IR-safe flavoured jet algorithms for the precision era

LoopFest XXI, SLAC, June 27 2023

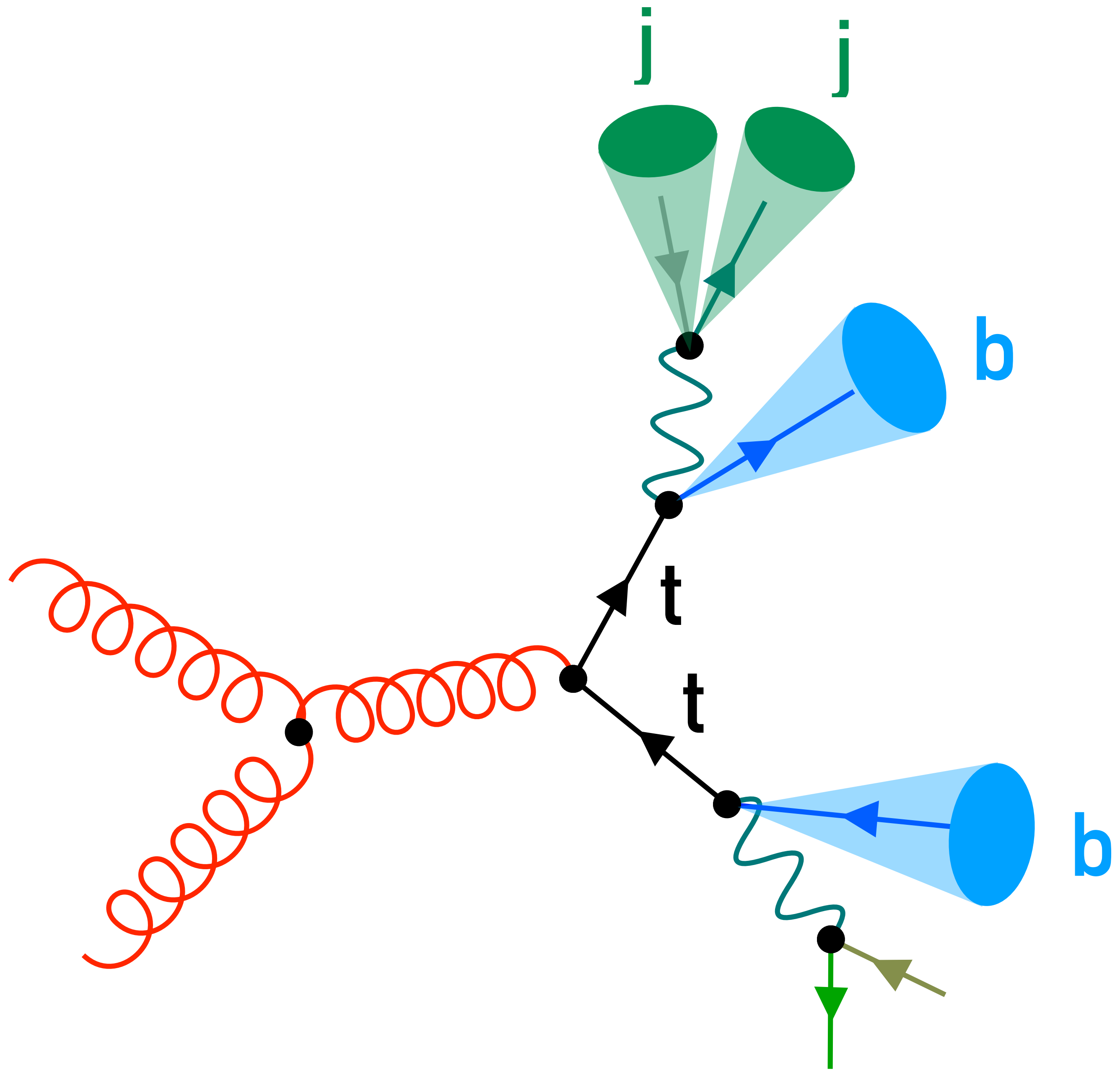
UNIVERSITY OF OXFORD

Fabrizio Caola, with R. Grabarczyk, M. Hutt, G. Salam, L. Scyboz and J. Thaler, arXiv:2306.07314

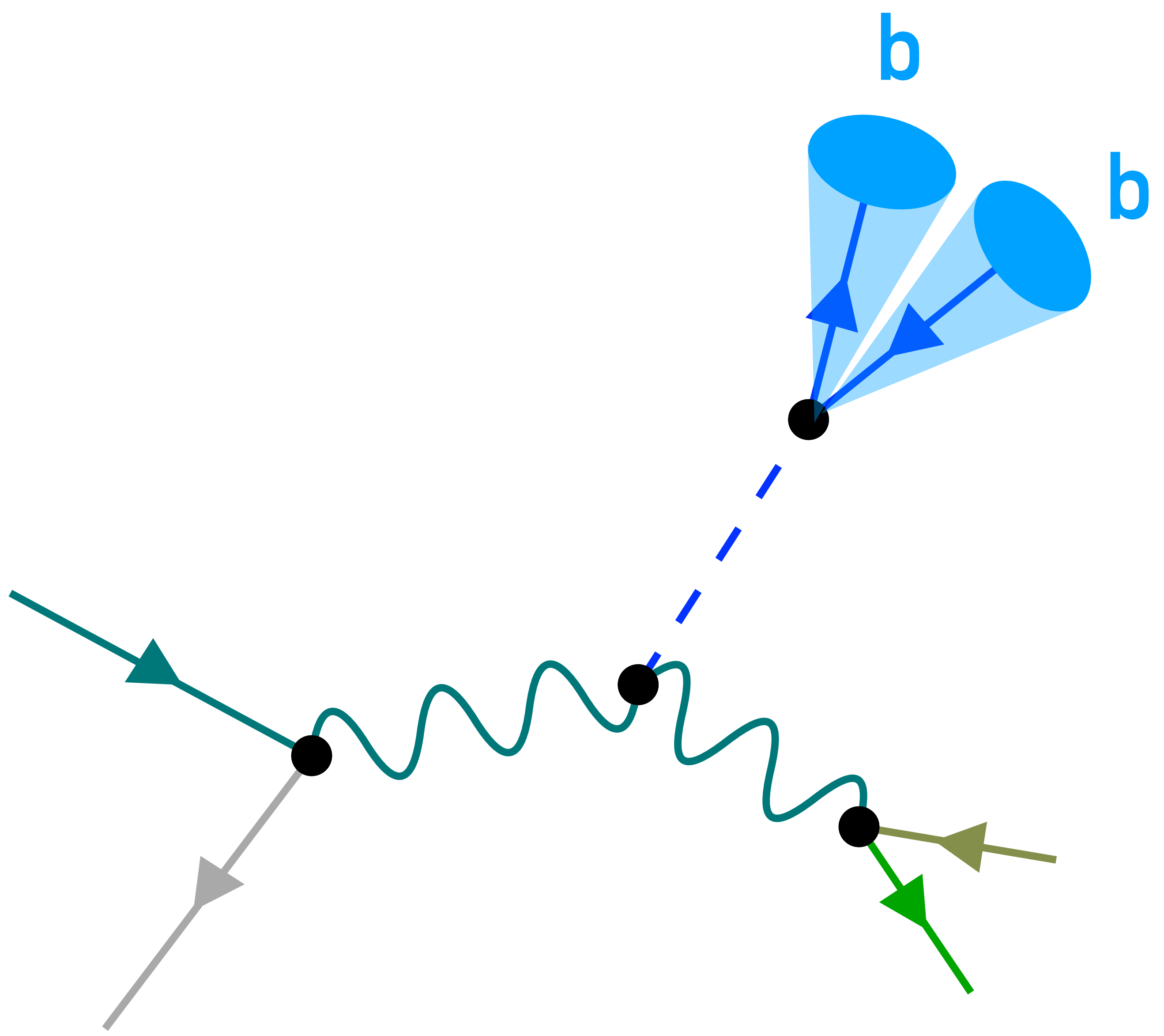
Rudolf Peierls Centre for Theoretical Physics & Wadham College

Tracking the flavour of a jet: more and more important

Top, ttH, ttV, …



VH, HH,
H→bb



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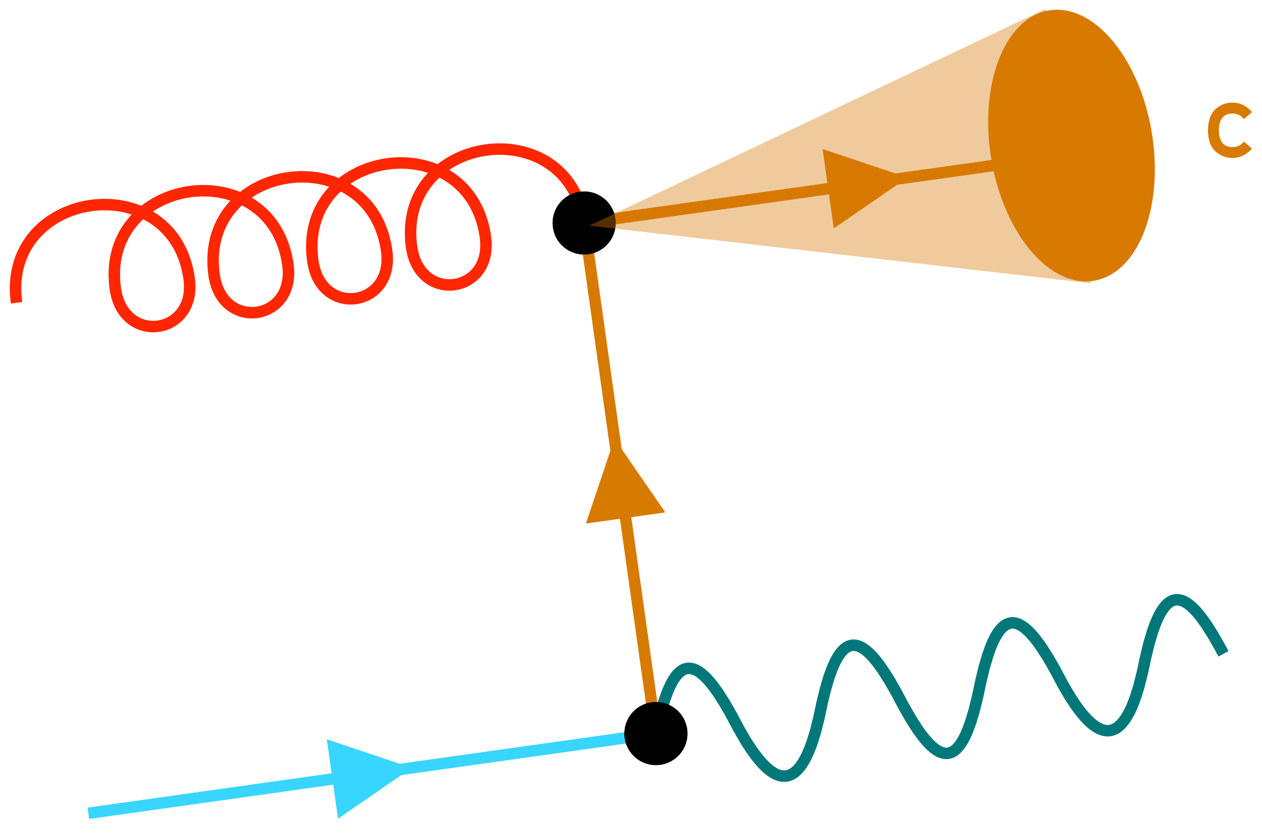


Quark/gluon discrimination, substructure…

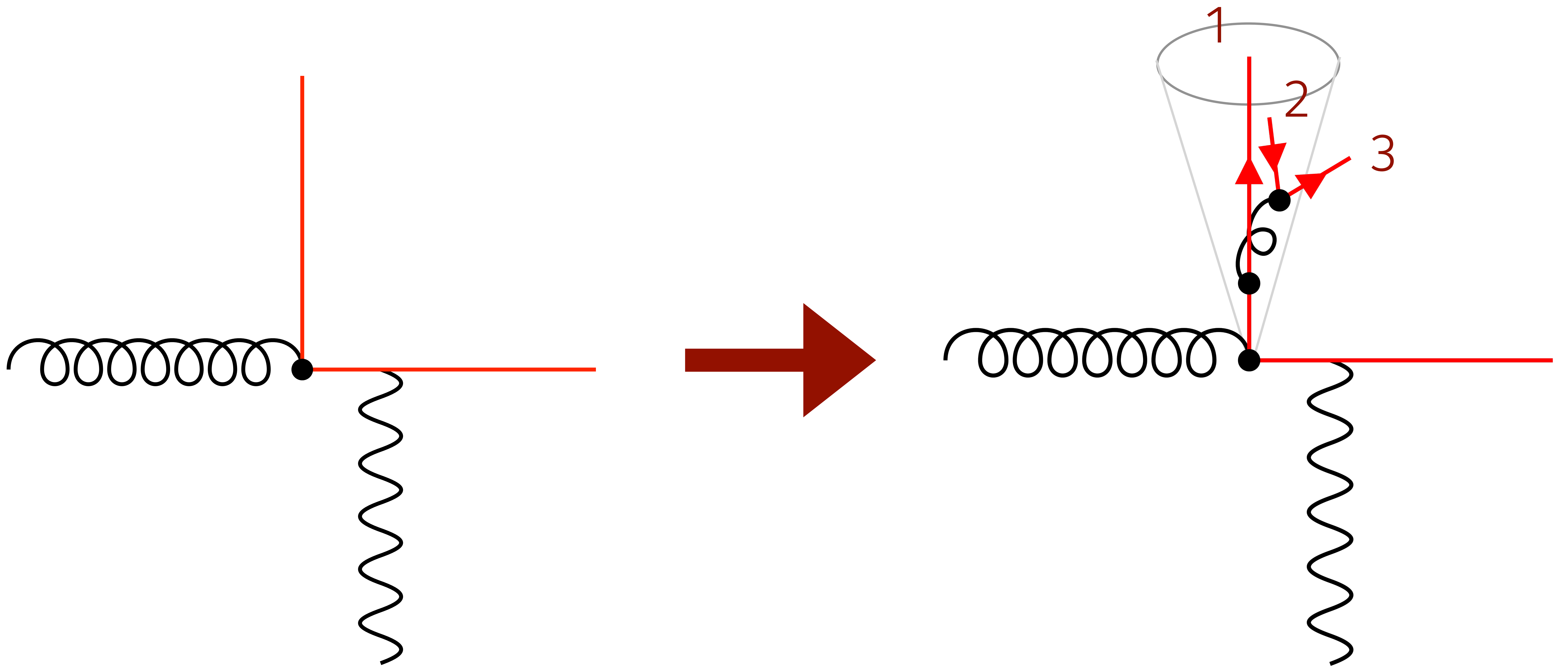
- More and more precise measurements
- More and more accurate predictions
- Apple-to-apple comparison difficult without suitable definition of "jet flavour"

The problem of jet flavour: IR-unsafe at higher orders

- Experimentally: anti-k_t, b-tagging
- Theory:

$$d_{ij} = \min(p_{t,i}^{-2}, p_{t,j}^{-2})\frac{\Delta R_{ij}^2}{R^2} \qquad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

$$d_{iB} = p_{t,i}^{-2}$$



$\min(d_{ij}, d_{iB}) = d_{12}$

- Cluster 1+2
- $b + \bar{b} \rightarrow$ no flavour

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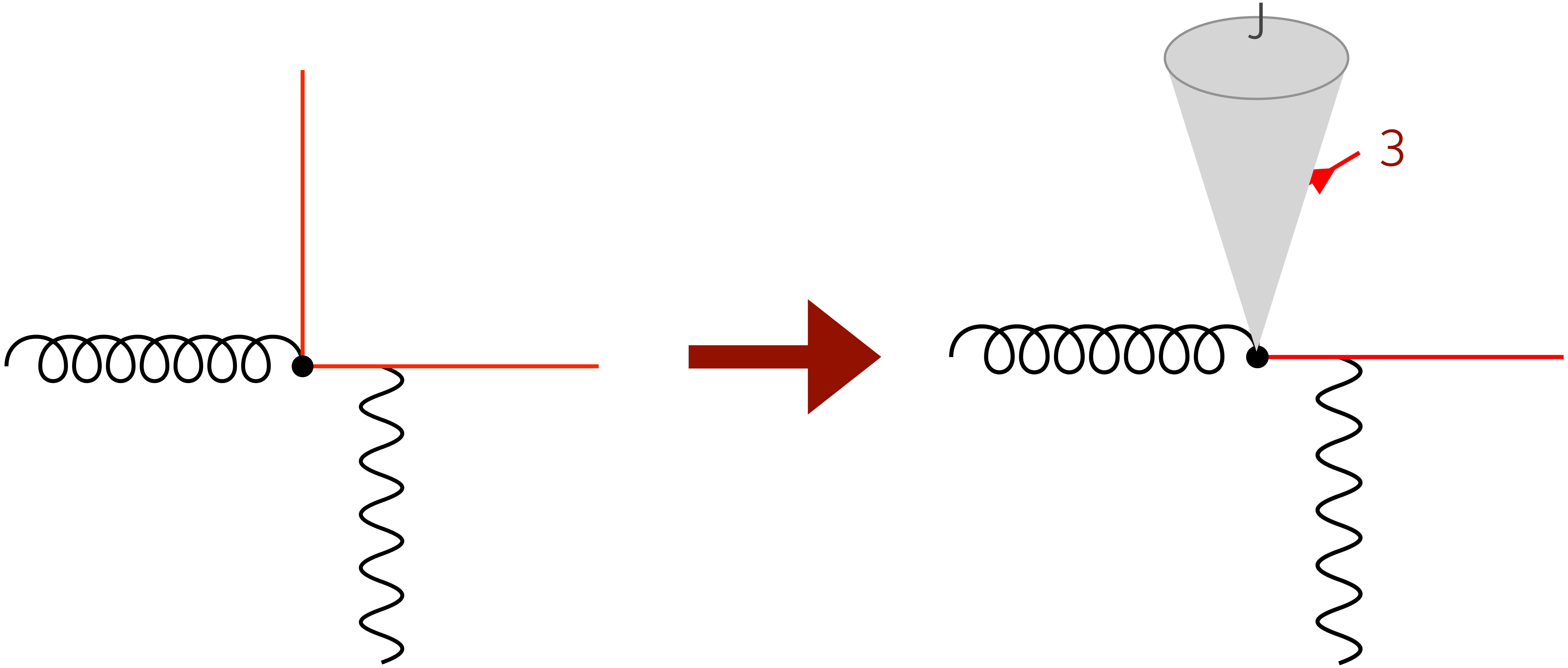

$$\min(d_{ij}, d_{iB}) = d_{jB}$$

- J and 3 jets
- 3: soft → removed by $p_{t,\min}$ requirement

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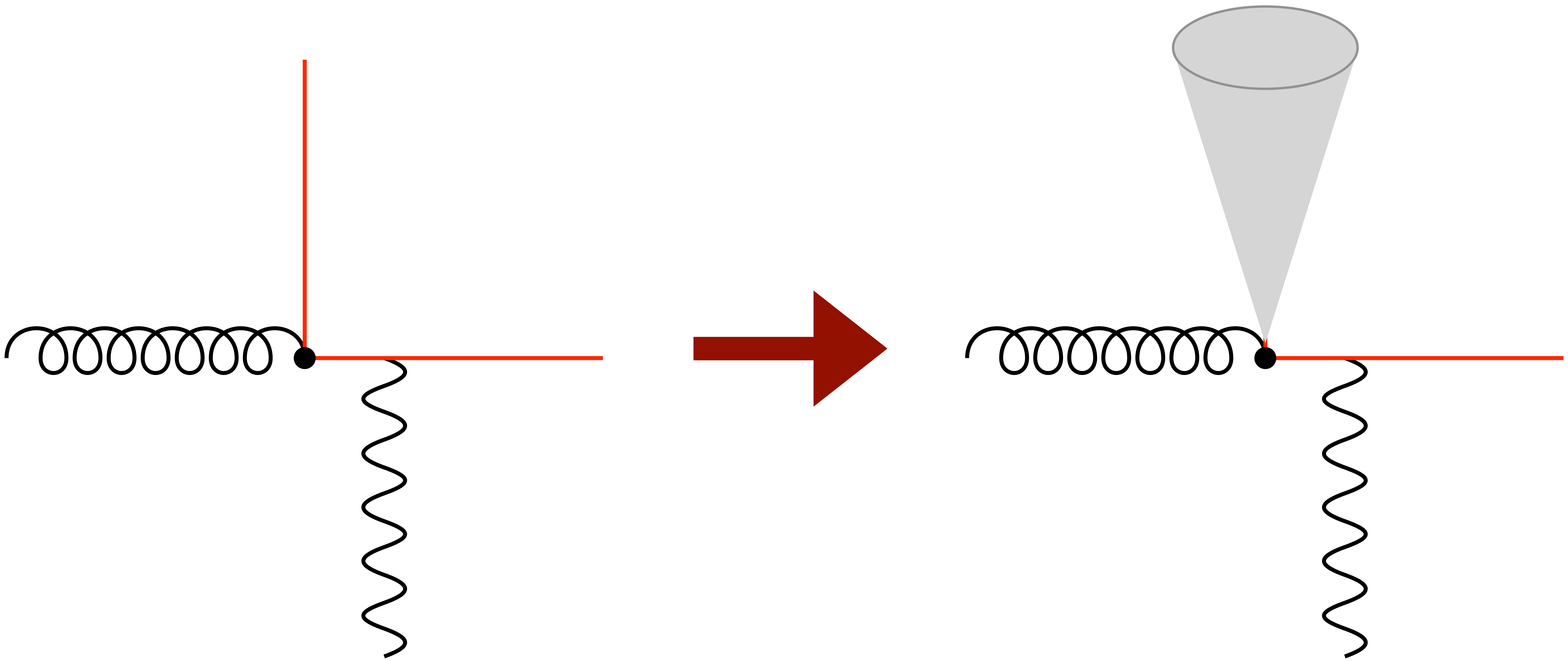

