

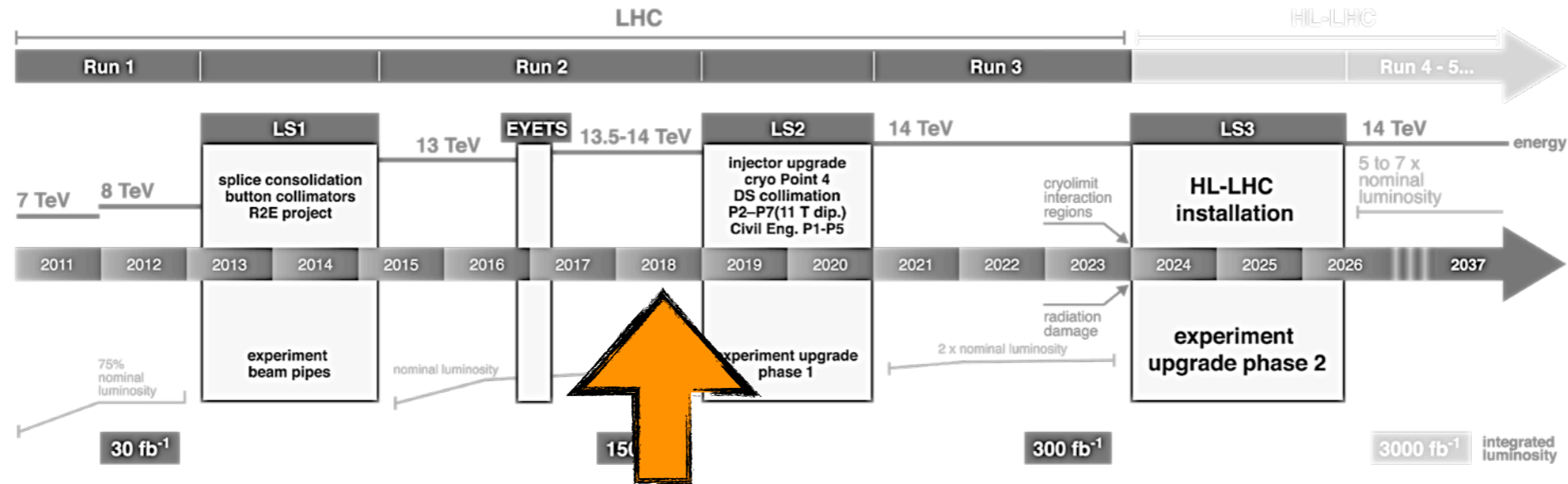
Quark jet rates and quark gluon discrimination in multi-jet final states

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LHC / HL-LHC Plan

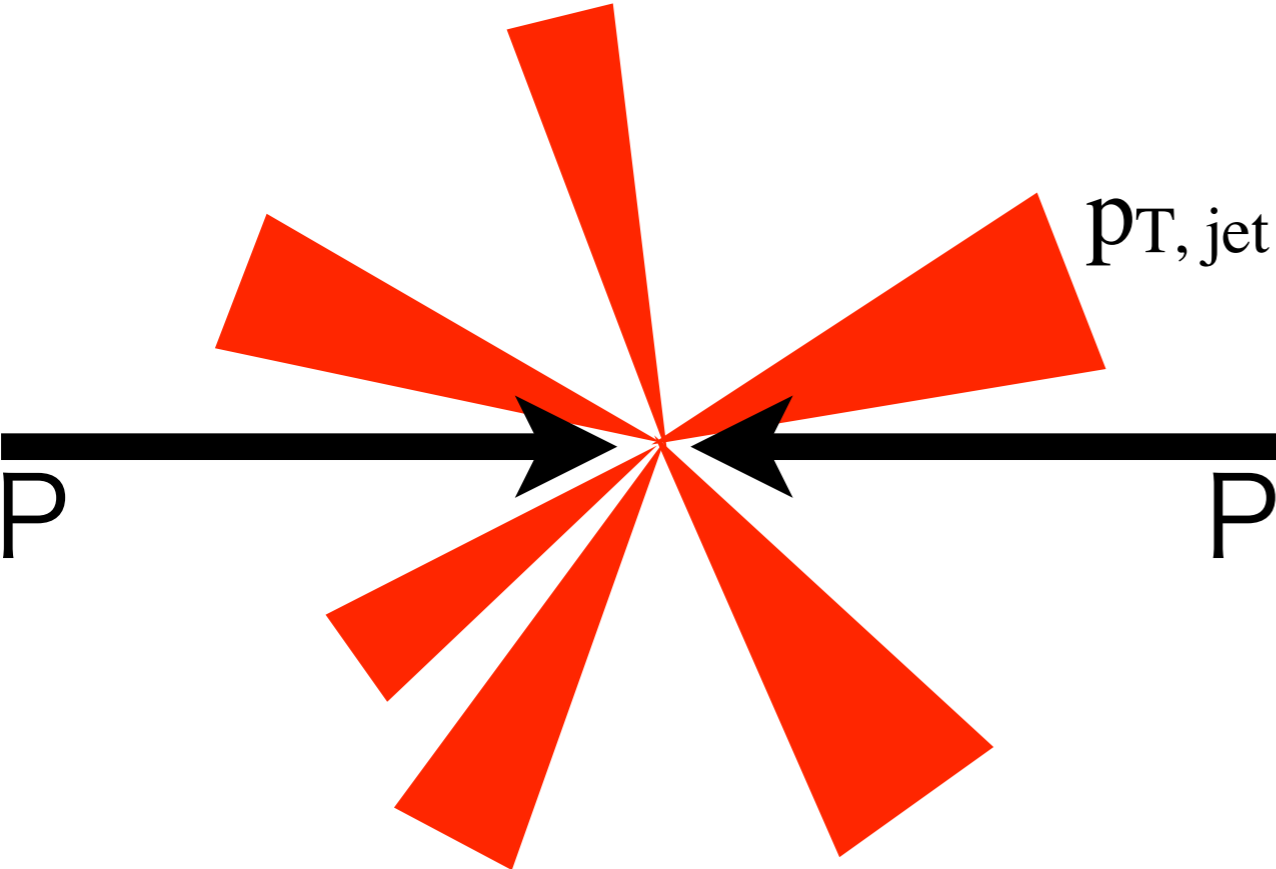


- No clear sign of BSM at the LHC
- **Need to examine final states more precisely**
- Final states are categorized by inclusive variables
 - ➔ $N(\text{jets}), N(\text{leptons}), H_T, \dots$
- Categories containing jets encounter a huge QCD background
- **As increasing $N(\text{jets})$,** kinematics and MC validation become more complicated
- LHC is jets production machine. We want to examine precisely even such multi-jet final state.

Multi-jet final state and New physics

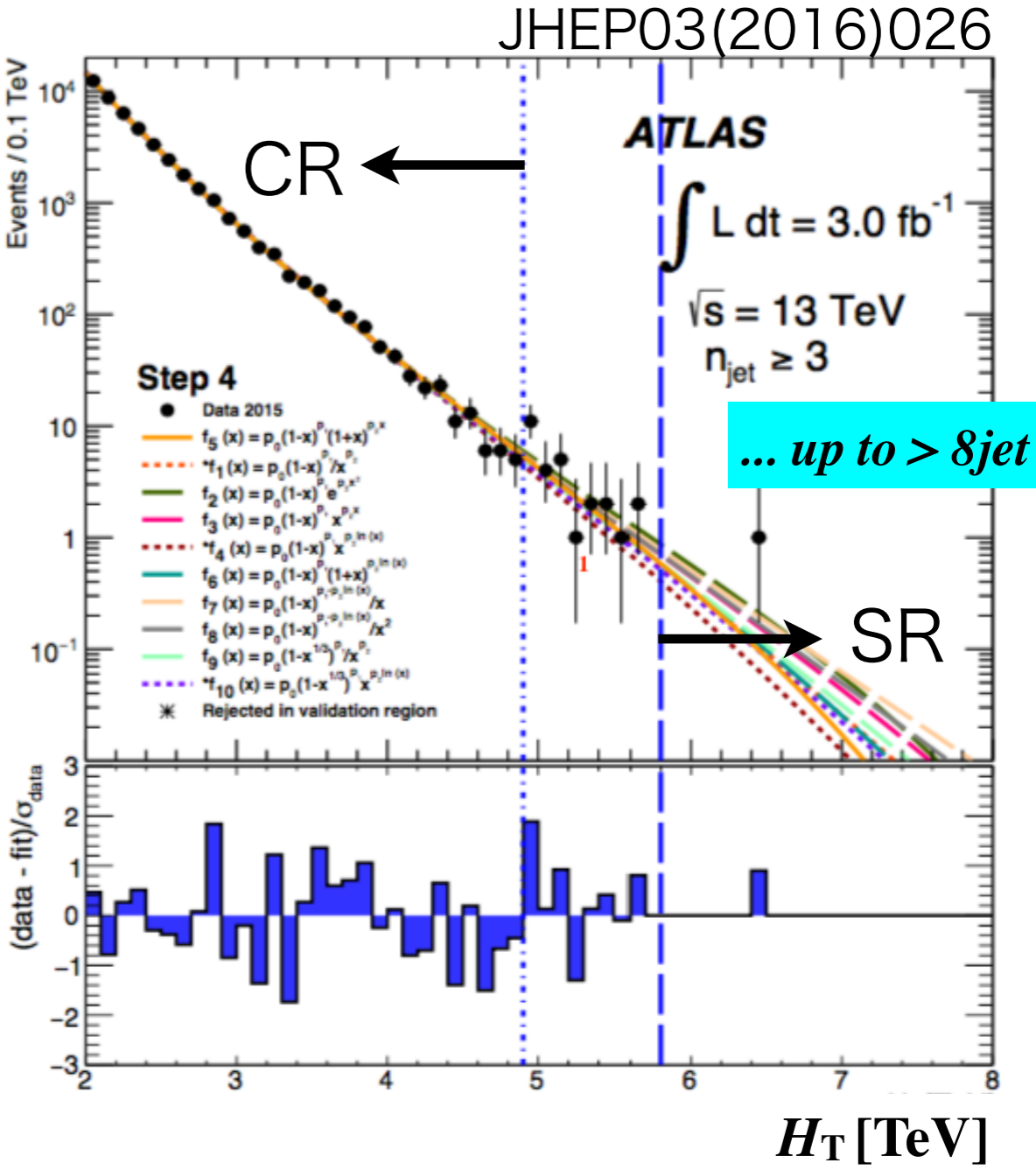
- **No accurate simulation** for the large jet multiplicity background due to the absence of higher-order, huge number of diagrams...

