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

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(work in progress)

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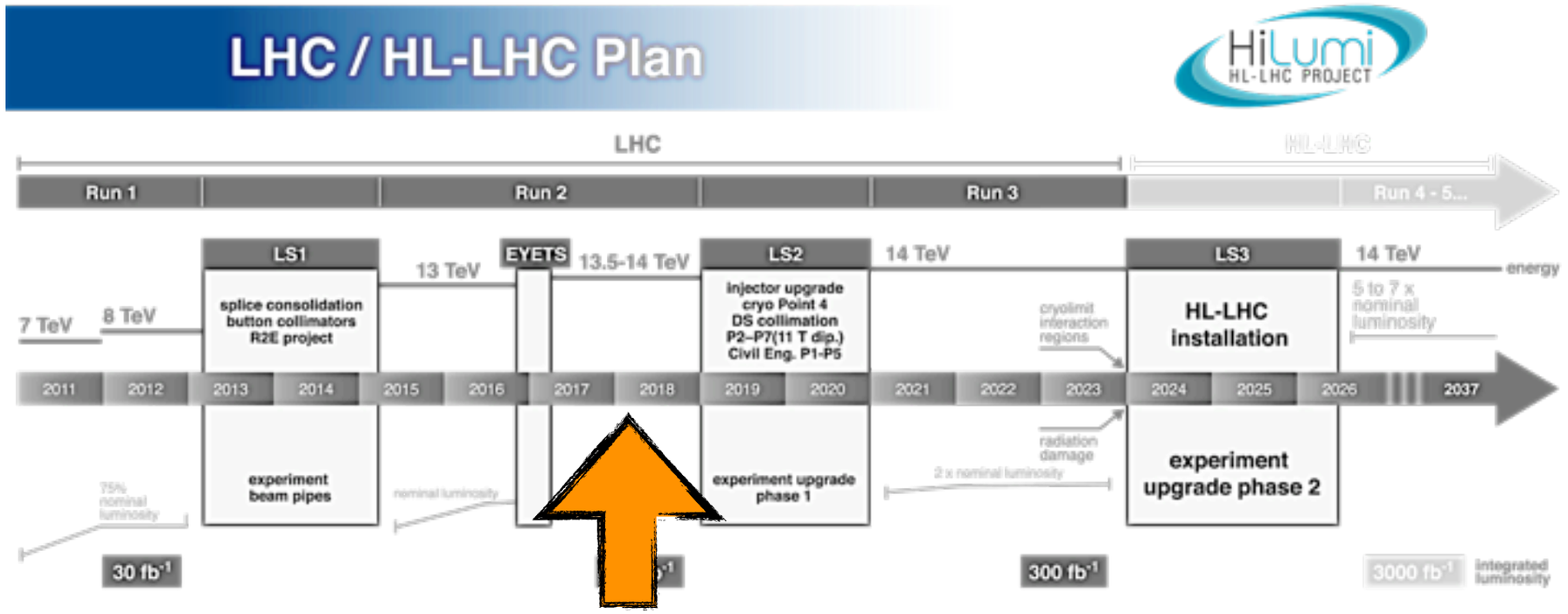
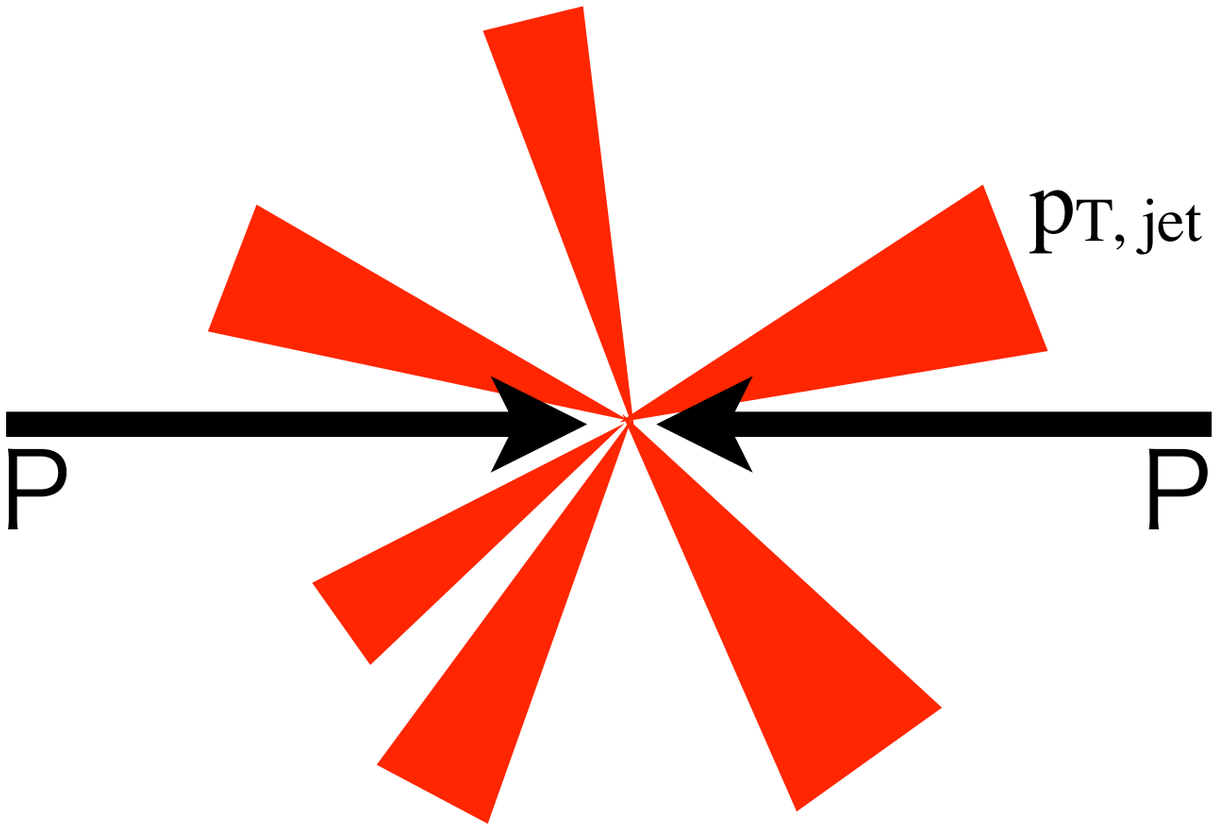


- No clear sign of BSM
- It will be needed to examine final states more precisely
- Final states are categorized by inclusive variables

  ➡ # of jets, b-jets, iso-leptons, iso-photons, MET, H_T....
- Signal regions containing jets tend to encounter huge QCD background
- As increasing # of 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

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



inclusive variable:

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

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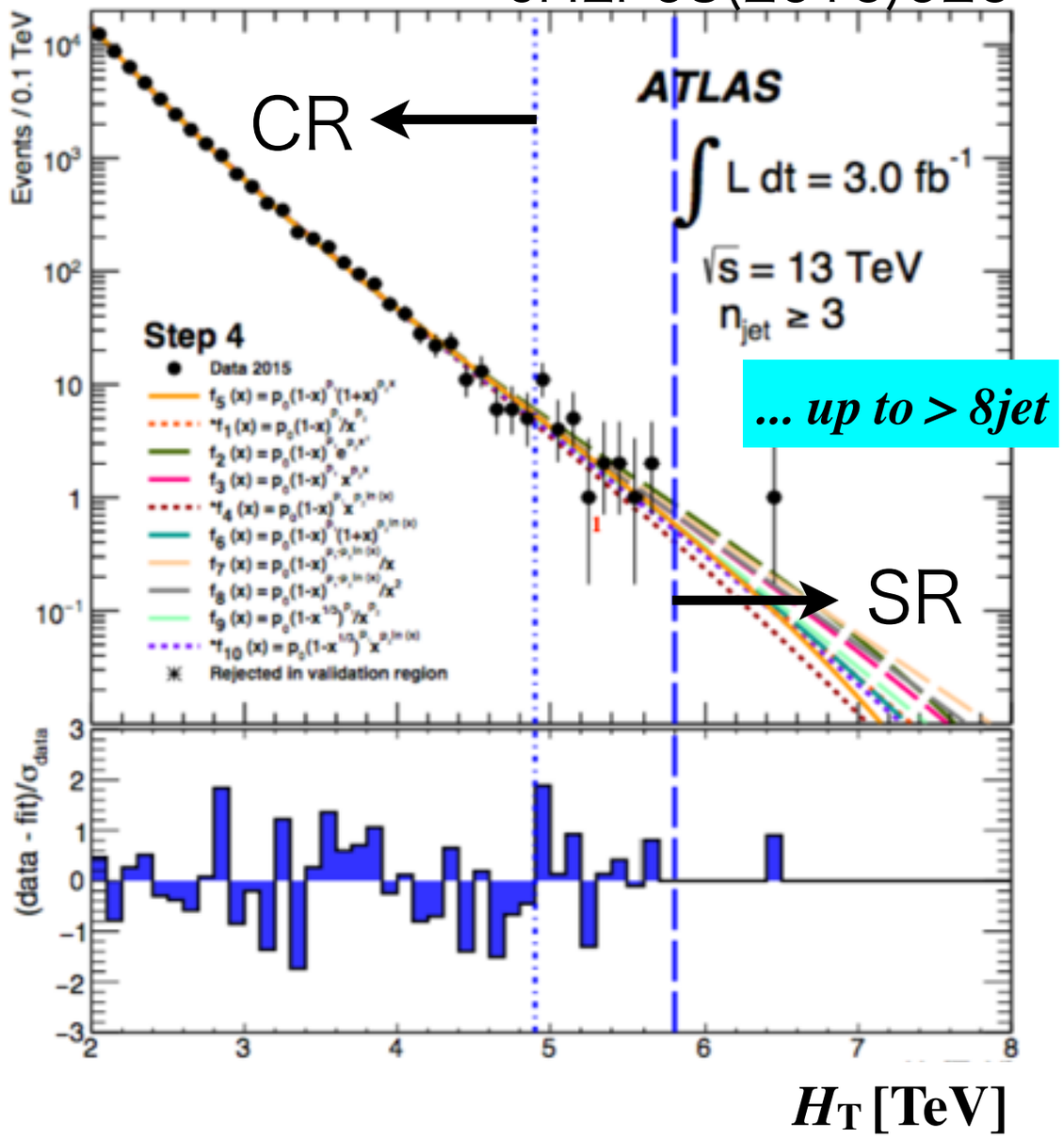

