LoopFest XXI

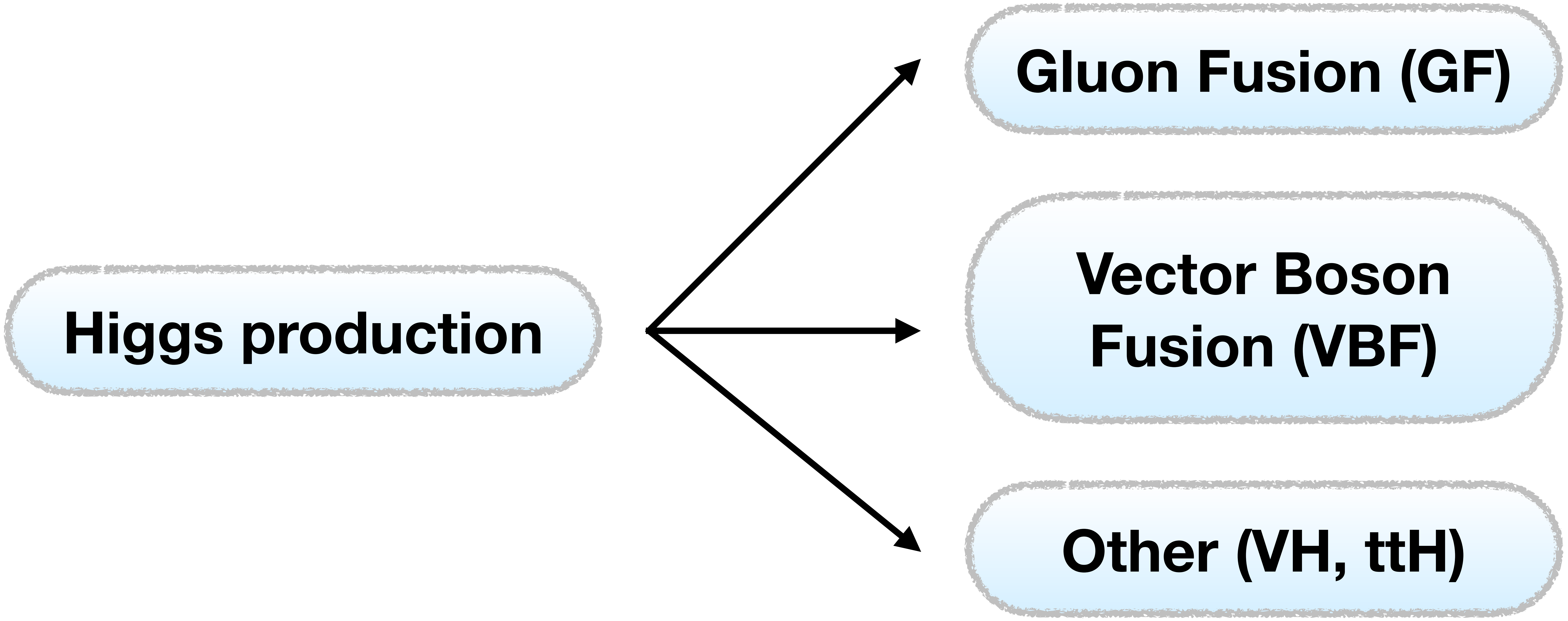
High Energy Jet (HEJ) Resummation at the LHC

Jérémy Paltrinieri
University of Edinburgh

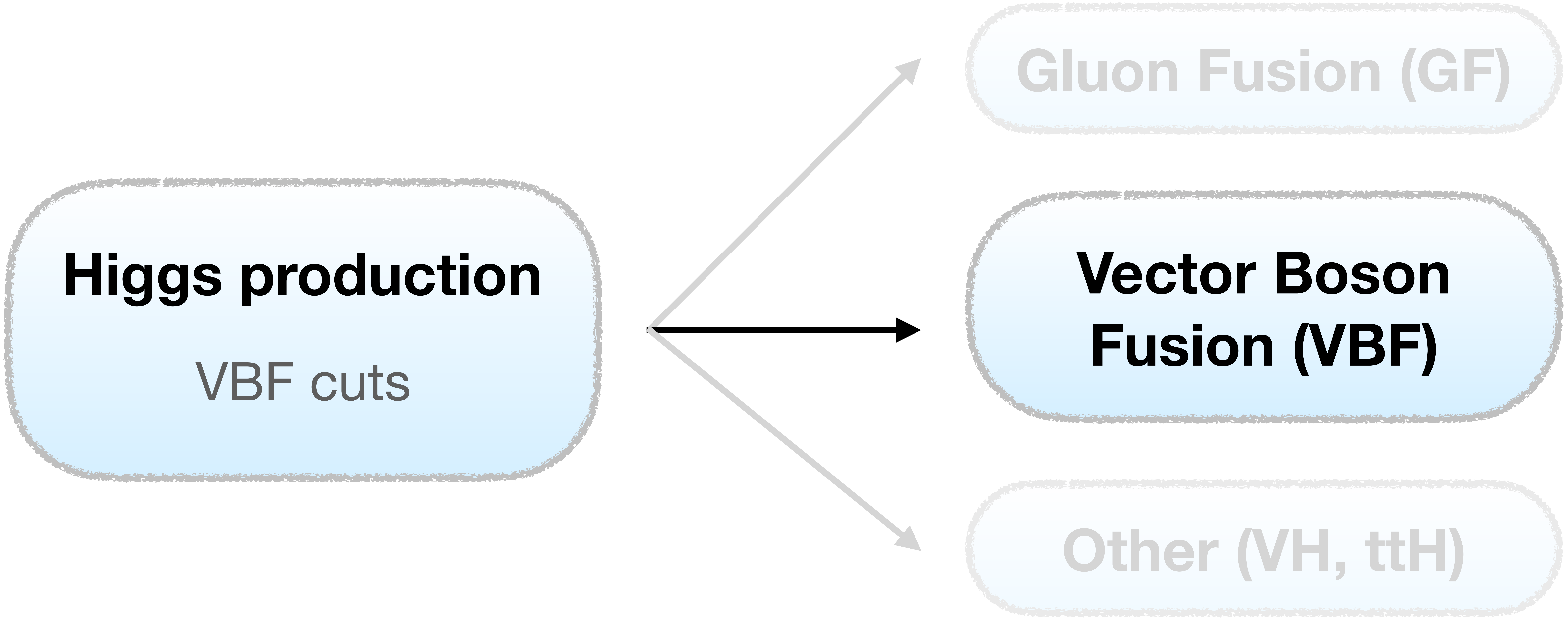
High Energy Jets (HEJ) Collaboration
Jeppe Andersen, Emmet Byrne, Bertrand Ducloué, Conor Elrick, Giulio Falcioni, Hitham Hassan, Sebastian Jaskiewicz, Andreas Maier, Andreas Papaefstathiou, Jenni Smillie

28 June 2023 - SLAC

Higgs production at the LHC



Higgs production at the LHC



Vector Boson Fusion (VBF) Cuts

Higgs production

VBF cuts

$$|\Delta y_{j_1 j_2}| > y_{\text{cut}}$$

$$m_{j_1 j_2} > m_{\text{cut}}$$

Vector Boson Fusion (VBF) Cuts

Higgs production

VBF cuts

$$|\Delta y_{j_1 j_2}| > y_{\mathrm{cut}}$$

$$m_{j_1 j_2} > m_{\mathrm{cut}}$$

→

Gluon Fusion (GF)

Enhance large logarithms
Damage perturbative expansion

VBF cuts make it difficult to get reliable QCD background predictions!

LoopFest XXI

HEJ Formalism

High Energy Limit
Resummation
Building Blocks
All-order results

LoopFest XXI

HEJ Formalism

High Energy Limit
Resummation
Building Blocks
All-order results

Higgs + dijet

Theory
Finite quark masses
Comparisons to FO
VBF cuts

LoopFest XXI

HEJ Formalism

High Energy Limit
Resummation
Building Blocks
All-order results

Higgs + dijet

Theory
Finite quark masses
Comparisons to FO
VBF cuts

Higgs + one jet

Theory
Comparisons to experimental data
Comparisons to FO

SLAC

THE UNIVERSITY OF EDINBURGH

LoopFest XXI

HEJ Formalism

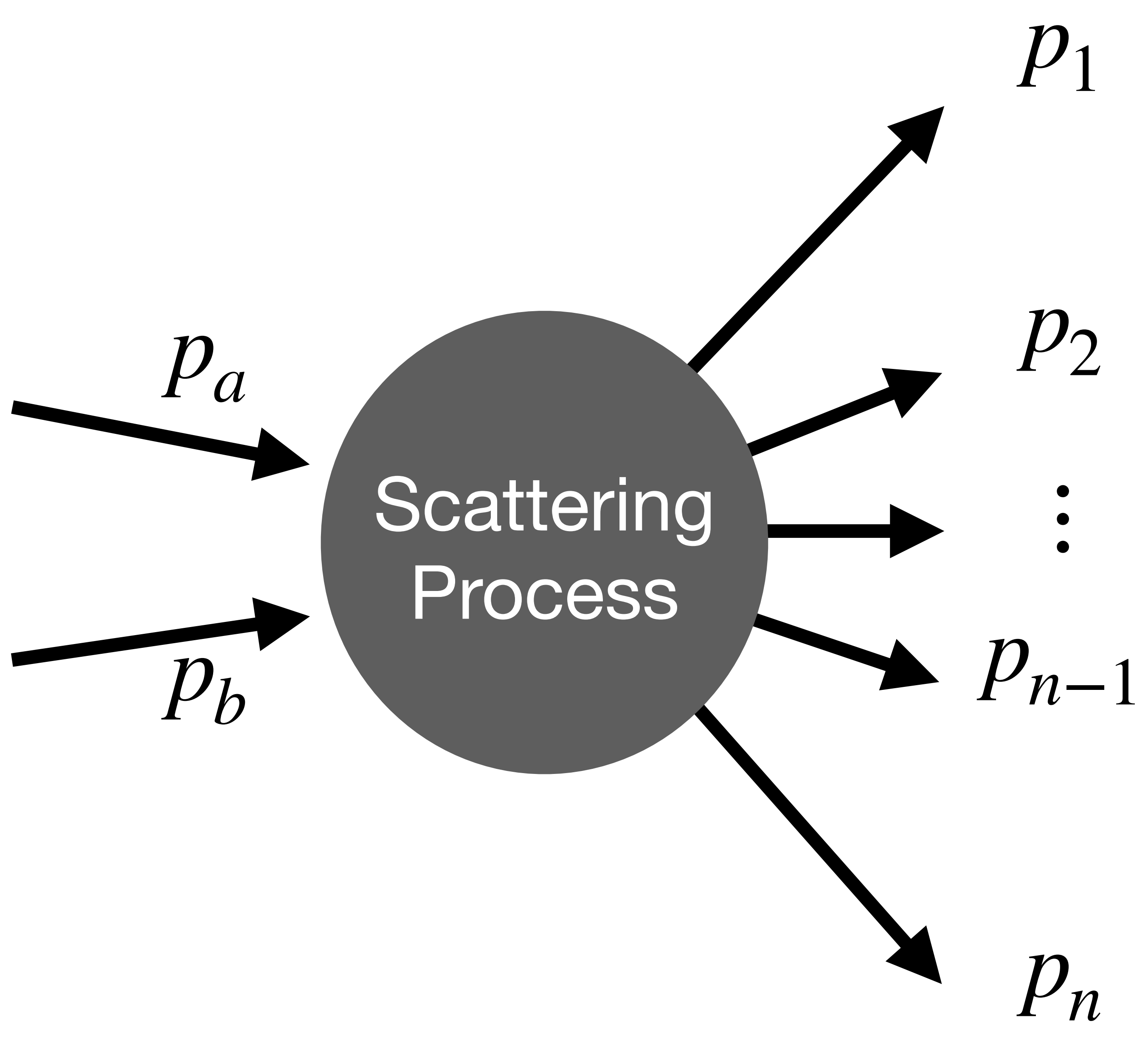
High Energy Limit
Resummation
Building Blocks
All-order results

HEJ References

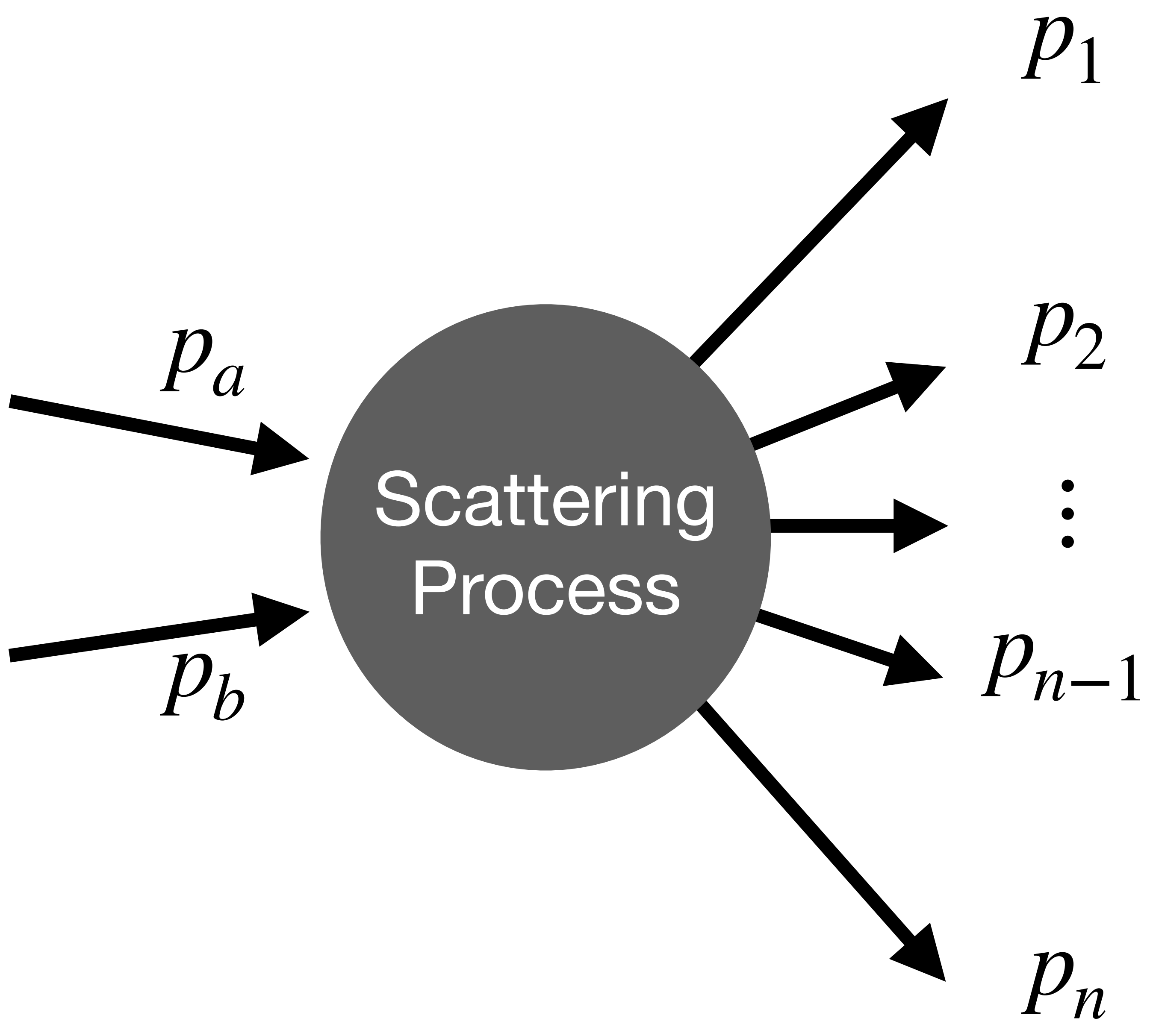
Constructing paper
[0908.2786]

Factorisation in qg
[0910.5113]

High Energy (HE) limit



High Energy (HE) limit



$$|p_{1\perp}| \approx |p_{2\perp}| \approx \cdots \approx |p_{n\perp}| \text{ finite}$$
$$y_1 \gg y_2 \gg \cdots \gg y_n$$

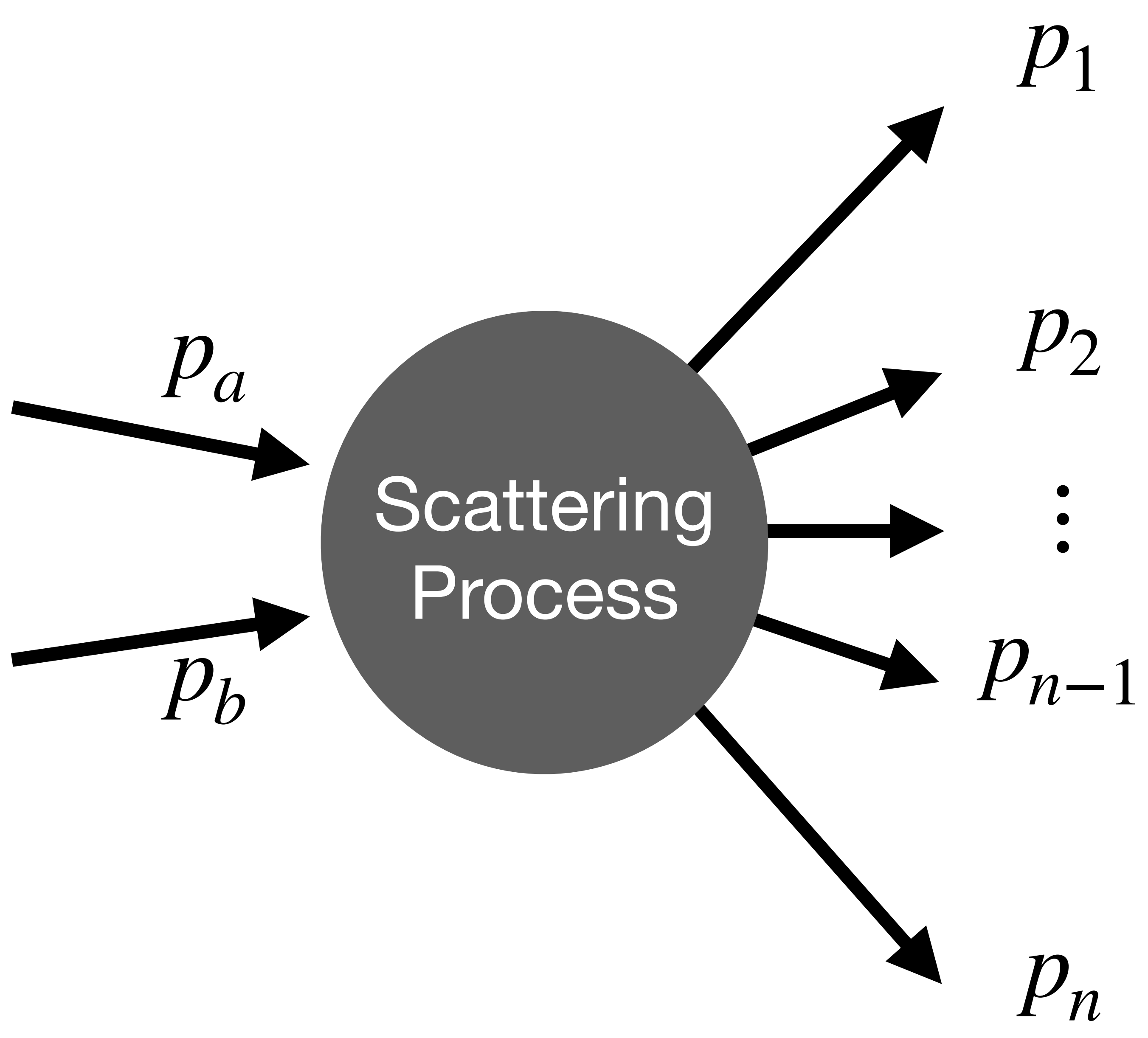
High Energy Limit

or equivalently

$t-$ channel momenta squared finite

large invariant dijet masses $s_{i,i+1}$

High Energy (HE) limit



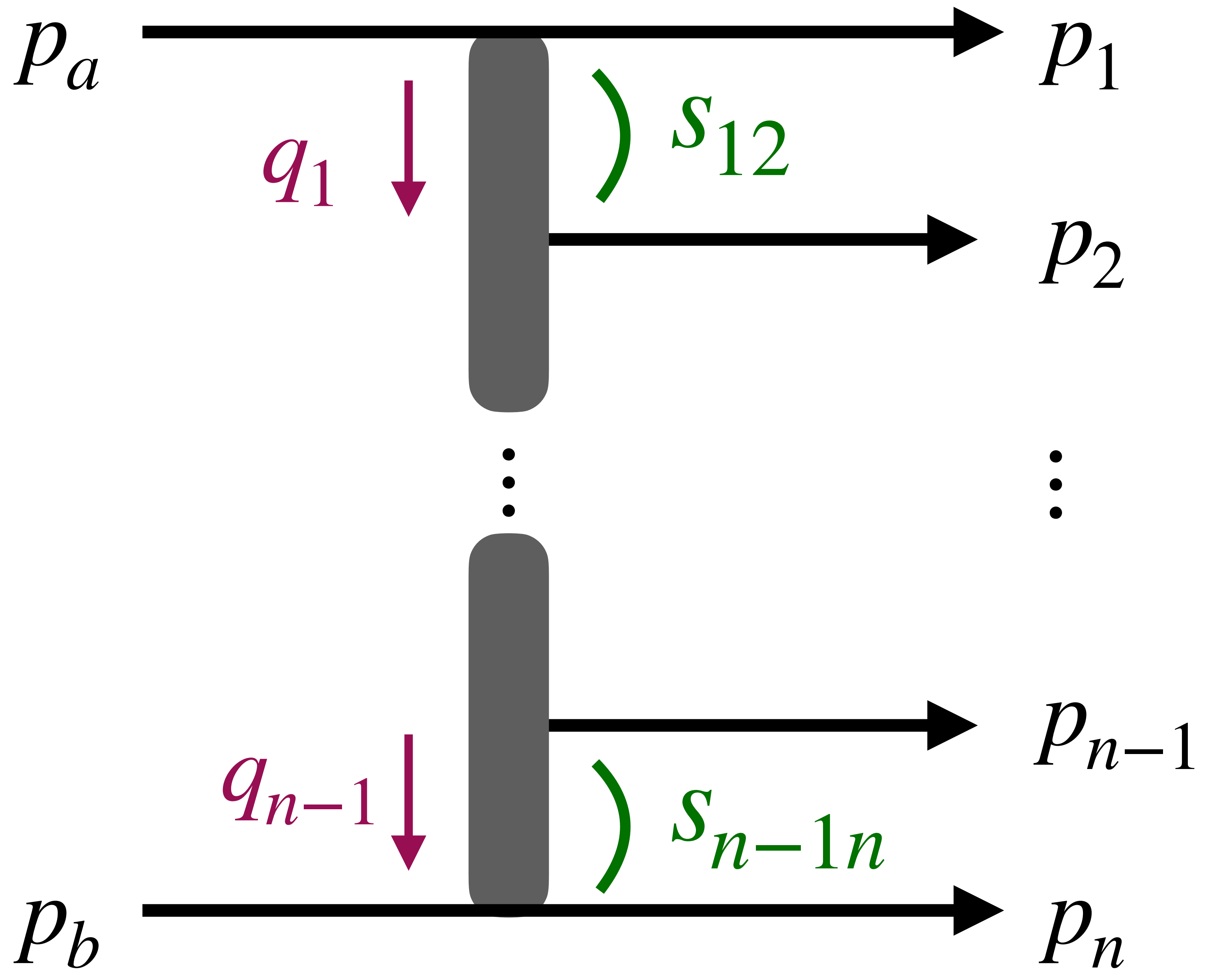
$$|p_{1\perp}| \approx |p_{2\perp}| \approx \cdots \approx |p_{n\perp}| \text{ finite}$$
$$y_1 \gg y_2 \gg \cdots \gg y_n$$

High Energy Limit

or equivalently

$t-$ channel momenta squared finite

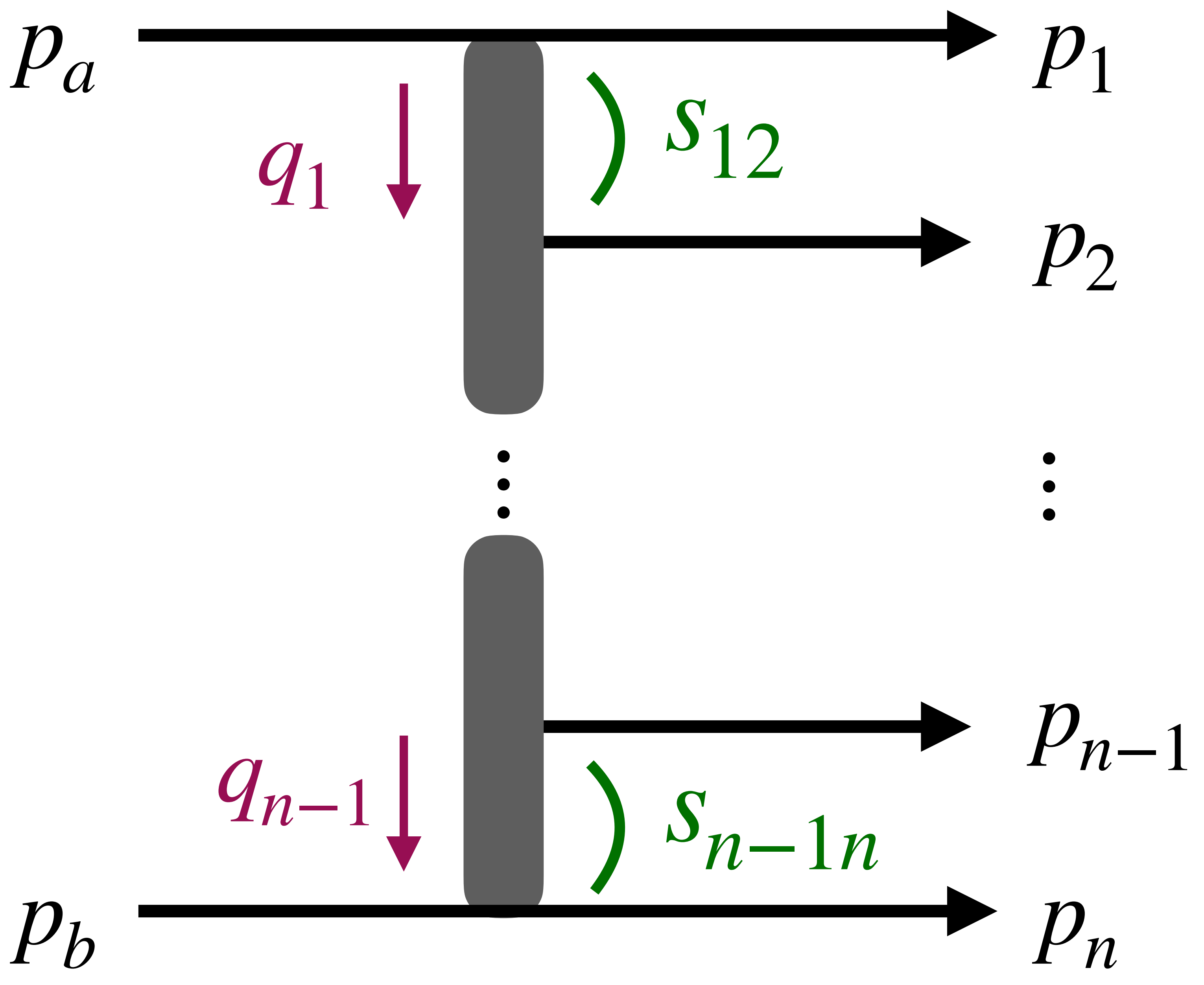
large invariant dijet masses $s_{i,i+1}$