➔ data-driven analysis



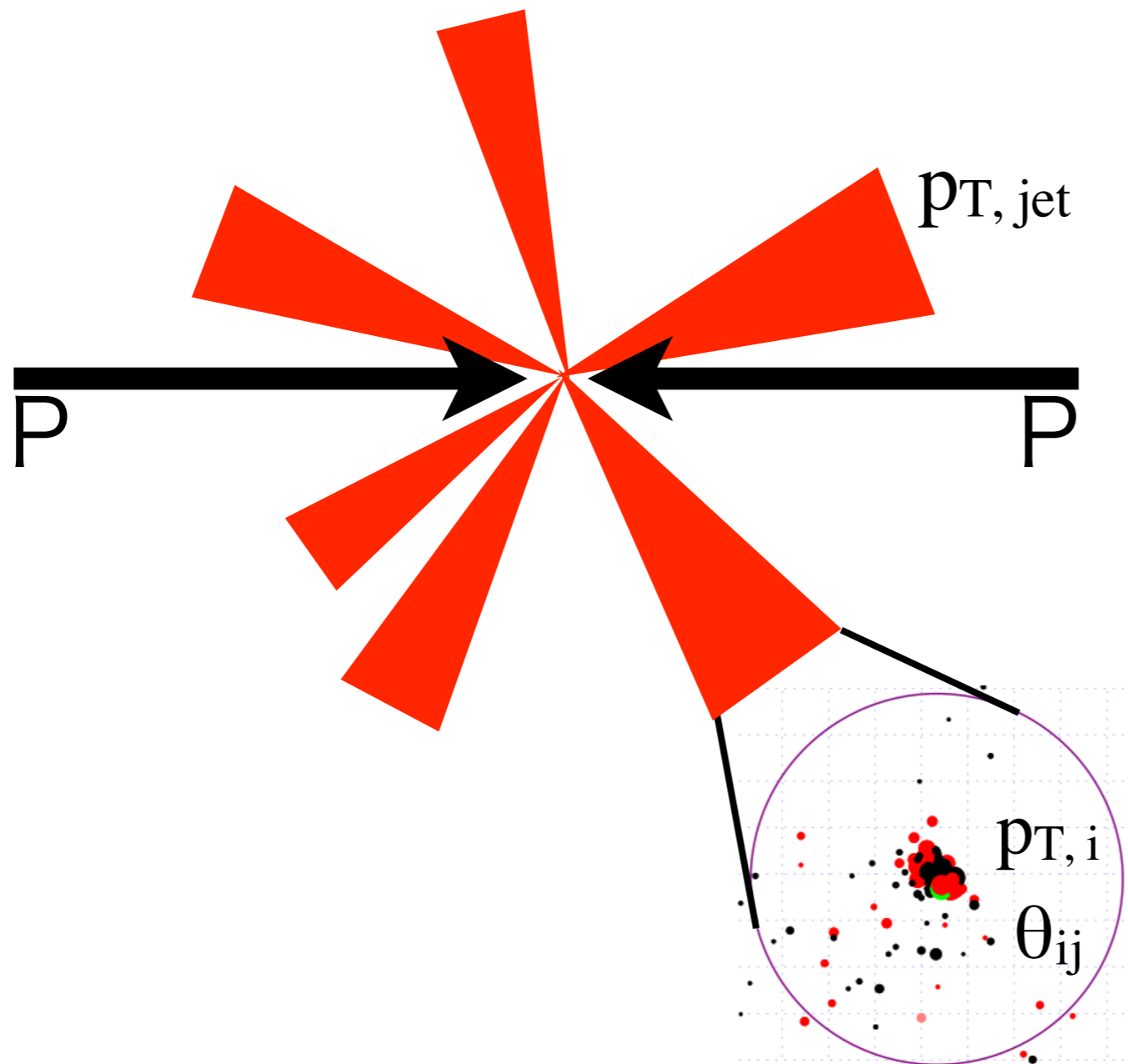
inclusive variable:

ex) $H_T = \sum p_{T,jet}$



Multi-jet final state and New physics

- Accurate simulation for the large jet multiplicity background does not exist due to the absence of higher-order, huge number of diagrams...



inclusive

$$\Sigma p_{T,jet}$$

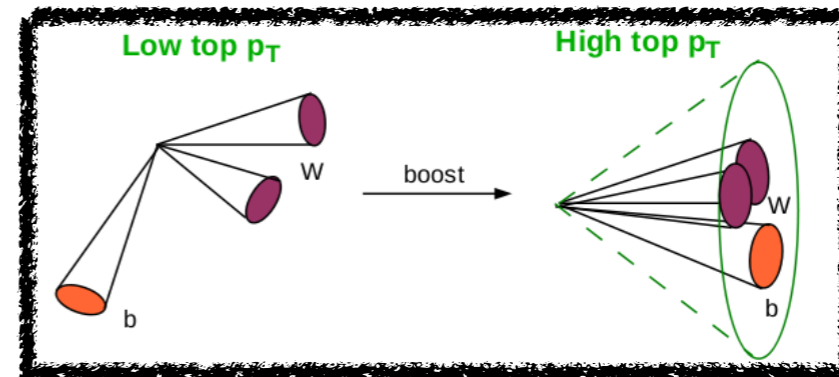
exclusive

$$\{p_{T,jet}\}, \{\Delta R\}$$

jet flavor/substructure

$$\{p_{T,i}\}, \{\theta_{ij}\}$$

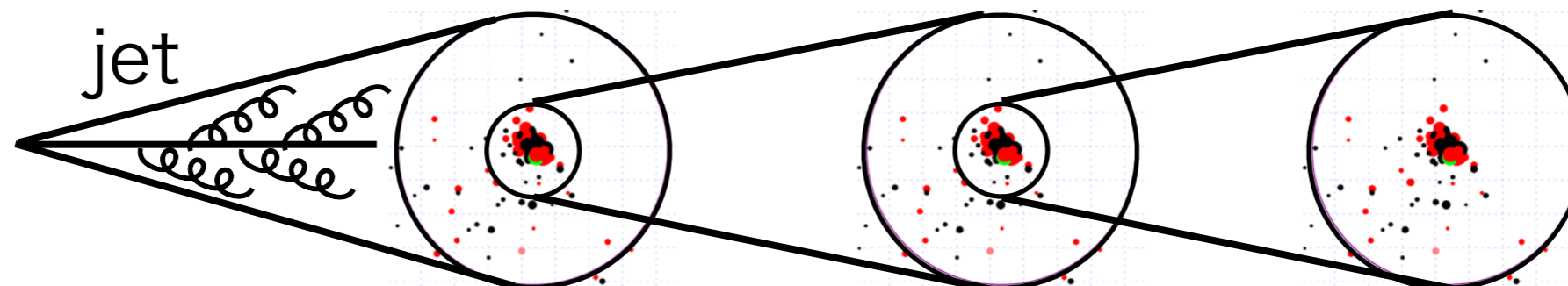
- Jet substructure technique established well as top/W/Z/H tagging tools (2-, 3-prong structure)



- Quark/Gluon discrimination is also available (1-prong structure)

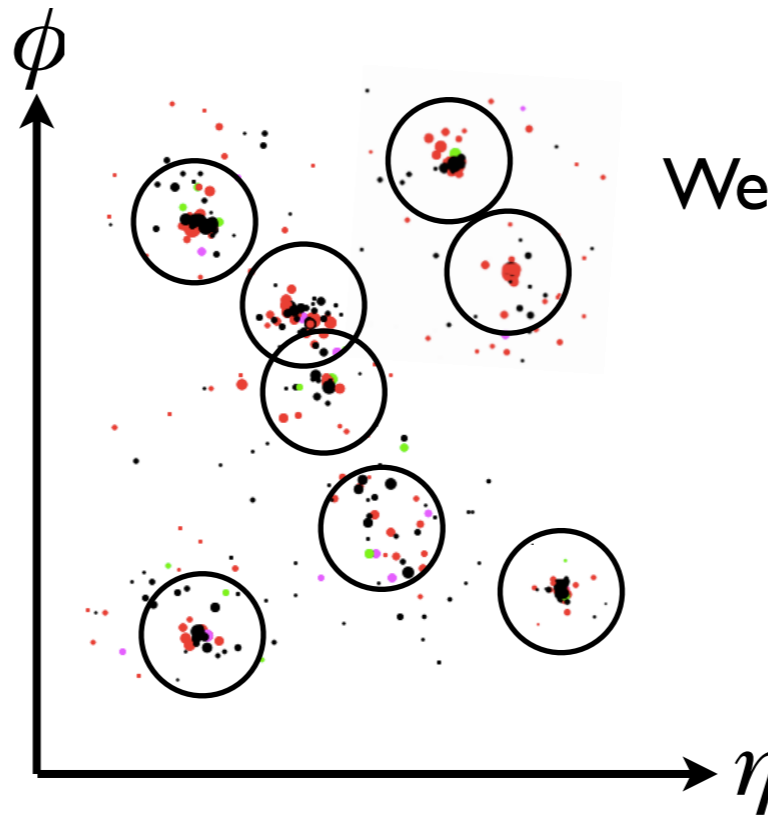
jet substructure	formed by	R (jet radius)
top W Z H	EW	~1.0 (fat jet)
quark gluon	QCD	0.4

- QCD radiation is approximately scale invariant



- Quark/Gluon discrimination works well even with small-R (even with $R < 0.4$)

Multi-jet final state and Jet substructure



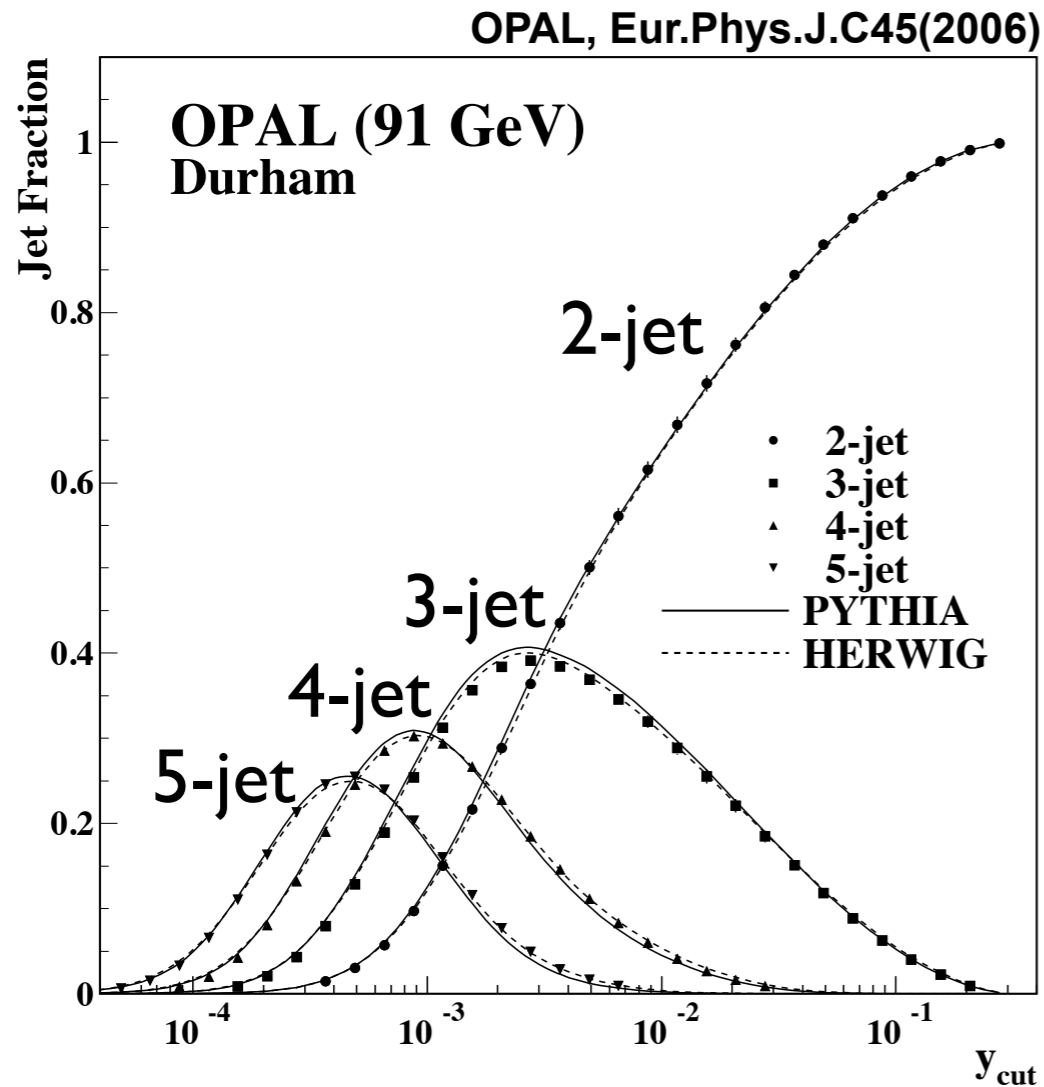
We can apply it N_{jets} times

$$\Delta N = \left| N_{\text{quark}}^{\text{signal}} - N_{\text{quark}}^{\text{BKG}} \right|$$
$$\Rightarrow \frac{S}{B} \propto \left(\frac{\epsilon_{\text{quark}}}{\epsilon_{\text{gluon}}} \right)^{\Delta N}, \quad \frac{\epsilon_{\text{quark}}}{\epsilon_{\text{gluon}}} > 1$$