... up to > 8jet

Multi-jet final state and New physics

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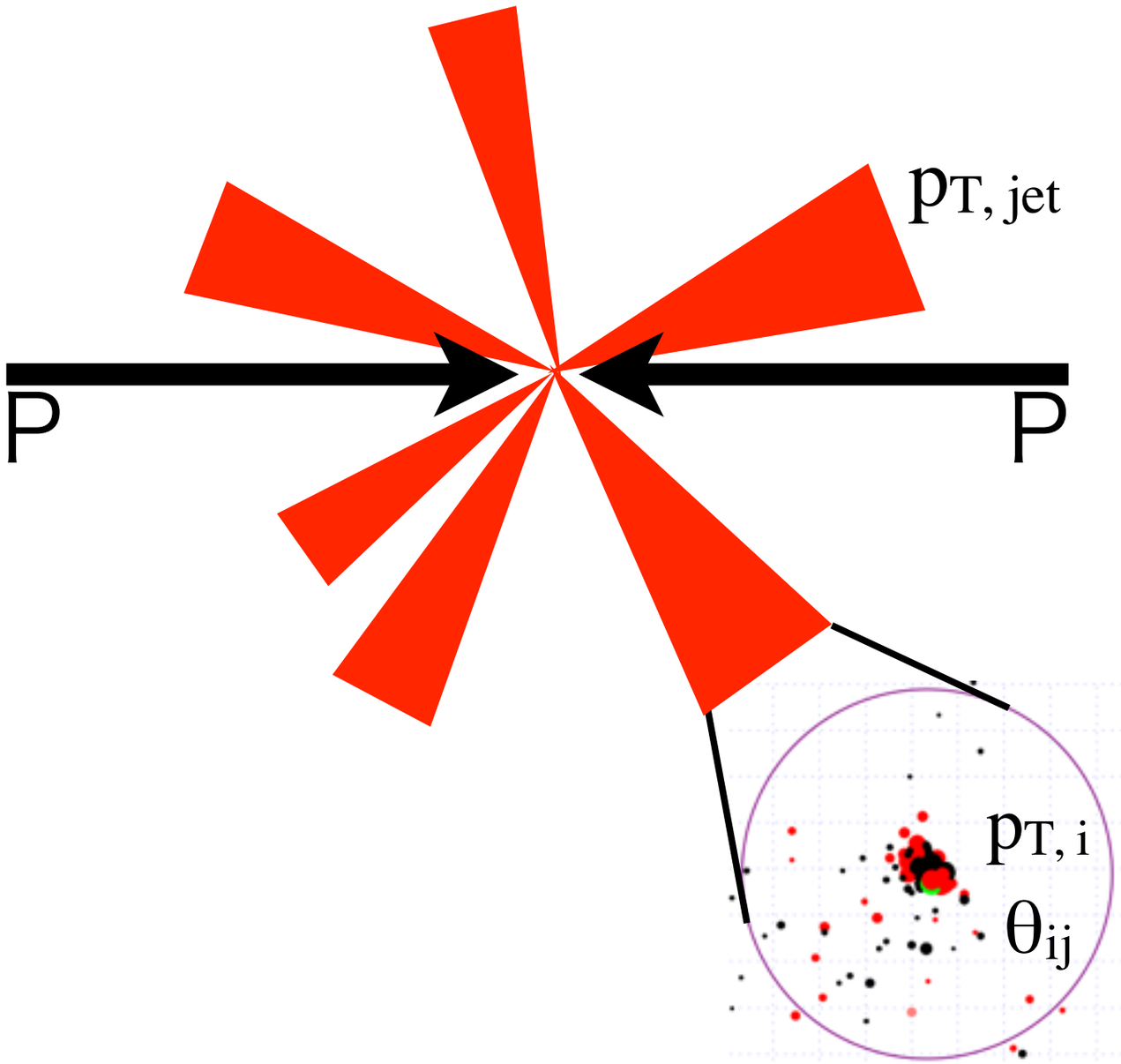


inclusive
$\Sigma p_{T,\,jet}$

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

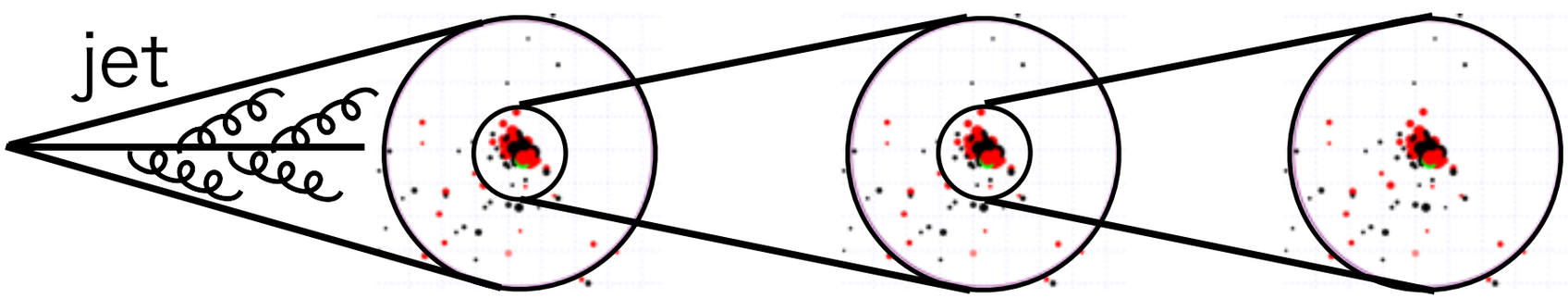
jet substructure
$\{p_{T,\,i}\},\{\theta_{ij}\}$

Multi-jet final state and Jet substructure

- Jet substructure technique have been established well as top/W/Z/H tagging tools (2-, 3-prong structure)
- Quark Gluon discrimination is also available (1-prong structure)

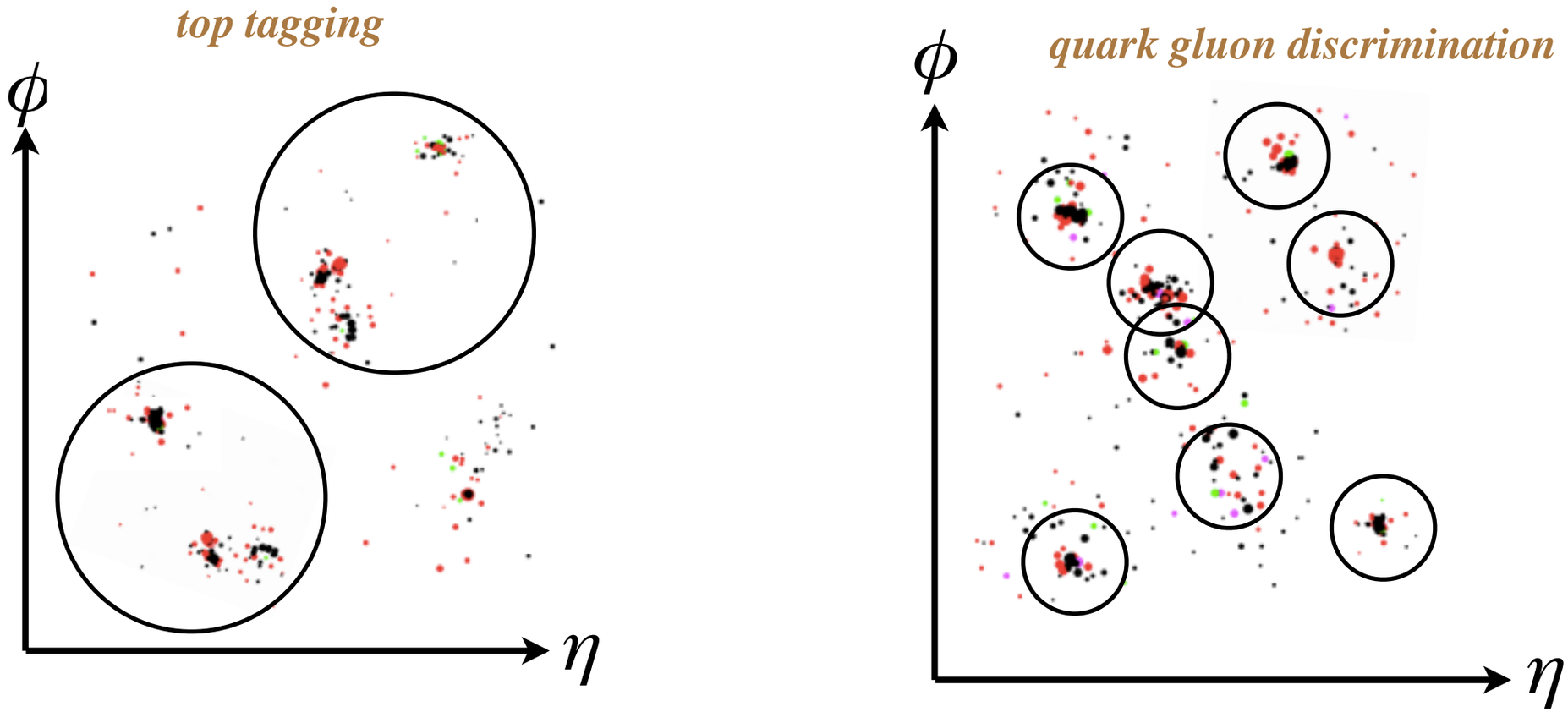
jet	formed by	R (jet radius)
top W Z H	EW	~1.0 (fat jet)
quark gluon	QCD	0.4

