Massive Quarks in Vincia

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in collaboration with A. Gehrmann-De Ridder and P. Skands

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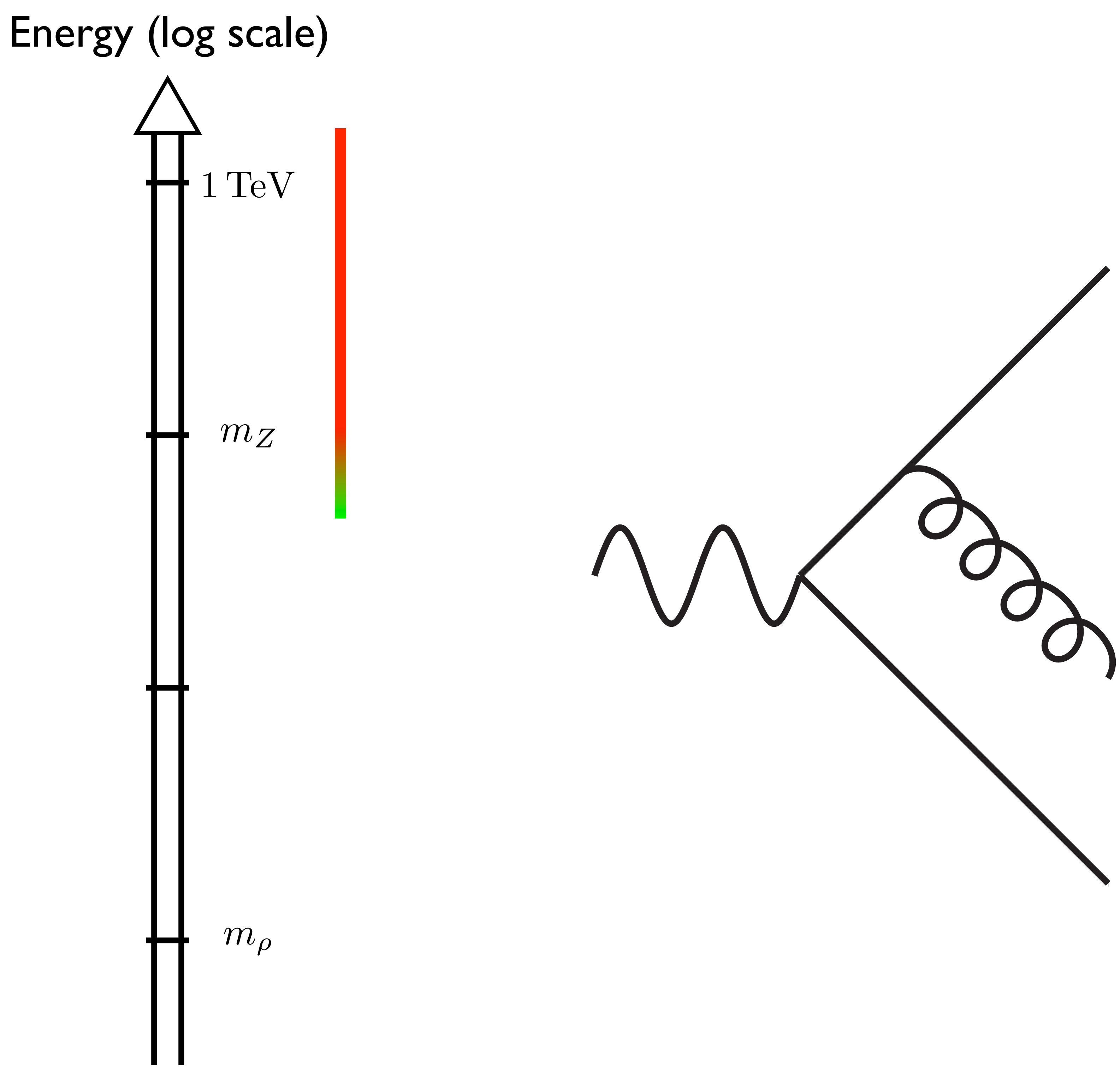
Swiss Federal Institute of Technology Zurich

Outline

- Introduction - Parton Showers
- Vincia - Principles
- Masses in Vincia

Energy Scales at a Collider



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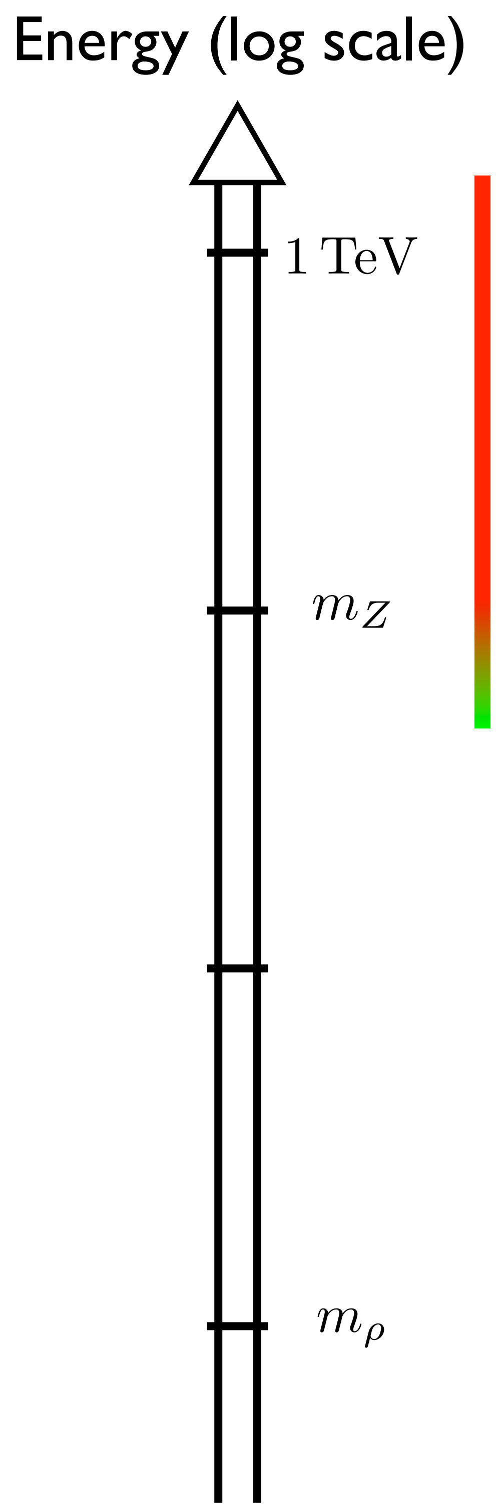
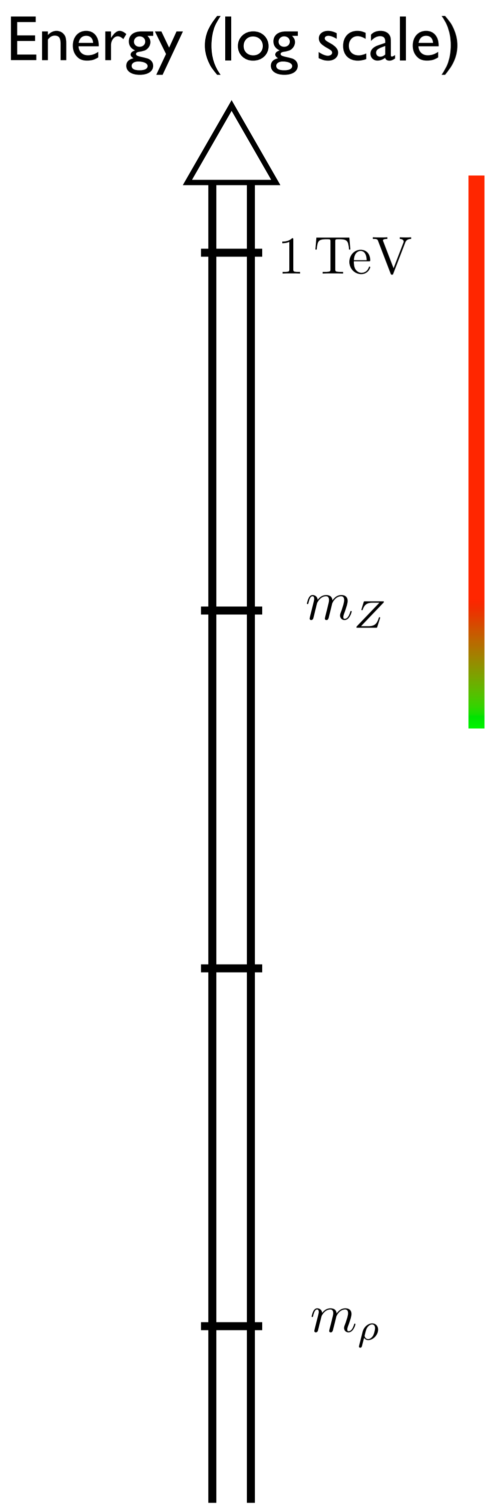


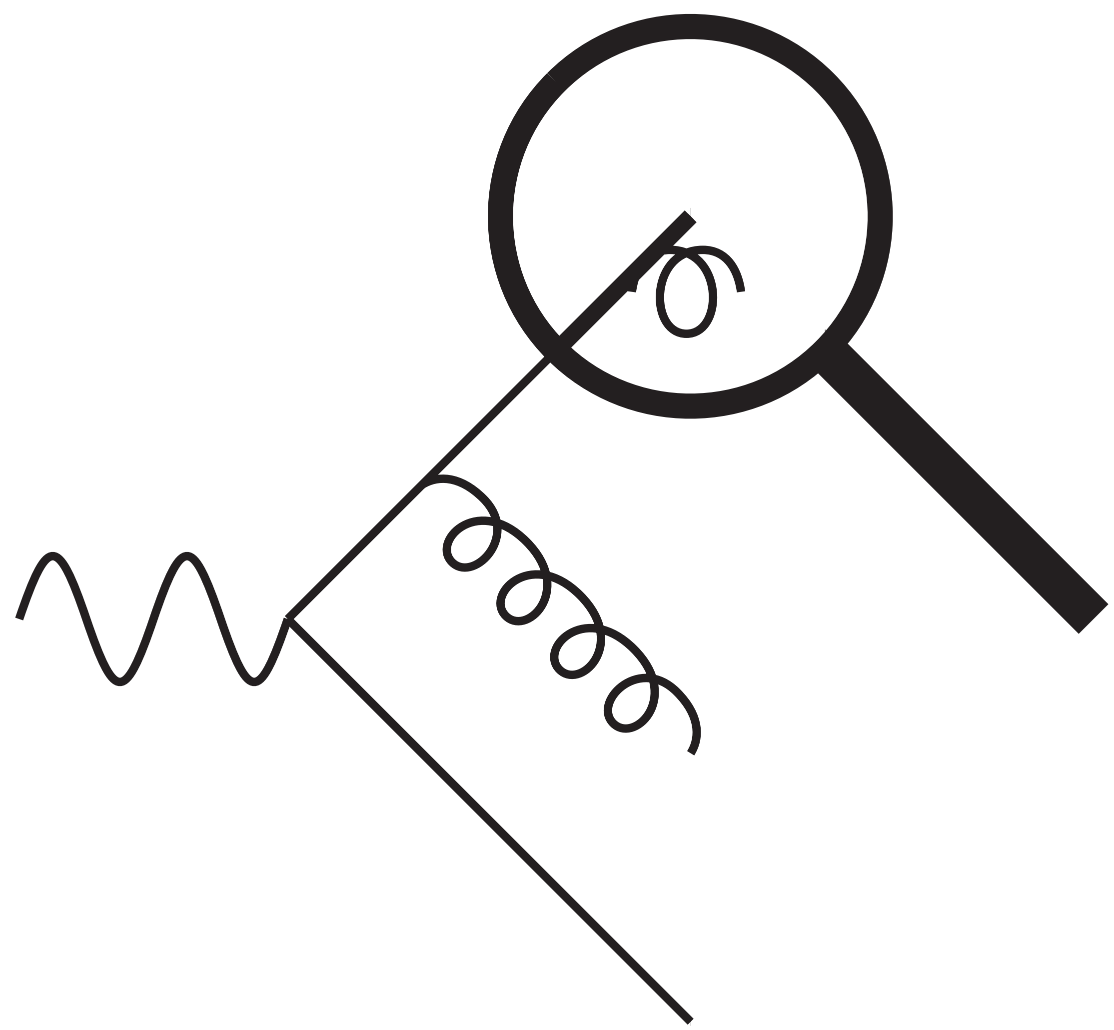
fixed order

full pQCD
(fixed order)

few partons

Energy Scales at a Collider





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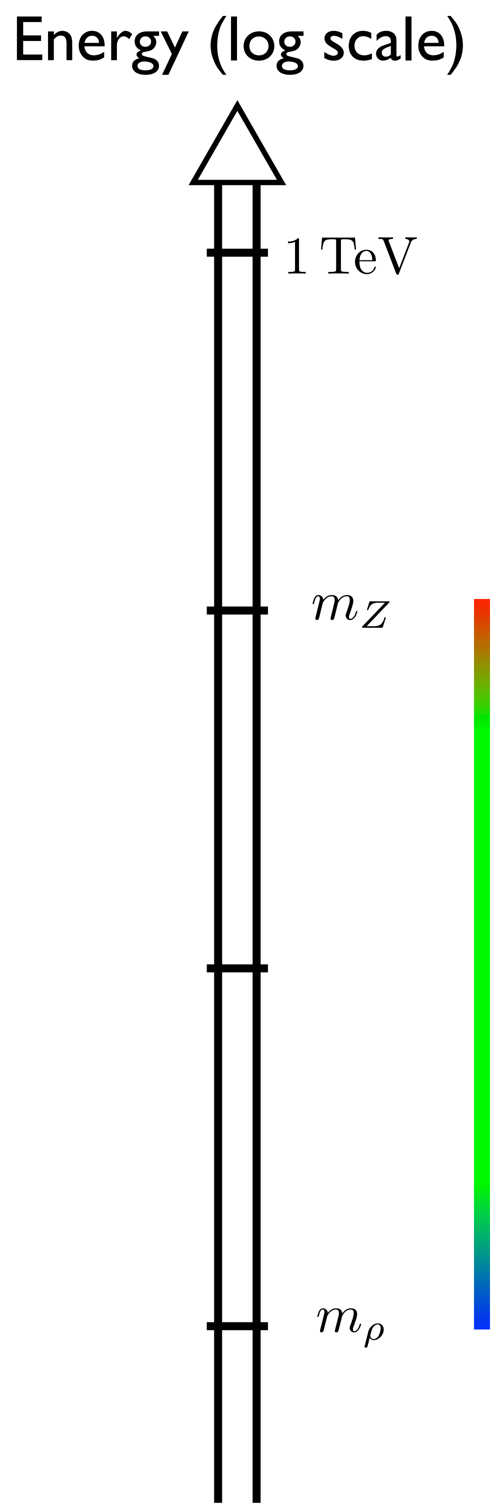

