Quantum Computing for High Energy Collider

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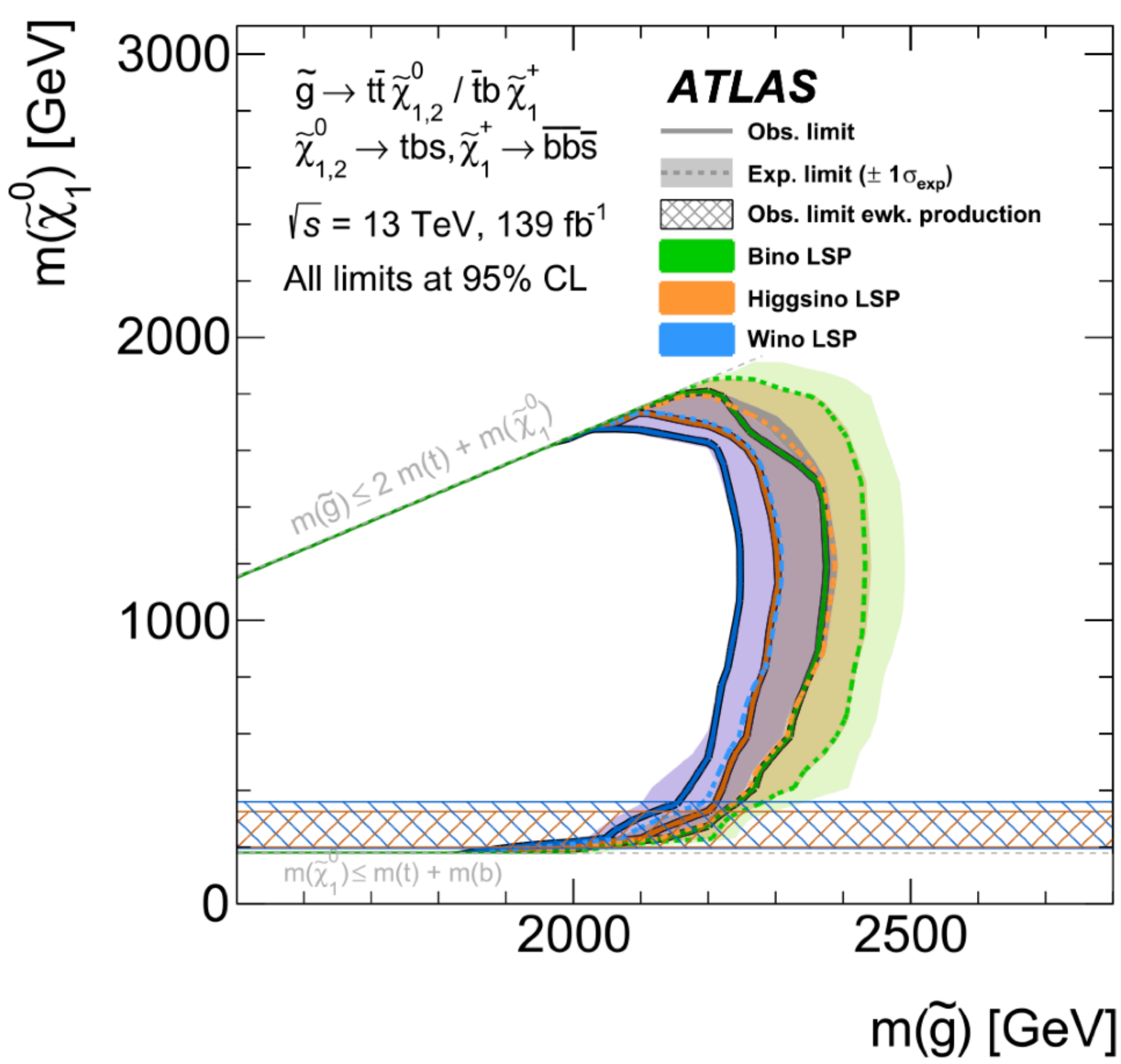
based on arXiv:2111.07806 with Minho Kim, Pyungwon Ko, Jae-hyeon Park

and arXiv:HOPE.SOON by MP, Ahmed, +

IBS-PNU Workshop 2022

Thanks to the LHC

- The old king is **dead**!!?



new possibilities

New king?

Hunt for new physics afterwards
"**Bottom-up approach**"

1. **Anomaly detection** (different from SM expectations)
   - Need to have precise tools (**importance of Monte Carlo Tools**)
   - Modern Machine Learning is focusing on!

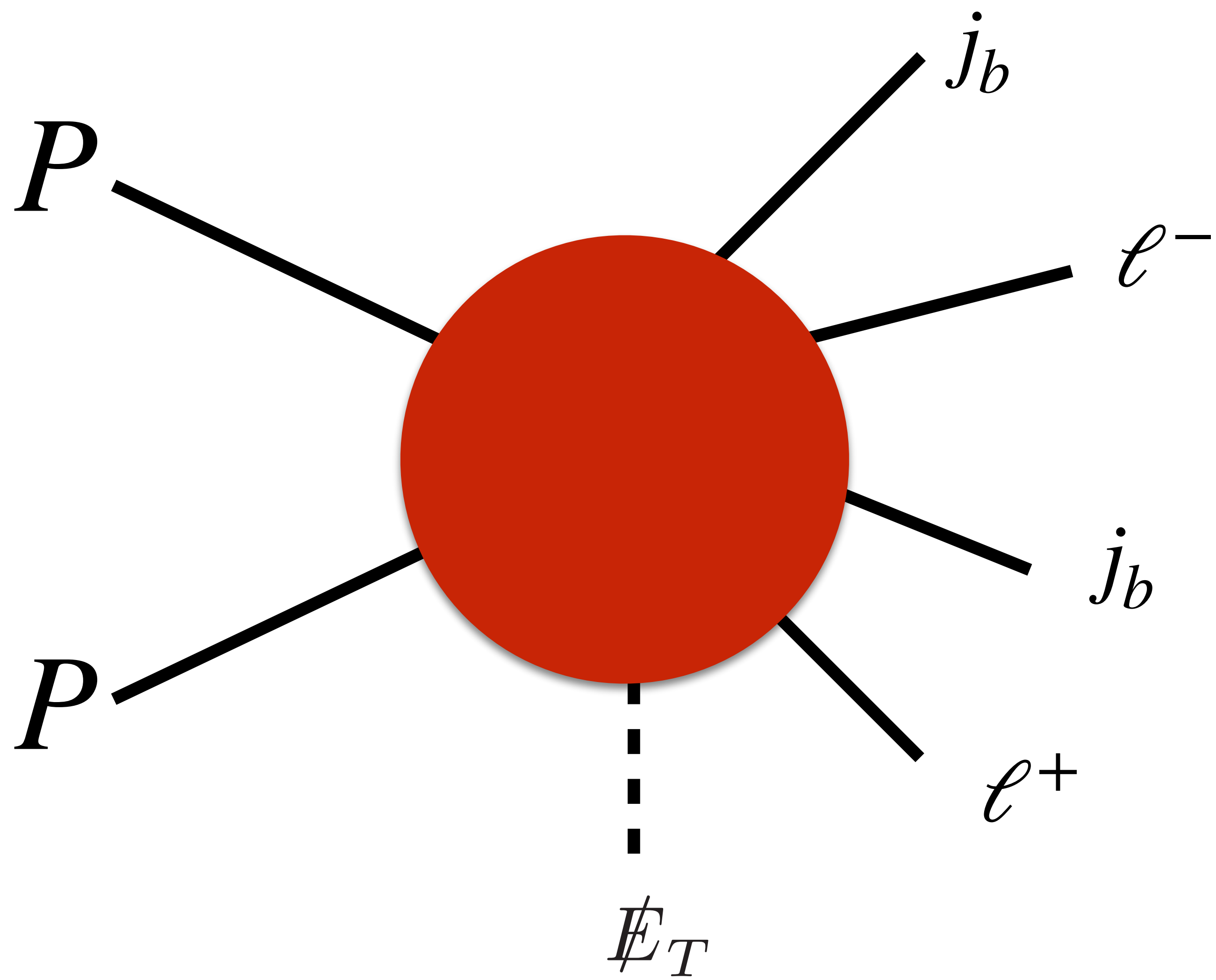
2. Try to interpret a new signal with **various** model assumptions or **Model-independent way**

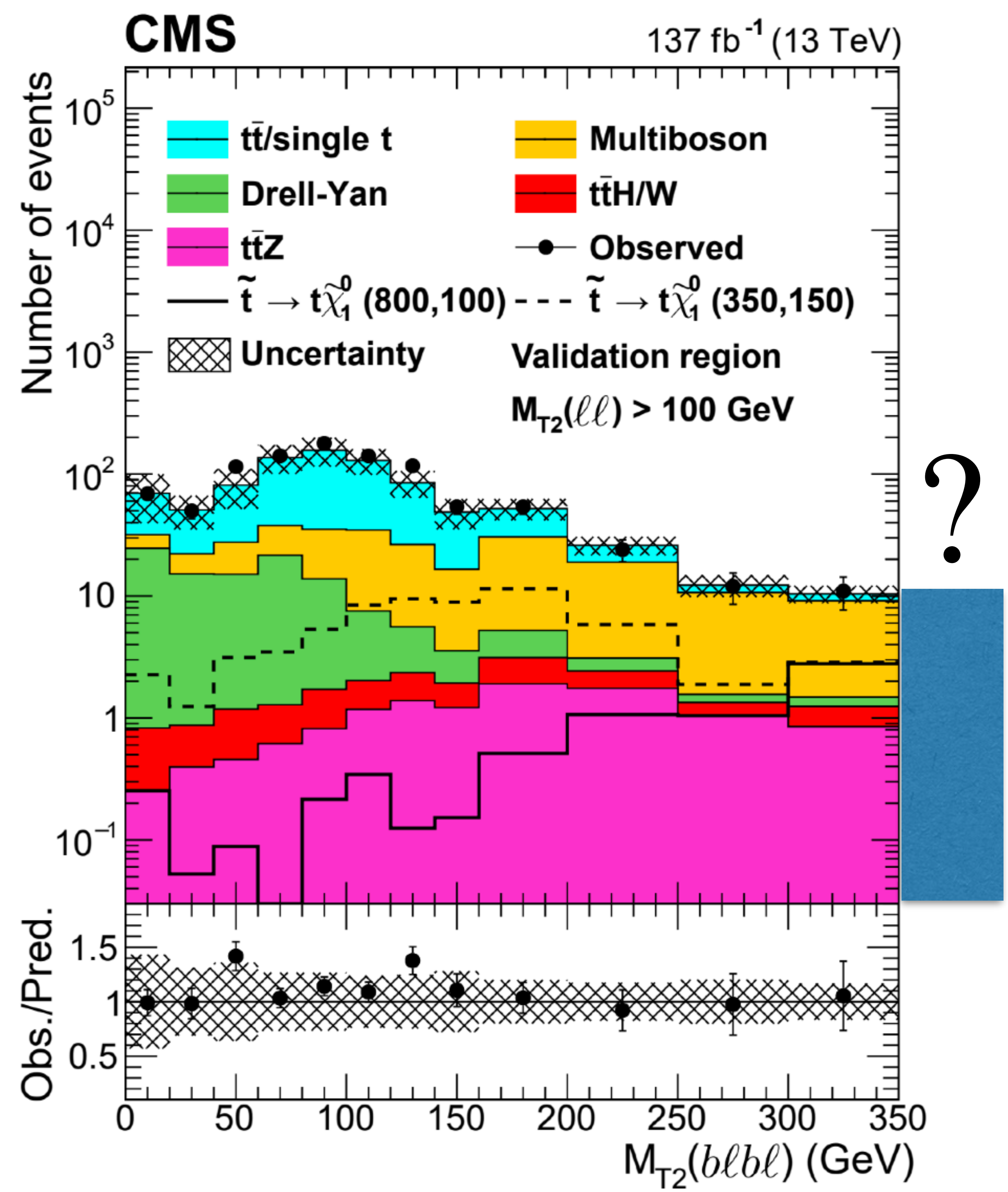
   1) Find out a relevant **event-topology** (how observed particles are produced) (feynman diagram without specific spin assignment.)

   2) Determine parameters (spin, mass) with various methods
   Current (mass, spin) measurement methods are based on a specific event-topology.

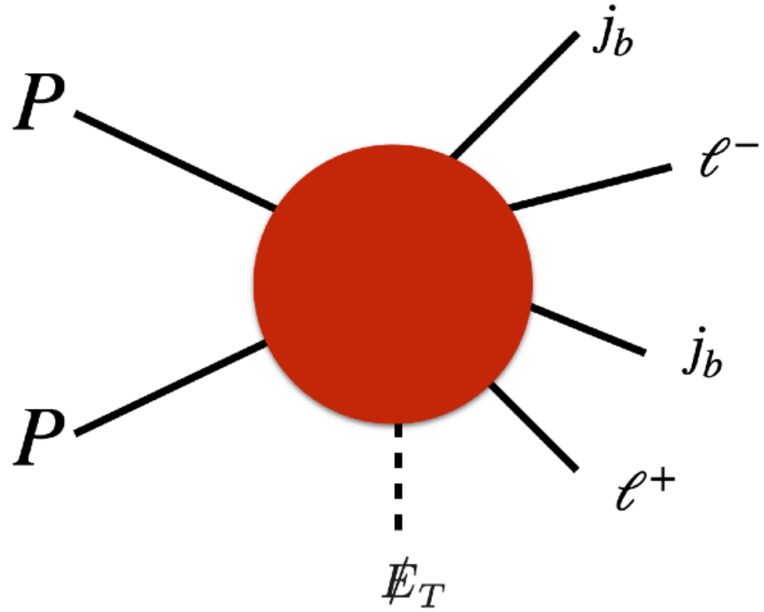
3. With "observed feynman-diagram", we can fit it to a relevant BSM model(s)