- QCD radiation is approximately scale invariant



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

Multi-jet final state and Jet substructure



- Small jet area ($\sim\pi R^2$) → We can apply quark gluon tagging N_{jet} times

$$\frac{S}{B} \propto \left(\frac{\epsilon_{\text{quark}}}{\epsilon_{\text{gluon}}}\right)^{N_{\text{jet}}}, \quad \frac{\epsilon_{\text{quark}}}{\epsilon_{\text{gluon}}} > 1$$

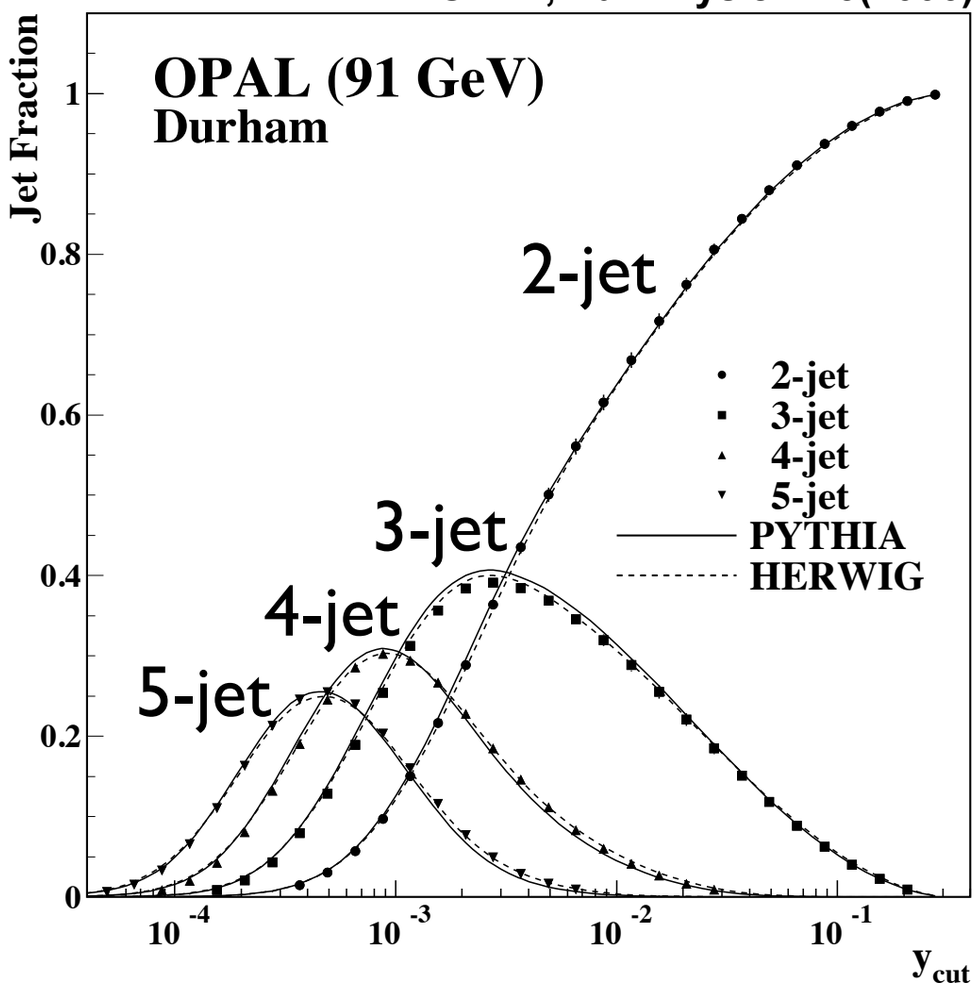
- We have a big chance to search signals that predicts the number of quark jets which is different from what the QCD background does

➡ Let's study **how many quark jets the QCD background contains.**

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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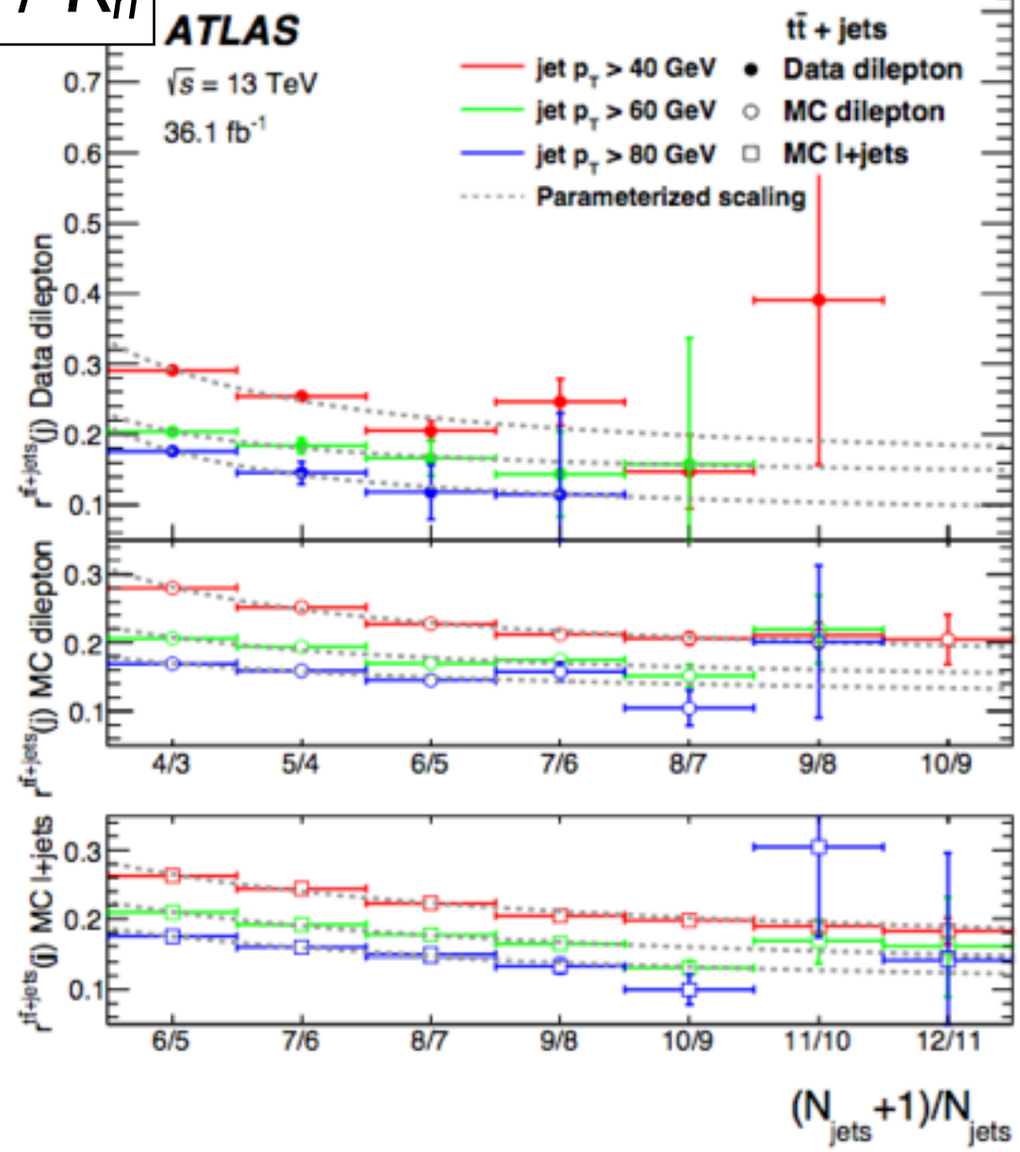
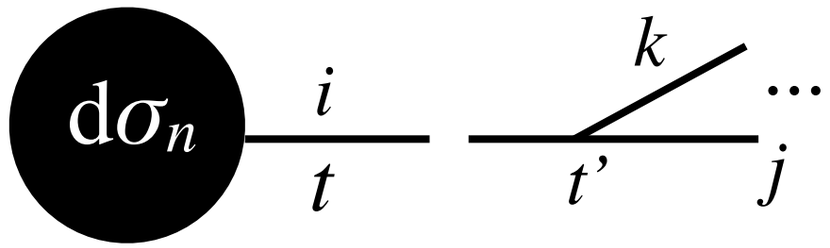