- Flavour contamination
- Log sensitivity to quark mass, $\ln(m_q/p_{t,j})$

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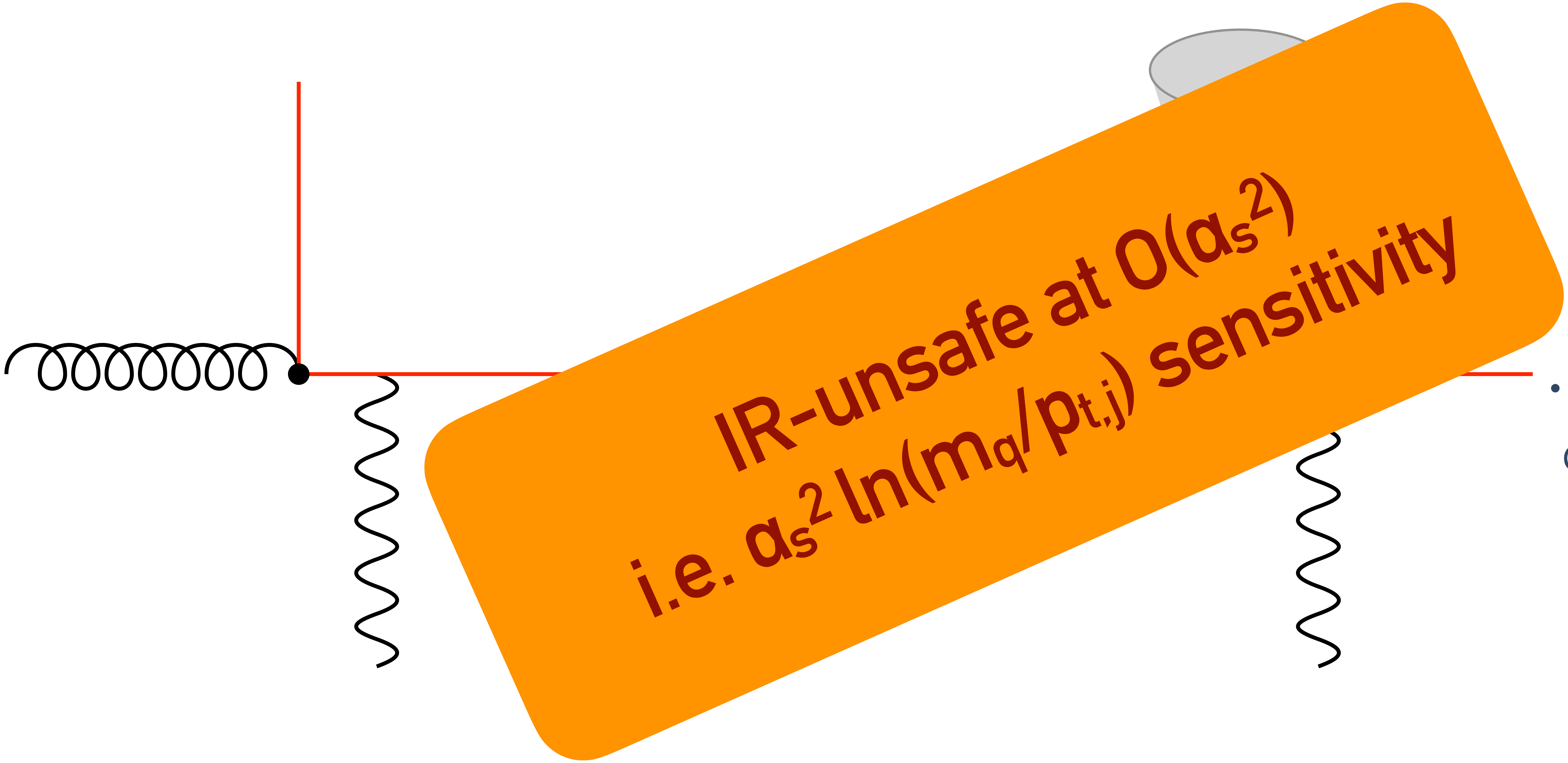


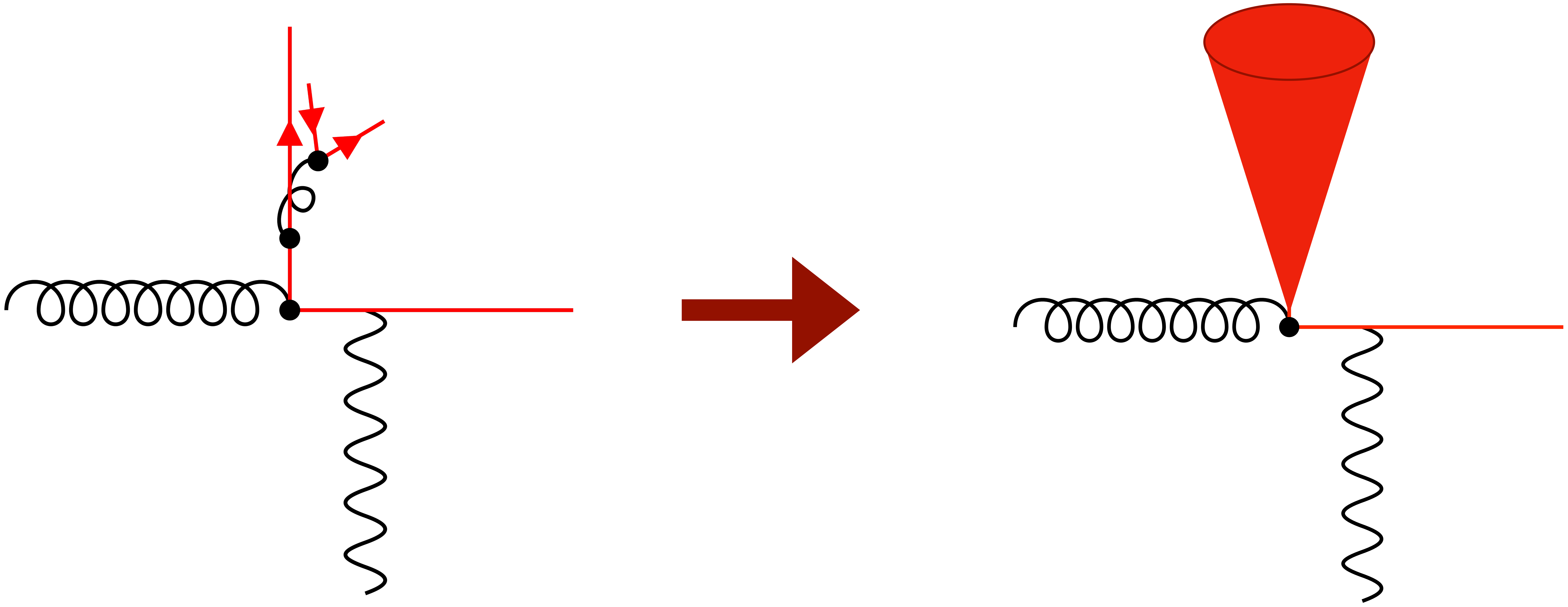
Flavour contamination

- Log sensitivity to quark mass, $\ln(m_q/p_{t,j})$

The “old” solution: flavour-k_t

Flavour-k_t [Banfi, Salam, Zanderighi (2006)]:

modify d_{ij}, d_{iB} to ensure that soft flavoured objects are clustered first



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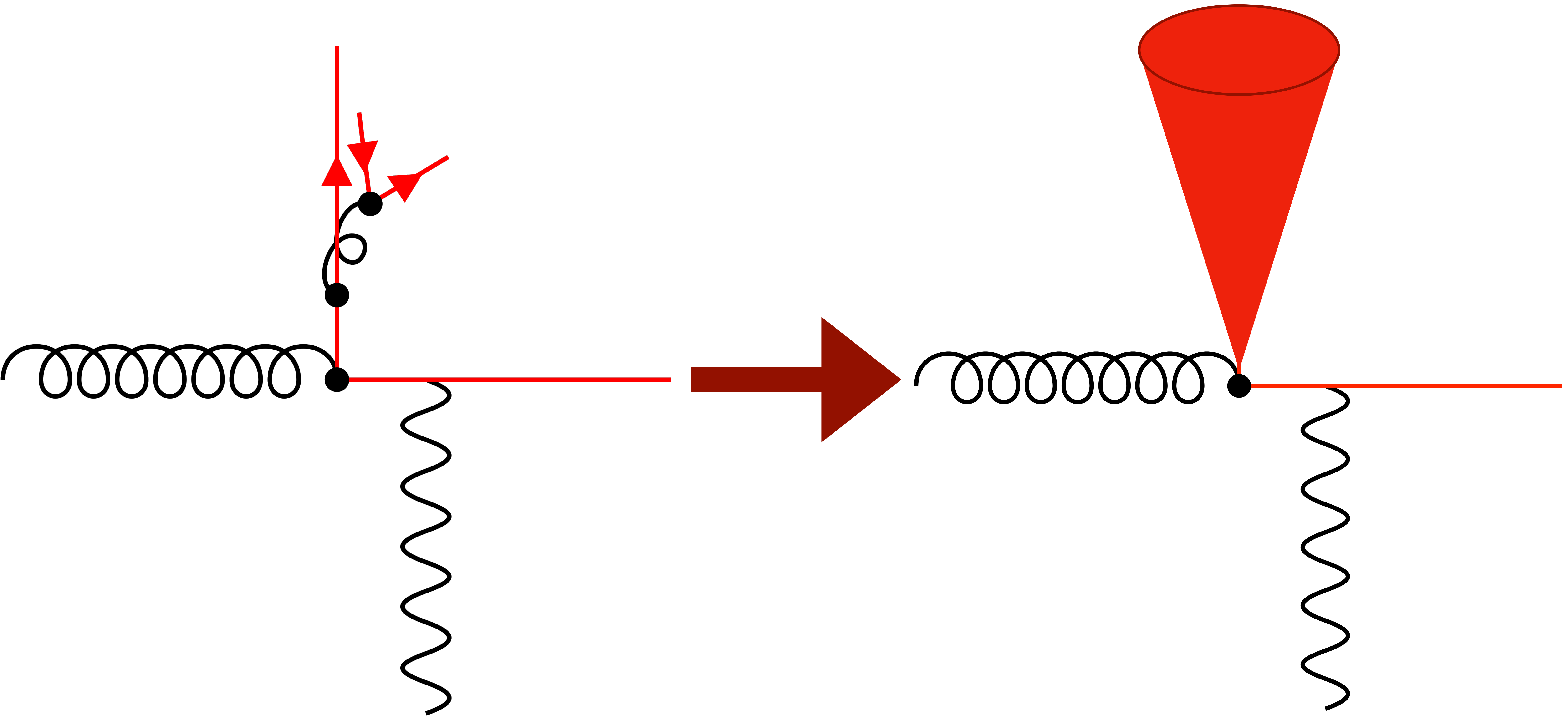
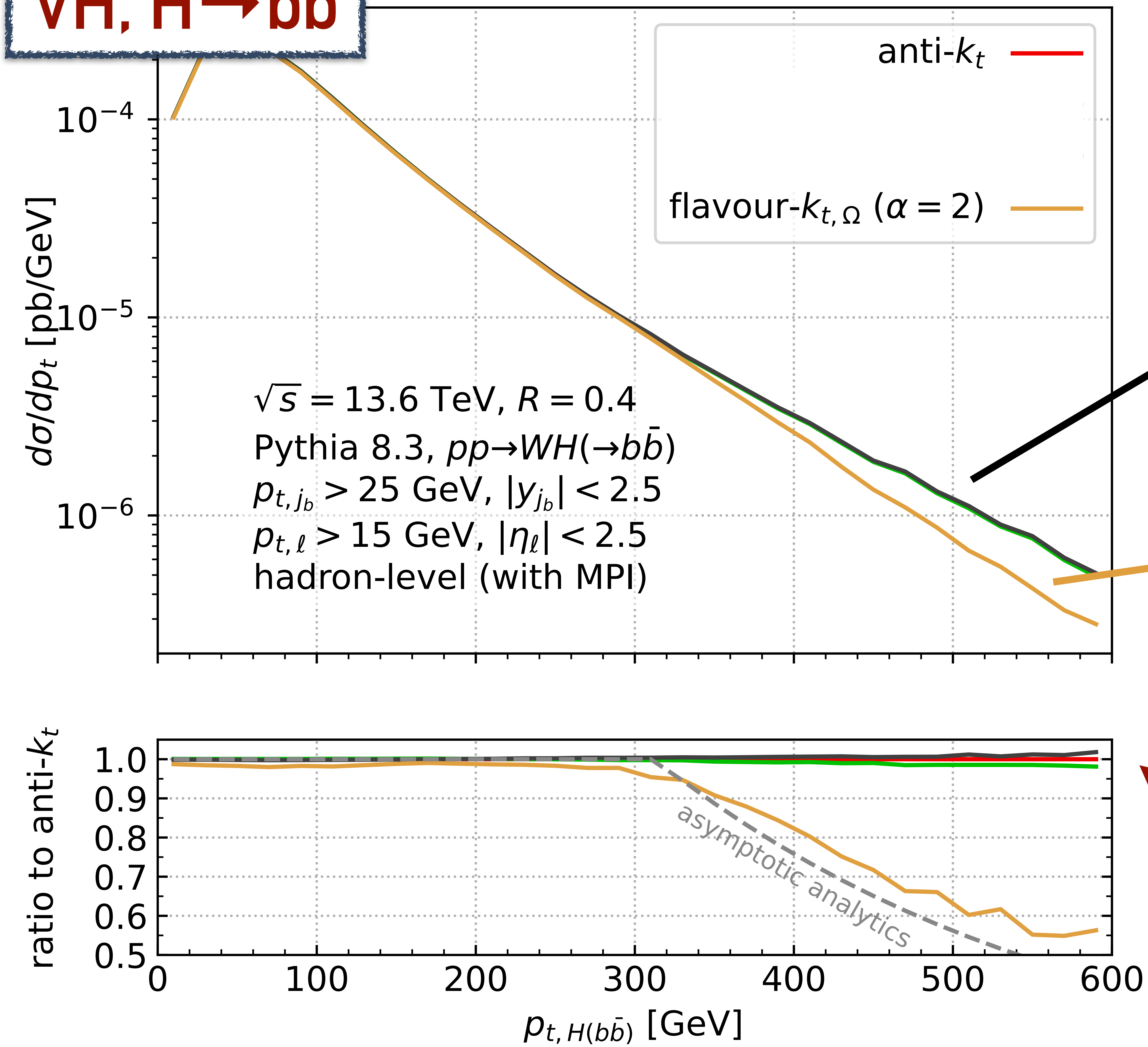


✔: remove the contamination

✘: different d_{ij} → different recombination → different kinematics w.r.t. anti-k_t!

The “old” solution: flavour-k_t

VH, H→bb



Reconstructed Higgs p_t, anti-k_t jets, b-tagging

Reconstructed Higgs p_t, Flavour-k_t

50% difference in the boosted region!

The "old" solution: flavour-k_t

Flavour-k_t ≠ anti-k_t

For a long time: flavour-k_t only option for higher-order (NNLO) calculations

↓

Precise calculations, but apples to oranges comparisons!

Recently: a flurry of activity

- Caletti, Larkoski, Marzani, Reichelt (2022): “Practical jet flavour through NNLO”

  Fix the problem at NNLO, ignoring higher-order issues

- Czakon, Mitov, Poncelet [CMP] (2022): “Infrared-safe anti-k_t jets”

  All-orders, modify the anti-k_t distance, but only close to “dangerous” configurations → similar kinematics to anti-k_t

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What are the features of an ideal flavoured-jet algorithm?

Flavoured-jet algorithms: wish-list

A good jet flavour algorithm should:

- allow for reliable data-theory comparisons, at high precision → exact anti-k_t kinematics
  - *Flavour-k_t: ✘*
  - *CMP: ~*
  - *GHS: ✔*
- allow for reliable jet substructure studies → track the flavour along the clustering sequence, Cambridge/Aachen
- be IR-safe to all-orders

Achieving this is more difficult than it may sound

Our proposal: Interleaved Flavour Neutralisation (IFN)

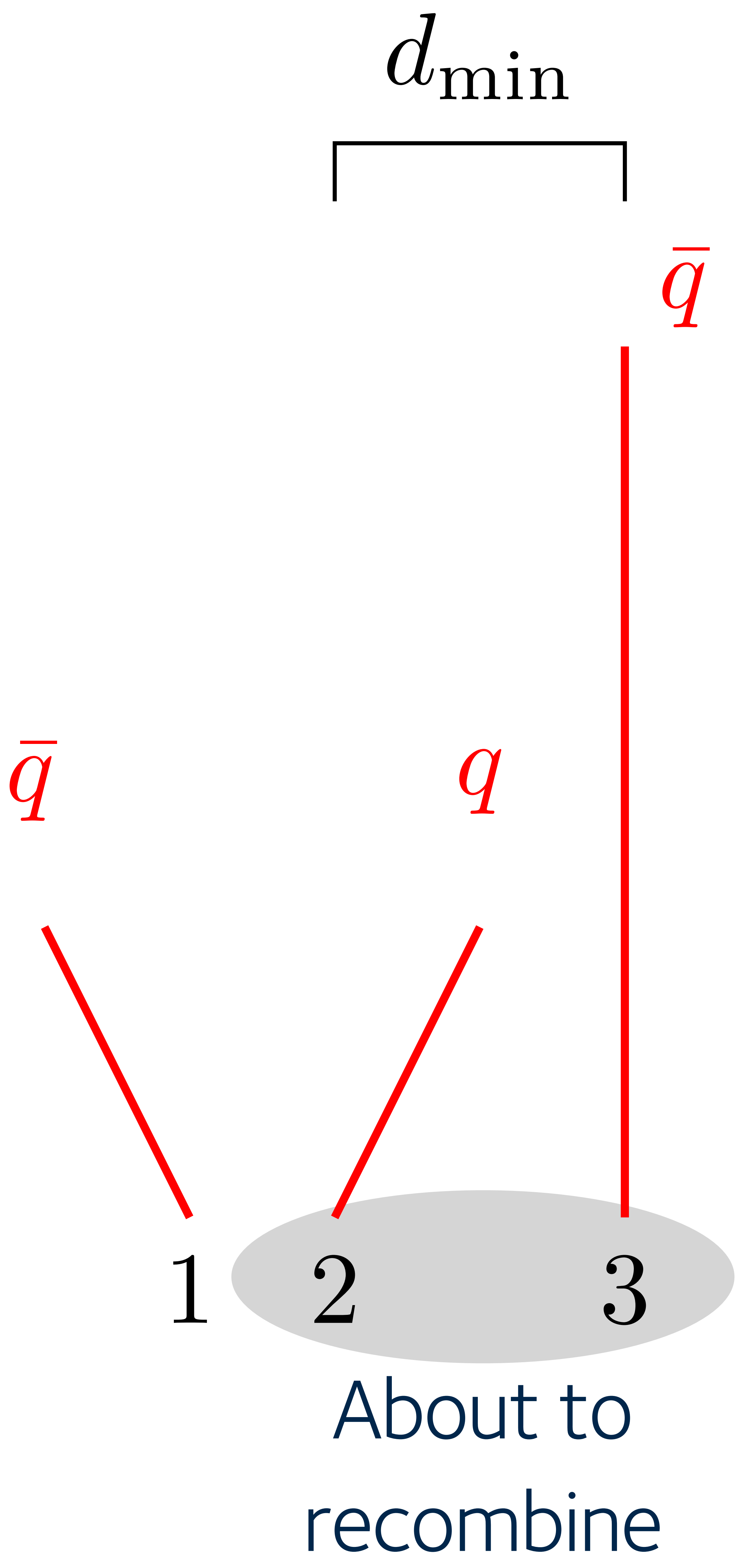
The main idea:

keep the standard clustering procedure (anti-k_t, C/A), but modify flavour-recombination at each step of the clustering sequence

By construction then:

- same identical kinematics of anti-k_t, C/A
- at each stage of the recombination: IR-safe (sub)-jets → substructure friendly

Integrated Flavour Neutralisation (IFN): a cartoon



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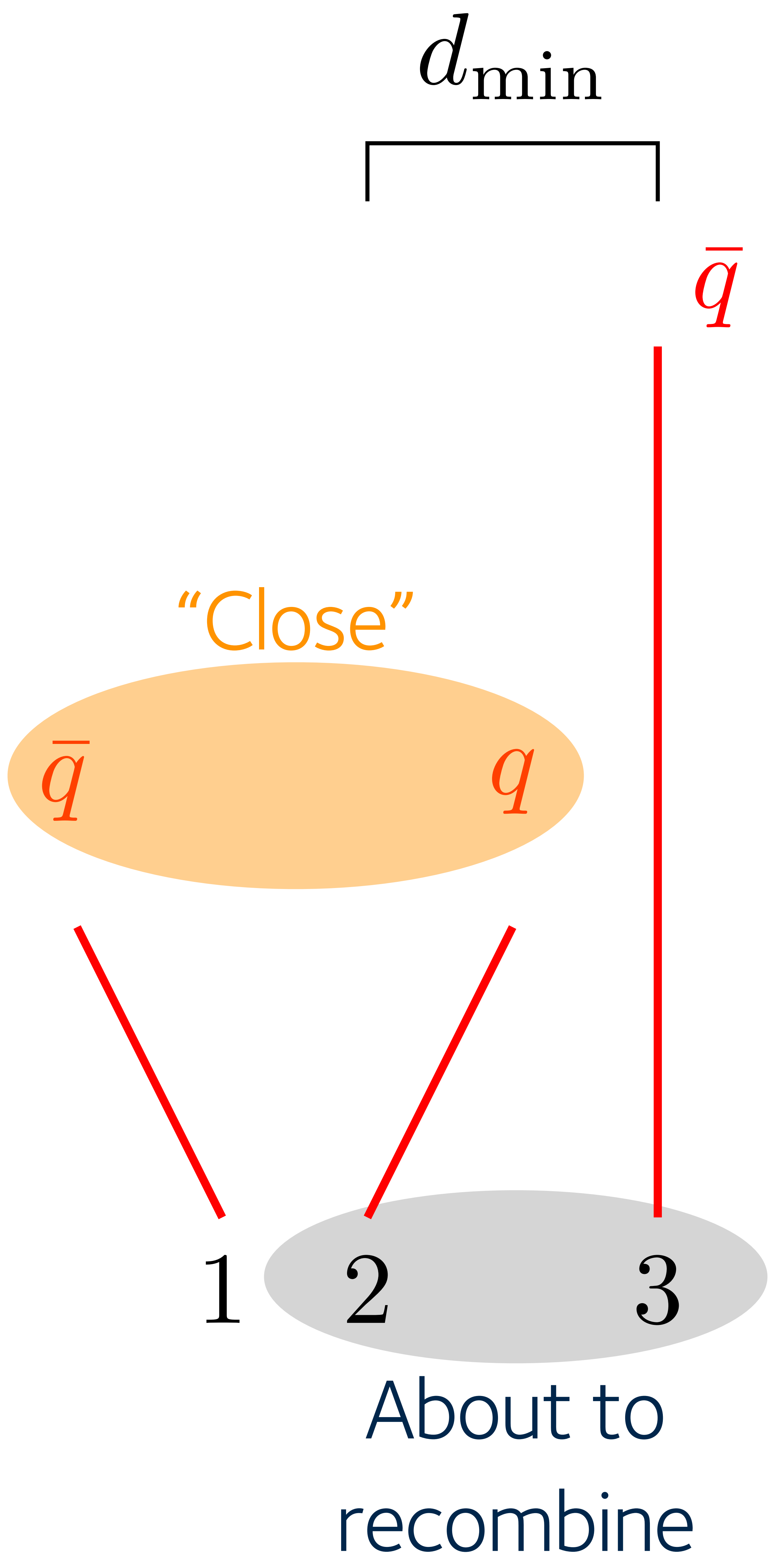