Example: anomaly





a simple kinematic variable



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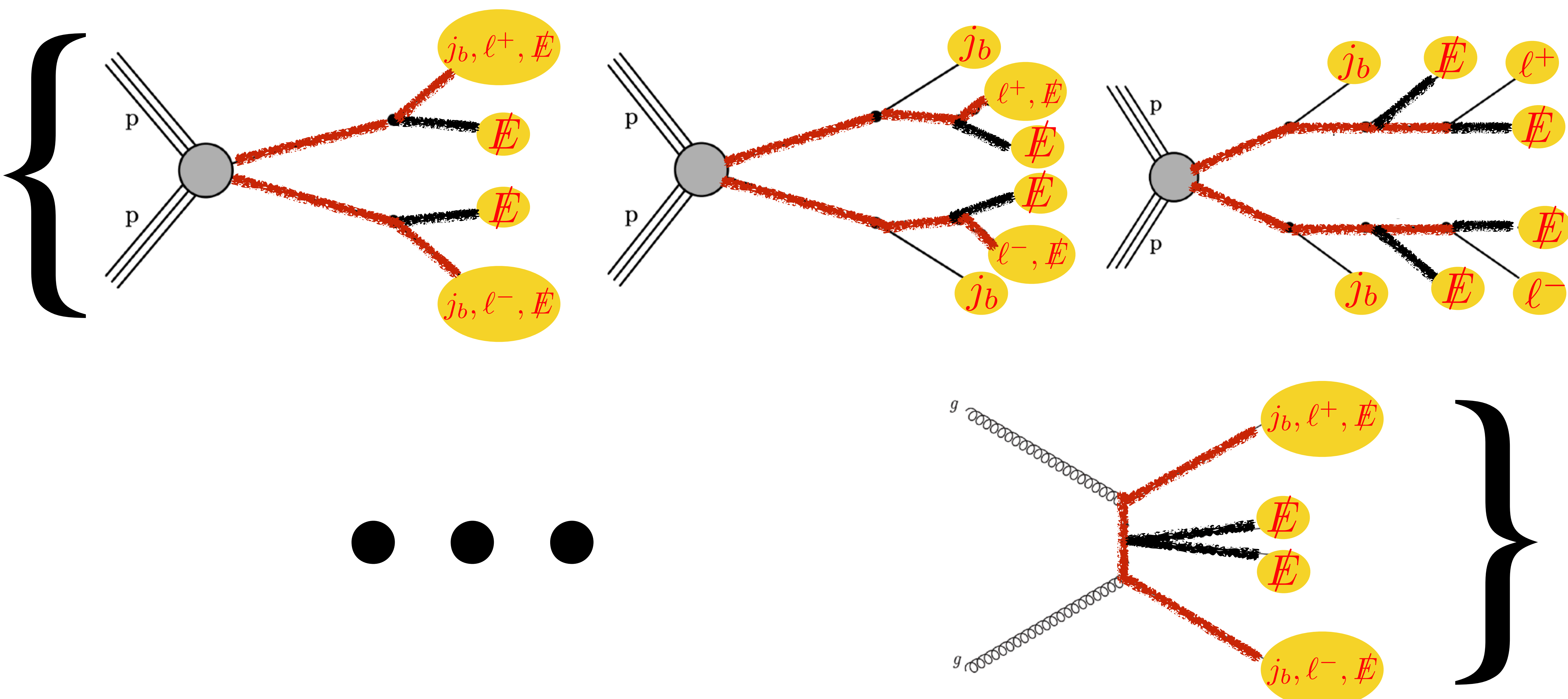
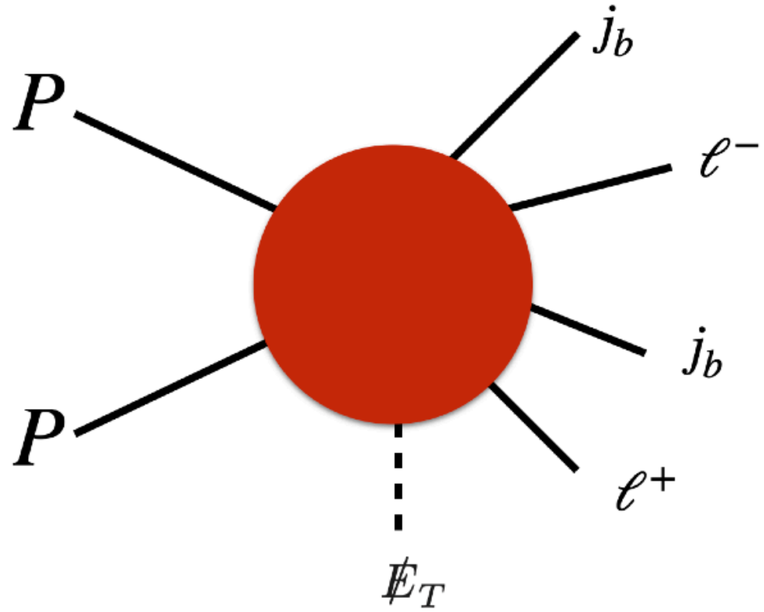
{Various event-topologies}

Red: Decaying particle

Black: stable particle





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Most of event-toplogies are based on (previously) favored models

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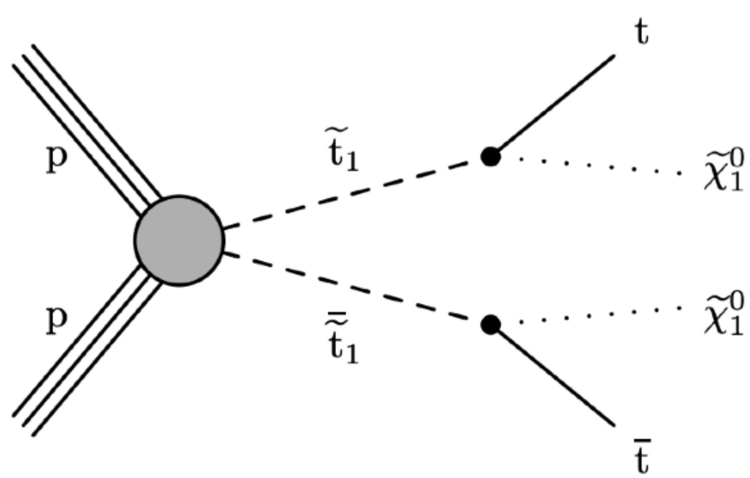

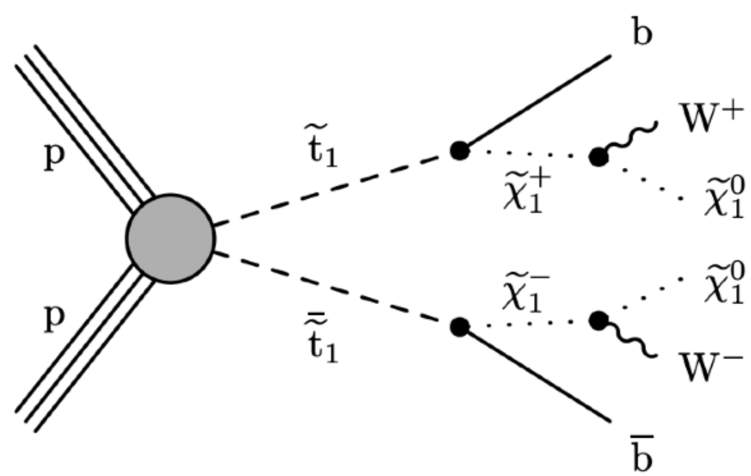

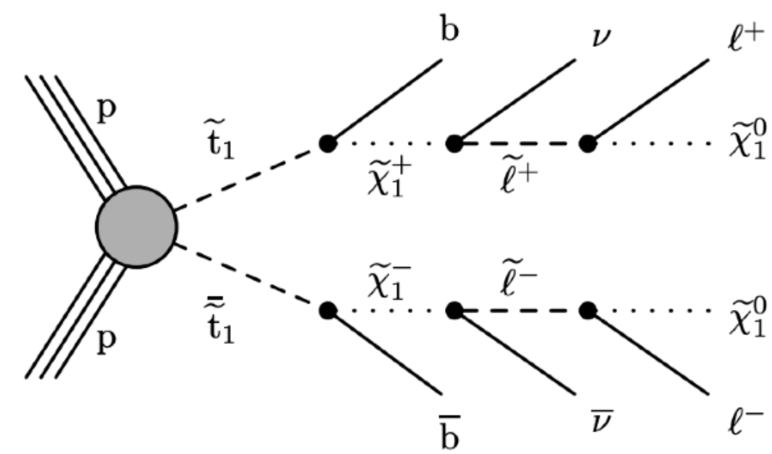

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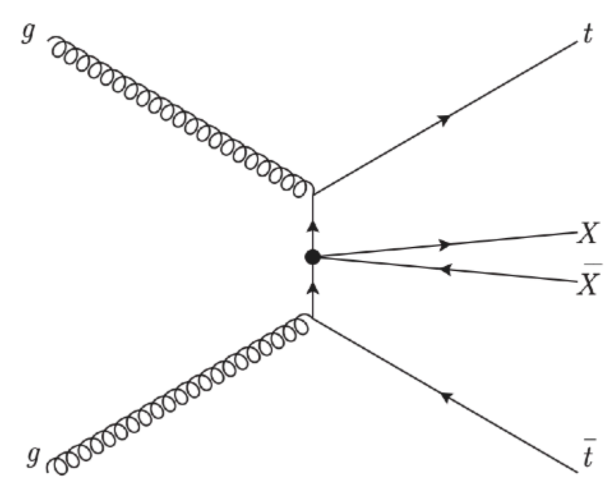

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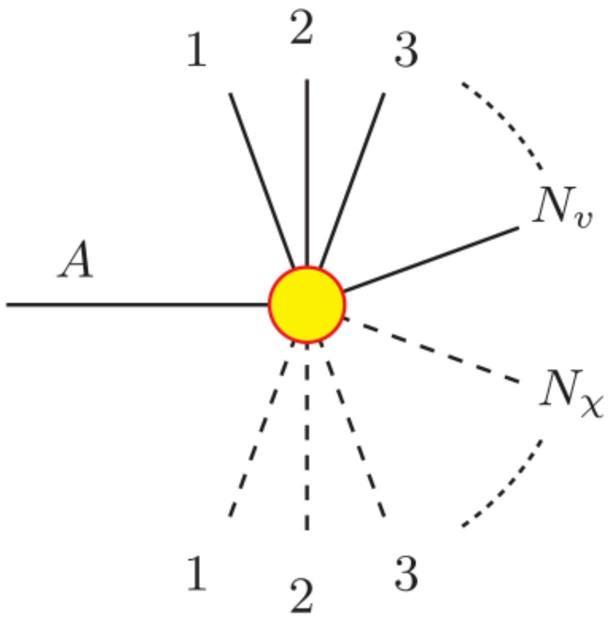
diagram from Lian-Tao Wang et.al. arxiv:1303.6638

NP-hard

- Identifying an event-topology is a "**combinatorial** problem".
  - One needs to assign observed particles into the decay of some particle.



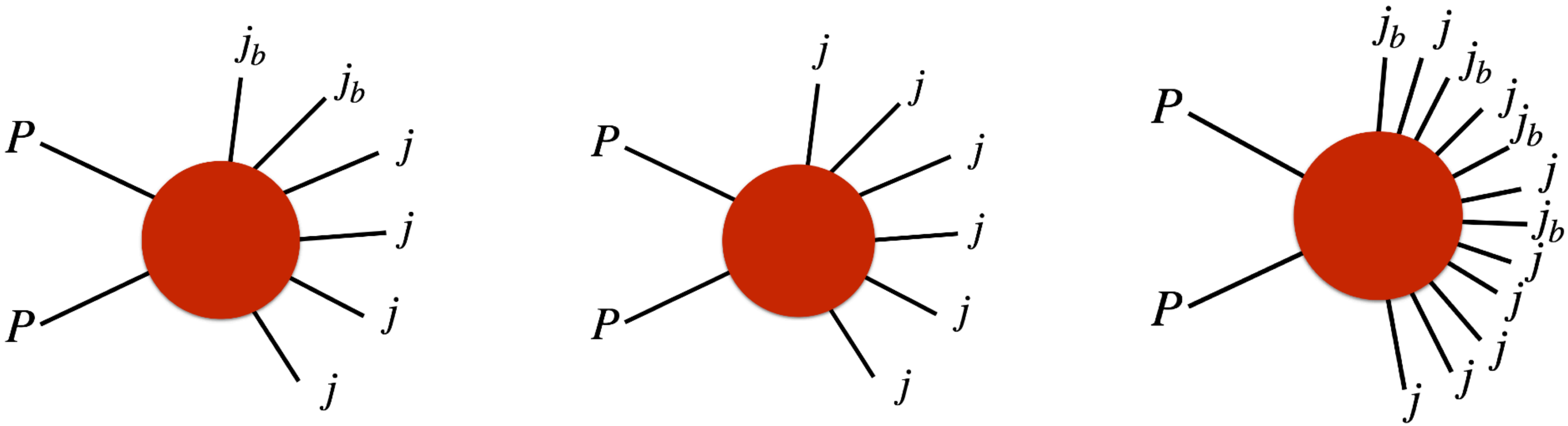
			N_χ		
N_v	1	2	3	4	5
1	1	2	4	8	16
2	2	7	20	55	142
3	4	20	78	270	860
4	8	55	270	1138	4294

• • •

even though we restricted "resonance" (A) scenario,
there are $\mathcal{O}(6000)$ event-topologies.

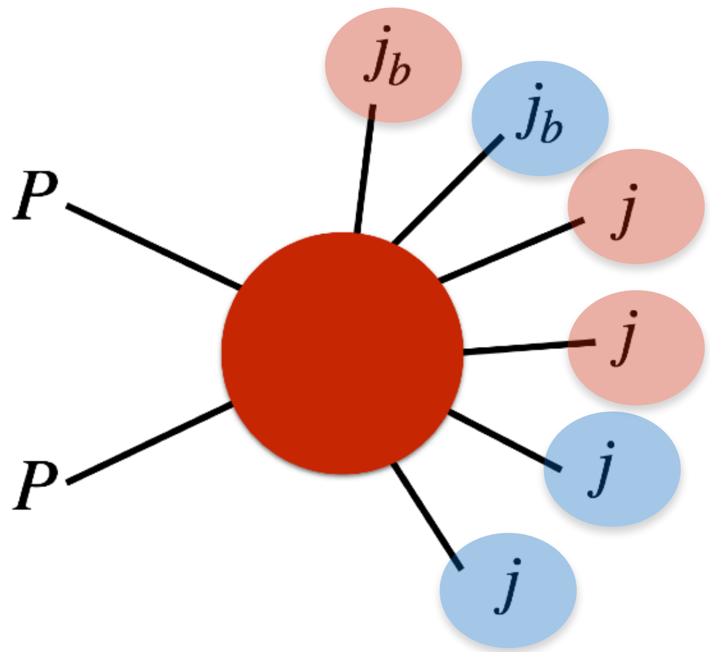
- Considering "missing energy (invisible particles)" are rather difficult due to "undetermined" number of invisible particles.
  - From now on, I will focus on reconstructible events (no MET)

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.



