrm{QUBO}} = \sum J_{ij}\sigma_i^z\sigma_j^z + \sum h_i\sigma_i^z$$

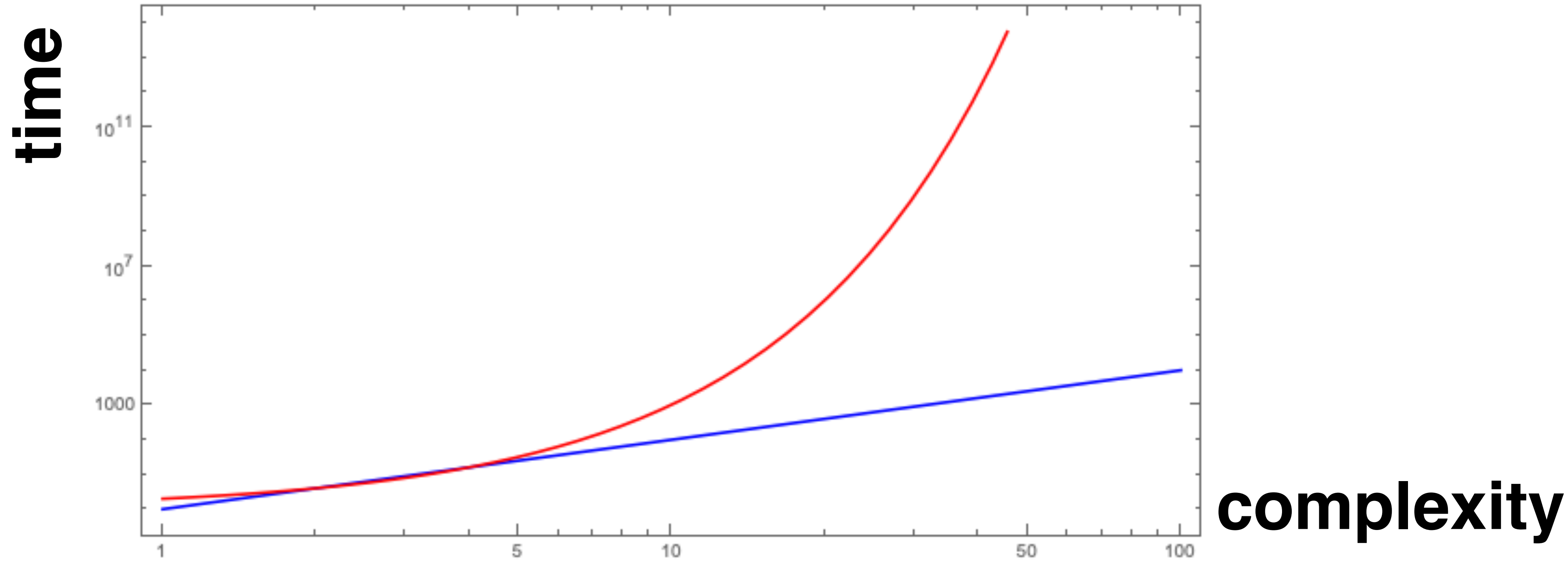
(T. Kadowaki and H. Nishimori, Quantum annealing in the transverse ising model, 1998)





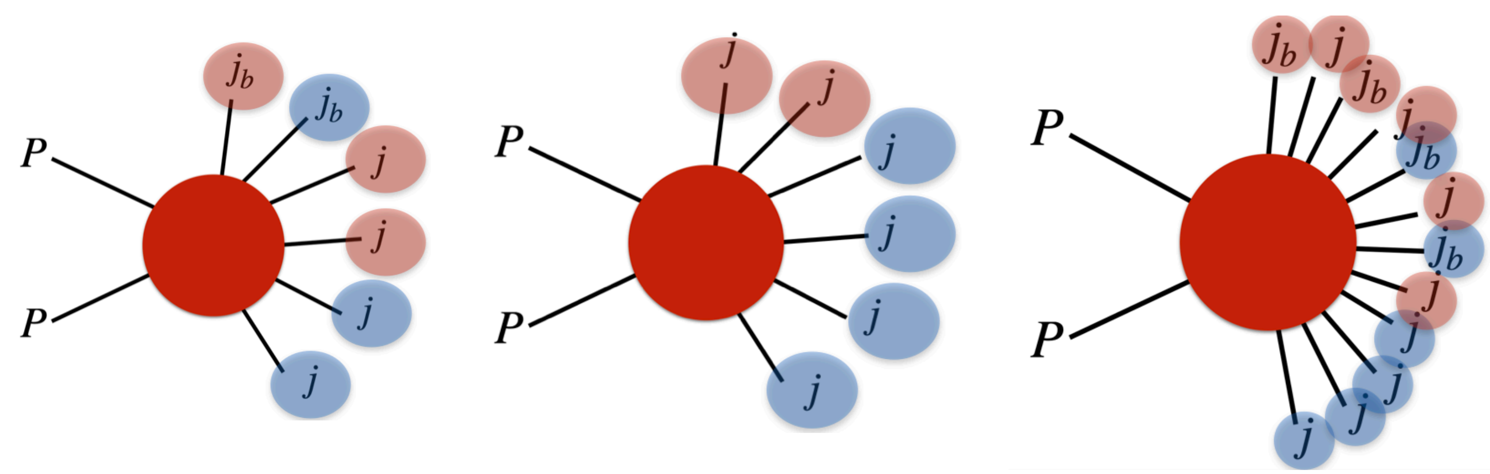
(small) Quantum advantage

- QA v.s. Brute-force scanning:
  The required time (mostly preparation time T_{QUBO}) of QA machine: $T_{\mathrm{QUBO}} = \mathcal{O}(n^2)$
  The complete scanning with n input takes $\mathcal{O}(2^n)$