SLAC

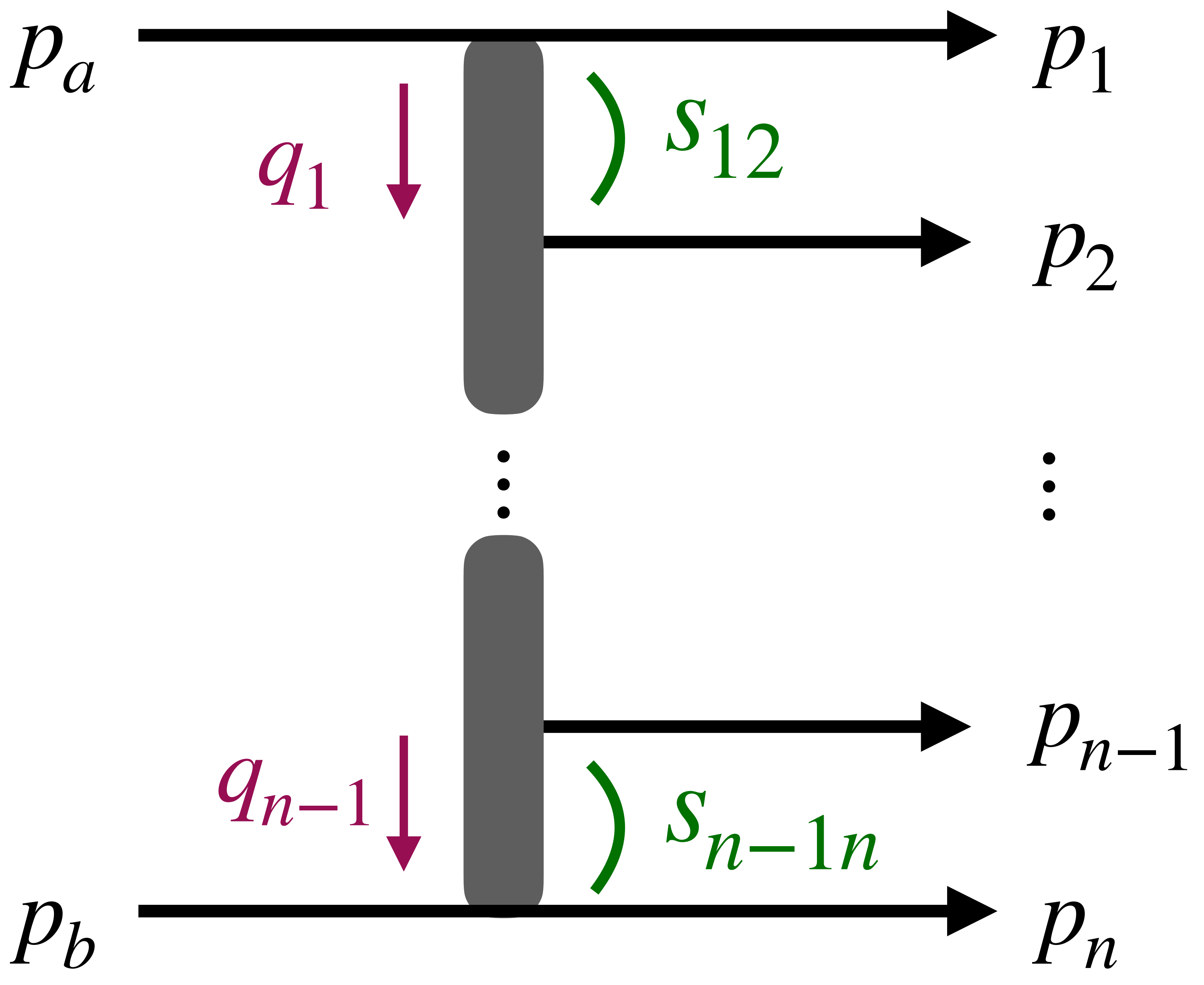
THE UNIVERSITY OF EDINBURGH

Regge scaling



Regge scaling

Regge scaling: amplitudes = product of pieces
Get leading configurations in the HE limit:



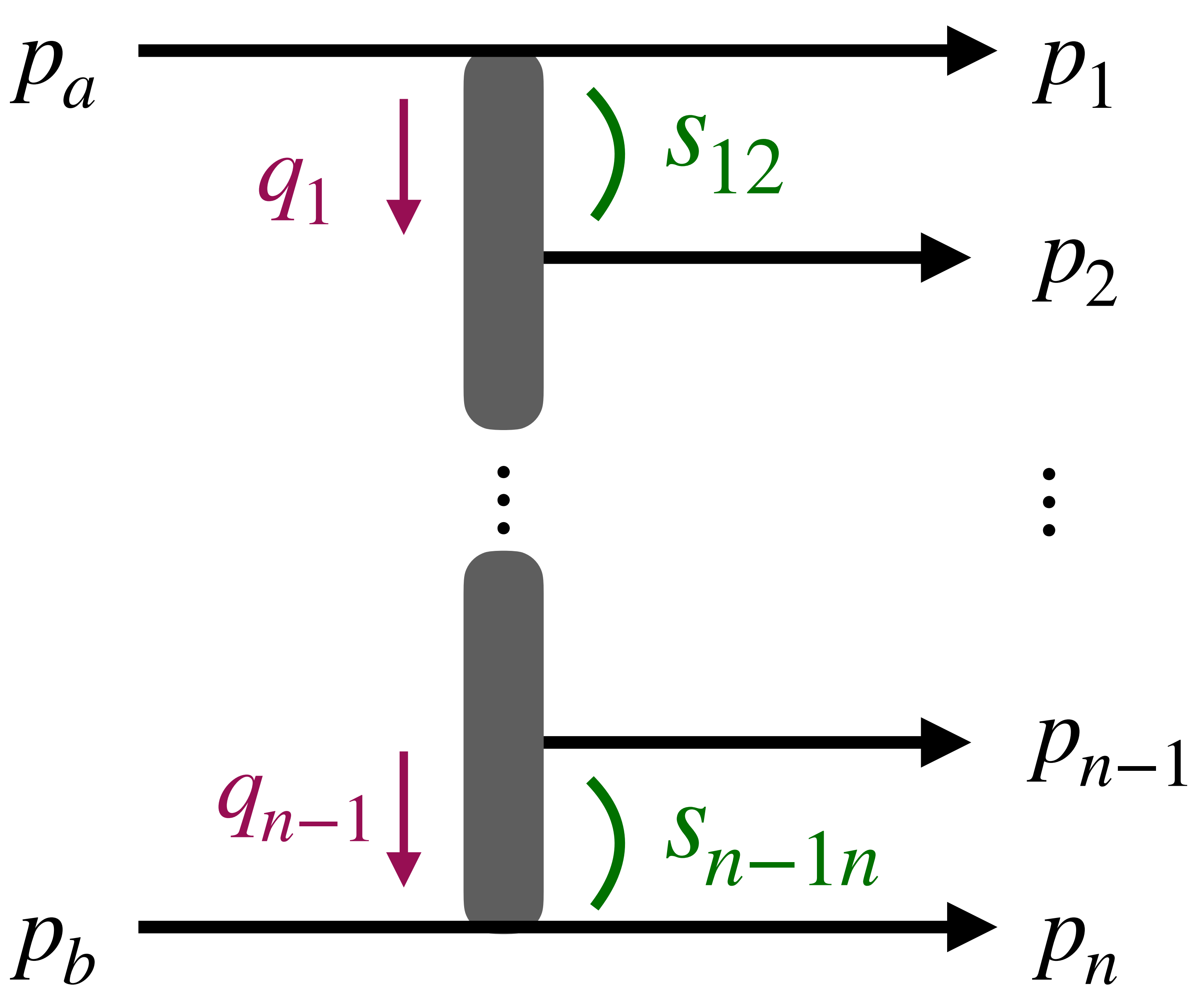
Regge scaling

Regge scaling: amplitudes = product of pieces
Get leading configurations in the HE limit:

Spin of particle q_1

$$\mathcal{M} = s_{12}^{\alpha_1(q_1)} \cdots s_{n-1n}^{\alpha_{n-1}(q_{n-1})} \times \Gamma\left(q_1^2, \cdots, q_{n-1}^2\right)$$

Finite factor in the HE limit



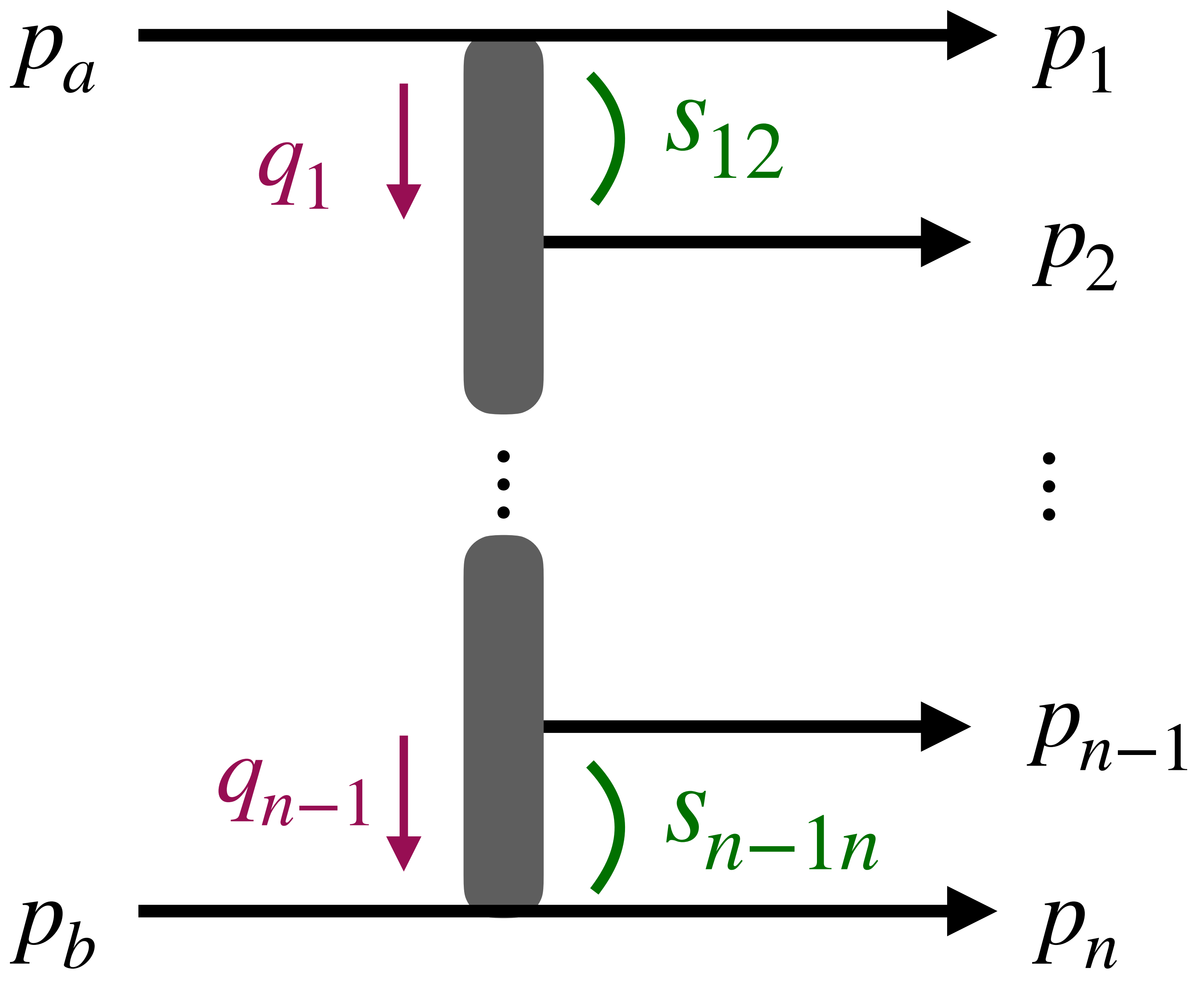
Regge scaling

Regge scaling: amplitudes = product of pieces
Get leading configurations in the HE limit:

Spin of particle q_1

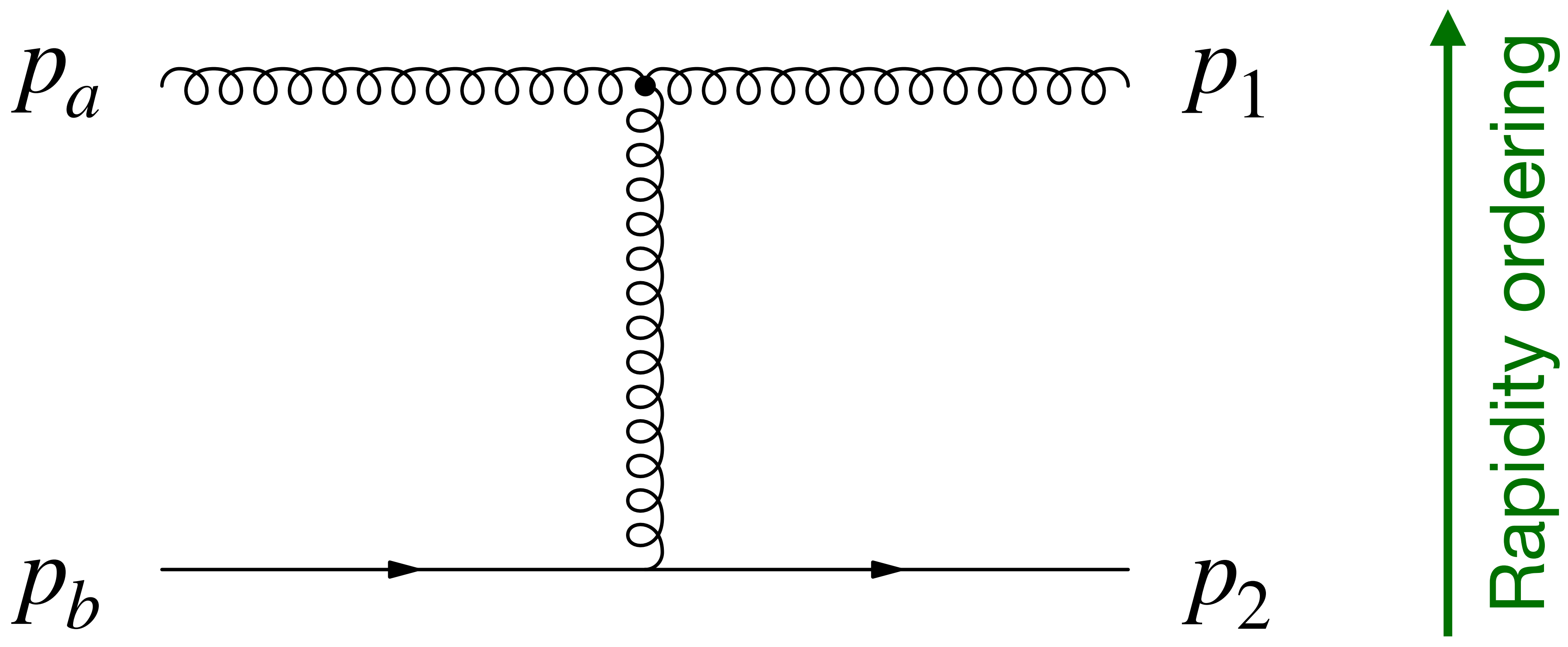
$$\mathcal{M} = s_{12}^{\alpha_1(q_1)} \cdots s_{n-1n}^{\alpha_{n-1}(q_{n-1})} \times \Gamma\left(q_1^2, \cdots, q_{n-1}^2\right)$$