- Standard example of six jets

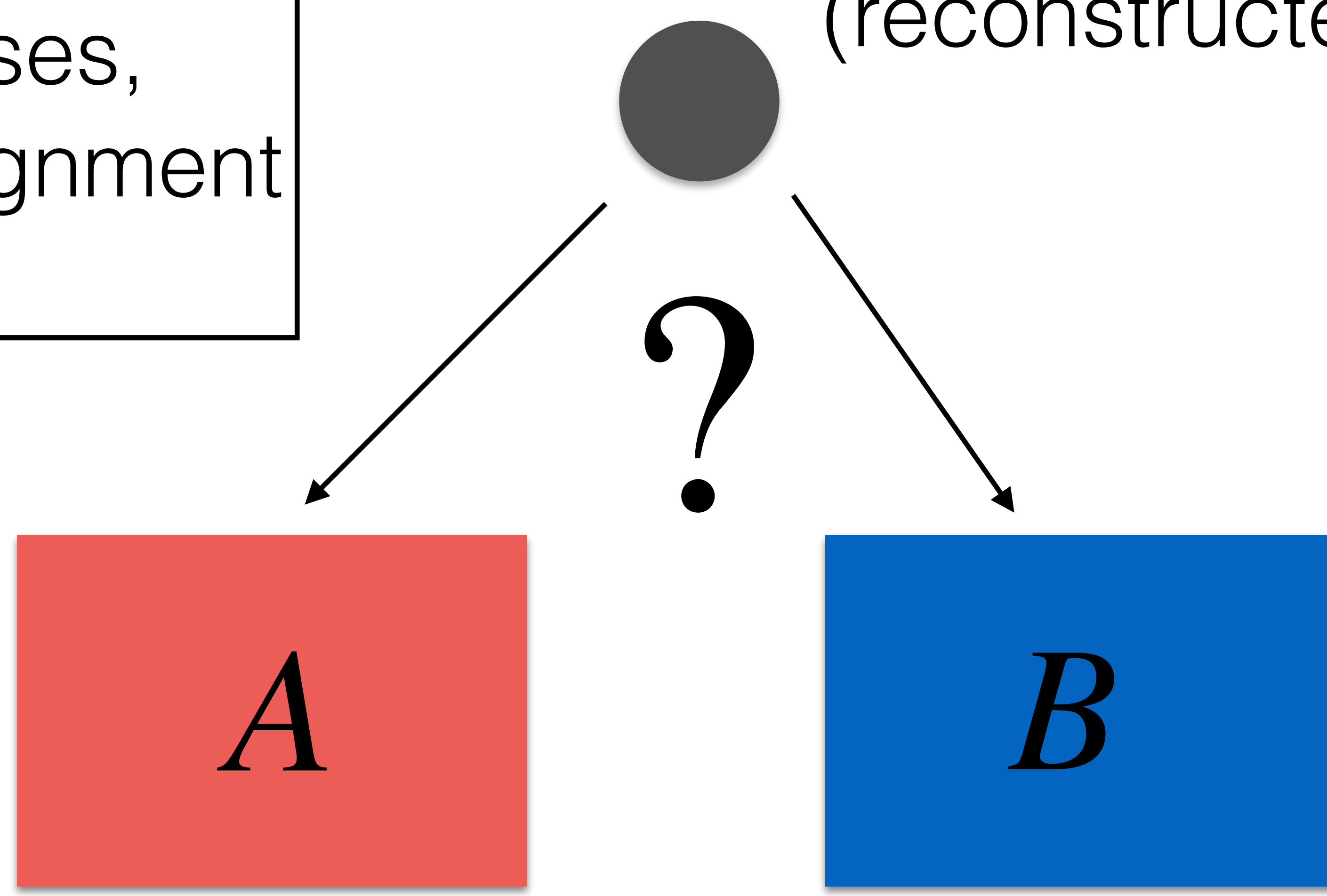
$$pp \to t\bar{t} \to \{j_b, (W \to jj)\} \cup \{j_b, (W \to jj)\}$$

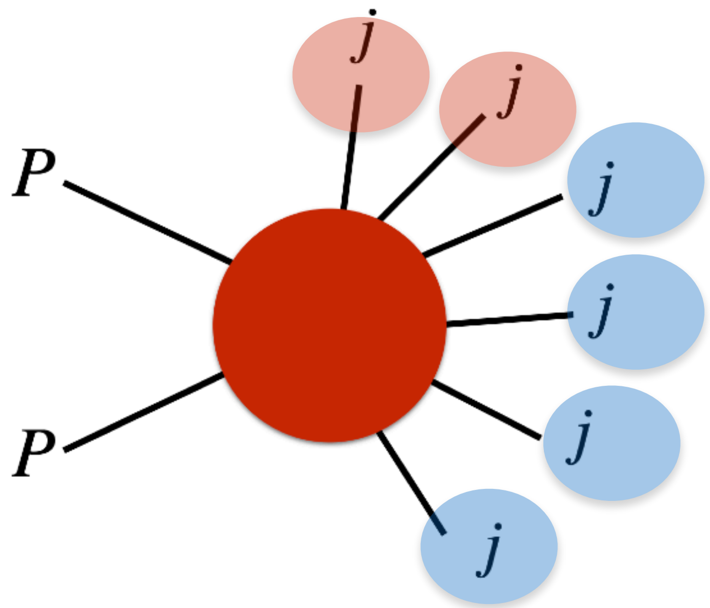
(when A and B have same mass)

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

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

(reconstructed) particle



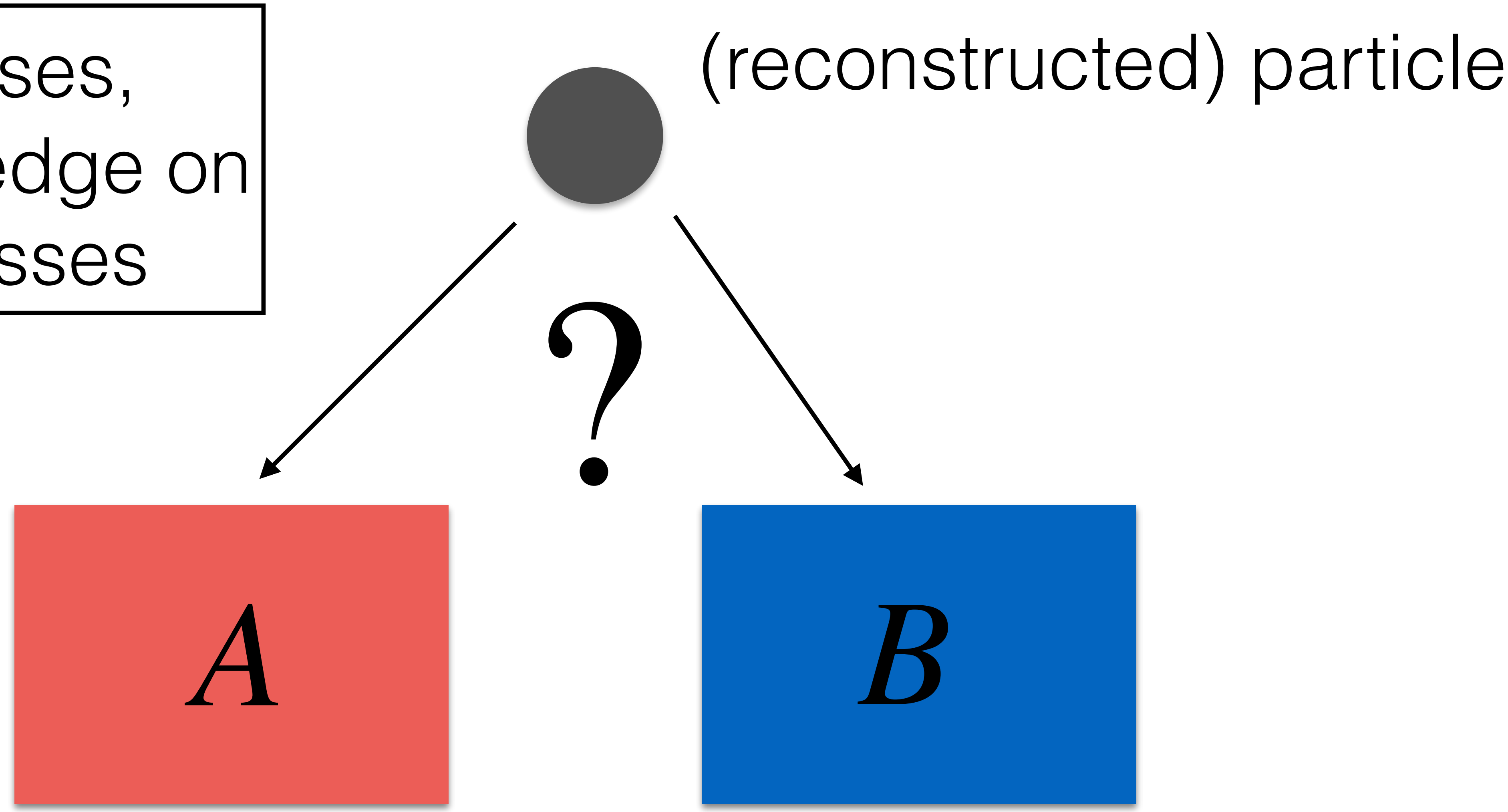


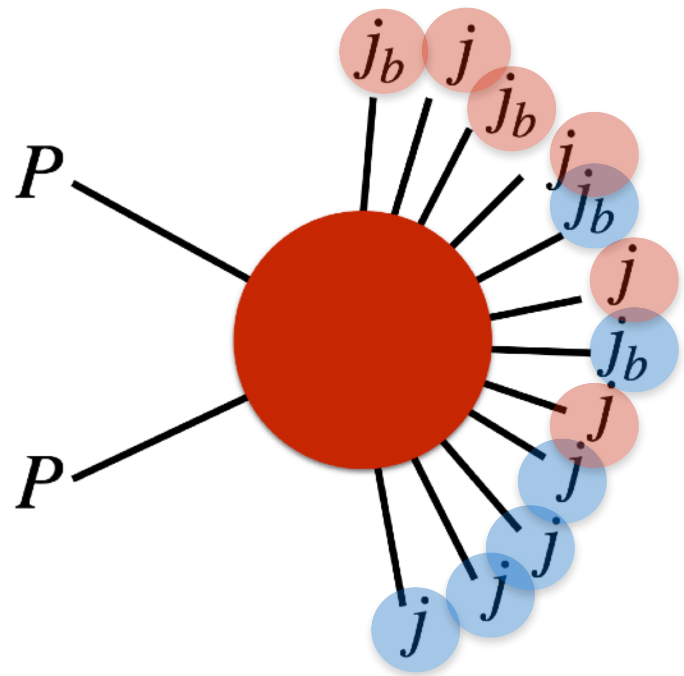
- Different mother particles

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

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

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





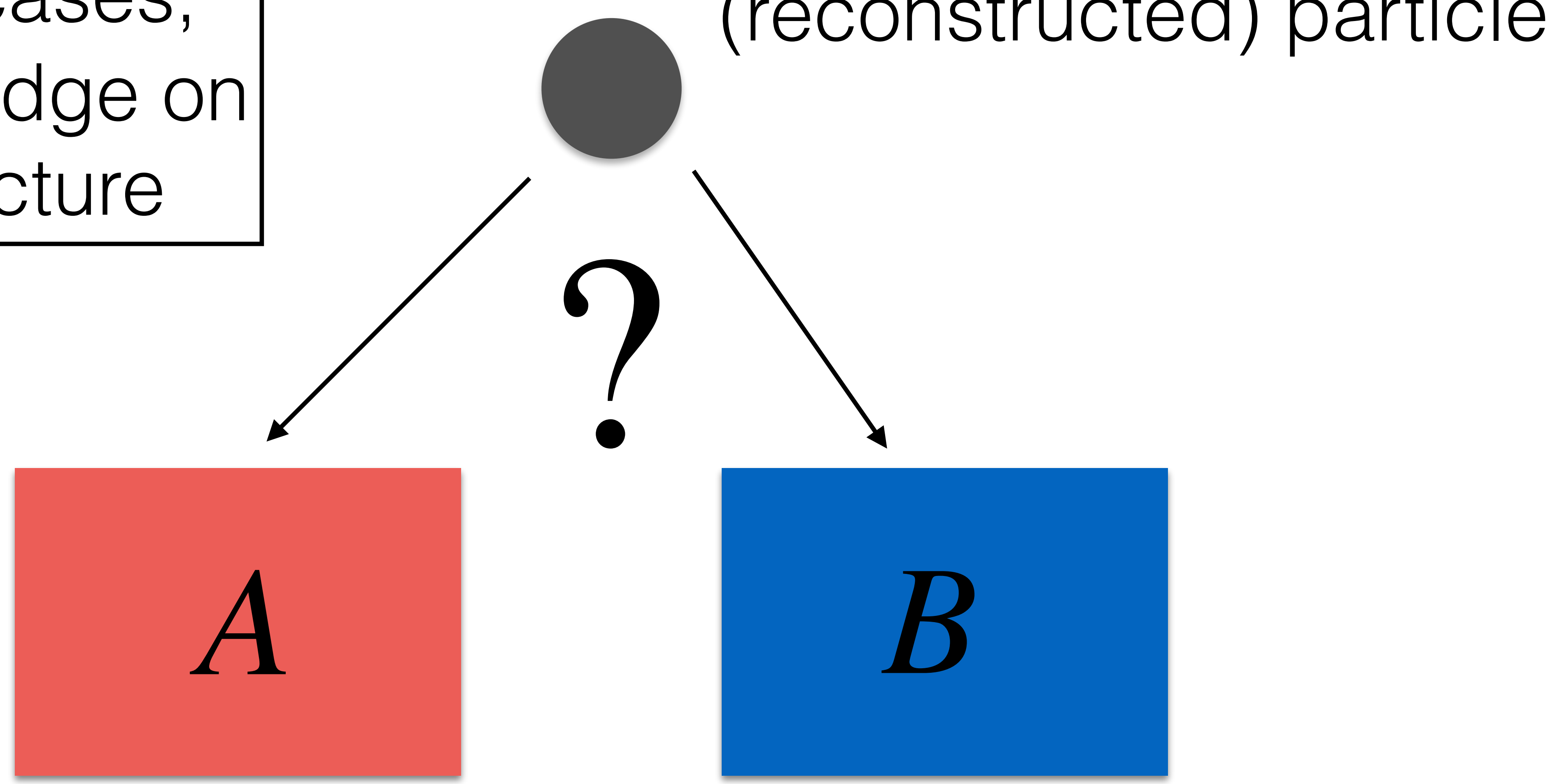
- Complicate situation (12 jets)

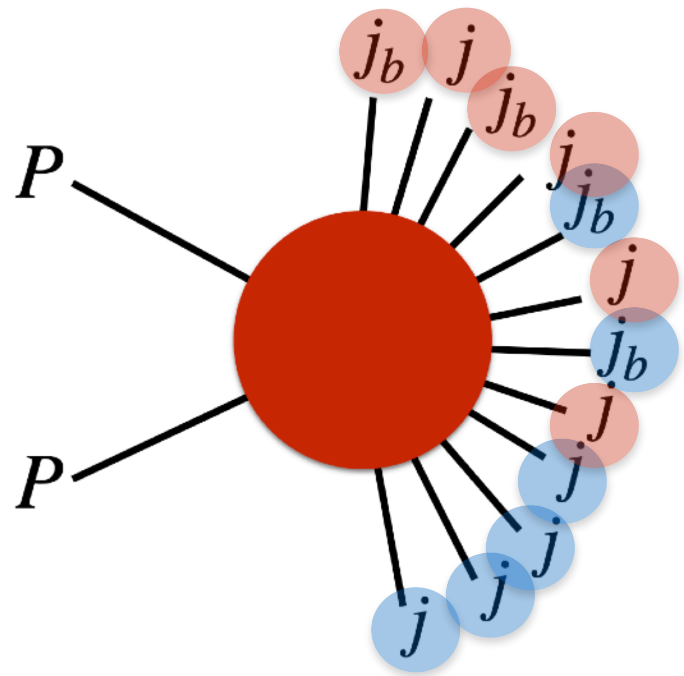
$pp \to o\tilde{o} \to \{t, \bar{t}\} \cup \{t, \bar{t}\}$

