IR - physics

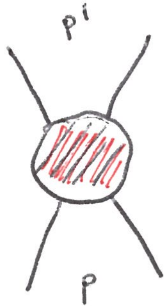
AND

CLASSICALIZATION

Brief Review of IR-physics

Elementary Well Known Facts

Loop IR-divergent corrections can be exponentiated



$$= \Gamma^0(p,p') \Big\{ 1 + $$

$$+ \cdots \Big\} \sim \Gamma^0(p,p') \left(\frac{\lambda}{\Lambda}\right)^{A(p,p')/2}$$

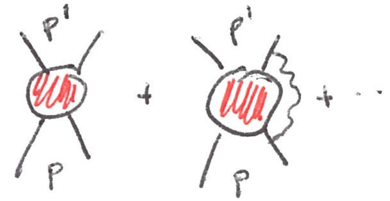
$$A(p,p') = \sum{}' \eta_n \eta_m e^2 \beta_{nm}^{-1} \ln\left(\frac{1+\beta_{nm}}{1-\beta_{nm}}\right) \qquad \beta_{nm} = \left[1 - \frac{m^4}{(p_n \cdot p_m)^2}\right]^{1/2}$$

$$\sim \frac{i}{(2\pi)^3} \int_\lambda^\Lambda \frac{d^4k}{k^2-\lambda^2} \left(\frac{2p'\cdot k}{2p'k - k^2} - \frac{2p\cdot k}{2p\cdot k - k^2}\right)^2$$

Note: Divergence of $A(p\,p')$ in the limit $m \to 0$

Due to collinear $p \cdot q = 0$ $\quad (\vec{p} \parallel \vec{q}$ if $m = 0)$

Thus generically scattering amplitudes



$+ \cdots = 0$ in the limit $\lambda = 0$

The case of gravity: graviton loop corrections lead to:

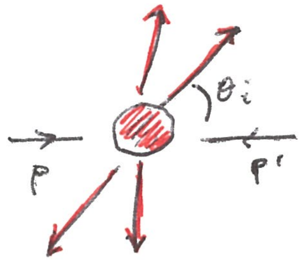
$$\Gamma_{gr}(p \to p') \approx \Gamma^{0}_{gr}(p \to p') \left(\frac{\lambda}{\Lambda}\right)^{B(p,p')}$$

$$\boxed{B(p,p') = \frac{G_N}{2\pi} \sum_{n,m} \eta_n \eta_m m_n m_m \frac{1+\beta_{nm}^2}{\beta_{nm}(1-\beta_{nm}^2)^{1/2}} \ln\left(\frac{1+\beta_{nm}}{1-\beta_{nm}}\right)}$$

Note: In the case of gravity no divergences of $B(p,p')$ in the $m=0$ limit i.e. no collinear divergences induced by

Important:

s



$$B(s,\theta_i) \simeq G_N s\, f(\theta_i) \begin{cases} 0 \\ \sim 1 \\ \ln 2 \end{cases}$$

small impact parameter.

Thus ultraplanckian scattering with small impact parameter

$$\boxed{B \sim N \qquad N \equiv G_N s}$$

Asymptotic Symmetries

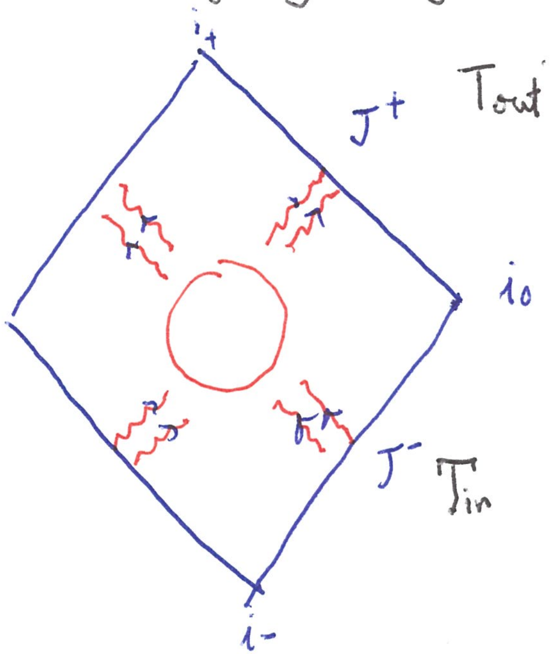
If $\quad B(p,p') = 0 \quad$ IR-finite.