(big) Quantum advantage

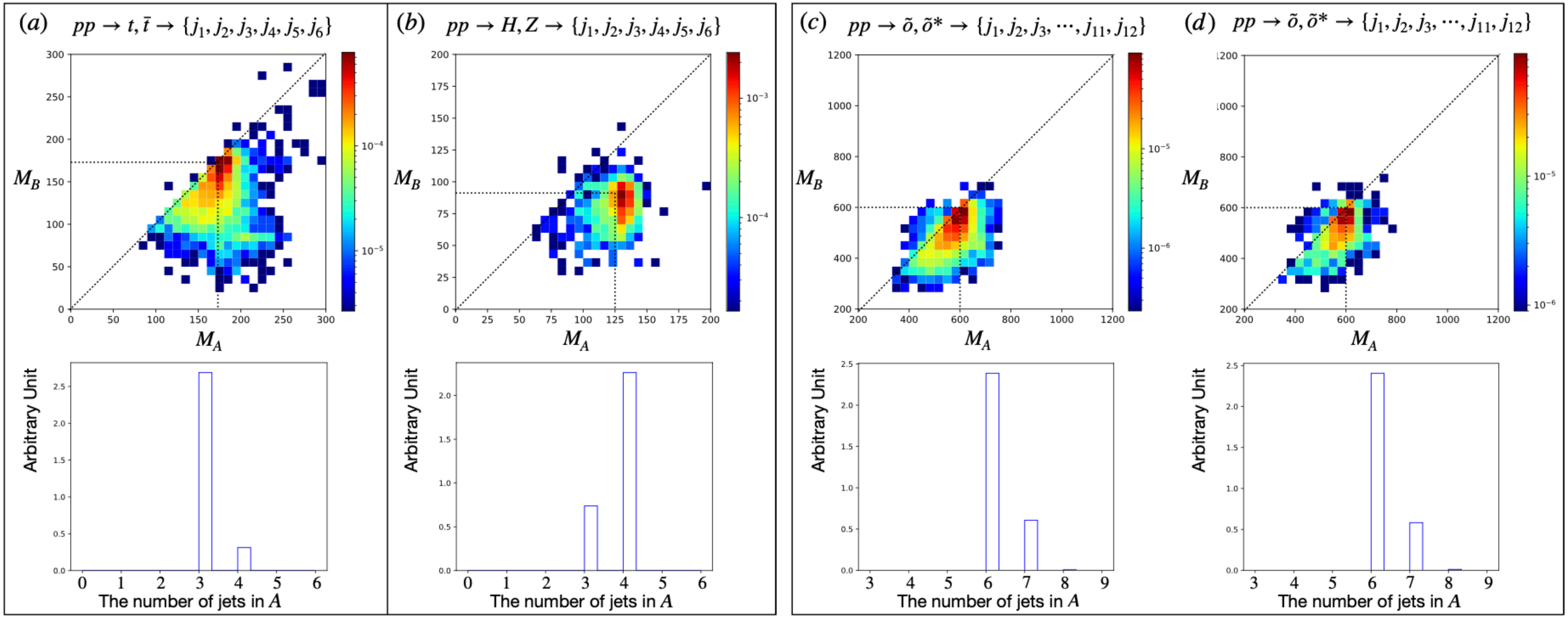
- QA v.s. SA



Process	$pp \to t\bar{t}$ $(2 \to 6)$	$pp \to HZ$ $(2 \to 6)$	$pp \to \tilde{o}\tilde{o}^*$ $(2 \to 12)$
Quantum annealing	100%	100%	74.3%
Simulated annealing	36.7%	45.7%	1%

Percentage to get a **global minimum energy state**
(**does not guarantee** a true combinatorial assignment)

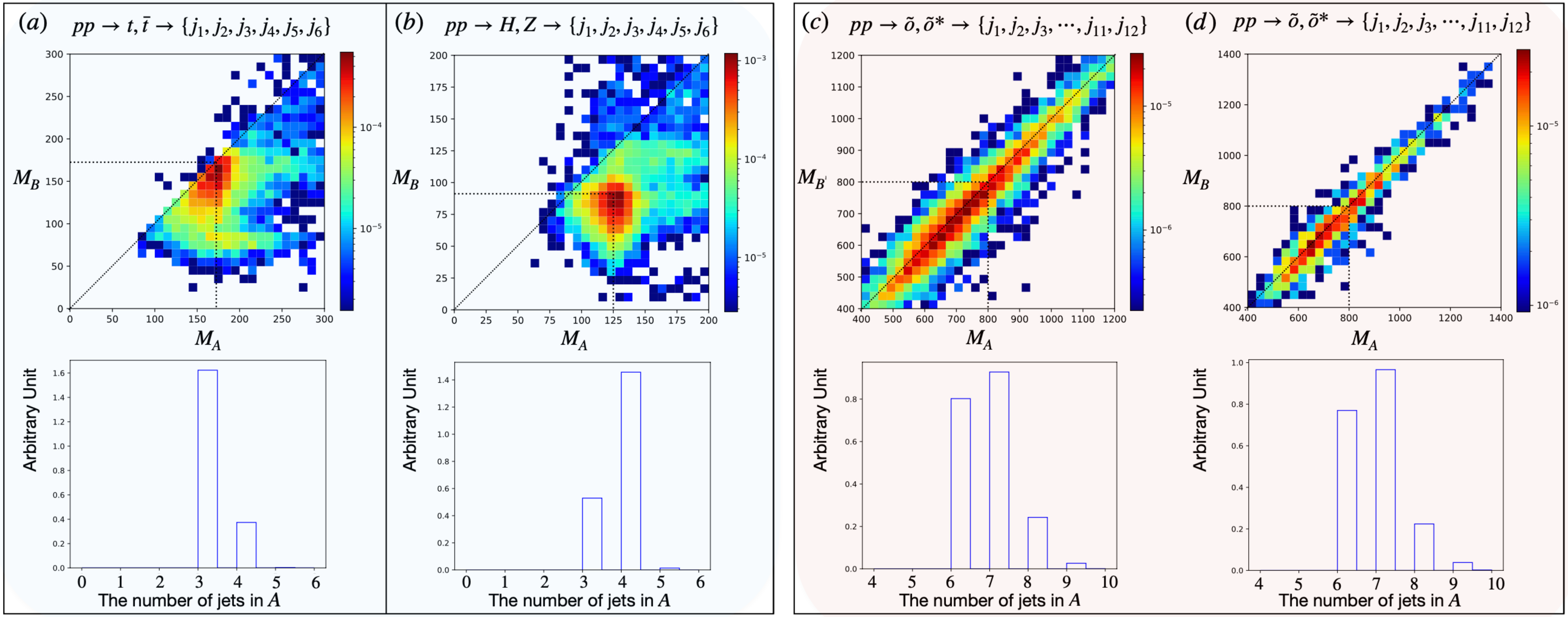
results



- Madgraph → Pythia (ISR/FSR/MPI turned off) → Delphes

*** a to c: brute force scanning for H_{QUBO} to check the fidelity of our algorithm**
d is from D-Wave computer (expensive...)

results



- Madgraph → Pythia (**ISR/FSR/MPI turned ON**) → Delphes

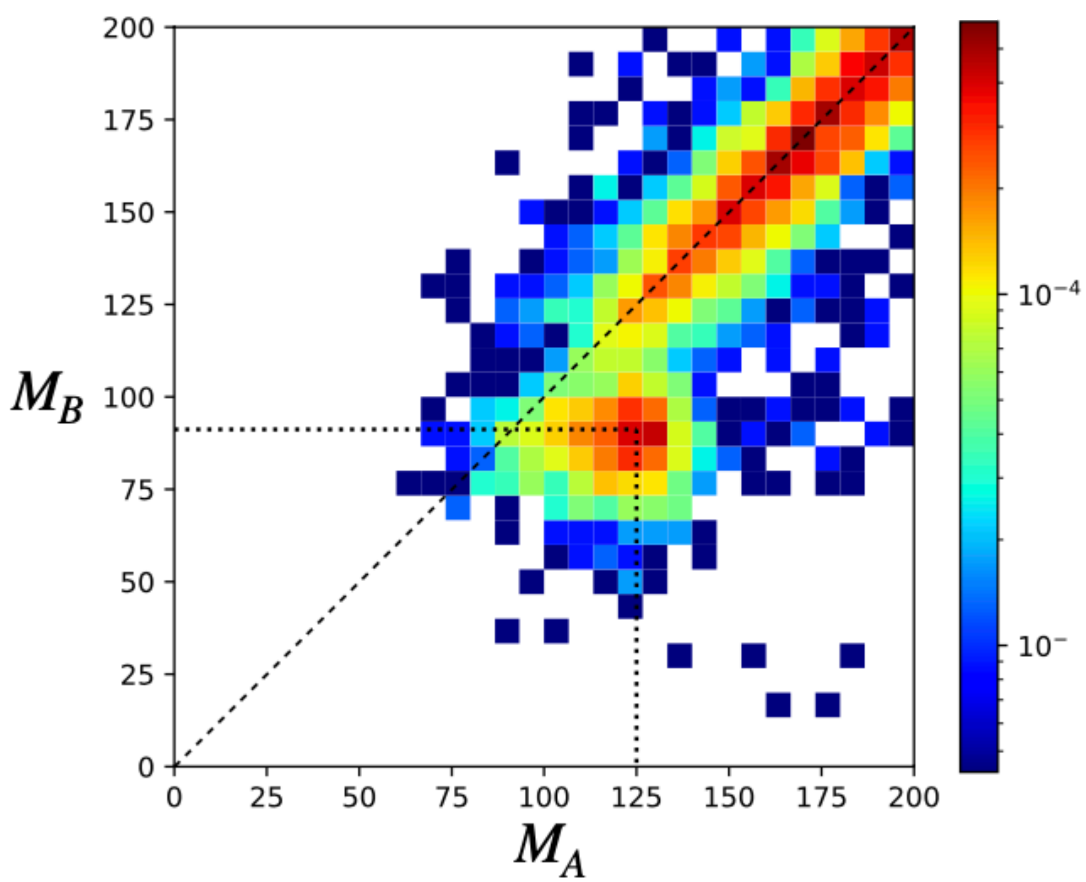
(As we give a priority to hardest jets,
effect of hard ISR is emerging for hard scale,
here $2m_{\tilde{o}} = 1.2\text{TeV}$)