Finite factor in the HE limit

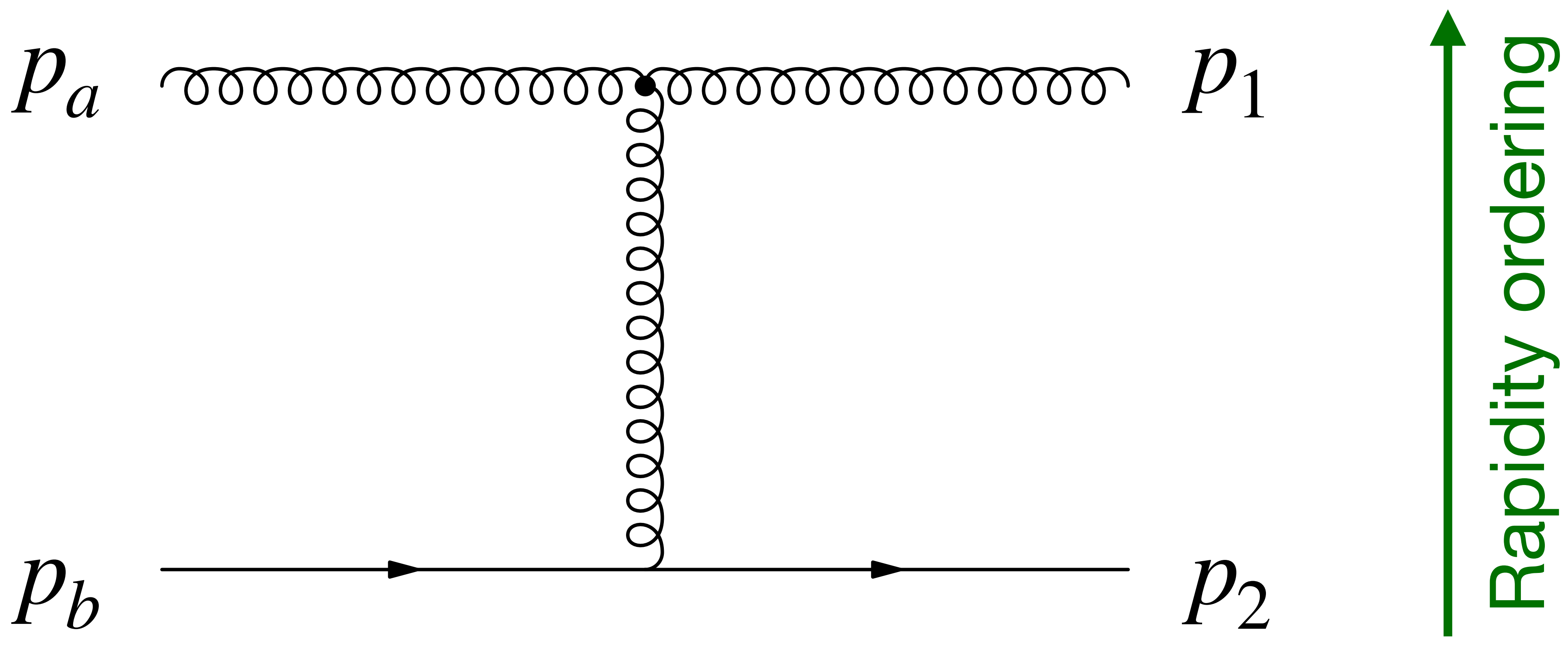


Leading configurations: maximise number of t-channel gluons exchanges

QCD scattering: quark-gluon

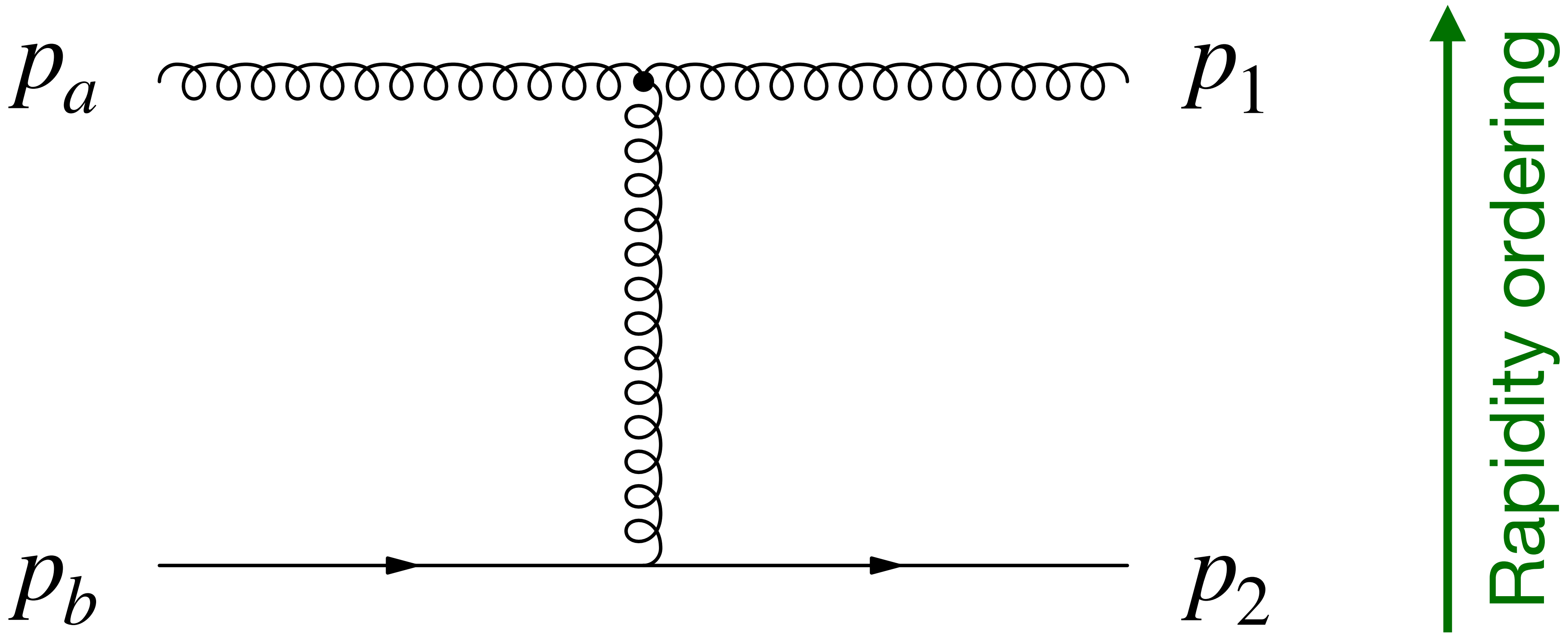


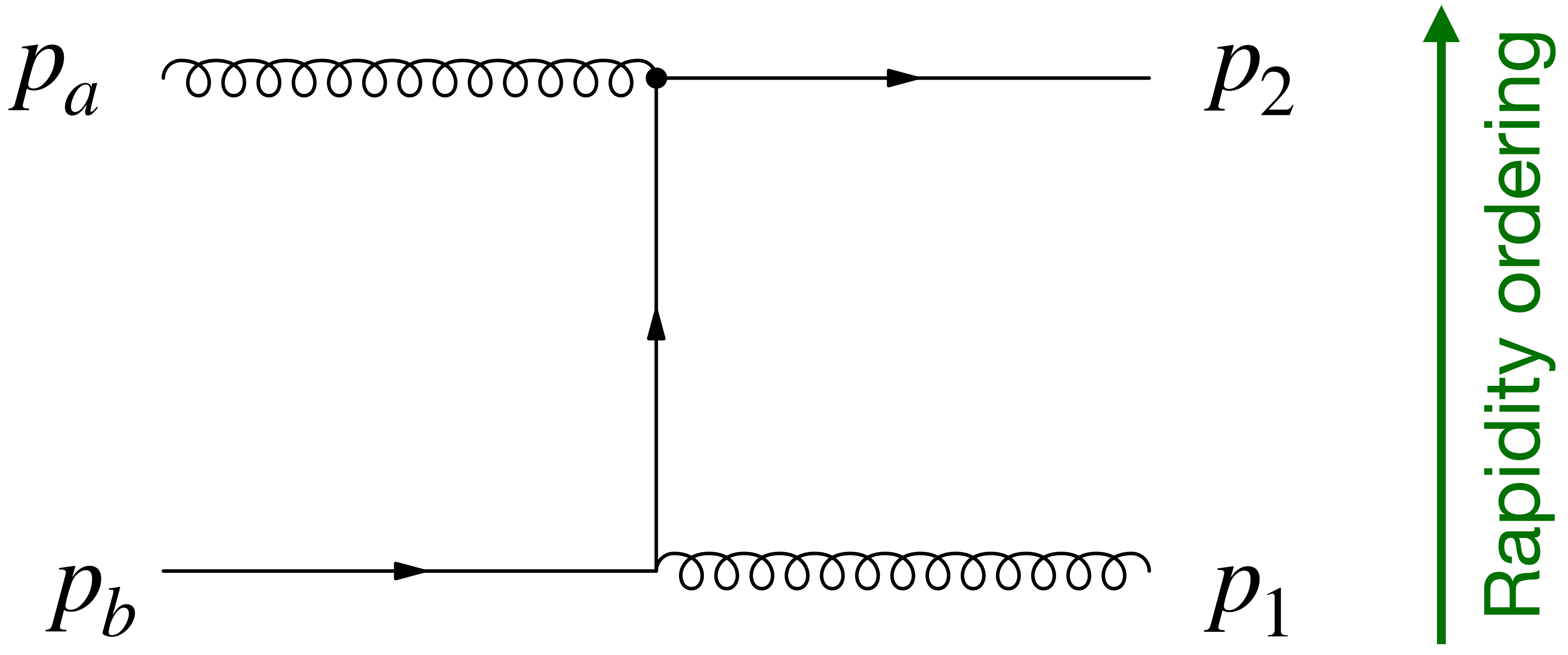
QCD scattering: quark-gluon



$$\mathcal{M} \propto s_{12}$$

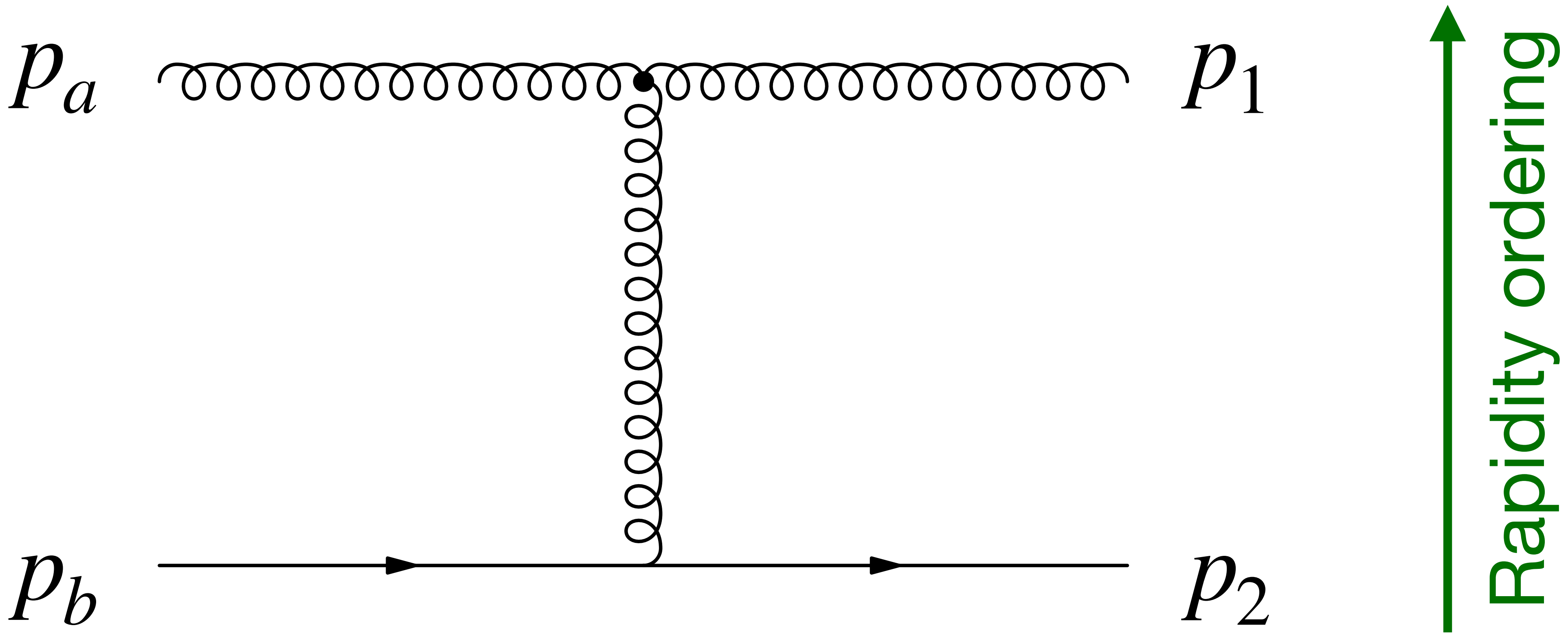
QCD scattering: quark-gluon



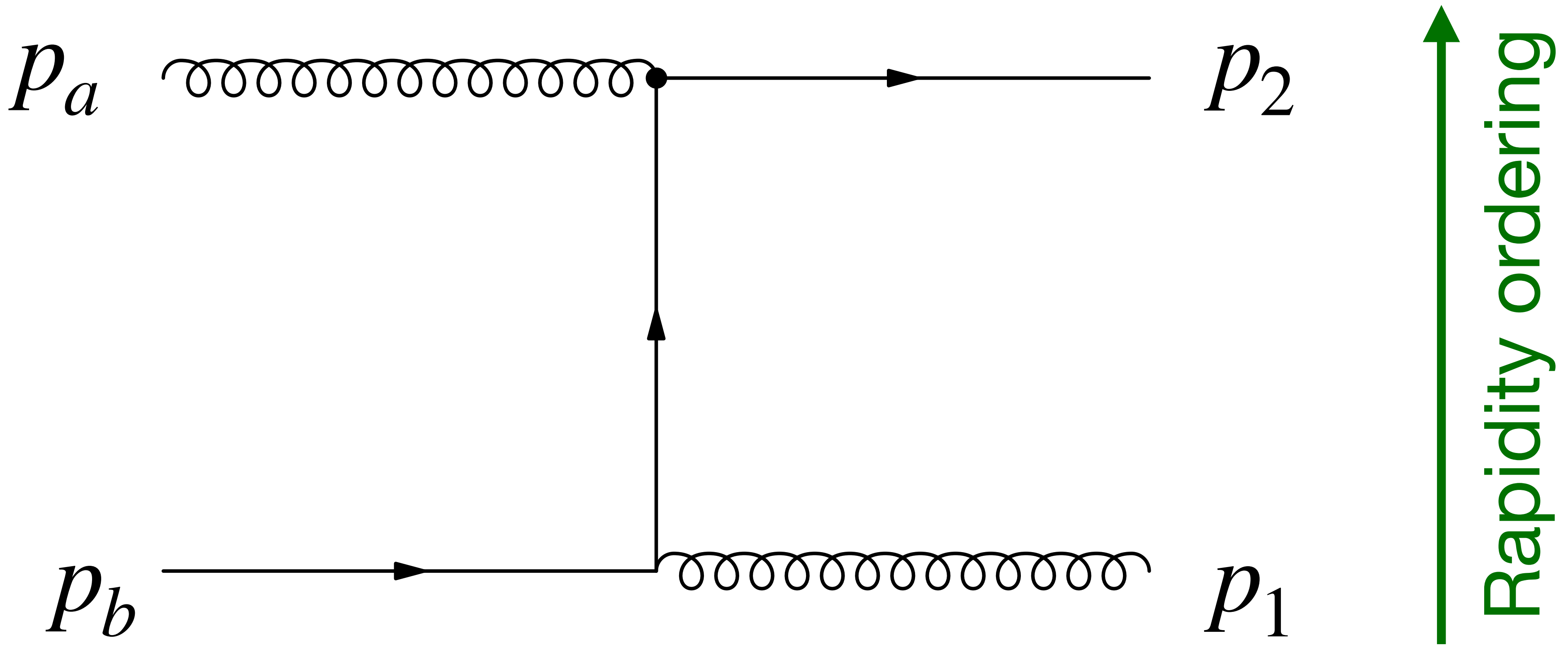


$$\mathcal{M} \propto s_{12}$$

QCD scattering: quark-gluon

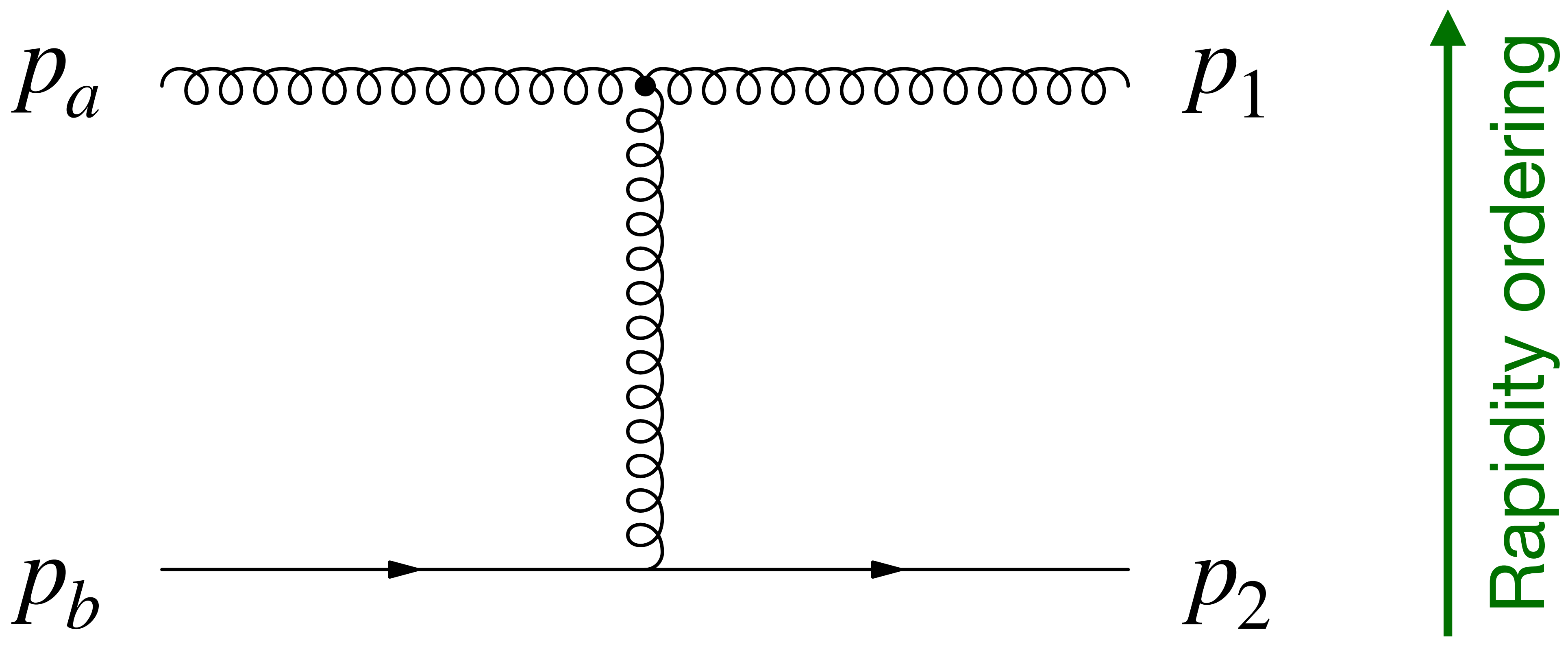


$$\mathcal{M} \propto s_{12}$$

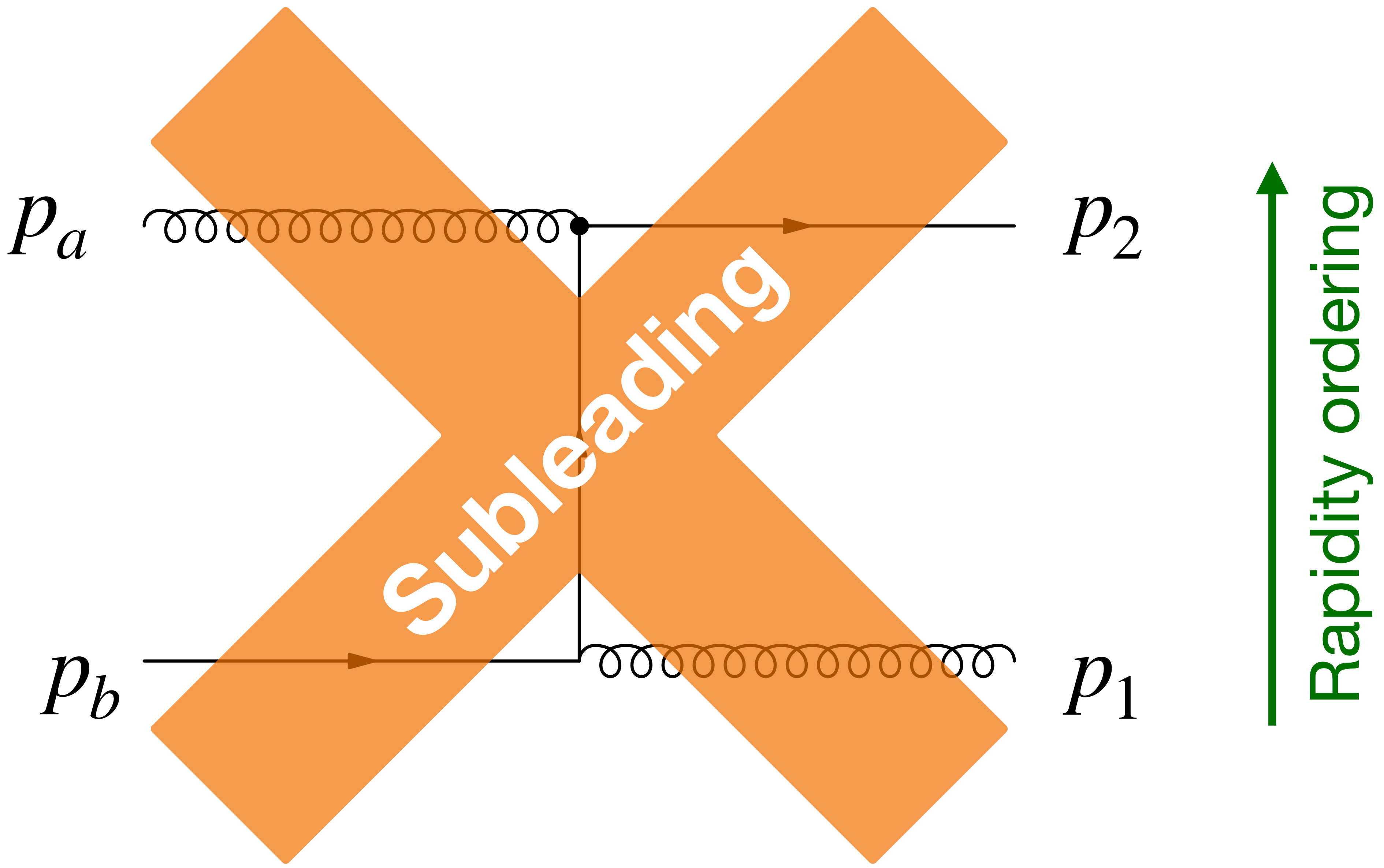


$$\mathcal{M} \propto \sqrt{s_{12}}$$

QCD scattering: quark-gluon



$$\mathcal{M} \propto s_{12}$$



$$\mathcal{M} \propto \sqrt{s_{12}}$$

The need for resummation

In the High Energy Phase-Space, the perturbative cross-section expansion contains factors of numerically significant logarithms:

$$
\begin{aligned}
|\mathcal{M}_{2j\ \text{inc.}}|^2 = \alpha_s^2 c_{\text{LO}} \\
+ \alpha_s^3 c_{\text{NLO}} \\
+ \alpha_s^4 c_{\text{NNLO}} \\
+ \dots
\end{aligned}
$$

Perturbative expansion valid as long as coefficients do not grow too much

The need for resummation

In the High Energy Phase-Space, the perturbative cross-section expansion contains factors of numerically significant logarithms:

$$
\begin{aligned}
|\mathcal{M}_{2j\ \mathrm{inc.}}|^2 = &\ \alpha_s^2 c_{\mathrm{LO}} \\
&+ \alpha_s^3 \left(c_{11} \log(s/|t|) \quad + c_{12}\right) \\
&+ \alpha_s^4 \left(c_{21} \log^2(s/|t|) + c_{22} \log(s/|t|) \quad + c_{23}\right) \\
&+ \ldots
\end{aligned}
$$

The need for resummation

In the High Energy Phase-Space, the perturbative cross-section expansion contains factors of numerically significant logarithms:

$$
\begin{aligned}
|\mathcal{M}_{2j\ \mathrm{inc.}}|^2 &= \alpha_s^2 c_{\mathrm{LO}} \\
&+ \alpha_s^3 \left(c_{11} \log(s/|t|) + c_{12}\right) \\
&+ \alpha_s^4 \left(c_{21} \log^2(s/|t|) + c_{22} \log(s/|t|) + c_{23}\right) \\
&+ \dots
\end{aligned}
$$

Leading Logarithm (LL)

The need for resummation

In the High Energy Phase-Space, the perturbative cross-section expansion contains factors of numerically significant logarithms:

$$
\begin{aligned}
|\mathcal{M}_{2j\ \mathrm{inc.}}|^2 &= \alpha_s^2 c_{\mathrm{LO}} \\
&+ \alpha_s^3 \left(c_{11} \log(s/|t|) + c_{12}\right) \\
&+ \alpha_s^4 \left(c_{21} \log^2(s/|t|) + c_{22} \log(s/|t|) + c_{23}\right) \\
&+ \ldots
\end{aligned}
$$

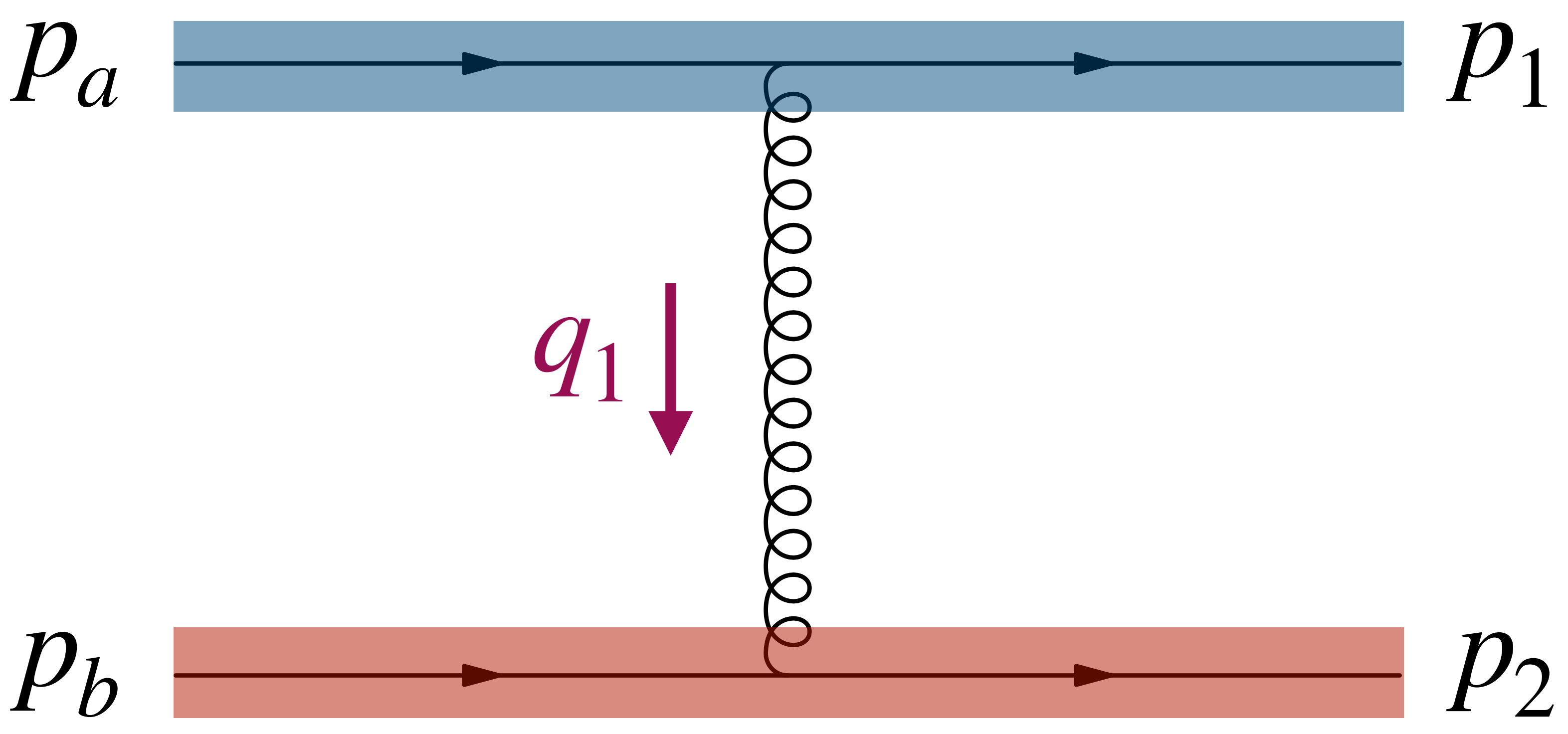
Leading Logarithm (LL)

Next-to-Leading Logarithm (NLL)

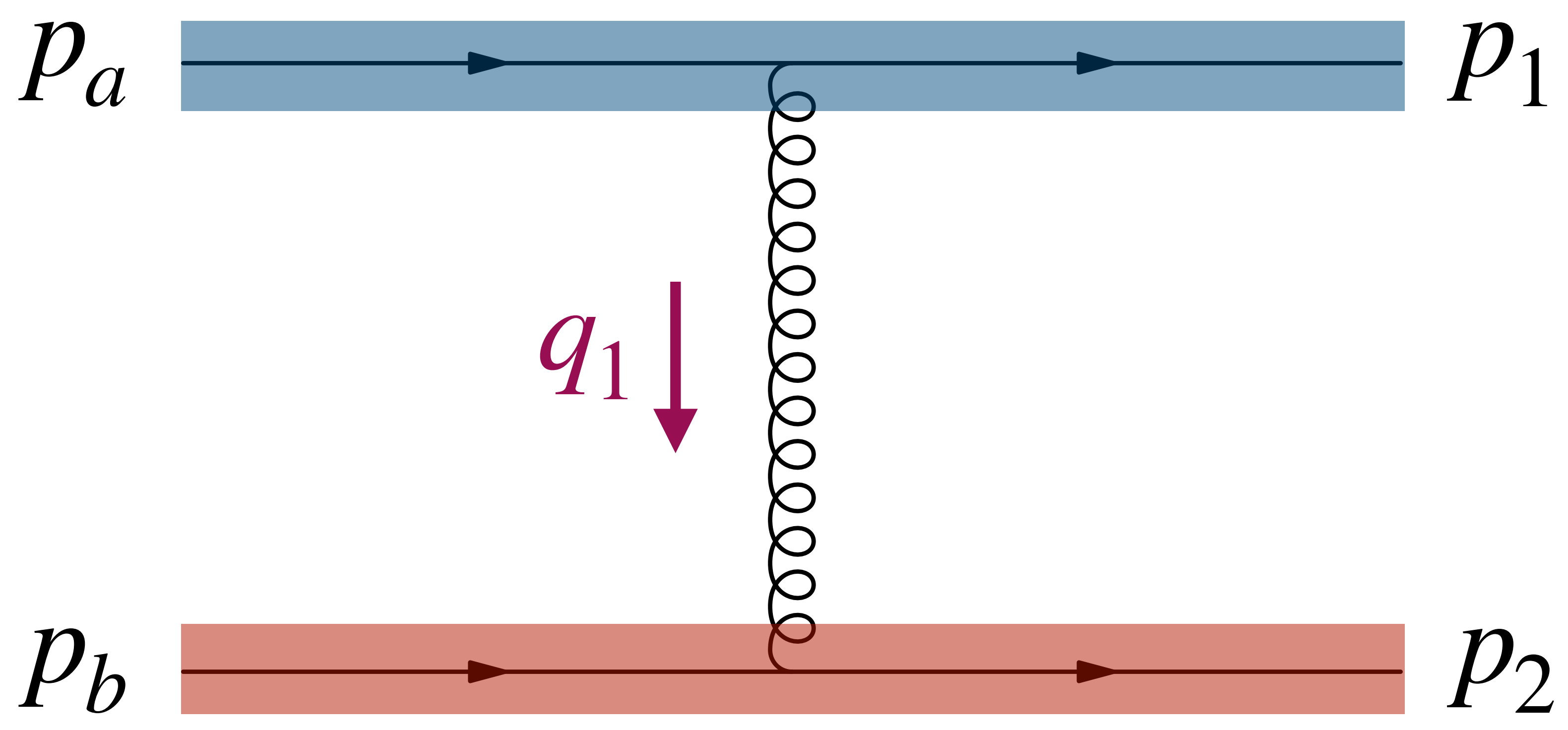
SLAC

THE UNIVERSITY OF EDINBURGH

Building blocks of HEJ



Building blocks of HEJ

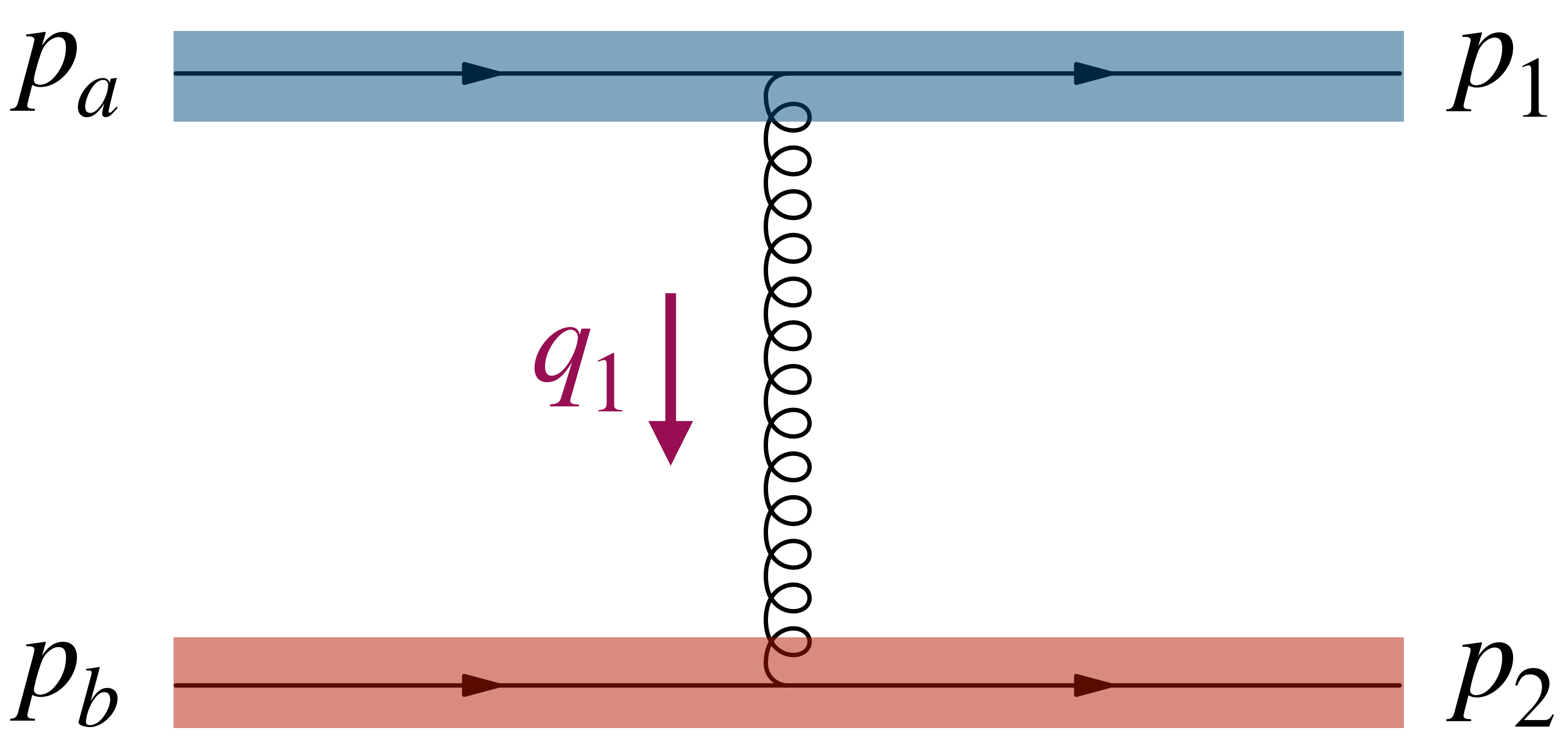


$$|\mathcal{M}|^2 \propto C_F^2 \left(\frac{1}{q_1^2}\right)^2 \left|j^\mu(p_1, p_a) j_\mu(p_2, p_b)\right|^2$$