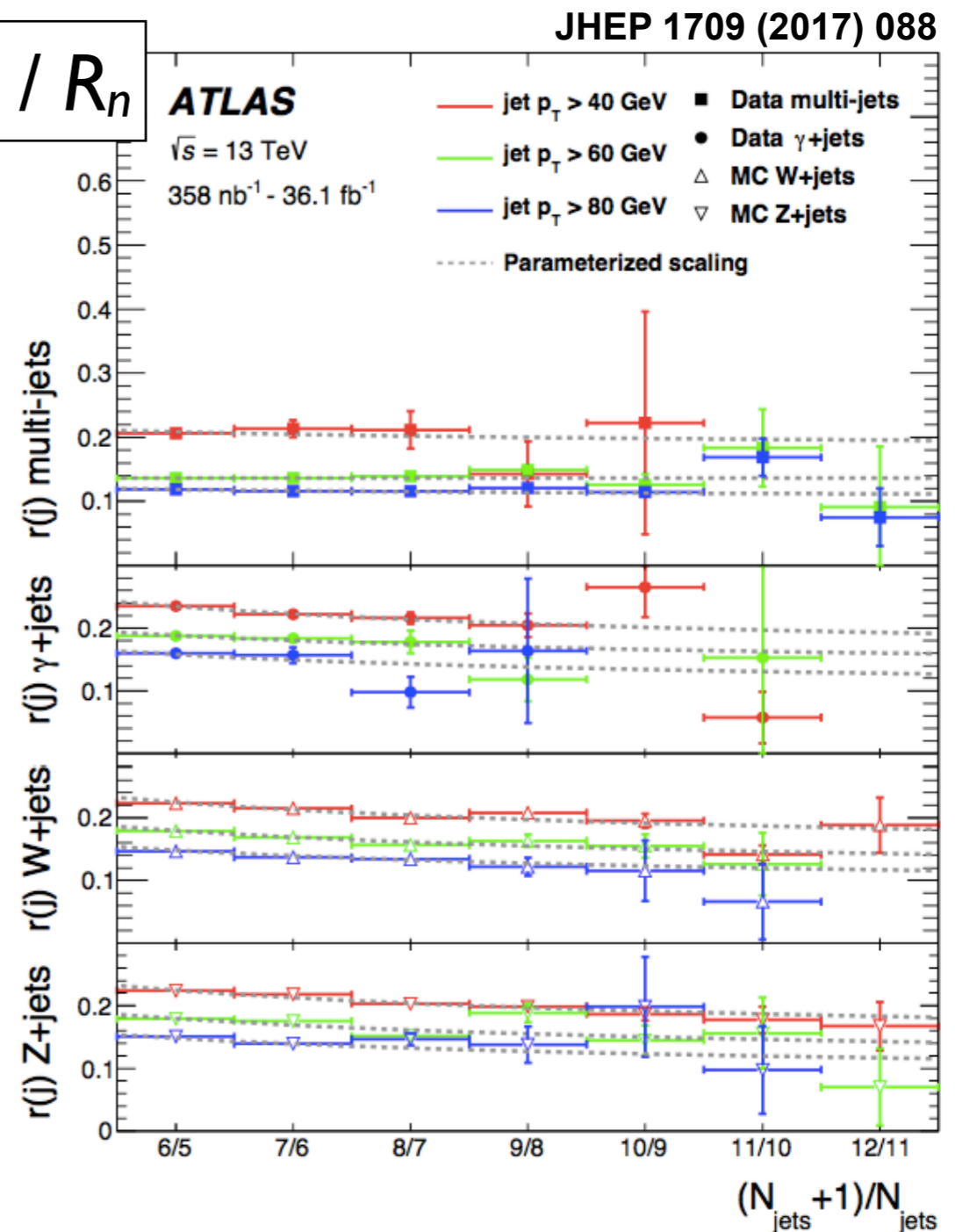
- Large enhancement of S/B for a signal that predicts the number of quark jets which is different from what the QCD background does
 - ➔ Let's see **how many quark jets are included in the QCD background.**

Jet rates

- $R_n(t)$: Probability that an event has n jet
- Studied well. Contribute to understanding of QCD
- and used ...

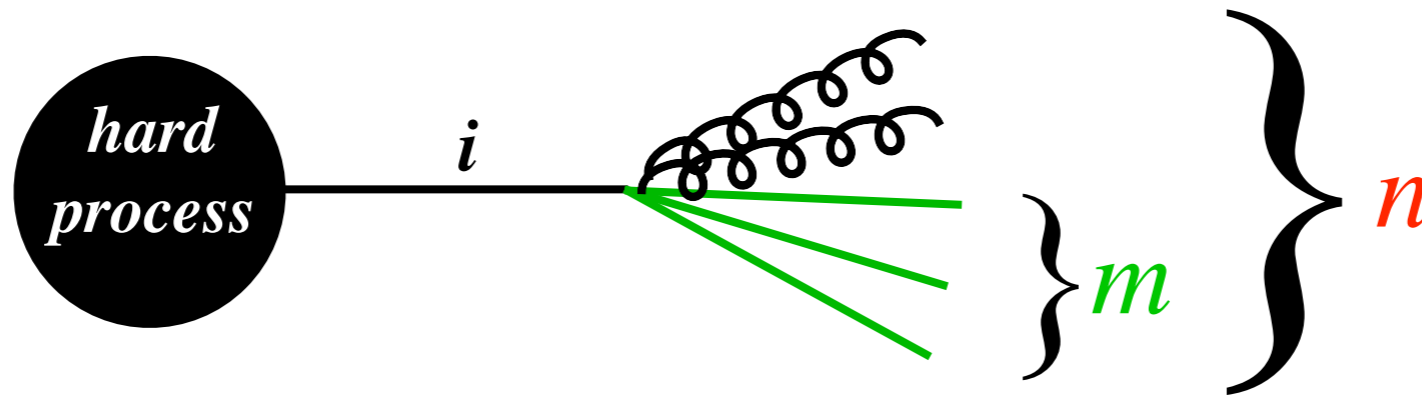


$$R_{n+1} / R_n$$



Quark jet rates

- $R_{n,m}^i$: Probability that i emits n jets in which m quark jets are contained



- Generating functional:

$$\Phi_i(p, t) = \sum_{n=1}^{\infty} \sum_{m=0}^n u^{N(\text{jets})} v^m R_{n,m}^i(p, t)$$

$N(\text{jets})$ $N(\text{quark jets})$
 ↓ ↓
 (points to n) (points to m)

$$\Phi_i(p, t) = u v_i \Delta_i(p, t) + \sum_k \int_{p_0/p}^1 dz \int_{t_0}^t \frac{dt'}{t'} \frac{\Delta_i(p, t)}{\Delta_i(p, t')} \mathcal{P}_{i \rightarrow jk} \Phi_j(p, t') \Phi_k(zp, t')$$

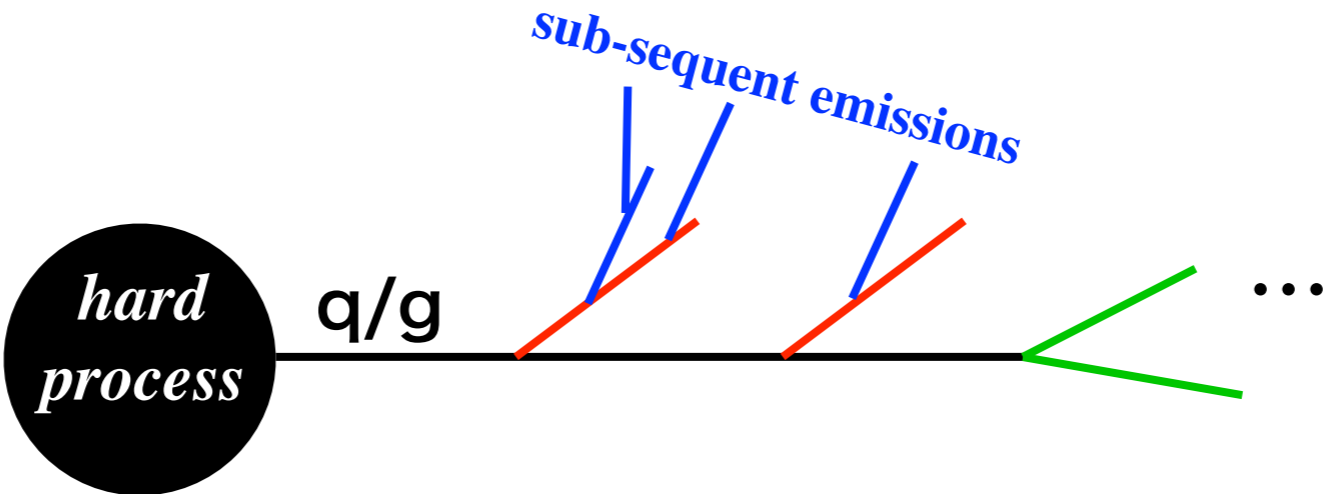
Solutions

$$\Phi_i(p, t) = \sum_{n=1}^{\infty} \sum_{m=0}^n u^{N(\text{jets})} v^{N(\text{quark jets})} R_{n,m}^i(p, t)$$

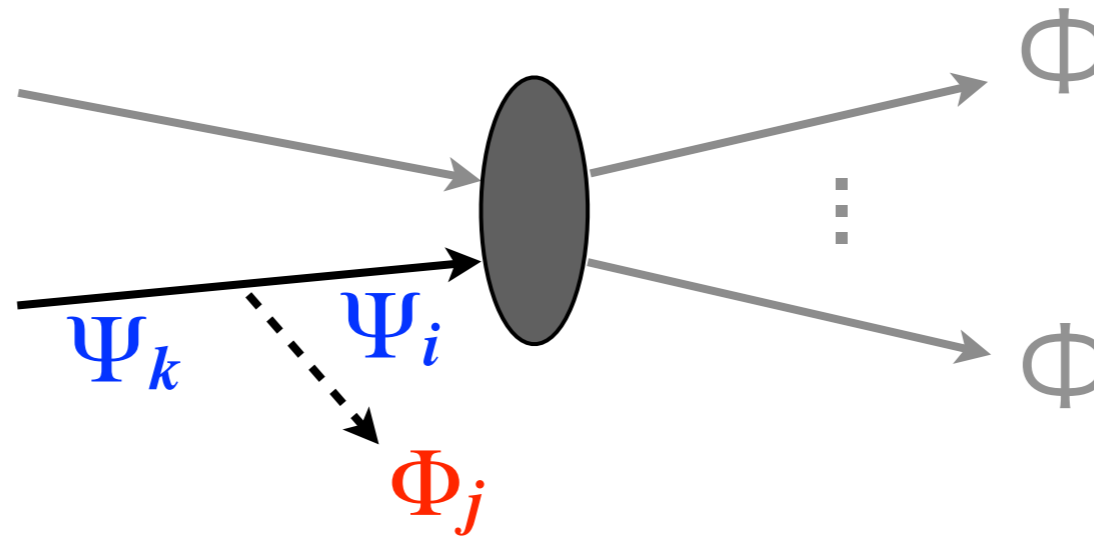
$$\begin{aligned} \Phi_q &= u^1 v^1 e^{-(1-u)a_q L^2} e^{S_q} \dots \\ \Phi_g &= u^1 v^0 e^{-(1-u)a_g L^2} e^{-(1-uv^2)a_{qq} L} e^{S_g} \dots \end{aligned}$$

↑
↑
↑
↑

0-th order
DL
(gluon jet)
SL(g→qq)
(quark jet)
subsequent emissions
(both)



ISR



- evolution equation

$$\Psi_i(x, t) = \Pi_i(x, t) + \sum_k \int_x^1 \frac{dx'}{x'} \int_{t_0}^t \frac{dt'}{t'} \frac{\Pi_i(x, t)}{\Pi_i(x, t')} \times \frac{f_k(x', t)}{f_i(x, t)} \mathcal{P}_{k \rightarrow ij} \Psi_k(x', t') \Phi_j((x' - x) p_{\text{beam}}, t')$$

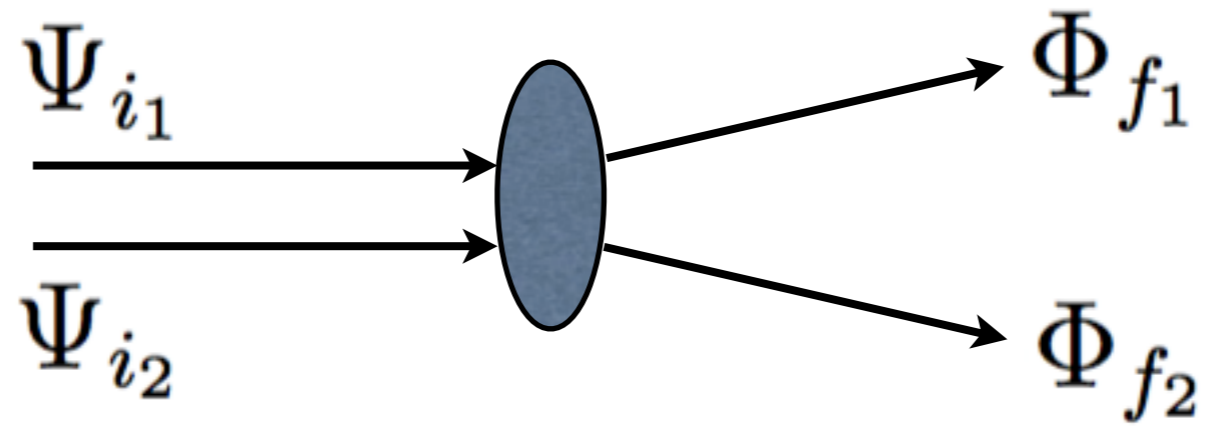
- solutions

$$\Psi_q = e^{-(1-u) a_q \kappa_q \lambda} e^{-(1-uv) a_{qq} c_q \lambda} e^{\mathcal{S}_g[f_{q/q}]} \dots$$

$$\Psi_g = e^{-(1-u) a_g \kappa_g \lambda} e^{-(1-uv) a_{qg} c_g \lambda} e^{\mathcal{S}_g[f_{g/g}]} \dots$$