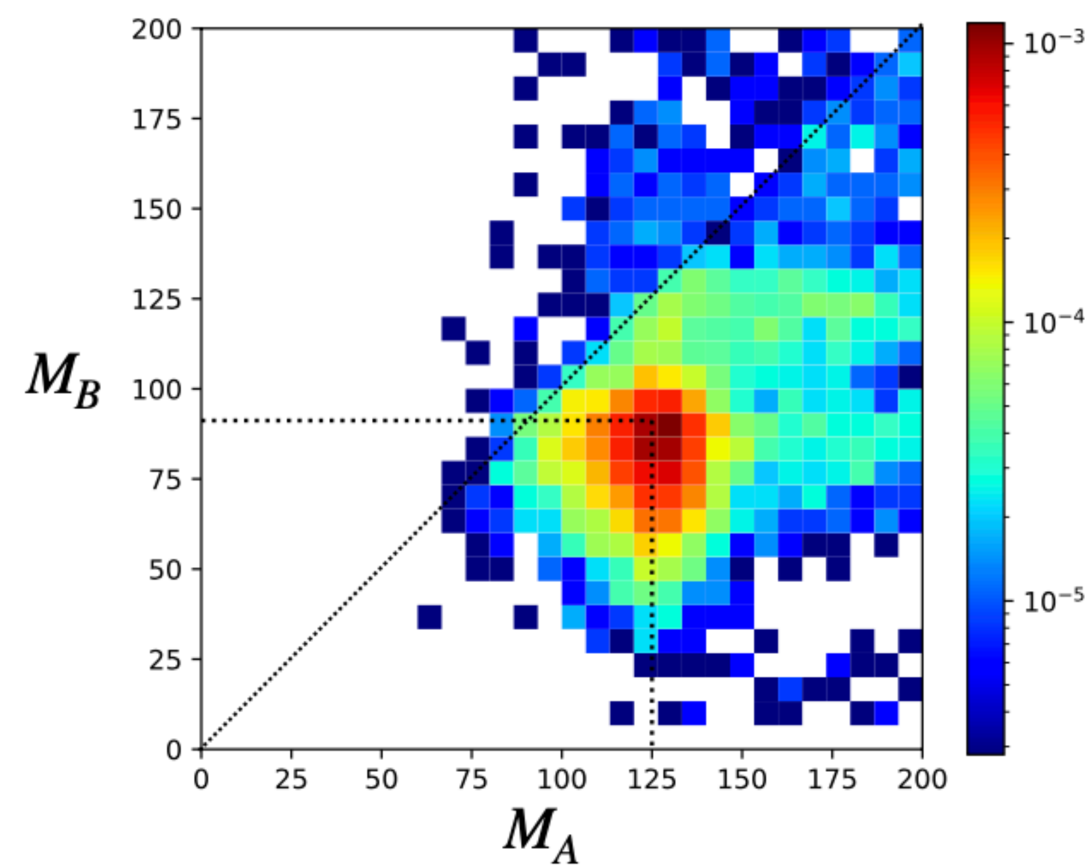
Effect of additional constraints

$$H = \left(P_1^2 - P_2^2\right)^2 \rightarrow H + \lambda\left(P_1^2 + P_2^2\right)$$

- For different mother particle cases: $pp \rightarrow HZ$

$$H = \left(P_1^2 - P_2^2\right)^2 \qquad\qquad H \rightarrow H + \lambda\left(P_1^2 + P_2^2\right)$$





