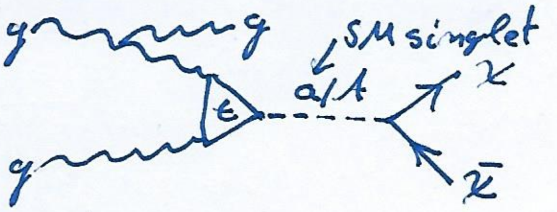
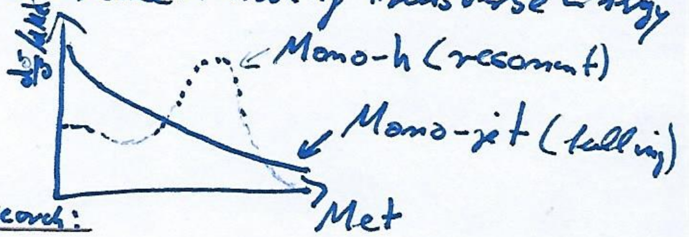
Lecture 3: From a Mono-jet Dark Matter Search to a Γ_Z(inv) measurement

Reminder: introduced renormalizable & gauge invariant Pseudoscalar Mediator to the dark sector (2HDM+a):



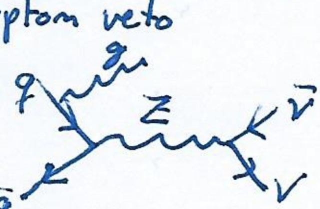
observable: Missing Transverse Energy



Can search for this signature with generic Mono-jet search:

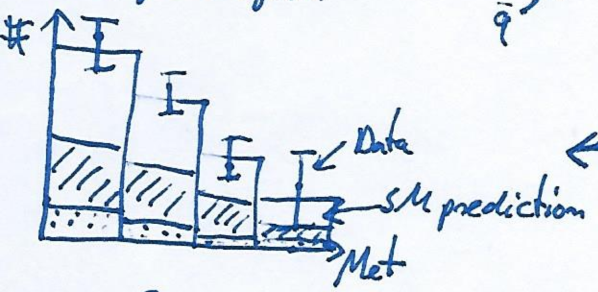
Main selection cuts:
- Met > 200 GeV
- at least 1 jet with $p_T > 120$ GeV
- lepton veto

Irreducible background:

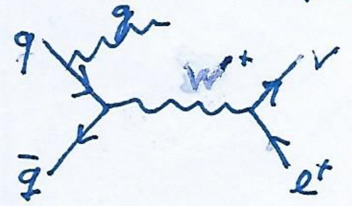


→ effectively measurement of $Z \to \nu\bar{\nu}$ + jets

Signal region



~50% $\nu\bar{\nu}$
~20% $\tau\nu$
~10% $\mu\nu$
~10% $e\nu$
~10% tops

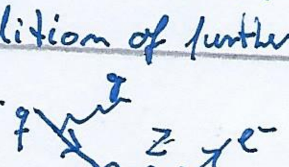


lepton could be lost due to:
- out-of-acceptance (tracker covers only $|\eta| < 2.4$)
- out-of-efficiency (reconstruction algorithm failed identification)

Monte-Carlo simulations provide shapes of those backgrounds but due to missing higher orders normalization to data often off
→ construct control regions to minimize normalization uncertainty
(data-driven background estimates)

Addition of further CR allows for reduction of systematic uncertainties:

e.g.



rather similar to $Z \to \nu\nu$ + jets, change observable to $p_T(Z \to \ell\ell)$ + Met
lepton veto → lepton pair, opposite charge, close to m_Z

can measure the ratio:

$$R_{miss} = \frac{\sigma(\text{Met} + \text{jets})}{\sigma(Z \to \ell\ell^- + \text{jets})}$$

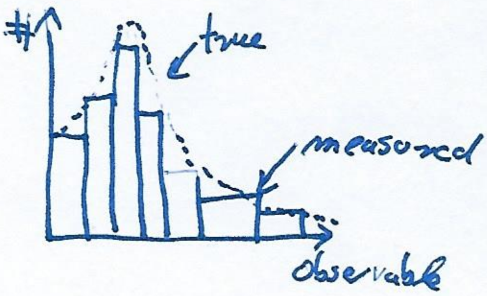
some systematics will cancel (e.g. jet systematics) → 5 Main control regions:

	Pros	Cons
Zee / Zμμ	Pure	low stats in tail
Weν / Wμν	high stats	top & W→τν backgrounds
γ	pure & high stats	larger extrapolation due to different kinematics

