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

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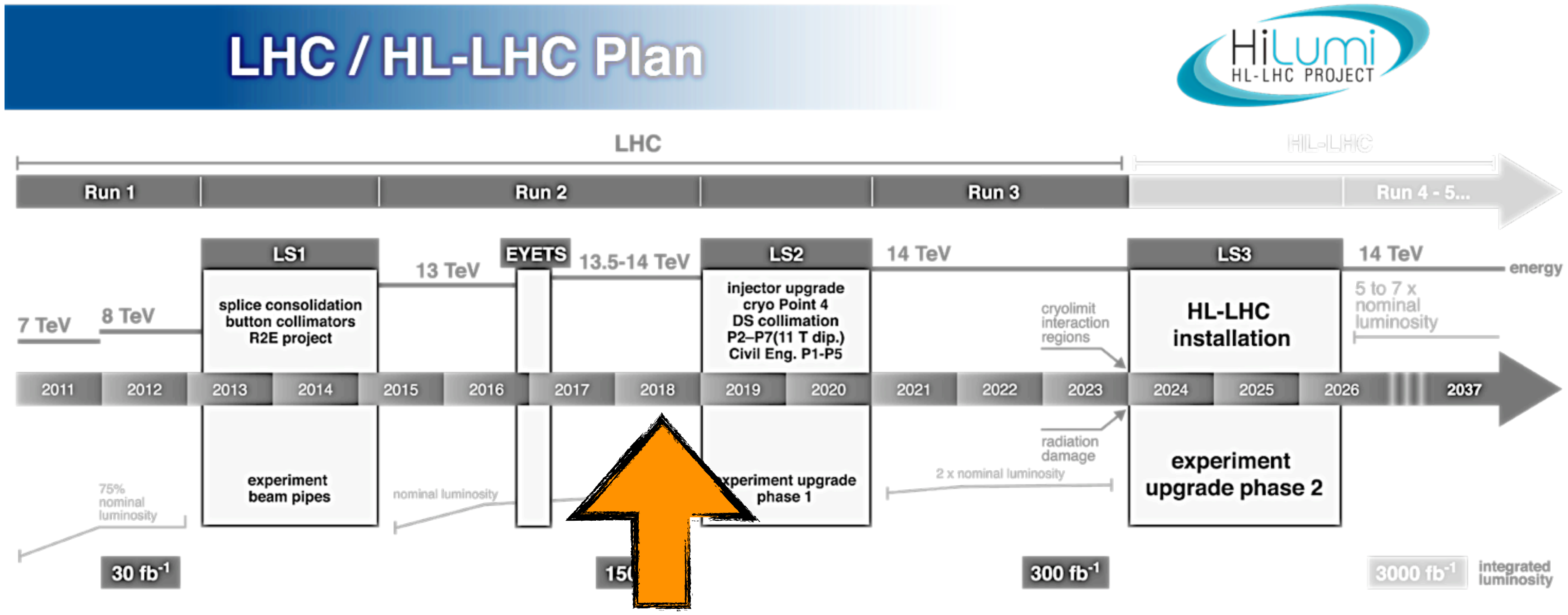
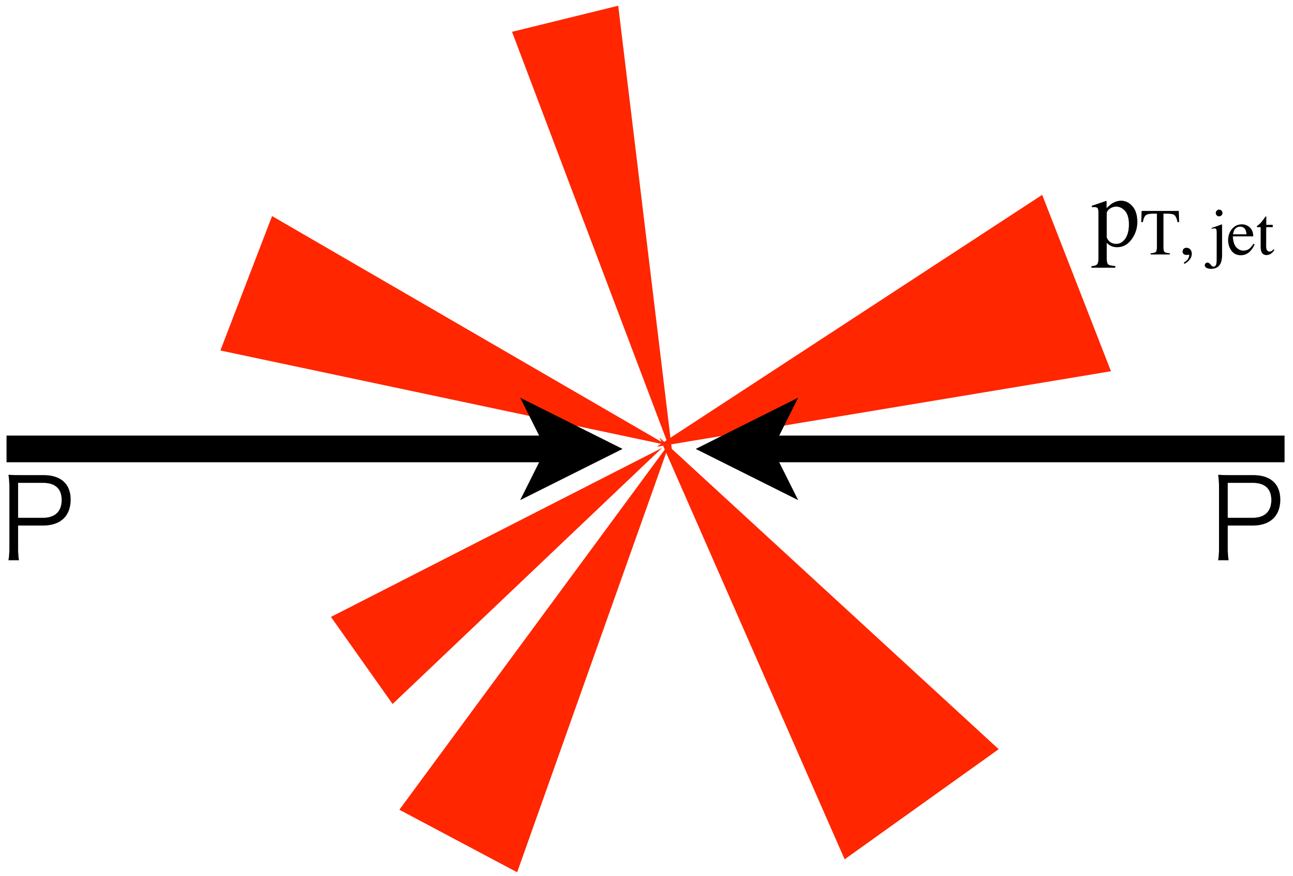


- No clear sign of BSM at the LHC
- Need to examine final states more precisely
- Final states are categorized by inclusive variables
  - ➡ N(jets), N(leptons), H_T, ...
- Categories containing jets encounter a huge QCD background
- As increasing N(jets), kinematics and MC validation become more complicated
- 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...