SLAC

THE UNIVERSITY OF EDINBURGH

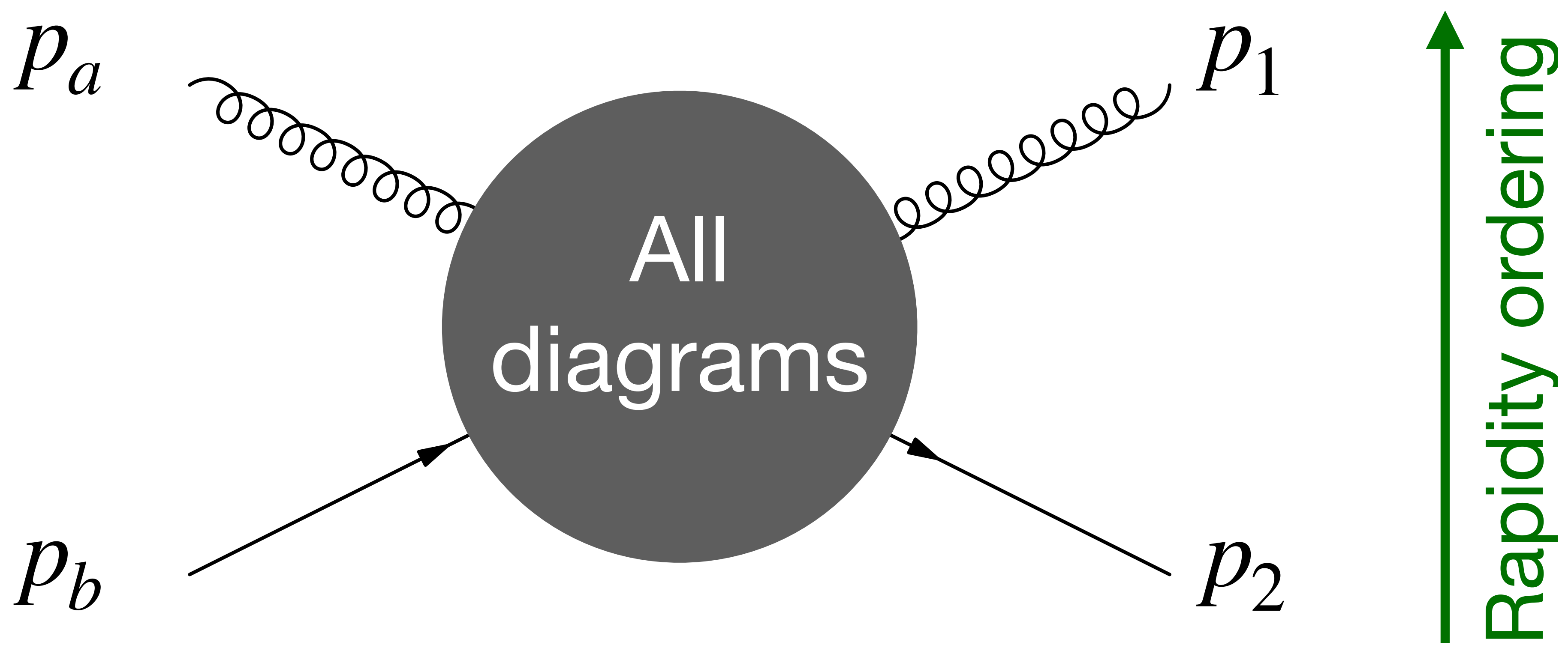
Building blocks of HEJ



- Contraction of currents over a t-channel pole
- Looks natural: only one diagram contributes at tree-level!
- What about gluon-induced processes?

$$|\mathcal{M}|^2 \propto C_F^2 \left(\frac{1}{q_1^2}\right)^2 |j^\mu(p_1, p_a) j_\mu(p_2, p_b)|^2$$

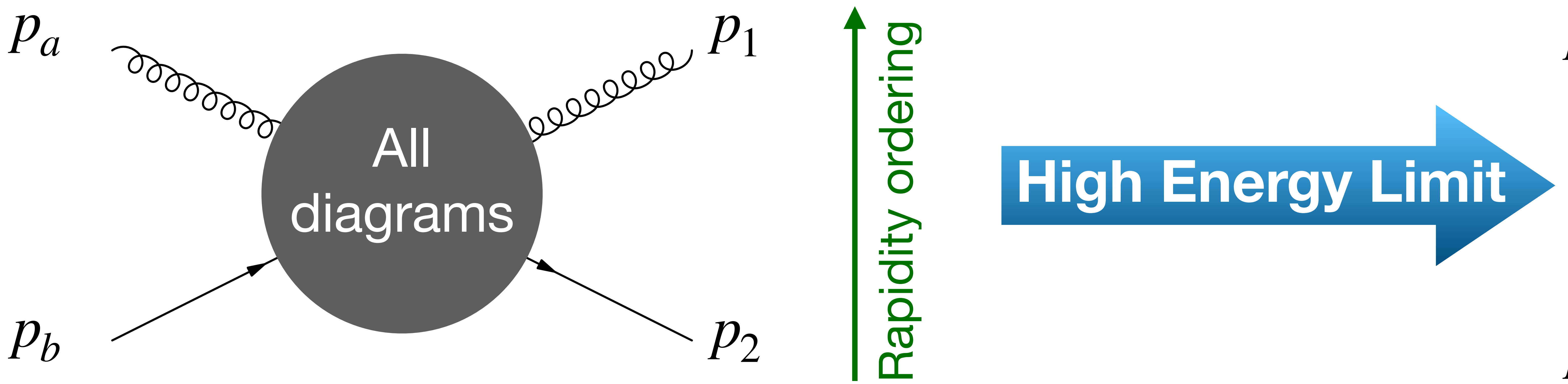
Building blocks of HEJ

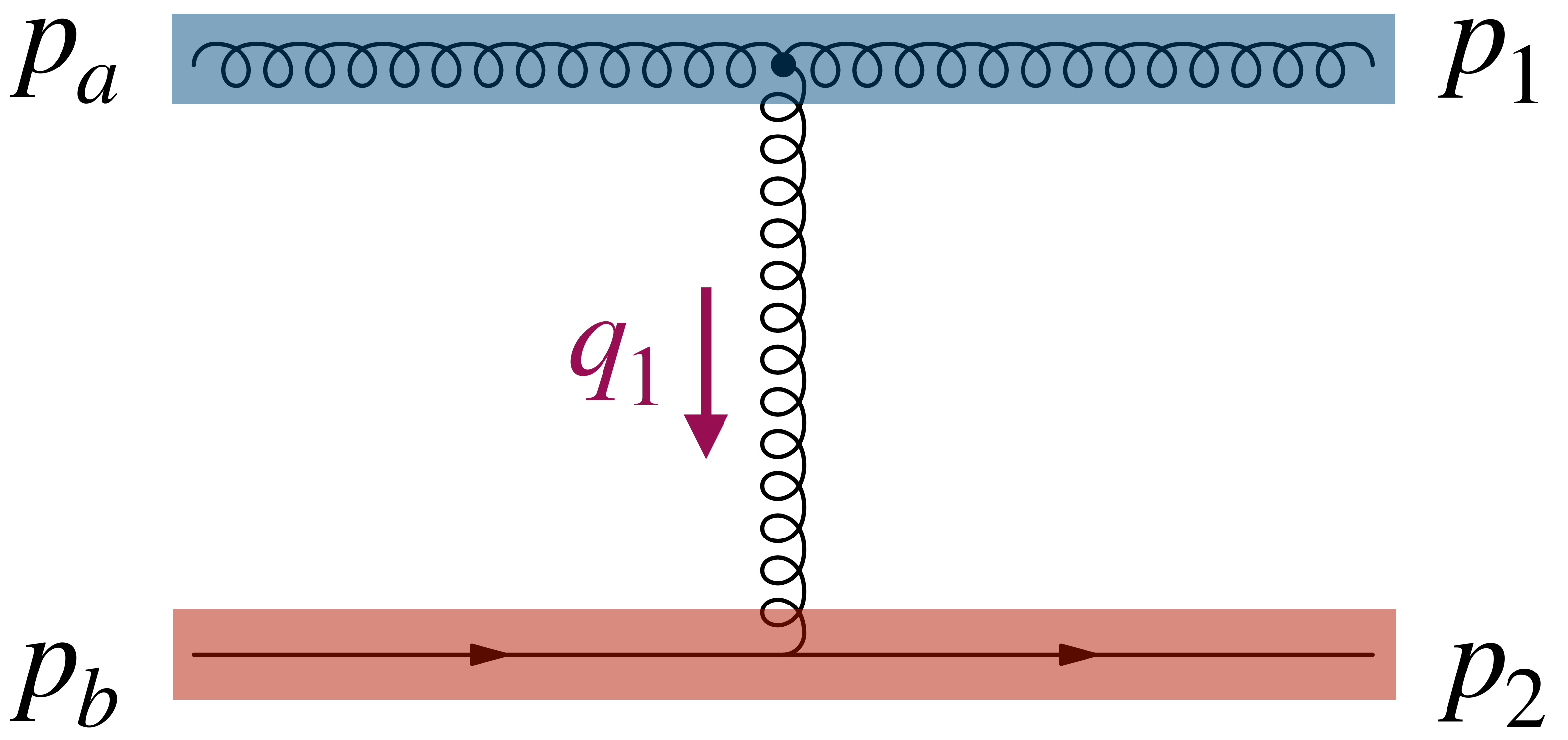


Building blocks of HEJ

SLAC

Building blocks of HEJ

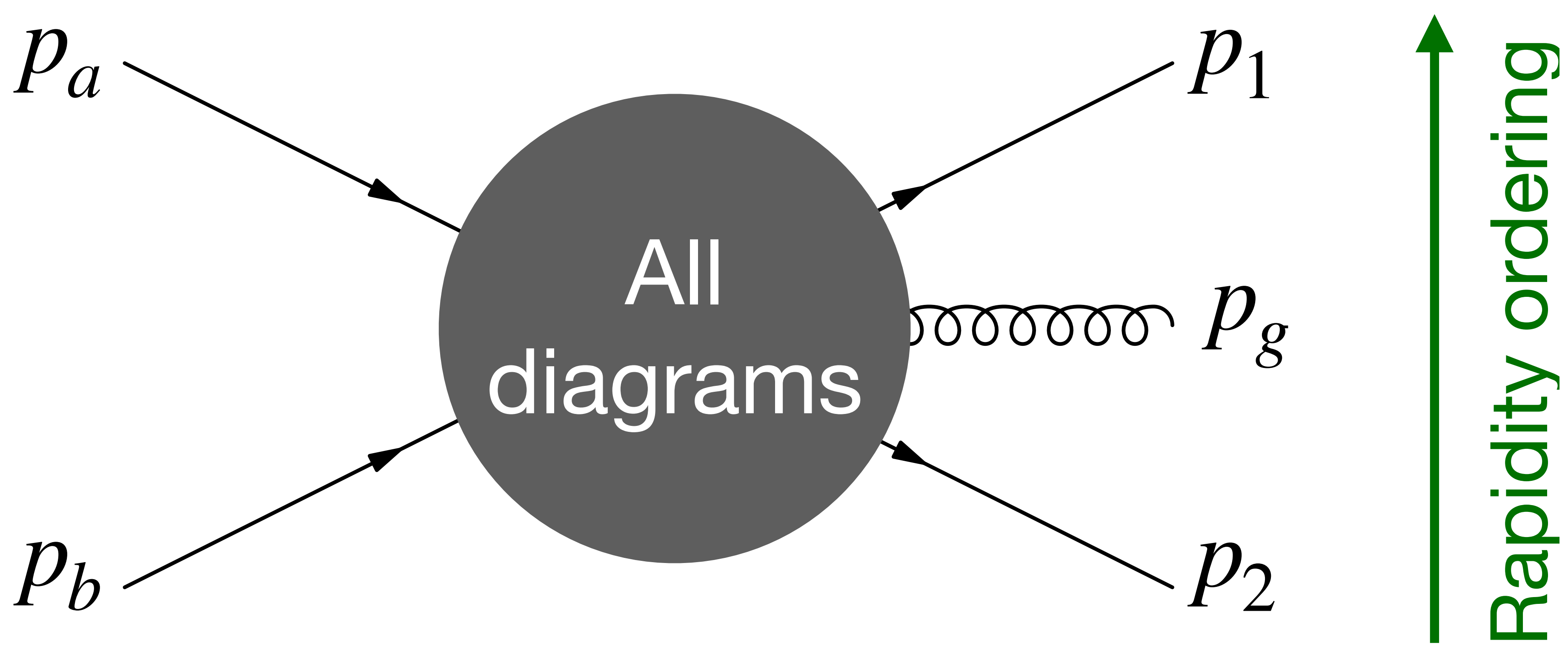




$$|\mathcal{M}|^2 \propto C_F \times \ \mathrm{CAM} \times \left(\frac{1}{q_1^2}\right)^2 |j^\mu(p_1, p_a) j_\mu(p_2, p_b)|^2$$

$\mathrm{CAM} \to C_A$ in the High Energy Limit

Real Corrections



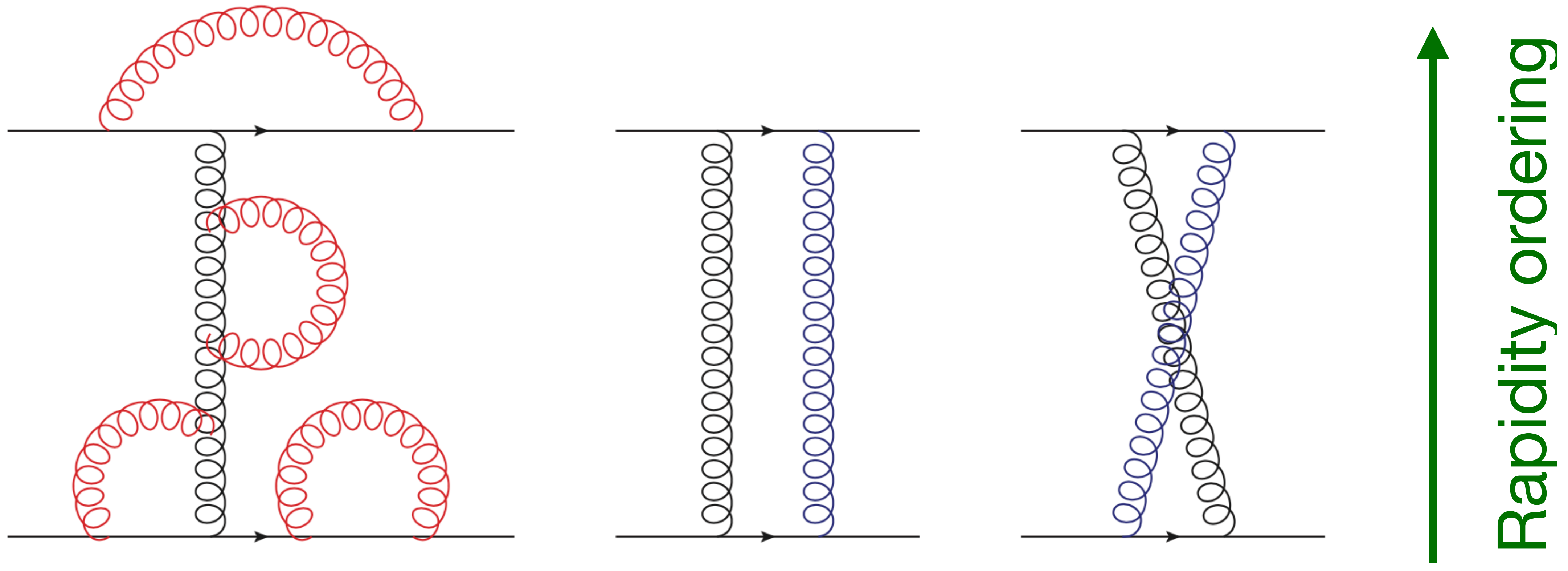
Real Corrections

Real Corrections

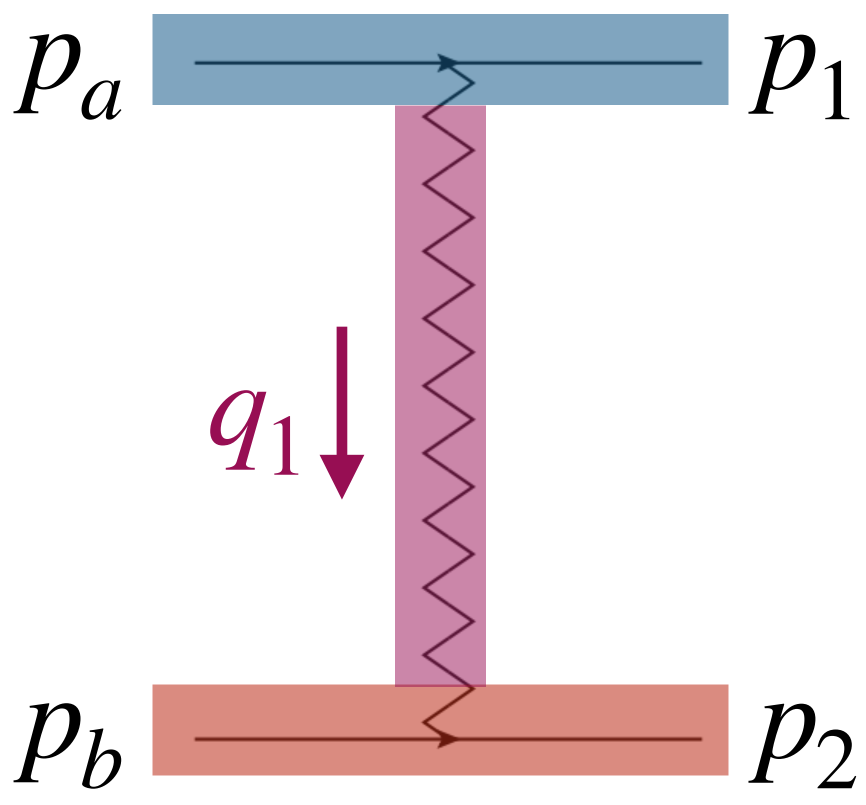
$$\mathcal{M} \propto \frac{1}{q_1^2}\frac{1}{q_2^2} j^\mu(p_1, p_a) j_\mu(p_2, p_b) V^\rho \epsilon_\rho^*(p_g)$$

Effective Lipatov vertex, gauge invariant

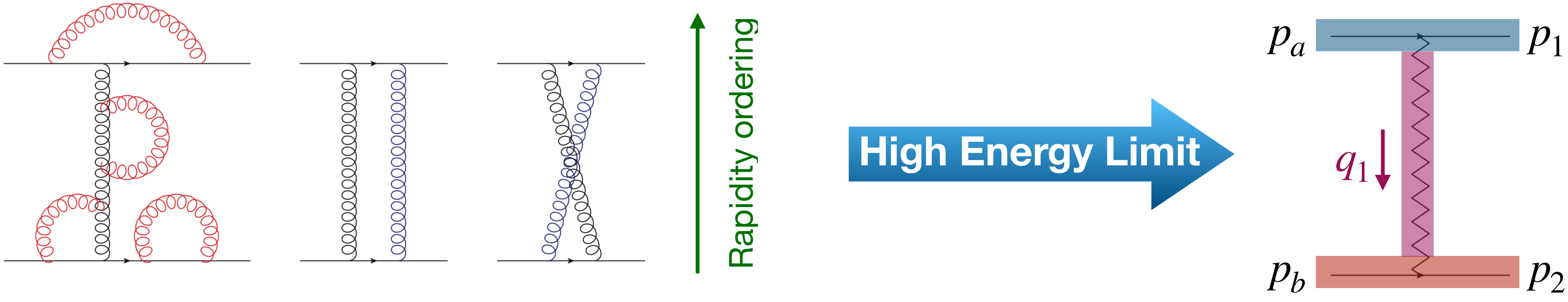
Virtual Corrections



High Energy Limit



Virtual Corrections



Finite expression: soft divergences cancel with real corrections

$$\mathcal{M} \propto \frac{\exp(\alpha(q_1)\Delta y_{12})}{q_1^2} j^{\mu}(p_1, p_a) j_{\mu}(p_2, p_b)$$

The gluon in the t-channel reggeizes: Lipatov Ansatz (valid even at NLL)

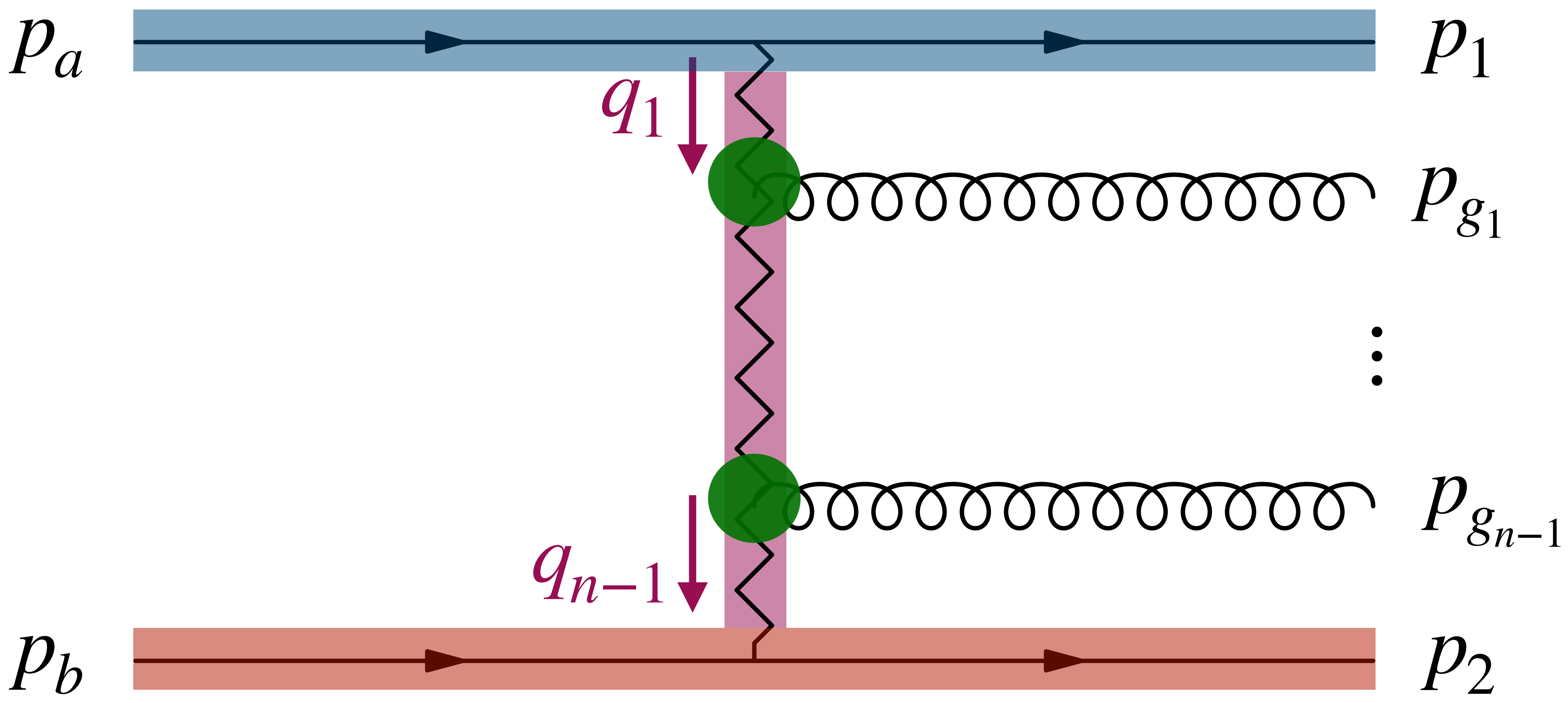
All-order Corrections

All-order Corrections

$$
\begin{aligned}
\mathcal{M} \propto\ & j^{\mu}(p_1, p_a) j_{\mu}(p_2, p_b) \\
\times\ & V_1^{\rho_1} \epsilon^*_{\rho_1}(p_{g_1}) V_1^{\rho_{n-1}} \epsilon^*_{\rho_{n-1}}(p_{g_{n-1}}) \\
\times\ & \frac{\exp(\alpha(q_1)\Delta y_{12})}{q_1^2} \cdots \frac{\exp(\alpha(q_n)\Delta y_{n-1n})}{q_n^2}
\end{aligned}
$$

All-order Corrections

- All-order leading-log results
- Gauge-invariant in all phase-space
- Phase-space not approximated
- Monte-Carlo integration
- IR divergences cancel



$$\mathcal{M} \propto j^\mu(p_1, p_a) j_\mu(p_2, p_b)$$
$$\times V_1^{\rho_1} \epsilon^*_{\rho_1}(p_{g_1}) V_1^{\rho_{n-1}} \epsilon^*_{\rho_{n-1}}(p_{g_{n-1}})$$
$$\times \frac{\exp(\alpha(q_1)\Delta y_{12})}{q_1^2} \cdots \frac{\exp(\alpha(q_n)\Delta y_{n-1n})}{q_n^2}$$

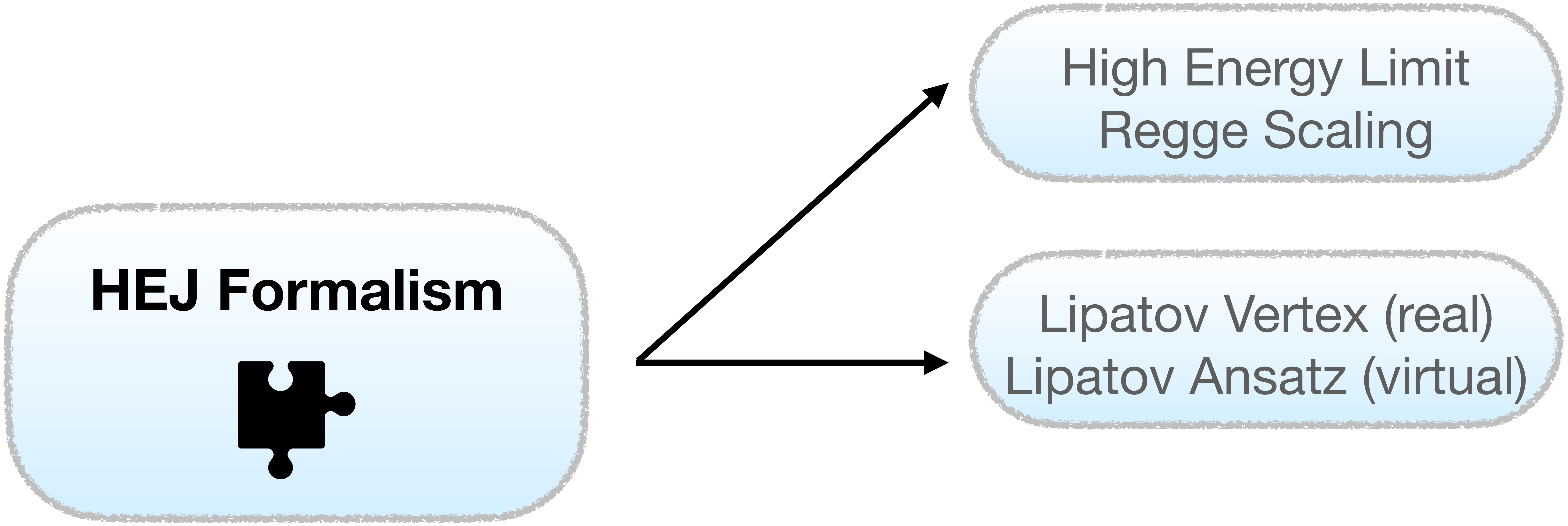
LoopFest XXI

HEJ Formalism

LoopFest XXI

High Energy Limit
Regge Scaling

HEJ Formalism


HEJ Formalism
High Energy Limit
Regge Scaling
Lipatov Vertex (real)
Lipatov Ansatz (virtual)