What is special about these processes?

They satisfy an ∞ # of conservation Laws.

$$\sum p = \sum p' \qquad \mathcal{P}^{in}_{tot}(\theta) = \mathcal{P}^{out}_{tot}(\theta) \quad \forall\, \theta$$

In case of gravity BMS - supertranslations



$$B(p,p') = 0 \iff T_{in} = T_{out}.$$

The set of processes satisfying
$B(p,p') = 0$
is of zero measure.

Standard Approach to IR-Divergences KLN-Theorem.

$A(p \to p')$ $\Rightarrow$ inclusive cross section $\displaystyle\sum_{\gamma} |A(p,p';\gamma)|^2 = \sigma(\varepsilon)$

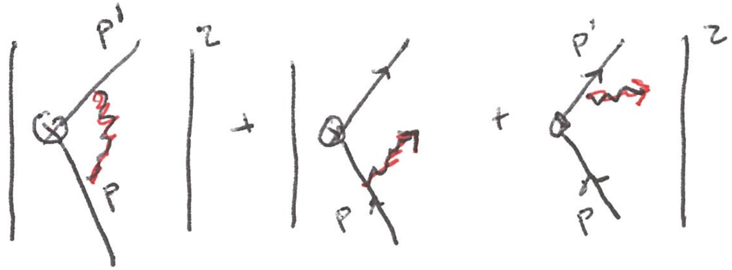
Soft radiation with total energy ε

$$\sigma(\varepsilon) \sim \left|\Gamma^{0}_{pp'}\right|^2 \left(\frac{\lambda}{\Lambda}\right)^{B} \left(\frac{\varepsilon}{\lambda}\right)^{\tilde{B}} f(B) \qquad B = \tilde{B}$$

real

virtual

Energy conservation.

$\sigma \sim$ 

- You need non zero radiated energy ε
- You need inclusive integration i.e unresolved soft radiation

Formal Approach

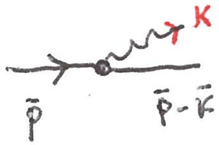
KLN - theorem

$$S_{\alpha\to\beta} \longrightarrow \text{IR-finite} \quad \boxed{\sum_{\substack{\alpha'\in\mathcal{D}(\alpha)\\ \beta'\in\mathcal{D}(\beta)}} |S_{\alpha'\beta'}|^2}$$

$\mathcal{D}(\alpha)$ ~ states degenerate with respect to α.

(e), $(e, \gamma_{\omega=0})$, $(e, \gamma_{\omega=0}\, \gamma_{\omega=0} \cdots)$ zero energy photon.

For massless fermions we find extra degeneration. LN



if $\bar{p} \parallel \bar{k}$ collinear radiation.

$T_\varepsilon : e \to (e, \gamma_\varepsilon)$ "zero energy" polarization ε

$$\sum_{\varepsilon,\varepsilon'} \left|\langle\alpha| T^+_\varepsilon S\, T_{\varepsilon'} |\beta\rangle\right|^2 =$$

$$= \sum \left|\langle\alpha| S' T_{\varepsilon,\varepsilon'} |\beta\rangle\right|^2 \qquad \text{(BN)}$$

if $[T_\varepsilon\, S'] = 0$

Decoupling of soft modes

Note that strict degeneration does not account for ε.