➡ <u>**data-driven analysis**</u>



inclusive variable:
ex) $H_T = \Sigma p_{T,\text{jet}}$

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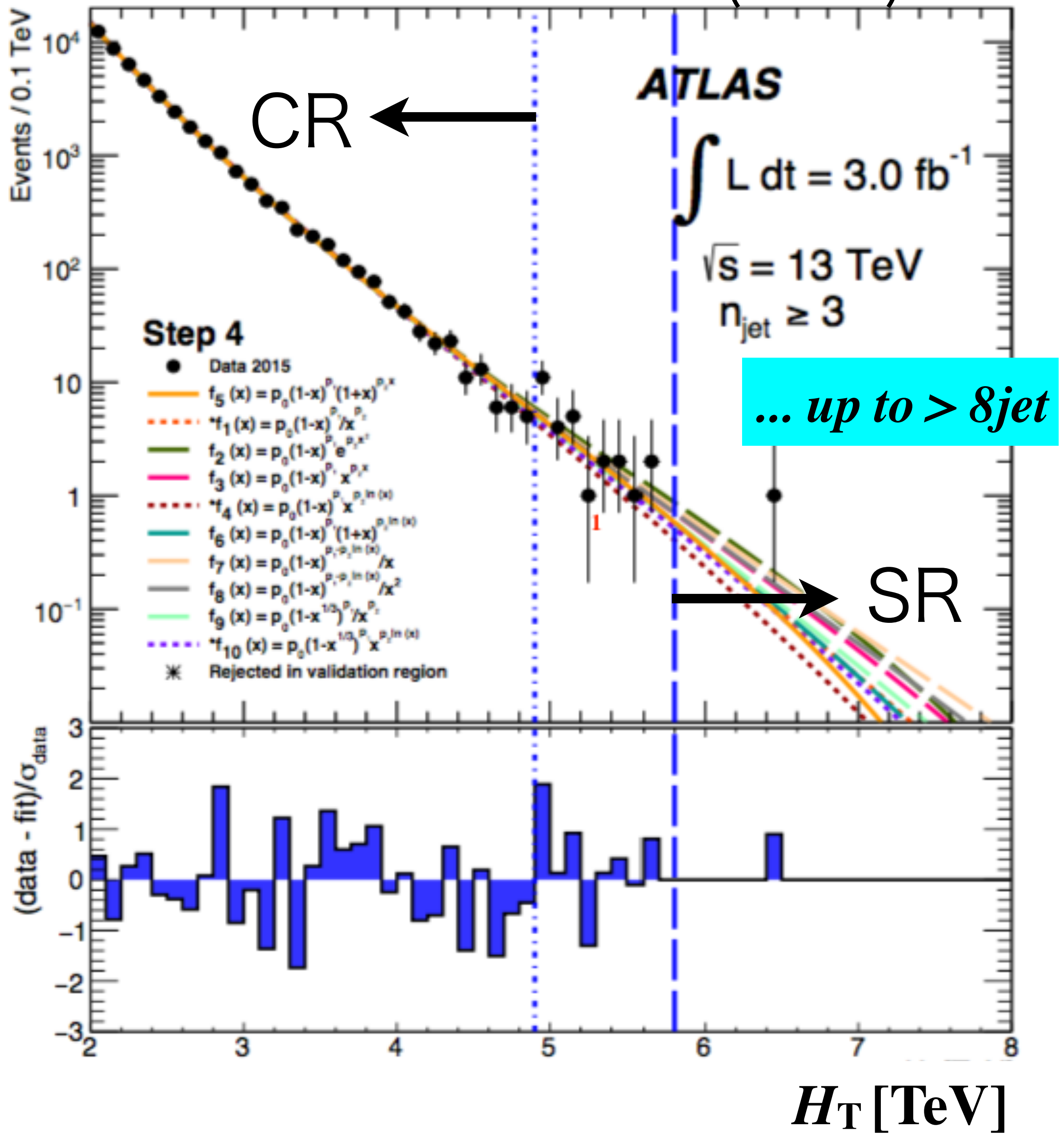
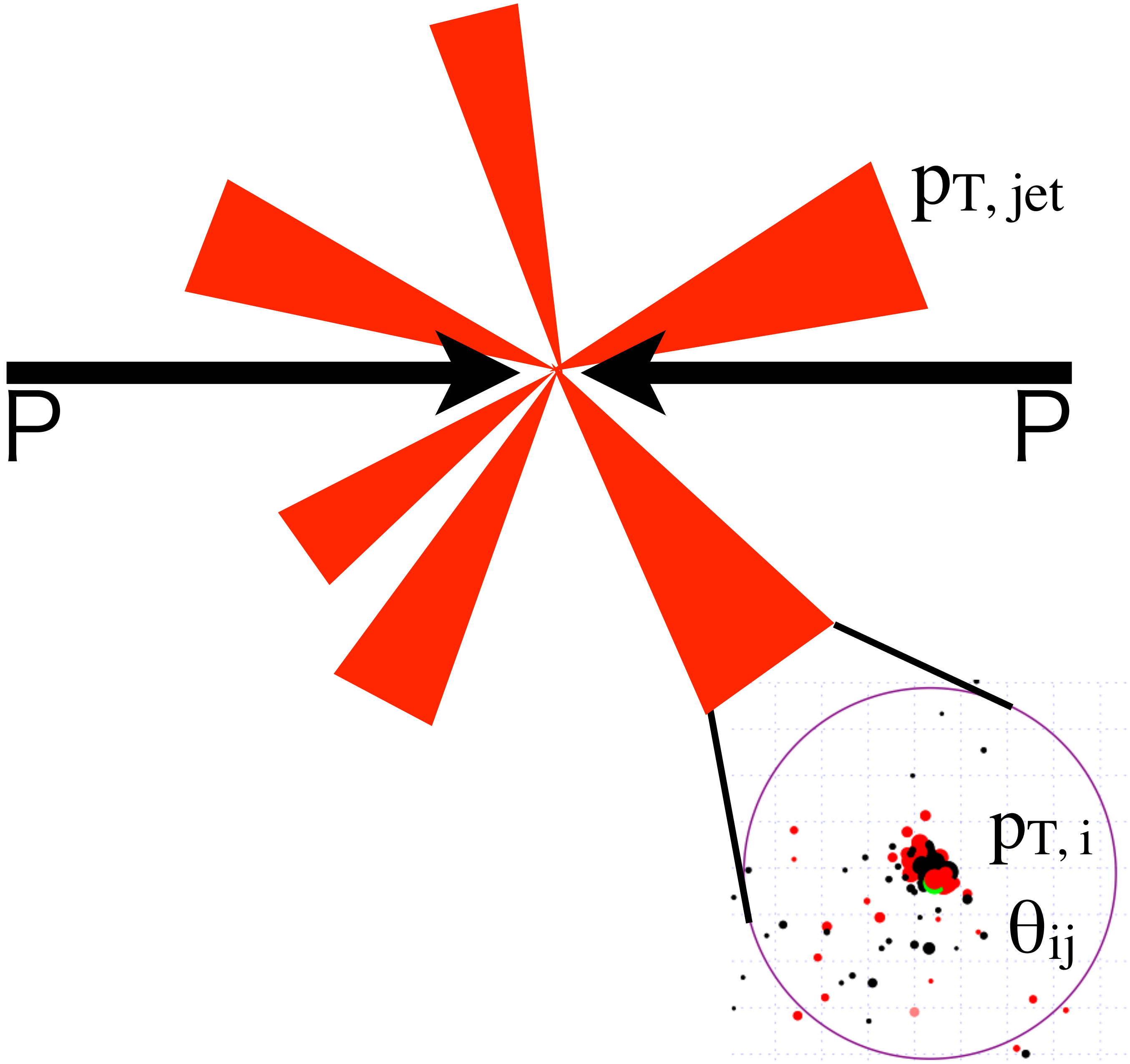


... up to > 8jet

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

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

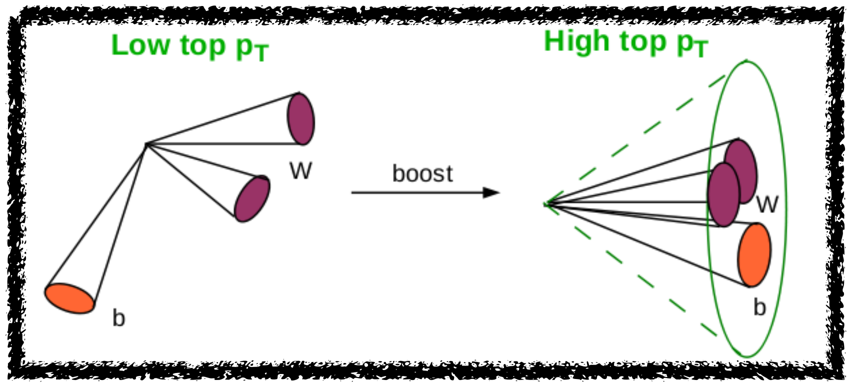
exclusive

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

jet flavor/substructure

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

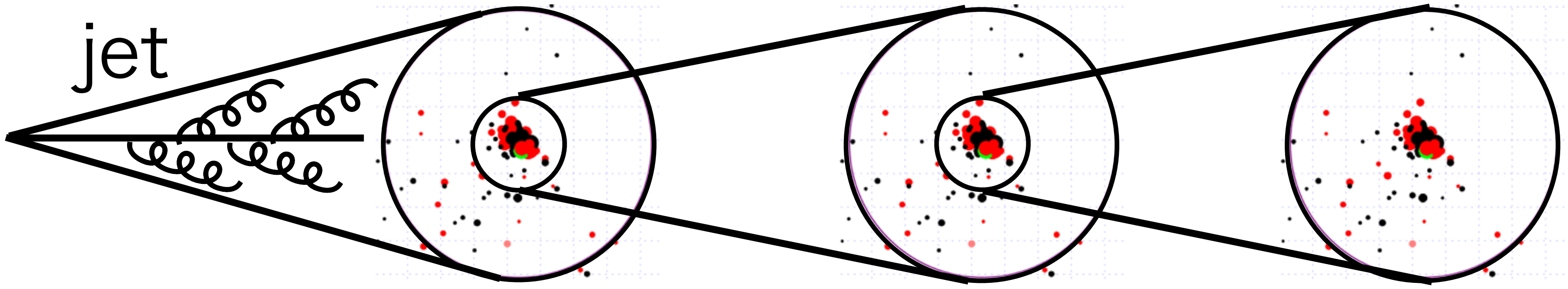
- Jet substructure technique established well as top/W/Z/H tagging tools (2-, 3-prong structure)



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

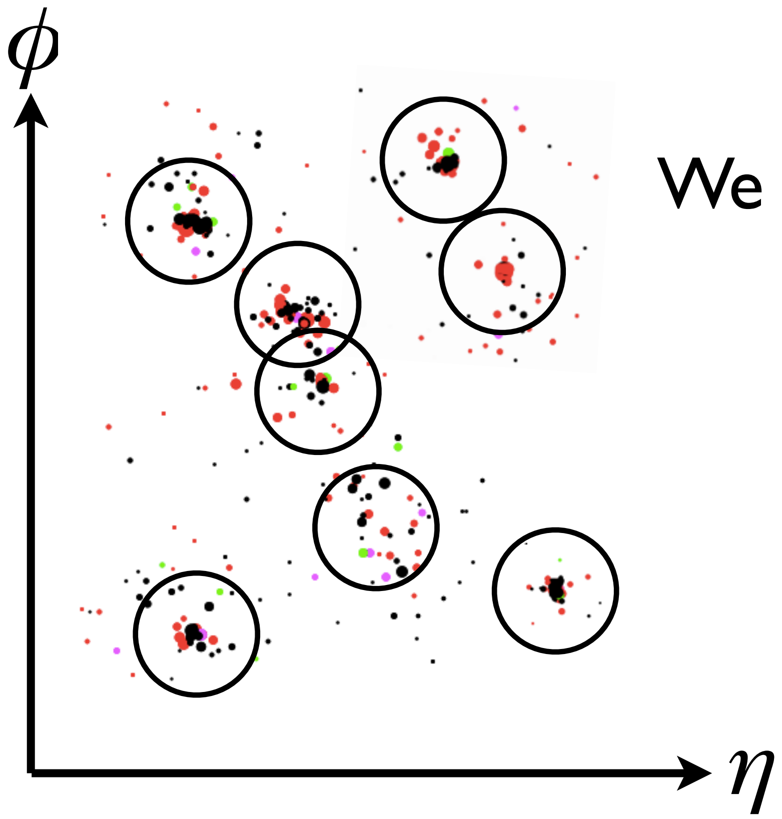
jet substructure	formed by	R (jet radius)
top W Z H	EW	~1.0 (fat jet)
quark gluon	QCD	0.4

- 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 $\boldsymbol{N}_{\mathbf{jets}}$ times

$$\Delta N = \left| N^{\text{signal}}_{\text{quark}} - N^{\text{BKG}}_{\text{quark}} \right|$$

$$\Rightarrow \frac{S}{B} \propto \left(\frac{\epsilon_{\text{quark}}}{\epsilon_{\text{gluon}}} \right)^{\Delta N}, \qquad \frac{\epsilon_{\text{quark}}}{\epsilon_{\text{gluon}}} > 1$$