↑ (gluon jet) ↑ (quark jet) ↑ subsequent emissions (both)

ISR+FSR



$$\Phi_{i_1 i_2 \rightarrow f_1 f_2} = \Psi_{i_1}(x_1, t_{i_1}) \Psi_{i_2}(x_2, t_{i_2}) \Phi_{f_1}(p_{f_1}, t_{f_1}) \Phi_{f_2}(p_{f_2}, t_{f_2})$$

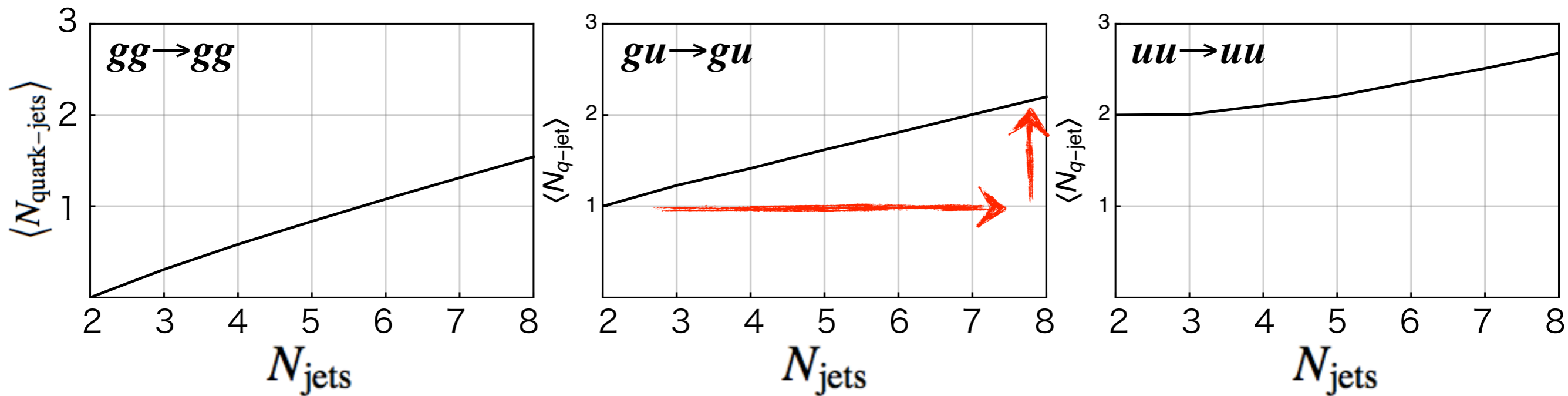
$$\hat{p}_T = p_{f_1} = p_{f_2} = x_1 p_{\text{beam}} = x_2 p_{\text{beam}}$$

- A whole generating functional for a matrix element is given by a product of FSR and ISR generating functionals.

$$R_{n,m} = \frac{1}{n! m!} \frac{\partial^n}{\partial u^n} \frac{\partial^m}{\partial v^m} \Phi_{i_1 i_2 \rightarrow f_1 f_2} |_{u=v=0}$$

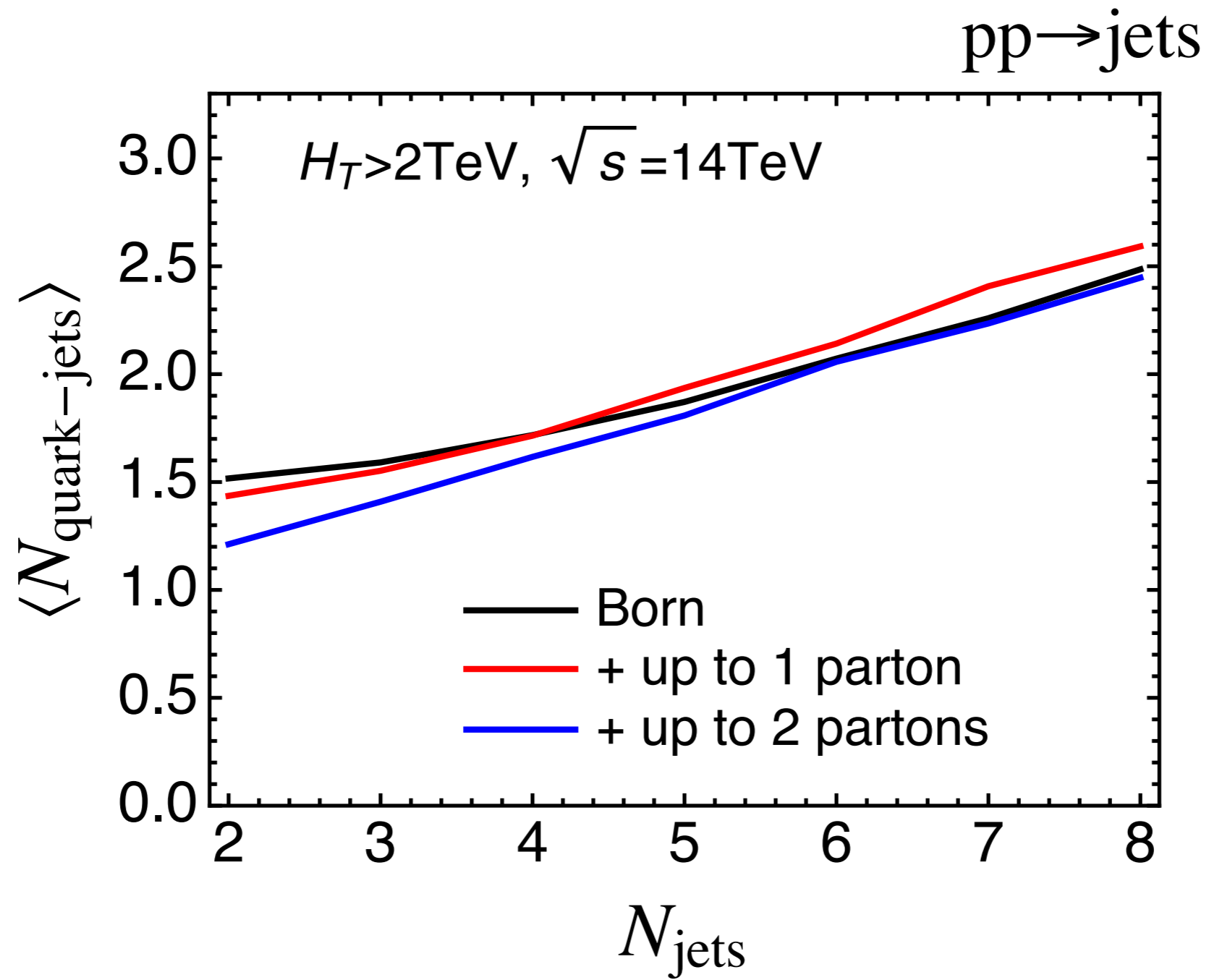
of quark jets

$$\sqrt{\hat{s}} = 2 \text{ TeV}$$

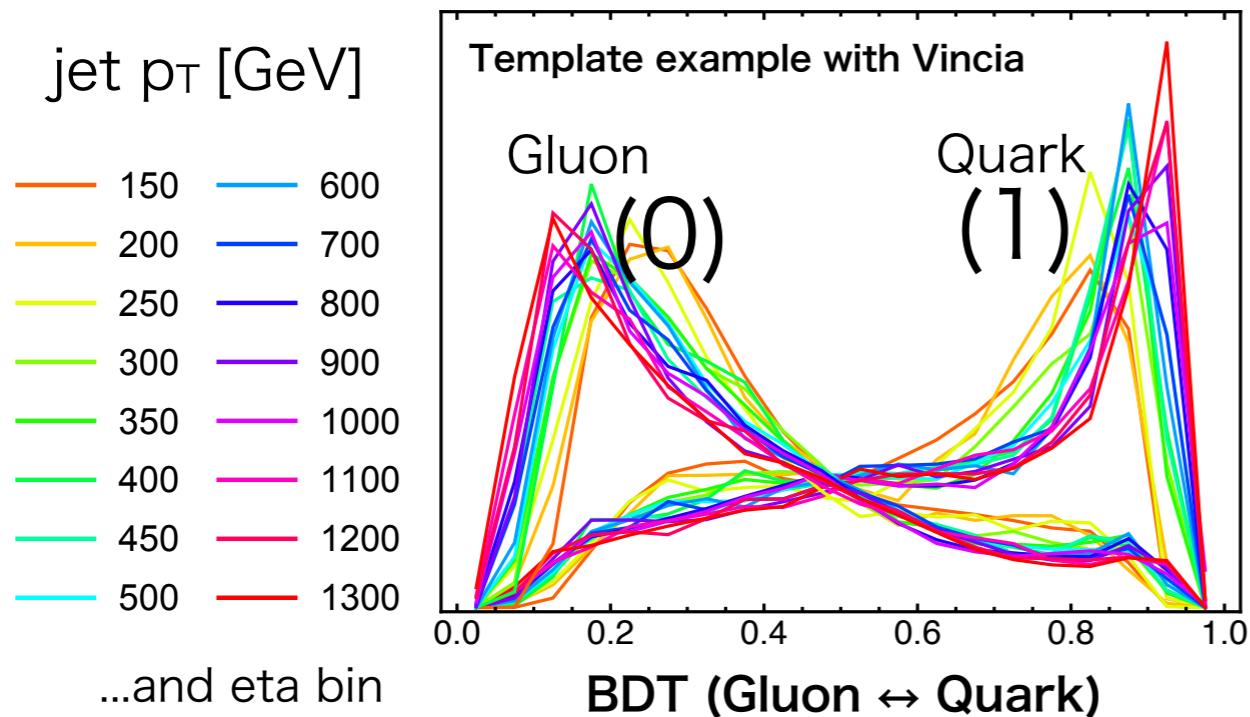


- Increase of gluon jet (double-log), quark jet (single-log)
- QCD multi-jets background is composed of few valence quark jets and many gluon jets
- W/Z/gamma + jets are also available
- It would be useful for MC tuning and development

