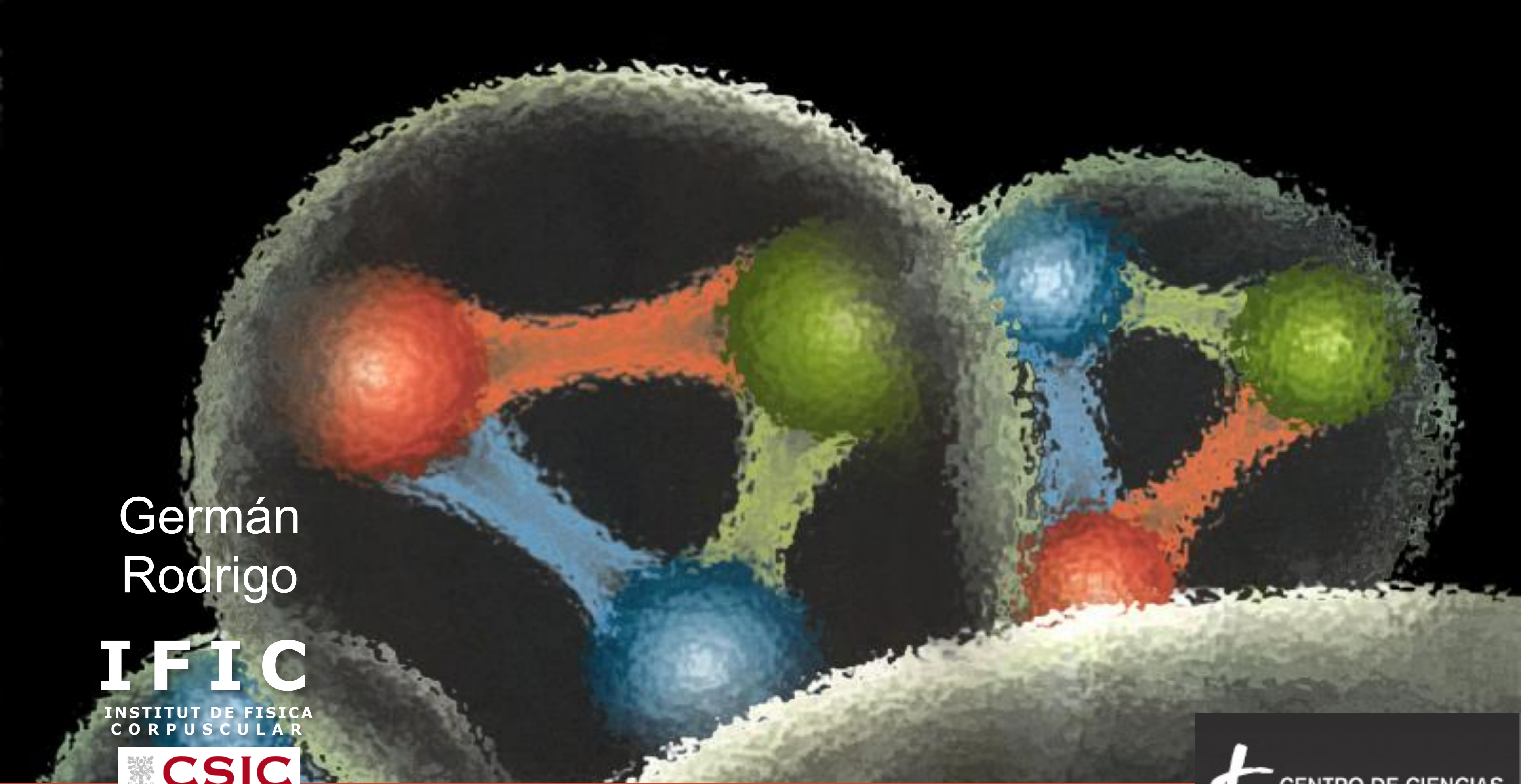

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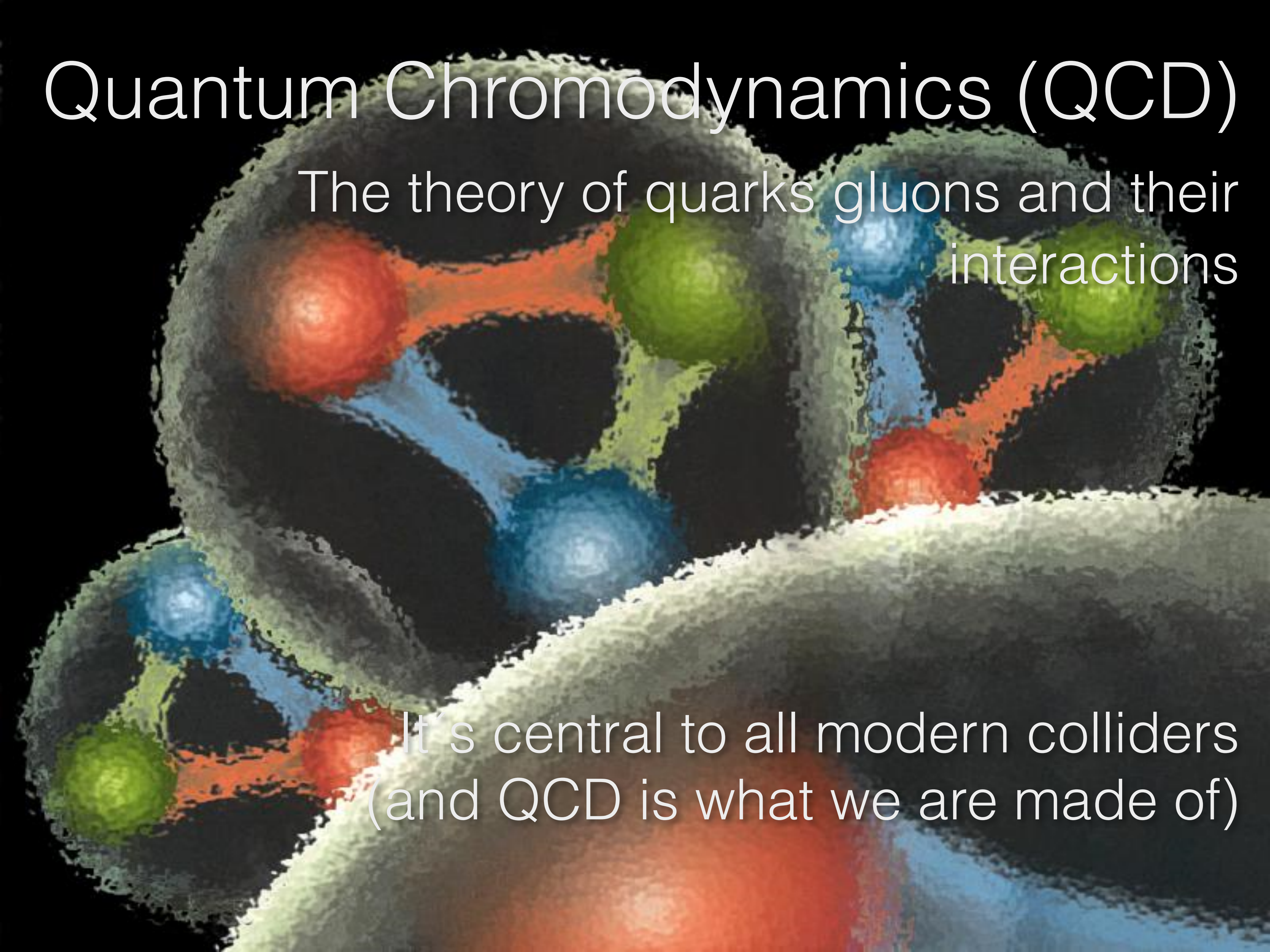
CENTRO DE CIENCIAS DE BENASQUE PEDRO PASCUAL