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

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

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





- Complicate situation (12 jets)

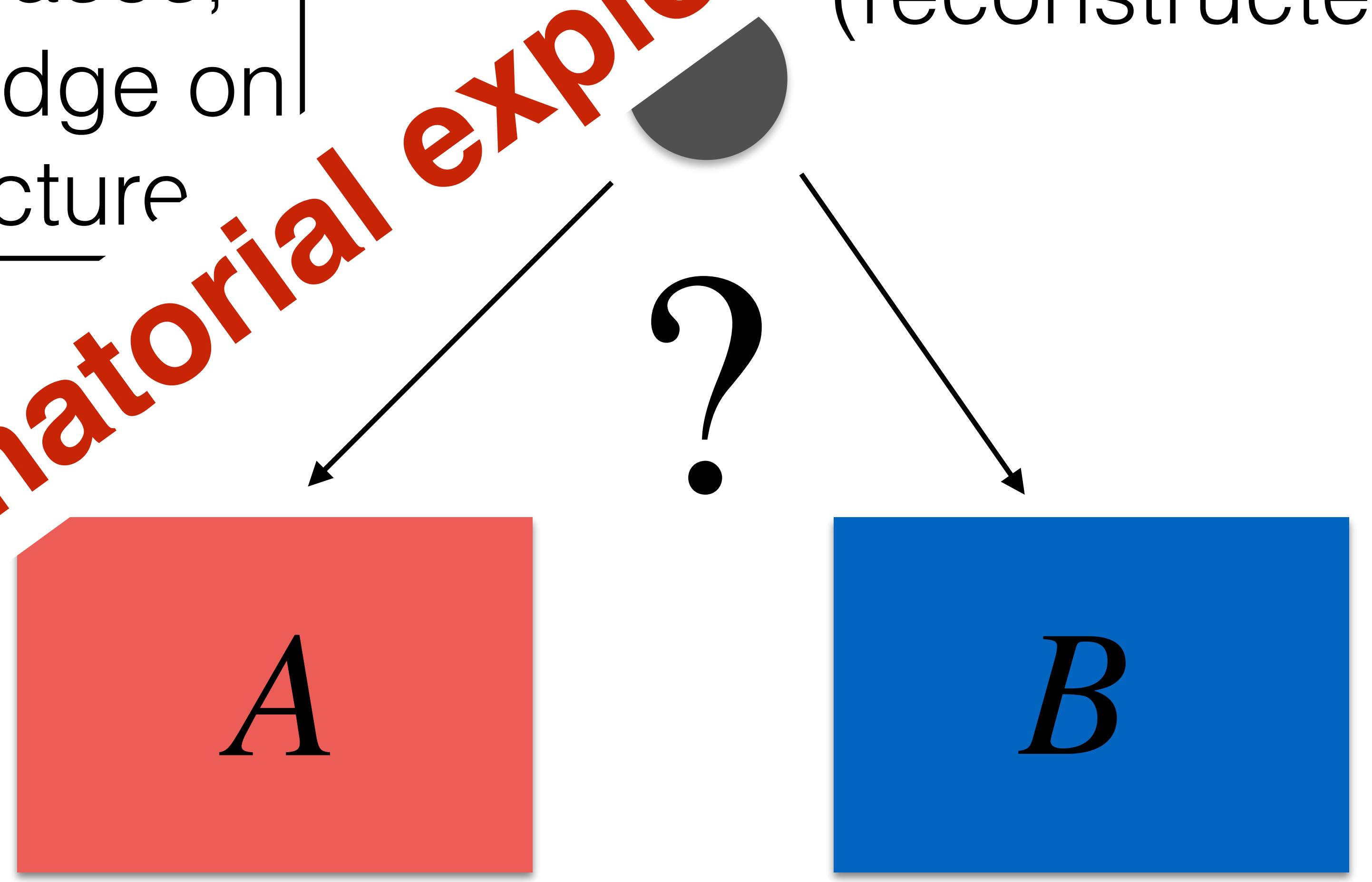
$pp \to o\tilde{o} \to \{t, \bar{t}\} \cup \{t, \bar{t}\}$

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

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

Combinatorial explosion will occur !

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



An algorithm ?

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

  - **No special treatment** on any flavor-tagged particle

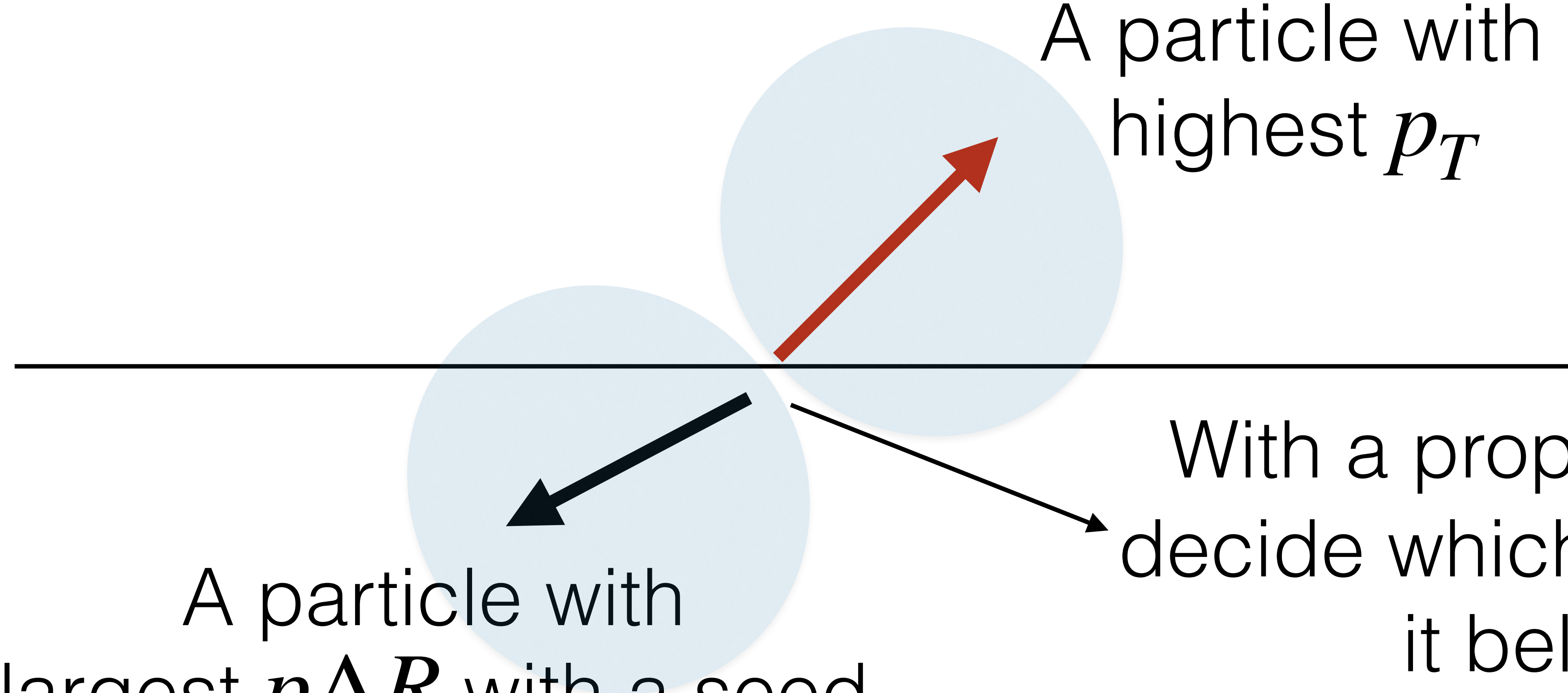
  - **No assumption** on masses, M_A and M_B

  - **No assumption** on any decaying structure

- What could be a good guide line ?
  - **BTW, have been any works on this subject?**

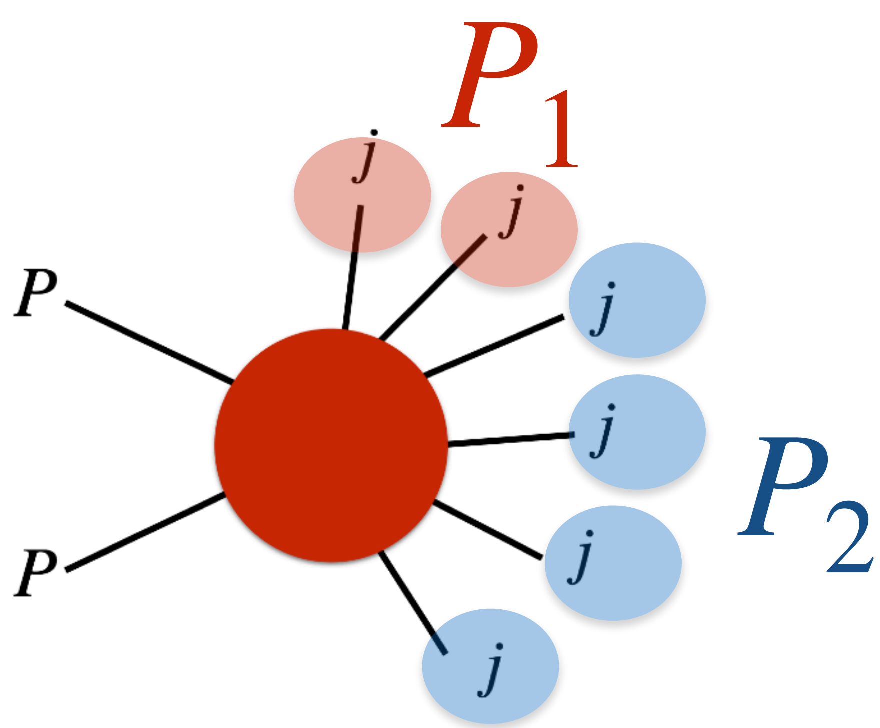
A Classic algorithm

- Hemisphere method: a seed-based method
- Divide multi-jets into two categories, (e.g. $pp \to \tilde{g}, \tilde{g}$)



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

Non-geometric algorithm



- $2 \to 2$ 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 $(x_i = 0)$

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

$$H = (P_1^2 - P_2^2)^2 = (M_A^2 - M_B^2)^2$$

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

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

- $M_A \neq M_B$ case can come from

  1) Different particle, namely $A \neq B$ (e.g. $pp \to HZ$)

  2) Non-negligible width of A and B

  3) Non-negligible smearing effects (mostly from jet) (e.g. $pp \to \tilde{o}\tilde{o} \to 12j$)

- We can apply **ML regularization method (penalty term)**

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

Calculate this "energy function" through all combinatorics!

Minimization using Ising model

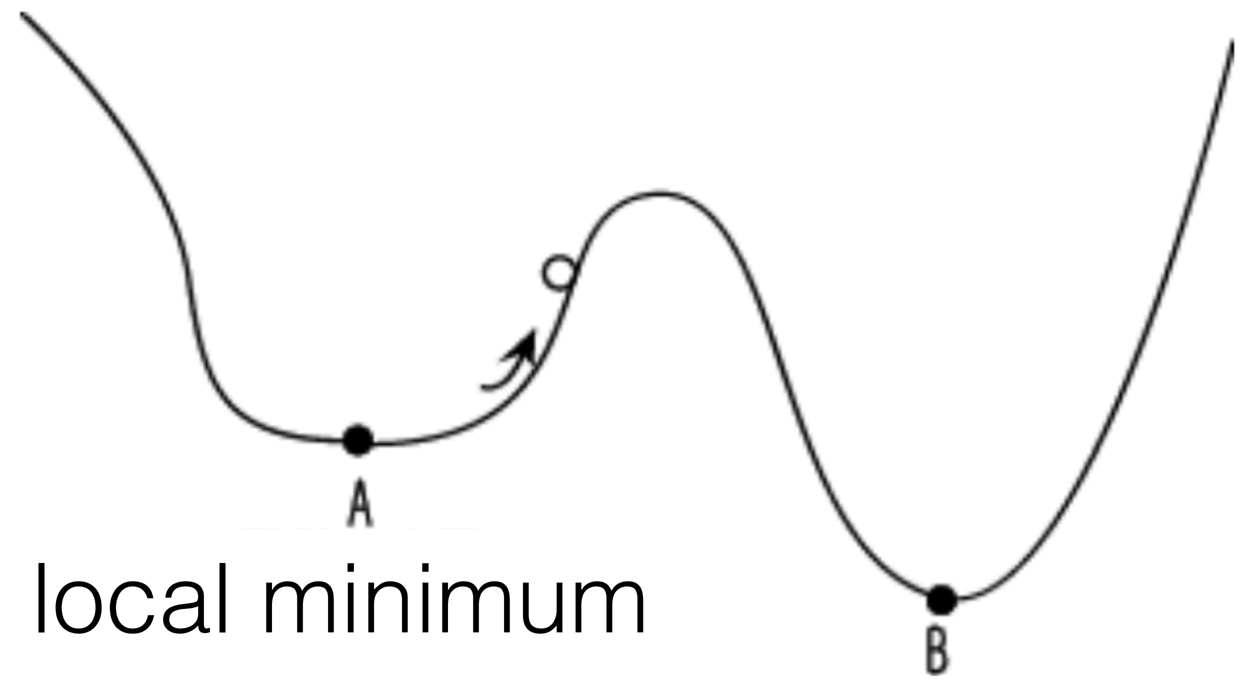
- If we replace $x_i \in \{1,0\} \to \dfrac{1+s_i}{2}$ with $s_i \in \{+1,-1\}$

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

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

here C_{ij} and S_{ij} are functions of four-vectors.