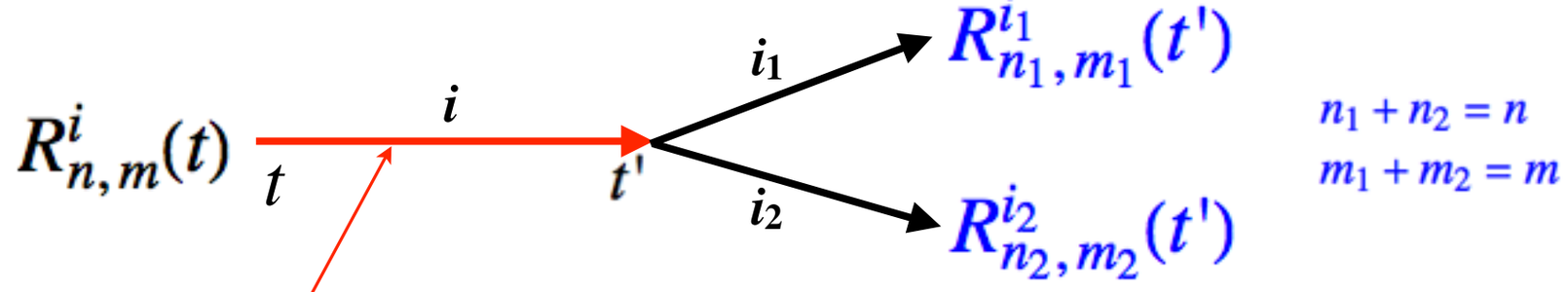
Quark jet rates

- $\underline{R_{n,m}(t)}$: Probability that an event has *n* jet and *m* quark jet



- Factorization: $\mathrm{d}\sigma_{n+1} = \mathrm{d}\sigma_n \times \frac{dt}{t}\,\Gamma_{i\to jk}(t)$

- Scale dependence (Evolution equation):



$\exp\left(-\int_{t'}^{t} \frac{dt''}{t''}\,\Gamma_{i\to \mathrm{all}}(t'')\right)$: Probability there is NO (resolved) emission between t and t'

$$R^i_{n,m}(t) = \sum_{\{i\},\{n\},\{m\}} \int^t \frac{dt'}{t'}\,\Delta_i(t,t')\,\Gamma_{i\to i_1\,i_2}(t')\,R^{i_1}_{n_1,m_1}(t')\,R^{i_2}_{n_2,m_2}(t')$$

$$R^q_{1,1} = \Delta_q,\ R^g_{1,0} = \Delta_g$$

- (FSR) Generating functional: $\Phi_i(t) = \sum_{n=1}^{\infty} \sum_{m=0}^{n} u^n v^m R^i_{n,m}(t)$

$$\Rightarrow \quad R^i_{n,m}(t) = \frac{1}{n!\,m!} \frac{\partial^n}{\partial u^n} \frac{\partial^m}{\partial v^m} \Phi_i(t) \Big|_{u=v=0}$$

$$\Phi_q(t) = uv\,\Delta_q \exp\left[\int^t \frac{dt'}{t'} \Gamma_{q\to qg}(t')\,\Phi_g(t')\right]$$

$$\Phi_g(t) = u\;\Delta_g \exp\left[\int^t \frac{dt'}{t'} \left\{\Gamma_{g\to gg}(t')\,\Phi_g(t') + \Gamma_{g\to qq}(t')\,\frac{\Phi_q(t')\,\Phi_q(t')}{\Phi_g(t')}\right\}\right]$$

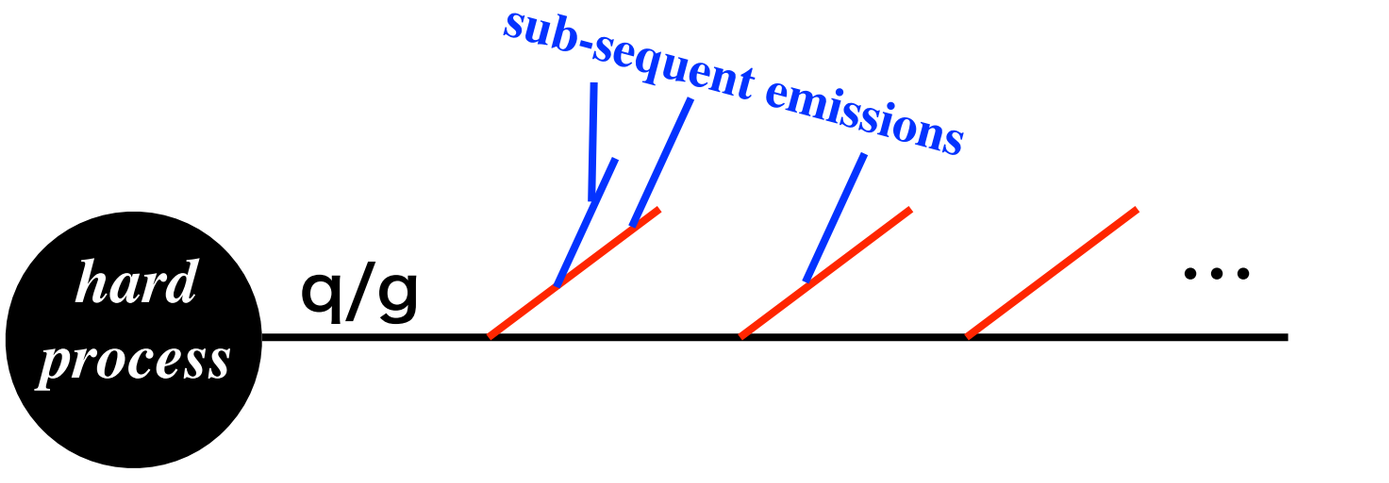
- Solutions:

$$\Phi_q \simeq uv\,\Delta_q^{1-u} \qquad \Delta_q^{-u\,\delta(A_g\,\kappa\,\lambda)}$$

$$\Phi_g \simeq u\;\Delta_{gg}^{1-u}\,\Delta_{qq}^{1-uv^2}\,\Delta_{gg}^{-u\,\delta(A_g\,\kappa\,\lambda)}$$

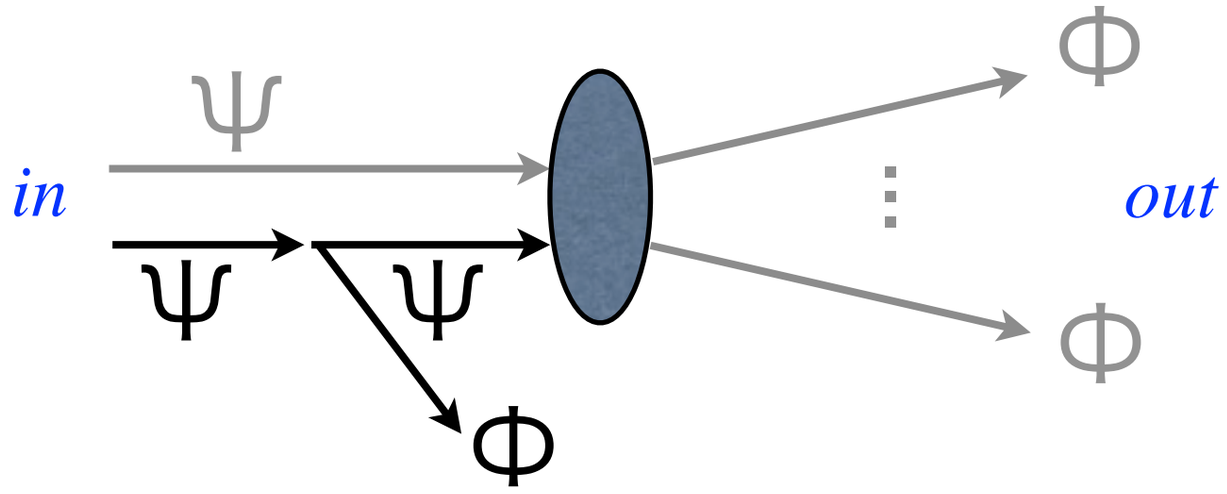
$$\delta(z) = -\sum_{n=2}^{\infty} \frac{(-1)^n\,z^{n-1}}{n\,n!}$$

0-th order — LL (gluon jet) — g→qq ∈ NLL (quark jet) — sub-sequent emissions (both)



Initial State Radiation (ISR)