QCD

Taller de Altas Energías TAE2015, September 2015

Quantum Chromodynamics (QCD)

The theory of quarks gluons and their interactions



It's central to all modern colliders
(and QCD is what we are made of)

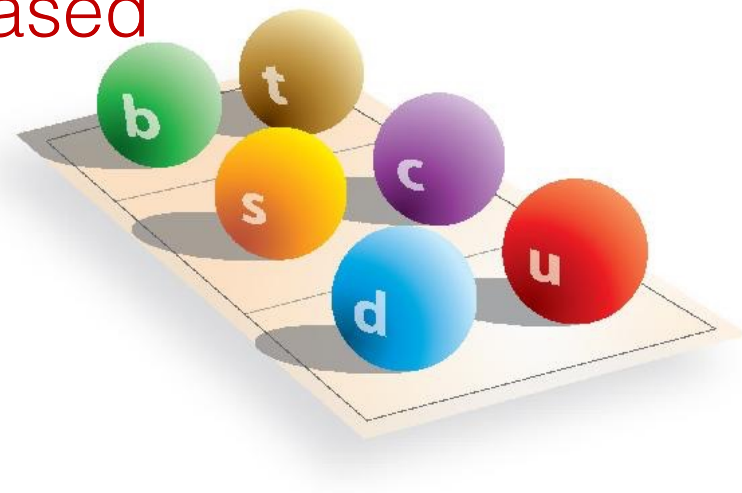
Outline

1. QCD Lagrangean, and IR divergences in e+e-.
2. pQCD at hadron colliders
3. New methods in pQCD: helicity formalism and generalized unitarity
4. The collinear limit of QCD
5. Parton distribution functions
6. Jets

QCD and e^+e^- colliders

The ingredients of QCD

QCD is a gauge invariant QFT, based on a local SU(3) symmetry group



- **Quarks** (and anti-quarks): six flavours
  - they come in 3 colours
- **Gluons**: massless gauge bosons
  - a bit like photons in QED
  - but there are 8 of them, and they are colour charged
- And the **coupling $\alpha_S(\mu)$**
  - that´s not so small and runs fast
  - at the LHC, in the range 0.08 @ 5 TeV to O(1) at 0.5 GeV

Quark Lagrangean + colour

The quark part of the Lagrangean

$$\mathcal{L}_q = \bar{\psi}_i \left(\delta_{ij}(i\not\partial - m) + g_S\, T^a_{ij}\, \not A^a\right)\psi_j$$

- where quarks carry three colours $\psi_i = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{pmatrix}$

- SU(3) local gauge symmetry: 8 (= 3^2 - 1) generators $T_{ij}{}^1 \ldots T_{ij}{}^8$ corresponding to 8 gluons $A_\mu{}^1 \ldots A_\mu{}^8$

- The fundamental representation: $\mathbf{T}^a = \frac{1}{2}\lambda^a$, Traceless and Hermitian

$$\lambda^1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda^2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda^3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda^4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

$$\lambda^5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix} \quad \lambda^6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad \lambda^7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} \quad \lambda^8 = \begin{pmatrix} \frac{1}{\sqrt{3}} & 0 & 0 \\ 0 & \frac{1}{\sqrt{3}} & 0 \\ 0 & 0 & \frac{-2}{\sqrt{3}} \end{pmatrix}$$

Gluon Lagrangean

The gluon part of the Lagrangean

$$\mathcal{L}_g = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu a}$$

where the field tensor is

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + i\, g_S \left(-i\, f_{abc}\right) A^a_\mu\, A^c_\nu$$

$$[\mathbf{T}^a, \mathbf{T}^b] = i f_{abc} \mathbf{T}^{\mathbf{c}}$$

f_{abc} are the structure constant of SU(3): antisymmetric in all indices.
Needed for gauge invariance of the Lagrangean

Gluon propagator: $\frac{1}{k^2 + i0} d^{\mu\nu}(k)$

Feynman gauge $d^{\mu\nu}(k) = -g^{\mu\nu}$ simpler but requires ghosts

Axial gauge $d^{\mu\nu}(k,n) = -g^{\mu\nu} + \frac{k^\mu n^\nu + n^\mu k^\nu}{n \cdot k}, \qquad n^2 = 0$

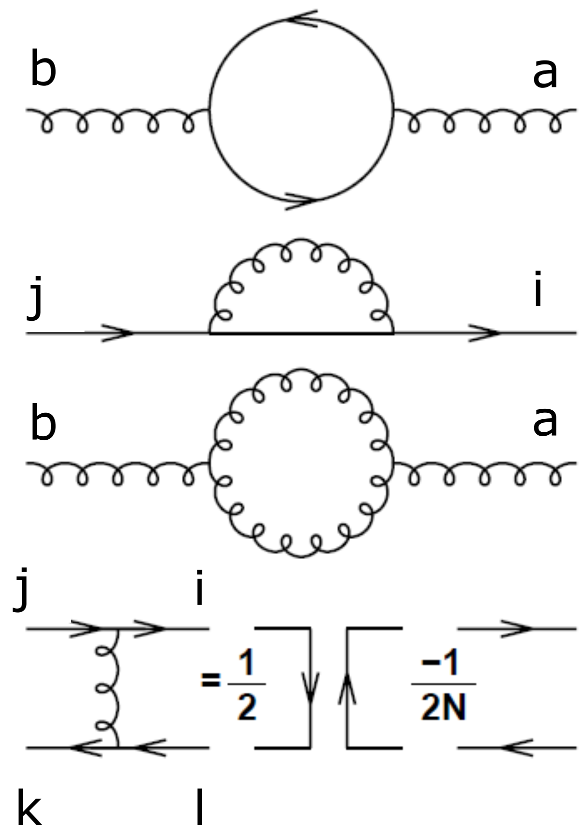
Colour algebra

$$\mathrm{Tr}(\mathbf{T}^a\mathbf{T}^b) = T_R\,\delta^{ab}\ , \qquad T_R = \frac{1}{2}$$

$$\sum_a T^a_{ik}T^a_{kj} = C_F\,\delta_{ij}\ , \qquad C_F = \frac{N_C^2-1}{2N_C} = \frac{4}{3}$$

$$\sum_{c,d} f^{acd}f^{bcd} = C_A\,\delta^{ab}\ , \qquad C_A = N_C = 3$$

$$T^a_{ij}\,T^a_{kl} = \frac{1}{2}\left(\delta_{jk}\delta_{il} - \frac{1}{N_C}\delta_{ij}\delta_{kl}\right)\ , \qquad \text{Fierz}$$




QCD and
Collider Physics
R.K. ELLIS, W.J. STIRLING
AND B.R. WEBBER
CAMBRIDGE MONOGRAPHS
ON PARTICLE PHYSICS, NUCLEAR PHYSICS
AND COSMOLOGY
8

