MiNLO

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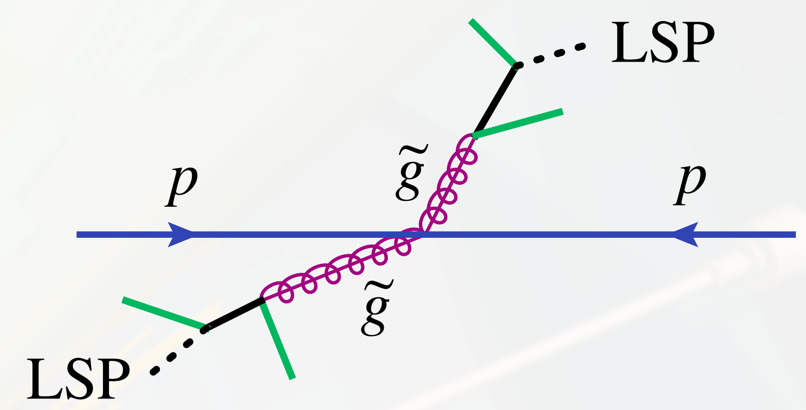
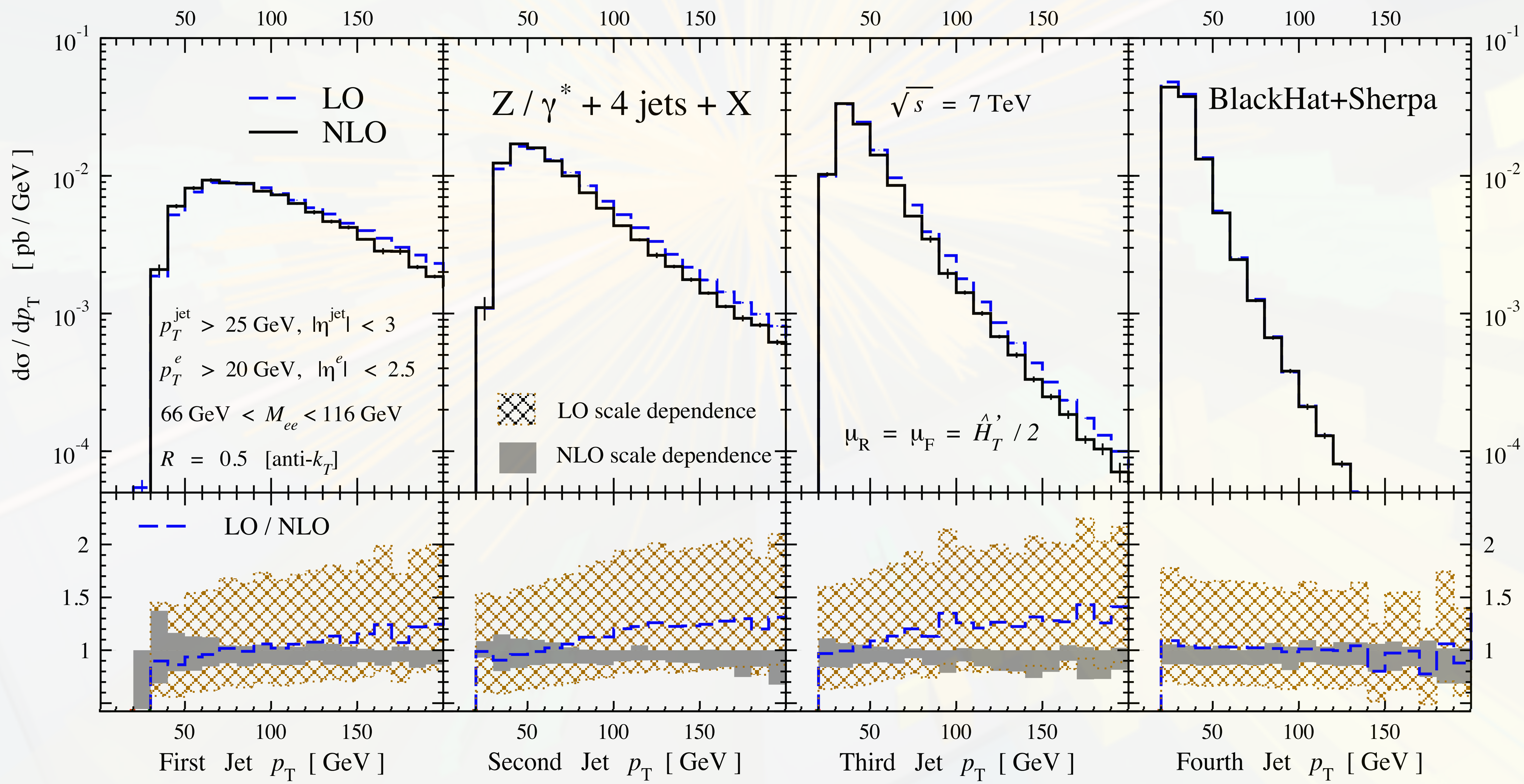
Outline

- MiNLO
  - Case for next-to-leading order calculations
  - Renormalization and factorization scales
  - Motivations for MiNLO
  - MiNLO example
  - Applications
  - MiNLO′

Case for next-to-leading order calculations

- Help looking for / setting limits on SUSY
- Take $\tilde{g}\tilde{g}$ product^n → 4 jets + MET
- Main bkg Z+4 jets [4 jet = 4 α_s's]



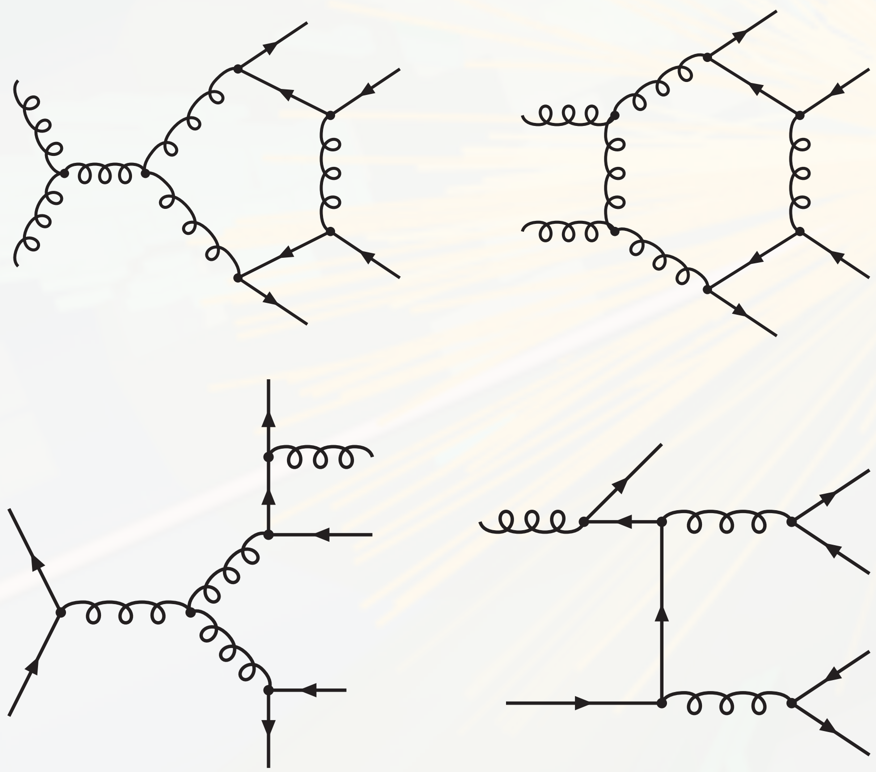


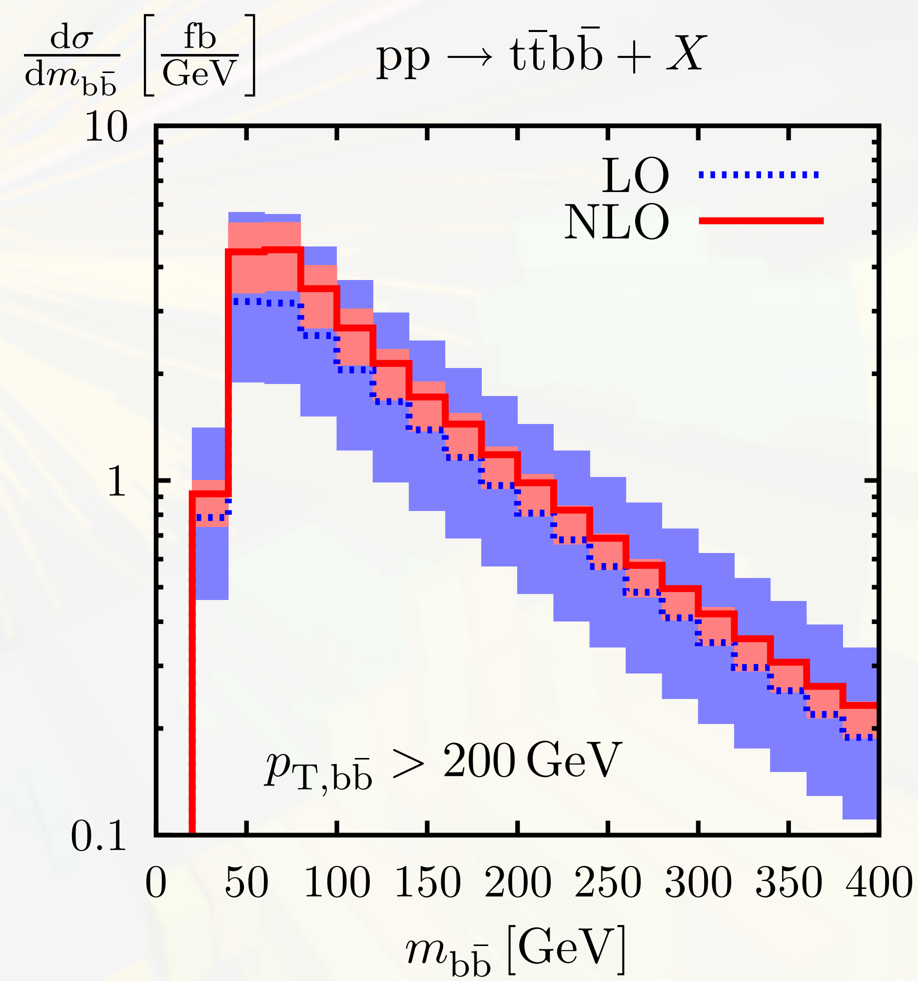
[BlackHat coll. PRD 85 (2012)]

- We prefer to know this bkg at NLO

Case for next-to-leading order calculations

- Precision Higgs physics
- pp → $t\bar{t}H$ probes top Yukawa at tree level
- Has significant irreducible background from pp → $t\bar{t}b\bar{b}$





