Last Lecture:

31.07.20

Indirect detection searches like

observation of dwarf galaxies $\frac{1}{A}\frac{dN}{dE\,dt} \sim \frac{1}{4\pi}\left(\frac{dN}{dE}\right)\frac{\langle \sigma v\rangle}{2m_{DM}^2}\int dr\, d\Omega\, \rho(\vec{r})^2$ (signals in telescopes)

and

measurement of the CMB $\frac{dE}{dt\,dV} \propto (1+z)^6 f_{eff}\frac{\langle\sigma v\rangle}{m_{DM}}\rho_{DM}^2$ (energy injection into CMB)

with $f_{eff} \sim \frac{1}{2m_{DM}}\int_0^{m_{DM}} E\,dE\left[2 f_{eff}^{e^+}(E)\left(\frac{dN}{dE}\right)_{e^+} + f_{eff}^{\gamma}(E)\left(\frac{dN}{dE}\right)_{\gamma}\right]$

⇒ strong constraints could be set for one class of models:

a velocity-independent annihilation process that fully determines the relic abundance ⇒ ruled out below ~10–100 GeV

↳ weaker constraints for other scenarios like

- velocity-suppressed cross-sections (at least some processes)
- thermal WIMP is subcomponent of total DM
- ...

⇒ explore GeV/sub-GeV region (where constraints are most stringent)

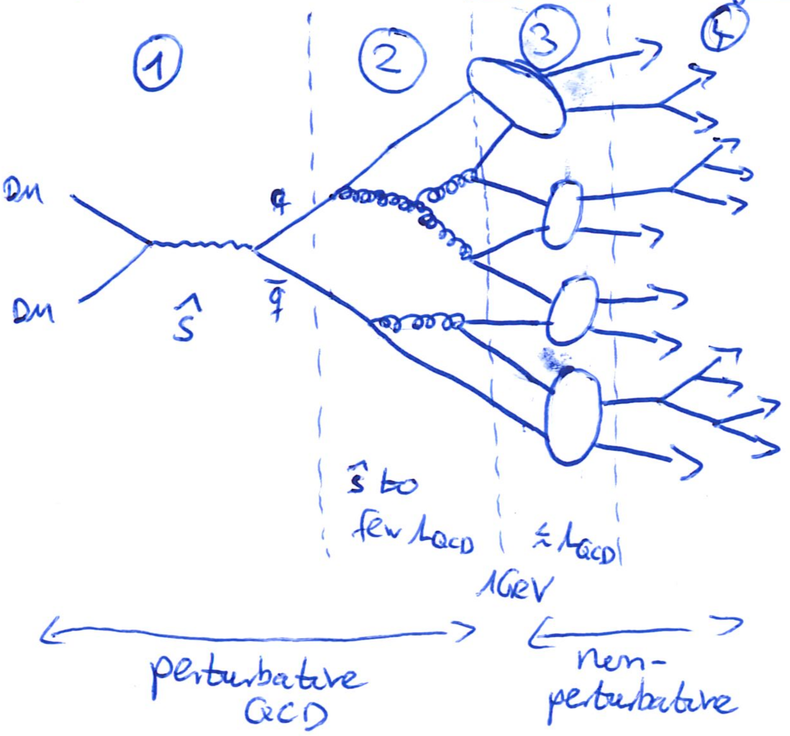
experimentally: INTEGRAL telescope (keV–MeV), eASTROGAM (300keV–3GeV) (no data yet)

theoretically: calculable for leptonic final states but almost unknown for hadronic final states

↳ no energy spectra available (yet) ⇒ why?