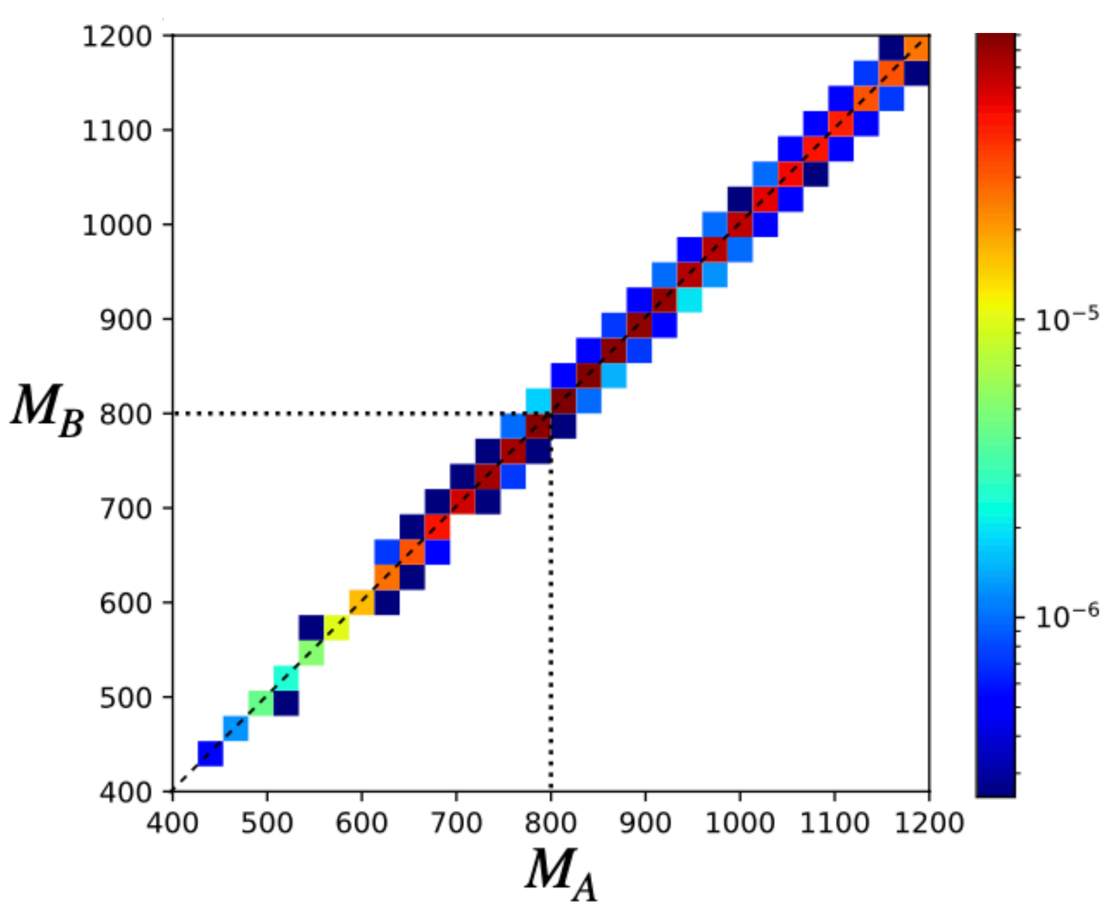
Effect of additional constraints

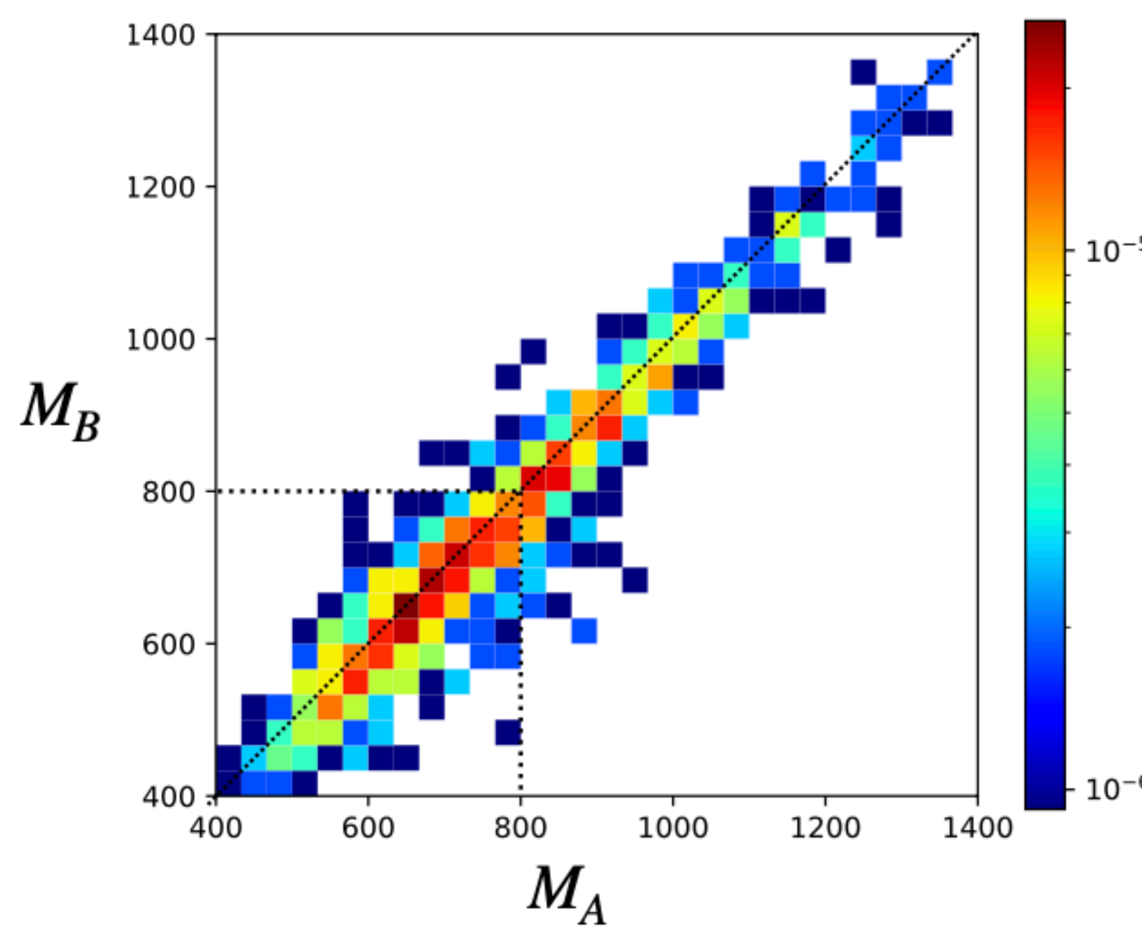
$$H = \left(P_1^2 - P_2^2\right)^2 \to H + \lambda\left(P_1^2 + P_2^2\right)$$