LoopFest XXI

HEJ Formalism

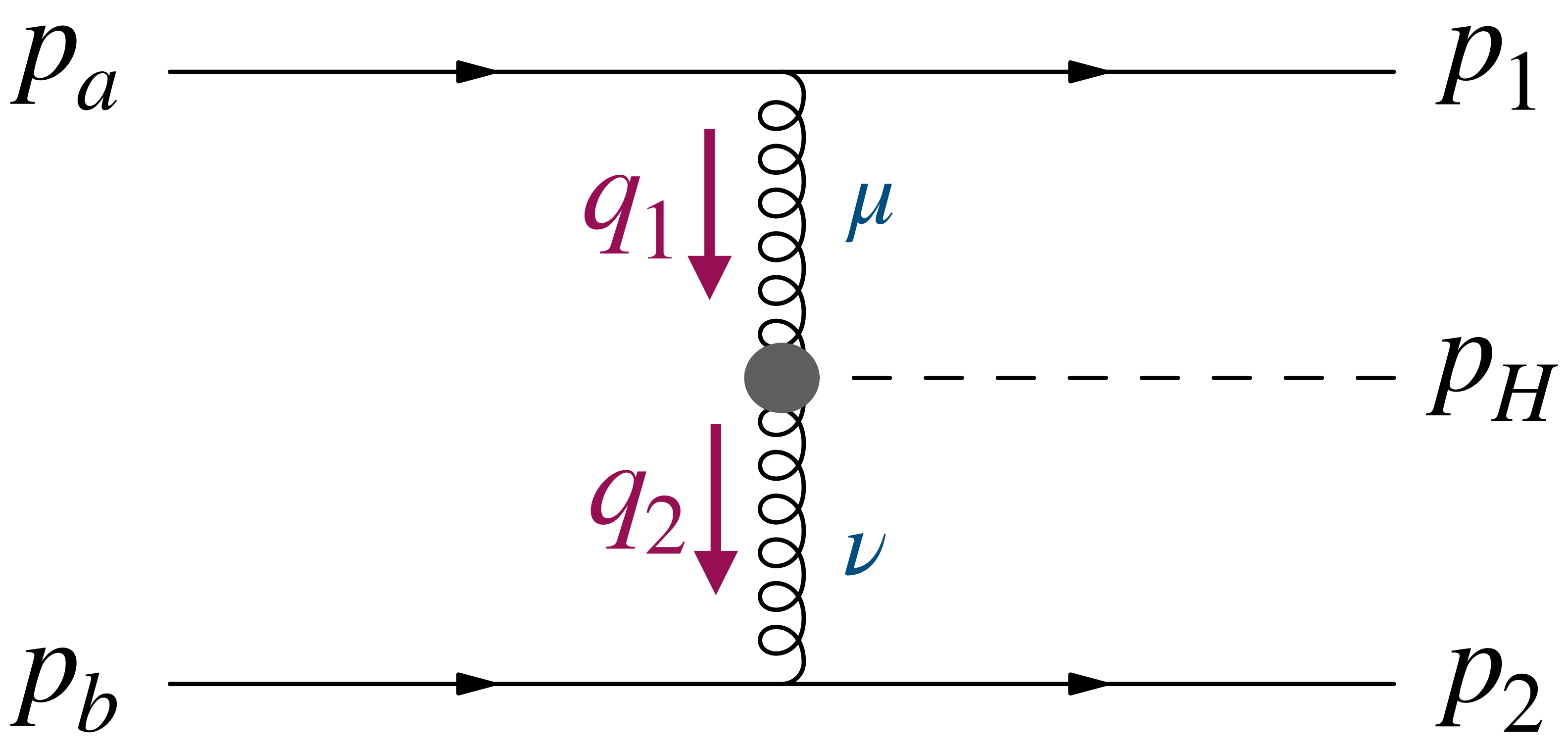
- High Energy Limit
  Regge Scaling
- Lipatov Vertex (real)
  Lipatov Ansatz (virtual)
- All-order LL result

LoopFest XXI

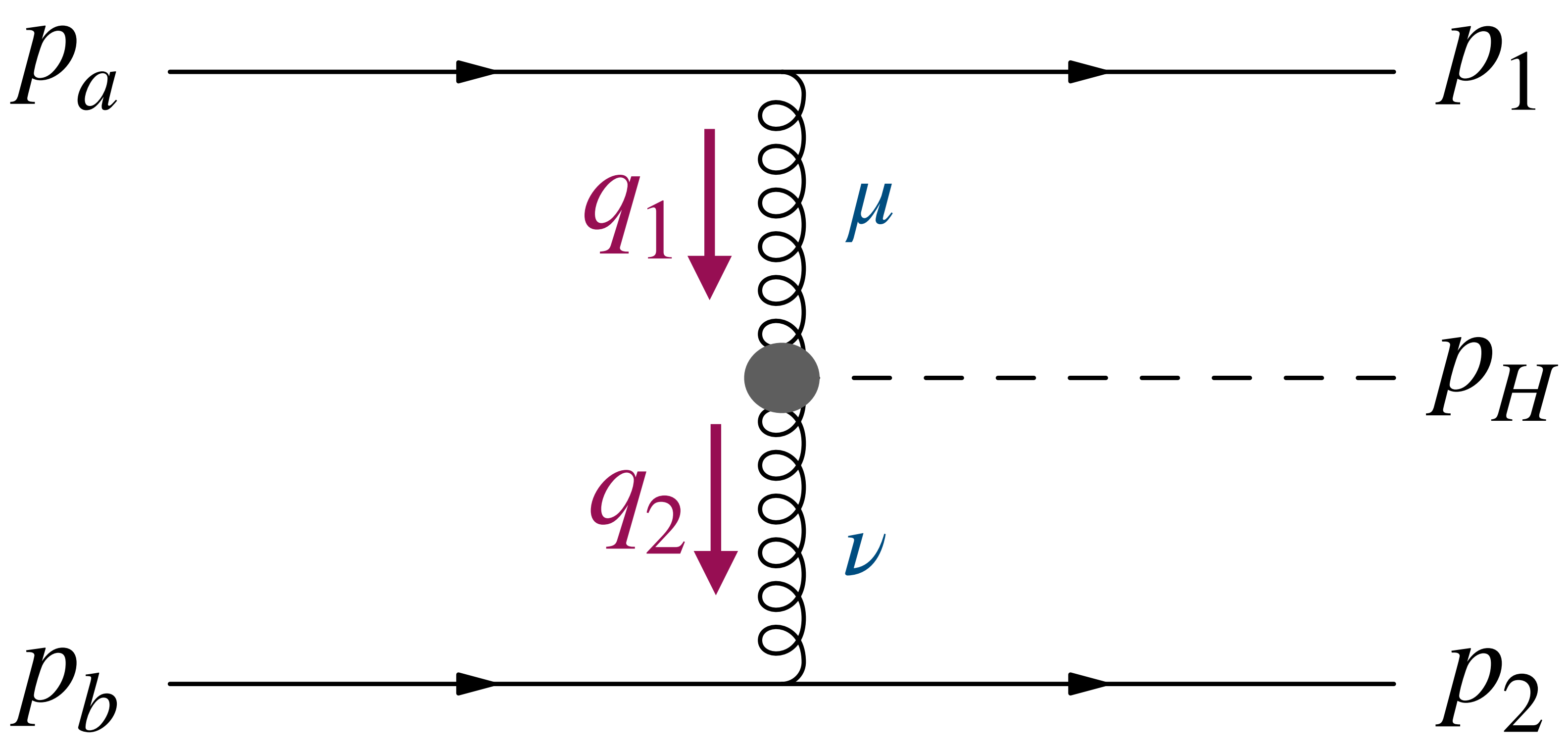
Higgs + dijet

Theory
Finite quark masses
Comparisons to FO
VBF cuts
[1812.08072]

Central Higgs Production



Central Higgs Production

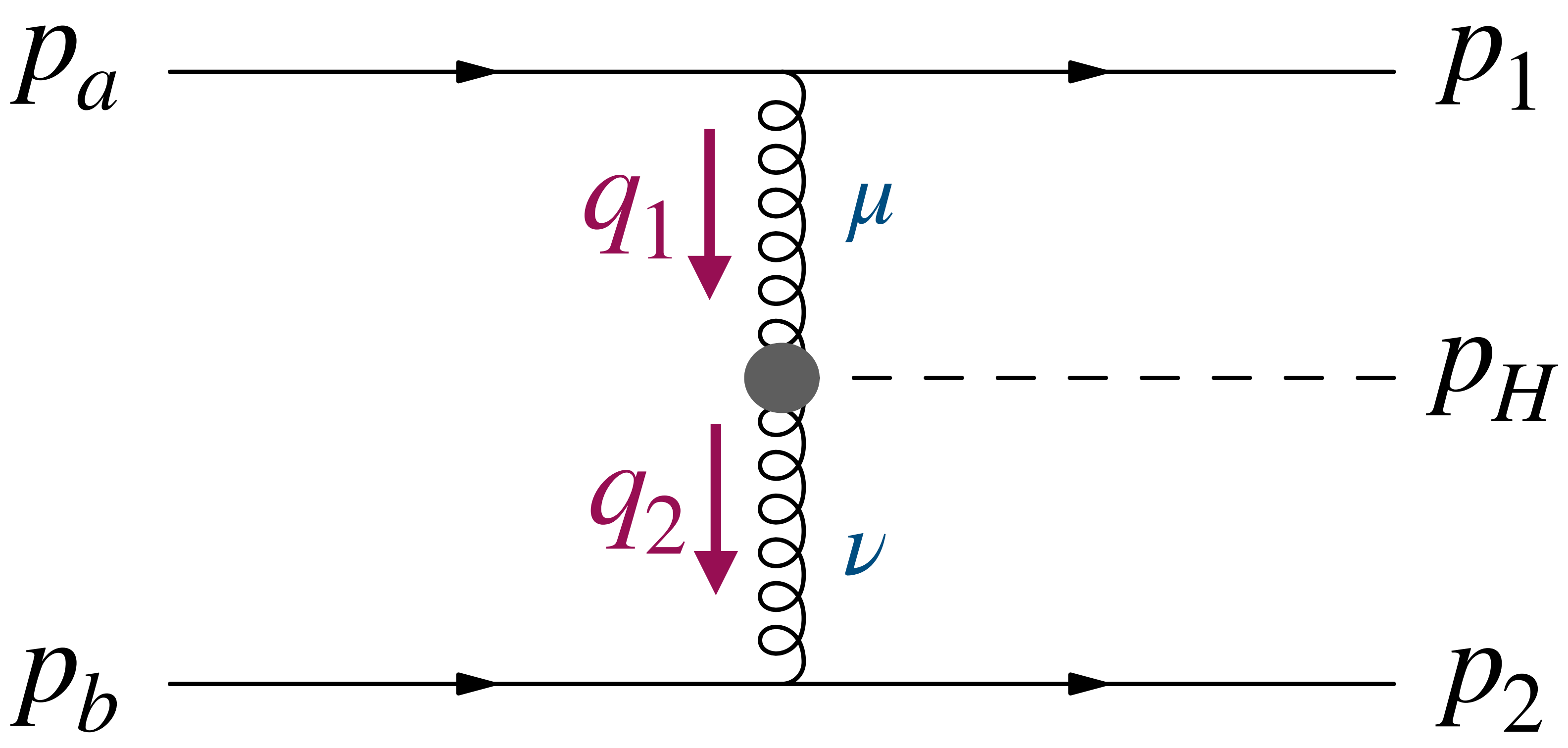


ggH vertex has the following tensor form:

$$V_H^{\mu\nu}(q_1, q_2) = \frac{\alpha_s m^2}{\pi v}\left(g^{\mu\nu} T_1(q_1, q_2) - q_2^\mu q_1^\nu T_2(q_1, q_2)\right)$$

$$\underbrace{\to}_{m\to\infty} \frac{\alpha_s}{3\pi v}\left(g^{\mu\nu} q_1 \cdot q_2 - q_2^\mu q_1^\nu\right)$$

Central Higgs Production

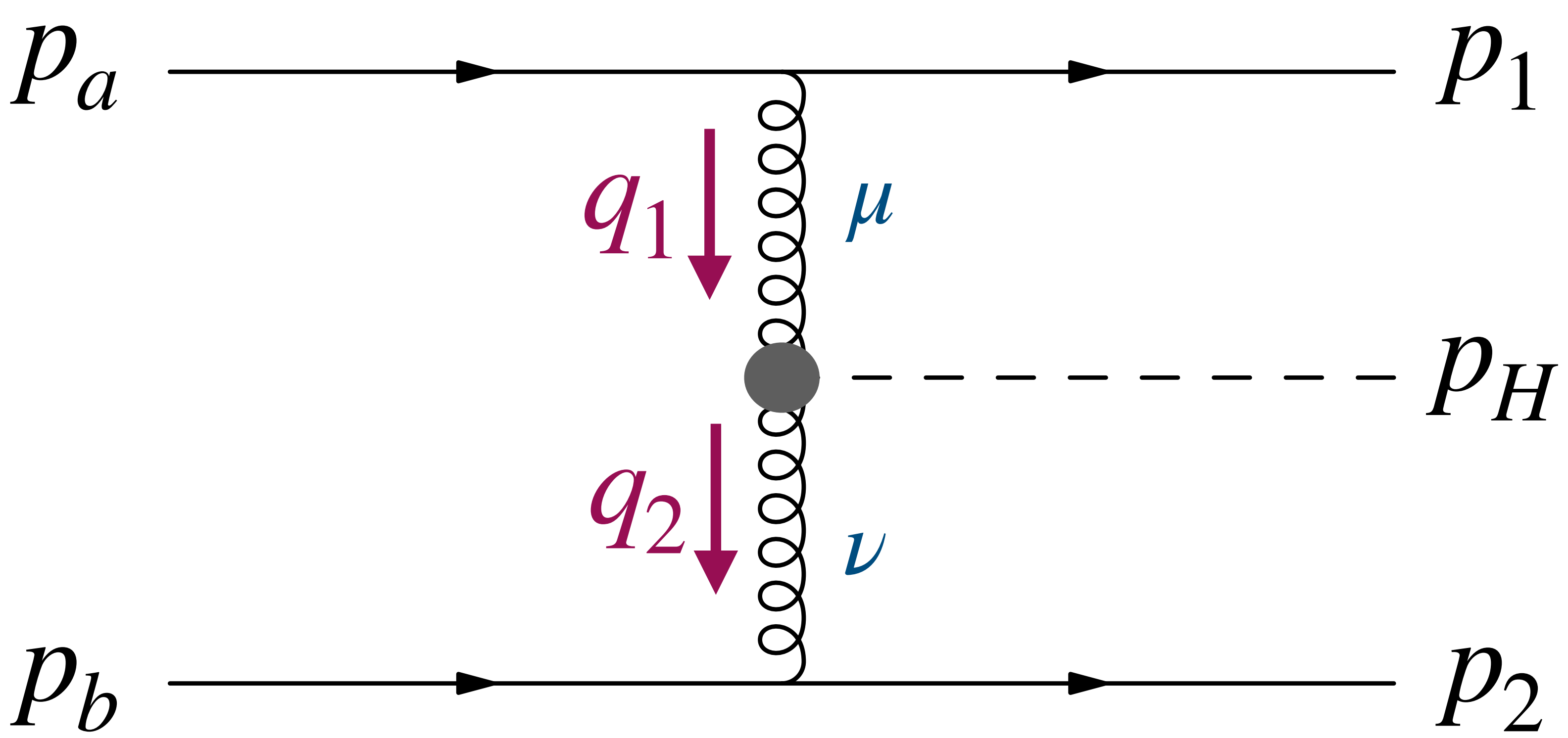


ggH vertex has the following tensor form:

$$V_H^{\mu\nu}(q_1, q_2) = \frac{\alpha_s m^2}{\pi v}\left(g^{\mu\nu} T_1(q_1, q_2) - q_2^\mu q_1^\nu T_2(q_1, q_2)\right)$$

$$\underset{m\to\infty}{\longrightarrow} \frac{\alpha_s}{3\pi v}\left(g^{\mu\nu} q_1 \cdot q_2 - q_2^\mu q_1^\nu\right)$$

Central Higgs Production



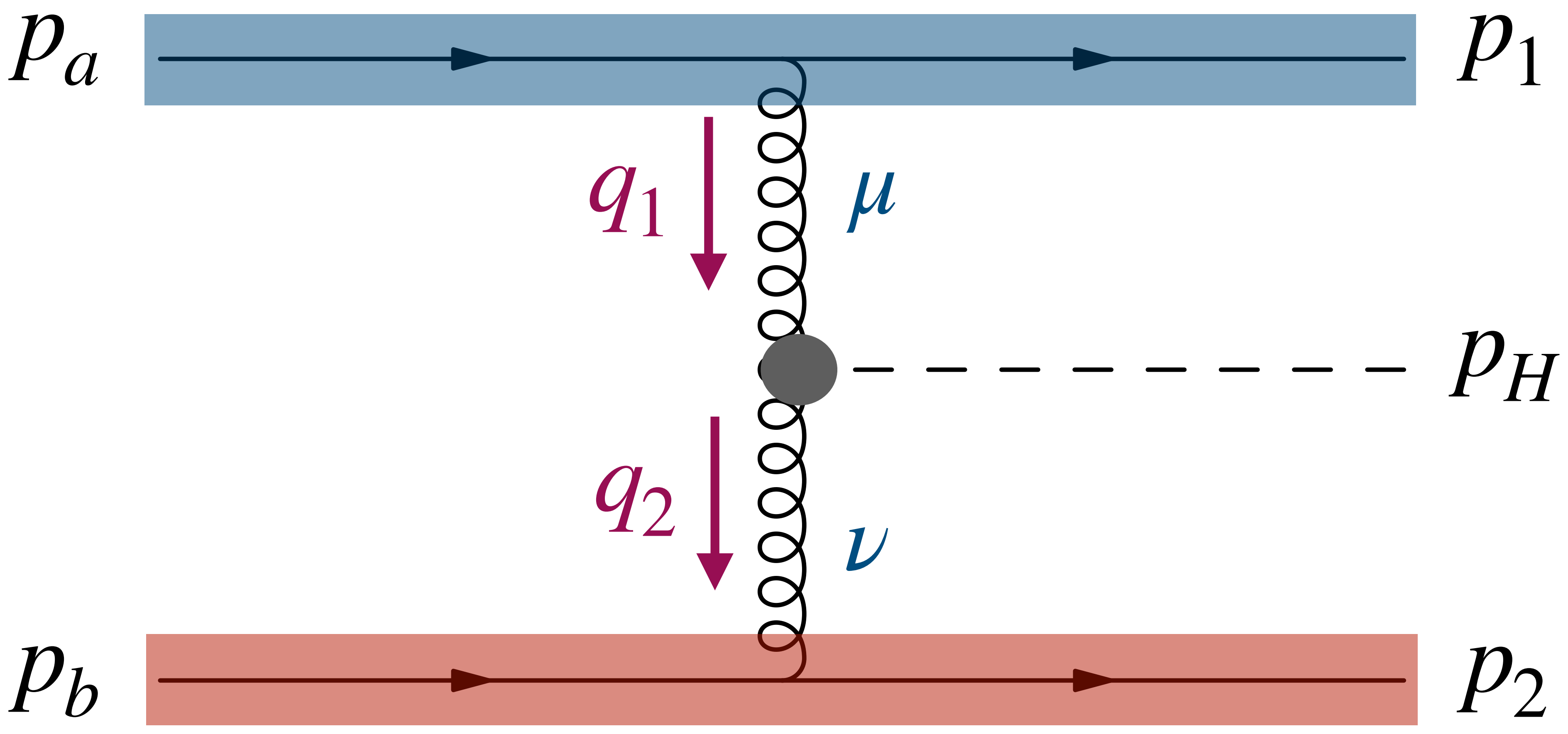
ggH vertex has the following tensor form:

$$V_H^{\mu\nu}(q_1, q_2) = \frac{\alpha_s m^2}{\pi v}\left(g^{\mu\nu} T_1(q_1, q_2) - q_2^\mu q_1^\nu T_2(q_1, q_2)\right)$$

$$\underset{m\to\infty}{\longrightarrow} \frac{\alpha_s}{3\pi v}\left(g^{\mu\nu} q_1 \cdot q_2 - q_2^\mu q_1^\nu\right)$$

t-channel factorised form allows us to keep the full quark masses dependence

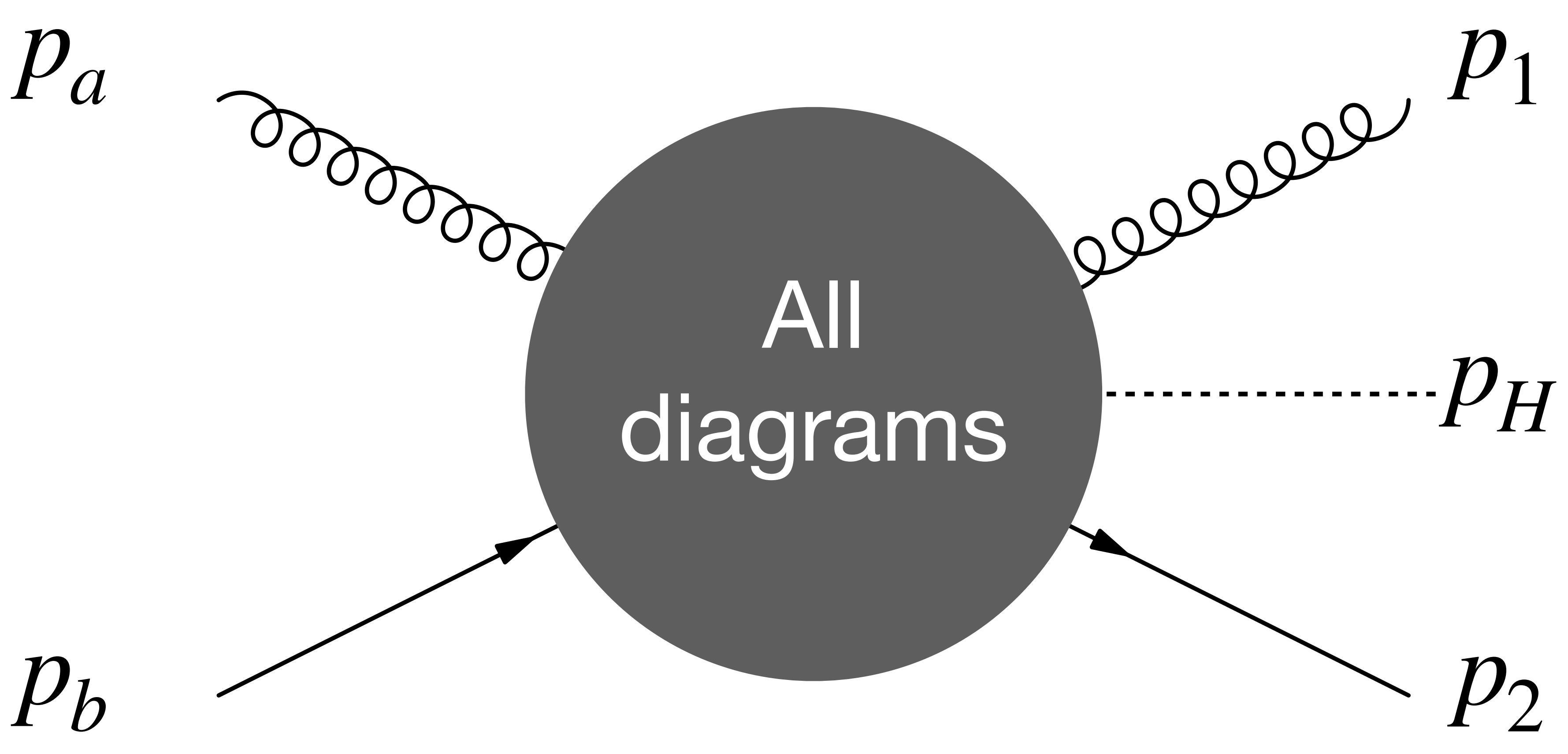
Central Higgs Production



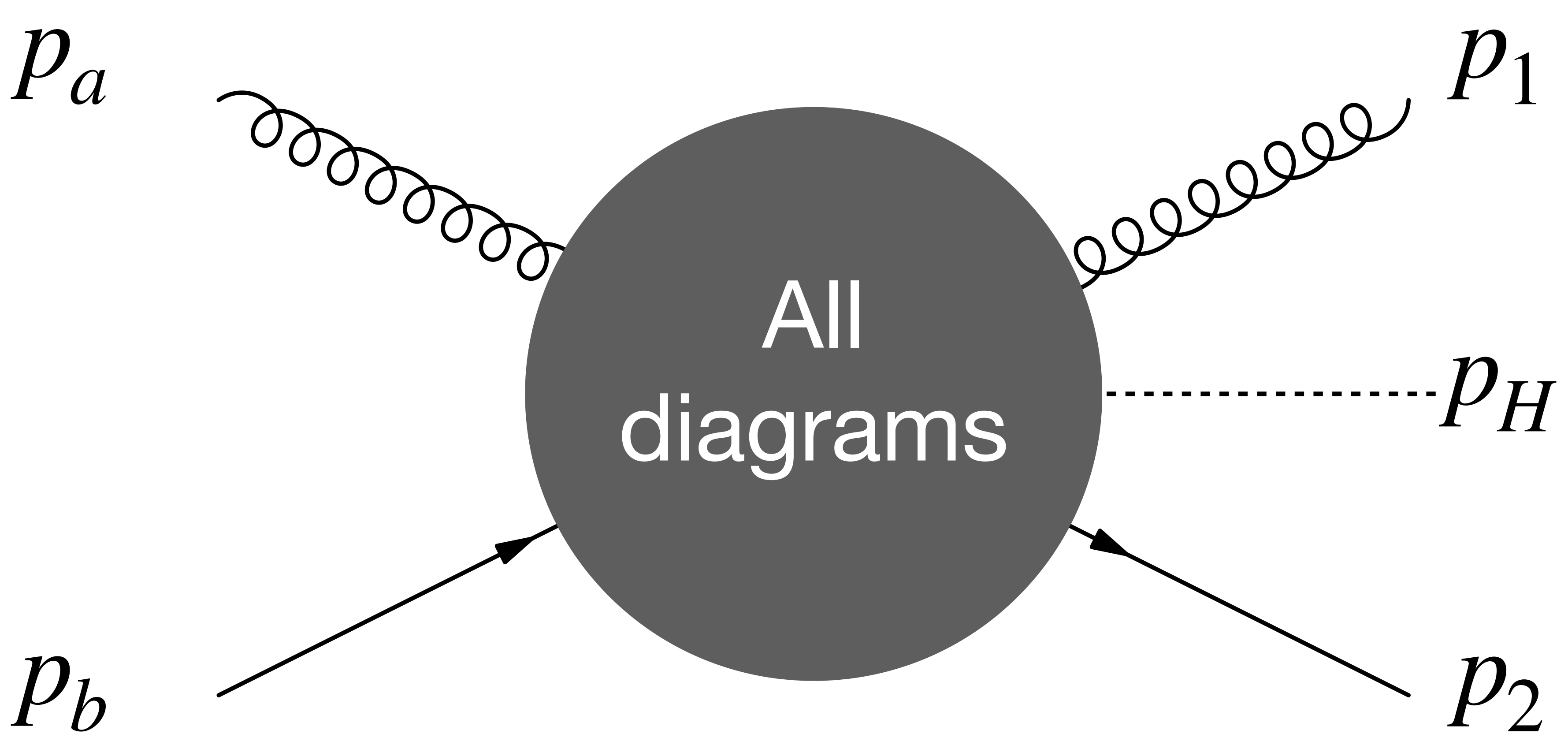
$$\mathcal{M} \propto \frac{1}{q_1^2}\frac{1}{q_2^2} j_\mu(p_1, p_a) j_\nu(p_2, p_b) V_H^{\mu\nu}(q_1, q_2)$$

Simple factorised expression, no approximations here!