"Classic" minimization method (for Ising hamiltonian)



Simulated annealing

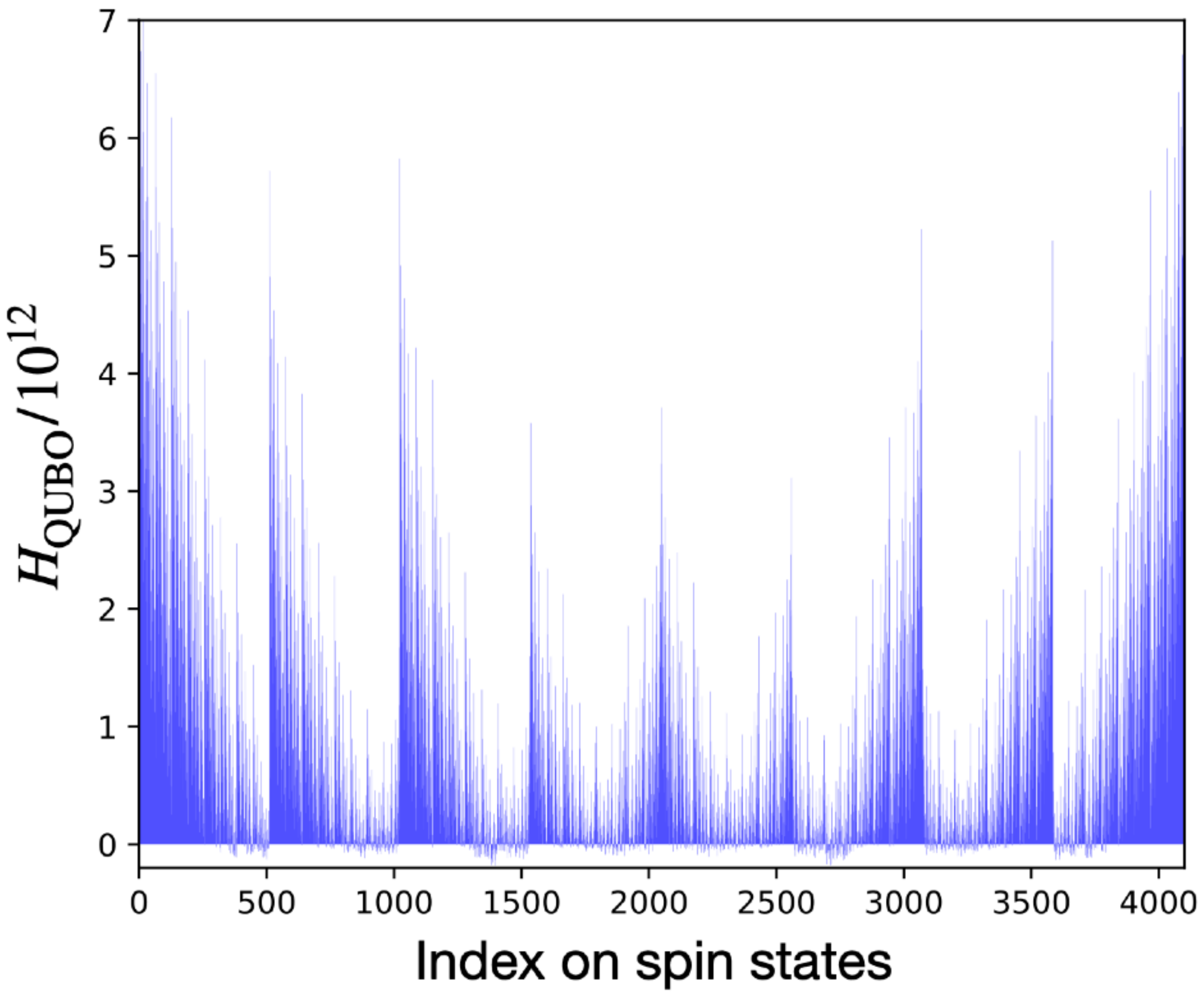
- Go to the next spin state $s_n \rightarrow s_{n+1}$
  1) If $E_n > E_{n+1}$: go to the lower energy
  2) If $E_n < E_{n+1}$, go with a probability of $e^{-\frac{E_{n+1} - E_n}{k_B T}}$ to **jump out**

(With large T, SA can jump out local minimum. Gradually we decrease T)

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

Combinatorial complexity arises (in a random Ising model)

Landscape of energy distribution



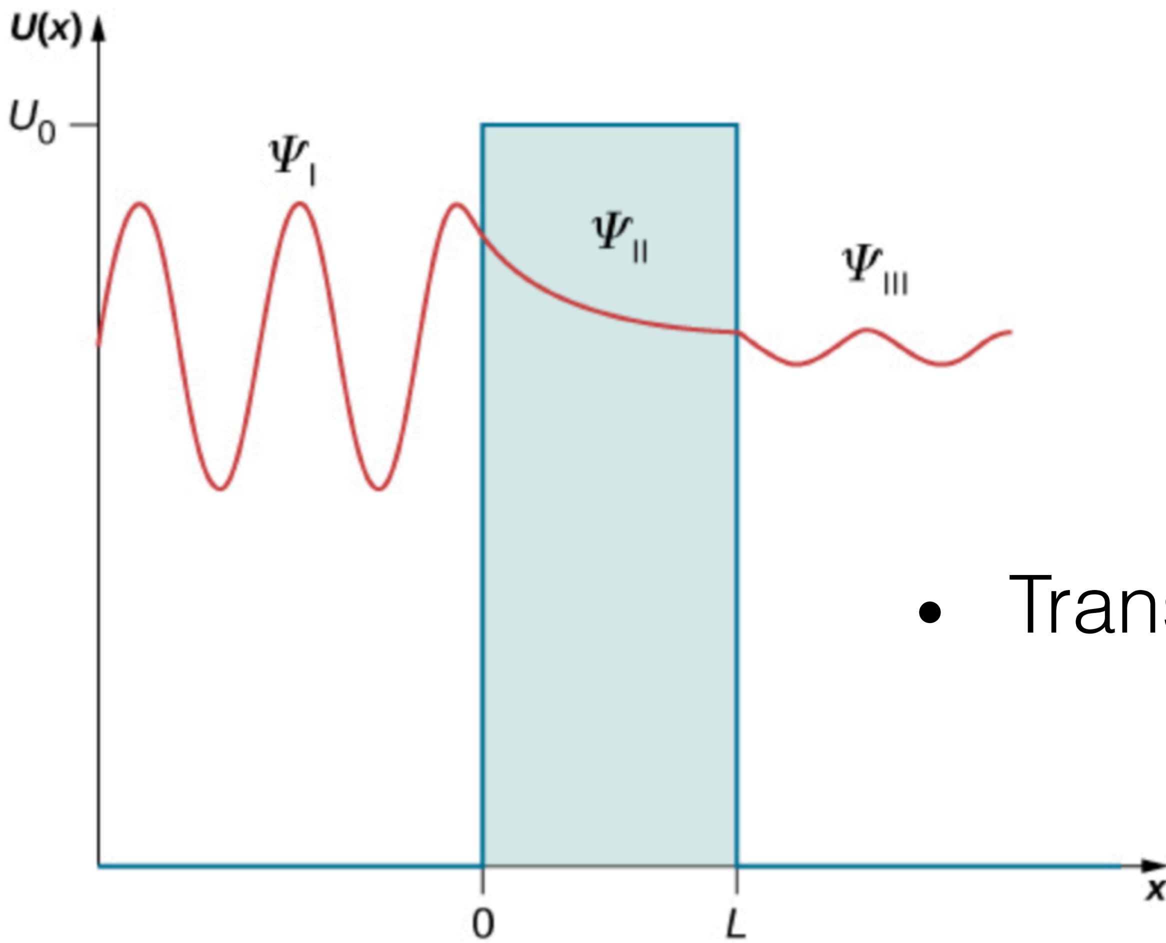
$\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow \to \uparrow\uparrow\uparrow\uparrow\uparrow\downarrow \to \cdots \to \downarrow\downarrow\downarrow\downarrow\downarrow\downarrow \quad (n_{\mathrm{spin}} = 2^{12} = 4096)$

Simulated Annealing cannot jump this random potential!

Any solution ?

The Quantum thing...

- In the **undergraduate QM** lecture, we learned / teach



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

1) The effect of energy difference ΔE becomes mild

2) Effective for **shallow barrier** L !

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

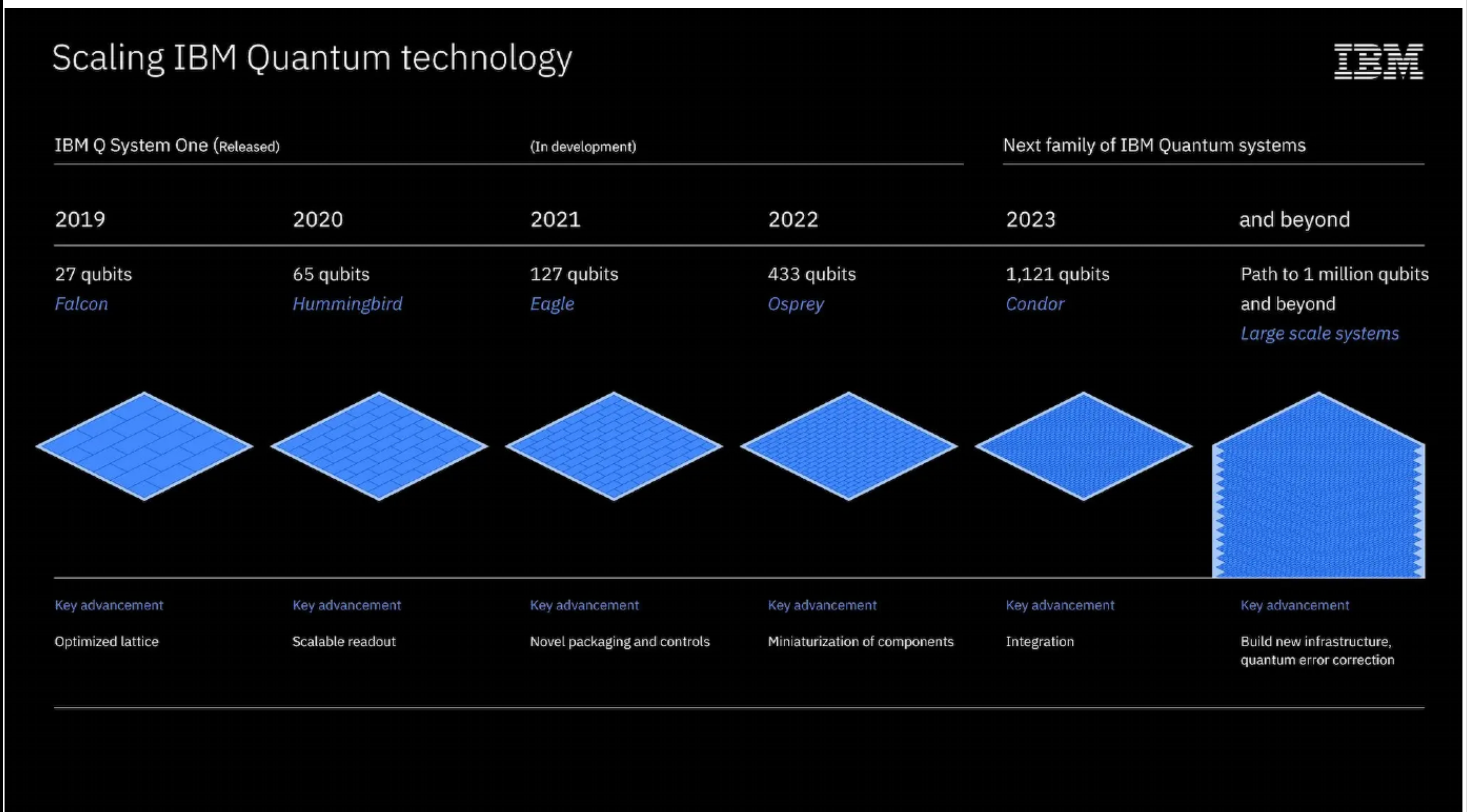
  our problem is a **simple and good example**
  to demonstrate an **advantage from Quantum tunneling**

Quantum Computer

- Gate type : IBM just announced **433 qubit** QPU. (using entanglement, superposition)

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

currently 433 Qubits (IBM Osprey)



Quantum Annealer

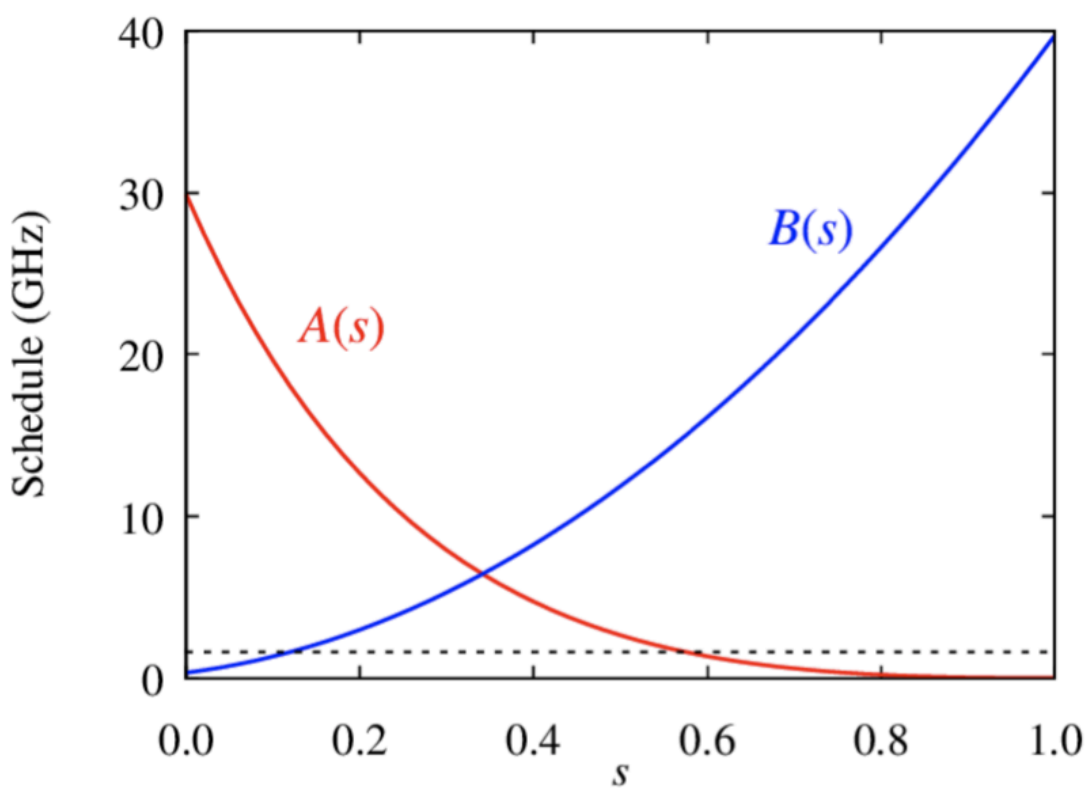
Temperature: below1.5×10^{-2}K
dimension: $3\text{m} \times 2.1\text{m} \times 3\text{m}$
Weight: 3800kg
Power: (max) 25kW