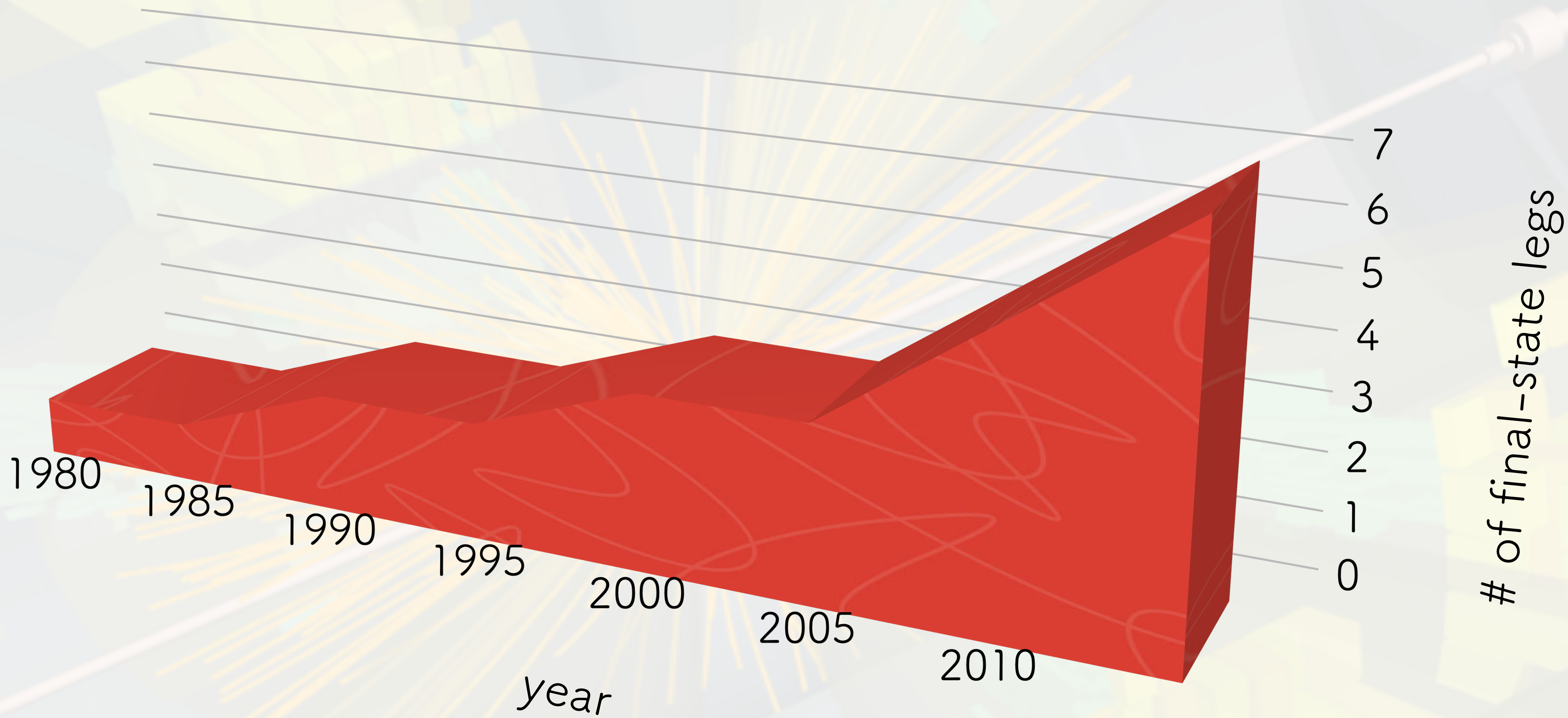
- We prefer to know this bkg at NLO

[Bredenstein, Denner, Dittmaier, Pozzorini PRL 103 (2009)]

[Bevilacqua, Czakon, Papadopoulos, Pittau, Worek JHEP 0909 (2009)]

Case for next-to-leading order calculations

- Recent years have seen amazing progress in NLO calculat^{n}s:



- Increasing complexity brings increasing powers of $\alpha_s(\mu)$
- More emphasis on choosing μ's carefully

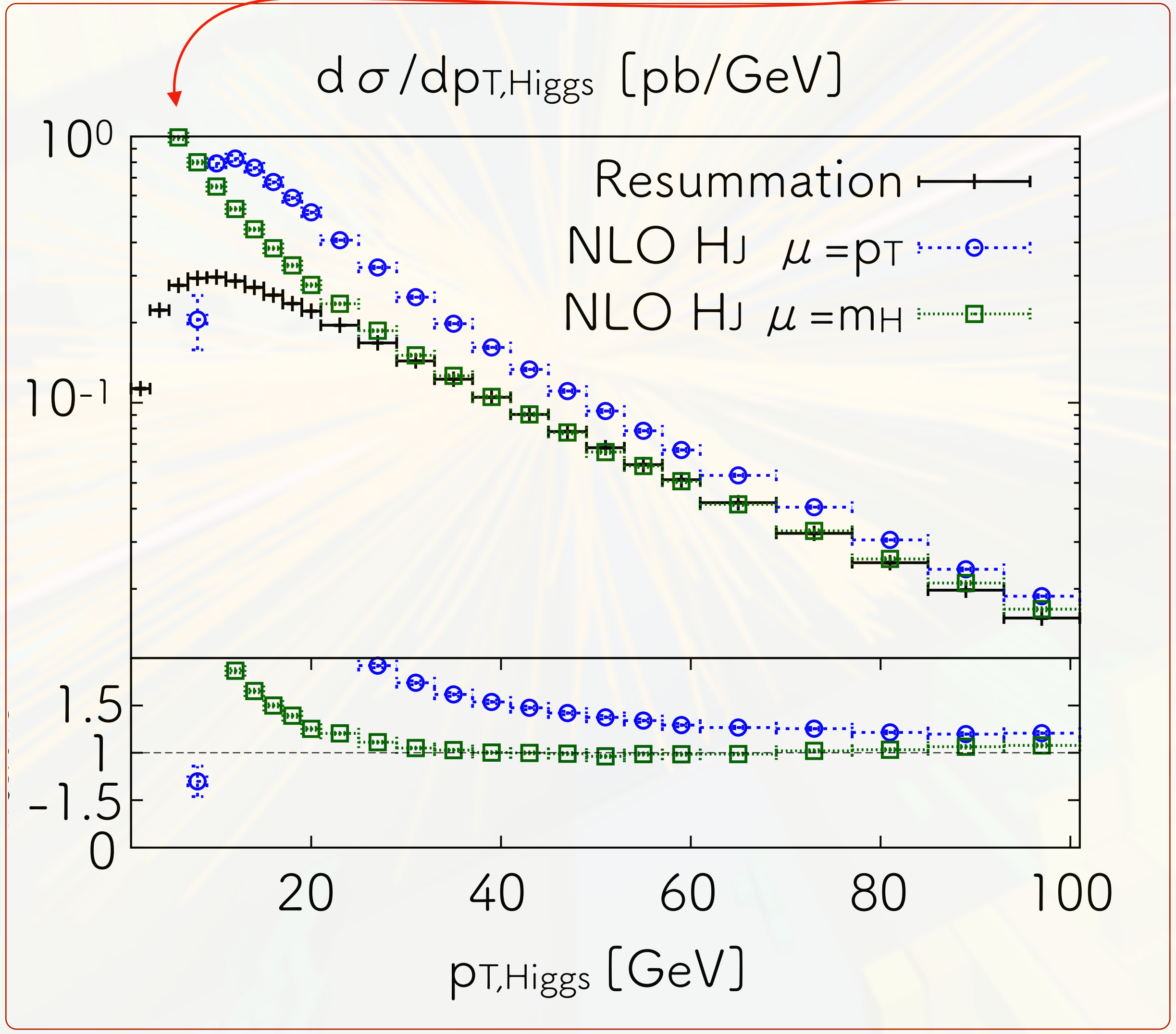
Renormalization and factorization scales

- ‘Good scales’ commonly considered to be so retrospectively on seeing higher order corr^{n}s and residual scale sensitivity are small

- ‘Bad scales’ commonly declared on finding large higher order corr^{n}s & res. scale sensitivity : typically diagnosed as large unphysical scale logs

Q1: are large higher order corr^{n}s all down to large $\mu_{R/F}$ logs?

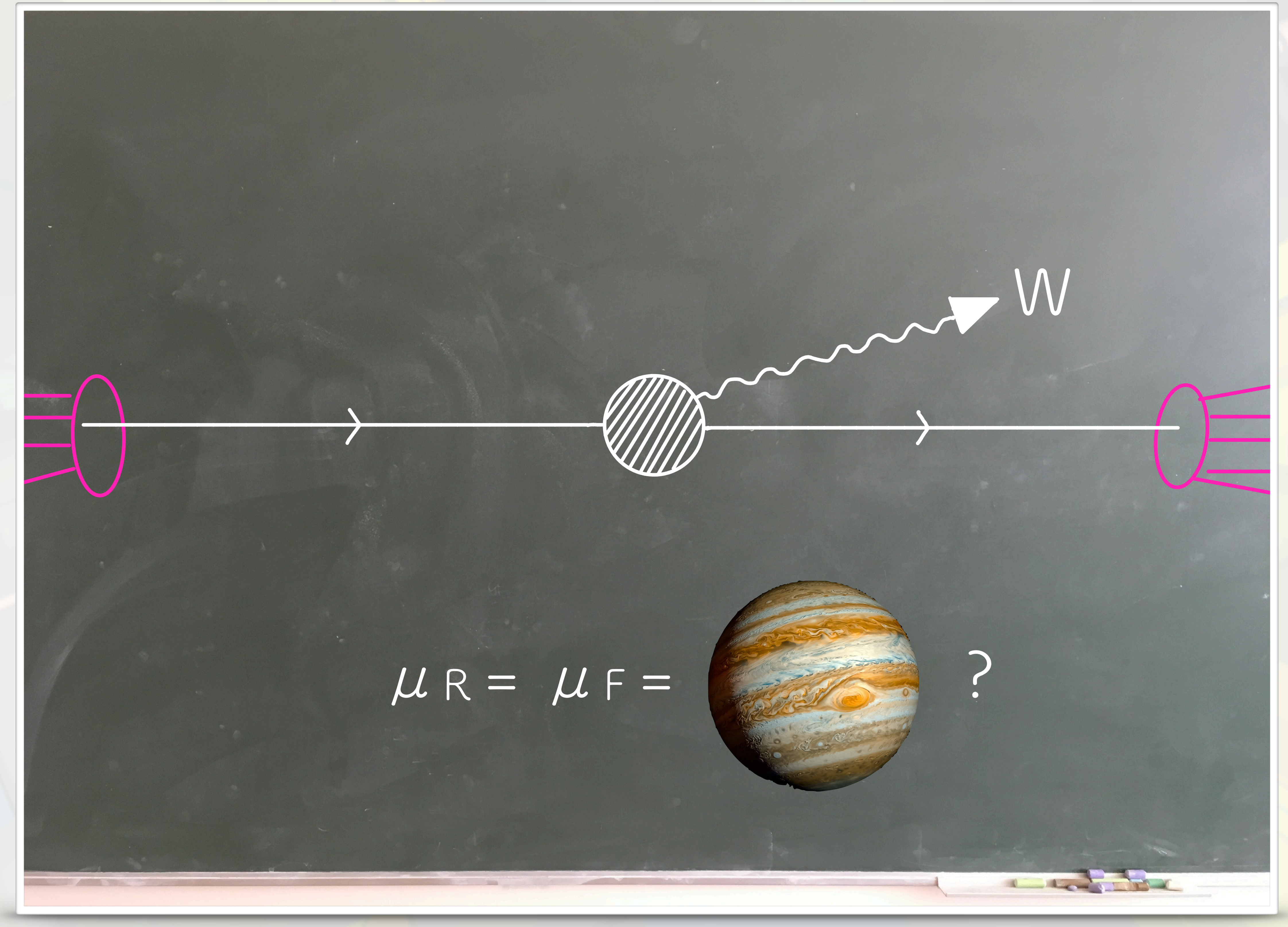
- Big higher order corr^{n}s can have real physical origins: new prod^n channels, big colour factors, large gluon flux, I.R. logs ...



- Adjusting scale to make corr^{n}s / sensitivity small can effectively 'eat' unrelated physics in scale choice

Q2: what if there are many scales to choose from?