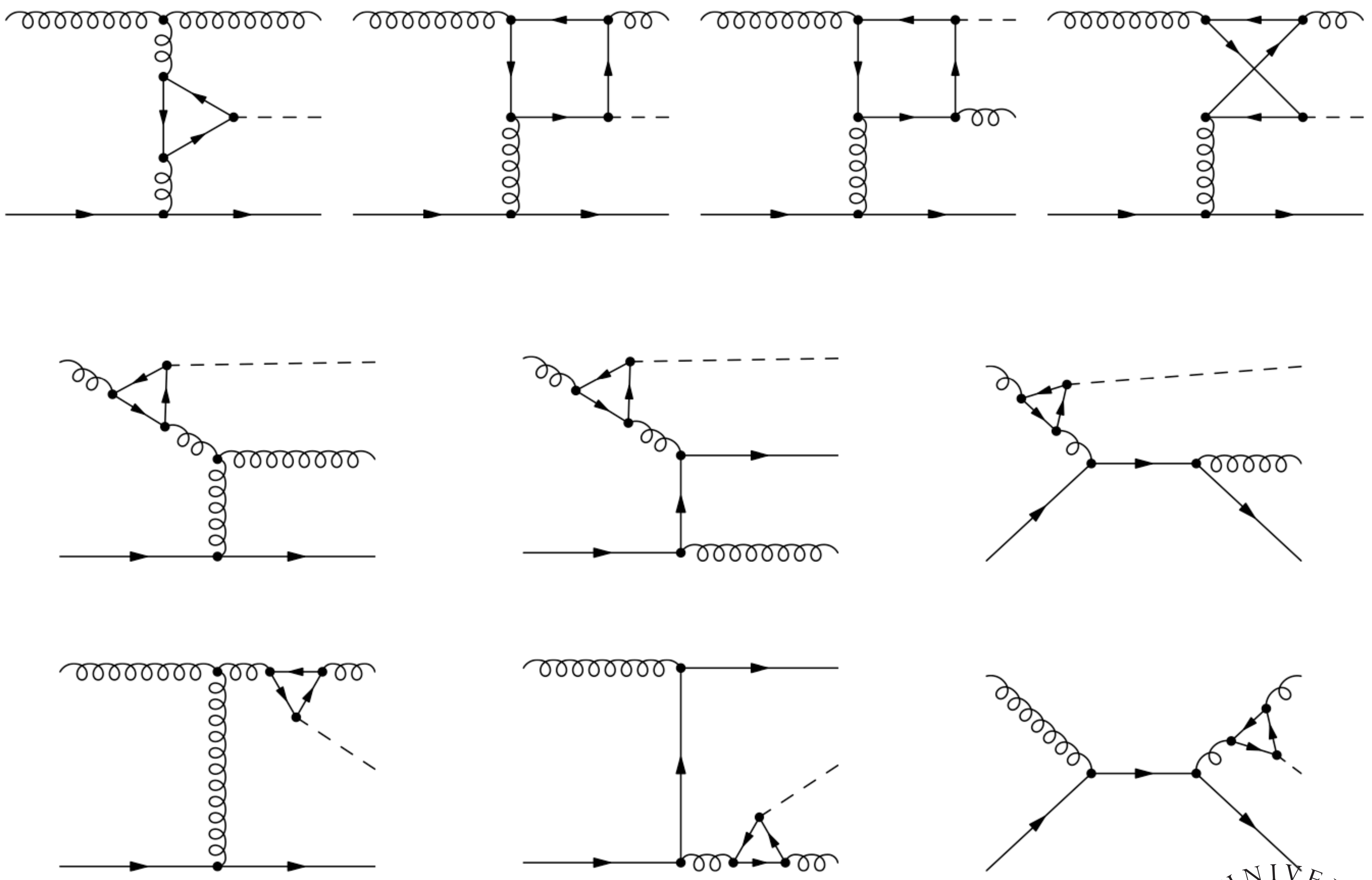
Central Higgs Production



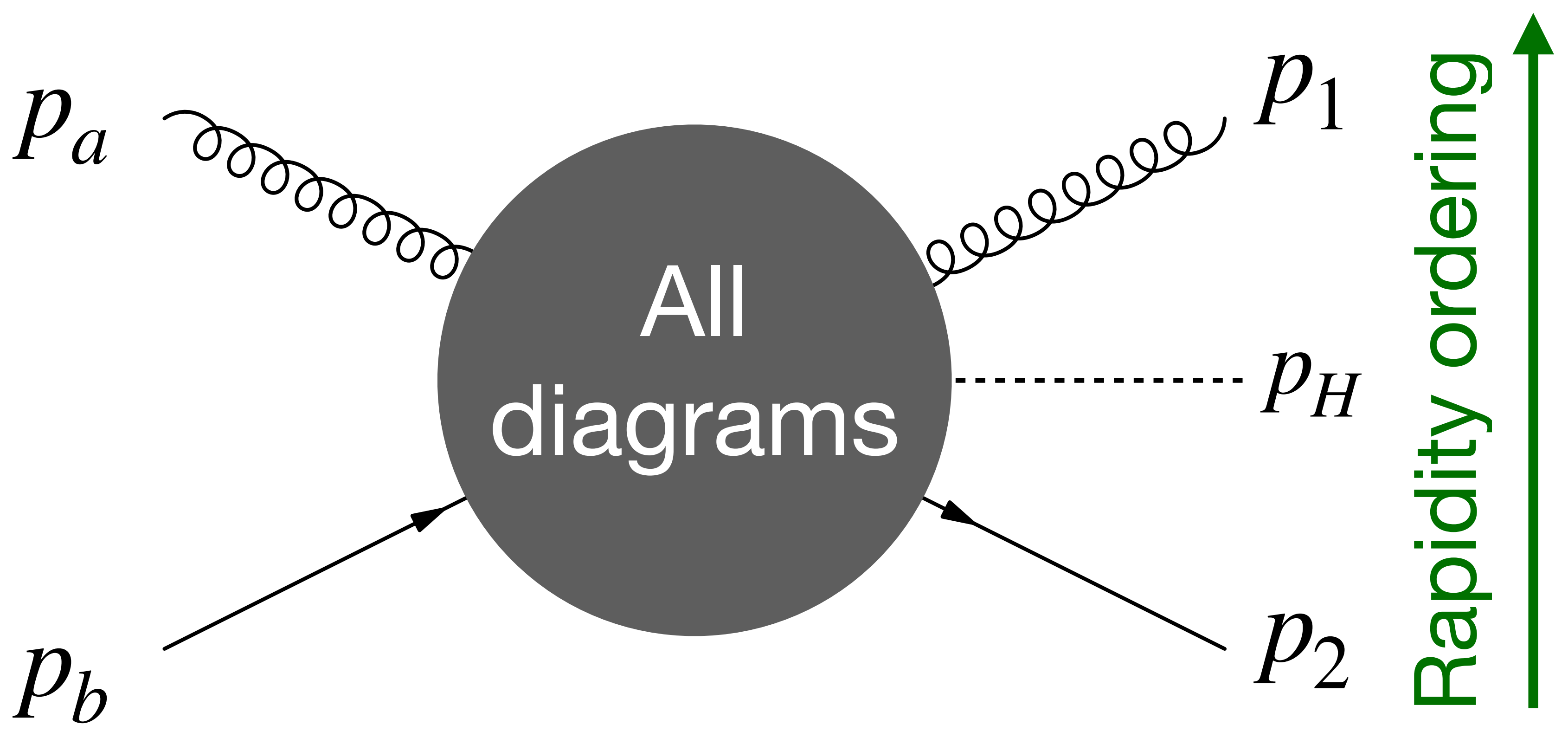
Central Higgs Production



=

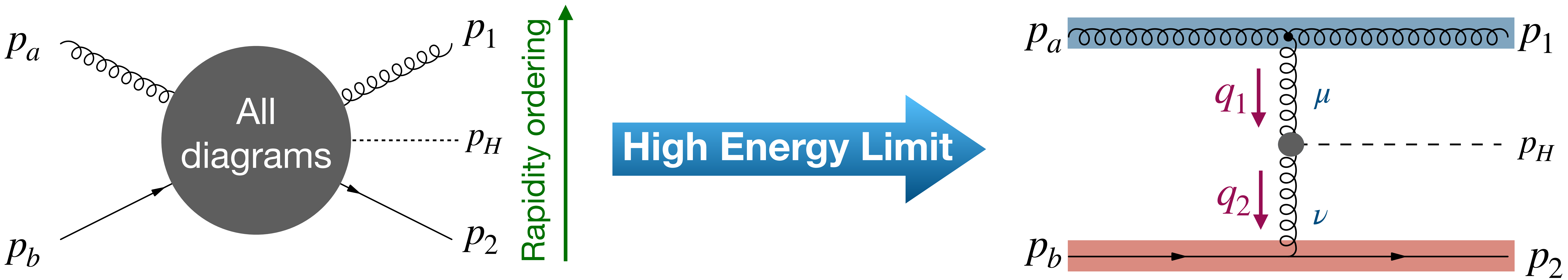


Central Higgs Production



$$\mathcal{M} \propto \frac{1}{q_1^2}\frac{1}{q_2^2} j_\mu(p_1, p_a) j_\nu(p_2, p_b) V_H^{\mu\nu}(q_1, q_2)$$

Central Higgs Production

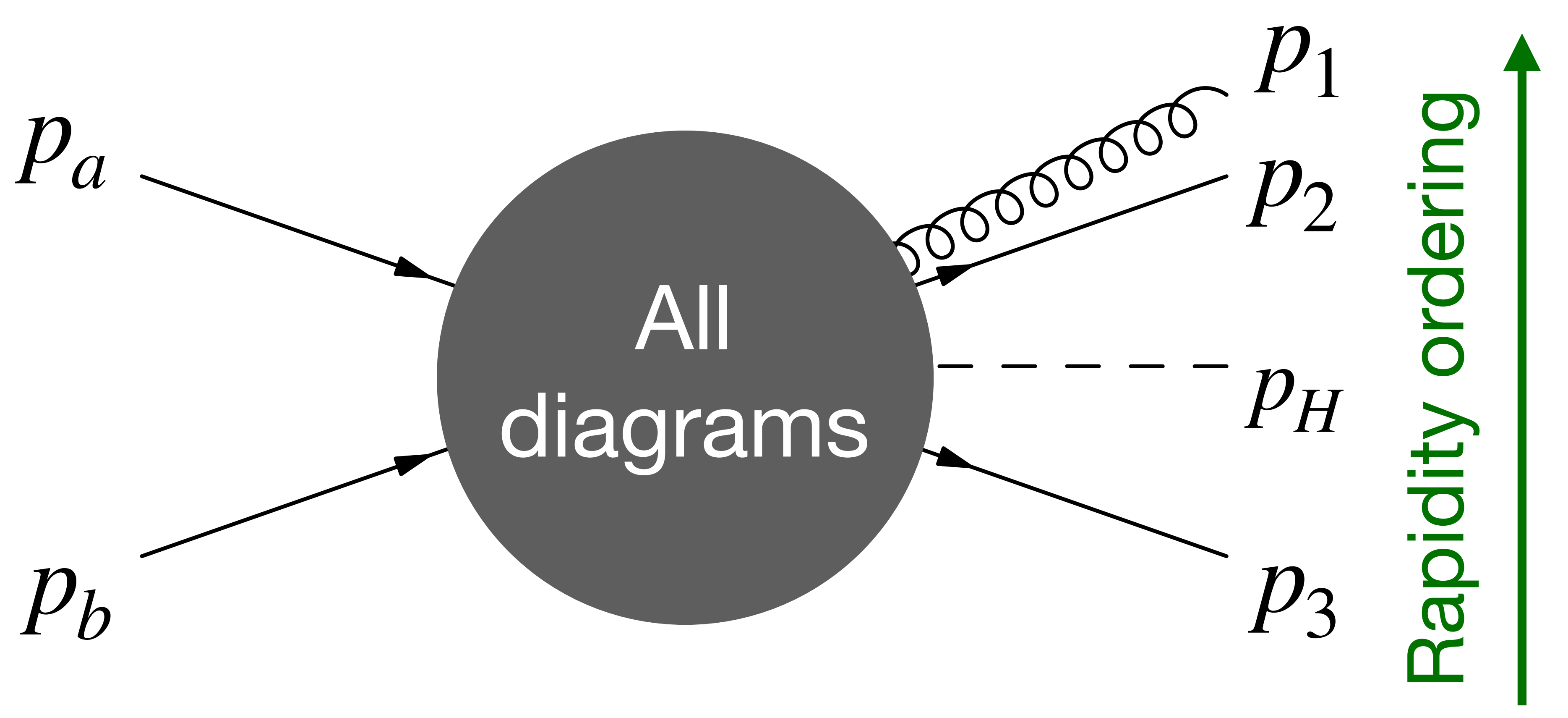


$$\mathcal{M} \propto \frac{1}{q_1^2}\frac{1}{q_2^2} j_\mu(p_1, p_a) j_\nu(p_2, p_b) V_H^{\mu\nu}(q_1, q_2)$$

SLAC

THE UNIVERSITY OF EDINBURGH

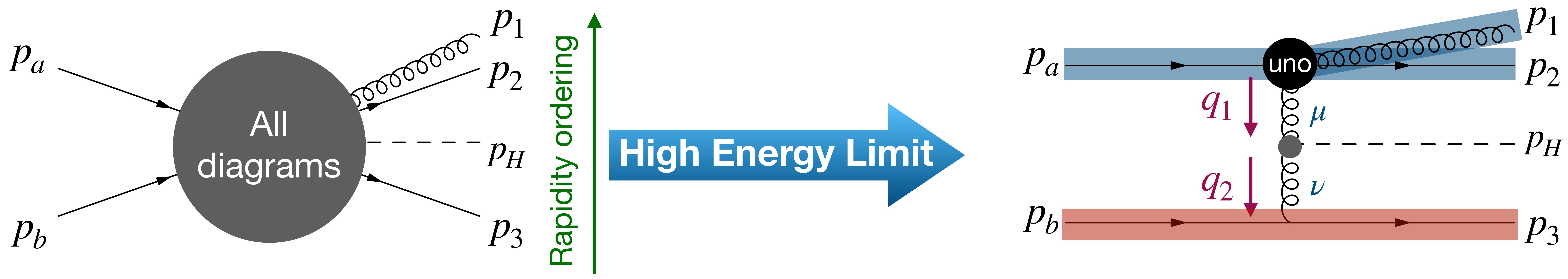
Unordered gluon emission



Set of gauge invariant NLL corrections

$$\mathcal{M} \propto \frac{1}{q_1^2}\frac{1}{q_2^2} j_\mu^{\text{uno}}(p_a, p_1, p_2) j_\nu(p_3, p_b) V_H^{\mu\nu}(q_1, q_2)$$

Unordered gluon emission



Set of gauge invariant NLL corrections

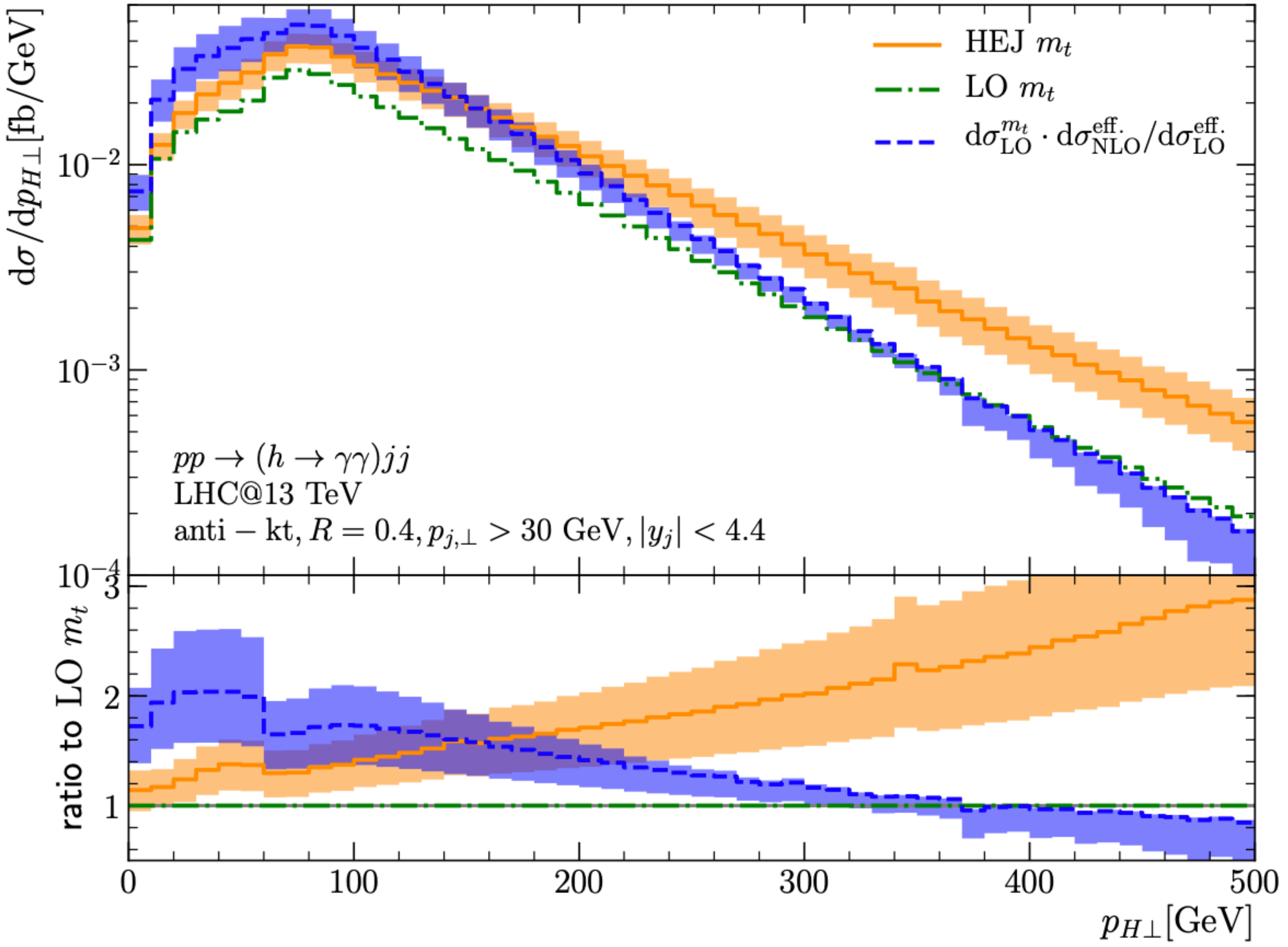
$$\mathcal{M} \propto \frac{1}{q_1^2}\frac{1}{q_2^2} j_\mu^{\text{uno}}(p_a, p_1, p_2) j_\nu(p_3, p_b) V_H^{\mu\nu}(q_1, q_2)$$

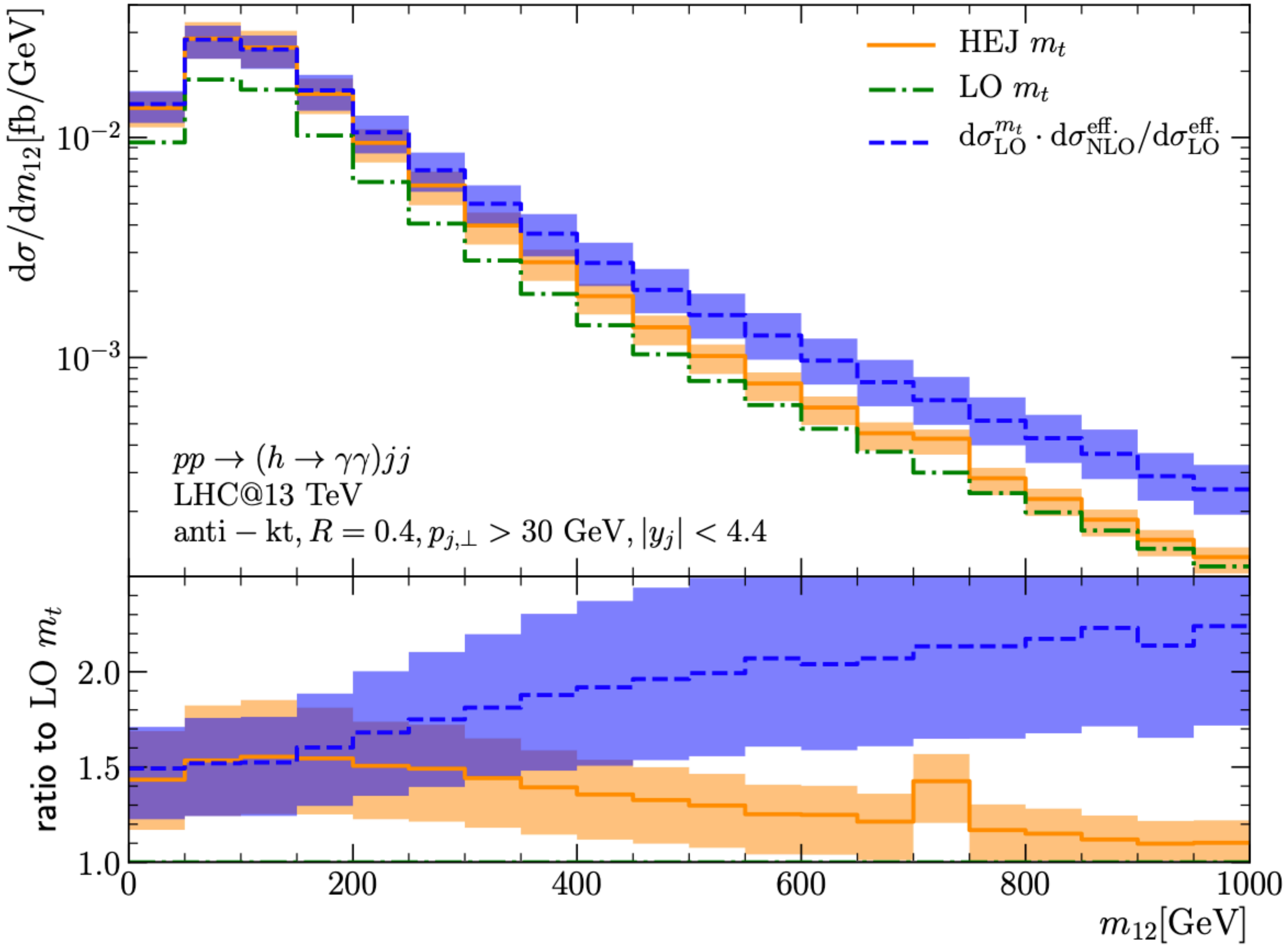
Higgs plus dijet

Adapted from ATLAS analysis [1407.4222]

Baseline Jet Cuts	
Rapidity	$\|y_j\| < 4.4$
Transverse momentum	$p_{\perp,j} > 30$ GeV
Baseline Photon Cuts	
Rapidity	$\|y_\gamma\| < 2.37$
Diphoton invariant mass	$105 \text{ GeV} < m_{\gamma_1\gamma_2} < 160 \text{ GeV}$
Transverse momentum hardest photon	$p_{\perp,\gamma_1} > 0.35\, m_{\gamma_1\gamma_2}$
Transverse momentum other photon	$p_{\perp,\gamma_2} > 0.25\, m_{\gamma_1\gamma_2}$
Vector Boson Fusion (VBF) Cuts	
Rapidity jet difference	$\|y_{j_1} - y_{j_2}\| < 2.8$
Invariant dijet mass	$m_{j_1 j_2} > 400$ GeV

Resummation Effects





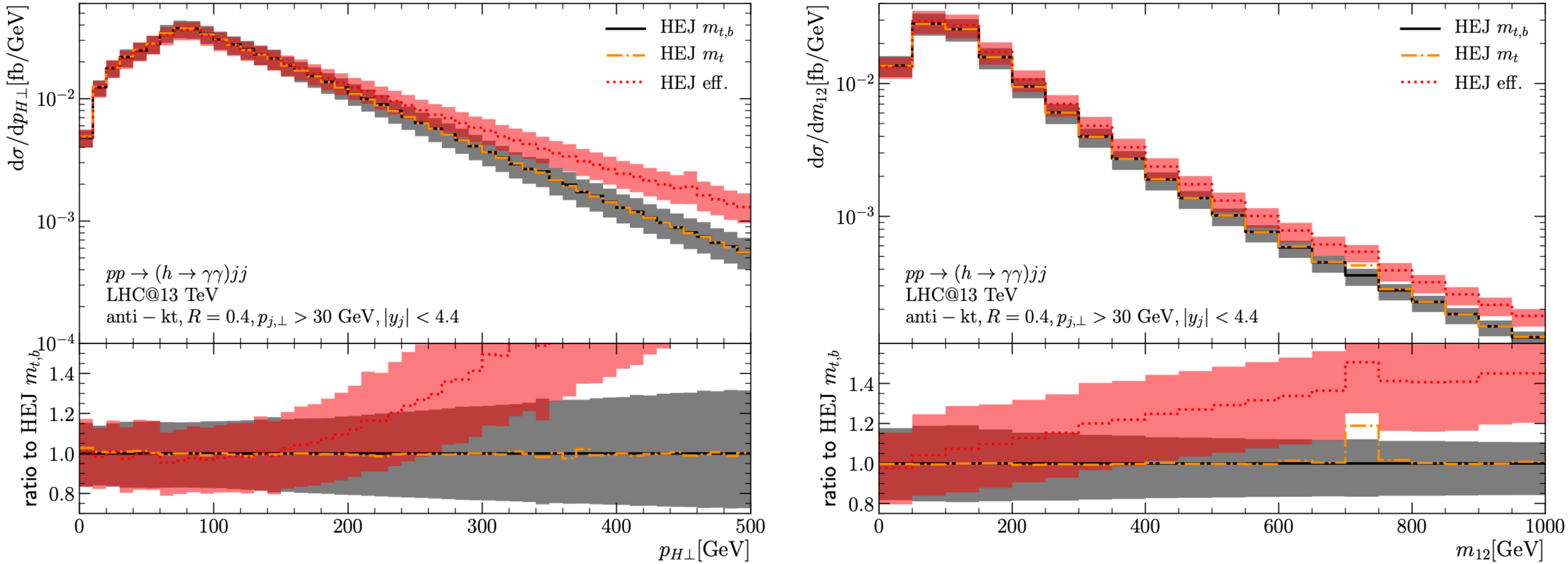
Transverse momentum sensitive to resummation

Resummation hardens the tail

Important observable for VBF cuts!