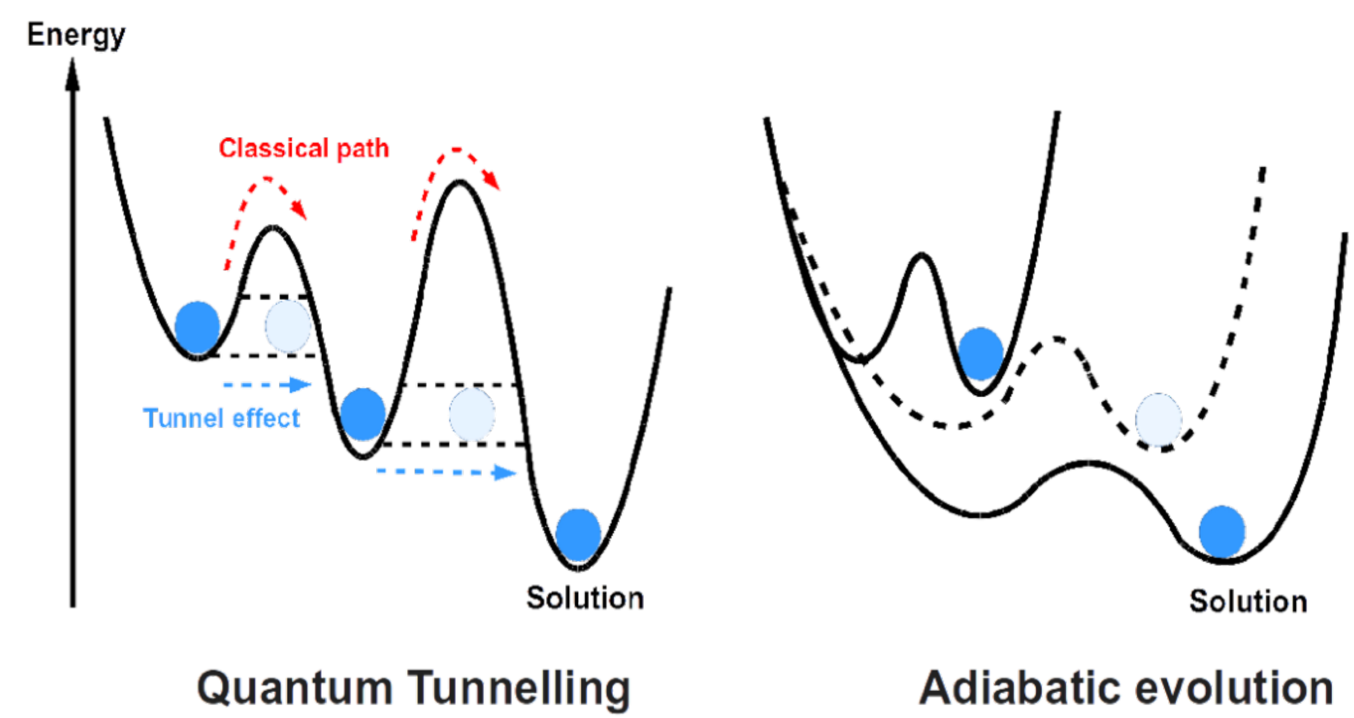
Quantum Annealing method

- With H_0, one can "mimic" the High Temperature in SA. (disorder spin state, linear combination of all states)

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

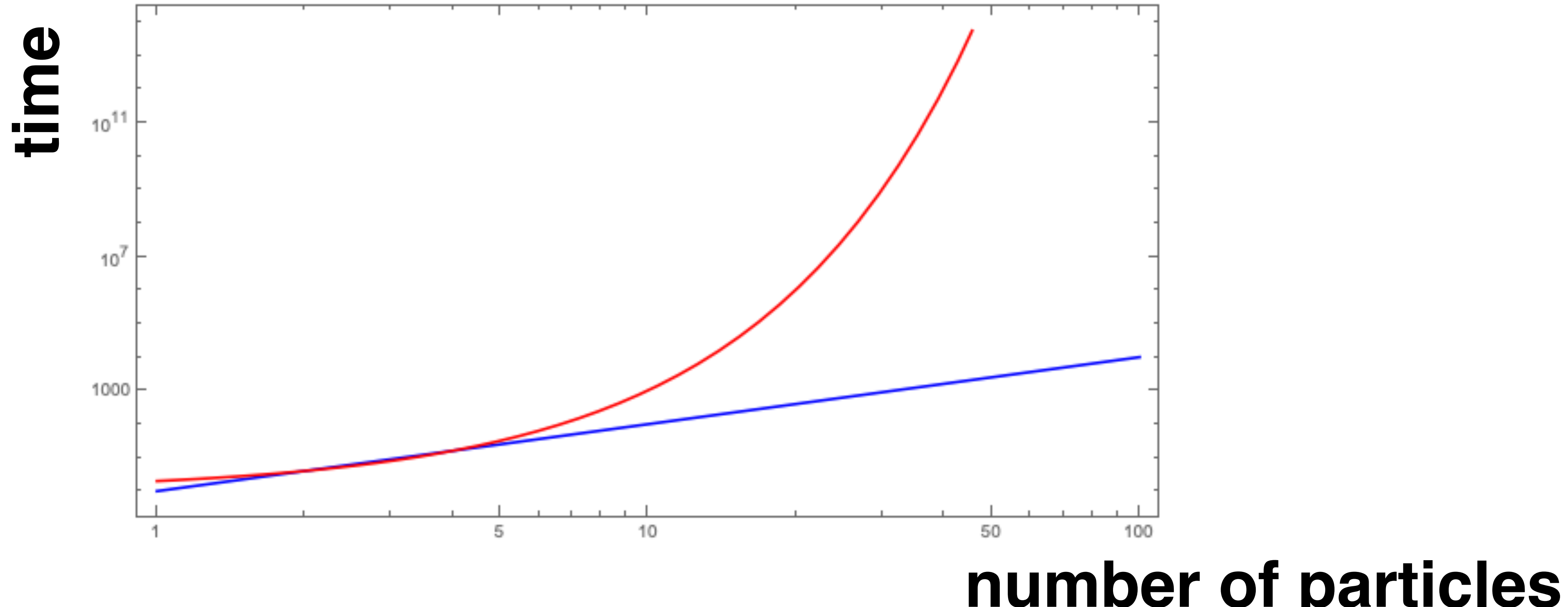
(T. Kadowaki and H. Nishimori, Quantum annealing in the transverse Ising model, 1998)





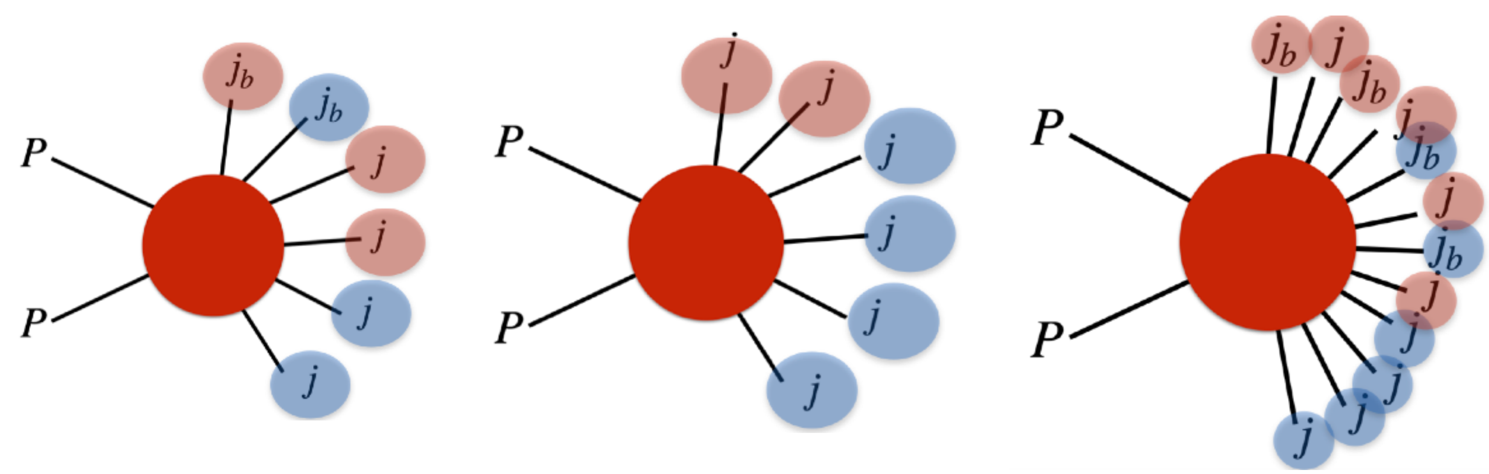
(small) Quantum advantage

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



(big) Quantum advantage

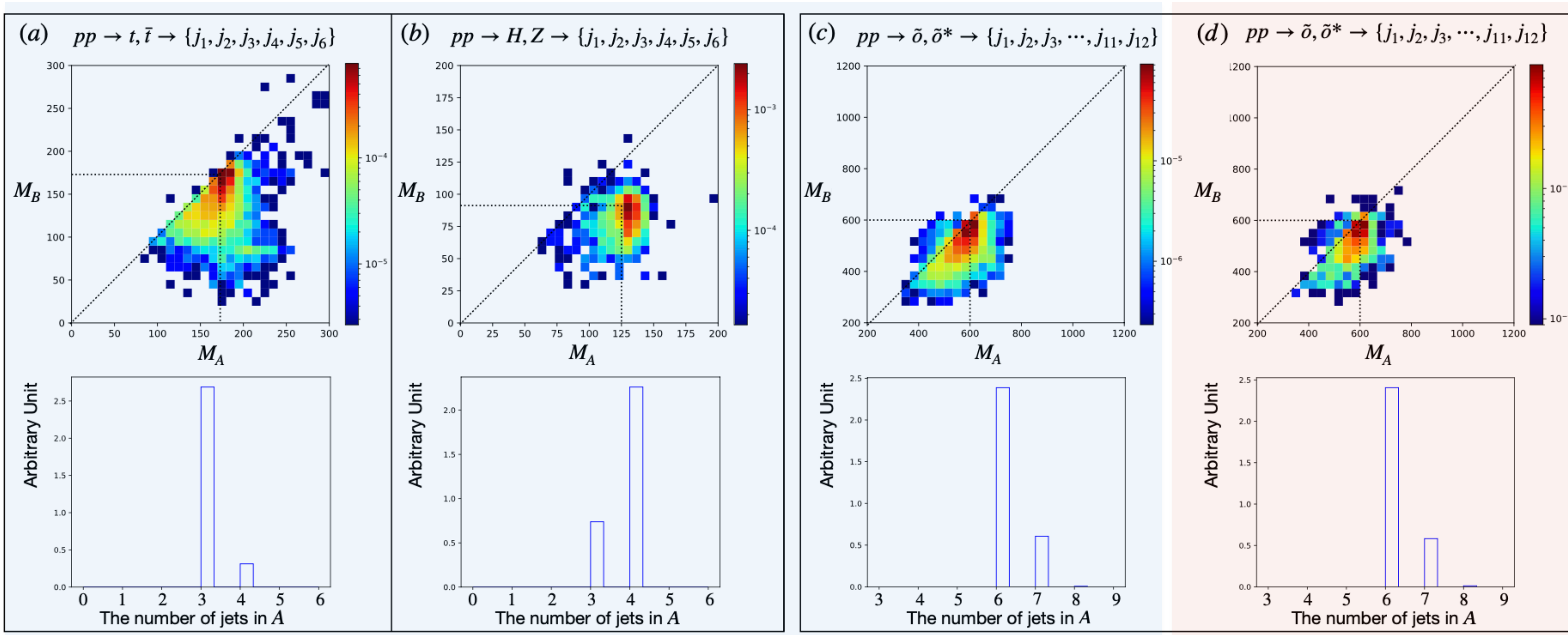
- QA v.s. SA



Process	$pp \to t\bar{t}$ (2 → 6)	$pp \to HZ$ (2 → 6)	$pp \to \tilde{o}\tilde{o}^*$ (2 → 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

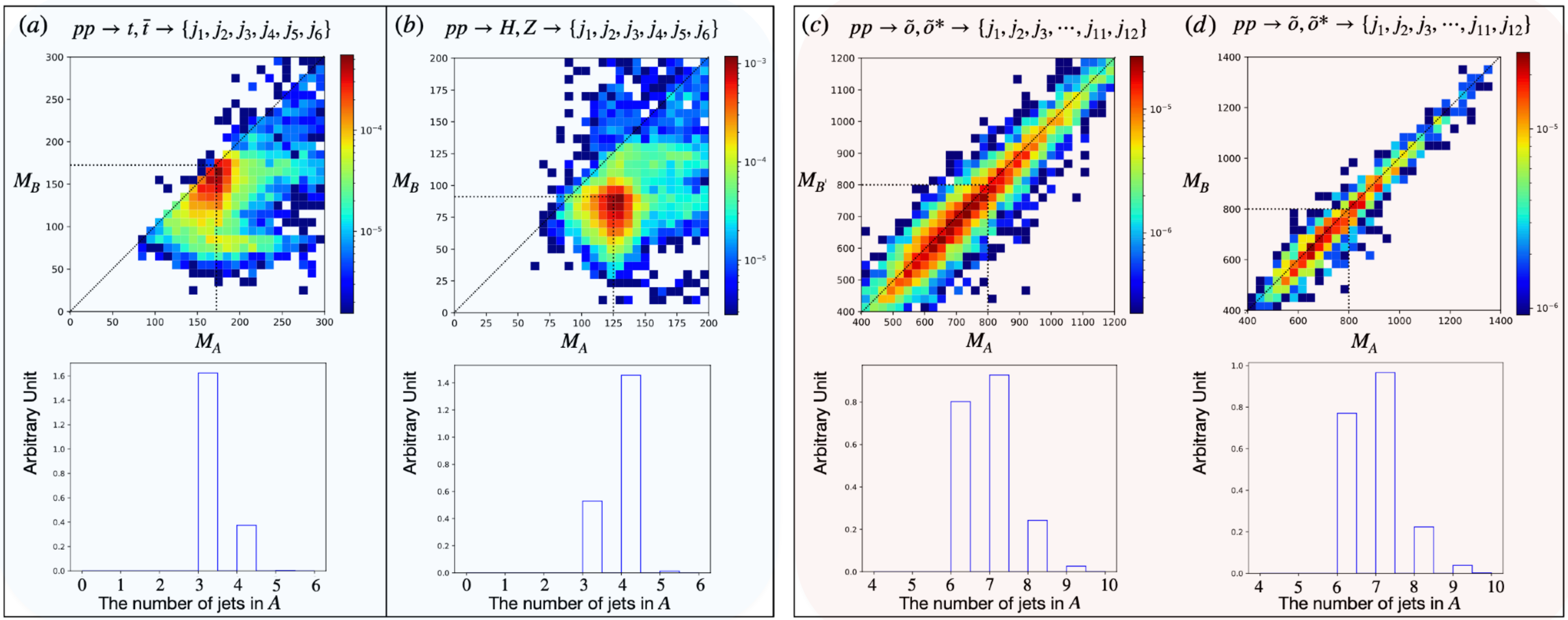


- Madgraph → Pythia (ISR/FSR/MPI **turned off**) → Fast Detector

*** a to c: brute force scanning for H_{QUBO} to check the fidelity of our algorithm**

For d, we use D-Wave computer (expensive...)