- LHC is hadron collider



- ISR Generating functional:

$$\Psi_q(x,t) = \Pi_q(x,t)\exp\left[\int^t dt' \int_x^1 \frac{dx'}{x'}\left\{\Gamma_{q\to qg}\,\frac{f_q(x',t')}{f_q(x,t')}\,\Phi_g(t') + \Gamma_{g\to qq}\,\frac{f_g(x',t')}{f_q(x,t')}\,\frac{\Psi_g(x',t')}{\Psi_q(x,t')}\,\Phi_q(t')\right\}\right]$$

$$\Psi_g(x,t) = \Pi_g(x,t)\exp\left[\int^t dt' \int_x^1 \frac{dx'}{x'}\left\{\Gamma_{g\to gg}\,\frac{f_g(x',t')}{f_g(x,t')}\,\Phi_g(t') + \sum_q \Gamma_{q\to gq}\,\frac{f_q(x',t')}{f_g(x,t')}\,\frac{\Psi_q(x',t')}{\Psi_g(x,t')}\,\Phi_q(t')\right\}\right]$$

PDF factors **FSR generating functionals**

- Solutions:

(gluon) LL **sub-sequent emissions (both)**

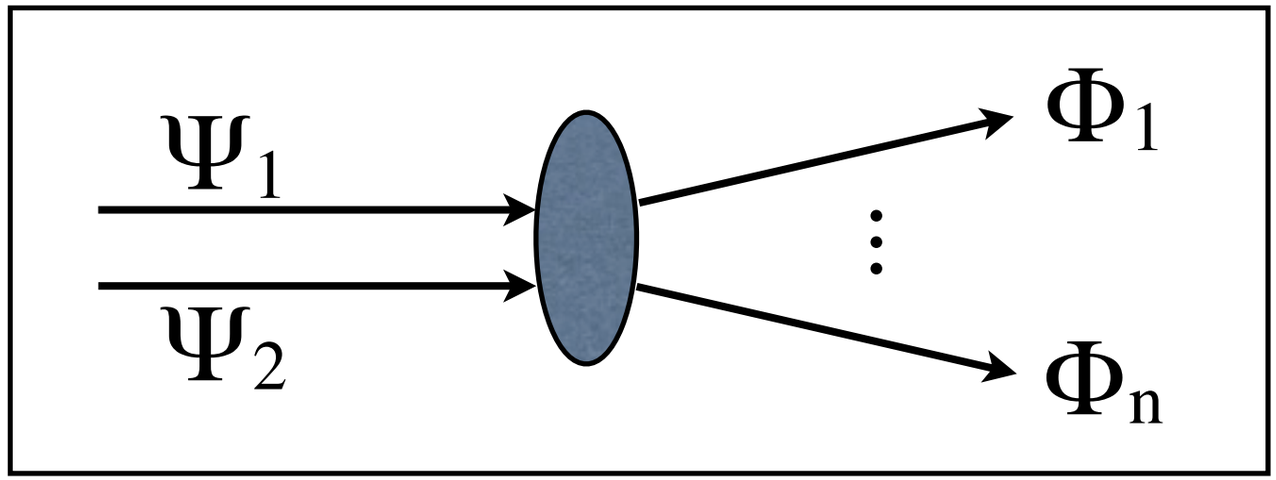
$$\Psi_q \simeq \Pi_q^{1-u}\,\Pi_{q,2}^{1-uv}\,\Pi_q^{-u\,\delta(\bar{A}_g\,\kappa\,\lambda,\,f_{g/g})}$$

$$\Psi_g \simeq \Pi_g^{1-u}\,\Pi_{g,2}^{1-uv}\,\Pi_g^{-u\,\delta(\bar{A}_g\,\kappa\,\lambda,\,f_{q/q})}$$

sub-leading (quark)

ISR+FSR

$W =$

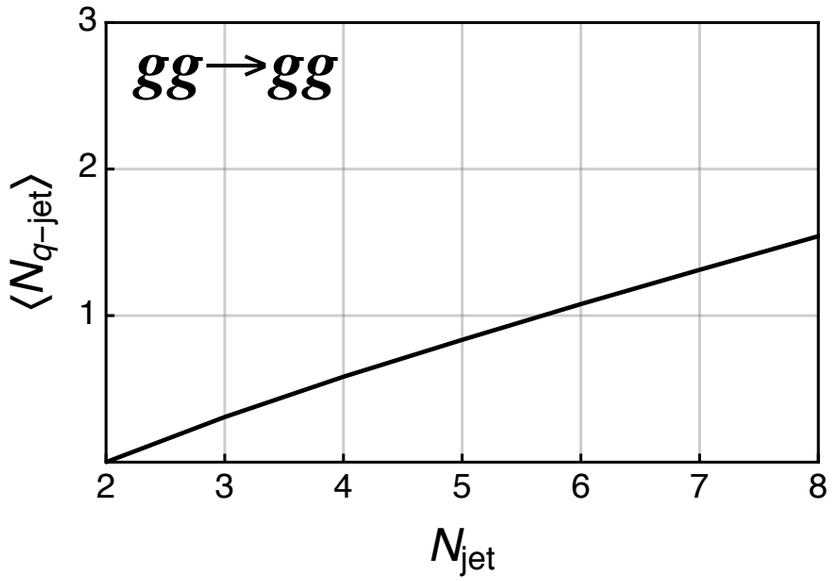


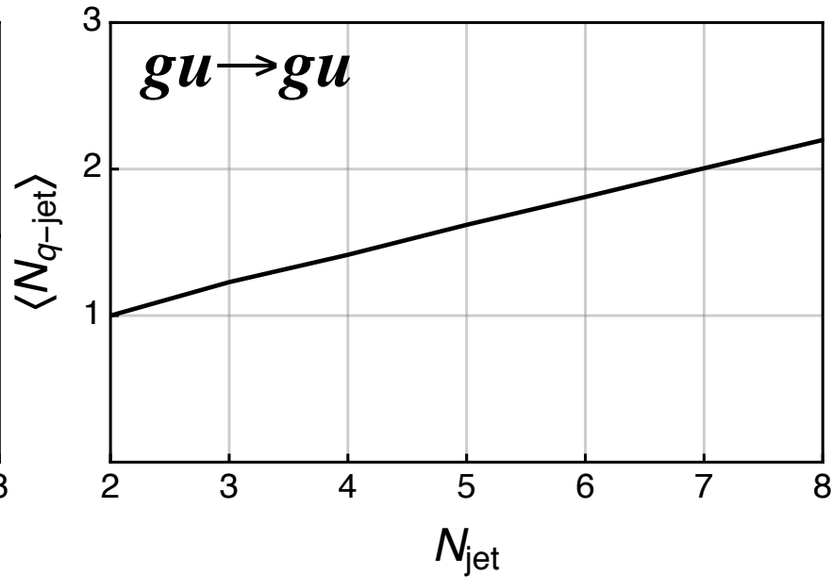
$$W(t) = \Psi_1 \Psi_2 \left(\prod_k \Phi_k \right) \qquad R_{n,m}(t) = \frac{1}{n!\, m!} \frac{\partial^n}{\partial u^n} \frac{\partial^m}{\partial v^m} W(t) \Big|_{u=v=0}$$

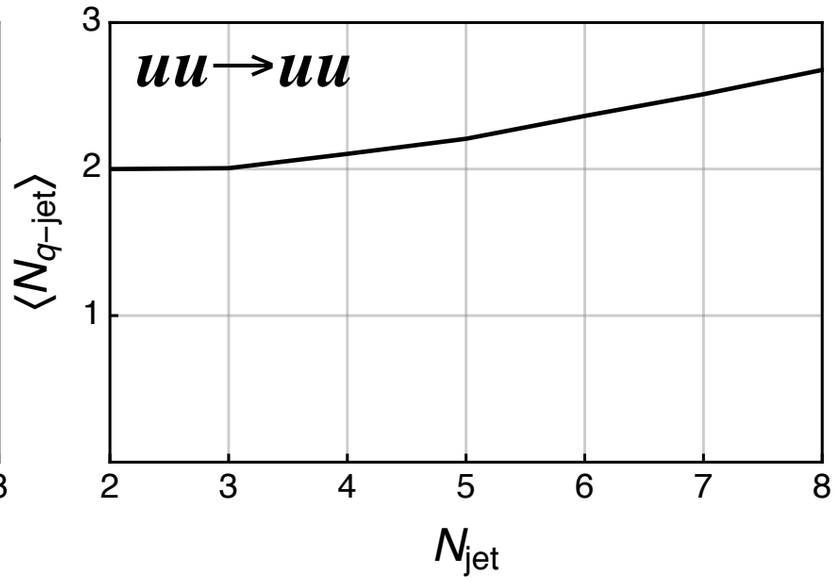
- A whole generating functional for a matrix element is given by a product of FSR and ISR generating functionals.