- In single/few scale processes it's harder to make a bad scale choice



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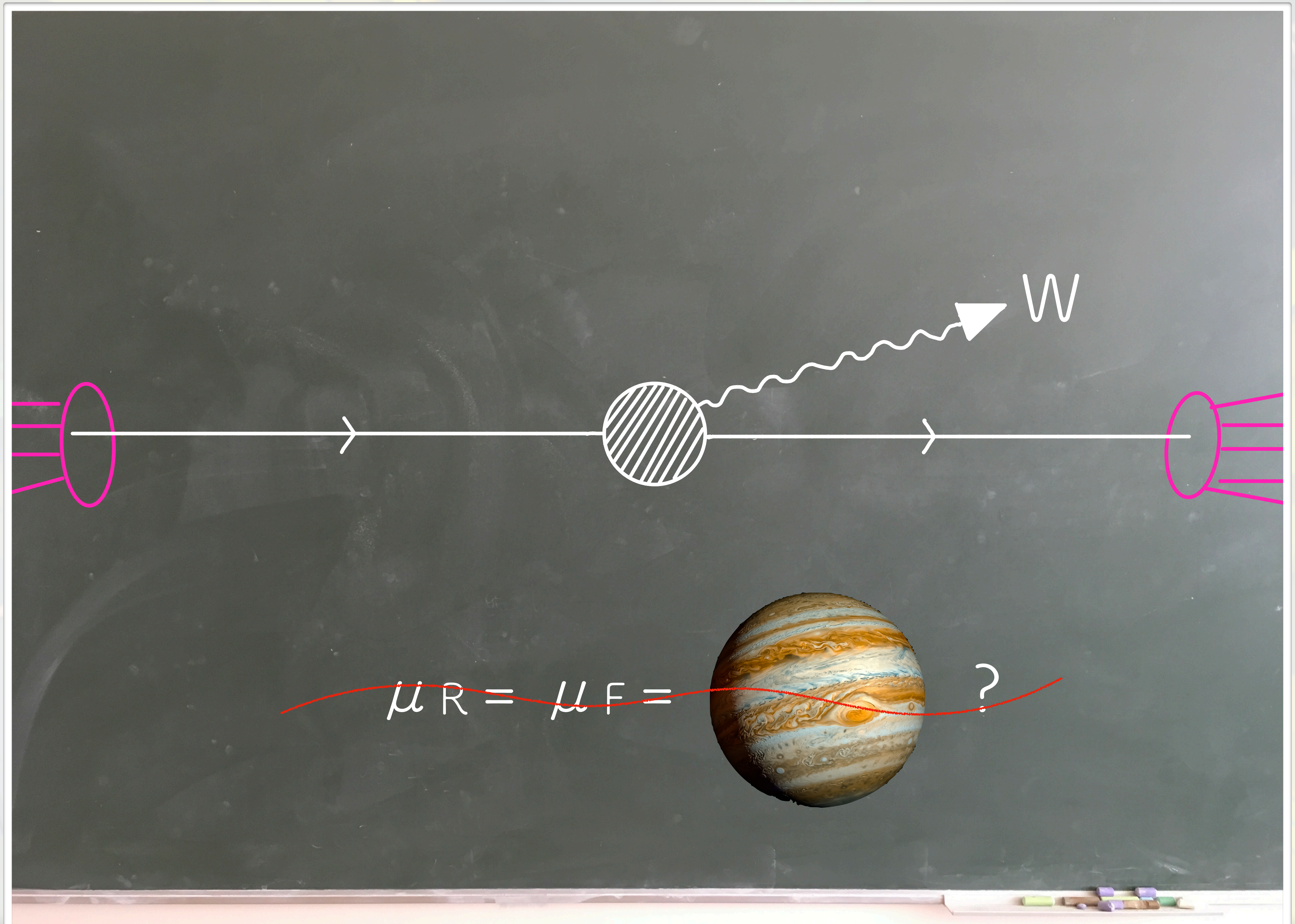

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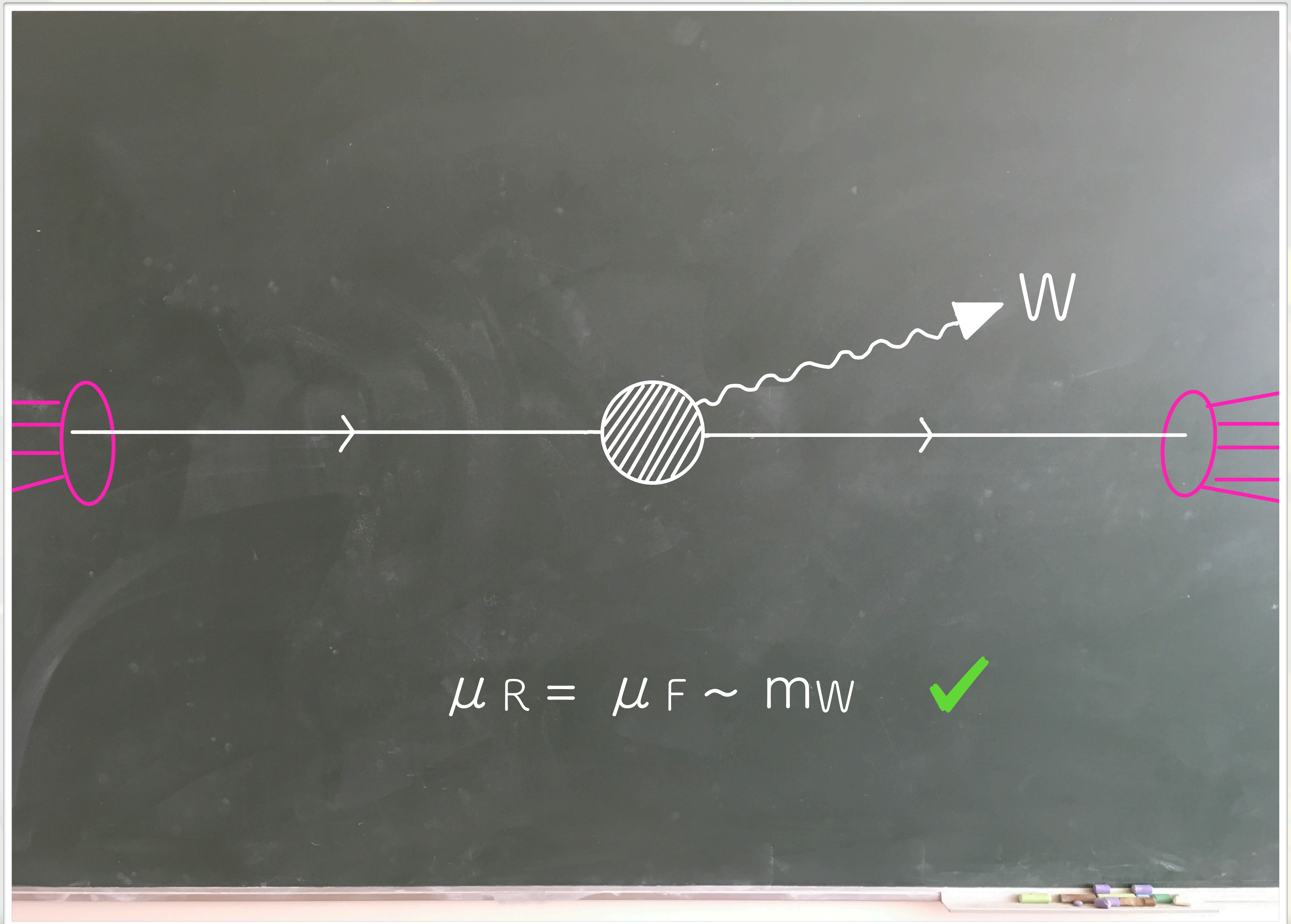
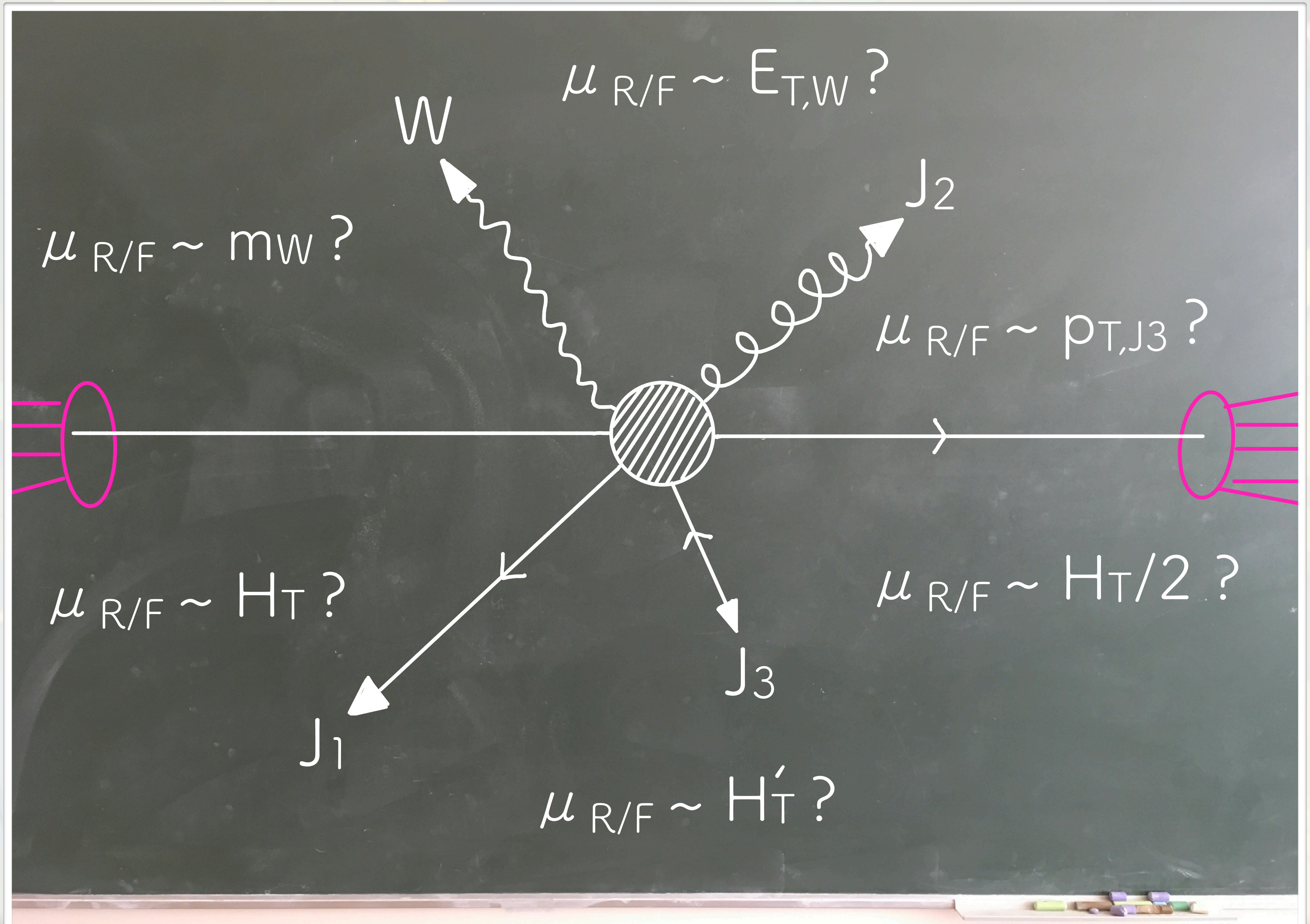


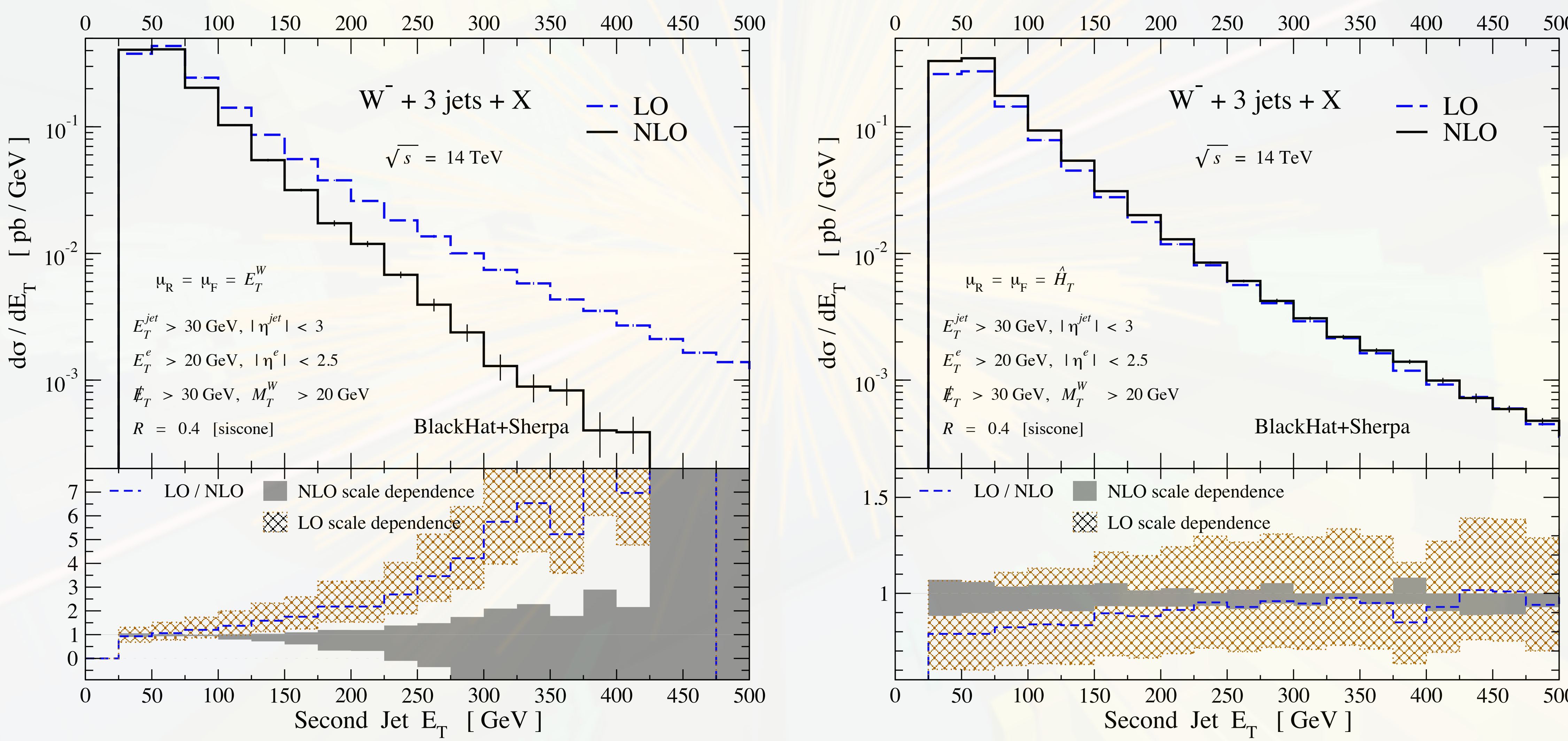
Q2: what if there are many scales to choose from?