Unfolding:

The measured spectra (SR & CR) are affected by 3 effects:

- statistical fluctuations $\updownarrow$
- backgrounds (will neglect as we subtracted them)
- detector effects:
  - acceptance & efficency $\downarrow$
  - resolution (bin migrations) $\leftrightarrow$
  - non-linear detector response $\swarrow$



Standard approach to search for new physics:

apply detector simulation to theory to transfer observables from particle (truth) level to detector (reconstruction) level:

$$\boxed{\text{DM theory @ truth}} \xrightarrow{\text{Full detector simulation}} \boxed{\text{DM theory @ reco}}$$

Problems:
- only a limited number of models can be tested at time of the analysis
- later reinterpretation is difficult as full simulation only available within experiment & parametric simulations (e.g. Delphes) introduce larger uncertainties

Solution: compare data & DM theory at particle level:

$$\boxed{\text{data @ detector}} \xrightarrow{\text{Full detector sim.}} \boxed{\text{data @ particle}} \quad \text{Unfolding}$$

general mathematical formulation:

Given observation $g(y)$ and kernel $h(x,y)$ solve for $f(x)$ in $\int h(x,y)\, f(x)\, dx = g(y)$

with finite binning: $g_i = \sum_j A_{ij} f_j$ with $A_{ij} \in \mathbb{R}^{n \times m}$

bin-by-bin unfolding:

- Resolution effects can be neglected
- efficiency factor can be determined by MC
- reco & truth have same binning ($n=m$)

$\Rightarrow A_{ij} \rightarrow \mathrm{diag}(\varepsilon_i)$

$$f_i = \frac{g_i}{\varepsilon_i}$$

for sizable migrations matrix inversion will lead to statistical fluctuations

$\rightarrow$ regularization required or circumvent by using probabilistic approach (Baysen)

Now ready to derive CLs limits on DM models s.a. 2HDM+a at particle level by using background subtracted unfolded Met spectra of SR & 5 CRs via combined fit

$\rightarrow$ If no hints for DM found $\rightarrow$ can reinterpreted $R_{miss} \times \Gamma_Z(ll) = \Gamma_Z(inv)$:

$$R_{miss} = \frac{\frac{d\sigma(Z+\text{jets})\, Br(Z\to\nu\nu)}{dP_T^Z}}{\frac{d\sigma(Z+\text{jets})\, Br(Z\to ll)}{dP_T^Z}} = \frac{\Gamma_Z(inv)}{\Gamma_Z(ll)} = \frac{\frac{e^2}{12\pi} N_\nu M_Z \left[g_{V,\nu}^2 + g_{A,\nu}^2\right] + \mathcal{O}\left(\frac{m_\nu^2}{M_Z^2}\right)}{\frac{e^2}{12\pi} M_Z \left[g_{V,e}^2 + g_{A,e}^2\right] + \mathcal{O}\left(\frac{m_e^2}{M_Z^2}\right)} \simeq \frac{\frac{1}{2} T_{3,\nu}^2 N_\nu}{\frac{1}{2} T_{3,l}^2 - T_{3,l} Q_l s_{\theta_W}^2 + Q_l^2 s_{\theta_W}^4}$$

$$\simeq 5.942$$

$\Gamma_Z(\text{inv})$ measurements @ LEP

Indirect: $\Gamma_Z(\text{inv}) = \Gamma_Z - \Gamma_{ee} - \Gamma_{\mu\mu} - \Gamma_{\tau\tau} - \Gamma_{had}$

$$R^0_{inv} = \left(\frac{12\pi\, R^0_\ell}{\sigma^0_{had}\, m_Z^2}\right)^{1/2} - R^0_\ell - (3 + \delta_\tau) = N_\nu \left(\frac{\Gamma_{\nu\nu}}{\Gamma_{\ell\ell}}\right)_{SM} = 5{,}943 \pm 0.016$$

mass correction (δ_τ)

with $\sigma^0_{had} \equiv \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{had}}{\Gamma_Z^2}$; $R_\ell \equiv \frac{\Gamma_{had}}{\Gamma_{\ell\ell}}$

$\Rightarrow \Gamma_Z(\text{inv}) = 499.0 \pm 1.5\ \text{MeV}$

$N_\nu = 2.9840 \pm 0.0082$ corresponding $\sim 2\sigma$ deviation (2006)