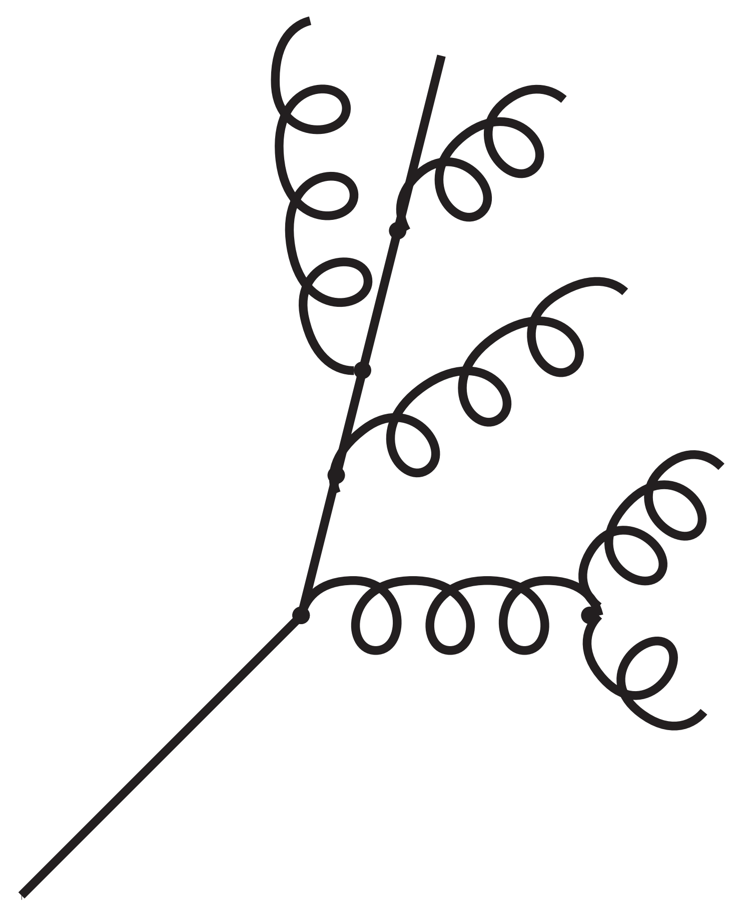

Energy Scales at a Collider

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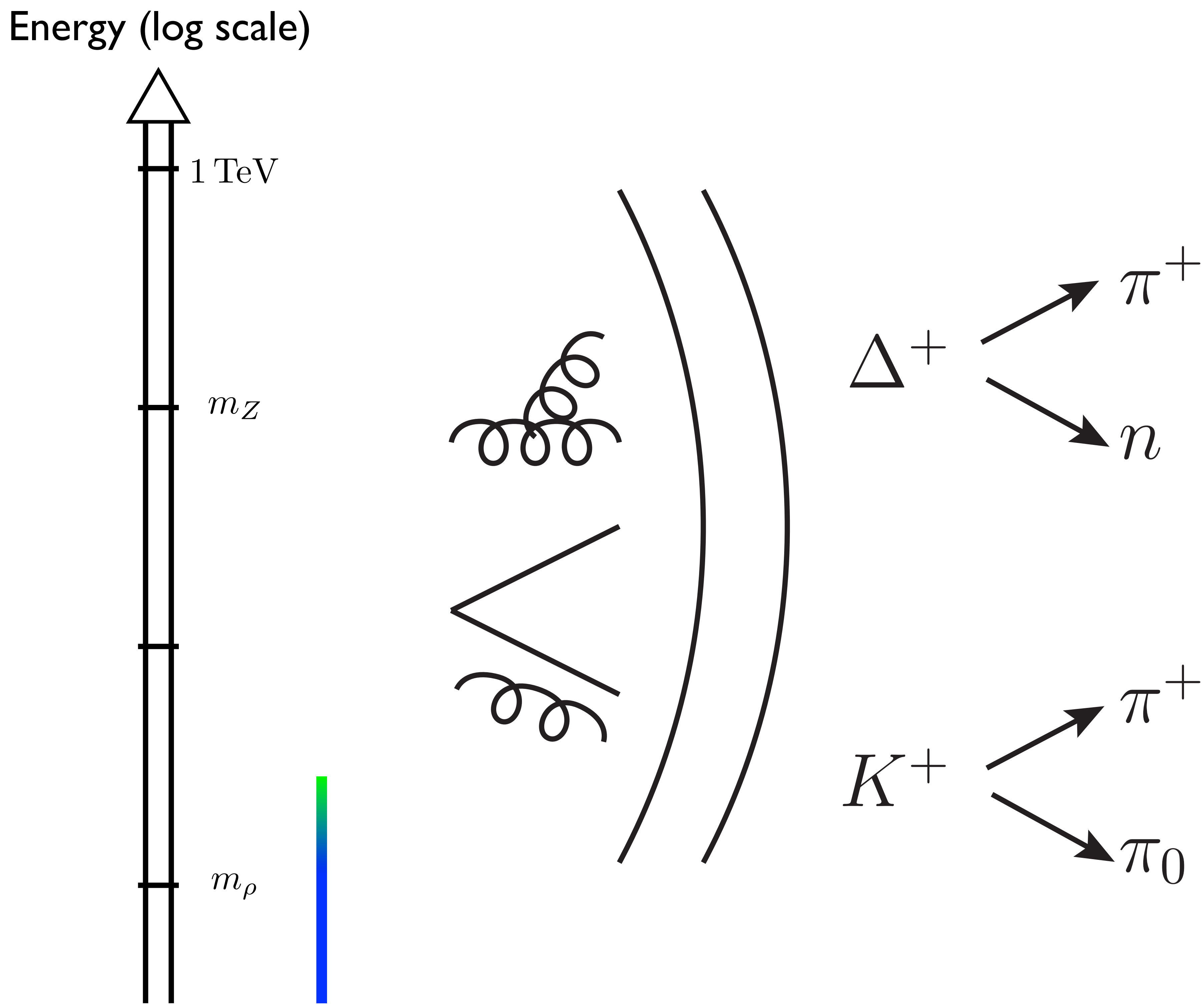

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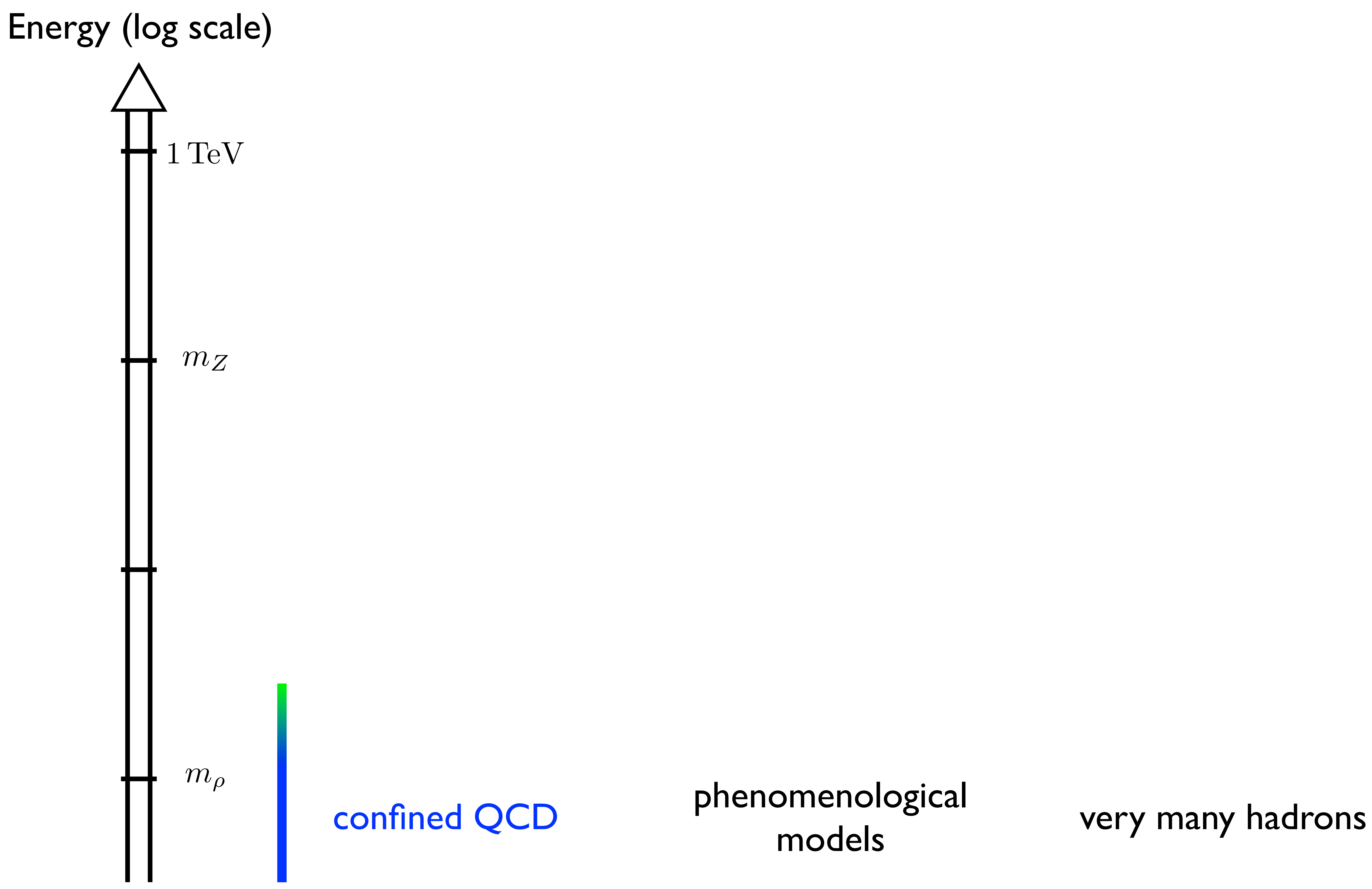

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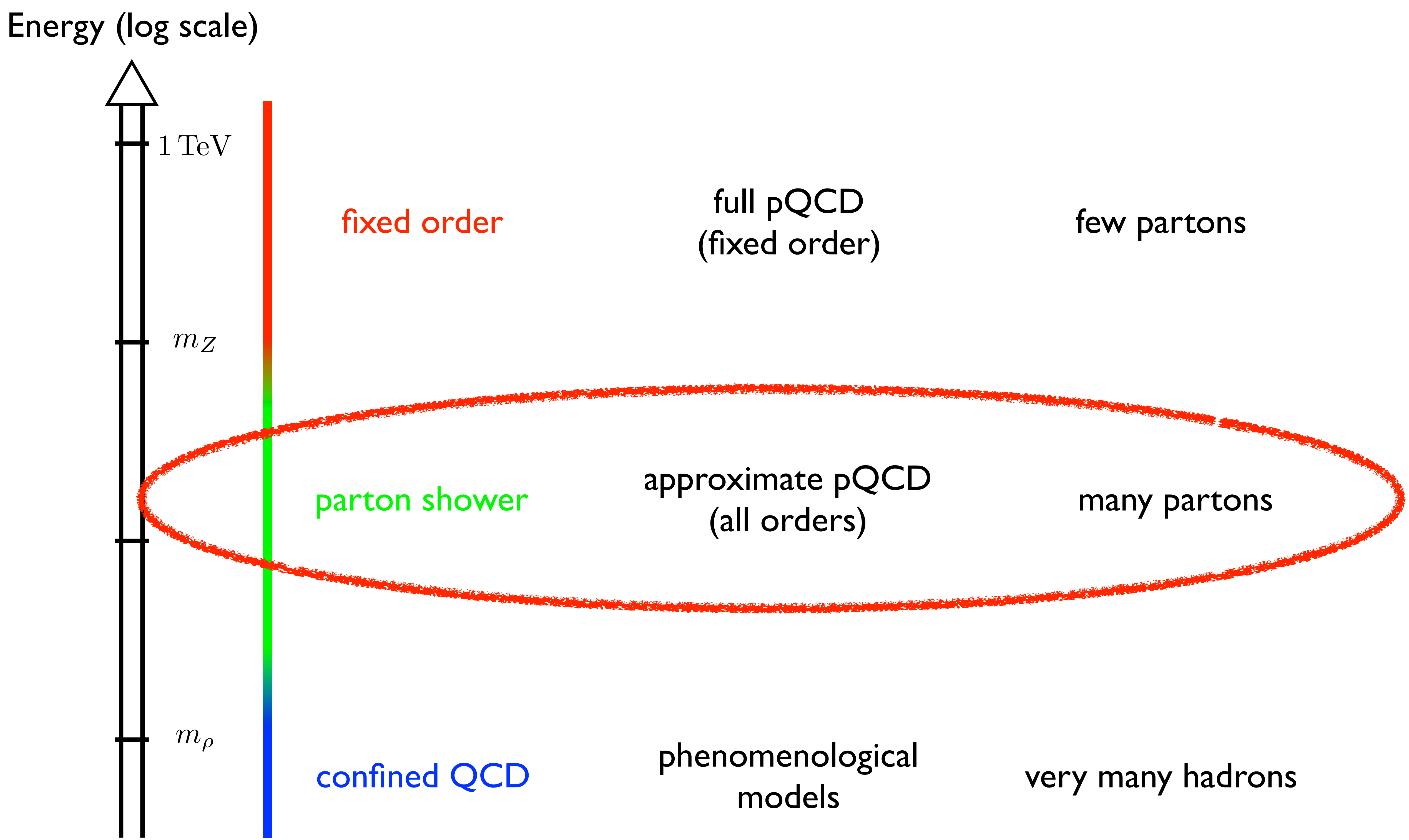


Parton Showers - Questions

- What governs the emission pattern?
- How are emissions ordered?
- How is colour coherence accounted for?