- For smearing effects : $pp \to \tilde{o}\tilde{o} \to t\bar{t}t\bar{t}$

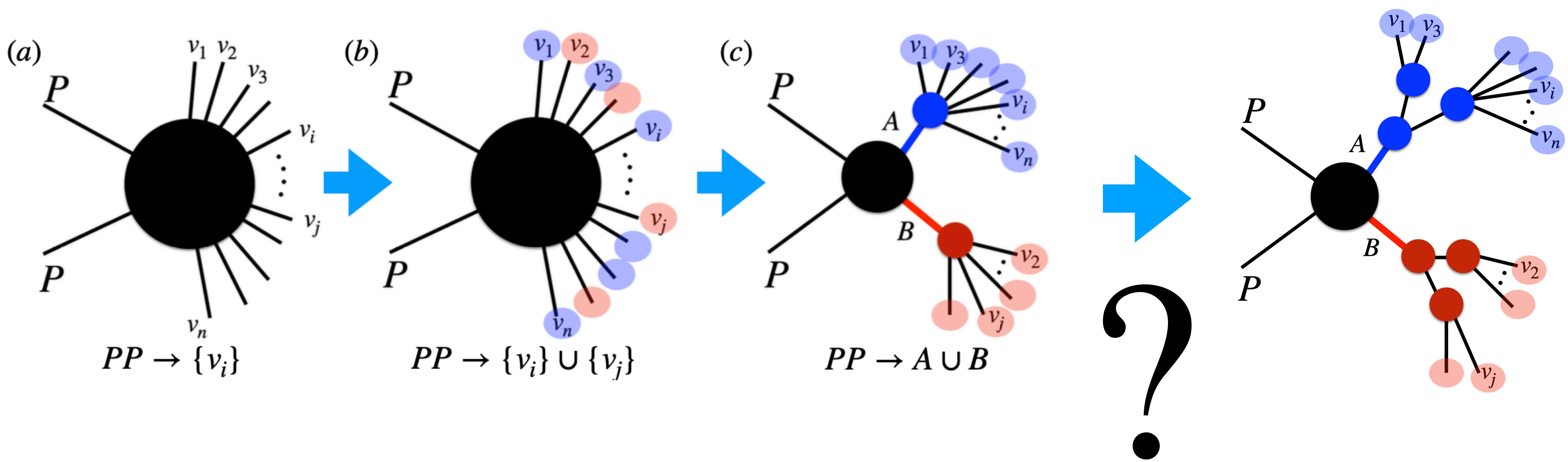
$$H = \left(P_1^2 - P_2^2\right)^2$$

$$H \to H + \lambda\left(P_1^2 + P_2^2\right)$$





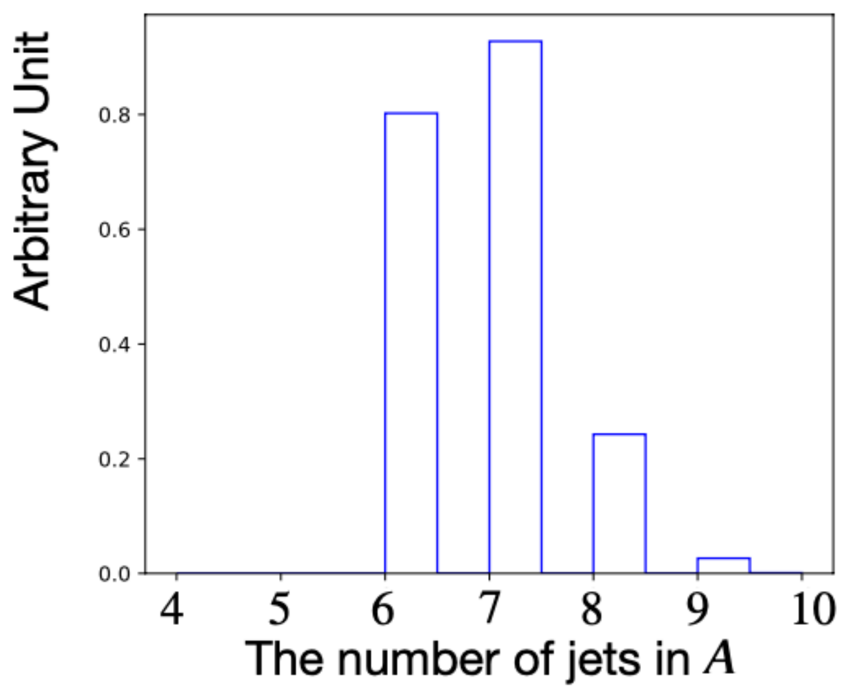
Sequential algorithm

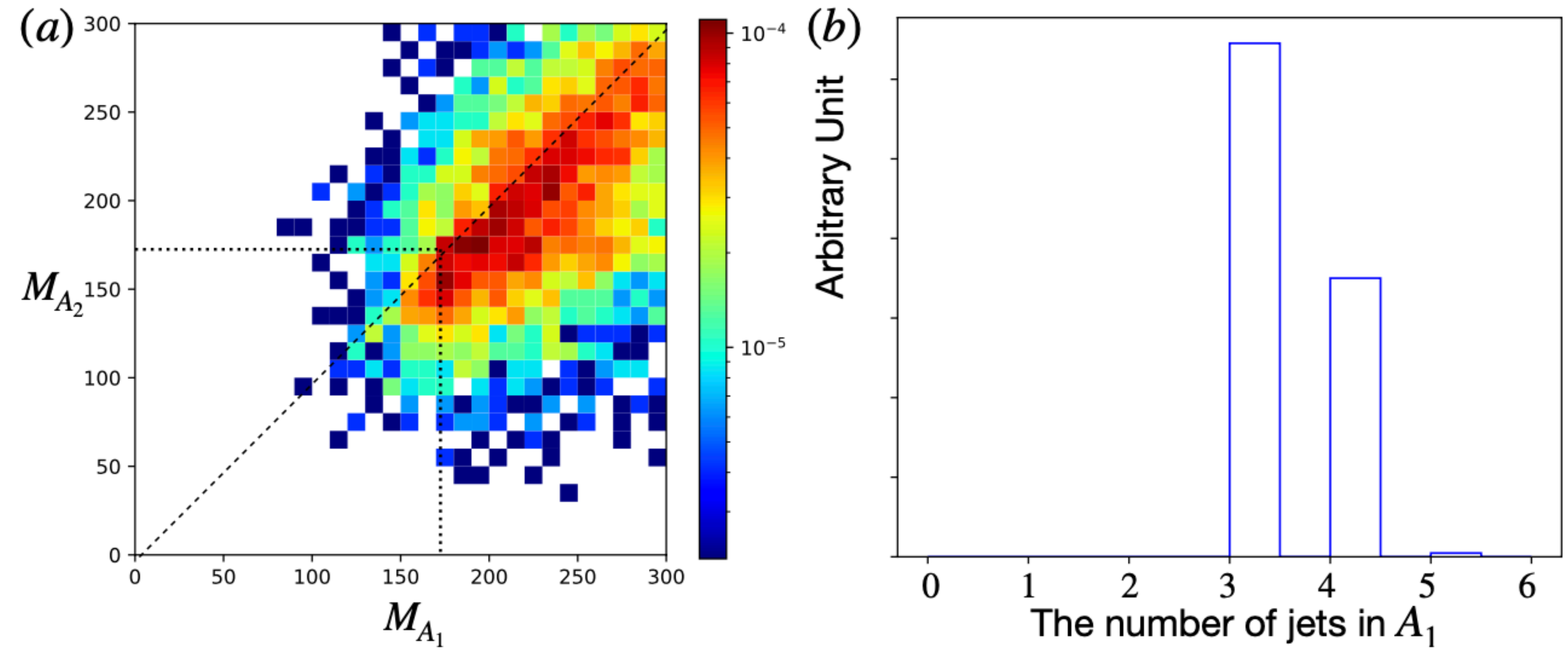


$$H_{\text{QUBO}}^{(A)} = \sum_{ij=1}^{\ell} J'^{\alpha}_{ij} s^{\alpha}_i s^{\alpha}_j + \sum_{i=1}^{\ell} h'^{\alpha}_i s^{\alpha}_i,$$

$$H_{\text{QUBO}}^{(B)} = \sum_{ij=1}^{m} J'^{\beta}_{ij} s^{\beta}_i s^{\beta}_j + \sum_{i=1}^{m} h'^{\beta}_i s^{\beta}_i,$$

- For 12 hard-jets production, it would be worthy if we can check whether this is four-tops events or not !





$pp \to A, B$

$A \to A_1, A_2$

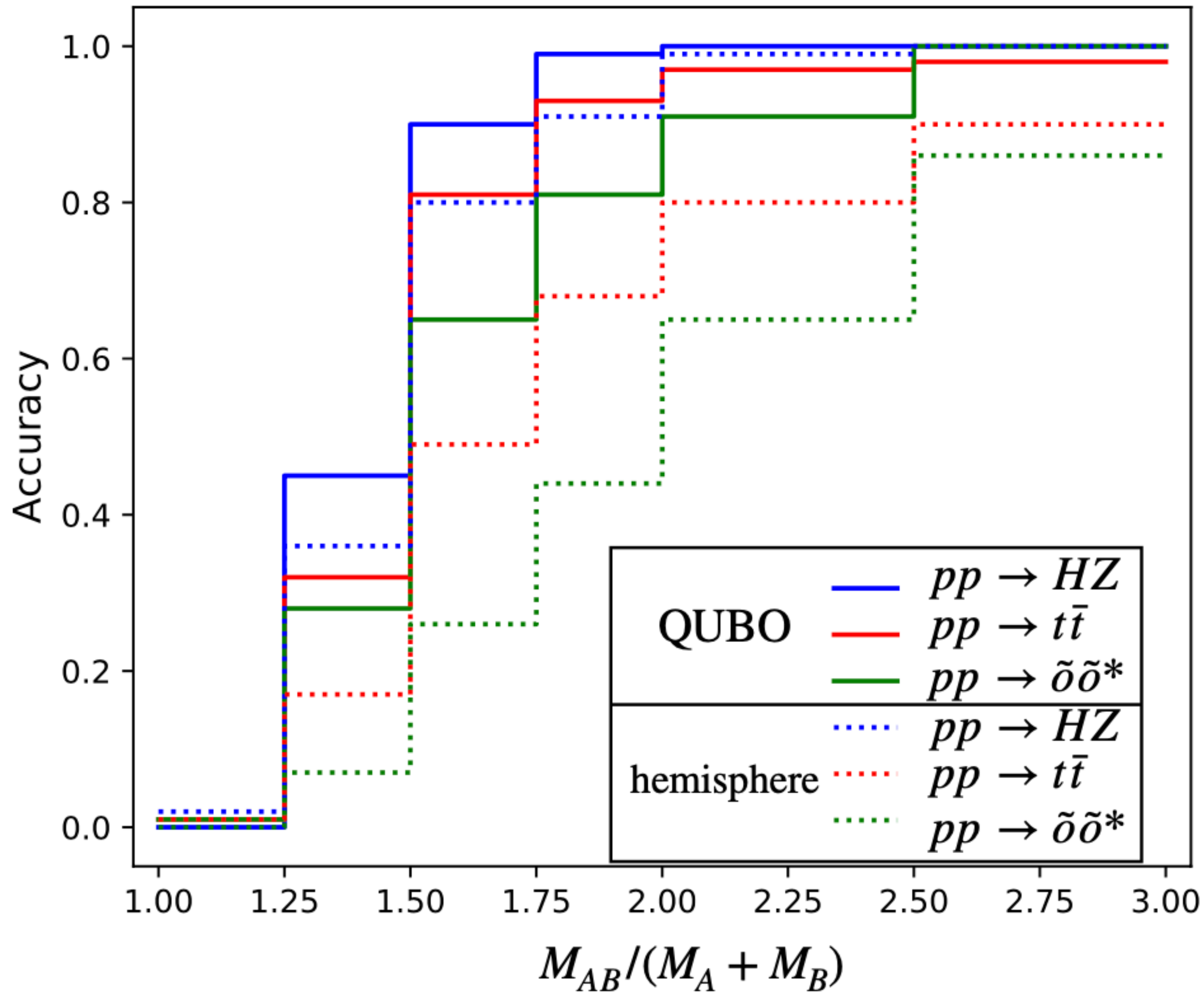
- We can "guess" that $A_i = t(\bar{t})$ as their **mass** and **number of children** are identical to the case of a top-quark.