of quark jets

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

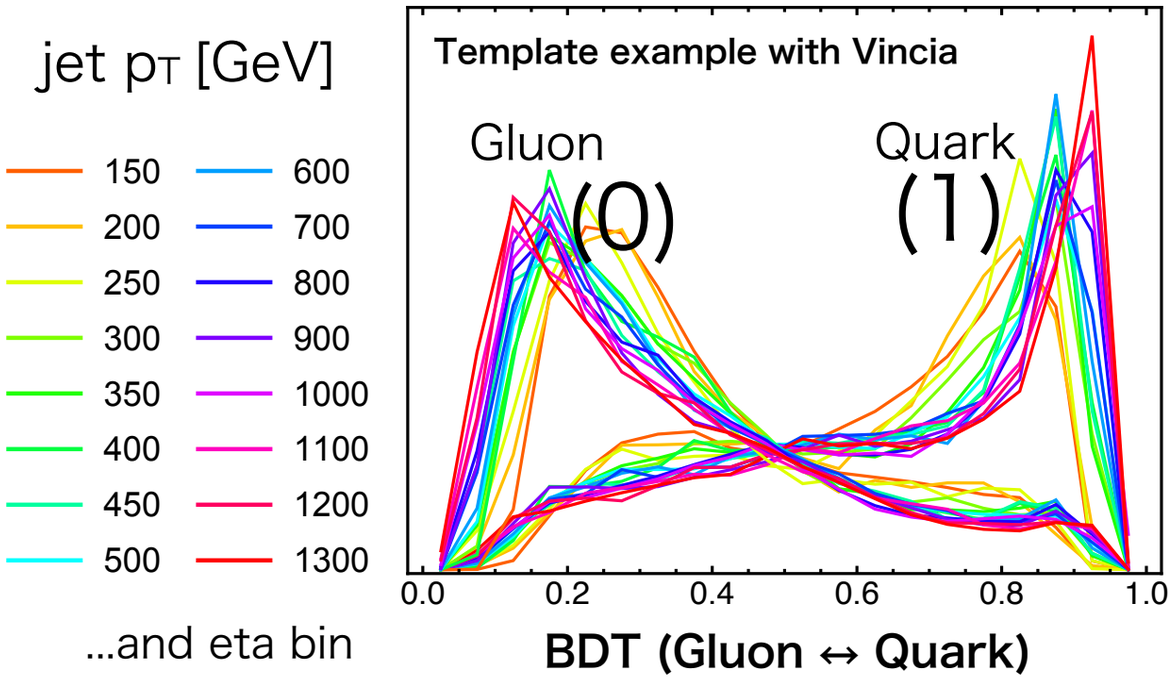




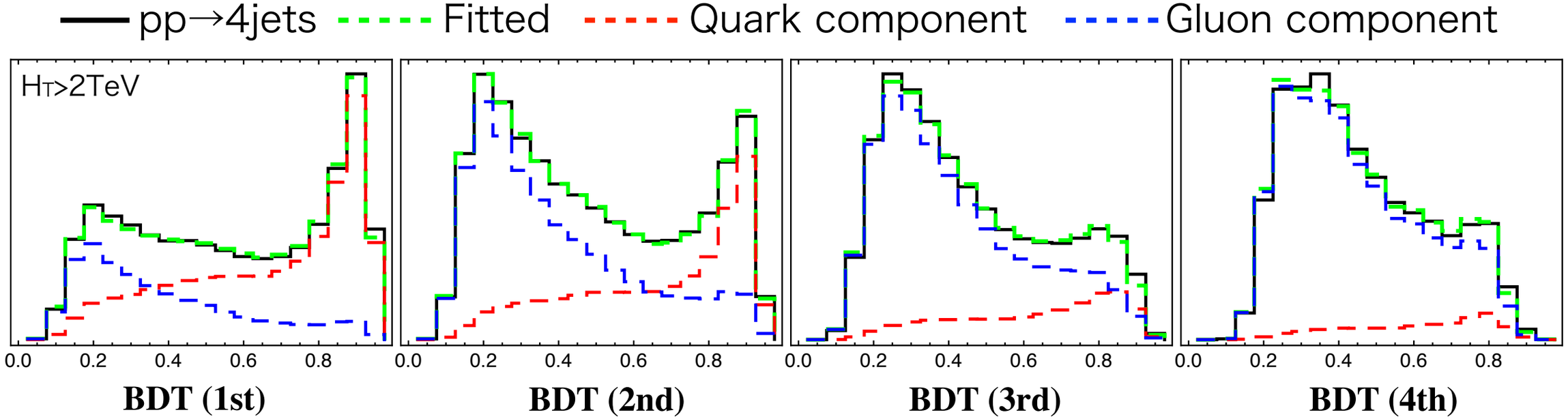


- Increment of jet (leading, LL), quark jet (sub-leading, NLL)
- QCD jets background is composed of 1 or 2 valence quark jets and many gluon jets
- W/Z/gamma + jets are also available
- It would be useful for MC tuning and development

How to measure quark jet rates in multi-jet final state



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



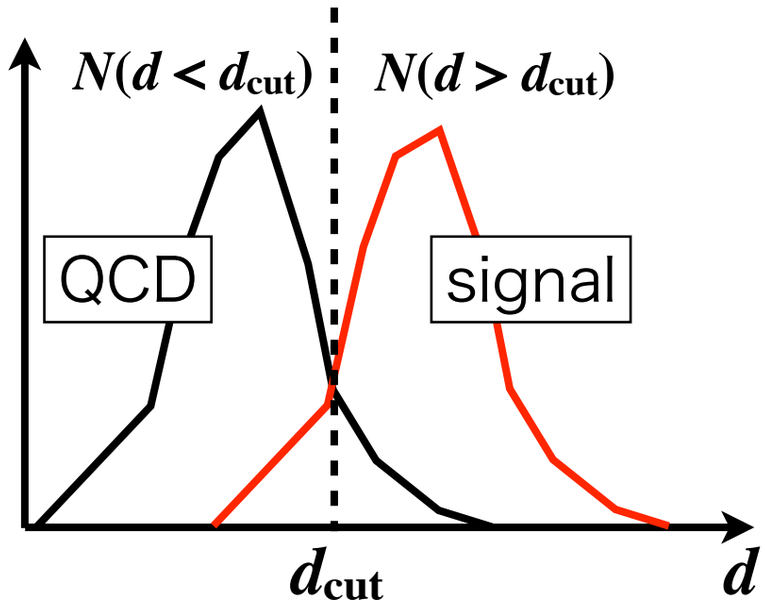
- Measurable, if the QCD jet substructure is universal (It depends on only p_T and rapidity, not # of jet)
- Many applications are conceivable

Quark Gluon discrimination in multi-jet final state

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

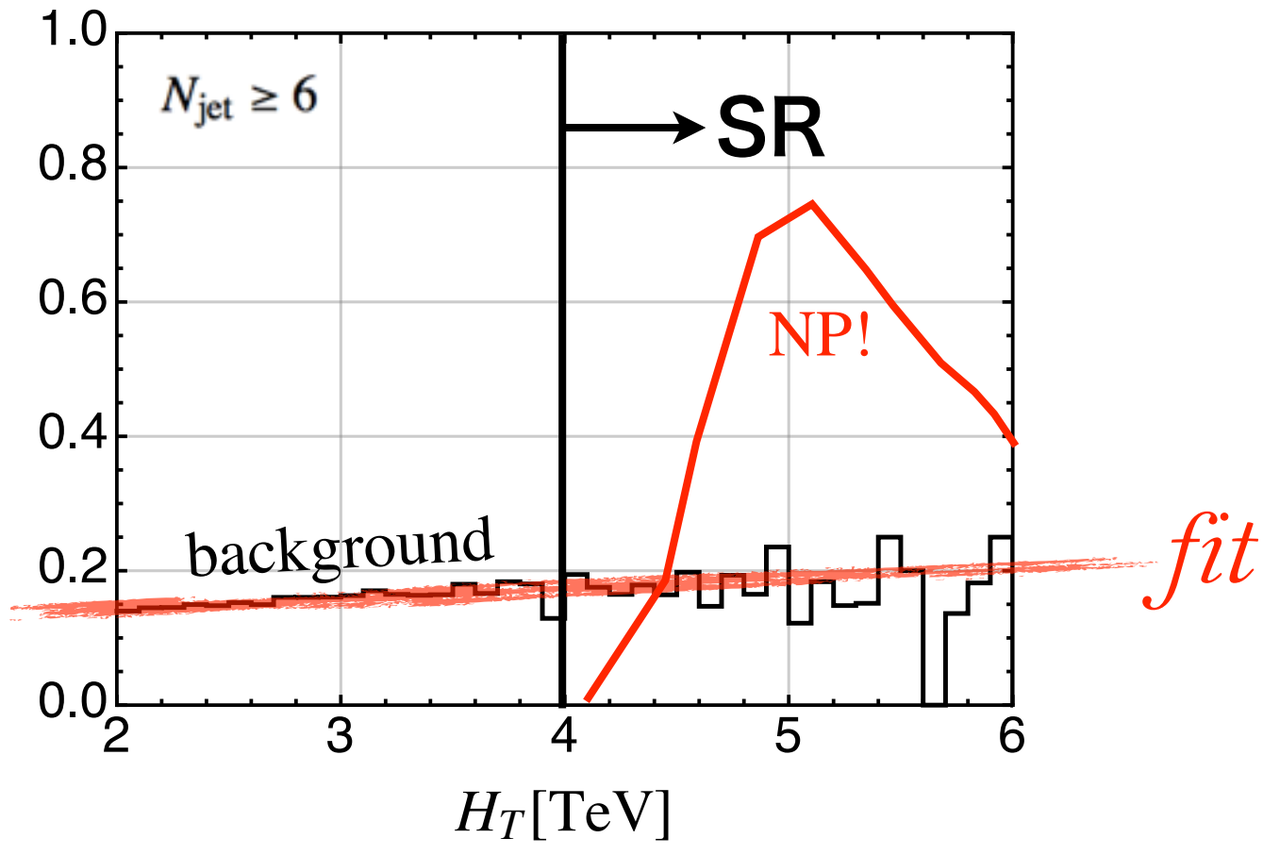
signal $\overrightarrow{\mathrm{BDT}} \sim (1, 1, 1, 1, 1, \ldots)$