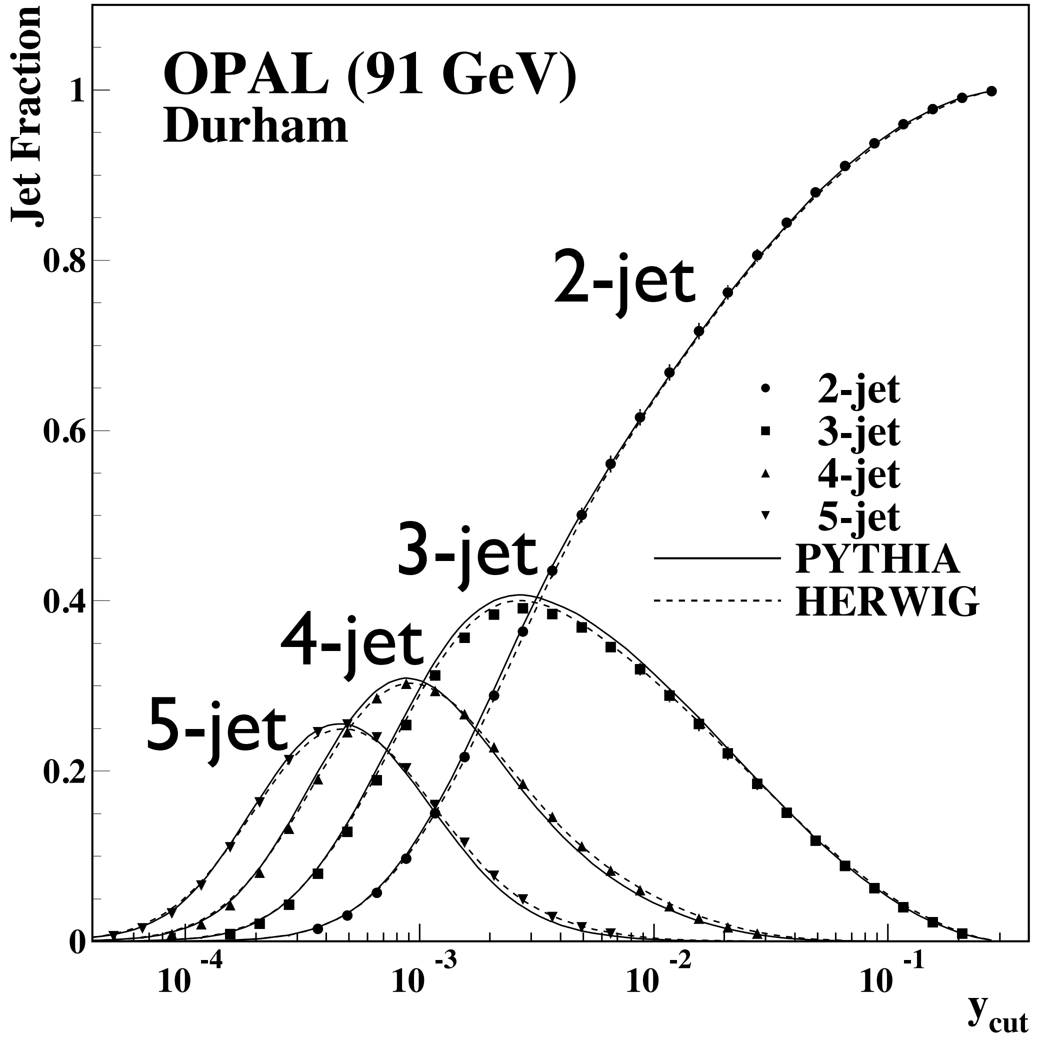
- Large enhancement of S/B for a signal that predicts the number of quark jets which is different from what the QCD background does

➡ 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 ...

OPAL, Eur.Phys.J.C45(2006)



R_{n+1} / R_n

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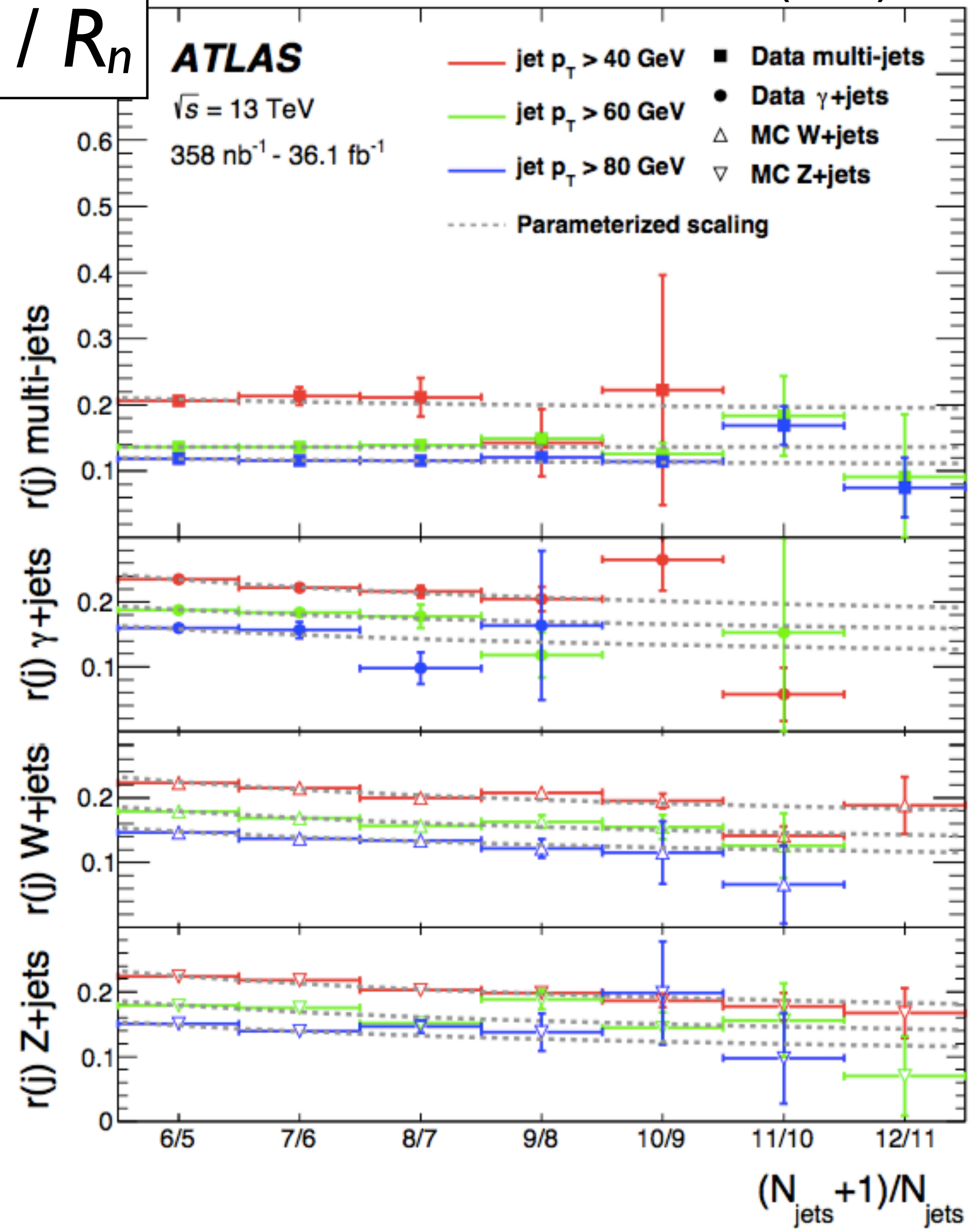
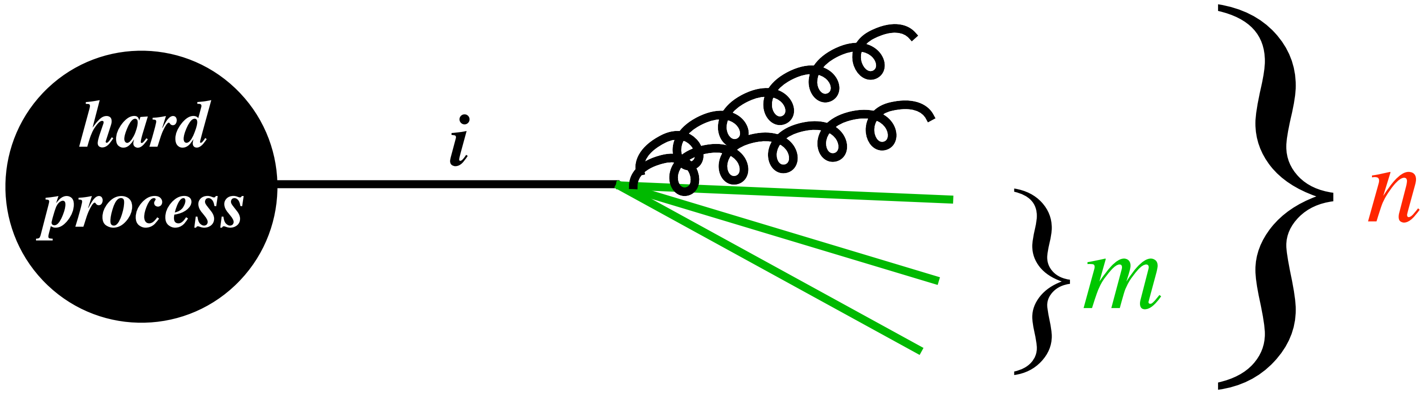


Quark jet rates

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



- Generating functional:

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

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

Solutions

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

$$\Phi_q = u^1 v^1 \; e^{-(1-u)\,a_q L^2} \qquad\qquad\qquad\qquad e^{S_q} \quad \cdots$$

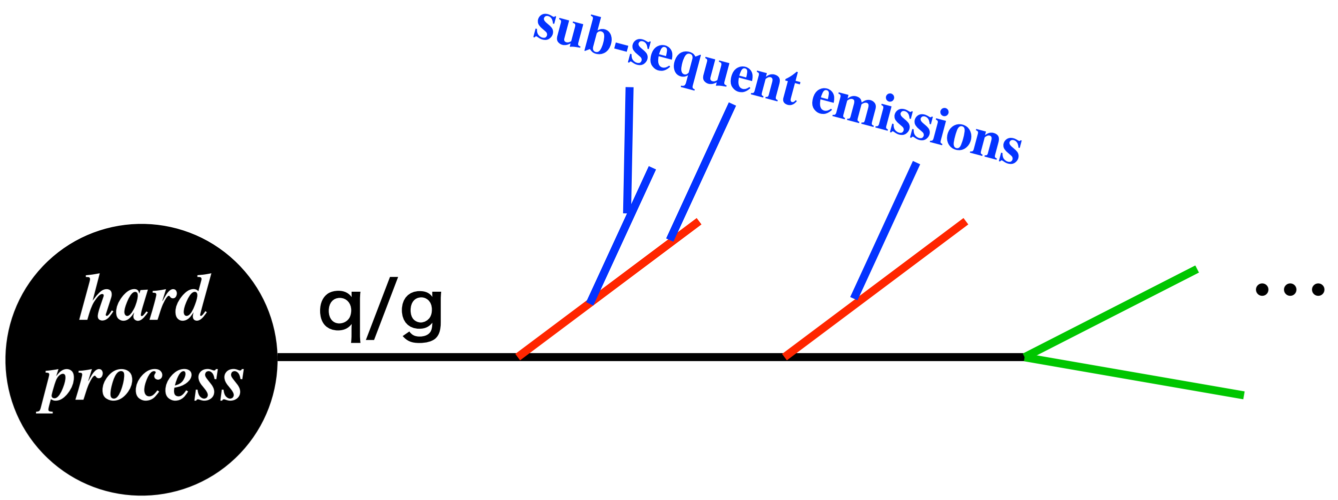
$$\Phi_g = u^1 v^0 \; e^{-(1-u)\,a_g L^2} \; e^{-(1-uv^2)\,a_{qq} L} \; e^{S_g} \quad \cdots$$