Perturbation Theory

- Relies on the idea of order-by-order expansion in the small coupling $\alpha_S \ll 1$

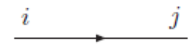
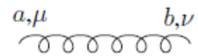
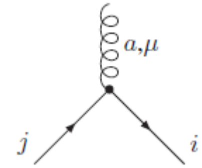
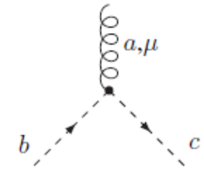
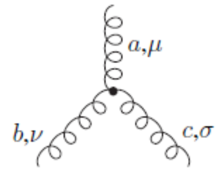
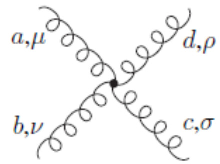
$$\alpha_S + \alpha_S^2 + \alpha_S^3 + \cdots$$

small

smaller

negligible ?

incoming quark	$u(p)$			$\overline{u}(p)$	outgoing quark
incoming antiquark	$\overline{v}(p)$			$v(p)$	outgoing antiquark
incoming gluon	$\varepsilon^a_\mu(k)$			$\varepsilon^{a*}_\mu(k)$	outgoing gluon

	$i\,\frac{1}{\not{p}-m+i0}\,\delta_{ij}$	fermion propagator, momentum q in the direction of the fermion arrow
	$i\,\frac{d_{\mu\nu}(k)}{k^2+i0}\,\delta_{ab}$	gluon propagator, momentum k
	$i\,\frac{1}{k^2+i0}\,\delta_{ab}$	ghost propagator, momentum k
	$i\,g_S\,T^a_{ij}\,\gamma_\mu$	fermionic vertex
	$ig_S\,(-i f_{abc})\,k^\mu$	ghost vertex
	$ig_S\,(-if_{abc})\,[g_{\mu\nu}(k_1-k_2)_\sigma + g_{\nu\sigma}(k_2-k_3)_\mu + g_{\sigma\mu}(k_3-k_1)_\nu]$	triple gluon vertex (outgoing momenta)
	$-i\,g_S^2\,[f_{abe}f_{cde}(g_{\mu\sigma}g_{\nu\rho}-g_{\mu\rho}g_{\nu\sigma})$ $f_{ace}f_{bde}(g_{\mu\nu}g_{\sigma\rho}-g_{\mu\rho}g_{\nu\sigma})$ $f_{ade}f_{cbe}(g_{\mu\sigma}g_{\nu\rho}-g_{\mu\nu}g_{\sigma\rho})]$	quartic gluon vertex

How big is the coupling ?

All the SM couplings (including $\overline{MS}$ mass/Yukawa) depend on the energy scale (obey Renormalization Group Equation RGE),
and the QCD coupling run fast

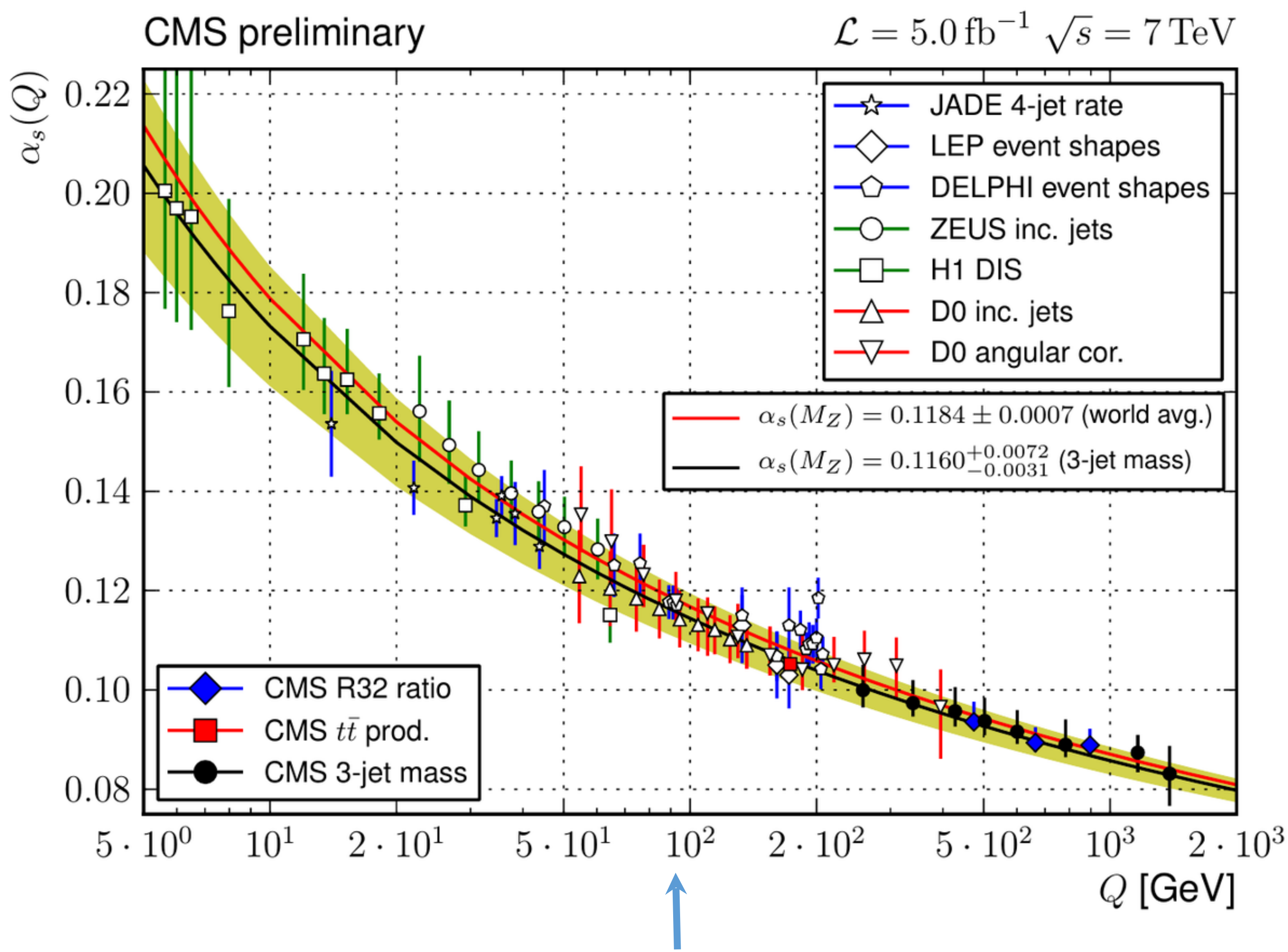
$$\frac{\partial a_S}{\partial \log \mu^2} = \beta(a_S) = -a_S^2 (b_0 + a_S\, b_1 + a_S^2\, b_2 + \ldots) \,, \qquad a_S = \frac{\alpha_S}{\pi}$$

$$\frac{\partial \log m_q}{\partial \log \mu^2} = \gamma_m(a_S) = -a_S (g_0 + a_S\, g_1 + a_S^2\, g_2 + \cdots) \,,$$

$$b_0 = \frac{1}{12}(11 C_A - 2 N_F) \,, \qquad b_1 = \frac{1}{24}\left(17 C_A^2 - (5 C_A + 3 C_F) N_F\right)$$

$$g_0 = 1 \qquad g_1 = \frac{1}{16}\left(\frac{202}{3} - \frac{20}{9} N_F\right)$$