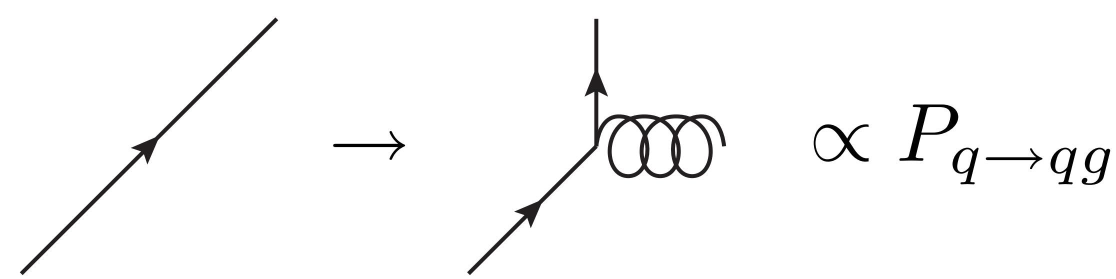
Examples of Parton Showers

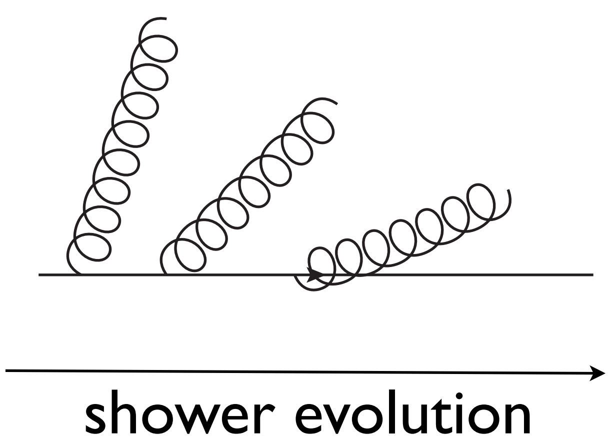
Examples of Parton Showers

based on
ordering
coherence

Examples of Parton Showers

	Herwig++[1]
based on	$1 \rightarrow 2$ Altarelli-Parisi splitting functions
ordering	angular ordering
coherence	





[1] M. Bähr, S. Gieseke, M.A. Gigg, D. Grellscheid, K. Hamilton, O. Latunde-Dada, S. Plätzer, P. Richardson, M.H. Seymour, A, Sherstnev, J. Tully, B. R. Webber arXiv:0803.0883

Examples of Parton Showers

<table>
<tr><th></th><th>Herwig++[1]</th><th>Sherpa [2]</th></tr>
<tr><td>based on</td><td>1 → 2
Altarelli-Parisi
splitting functions</td><td>1 → 2
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<tr><td>ordering</td><td rowspan="2">angular ordering</td><td>particle virtuality</td></tr>
<tr><td>coherence</td><td>angular ordering
superimposed</td></tr>
</table>

[2] T. Gleisberg, S. Höche, F. Krauss, M. Schönherr,
S. Schumann, F. Siegert, J. Winter
arXiv: 0811.4622

Examples of Parton Showers

	Herwig++[1]	Sherpa [2]	Sherpa [3]
based on	$1 \rightarrow 2$ Altarelli-Parisi splitting functions	$1 \rightarrow 2$ Altarelli-Parisi splitting functions	$2 \rightarrow 3$ Catani-Seymour dipoles [a, b]
ordering	angular ordering	particle virtuality	transverse momentum p_T
coherence		angular ordering superimposed	p_T ordering + $2 \rightarrow 3$ kinematics + C.-S. dipoles

[a] S. Catani, M. H. Seymour arXiv: hep-ph/9602277

[b] Z. Nagy, D. E. Soper arXiv: hep-ph/0601021

[3] S. Schumann, F. Krauss arXiv: 0709.1027

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A-P s. functions
($2 \to 3$ kinematics)</td></tr>
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+ C.-S. dipoles</td><td>p_T ordering +
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</table>

[4] T. Sjöstrand, S. Mrenna, P. Skands
arXiv: 0710.3820

Vincia

W. Giele, D. Kosower, P. Skands
arXiv:0707.3652

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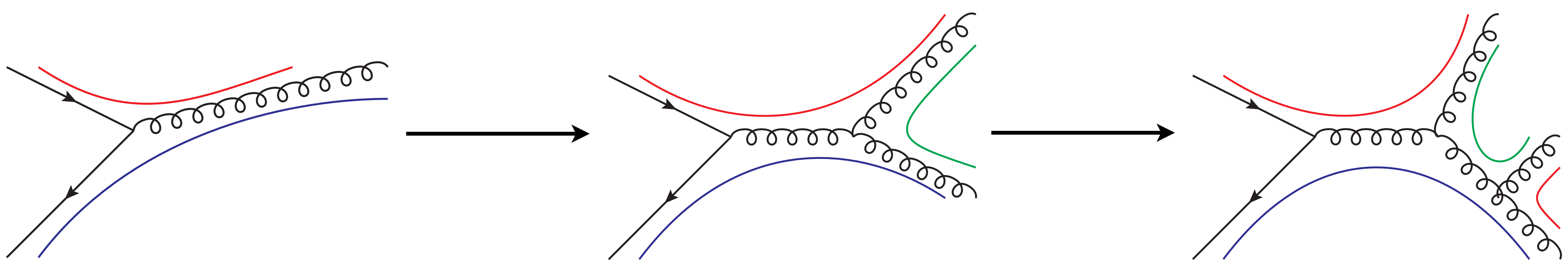
W. Giele, D. Kosower, P. Skands
arXiv:0707.3652

- based on 2→3 splittings (antenna cascade, as pioneered by Ariadne [1])



[1] G. Gustafson, U. Pettersson
Nucl.Phys.B306:746,1988

- based on 2→3 splittings (antenna cascade, as pioneered by Ariadne [1])

for other projects inspired by Ariadne, see e.g.

J.-C. Winter, F. Krauss
arXiv: 0712.3913

A. J. Larkoski, M. E. Peskin
arXiv: 0908.2450

[1] G. Gustafson, U. Pettersson
Nucl.Phys.B306:746,1988

Vincia

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- closely related to antenna subtraction[2]

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arXiv:hep-ph/0505111

Vincia

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- based on $2 \rightarrow 3$ splittings (antenna cascade, as pioneered by Ariadne [1])
- flexible with regards to ordering variable
- closely related to antenna subtraction[2]
- implemented for e^+-e^- collisions at present

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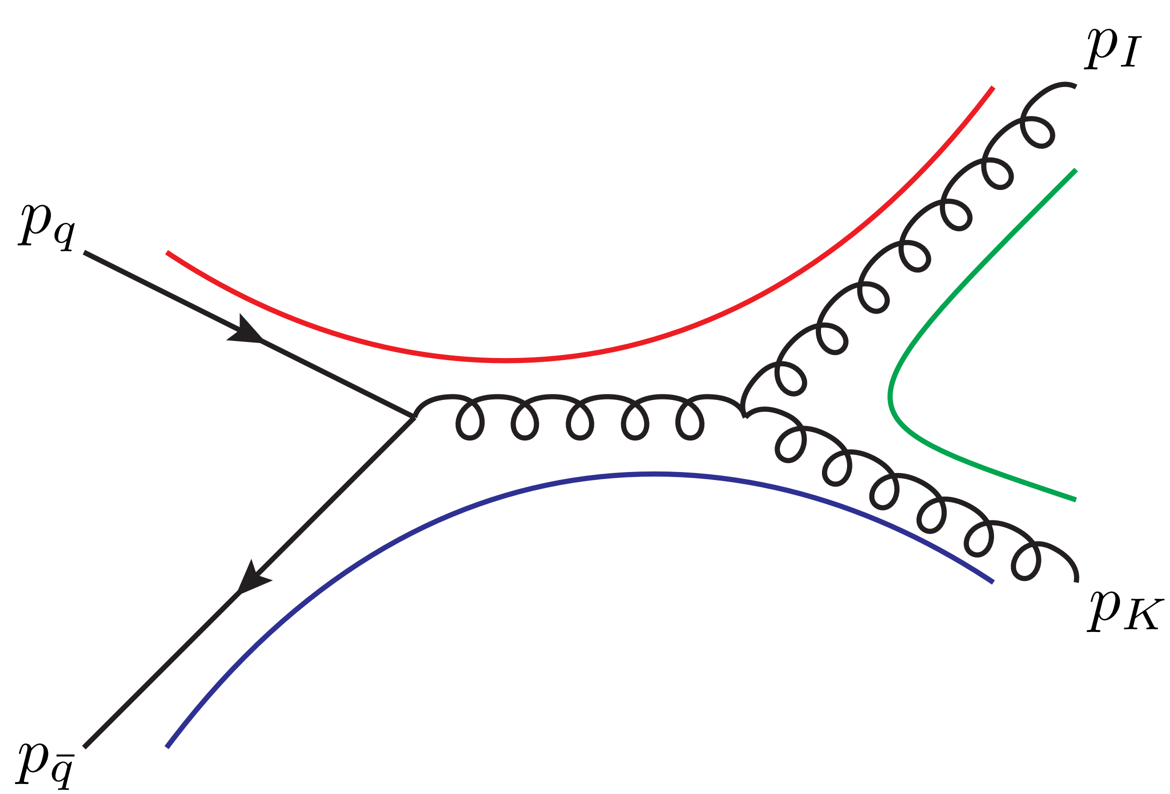
Goals of Vincia

a parton shower which

- improves the description of QCD radiation
- facilitates matching with fixed order results
- helps estimating its “theory error”
- can be used from within Pythia 8

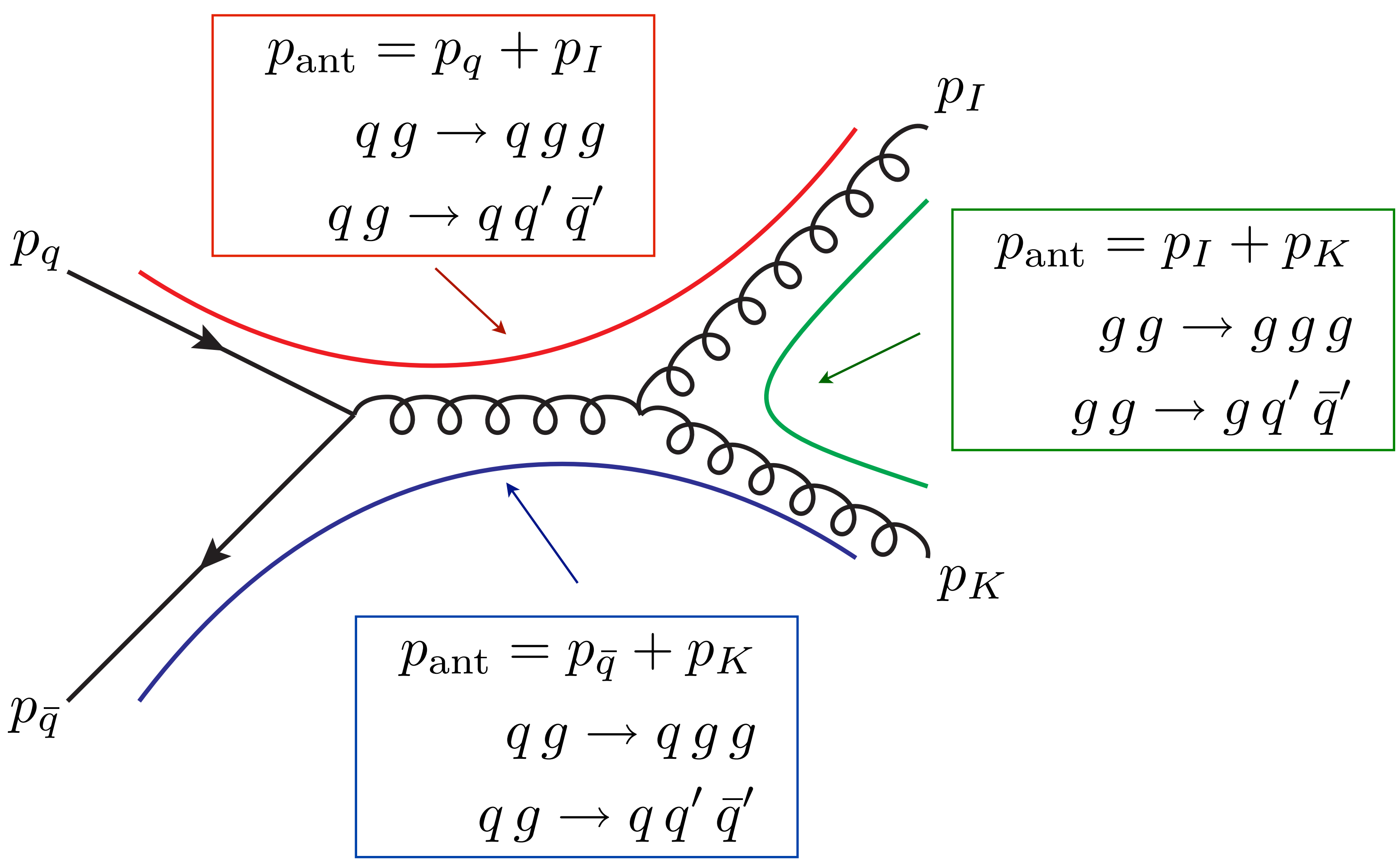
Antenna Shower - Cartoon

at what value of the ordering variable Q will each antenna emit?