0-th order

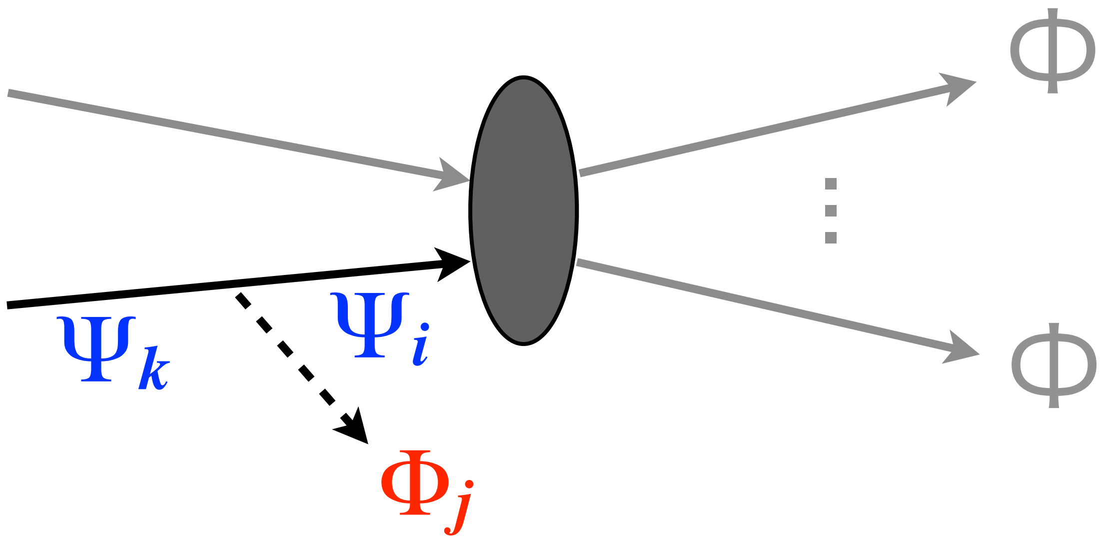
DL
(gluon jet)

SL(g→qq)
(quark jet)

subsequent emissions
(both)



ISR



- evolution equation

$$\Psi_i(x,t) = \Pi_i(x,t) + \sum_k \int_x^1 \frac{dx'}{x'} \int_{t_0}^t \frac{dt'}{t'} \frac{\Pi_i(x,t)}{\Pi_i(x,t')}$$

$$\times \frac{f_k(x',t)}{f_i(x,t)} \mathcal{P}_{k\to ij} \Psi_k(x',t') \Phi_j((x'-x)\, p_{\mathrm{beam}}, t')$$

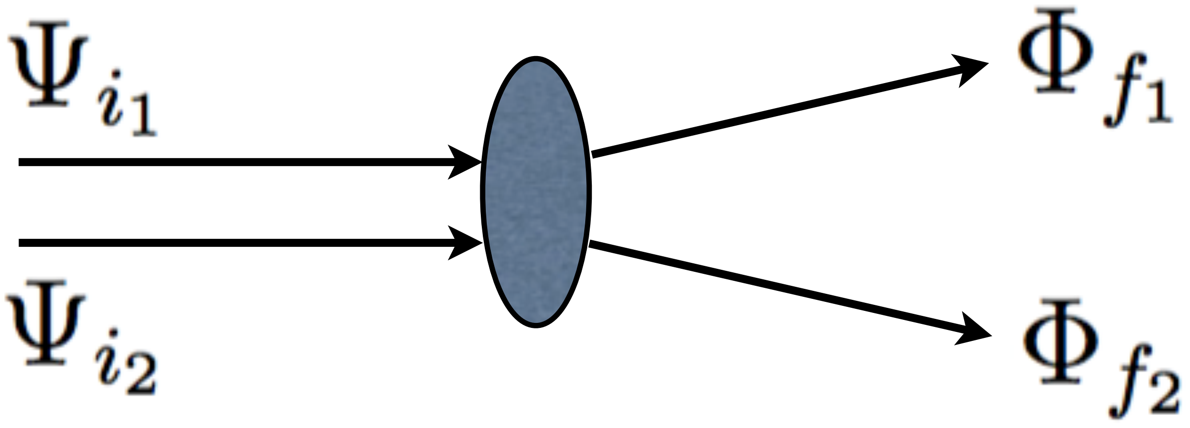
- solutions

$$\Psi_q = \mathrm{e}^{-(1-u)\, a_q \bar{\kappa}_q \lambda} \; \mathrm{e}^{-(1-uv)\, a_{\mathrm{qq}} c_q \lambda} \; \mathrm{e}^{S_g[f_{q/q}]} \; \cdots$$

$$\Psi_g = \mathrm{e}^{-(1-u)\, a_g \bar{\kappa}_g \lambda} \; \mathrm{e}^{-(1-uv)\, a_q c_g \lambda} \; \mathrm{e}^{S_g[f_{g/g}]} \; \cdots$$

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

ISR+FSR



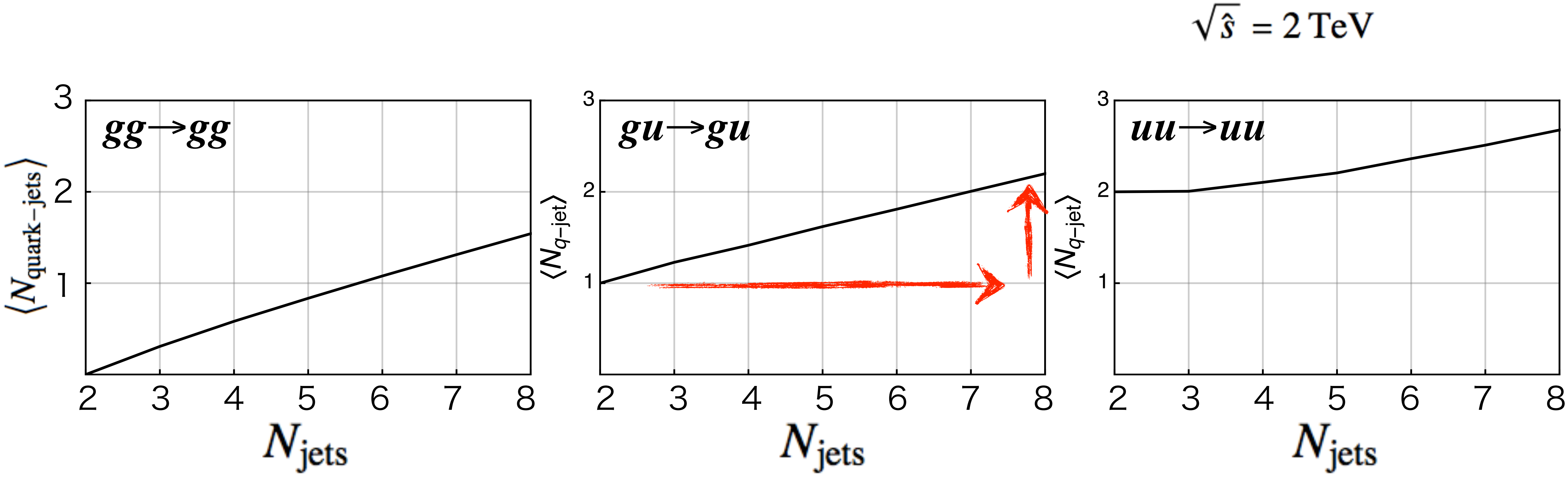
$$\mathbf{\Phi}_{i_1 i_2 \to f_1 f_2} = \Psi_{i_1}(x_1, t_{i_1})\Psi_{i_2}(x_2, t_{i_2})\Phi_{f_1}(p_{f_1}, t_{f_1})\Phi_{f_2}(p_{f_2}, t_{f_2})$$

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

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

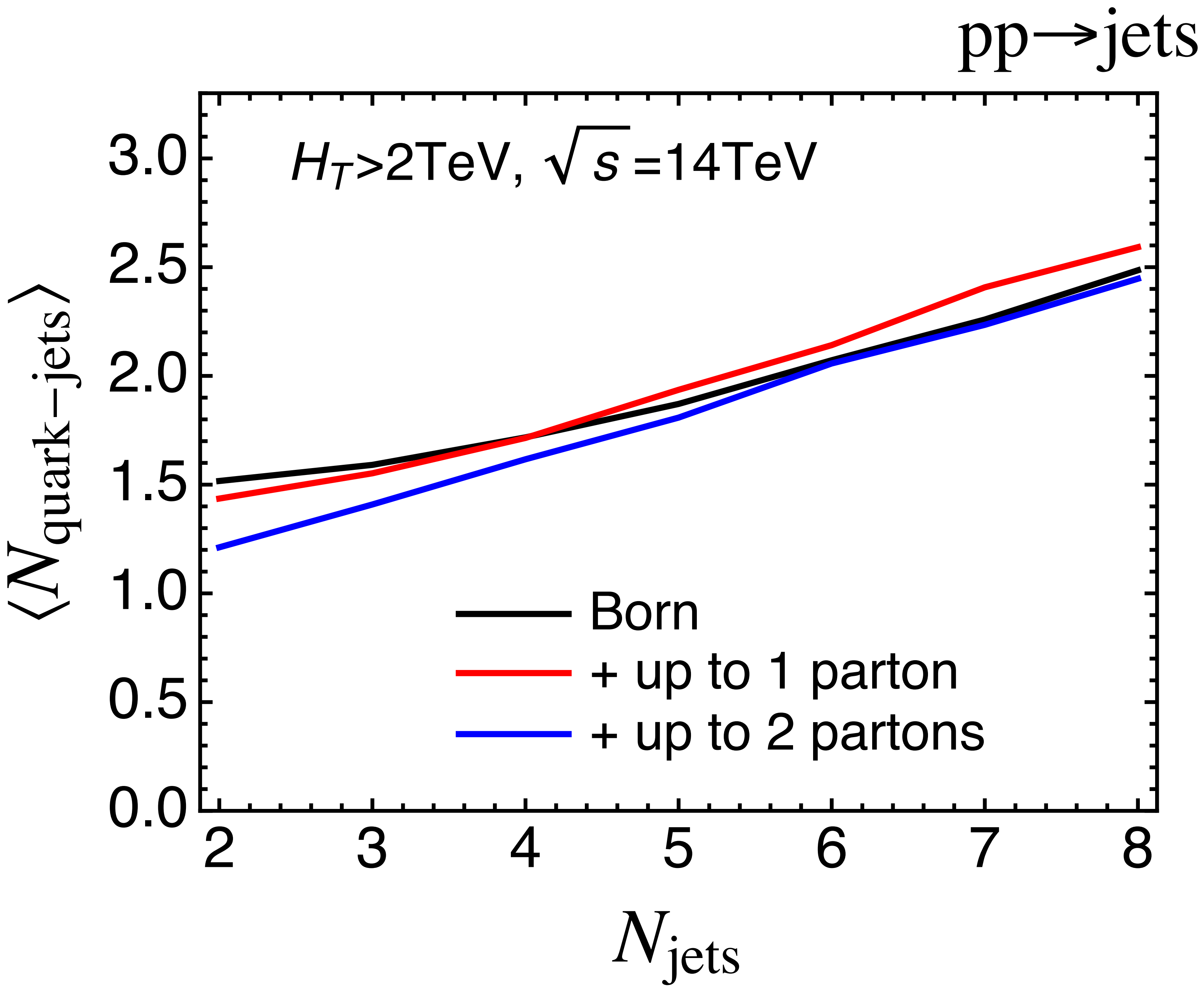
$$R_{n,m} = \frac{1}{n!\, m!} \frac{\partial^n}{\partial u^n} \frac{\partial^m}{\partial v^m} \Phi_{i_1\ i_2 \to f_1\ f_2} |_{u=v=0}$$