The KLN - Theorem:

$$\sum_{\substack{\alpha' \in \mathcal{D}(\alpha) \\ \beta' \in \mathcal{D}(\beta)}} |S_{\alpha'\beta'}|^2 \sim \underset{\substack{\downarrow \\ \infty}}{N_{deg}} \cdot \underset{\substack{\downarrow \\ 0}}{|S_{\alpha\beta}|^2} \sim \sigma(\underset{\substack{\uparrow \\ \text{undefined} \\ \text{BUT non zero!}}}{\overset{\substack{\text{unresolved energy.} \\ \downarrow}}{\varepsilon}})$$

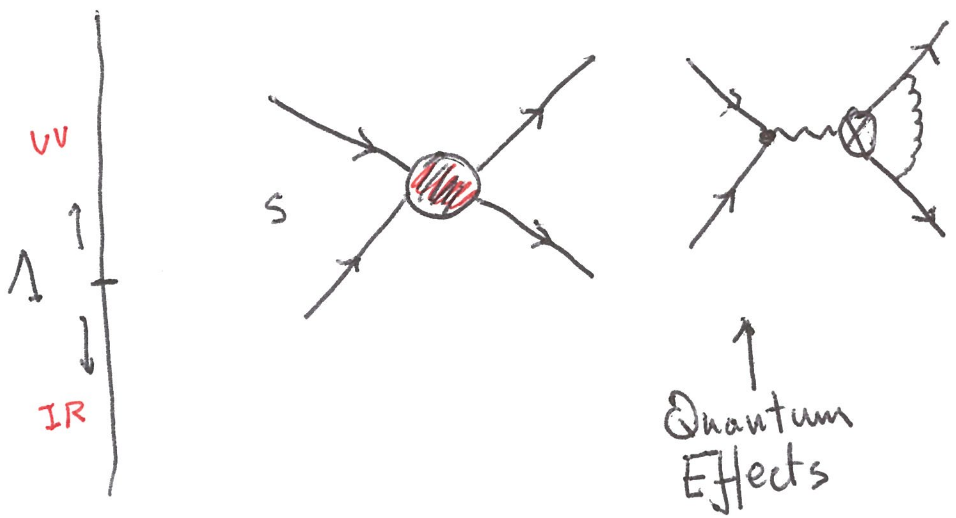
Key Questions:

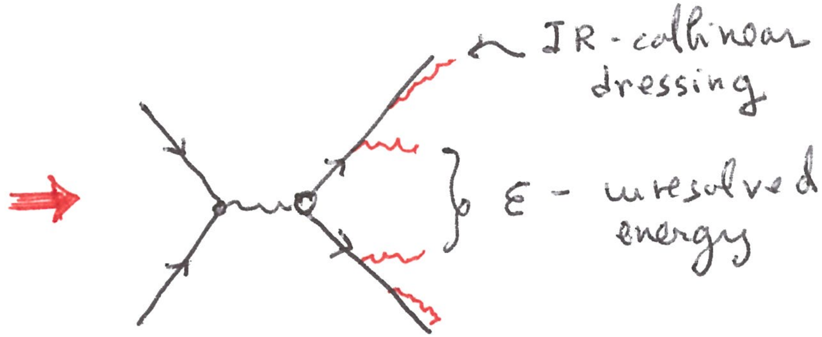
- What physics fixes the value of ε?
- Why the limit $\varepsilon = 0$ (i.e resolving IR-degeneracy) leads to vanishing amplitudes?

related with a very popular problem:

$$\boxed{\underset{\substack{\uparrow \\ \text{observable}}}{\exists} \text{ classical "Soft" hair} \Longleftrightarrow \text{resolving IR-degeneracy}}$$

The underlying Physics.