Matrix element correction

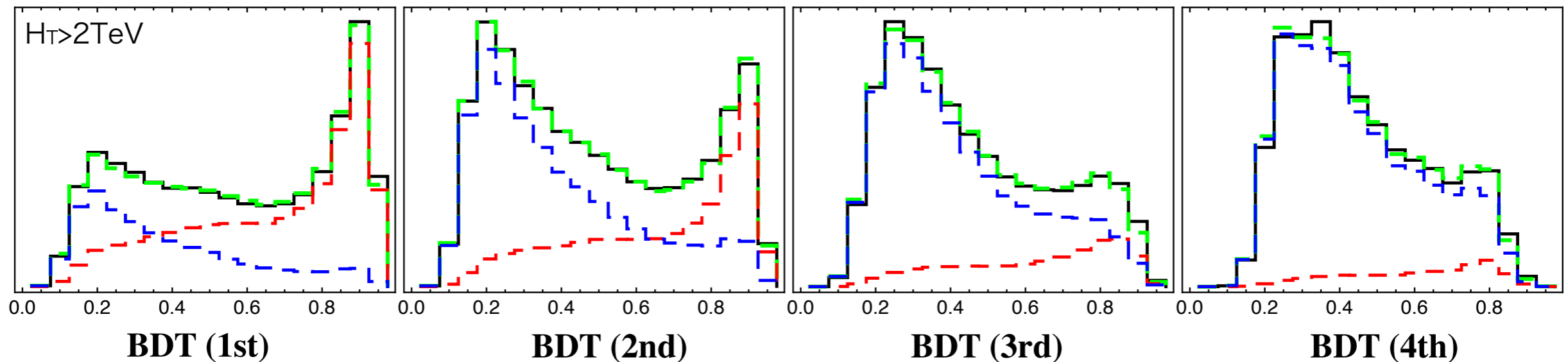


How to measure quark jet rates



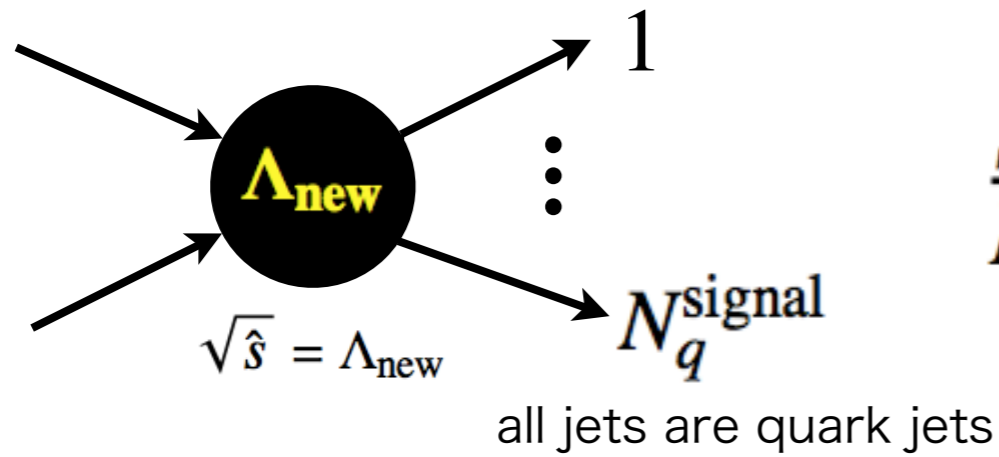
- Make quark/gluon jet templates for a variable from di-jet, Z/γ +jet sample

— $pp \rightarrow 4\text{jets}$ - - - Fitted - - - Quark component - - - Gluon component

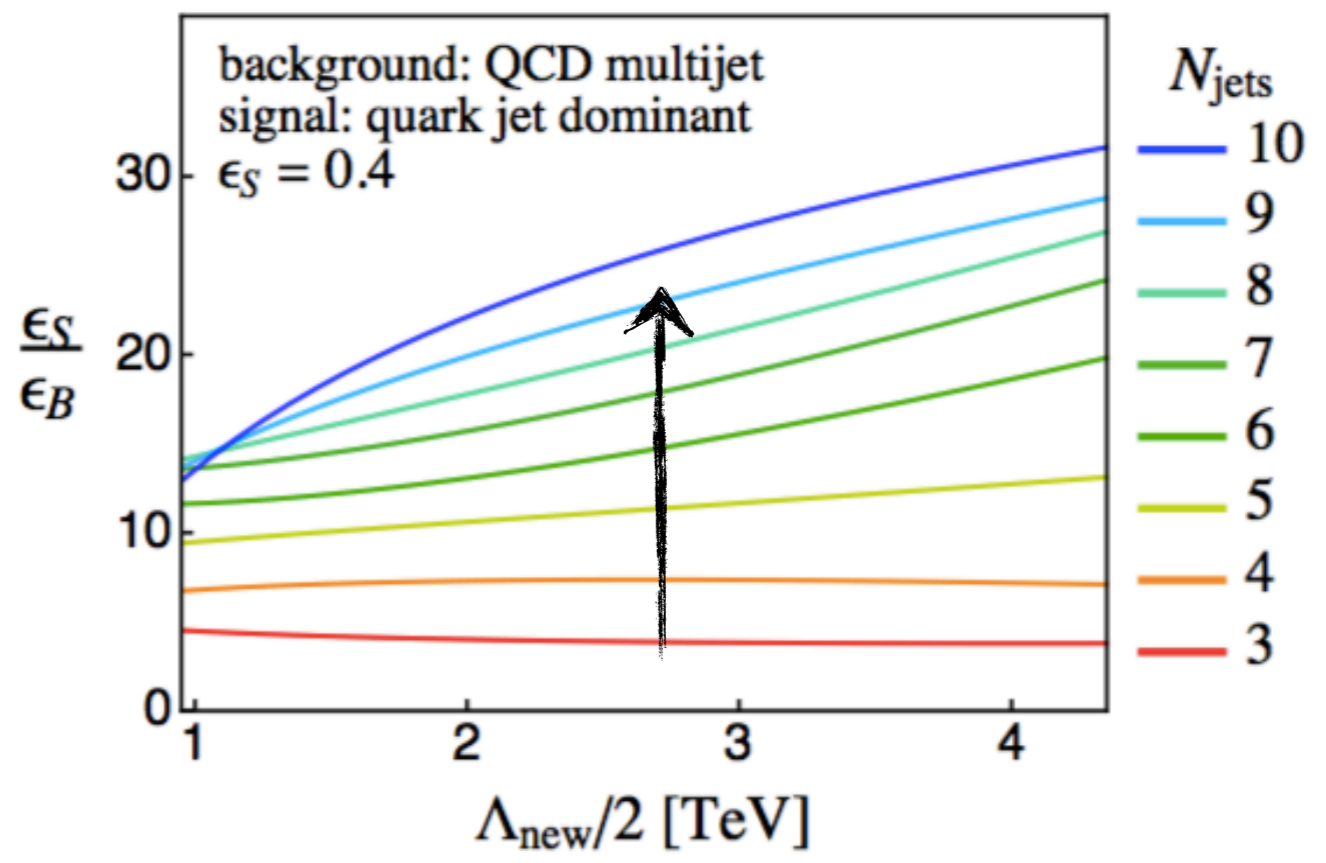
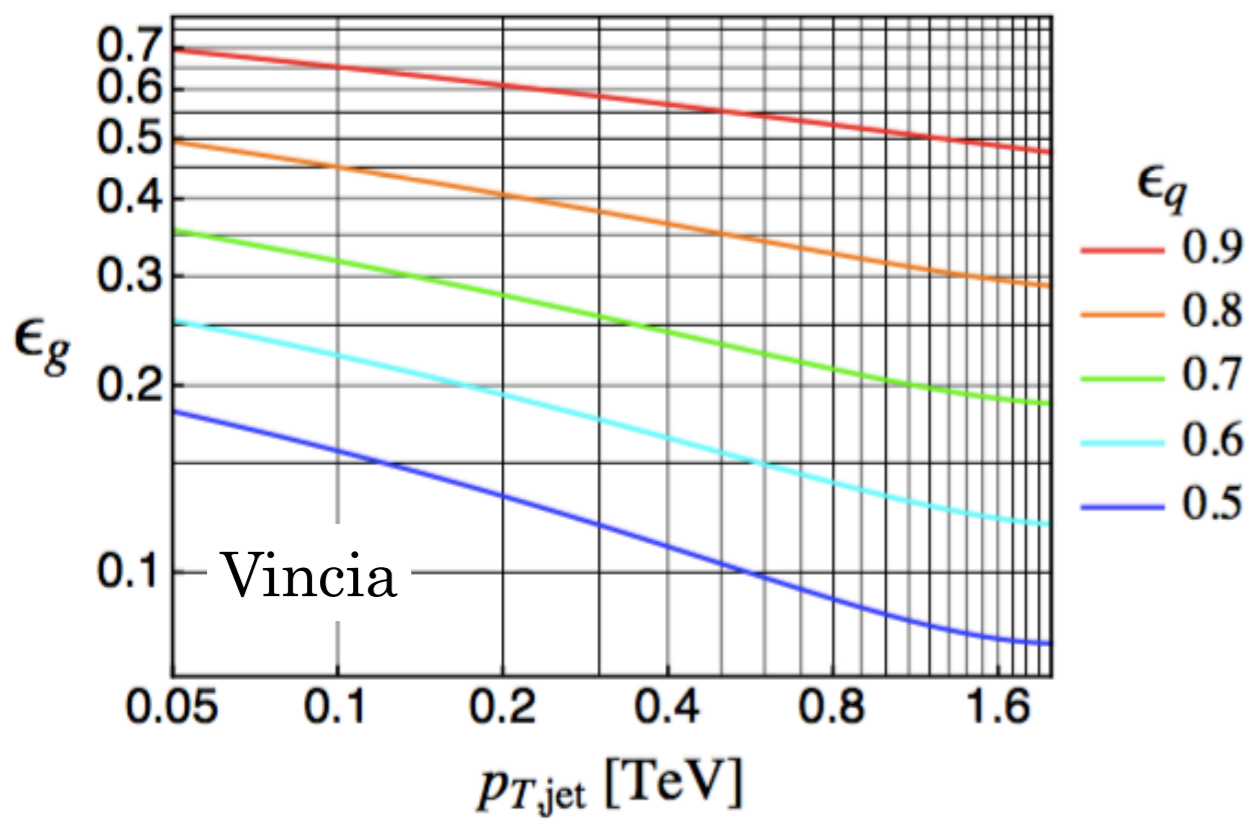


- Measurable, if the QCD jet substructure is universal (It depends on only p_T and rapidity, not # of jet)
- Many applications are conceivable

Expected improvement of S/B



$$\frac{S}{B} \propto \frac{\epsilon_S}{\epsilon_B} \sim \left(\frac{\epsilon_q}{\epsilon_g} \right)^{N_q^{\text{signal}} - N_q^{\text{QCD-bkg}}}$$



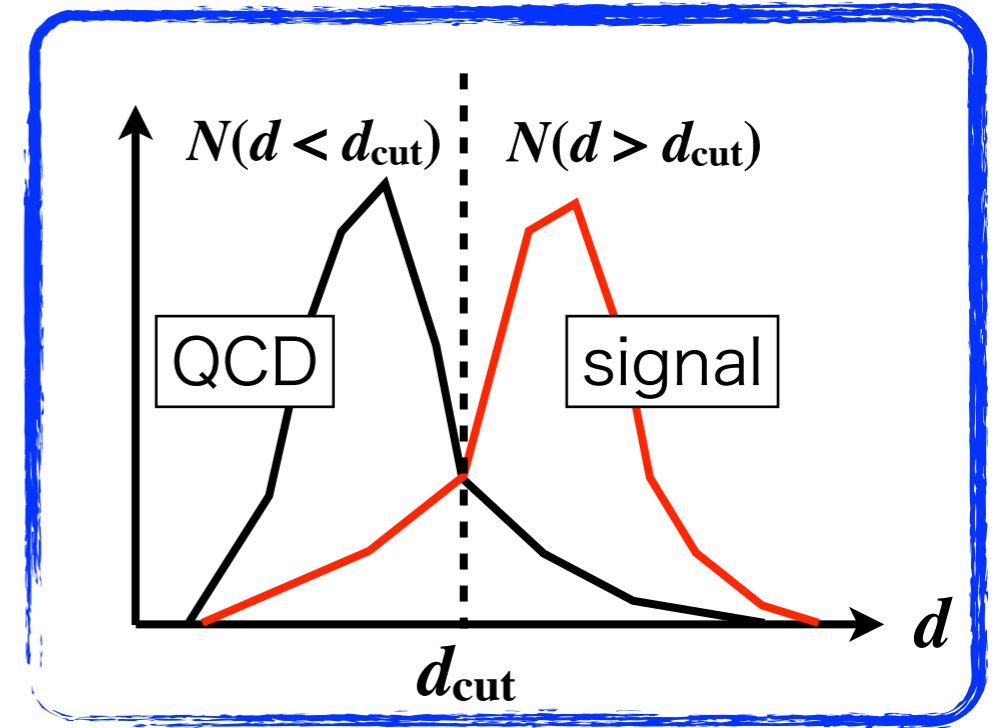
$$\hat{p}_T = \Lambda_{\text{new}}/2 \quad \mu_F = \hat{p}_T$$