of quark jets

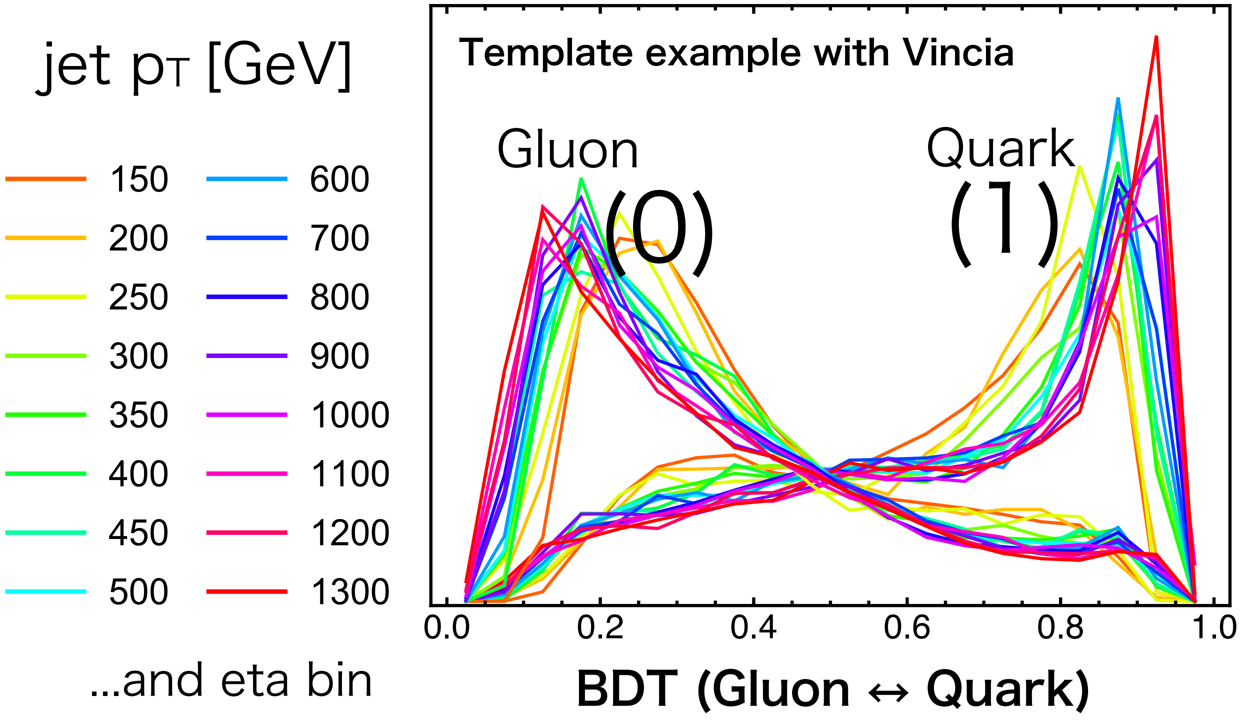


- Increase of gluon jet (double-log), quark jet (single-log)
- QCD multi-jets background is composed of few valence quark jets and many gluon jets
- W/Z/gamma + jets are also available
- It would be useful for MC tuning and development

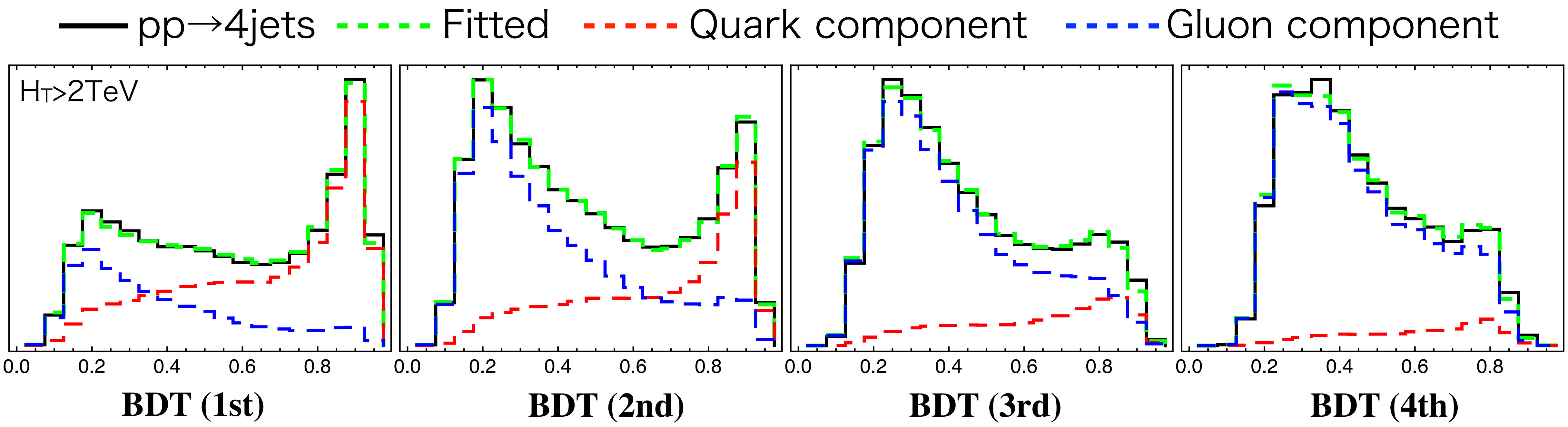
Matrix element correction



How to measure quark jet rates

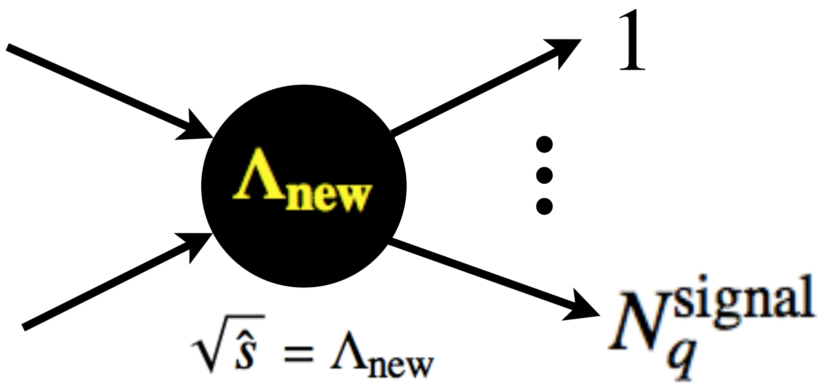


- Make quark/gluon jet templates for a variable from di-jet, Z/γ+jet sample



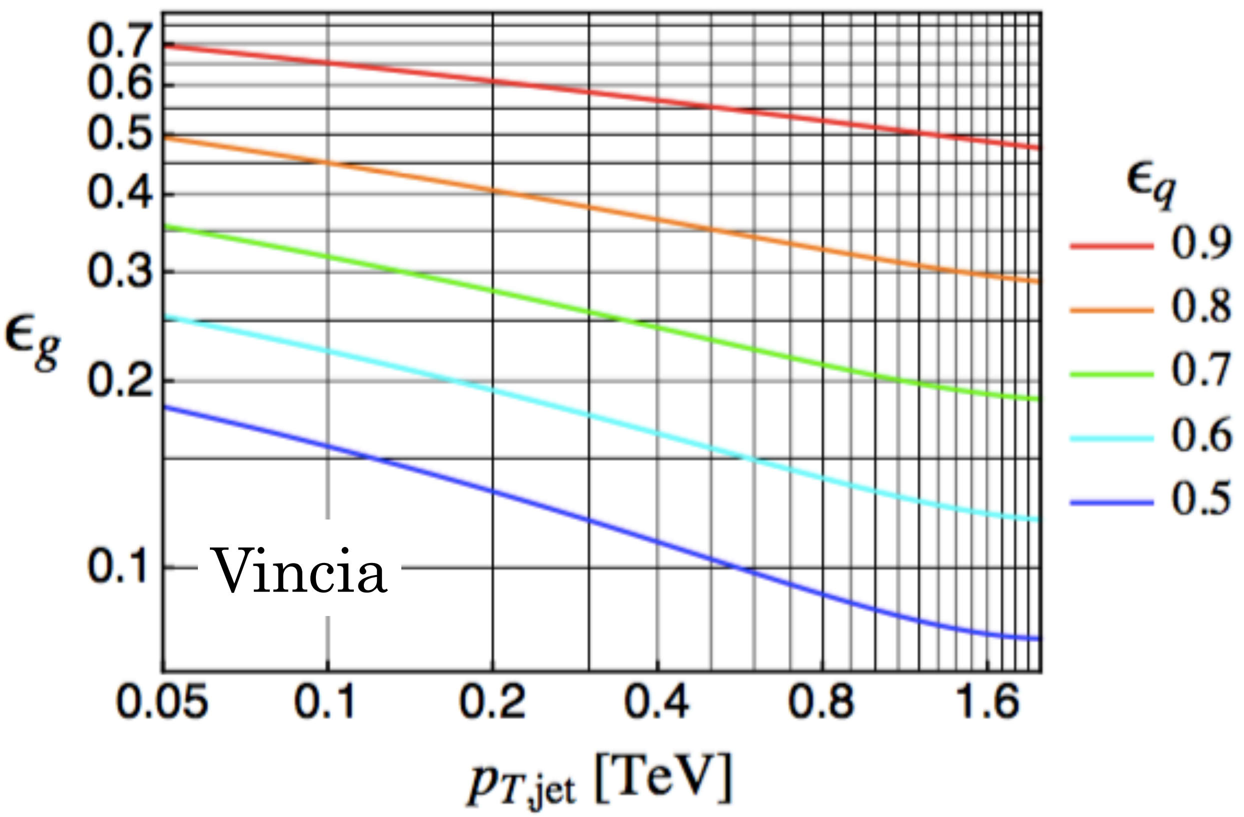
- Measurable, if the QCD jet substructure is universal (It depends on only p_T and rapidity, not # of jet)
- Many applications are conceivable