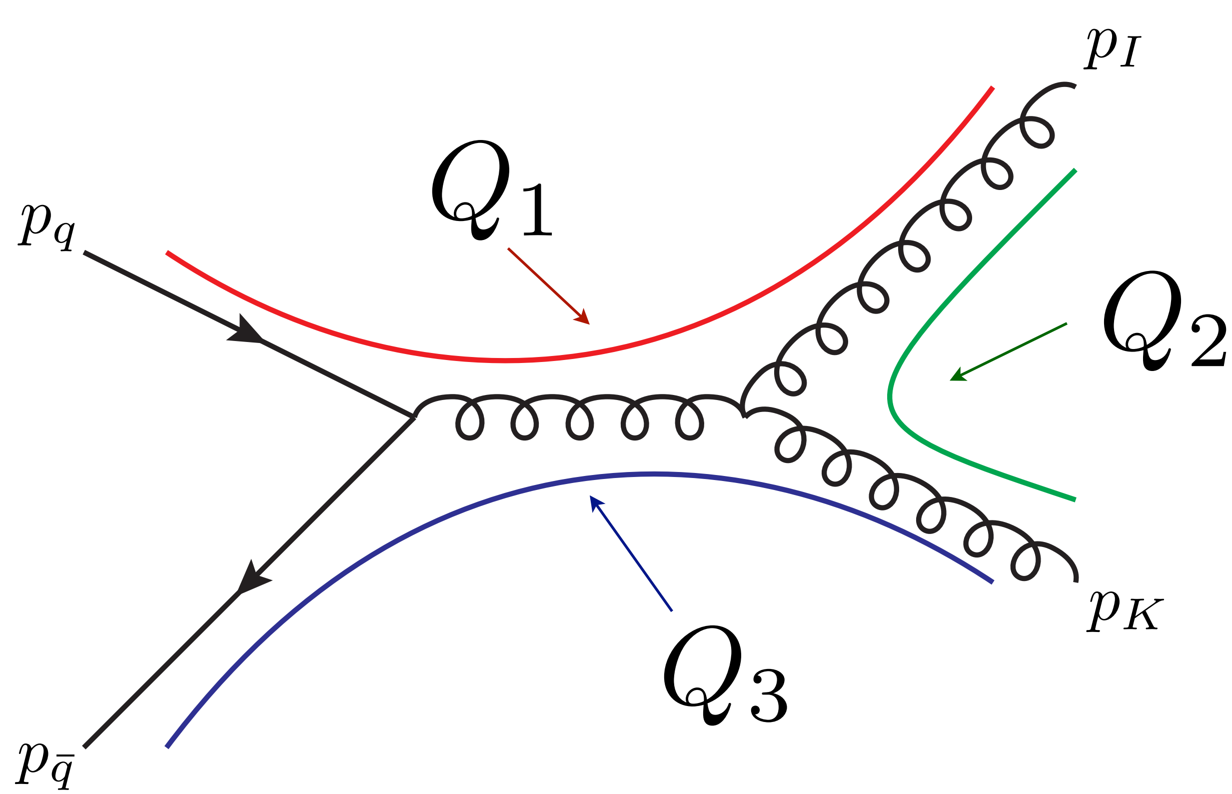
Antenna Shower - Cartoon

determined by evolution integral $\mathcal{I}_A\left(p^2_{\text{ant}}, Q^2_{\text{start}}, Q^2_{\text{emit}}\right)$