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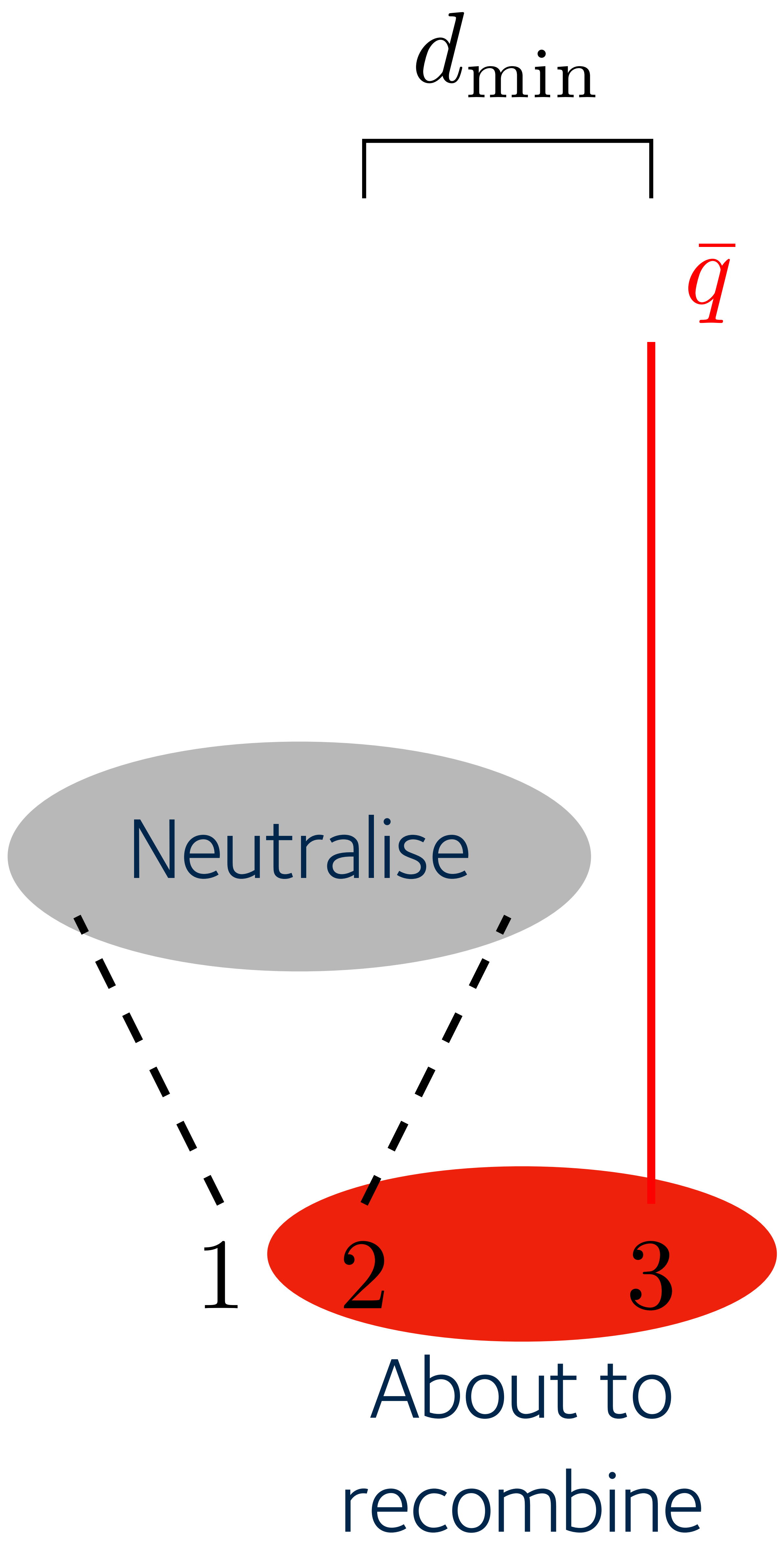

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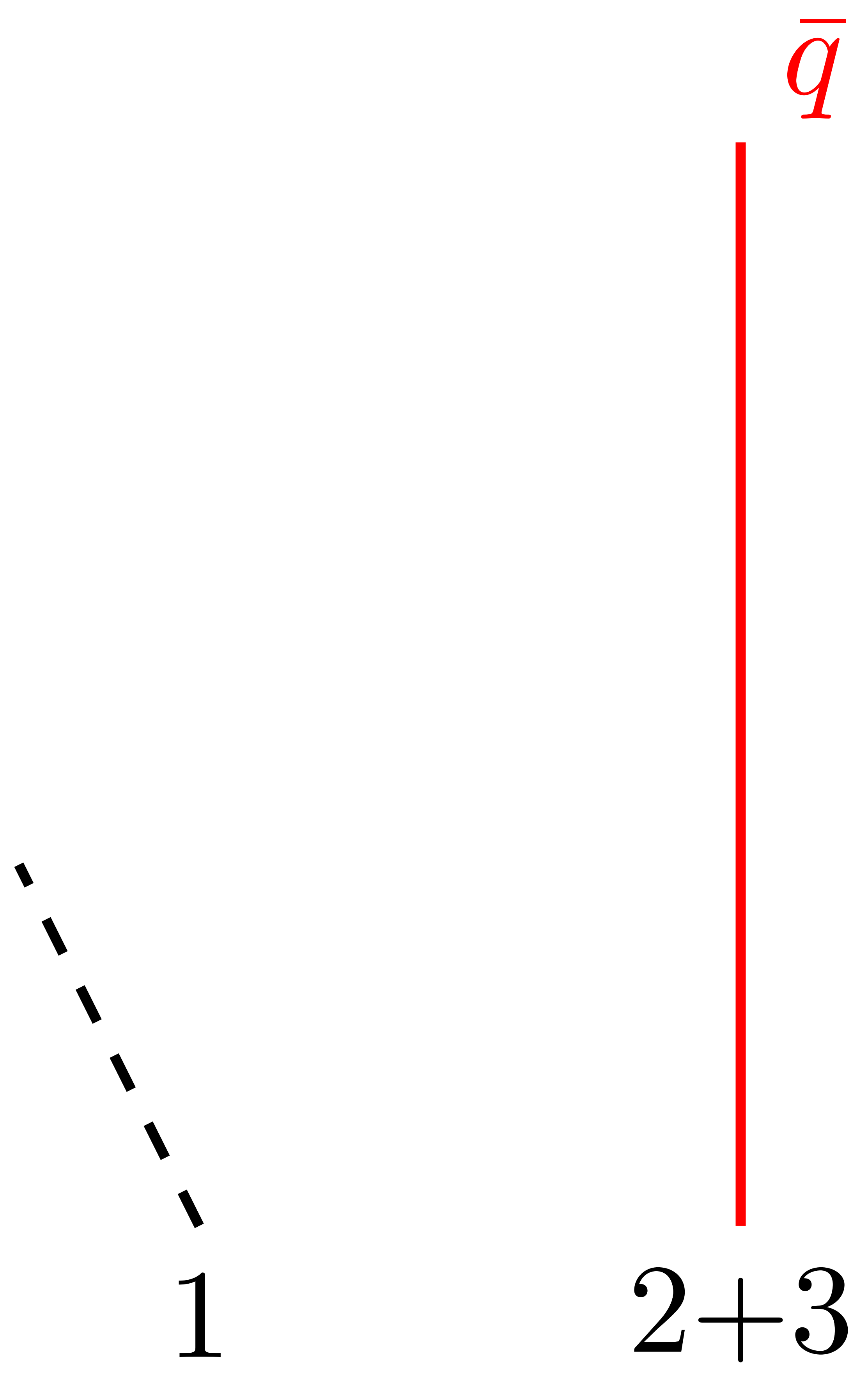

- soft flavoured object (2) about to kinematically recombined per (anti-k_t/CA...) → trigger a "flavour neutralisation" search
- look globally in the event for objects that should neutralise → identify 1
- neutralise 1 and 2, then recombine
- Flavoured jets with anti-k_t/CA kinematics

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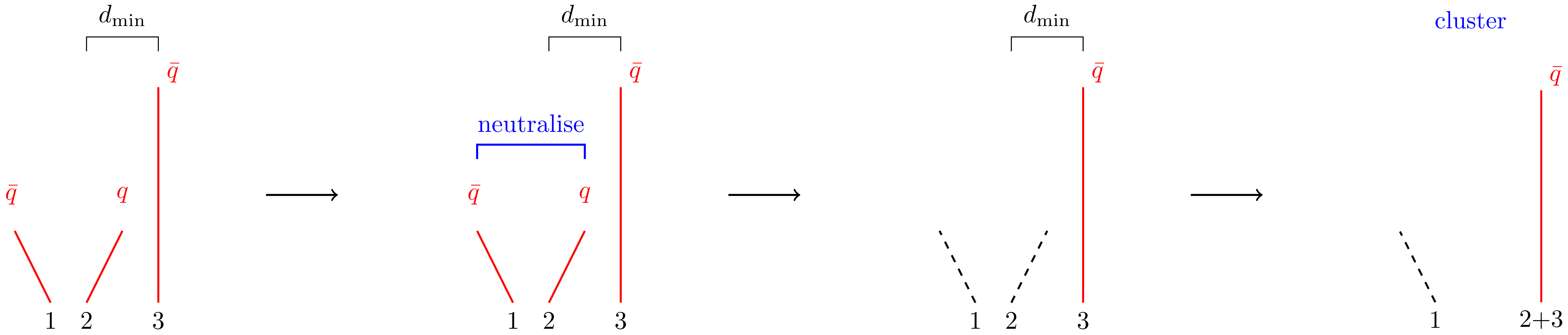

Flavoured jets with anti-k_t/CA kinematics

Crucial for IR-safety + good behaviour

- proper choice of a "flavour distance"
- making sure neutralising partner is not "stolen" from more suitable candidate (→recursion)

Integrated Flavour Neutralisation (IFN): a cartoon

The neutralisation distance

$$u_{ik} \equiv [\max(p_{ti}, p_{tk})]^{\alpha} [\min(p_{ti}, p_{tk})]^{2-\alpha} \times \Omega^2_{ik} \, ,$$

~ flavour-k_t, soft objects are close

Angular distance.

Critical: able to compare objects event-wide → far apart

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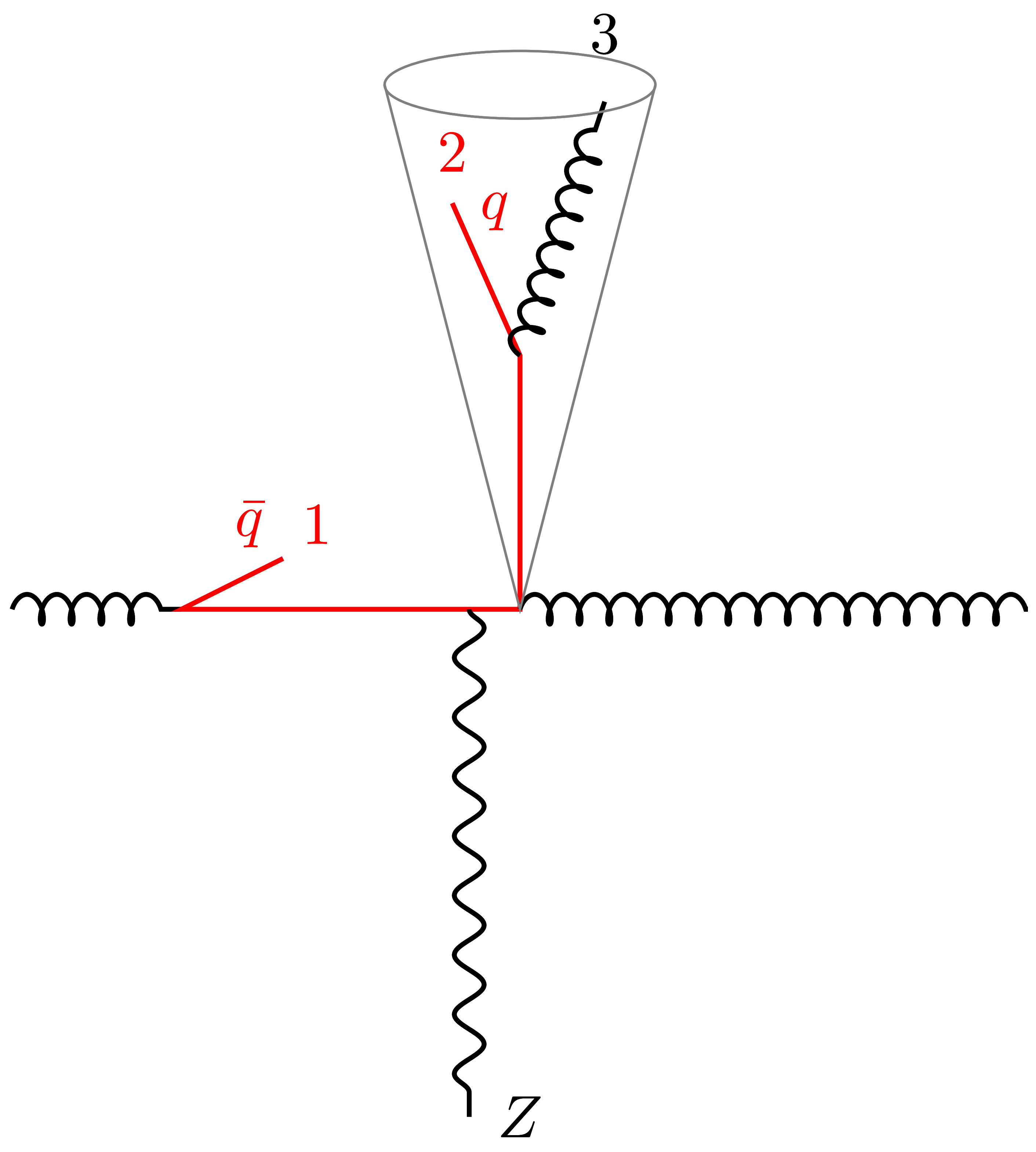

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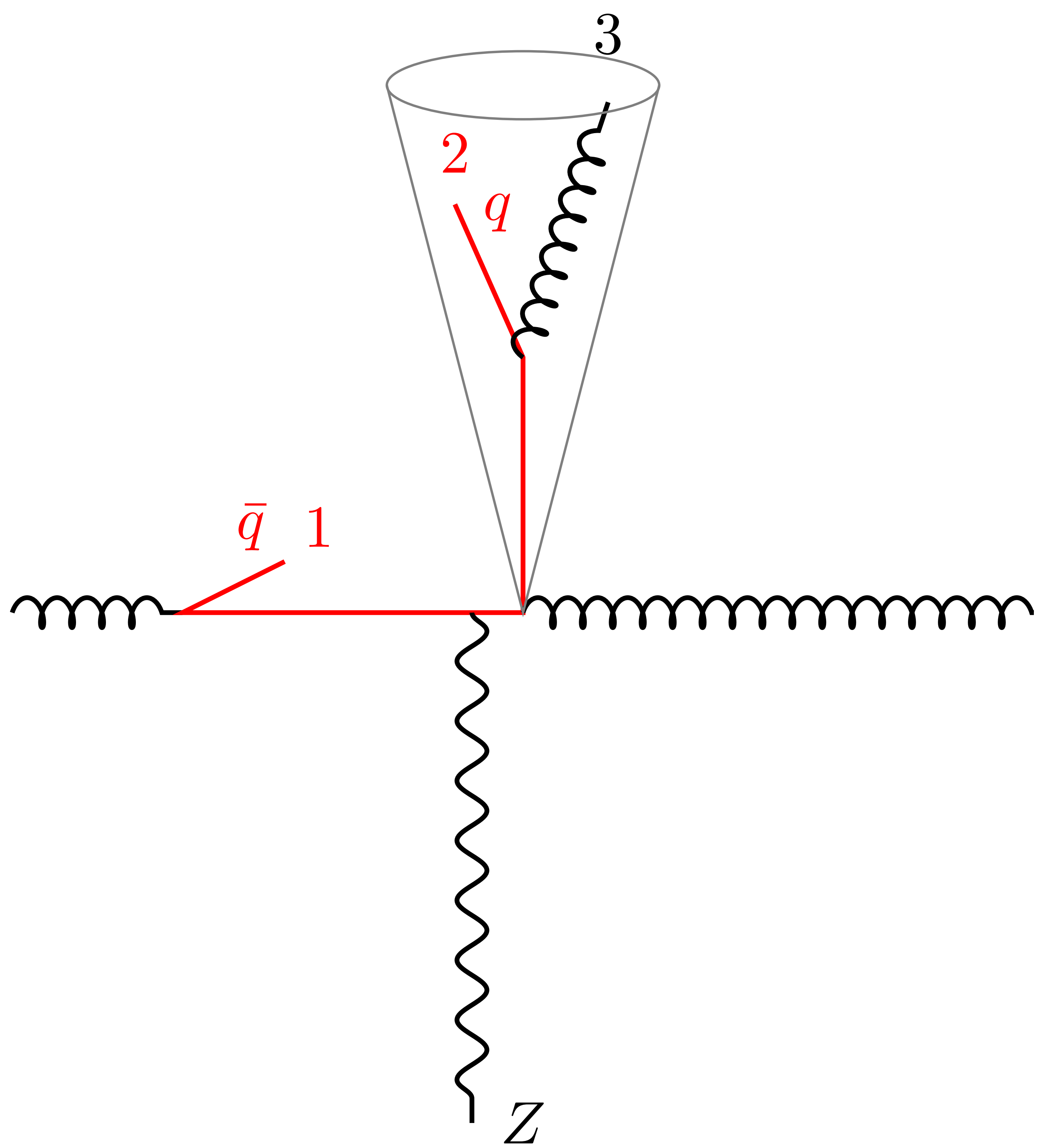
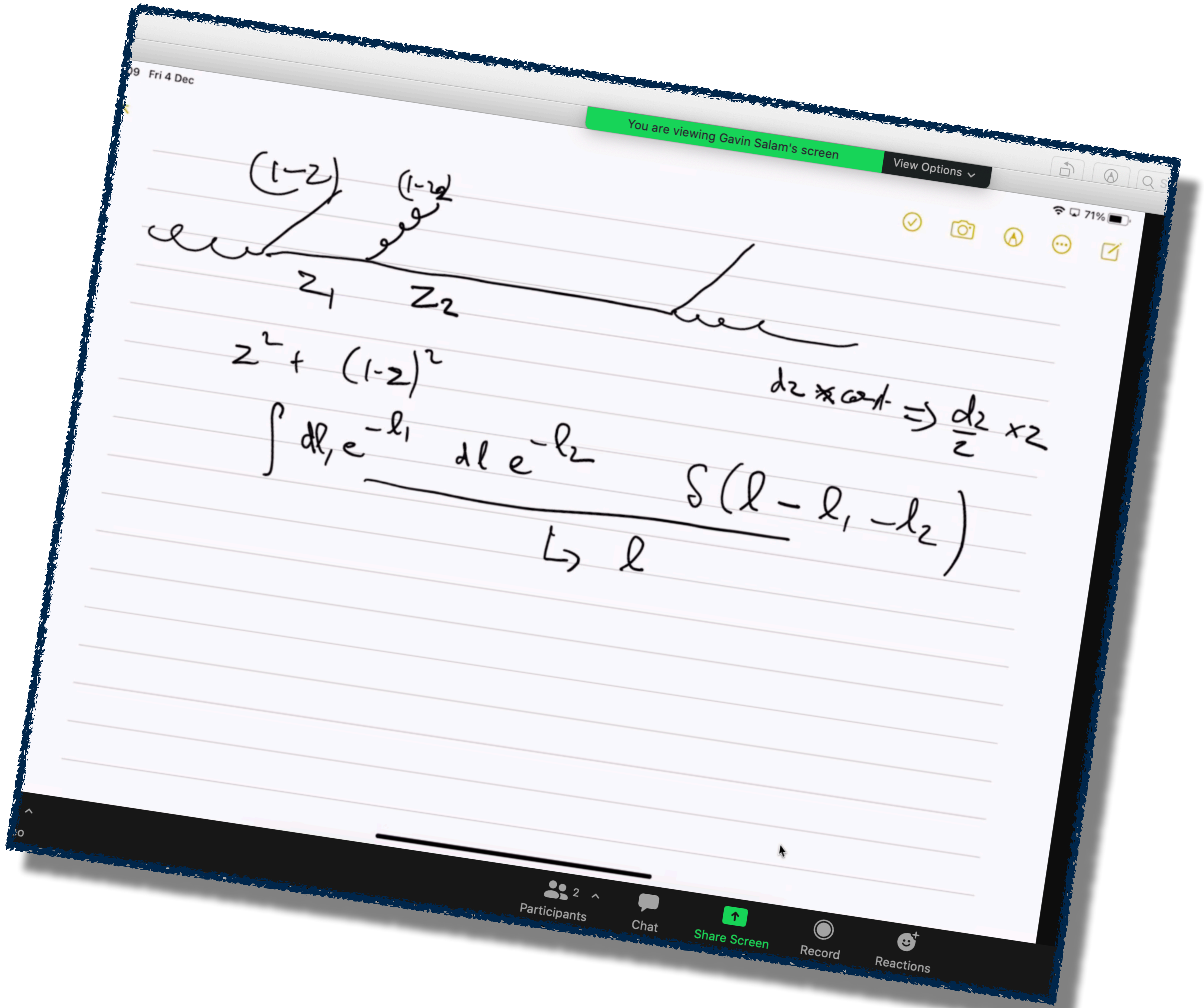


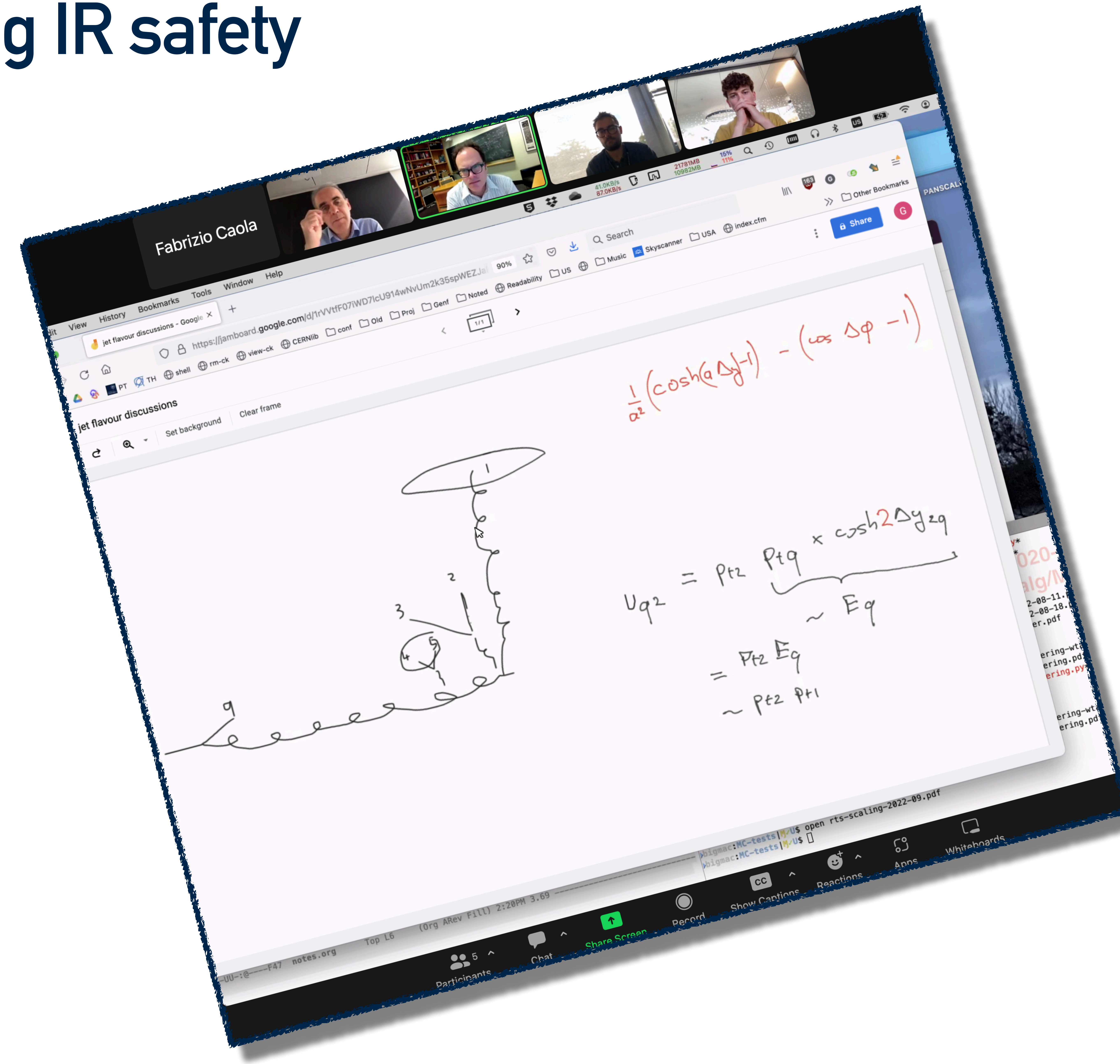
$$\Omega^2_{ik} \equiv 2\left[\frac{1}{\omega^2}\left(\cosh(\omega \Delta y_{ik}) - 1\right) - \left(\cos \Delta\phi_{ik} - 1\right)\right]$$