- BDT distance: $d = \sqrt{\left|\overrightarrow{\mathrm{BDT}}\right|^2}$



- We can estimate # of backgroud of each bin by data-driven extrapolations

$$\frac{N(d > d_{\mathrm{cut}})}{N}$$



Impact of quark gluon discrimination

selection cut

jet substructure cut (cut on *d*)

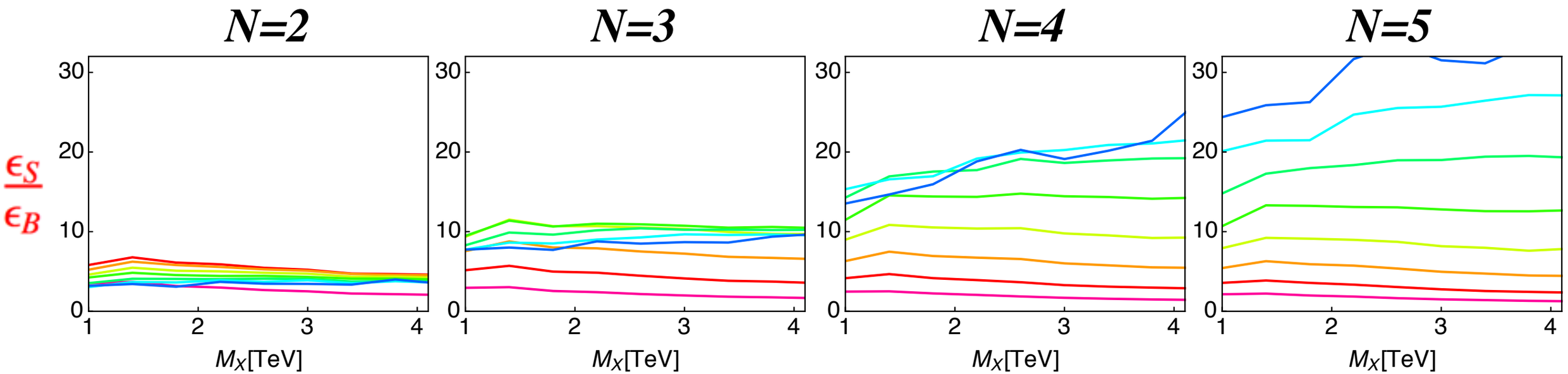
$$\frac{S}{B} \sim \frac{\sigma_S}{\sigma_B} \times \left(\frac{\epsilon_S}{\epsilon_B}\right) \times \left(\frac{\epsilon_S}{\epsilon_B}\right) \times \left(\frac{\epsilon_S}{\epsilon_B}\right)$$

cut on H_T

$N_{jet} \geq 10$
≥ 9
≥ 8
≥ 7
≥ 6
≥ 5
≥ 4
≥ 3

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

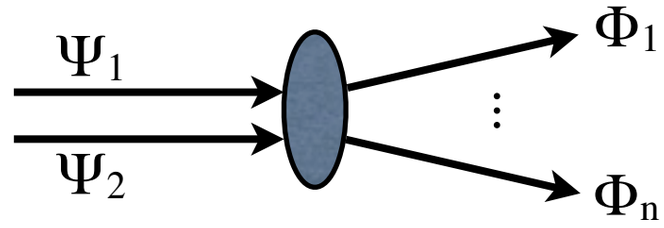
After imposing H_T cut. Fixed at $\epsilon_S = 0.4$



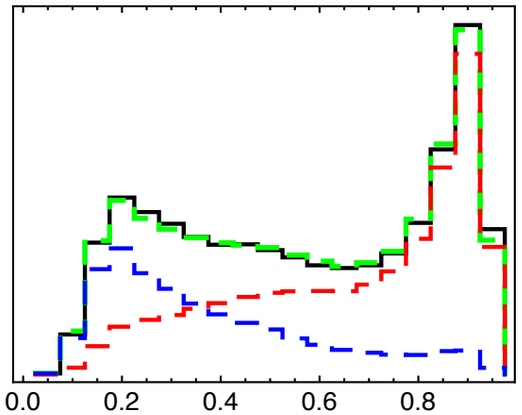
- We can get an large enhancement of S/B

Summary

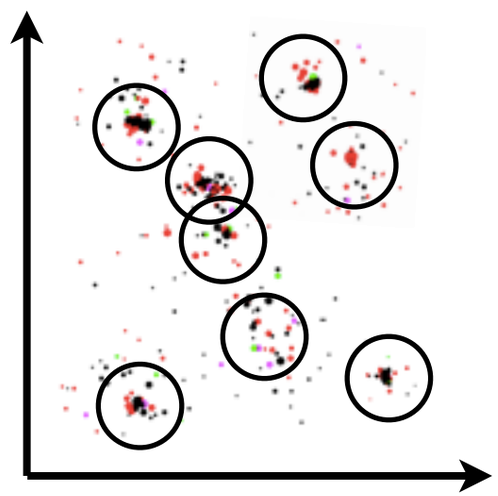
- Quark jet rates in multi-jet final state for the hadron collider are evaluated.



- A simple way to measure the rates is also introduced.



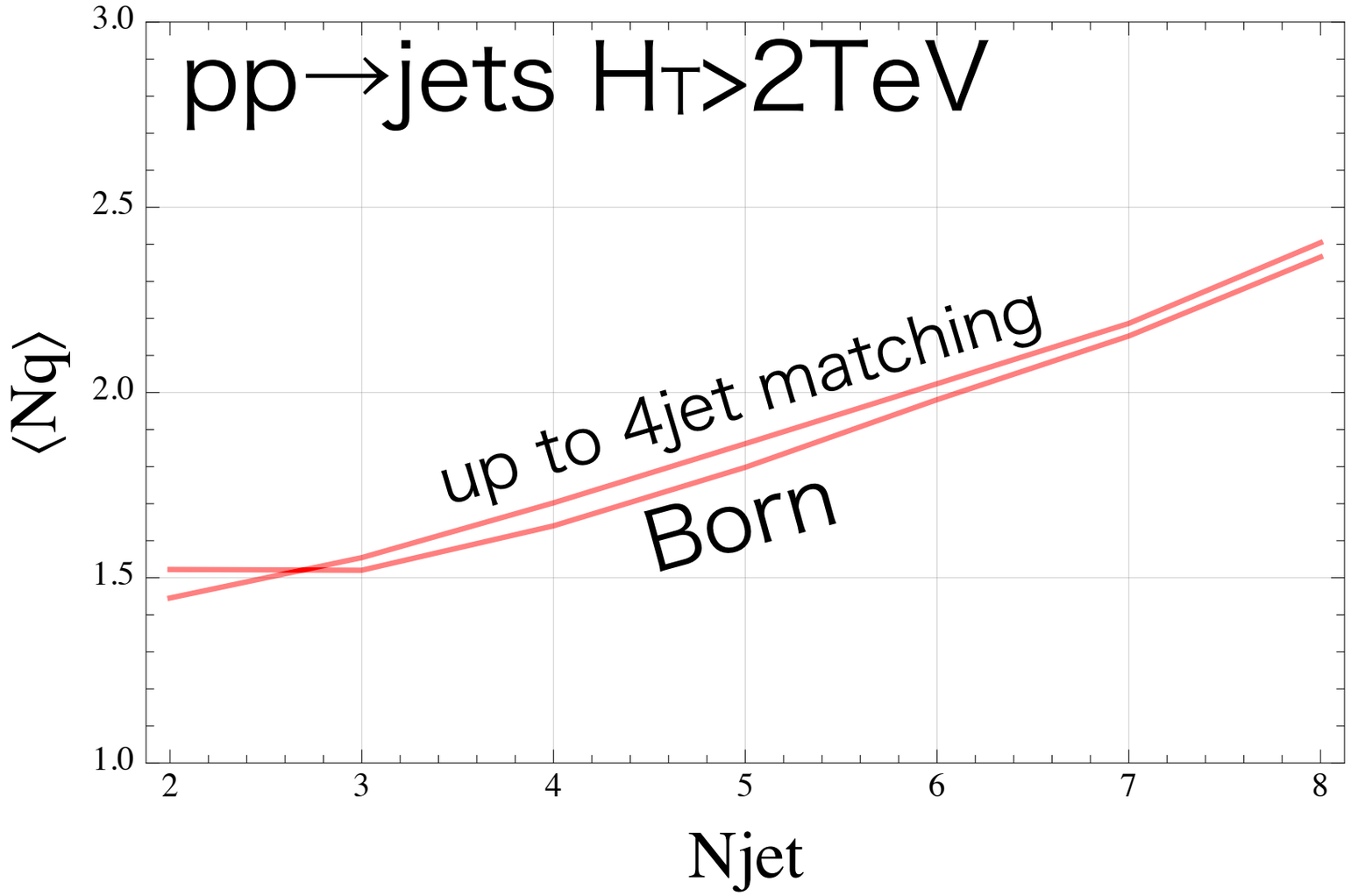
- Quark gluon jet discrimination has benefit a lot by applying it to the multi-jet final state, and the impact for a toy-signal is estimated.