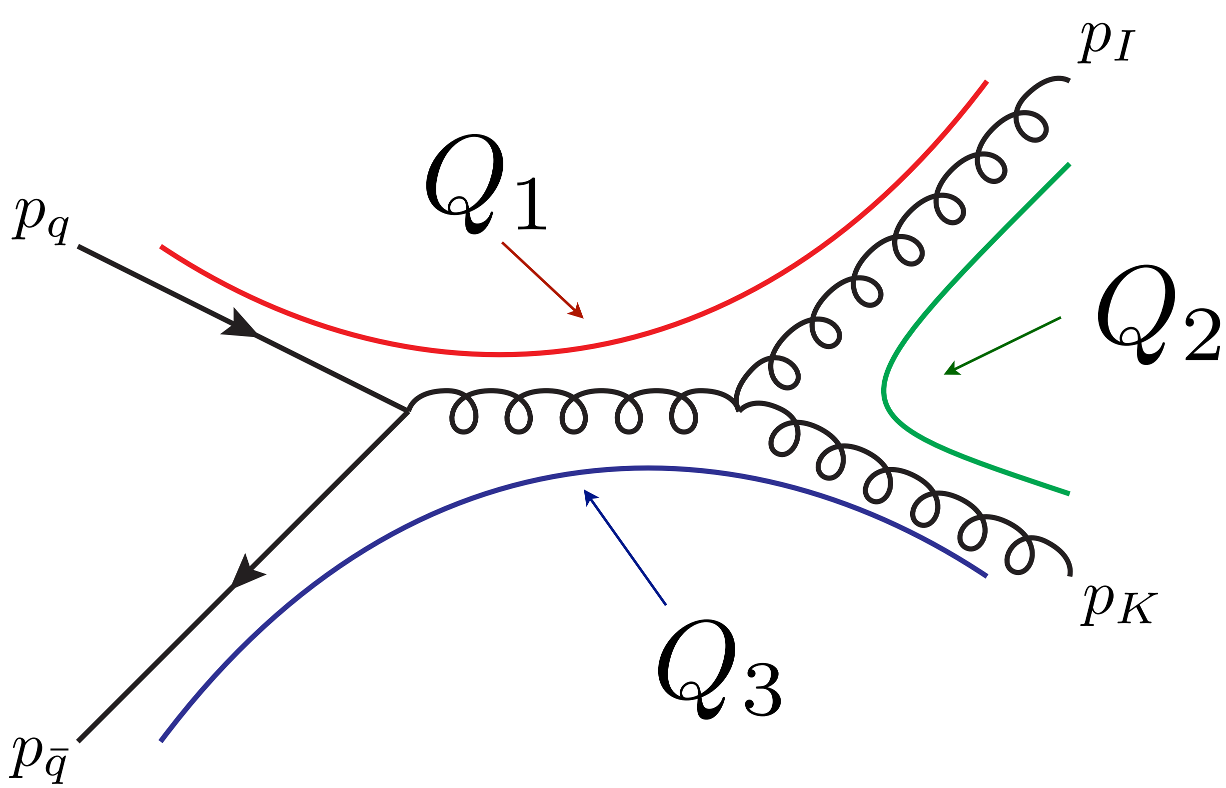
Antenna Shower - Cartoon

determine scales



Antenna Shower - Cartoon

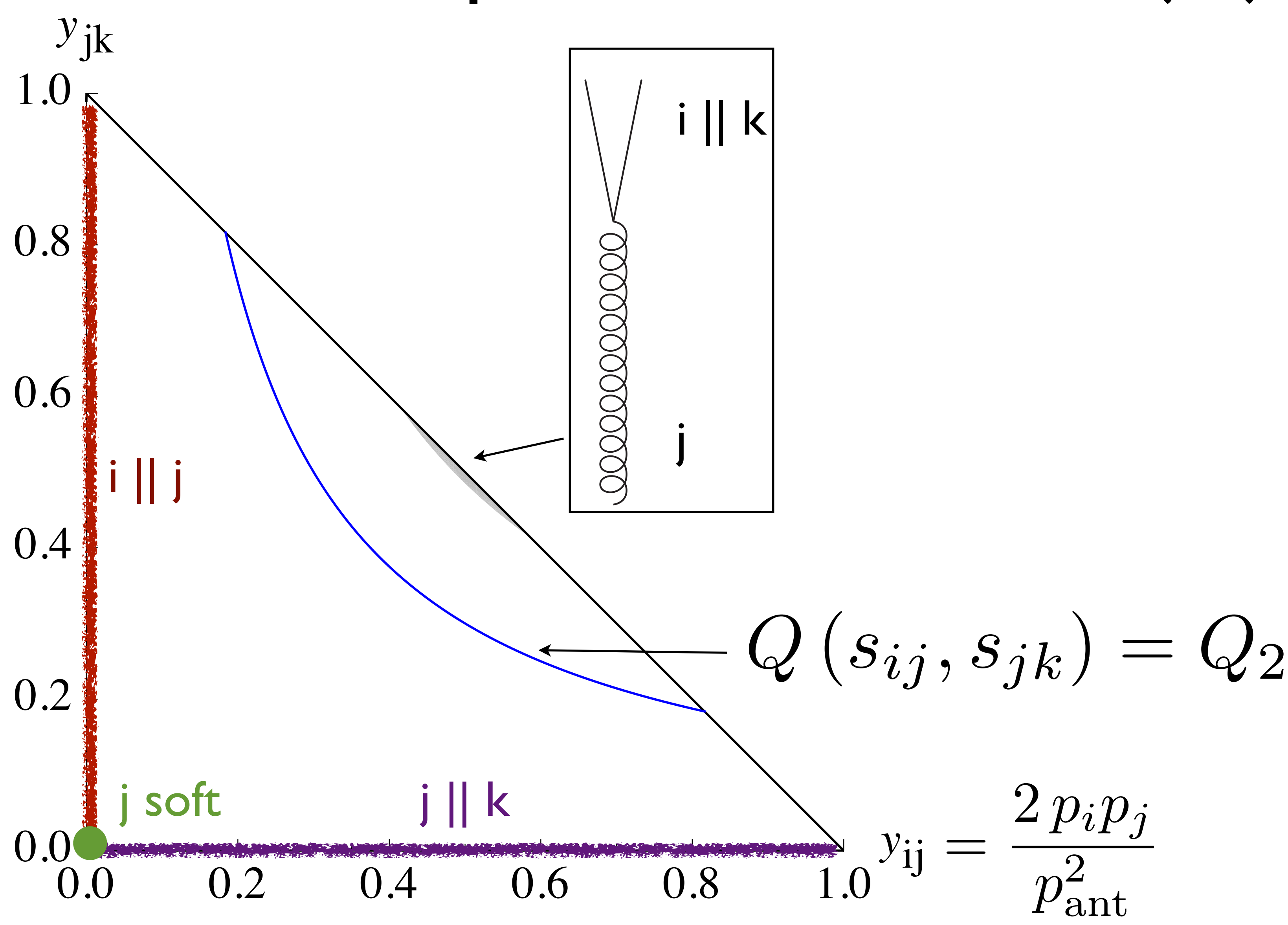
determine scales



$$Q_2 > Q_1 > Q_3 \Rightarrow \text{split}\,\{p_I, p_K\} \to \{p_i, p_j, p_k\}$$

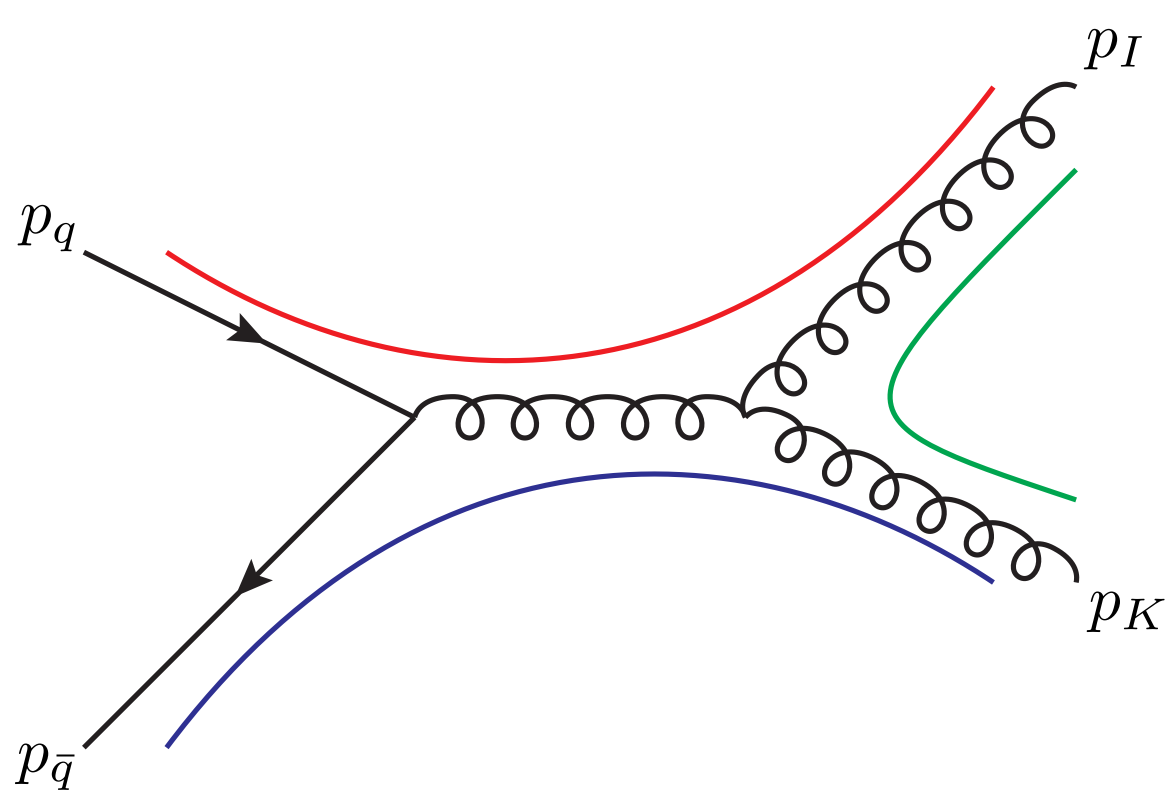
Dipole-Antenna Shower - Cartoon

given Q_2, determine 3-particle invariants s_{ij}, s_{jk}



Dipole-Antenna Shower - Cartoon

from s_{ij}, s_{jk} , determine p_i, p_j, p_k with momentum mapping



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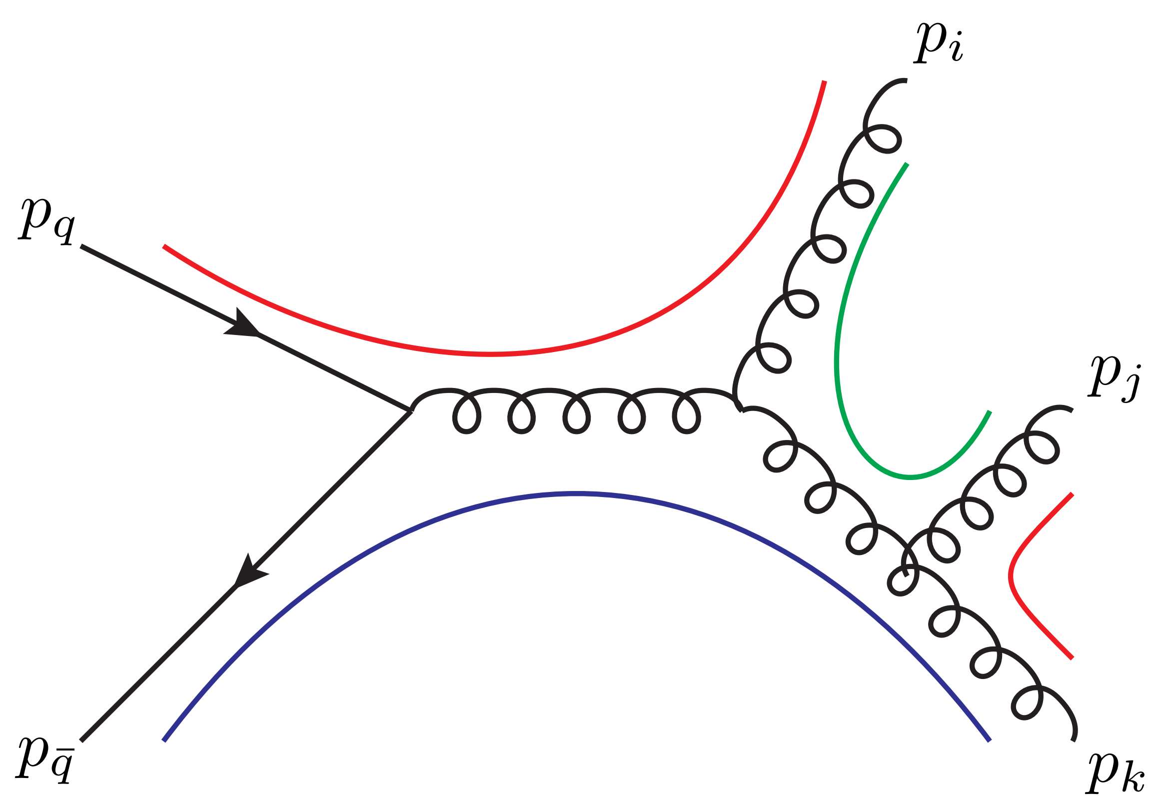
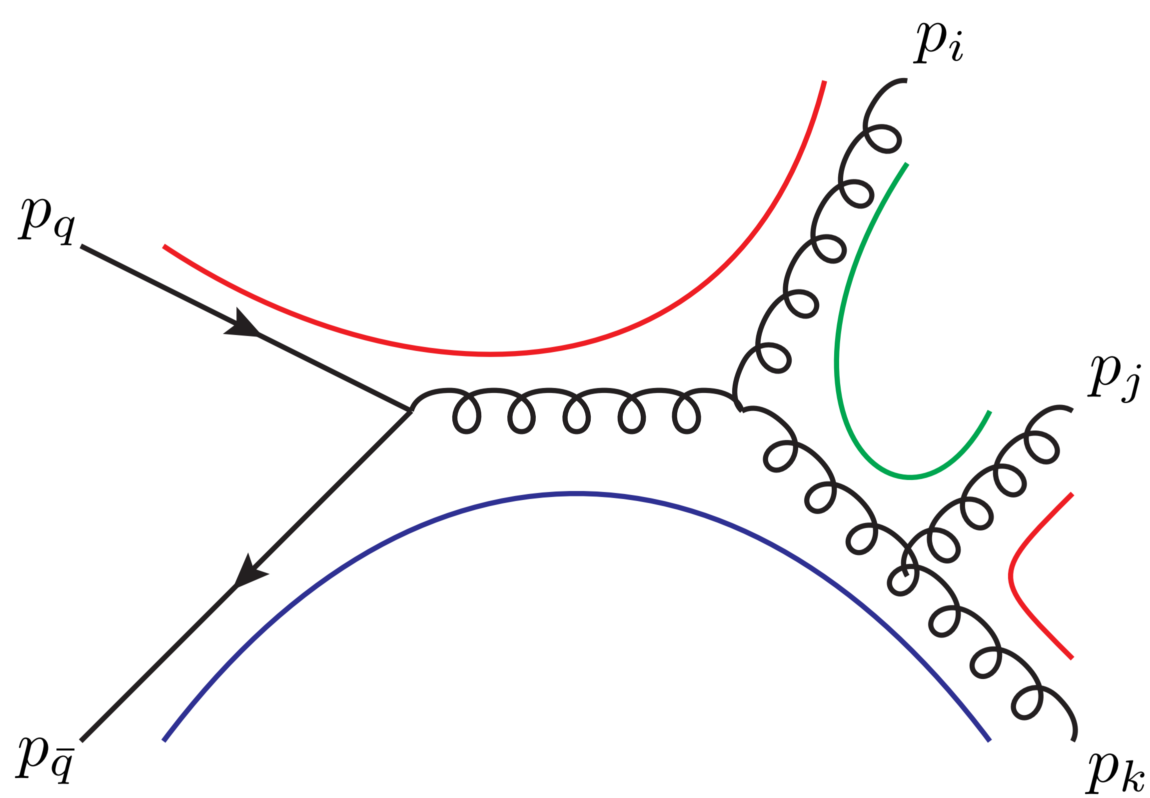


replace

Dipole-Antenna Shower - Cartoon

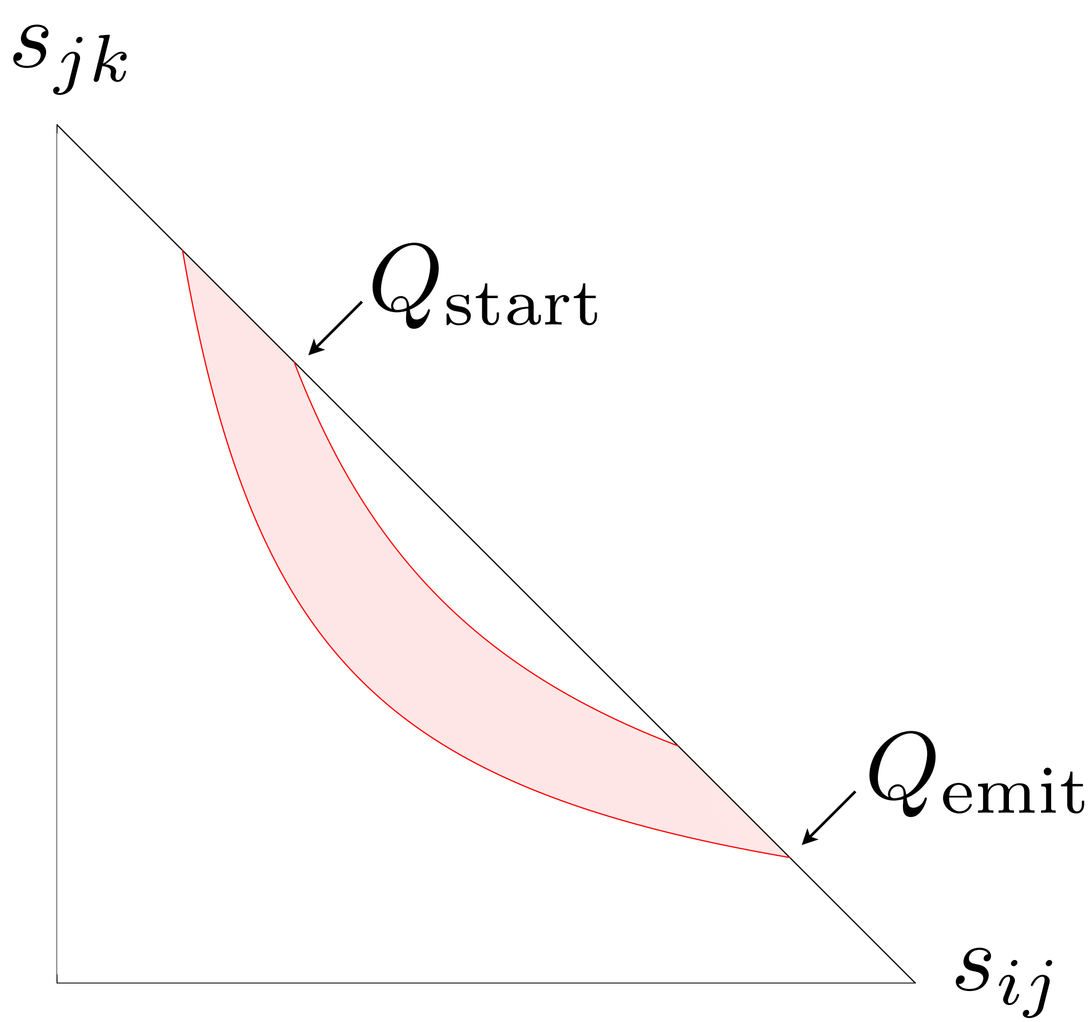
restart



Evolution Integral $\mathcal{I}_A$

$$\mathcal{I}_A\left(p_{\mathrm{ant}}^2, Q_{\mathrm{start}}^2, Q_{\mathrm{emit}}^2\right) =$$

$$\frac{1}{\lambda}\int_{Q_{\mathrm{emit}}^2}^{Q_{\mathrm{start}}^2} \mathrm{d}s_{ij}\mathrm{d}s_{jk}\frac{\alpha_s\left(s_{ij}, s_{jk}\right)}{4\pi}C_{ijk}A_{IK\to ijk}(s_{ij}, s_{jk}, \ldots)$$



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Q : evolution variable

$s_{ij} = 2\, p_i\, p_j$

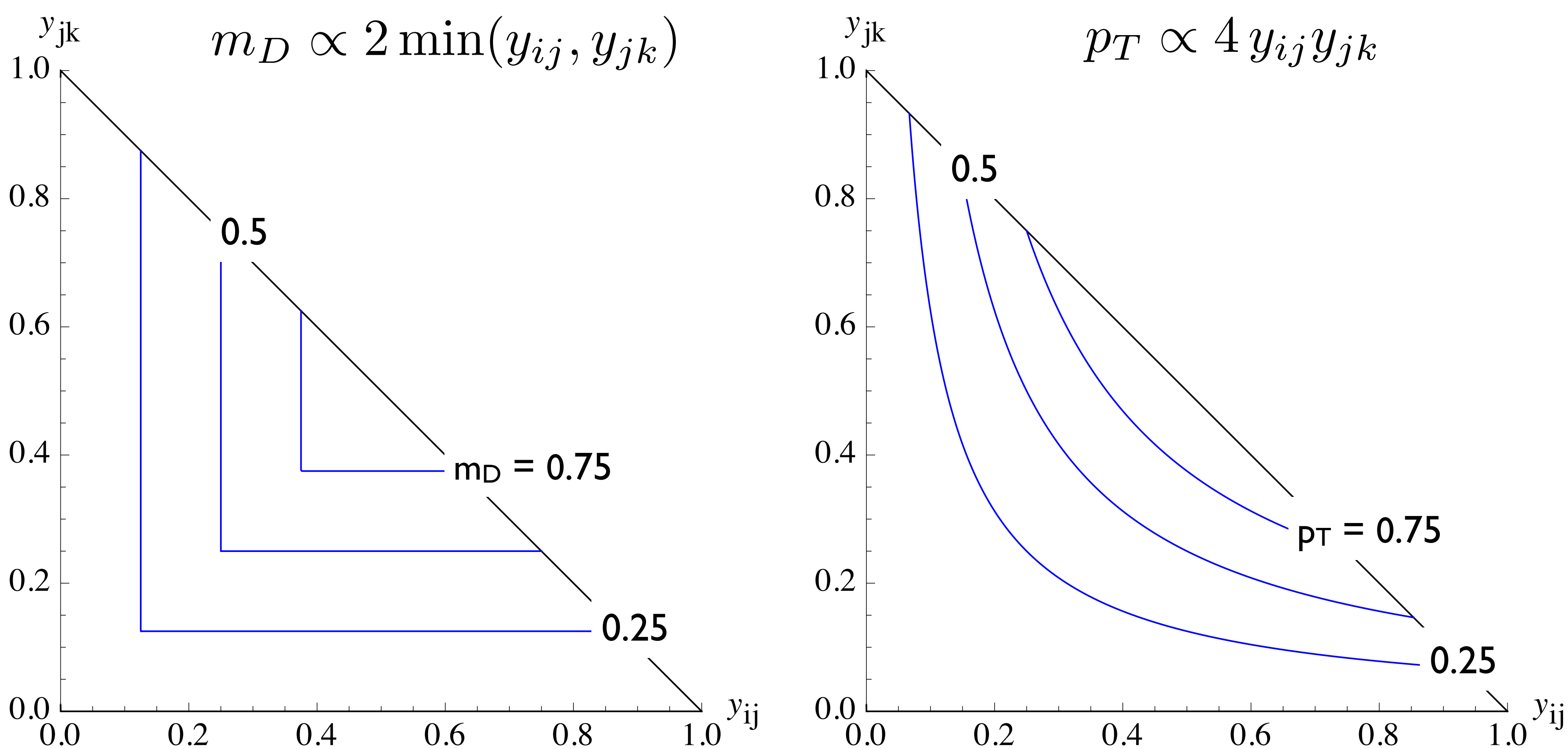
C_{ijk} : colour factor

$A_{IK\to ijk}(p^2_{\mathrm{ant}}, s_{ij}, s_{jk}, m_i^2, m_j^2, m_k^2)$: antenna function