- Ω~ΔR for small distances
- Exponentially large distance if far apart in rapidity

IR-safety: $0 < \alpha \leq 2; \quad \alpha + \omega > 2$

Testing IR safety





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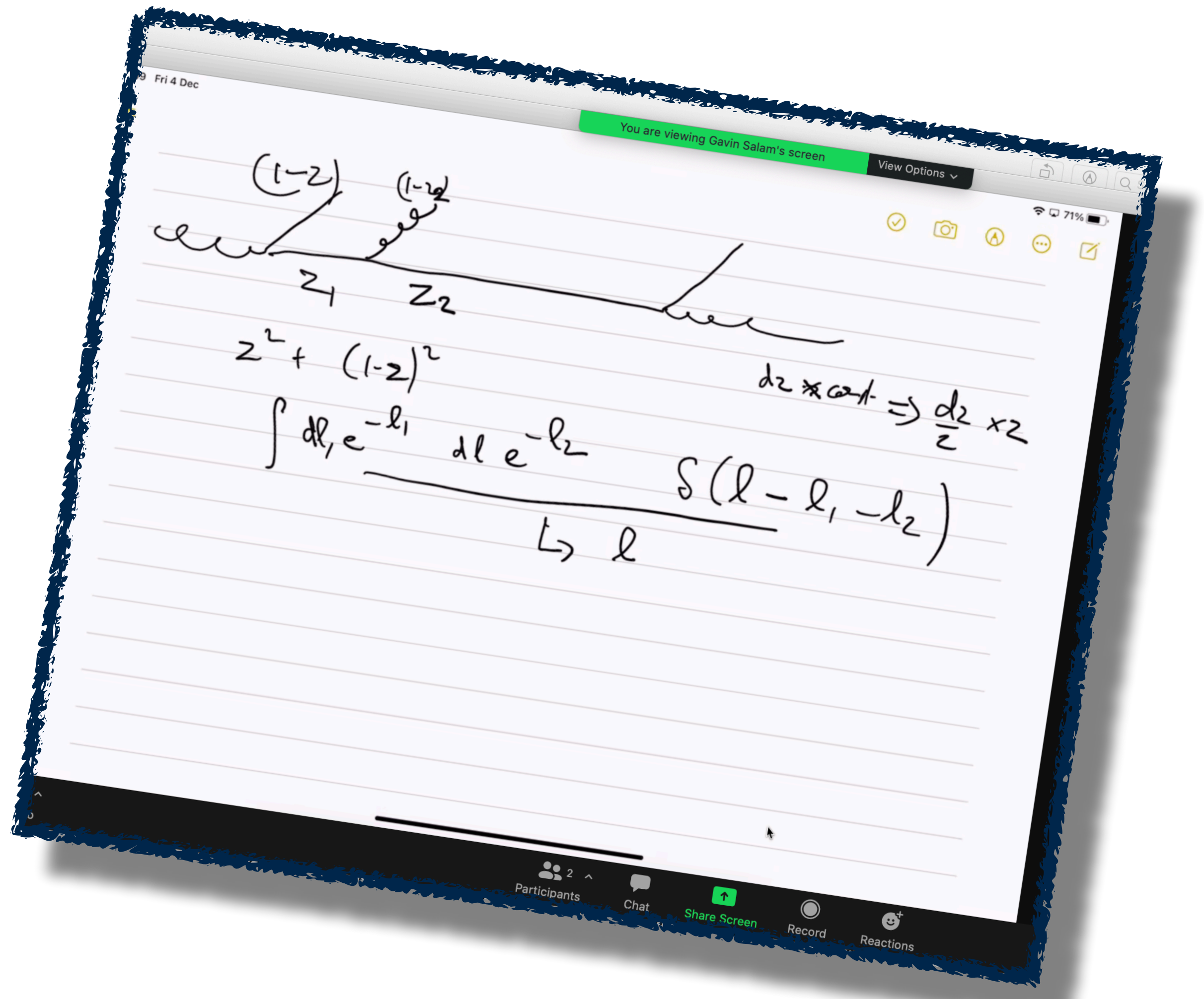