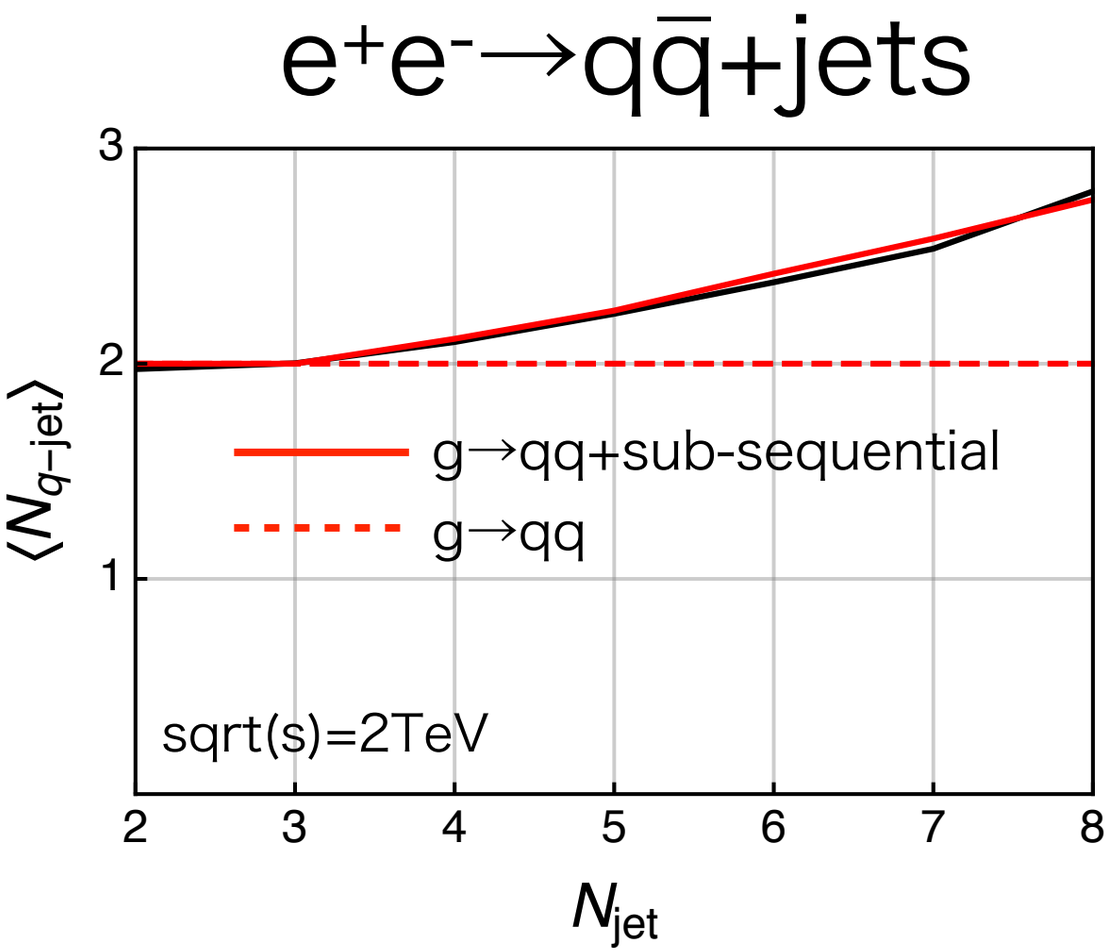
Back up

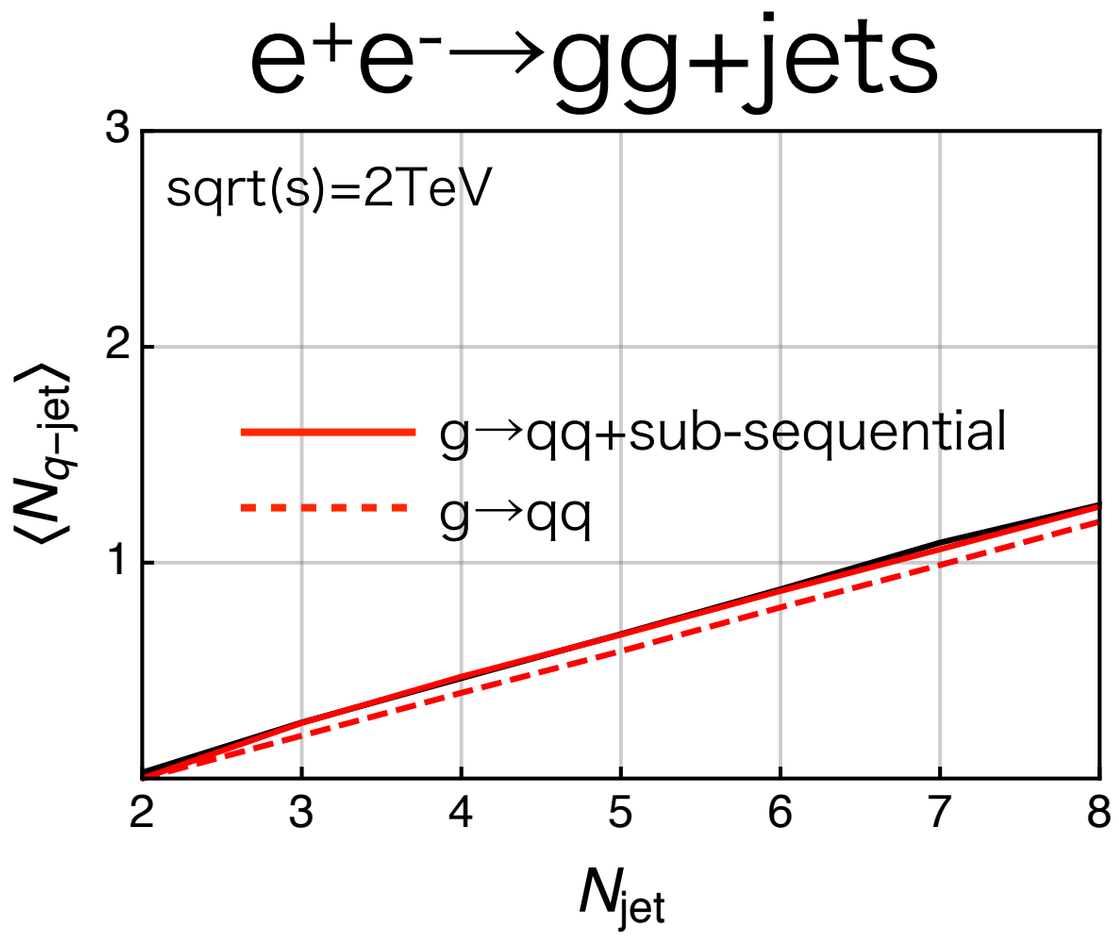
Belle II

MEC


pp→jets HT>2TeV
up to 4jet matching
Born
⟨Nq⟩
Njet
3.0
2.5
2.0
1.5
1.0
2
3
4
5
6
7
8

FSR from $q\bar{q}$ and gg





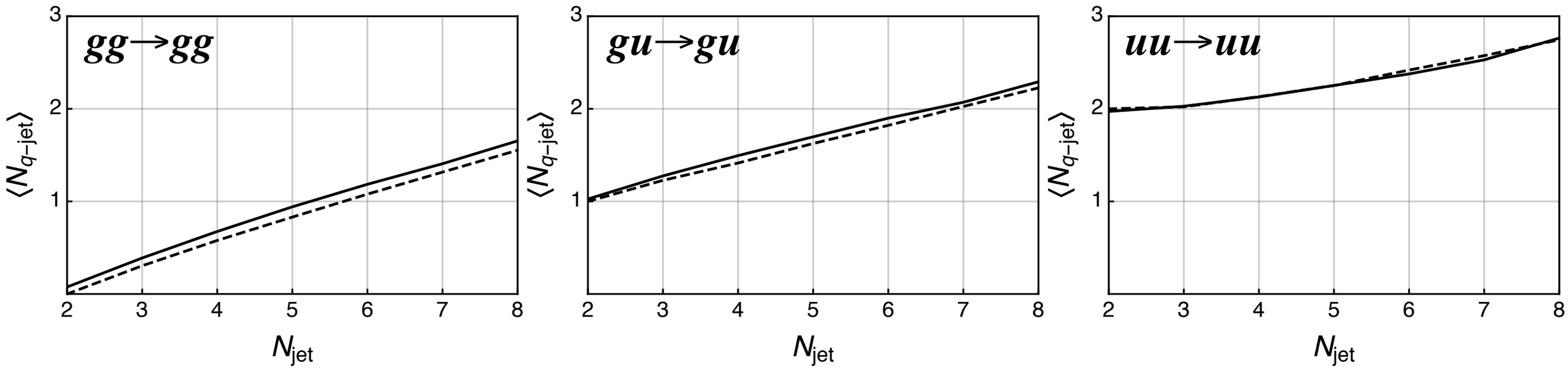
- For quarks, sub-sequential emissions increase number of quark jets
- For gluons, sub-sequential and g→qq effects are almost comparable
- Increment of # of quark jets stems from NLL, so it's mild.

MC comparison

—— MC (Herwig++)

------ Analytic (LL + g→qq + subsequent + ISR)

$\sqrt{s}$ =1TeV



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