- In procs with more jets, i.e. more scales, it's hard to know what to do



Q2: what if there are many scales to choose from?

- BSM background: W+3 jets [3 jets = 3 α_S's]
- BlackHat paper points out physical distⁿs can go -ve for $\mu_R = \mu_F = E_{T,W}$

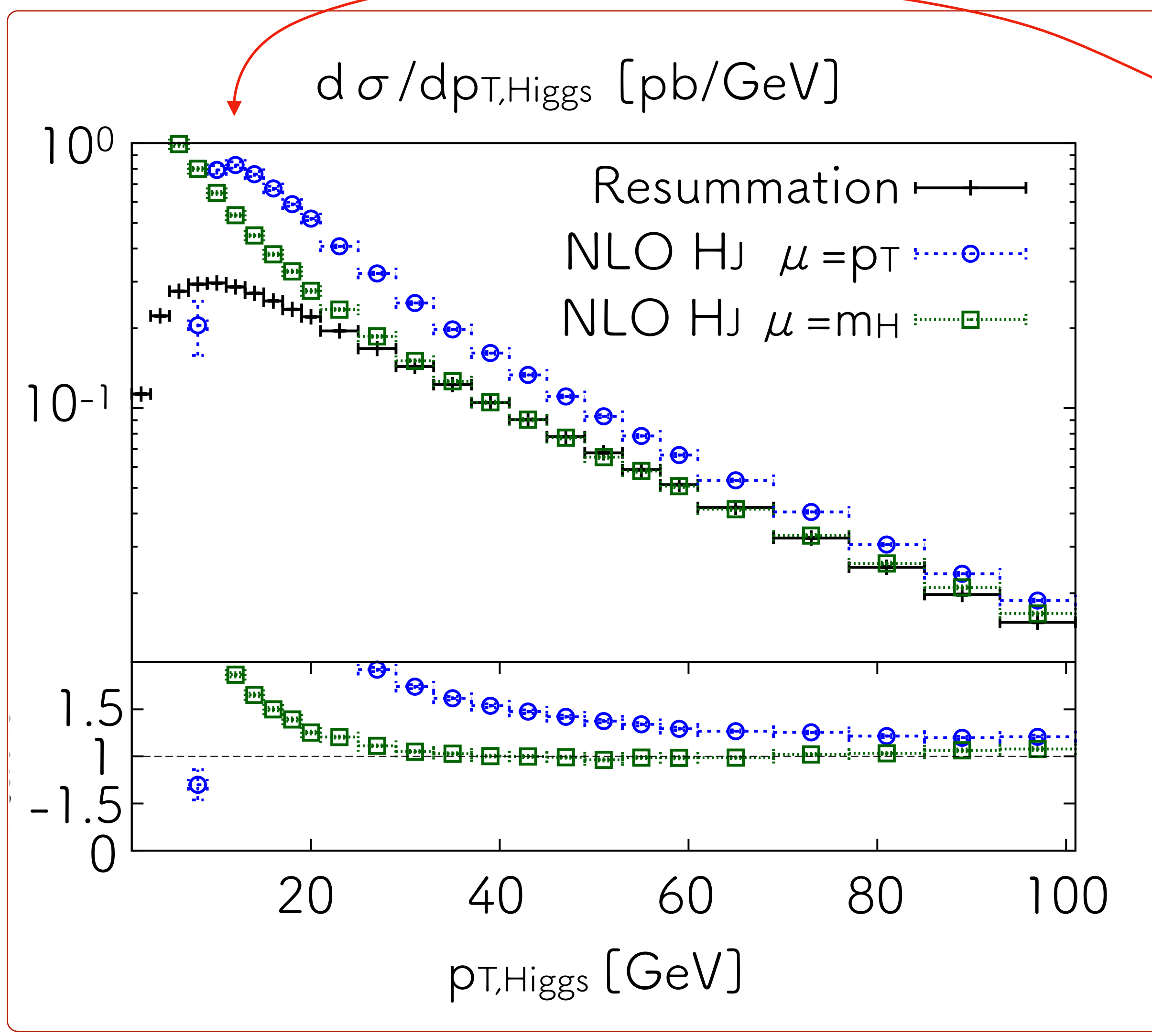


$\mu_R = \mu_F = E_{T,W}$ $\qquad$ $\mu_R = \mu_F = \hat{H}_T$

- For sufficiently poor choices [of scales] large logs can appear in some distributions, invalidating even an NLO prediction —— BlackHat collaboration

Q3: if worrying about scale logs why not other large logs?

- Residual scale dependence of NLO calcⁿs goes as $\sim\ \alpha_S^n \log^n \frac{\mu_R^2}{Q^2}$ [n≥2]
- But often have situations were NNLO etc corrⁿs go as $\sim\ \alpha_S^n \log^{2n} \frac{Q^2}{p_T^2}$ [n≥2]



- Is it reasonable to worry about single log terms beyond NLO & not also worry about IR Sudakov double logs?

MiNLO: Multi-scale improved Next-to-leading Order

Nason, Zanderighi, KH

- In a nutshell:
  - Determine the parton shower branching history associated with the kinematic configⁿs in the NLO events in the x-secⁿ integrals.
  - Take **all-orders rad corrⁿs** that the shower would associate to such configⁿs, as in CKKW*, and **match** them with the exact NLO corrⁿs
- Addressing questions / objections of last few slides:
  - A1: small/moderate NLO corrⁿs/scale sensitivity isn't a consideration
  - A2: PS have natural uniquely defined scale setting for multi-scale probs
  - A3: PS resum large IR double logs as well as single scale logs

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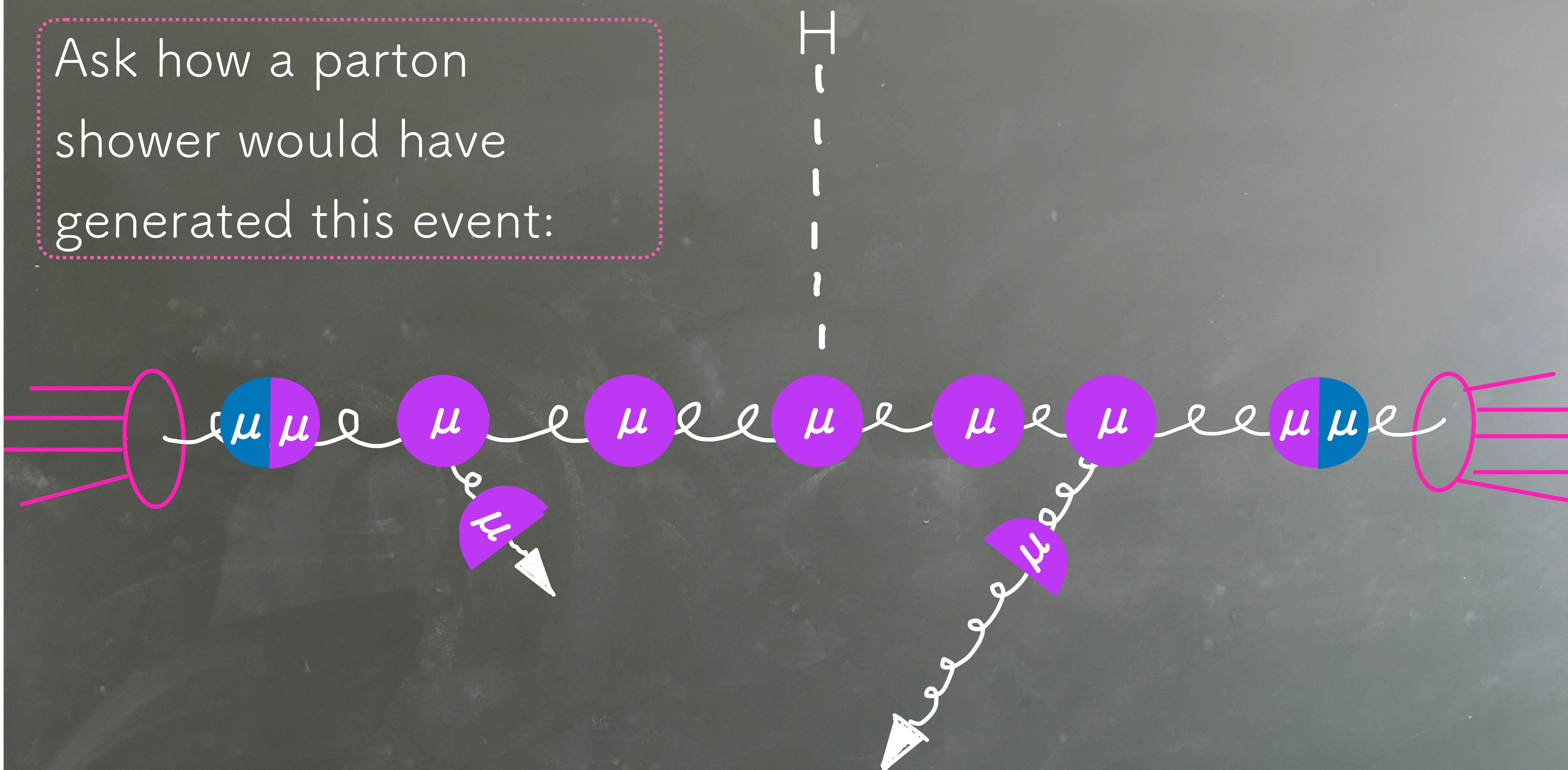
- Catani, Krauss, Kuhn, Webber