- Sign $\beta(\alpha_S) < 0$: Asymptotic Freedom due to gluon self-interactions
  [Nobel Prize 2004, Gross, Politzer, Wilczek]
- At high scales: coupling becomes small, quarks and gluons are almost free, strong interactions are weak
- At low scales: coupling becomes large, quarks and gluons interact strongly, confined into hadrons, perturbation theory fails

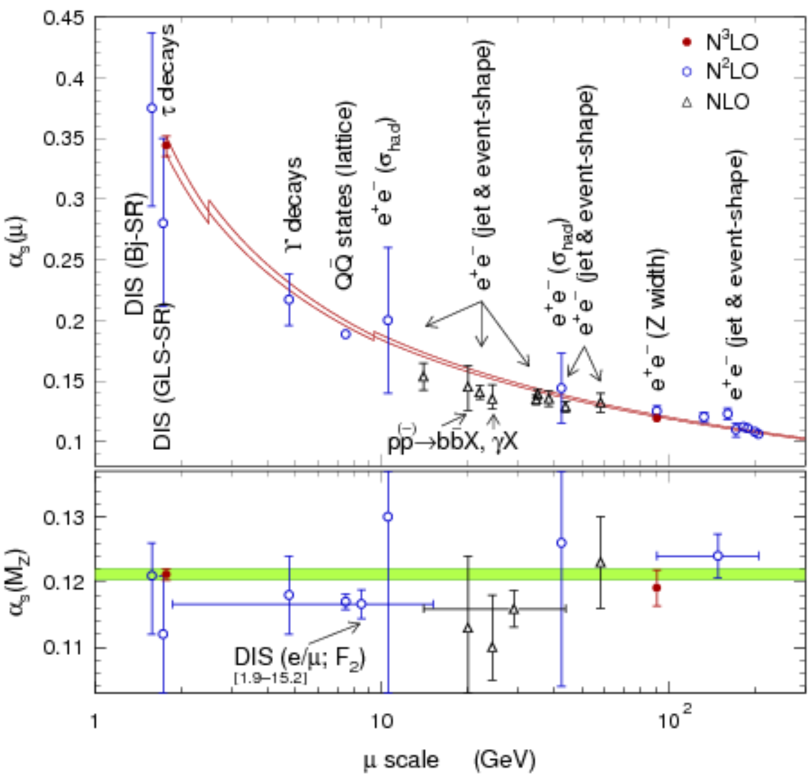

CMS preliminary
$\mathcal{L} = 5.0\,\mathrm{fb}^{-1}$ $\sqrt{s} = 7\,\mathrm{TeV}$
$\alpha_s(Q)$
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
JADE 4-jet rate
LEP event shapes
DELPHI event shapes
ZEUS inc. jets
H1 DIS
D0 inc. jets
D0 angular cor.
$\alpha_s(M_Z) = 0.1184 \pm 0.0007$ (world avg.)
$\alpha_s(M_Z) = 0.1160^{+0.0072}_{-0.0031}$ (3-jet mass)
CMS R32 ratio
CMS $t\bar{t}$ prod.
CMS 3-jet mass
$5 \cdot 10^0$
10^1
$2 \cdot 10^1$
$5 \cdot 10^1$
10^2
$2 \cdot 10^2$
$5 \cdot 10^2$
10^3
$2 \cdot 10^3$
Q [GeV]

m_Z

Flavour thresholds

$$a_S^{(N_F)}(\mu_{th}) = a_S^{(N_F-1)}(\mu_{th}) \left[1 + \sum C_k(x)\,(a_S^{(N_F-1)}(\mu_{th}))^k\right]$$

$$m_q^{(N_F)}(\mu_{th}) = m_q^{(N_F-1)}(\mu_{th}) \left[1 + \sum H_k(x)\,(a_S^{(N_F-1)}(\mu_{th}))^k\right] \ , \qquad x = \log(\mu_{th}^2/m_q^2)$$



$$C_1 = \frac{x}{6}\ , \qquad C_2 = -\frac{11}{72} + \frac{19}{24}x + \frac{x^2}{36}$$

$$H_1 = 0\ , \qquad H_2 = -\frac{89}{432} + \frac{5}{36}x - \frac{x^2}{12}$$

- The $\beta(\alpha_S)$ and $\gamma_m(\alpha_S)$ functions depend on N_F
- Interpret it in the context of Effective Theories with different number of active flavours, and match the couplings at threshold
- Matching is independent of μ_{th} (up to higher orders)

- α_S might become discontinuous, is that a problem ?
- Similar discussion for PDFs

Exercises:

1. Integrate analytically the one-loop and two-loop RGE for the strong coupling, and one-loop for a quark mass
2. Calculate $\alpha_S(10\ \mathrm{GeV})$ and $\alpha_S(1\ \mathrm{TeV})$ from $\alpha_S(m_Z) = 0.1184\ \pm 0.0007$
3. If $m_b(m_b) = 4.2 \pm 0.1\ \mathrm{GeV}$, what is $m_b(m_Z)$
4. Hint

$$a_{\rm S}(\mu) = \frac{a_{\rm S}(\mu_0)}{1 + b_0\, a_{\rm S}(\mu_0) \log \frac{\mu^2}{\mu_0^2}} \qquad \alpha_{\rm S}(\mu) = \frac{\pi}{b_0 \log \frac{\mu^2}{\Lambda^2_{\rm QCD}}}$$

Then calculate Λ_{QCD}, the "fundamental" scale of QCD, at which coupling blows up (NB: it is not unambiguously defined at higher order)

The infrared problem in gauge theories

- Soft divergences (=IR) because gluons are massless and can be emitted with zero energy (same phenomenon as in QED with soft photons)
- Collinear divergences (=mass singularities): when either gluons or massless quarks are produced with parallel momenta

  Formally could keep $m_q \neq 0$ but perturbative results will depend on large $\log(m_q)$, and are not trustworthy

Ultraviolet divergences are removed by renormalization
Soft and collinear divergences should cancel ➔ results dominated by large virtualities

Theorems about cancellation of divergences

- BN (Block-Nordsieck): QED (with finite fermion mass) IR divergences cancel is sum over soft (unobserved) photons in the **final state**
- KLN (Kinoshita, Lee, Nauenberg): IR and collinear divergences cancel if sum over degenerate **final** and **initial** states (γ^* →hadrons need only sum in final state)

Definition of infrared and collinear safety

For an observable´s distribution to be calculable in [fixed order] perturbation theory, the observable should be infrared safe, i.e. insensitive to the emission of soft or collinear gluons. In particular if $\vec{p}_i$ is any momentum occurring in its definition, it must be invariant under the branching

$$\vec{p}_i \to \vec{p}_j + \vec{p}_k$$

whenever $\vec{p}_j$ *and* $\vec{p}_k$ are parallel (collinear) or one of them is small (soft)
[Ellis, Stirling, Webber, QCD and Collider Physics]