MC analysis

QCD jets $\vec{\text{BDT}} \sim (1, 0, 0, 0, 0, \dots), (1, 1, 0, 0, 0, \dots)$

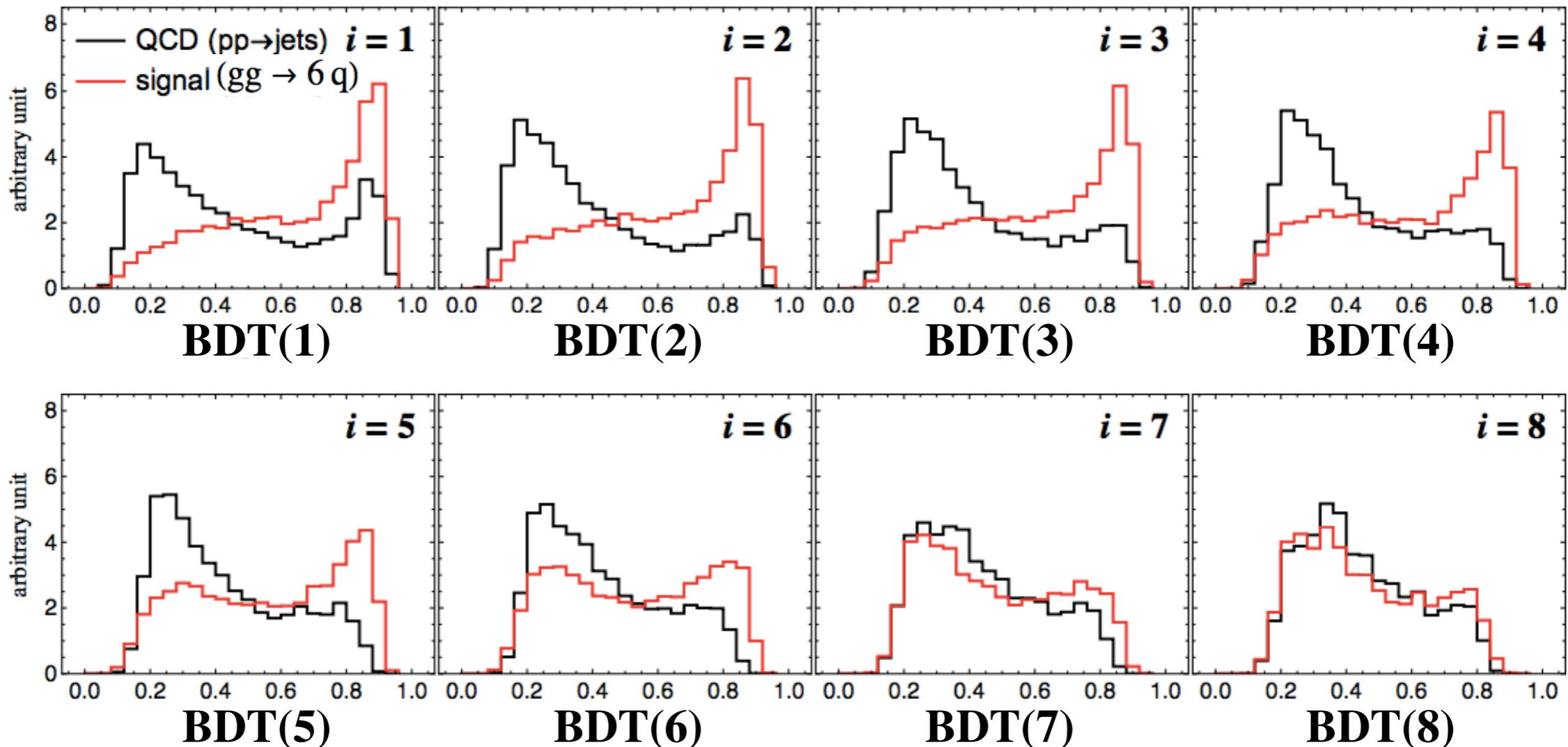
signal $\vec{\text{BDT}} \sim (1, 1, 1, 1, 1, \dots)$

- Distance: $d = \frac{1}{n} \left\| \vec{\text{BDT}} \right\|$, (simply, Euclidean norm)



$N_{\text{jets}} \geq 8, H_T > 2 \text{ TeV}$

toy-signal: $gg/u\bar{u} \rightarrow XX, X \rightarrow N\text{-quarks}$

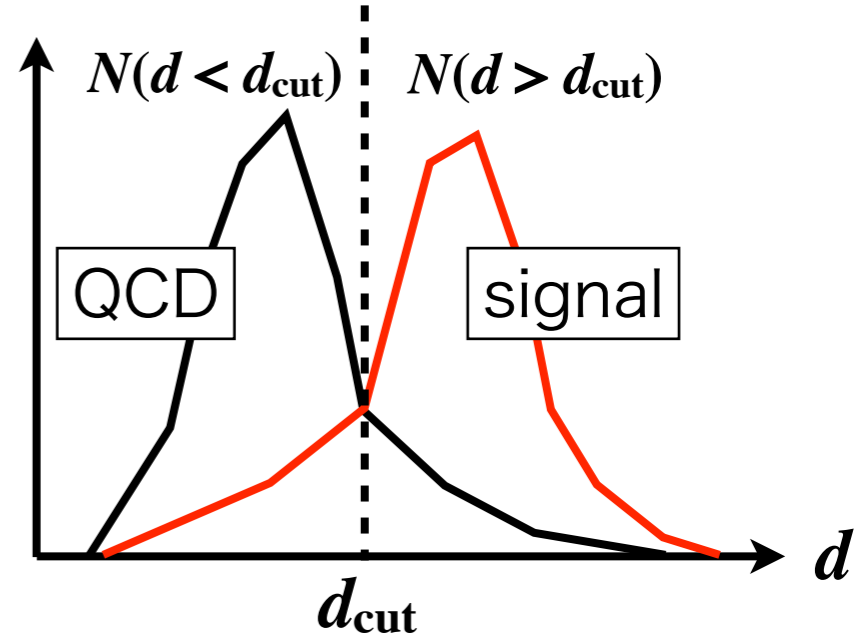


MC analysis

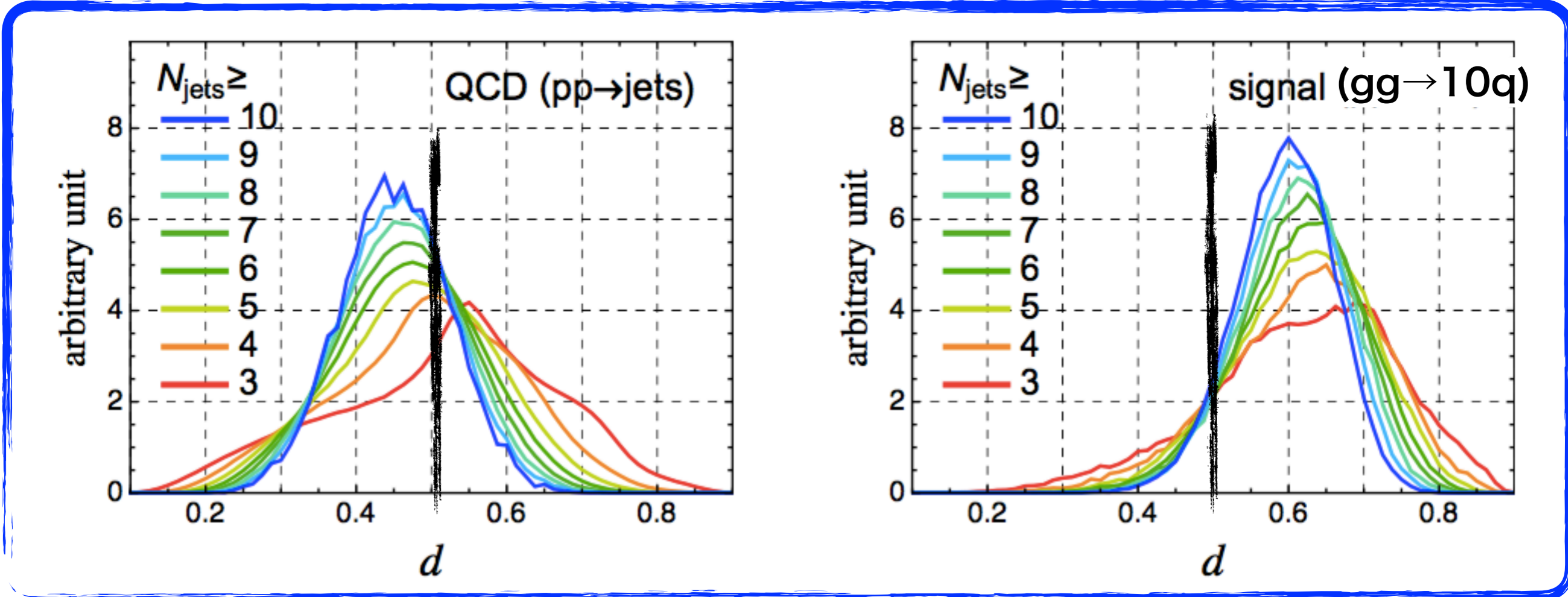
QCD jets $\vec{\text{BDT}} \sim (1, 0, 0, 0, 0, \dots), (1, 1, 0, 0, 0, \dots)$

signal $\vec{\text{BDT}} \sim (1, 1, 1, 1, 1, \dots)$

- Distance: $d = \frac{1}{n} \left\| \vec{\text{BDT}} \right\|$, (simply, Euclidean norm)