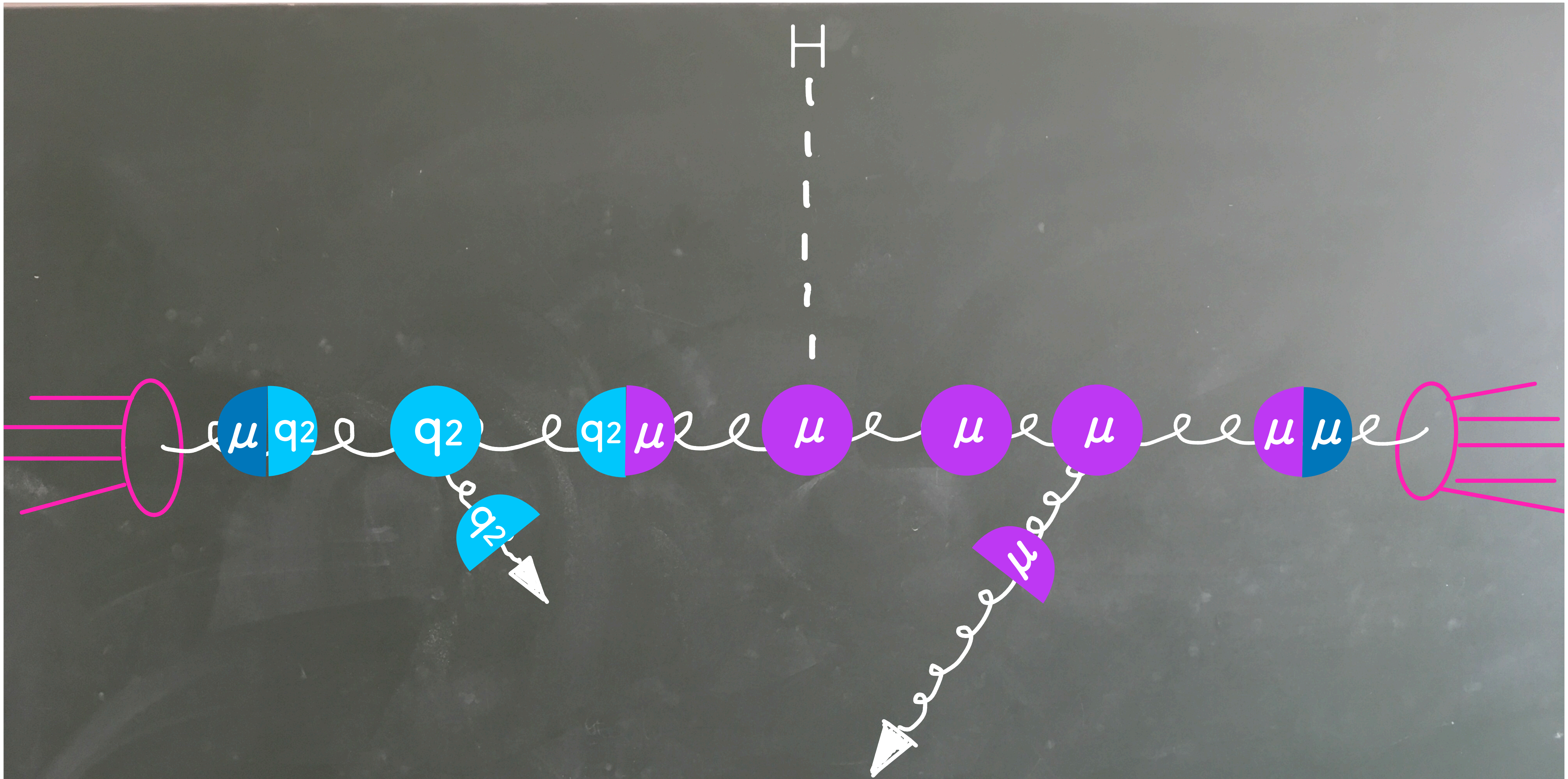
Example: H+2 jets MiNLO at leading order with a big brush

Ask how a parton shower would have generated this event:



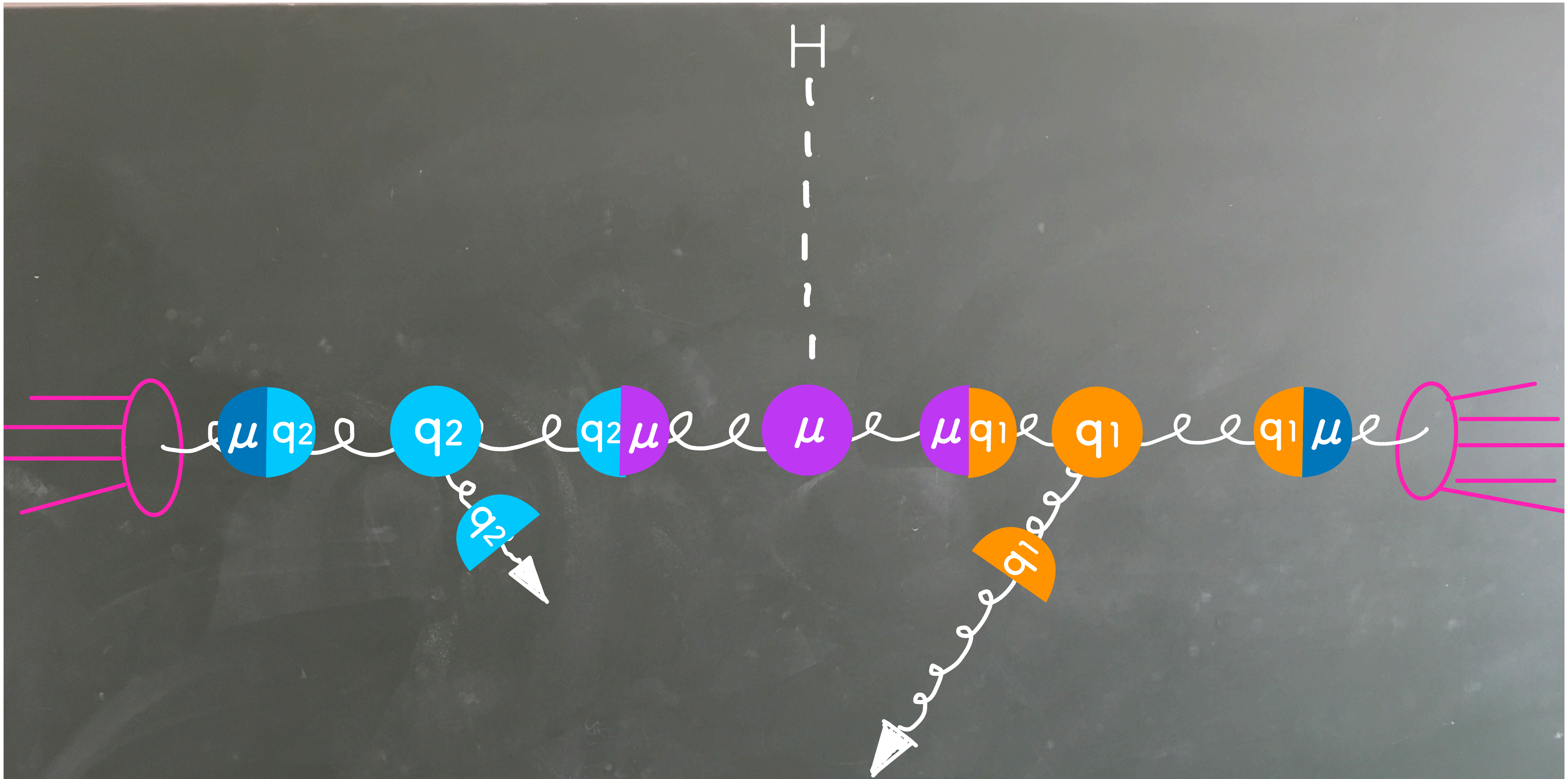
- Emissions strongly ordered in hardness factorise from one another
- In PS each branching is like its own <u>simple</u> process with own scale
- Evaluating each $\alpha_S(\mu)$ associated to a branching vertex at branching's own p_T sums large class of higher order corr^{ns}

Example: H+2 jets MiNLO at leading order with a big brush



- Relative to conventional fixed order the shower is including extra coupling constant ratios: $\frac{\alpha_S(q_2)}{\alpha_S(\mu)}$

Example: H+2 jets MiNLO at leading order with a big brush



- Relative to conventional fixed order the shower is including extra coupling constant ratios: $\frac{\alpha_s(q_2)}{\alpha_s(\mu)} \quad \frac{\alpha_s(q_1)}{\alpha_s(\mu)}$

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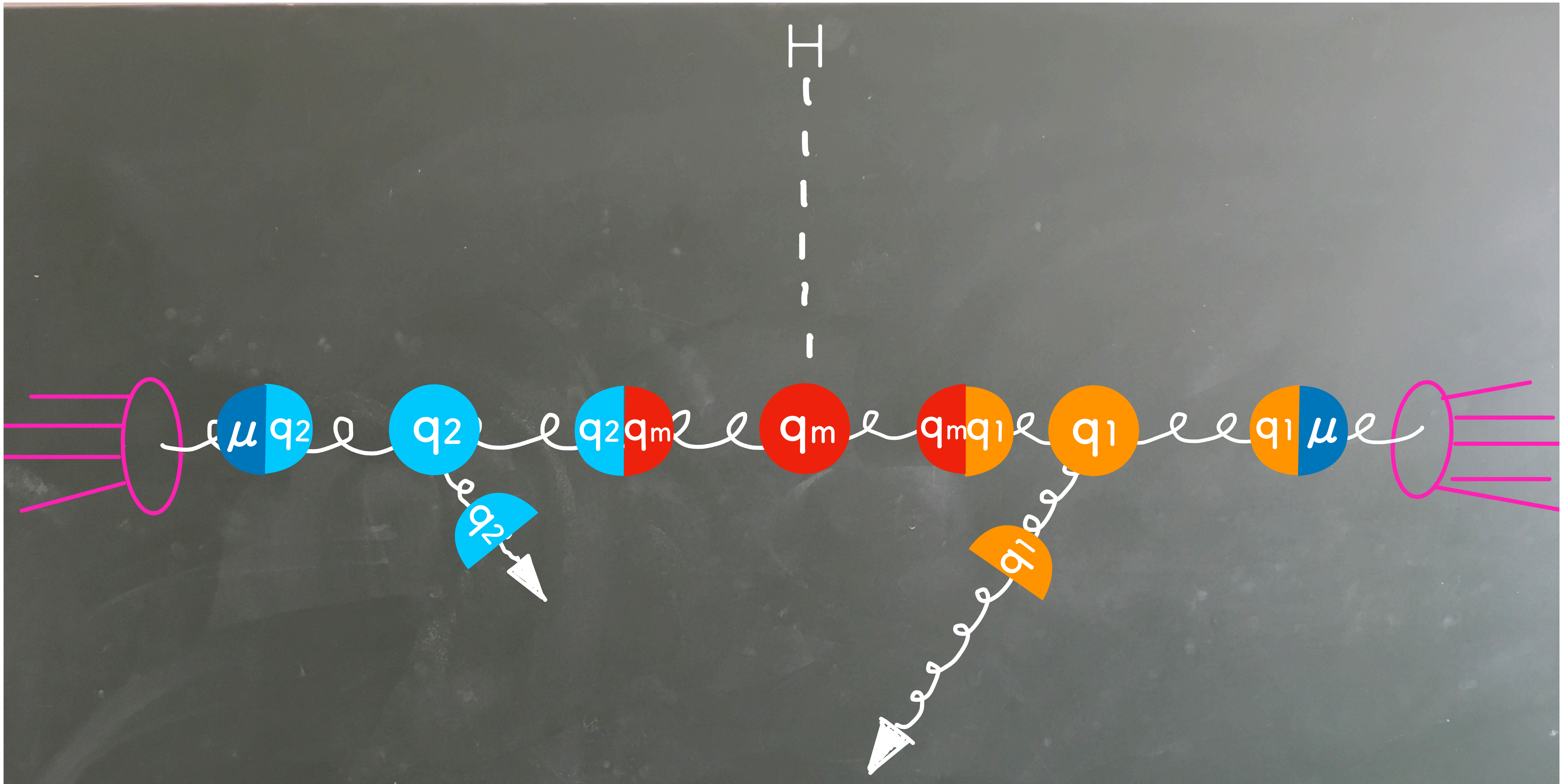
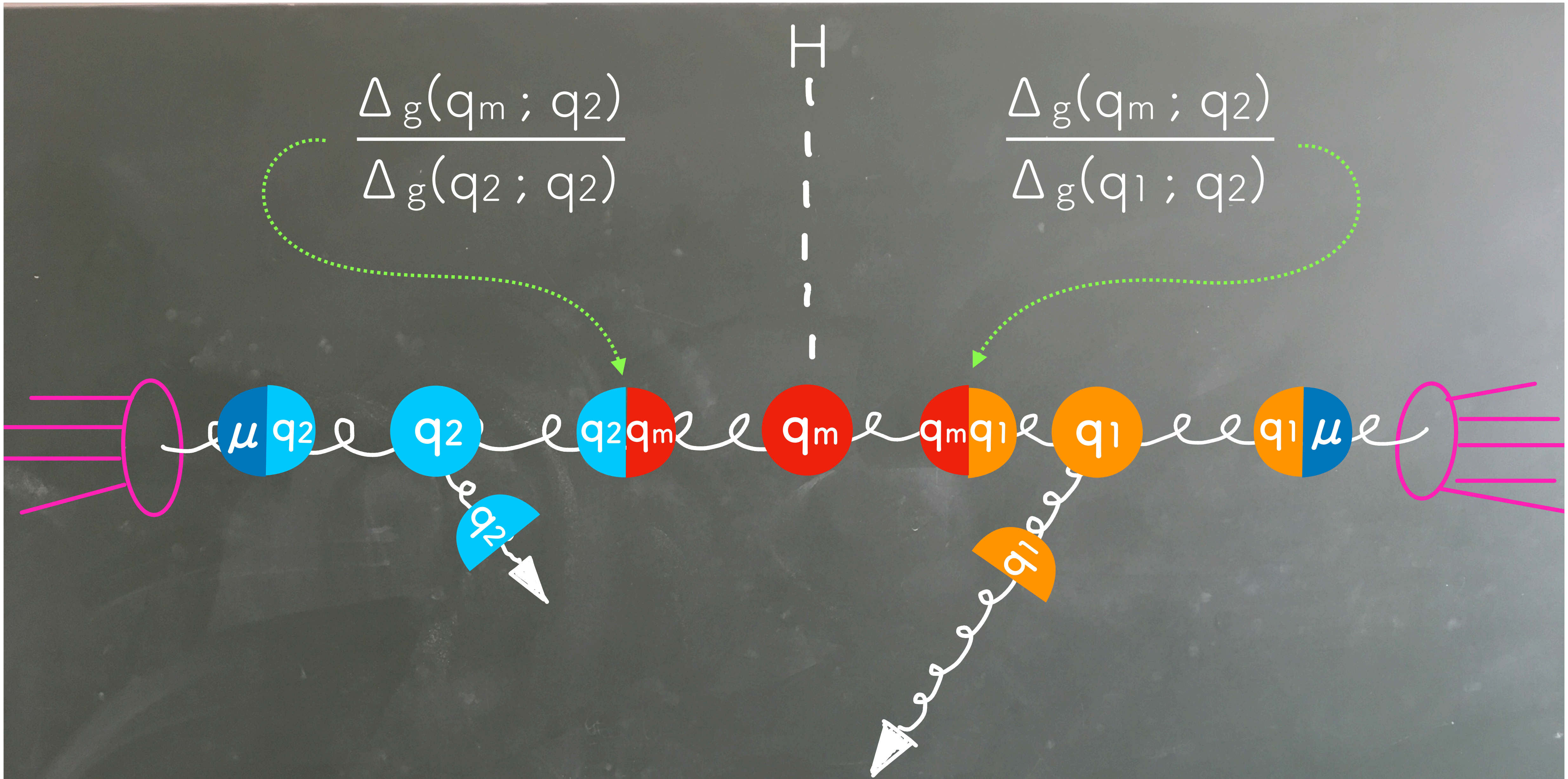