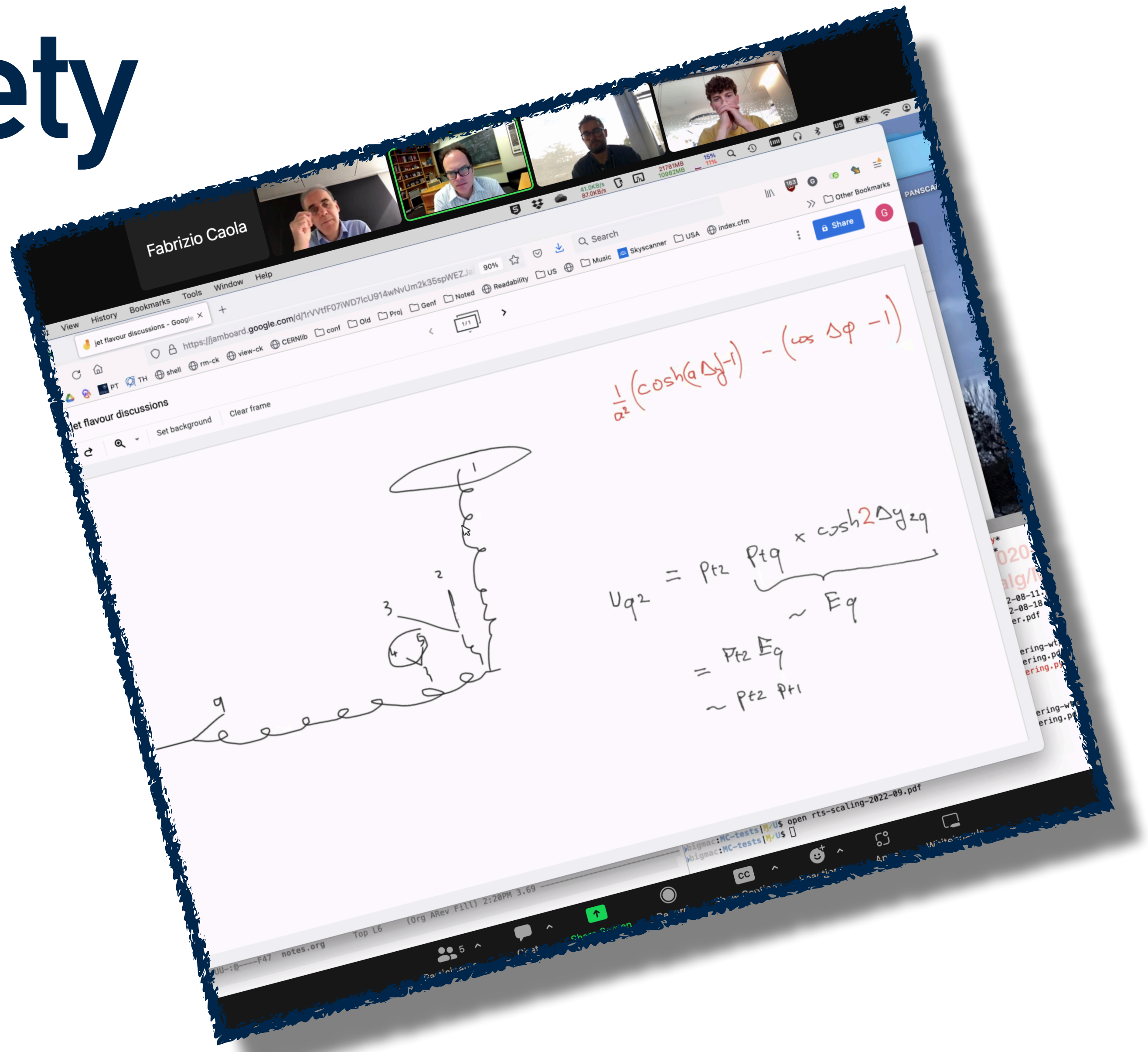

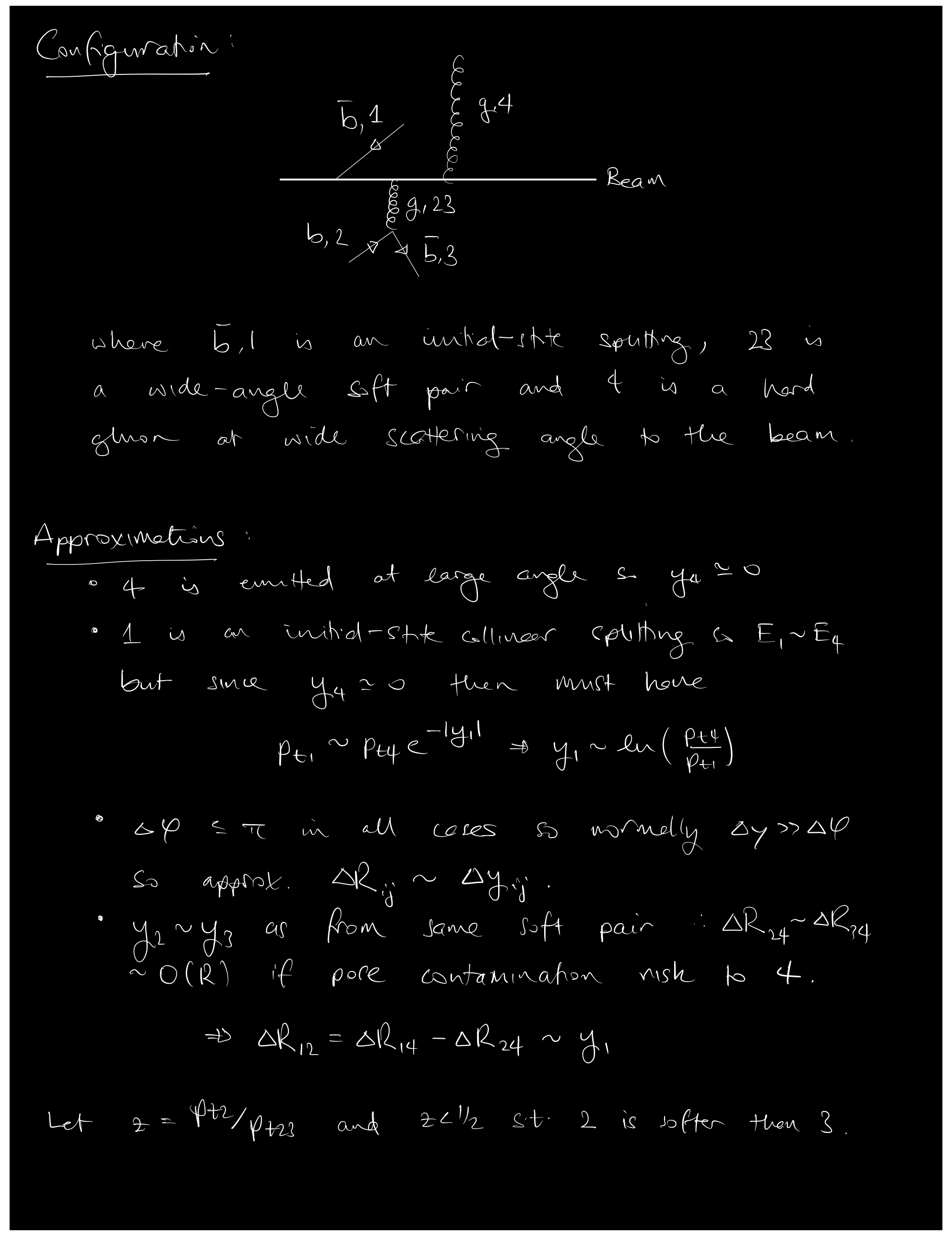

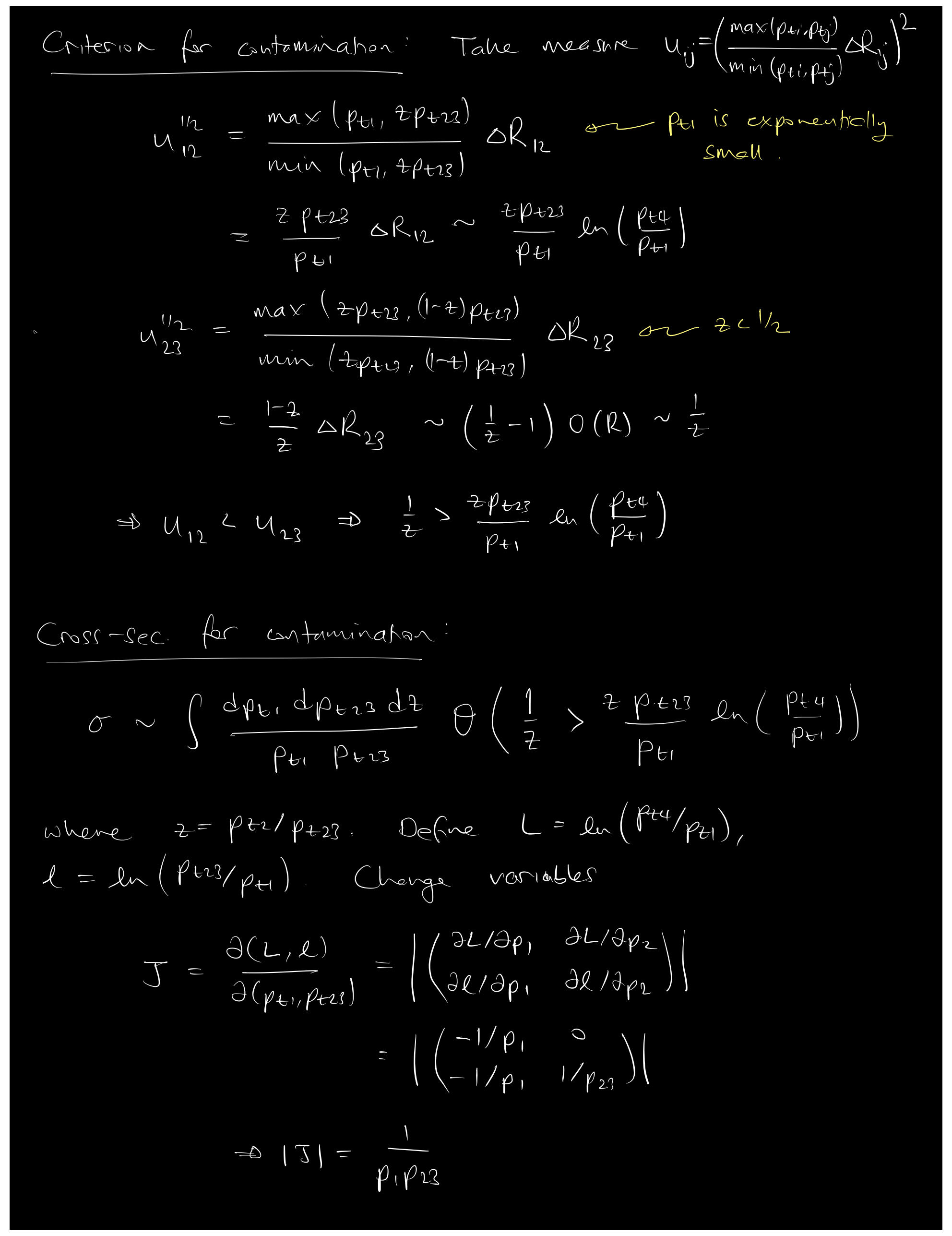

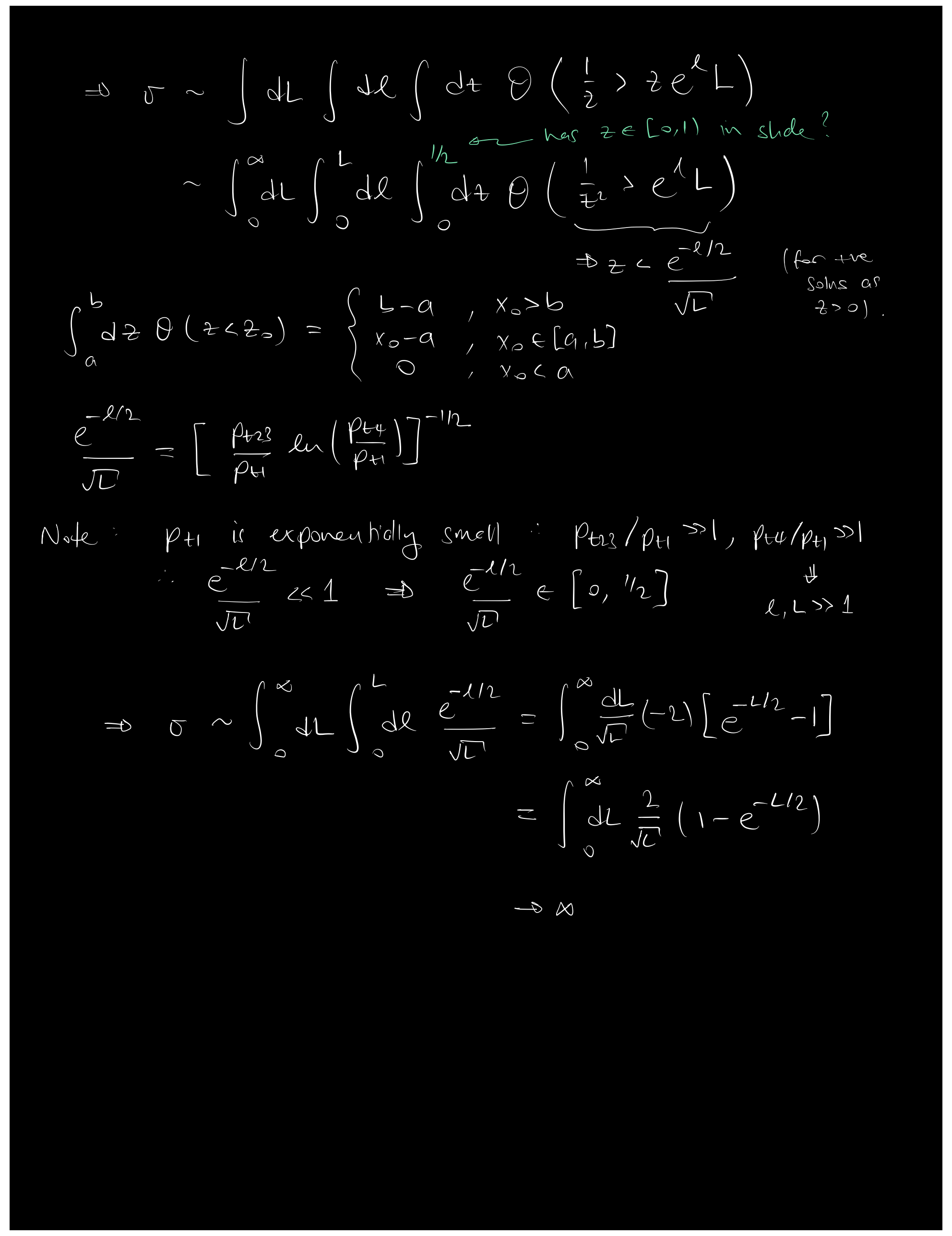

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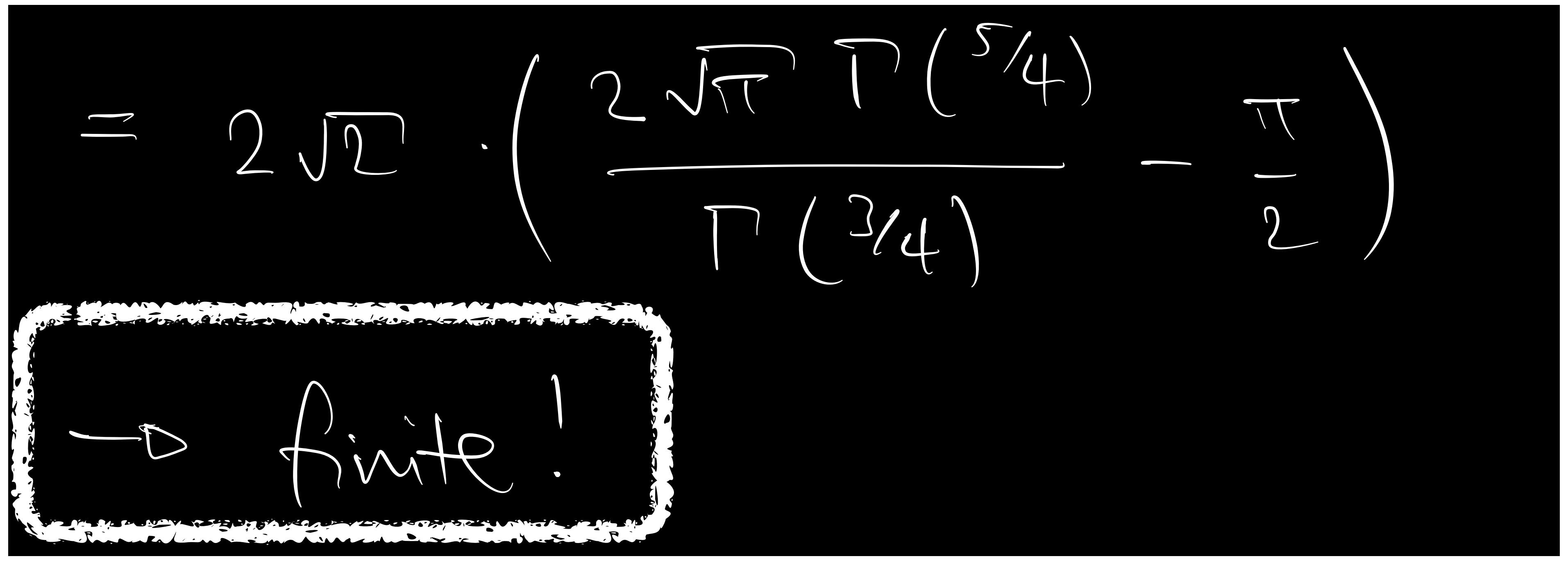
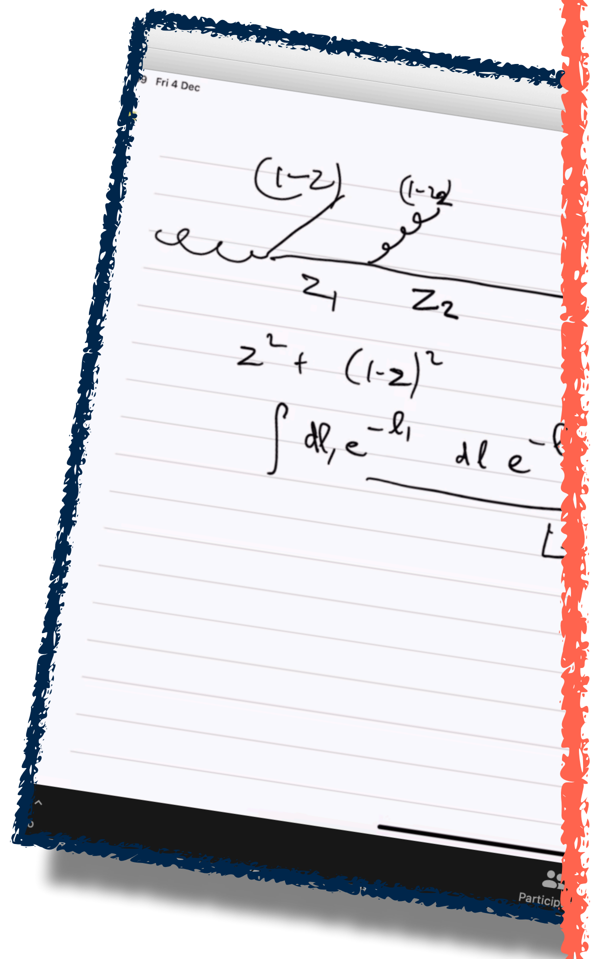
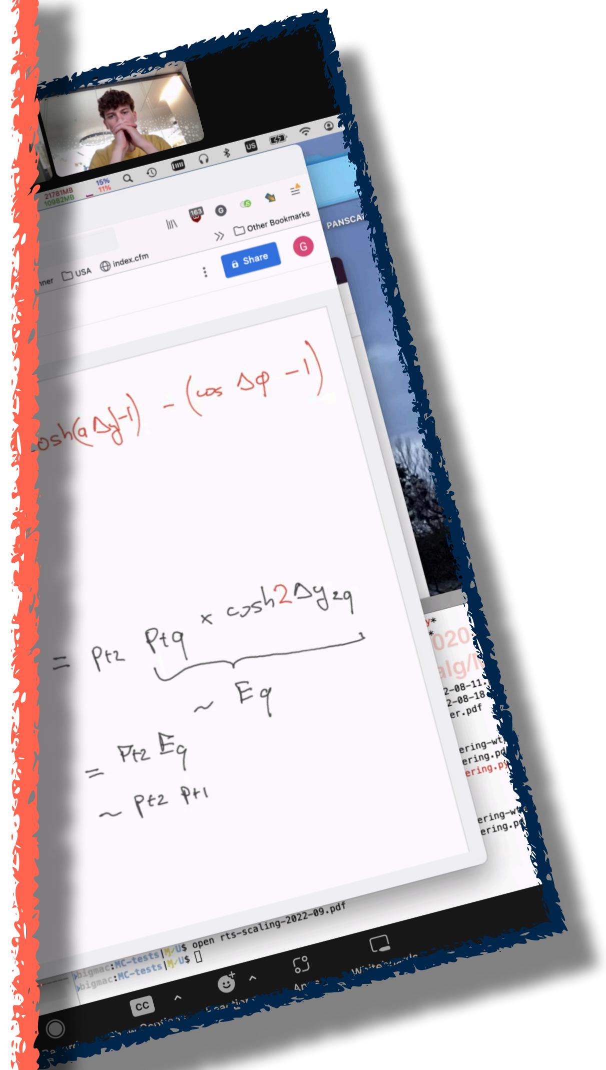
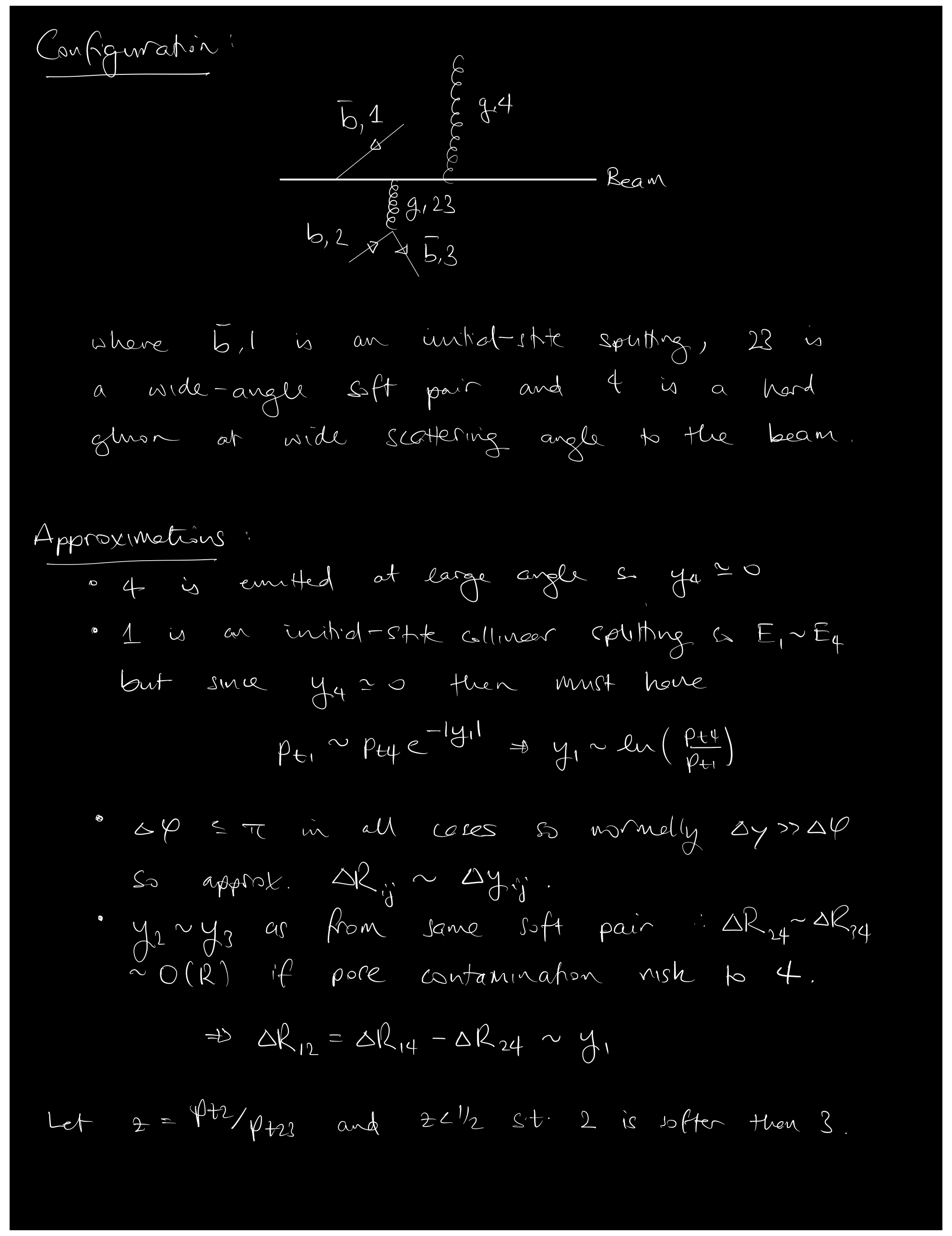
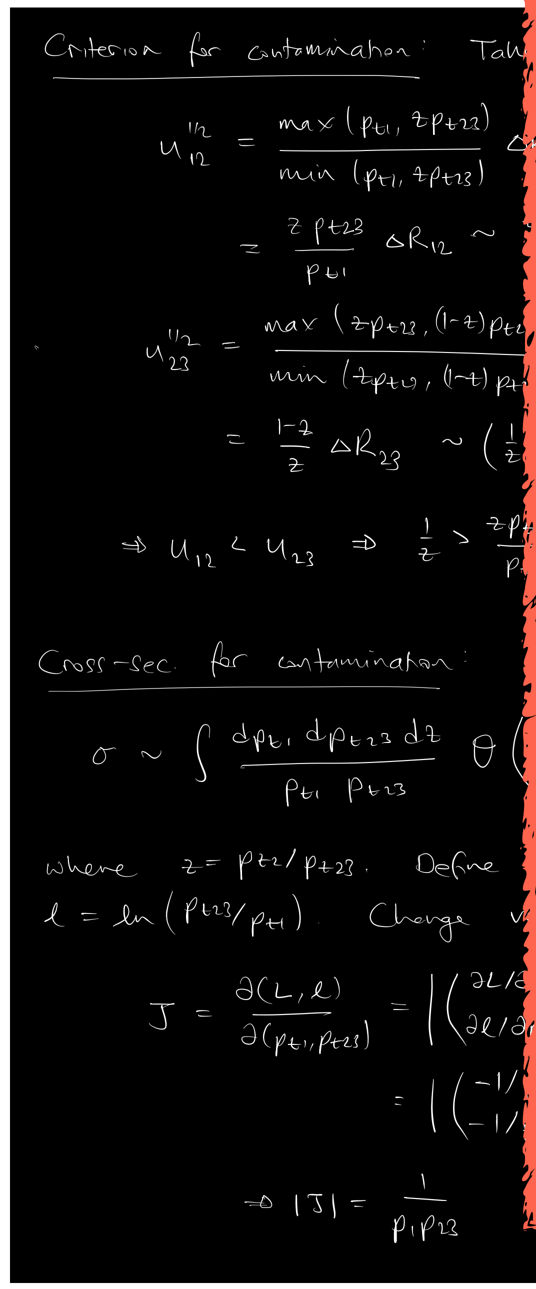
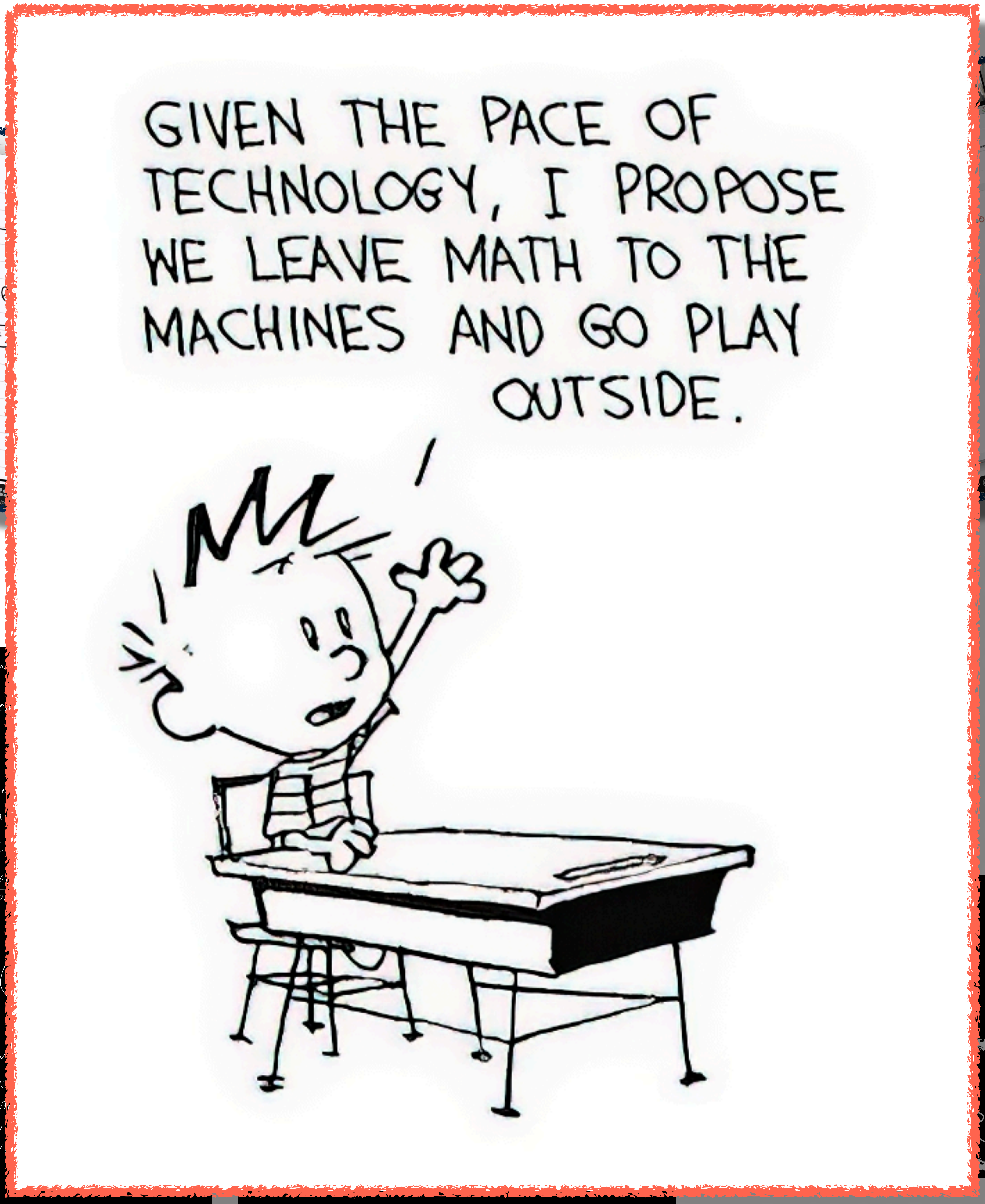




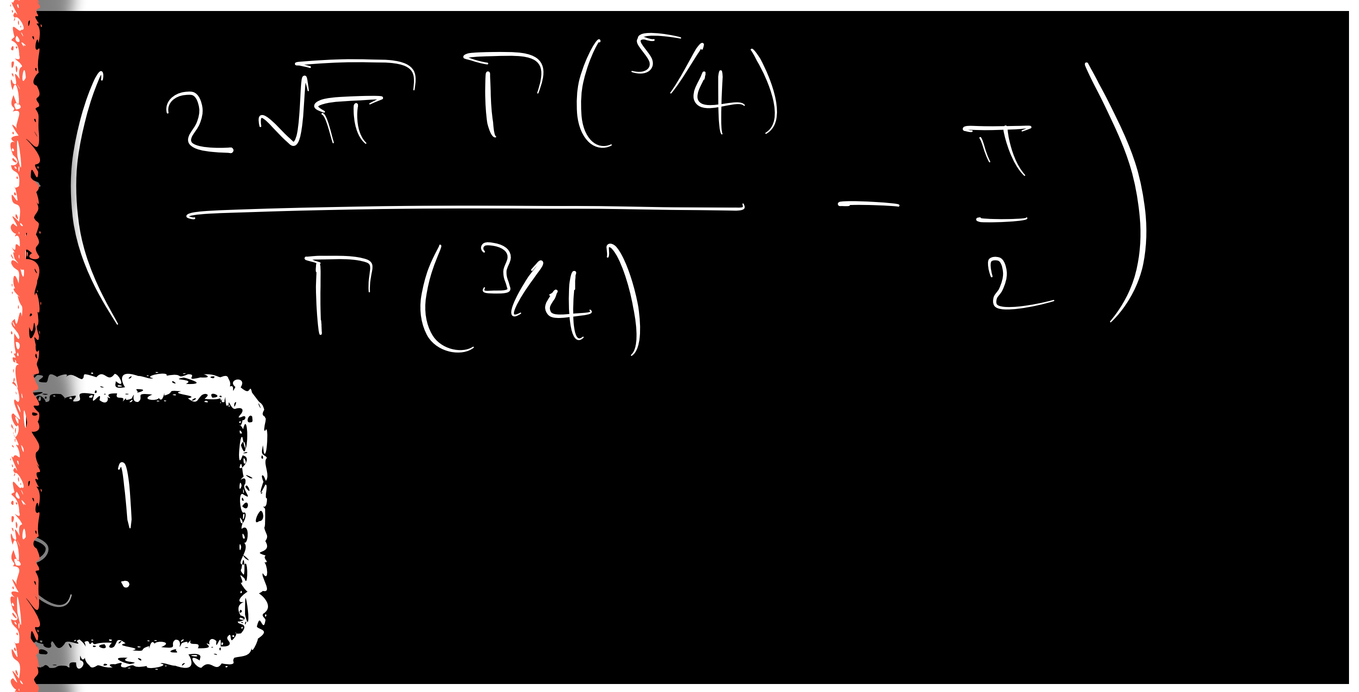




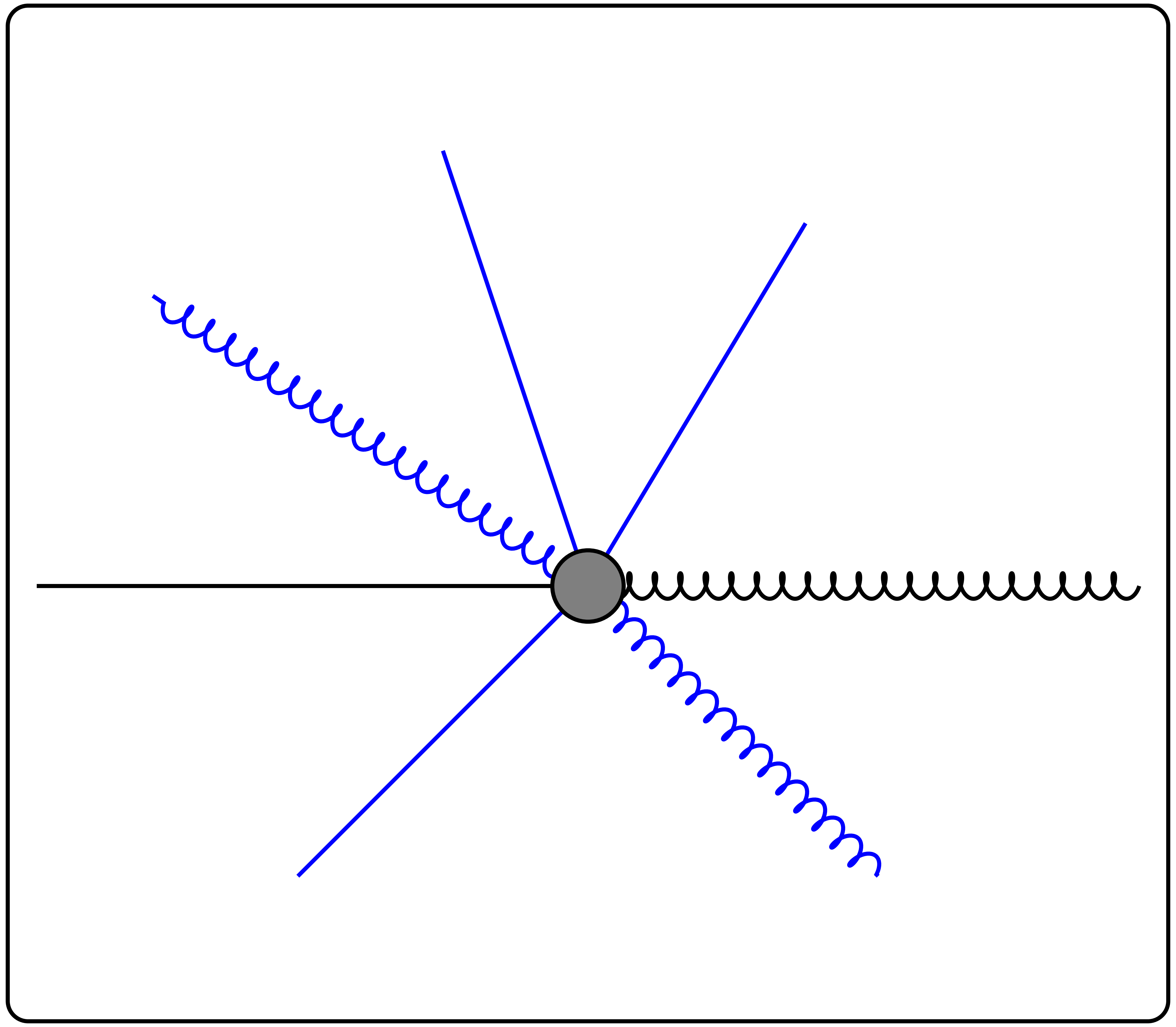



GIVEN THE PACE OF TECHNOLOGY, I PROPOSE WE LEAVE MATH TO THE MACHINES AND GO PLAY OUTSIDE.

...