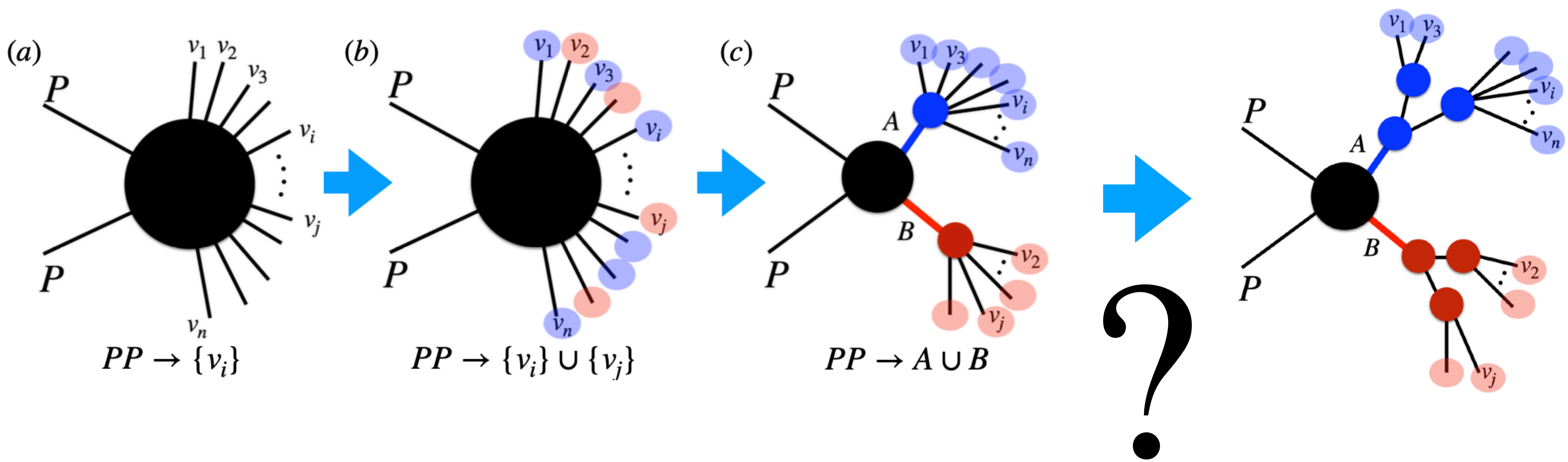
results



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

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

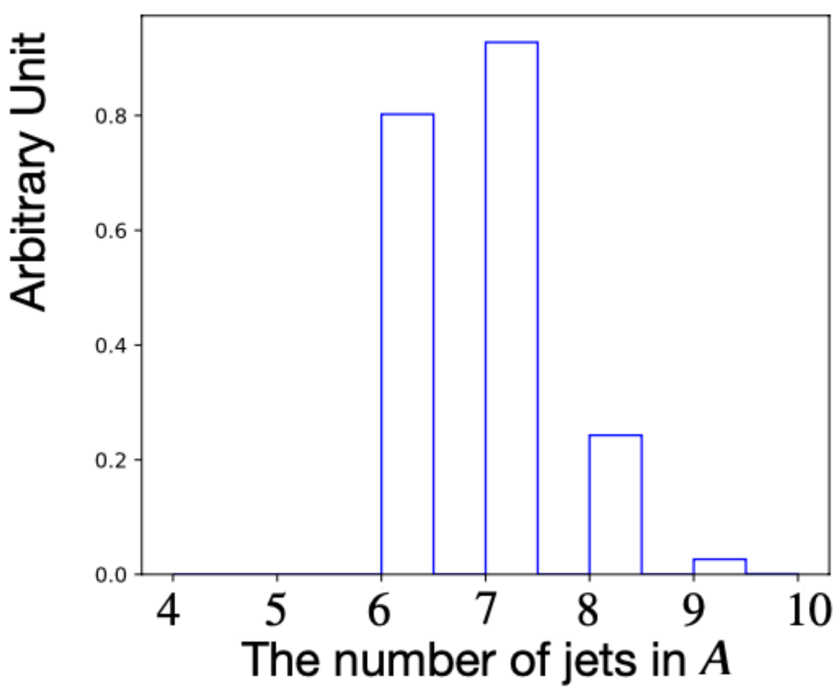
Sequential algorithm



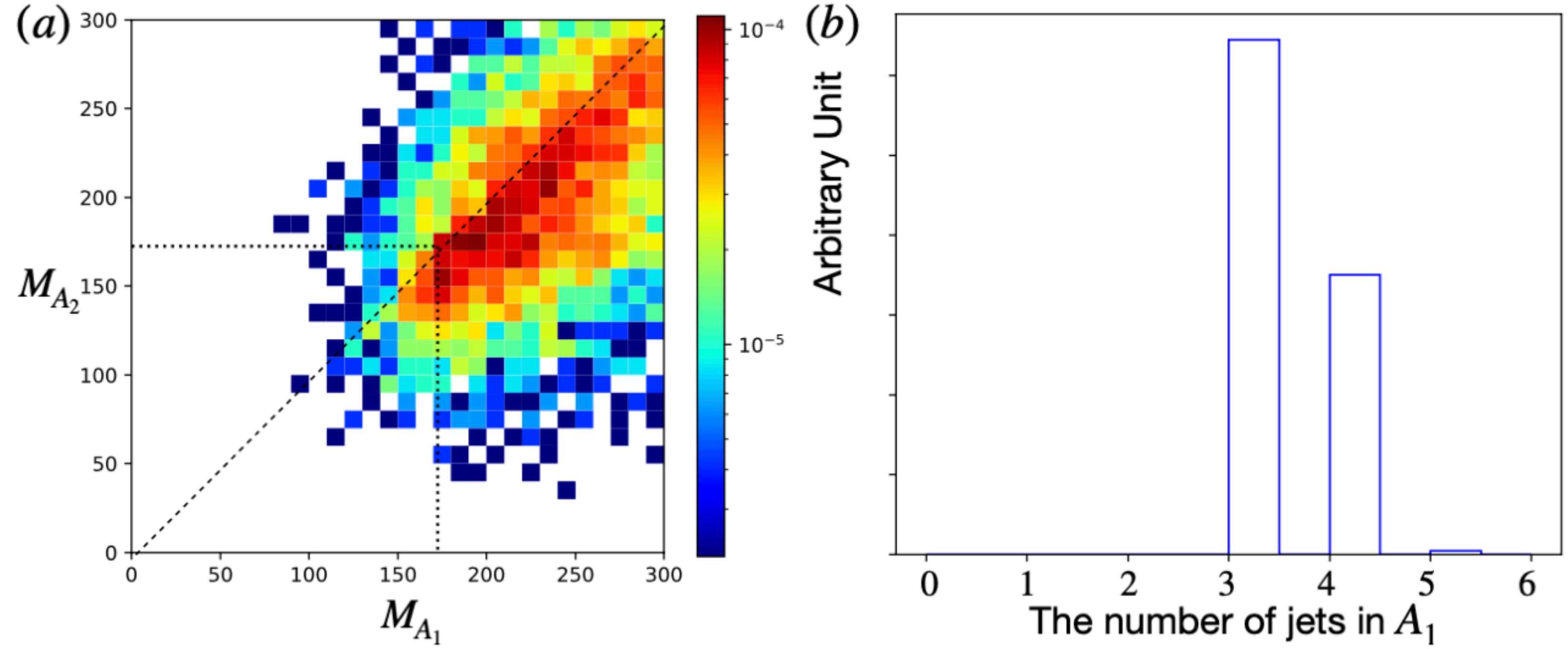
$$H^{(A)}_{\text{QUBO}} = \sum_{ij=1}^{\ell} J'^{\alpha}_{ij} s^{\alpha}_i s^{\alpha}_j + \sum_{i=1}^{\ell} h'^{\alpha}_i s^{\alpha}_i,$$

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

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



$$pp \to A, B$$



$$A \to A_1, A_2$$

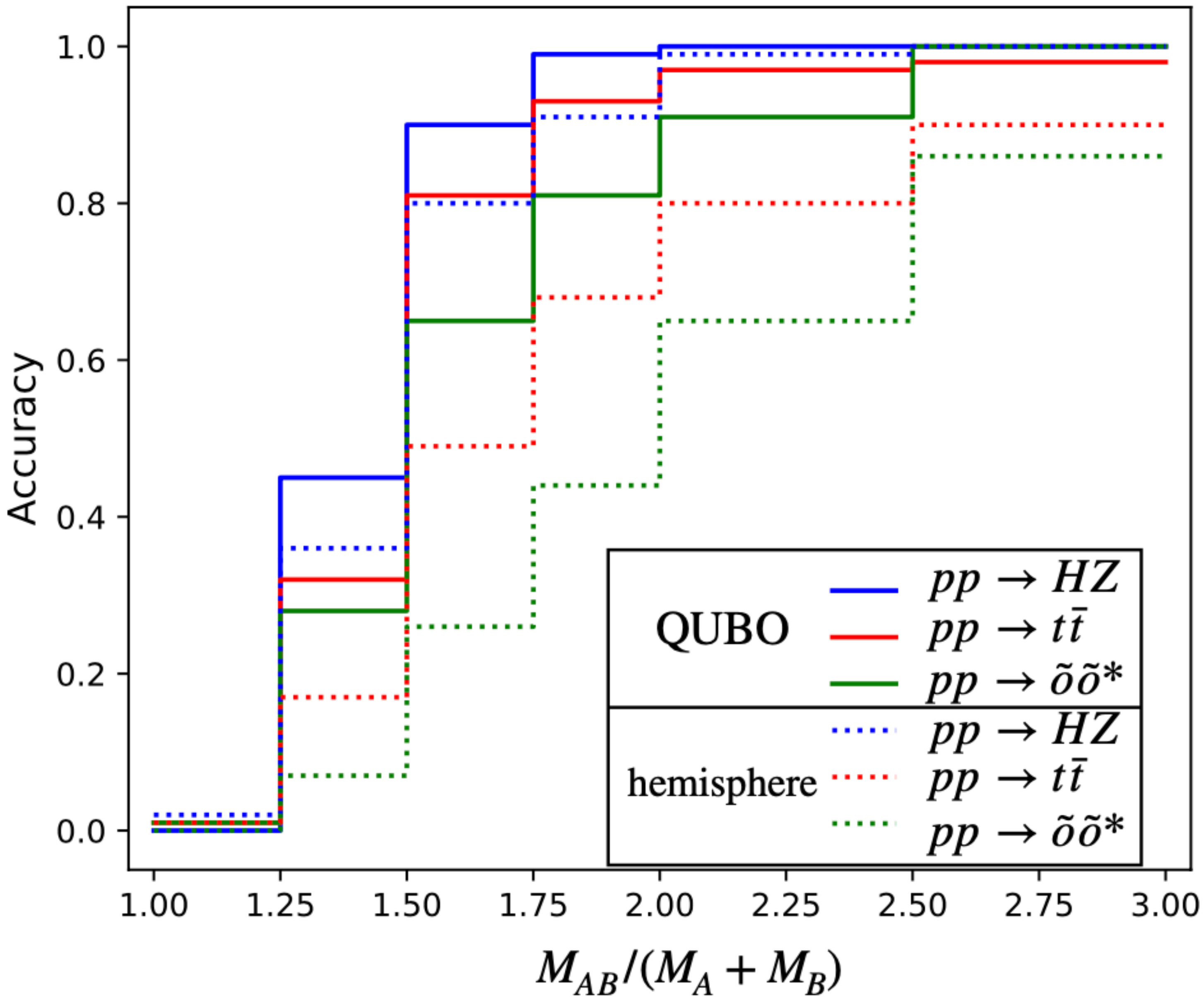
- We can "guess" that $A_i = t(\bar{t})$ as their **mass** and **number of children** are identical to the case of a top-quark.

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)



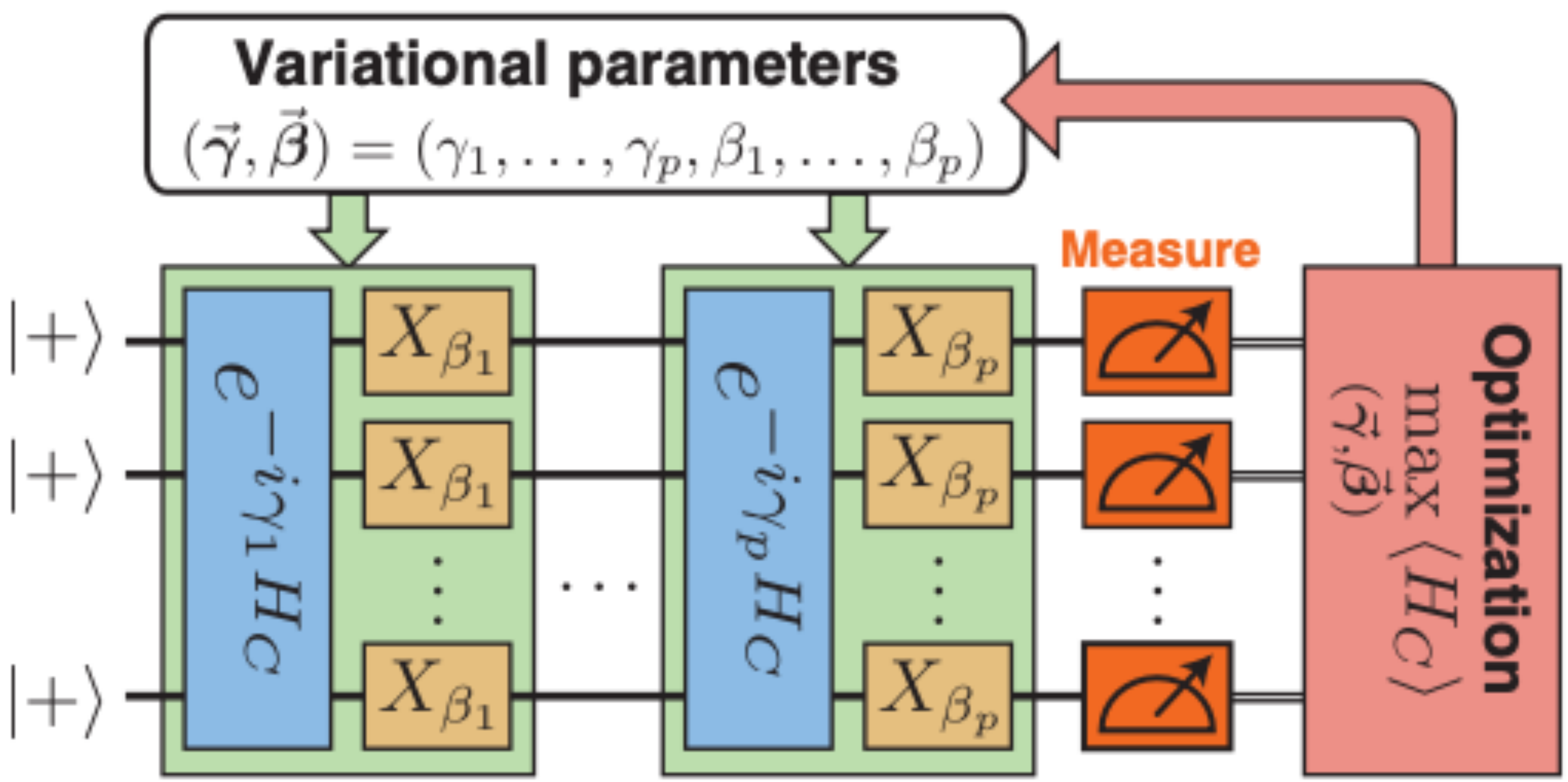
- Performance of an algorithm based on "**seed**" becomes weak when particles are **not boosted enough to develop structures.**
- Lorentz boost factor $\gamma_A = \dfrac{E_A}{M_A} = \dfrac{M_{AB}}{2M_A}$ (for A=B case)

Next step

- I presented a **simple quantum annealing method for clustering** reconstructed particles.