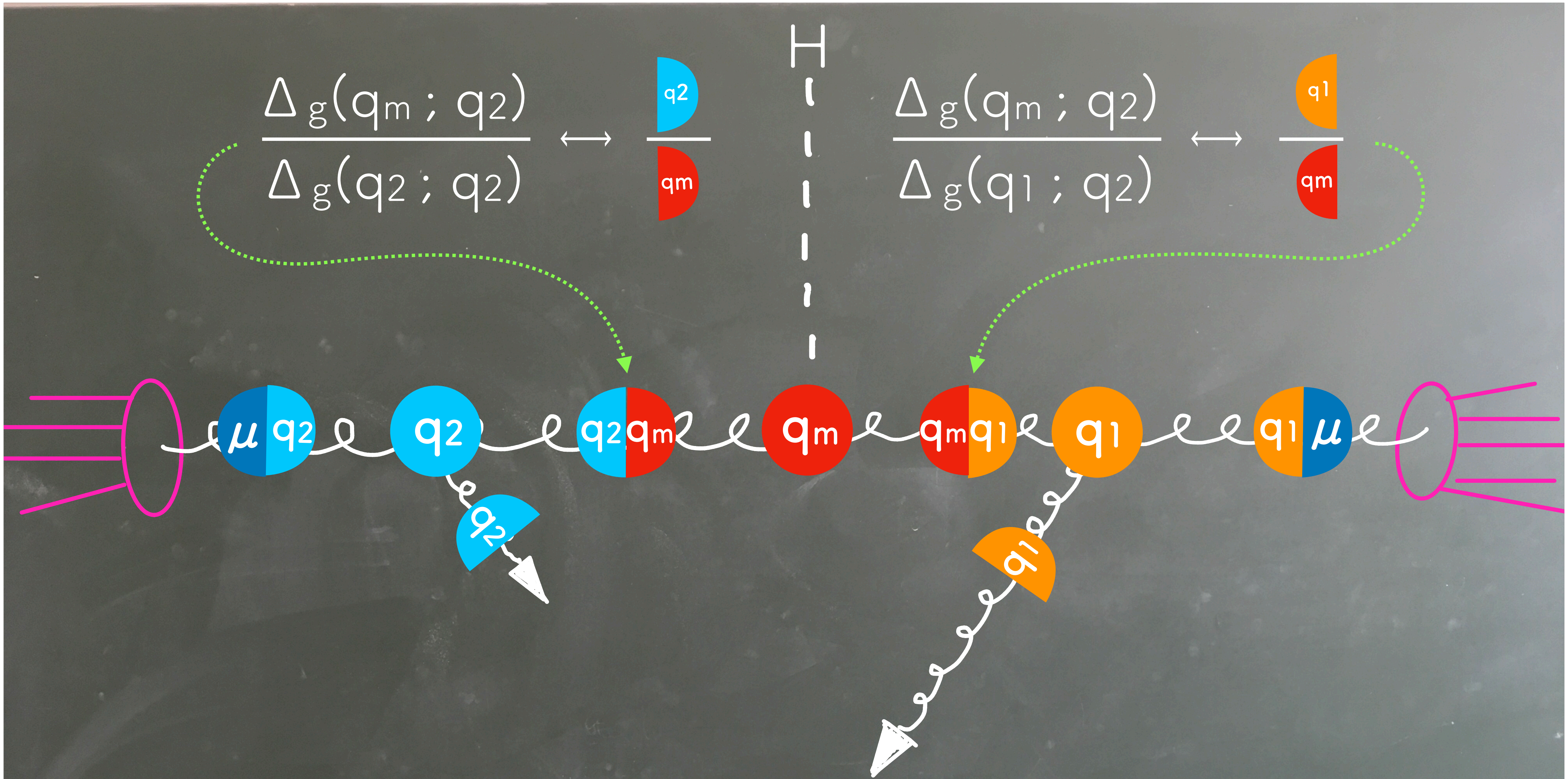
- Relative to conventional fixed order the shower is including extra coupling constant ratios: $\frac{\alpha_S(q_2)}{\alpha_S(\mu)}$ $\frac{\alpha_S(q_1)}{\alpha_S(\mu)}$ $\frac{\alpha_S^2(q_m)}{\alpha_S^2(\mu)}$

Example: H+2 jets MiNLO at leading order with a big brush



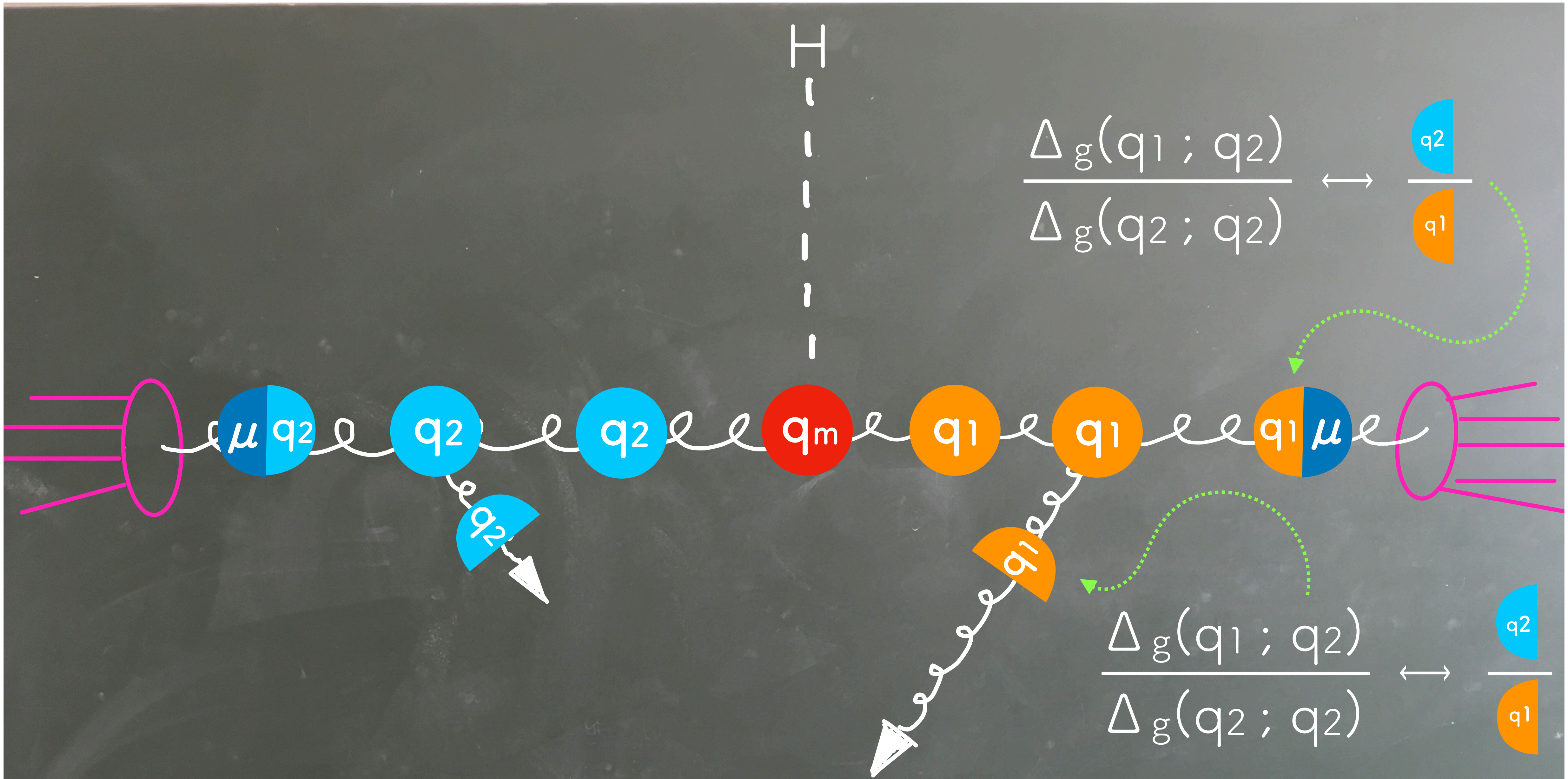
- Showers also account for the probability that the gluons exiting $gg \to H$ vertex evolve from q_m to q_1 and q_2 without emitting any resolvable rad^n $[q>q_2]$: Sudakov form factors

Example: H+2 jets MiNLO at leading order with a big brush



- In certain gauge(s) single logs in PS Sudakov factors can be associated with ratios of self-energies [ratios of self-energies in this cartoon]

Example: H+2 jets MiNLO at leading order with a big brush



- Since we integrate over all activity occurring below q_2 Sudakov factors are also needed to account for any external legs produced above q_2 evolving down to q_2

Example: H+2 jets MiNLO at leading order with a big brush

- Parton shower also effectively sets the factorisation scale for such a configuration to the scale beneath which all activity is integrated out, $q_2 \cdots$

Example: H+2 jets MiNLO at leading order with a big brush

$$d\sigma^{LO}_{HJJ} = dx_1\, dx_2\, d\Phi_{HJJ}\; f_{h_1}(x_1, \mu_F)\, f_{h_2}(x_2, \mu_F)\, \frac{1}{2\hat{s}}\, M(\Phi_{HJJ}, \mu_R)$$

LO terms $\simeq O(\alpha_s^4)$

$$d\sigma^{P.S.}_{HJJ} = dx_1\, dx_2\, d\Phi_{HJJ}\; f_{h_1}(x_1, \mu_F)\, f_{h_2}(x_2, \mu_F)\, \frac{1}{2\hat{s}}\, M^{P.S.}(\Phi_{HJJ})$$

$$\times\; \frac{\alpha_s(q_2)}{\alpha_s(\mu)} \cdot \frac{\alpha_s(q_1)}{\alpha_s(\mu)} \cdot \frac{\alpha_s^2(q_m)}{\alpha_s^2(\mu)}$$

$$\times\; \frac{\Delta_g(q_m; q_2)}{\Delta_g(q_2; q_2)} \cdot \cdots\cdots \cdot \frac{\Delta_g(q_1; q_2)}{\Delta_g(q_2; q_2)}$$

$$\times\; \frac{f(x_1, q_2)}{f(x_1, \mu_F)} \cdot \frac{f(x_2, q_2)}{f(x_2, \mu_F)}$$