A framework for IR-safety tests



- Consider a hard underlying event

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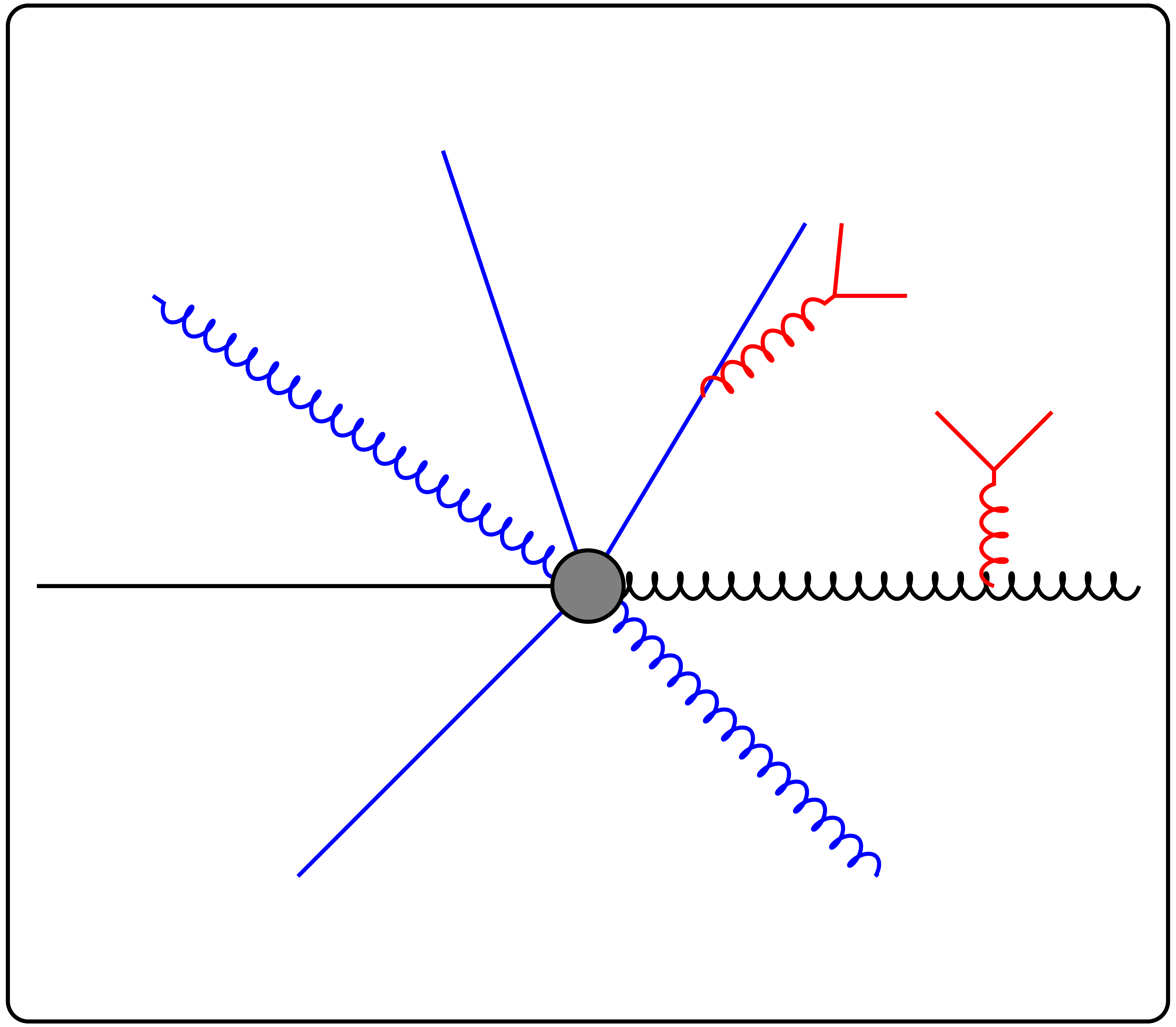

- Consider a hard underlying event
- Dress with
  - (IR/FS) DS

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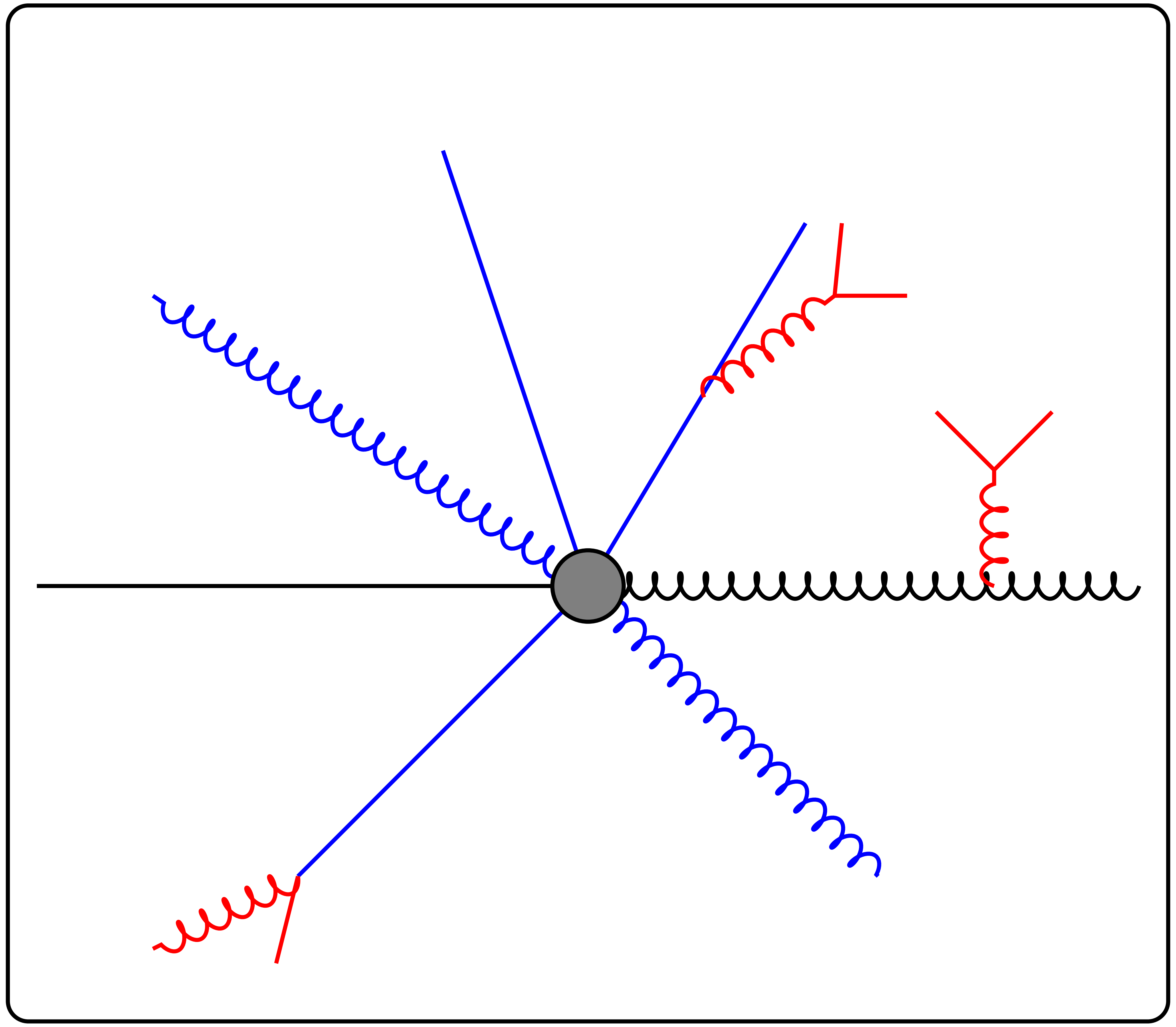

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  - FS hard collinear (FHC)

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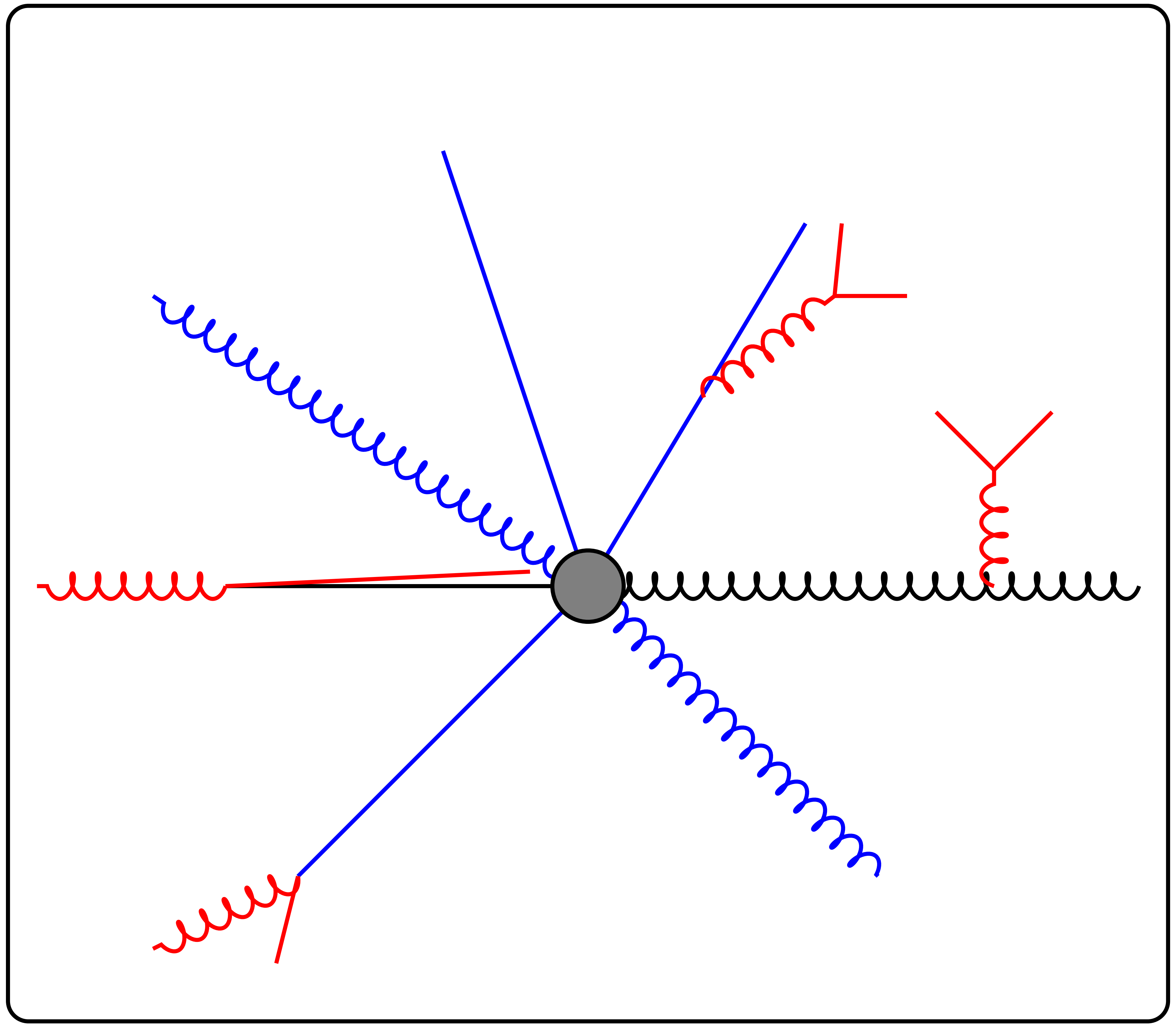

- Consider a hard underlying event
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  - FS hard collinear (FHC)
  - IS hard collinear (IHC)

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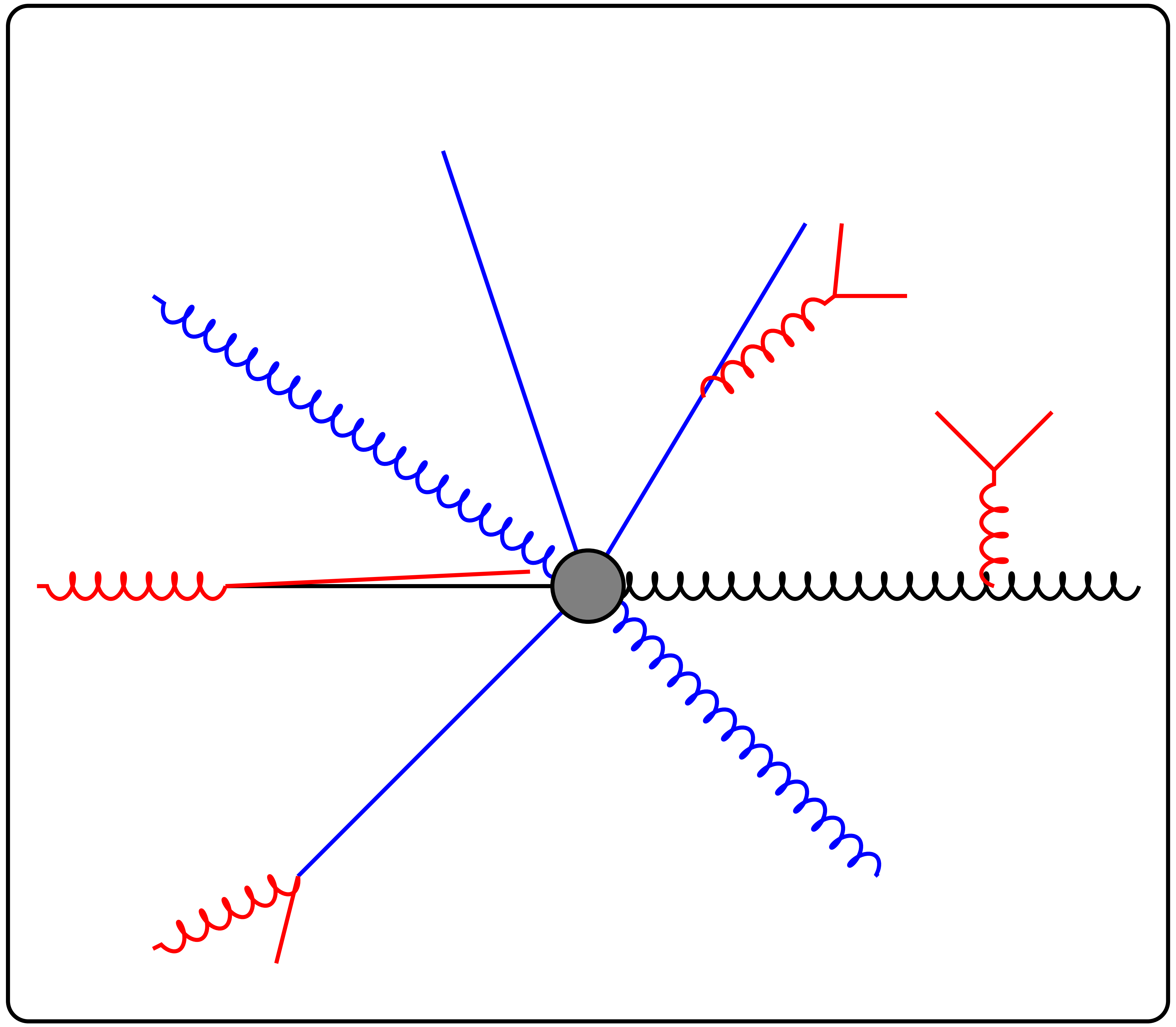

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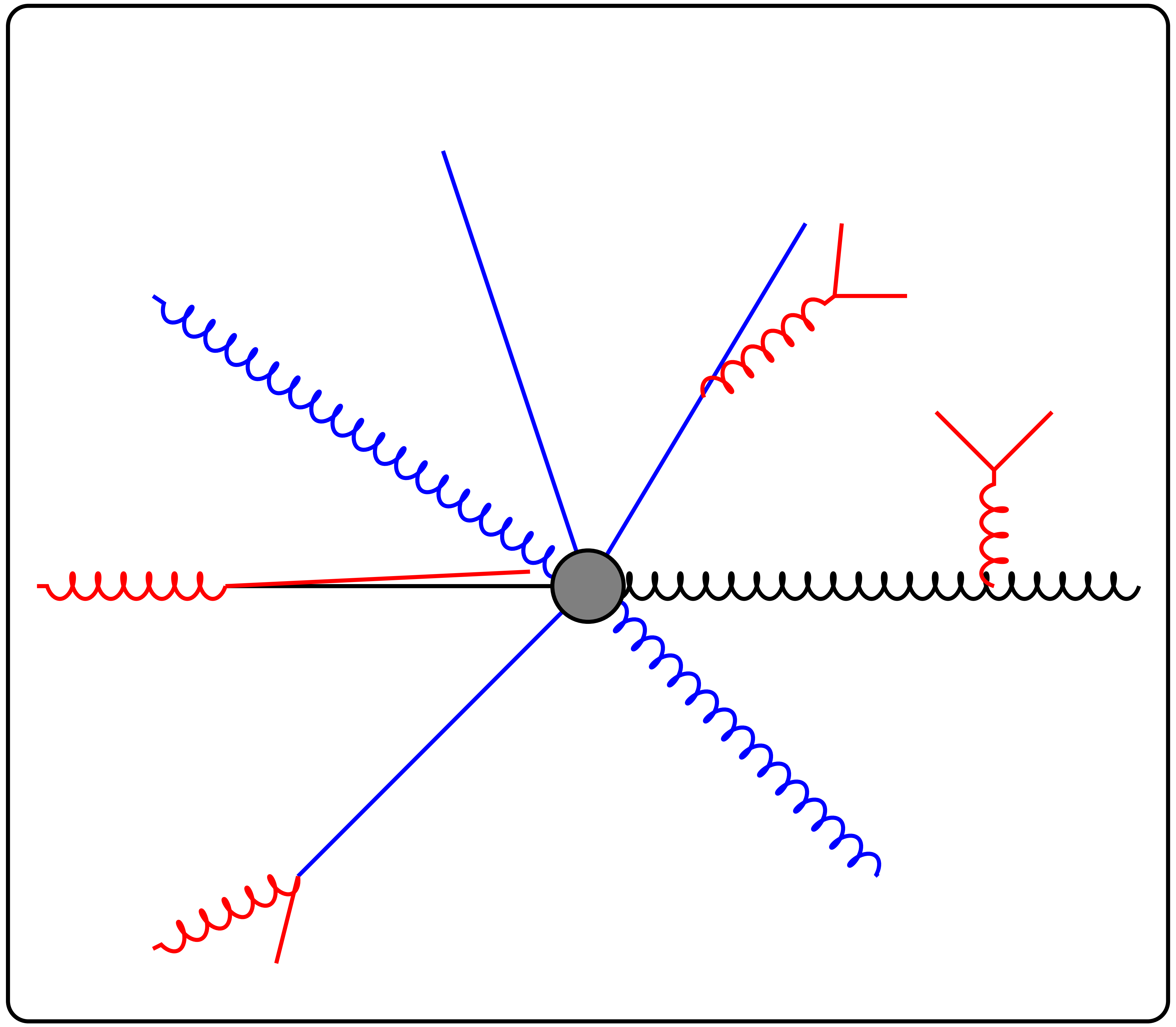
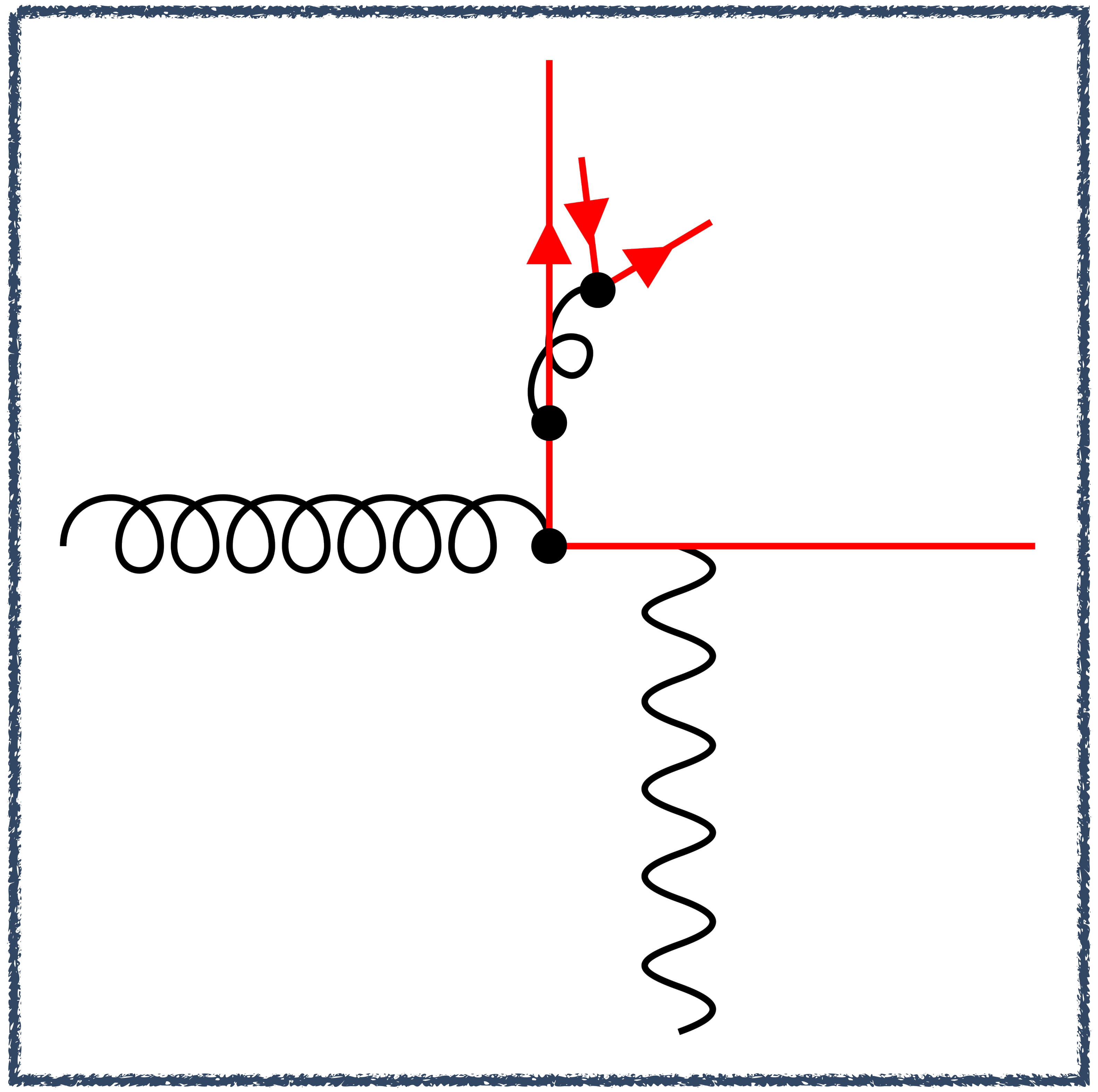
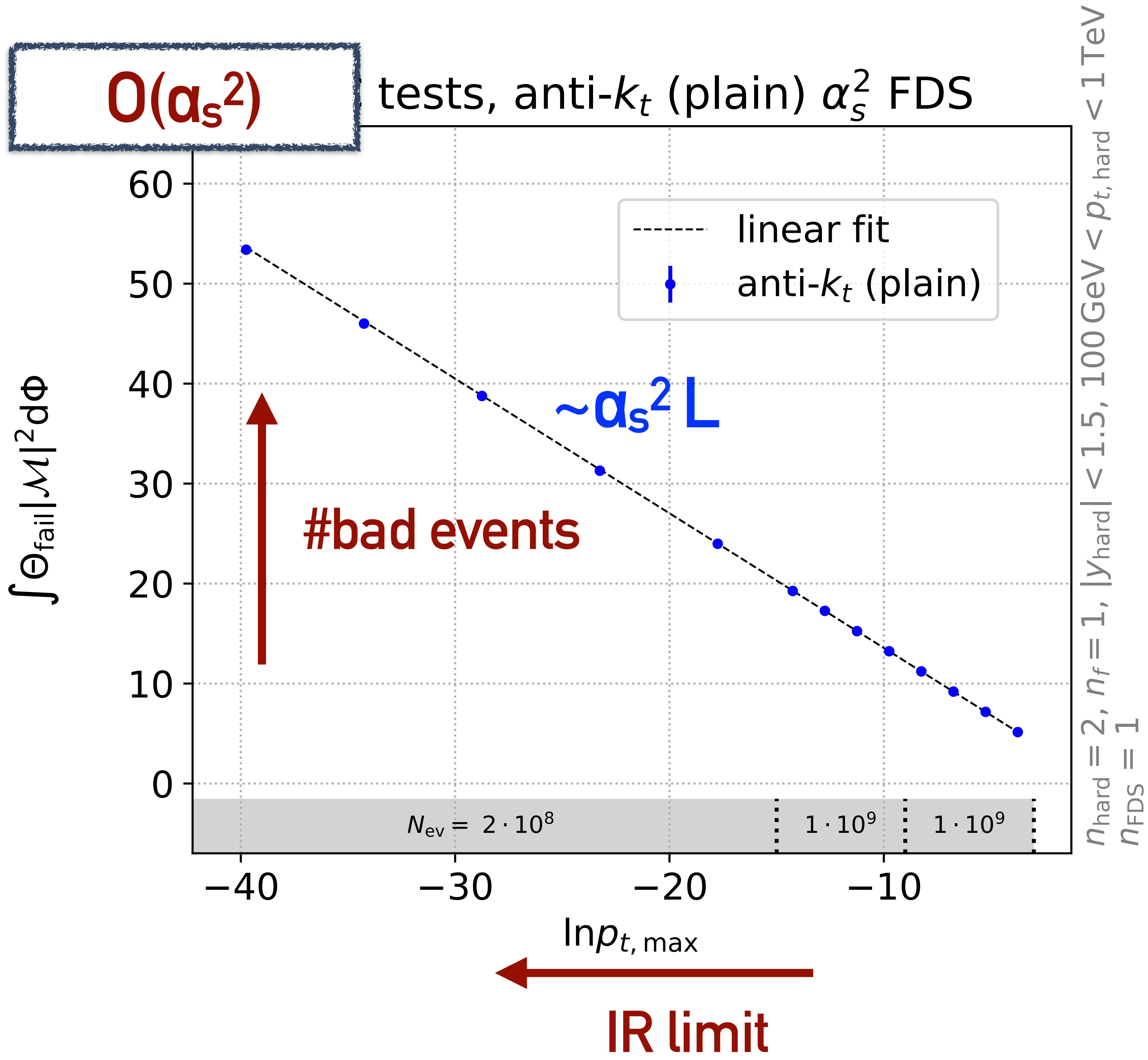