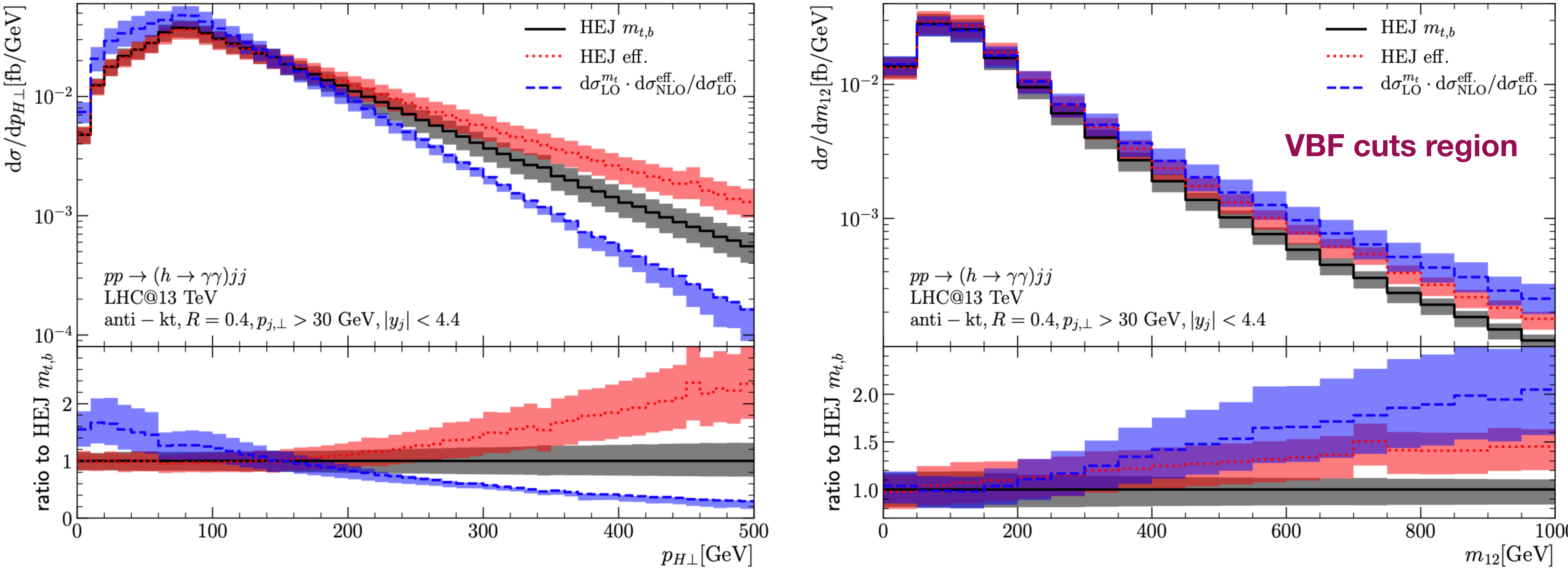
Resummation softens the tail

Finite Quark Masses Effects

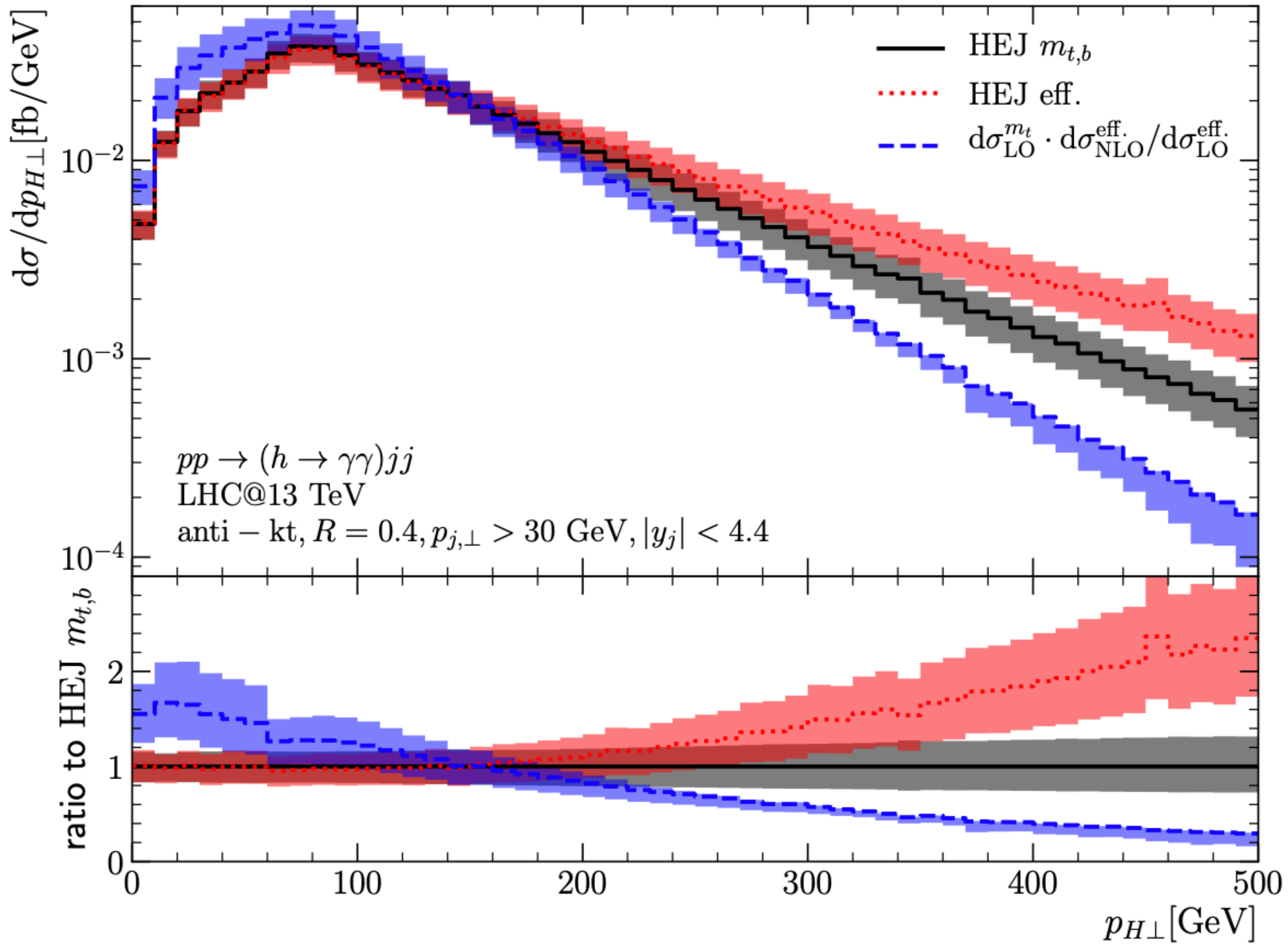


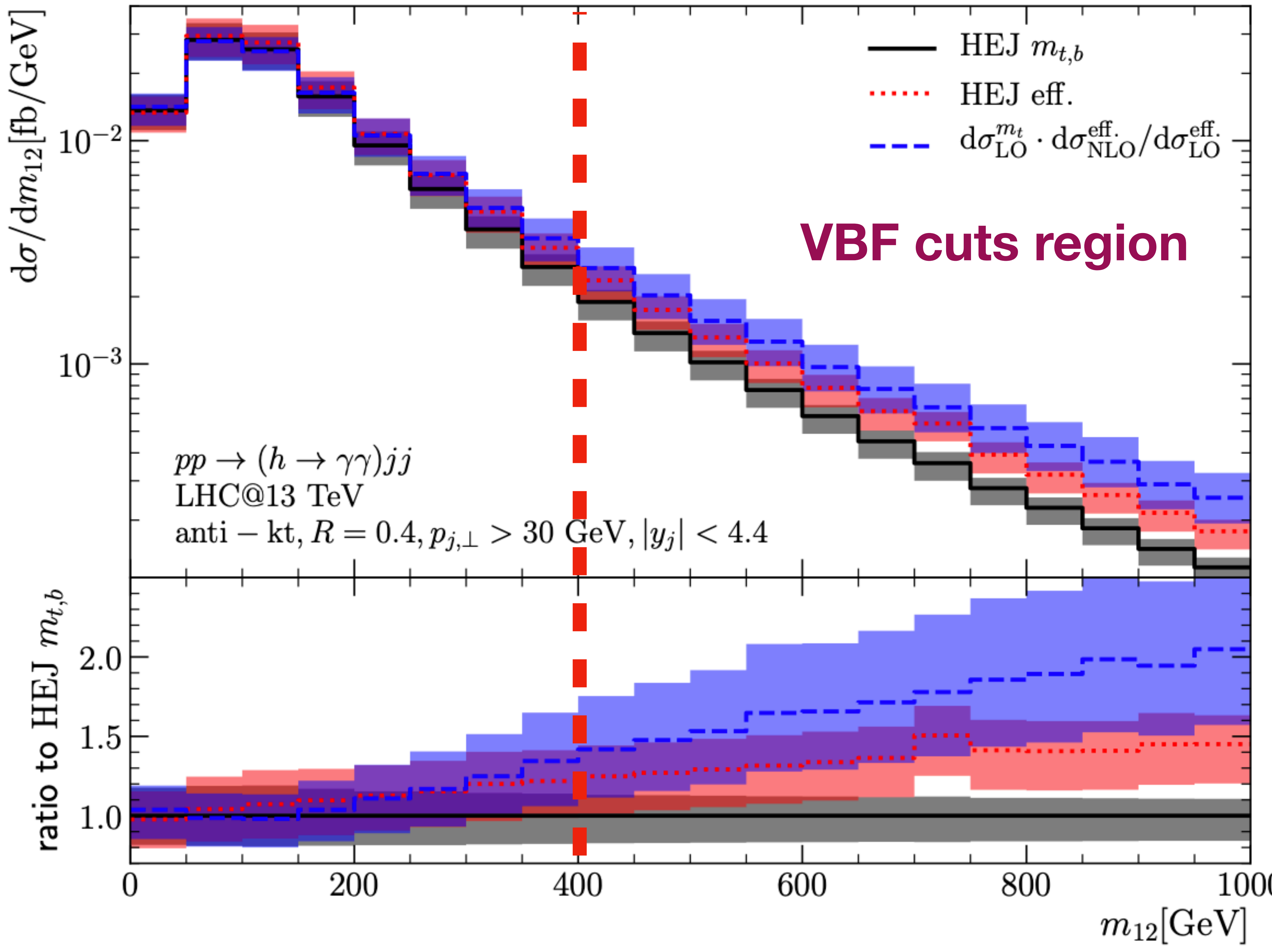
Finite top mass effects is sizeable (bottom mass is not)

Combined effects

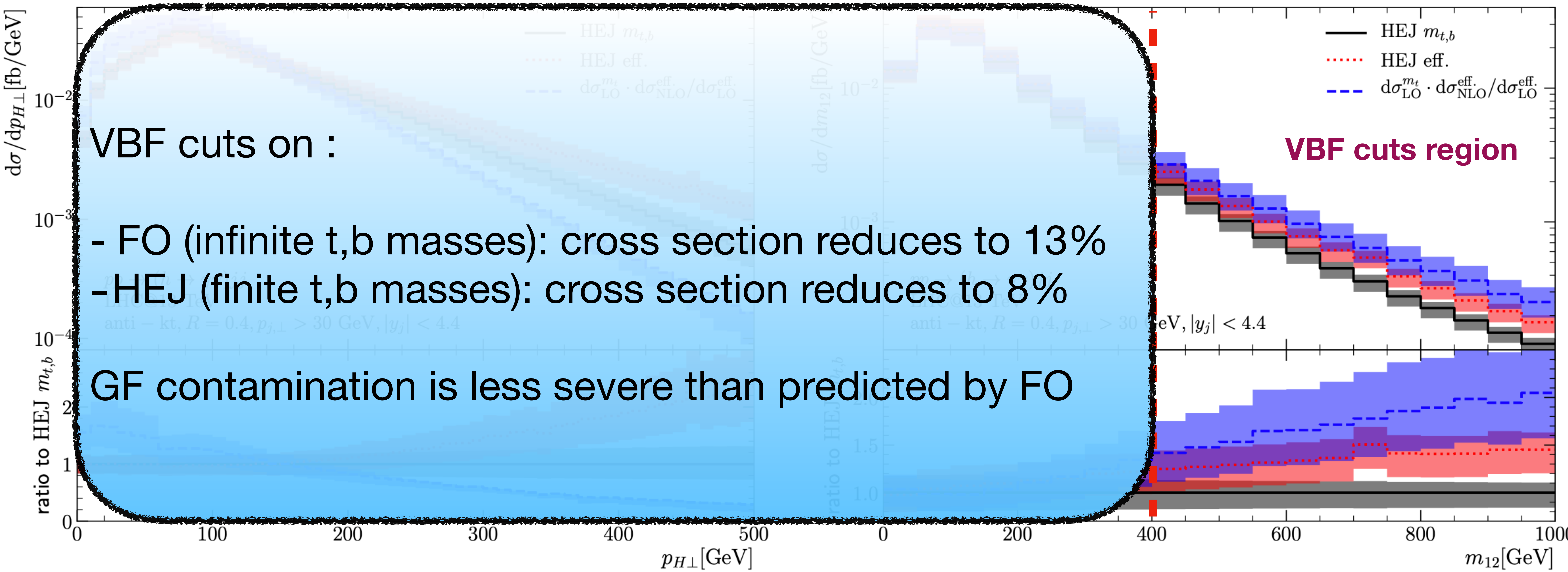


Combined effects





Combined effects

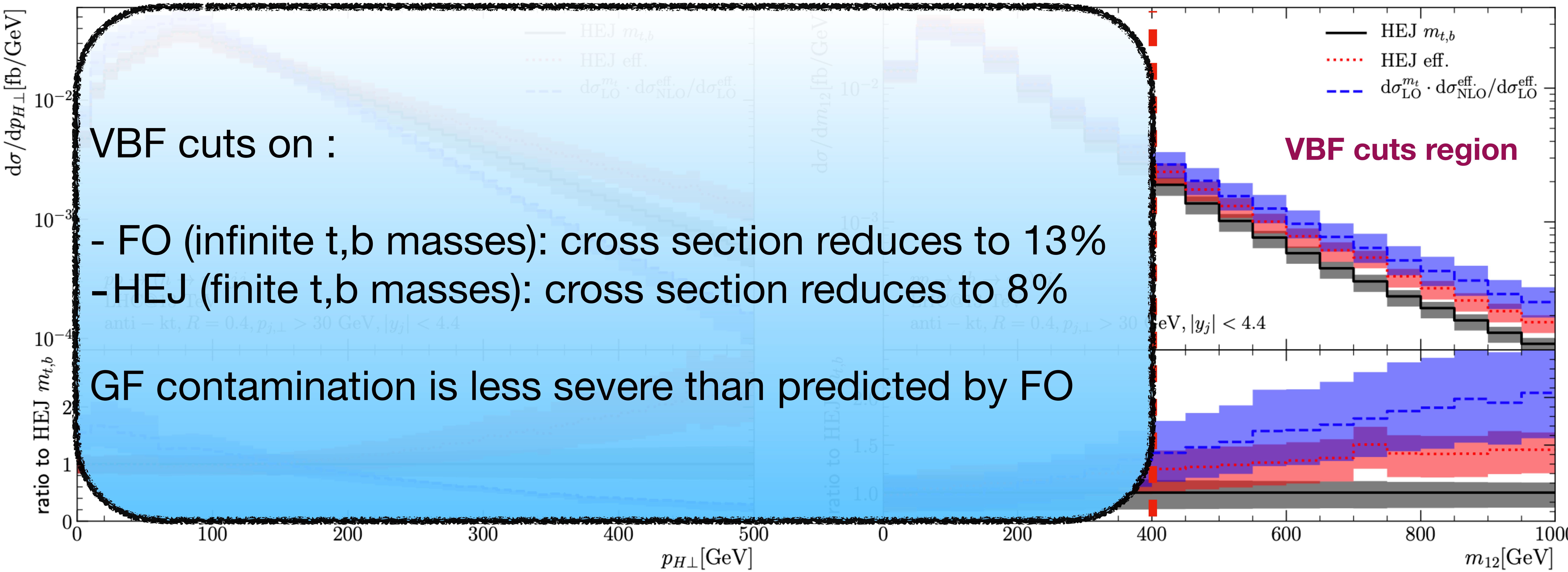


VBF cuts on :

- FO (infinite t,b masses): cross section reduces to 13%
- HEJ (finite t,b masses): cross section reduces to 8%

GF contamination is less severe than predicted by FO

Combined effects



VBF cuts on :

- FO (infinite t,b masses): cross section reduces to 13%
- HEJ (finite t,b masses): cross section reduces to 8%

GF contamination is less severe than predicted by FO

Effects add up: VBF cuts are more efficient than predicted by FO

SLAC

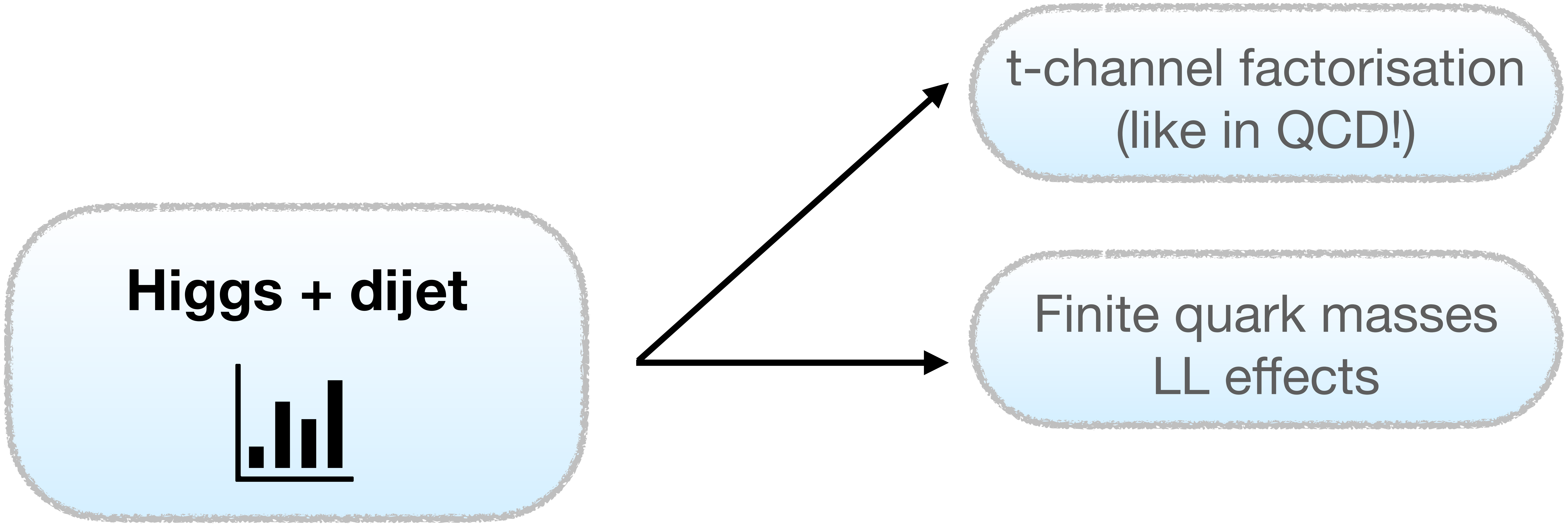
THE UNIVERSITY OF EDINBURGH

LoopFest XXI

Higgs + dijet

t-channel factorisation
(like in QCD!)

Higgs + dijet


Higgs + dijet
t-channel factorisation
(like in QCD!)
Finite quark masses
LL effects

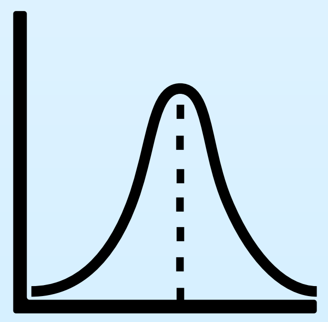
Higgs + dijet

- t-channel factorisation (like in QCD!)
- Finite quark masses LL effects
- VBF cuts are efficient!

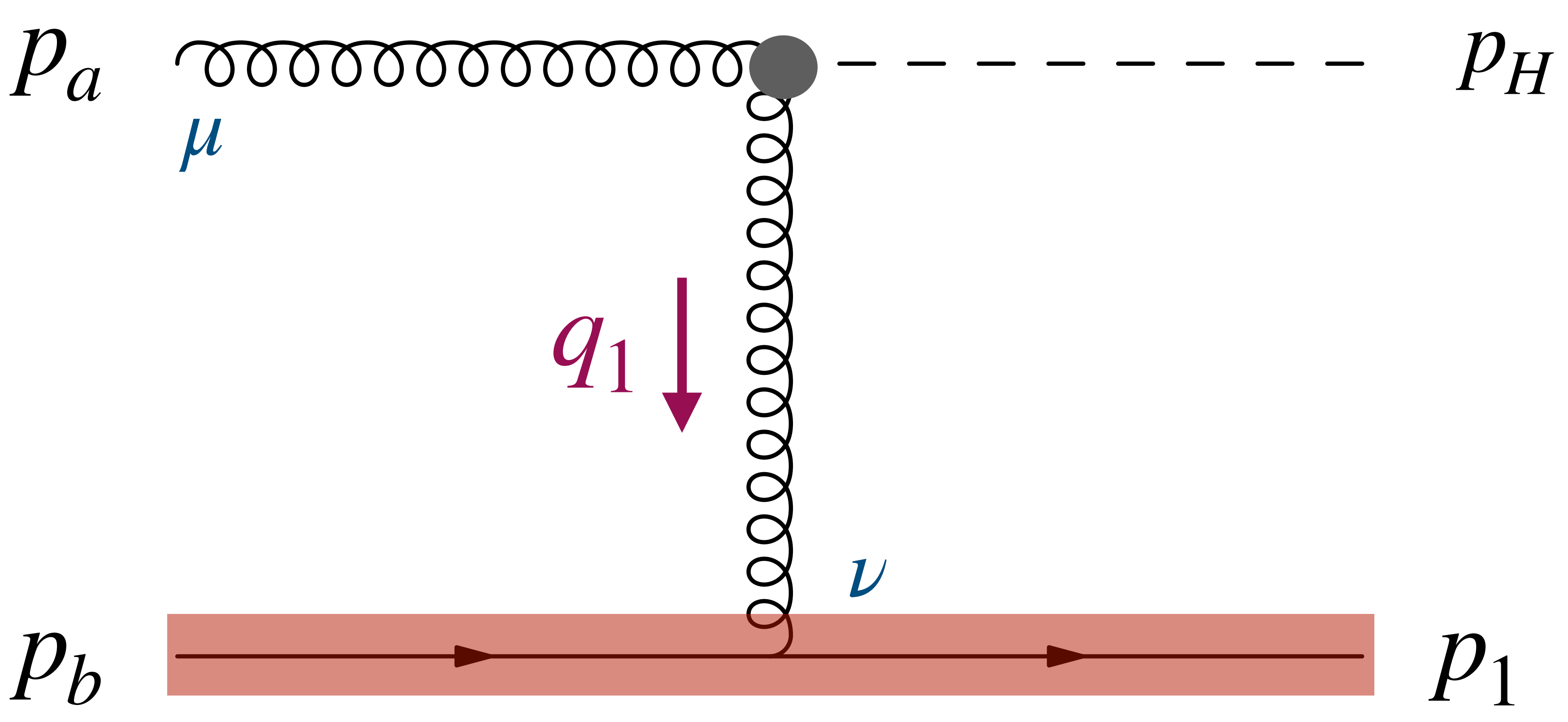
LoopFest XXI

Higgs + one jet

Theory
Comparisons to experimental data
Comparisons to FO
[2210.10671]

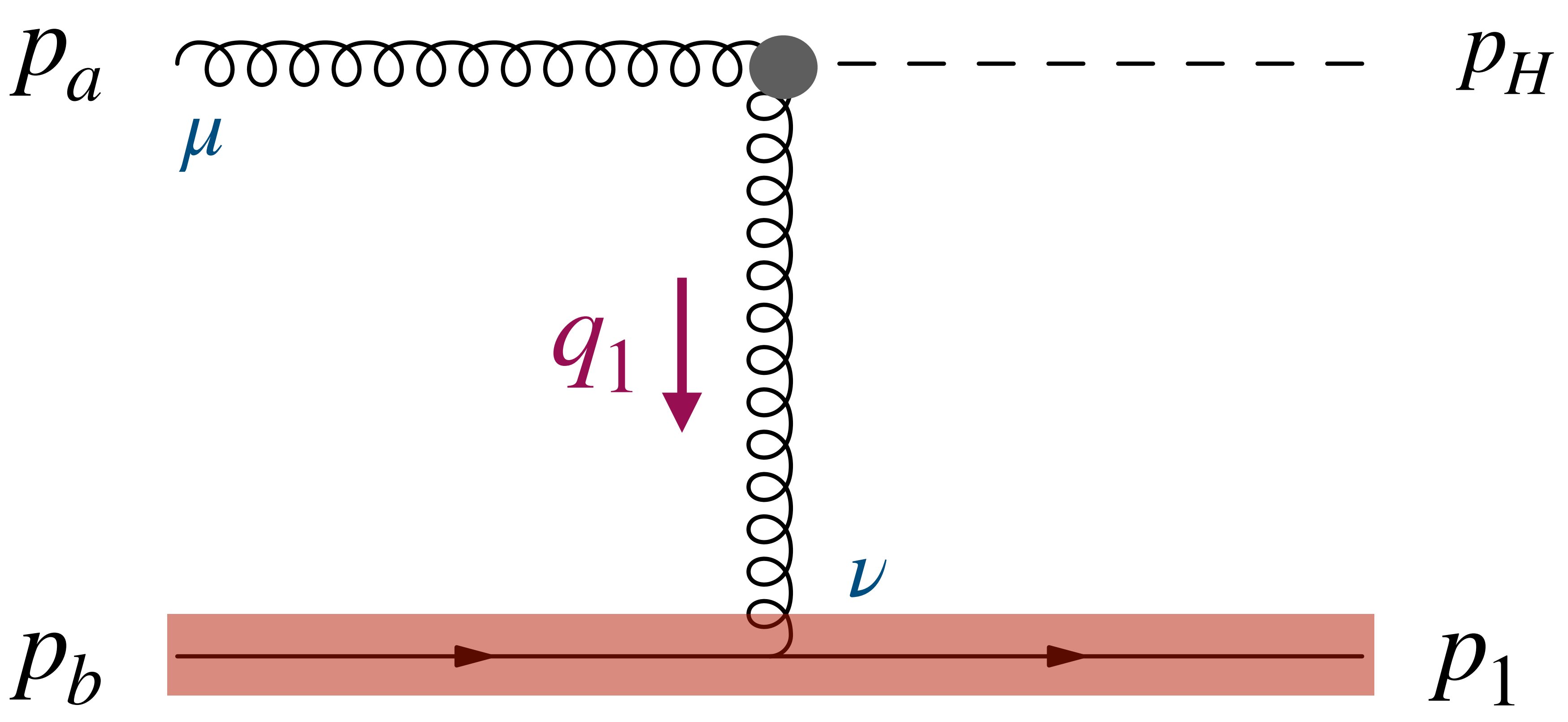


New Components for H+1j



$$\mathcal{M} \propto \frac{1}{q_1^2} \epsilon_\mu(p_a) j_\nu(p_1, p_b) V_H^{\mu\nu}(p_a, q_1)$$