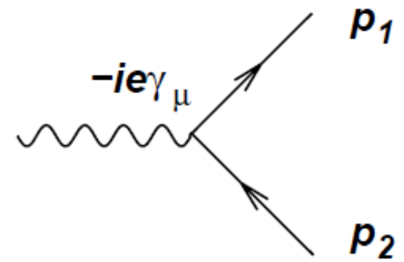
Examples

- Multiplicity of gluons — not IRC safe, modified by soft/collinear splitting
- Energy of hardest particle — not IRC safe, modified by collinear splitting
- Energy flow into a cone — is IRC safe, soft emissions don´t change energy flow and collinear emissions don´t change its direction

e^+e^-: soft-collinear gluon amplitude

- At leading-order (LO):

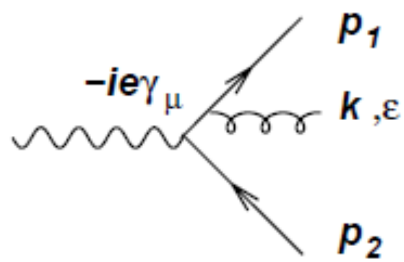
$$M_{q\bar{q}}^{(0)} = (-ie_q)\,\bar{u}(p_1)\,\gamma^\mu\,v(p_2)$$

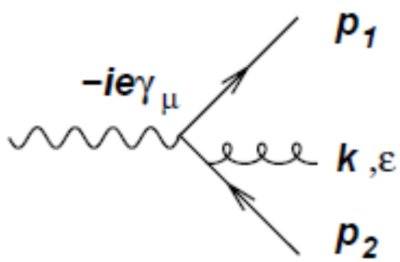


- Then emit a gluon

$$M_{q\bar{q}g}^{(0)} = (-ie_q)(i\,g_S)\,\mathbf{T}^a\,\bar{u}(p_1)\left(\not{\varepsilon}(k)\,\frac{i}{\not{p}_1+\not{k}}\,\gamma^\mu - \gamma^\mu\,\frac{i}{\not{p}_2+\not{k}}\,\not{\varepsilon}(k)\right)v(p_2)$$

Using equation of motion $\not{p}_2\,v(p_2)=0$
and $\not{p}_2\,\not{\varepsilon} = 2\varepsilon\cdot p_2 - \not{\varepsilon}\,\not{p}_2$
in the soft ($\not{k}\to 0$) and
collinear ($\not{k}\,v(p_2)\to 0$) limits





$$(\not{p}_2+\not{k})\,\not{\varepsilon}(k)\,v(p_2) \simeq 2\varepsilon\cdot p_2\,v(p_2)$$

Then

$$M_{q\bar{q}g}^{(0)} \simeq (-ie_q)\,(i\,g_S)\,\mathbf{T}^a\,\bar{u}(p_1)\,\gamma^\mu\,v(p_2)\,\left(\frac{p_1\cdot\varepsilon}{p_1\cdot k} - \frac{p_2\cdot\varepsilon}{p_2\cdot k}\right)$$

e^+e^-: square amplitude

$$|M^{(0)}_{q\bar{q}g}|^2 \simeq \sum_{a,pol} \left| i\, g_S \mathbf{T}^a M^{(0)}_{q\bar{q}} \left(\frac{p_1 \cdot \varepsilon}{p_1 \cdot k} - \frac{p_2 \cdot \varepsilon}{p_2 \cdot k} \right) \right|^2$$

$$= -|M^{(0)}_{q\bar{q}}|^2\, g_S^2\, C_F \left(\frac{p_1}{p_1 \cdot k} - \frac{p_2}{p_2 \cdot k} \right)^2 = |M^{(0)}_{q\bar{q}}|\, g_S^2\, C_F\, \frac{2 p_1 \cdot p_2}{(p_1 \cdot k)(p_2 \cdot k)}$$

Include phase space

$$d\Phi_{q\bar{q}g} |M^{(0)}_{q\bar{q}g}|^2 \simeq \left(d\Phi_{q\bar{q}} |M^{(0)}_{q\bar{q}}|^2 \right) \frac{d^3 k}{2E(2\pi)^3}\, g_S^2\, C_F\, \frac{2 p_1 \cdot p_2}{(p_1 \cdot k)(p_2 \cdot k)}$$

Note factorization into hard and soft-collinear-gluon emission

e^+e^-: square amplitude

The squared matrix element in terms of energy and angle

$$\frac{2p_1 \cdot p_2}{(p_1 \cdot k)(p_2 \cdot k)} = \frac{4}{E^2(1-\cos^2\theta)}$$

- It diverges for $E \to 0$: infrared (or soft) emission
- It diverges for $\theta \to 0$ and $\theta \to \pi$: collinear singularities

Use dimensional regularization to integrate analytically over the soft and collinear region of the phase-space

$$\frac{d^3k}{2E(2\pi)^3} \to \frac{d^{d-1}k}{2E(2\pi)^{d-1}} \qquad d = 4 - 2\epsilon$$

Leads to poles in $1/\epsilon^2$, $1/\epsilon$, and a finite remainder

Isolating the poles in ε

- Slicing method: split phase-space in two regions

$$\int_0^1 \frac{f(x)}{x} \quad \to \quad \int_0^1 x^{-1+\epsilon} f(x) \simeq f(0) \int_0^\omega x^{-1+\epsilon} + \int_w^1 \frac{f(x)}{x}$$

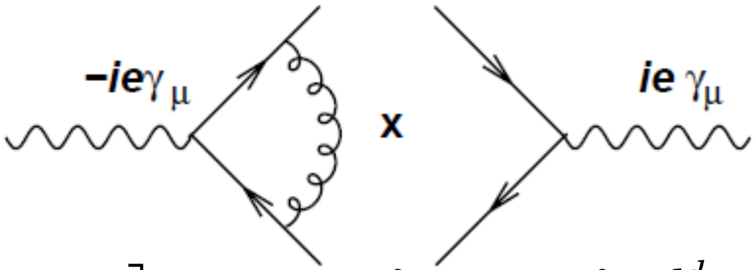
$$= \quad f(0) \left(\frac{1}{\epsilon} + \log w \right) + \int_w^1 \frac{f(x)}{x}$$

- Subtraction method: add and subtract back an approximation having the same singular behaviour

$$\int_0^1 x^{-1+\epsilon} f(x) = f(0) \int_0^1 x^{-1+\epsilon} + \int_0^1 \frac{f(x) - f(0)}{x}$$

e^+e^-: virtual amplitude

- The one-loop amplitude:



$$M^{(1)}_{q\bar{q}} = (-ie_q)\, g_S^2\, C_F\, \bar{u}(p_1)$$
$$\times \left[\int_q \frac{\gamma^\nu\,(\not{q} - \not{p}_1)\,\gamma^\mu\,(\not{q} + \not{p}_2)\,\gamma_\nu}{[(q-p_1)^2 + i0][(q+p_2)^2 + i0](q^2 + i0)} \right] v(p_2) \qquad \int_q = -i \int \frac{d^d q}{(2\pi)^d}$$

- Set the virtual gluon on-shell $\frac{1}{q^2 + i0} \to -2\pi\, i\, \theta(q_0)\, \delta(q^2) = -\tilde{\delta}(q)$