- Consider a hard underlying event
- Dress with
  - (IR/FS) DS
  - FS hard collinear (FHC)
  - IS hard collinear (IHC)
  - Possibly nested
- As extra radiation becomes unresolved:

Hard+IR → Hard

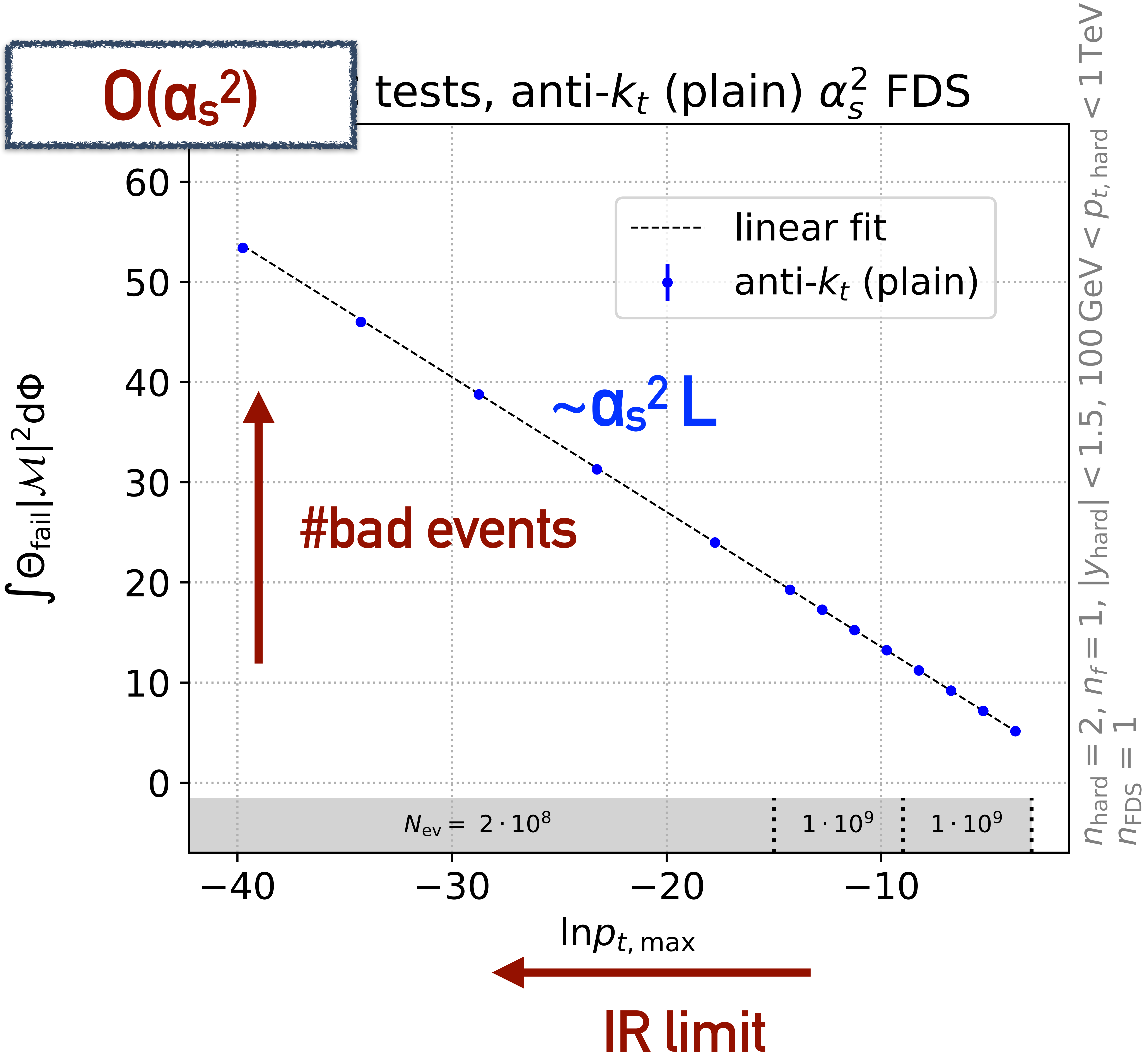
Example: plain anti-k_t+DS





Example: plain anti-k_t+DS

order relative to Born		anti-k_t
α_s	FHC	✓
	IHC	✓
α_s^2	FDS	× II B
	IDS	× II B
	FHC×IHC	✓
	IHC^2	✓
	FHC^2	✓



IR-safety tests: results

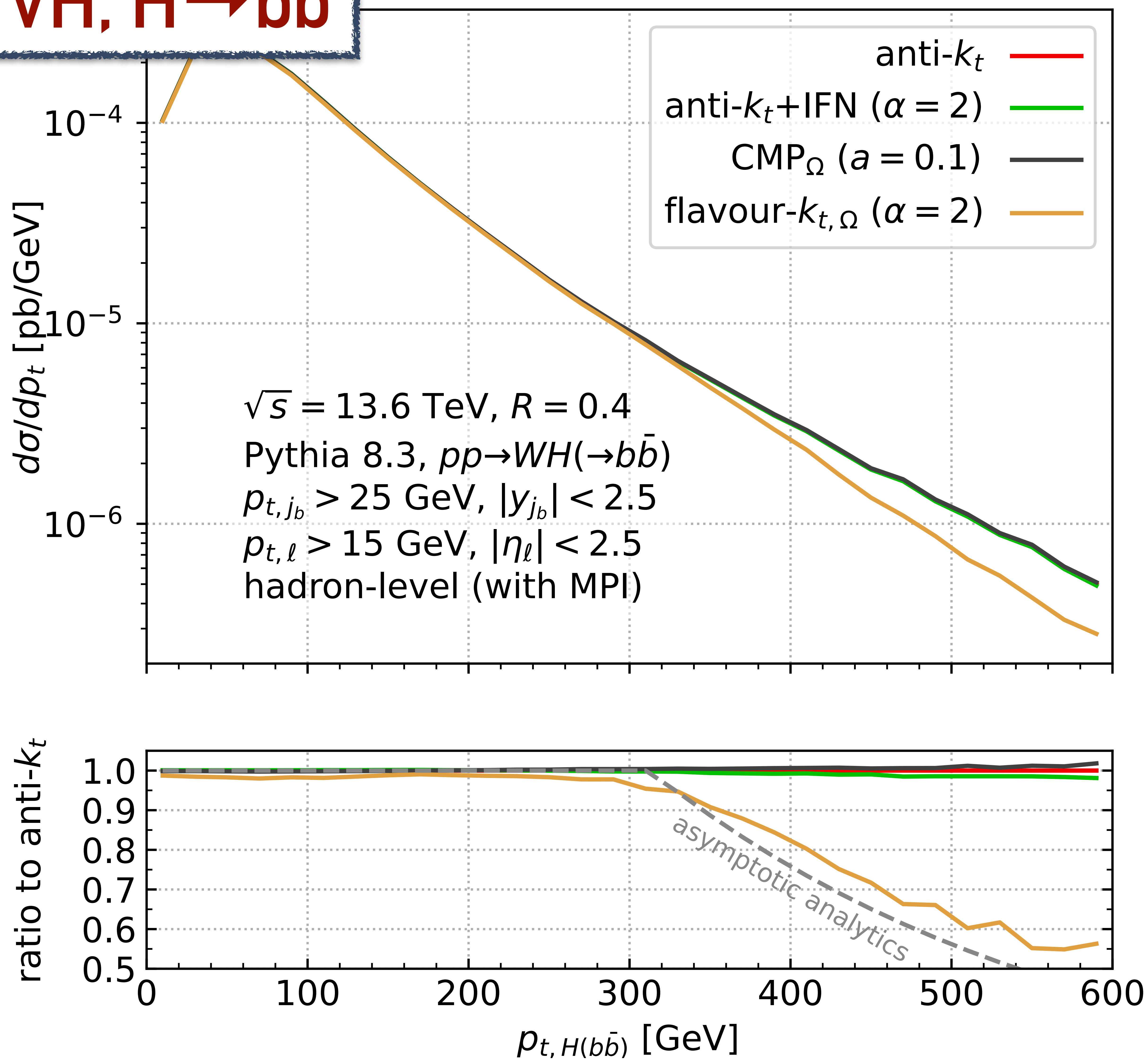
order relative to Born		anti-k_t	flav-k_t ($\alpha = 2$)	CMP	GHS$_{\alpha,\beta}$ (2, 2)	anti-k_t+IFN$_\alpha$	C/A+IFN$_\alpha$
α_s	FHC	✓	✓	✓	✓	✓	✓
	IHC	✓	✓	✓	✓	✓	✓
α_s^2	FDS	×IIB	✓	✓	✓	✓	✓
	IDS	×IIB	✓	✓	✓	✓	✓
	FHC×IHC	✓	✓	✓	✓	✓	✓
	IHC^2	✓	✓	×C2	✓	✓	✓
	FHC^2	✓	✓	✓	×C4	✓	✓
α_s^3	IHC×IDS		∼C1	×C3	∼C1	✓	✓
	rest					✓	✓
α_s^4	IDS×FDS				×C5	✓	✓
	rest					✓	✓
α_s^5						✓	✓
α_s^6						✓	✓

Easy to fix

IFN passes IR-safety tests, up to highest order we were able to probe

Pheno results: Pythia8, Hadron-level + MPI

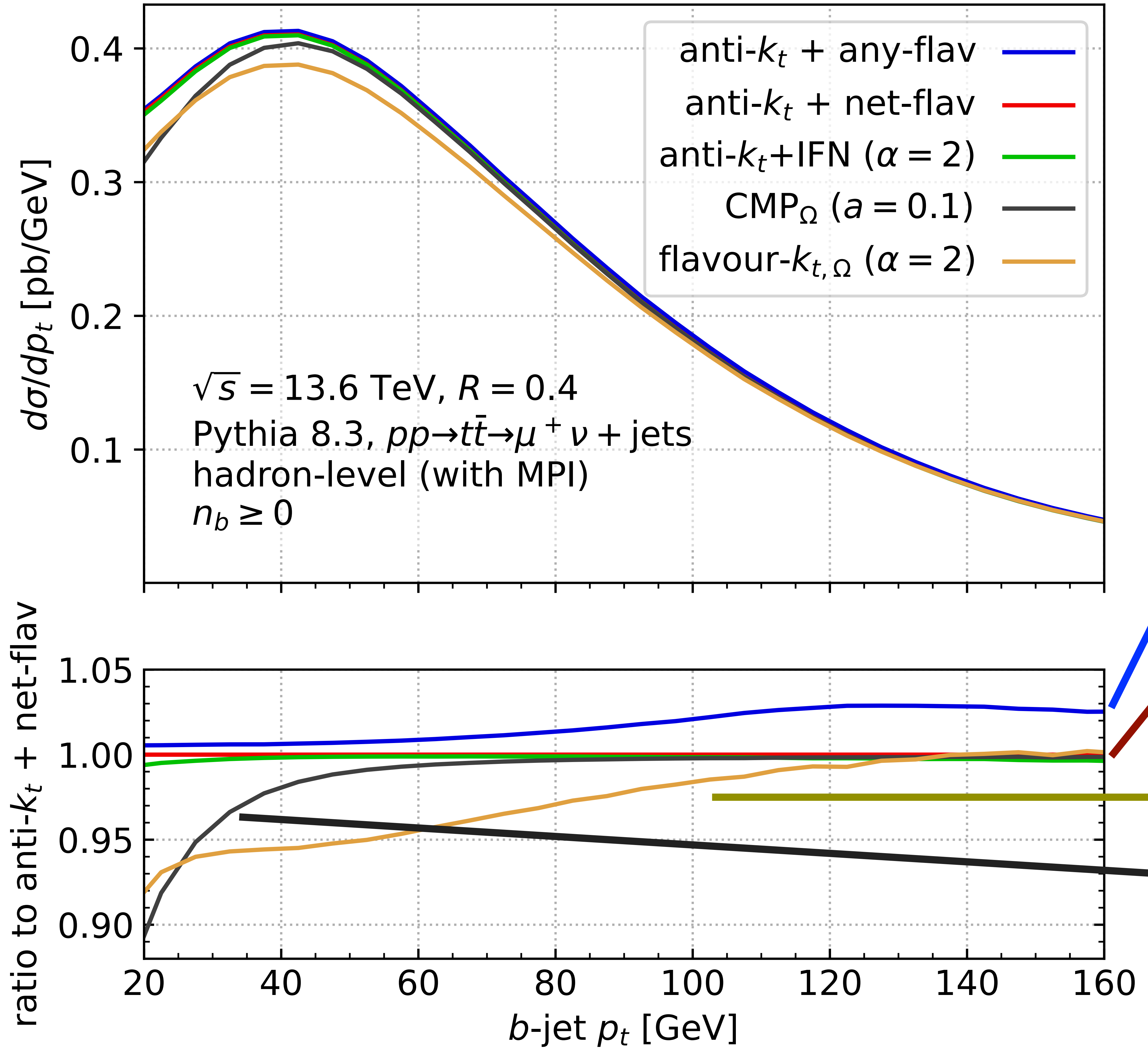
VH, H→bb



Both IFN & CMP$_\Omega$ indistinguishable from plain anti-k_t

Pheno results: Pythia8, Hadron-level + MPI

Semileptonic tt



Plain anti-k_t, at least 1 b-tag

Plain anti-k_t, net flavour ≈ IFN

Flavour-$k_{t,\Omega}$

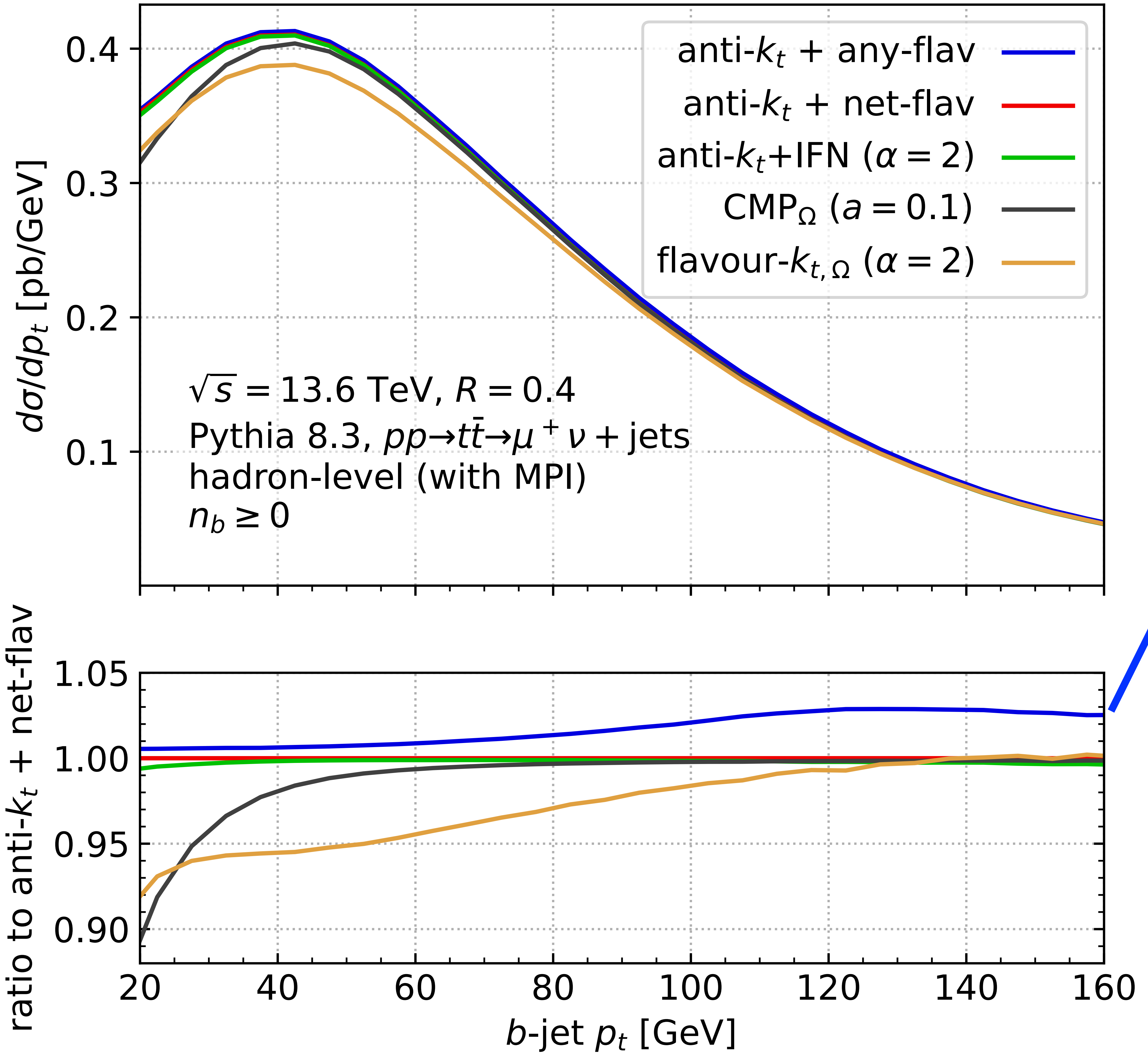
CMP$_\Omega$

~10% differences at low p_t

Inclusive b-jet p_t

Pheno results: Pythia8, Hadron-level + MPI

Semileptonic tt



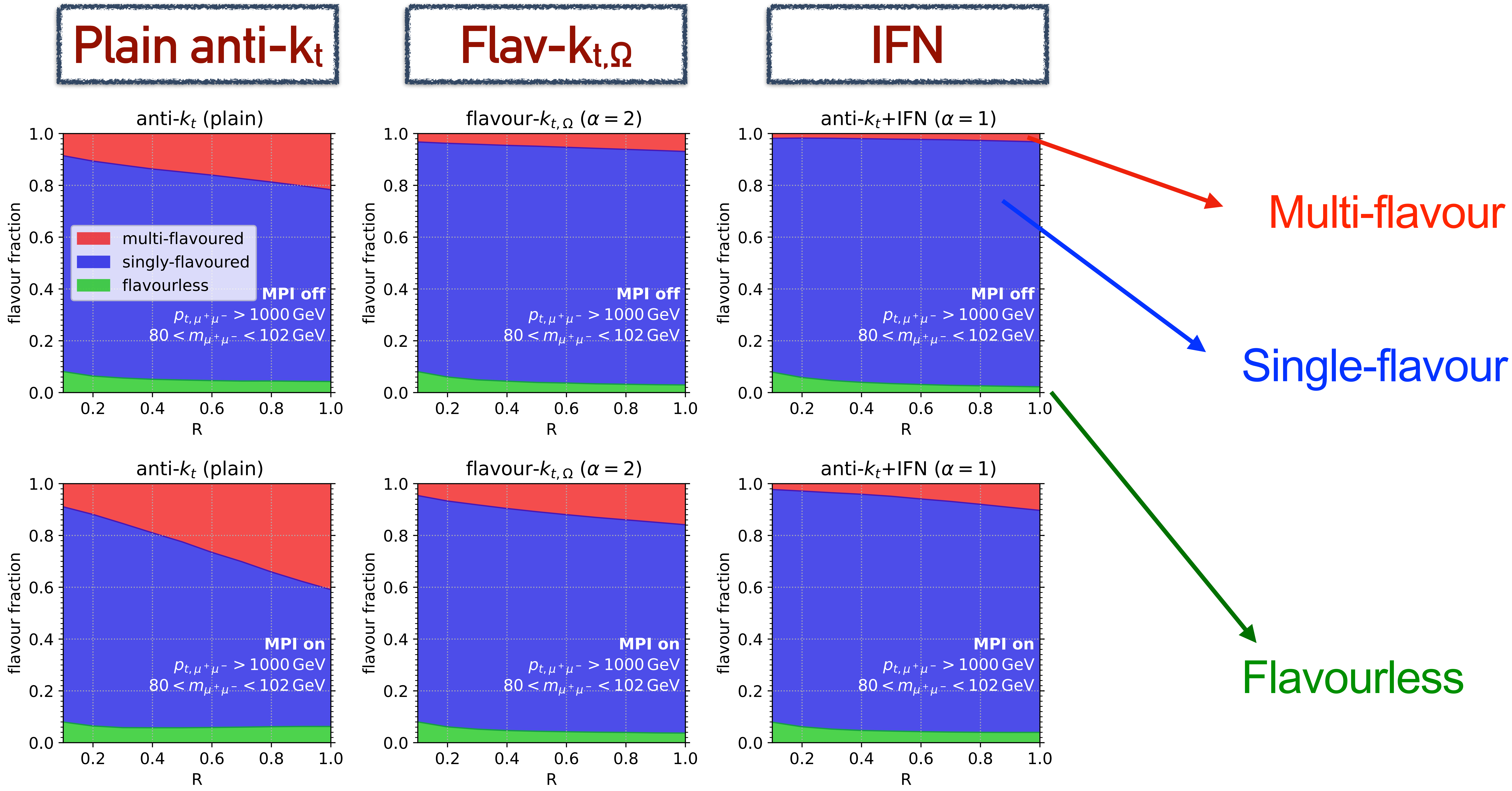
Inclusive b-jet p_t

Plain anti-k_t, at least 1 b-tag

Plain anti-k_t, net flavour ≈ IFN

- IFN behaves very well
- Less than 5% off w.r.t. proxy for current analysis → unfold?