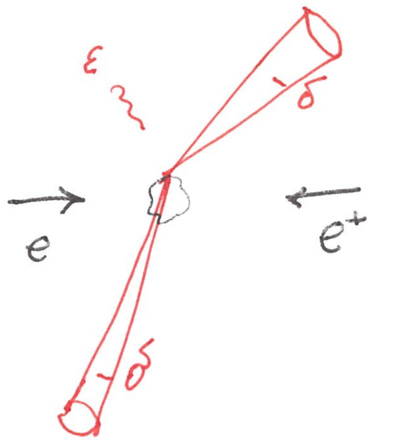




Q.1) How much energy ε?

Q.2) Typical # of constituents of unresolved energy?

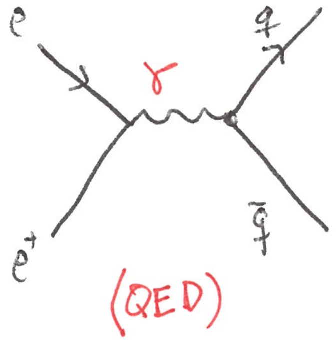
A nice example: Jets in QCD

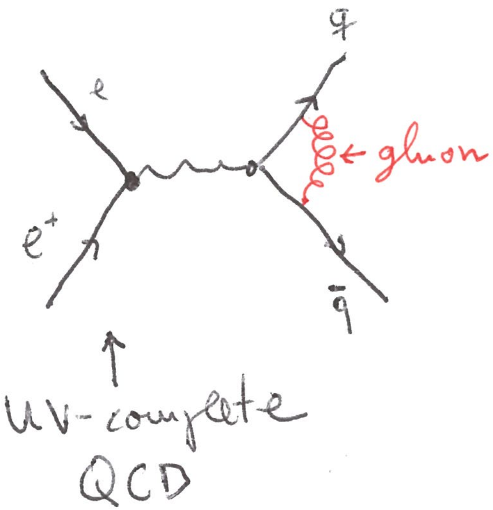


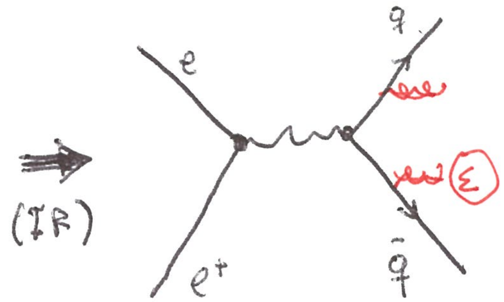
$\sigma(\text{2-jets}, \delta, \varepsilon)$

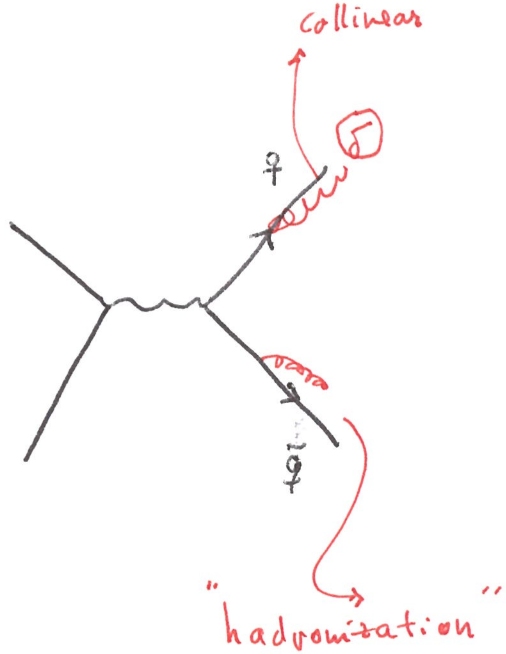
small unresolved energy.

Start with



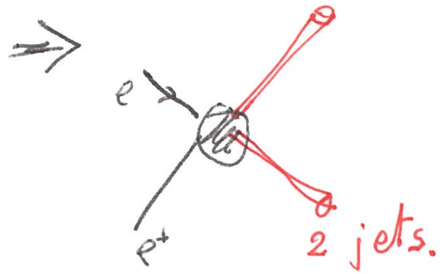




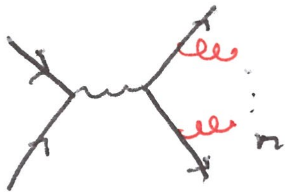


So what we observe 2-jets (80%) ⇒

ε should be small.