Bench mark?

- There are not many studies on identifying event-topology. (as far as I have searched... if I missed, plz let me know)
- Hemisphere method: **seed-based** algorithm (**our algorithm is seedless** one)

Process		$pp \to t\bar{t}$ Eq. (7a)	$pp \to HZ$ Eq. (7b)	$pp \to \tilde{o}\tilde{o}^*$ Eq. (7c)
Algorithm	QUBO	47.3%	89.5%	15.1%
	Hemisphere	33.6%	86.2%	5.84%

(Parton-level analysis with detector cuts)



- Performance of an algorithm based on "**seed**" becomes weak when particles are **not boosted enough to develop structures.**
- Lorentz boost factor $\gamma_A = \dfrac{E_A}{M_A} = \dfrac{M_{AB}}{2M_A}$ (for A=B case)

Current limits for QA

- Number of couplers is limited
  - **spin-chain** method to encode a hamiltonian (connections)

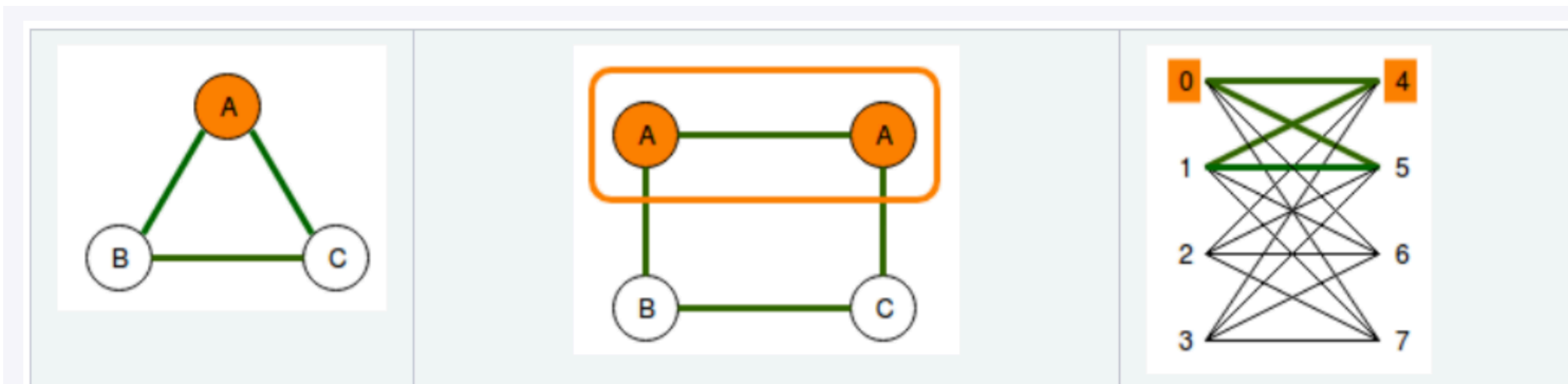
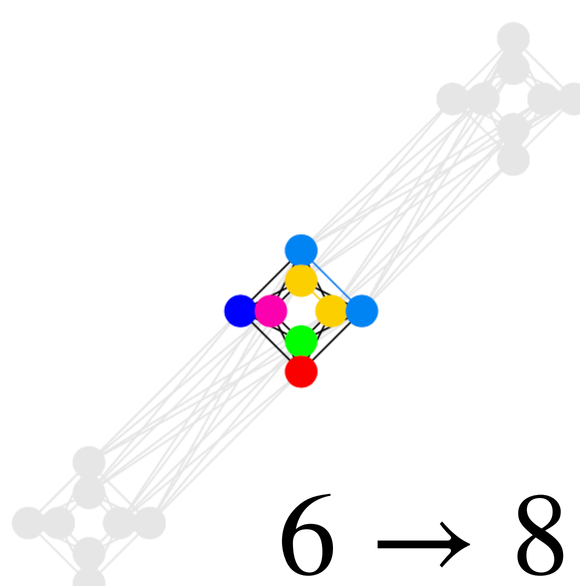
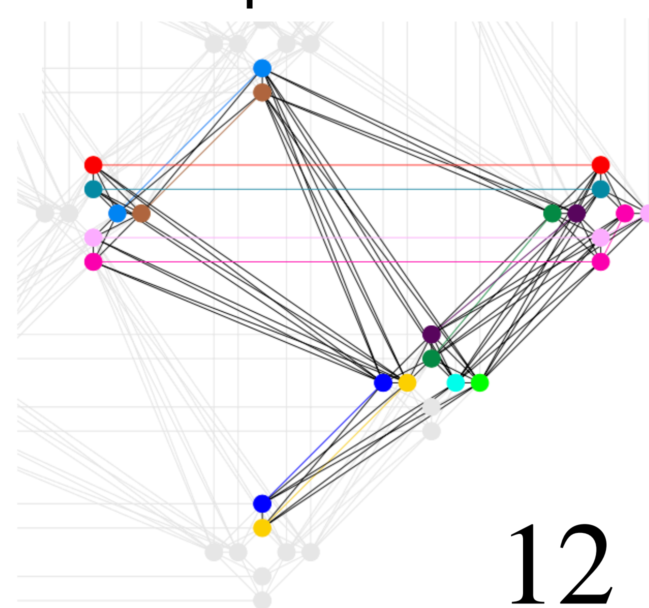


Fig 1: Abstract graph | Fig 2: Intermediate representation of the graph | Fig 3: Embed graph onto QPU