Beyond LO corrections

$\sim 1 + O(\alpha_s) + \ldots$

Example: H+2 jets MiNLO at leading order with a big brush

$$d\sigma^{LO}_{HJJ} = \underbrace{dx_1\, dx_2\, d\Phi_{HJJ}\, f_{h_1}(x_1,\mu_F)\, f_{h_2}(x_2,\mu_F)\, \frac{1}{2\hat{s}}\, M(\Phi_{HJJ},\mu_R)}$$

LO terms $\simeq O(\alpha_s^4)$

$$d\sigma^{P.S.}_{HJJ} = \overbrace{dx_1\, dx_2\, d\Phi_{HJJ}\, f_{h_1}(x_1,\mu_F)\, f_{h_2}(x_2,\mu_F)\, \frac{1}{2\hat{s}}\, M^{P.S.}(\Phi_{HJJ})}$$

$$\left.\begin{array}{l}
\times\ \dfrac{\alpha_s(q_2)}{\alpha_s(\mu)} \cdot \dfrac{\alpha_s(q_1)}{\alpha_s(\mu)} \cdot \dfrac{\alpha_s^2(q_m)}{\alpha_s^2(\mu)} \\[2ex]
\times\ \dfrac{\Delta_g(q_m\,;\,q_2)}{\Delta_g(q_2\,;\,q_2)} \cdot \cdots\cdots \cdot \dfrac{\Delta_g(q_1\,;\,q_2)}{\Delta_g(q_2\,;\,q_2)} \\[2ex]
\times\ \dfrac{f(x_1,q_2)}{f(x_1,\mu_F)} \cdot \dfrac{f(x_2,q_2)}{f(x_2,\mu_F)}
\end{array}\right\} = \boxed{\dfrac{d\sigma^{P.S.}_{HJJ}}{\left[d\sigma^{P.S.}_{HJJ}\right]_{LO}}}$$

Example: H+2 jets MiNLO at leading order with a big brush

$$d\sigma^{LO}_{HJJ} = dx_1\, dx_2\, d\Phi_{HJJ}\, f_{h_1}(x_1,\mu_F)\, f_{h_2}(x_2,\mu_F)\, \frac{1}{2\hat{s}}\, M(\Phi_{HJJ},\mu_R)$$

$$d\sigma^{MiLO}_{HJJ} \equiv d\sigma^{LO}_{HJJ} \times \frac{d\sigma^{P.S.}_{HJJ}}{\left[d\sigma^{P.S.}_{HJJ}\right]_{LO}}$$

$$\frac{\alpha_s(q_2)}{\alpha_s(\mu)} \cdot \frac{\alpha_s(q_1)}{\alpha_s(\mu)} \cdot \frac{\alpha_s^2(q_m)}{\alpha_s^2(\mu)}$$

$$= d\sigma^{LO}_{HJJ} \times \frac{\Delta_g(q_m\,;\,q_2)}{\Delta_g(q_2\,;\,q_2)} \cdot \ldots\ldots \cdot \frac{\Delta_g(q_1\,;\,q_2)}{\Delta_g(q_2\,;\,q_2)}$$

$$\frac{f(x_1,q_2)}{f(x_1,\mu_F)} \cdot \frac{f(x_2,q_2)}{f(x_2,\mu_F)}$$

Example: H+2 jets MiNLO at next-to-leading order

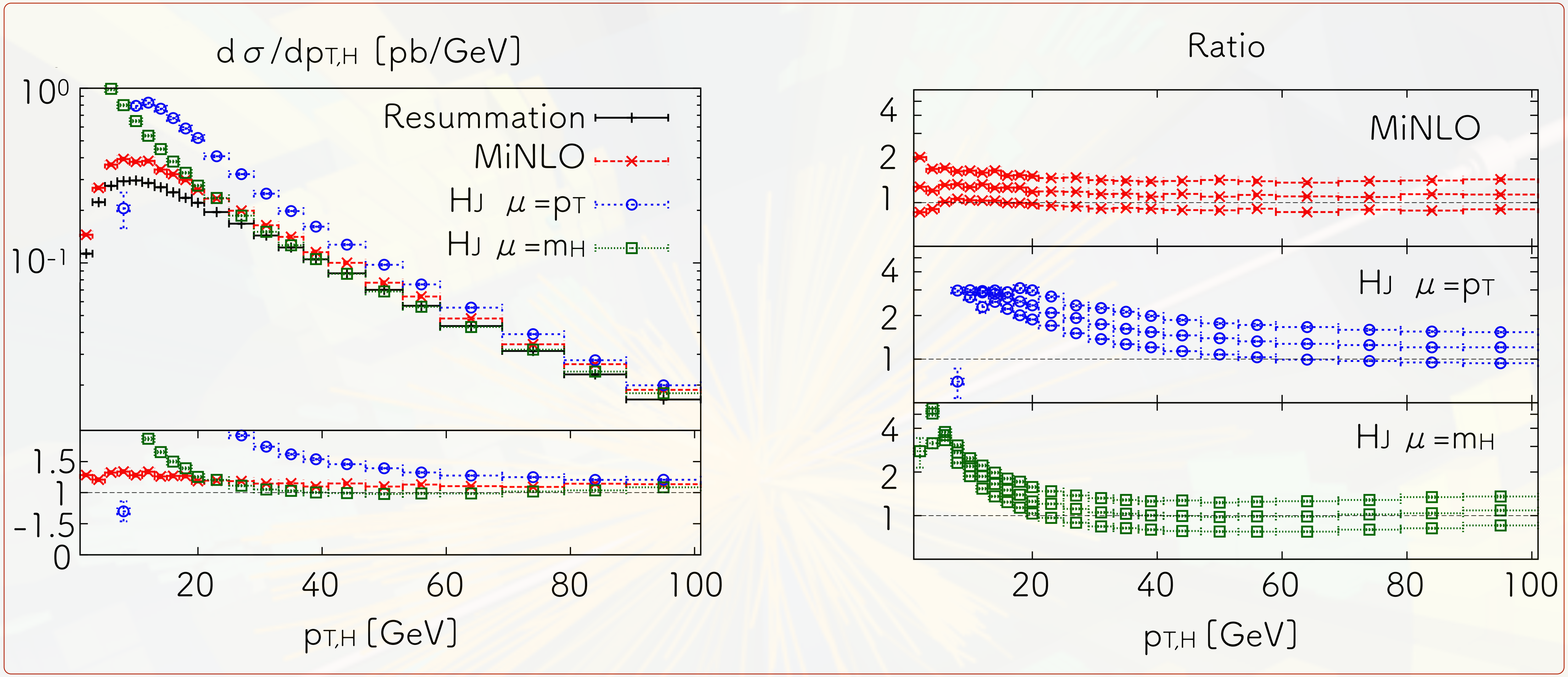
- To extend from LO `MiLO' example to NLO apply the same all orders shower corr^{n}s to the conventional NLO HJJ computation

$$d\sigma_{HJJ}^{MiNLO} \equiv d\sigma_{HJJ}^{NLO} \times \frac{d\sigma_{HJJ}^{P.S.}}{\left[d\sigma_{HJJ}^{P.S.}\right]_{LO}}$$

$$- \, d\sigma_{HJJX}^{LO} \times \left[\frac{d\sigma_{HJJ}^{P.S.}}{\left[d\sigma_{HJJ}^{P.S.}\right]_{LO}}\right]_{\alpha_s\text{-term only}} \times \frac{d\sigma_{HJJ}^{P.S.}}{\left[d\sigma_{HJJ}^{P.S.}\right]_{LO}}$$

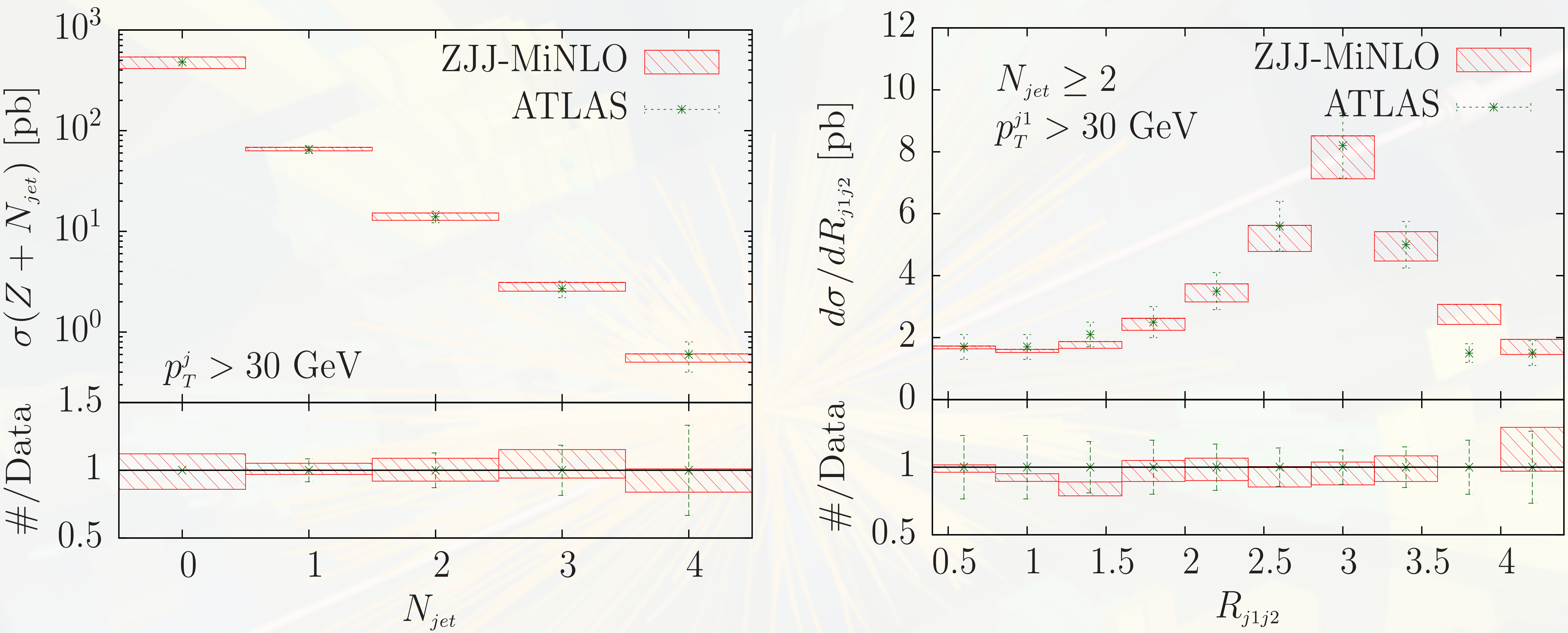
- And subtract a term to render the expansion in α_s unchanged to NLO

Application: H+1 jet MiNLO at next-to-leading order



- Resummation matched to NLO inclusive gg → H xsec^n [≡ 1 in ratios]
- HJ RUN: NLO H + 1 jet with $\mu_R = \mu_F = p_{T,H}$
- HJ FXD: NLO H + 1 jet with $\mu_R = \mu_F = M_H$
- HJ-MiNLO → conventional NLO H + 1 jet at high p_T
- HJ-MiNLO → resummation result at low p_T
- HJ-MiNLO → sensible scale unc. band [doesn't shrink as $p_T \to 0$]

Application: Z+2 jet MiNLO ⊕ Pythia vs ATLAS



- Left: improves Z + 2 NLO s.t. gives even predict^n for ≥ 0 jet evts!
- Right: NLO accuracy retained [& improved] for ≥ 2 jet events
- Equally nice improvement & agreement for ATLAS W+jets data

[Campbell, Ellis, Nason, Zanderighi]