Here A.F is important.

Amplitude  $\sim \frac{1}{n!}[B]^n F(B)$; $B = \alpha(s) f(s,t)$

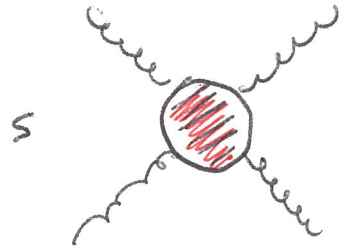
$\searrow$ UV-effects running c.c

typical # $n \sim B$ small at h. energies (A.F)

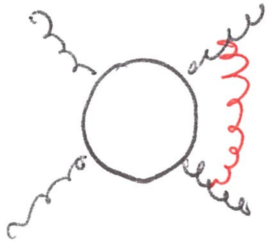
$$E \lesssim n \Lambda_{IR}$$

QCD UV-completion consistent with two jet dominance.

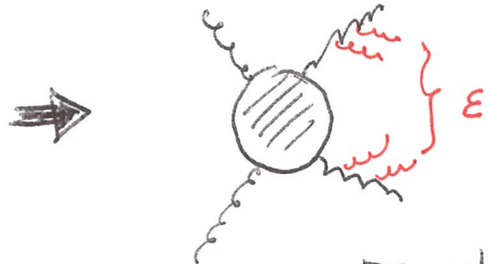
What happens with H.E Two graviton scattering?



graviton scattering
unit- problems



Q Gravity
Effects



no collinear effects.
(due to the nature of grav. radiation)

We need : $\left\{ \begin{array}{l} \text{IR - Scale} \\ n \end{array} \right.$

$$\text{Amplitude}_{IR} \sim \frac{1}{n!}[B]^n \qquad B \sim G_N\, s\, \underbrace{f(\text{Kinematics})}_{O(1)}$$

Small impact parameter

$$\Lambda \sim \frac{\hbar}{r_g(s)} \sim T_H$$

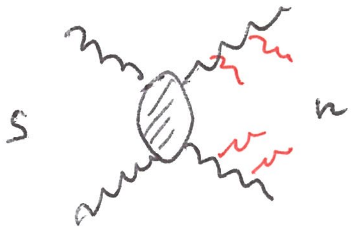
For large energies and small impact parameter

$$B \sim G_N\, s \qquad \text{i.e. } n \sim N_{BH}$$

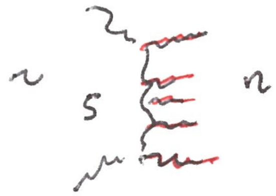
unresolved Energy:

$$\varepsilon \gtrsim B.\Lambda \sim N_{BH}\, T_H$$

Classicalization Regime



(IR-amplitude)



perturbative
$2 \to n$
(amplitude)

$\frac{1}{n!}\,[B]^n$

$\downarrow$

$B \sim n$

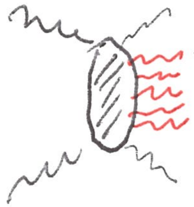
$n!\,(\alpha_{eff})^n$

$\downarrow$

$\alpha_{eff} \sim \frac{1}{n}$

Note that this is NOT the case in AF. theories where α_{eff} only depends on energy through RG.

Parton Picture: BH-portrait.