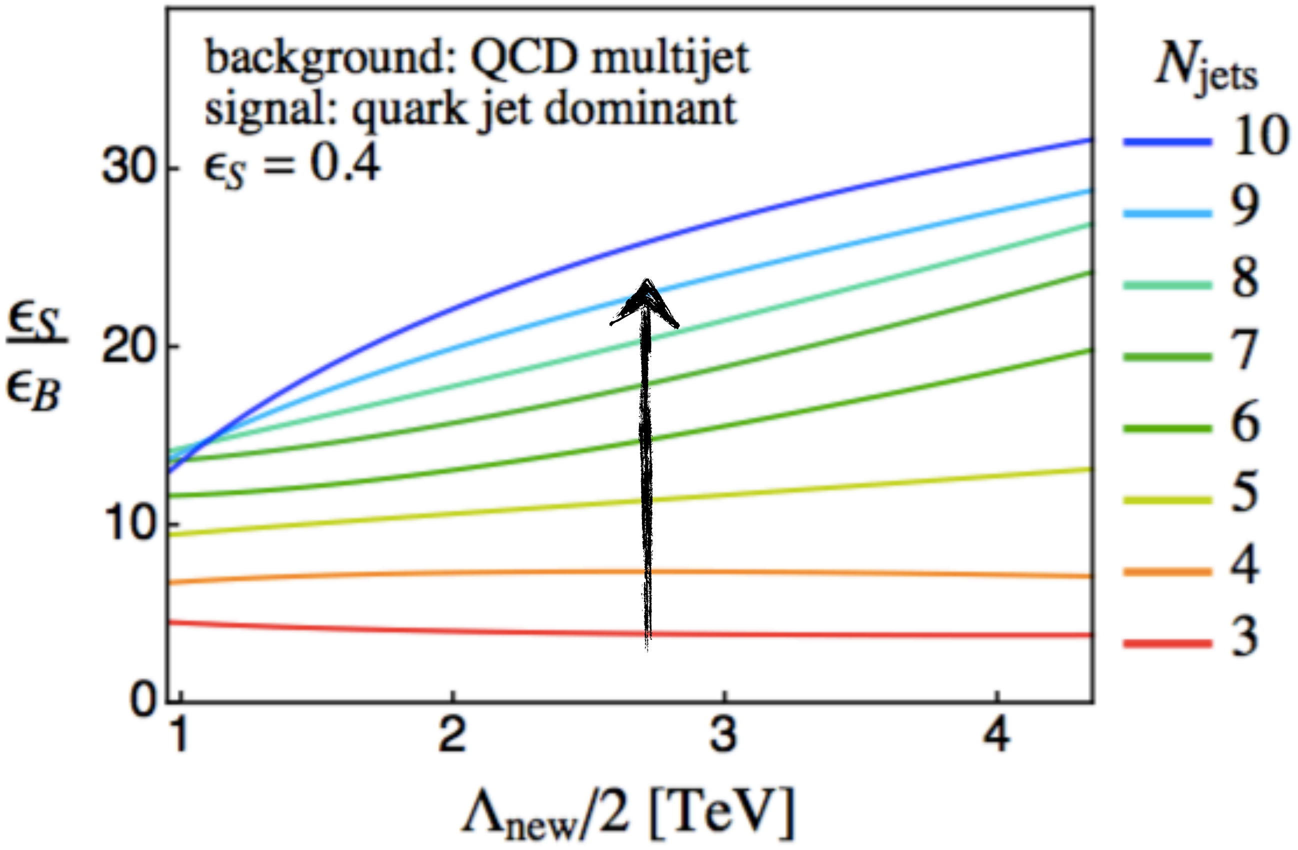
Expected improvement of S/B



all jets are quark jets

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





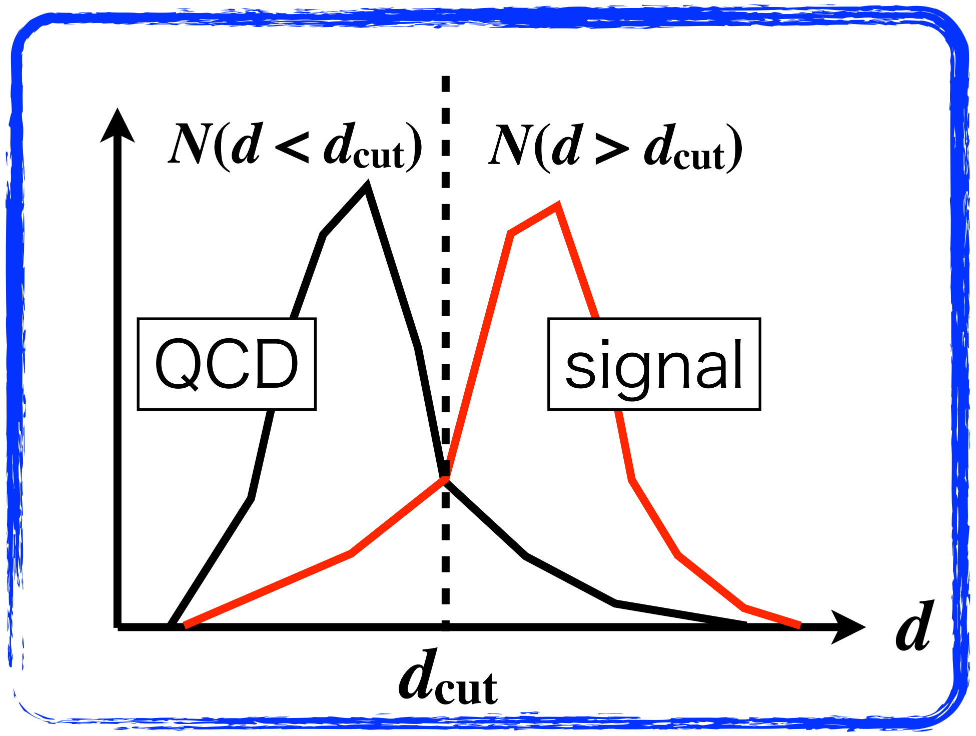
$\hat{p}_T = \Lambda_{\text{new}}/2$ $\qquad$ $\mu_F = \hat{p}_T$

MC analysis

QCD jets $\overrightarrow{\mathrm{BDT}} \sim (1, 0, 0, 0, 0,\ \ldots),\ (1, 1, 0, 0, 0,\ \ldots)$

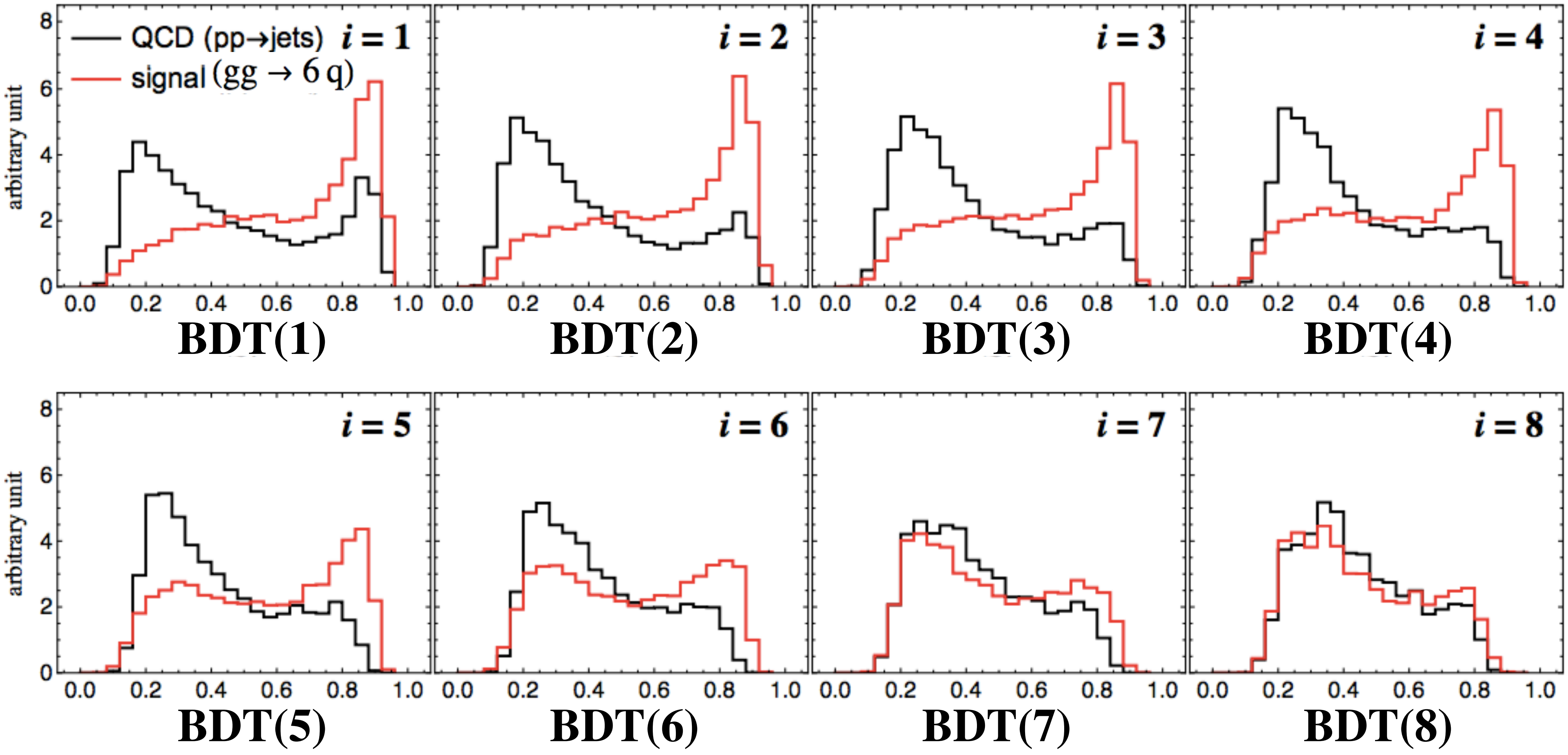
signal $\overrightarrow{\mathrm{BDT}} \sim (1, 1, 1, 1, 1,\ \ldots)$