toy-signal: $gg/u\bar{u} \rightarrow XX, X \rightarrow N\text{-quarks}$

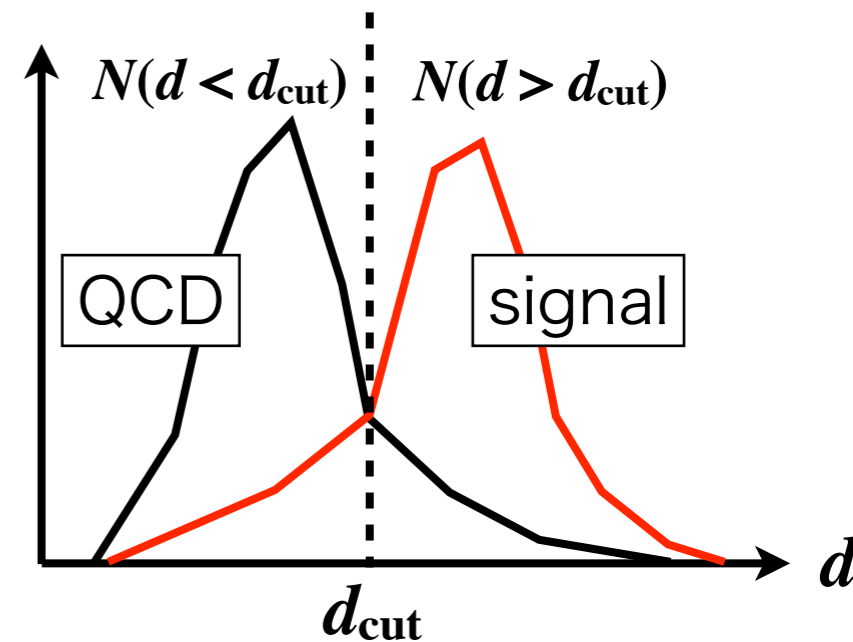


MC analysis

QCD jets $\vec{\text{BDT}} \sim (1, 0, 0, 0, 0, \dots), (1, 1, 0, 0, 0, \dots)$

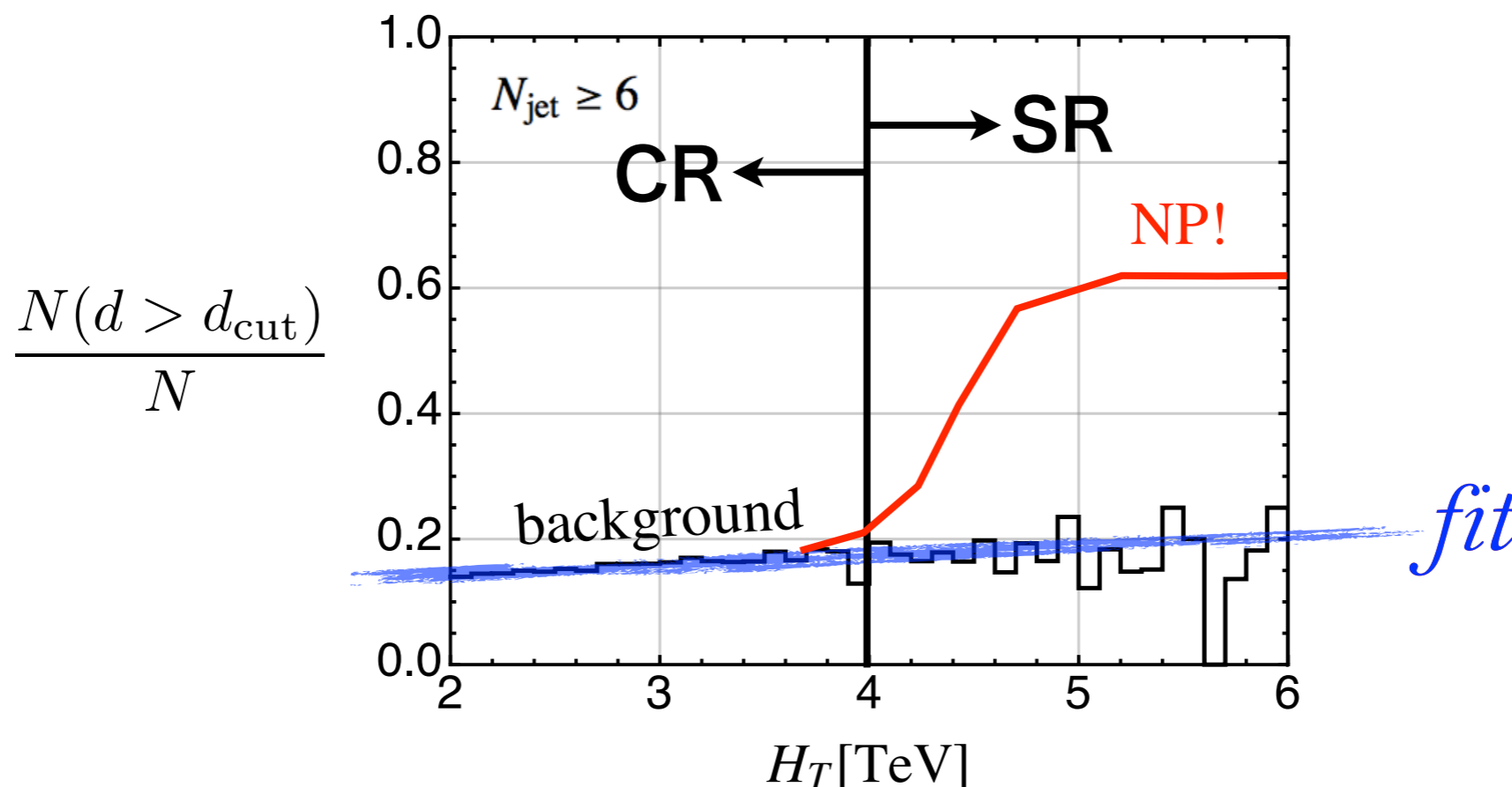
signal $\vec{\text{BDT}} \sim (1, 1, 1, 1, 1, \dots)$

- Distance: $d = \frac{1}{n} \left\| \vec{\text{BDT}} \right\|$, (simply, Euclidean norm)



toy-signal: $gg/u\bar{u} \rightarrow XX, X \rightarrow N\text{-quarks}$

- We can estimate # of background of each bins by data-driven extrapolations



Enhancement of S/B with d

$$\frac{S}{B} \sim \frac{\sigma_S}{\sigma_B} \times \left(\frac{\epsilon_S}{\epsilon_B} \right) \times \left(\frac{\epsilon_S}{\epsilon_B} \right) \times \left(\frac{\epsilon_S}{\epsilon_B} \right)$$

selection cut jet substructure cut (d cut)
 \downarrow \downarrow
 \uparrow H_T cut

toy-signal: $gg/u\bar{u} \rightarrow XX$, $X \rightarrow N$ -quarks

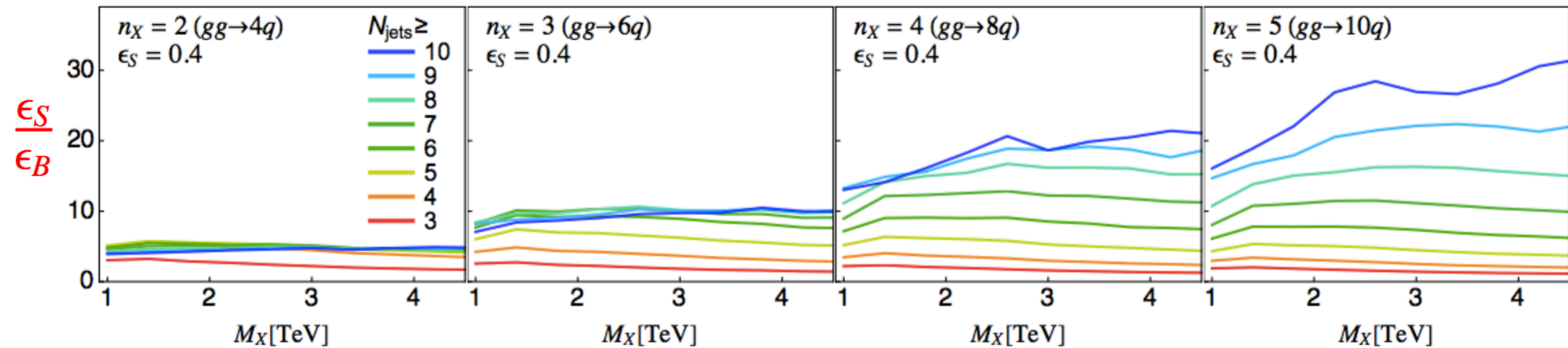
After imposing H_T cut. Fixed at $\epsilon_S = 0.4$

$N=2$

$N=3$

$N=4$

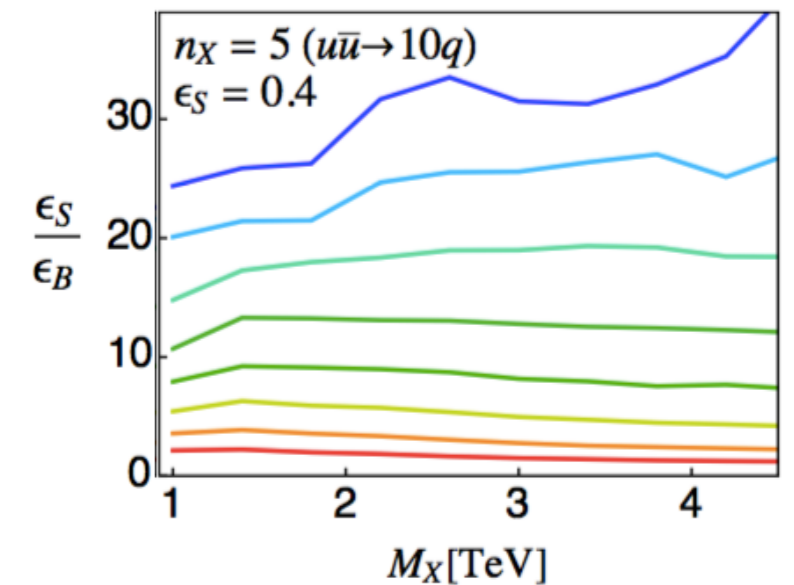
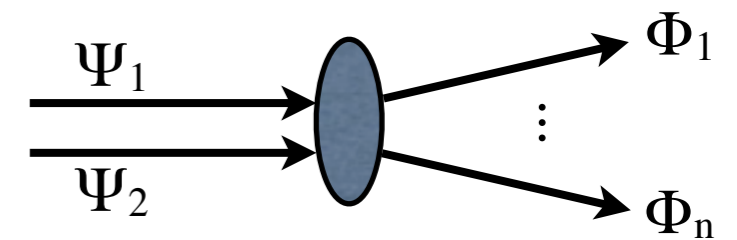
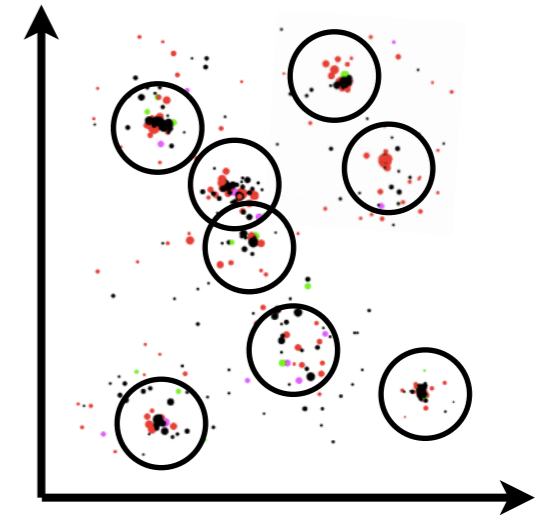
$N=5$



- Large enhancement of S/B

Summary

- Quark/gluon discrimination can be maximally utilized for BSM searches in multi-jet final states.
- Quark and gluon jet fraction in QCD multi-jet background was estimated.
- Introducing a variable for the data-driven analysis in multi-jet final states, we checked the large improvement of S/B using the variable.



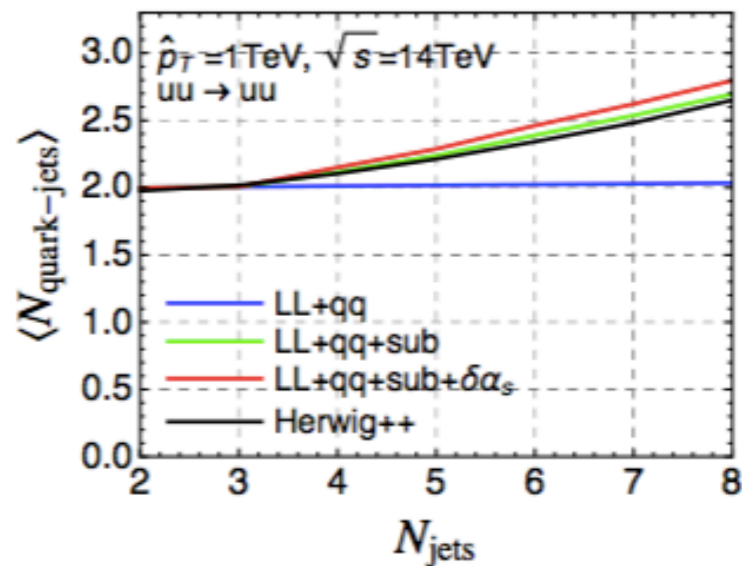
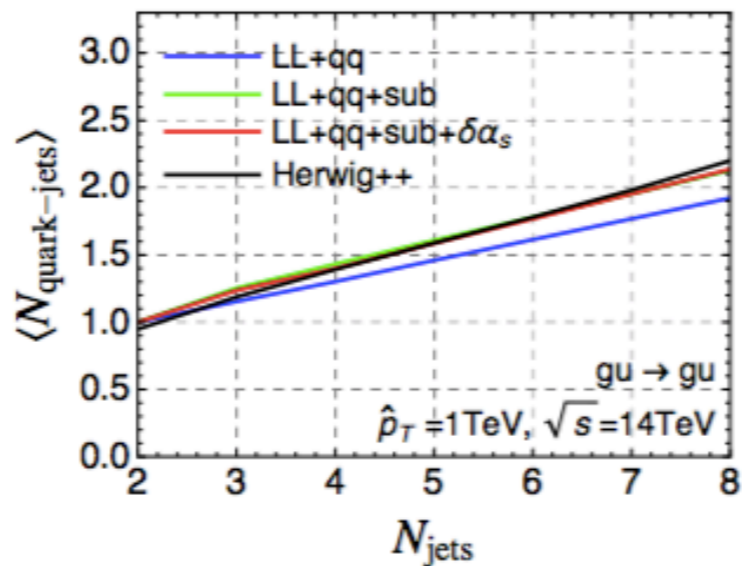
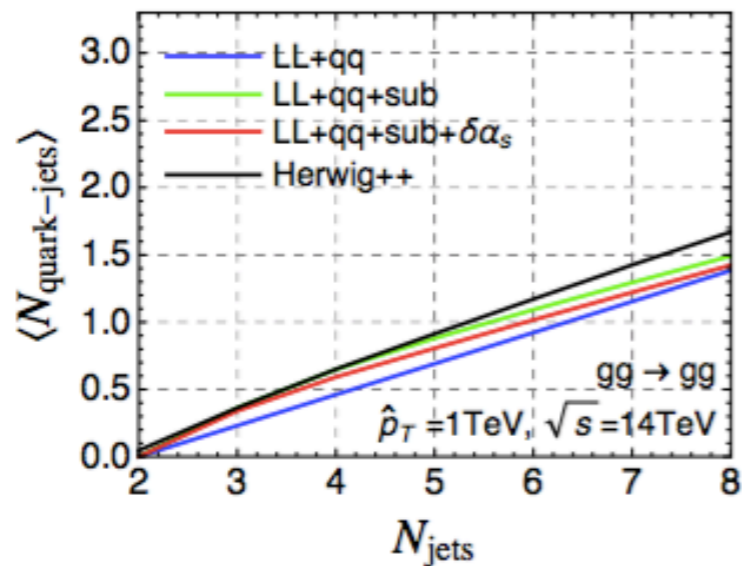
*B*ack up
Belle II