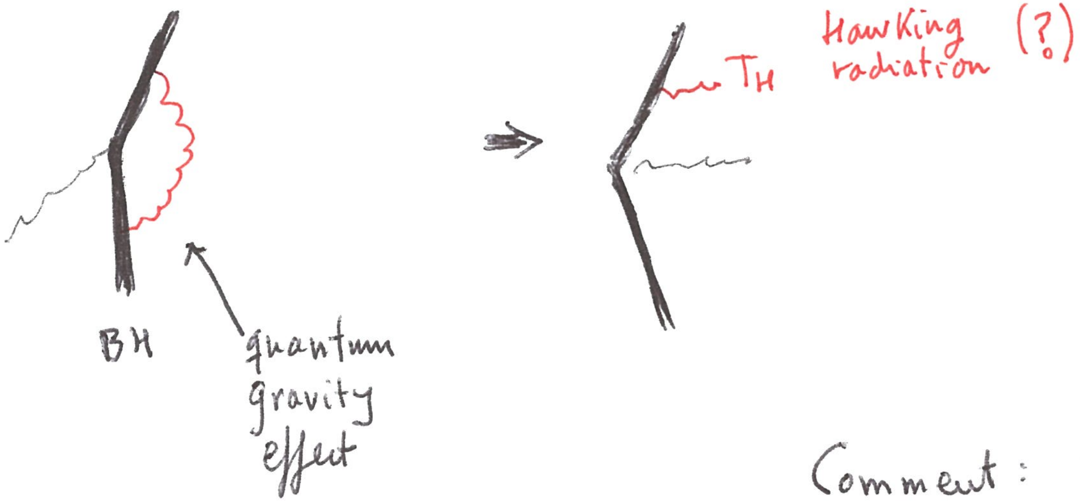


$\Big\}$ unresolved Energy
$n = G_N s$ - constituents

("unresolved" $\Longleftrightarrow$ hidden inside horizon)

Large fraction of unresolved energy $\Longleftrightarrow$ $\exists$ of horizon.

An IR-view of Hawking Radiation.



Note for extremal

$= 0$ no radiation.

Comment: For Large BH's (AdS)

natural IR-cutoff $\frac{1}{L}$ ← curvature radius.

i.e (no radiation) (?)

Final Comments

(1) Can we use IR - physics to create Quantum Decoherence ?

Simple Argument :

$$S|\alpha\rangle = \sum_{\beta}{}' C_{\alpha\beta} |\beta\rangle \otimes |\gamma_\beta\rangle$$

$$E_\beta + E_\gamma = E_\alpha$$

decoherence requires:
(after tracing radiation)

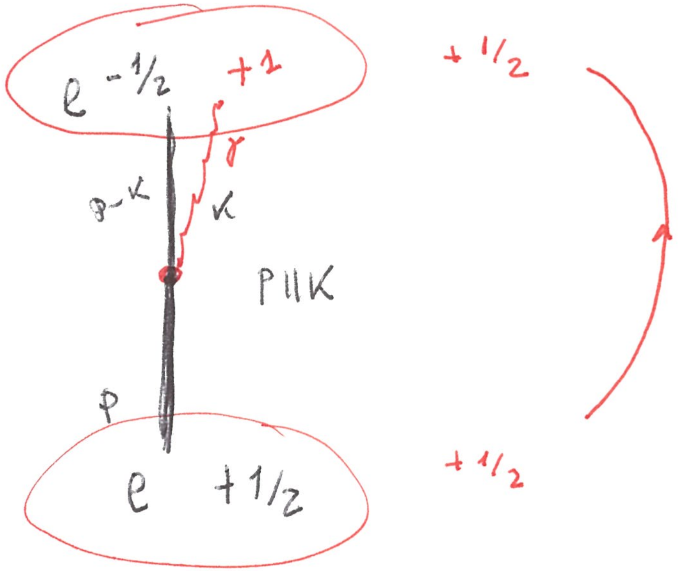
$$\langle \gamma_\beta | \gamma_{\beta'} \rangle = \delta_{\beta\beta'}$$

Only possible if collinear radiation

i.e. $m \to 0$ limit.

② Existence of Observable SOFT Hair ?

A toy model example



IR degeneration

BUT (you can say)

Different helicity for the electron

(superrotation charges)

HPS

Observability = resolving IR degeneration

$\Downarrow$

IR-catastrophe ....