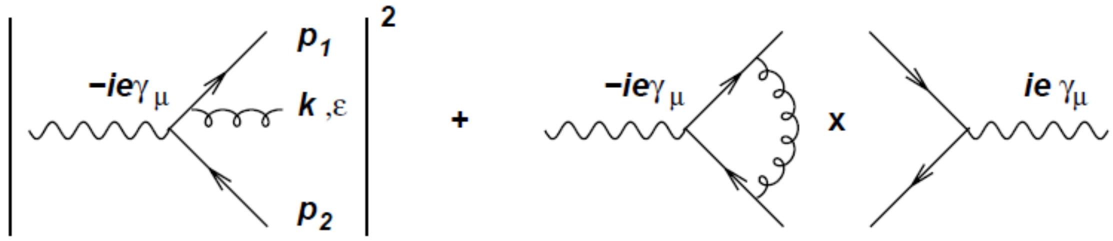
$$(\not{q} + \not{p}_2)\gamma^\nu v(p_2) = [2(q+p_2)^\nu - \gamma^\nu \not{q}]v(p_2)$$

$$M^{(1)}_{q\bar{q}} \simeq -g_S^2\, C_F\, M^{(0)}_{q\bar{q}} \int_q \frac{p_1 \cdot p_2}{(q\cdot p_1)(q \cdot p_2)}\, \tilde{\delta}(q)$$

Total cross-section must be finite: if real part has poles in $1/\epsilon$, integration of the virtual part should exhibit the same poles of opposite sign (Unitarity, conservation of probability)

e^+e^-:total cross-section

The total cross-section is the sum of all real and virtual diagrams



- Corrections to σ_{tot} come from hard ($E{\sim}Q$) large-angle gluons, and large virtualities ($q{\sim}Q$): physics at short-distance
- Soft gluons are emitted on long timescale $\sim 1/(E\,\theta^2)$ relative to the collision scale ($1/Q$) and cannot influence the cross-section
- Transition to hadrons also occurs on long time scale ($1/\Lambda_{\rm QCD}$) and then is factorized
- Correct renormalization scale for α_S is $\mu{\sim}Q$

Anatomy of a fixed order calculation

leading order (LO)

$$\sigma^{\mathrm{LO}} = \int d\Phi_n(\{p_i\}) \times |M_n^{(0)}(\{p_i\})|^2 \times F_n(\{p_i\})$$

phase-space: multidimensional integral

tree-level Feynman graphs, can be obtained by analytical/numerical methods

selection cuts + observable dependent function

computable numerically by using e.g. MC methods
practical limitation: m_{max}~ 10 at present

$$d\Phi_n(\{p_i\}) = \frac{1}{2s} \times \left(\prod \frac{1}{(2\pi)^{d-1}} \frac{d^{d-1}p_i}{2E_i} \right) \delta^{(d)}(p_1 + p_2 - \sum p_i)$$

Initial state flux

Momentum conservation

Anatomy of a fixed order calculation

leading order (LO)

$$\sigma^{\rm LO} = \int d\Phi_n(\{p_i\}) \times |M_n^{(0)}(\{p_i\})|^2 \times F_n(\{p_i\})$$

phase-space: multidimensional integral

tree-level Feynman graphs, can be obtained by analytical/numerical methods

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practical limitation: m_{max}~ 10 at present

next-to-leading order (NLO)

$$\sigma^{\rm NLO} = \int_n d\sigma^{\rm V} + \int_{n+1} d\sigma^{\rm R}$$

virtual contribution

real radiation

new feature wrt LO: combine n with n+1

A) real radiation

$$\int_{n+1} d\sigma^{\rm R} = \int d\Phi_{n+1}(\{p_i\}) \times \underbrace{|M^{(0)}_{n+1}(\{p_i\})|^2 \times F_{n+1}(\{p_i\})}$$

several well known/tested working methods (subtraction, dipole, slicing, mixed, ...)

split phase-space integrand in two parts

$(\ldots)_{\rm div} + (\ldots)_{\rm fin}$

- IR singular: analytically computable up to O(ε)
- cancels with virtual

IR finite: computable numerically as LO

B) virtual contribution

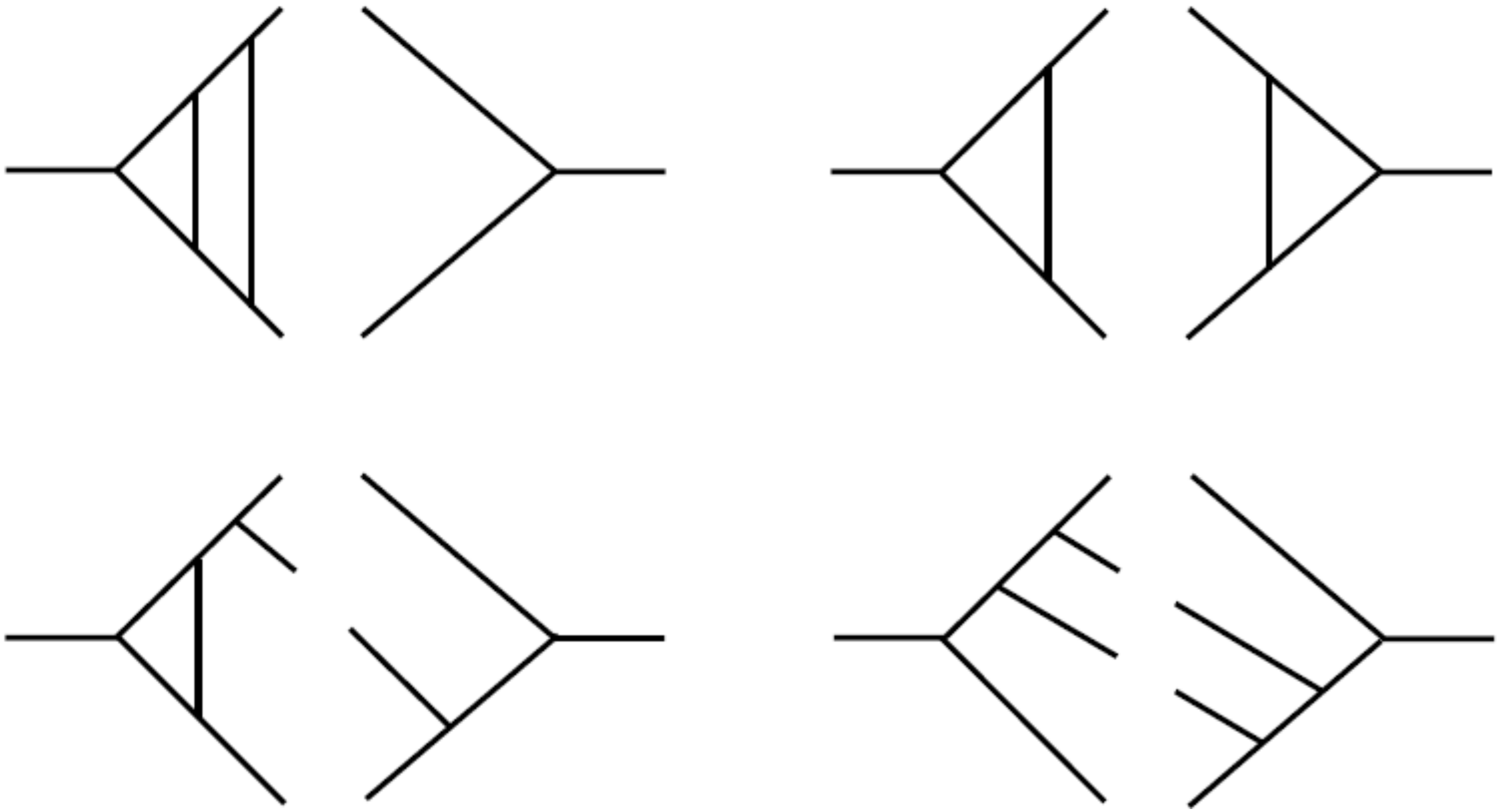
$$\int_{n} d\sigma^{\rm V} = \int d\Phi_{n}(\{p_i\}) \times 2{\rm Re}\langle M^{(0)}_{n}(\{p_i\})| \underbrace{\int d^d q \, M^{(1)}_{n}(\{q,p_i\})\rangle} \times F_{n}(\{p_i\})$$