$\lambda = \lambda(p^2_{\mathrm{ant}}, m_I^2, m_K^2) = (2\, p_I\, p_K)^2 - (2 m_I m_K)^2$

Evolution Variables

several options implemented



Antenna Functions

$$\mathcal{I}_A\left(p^2_{\rm ant}, Q^2_{\rm start}, Q^2_{\rm emit}\right) =$$

$$\frac{1}{\lambda}\int_{Q^2_{\rm emit}}^{Q^2_{\rm start}} {\rm d}s_{ij}{\rm d}s_{jk}\,\frac{\alpha_s\left(s_{ij},s_{jk}\right)}{4\pi} C_{ijk} A_{IK\to ijk}(s_{ij},s_{jk},\dots)$$

- reproduce (quasi-)collinear splitting functions / soft eikonals in unresolved limits
- parts which do not contribute in unresolved limits are irrelevant for fixed order, but influence the shower

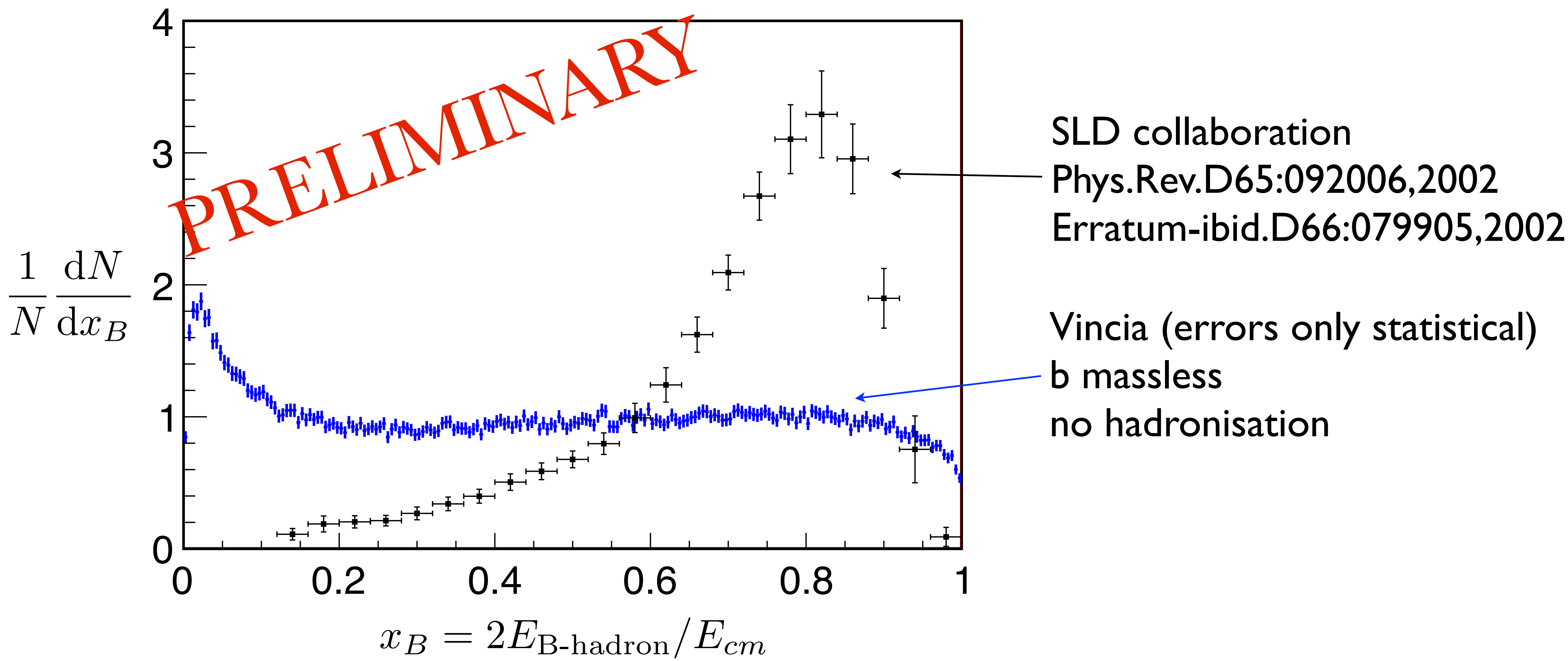
$\Longrightarrow$ handle on shower uncertainty

Masses - needed?

- secondary production of beauty and charm are highly relevant to phenomenology
- during the shower evolution, quark masses will become important inevitably
- want to be consistent with the production of heavy mesons

Masses - needed?

$$e^+e^- \to \text{B-hadron(s)} + \text{X}, \quad \sqrt{s} = 91.28\,\text{GeV}$$



Masses in Vincia

A. Gehrmann-De Ridder, MR, P. Skands
in preparation

masses have to be implemented in

- phase space
- antenna functions[1]
- momentum mapping

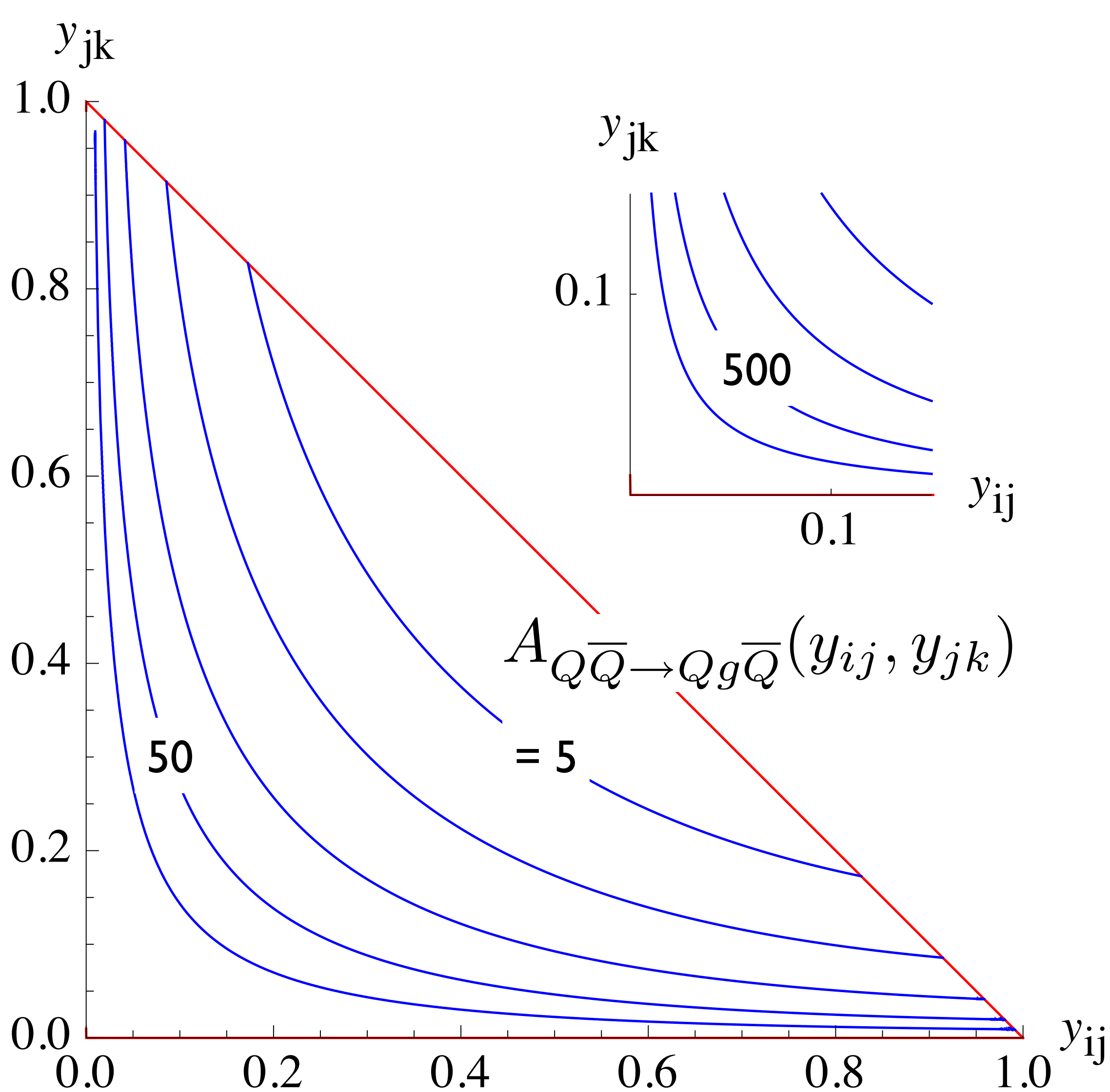
[1] A. Gehrmann-De Ridder, MR
arXiv:0904.3297

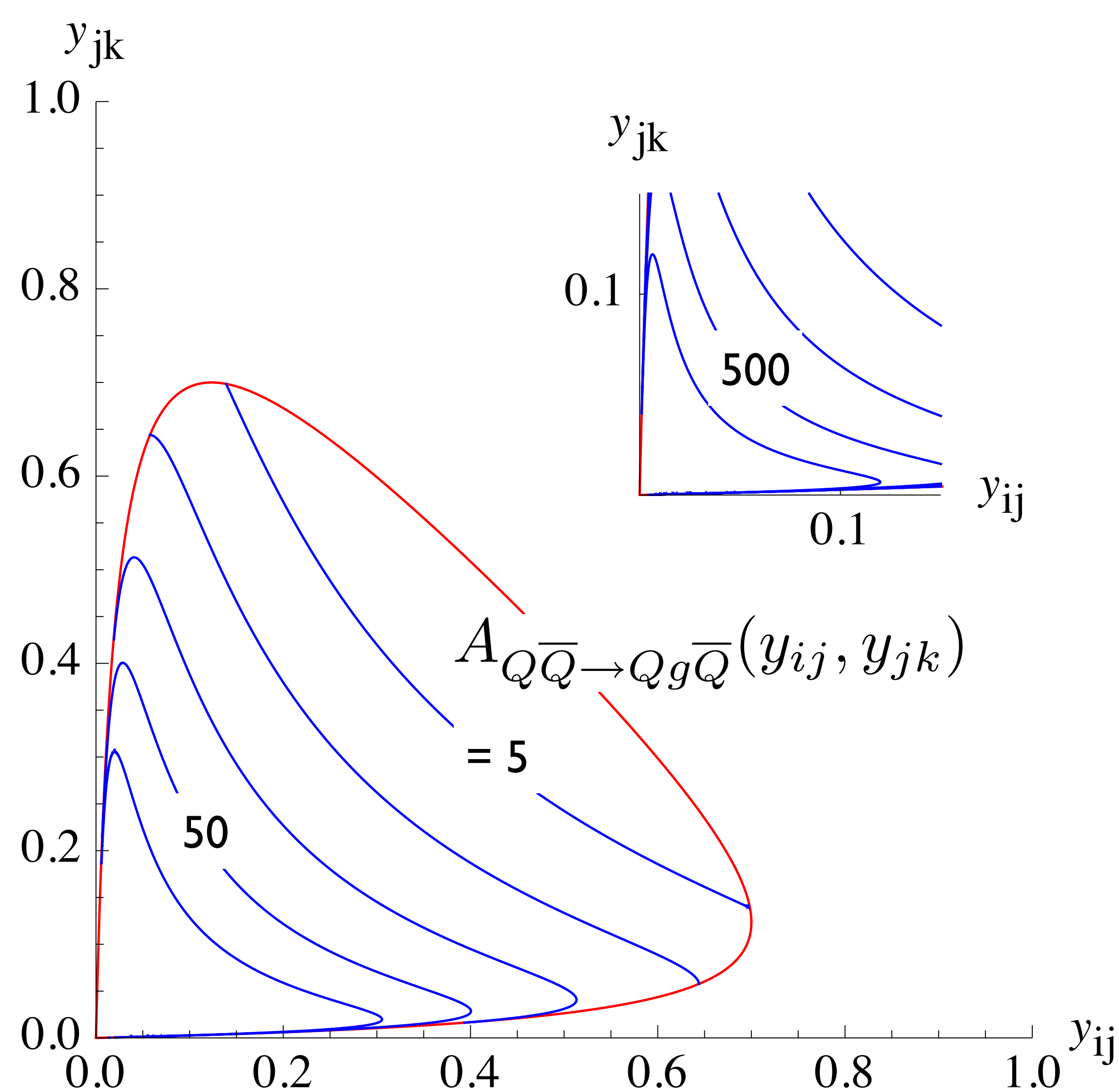
Massive Antennae:

$$Q\overline{Q} \to Qg\overline{Q}$$

massless

$$m_Q = m_{\overline{Q}} = 0.15\sqrt{p^2_{\mathrm{ant}}}$$



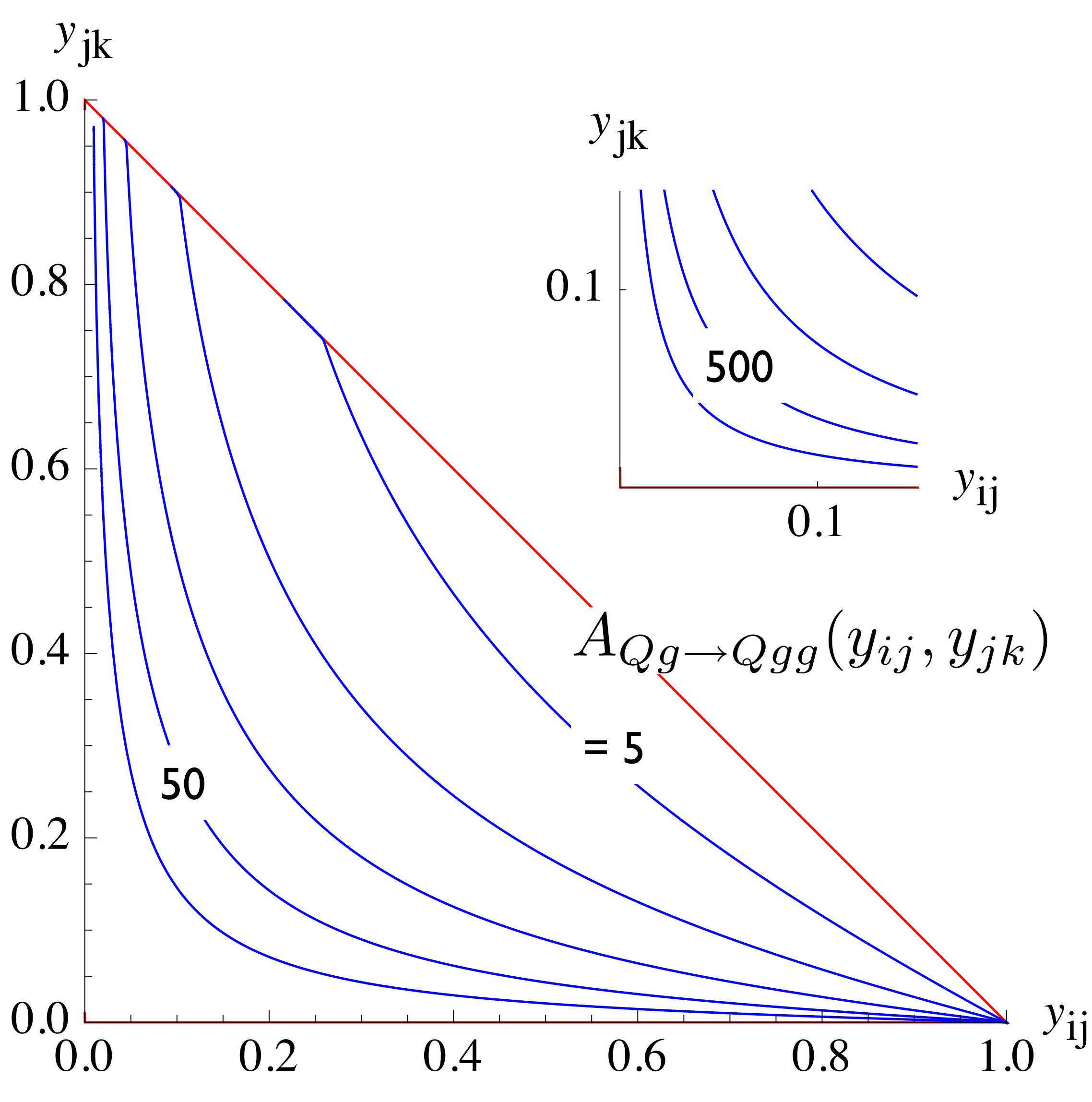


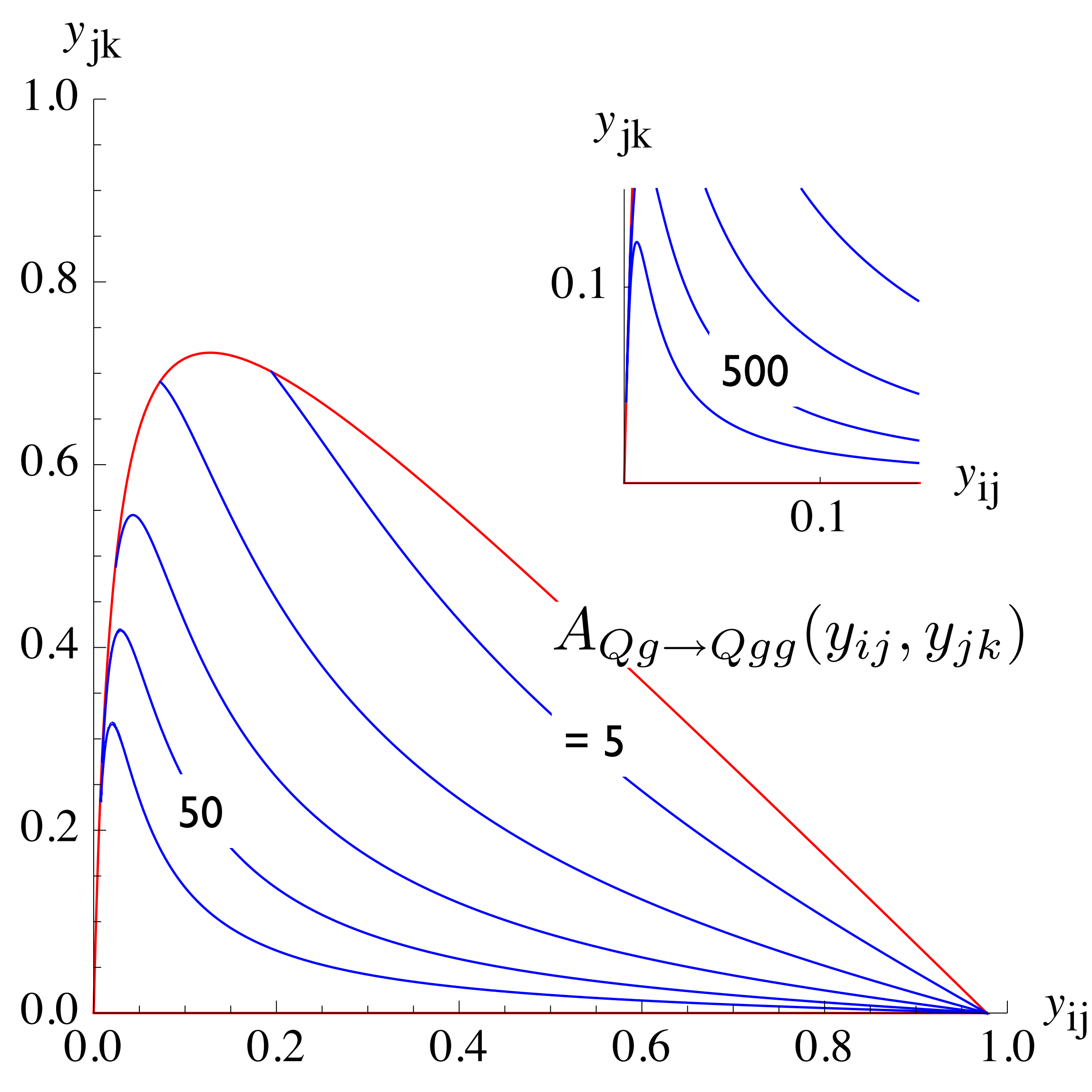
Massive Antennae:

$$Qg \to Qgg$$

massless

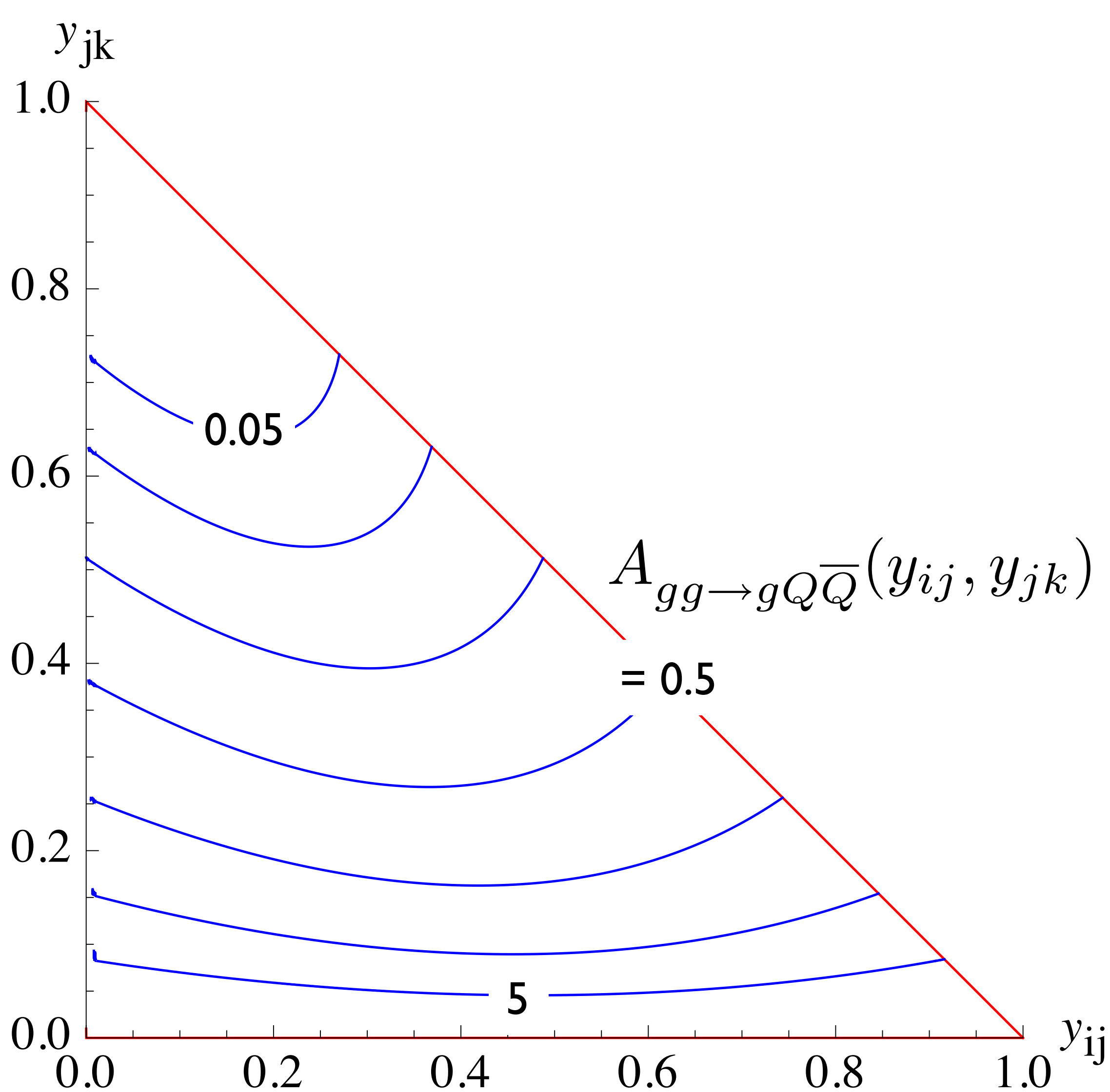
$$m_Q = 0.15\,\sqrt{p^2_{\rm ant}}$$





Massive Antennae: $gg \to gQ\overline{Q}$

massless



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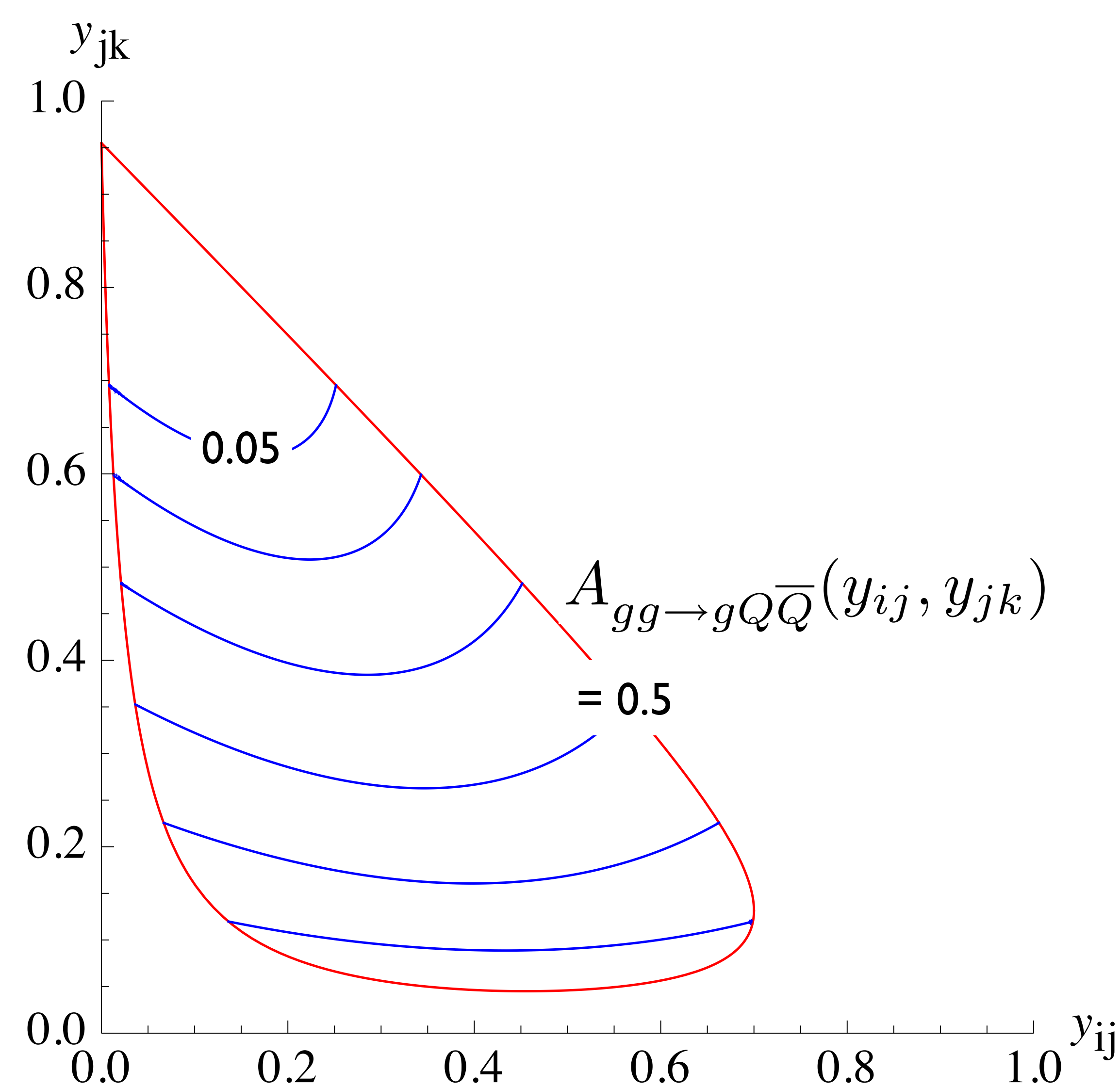