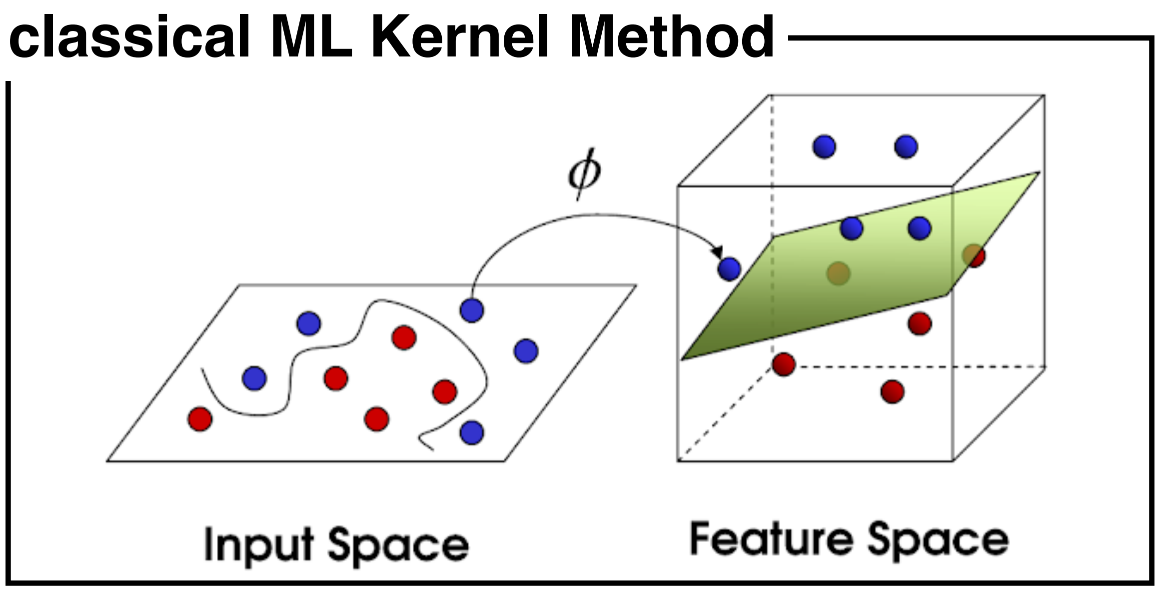
- Gate-based QC can be used via a variational algorithm.

- We are applying Gate-based QC to this clustering problem.



Good part of Gate-Quantum Computing

- At the early stage of Machine Learning

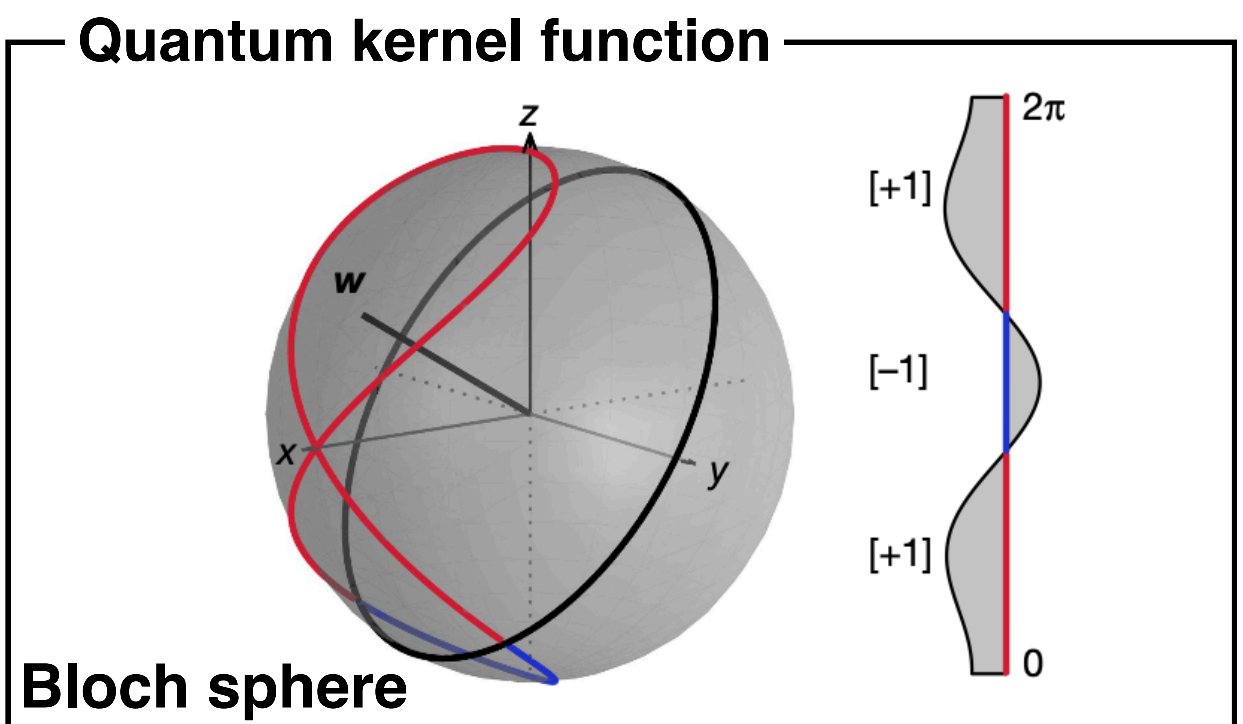


- Kernel method can help to **separate** "non-linearly" distributed inputs **linearly**!

- N qubits have 2^N data space (qubit = spinor)

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

2) Big memory computing



Conclusion

- 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 Supremacy** in the field of HEP.
- **Stay tuned**...

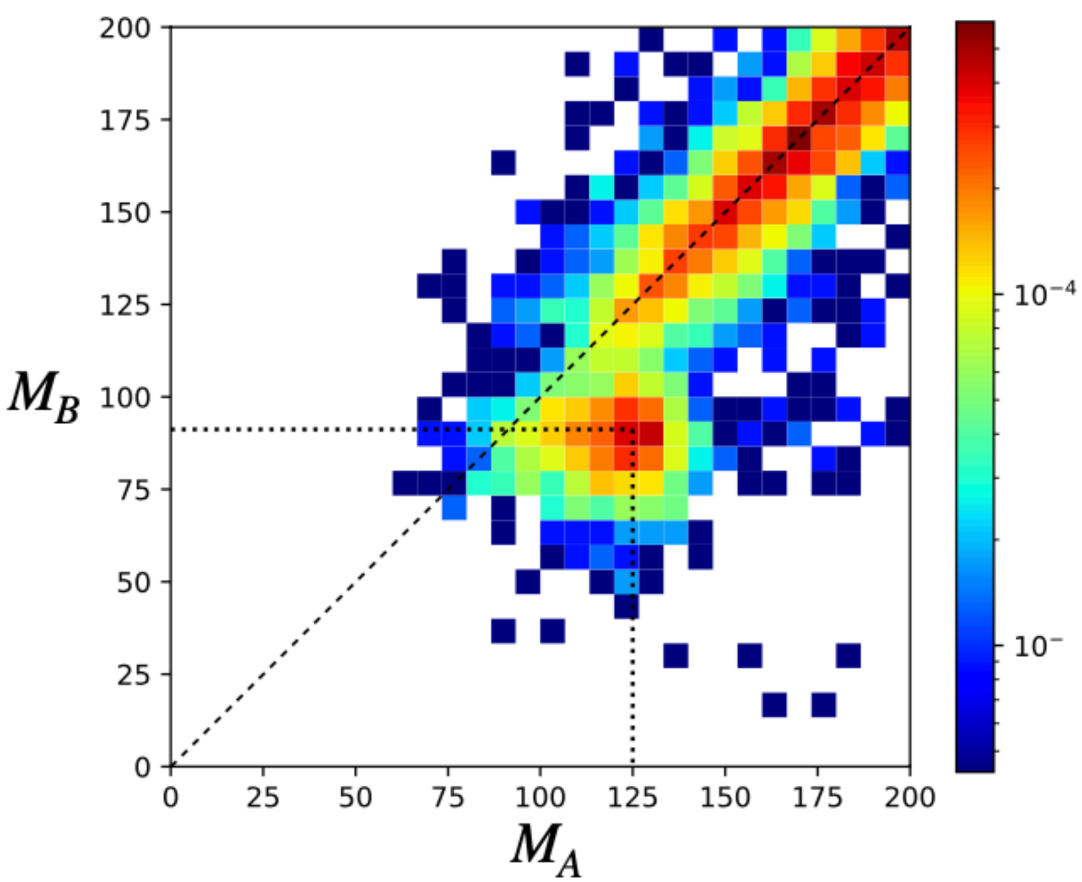
Back up

Effect of additional constraints

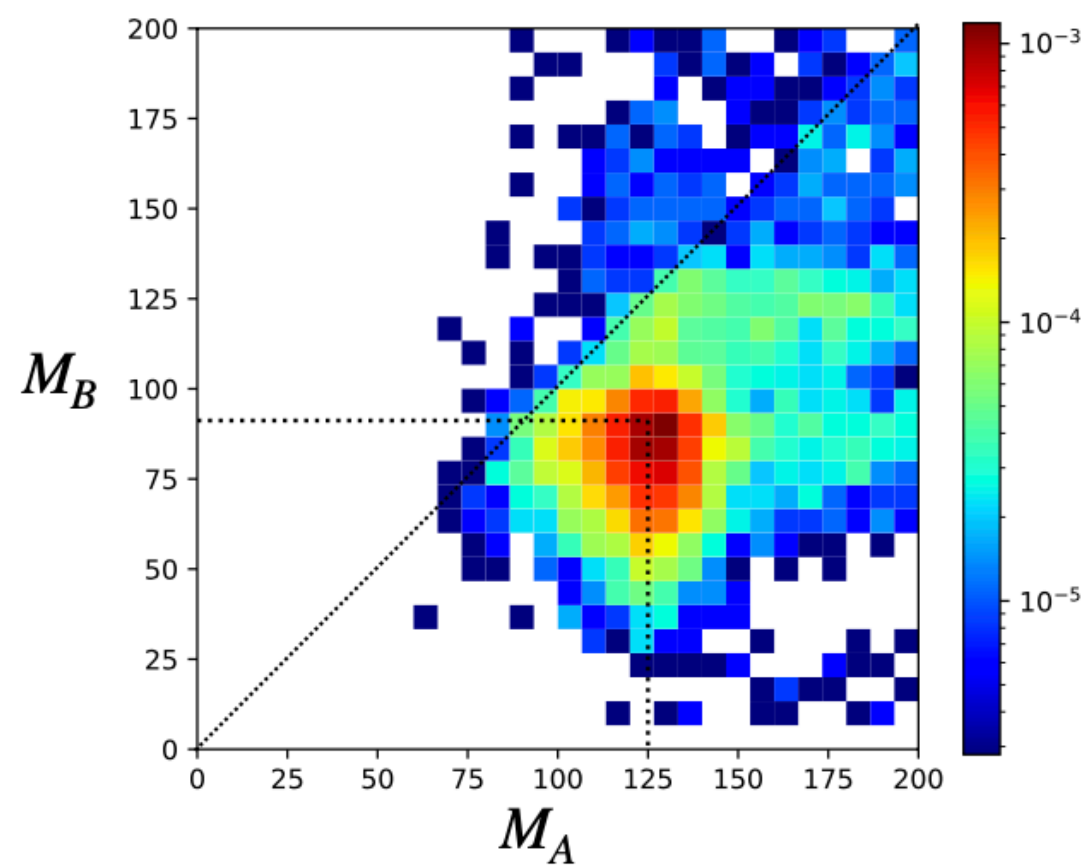
$$H = \left(P_1^2 - P_2^2\right)^2 \rightarrow H + \lambda\left(P_1^2 + P_2^2\right)$$

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

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



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

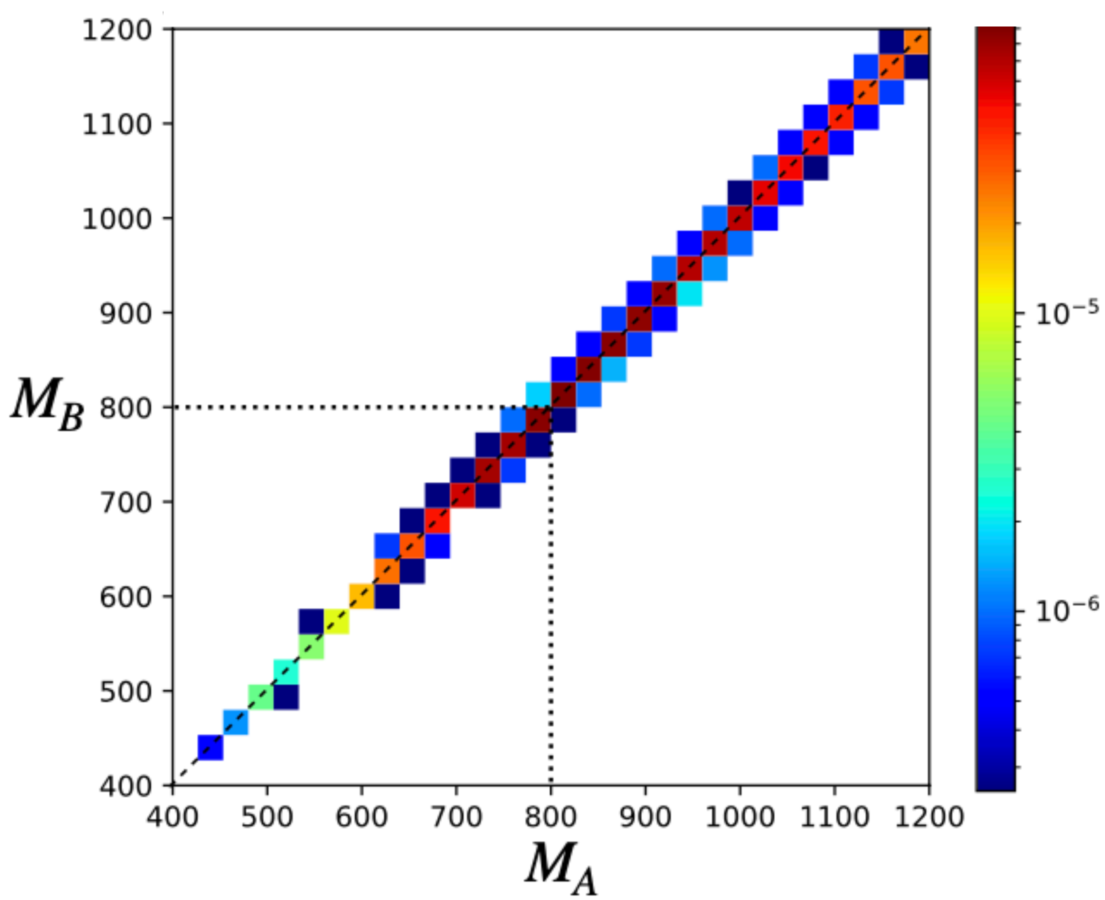


Effect of additional constraints

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

- Check smearing effects : $pp \rightarrow \tilde{o}\tilde{o} \rightarrow t\bar{t}t\bar{t}$

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



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