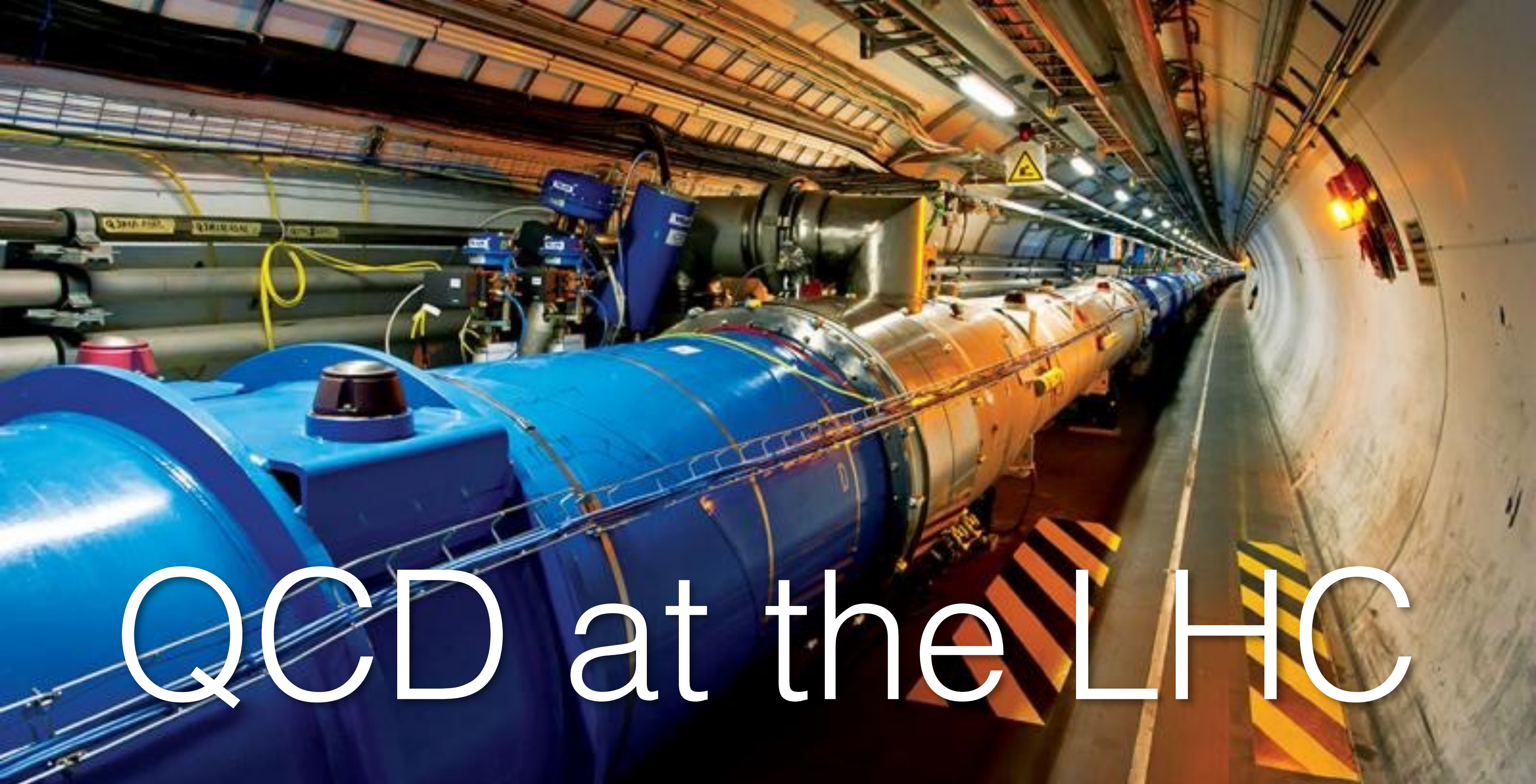
loop integral: in multiparton processes (m≥5) was regarded as main bottleneck

- hard to get in analytic form
- Feynman parametrization costs one extra Feynman parameter per extra parton
- numerical methods/reduction formalism (pentagons, hexagons → boxes) have to eliminate/control numerical instabilities (many terms, Gram determinants)
- Many new developments in recent years

NNLO ingredients

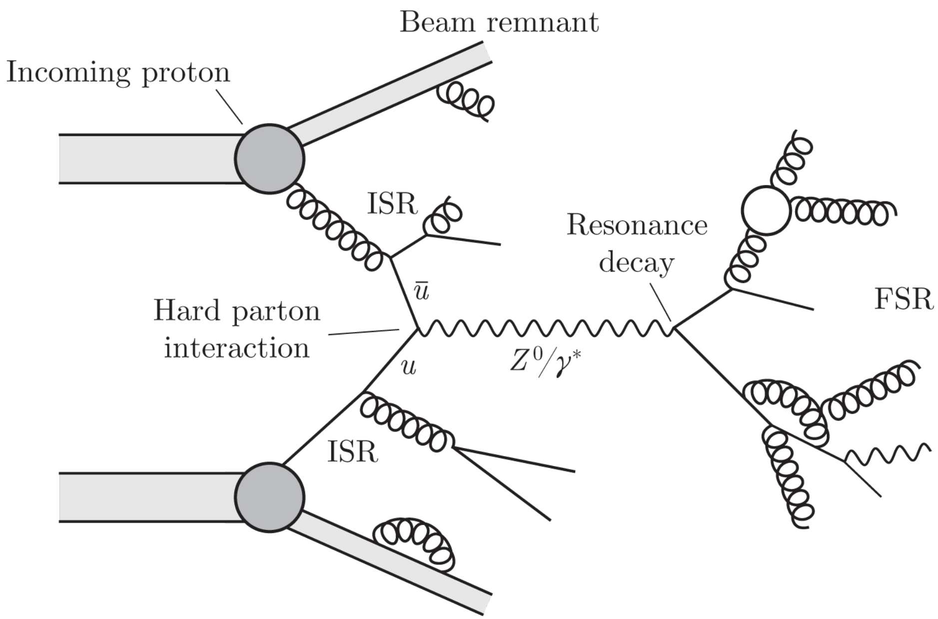
$$\sigma^{\mathrm{NNLO}} = \int_m d\sigma^{\mathrm{VV}} + \int_{m+1} d\sigma^{\mathrm{VR}} + \int_{m+2} d\sigma^{\mathrm{RR}}$$