Massive Antenna Mapping

- conserves four-momentum
- keeps all particles on-shell

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} one parameter remaining

Massive Antenna Mapping

- conserves four-momentum
- keeps all particles on-shell

} one parameter remaining

- generalises massless antenna mapping[1]
- treats emitters of identical mass symmetrically

[1] D.A. Kosower
arXiv:hep-ph/0212097

Massive Antenna Mapping

$$\{p_I, p_K\} \to \{p_i, p_j, p_k\}\,, \quad p_I^2 = M_I^2, p_i^2 = m_i^2, \ldots$$

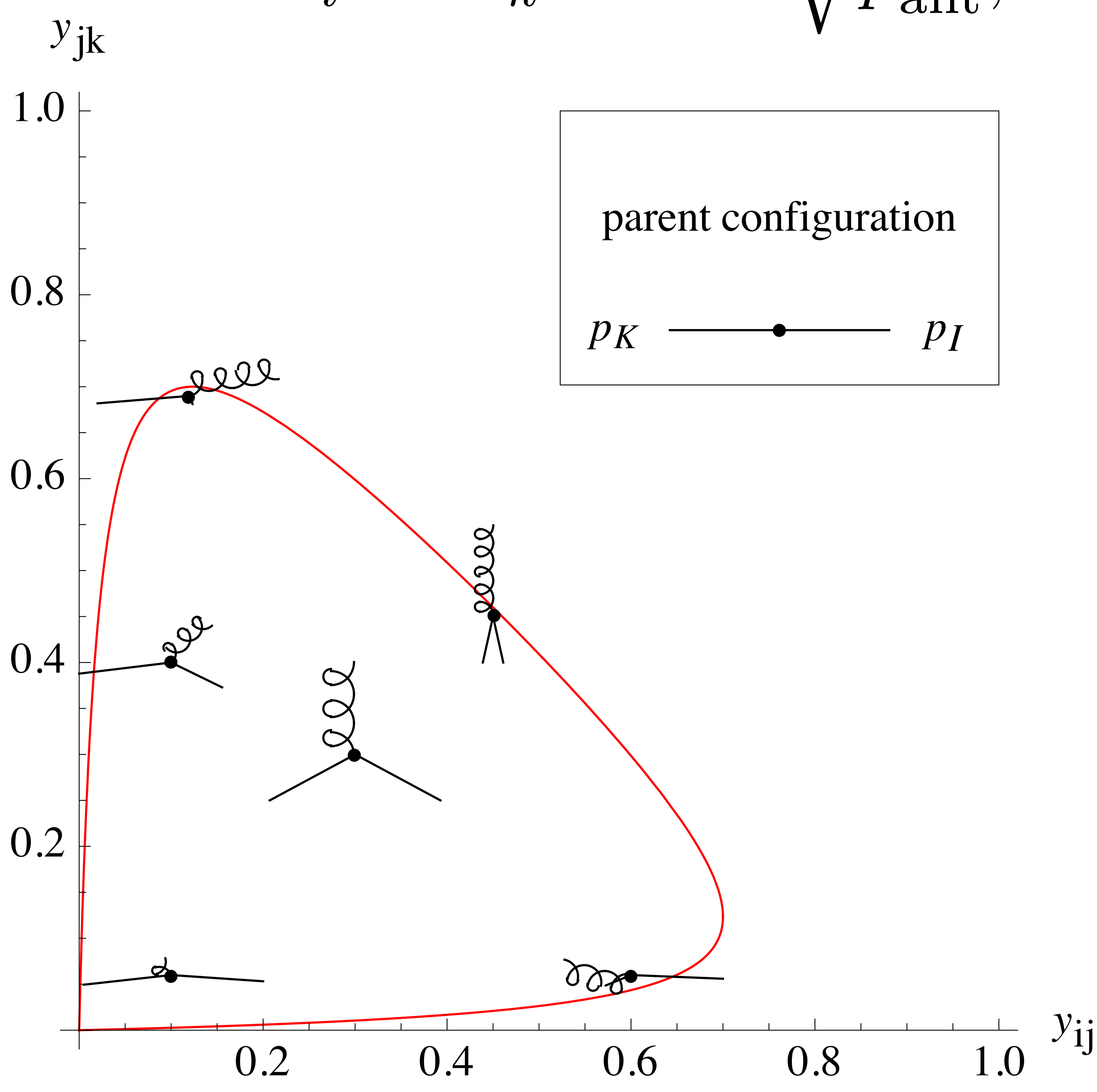
$$p_I = x\, p_i + r\, p_j + z\, p_k$$

antenna mapping given by

$$r = \frac{p_{\rm ant}^2 + M_I^2 - M_K^2}{2\, p_{\rm ant}^2} + \frac{\sqrt{s_{IK}^2 - (s_{IK}^{\rm min})^2}}{2\, p_{\rm ant}^2} \frac{(s_{jk} - \overbrace{s_{jk}^{\rm min}}^{2\, m_j m_k}) - (s_{ij} - s_{ij}^{\rm min})}{s_{jk} - s_{jk}^{\rm min} + s_{ij} - s_{ij}^{\rm min}}$$

Mapping - Examples

$$m_i = m_k = 0.15\sqrt{p^2_{\text{ant}}}, \quad m_j = 0$$



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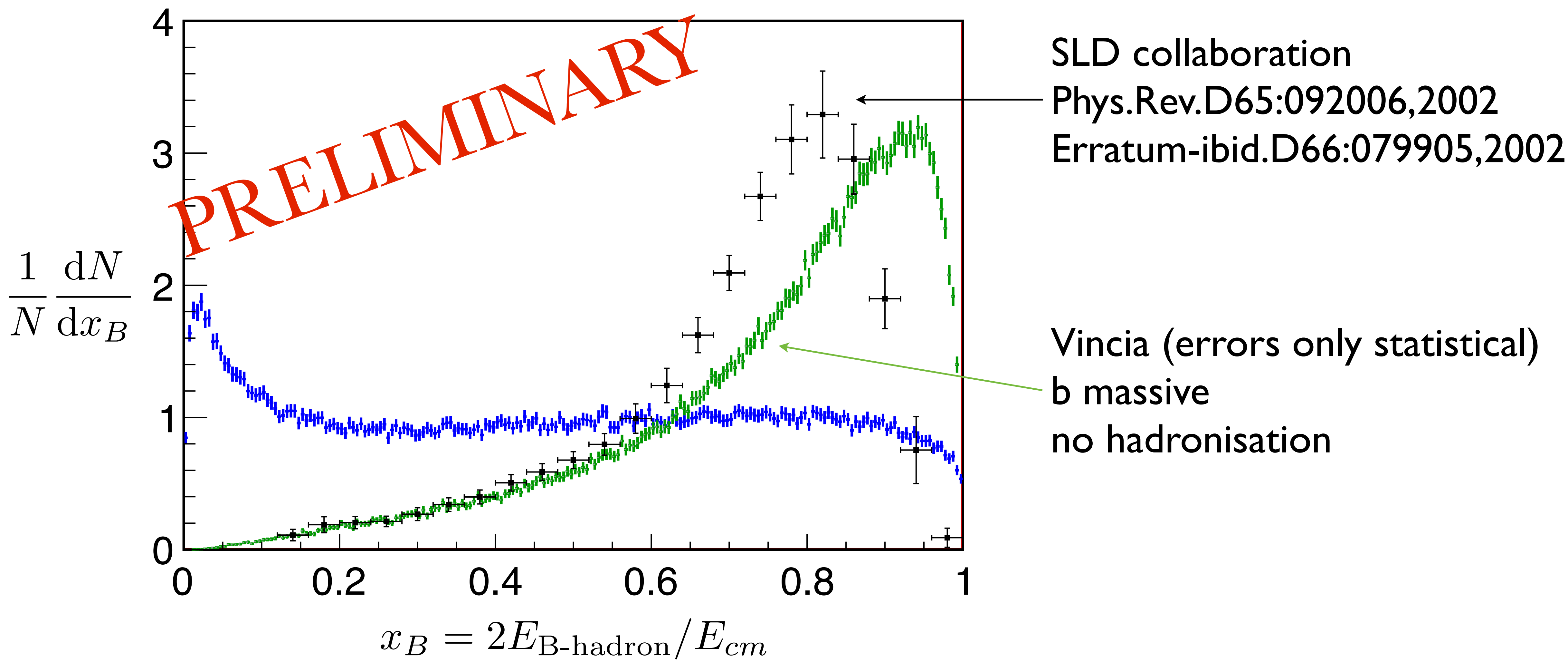

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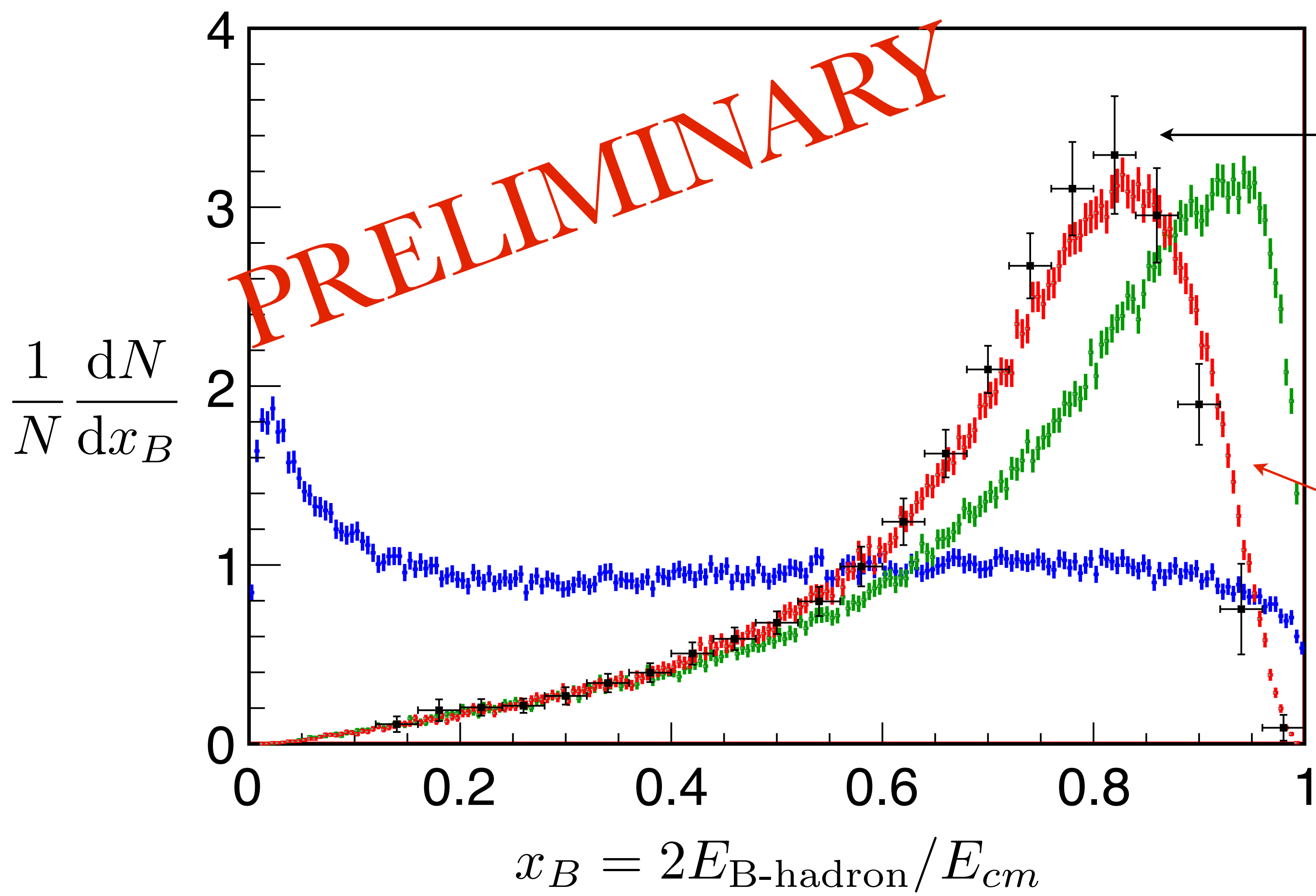

SLD collaboration
Phys.Rev.D65:092006,2002
Erratum-ibid.D66:079905,2002

Vincia (errors only statistical)
b massive
default Pythia 8 hadronisation

Conclusions

- Vincia has been extended to include quark masses in electron-positron collisions
- next: finish tests and tune hadronisation on LEP data
- next-to-next: extend to initial state partons