⇒ take a look at how energy spectra are usually calculated

Spectra based on Monte-Carlo-Generator simulations (→ Pythia)



(1) Calculation of Hard Process

(2) Parton Shower

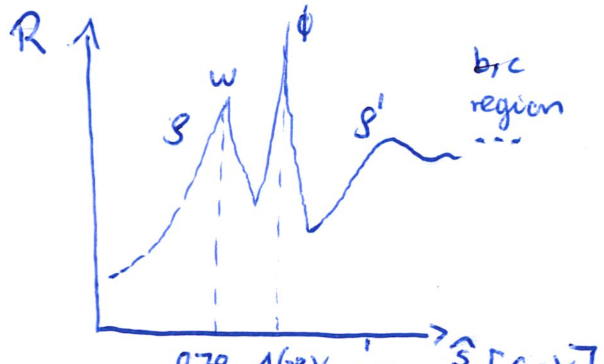
(3) Hadronization

(4) Decay to stable particles

$e^\pm, \bar{p}/p, \nu's, \gamma$

<u>Problem:</u> below ~5GeV no intermediate step of parton shower and transition from perturbative matrix element and parton level to non-perturbative hadron level → direct production of hadrons?

+ below ~few GeV: hadronic resonance region (known from e^+e^--annihilations)



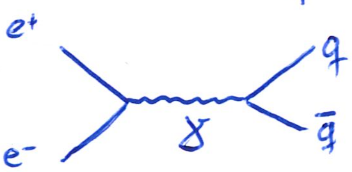
$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

⇒ indicates that processes are like

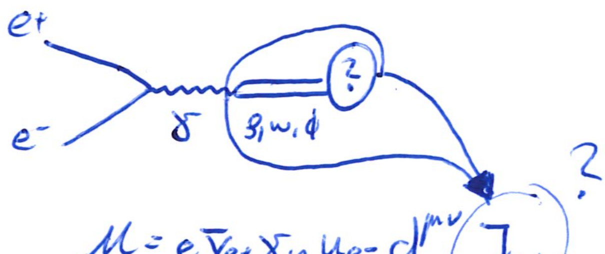
$e^+e^- \to \gamma \to \rho, \omega, \phi \to$ hadrons

with intermediate vector meson

So we instead of (consider $e^+e^- \to$ hadrons for now)



⟹



$$\mathcal{M} = e\, \bar{v}_{e^+} \gamma_\mu u_{e^-} d^{\mu\nu} e_q \bar{q} \gamma_\nu q$$

propagator $d^{\mu\nu} = \frac{g^{\mu\nu}}{\hat{s}}$

$$\mathcal{M} = e\, \bar{v}_{e^+} \gamma_\mu u_{e^-} d^{\mu\nu} J_\nu$$

→ translated to DM particles; DM mediator

$$J_\nu = \langle \text{had} | J_{em,\nu} | 0 \rangle$$

$$J_{em,\nu} = \sum_{q=u,d,s} a_q \bar{q} \gamma_\nu q \quad , a_u = \frac{2}{3} \, , a_{d,s} = -\frac{1}{3}$$

How do we relate e.m. current to resonances?

Consider isospin doublets $\Psi_q = \begin{pmatrix} u \\ d \end{pmatrix}$ & $\bar{\Psi}_q = (\bar{u}, \bar{d})$

Form isospin I=1 current

$$J^{I=1,\mu} = \sqrt{2}\, \bar{\Psi}_q \gamma^\mu \frac{\sigma^a}{2} \Psi_q = \frac{1}{\sqrt{2}} \begin{pmatrix} i\frac{1}{2}(\bar{u}\gamma^\mu d + \bar{d}\gamma^\mu u) \\ i\bar{u}\gamma^\mu d - \bar{d}\gamma^\mu u \\ i\frac{1}{2}(\bar{u}\gamma^\mu u - \bar{d}\gamma^\mu d) \end{pmatrix}$$

} charged currents used for τ decay $J^\pm$

⇒ neutral

and isospin singlet

$$J^{I=0,\mu} = \frac{1}{\sqrt{2}} (\bar{u}\gamma^\mu u + \bar{d}\gamma^\mu d)$$

⇒ re-express J^μ_{em}: $J^\mu_{em} = \frac{2}{3}\bar{u}\gamma^\mu u - \frac{1}{3}\bar{d}\gamma^\mu d - \frac{1}{3}\bar{s}\gamma^\mu s$

$$= \frac{1}{\sqrt{2}} \left(J^{I=1,3,\mu} + \frac{1}{3} J^{I=0,\mu} \right) - \frac{1}{3}\bar{s}\gamma^\mu s$$

and in general:

$$\boxed{J^\mu_{em} = \frac{1}{\sqrt{2}} \left((a_u - a_d) J^{I=1,3,\mu} + (a_u + a_d) J^{I=0,\mu} \right) + a_s J^{s,\mu}}$$

Now we associate: $I=1$: ρ

$I=0$: ω

and $\phi \to J^{s,\mu}$

How do we know about the final states?