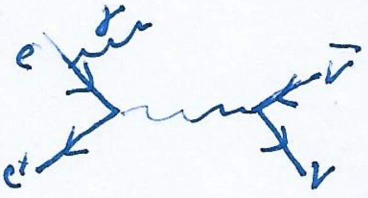
largest uncertainty on N_ν from luminosity as $\sigma^0_{had} = N_{had}/L$

with $L = N_{bahbar}/\sigma_{bahbar}$; L was underestimated (Moriond 21')

N_{bahbar}: beam effects; σ_{bahbar}: theory corrections

Direct: $\Gamma_Z(\text{inv}) = 498 \pm 12\,(\text{stat}) \pm 12\,(\text{syst})\ \text{MeV}$

$N_\nu = 2.98 \pm 0.07\,(\text{stat}) \pm 0.07\,(\text{syst})$ (L3 @ LEP)



via crosssection measurements at 7 $\sqrt{s}$ (1991–1994)

$$\sigma_0(s) = \frac{12\pi}{m_Z^2}\,\frac{s\,\Gamma_{ee}\Gamma_{inv}}{(s-m_Z^2)^2 + s^2\Gamma_Z^2/m_Z^2}$$

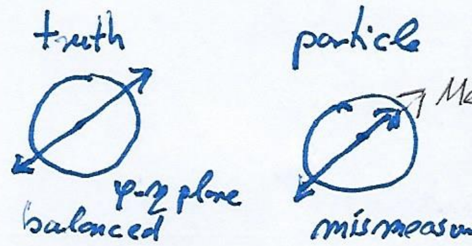
$\Gamma_Z(\text{inv})$ measurement via R_{miss} at ATLAS

Aim: $\Delta\Gamma_Z(\text{inv}) \sim 3\text{–}5\%$

Challenges:
- R_{miss} should be a flat function of p_T^Z → $Z \to \ell\ell$ + jets needs to be corrected for acceptance & efficiency and hence unfolded to full phase space
- increasing stats compared to DM search → lower Met cut
  → increasing "multi-jet" background compared to DM search

Multijet-background estimation:

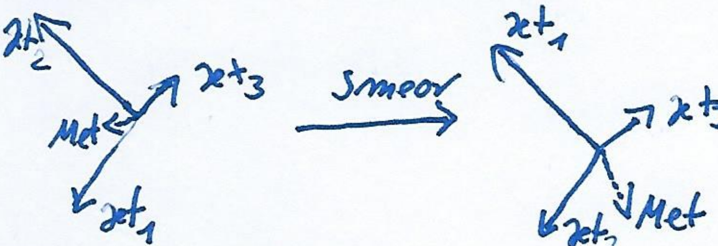
- mismeasurement of jet energies rare but di-jet crosssection extremely large
- effect too rare to be well modelled in MC
- data-driven approach:
  - Met points along 1 of the two jets
  - apply $\Delta\varphi(\text{Met}, \text{jet}_{1\ldots4}) < 0.4$ cut to suppress bkg in SR
  - invert $\Delta\varphi$ cut to construct enriched CR → shape of bkg.



- $N^{SR}_{multij,i} = \underbrace{\frac{N^{SR}_{smear}}{N^{CR}_{smear}}}_{\text{transfer factor}} \times N^{CR}_{multij,i}$

deriving transfer factor from pseudodataset:

- selection of clean di-jet sample $\left(\frac{p_T^{miss} - 8\,GeV}{\sqrt{\sum E_T^{miss}}} < 0.05\,\sqrt{GeV}\right)$
- smearing of those jets with response function derived from MC



(subleading jet becomes leading)

- apply SR & CR cuts to pseudodataset & calculate transfer factor

Additional problem arises at Met $\lesssim$ 200 GeV:

Jet-vertex-tagging inefficiencies:

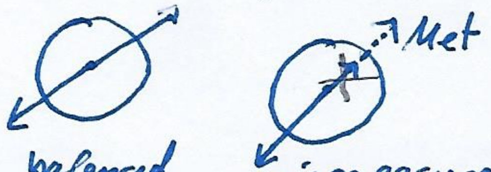
JVT used for removing jets which are not from actual event but from underlying one (pile-up)

Due to inefficiency Hard Scattered jets with $p_T < 60$ GeV can be falsely removed

$\Delta\varphi$-cut won't prevent those events to enter SR

Can adjust $\Delta\varphi$ cut:

$\Delta\varphi(Met, jet_{removed}) < 0.4$



Next step: Need to check that this reduces multijet-background significantly at low Met as the estimate comes with large uncertainties