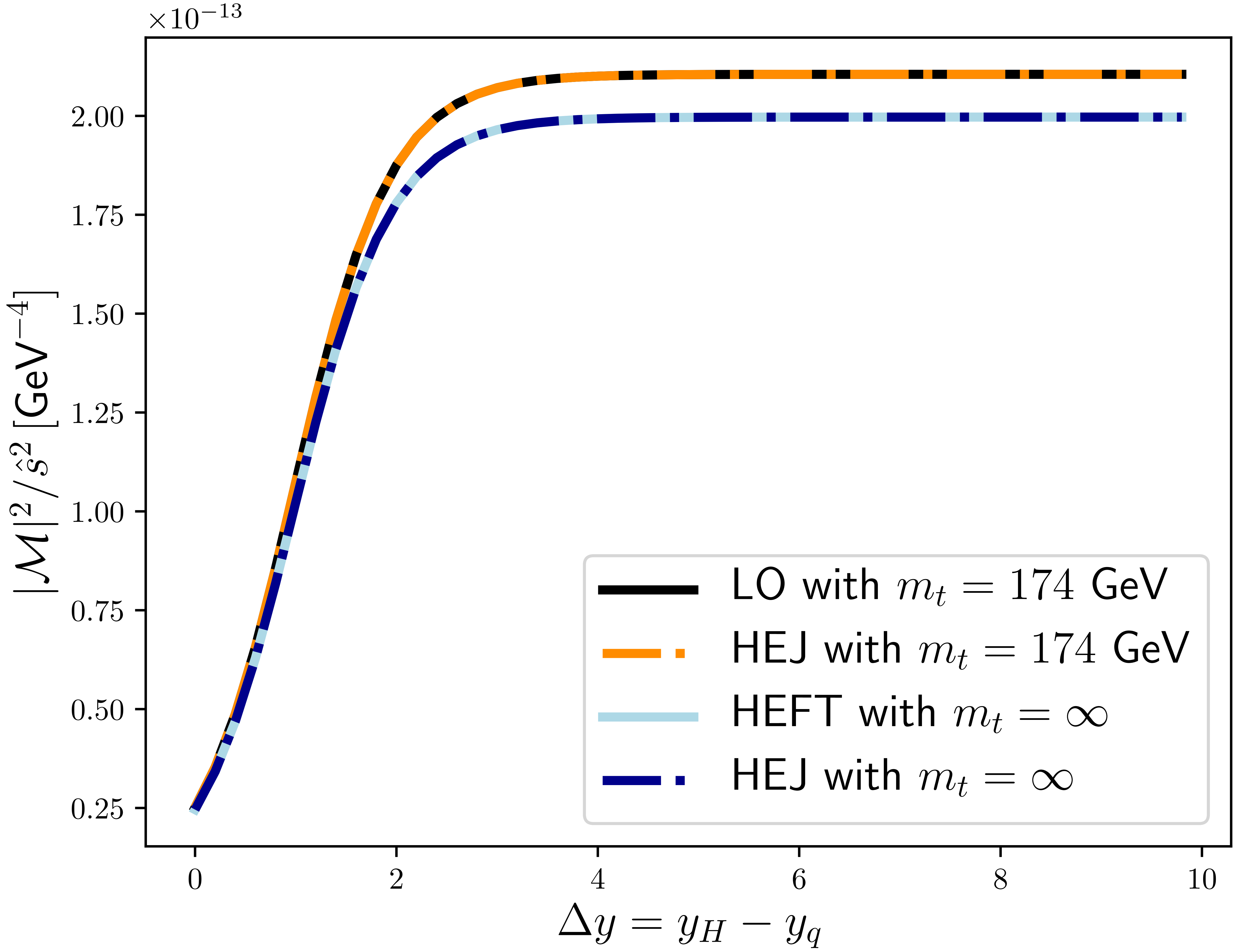
New Components for H+1j



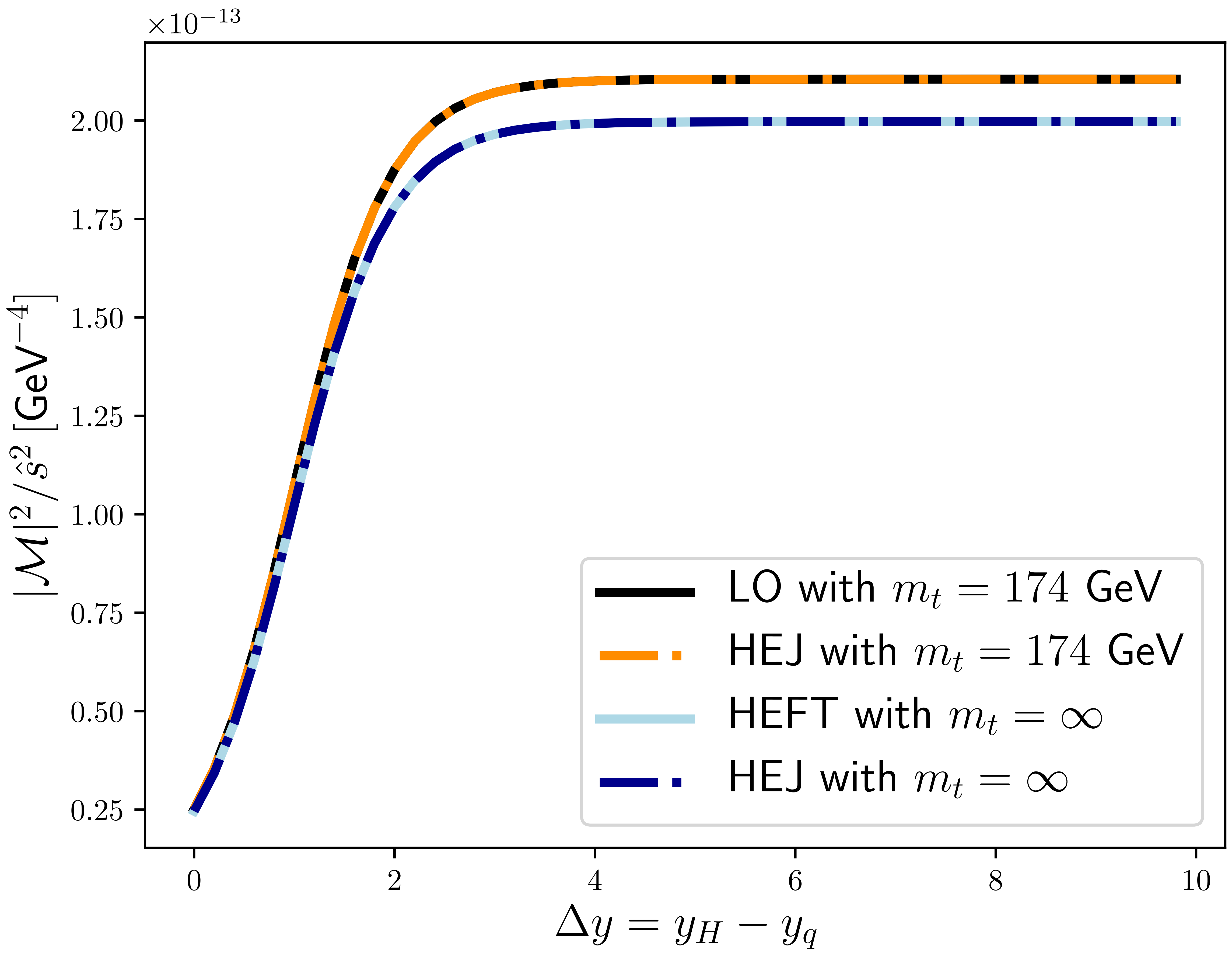
$$\mathcal{M} \propto \frac{1}{q_1^2} \epsilon_\mu(p_a) j_\nu(p_1, p_b) V_H^{\mu\nu}(p_a, q_1)$$

Simple factorised expression, no approximations here!
Before moving on, check Regge scaling

New Components for H+1j



New Components for H+1j



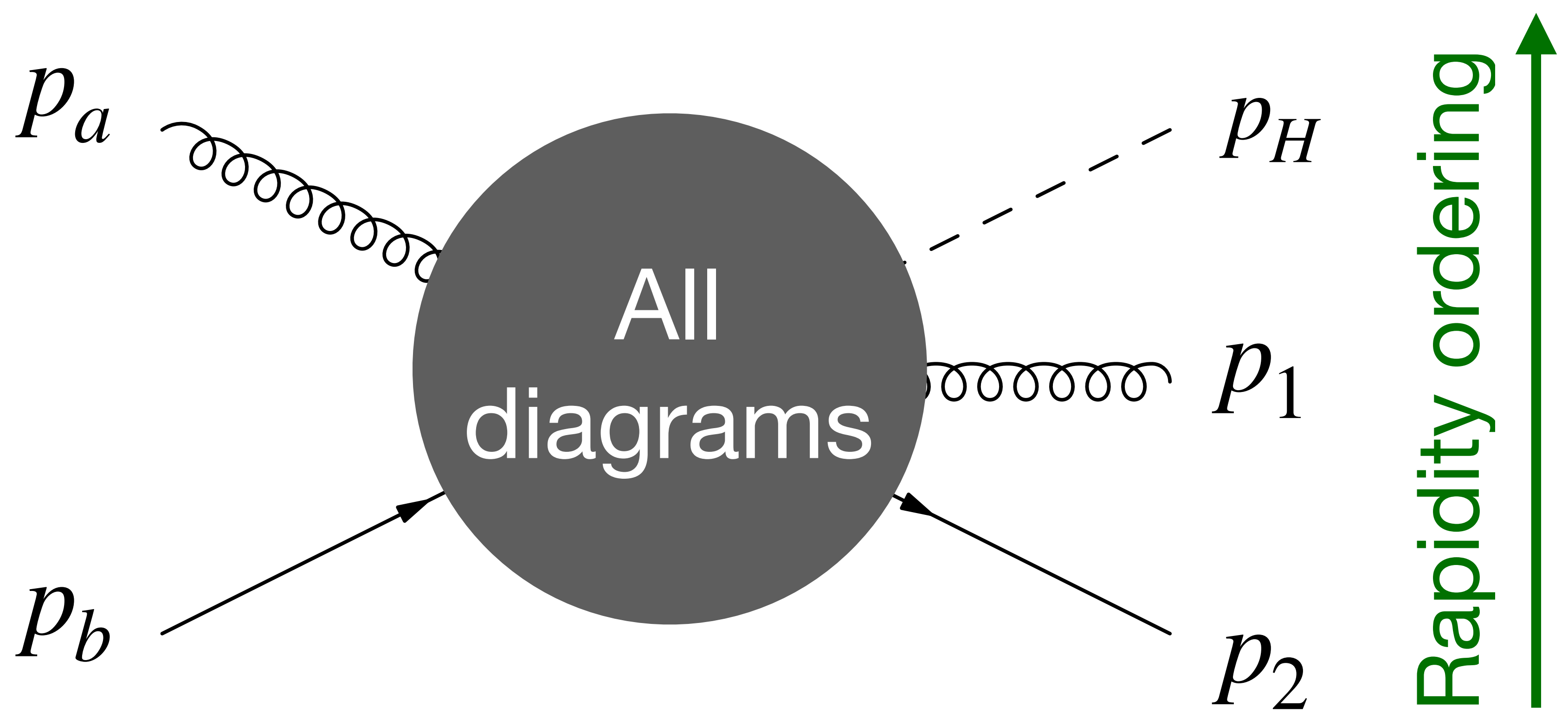
Indeed, no approximations, exact LO description with or without finite top mass

Regge scaling is verified:

$$\mathcal{M} \propto s_{Hq}^1$$

Even though the Higgs is not a coloured particle

New Components for H+1j

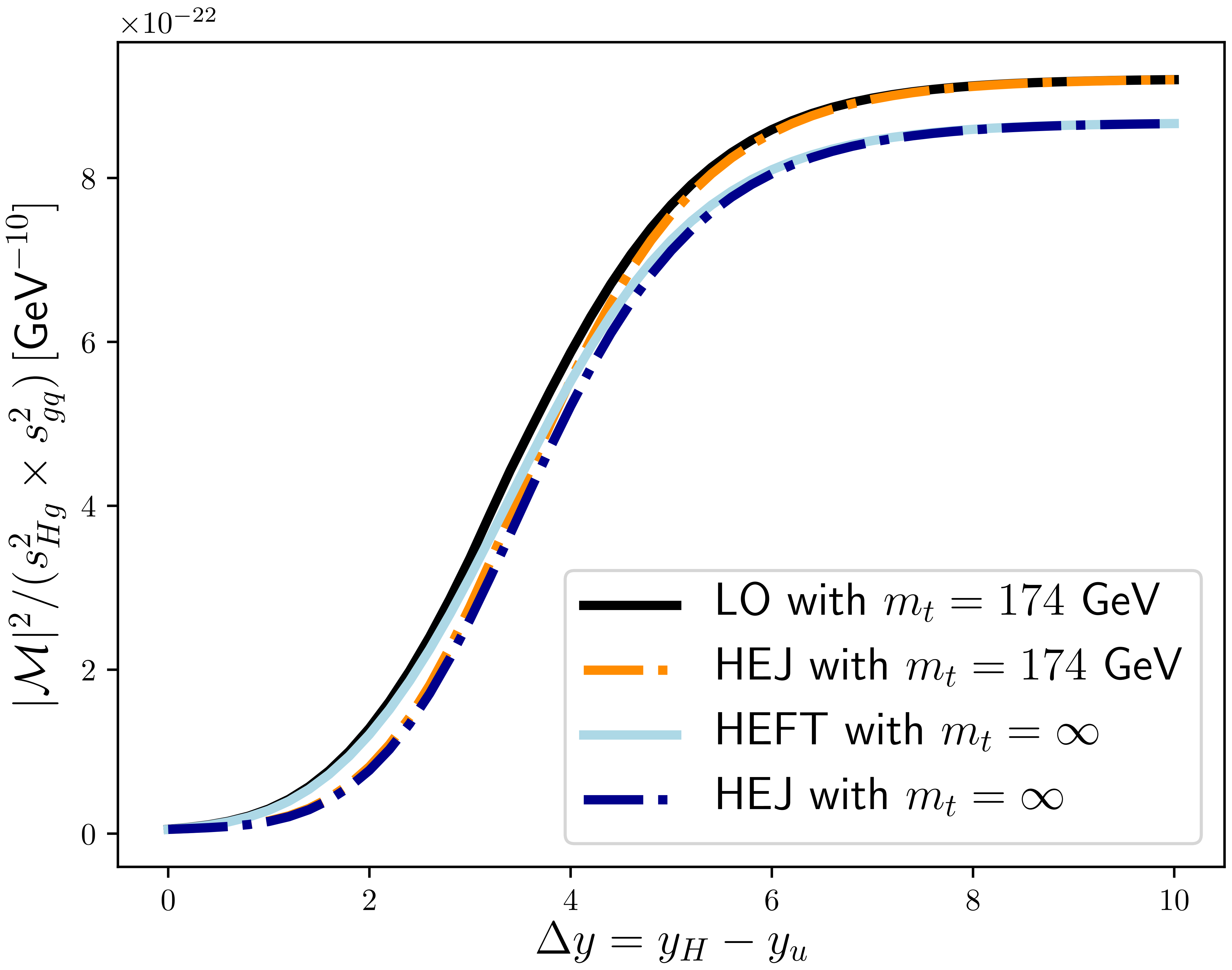


$$\mathcal{M} \propto \frac{1}{q_1^2}\frac{1}{q_2^2}\epsilon_\rho(p_a) j_\mu(p_2, p_b) V_H^{\rho\mu}(p_a, q_1) V^\lambda \epsilon^*_\lambda(p_1)$$

New Components for H+1j

$$\mathcal{M} \propto \frac{1}{q_1^2}\frac{1}{q_2^2}\epsilon_\rho(p_a) j_\mu(p_2,p_b) V_H^{\rho\mu}(p_a,q_1) V^\lambda \epsilon^*_\lambda(p_1)$$

New Components for H+1j



Approximations remain decent at low rapidity difference with or without finite top mass.

Regge theory is verified!

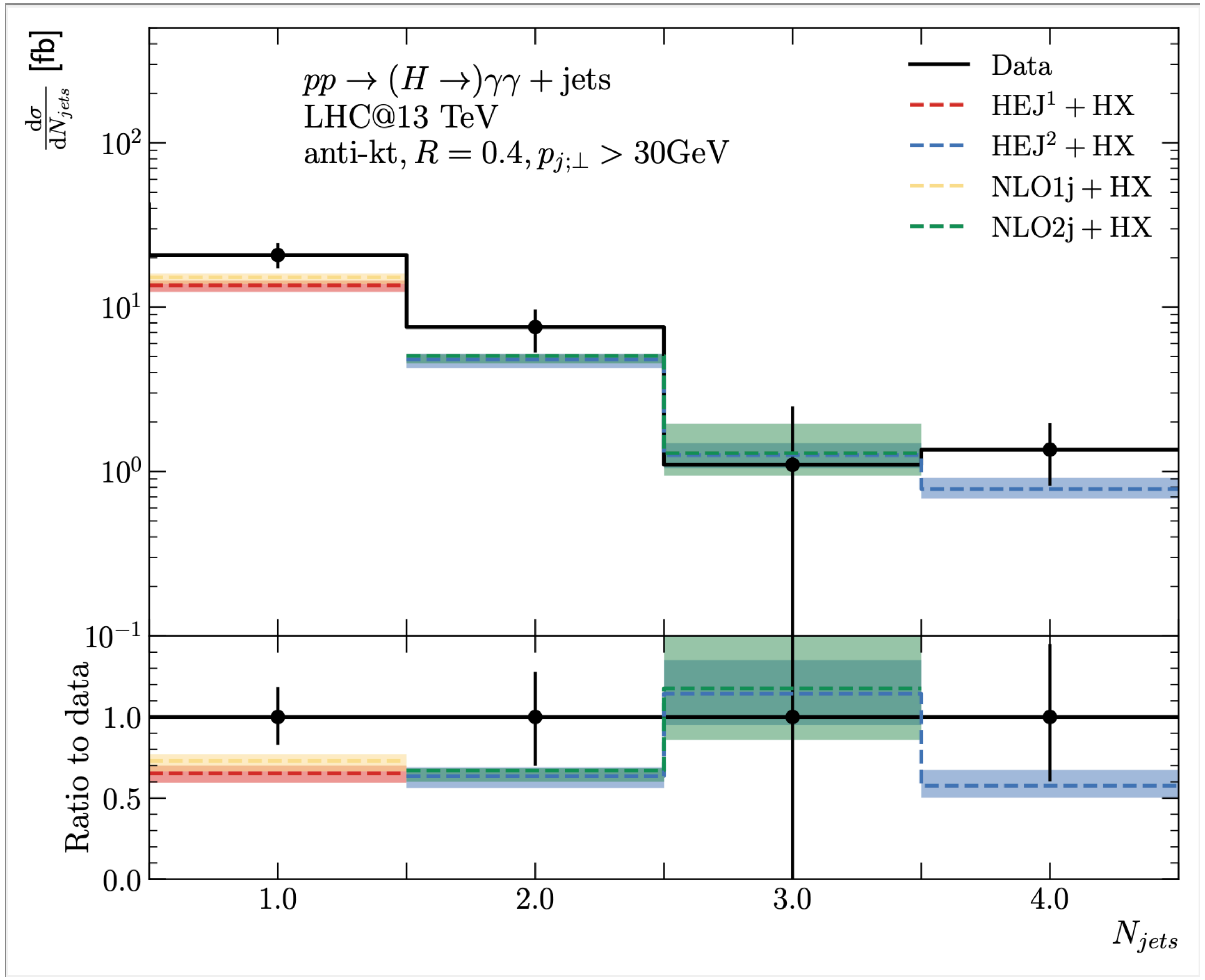
$$\mathcal{M} \propto s_{Hg}^{1} \times s_{gu}^{1}$$

Higgs plus one jet results

CMS analysis [1807.03825, 2208.12279]

Baseline Jet Cuts	
Pseudo-Rapidity	$\lvert\eta_j\rvert < 4.7$
Transverse momentum	$p_{\perp,j} > 30$ GeV
Baseline Photon Cuts	
Pseudo-Rapidity	$\lvert\eta_\gamma\rvert < 2.5$
Diphoton invariant mass	$m_{\gamma_1\gamma_2} > 90$ GeV
Transverse momentum hardest photon	$p_{\perp,\gamma_1} > \max(1/3 m_{\gamma_1\gamma_2}, 30 \text{ GeV})$
Transverse momentum other photon	$p_{\perp,\gamma_2} > 0.25\, m_{\gamma_1\gamma_2}$

Higgs plus one jet results



Resummed HEJ with finite m_t matched to NLO $1j$

Resummed HEJ with finite m_t matched to NLO $2j$

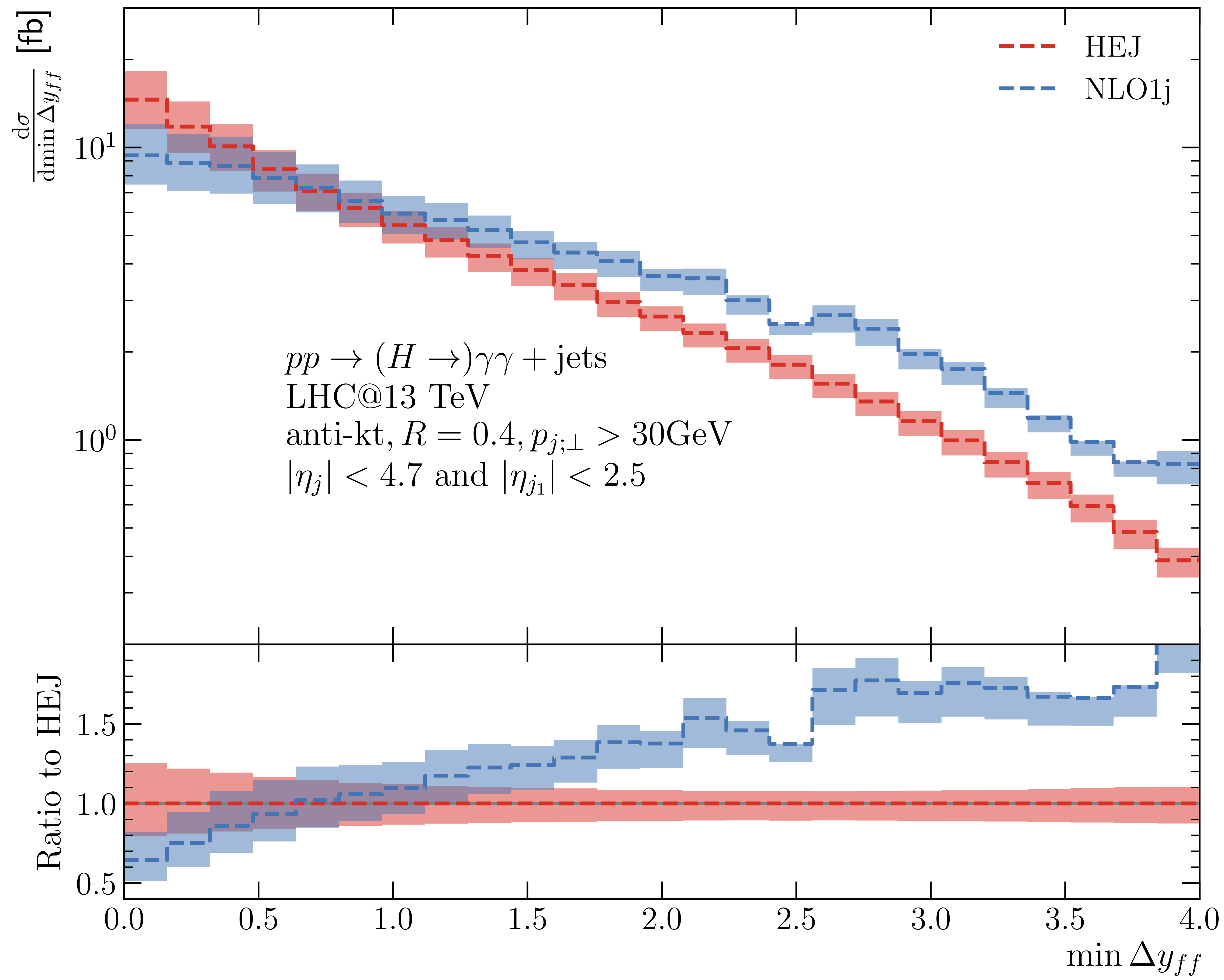
NLO $1j$ with infinite m_t

NLO $2j$ with infinite m_t

Resummed predictions for 4 jets and more

Electroweak (HX) added on top neglecting Interferences

Higgs plus one jet results



Resummed HEJ with finite m_t matched to NLO $1j$

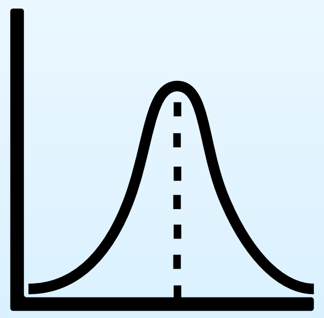
NLO $1j$ with infinite m_t

NLO effects harden the tail of large dijet rapidity separation

HEJ resummation soften the tail: the logarithms are numerically significant!

LoopFest XXI

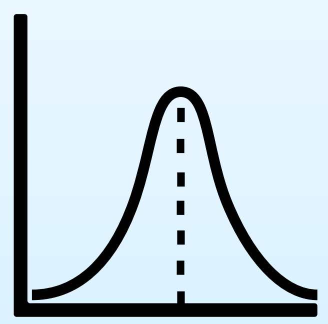
Higgs + one jet



LoopFest XXI

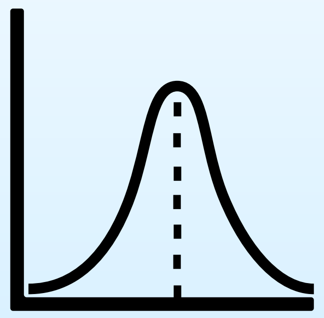
t-channel factorisation
still valid

Higgs + one jet



LoopFest XXI

Higgs + one jet

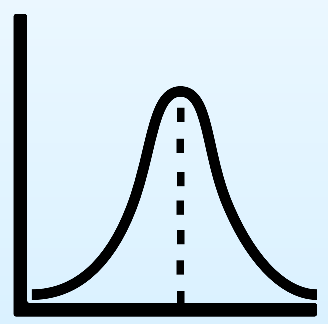


t-channel factorisation still valid

Finite quark masses still important

LoopFest XXI

Higgs + one jet



t-channel factorisation still valid

Finite quark masses still important

logs are significant in tails of distributions

Conclusion

HEJ publicly available on [here]()

Resums High-Energy large logarithms to LL accuracy, work is ongoing towards NLL accuracy.

Conclusion

HEJ publicly available on [here]()

Resums High-Energy large logarithms to LL accuracy, work is ongoing towards NLL accuracy.

H+1j inclusive

Takes into account finite quark masses unlike FO approaches, more observables are compared in paper

Conclusion

HEJ publicly available on here

Resums High-Energy large logarithms to LL accuracy, work is ongoing towards NLL accuracy.

H+2j inclusive

VBF cuts are more efficient than what FO predicts, finite quark masses effects and High-Energy Logarithms work together

H+1j inclusive

Takes into account finite quark masses unlike FO approaches, more observables are compared in paper

Conclusion

HEJ publicly available on here

Resums High-Energy large logarithms to LL accuracy, work is ongoing towards NLL accuracy.

H+2j inclusive

VBF cuts are more efficient than what FO predicts, finite quark masses effects and High-Energy Logarithms work together

H+1j inclusive

Takes into account finite quark masses unlike FO approaches, more observables are compared in paper

Ongoing work

Merging with parton shower, reaching NLL accuracy, amplitudes for Vector Boson production

Thank you for listening