⇒ G parity: multiplicative quantum number combining ~~generalization of~~ C-parity and isospin symmetry

e.g. all pions have same G-parity $G=-1$

for mesons $G = (-1)^{S+I}$

example: 2 Pions $\pi^+\pi^-$ ⇒ $(-1)(-1) = +1$ ⇒ for vector mesons $G = (-1)^{1+I} \stackrel{!}{=} +1$

⇒ $I=1$

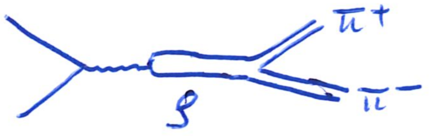
⇒ ρ meson as intermediate resonance

3 Pions $\pi^+\pi^-\pi^0$ ⇒ -1 ⇒ $I=0$

⇒ dominated by ω, ϕ

So we have for example:

$e^+e^- \to \pi^+\pi^-$:



since π's pseudoscalar particles

$$J^\mu = \langle \pi^+\pi^- | J^\mu_{em} | 0 \rangle = g\,(p^+ - p^-)^\mu\, F_\pi(q^2)$$

with $F_\pi \propto \dfrac{m_\rho^2}{m_\rho^2 - \hat{s} - i m_\rho \Gamma_\rho}$

or $e^+e^- \to \pi^+\pi^-\pi^0$

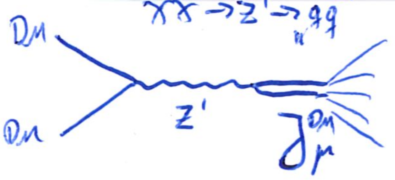
$$J^\mu = \langle \pi^+\pi^-\pi^0 | J^\mu_{em} | 0 \rangle = g\, \varepsilon^\mu_{\alpha\beta\gamma}\, q_+^\alpha q_-^\beta q_0^\gamma\, F_{3\pi}(q_+, q_-, q_0)$$

in total 15 processes : $\pi\gamma$, 2-5 π's, KK, $KK\pi$, $\eta\phi$, $p\bar{p}/n\bar{n}$, ...

↳ parametrizations from literature and own

↳ fit to e^+e^- data to fix parameter of currents $J^{I=1,3\mu}$, $J^{I=0,\mu}$, $J^{s,\mu}$

↳ translate to DM process:



$$\mathcal{M} = a_{DM}\, \bar{v}(p_1)\gamma^\nu u(p_2)\, d^{DM}_{\nu\mu} \langle \text{had} | J^\mu_{DM} | 0 \rangle$$

with $J^\mu_{DM} = \frac{1}{\sqrt{2}}\left((a_u - a_d) J^{I=1,3,\mu} + (a_u + a_d) J^{I=0,\mu} \right) + a_s J^{s,\mu}$

Examples: B-L models : $q_i = \frac{1}{3}$ ⇒ no I=1 current ⇒ no $\pi^+\pi^-$, ... channel

meson decay as already implemented in Herwig

$\pi^0 \to \gamma\gamma$

$\pi^\pm \to \mu^\pm \overset{(-)}{\nu}_\mu \to (e^\pm \overset{(-)}{\nu}_e \overset{(-)}{\nu}_\mu) \overset{(-)}{\nu}_\mu$

...

Conclusion:

- implemented in Herwig → available soon
- tables provided for DM tools → DarkSUSY
- suggested for Indirect Detection
  - → Integral telescope 2007.11493
  - → DM bound states: dark photon emission after bound state formation or transition 2007.13787

Outlook: ⇒ finally work with spectra to fill „MeV gap" with robust constraints on annihilation channels and possible signatures for indirect det. experiments