ISR+FSR

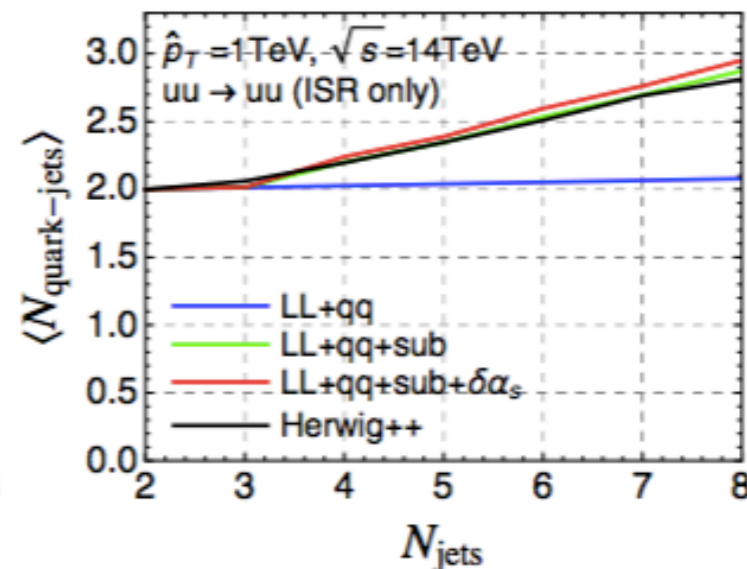
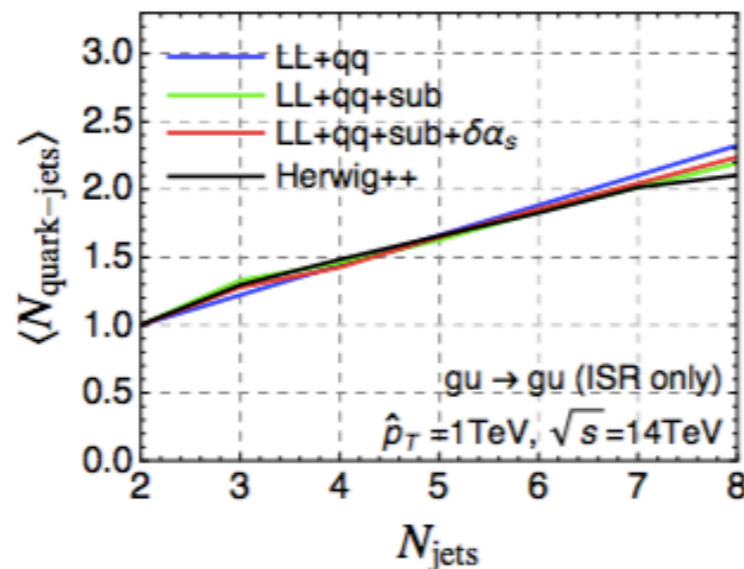
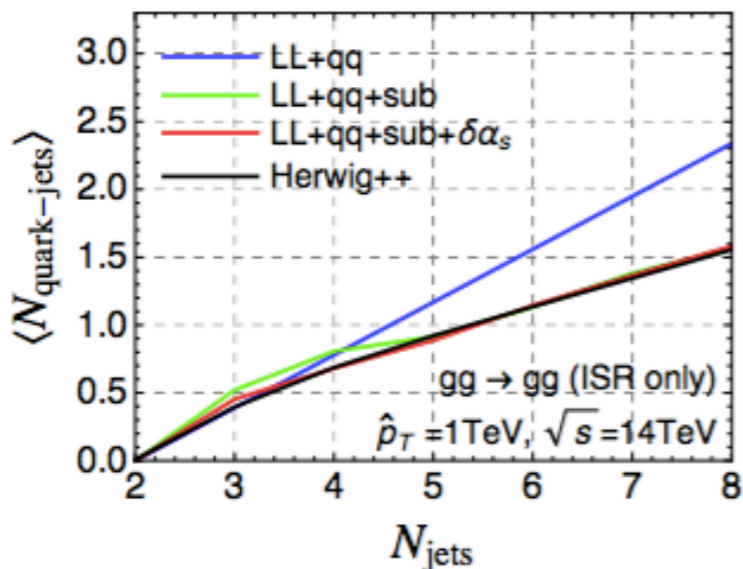
$gg \rightarrow gg$

$gu \rightarrow gu$

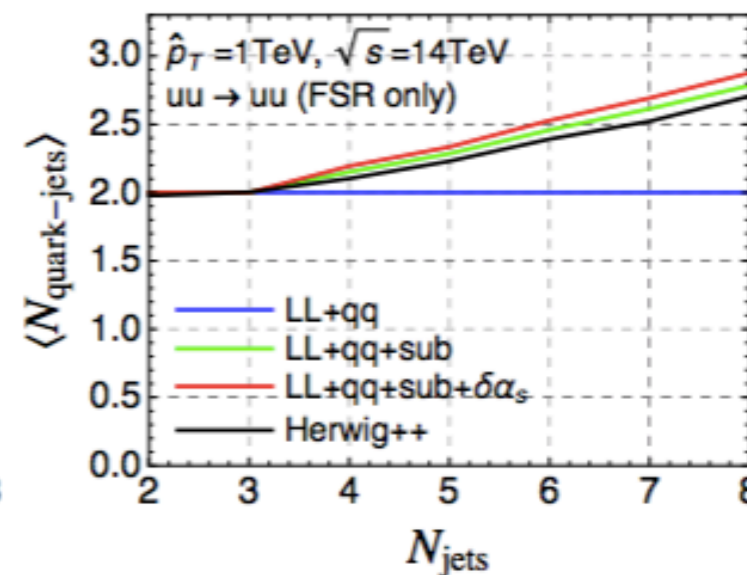
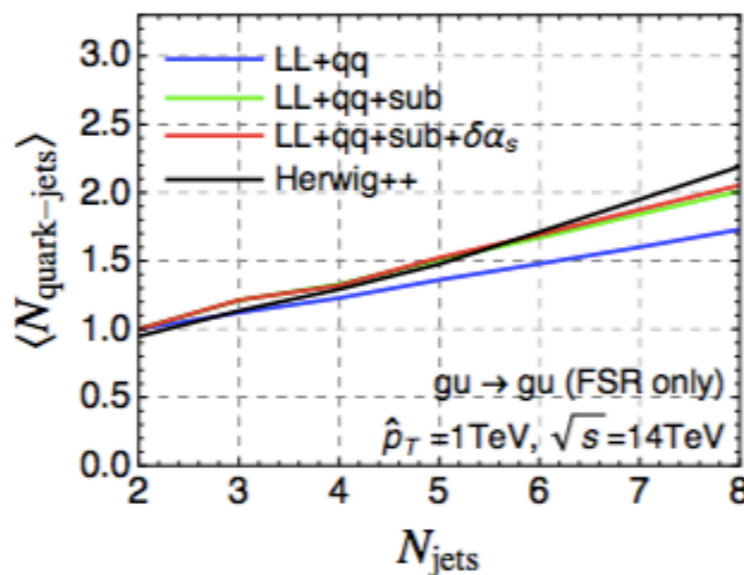
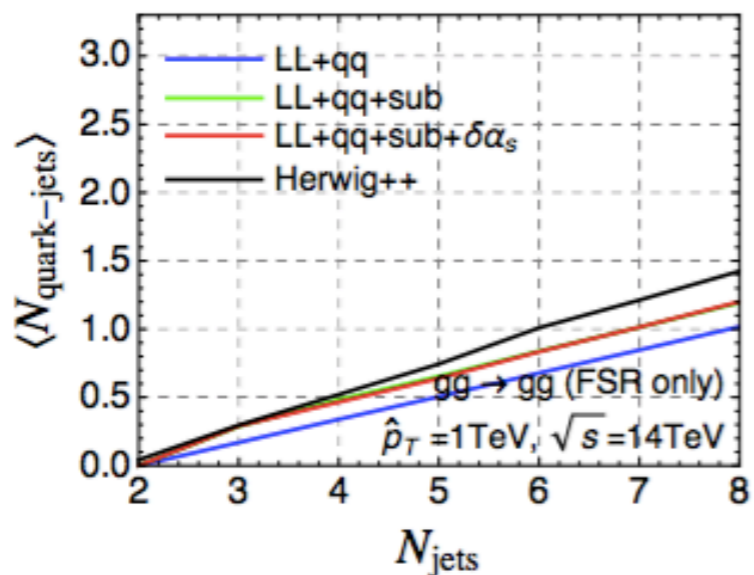
$uu \rightarrow uu$



ISR-only



FSR-only



Enhancement of S/B with d

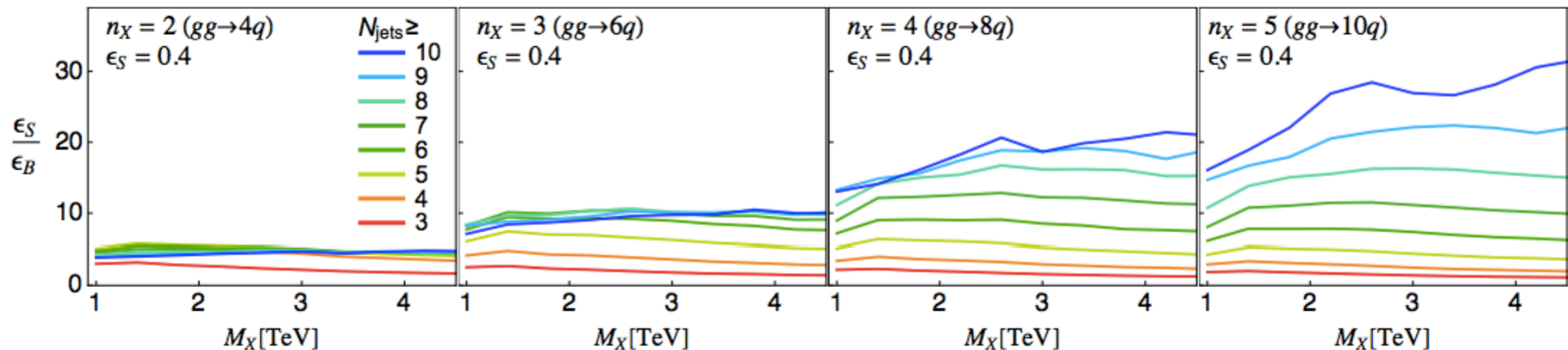


Figure 8: M_X -dependence on the efficiency ratio. We can see how the ratio changes with increasing the lower bound of N_{jets} from 3 to 10, and n_X from 2 (left-most) to 5 (right-most).

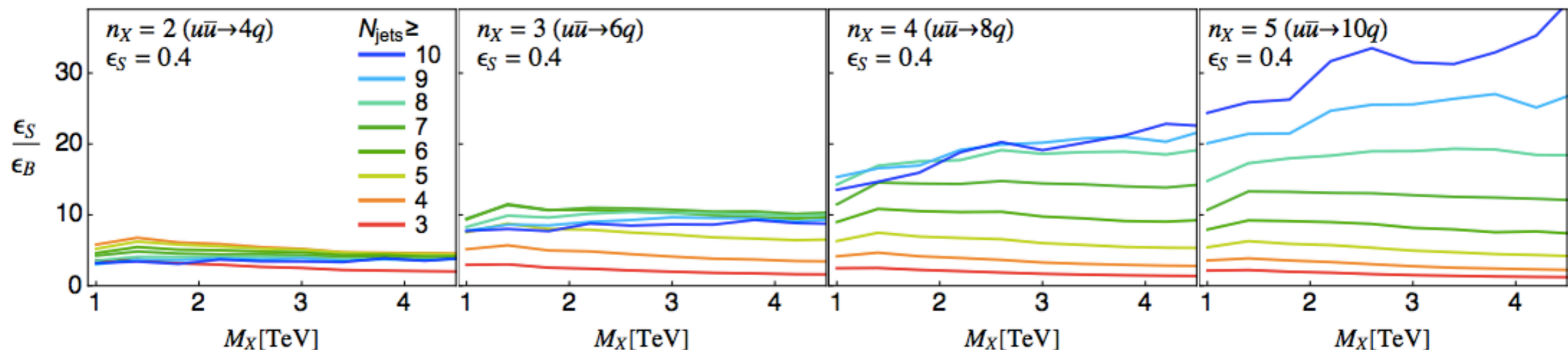


Figure 9: Same as Fig. 8, with the initial states $u\bar{u}$.