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



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

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



MC analysis

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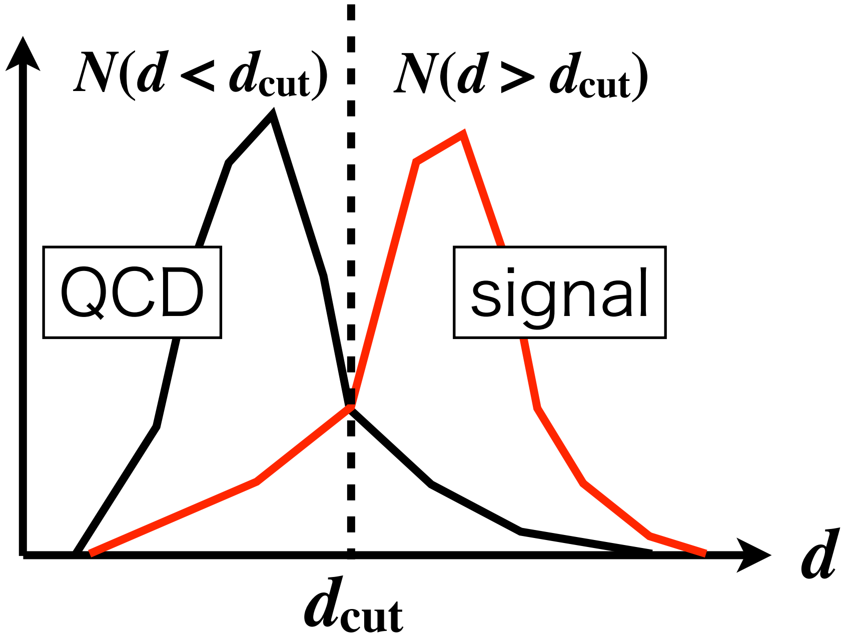
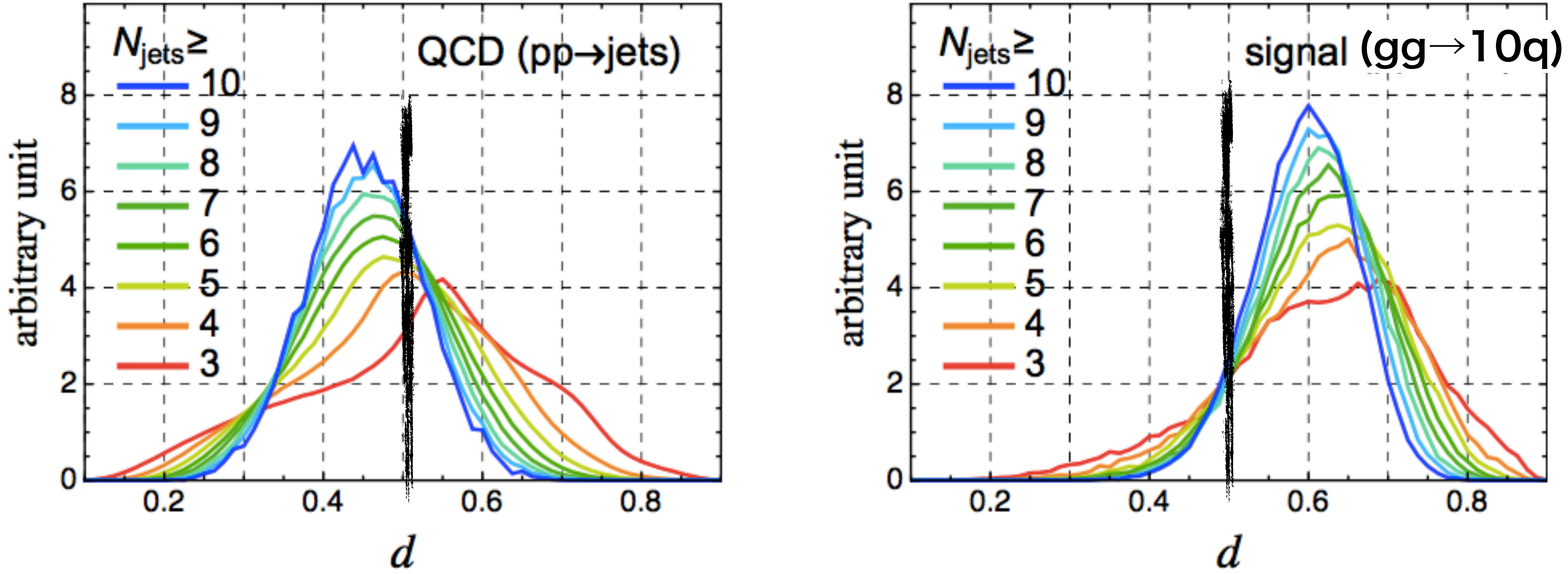


toy-signal: $gg/u\bar{u} \to XX,\ X \to N$-quarks



MC analysis

QCD jets $\overrightarrow{\text{BDT}} \sim (1, 0, 0, 0, 0,\ \ldots),\ \ (1, 1, 0, 0, 0,\ \ldots)$

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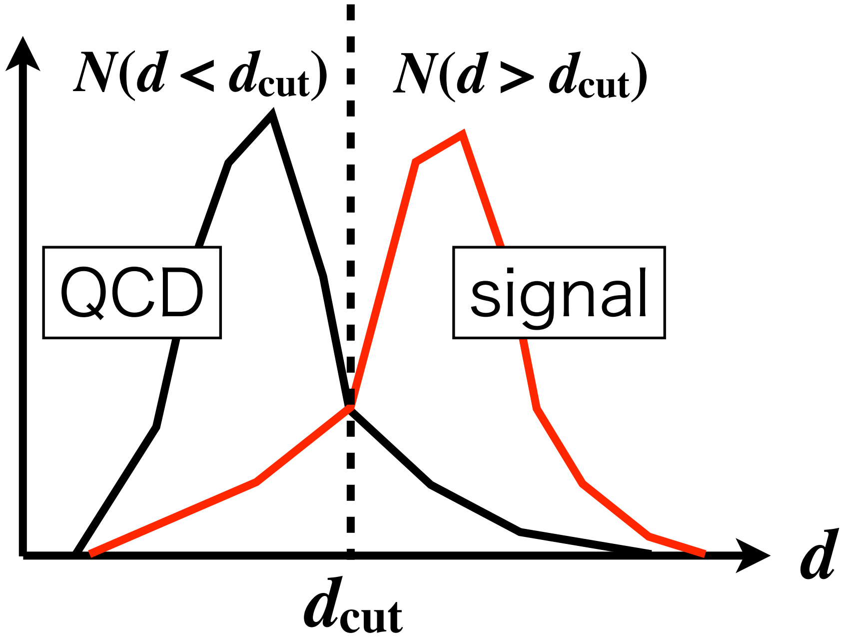
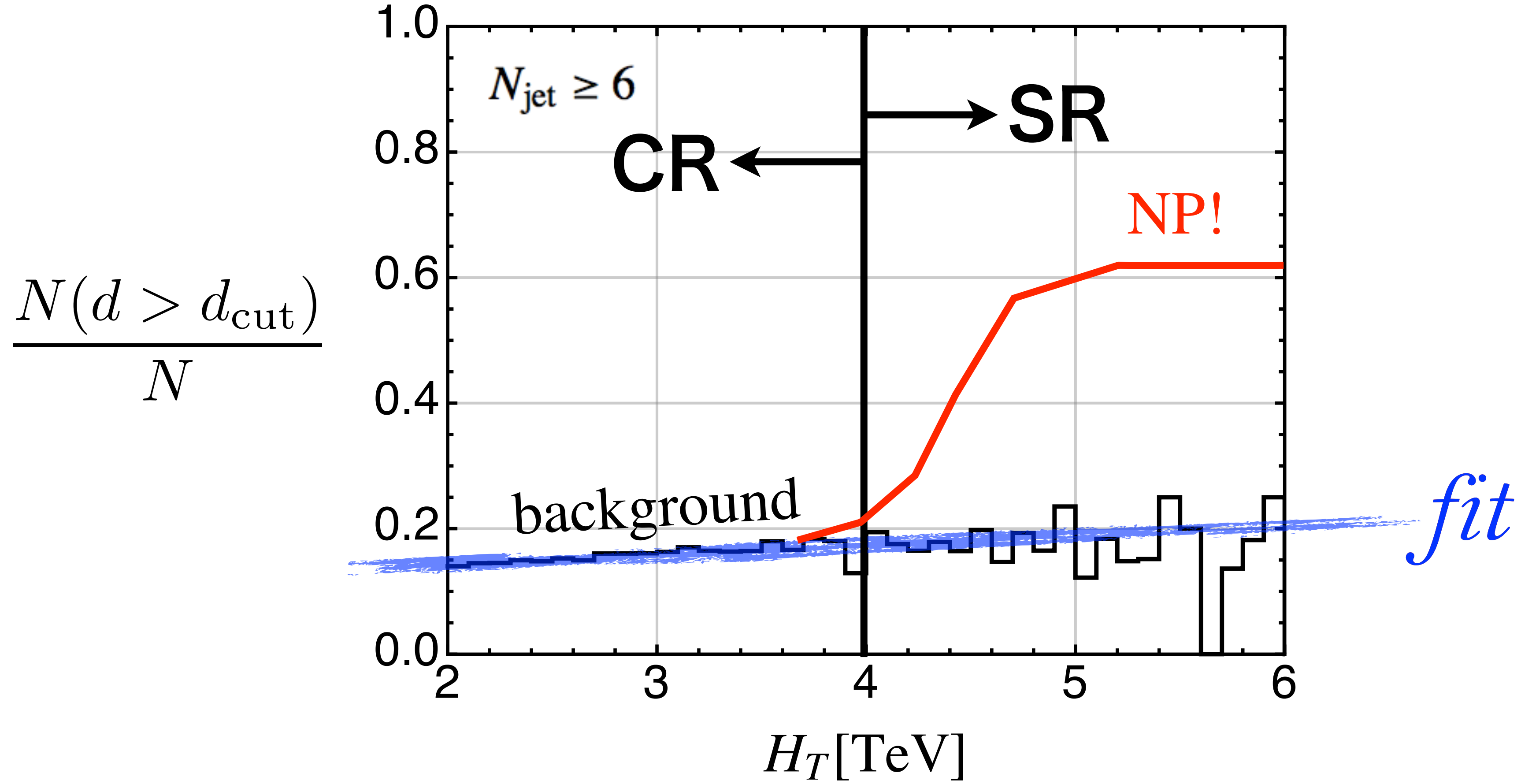
- Distance: $d = \frac{1}{n}\left|\left|\overrightarrow{\text{BDT}}\right|\right|$, (simply, Euclidean norm)



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

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



Enhancement of S/B with *d*

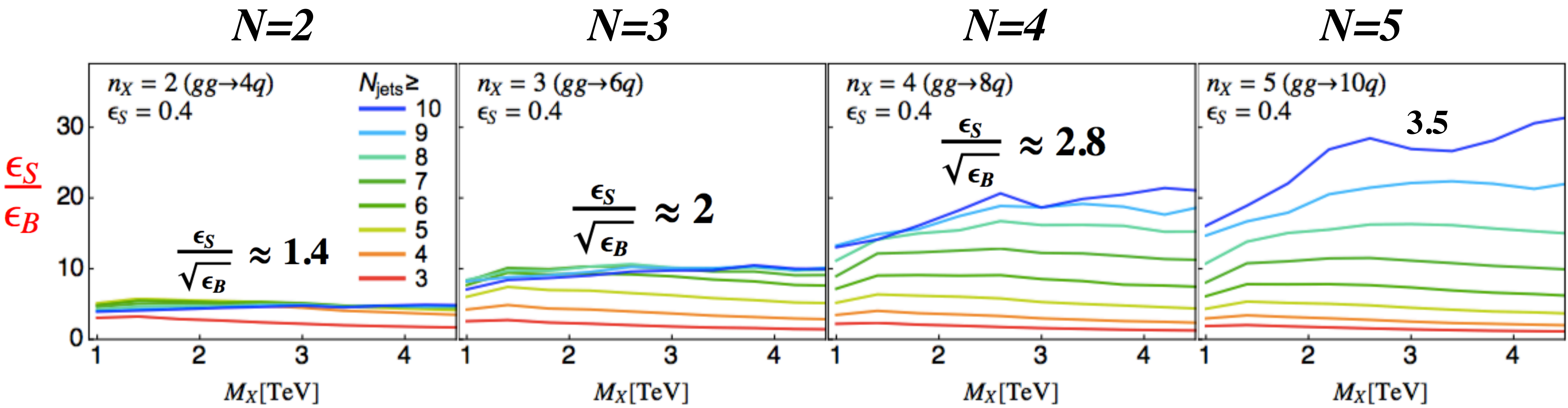
selection cut　　　　jet substructure cut (*d* cut)