QCD at the LHC

Factorization in hadronic collisions



- Factorize physics into long distance (hadronic ~ $M_{\rm had}$), and short distance (partonic $Q \gg M_{\rm had}$),
- factorization violation is power supressed ~ $\mathcal{O}\left(M_{\rm had}/Q\right)^q$

Parton densities PDF

Hard scattering cross-section

$$\sigma = \sum_{a,b} \int dx_1\, dx_2\, f_a(x_1, \mu_F)\, f_b(x_2, \mu_F)\, \hat{\sigma}_{ab}(x_1 p_A, x_2 p_B; \mu_F, \mu_R) + O\left(\frac{1}{Q}\right)$$

Factorization and renormalization scales

Higher twist

Partonic cms energy $\hat{s} = x_1\, x_2\, s$

Collinear factorization

theorem proven for sufficiently inclusive observables in the final state of the scattering of colorless hadrons
[Collins, Soper, Sterman]

- Offen assumed that partonic scattering amplitudes factorize: fixed order and resummations
- Monte Carlo event generators are based on factorization
- In neither of these cases factorization is guaranteed.

pQCD for hard-scattering processes based on universality:

- the sole uncancelled IR divergences are due to partonic states whose momenta are collinear to the collider partons
- removed by redefinition of bare parton densities

The LHC is a hadronic machine working at higher energies than ever before

- larger phase-space for hard radiation
- higher multiplicities (external legs)
  - more powers of α_S
  - multi-particle final states are the signal for new physics
  - multi-scale processes: logs of the ratio of very different scales
- proton is not elementary:
  - need to know PDF accurately
  - new channels open at higher orders in pQCD

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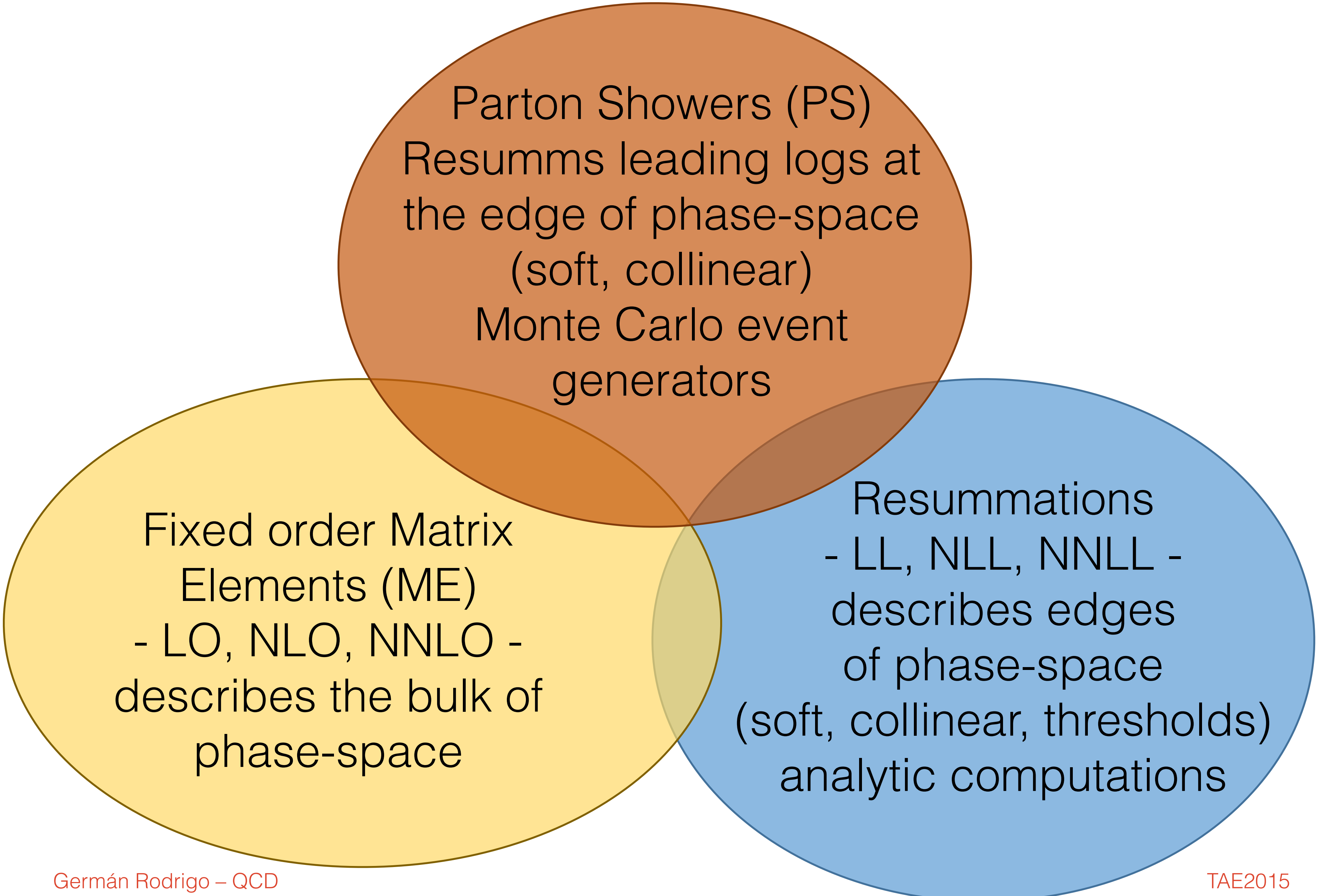
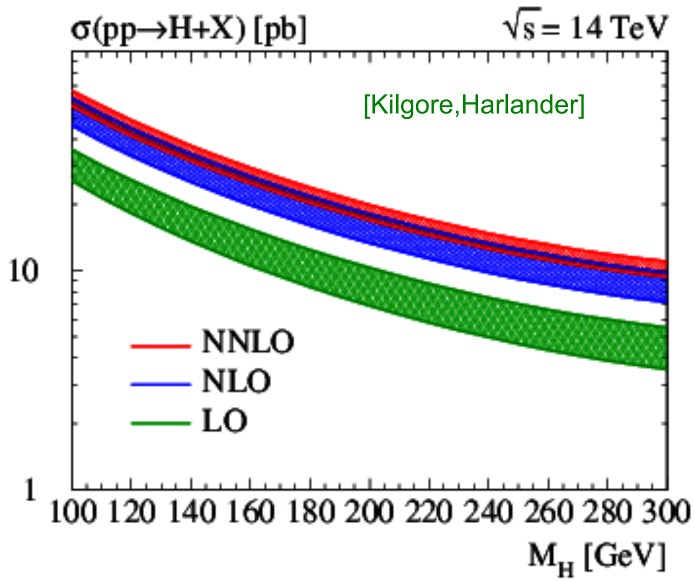
Huge radiative corrections

The absence so far of a clear signal BSM makes even more relevant the role of precision physics

The path to precision





Perturbative view: higher orders improve systematically the precision of the theoretical predictions (estimated by varying the renormalization/factorization scales) for background and signal

- LO: fails to describe normalization (up to a factor 2). Monte Carlo event generators (LO + parton showers) : improves the shape of distributions, but normalization still underestimated
- NLO: first reliable estimate of central value
- NNLO: first serious estimate of the theoretical error