Pheno results: Z+q results



Conclusions

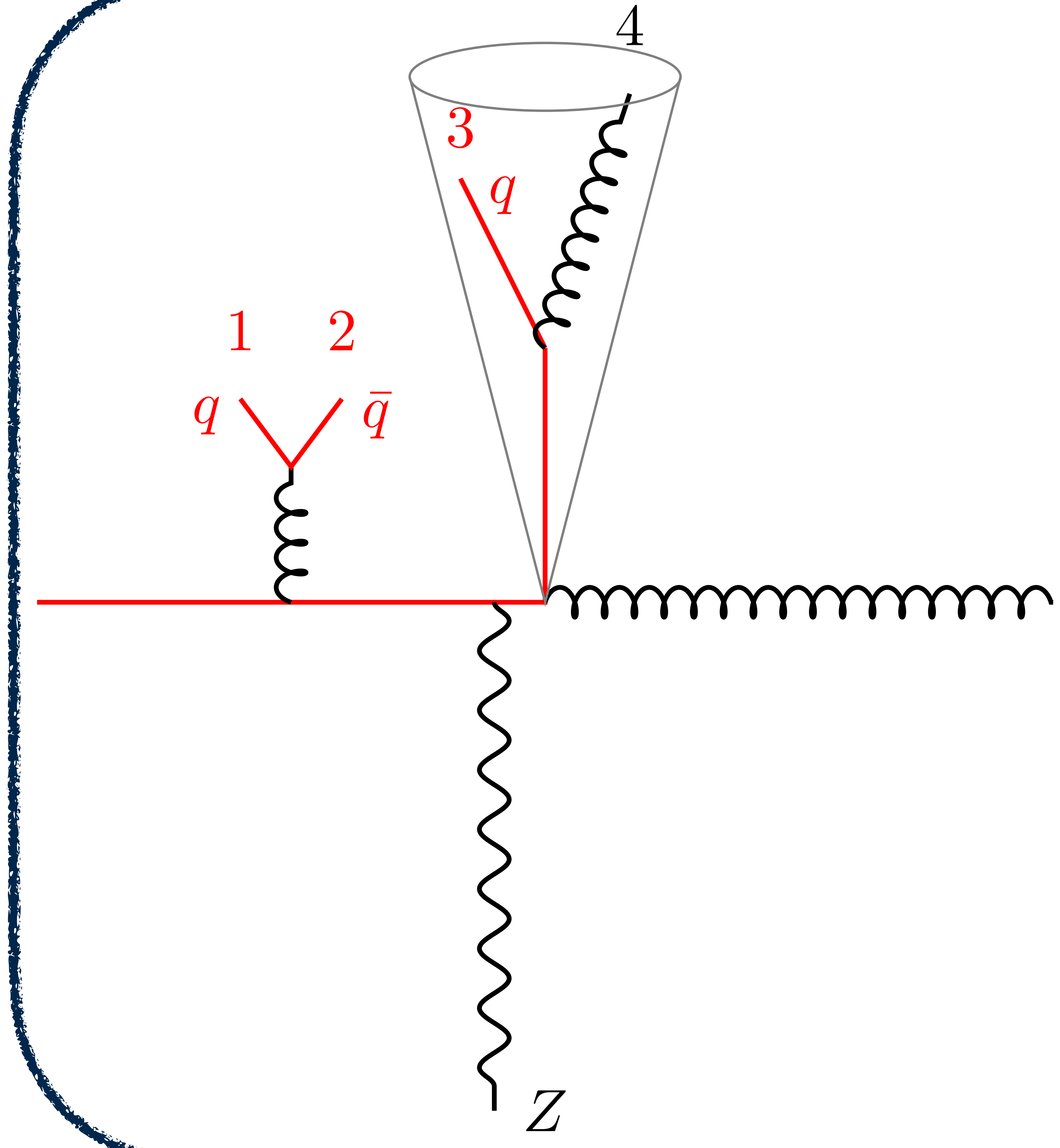
- A proper definition of jet flavour is non-trivial
- Multiple attempt in the past to define IR-safe algorithms with kinematics identical or very similar to anti-k_t. Subtle IR-safety issues
- Our proposal: Interleaved Flavour Neutralisation
  - Definition of flavour interleaved but distinct from kinematics clustering
  - Kinematics unchanged, neutralisation based on suitable flavour distance
- Passed non-trivial IR-safety tests
- Promising phenomenology → interesting investigations ahead + experimental feasibility

Thank you very much for your attention!

Integrated Flavour Neutralisation (IFN): a cartoon

Crucial for IR-safety + good behaviour

- proper choice of a "flavour distance"
- making sure neutralising partner is not "stolen" from more suitable candidate



- (34) recombination → trigger neutralisation search
- find 2 as a potential candidate
- if used: neutralised hard jet + soft flavoured jet 😟

Integrated Flavour Neutralisation (IFN): a cartoon

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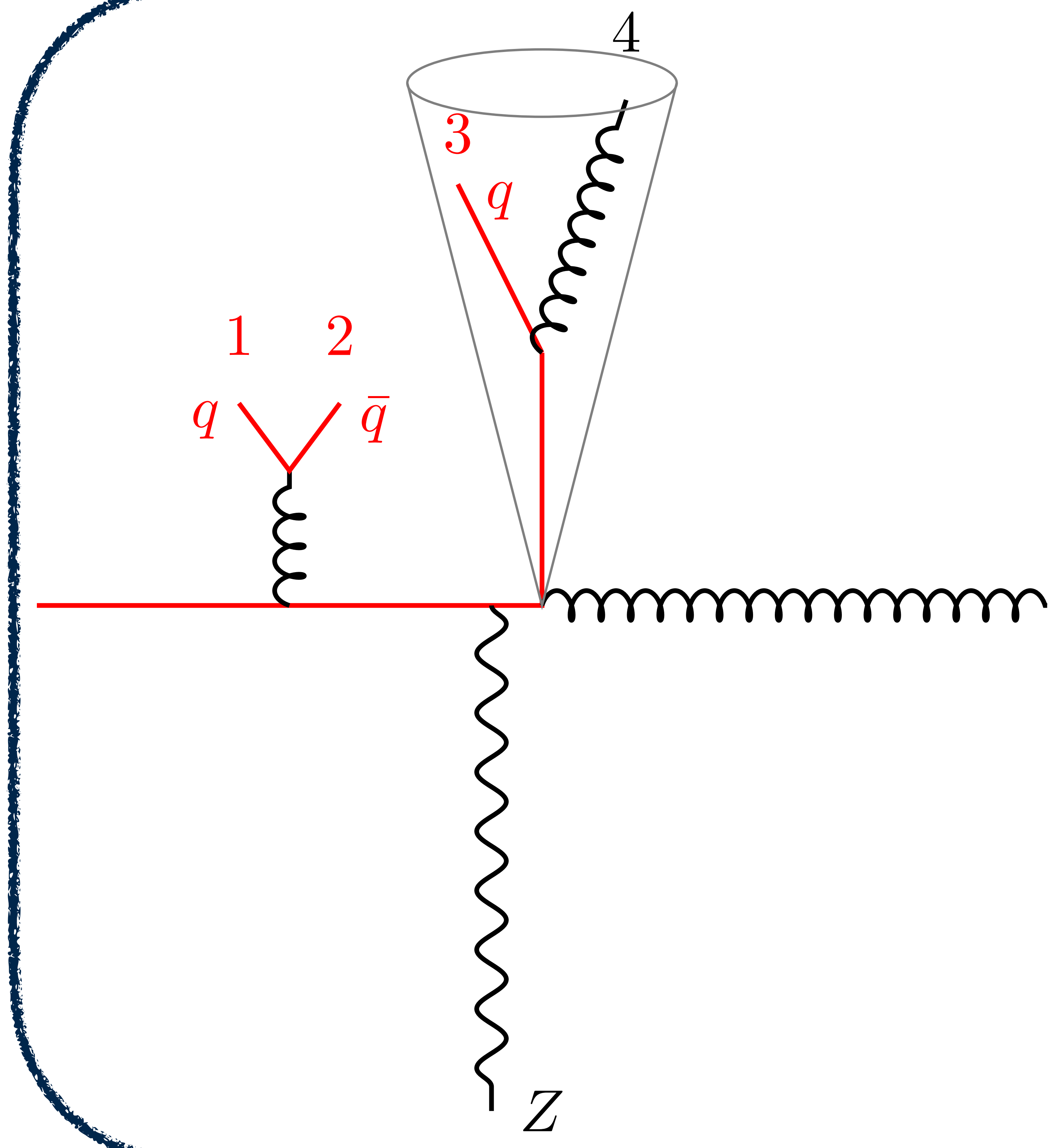
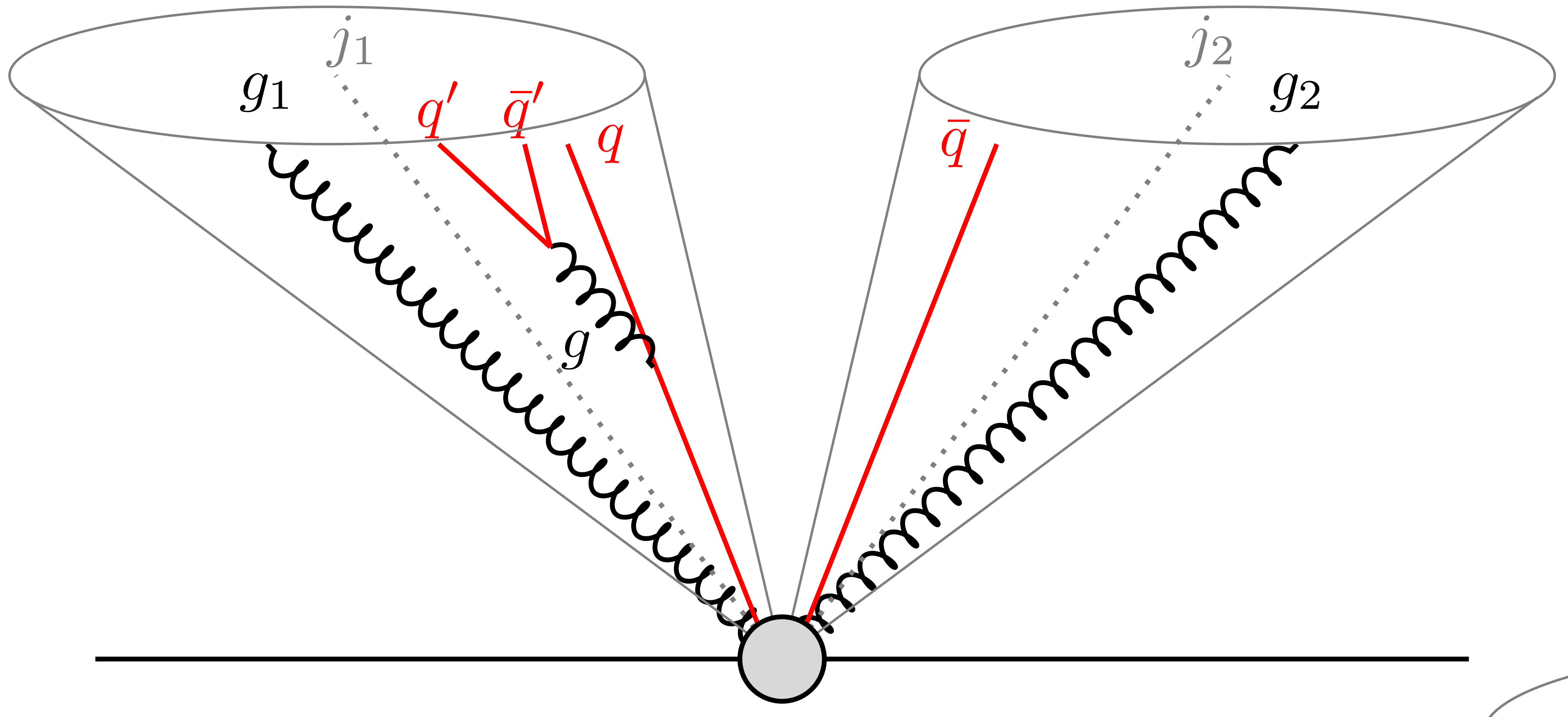
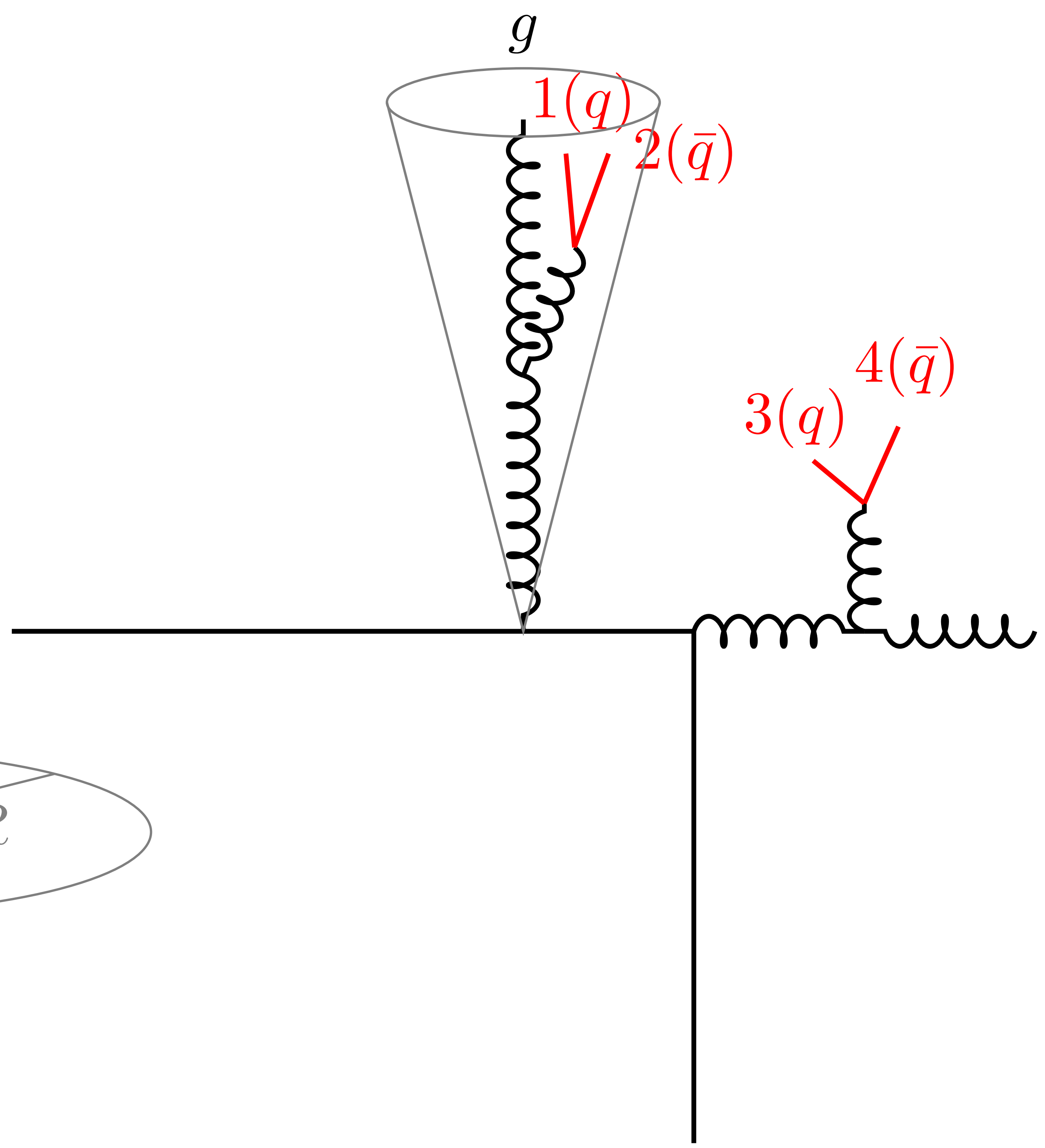
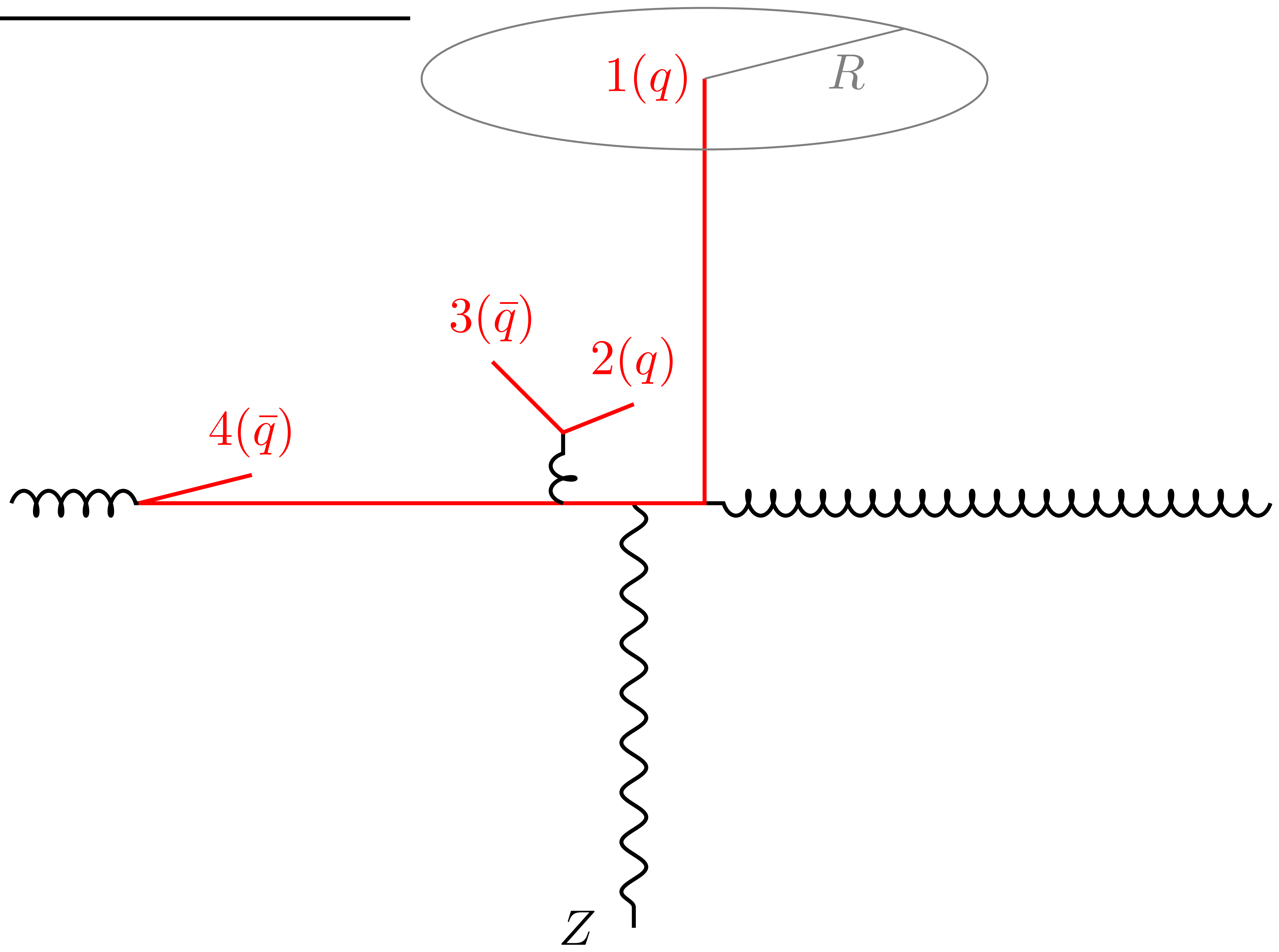


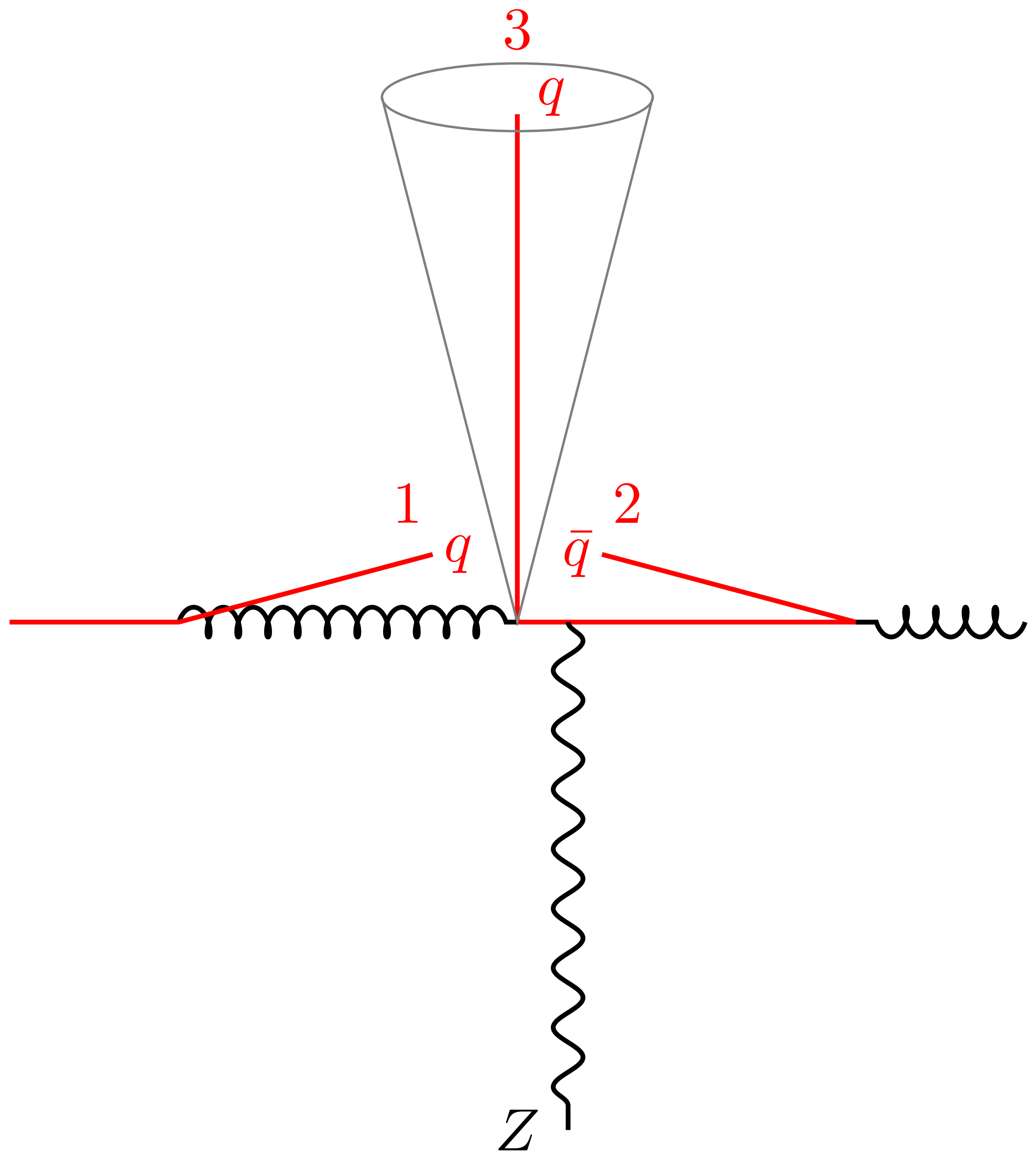
- (34) recombination → trigger neutralisation search
- find 2 as a potential candidate
- way out: recursion
- before (23) neutralisation, look elsewhere to neutralise 2 → find 1and neuralise
- $\Longrightarrow$ Hard (34) flavour jet, soft (12) gluon jet ✔

Problematic configurations









Flavour-k_t and CMP distances

$$d_{ij}^{\text{flav-}k_t} = [\max(p_{ti}, p_{tj})]^\alpha [\min(p_{ti}, p_{tj})]^{2-\alpha} \frac{\Delta R_{ij}^2}{R^2}\,,$$
$$\text{if softer of } i \text{ and } j \text{ is flavoured}\,,$$
$$d_{iB}^{\text{flav-}k_t} = [\max(p_{ti}, p_{tB}(y_i))]^\alpha [\min(p_{ti}, p_{tB}(y_i))]^{2-\alpha},$$

$$d_{ij}^{\text{flav-anti-}k_t} = d_{ij}^{\text{anti-}k_t} \times \mathcal{S}_{ij}\,,$$
$$\text{if } i \text{ and } j \text{ are oppositely flavoured}\,,$$

where

$$\mathcal{S}_{ij} = 1 - \Theta(1-\kappa)\cos\left(\frac{\pi}{2}\kappa\right), \quad \kappa \equiv \frac{1}{a}\frac{p_{ti}^2 + p_{tj}^2}{2p_{t,\max}^2}\,,$$