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

H_T cut

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

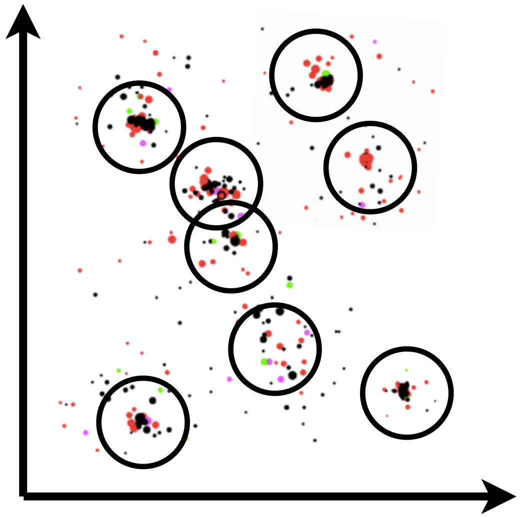
After imposing H_T cut. Fixed at $\epsilon_S = 0.4$



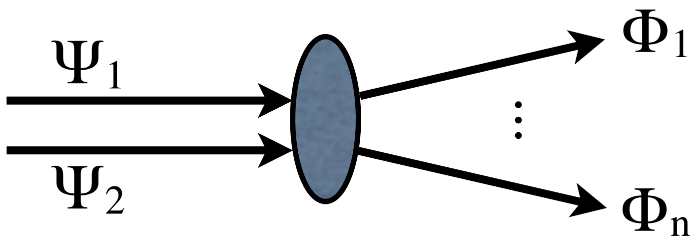
- Large enhancement of S/B

Summary

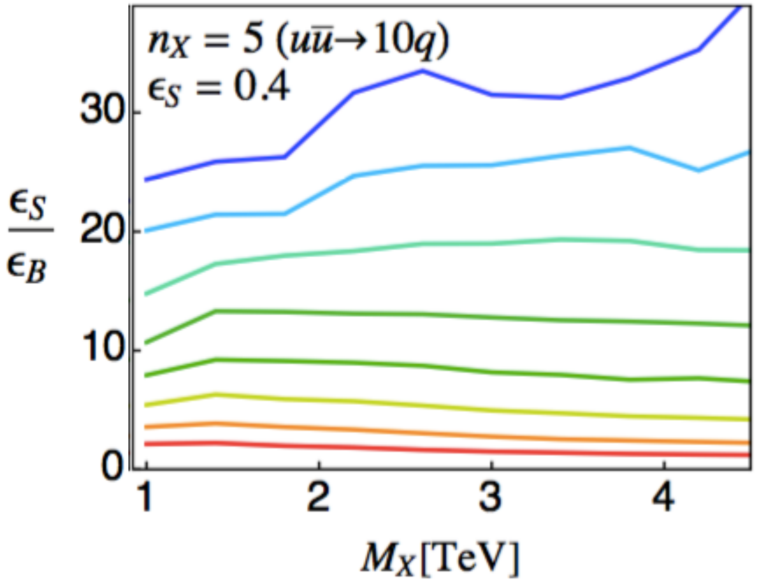
- Quark/gluon discrimination can be maximally utilized for BSM searches in multi-jet final states.



- 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.



Back up

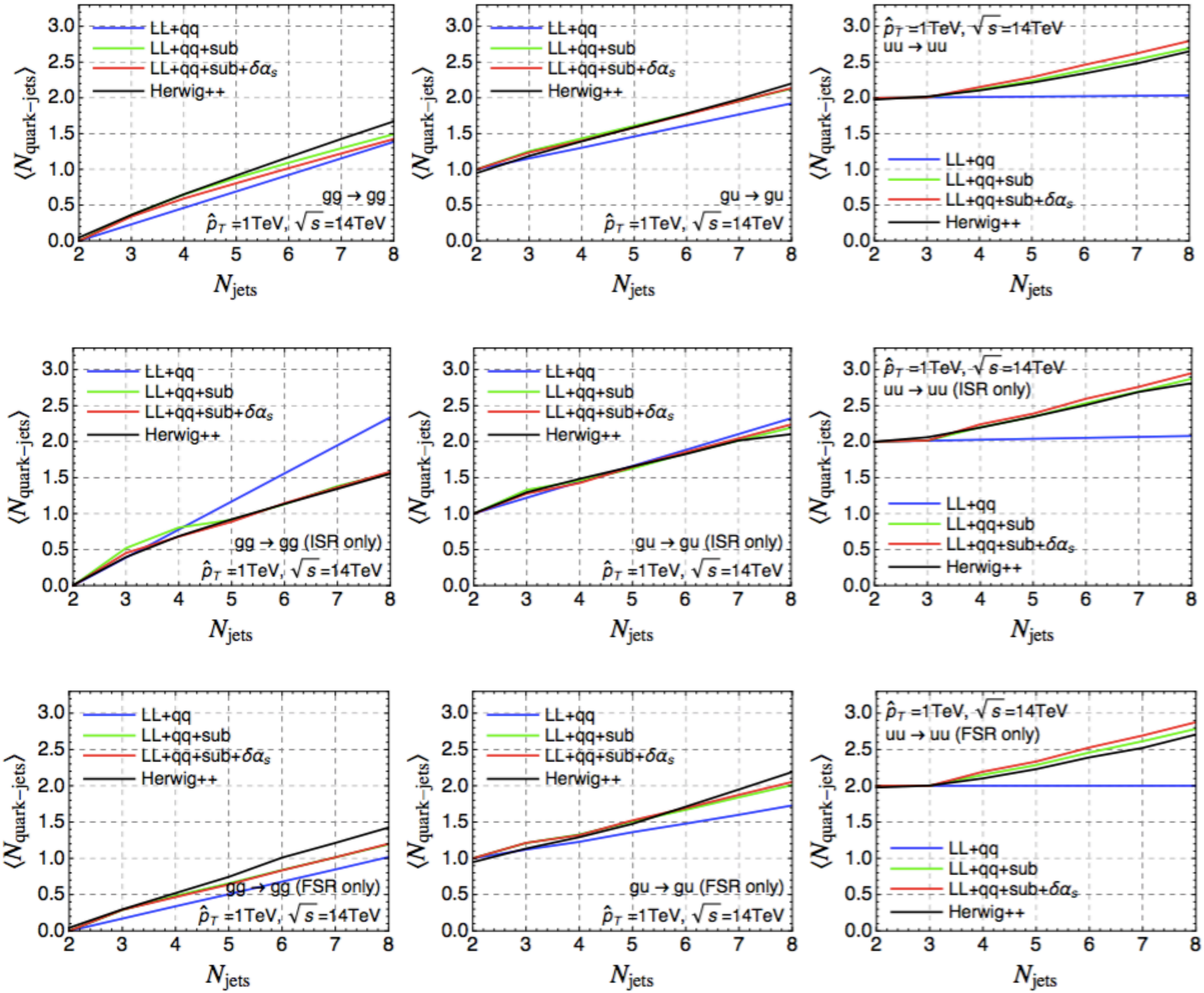
Belle II

gg→gg gu→gu uu→uu

ISR+FSR

ISR-only

FSR-only



Enhancement of S/B with *d*

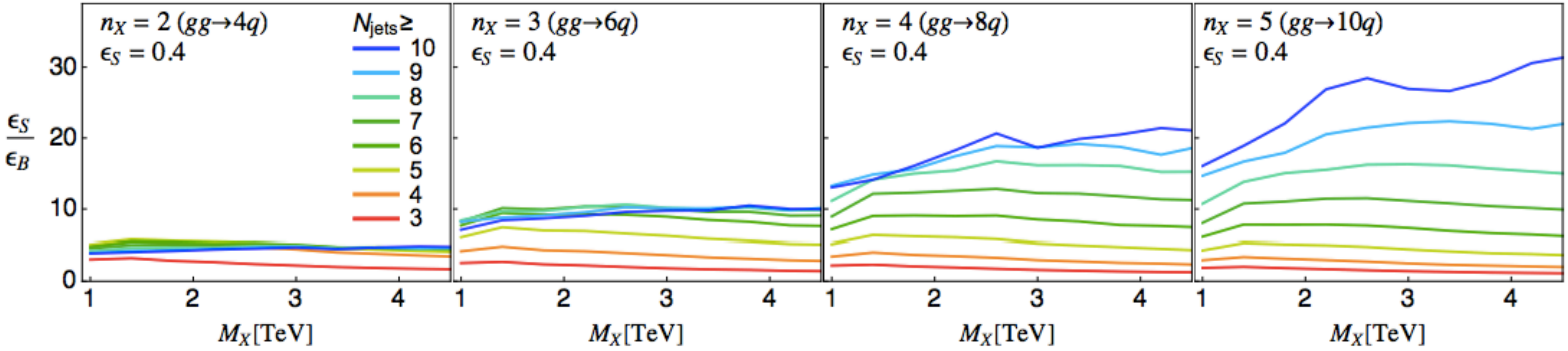


Figure 8: M_X-dependence on the efficiency ratio. We can see how the ratio changes with increasing the lower bound of N_{jets} from 3 to 10, and n_X from 2 (left-most) to 5 (right-most).

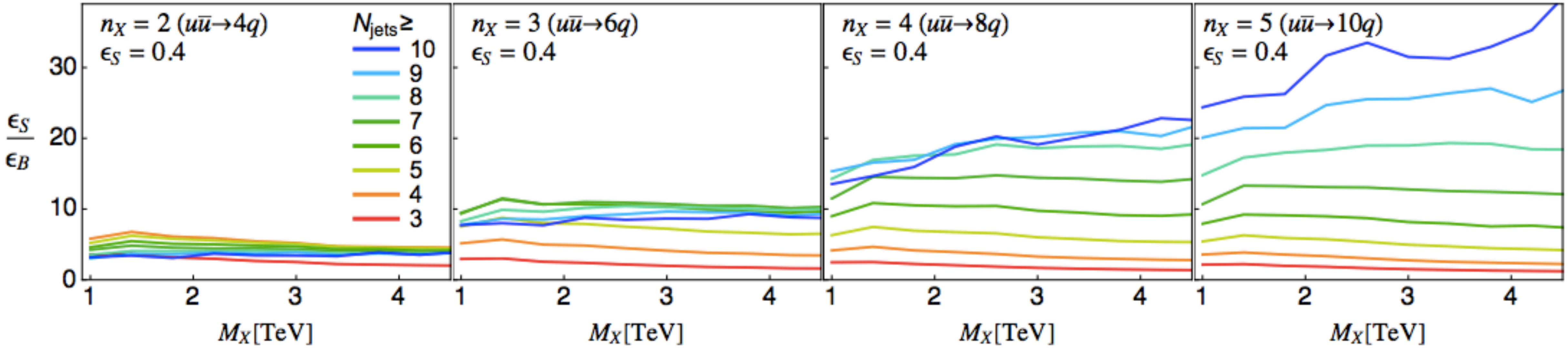


Figure 9: Same as Fig. 8, with the initial states $u\bar{u}$.