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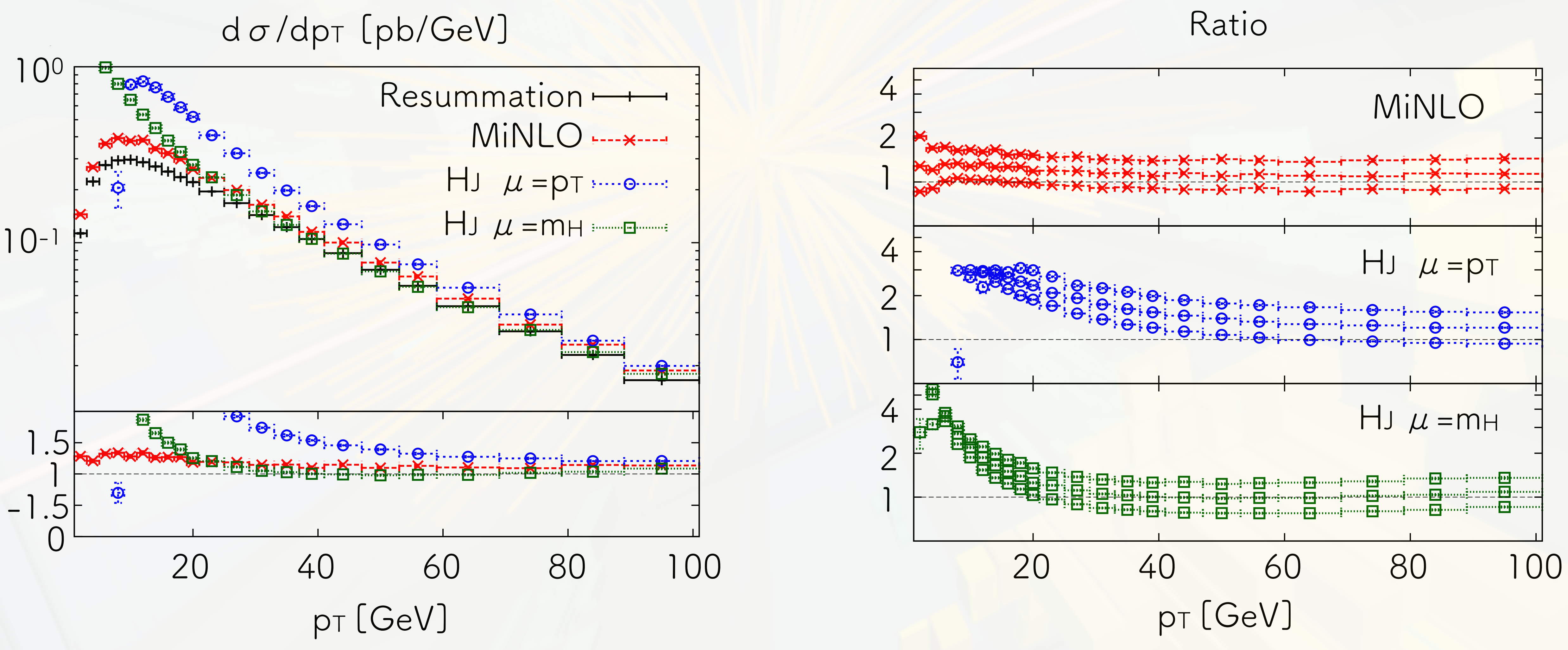
MiNLO′ for H+1-jet

- MiNLO matches fully differential NLO to LL [NLL$_\sigma$] resummation
- MiNLO finite in all ph.space: no need of gen. cuts



Question: what's MiNLO accuracy for inclusive quantities?

MiNLO′ for H+1-jet

- H+1-jet spectrum known analytically to high accuracy
- Allows to determine Sudakov s.t. H+1-jet is NLO for H+0-jet

MiNLO → MiNLO′

$$\Delta(Q, p_{\mathrm{T}}) \to \Delta'(Q, p_{\mathrm{T}}) = \Delta(Q, p_{\mathrm{T}})\, \delta\Delta(Q, p_{\mathrm{T}})$$

$$\delta\Delta(Q, p_{\mathrm{T}}) = \exp\left[\int_0^L dL'\, \bar{\alpha}_{\mathrm{S}}^2(p'_{\mathrm{T}}) \left[\widetilde{R}_{21}\, L' + \widetilde{R}_{20} - \bar{\beta}_0 \mathcal{H}_1\right]\right]$$

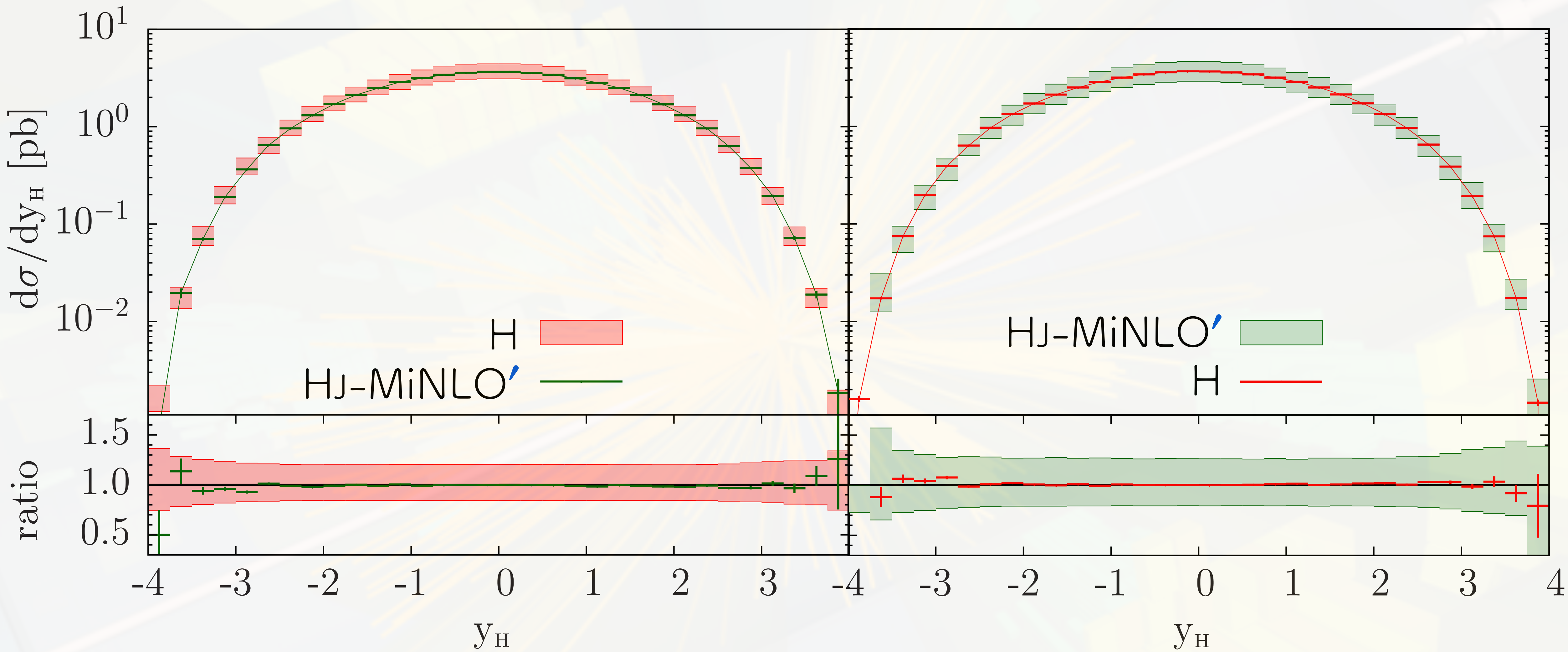
$$\frac{d\sigma'_{\mathcal{M}}}{d\Phi} = \int_L \frac{d\sigma'_{\mathcal{R}}}{d\Phi dL} + \int_L \frac{d\sigma_{\mathcal{F}}}{d\Phi dL} = \frac{d\sigma_{\mathrm{NLO}}}{d\Phi}$$

- MiNLO′ simultaneously NLO for H & H+1-jet prod^n

MiNLO′ for H+1-jet

[Nason, Oleari, Zanderighi, KH]

- Higgs rapidity



- Conventional NLO H prod^n: red
- MiNLO′ H+1-jet+parton shower: green
- Agree with each other ~ to within the line thickness

Summary

- Conventional scale setting in complex processes subject to large ambiguities, and lacking physical justifications

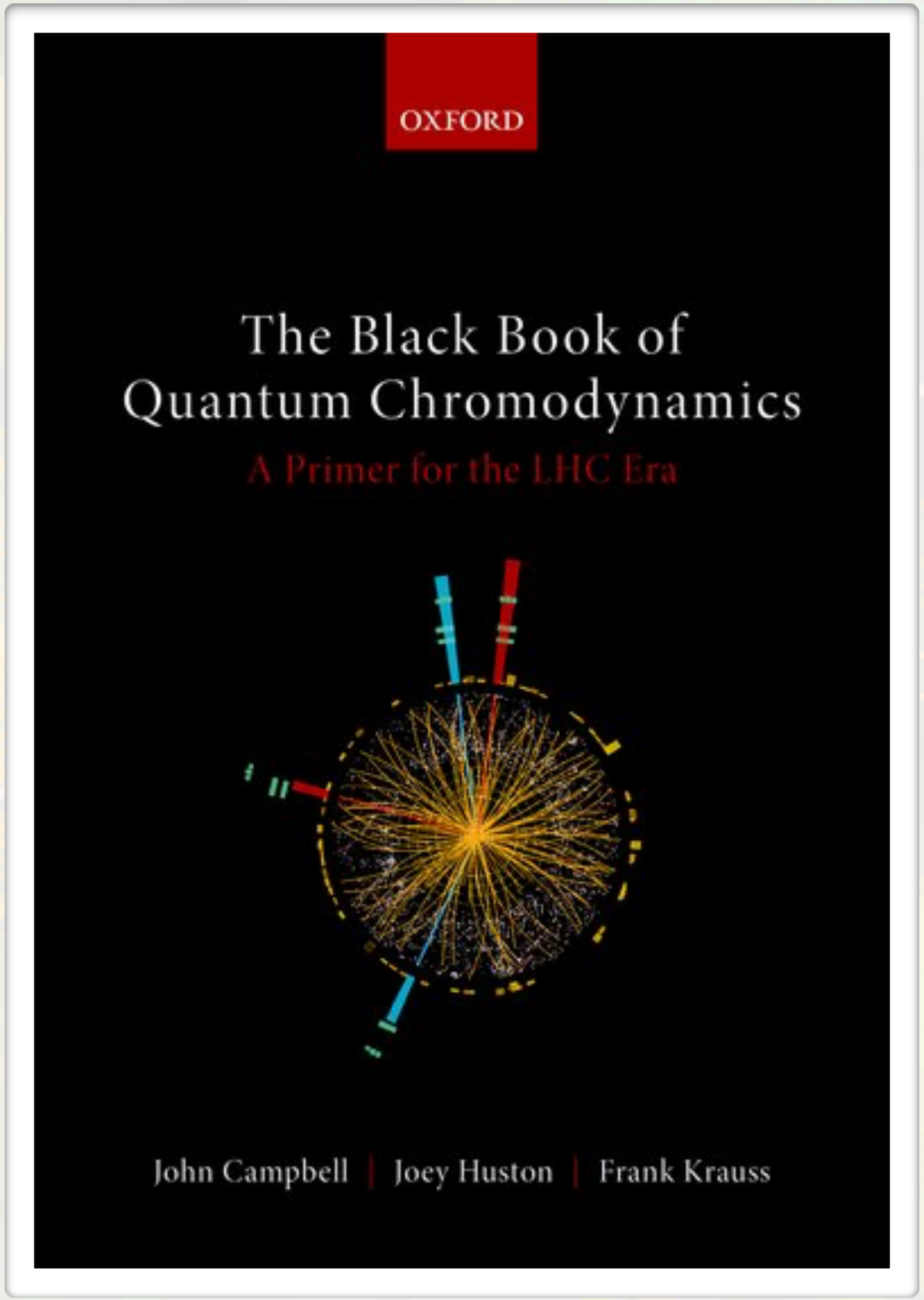
- MiNLO is a physically well motivated scale setting for processes with jets: identifies all important scales, treats all coherently

- MiNLO taken up by independent groups: applied in complex processes, used in new NLO merging schemes [e.g. FxFx]

- MiNLO′ = NLO x NLO calc^{n}s w.o. merging scales

- MiNLO′ extended to (N)NLO x NLO x NLO accuracy in H+2 jets

Messages



MiNLO pgs. 394 - 398

Thank you Paolo