- Number of required qubits for our problem



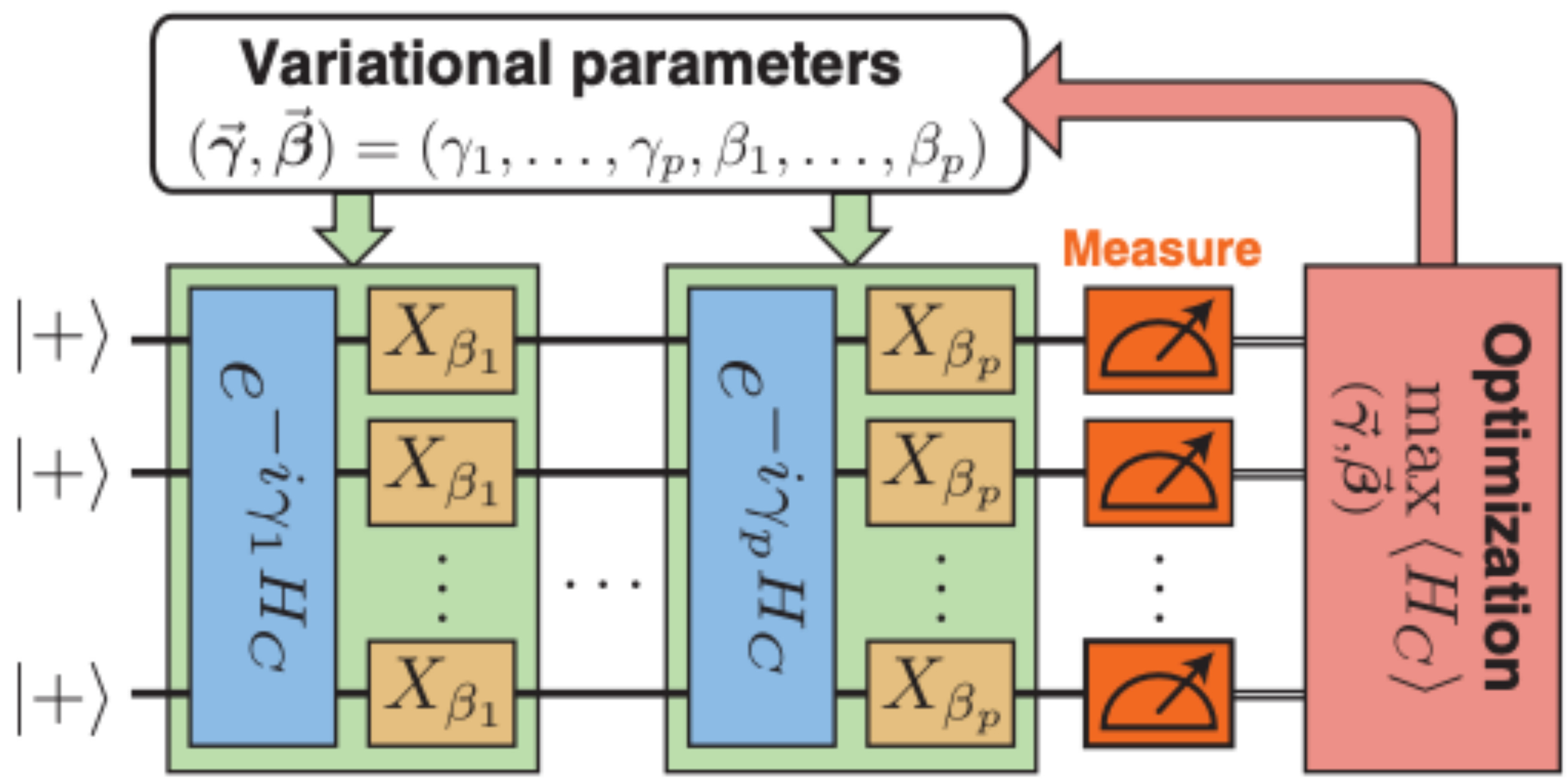
$6 \rightarrow 8$



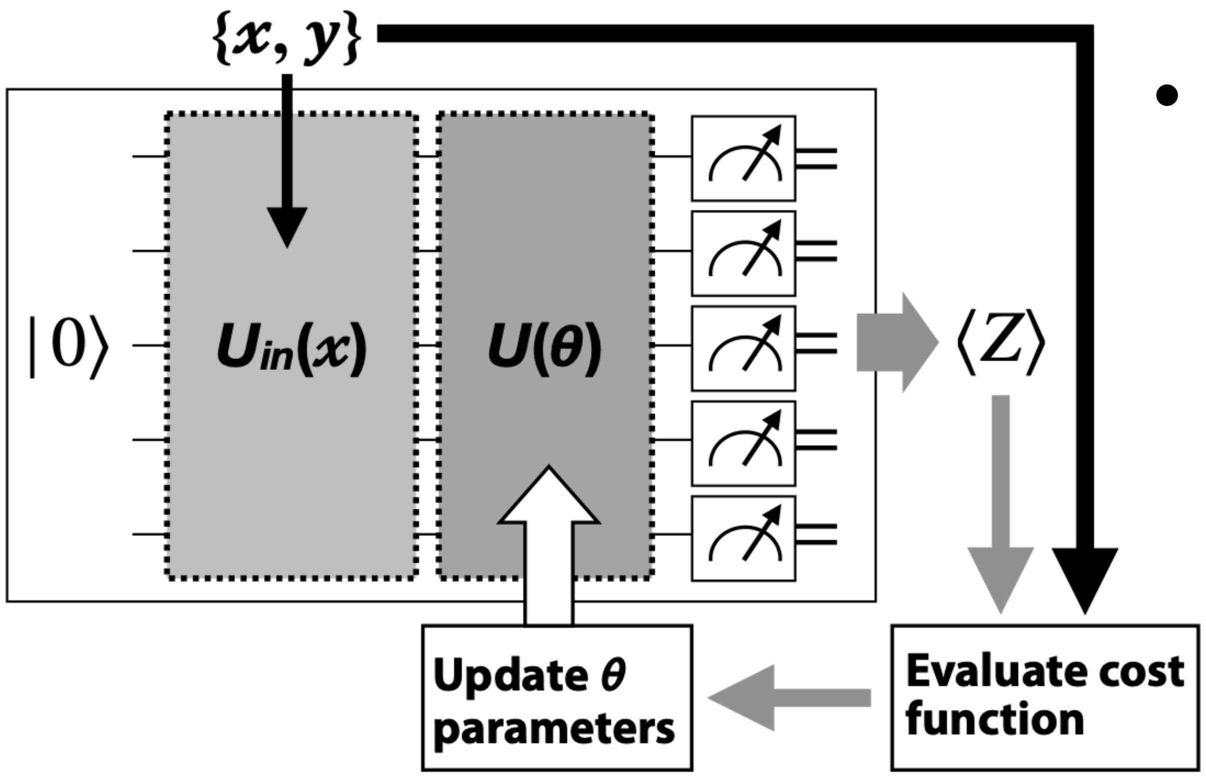
$12 \rightarrow 24$

Conclusion@QC

- I presented a **simple quantum annealing method for clustering** reconstructed particles.
- Gate-based QC can be used via a variational algorithm.
- I am very interested in this new possibility (Now ongoing)



- Hybrid Quantum Classifier: Variational Quantum Approaches

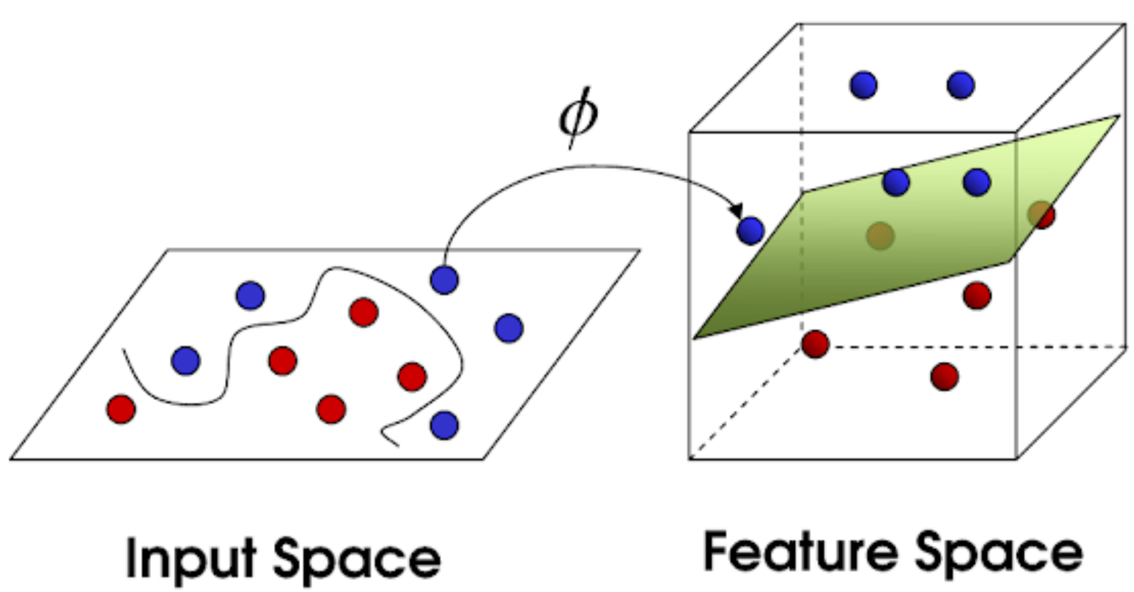


- Supervised Machine Learning with a label y and expectation $\langle Z \rangle$ from QC.

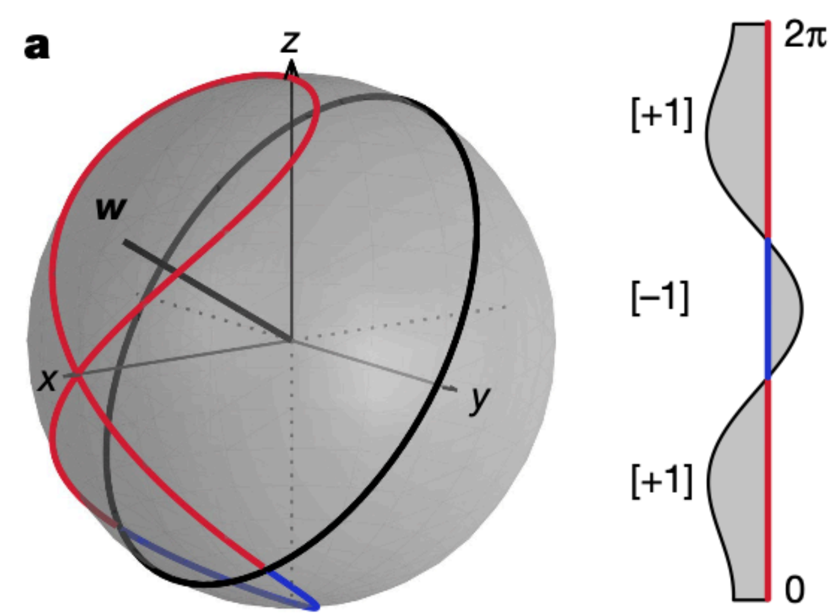
  Update learnable parameters θ by a classical computer

- Mapping input data **to an exponentially large Quantum Hilbert Space**.

classical ML Kernel Method



Quantum kernel function



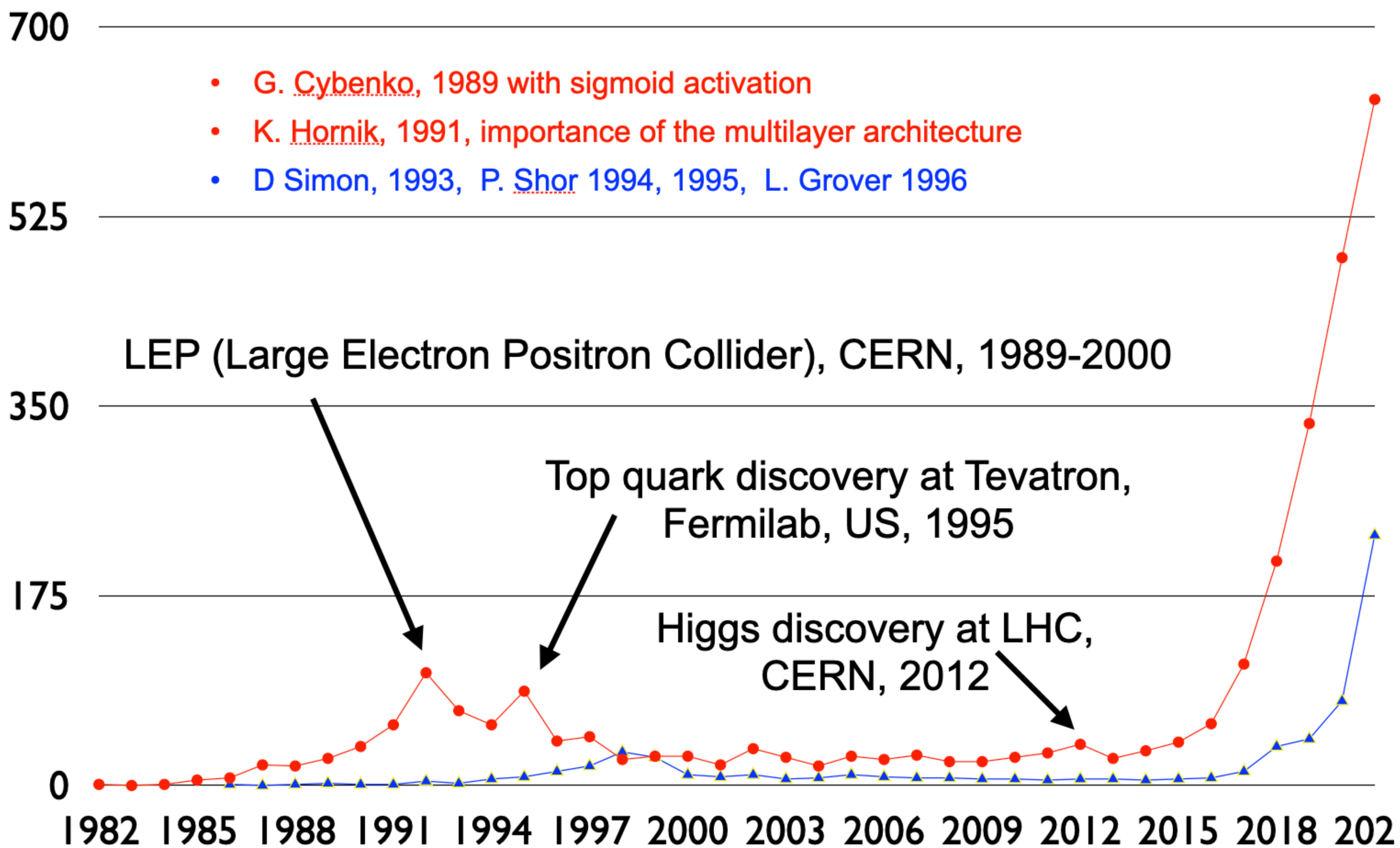
Conclusion

Credit to KC. Kong

Data is obtained via **InspireHEP**

● The number of papers (in high energy physics) that has a keyword "Machine Learning", "Deep Learning", "Artificial Intelligence" or "Neural Networks" in their title.

▲ The number of papers that has a keyword "Quantum Computer", "Quantum Computing","Quantum Annealing" or "Quantum Machine Learning" in their title.



- As a **desperate** seeker, we have tried to take advantages of new computing methods, ML, QC, QML.
- In this talk, I presented a **bottom-up** collider algorithm to identify a new physics from a signal (if we can have)
- There could be many examples to demonstrate **Quantum Advantage** in the field of HEP.
- **Stay tuned**...